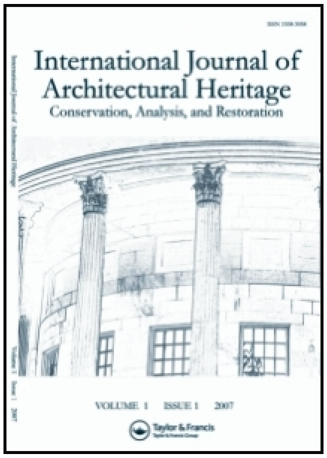

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TRADITIONAL TURKISH MASONRY MONUMENTAL STRUCTURES AND THEIR EARTHQUAKE RESPONSE

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Many historical and new masonry minarets were damaged or collapsed during the 1999 earthquakes in Kocaeli and Duzce, Turkey. These and other recent earthquakes not only caused loss of property but also loss of many lives. The structural failures and resulting casualties have led to discussion and investigation of potential reasons for poor seismic performance of masonry minarets. The primary goal of this study is to review the construction practices for historical and new masonry minarets in Turkey and to discuss the seismic damage observed in those structures. The architectural and structural properties of contemporary and historical Ottoman minarets and their components are presented. For example, a very old special technique for reinforcing and linking adjacent stone blocks with iron pieces in the vertical and horizontal directions is discussed. The structural damage examples are used to better understand the reasons for the observed failure mechanisms. It is concluded that the transition region between the square minaret boot and cylindrical body was most vulnerable to damage, and the iron clamps used in historical minarets effectively prevented structural damage.

KEY WORDS: traditional Turkish minaret, masonry, earthquake, damage

1. INTRODUCTION

A minaret is a slender tower structure built into or near a mosque structure. Historically, it was used by a *muezzin* to call out prayers in Islam. During the early periods of Islam, the call for prayer or *adhan* was performed at a rooftop or at an elevated platform or the roof of the mosque. In Islamic architecture the first minarets

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were constructed in the corners of the Mosque of Amr by Fustat bin Maslama, the governor of Egypt, in 673 AD. In the course of time, numerous magnificent minarets have been constructed with different materials and structural systems in various regions of the world. Although their variations seem endless to the inexperienced observer, minarets generally fall into one of four characteristic types as isolated by T. F. Hamlin (SAW 1964):

1. Minarets of Cairo and Syria usually have several balconies, with the tower size decreasing as the elevation increases. The top is capped with a bulbous dome, and the lowest section can be square.
2. Minarets of Morocco and Spain are generally large square towers, richly decorated, with a smaller pavilion at the top. The usual building material is brick, laid with patterns on all sides. The balcony of the lower stage serves for the prayer call.
3. Persian minarets are normally high, slender, tapered, and round turrets. Often, pairs of these minarets flank a great entrance way (similar to those in Figure 1). The balcony is usually placed very high on the minaret, and a low dome caps the tower.
4. The fourth type, the Turkish minaret, is also slender, sometimes tapered, and may be round or polygonal. But unlike the Persian minaret, the Turkish type may have two or even three balconies.

This article focuses on minarets in Anatolia or today's Turkey, which was opened to Muslim settlements after the battle of Malazgirt in 1071. The first Turkish minarets

Figure 1. Photograph of typical Seljuk masonry minarets (Turkey, 2006).

(a) (b)

Figure 2. Photographs of typical Ottoman minarets: (a) Selimiye mosque with four minarets, and (b) Blue mosque with six minarets (VGM, 2006).

followed the minarets having slender cylindrical or polygonal shafts common in Turkistan and Horasan in Central Asia. Most early Anatolian Seljuk structures are of dressed stone, with brick reserved for minarets (eleventh and twelfth centuries). A pair of minarets constructed by Seljuk Turks is shown in Figure 1.

During the Ottoman period (1299–1922), slender cylindrical and polygonal shafts with conical caps became the exclusive form for Turkish minarets. During the early Ottoman period (1299–1437), the number or location of the minarets did not symbolize anything. Starting with the classical Ottoman period (1437–1703) the number of minarets was incorporated into the architectural composition. As a rule, only the mosques built by sultans were allowed to have more than one minaret, usually placed at the junction of the *haram* (central space of the mosque) and the *sahn* (naves at the entrance). The minaret of other mosques was often placed in the corner at the right end of the entrance arcade. Kuran (1968 and 1987) provides a detailed survey and description of early Ottoman mosques as well as those built the architect Sinan, the greatest Ottoman architect (1489–1588). Sinan constructed many marvelous mosques with minarets. Selimiye mosque (Figure 2a) designed by Sinan for the sultan Selim II and was constructed in 1574 in Edirne. It has four identical minarets 70 m high, each with three balconies reached by three nested helical staircases. In the early seventeenth century, the Sultan Ahmet mosque or the Blue mosque was constructed in Istanbul with six minarets, a pair with two balconies and a quartet with three balconies (Figure 2b).

