Research Article

Seismic Performance Assessment of Medieval Turkic Brick Minarets: A Comparative Study

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Abstract

Historical structures are key elements of cultural heritage, offering insights into past societies and linking them to the present. Many were built using masonry, which is strong in compression but weak in tension. Advances in computational technologies have allowed more precise analysis of such structures, especially under seismic effects.

This study examines three notable Turkish minarets from the 12th to13th centuries: The Kalyan Minaret, the Jam Minar, and the Sivas Great Mosque Minaret. The historical development of minarets and their significance in art history are briefly reviewed, along with the evolution of construction techniques, such as brick and brick–stone masonry. Structural behaviour was analysed through the Finite Element Method, and seismic performance was assessed using Time History Analyses with acceleration records from the 1999 Kocaeli Earthquake.

Results reveal that seismic responses vary significantly depending on material, geometry, and construction methods. The Kalyan Minaret, with its thick conical shaft, displayed the best performance, showing limited displacements and stress levels. The Jam Minar, the tallest and slenderest, experienced greater stresses, particularly in its upper sections, consistent with its current partial collapse. The Sivas Great Mosque Minaret performed least favourably, with high tensile and compressive stresses concentrated at the pedestal and transition zone.

Overall, the study highlights that the design of masonry minarets was influenced not only by artistic and symbolic concerns but also by structural needs. Their development reflects efforts to ensure earthquake resistance and stability under lateral loads, emphasising the integration of aesthetic and engineering considerations in medieval architecture.

Keywords: Earthquake Performance, Jam Minaret, Kaluyan Minaret, Sivas Great Mosque, Turkic Historical Masonry Minarets.

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Araştırma Makalesi

Orta Çağ Türk Tuğla Minarelerin Sismik Performans Değerlendirmesi: Karşılaştırmalı Bir Çalışma

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Özet

Tarihi yapılar, geçmiş toplumlara dair önemli bilgiler sunarak onları günümüze bağlayan kültürel mirasın temel öğeleridir. Bu yapılar çoğunlukla basınca dayanıklı ancak çekmeye zayıf yığma teknikleriyle inşa edilmiştir. Hesaplama teknolojilerindeki ilerlemeler, özellikle sismik etkiler altında bu yapıların daha hassas analizine imkân tanımıştır.

Bu çalışma, 12–13. yüzyıllara ait üç önemli Türk minaresini incelemektedir: Kalyan Minaresi, Jam Minaresi ve Sivas Ulu Cami Minaresi. Öncelikle minarelerin tarihsel gelişimi ve sanat tarihi içindeki önemi özetlenmiş, ardından tuğla ve tuğla–taş örgü kombinasyonları gibi inşaat tekniklerinin evrimi ele alınmıştır. Yapısal davranışlar Sonlu Elemanlar Yöntemi ile, sismik performans ise 1999 Kocaeli Depremi'ne ait ivme kayıtları kullanılarak Zaman Tanım Alanı Analizleri ile değerlendirilmiştir.

Sonuçlar, sismik performansın malzeme, geometrik form ve yapım yöntemine göre büyük farklılıklar gösterdiğini ortaya koymuştur. Kalın konik gövdesiyle Kalyan Minaresi en iyi performansı sergileyerek sınırlı deplasman ve gerilme değerleri göstermiştir. En ince ve en yüksek olan Jam Minar ise üst kısımlarında yüksek gerilmelere maruz kalmış, bu durum kısmi çöküşüyle de örtüşmektedir. Sivas Ulu Cami Minaresi ise en zayıf performansı göstererek özellikle kaide ve pabuç bölgesinde yüksek çekme ve basınç gerilmeleri ortaya koymuştur.

Genel olarak, minarelerin gelişiminin sadece estetik kaygılarla değil, aynı zamanda deprem dayanımı ve yatay yüklere karşı stabilite gibi yapısal gerekliliklerle de şekillendiği sonucuna ulaşılmıştır.

Anahtar Kelimeler: Deprem Performansı, Jam Minaresi, Kaluyan Minaresi, Sivas Büyük Camii, Türk Tarihi Taş Minareleri.

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INTRODUCTION

Historic masonry structures, whose structural systems predominantly function in compression, embody the accumulated construction knowledge and craftsmanship passed down through generations. When subjected to tensile stresses, these structures were stabilised through the incorporation of timber ties, iron clamps, and rods. Those that proved deficient against environmental influences eventually collapsed or fell into disuse. In recent decades, advancements in computer-aided analysis have contributed to a more objective basis for diagnosis, repair and strengthening of historic structures. Within this framework, the minaret—an element of both architectural—/typological and structural/engineering significance- emerges as a defining feature of the Islamic urban skyline while also constituting one of the masonry components most vulnerable to seismic and wind actions.

Objectives and Research Questions

The primary aim of this study is to investigate the structural behaviour of original minarets constructed in the 12th-13th century within the Turkic–Islamic cultural sphere and to conduct a comparative evaluation of these examples. The research seeks to establish correlations among form-structure interaction and numerical findings. In doing so, it intends to provide period-specific and technical guidance for conservation and strengthening practices, while also aligning historical design rationales with contemporary engineering criteria in new architectural works.

The central research questions addressed in the article are:

- How do the formal characteristics of minarets —such as slenderness, height, and the relative proportions of plinth (*kürsü*), the transitional base section (*pabuç*), shaft (*gövde*), balcony (*şerefe*), lantern (*petek*), and spire (*külah*)— affect seismic performance?
- To what extent are construction techniques, particularly the configuration of staircase, are they associated with characteristic patterns of damage?
- In what ways do chronological differences influence the design and structural performance of minarets?
- The study anticipates the following outcomes:
- As the slenderness ratio and overall height increase, relative top displacement also rises. Junctions between the shaft and base are expected to become critical under such conditions.
- Stairway configuration, whether single or double flight and with or without a central core, contributes to the stiffness of the shaft. In multi-flight arrangements, torsional demands are reduced.

MATERIAL AND METHOD

The analyses were conducted on selected the 12th -13th century Turkic minarets: the Kalyan Minaret in Bukhara, the Minaret of Jam in Ghor, and the Minaret of the Great Mosque of Sivas. These cases were chosen based on their representativeness of the period, formal distinctiveness —such as tall and slender shafts or multiple stairway systems— and accessibility of reliable data. This selection enables comparative evaluation of architectural and structural continuities and divergences among minarets erected in different geographical regions but within close historical periods.

The study employed the Finite Element Analysis method. The process included geometry modelling, material definition, element and section selection, mesh generation, and the specification of boundary conditions. Owing to the complexity of minaret geometries, the models were initially created in AutoCAD as three-dimensional solids, based on measured drawings available in the literature (Kulaç, 1979; Başar, 1997). Each component —plinth (*kürsü*), the transitional base section (*pabuç*), shaft (*gövde*), balcony (*şerefe*), lantern (*petek*), spire (*külah*), staircase, and core— was modelled separately, with material heterogeneity preserved. The models were then imported into ABAQUS software. Because the transfer of moment in frame and shell elements introduces uncertainties in out-of-plane stresses (Ertek, 2009), solid elements were preferred. Helical staircases were included to capture their influence on dynamic response.

Generating hexahedral meshes for helical and complex forms proved difficult, so second-order tetrahedral C3D10 elements were adopted. Mesh density was optimised to maintain a balance between computational accuracy and efficiency. Each node was assigned three translational degrees of freedom in the X, Y, and Z directions.

For boundary conditions, all minarets were assumed to be fully fixed at their bases, resting on rigid ground. Soil–structure interaction and base rotations were disregarded to isolate differences attributable solely to form and material. Material behaviour was defined under the homogeneous–isotropic assumption, widely recognised as a practical and reliable scheme for historic masonry (Anthoine, 1995; Koçak, 1999). Based on existing literature and limited laboratory data, the compressive strength of brick was taken as approximately 9.18 MPa, its unit weight as 12.9 kN/m³, and its elastic modulus estimated in the range of 1.8–3.2 GPa using the relation Ed = 200 fd. For stone, the following values were adopted: E ≈ 7.76 GPa, γ ≈ 25 kN/m³, and fc ≈ 28 MPa (DBYBHY, 2007; Oğuzmert, 2002; Turk & Coşgun, 2012; Turk, 2013; Başar, 2011; Aktaş, 2006). Average literature values were also used for timber and lead. Macro-modelling was selected as the modelling strategy, justified by its applicability and computational efficiency (Lourenço, 2002).

Self-weight was modelled by assigning gravitational acceleration and mass density to materials. For seismic input, the ground motion record of the 17 August 1999 Kocaeli–Düzce earthquake was applied simultaneously in three directions (N–S, E–W, and U–D). The record, with a peak ground acceleration of approximately 0.37 g, was obtained from the Kandilli Observatory. To manage the analysis duration, a 27-second segment representing the most energetic portion of the event was used. Dynamic analyses comprised both modal analysis —identifying natural frequencies, periods, and mode shapes— and time-history seismic analysis. Linear-elastic material behaviour was assumed. In resonance assessment, damping was disregarded at low levels (Chopra, 1995; Dabanlı, 2008; Sarıgül, 2015).

Performance evaluation was based on relative displacement (drift), principal stresses, and base shear. For brittle materials such as stone and brick, the Maximum Normal Stress criterion was adopted, monitoring S-Max in tension and S-Min in compression. For drift, the 1% limit specified in FEMA-356 (2000) for masonry systems was taken as reference. In addition, the shear safety of base and shaft–base junctions were verified. This methodological framework permits an objective comparison of the interaction between form and structure in minarets.

HISTORICAL DEVELOPMENT OF MINARETS

Since the earliest phases of human history, the human search for connection with a transcendent power has given rise to places of worship. These spaces represent some of the earliest manifestations of architecture. Göbekli Tepe, Mesopotamian ziggurats, Stonehenge, the Parthenon, and the Pantheon are among the oldest known religious structures. With the emergence of monotheistic religions, structures such as synagogues, churches, monasteries, and mosques were constructed. Mosques, distinguished by their mihrabs, pulpits, galleries, and minarets, acquired a distinctive identity within Islamic architecture. The call to prayer (adhan), introduced to announce the time of prayer, led to the appearance of minarets (Özcan, 2013; Ateş, 2014), first built in the Umayyad period in Damascus and Fustat. Earlier precedents of minarets include ziggurats, watchtowers, stupas, and the Lighthouse of Alexandria (Creswell, 1926a; 1926b; 1926c).

