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Architectural and structural analysis of historical structures

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Professional paper

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Architectural and structural analysis of historical structures

Historical structures are integral to the cultural heritage of the world and ought to be safely preserved for posterity. An interdisciplinary approach is critical in the conservation and restoration of masonry structures. Taking this into consideration, this study discusses Gok Madrasah, a 750 year-old structure situated in Amasya, Turkey, in terms of art history and structural engineering. An analysis of decorative elements is made in the paper from an art-history aspect, and a detailed three-dimensional finite element analysis of the structure is conducted.

Ključne riječi:
antique ornaments, historical structure, finite-element method, masonry structures, structural behavior

Stručni rad

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Analiza konstrukcije povijesnih građevina iz arhitektonskog i građevinskog aspekta

Povijesne građevine značajan su dio svjetske kulturne baštine i trebaju se na siguran način sačuvati za buduće naraštaje. Interdisciplinarni pristup izuzetno je važan za očuvanje i restauraciju zidanih građevina. Imajući to na umu, u radu se s aspekta povijesti umjetnosti i stabilnosti konstrukcije razmatra medresa Gok, građevina stara 750 godina, smještena u Amasyji u Turskoj. U radu je provedena analiza dekorativnih elemenata iz povijesno-umjetničkog aspekta te detaljna prostorna analiza konstrukcije metodom konačnih elemenata.

Ključne riječi:
antički ornamenti, povijesna građevina, metoda konačnih elemenata, zidane konstrukcije, ponašanje konstrukcije

Fachbericht

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Architektonische und baustatische Analyse historischer Bauwerke

Historische Bauwerke stellen einen bedeutenden Teil des Kulturerben dar und sollen auf sichere Weise für zukünftige Generationen erhalten werden. Interdisziplinierte Lösungen sind ausgesprochen wichtig für die Erhaltung und Restauration von Mauerwerksbauten. Daher werden in dieser Arbeit kunstgeschichtliche und bautechnische Aspekte der Medresse Gok, eines 750 Jahre alten Bauwerkes in Amasya in der Türkei, untersucht. Die Arbeit umfasst Analysen dekorativer Elemente vom kunsthistorischen Aspekt, sowie eine detaillierte räumliche Analyse des Tragwerks mittels der Finite-Elemente-Methode.

Ključne riječi:
antike Ornamente, historische Bauwerke, Finite-Elemente-Methode, Mauerwerkskonstruktionen, Verhalten von Konstruktionen

1. Introduction

The term "madrasah", which is an Arabic word, means "religious school". A madrasah specifically provides instruction on religious laws and Islamic theology. The concept of madrasah has been in use for at least a thousand years. There are numerous madrasahs in Turkey. These structures were the most important centres of education in ancient times. Many madrasahs were constructed in Turkey during the Seljuk, Anatolian Seljuk, and Ottoman Empire periods in particular.
Many madrasahs in Turkey were built in honour of former viziers and Sultans. Therefore, the madrasahs were among the most respected and prestigious structures. Presently, dozens of these structures are still being used all over Turkey for a variety of different functions. Many of them are considered to be national monuments. These structures are valued as the common heritage of humanity, the preservation of which, based on appropriate techniques, is of global importance as it enables us to pass on this significant heritage to future generations.
Proper understanding of structural behaviour of historical structures requires information about their structural components. This information is especially critical for understanding their need for restoration and preservation, especially in areas prone to seismic activities. Therefore, researchers have been placing a strong emphasis on historical structures and their structural behaviour. Structural performance of different styles of historical structures has been investigated by researchers in a number of previous studies [1-9]. However, Madrasahs, and their structural behaviour, have yet to be the subject of a thorough research and analysis. In this respect, this study mainly focuses on Gok Madrasah and its architectural properties and structural behaviour.

2. Description of historical structure - Gok Madrasah

2.1. General description

Amasya is an important city located in the Central Black Sea Region of Turkey. Amasya is one of the oldest settlements in Anatolia and it has a magnificent history that goes back to the Hittite civilization [10]. It has been a loyal host to several civilizations and cultures. Amasya was the imperial capital for many different empires and is home to a number of buildings reflecting the power of the empires. Dozens of monuments, such as mosques, tombs, madrasahs, caravanserais, bazaars, khans, baths, bridges and pavilions, reflect many different cultures and many of them represent architectural milestones. Amasya, with its rich cultural heritage, is primarily a cultural destination. It is considered a valuable ancient city not only in Turkey, but also on a worldwide scale, due to its natural, historical, and archaeological assets and landmarks.
One of the most notable examples of Amasya's cultural heritage is Gok Madrasah (literally: Sky or Blue Madrasah). Gok Madrasah was built in a central location in Amasya. Because of blue glazed bricks used in the structure, the structure has been named Gok Madrasah (Sky or Blue Madrasah) (Figures 1 and 2). Since there is no inscription, the precise construction date is unknown. However, according to its patrons, the madrasah was constructed by Seyfeddin Torumtay, who was a governor in Amasya during the Seljuk period.