2. ARCHITECTURAL AND STRUCTURAL PROPERTIES OF TURKISH MASONRY MINARETS

2.1. Segments of Minarets

The architectural styles and structural systems of Turkish minarets vary greatly depending on the materials used, quality and background of workers, structural and construction methods, and facilities available at that time. As a result, minarets can be separate or contiguous and integral with the mosque structure, may have been built using stone, wood, or brick materials, and can be cubic, cylindrical, or polygonal in shape. In Turkish architecture, classical Ottoman minarets may be assumed as the final stage of Turkish minarets with slim cylindrical or polygonal body/shafts and conical roofs.

A classical Ottoman minaret has a standardized assembly of components or segments as shown in Figure 3. The basic elements of the minaret are: footing (*temel* in Turkish), boot/pulpit (*kaide*), transition segment (*küp*), cylindrical or polygonal body-shaft (*gövde*), stairs (*merdiven*), balcony (*şerefe*), upper part of the minaret body (*petek*), spire (*külah*), and end ornament (*alem*).

2.1.1. Footing The footing is constructed using very thick rigidly connected stone blocks. This segment is sometimes connected to the adjacent bearing walls of the mosque.

2.1.2. Boot The boot, sometimes called the *pulpit*, is the bottom part of the minaret rising above footing. The minarets from Turkish Seljuk periods (1077–1307) had boots with usually square or less frequently octagonal shapes. Minarets having polygonal boots with 10, 12, or 16 faces were seen in the early Ottoman period. The great architect Sinan generally used taller square minaret boots that were not separated from mosque body (Tayla 1988). However, Sinan preferred the boots with eight corners for the Süleymaniye mosque (1557) in Istanbul and Selimiye mosque in Edirne (Figure 2a). The height of a typical boot ranges from 5–10 m. The typical boot width varies between 3–6 m. The overall boot width of the tallest masonry minaret in Turkey is approximately 6 m (Selimiye mosque in Figure 2a).

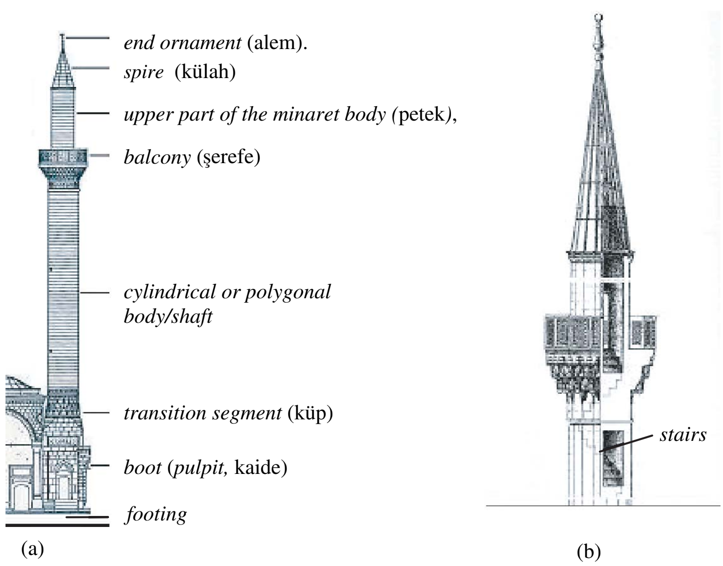


Figure 3. Elevation of (a) a typical classical Ottoman minaret (Tuncer, 1996), and (b) spiral stairs inside the minaret (Uluengin, 2001).

2.1.3. Transition Segment The transition segment provides an uninterrupted and smooth transition from the larger-size boot to the smaller-size cylindrical or polygonal body. Accordingly, its geometric shape and size change over the height depending on the shape of the boot and body. Even transition between boot and cylindrical body was ensured using various pyramids, planes, or inverted triangular-shaped elements, usually cut stones, systematically. The larger-size square or polygonal cross section of the transition segment at the bottom is reduced to a smaller-size circular section at the top of the segment. The height of a typical transition segment varies between 2–3 m.

2.1.4. Cylindrical or Polygonal Body/Shaft The cylindrical or polygonal body-shaft is the longest segment of the minaret. The most preferred shape for the body is circular, less frequently square or octagonal sections were used, especially during the Seljuk times. However, minaret bodies with 16 corners were very common during the classical Ottoman period. Although tapered towers with smaller cross sections near the top were widespread during the Seljuk periods, since then constant cross-sectional size and shape have been adapted for the body along the height of the minaret. While the diameter of most minarets is approximately 1.5–3 m, the diameter usually decreases above the upper balcony level, or it can be as large as 4 m as in the minaret of the Selimiye mosque (Figure 2a). In general, the height of the circular or octagonal minaret body is approximately two-thirds of the total minaret height.

2.1.5. Stairs Different structural materials are used for stairs, which are used by people to climb up to balconies. Timber, steel, and masonry were frequently used in older minarets, and reinforced concrete has become the most common material in recent decades. Stairs are usually part of the load-resisting structural system of the minarets. The end constraints of stairs or the nature of connections between the individual steps and the minaret body strongly affect the structural performance of minarets when subjected to lateral loads such as wind or earthquakes.