Among the earliest examples, Mesleme added four square towers to the Mosque of Amr in Fustat (Creswell, 1926c; Arseven, 1950; Yücel, 1966). Square minarets were also erected at the Basra Congregational Mosque and al-Masjid al-Nabawi (Gottheil, 1910; Creswell, 1926b; Sauvaget, 1947; Nefes, 1996; Battuta, 2004). The Umayyad Mosque in Damascus, adapted from a church, originally possessed four towers (Nefes, 1996; Asfour, 1997). Prominent minarets of this era include those of the Mosque of Sidi Uqba in Kairouan (Uysal, 1990; Asfour, 1997), the Mosque of Umar in Basra (Creswell, 1989), the Great Mosque of Harran (Lloyd and Brice, 1951; Bloom, 1989), the spiral Malwiya Minaret of the Great Mosque of Samarra (Çam, 1994; Nefes, 1996), and the minaret of Abu Dulaf. Through such examples, minarets became defining features of mosque identity and the urban silhouette.

Following the conversion of the Turks to Islam, their earliest minarets included the spiral Malwiya-type minaret of the Mosque of Ibn Tulun in Cairo (Yazici, 2002), the Karakhanid Burana Tower, the minarets of Uzgend, the Kalyan Minaret in Bukhara, and the Vabkent Minaret (Cezar, 1977; Başar, 1997). These were distinguished by ornate decoration, conical forms, and slender profiles. The minarets Damghan and Saveh were circular brick structures (Stark, 1935). The Jam and Qutb Minarets have also been interpreted as having served commemorative or watchtower functions (Kulaç, 2002). The Great Seljuks built minarets that were slenderer and taller than those of the Karakhanids, introducing balconies supported by muqarnas corbels (Uysal, 1990). The Anatolian Seljuks introduced the base section (*pabuç*) into minaret architecture and enriched their works with brick ornamentation and glazed tile decoration. The İnce Minaret in Konya is a prominent example of this tradition (Başar et al., 2007).

During the Beylik period, alternating use of stone and brick became characteristic. In the classical Ottoman period, minaret architecture reached its highest development. Stone became the principal construction material, and mosques with multiple balconies and minarets were erected (Onur, 1974). In notable cases such as the Üç Şerefeli Mosque in Edirne and Mimar Sinan's Selimiye Mosque, minarets reached more sophisticated forms through their slender proportions, considerable height, and multi-flight staircases.

From the Karakhanids to the Ottomans, Turkic–Islamic minarets evolved into increasingly refined, balanced, and functional structures. In the classical Ottoman period, they achieved their mature composition, consisting of pedestal, base, shaft, balcony, lantern, spire, and finial (Şapolyo, 1969; Başar, 1997). Minarets were built either freestanding or attached to the main mosque, with foundations reinforced by stone blocks and in some cases supported by timber isolators (Ahunbay, 1988; Aksoy, 1982). Shafts were predominantly cylindrical and contained helical staircases. Balconies were functional for the call to prayer but also occasionally used as vantage points. The lantern, spire, and crescent finial formed the concluding architectural components. Staircases were constructed of brick, stone, or composite materials, with or without central cores.

Construction techniques employed stone, brick, timber, and lime–pozzolanic mortar (Khorasan). This mortar provided structural integrity and exhibited properties comparable to modern concrete. In stone minarets, iron clamps and lead were used, whereas in brick minarets structural cohesion was ensured by timber ties.

Throughout history, minarets have served not only as integral components of mosques but also as architectural and engineering landmarks that shaped urban skylines. Although masonry minarets were seismically vulnerable, advances in construction methods and material use nevertheless enhanced their durability. Consequently, minarets became one of the most symbolic and structurally sensitive elements of Islamic architecture.

ANALYSES OF THE SEISMIC PERFORMANCE OF TURKISH MINARETS

The Kalyan Minaret in Bukhara

The Kalyan Minaret is regarded as one of the earliest and most resilient surviving examples of the Turkic minaret tradition. An inscription in glazed tiles on its walls states that it was commissioned by Arslan Khan in AH 521 (AD 1127) (Aslanapa, 1984; Saoud, 2003). Constructed of brick on a polygonal plinth, the minaret rises with a thick, tapering conical shaft. Since the dimensions of the plinth and the shaft are nearly equivalent, no transitional base section (*pabuç*) was incorporated. Characteristic of Karakhanid minarets, the balcony (*şerefe*) is formed in the style of a baldachin with small muqarnas corbels, and no lantern (*petek*) is placed above it (Figure 1).

The Kalyan Minaret closely resemblance to the earlier eleventh-century Uzgend Minaret, while the Vabkent Minaret, constructed in 1196–97, appears as a later and more modest counterpart (Aslanapa, 1984). The Kalyan Minaret rises to a height of 46.5 metres and is constructed of fired brick. Its brick plinth is sixteen-sided, with a base diameter of 9 metres at ground level and a height of 6 metres. A single-flight brick staircase of 105 steps ascends to the domed balcony platform at the top of the structure (Peter, 2007).

Figure 1. Kalyan Minaret, Bukhara (wikimedia.org).

Modal Analysis

A modal analysis of the Bukhara Kalyan Minaret was conducted using the Lanczos Eigen-solver for the first fifteen modes. The resulting frequencies and periods are presented in Table 1, while the mode shapes corresponding to the first seven modes are illustrated in Figure 2.

The first and third modes occur in the X–Z plane, whereas the second and fourth modes appear in the Y–Z plane. Modes 1 and 2, as well as Modes 3 and 4, are successive and, although they occur in orthogonal planes, they are essentially identical in nature. The fifth mode represents torsional behaviour. When the structure is subjected to excitation close to this frequency, torsional effects and shear forces are expected to become significant.

The sixth mode corresponds to vertical deformation (axial elongation and shortening) along the Z-axis. Owing to the relatively large base diameter and massive form of the Kalyan Minaret, no pronounced "S-shaped" sway motion can be identified in the first seven modes. Instead, oscillatory effects are more concentrated in the balcony (*şerefe*) region.

Table 1. Frequencies and periods of the first 15 modes of the Bukhara Kalyan Minaret.

Mode	Period (s)	Frequency (Hz)	Frequency (rad/s)
1	0.8141	1.2284	7.7190
2	0.8045	1.2430	7.8100
3	0.2405	4.1579	26.1250
4	0.2394	4.1764	26.2410
5	0.1777	5.6284	35.3640
6	0.1288	7.7641	48.7830
7	0.1142	8.7571	55.0230
8	0.1133	8.8233	55.4390
9	0.1008	9.9191	62.3230
10	0.0708	14.1230	88.7390
11	0.0703	14.2250	89.3760
12	0.0617	16.1960	101.7700
13	0.0611	16.3710	102.8600
14	0.0604	16.5530	104.0100
15	0.0600	16.6640	104.7000

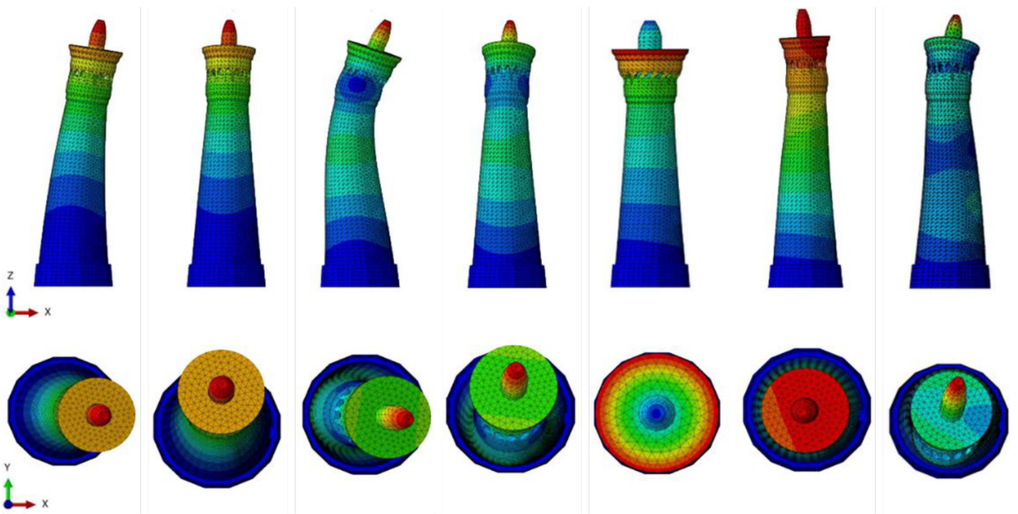


Figure 2. The first 7 mode shapes of the Kalyan Minaret from different views.

Seismic analysis

The seismic analysis of the Kalyan Minaret was conducted along all three axes using the ground motion records of the 17 August Kocaeli–Düzce earthquake. Figure 3 illustrates the distribution of relative displacements along the height of the minaret at the moment of maximum displacement.

The results indicate that the absolute maximum displacement occurred at 9.989 seconds of the record in the north–south direction, with a value of 13.86 cm. In the east–west direction, the maximum displacement was recorded at 9.829 seconds, with a value of 22.71 cm. The resultant displacement of the minaret reached its maximum at 9.459 seconds of the earthquake record, with a magnitude of 25.09 cm.