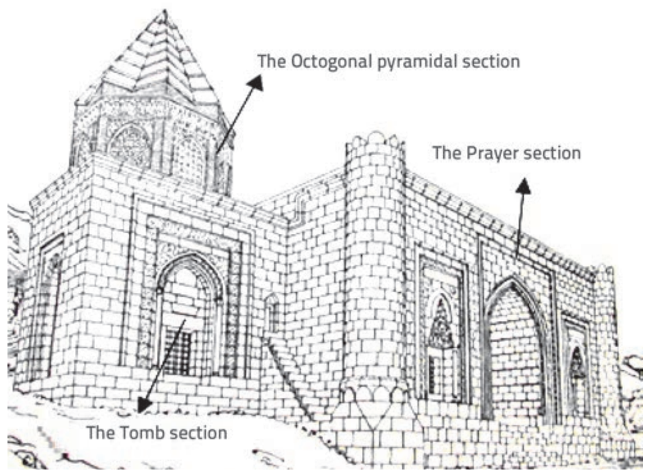

Figure 1. General view of Gok Madrasah [11]

The only inscription found at the structure is the one figuring on a wooden door, now exhibited in the Amasya museum. The inscription reads "Min Amel'i Abu's Silm el-Neccar" (literally: it was made by carpenter Abu's Silm) with thuluth calligraphy (a style of Arabic script known as "Sülüs" in Turkey). Gabriel (1934) [11] and Husamettin(1914) [12] claimed that the carpenter cited on the door was also the architect of Gok Madrasah. However, as stated on the inscription, Abu's Silm was only the carpenter who made the door [13].

Figure 2. Plan and cross section and general view of Gok Madrasah [14]

Although Gok Madrasah is contemporarily used as a mosque, the main purpose for building this structure still remains unknown. Moreover, no accurate records exist about when the building ceased to be used as a madrasah. It can be assumed that education came to a halt at Amasya's Gok Madrasah, like in other madrasahs in the Republic of Turkey, with The Law on Unity of Education, passed on 3 March 1924. Many Turkish researchers believe that the structure was originally constructed as an angular mosque (a small Islamic monastery, also known as corner, prayer room, Arabic: Zawiya, Turkish: Zaviye). Moreover, according to another study, this structure was constructed as an observatory structure and served as an astronomy madrasah much like Cacabey Madrasah in Kirsehir, Turkey [15, 16]. In addition, according to Hüsameddin [12], there were many small rooms that were built with cut stone on the north side of the structure. Moreover, there was a classroom, which was constructed in octagonal shape and in hypaethral form, on the east side of the structure [12].

2.2. Architectural properties of a structure

Although Gok Madrasah is a very complex structure, it is very simple in its architectural shape. The shape of a masonry structure is one of the most important factors for determining structural behaviour. Therefore, an architectural survey was conducted in the first phase of this study. According to this survey, the madrasah consists of three major parts. The first part is the prayer section, the second part is the tomb section, and the third part is the octagonal pyramidal section above the tomb [12].

A portal (crown gate) in the north side, arranged as an *iwan,* serves as the entrance and leads into the prayer section. The portal is surrounded by a rectangular frame, which is adorned with a half six-pointed star. The *iwan* of the portal is comprised of a three-staged frame. The outermost frame is adorned with geometrical motifs. The innermost frame is decorated with guilloche motifs, which is known as "Zencirek" in Turkey. There are two colonnades at both sides of the portal. In addition, two symmetrical rectangular windows are located on the front facade of the structure. The upper sides of the windows, which are enclosed with a geometric motif frame, are covered with

Figure 3. Decorative adornments of the structure

muqarnas niches (decorative stalactite in Islamic architecture). Both sides of the niches are adorned with two colonnades with geometrical motifs (Figure 3). The corners of the colonnades are finished with ornamental headed boss, which is known "Kabara" in Turkey. The outside sections of the window frame are carved using graven technique. The carved motifs are not symmetrical and appear to be incomplete. In addition to the main entrance gate on the North façade, there is a small entrance gate on the east façade.

According to Gabriel, it has a circular opening in the central portion of the first dome and a drain hole, which was adorned with an eight-pointed star motif. It is located on the floor under the first dome. Today, although there are still drain holes, they do not appear in the circular openings.

The mihrab, a niche showing the direction of Mecca, is situated in the south side of the structure. As it can be seen from the traces of plaster, the mihrab is not an original structure. The current mihrab was made of gypsum plaster and it was painted with yellow coloured oil painting. It is estimated that the current mihrab was built during the restoration work in 1963 [13]. The mihrab is covered with a frame, which is decorated with geometrical motifs and muqarnas. Both sides of the mihrab are adorned with two colonnades with geometrical motifs.