2.1.6. Balcony In the past, the purpose of balconies built at a certain height above ground was to let the sound of muezzin (person calling for prayers) reach far distances. Although, this purpose has lost its effectiveness in recent years after the advent of loudspeakers, the balconies have been built and maintained because of their attractive visual aspect and other architectural reasons. Decoration of balconies was accepted to be vitally important for the magnificence of minarets, and the talents of workers were made public through their decoration work on the minaret, especially around the balconies. An increase in the number of balconies per minaret, as well as minarets per mosque, was seen during the expansion of Ottoman empire.

2.1.7. Upper Part of the Minaret Body *(petek)* The upper part of the minaret body (*petek*) is between the last balcony and spire. The properties of this segment are in general similar to those of the cylindrical or polygonal body. Sometimes smaller cross-sectional size or different geometric properties were used, especially during the Seljuk period.

2.1.8. Spire/Cap The spire of the minaret functions as a roof with a usual conical shape, or rarely domed, supported by a timber structural frame covered with lead plates. Thus, the spire has sometimes different structural properties from those of the upper part of the minaret body. It is also common to see the minaret body and spire constructed using the same structural materials, particularly in reinforced concrete or masonry minarets.

2.1.9. End Ornament This piece is usually made of metal placed at the very top of the minaret symbolizing the end of the minaret.

2.2. Minaret Locations on the Mosque Plans

The number and position of minarets were not standard before the classical Ottoman period. They were either constructed as part of the adjacent walls of the mosque or constructed separately from the mosque. Minaret boots were commonly attached to the adjacent mosque walls during the classical Ottoman period (Ülgen, 1996). Furthermore, the minarets were sometimes treated as a structural member or part of the load-resisting structural system for the mosque structure mainly due to their location with respect to the structural system. In some cases, relatively rigid minaret boot was used to provide lateral resistance for the adjacent load-bearing walls in the out-of-plane or transverse direction. Where the minarets are constructed as an integral part of the mosque walls, they perform more like a strong column or pedestal element. Turkish minarets are traditionally placed on the two sides of the mosque, yet a single minaret is typically placed in the right back (entrance) corner of the mosque as shown in Figure 4. A careful investigation of the mosque in the picture indicates that the symmetry was maintained by placing a small dome over a stairwell having the same dimensions as the minaret boot on the opposite side of the minaret.

Figure 4. Photograph of Tophane Kılıç Ali Paşa mosque (Sözen and Güner, 1992).

2.3. Structural System of Minarets

In historical stone masonry minarets, most commonly limestone with varying mechanical properties was used. Oguzmert (2002) tested high-quality limestone used in minarets and reported the following material properties: dry density is 23.9 kN/m^3, fully saturated density is 24.5 kN/m^3, uni-directional compressive strength is 16.8 MPa, tensile strength is 0.90 MPa, modulus of elasticity 5860 MPa, and Poisson's ratio is 0.24. It should be emphasized here that these experimental results are for high-quality limestone, and for ordinary limestone the compressive strength and modulus of elasticity can be as low as 5 MPa and 3000 MPa, respectively.

The relatively small tensile strength of mortar placed between the masonry blocks presents a major problem for slender masonry structures such as minarets in regions of high seismicity. The brick or stone blocks have fairly large compressive strength; however, unreinforced masonry lacks tensile strength required to resist bending moments imposed by the lateral loads due to wind or earthquakes. Older masonry minarets were typically constructed using stone blocks or solid clay bricks or a combination of two, whereas unreinforced lightweight stone blocks are preferred in new construction.

After a major earthquake in 1509, Ottomans tackled the problem of constructing tall earthquake-resistant minarets (Oğuzmert, 2002). They started to use a special technique for linking adjacent stone blocks with iron pieces and clamps in the vertical and horizontal directions as shown in Figure 5 (Doğangün et al., 2006a). Use of iron clamps in the two perpendicular directions has improved the lateral load-carrying capacity of slender masonry structures significantly under wind and earthquake loads.

The iron reinforcement was prepared by blacksmiths using special forging techniques. The horizontal bent iron pieces may be called a *clamp* and was originally called *kenet* in Turkish. The oldest known application of the clamps in Ottoman architecture is found on the columns of Bursa Osman mosque (1339) (Oğuzmert 2002). The clamps were used more frequently than ever before during the period of sultan Beyazıt II (1481–1512). Sinan used them more effectively in the sixteenth century and the method reached its ultimate standard at the end of that century. The vertical iron reinforcement or vertical bars were originally called *zıvana* in Turkish. There is no evidence of application of steel or iron bars in minarets constructed before the sixteenth century (Oğuzmert, 2002). Ottomans started to use the vertical bars widely in the seventeenth century (Tanyeli, 1990).

The clamps and vertical bars were placed inside anchorage holes in the stone blocks, and melted lead was poured inside the hole to provide bond between the stone and iron clamp or vertical bars. Approximately 2000 kg of this heavy metal, lead, was used for the construction of a typical masonry minaret. It is likely that this additional mass changes the natural structural period and affects the seismic behavior of the minaret. In another regard, the lead performs as intended for centuries because it is hardly ever influenced by the adverse environmental conditions.