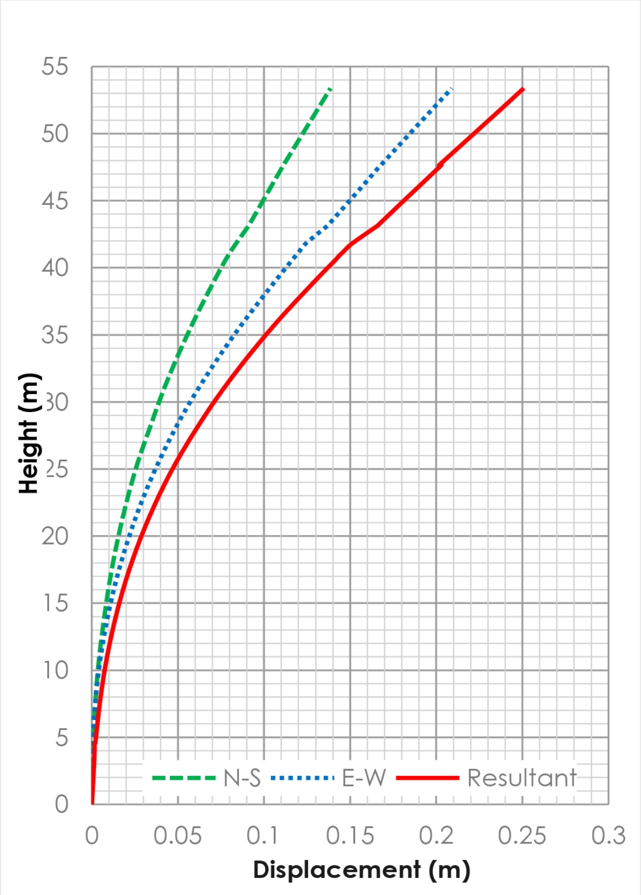


Figure 3. Relative displacements along the height of the Kalyan Minaret.

Principal Stress Analysis

The maximum and minimum principal stress diagrams of the Bukhara Kalyan Minaret are presented in Figure 4. The stress–time histories indicate that the maximum principal stress reached 5.115 MPa at 9.459 seconds of the earthquake record, while the minimum principal stress reached –6.652 MPa at 9.829 seconds. The spatial distributions of principal stresses at the instants of maximum and minimum values are illustrated in Figure 5.

In the Kalyan Minaret, the peak compressive and tensile stresses are concentrated at the arch springing line, and the arch supports of the baldachin-type balcony (*şerefe*). As the minaret lacks a well-defined plinth (*kürsü*) and transitional base section (*pabuç*) and instead rises directly from a broad and symmetrical foundation plan into a tapering, massive shaft, stresses are distributed along the body of the structure. However, owing to the structurally weaker configuration of

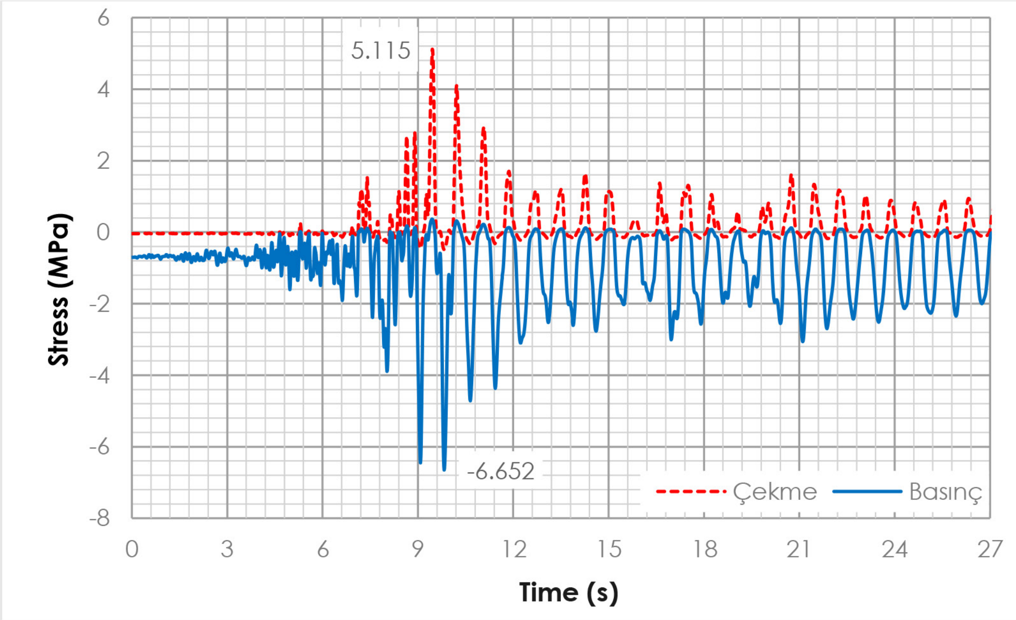


Figure 4. Principal Stresses in the Kalyan Minaret.

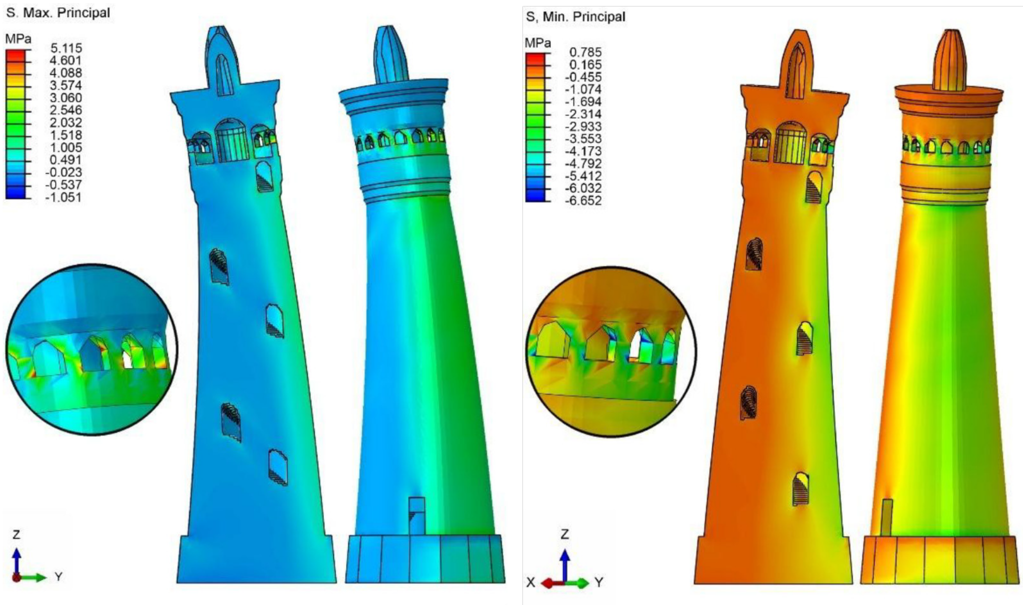


Figure 5. Maximum and Minimum Principal Stress Distribution of Kalyan Minaret.

the arched balcony zone, stresses reach peak levels in this region, subjecting it to critical demand. Under an event like the 17 August Kocaeli–Düzce earthquake, damage in these regions would be expected.

Additionally, stress concentrations were observed in the arches supporting the loads above the internal stairway. Along the shaft, stress intensity was found to be higher in areas adjacent to the line of the inner stair.

Ghor Jam Minaret

The minaret stands in an isolated location near the historic trade route that once connected Istanbul to India via Herat and Kabul (Menon et al., 2004). It was rediscovered in 1943 by the Governor of Herat, S. Abdullah Malikyar (Stark, 1991). After the Qutb Minar in New Delhi, it is regarded as the second tallest brick minaret in the world (Figure 6). Both minarets were erected during the reign of Sultan Ghiyath al-Din bin Sam (1165–1202) (Thomas et al., 2006).

Figure 6. Jam Minaret (wikimedia.org).

Although the inscription on the minaret cannot be read in full —dated either to AH 570 or AH 590— it is assumed that the structure was built between 1192 and 1194 (Pinder-Wilson, 2001; Sourdel-Thomine, 2004). Located on the southern bank of the Hari Rud River, the minaret now stands alone, as the adjacent mud-brick mosque is believed to have been destroyed. Trousdale (1965), however, contested this view, noting that there is no definitive evidence of such a mosque and observing only the remains of small defensive structures around the minaret. The architect's name has been partially deciphered as Ali, son of Ibrahim of Nishapur, though several portions of the inscription are damaged, making full identification uncertain (Anonymous; Trousdale, 1965; Kulaç, 2002).

The minaret rises on an octagonal plinth (kürsü) measuring 3.80 m on each side, with an internal diameter of 9.20 m and a height of 4 m (Kulaç, 1979). Above this base stands a cylindrical shaft composed of three stages, tapering upwards and reaching a total height of 65.5 m. The lower shaft measures 9.74 m in external diameter at its base and 6 m at the top, with the first balcony (*şerefe*) located 34.55 m above ground level (Anonymous; Clemente et al., 2015). The second shaft is 16 m high, with a lower external diameter of 5 m and an upper diameter of 3.60 m. The third shaft begins with a diameter of 3.10 m, narrows to 2.20 m, and rises to a height of 6 m.

The summit of the minaret terminates in a pavilion composed of six open arches, covered by a dome. Including the dome, this section measures approximately 4.30 m in height. At the transitional zones between the cylindrical shafts, balcony projections are formed, supported by timber tie-beams embedded in the masonry and oriented towards the minaret's core. These projections are reinforced with curved or muqarnas-style plaster corbels.

The internal configuration, consisting of double-flight brick staircases and a central core, extends up to the roof of the first balcony located above the lower shaft (Kulaç, 2002). The stair treads are constructed of three layers of brick, each course staggered to form an interlocking stepped system. The staircase continues to nearly half the height of the second shaft, after which a different stair system provides access to the level of the second balcony. The final staircase, which once led to the now-collapsed upper section, may have been constructed of timber elements (Clemente et al., 2015) (Figure 7).

Figure 7. View of the Jam Minaret's upper body (petek), staircase, and core (wikimedia.org; photoshelter.com).

Modal analysis

Slender and tall minarets generally possess low flexural resistance and therefore may undergo significant lateral displacements under horizontal loading. In cases of dynamic resonance, such structures are particularly prone to collapse. As minarets are typically constructed in polygonal or cylindrical forms with geometrical symmetry, their successive natural frequencies along the vertical axis tend to be very close in value.

