

An Outline of the Seismic Behavior of Historical Structures in North Western Anatolia

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ABSTRACT: An extensive and interdisciplinary study is necessary to preserve the historical structures, as well restoring and strengthening them. Investigations concerning historical seismicity and its affects on structures provide useful information to evaluate the earthquake hazards of areas searched, the seismic performance and the structural deficiencies of these buildings. Our intentions in this paper are twofold: first, to present some examples of historical earthquakes and of historical structures affected by these earthquakes using contemporary sources; and secondly, to evaluate the seismic behavior of these structures according to information obtained.

1 INTRODUCTION

Historical structures should be preserved due to their cultural significance. The wish to protect them for the future requires evaluating the present situation of them. One of the necessary steps for structural evaluation of the existing historical structures is to investigate their responses against the historical seismic activity.

While damages after historical earthquakes may be a good indication to define the seismic vulnerability of the structural system, historical structures which have not been damaged by the past seismic actions can be evaluated in order to better comprehend the properties of an adequate structural system and compare with other structures. Moreover, the location and the type of these damages are important information sources to understand the structural deficiencies and possible causes of these damages.

Historical earthquakes and historical structures taken as cases of this study are chosen from the Marmara region in north-western Anatolia since this area has been exposed to numerous destructive earthquakes during the history. The earthquakes of 1509, 1754, 1766 and 1894 and the historical structures of Hagia Sophia Museum, Chora Museum and Fatih Mosque are selected as cases of the study. The common property of these earthquakes is that they occurred in the western part of the North Anatolian Fault and these structures are located on the Historical Peninsula of Istanbul, (Fig. 1). While the characteristics of these earthquakes and buildings are compiled from various contemporary sources, an attempt is made to explain the correlation between case earthquakes, case structures and experienced structural damages of these structures.

2 CASE HISTORICAL EARTHQUAKES

Out of several earthquakes struck in the last five centuries, the major earthquakes of 1509, 1754, 1766 and 1894 significantly left their traces on the walls of several structures and in the memories of the Ottoman society. In order to give a rather detailed definition some main characteris-

tics of these earthquakes are given in Table 1. Locations of the case earthquakes and the places cited in this paper are shown in Fig. 1 (Satellite views by Google Earth software).

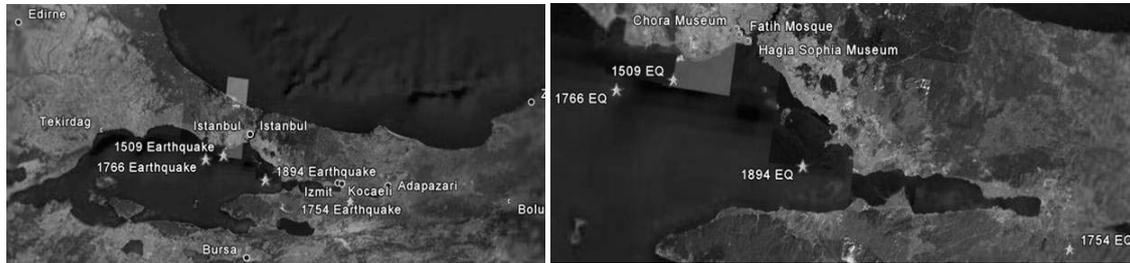


Figure 1 : Case earthquakes and structures, epicenters are from Ambraseys and Finkel (1991).

Table 1 : Case Earthquakes

| Earthquake | Epicentre* | Magnitude* | Intensity I** | Regions Affected**** | Casualties/Total Population***** |
|------------|---------------|------------|------------------|-------------------------|-------------------------------------|
| 10.10.1509 | 40.9°N-28.7°E | 7.2 | IX | Bolu-Edirne | 5000 / >160000 |
| 02.10.1754 | 40.8°N-29.2°E | 6.8 | IX | Izmit-Istanbul-Bursa | 800 / ? |
| 22.05.1766 | 40.8°N-29.0°E | 7.1 | IX | Izmit-Tekirdag | 5000 / 500000 |
| 10.07.1894 | 40.8°N-29.0°E | 7.3 | X*** | Istanbul-Adapazari | 280 / ? |

*: Ambraseys (2002) and Erdik et al. (2004), **: Ozmen (1999), ***: Ozmen (1999) stated that the value of intensity was controversy, ****: Ambraseys and Finkel (1995), Genc and Mazak (2001) and Sakin (2002), *****: Ambraseys (2001), Ambraseys and Finkel (1995) and Mazlum (2001)

2.1 The earthquake of 10 September 1509

The earthquake took place without a foreshock on the night of 10 September 1509 in the Marmara Sea, Turkey. Aftershocks of the earthquake lasted intermittently for over a month in Istanbul and its surroundings (Ambraseys and Finkel 1990, Ambraseys and Finkel 1995 and Pamukciyan 1994).