As a binding agent between the solid blocks, a special mortar named *Horasan mortar* was used in historical minarets and other Turkish monuments. The Horasan mortar mixture including lime was filtered and left to yeast to gain strength for almost 10 to 15 years underground before it was ready to use in construction.

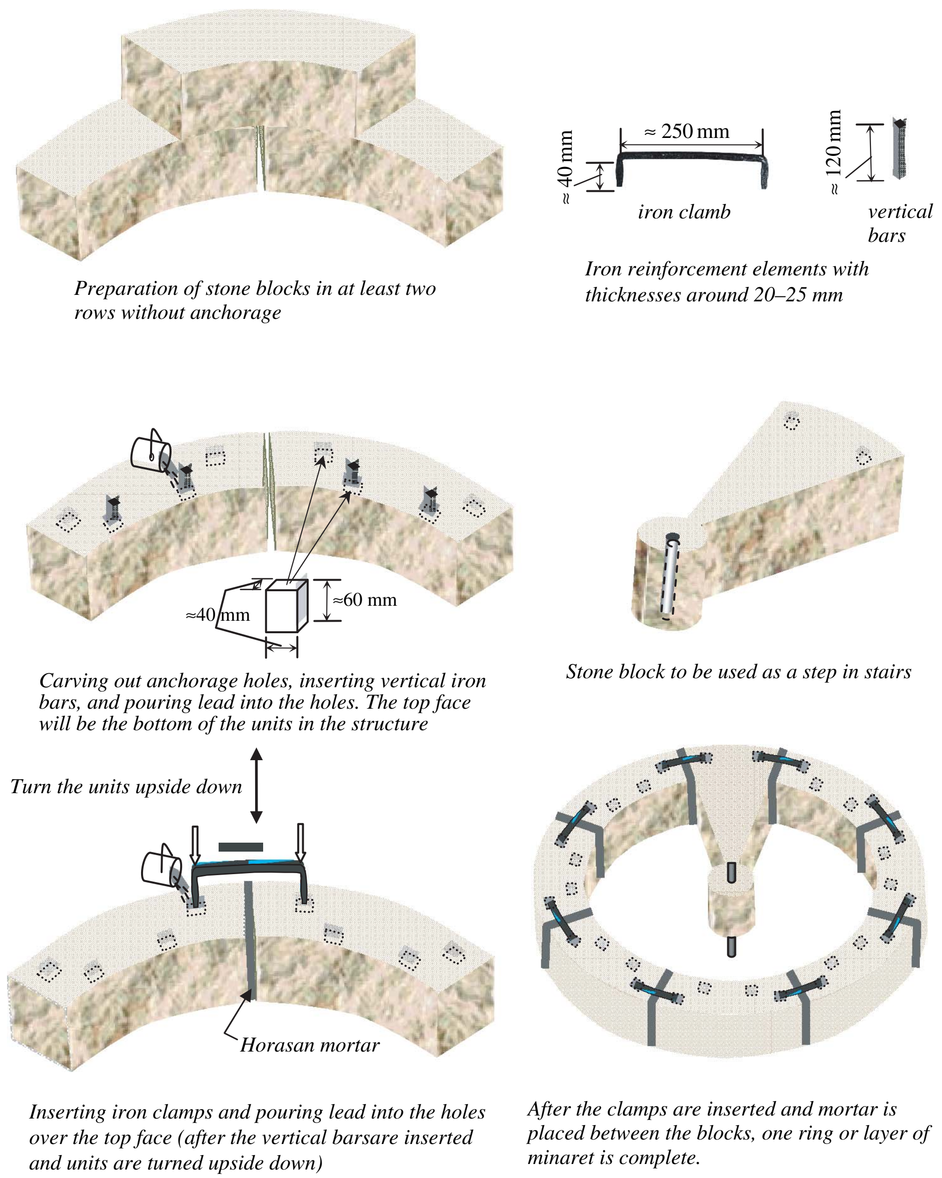


Figure 5. Schematic illustration of the construction of traditional Turkish minarets using stone blocks reinforced and anchored with iron bars and clamps.

3. OBSERVED EARTHQUAKE DAMAGE

As the minarets are slender tower structures, their modal and dynamic response characteristics are quite different from those of the traditional building structures. The studies conducted by the authors indicated that the elastic natural period of a masonry minaret 20–25 m high is approximately 0.5–1 seconds. The fundamental period of a minaret 30 m high could be approximately 1.5 seconds. It should be noted that these structural periods are for the typical minaret models used, and largely depend on the specified material and geometric properties.

Although many lives were lost as a result of collapse of minarets during earthquakes or strong wind, there are only a few studies investigating the behavior and performance of historical and modern Turkish minarets (e.g., Oğuzmert, 2002; Nuhoğlu and Sahin, 2005; and Doğangün et al., 2006b). Most historical documents and even recent earthquake reconnaissance reports provide very limited or no information on the damage experienced by these unusual structures. For example, the report describing the earthquake on July 3, 1709, in İzmir, Turkey states that "the minaret of the mosque of Sultan Mehmed, above its balcony, fell onto the dome and the dome is cracked in several places" (Ambraseys and Finkel, 1993, pp. 173). The damage information provided in written documents and observations from post-earthquake reconnaissance trips of authors are summarized in the following text for traditional Turkish masonry minarets subjected to the earthquakes in recent years.