Table 2 presents the frequencies corresponding to the first fifteen modes of the Jam Minaret, while Figure 8 illustrates the associated mode shapes. Owing to its more slenderer proportions relative to its height, the Jam Minaret exhibits longer natural periods and lower natural frequencies compared with the Kalyan Minaret. The seventh mode of the Jam Minaret corresponds to torsional behaviour, whereas in the case of the Kalyan Minaret, the torsional mode appears as the fifth mode. The results of the modal analysis of the Jam Minaret are consistent with the findings reported by Menon et al. (2004).

Table 2. Frequencies and periods of the first 15 modes of the Jam Minaret.

Mode	Period (s)	Frequency (Hz)	Frequency (rad/s)
1	1.1659	0.8577	5.3890
2	1.1444	0.8738	5.4900
3	0.4450	2.2474	14.1210
4	0.4295	2.3282	14.6280
5	0.2149	4.6542	29.2430
6	0.2126	4.7035	29.5530
7	0.1677	5.9625	37.4640
8	0.1557	6.4242	40.3650
9	0.1522	6.5721	41.2940
10	0.1339	7.4670	46.9160
11	0.1004	9.9623	62.5950
12	0.0996	10.0380	63.0730
13	0.0965	10.3610	65.0980
14	0.0855	11.6910	73.4560
15	0.0791	12.6480	79.4700

Seismic analysis

The seismic analyses of the Jam Minaret, conducted using earthquake acceleration records, indicate that the top of the structure reached maximum displacements of 42.5 cm in the north–south direction at 9.05 s and 78.9 cm in the east–west direction at 8.75 s. Considering the resultant displacement, which best reflects the actual motion of the minaret, the distribution of relative displacements along the height is shown in Figure 9.

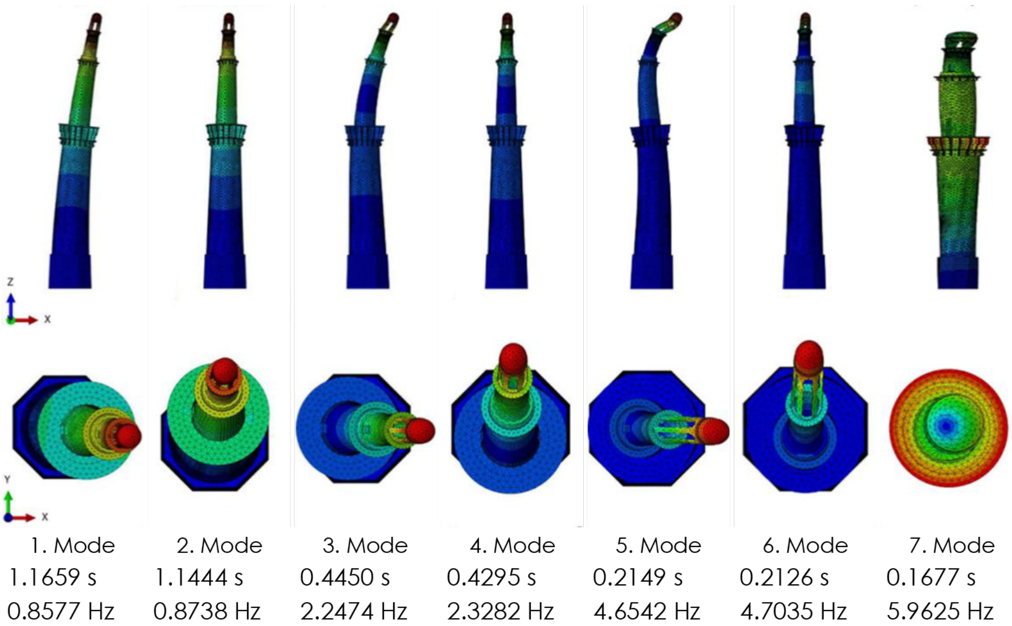


Figure 8. Jam Minaret 1. mode

According to the displacement profile of the 65.5 m-high minaret, the east–west and resultant displacements are nearly coincident. This confirms that, at the corresponding instant, motion in the east–west direction dominated, while displacement in the north–south direction remained limited. The maximum top displacement was 78.9 cm. Such a high value can be attributed to several factors: the considerable height of the structure, its slender shaft, the very thin lantern (*petek*) above the second balcony, as well as the use of brick as the primary construction material.

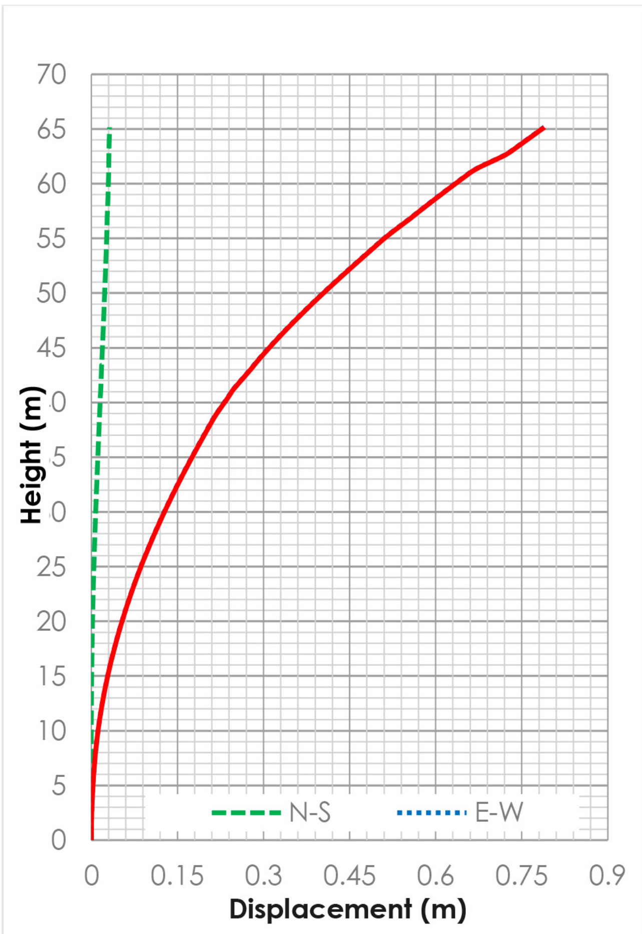


Figure 9. Relative displacements along height of the Jam Minaret,

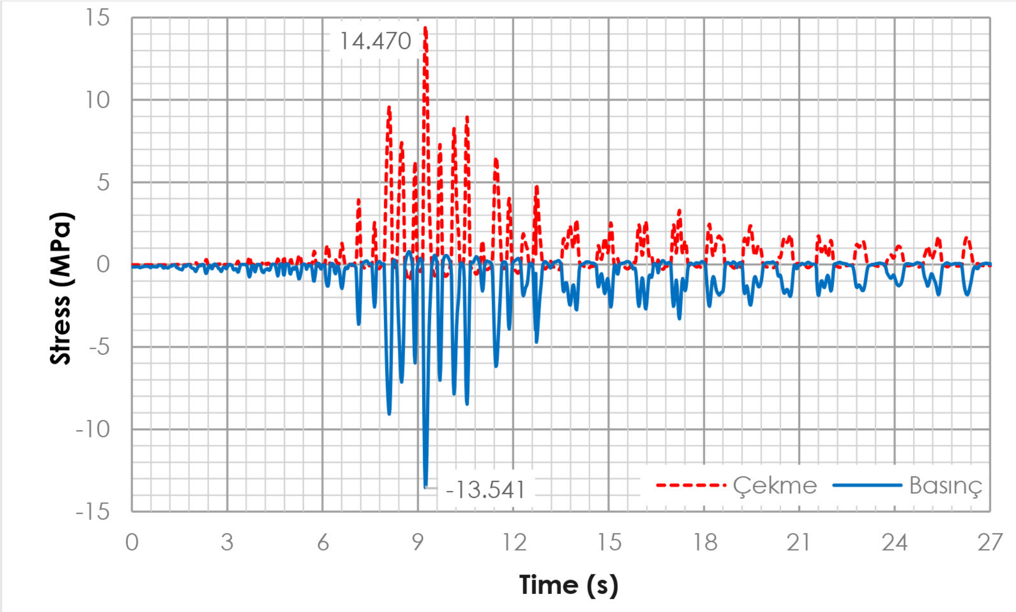


Figure 10. Principal Stresses in Jam Minaret.

According to the seismic analysis of the Jam Minaret, the stress distributions are illustrated in Figure 10. At the moment of peak structural demand (i.e., maximum tensile stress), the S-Max principal stresses are concentrated in the uppermost section of the structure, corresponding to the spire (*külah*). These stresses reach peak levels particularly at the springings of the arches. Tensile stresses are also observed to intensify in the transition zones between the balconies (*şerefes*) and the shaft.

Due to the absence of a pronounced transitional base section (*pabuç*) and the formal similarity between the plinth (*kürsü*) and the shaft, stress concentrations in the lower region remain relatively limited. Compressive stresses are found to accumulate in the same structural regions where tensile stresses are concentrated. The correspondence between tensile and compressive stress distributions reflects the morphological characteristics of the minaret.