The earthquake was one of the largest and most destructive earthquakes of the last five centuries in the Eastern Mediterranean region. It was stated in the studies of Rockwell et al. (2001) that although affected by many historical earthquakes over the past millennia, Istanbul has not been strongly devastated since the great shock of 1509. Damage in Istanbul was very significant, particularly in the west provinces of the city, (Sakin 2002).

Both the land walls and the sea walls of Istanbul were affected seriously. This earthquake caused varying damage levels from slight to severe to mosques, churches, palaces, hans, free-standing columns, aqueducts, caravanserais, baths and courtyards.

2.2 The earthquake of 2 September 1754

A destructive earthquake, preceded by a period of foreshocks, occurred in the Gulf of Izmit on the night of 2 September 1754.

The studies of Ambraseys and Finkel 1995 and Genc and Mazak 2001) gave the following information. The effects of the earthquake in Istanbul and Izmit were considerable. Walls, towers, mosques, hans, baths, palaces of Istanbul were damaged. Damage to the land walls and their towers was in different levels; some of them were partly fell down, and others were nearly ruined. Domes and/or minarets of some mosques were either cracked or destroyed. Some examples of the effects are: Severe damage to the Kucuk Ayasofya Mosque, collapse of the Vezir Hani, damages dealt to two pavilions in Topkapi Palace Complex.

There is little information concerning the effects of the shock in Karadeniz Ereglisi, Iznik and Bursa. Regarding the damage in these places Ambraseys and Finkel (1995) and Genc and Mazak (2001) stated that a lighthouse was demolished in Karadeniz Ereglisi and a few houses were collapsed in Iznik and Bursa.

2.3 The earthquake of 22 May 1766

A great earthquake with an epicentre in the east of the Marmara Sea occurred half an hour after sunrise on 22 May 1766. Sakin (2002) suggests that this earthquake resembled the earthquake of 1509 due to both its damaging and general characteristics. The duration of main shock was about 2 minutes, (Ambraseys and Finkel 1995 and Genc and Mazak 2001). Aftershocks of the earthquake continued intermittently for about eight months, (Pamukciyan 1994). The earthquake affected an extensive area of Istanbul, from Galata and Pera to Uskudar.

Some buildings like walls, mosques, churches, hans in Istanbul were damaged in different levels. The list of these buildings are available in studies of Ambraseys and Finkel (1995), Genc and Mazak (2001), Mazlum (2001, 2003), Pamukciyan (1994) and Sakin (2002). A great portion of land walls of the city were shattered. Domes and minarets of the Ali Atik Pasa Mosque fell down. Although there were a number of churches ruined, the details on this subject are lacking. The Vezir Hani was almost completely overturned.

2.4 The earthquake of 10 July 1894

A damaging earthquake occurring on 10 July 1894 was felt at 12:21 pm in Istanbul (Ambraseys 2001). The duration of the main shock including three consecutive shocks was 12 to 18 seconds according to Ambraseys (2001), Genc and Mazak (2001) and Sakin (2002).

Damage to Istanbul was widespread, but its level was not severe. Buildings like mosques, churches, hans, public buildings, dwellings exposed to damage in varying levels. Many minarets collapsed (Ambraseys 2001). The names of these buildings were given by Pamukciyan (1994), Ambraseys (2001), Genc and Mazak (2001) and Sakin (2002). Some examples of these buildings are the mosque of Mihrimah Sultan at Edirnekapi, the Catholic Church at Yesilkoy, Covered Bazaar at Eminonu. While Ambraseys (2001) defined the damage to the mosque of Mihrimah Sultan as slightly damaged, Genc and Mazak (2001) and Pamukciyan (1994) stated that the damage was severe. Sakin (2002) stated that the minaret of the mosque of Mihrimah Sultan collapsed. The Catholic Church at Yesilkoy was demolished, (Pamukciyan 1994, Ambraseys 2001, Genc and Mazak 2001 and Sakin 2002). The earthquake induced severe damage to several shops in Covered Bazaar (Kapali Carsi), Fig. 2.