Two very strong and destructive earthquakes occurred in 1999 on August 17 (M_w=7.4) and November 12 (M_w=7.2) along the North Anatolian fault in Northwestern Turkey, causing widespread structural damage and loss of more than 20,000 lives. Many minarets damaged during the August 17 (Kocaeli) earthquake collapsed during the November 12 (Duzce) earthquake. Detailed surveys of minarets were carried out and some damage photos were presented after these earthquakes (JSCE, 1999; Bilham, 1999; PU, 2000; Motosaka and Somer, 2002; Sezen et al., 2003). The severity of observed damage, construction details and materials, and locations of the surveyed mosques and minarets are reported. Survey results indicated, for instance, that most (70%) of the masonry and reinforced concrete minarets surveyed in the city of Duzce with a population of approximately 350,000 was observed to sustain damage of intensity severe to collapse (Sezen et al., 2003).

Collapse of the minarets constitutes a hazard to life and to the adjacent mosque and surrounding buildings. During the March 13, 1992, Erzincan earthquake (M_s=6.8) a masonry minaret fell on the roof of a mosque. Part of the failed minaret punched through the wooden mosque roof and fell on the people praying in the mosque; 30 people lost their lives during this incident (Karaesmen et al., 1992). Similar casualties were reported after the November 12, 1999, Duzce earthquake.

Table 1 presents a summary of the damage observed in historical and modern masonry minarets in several cities following the 1999 earthquakes. The surveys were carried out and reported previously by Firat (1999) and Sezen et al. (2003). The minaret locations in Duzce and Bolu were identified using a global positioning system device during the field survey. The distance to the November 12 Duzce earthquake epicenter with 40.78N latitude and 31.16E longitude is then calculated assuming earth is a perfect sphere. A minaret may either have a foundation and boot separate from the mosque structure (referred to as *Type I minaret* in Table 1) or the foundation and boot may be attached to the mosque (*Type II minaret*). The most common structural failure was observed near the bottom of the cylindrical body of the minaret. Some of the historical masonry mosques and minarets listed in the Table 1 include the approximately 450-year-old Mihrimah Sultan, 540-year-old

Table 1 Masonry minarets surveyed after the 1999 earthquakes (Firat 1999, and Sezen et al. 2003)

Name	City	Location or coordinates	Date of construction	Type of construction	Boot height (m)/total minaret height from ground (m)	Minaret diameter (m)	Distance to epicenter (km)	Type	Observed damage
Kubbeli	Yalova	Istiklal Cad.	1969	200 mm thick briquette	7/32	2.0	34.5	I	Failed at the bottom of cylinder and collapsed
Haci Hayriye	Yalova	Altinkuyu Cad.	1966	200 mm thick briquette	6/23	1.8	37.5	II	Failed 7 m above the bottom of cylinder and collapsed
Haci Saffet	Yalova	Baglaralti Cad.	1954	200 mm thick briquette	5/20	2.0	34.5	I	Failed at the bottom of cylinder and collapsed. Minaret fell down on the mosque
Bilali Habesi	Yalova	Istanbul Cad.	1987	200 mm thick briquette	7/20	1.7	32.5	I	Sheared off at the base
Bahcelievler	Yalova	Fatih Cad.	1980	200 mm thick briquette	7/22	1.7	42	I	Broke at base
Emir Bayir	Yalova	Fatih Cad.	1991	200 mm thick briquette	5/17	1.7	44	I	Failed above the bottom of cylinder and collapsed
Kuskonmaz	Istanbul	Uskudar	1940	Stone blocks	5/15	2.0	66.5	II	Damaged near the top
Sinan Pasa	Istanbul	Besiktas	1565	Stone blocks	7/20	1.7	69.5	II	Failed near the top
Mihrimah Sultan	Istanbul	Edirnekapi	1557	Stone blocks	7/25	2.0	68	II	Mosque damaged, no damage in minarets
Selmanağa	İstanbul	Üsküdar	1548	brick	5/17	2.5	68		Only the brick like cladding had micro-cracks over the surface
Fatih	Istanbul	Fatih		Stone blocks	8/36	2.0	73	I	Mosque damaged, no damage in minarets
Hirka-i Serif	Istanbul	Fatih	1851	Stone blocks	8/28	1.7	73	II	The spire leaned
Iskender Pasa	Istanbul	Fatih		Stone blocks	4/24	2.0	73	II	The spire fell down
Aziziye Merkez	Düzce	40.50N-31.08E	1995	Stone blocks	6/26	2.0	19.8	II	Failed at the bottom of cylinders and collapsed
Cedidiye Merkez	Düzce	40.50N-31.09E	1976	Stone blocks	5/35	2.0	19.7	I	Failed at the bottom of cylinders and collapsed