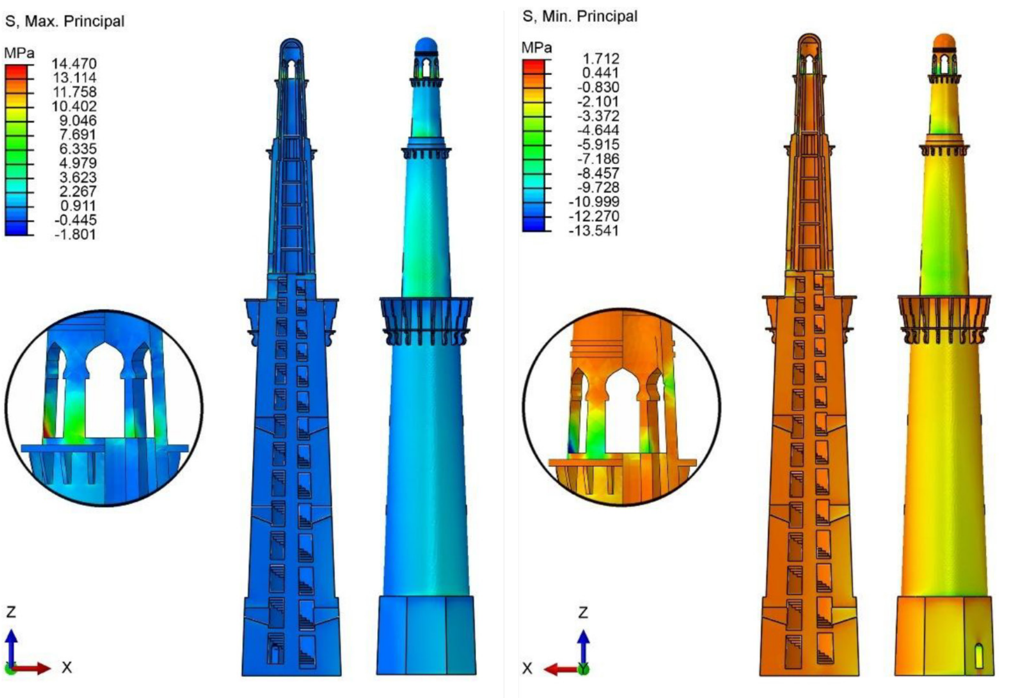


Figure 11. Maximum and Minimum Principal Stress Distribution of the Jam Minaret.

The location of the minaret along the bank of a river presents a problematic condition in terms of ground movements. Its present inclination towards the riverside provides clear evidence of this issue. Accordingly, the horizontal and vertical loads acting on the base of the minaret are as critical as those acting upon its upper sections.

The seismic analyses indicate that the base shear forces at the foundation of the Jam Minaret reached a maximum of 5,788 kN in the north–south direction. In the east–west direction, this value roseto 21,446 kN.

The Minaret of Sivas Great Mosque

The minaret, commissioned during the Danishmend period (1071–1174) but dated to the early thirteenth century, towards the end of the Anatolian Seljuk era, has no surviving records concerning its patron or architect (Arseven, 1955; Kuban, 1965; Kulaç, 1979). It was constructed adjoining the Great Mosque, positioned 3.30 m from the south-eastern corner of the building (Figure 12).

Figure 12. The Minaret of Sivas Great Mosque (Author's archive).

The minaret rises on an octagonal plinth (kürsü), of which 70 cm remains above ground level. Several sides of the plinth are embedded within the walls of the mosque. The height up to the balcony (*şerefe*) is 28 m, while the total height of the structure reaches 32 m (Başar, 1997; Kulaç, 2002). The shaft (*gövde*) was constructed using a keyed brick-bonding technique achieved by recessing the mortar joints. The balcony, 3.20 m in height, was formed with three courses of corbelled brick eaves (kirpi saçak). Both the lantern (*petek*) and the balcony floor were later additions. With a height of 4.55 m, the lantern is slender in proportion to the shaft. The balcony balustrade is brick, the spire (*külah*) is timber, and its exterior is covered with lead sheeting (Başar, 1997).

The shaft is inclined by approximately 1 m towards the north-west, measured from the plinth level, while the lantern remains vertical (Kulaç, 2002). This suggests that the minaret may have collapsed above the balcony level owing to external action. The shaft wall is 0.65 m thick.

Access to the stairway is provided from within the mosque, through a doorway located at the south-eastern corner of the qibla wall, leading into a vaulted corridor. The staircase ascends counterclockwise. The first eleven steps are of cut stone, while the remainder are constructed of brick and timber. The diameter of the central core measures 0.80 m at ground level and reduces to 0.70 m at the balcony. The brick treads are topped with timber coverings (Başar, 1997; Kulaç, 2002). The steps are built with a corbelling technique, and the section height reaches approximately 3 m. There are 115 risers up to the balcony, with access provided by a small landing.

The lantern has undergone repairs and remains hollow inside. There is no vertical post connecting the core to the spire. Instead, the spire is supported by timber tie-beams and posts located at the upper level of the lantern (Başar, 1997; Kulaç, 2002).

Modal analysis

The modal analysis of the finite element model of the Sivas Great Mosque Minaret produced the first fifteen vibration modes, with their corresponding frequencies listed in Table 3 and their mode shapes illustrated in Figure 13. In analyses performed using the modal superposition method, the cumulative mass participation ratio of the included modes must reach at least 90%; only under this condition are the modes considered adequate for calculation.

The vibration modes of the Sivas minaret reveal that the first mode occurs in the x-axis direction, while the second mode occurs in the y-axis direction. The fifth mode corresponds to torsional behaviour, with the structure vibrating in a twisting form at a frequency of 1.71 Hz. The sixth and seventh modes demonstrate a distinct "S-shaped" sway pattern. The remaining modes and their associated frequencies are provided in Table 3.

Table 3. Frequencies and periods of the first 15 modes of the Sivas Ulu Mosque Minaret.

Mode	Period (s)	Frequency (Hz)	Frequency (rad/s)
1	1,6562	0,6038	1.5556
2	1,6491	0,6064	2.0412
3	0,2940	3,4016	5.9170
4	0,2931	3,4114	5.9484
5	0,1657	6,0343	10.7640
6	0,1213	8,2412	12.8920
7	0,1183	8,4519	26.1940
8	0,1158	8,6367	26.3410
9	0,0705	14,178	30.7880
10	0,0691	14,472	35.5310
11	0,0618	16,194	42.1230
12	0,0488	20,476	50.7470
13	0,0481	20,787	51.4520
14	0,0400	25,021	51.6300
15	0,0365	27,414	60.3250

Seismic analysis

The 27-second displacement record for the north–south direction shows that the maximum relative displacement of the Sivas Great Mosque Minaret occurred at 12 s, reaching 32.9 cm. In the east–west direction, the maximum relative displacement was observed at 8.36 s, with a value of 69.3 cm. The more representative measure, the resultant relative displacement at the top of the minaret, reached 73.3 cm at approximately the ninth second of the earthquake (Figure 14).

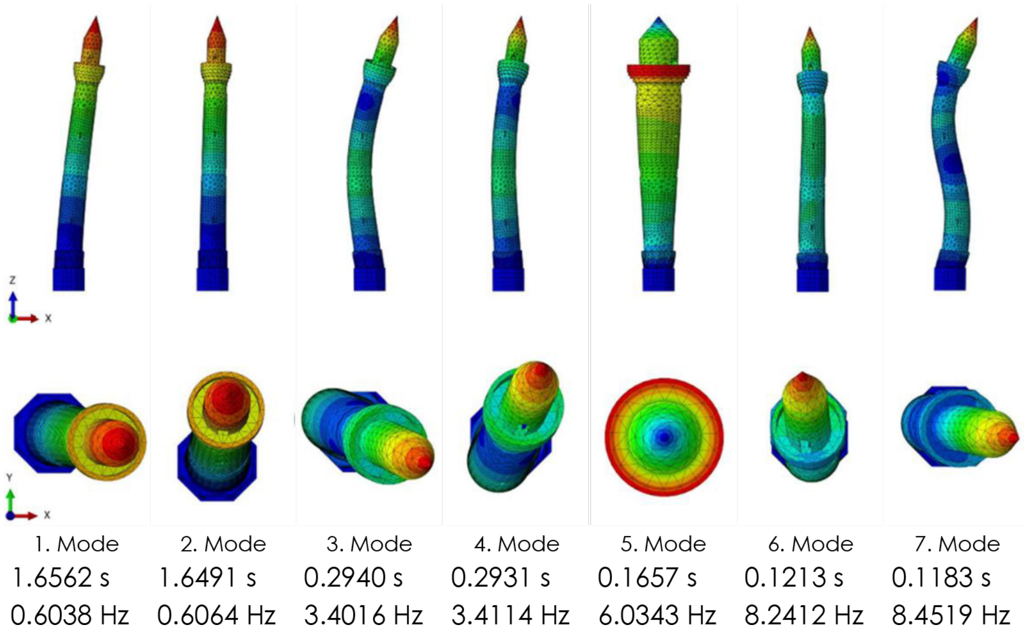


Figure 13. First 7 modes of the Sivas Ulu Mosque Minaret.

The graph in Figure 14 was plotted using displacement data extracted from points located near the centre of the core along the height of the minaret at the instant of maximum resultant displacement. The curves of the east–west displacement and the resultant displacement appear to be closely aligned.

According to the stress results obtained from the analyses of the Sivas Great Mosque Minaret, the maximum tensile stress was calculated at 23.217 MPa, while

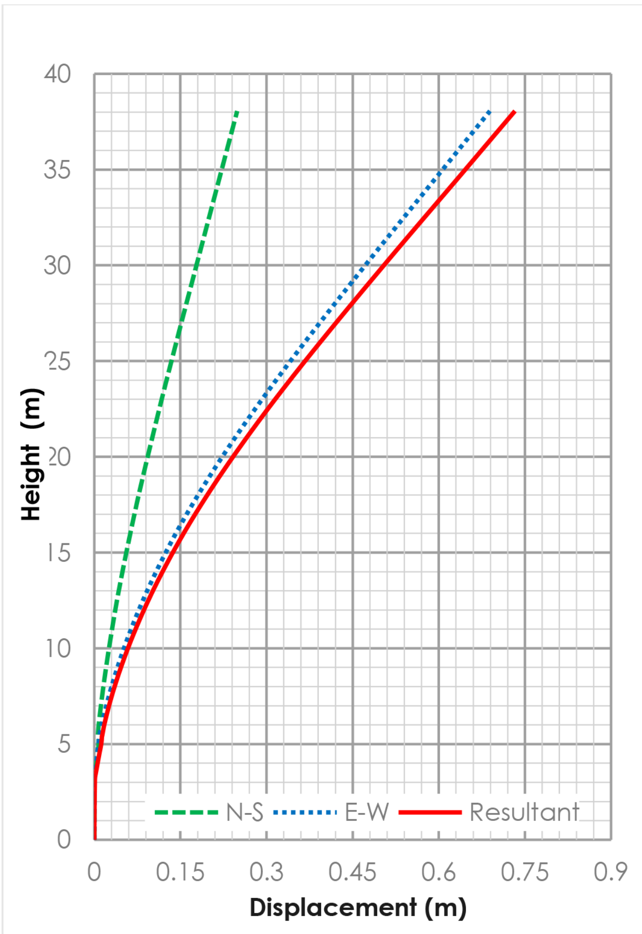


Figure 14. Sivas Ulu Mosque Minaret, relative displacements along height.

