Bulletin of Earthquake Engineering
https://doi.org/10.1007/s10518-025-02169-y

ORIGINAL ARTICLE

Determination of earthquake resistance of historical masonry inn with finite element analysis

Rüya Kılıç Demircan[1]

Received: 24 July 2024 / Accepted: 1 April 2025

Abstract
The protection of historic masonry structures against earthquakes is only possible by accurately assessing their non-linear behaviour, in particular their potential for severe damage and collapse. Experimental investigations on historic structures can be damaging, time consuming and costly. Therefore, in recent years, numerical modelling and analysis techniques have become common and reliable methods for determining the structural behaviour of historic structures. Turkey, which is located in a seismic zone, is home to many historical and cultural heritage sites. This study investigates the seismic performance of the historic Durak Han, located in the Durağan district of Sinop province due to its proximity to the North Anatolian Fault Line. The inn has been heavily damaged due to careless use and earthquakes and has been repaired many times. The seismic behaviour, force-displacement capacity and collapse mechanism of the stone vaulting have been investigated. A numerical simulation method had never been applied to the inn before. A comprehensive finite element model was constructed based on the architectural survey projects of the inn and this model was corrected using the experimental modal analysis results available in the literature. In order to determine the seismic behaviour and collapse mechanisms of the inn, nonlinear dynamic analyses were performed using the ground motion records of the 2023 Kahramanmaraş earthquakes. The maximum principal stresses, maximum displacements and damage distributions of the inn were evaluated.

Keywords Finite element analysis · Historical inn · Seismic performance · Durak Han

1 Introduction

Preserving and passing on the world's natural and cultural heritage to new generations is one of the United Nations (UN) goals for sustainable development. Cultural heritage structures serve as a bridge between the time in which they were built and the future. It is one of the

---

✉ Rüya Kılıç Demircan
ruyakilic86@gmail.com; rkdemircan@sinop.edu.tr

[1] Department of Civil Engineering, Sinop University Boyabat Vocational School, Sinop, Türkiye

fundamental responsibilities of nations to preserve these structures, which have witnessed many eras, and pass them on to future generations. Historic buildings that have survived to the present day shed light on the materials used at the time of their construction, the methods of workmanship, the techniques of reinforcement and repair, and the structures of the time. Historic buildings are damaged by both natural and man-made factors.

Seismic forces caused by earthquakes, the largest of the natural factors, affect these structures and generally cause serious damage or destruction (Schiavoni et al. 2023; Valente 2023; Bozyigit et al. 2024; Valente and Milani 2018; Krentowski et al. 2023; Kocaman et al. 2024). Historic masonry structures exhibit poor tensile strength and inadequate out-of-plane strength due to the inadequate connections between masonry building materials. Due to various reasons such as non-linear behaviour of structural units such as domes, vaults and arches and deterioration of the materials used over time, they may suffer serious damage under seismic loads (Şentürk et al. 2022; Binici et al. 2016; Koseoglu et al. 2015; Cakir et al. 2015; Bayraktar et al. 2022; Lourenço et al. 2012; Kocaman et al. 2023a; Genç et al. 2023; Tapan et al. 2013; Valente et al. 2019). Many conservation specialists, including architects, engineers, and art historians, must collaborate to mitigate the adverse impacts of seismic activity on historic masonry structures and ensure their stability. Addressing these effects and implementing new measures has become a significant research focus in recent years (Sezen et al. 2013; Mendes et al. 2020; Bozdoğan et al. 2024; Couto et al. 2020; Özmen et al. 2007).

Due to its geological and geopolitical location, Turkey has hosted many civilisations. The architectural heritage of these civilisations, such as mosques, inns, madrasahs, bridges, churches and baths, are important immovable cultural assets that reflect Turkey's cultural diversity. Although many of these structures are still in use today, they shed light on the cultural diversity, socio-economic levels, technological developments, architectural styles and engineering principles of past civilisations. Therefore, determining the seismic performance of these historic buildings and improving their earthquake resistance is a very important issue.

The seismotectonics of Turkey and its surrounding regions is the result of the relative movement of the African and Arabian plates to the north with respect to the Eurasian plate. The collision and tectonic movements of these plates create the North Anatolian Fault (NAF) and the East Anatolian Fault (EAF). This northward relative motion drives the westward movement of the Anatolian plate along the right-lateral North Anatolian Fault Zone (NAFZ) and the left-lateral East Anatolian Fault Zone (EAFZ) at a rate of approximately 24 mm/year, while also rotating counterclockwise (Fig. 1). These tectonic movements produce seismic effects (Kocaman et al. 2024; Yalçın et al. 2013).

Being an earthquake country, Turkey has been exposed to destructive earthquakes throughout history. As shown in Fig. 2, Turkey has experienced many earthquakes of magnitude 7 and above in the last century, leaving socio-economic damages as a result of these earthquakes and emphasizing the basic requirement of seismic preparedness and resilient infrastructure.

These earthquakes also damaged and/or destroyed historical buildings that have been home to many civilisations. Eleven districts were affected by the twin earthquakes of 6–7 February 2023 in Kahramanmaraş, which was the strongest earthquake in Turkey in the last century. According to the Disaster and Emergency Management Presidency (AFAD) of the Ministry of Interior of the Republic of Turkey (AFAD 2023), an earthquake with a

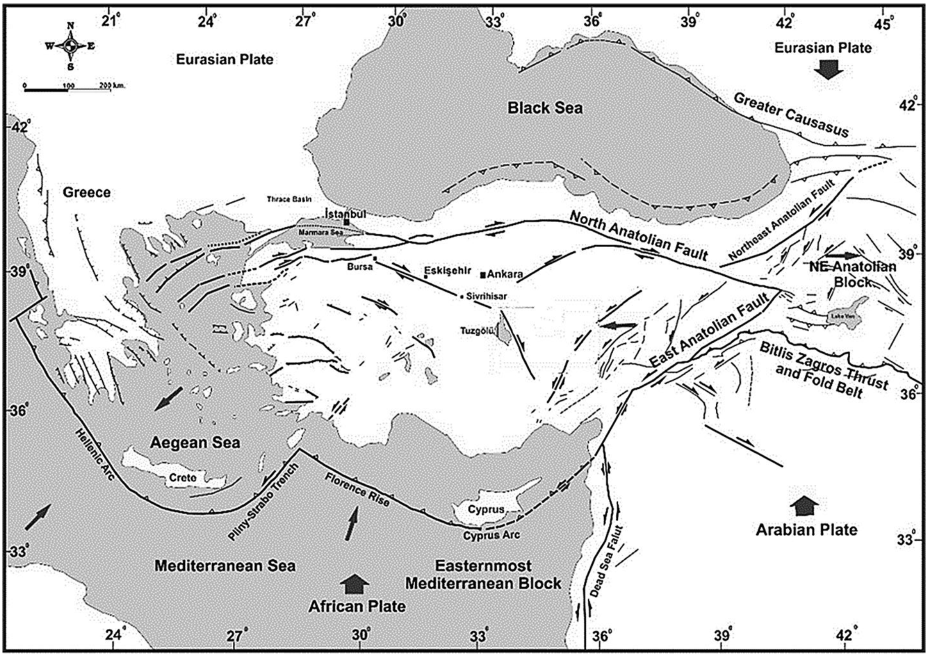


Fig. 1 The location of the study area within the eastern Mediterranean geodynamic setting has been adapted from the works of Şengör (1979) and Barka (1992). (Ozden et al. 2015; Işık et al. 2023)

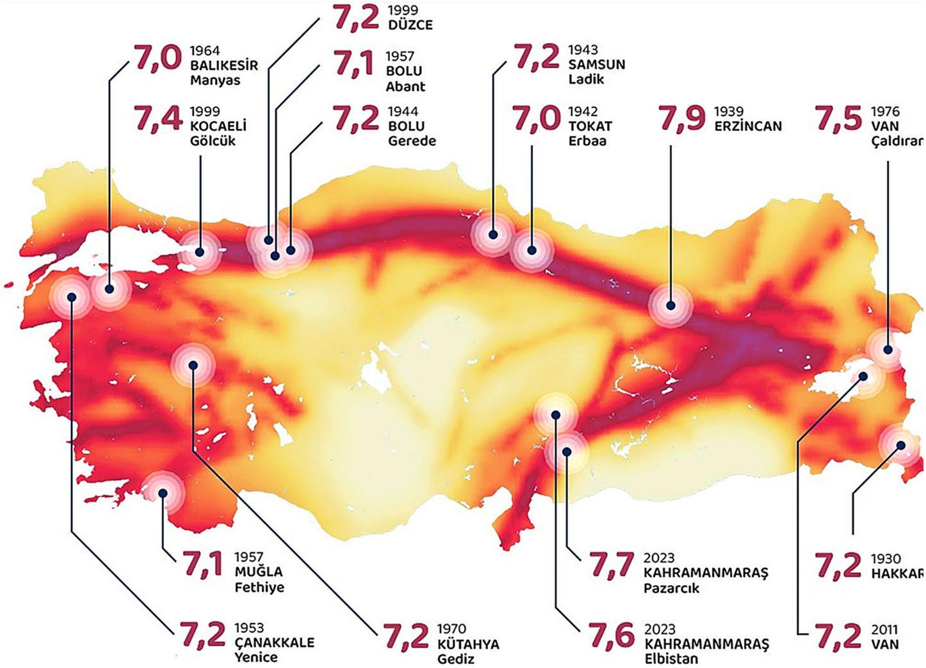


Fig. 2 Earthquakes of 7 or more in the last 100 years in Turkey (RETMC 2024)