Oksuztekke	Bolu	40.44.488N-31.35.851E	1993	Lightweight stone blocks	8/unknown	1.7	24.1	I	Minaret segment above the 2nd balcony level collapsed
Semsi Ahmet Pasa (Imaret)	Bolu	40.43.852N-31.36.635E	16th century	Brick-stone	7/unknown	2.0	24.1	I	Failed near the bottom of the cylinder and collapsed
Sarachane	Bolu	40.43.935N-31.36.513E	1750	Brick	8/24	1.7	23.9	I	Cracks in stone blocks in the mosque – no observed minaret damage
Yildirim Bayezid	Bolu	40.44.040N-31.36.576E	1899	Stone blocks	7/22	1.7	24.1	II	Dislocation of stone blocks in the mosque – no observed damage in minarets
Kadi	Bolu	40.43.901N-31.36.495E	16th century	Stone blocks	7/unknown	2.0	23.9	I	Severe damage to mosque, minaret collapsed above the boot
Merkez Yeni	Izmit	Degirmendere	1971	Stone blocks	7/35	1.7	–	I	Dislocation of blocks at the bottom of the cylinder
Orta	Izmit	Kavakli	–	Stone blocks	10/40	1.7	–	I	Dislocation of blocks at the bottom of the cylinder
Uzunciftlik	Izmit	Acisu	1987	Stone blocks	8/39	1.7	–	I	Dislocation of blocks at the bottom of the cylinder

Fatih, and 150-year-old Hirka-i Serif mosques in Istanbul, and the 600-year-old Semsi Ahmet Pasa (Imaret), 500-year-old Kadi, 300-year-old Sarachane, and 200-year-old Yildirim Bayezid mosques in Bolu. The fault lines ruptured during the Kocaeli and Duzce events, maximum-recorded ground accelerations, and location of the minarets are shown in Figure 6. The next section describes the typical observed damage in masonry minarets starting from top to bottom of the minaret.

Other than the minarets listed in Table 1, many more minarets were damaged or collapsed during recent earthquakes in Turkey. The basic seismic information and maximum recorded ground accelerations are presented in Table 2 for the recent destructive earthquakes. On average, one magnitude 5 or larger earthquake occurs in Turkey. Post-earthquake reconnaissance reports indicate that masonry minarets are susceptible to damage or collapse during earthquakes with a magnitude 6 or larger. Most of the quantitative earthquake data provided in Table 2 were reported in the references listed at the end of this article.

The elastic response spectra are calculated and shown in Figure 7 for the ground accelerations recorded during the 1999 Duzce and Kocaeli earthquakes, which caused damage in the minarets shown in Table 1. Considering that the fundamental period of a minaret 20–30 m high is approximately 0.5–1 seconds, the spectral acceleration could be larger than 1 *g* for 5% damping ratio within that period range. The calculated elastic spectra show that, even for taller larger period minarets, the seismic demand was larger during the November 12 Duzce event. This finding is consistent with the observation of more widespread minaret damage and collapse in and around the city of Duzce and nearby Bolu.

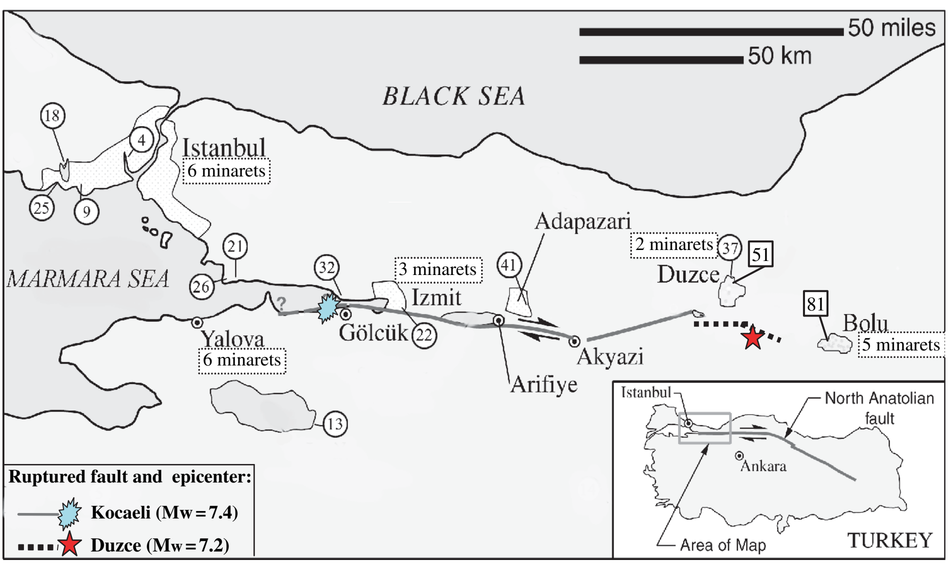
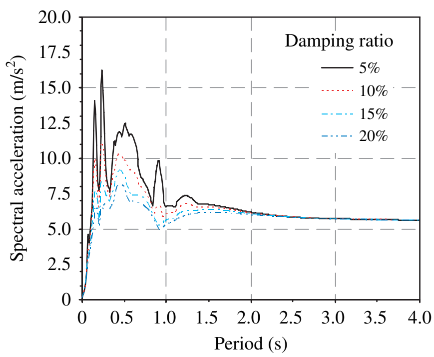