Figure 4. Octagonal pyramidal section

The tomb section is located on the north-eastern side of the prayer section. It is known that the tomb was initially a classroom but was converted into a tomb for the relatives of Torumtay, a

Seljuk Amir [16, 17]. It has a rectangular plan and two storeys; the ground floor is the tomb and the basement is the burial chamber. On the ground floor, there are six sarcophaguses (Sanduka), which are thought to have been placed over the grave of an eminent person. Although the basement is currently empty, several graves used to be there, according to elderly people of Amasya. Gabriel (1934) [11] claimed that the entrance to the tomb section was situated outside of the structure. Nevertheless, there is no evidence pointing to an outside entrance and the burial chamber. Additionally, it has also been proposed that the current entrance to the tomb, opening towards the wall of the prayer section, was subsequently installed because its form does not fit the structure. The octagonal pyramidal section is situated on the north-eastern side of the prayer section above the tomb. This section is the most spectacular part of the structure. There we have the blue glazed bricks that give the madrasah its name (Figure 4). Most of the geometric ornamentations in the pyramidal section have been destroyed, but some small parts have survived. The main purpose of this structure is unknown.

2.3. On-site investigation and damage observed

In the second phase, an in-situ investigation was carried out by the authors in order to evaluate the present condition and structural problems of the madrasah. As for construction materials, the madrasah was built with cut stones and solid bricks. Traditional mortar was used as a binding material between masonry units. The interior section of the madrasah was covered with traditional plaster (Figure 5). Because of flaking of the plaster, it is understandable that the domes of the structure were made of solid bricks and the lower parts of the structure were made of cut stones.

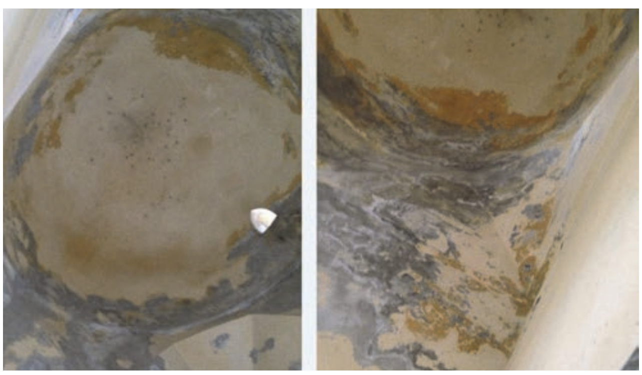

Figure 5. Flaking of plaster

During its existence, the madrasah was damaged on several occasions, either as a result of environmental factors, natural disasters, or human intervention. Thus, the structure was renovated, but not technically repaired, using different materials such as stones and mortar. However, these inadvertent repairs have caused more damage to the structure. Visible signs of deterioration in the structure were visually examined in the light of its structural features and architectural characteristics. Structural materials have decayed and environmental factors have caused the construction materials to deteriorate (Figure 6). The structure's main problems are the damage to structural elements, loss of material, and decrease in structural strength. The mortar between the stone units on the main façade of the structure has partially eroded (Figure 7) and many irregular micro-cracks were observed on the stones.

Figure 6. Material deterioration on the structure

Figure 7. Local mortar damage (mortar between the stone units)

The binding material between the masonry units was partially eroded. The most deteriorated parts of the madrasah are on the octagonal pyramidal section. In some cases, the abrasion and degradations are noticeable on the stone units of the masonry facades. In addition, the madrasah has been subjected to natural disasters and destruction by human hands (Figure 8). Some of this damage is very dangerous because it may cause fatal and destructive cracking and fracturing. In addition, it can cause differential movement of the madrasah components. Consequently, such damage should be taken seriously and precautions should be taken to avoid or to abate its effects.

Figure 8. Deep cracks on octagonal pyramidal section

3. Numerical analysis of structure

3.1. Material characterization

Mechanical properties of stones and bricks were investigated by Seker et al. (2014) [9]. Kara Mustafa Pasha Mosque, located in a county of Amasya called Merzifon, is discussed in that study. The construction materials were investigated in terms of mechanical properties (Figure 9). It is assumed that these material tests can be considered representative of the behaviour of the materials used in Gok Madrasah.

In laboratory tests, the compressive strength values of the stones varied between 43.96 to 57.19 MPa. An average compressive strength was determined to be 50.92 MPa. The tensile strength values varied between 7.45 MPa and 7.61 MPa. An average tensile strength was 7.55 MPa. As for bricks, the compressive strength values ranged from 15.85 to 19.32 MPa, and an average compressive strength was 17.49 MPa. The tensile strength varied between 2.64 MPa and 2.82 MPa, and an average tensile strength was 2.69 MPa [9]. Mechanical properties used in all numerical analyses are summarized in Table 1.

Figure 9. Mechanical testing of materials

Table 1. Material properties

Materials	Young's modulus [MPa]	Poisson's ratios	Density [kg/m³]
Stone	10000	0.17	2358
Brick	3500	0.15	2037

3.2. Numerical model

The most critical part of the structural analysis for Gok Madrasah is to develop a numerical model with finite element members and nodes. Ideally, the numerical model should represent the structure that is being studied. In this study, a three-dimensional finite element model was developed based on the geometrical constraints and structural condition of the structure (Figure 10).