magnitude of 7.7 (focal depth: 8.6 km) struck near Pazarcık, Kahramanmaraş, at 4:17 a.m. (GMT + 3) on 6 February 2023. This was followed by another earthquake at 13:24 (GMT + 3) with a magnitude of 7.6 (focal depth: 7 km) centred on Elbistan, Kahramanmaraş, as shown in Fig. 1a. On 20 February 2023, at 20:04 Turkish time (GMT + 3), a magnitude 6.4 earthquake occurred with its epicentre in Yayladagi, Hatay. These earthquakes were accompanied by numerous aftershocks, and seismic activity in the region has continued for a year and a half since the initial event. As stated in the "Kahramanmaraş and Hatay Earthquake Report" by the Strategy and Budget Directorate of the Presidency of the Republic of Turkey, these earthquakes caused more than 48,000 deaths and damaged more than half a million buildings, including essential infrastructure in the communications and energy sectors. As of 25 February 2023, inspections coordinated by the Directorates of Surveying and Monuments reported that out of 8444 cultural heritage buildings in the 11 affected districts, 2863 had been inspected, of which 169 collapsed, 535 were heavily damaged, 390 were severely damaged, 721 were partially damaged, 721 were slightly damaged and 1,048 were undamaged (TRSBO 2023).

Finite element method has been widely studied in the literature to analyse the structural behaviour of historic masonry buildings years (Sezen et al. 2013; Mendes et al. 2020; Bozdoğan et al. 2024; Couto et al. 2020; Özmen et al. 2007, Bui et al. 2017; Valente et al. 2016a, b; Erkek et al. 2023; Acito et al. 2016; Hejazi et al. 2016; Bartoli et al. 2017; Bayraktar et al. 2018; Minghini et al. 2016; Demircan et al. 2022; Ferraioli et al. 2017; Demircan 2023a). In order to evaluate the structural behaviour of masonry buildings under loads, macro-modelling, micro-modelling and simplified micro-modelling methods are applied by developing finite element models in the literature. Micro-modelling methods offer the possibility of modelling each building unit separately. As the surface adhesion between the discrete modelled units is mathematically modelled, it will be difficult for computer systems to solve the analysis of the entire wall element. Macro modelling methods, on the other hand, treat large walls as a homogeneous continuum and are more suitable for mathematical modelling and analysis (Meftah et al. 2024; Szabó et al. 2023; Chen et al. 2023; Drougkas 2022; Palhares et al. 2023; Murano et al. 2023; Kocaman 2023). Non-linear static analysis using the macro modelling approach is widely used for the seismic evaluation of masonry buildings. Despite the complexity involved in modelling the dynamic behaviour of materials and finite elements, nonlinear dynamic analysis remains the most accurate and reliable method for structural evaluation (Kocaman 2023).

Inn-type structures; It is known as accommodation structures located on the passage routes in history. The countries of Turkey are home to many historical inn-type structures dating back to the Seljuk and Ottoman Empires. Historical inns from the Seljuk and Ottoman Empires; They usually consist of stone masonry structures. These cultural heritages, which have survived to the present day, are used for different purposes through restoration today. There is not much data in the literature to analyse the structural behaviour of historical inns. Inn-type buildings are an important part of our cultural heritage, but they have not been the subject of sufficient research. In regions with intense seismic activity, inn-type structures are damaged. The lack of information on the structural behaviour of these structures, with the necessary research and studies, does not allow the structures to be evaluated in advance against seismic effects. One of the main objectives of this study is Durak Han, which is a region of high seismic activity; the Durağan district of Sinop province is close to the North Anatolian Fault Line and is in the centre of the first class earthquake zone according to the AFAD data system. The aim is to show the importance of obtaining information on the structural behaviour of this inn after earthquakes that may occur. In their study, Yazgan and Ünay applied macro modelling approach under seismic loading and nonlinear static analysis of an inn type structure (Yazgan and Ünay 2019,2023).

In this study, Durak Han in Durağan district of Sinop province dating back to the Seljuk period was selected as a case study. The inn has been repaired many times and, due to its proximity to the North Anatolian Fault Line, the building is exposed to significant seismic effects. However, its behaviour under these seismic conditions has not been investigated so far. In this paper, nonlinear static, modal and dynamic (time-history) analyses of the inn are performed using the macro modelling approach. The local acceleration records of the 2023 Kahramanmaraş earthquake on the East Anatolian Fault (EAF) line were used for these analyses.

2 Historical and architectural properties of Durak Han

The architectural projects and reports of Durak Han have been accessed with the legal permission of the Regional Directorate of Foundations in Samsun.

Durak Han is located on the Kastamonu-Samsun-Amasya road, 55 km south of Sinop and 30 km east of Boyabat, at the junction of the Gök Irmak and Kızılırmak rivers in the Durağan district, along the Vezirköprü road. It is located in the northeastern part of the city.

According to the inscription, the building was built in 1265 by the Anatolian Seljuq ruler Gıyaseddin Keyhüsrev III and the vizier Pervane Muinüd din Süleyman bin Ali. There are opinions that the building was built as a complex. According to this, there is a madrasah to the west of the building, a mosque to the south-west, a ruin with collapsed vaults and domes 5 m from the eastern façade and the remains of a bath filled with earth. The existence of the mosque and the madrasa could not be confirmed. The existence of the bath is mentioned in the literature (Duragan Han 2024; Conservation Report of Durak Han 2015). Photo 1. Photographs of Durak Han taken in the early 1900s.

Durak Han is a rectangular building with dimensions of 42.64 × 51.33 m. The building material is stone. There is a 32 × 47 m courtyard in the centre of the service area. The building has a plan that is common among Seljuk caravanserais. The building has a plan type consisting of open and closed (service and shelter) sections. In this type of plan, different principles are followed in the planning of the courtyard and the shelter section. While the courtyard is parallel to the shelter section, in some sources it is wider and placed horizontally to the shelter section. Durak Han is one of these building types. The courtyard is both wide and perpendicular to the shelter section. The building is supported by a total of six square buttresses, circular at the outer corners and square in between. The building has a north-south orientation, and the portal is located on the western façade. Before the last restoration of the inn, it was noted that the outer walls were largely intact, but the upper roof had collapsed in many places. During the restoration, the upper roof of the building was rebuilt. In the other rooms of the building, the missing pillars and arches were completed (Conservation Report of Durak Han 2015).

Photo 1 Durak Han in the early 1900s (Conservation Report of Durak Han 2015)

3 Historical damage and final restoration of Durak Han

When the restoration and publication studies of the building were examined, it was found that periodisation had been made and the first of these periodisations was the classical Seljuk early period in shaping, which consisted only of the shelter section. In this period; it can be assumed that the entire building was constructed with rough masonry of rubble stone material. In this period; it can be assumed that the crown gate of the building was constructed with a slightly thinner sectioned stone material. Spolia was not used in the building at this time (Fig. 3).

The second period refers to the situation before the building was destroyed by natural causes. The identification of the building has been based largely on visual data, comparative studies and on-the-spot determinations. It is believed that there was a serious collapse, especially in the upper roof, almost down to the walls, and that the building was reinforced horizontally with brick beams at this time, and this is supported by old photographs. The second

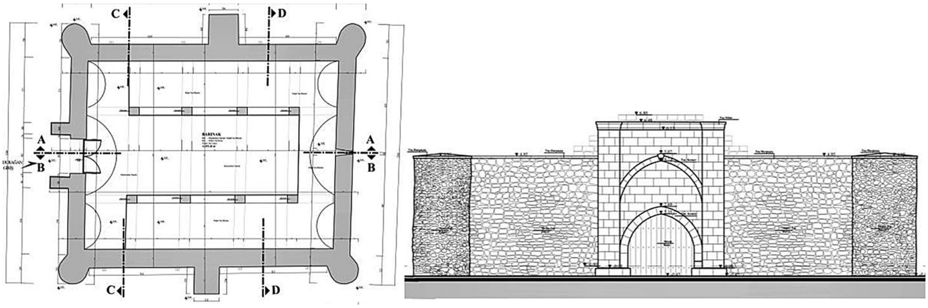


Fig. 3 1st period of inn planned entrance façade (Conservation Report of Durak Han 2015)