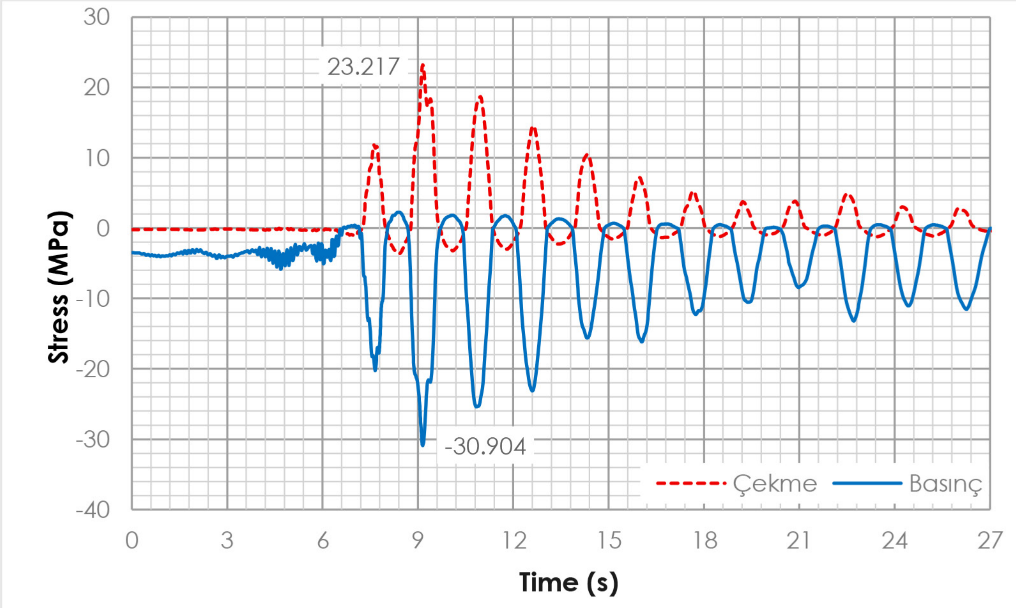


Figure 15. Principal Stresses in the Minaret of Sivas Ulu Mosque.

the maximum compressive stress reached 30.904 MPa (Figure 15). These values are considerably high for a brick masonry minaret. At present, the minaret leans westwards from its plinth. Çılı and Üstündağ (2011) suggest that this inclination may have resulted from materials deformations at the transition from the plinth (*kürsü*) to the shaft, combined with ground movements.

As illustrated in the stress distribution diagrams at the instant of peak demand, both tensile and compressive stresses are concentrated particularly at the junction between the stone plinth and the brick plinth. Stress intensification is also evident at the transition from the polygonal base to the cylindrical shaft (Figure 16). This finding is significant, as it corresponds to the section where the present inclination of the minaret is observed. Under seismic actions of such magnitude, the Sivas Great Mosque Minaret would be expected to sustain severe damage, with the potential for collapse.

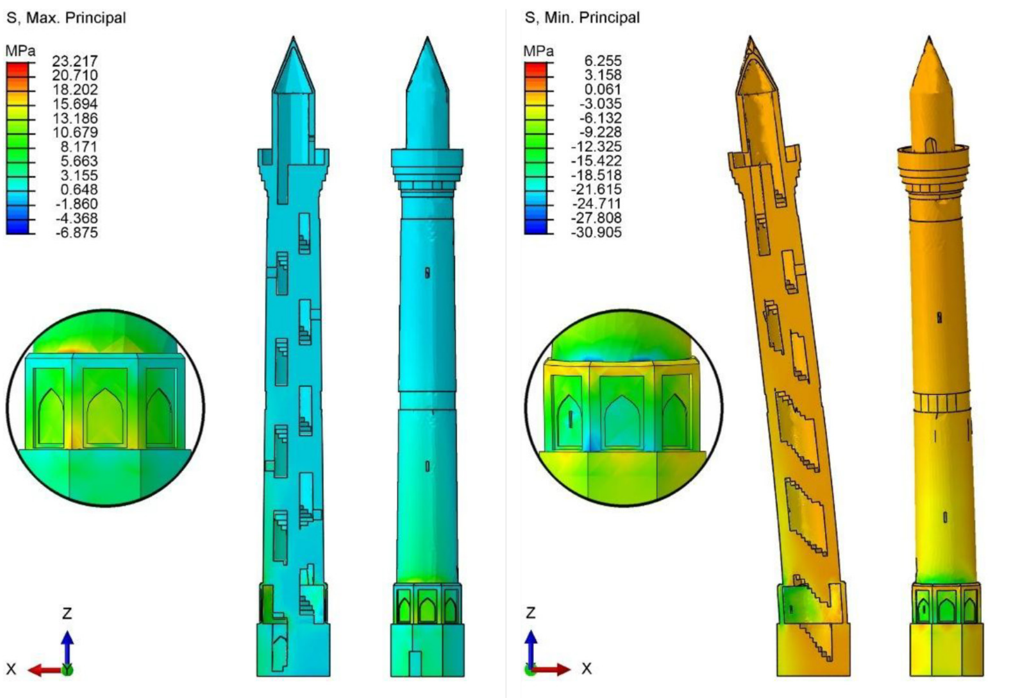


Figure 16. Maximum and minimum principal stress distribution of the Sivas Ulu Mosque Minaret.

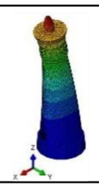
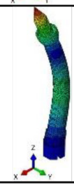
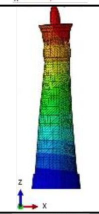
EVALUATION OF SEISMIC PERFORMANCE ANALYSES

In this study, three examples of traditional Turkish minarets —the Bukhara Kalyan Minaret, the Ghor Jam Minar, and the Minaret of the Great Mosque of Sivas— were modelled in a computer environment and analysed using the finite element method with an actual earthquake record. The findings demonstrate that the formal evolution of minarets requires assessment not only from an architectural and artistic standpoint but also from the perspectives of structural engineering and conservation.

Comparison of Modal Analysis Results

Based on the modal analysis of the three minarets examined in this study, the mode shapes and frequency/period comparisons of the first seven modes reveal that the mode shapes of the first four modes are similar across all cases. However, from the fifth mode onwards, notable differences are observed. For the Bukhara Kalyan Minaret and the Sivas Great Mosque Minaret, both measuring 55 m or

Table 4. Modal shapes, frequency, and period table for three minarets.

	Bukhara Kalyan M.		Ghor Jam Minaret		Sivas Great Mosque M.	
1. Mode		0.8141 s 1.2284 Hz		1.1659 s 0.8577 Hz		1.6562 s 0.6038 Hz
2. Mode		0.8045 s 1.2430 Hz		1.1444 s 0.8738 Hz		1.6491 s 0.6064 Hz
3. Mode		0.2405 s 4.1579 Hz		0.4450 s 2.2474 Hz		0.2940 s 3.4016 Hz
4. Mode		0.2394 s 4.1764 Hz		0.4295 s 2.3282 Hz		0.2931 s 3.4114 Hz
5. Mode		0.1777 s 5.6284 Hz		0.2149 s 4.6542 Hz		0.1657 s 6.0343 Hz
6. Mode		0.1288 s 7.7641 Hz		0.2126 s 4.7035 Hz		0.1213 s 8.2412 Hz
7. Mode		0.1142 s 8.7571 Hz		0.1677 s 5.9625 Hz		0.1183 s 8.4519 Hz

less in height, the fifth mode corresponds to torsional behaviour. In contrast, for the Jam Minaret, which exceeds 55 m in height and contains multiple balconies (*şerefes*), appears as the seventh mode. This distinction can be attributed to differences in height, slenderness, and the number and position of balconies.

In the Jam Minaret, the fifth and sixth modes exhibit S-shaped sway patterns, whereas the same forms occur in the sixth and seventh modes of the Sivas Great Mosque Minaret. In the Bukhara Kalyan Minaret, the sixth mode corresponds to axial elongation, while S-shaped sway patterns are observed in the seventh and eighth modes. This divergence is primarily related to the massive and stocky form of the Kalyan Minaret (Table 4). The geometry and dimensions of the plinth (*kürsü*) also influence the variation of frequencies and mode shapes along the vertical axis. Furthermore, increases in minaret height and reductions in cross-sectional area exert a lengthening effect on the natural period.

Comparison of Displacement Results

Relative displacement profiles along the height of the minarets, plotted at the instants of maximum resultant top displacement, are presented in Figure 17. According to these results, the Jam Minaret exhibited a maximum displacement of 78.9 cm, the Kalyan Minaret 25.1 cm, and the Sivas Great Mosque Minaret 73.3 cm. Although the Jam Minaret shows the largest absolute displacement, the graphs clearly indicate that, when normalised to height, the Sivas Minaret experienced proportionally greater displacements.

At its top, the Sivas Minaret exhibits an inclination of 1.1028°, corresponding to 0.0192, which represents the poorest displacement performance among the three minarets. By contrast, the Kalyan Minaret shows an inclination of only 0.2692°, corresponding to 0.0046, reflecting the most favourable displacement performance. This behaviour is attributed to its massive and conical form. The Jam Minaret, despite its greater height and slender proportions, demonstrates a relatively better performance than the Sivas Minaret, with an inclination of 0.6941° corresponding to 0.0121.