The nite element model of Gok Madrasah was created using the finite element software ANSYS Workbench [18]. In the numerical model, the structure was constituted with 135311 nodes and 55373 Solid186 elements, which have 20 nodes and three degrees of freedom per node. The numerical model for Gok Madrasah is shown in Figure 11. The scope of this paper deals mainly with solids and structures of elastic materials.

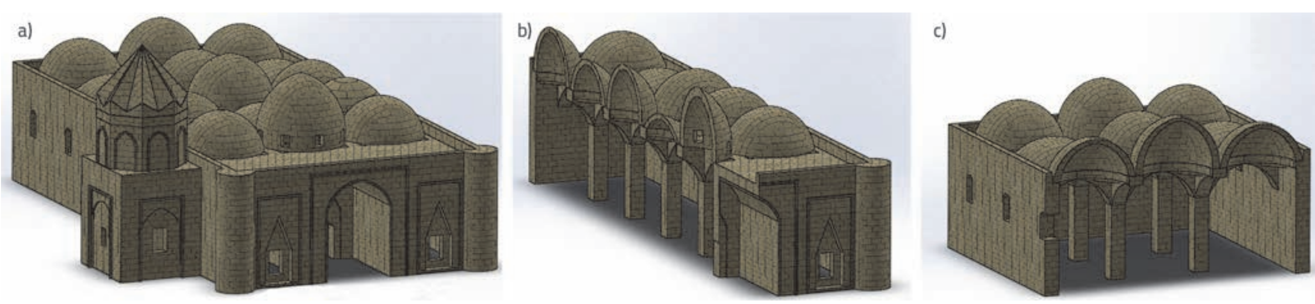

Figure 10. a) Three dimensions model; b) Longitudinal section; c) Transverse section of the structure

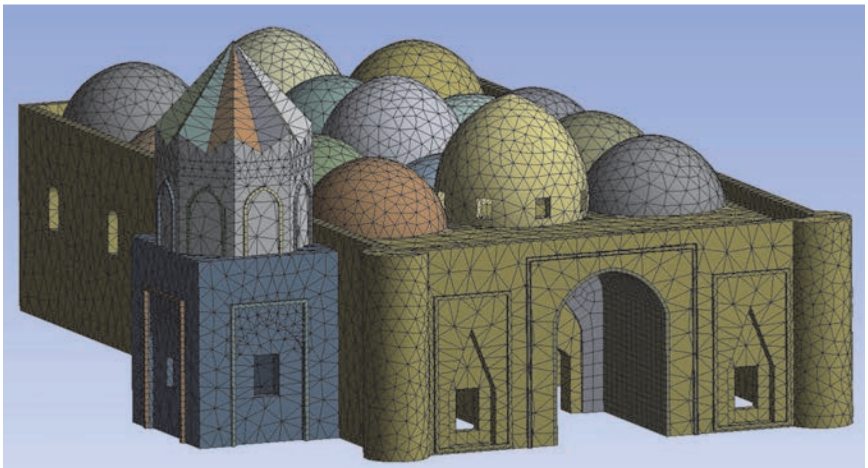

Figure 11. Finite element model of the structure

considered and the stiffness degradation was ignored in this study.

3.3. Static analysis

The influence of geometry has an important role in the structural behaviour of structures. Therefore, as the first step of the finite element analysis, the linear static analysis was performed in ANSYS Workbench using vertical loads corresponding to self-weight.

According to static analysis, maximum displacements occurred on top of the middlemost dome and were found to be 2.647 mm (Figure 12). The maximum principal stress was calculated as 1.169 MPa and it occurred at the sub of the pulleys (Figure 13). Additionally, the minimum principal stress found to be 2.755 MPa occurred at the sub of the main columns (Figure 14).

Additionally, this paper considers only the problems of very small deformations where the deformation and load are in a linear relationship. Hence, linear elastic material behaviour was