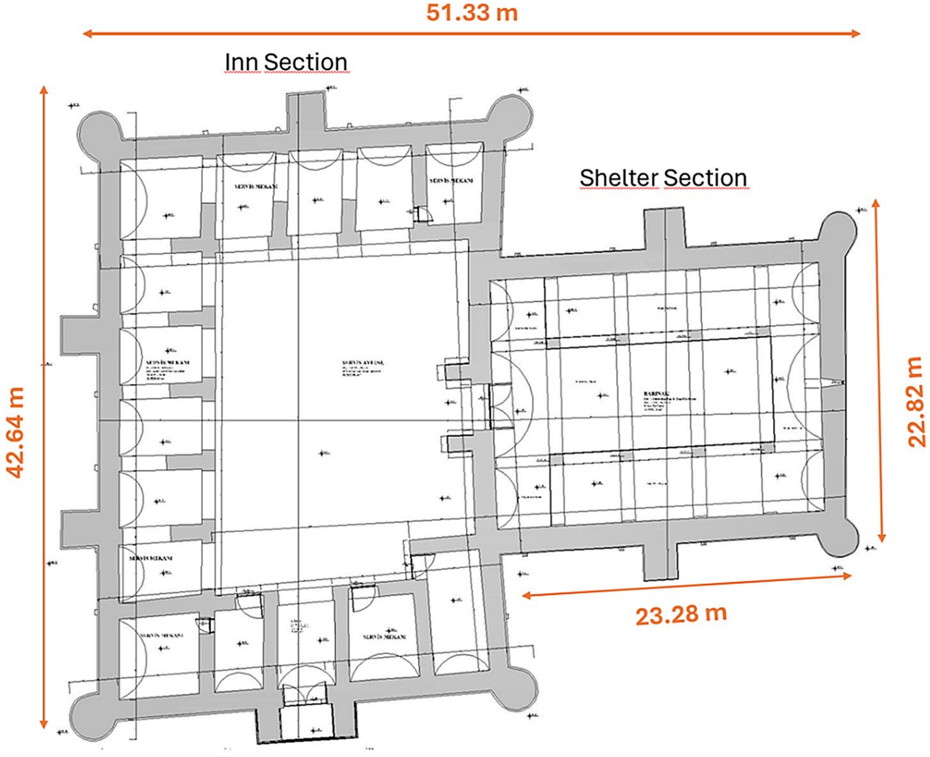


Fig. 4 2nd period inn plan (adopted from conservation report)

period plan, elevation and period photographs of the building are given below (Figs. 4, 5 and 6 - Photo 2 and Photo 3). The inn part of the project dates back to the Seljuk period. The shelter part was added later. The numerical modelling of the inn was carried out using data from the second period. The inn section is divided into 14 rooms and covered with vaults.

The third period restoration can be read by the changes in the material and weave of the third period interventions. The third period represents the final restored version (Fig. 7).

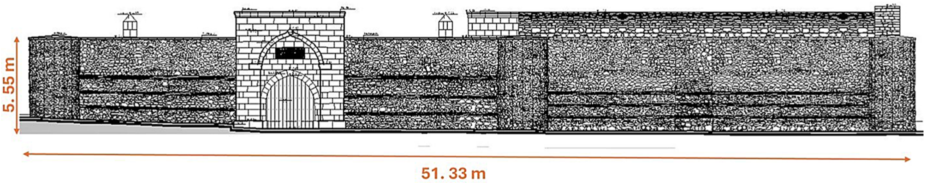


Fig. 5 2nd period inn plan-entrance façade (adopted from conservation report)

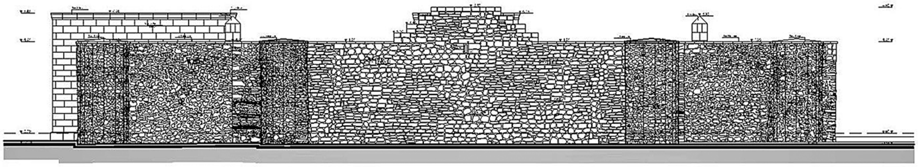


Fig. 6 2nd period inn plan-south façade (Conservation Report of Durak Han 2015)

Photo 2 2nd period inn photograph-shelter section (Conservation Report of Durak Han 2015)

Photo 3 2nd period inn photograph-inn section (Conservation Report of Durak Han 2015)

Fig. 7 3rd period of inn photographs (inside the yard and entrance façade) (Conservation Report of Durak Han 2015)

4 Finite element modelling of Durak Han

n the past, determining the behaviour of historic buildings under seismic action involved lengthy and costly methods such as extensive field studies and experimental investigations. However, recent advances in computer technology have made the earthquake resistance of historic buildings an important area of research. These technologies now provide accurate insights into the structural behaviour of various buildings, including historic mosques, madrasas, bridges and inns, under seismic action in a much shorter time. The finite element method is a commonly chosen approach to address the seismic behaviour issues of historic structures and plays a crucial role in analysing and evaluating how these buildings respond to earthquake forces [Kocaman et al. 2024; Valente 2022, 2021]. The finite element method can be modelled using micro and macro modelling approaches, depending on the level of importance of the structure. Nonlinear static and dynamic analyses provide the most accurate and reliable solutions for understanding the behaviour of structures. In this study, macro modelling and dynamic analysis techniques were used to determine the seismic behaviour of the historic inn walls. This approach allows a detailed investigation of the damage mechanisms affecting the inn walls under seismic loading.

Due to their complex geometries, historic masonry structures can be easily solid modelled and structurally analysed in packaged programs (Silva et al. 2018).

The 3D solid model of the inn was generated using the Structural Analysis Programme-SAP 2000 software. Shell elements were used in the vault sections of the inn. SAP 2000 software is a widely used programme developed specifically for solving structural problems. SAP2000 is a versatile civil engineering software that is ideal for the analysis and design of various types of structural systems (SAP 2000 software).

In SAP 2000, eight-node solids are utilized for modeling three-dimensional structural systems. These solid elements facilitate both linear and nonlinear static and dynamic stress analyses. Each solid is composed of six quadrilateral faces, with a joint located at every corner (Fig. 8). This structural configuration allows for a comprehensive understanding of the element's geometry, node positions, and coordinate system. By collapsing nodes, solids can form wedges, tetrahedra, and other irregular shapes. The isoparametric formulation includes nine optional incompatible bending modes to improve bending behavior. Solids can be assigned material properties, temperature-dependent characteristics, and anisotropic qualities, and subjected to gravity loads, surface pressures, pore pressures, and thermal

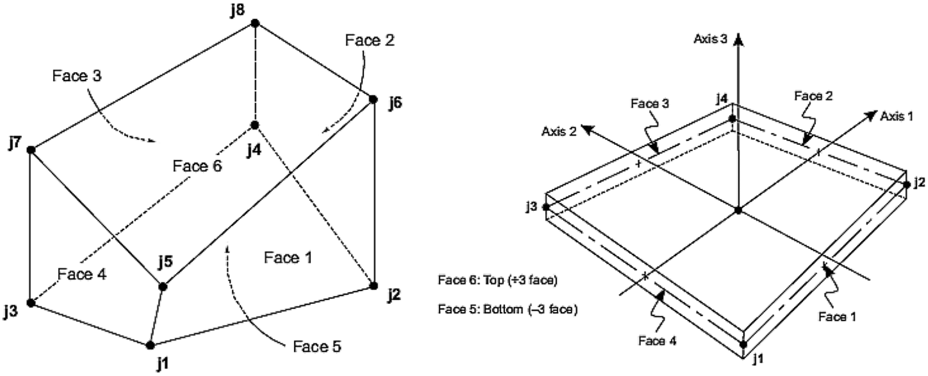


Fig. 8 Geometry of solid and shell elements (SAP 2000, 2024)

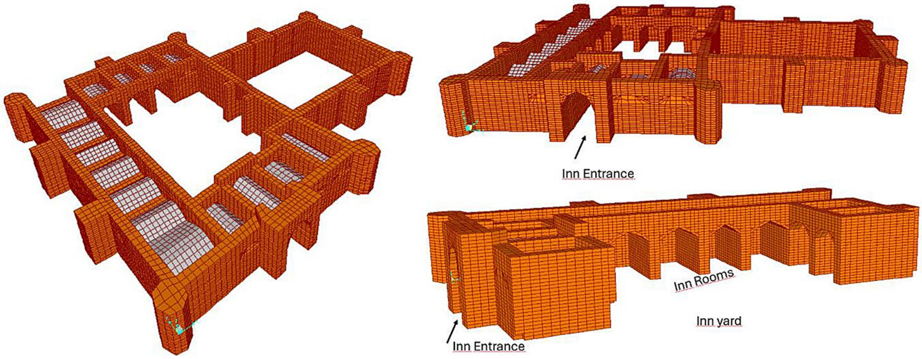


Fig. 9 3D modelling of Durak Han and 3D modelling of Inn and Section of Inn

loads. The best results are achieved with aspect ratios close to unity, and they should not exceed four.

Furthermore, shells are area objects with three or four nodes, used to model both membrane and plate-bending behavior. These shells can be either homogeneous or layered in their thickness. Layered shells can have temperature-dependent, orthotropic, and nonlinear material properties, leading to localized nonlinear behavior. They can also be given edge constraints and subjected to loads in any direction along any side (SAP 2000, 2024).