Figure 2 : Covered Bazaar after 1894 earthquake (Genc and Mazak 2001).

3 CASE STRUCTURES

Three historical structures, namely Hagia Sophia Museum, Chora Museum and Fatih Mosque, are selected as the cases of the study. All of these religious structures were built in the vicinity of Historical Peninsula of Istanbul. These structures are located on the border of the first and second seismic zones, representing the highest and the second highest risk of seismic activity in Turkey, respectively, according to Seismic Zoning Map of Turkey. The foundations of Hagia Sophia are on a soil profile including a thin top soil, fill and bedrock. The soil of Chora Museum consists of sand-gravel banded clay marls. Fatih Mosque was erected on the soil that is over consolidated green stiff Istanbul clay.

3.1 Hagia Sophia

The monument was constructed as a church between 532 and 537 AD. The building had served as the biggest church of the Byzantine Empire until the conquest of Constantinople in 1453. During the Ottoman period the building was used as a grand mosque. Today Hagia Sophia is serving as a museum.

The structure is a centrally-planned domed basilica. Its structural system consists of main dome, semi-domes, vaults, arches, pendentives, buttresses, and four massive piers that bear the main dome, Fig 3. Hagia Sophia has a rectangular plan with dimensions of about 70 m x 92 m externally, including the two nartexes and excluding the atrium in the west direction (Freely and Cakmak 2004). The central nave is a square bay of 31 m, and four piers bearing dome have a height of 23 m (Kleinbauer et al. 2004). There are four thick arches bound by pendentives, spanning between these piers, Figs. 3 and 4. The height of dome from the ground is 55 m (Eyice 1994a). Since the dome is not completely a hemisphere the diameter of the dome changes between 31.2 m and 32.8 m, (Eyice 1994a).

The materials used in the construction are stone for the piers, brick and mortar for the dome and the walls and marble for the columns. Iron was used for different aims such as the cramps between adjacent blocks of stone in the cornices and for long tie bars spanning across the springings of arches and vaults. Lead sheets were used to protect the outer surfaces of the vaults and dome.

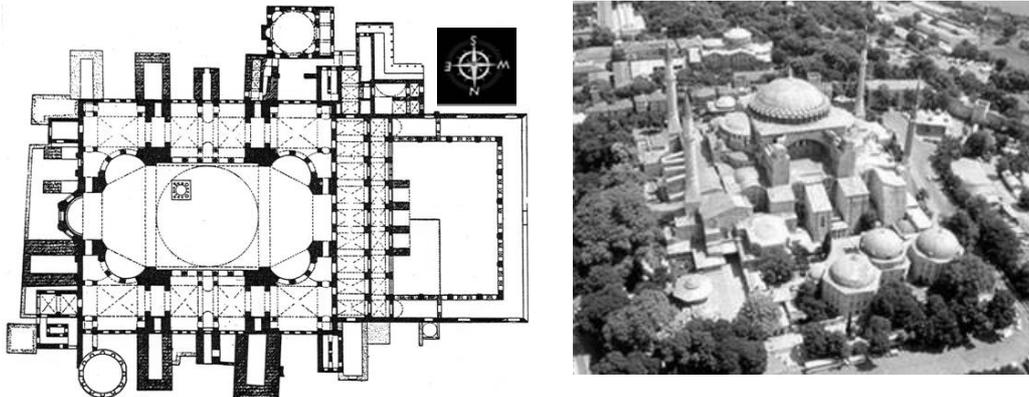


Figure 3 : Plan and aerial view of Hagia Sophia (Eyice 1994a) (aerial photo by Oguz Celik) .

The monument has undergone failures, reconstructions, enlargements, restorations, and transformations over years. According to Eyice (1994a) and Kleinbauer et al. (2004) several parts of the church and the main dome were ruined by devastating earthquakes. Required repairing was carried out after each of these earthquakes. Besides these reconstructions, massive exterior buttresses were built to support the north and east sides of the building in 1317. The four flying buttresses leaning against the upper narthex wall might have been constructed either after 869 or 989 (Kleinbauer et al. 2004). During the Ottoman period four minarets were added at the corners of the building.