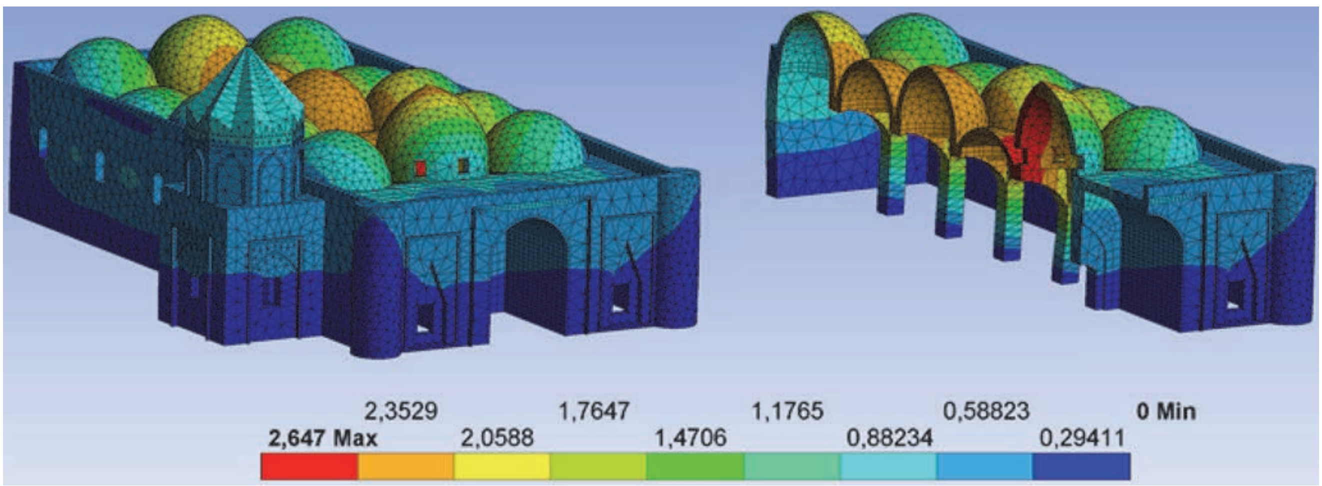

Figure 12. Maximum vertical displacement [mm]

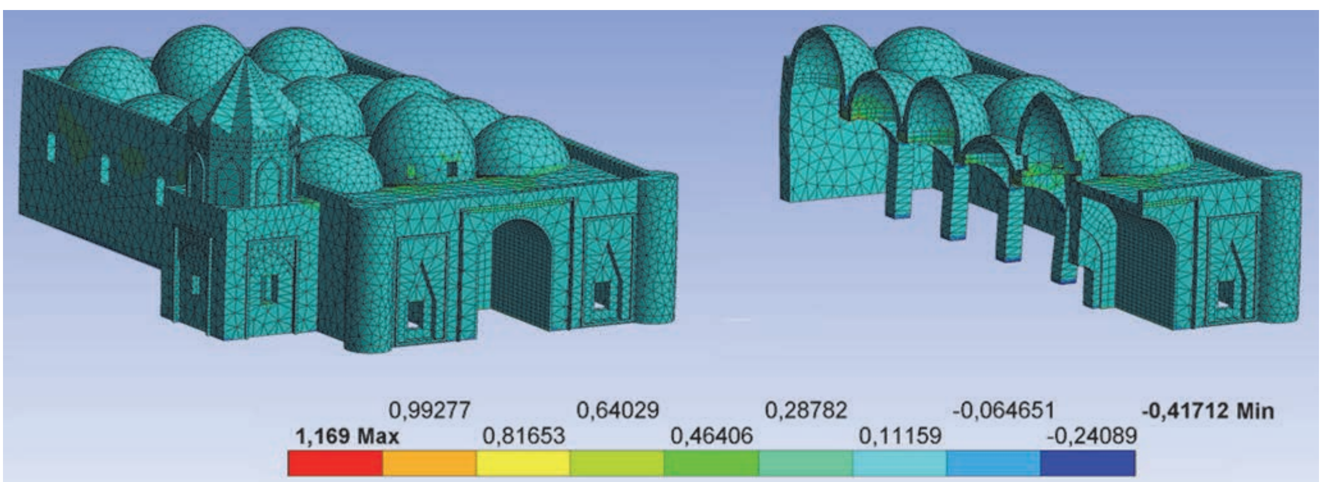

Figure 13. Maximum principal stress obtained from static analysis [MPa]

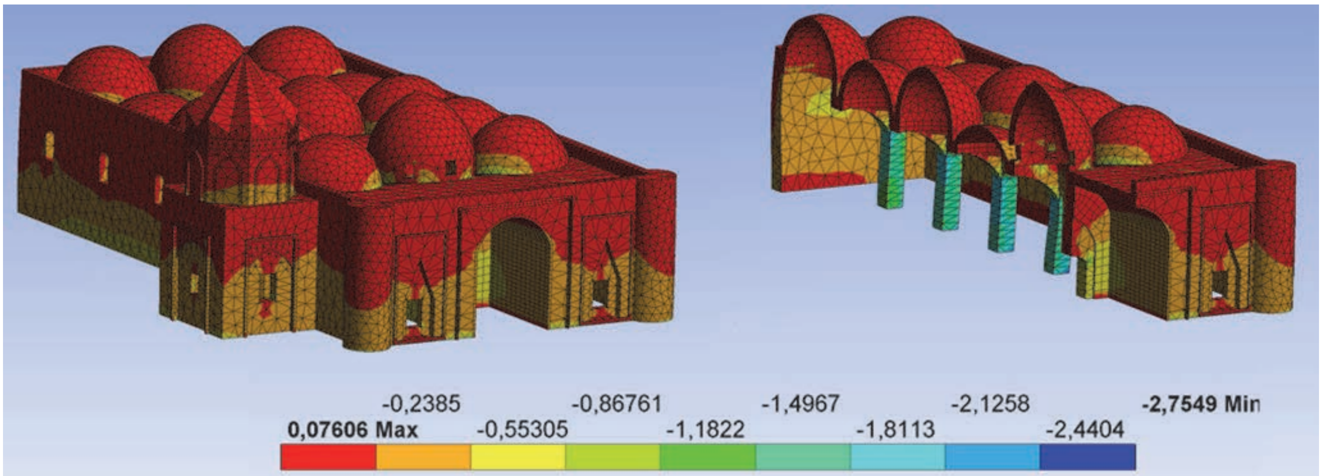

Figure 14. Minimum principal stress obtained from static analysis [MPa]