The nonlinear behavior of the materials was depicted using an elastoplastic model, based on the Mohr-Coulomb criterion. This criterion establishes a linear correlation between normal and shear stresses, or between the maximum and minimum principal stresses at failure. To simulate the discontinuity surfaces of the walls, which are expected to significantly influence collapse mechanisms, a reduced modulus of elasticity and strength was assigned to the relevant finite elements (Demircan 2023b).

Durak Han was modelled using the SAP 2000 program with a hexahedral eight-node solid element with three degrees of freedom at each node, as shown in Fig. 9. The inn was modelled using the macro modelling method. The three-dimensional model of the inn consisted of two elements: the vault and the side walls. The vault was modelled using a shell element and the walls were modelled using a solid element. There are two types of shell elements: triangular shell elements with three nodes (T3) and quadrilateral shell elements with four nodes (Q4). In this model, four-node quadrilateral shell elements have been modelled. The Inn model was made up of 94,635 solid elements, 2547 surfaces, 128,164 points. In the finite element model of the inn, all degrees of freedom were fixed at the floor level.

4.1 Material properties

Historic masonry structures are durable structures that combine different unit materials found in nature. The combination of different materials moves the structure away from homogeneity. Material non-linearity makes the overall assessment difficult. Researchers have used a range of experimental methods on both damaged and undamaged samples to assess the material properties of historic masonry structures, as reported in the literature (Portioli et al. 2011; Dinani et al. 2021). The determination of the material properties of historic masonry structures requires the use of different approaches. These approaches, obtained as a result of experimental research, are an important step for the determination of the characteristic properties of the structures in a numerical environment.

The mechanical properties of the materials used in the Inn model were based on the results listed in Table 1, which were derived from studies and research on similar structures [Barnaure and Cincu 2020; Wonganan et al. 2021; Pohle and Jäger 2003]. The average compressive strength has been taken as 3 MPa in the studies and regulations (Italian Code 2009). It should also be noted that historic buildings are often controlled by geometry (due to their low compressive stresses and very low tensile strength), making compressive strength values less relevant. It is important to note that historic structures have low compressive stresses and insufficient tensile strength. Empirical and analytical studies of historic masonry structures (Kocaman 2023; Bartoli et al. 2015; Betti et al. 2016) have shown that tensile strength is approximately 10% of compressive strength, with Poisson's ratio ranging from 0.17 to 0.2.

4.2 Numerical analysis

The acceleration data of the 2023 Kahramanmaraş earthquakes were used in the dynamic analysis of Durak Han. The regional coordinates of the earthquakes are given in Table 2. The spectral curves were determined according to the values recommended for Antakya in the Turkish Building Earthquake Code. In the dynamic analyses performed according to the pre-damage condition of the structure, the elastic spectrum was determined by considering the soft soil type (ZE type) with loose sand and clay layer characteristics and the DD-2 earthquake ground motion level-2 (DD-2) category in the latest Turkish Earthquake Regulations (TBEC 2019-Turkish Building Earthquake Code). DD-2 earthquake ground motion is characterised by infrequent earthquake ground motion with a 10% probability of exceeding

Table 1 Material properties of finite element model

Type	Tension strength	Compression strength	Unit weigth	Poisson ratio	Modulus of elasticity	Mass
	f_t (MPa)	f_c (MPa)	γ (kN/m)^3	ν	E (MPa)	t/m^3
Wall (Natural Stone)	0.30	3.00	24	0.18	450	2.45

Table 2 Antakya provice earthquake station information

Earthquake	Station code	Longitude	Latitude	Province	District	PGA_NS	PGA_EW
6th February 2023-Kahramanmaraş	3138	37,288	37,043	Antakya	Antakya Midtown	363,0329	366,0505

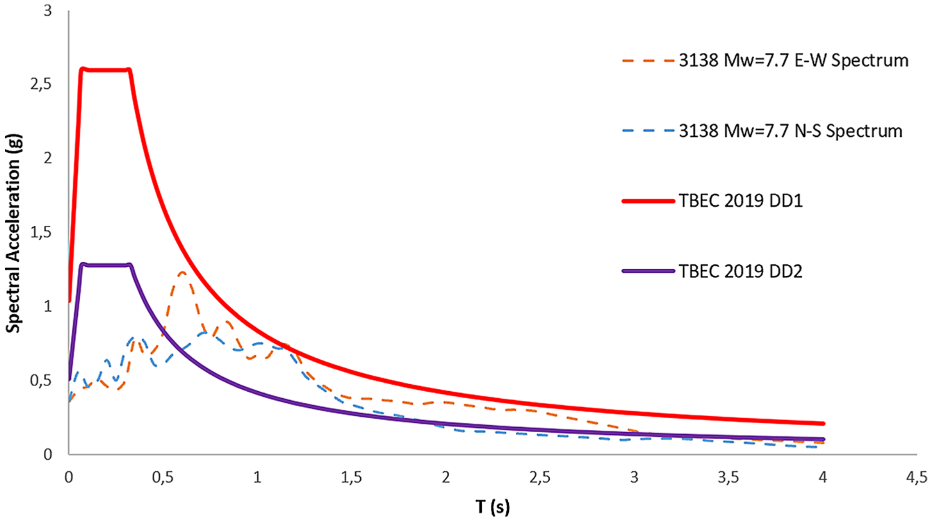


Fig. 10 Horizontal elastic design specturum for antakya district

spectral magnitudes within 50 years and a corresponding recurrence period of 475 years. This earthquake ground motion is also referred to as the standard design earthquake ground motion (Türkiye Building Code 2018). Accordingly, the spectral acceleration coefficient (PGA) for Antakya was taken as 1.11, which is equal to 111% of the gravitational acceleration. The earthquake acceleration data and design spectral data were obtained from the database of the Disaster and Emergency Management Authority of the Republic of Turkey (AFAD). Figure 10. shows the horizontal elastic design spectrum for the Antakya region and the spectral acceleration data of the Kahramanmaraş earthquake at the station of 3138. Figure 11 shows the acceleration data of the 2023 Kahramanmaraş earthquake from station 3138 in Antakya region in east-west and north-south directions, respectively.

4.2.1 Modal analysis

The vibration frequencies, periods and mass participation ratios of Durak Han were determined by modal analysis, focusing on the first three modes out of a total of 30. Table 3 shows the frequency values, periods and mass participation ratios for these modes, together with details of the horizontal and vertical movements of the inn. The first mode corresponds to north-south translation (Y direction), the second mode to east-west translation (X direction) and the third mode to torsional motion (Z rotation).

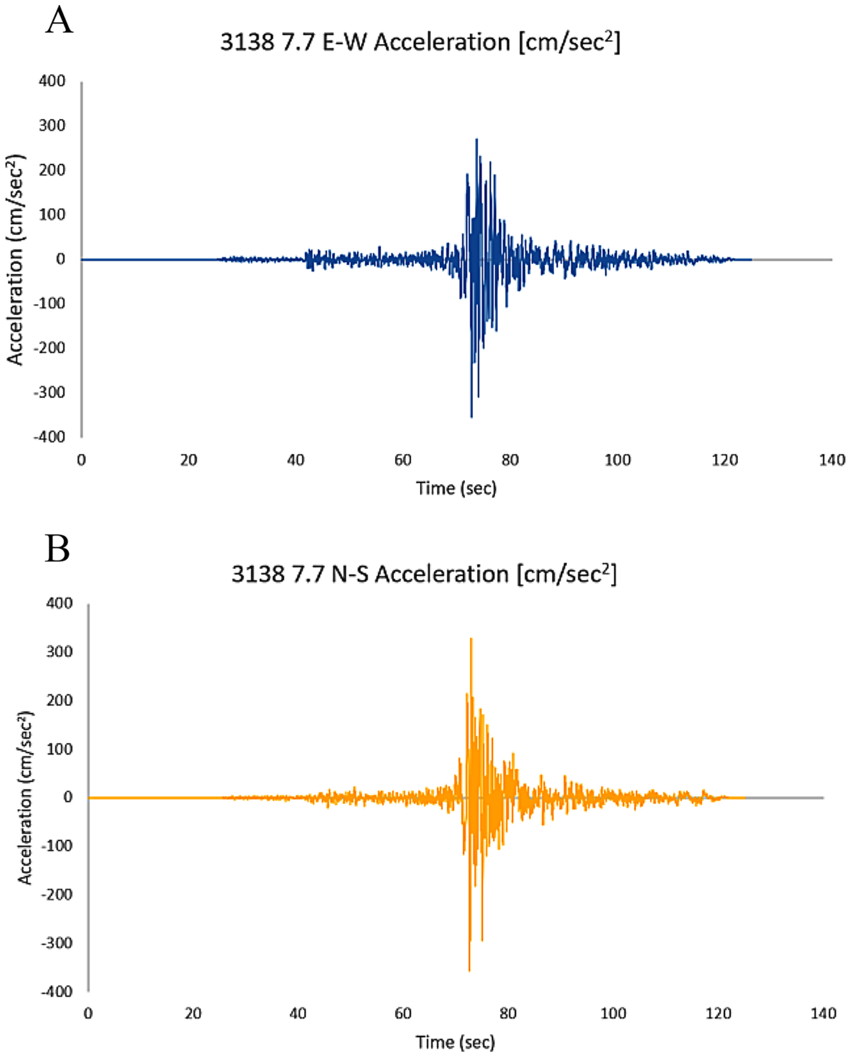


Fig. 11 **A** Accelerogram of Antakya midtown (3138 St. E-W Dir.). **B** Accelerogram of Antakya midtown (3138 St. N-S Dir.)