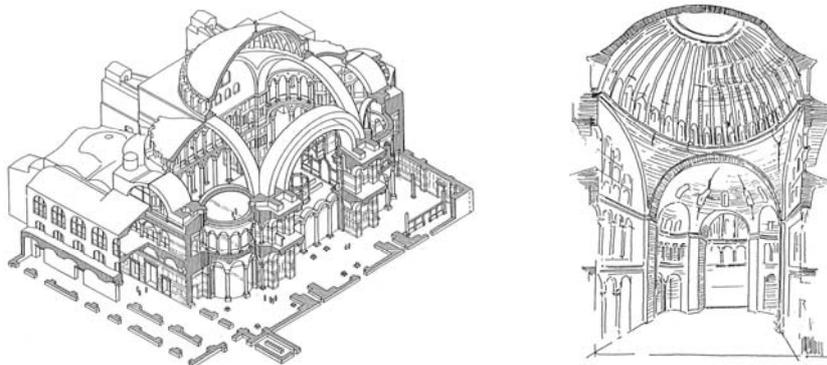


Figure 4 : The view of Hagia Sophia (Eyice 1994a) and the crack pattern sketched after the 1894 earthquake (Batur and Tanyeli 1993).

Information, regarding the damages caused by the earthquakes of 1509, 1754, 1766 and 1894 are tabulated in Table 2. A drawing that described the damage situation of Hagia Sophia after the earthquake is presented in Fig. 4, (Batur and Tanyeli 1993).

3.2 Chora Museum

Chora Museum was originally built as a church to be a part of Chora Monastery. Though date of the construction of the structure is not clear, the Monastery was mentioned in history for the first time in the 8th and 9th centuries, (Gulersoy 1976). In the 14th century due to an unknown reason, the Monastery and its church was repaired, extended and the interior of the church was adorned with mosaics and frescos (Eyice 1994b, Ogan and Mirmiroglu 1955). The church was converted to a mosque in 1511, (Ogan and Mirmiroglu 1955). While the building was servicing as a mosque, a minaret was erected. The Chora Mosque was converted to a museum after 1948 (Eyice 1994b).

The studies of Gulersoy (1976) and Ogan and Mirmiroglu (1955) include information regarding its geometrical properties as follows, Fig.5. The main building was located on an area of 27.5 m x 27 m. While parecclesion is 29 m long, the outer narthex is 23.3 m long. The width of the outer and inner narthexes is 4 m each. The central dome over the Nave has a diameter of 7.7 m. The second largest dome with the diameter of 4.5 m covers the parecclesion. The inner narthex is covered by two domes and the other domes are over the north and south of the apse.

During the past centuries, Chora Museum faced several earthquakes. Unfortunately it is a challenging task to identify the level of damages occurred in those earthquakes. Damages, which could be identified in the literature, induced by the case earthquakes are summarized in Table 2.

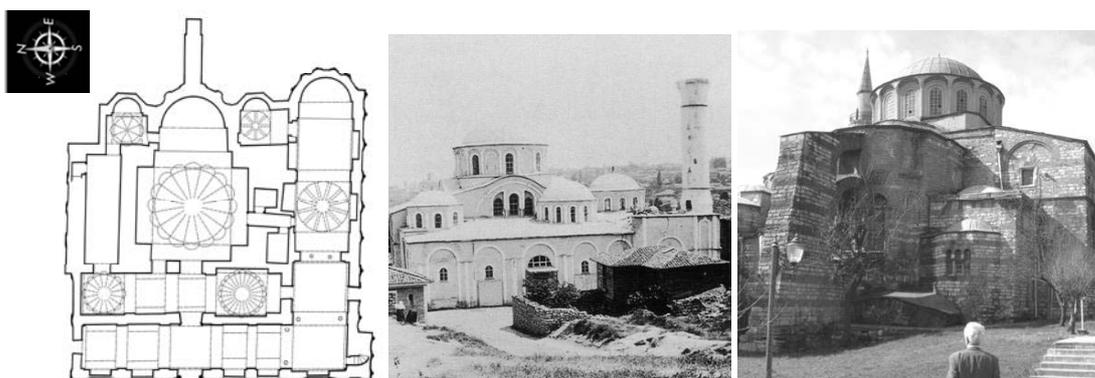


Figure 5 : The plan (Underwood 1966), post 1894 earthquake (Genc and Mazak 2001) and present day views of Chora Museum.