Table 2. Frequencies, periods and participation ratios

Mode shape	Frequency [Hz]	Period [s]	Participation ratio		
			X	Y	Z
1	4.9391	0.2025	0.5415	$0.9 \cdot 10^{-5}$	$0.1 \cdot 10^{-4}$
2	7.8155	0.1279	$0.1 \cdot 10^{-2}$	0.3021	$0.2 \cdot 10^{-3}$
3	8.0727	0.1238	$0.4 \cdot 10^{-2}$	0.1536	$0.3 \cdot 10^{-3}$
4	9.3521	0.1069	$0.1 \cdot 10^{-2}$	0.1013	$0.5 \cdot 10^{-2}$
5	9.6528	0.1036	$0.2 \cdot 10^{-3}$	$0.1 \cdot 10^{-2}$	$0.5 \cdot 10^{-2}$
6	9.9949	0.1001	$0.9 \cdot 10^{-2}$	$0.7 \cdot 10^{-2}$	$0.3 \cdot 10^{-3}$

3.4. Modal analysis

Modal analysis is used to estimate and to analyse the dynamic response of structures. The aim of modal analysis is to define the frequencies and mode shapes. In this study, the modal analysis was primarily used for the dynamic behaviour and it was considered for the first six modes. The frequencies, periods, and participation ratios are presented in Table 2, and the first mode shapes and directions are presented in Figure 15.

3.5. Time history analysis

According to the Turkish Disaster and Emergency Management Ministry, Amasya is situated in a first-degree (the most dangerous) earthquake prone zone in which an acceleration value of more than 0.4 g is expected. Amasya is positioned on the North Anatolia Fault Line (NAFL) which is a dangerous and active line in Turkey [19]. Time history analysis was therefore considered in this study.

In the time history analysis, the Rayleigh damping with 5% damping ratio was used. The dynamic time history analysis was conducted using a ground motion record from the March 13, 1992 Erzincan earthquake, which has been one of the strongest earthquakes in Turkey to date, with a magnitude of 6.8. The acceleration records of the Erzincan earthquake at central station were considered. The raw PGA Values are 404.97, 470.91 and 238.55 cm/s^2 in the North – South, East – West and Up – Down, respectively [20], and the structure was only

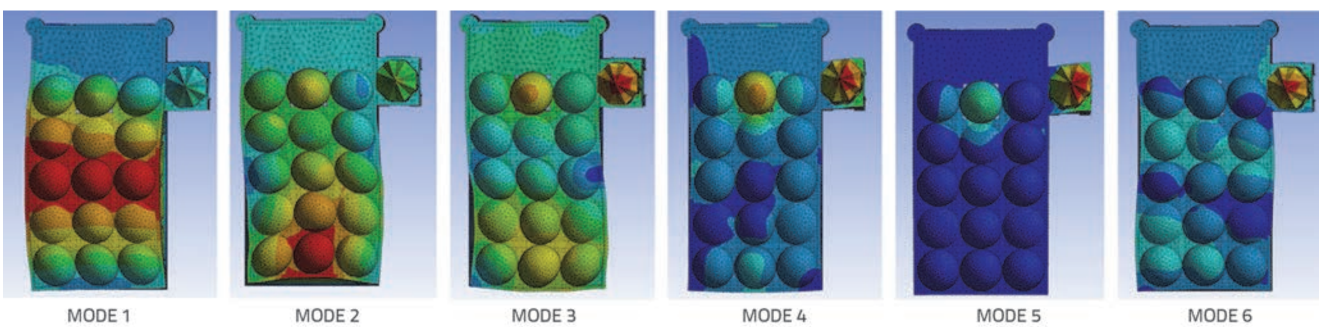

Figure 15. Mode shapes and directions of the first six modes

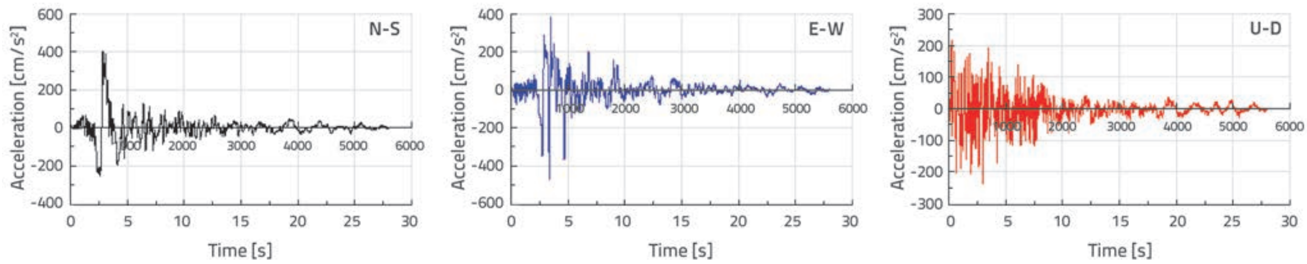

Figure 16. Ground motion record of Erzincan earthquake: North–South (left), East–West (middle) and Up–Down (right), [20]

subjected to the north-south direction, which is the biggest component (Figure 16). Moreover, Rayleigh damping with five percent damping ratio is used in the time history analysis.