Table 3 Frequencies, periods and mass participation rates for the first three modes (MPR)

Mod	Frequency (Hz)	T(Period)(s)	MPR (X dir.)	MPR (Y dir.)	MPR (Z dir.)
1	4,32	0,23138	0,02849	1,808E-06	2,137E-06
2	4,74	0,21065	0,02987	0,05298	2,142E-06
3	5,00	0,1998	0,03364	0,09926	2,515E-06

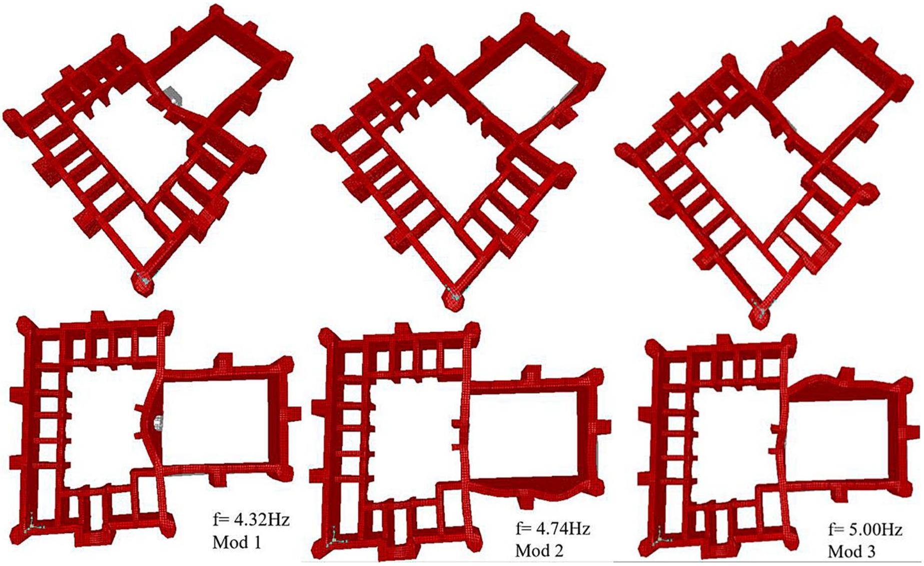


Fig. 12 Modal forms of the first three modes of Durak Han respectively

Table 4 Base shear reactions

OutputCase	CaseType	GlobalFX	GlobalFY	GlobalFZ
		KN	KN	KN
EQX	LinRespSpec	36828,505	5597,935	511,318
EQY	LinRespSpec	5601,046	37113,531	1167,924
GRAVITY	LinStatic	-9,188E-12	-2,275E-12	62831,257
EQZ	LinRespSpec	422,302	930,757	903,058
G+EQX	Combination	36828,505	5597,935	63342,575
G+EQY	Combination	5601,046	37113,531	63999,182

Figure 12 provides graphical representations of these three mode shapes and illustrates the response of the structure to different vibration patterns. The total mass of the structure, recorded as 62,831 tonnes, has a significant effect on its dynamic behaviour, as detailed in Table 4. In addition, Table 4 shows the maximum values of the base shear force (EQx) in the X-direction and the base shear force (EQy) in the Y-direction. The combination of these seismic forces with the total weight of the structure is shown in Table 4 as G+EQx and G+EQy. These results provide a comprehensive overview of the basic vibration characteristics of Durak Han and provide a basis for further evaluation and potential structural optimisation.

As seen in the first 3 modes of the inn, the frequency varies between 4.32 and 5.00 Hz. In the first mode, the mass participation is between 2% and 4%. From the 4th mode, it exceeds 20%. In the 15th mode it reaches 55%. As shown in Fig. 12, the first mode of the building involves a lateral displacement with significant out-of-plane deformation of the weak wall elements in the transition zone from the main structure to the later addition. The second mode shape shows the longitudinal displacement in the wall section of the later addition. The third mode shape shows torsional deformations confirming the balanced distribution

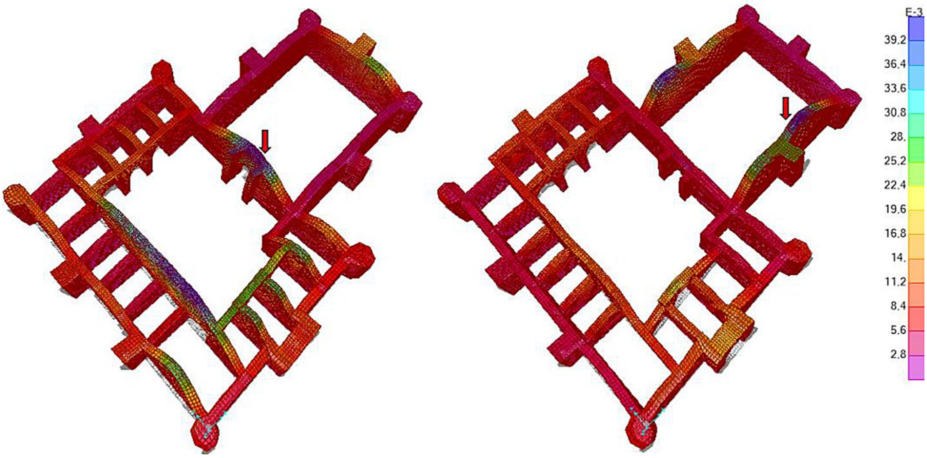


Fig. 13 Deformed shapes resulting from EQx and EQy loadings (mm)

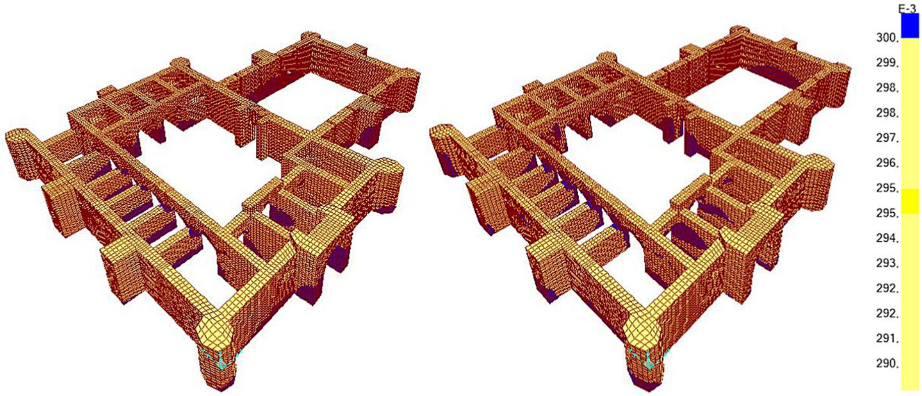


Fig. 14 Solid stress distributions under EQx and EQy loadings (MPa)

between the transverse and longitudinal structural elements of the inn. Although the distribution of mode shapes is as expected for a large mass structure, it shows that there are significant out-of-plane deformations in the perimeter walls with torsional stiffness.

Analyses using large finite element models with a large number of nodes require powerful computer hardware and take longer to complete. It should be noted that due to the complex geometry of historic masonry structures, the finite element mesh, if not properly integrated, may introduce unpredictable errors into the matrix formulations and solutions.

The base shear forces shown in Table 4 and the displacements and stress distributions shown in Figs. 13 and 14 were obtained by modal response spectrum analysis of the structure. This analysis was carried out to evaluate the response of the structure by considering the modal characteristics of the structure in more detail.

According to Table 4, the base shear force of the inn is 62831,257 kN. The earthquake forces applied to the structure in the EQx direction is 36828,505 kN, which corresponds to approximately 58% of the total mass. In EQy direction, it is 37113,531 kN tonnes and 59% of the total mass.

Figure 13 shows the displacements resulting from EQx and EQy earthquake loads. In EQx loading, the maximum value is shown as 41,8 mm in the exceeding zone. For EQy loading, the maximum value is shown as 40,2 mm. Figure 14 shows the stress distribution in the combinations (G + EQx and G + EQy) of earthquake loads in X and Y directions. The regions where the stress values are exceeded are shown in dark blue. Stresses resulting from the combination of earthquake forces and self-loading of the building and the exceeded regions show the correct limits.