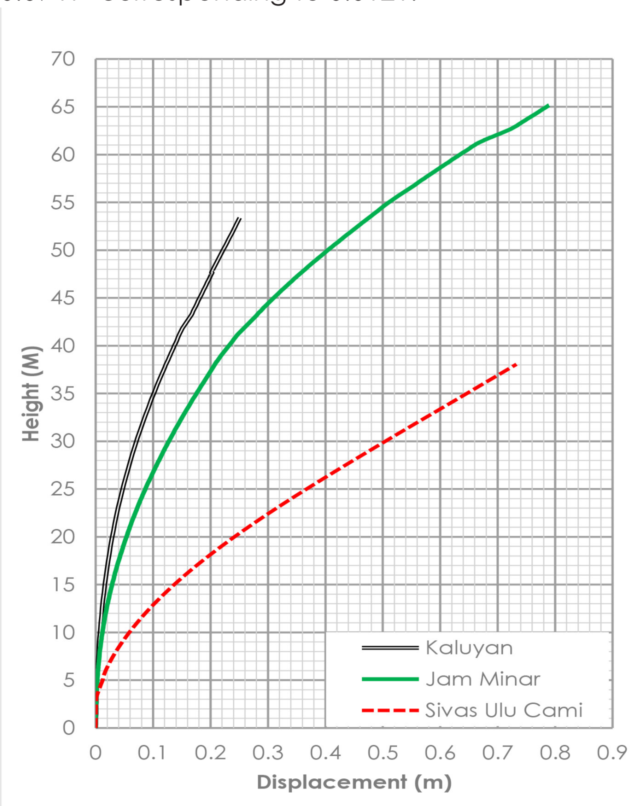


Figure 17. Comparison of relative displacements along the heights of the minarets.

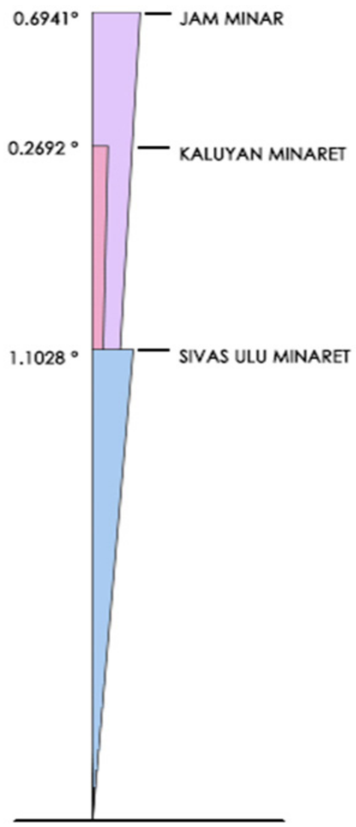


Figure 18. Angles and inclinations of displacement at the tops of minarets.

Figure 18 presents the inclination angles of the minaret tops relative to the vertical axis, together with their drift ratios. According to the displacement limits defined in the Turkish Earthquake Code (TDY-2007), all of the minarets remain below the 3% threshold and therefore fall within the safe zone (GV). Furthermore, FEMA-356 specifies a drift limit of less than 1% for masonry walls considered to be in the safe range. This requirement is satisfied by both the Jam Minaret and the Kalyan Minaret.

Consequently, under the Kocaeli earthquake record, these minarets may be regarded as compliant with present-day seismic code provisions in terms of displacement limitations.

Nevertheless, owing to the variations in height and construction materials among the minarets, the comparative analysis can be further substantiated by examining the displacements at equivalent elevations together with their ratios to the total height. Accordingly, the drift ratios of each minaret, calculated at 3-metre height intervals, are presented in Figure 19. As illustrated in the graph, the inclination of the Sivas Great Mosque Minaret exhibits a sudden increase at approximately 3 metres. This phenomenon suggests that the pedestal section of the minaret is structurally inadequate in resisting lateral forces. By contrast, the other minarets (Kalyan and Jam), which display a more conical elevation from ground level upwards, do not reveal such an abrupt increase in inclination at these elevations.

Further inferences may also be drawn from this graph. The abrupt change observed between 42 and 48 metres in the Kalyan minaret can be attributed to the conical cap at its apex, while the shaft itself appears to undergo displacement with an almost constant inclination. In the case of the Jam Minar, sudden variations in inclination are observed between 39 and 42 metres, corresponding to the lower part of the second shaft; however, the principal

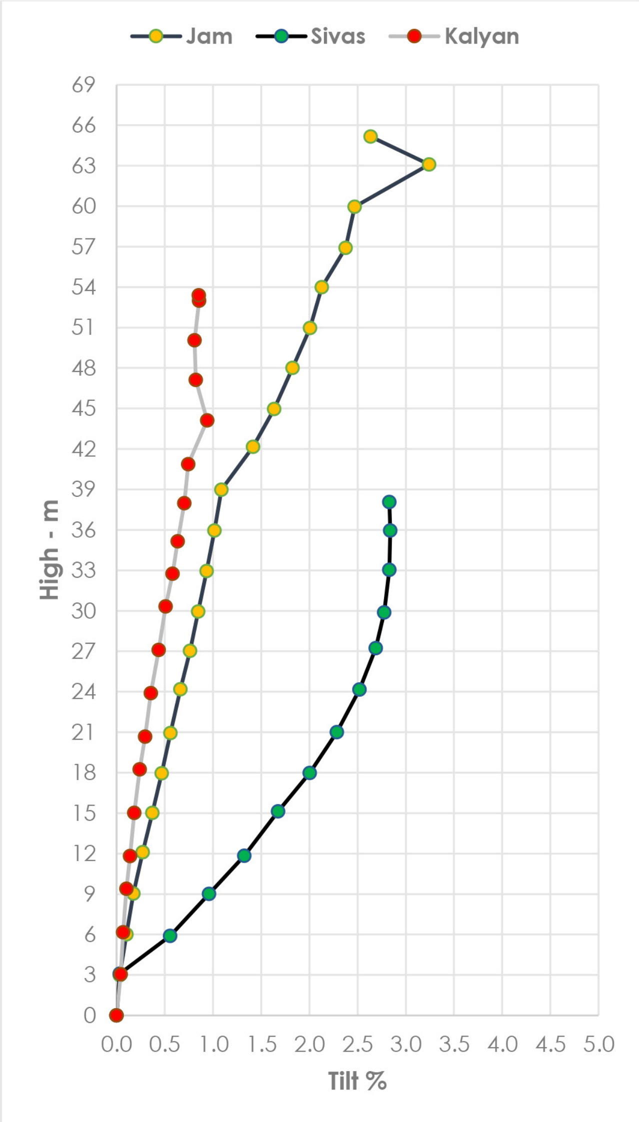


Figure 19. Inclination/ratio (drift ratio) at every 3 meters of height of minarets.

abrupt change occurs between 60 and 65 metres, at the level of the arched section surmounted by a domed conical cap. This behaviour appears to be consistent with the concentration of stresses in these regions.

Comparison of principal (compressive and tensile) stresses

By means of Time History Analysis, a method widely employed in the detailed assessment and structural evaluation of buildings, the seismic responses of the minarets were examined. This approach enabled the identification of their structural behaviour under earthquake loading, together with the deformations of individual structural elements and the concentration of stresses. Within this scope, the acceleration records of the 17 August Kocaeli–Düzce earthquake were applied to all minarets along three orthogonal axes (x, y, z). For historic structures constructed with brittle materials, stresses constitute a critical parameter for assessing performance, alongside displacements.

The present study sought to determine the maximum and minimum stresses generated in the minarets during the seismic event, the distributions of these stresses along the minaret height at the instant of peak loading, and the specific regions where stress concentrations occurred. A colour scale was employed to illustrate the distributions of the maximum and minimum principal stresses (S-Max and S-Min). In these visualisations, red zones in the S-Max diagrams denote regions subjected to tensile stresses, whereas blue zones in the S-Min diagrams indicate compressive stress regions.

Following the comparative evaluation of the principal stress diagrams, all minarets were assessed with respect to the stress concentrations arising along their height at the instant of maximum seismic demand, and their morphological responses were interpreted accordingly.

As illustrated in Figure 20, the stress analyses based on the 27-second earthquake record applied to the Bukhara Kalyan Minaret, the Jam Minar, and the Sivas Great Mosque Minaret reveal distinct differences in performance. The Sivas Great Mosque Minaret exhibited the highest stress values, with tensile stresses of up to 23.217 MPa and compressive stresses of 30.904 MPa, which can be regarded as exceptionally high for a brick masonry structure. In comparison, the maximum and minimum principal stresses of the Kalyan Minaret were 5.115 MPa and -6.652 MPa, respectively, while the Jam Minar reached 14.470 MPa in tension and -13.541 MPa in compression. These results indicate that, relative to the other two minarets, the Sivas Great Mosque Minaret demonstrates markedly inferior seismic performance.