As seen from the time history analyses, the maximum lateral displacement occurred at the top of the eastern walls at about 7.62 mm (Figure 17). The maximum principal stress was found to be 4.43 MPa around the pulley of the eastern dome and the facades of the eastern wall (Figure 18). Furthermore, the minimum principal stress was found to be about 3.57 MPa around the lower parts of the main columns (Figure 19).

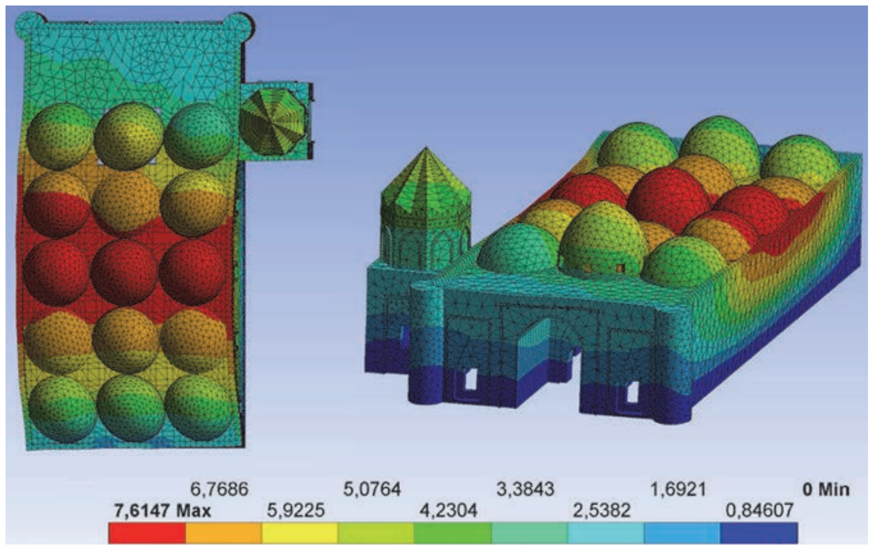

Figure 17. Maximum lateral displacement [mm]

4. Results and discussion

In this section, the structure is investigated primarily in terms of architectural properties and construction date. Then, the numerical analyses are discussed and the results are compared with other studies.

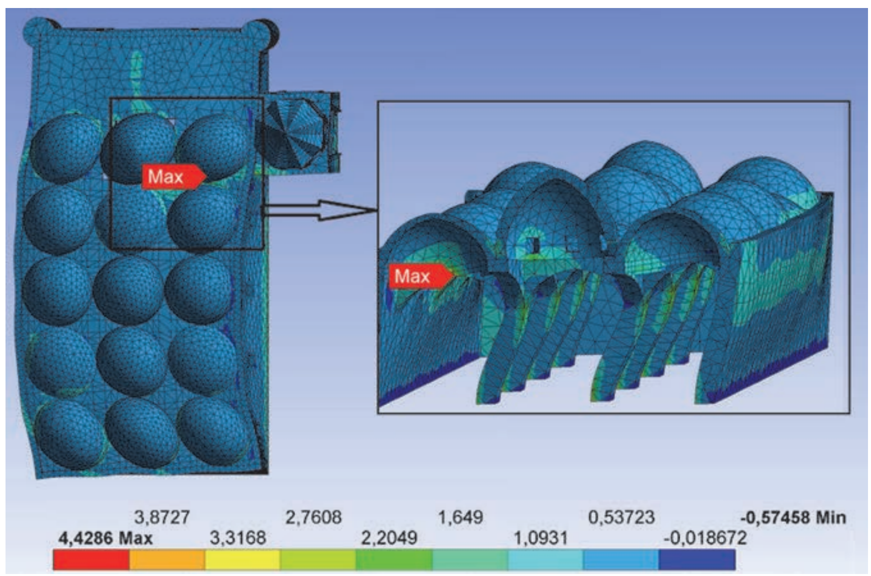

Figure 18. Maximum principal stress obtained from time history analysis [MPa]