A modal analysis was conducted to ascertain the dynamic behaviour of the structure and the frequencies and periods of the first three modes. The analysis encompassed 30 modes. These modes reveal the most significant dynamic characteristics of the structure. The first mode corresponds to a translational movement in the north-south direction, with a frequency of 4.32 Hz. This mode exerts a critical influence on the structure’s dynamic behaviour in this direction, as it demonstrates the highest mass participation rate. Notably, outward deformation of the weak wall elements was observed, particularly in this mode.

The second mode represents a translational movement in the east-west direction, with a frequency of 4.74 Hz. In this mode, a notable longitudinal displacement of the structure was observed, particularly in the region of the annex. This result provides crucial insight into the structural response to an earthquake in this direction.

The third mode demonstrates a torsional movement with a frequency of 5.00 Hz. This mode demonstrates a balanced distribution of structural elements, both transverse and longitudinal, throughout the structure. However, the torsional shape changes indicate imbalances in the stiffness distribution in the corner regions of the structure. While these mode shapes facilitate comprehension of the structure’s dynamic behaviour, they also play a pivotal role in determining strengthening strategies. For instance, the outward deformation observed in the first mode indicates that the wall elements in these regions should be reinforced. Similarly, the longitudinal displacement observed in the second mode suggests that supplementary strengthening measures should be implemented in the additional structure region.

4.2.2 Time-history analysis

The time-history dynamic analysis of the Han involved applying two horizontal components of a chosen acceleration record in orthogonal directions (X and Y). In this study, linear time-history analyses were performed to evaluate the dynamic response of the Durak Han structure under seismic loads. The analysis was conducted by applying two horizontal components of ground motion records in orthogonal directions (X and Y) to capture the structural response in terms of displacements and stresses. The linear approach allows for the assessment of the building’s behavior without considering material or geometric nonlinearities.

In historic masonry structures, the vertical component of ground motion has a lesser impact compared to the horizontal component. For this reason, horizontal acceleration components that generate shear and tensile stresses were applied (Kocaman et al. 2024; Onat et al. 2023). Damping ratios of historic masonry structures show similar characteristics depending on material and geometry properties. In dynamic analyses, Rayleigh damping ratio is applied as a suitable method with its compatibility in different package software

(Karaahmetli and Dündar 2017; Öztürk et al. 2023). Researchers have conducted experimental modal analysis tests on various types of historical masonry structures, revealing damping ratios ranging from 1 to 4% (Aşıkoğlu et al. 2019; Kocaman et al. 2023b). For the dynamic analyses, a 5% damping ratio was used for Rayleigh damping coefficients. The integration time step was set at 0,01 s, and the HHT-α algorithm was employed for the analyses. As a result, the maximum stresses and displacements occurring in the inn were analyzed.

The time-history analysis gives indications compatible with the modal analysis. The maximum force values of solid element 1604 and nodal point 175 in the model are 28794kN, 25679kN and 42095kN respectively. Large deformations are observed in the structure under these forces. As can be seen in Fig. 16, in the max relative displacement results, the limit values were exceeded in the same region with the 1st mode of the structure (weak region where the main structure is connected to the additional structure).

As illustrated in Fig. 15, the maximum relative displacements documented during the time-history analysis are presented. These displacements, which reach peak values in the region where the main structure connects to the later addition, serve to highlight the structural weaknesses of Durak Han in this transition zone.

The results of the analyses indicate that, at 10 s, the maximum displacement of the structure under EQx loading was calculated to be 418 mm. This displacement resulted in significant deformations in the additional structure region. In the case of EQy loading, the maximum displacement was 402 mm, a value that was similarly observed in the regions

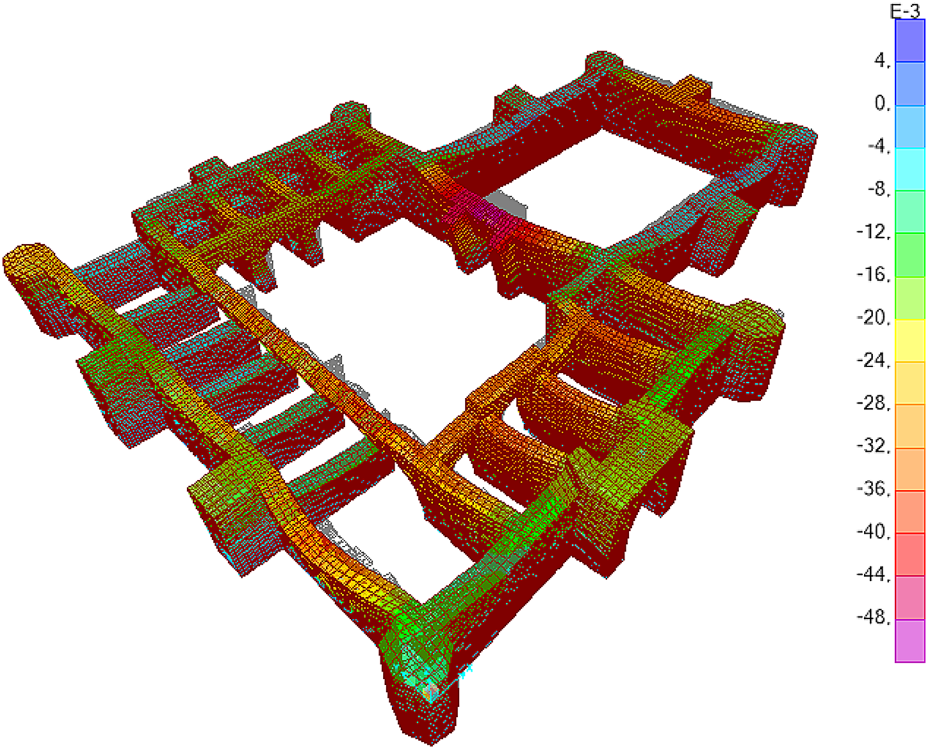


Fig. 15 Maximum relative displacement of time-history analysis results (mm)

where the structural elements of the weak wall were located. Such deformations present a significant risk of critical damage, in particular within the transition zones between the annex and the main structure.

Additionally, Fig. 16 illustrates the relative displacements as 15 mm at the 3rd second, 26 mm at the 5th second, and 35 mm at the 7th second, respectively. The significant deformation observed in this area can be attributed to the lack of torsional stiffness, as well as the discontinuity between the structural elements of the main and additional sections.

Moreover, the considerable relative displacements in this region indicate that the building's response to seismic forces is highly sensitive to the interaction between these two sections. Strengthening measures, particularly in the transition zone, are crucial to mitigate potential failure mechanisms under future seismic events. The time-history analysis results

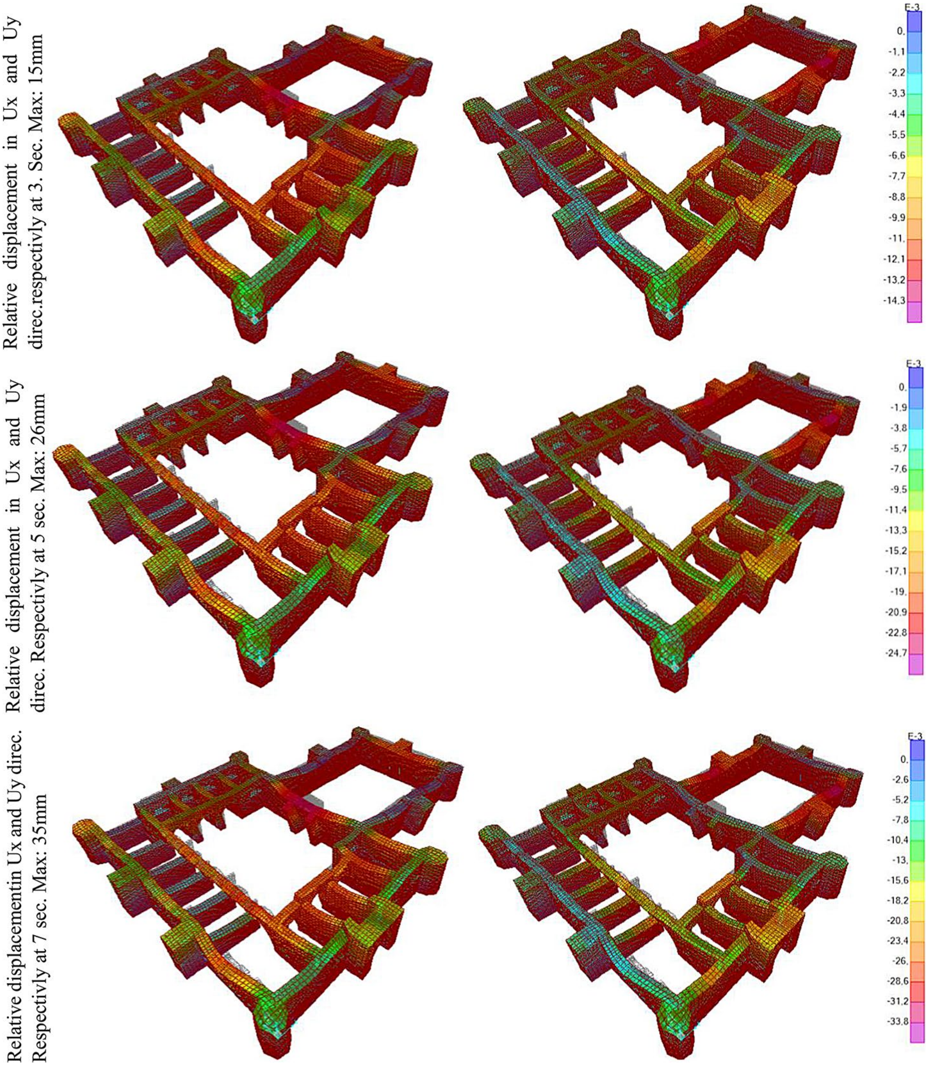


Fig. 16 Relative displacements in Ux and Uy directions at 3,5,7 s respectively

confirm that the structure exhibits significant deformation in response to lateral forces, which poses a risk to its overall stability.