3.3 Fatih Mosque

Being among the first imperial structures constructed after the conquest of Istanbul, the mosque was built as a part of a large complex which included a mosque, two mausolea (turbe), sixteen medreses, a hospital (darussifa), a hospice (tabhane), a kitchen (imaret), a caravanserai (kervansaray), a library, a Koranic school (mektep) and a bath (hamam). Construction was begun in February, 1463 and was completed in December, 1470.

The system of the mosque consisted of a central dome, a semi dome over the mihrap and lower three lateral domes at each side, Fig. 6a, b. The semi dome and the central dome were supported by piers and by two elephant feet, (Goodwin 1971). The building with a rectangular plan was about 57 m x 49 m externally, excluding the courtyard with revaks, Fig. 6a, b. The diameter of the main dome that was set on a square was 26 m.

Since during the 1766 earthquake the structure saw great damage and it was not feasible to repair it, the mosque was reconstructed with a different plan, Fig. 6c. The new mosque (the present mosque) was built on the foundations of the old mosque between 1767 and 1771. The main space of the mosque was formed on a system of four semi domes that supported the central dome in four directions. The main dome over four arches was carried by four big piers, Fig. 6c,

d. Being smaller than the older one, dome has a diameter of 19 m, and is higher than the old one, (Unan 2003). Damages caused by the case earthquakes are tabulated in Table 2.

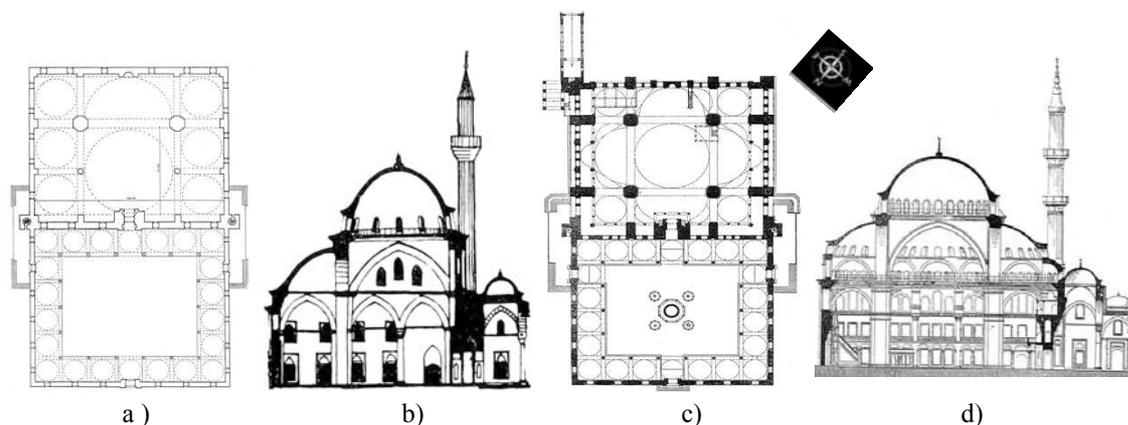


Figure 6 : The plans and sections of earlier and later Fatih Mosques, respectively (a, c, d are modified from Ayverdi 1953 and b is modified from Kunter and Ulgen 1939).