All architectural evaluations to date have demonstrated that the structure is different from the other madrasah and mosques in terms of usage aim and design. Although Gok Madrasah was initially thought to be an angular mosque, the structure, which is neither madrasah nor mosque, is also different from the angular mosques because of its structural plan and location. Besides, the angular mosques are generally located in rural areas and they contain some additional structures, such as a square house, guesthouse, kitchen, storeroom, and cow house. Therefore, it is assumed that Gok Madrasah is not an angular mosque. Moreover, the structure is not an observatory structure either since an observatory structure generally has a hypaethral dome and an observation welt. In addition, Andreas David Mordtmann [21], who was a German naturalist and traveller, said that the observation structure was a different building from Gok Madrasah and it was ruined when he visited in Amasya in 1850. When the foundation of benefactors

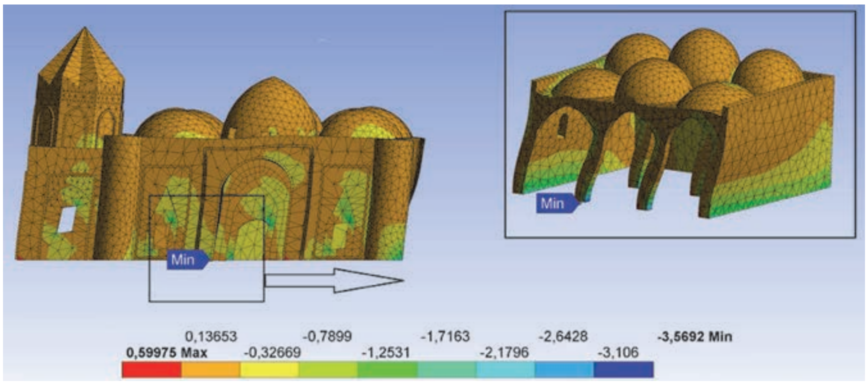

Figure 19. Minimum principal stress obtained from time history analysis [MPa]

to the mosque analysed the structure, it was decided that Gok Madrasah had been used as both a mosque and a madrasah. It is generally agreed that the structure was primarily constructed as a mosque, and was used as a madrasah for a small number of students. Moreover, Vitale (Casimir) CUINET [22], a French diplomat and traveller, reported that the structure was used as a mosque and a madrasah for education.

Since Gok Madrasah has no inscription, it should be assigned a new construction date. In the retroactive dating study, the structure was compared with other structures that were constructed at that period. Gok Madrasah Mosque shows various similarities with Ani (1064–1092) and Divrigi mosques (1229) in terms of the upper covering elements. Moreover, the structure resembles HanudHatun Madrasah (1238) and Sahabiye Madrasah (1267) in Kayseri, Gok Madrasah (1271) in Sivas, Cacabey Madrasah (1273) in Kırsehir, and Yakutiye Madrasah (1310) in Erzurum. Moreover, when the structure is analysed in relation to blue glazed bricks, such brick style was usually seen in the first quarter of the 13th century [23]. As for the adornments, these types of adornments were usually seen in the first half of the 13th century. It can therefore be assumed that Gok Madrasah may have been built in the first half of the 13th century. Similarly, Vitale (Casimir) CUINET concluded that Gok Madrasah was constructed in 1231 [22].

As for the static and dynamic analyses, the static analysis results show that the maximum compressive and tensile stresses occurs at the base of the main columns and on the lower sections and pulley of the middlemost dome. When the maximum tensile stress contour is examined, it can be observed that the stresses change considerably in the corner points of the dome arches. A similar study on a domed mosque conducted in Turkey has shown that the maximum tensile stresses generally occur on top of the main domes and the main arches. Furthermore, the maximum compressive stresses similarly occur at the base of the main columns and on top of the arch at the entrance of the mosque [9]. The modal and dynamic time history analyses show that the maximum compressive and tensile stresses occur at the domes of the structure and the octagonal pyramidal section. The vibration periods of the mosque are found to be acceptable for such type of structures, according to the modal analysis results [9, 24]. The time history analysis indicates that the most critical sections of the structure are the pulleys and eastern arches at the upper sections of the main columns.

6. Conclusion

Historical Gok Madrasah in Amasya, Turkey, was investigated in this paper from both architectural and structural perspectives. The primary objective of this paper was to investigate the architectural properties and to understand the static and dynamic behaviour of the historical structure.

The architectural overview and site investigation indicated that the information about this structure is quite scarce, which is due to the absence of historical records. Since the structure does not have any inscription, an exact construction date of the structure is not known. However, as a result of architectural examinations, literature review, and study of similar buildings, it can be concluded that the structure was built in the first half of the 13th century.

In the scope of structural assessment, it was established by numerical analyses that the maximum compressive and tensile stresses occur at the bottom of the main columns, and at the lower sections and the pulley of the middlemost dome in the static case. It was observed that the stresses greatly differ in the support sections of the dome arches. Moreover, the critical compressive stresses occur at the base section of the main columns and at the top section of the arch at the entrance to the mosque. The dynamic analyses show that critical sections of the structure are the domes and the octagonal pyramidal section. Furthermore, the time history analysis has revealed that the most critical sections are the pulleys and arches at the upper sections of the main columns. Different materials, geometrical forms, and different earthquake ground motions must be studied in greater detail to enable better understanding of the architectural and structural features of historical madrasahs.

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