In addition to the relative displacements, the time-history analysis revealed the presence of significant stress concentrations in specific regions of the structure. As illustrated in the stress distribution results, the highest stresses are observed in the transition zone between the main structure and the subsequent addition. The aforementioned stress concentrations indicate that this area is particularly susceptible to seismic forces and may experience localised damage under intense loading conditions.

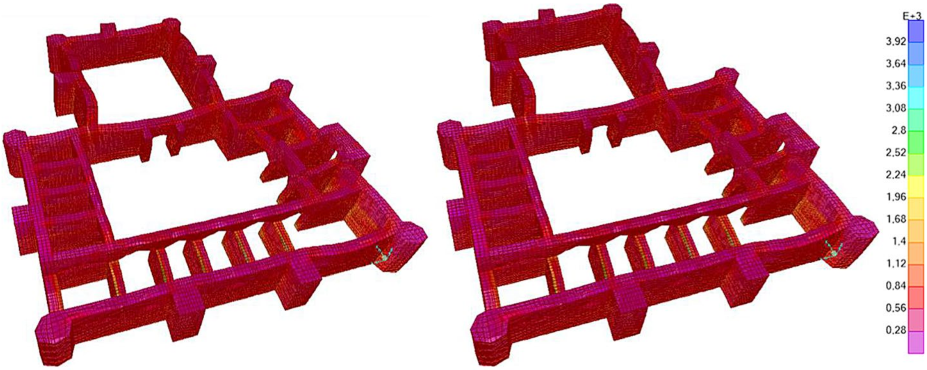
The damage distribution results, derived from the analysis, corroborate the hypothesis that the most critical regions for potential failure are those where the structural continuity is interrupted, particularly around the corners and junctions of the additional sections. The combination of high stress and displacement in these regions indicates an elevated risk of cracking and structural degradation, which could result in partial collapse if not addressed through strengthening measures.

Moreover, the analysis emphasises the necessity of evaluating not only displacements but also stress patterns to comprehensively comprehend the vulnerability of historical masonry structures like Durak Han. By characterising these stress and damage hotspots, restoration and retrofitting efforts can be more efficiently targeted to enhance the building's seismic resilience. Figure 17 illustrates the stress distribution at 3, 5, 7, and 10 s.

Von Mises stress was selected for this analysis because it accounts for both normal and shear stresses (such as S11, S22, S33) in all directions, thereby providing a comprehensive measure of overall stress intensity. This makes it particularly useful in dynamic analyses, where an understanding of the combined effects of multi-directional forces is crucial for the identification of critical stress zones. Von Mises stress is particularly reliable in multiaxial loading scenarios, as it indicates the material's potential for yielding or failure. Consequently, it facilitates the discernment of vulnerable areas within the structure and the evaluation of the influence of critical stresses on the overall stability under intricate loading circumstances.

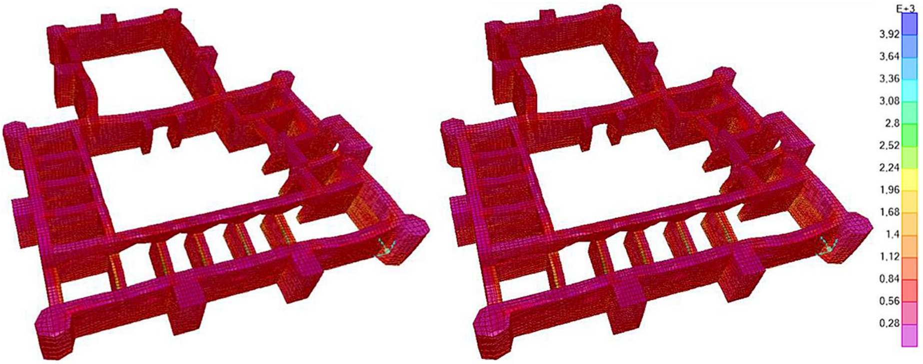
The results of the time history analysis (Fig. 17) indicate that the dynamic loads applied to the Durak Han structure resulted in maximum von Mises stress values at 3, 5, 7, and 10 s, reaching 1768 MPa, 2927 MPa, 4073 MPa, and 5822 MPa, respectively. The increasing stress values indicate critical stress intensities in specific regions of the structure over time. At the 10-second interval, the stress level of 5822 MPa is approaching or exceeding the material's tolerance. This elevated stress level indicates an increased probability of cracking or localised failure, emphasising the importance of reinforcing high-stress regions to enhance structural resilience.

Furthermore, the time-history analyses demonstrate how the time-varying forces act on the structure. The maximum forces acting on the structure reached their peaks at specific time intervals, resulting in significant stress accumulations in the critical areas of the structure. These accumulations may potentially lead to damage in the weak areas of the structure, necessitating the implementation of strengthening measures in these regions.



Von Mises Stress at 3 sec. Max:1768 Mpa

Von Mises Stress at 5 sec. Max:2927 Mpa



Von Mises Stress at 7 sec. Max:4073 Mpa

Von Mises Stress at 10 sec. Max:5822 Mpa

Fig. 17 Von Mises Stress Distribution at 3, 5, 7, and 10 s

5 Findings and conclusions

This study investigates the seismic performance of Durak Han, a medieval masonry building located near the North Anatolian Fault Zone in the Durağan region of Sinop. The study evaluates the displacement capacities, stress distributions, and structural behaviour of Durak Han under seismic loading using numerical simulations, namely modal and linear time history studies. The main findings and conclusions are summarised below:

1. Structural evaluation of Inn-type buildings: There is a gap in the in-depth study of Inn-type buildings, as evidenced by the lack of references in the literature on their structural analysis. Given the significant seismic risks associated with areas such as Durak Han, which is close to the North Anatolian Fault Line, it is imperative that such buildings be assessed quickly after an earthquake in order to take protective measures as soon as possible.
2. Results of the modal analysis: Durak Han's modal analysis shows low natural frequencies with the X and Y directions showing the majority of modes. In particular, the transition zones and weak wall parts exhibit the majority of the out-of-plane displacements

seen in the first three mode types. Greater sensitivity to dynamic loading is indicated by the natural frequencies of 4.32 Hz, 4.74 Hz and 5.00 Hz. This could amplify the torsional effects and create more structural stress in the identified weak points. The importance of targeted strengthening to reduce potential instability is demonstrated by the significant mass ratios associated with these modes, which also highlight Durak Han's vulnerability to seismic excitation.

3. Analysis of Time-History Results: With stress and displacement levels gradually increasing over predetermined time intervals, time-history analysis provides a comprehensive insight into the dynamic response of the structure under seismic loading. Von Mises reported stresses of 1768 MPa, 2927 MPa, 4073 MPa and 5822 MPa respectively, reaching critical levels at 3, 5, 7 and 10 s. These high stress levels indicate a significant risk of localised failure or cracking in high stress areas, particularly near joints and transitions. The new shelter component also had the highest relative displacements, indicating that the building's seismic resistance is compromised by structural discontinuities caused by subsequent additions.The displacement values suggest a lack of torsional stiffness in certain areas, which can significantly increase the risk of failure during seismic events.
4. Significance of structural additions: The linear behaviour study shows that the shelter section, built in later years, has an impact on the seismic behaviour of Durak Han because it is a huge masonry inn with a regular shape. This extension causes large displacements in certain places, indicating a change in the initial load distribution of the building and increased seismic sensitivity. These findings highlight the importance of maintaining the structural soundness of older buildings and assessing how subsequent modifications affect seismic response.
5. Advantages of finite element and macro modelling: Finite element models provide a reliable and useful tool for evaluating the structural performance of old brick buildings. The use of macro modelling techniques provides insight into the complex behaviour of historic buildings under seismic loading. In addition, comprehensive earthquake responses can be captured using modal and non-linear time history analyses, improving our understanding of the dynamic properties of these structures. The usefulness of macro modelling for massive masonry structures has been validated by the numerical simulations in SAP 2000, suggesting its use in heritage conservation procedures.
6. The impact of restoration and reinforcement is as follows: Durak Han was last restored in 2015 and is now operational. However, there is an urgent need to re-evaluate the structure under current seismic conditions, as previous restorations in Turkey have demonstrated a vulnerability to collapse during earthquakes. This study highlights the need for accurate structural assessments as part of standard conservation procedures and suggests priority areas for strengthening in the event of a destructive earthquake, with particular emphasis on the transition and shelter sections.
7. Regulatory implications and load bearing capacity: The results highlight the importance of determining the load-bearing and displacement capacities of historic structures and incorporating this information into national codes and regulations. In order to better preserve historic buildings, this study promotes the inclusion of rapid post-earthquake assessments in regulatory frameworks and emphasises the need for proactive steps to preserve historic buildings.