Table 2 : Earthquake damage summary of the case structures

| Earthquake | Hagia Sophia Museum | Chora Museum | Fatih Mosque |
|------------|---|---|---|
| 10.10.1509 | Minarets collapsed, plaster covering the mosaics of the walls and of the vault of the dome fell out, (Ambraseys and Finkel 1990, Ambraseys and Finkel 1991, Pamukciyan 1994, Ambraseys and Finkel 1995 and Genc and Mazak 2001). [slight damage] | No available information, (Akyurek 1996). | The capitals of four great columns cracked, the main dome was badly cleft, its plaster shattered, iron joists on both left and right sides of the mosque buckled, (Ambraseys and Finkel 1990, 1995 and Sakin 2002). [severe damage] |
| 02.10.1754 | Some of the marble columns supporting the capitals which in turn supported the colonnade were overthrown, (Ambraseys and Finkel 1995). [severe damage] | No available information, (Akyurek 1996). | Domes of the porch of the mosque collapsed, the main dome was seriously damaged, (Ambraseys and Finkel 1995). [severe damage] |
| 22.05.1766 | The building was damaged slightly, (Mazlum 2001, Genc and Mazak 2001 and Mazlum 2003). [slight damage] | The main dome collapsed (Guler soy 1976, Pamukciyan 1994). [severe damage] | The main dome collapsed, the damage level of minarets was very serious, (Sakin 2002 and Unan 2003) .The mosque was reconstructed after the earthquake, Fig. 6. [severe damage] |
| 10.07.1894 | One of its columns, western part of its great apse and the decorations of cupola required repair, (Ambraseys 2001). Main dome was deformed, settlement and horizontal cracks were observed on the piers supporting the main dome and vertical cracks were formed in the vault of windows of dome, (Batur and Tanyeli 1993). | Half of the minaret fell down, (Genc and Mazak 2001 and Sakin 2002). [slight] | The minarets were damaged slightly, (Ambraseys 2001). Two minarets were collapsed, (Pamukciyan 1994 and Genc and Mazak 2001). [slight] |

4 DISCUSSIONS

As it can be seen from Table 2, the level of damages of case structures during the case earthquakes vary in different extents. Earthquake characteristics, such as distance of the epicenter, focal depth, duration and directionality; and structural aspects such as structural system, material deterioration by time and environmental effects; and existing damages due to soil settlement, as well as the local soil conditions may play a crucial role in the formation of seismic damages.

Comparing the consequences of 1509 earthquake for Hagia Sophia and the Fatih Mosque it is interesting to notice that the level of damage was slight for Hagia Sophia while it was severe for the Fatih Mosque. Although there are many factors affecting the seismic performances of structures this difference may possibly attributed to the experience that had been accumulated on Hagia Sophia. Though the Fatih Mosque had been built only 38 years before the 1509 earthquake, Hagia Sophia with approximately one millennium, numerous destructive earthquakes and reconstructions being improved after each event exhibited a better performance. On the other hand structural system of Faith Mosque, which is pronounced among the first imperial structures constructed after the conquest of Istanbul, was built up in some sort of a hurry, without much experience, aiming to quickly reshape the new capital of Ottoman Empire, (Mazlum 2001).

However, during the 1754 earthquake both Hagia Sophia and the Fatih Mosque were damaged severely. Had been slightly damaged by the 1509 earthquake, Hagia Sophia possibly had not gone under an extensive maintenance for the last 250 years. Consequently time dependent factors and the structural system weakness in the east-west direction of the structure (Keypour 2001) might have led to such damage. As for the Fatih Mosque, structural defects such as the asymmetric structural system causing insufficient lateral strength and stiffness, different dimensions of piers carrying the main dome and rather small height of the main dome might have caused the damage.

Only 12 years later, another major earthquake, which resembled the earthquake of 1509 due to both its damaging and general characteristics (Sakin 2002), struck. Similar to the 1509 earthquake Hagia Sophia did not suffer much damage, but Fatih and the Chora Mosques suffer badly. Possibly the above mentioned structural defects together with the deteriorations caused by the time brought the Fatih Mosque to collapse.

Although there is a controversy for the level of damage at the Hagia Sophia, it is possible to say that the 1894 earthquake brought less destruction to our case structures. Thanks to its new structural design and construction only the minarets of the Fatih Mosque saw some damage. In this new design structural system was designed symmetrical in plan and diameter of the dome, resting on four identical piers, was decreased. About nine years after the restoration works carried out at the Chora Mosque the structure experienced the 1894 earthquake only with some minaret damages.

Apart from the parameters given above paragraphs, other parameters like lack of maintenance, water leakage into foundations and inadequate drainage, causing settlement might have induced non-seismic damages to these structures, which could adversely affect their seismic performance.

5 CONCLUSIONS

Knowledge on the past seismic performances of historical structures may be very useful for predicting the future seismic performances of these structures. However, it is very difficult to assess the past seismic performance of these structures due to insufficient sources, some of which are in contradiction with some other sources. The aim of this study is to research four strong seismic events that affected North Western Anatolia and the damage to three structures due to these earthquakes using available references. It is concluded that the present information related to history of these structures is not enough to completely evaluate the past and/or future seismic performances of these structures. Further collaboration of historians, architects and structural engineers is needed for better documentation of past seismic performances of historical structures.

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