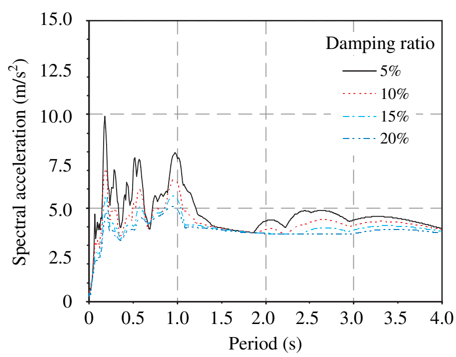
Figure 6. Map of the ruptured fault lines and epicenters of the 1999 Kocaeli and Duzce earthquakes and minaret locations (percentage of recorded peak ground accelerations in terms of *g* are shown in circles and rectangles for the Kocaeli and Duzce earthquakes, respectively).

Table 2 Recent destructive earthquakes with reported damage to minarets in Turkey (GDDA, 2007)

Earthquake name or location	Date	M_w or M_s	People		Recorded maximum ground acceleration (g in %)			Dept of focus (km)
			Death	Injured	E-W	N-S	Vert.	
Bingöl	May 1, 2003	6.4	168	520	54.6	27.7	47.3	5
Sultandağı	February 3, 2002	6.3	42	325	9.4	11.3	3.6	10
Cankırı	June 6, 2000	5.9	3	200	6.3	6.2	4.0	10
Duzce	November 12, 1999	7.2	950	3300	74.0	80.6	20.0	12
Kocaeli	August 17, 1999	7.4	17322	23954	37.4	40.7	48.0	16
Ceyhan	June 27, 1998	6.2	146	940	27.4	22.3	8.6	23
Erzincan	March 13, 1992	6.8	653	3850	40.5	47.1	23.9	27



(a) Elastic response acceleration spectra for East-West component of November 12, 1999 Düzce Earthquake



(b) Elastic response acceleration spectra for North-South component of August 17, 1999 Kocaeli Earthquake

Figure 7. Graphs of the elastic acceleration response spectra for ground accelerations of 1999 Turkey earthquakes.

3.1. Damage at the Roof Level or Spire

In masonry minarets, the spire is either constructed monolithically with the rest of the minaret using the same masonry units or constructed as a wood frame covered by metal, typically lead plates. In cases in which the structural systems of the minaret body and spire are different, the stiffness and strength and the resulting structural response appear to be different for the two components. Especially when the spire is not anchored properly to the minaret body, spire damage similar to that shown in Figure 8 is observed after the earthquakes. Proper anchorage of spire may limit the damage to spire and prevent it from falling down. As listed in Table 1, a couple of minarets had damage to their spires in Istanbul during the 1999 earthquakes.

Figure 8. Photograph of damage to minaret spire after the 1999 earthquakes (SDR 2005).

3.2. Damage Above the Balcony

Damage to the upper portion of the minaret body is observed less frequently. One reason for this is the bending moment demand imposed by the lateral loads, either by wind or earthquakes, is relatively small compared to the lower parts of the minaret. Figure 9 shows one rare example of minaret sustained damage above the balcony level. The inclined failure surface is an indication of shear failure rather than a flexure or bending moment failure; however, the shear forces should be relatively low compared to the bending moments at that elevation.

Figure 9. Photograph of damage to a minaret above of its balcony level (CIAI'S 2006).

3.3. Damage at the Balcony Level

The location, size, and decoration of balconies are important for architectural reasons; however, they typically create structural irregularities over the height of masonry minarets. This irregularity is mainly because the uniform size of the minaret body increases at the balcony level by addition of tapered cantilevers around the perimeter. The detailing and construction of cantilevered masonry balconies are usually very difficult and require high-quality workmanship. The tapered bottom face of the balcony and the balcony itself are normally used for decoration purposes. Even though a moderately gradual diameter increase is provided just below the balcony, the local structural behavior highly depends on the details of the connections between the masonry units in that region. Usually because of poor detailing, the minarets tend to fail around the balcony level as shown in Figure 10. The other common reason for failure at the balcony level is the existence of a door (a rectangular opening) in the minaret body, which abruptly reduces the shear and flexural strength of the minaret significantly.

3.4. Damage in the Minaret Body

Failures within the cylindrical minaret body were occasionally observed between the transition region and balcony. Figure 11 shows one such failure in a brick masonry minaret after the 2002 Sultandagi earthquake. Inclined failure surface suggests that the collapse was most likely due to shear rather than the bending effects. Figure 12 shows another similar example where the square boot of the collapsed minaret was constructed separately but very close to the mosque walls. It is possible that the observed damage was caused by the impact between the minaret and mosque structure.