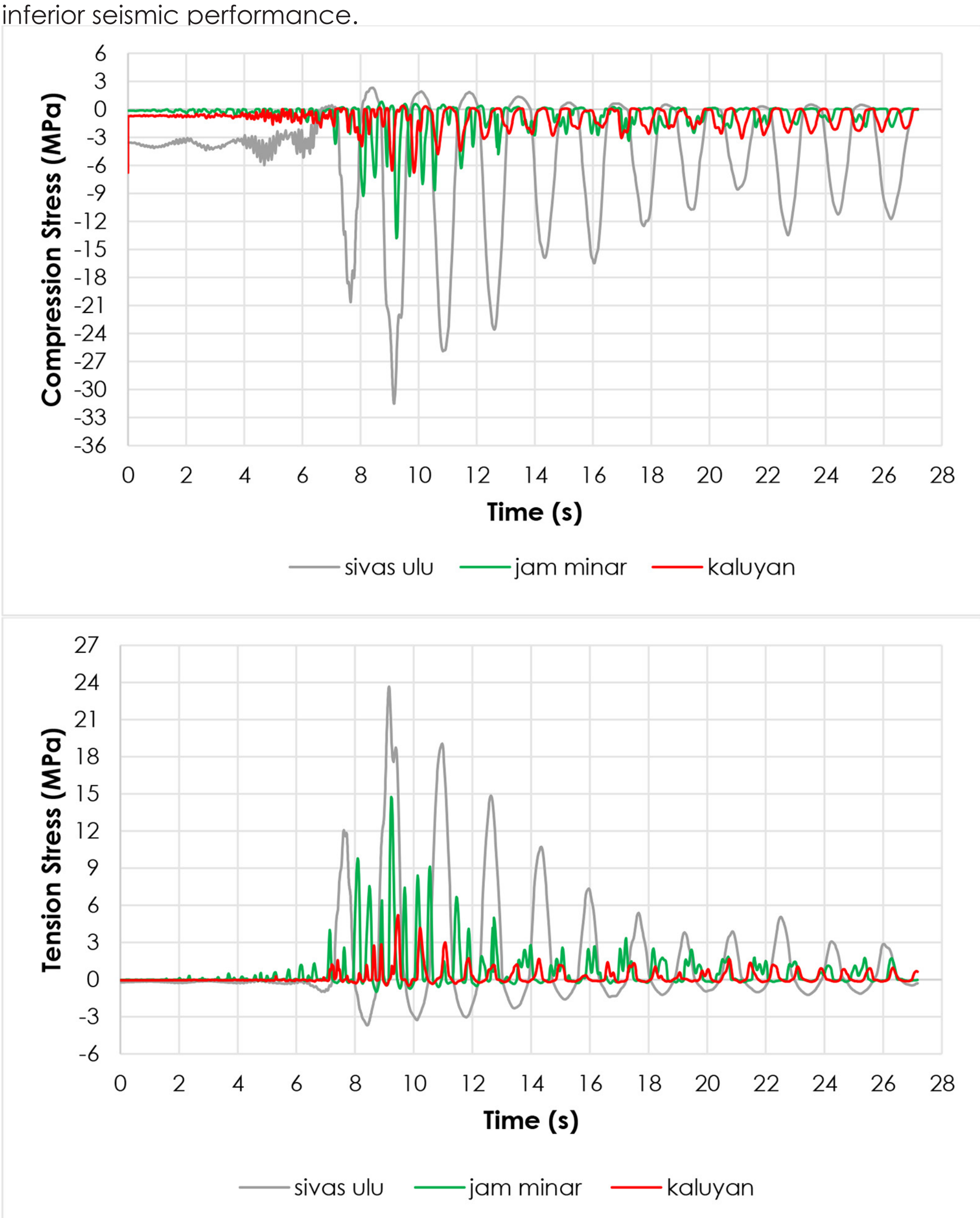


Figure 20. Comparison of the minimum and maximum principal stresses of the Kalyan, Jam Minar, and Sivas Great Mosque minarets.

The Kalyan Minaret, owing to its conical and relatively thick shaft, is evidently the least affected by stress concentrations. The Jam Minar, being the tallest and slenderest among the three, is subject to higher stress levels than the Kalyan Minaret, though considerably lower than those observed in the Sivas Great Mosque Minaret. It is noteworthy that the peak stresses in the Jam Minar occur at its upper section, implying that the main shaft experiences lower stresses, whereas the apex is structurally more vulnerable. This observation is consistent with the current collapsed state of the Jam Minar's upper section.

Furthermore, the stress distributions throughout the duration of the seismic record demonstrate that the Sivas Great Mosque Minaret was subjected to sustained stresses ranging between approximately 5–20 MPa, while the Kalyan Minaret experienced 2–5 MPa and the Jam Minar 2–10 MPa. These findings confirm that the Sivas Great Mosque Minaret not only endured the highest stresses, but also remained continuously exposed to them during the earthquake.

A comparative assessment was conducted based on the stress distributions along the minaret shafts at the instant of maximum principal stresses. As illustrated in Figure 21, the distributions of compressive and tensile stresses indicate that, in the conical forms of the Kalyan and Jam Minarets, stresses tend to propagate along the shaft, with the highest concentrations observed in the arched sections at their uppermost zones. In contrast to the Kalyan Minaret, the Jam Minar also exhibits a degree of stress concentration at the junction of its first balcony (*şerefe*).

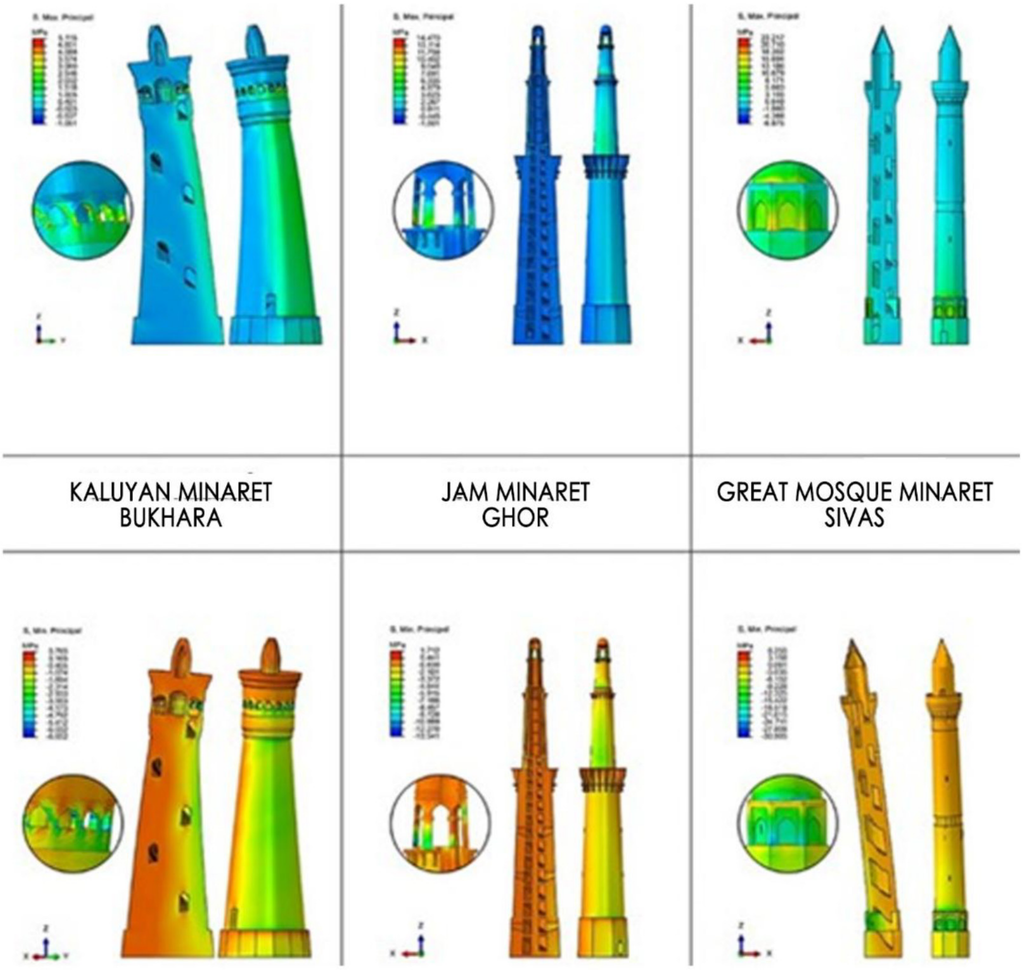


Figure 21. Compressive and tensile stress distributions of the minarets.

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In the Sivas Great Mosque Minaret, stresses predominantly occur at the pedestal and at the transition zone from the pedestal to the shaft. Among the three structures, it is evident that the poorest seismic performance is demonstrated by the Sivas Great Mosque Minaret. As highlighted in previous studies (Sezen et al., 2003), the most critical region of a minaret is typically the transition from the pedestal to the shaft where stress concentrations are strongly influenced by cross-sectional discontinuities.

CONCLUSIONS

This study compared the Kalyan Minaret, the Jam Minar, and the Sivas Great Mosque Minaret, which are all pedestal-less minarets constructed within similar historical periods and displaying comparable morphological characteristics. The analyses indicate that the Sivas Great Mosque Minaret exhibits the poorest relative displacement performance among the three. By contrast, the Kalyan Minaret, owing to its massive and conical form, demonstrates the most favourable displacement behaviour. When the displacements along the height of the minarets are compared collectively, the greatest top displacement is observed in the Sivas Great Mosque Minaret, whereas the smallest is found in the Kalyan Minaret. Accordingly, ranking the minarets from the least to the greatest displacement yields the following order: Kalyan, Sivas Ulu Cami Minaret, Jam Minar.

In terms of principal (compressive and tensile) stresses, the Kalyan Minaret, with its conical and thick shaft, is the least affected by stresses, while the Sivas Great Mosque Minaret demonstrates significantly inferior performance compared with the other two. Despite its relatively modest height, the Sivas Great Mosque Minaret's vulnerability can be attributed to its brick construction, its morphological features, and particularly the underdeveloped pedestal and *pabuç* sections. In this structure, stresses are predominantly concentrated at the pedestal and the transition zone from pedestal to shaft.

The Kalyan Minaret occupies a distinct position among these examples. It is characterised by a wide base and a conical elevation, with minimal structural vulnerability due to morphological factors compared with the other six reference examples.

Consistent with previous findings (Clemente et al., 2014), the present study confirms that the greatest tensile and compressive stresses occur in the *pabuç* section, i.e. the transition from pedestal to shaft, where cross-sectional reductions and discontinuities are present.

The study further concludes that in conical minarets without pedestals or without significant cross-sectional discontinuities between pedestal and shaft (such as the Kalyan, Jam Minar, and Qutb Minar), stress concentrations typically occur at the base under static conditions. However, when subjected to dynamic effects, stress accumulation and damage predominantly occur in the upper sections, rendering the upper portions of the structure the most vulnerable. This observation corroborates the findings of Peña et al. (2010) in their study of the Qutb Minar.

Finally, despite being constructed from brick, the Jam Minar remains an outstanding example of architectural, artistic, and engineering excellence. For its period, it represents a highly advanced and inspiring work, distinguished both structurally and aesthetically.

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