(a) (b) (c)

Figure 10. Photographs of damage at the balcony level during recent earthquakes: (a) February 3, 2002 Sultandagi earthquake (KOERI 2002), (b) February 3, 2002 Sultandagi earthquake (Utku et al., 2003), and (c) November 12, 1999 Duzce earthquake.

Figure 11. Photograph of damage from failure within the cylindrical minaret body (KOERI 2002).

Figure 12. Photographs of damage from failure due to crushing at minaret of Emir Bayır mosque (Fırat 1999).

3.5. Damage at the Bottom of Cylindrical Body

Most of the surveyed masonry minarets were reported to fail near the bottom of the polygonal or cylindrical body. This finding is mainly because of relatively sudden reduction in the cross-sectional area and flexure and shear stiffness just above the transition segment where the cross-sectional shape changes from square to a smaller size circle within a very short height, typically within 1–3 meters. Figure 13 shows damage to the minaret of the Cambazzade Ahmet mosque built in 1802, as a result of the moderate-size earthquake (M_s=6.1) on June 6, 2000, on Orta, Cankiri. The

Figure 13. Photograph of damage from cracking and damage in the minaret of the Cambazzade Ahmet mosque in Orta, Cankiri (Kasapoğlu et al., 2000).

observed damage, including cracks concentrated on each side of the minaret, is an indication of large bending stresses rather than shear effects. It appears that this more than 200-yearold minaret, if not strengthened, will probably collapse during a potential future stronger earthquake. Cankiri is within a close distance to the very active North Anatolian fault, which has produced and is likely to produce much stronger earthquakes in the near future.

The type of damage seen in Figure 13 usually occurs in slender and taller minarets where the bending demands can easily surpass shear demands near the bottom of the minaret body. In shorter masonry minarets, in addition to large bending moments, the shear forces can be relatively large with resulting failures similar to those shown in Figure 14. The historical minarets shown in Figure 14 collapsed during the earthquakes in August 17 and November 12, 1999. The Imaret mosque is one of the oldest structures in the region, and its minaret was built using combination of stone blocks and small bricks bounded by a thick layer of mortar (Figure 14a). Similar

(a) 600 year old Imaret mosque in Bolu

(b) 500 year old Kadi mosque in Bolu

Figure 14. Photographs of damage from failures near the bottom of the polygonal and cylindrical minaret body.

(a) Collapsed minaret during the June 6, 2000 Çankırı-Orta ($M_s = 6.1$)

(b) Collapsed minaret during the June 27, 1998 Adana-Ceyhan earthquake ($M_s = 5.9$)

(c) Collapsed minaret during the February 3, 2002 Sultandağı earthquake ($M_w = 6.5$)

(d) Collapsed minaret during the May 1, 2002 Bingöl earthquake (M_w=6.4)

Figure 15. Photograph of damage from collapsed masonry minarets in recent earthquakes: (a) Taşkın et al., 2003, (b) Wenk et al., 1998, (c) Ulusay et al., 2002, and (d) Doğangün 2004.

damage along an inclined failure plane occurred in the Kadi mosque minaret (Figure 14b), which was constructed using stone blocks reinforced with iron clamps as illustrated in Figure 5.

A large number of minarets experienced severe damage or collapse within the minaret body just above the transition segment during the August and November 1999 earthquakes in Kocaeli and Duzce (Table 1). This type of widespread damage was not unique for these two earthquakes. Figure 15 shows more examples of similar failures from around Turkey during other recent earthquakes. In almost all examples, the main mosque building survived while the minarets collapsed above the transition segment.

4. CONCLUSIONS

There are only a few studies investigating and documenting the construction techniques and seismic performance of historical masonry minarets in Turkey. In this article, architectural and structural properties, commonly used construction materials and methods, observed seismic damage, and structural vulnerabilities of historical and contemporary Turkish masonry minarets are presented. Not well-known historical construction techniques were introduced and discussed in terms of architectural and engineering aspects. Steps for construction of historical reinforced masonry minarets are illustrated. A special mortar, called *Horasan mortar* was used between the cut stone blocks. Use of vertical iron bars and clamps connecting the adjacent stone units was effective in improving the earthquake resistance of historical minarets.

Although there were many traditional minarets in the heart of earthquake hit areas in Turkey, many historical minarets have survived and in general suffered less damage compared to the newer reinforced concrete and masonry minarets, especially during the 1999 earthquakes in Kocaeli and Duzce. New masonry minarets usually constructed without reinforcement. During destructive earthquakes, damage was observed at different levels of masonry minarets including the spire and balconies. However, most failures concentrated near the bottom of the polygonal or cylindrical body (shaft) of the minaret where the cross-sectional size typically becomes smaller and the flexural and shear stiffness decrease. The elastic response spectra calculated for the 1999 earthquakes showed that, in general, the spectral acceleration demand was larger for the minarets affected by the Duzce event. The field investigation also showed that a relatively large number of minarets in a smaller area were damaged or collapsed during this earthquake.

Historical masonry minarets located in high seismic regions need to be re-evaluated, analyzed, and retrofitted if deemed necessary. In addition, specifications and code standards are needed to strictly regulate the construction of new masonry minarets that may be subjected to high wind and/or seismic loads.

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