In conclusion, this study shows how well macro and finite element modelling work to assess the seismic performance of Durak Han and other historic buildings. The results indicate areas that need strengthening to increase seismic resilience, strengthening the argument for stronger national legislation and the urgent need for preventive measures to protect old masonry structures in seismically active areas.

Author contributions All of the study conception and design were prepared by corresponding author [Ruya Kılıç Demircan].

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The author has no relevant financial or non-financial interests to disclose.

References

Acito M, Chesi C, Milani G, Torri S (2016) Collapse analysis of the clock and fortified towers of finale Emilia, Italy, after the 2012 Emilia Romagna seismic sequence: lesson learned and reconstruction hypotheses. Constr Build Mater 2016(115):193–213

AFAD (2023) General Directorate of Earthquake and Risk Mitigation, Department of Earthquake. 02.06.2023 06 Şubat 2023 Pazarcik-Elbistan Kahramanmaraş (Mw: 7.7 – Mw: 7.6) Depremleri Report

Aşıkoğlu A, Avşar Ö, Lourenço PB, Silva LC (2019) Effectiveness of seismic retrofitting of a historical masonry structure: Kütahya Kurşunlu mosque, Turkey. Bull Earthq Eng 17:3365–3395. https://doi.org/10.1007/S10518-019-00603-6

Barka AA (1992) The North Anatolian fault zone. Ann Tect Sp Publ VI, 164e195

Barnaure M, Cincu M (2020) Testing methods for the assessment of material properties in historical masonry structures: a review. IOP Conf Series: Mater Sci Eng 789:012003. https://doi.org/10.1088/1757-899X/789/1/012003

Bartoli G, Betti M, Borri C (2015) Numerical modeling of the structural behavior of Brunelleschi's dome of Santa Maria Del Fiore. Int J Archit Herit 9:408–429. https://doi.org/10.1080/15583058.2013.797038

Bartoli G, Betti M, Monchetti S (2017) Seismic risk assessment of historic masonry towers: comparison of four case studies. J Perform Constr Facil 2017;31:04017039

Bayraktar A, Hökelekli E, Halifeoglu FM, Mosallam A, Karadeniz H (2018) Vertical strong ground motion effects on seismic damage propagations of historical masonry rectangular minarets. Eng Fail Anal. 2018;91:115–28

Bayraktar A, Hökelekli E, Yang TTY (2022) Seismic failure behavior of masonry domes under strong ground motions. Eng Fail Anal 142:106749. https://doi.org/10.1016/j.engfailanal.2022.106749

Betti M, Galano L, Vignoli A (2016) Finite element modelling for seismic assessment of historic masonry buildings (Chapter). Earthquakes their Impact Soc 377–415. https://doi.org/10.1007/978-3-319-21753-6_14

Binici H, Kapur S (2016) The physical, chemical, and microscopic properties of masonry mortars fromalhambra palace (Spain) in reference to their earthquake resistance. Front Architectural Res 5:101–110. https://doi.org/10.1016/j.foar.2015.10.003

Bozdoğan Ö, Erdağ A, Özdemir A (2024) Determination of mechanical properties of concrete and steel materials taken from buildings in Antakya after the Kahramanmaraş earthquakes. Case Studies in Construction Materialshttps://doi.org/10.1016/j.cscm.2024.e03445

Bozyigit B, Eeri M, Özdemir A, et al (2024) Damage to monumental masonry buildings in Hatay and Osmaniye following the 2023 Turkey earthquake sequence: The role of wall geometry, construction quality, and material properties. Earthquake Spectra (2024) 1–35. https://doi.org/10.1177/87552930241247031

Bui TT, Limam A, Sarhosis V, Hjiaj M (2017) Discrete element modelling of the in-plane and out-of-plane behaviour of dry-joint masonry wall constructions. Eng Struct 136:277–294

Cakir F, Uckan E, Shen J et al (2015) Seismic damage evaluation of historical structures during Van earthquake. Eng Fail Anal 58 October 23:249–266. https://doi.org/10.1016/j.engfailanal.2015.08.030

Chen Z, Zhou Y, Lie W, Fang X (2023) Macro-modelling method for the in-plane behaviour of the damped masonry infill wall in a frame structure. J Building Eng 80:108114. https://doi.org/10.1016/j.jobe.2023.108114

Couto R, Bento R, Gomes RC (2020) Seismic performance and fragility curves of historical residential buildings in Lisbon downtown affected by settlements. Bull Earthq Eng 18:5281–5307. https://doi.org/10.1007/s10518-020-00906-z

Demircan RK (2023a) Simplified structural analysis method for traditional timber buildings with cross frame. Megaron 18(3):312–327. https://doi.org/10.14744/megaron.2023.52284

Demircan RK (2023b) A simplified numerical modeling approach for the structural analysis of historical massive masonry structures. Advances in architecture, planning and design. ISSN:978-625-6454-08-8. Platanus Publishing Press Ankara Türkiye

Demircan RK, Ünay Aİ (2022) Büyük Kütleli Tarihi Kale ve Sur Duvarlarının Çevresel Etkiler Altında Yapısal Dengelerinin analitik Yöntemlerle değerlendirilmesi. J Politechnic. https://doi.org/10.2339/politeknik.794802

Dinani AT, Bisol GD, Ortega J, Lourenço PB (2021) Structural performance of the Esfahan Shah mosque. J Struct Eng 147:05021006. https://doi.org/10.1061/(ASCE)ST.1943-541X.0003108

Drougkas A (2022) Macro-modelling of orthotropic damage in masonry: combining micro-mechanics and continuum FE analysis. Eng Fail Anal 141:106704. https://doi.org/10.1016/j.engfailanal.2022.106704

Duragan Han (2024) web site http://www.turkishhan.org/duragan.htm

Durak Han Koruma Raporu (Conservation report of Durak Han 2015). Samsun Vakıflar Bölge Müdürlüğü

Erkek H, Yetkin M (2023) Assessment of the performance of a historic minaret during the kahramanmaras¸ earthquakes (Mw 7.7 and Mw 7.6). https://doi.org/10.1016/j.istruc.2023.105620. Structures 58:105620

Ferraioli M, Miccoli L, Abruzzese D, Mandara A (2017) Dynamic characterisation and seismic assessment of medieval masonry towers. Nat. Hazards 2017;86:489–515

Genç AF, Atmaca EE, Günaydın M et al (2023) Evaluation of soil structure interaction effects on structural performance of historical masonry buildings considering earthquake input models. Structures 54:869–889. https://doi.org/10.1016/j.istruc.2023.05.082

Hejazi M, Moayedian SM, Daei M (2016) Structural analysis of Persian historical brick masonry minarets. J Perform Constr Facil 2016;30:04015009

Işık E, Avcil F, Büyüksaraç A et al (2023) Structural damages in masonry buildings in Adıyaman during the kahramanmaras¸ (Turkiye) earthquakes (Mw 7.7 and Mw 7.6) on 06 February 2023. Eng Fail Anal 151:107405. https://doi.org/10.1016/j.engfailanal.2023.107405

Italian Code C (2009) Technical standards for constructions, In: Gazzetta Ufficiale Serie Generale n.47 del 26/02/2009, Italy

Karaahmetli S, Dündar C (2017) Yapıların Dinamik analizinde Kullanılan sönüm modellerinin incelenmesi. Çukurova Univ J Fac Eng Archit 32(2):23–35

Kocaman İ (2023) Effect of restoration interventions on the seismic behavior of historical masonry buildings: the case of molla Siyah mosque. Eng Fail Anal 148:107206. https://doi.org/10.1016/j.engfailanal.2023.107206

Kocaman I, Kazaz I (2023a) Global drift ratio limits for historical masonry mosques. Bull Earthq Eng. 1–30 https://doi.org/10.1007/s10518-023-01613-1

Kocaman I, Kazaz I (2023b) Collapse mechanism of historical masonry mosques under strong ground motions. Eng Fail Anal 144:106983. https://doi.org/10.1016/j.engfailanal.2022.106983

Kocaman İ, Mercimek Ö, Gürbüz M et al (2024) The effect of kahramanmaras¸ earthquakes on historical Malatya Yeni mosque. Eng Fail Anal 161:108310. https://doi.org/10.1016/j.engfailanal.2024.108310

Koseoglu GC, Canbay E (2015) Assessment and rehabilitation of the damaged historic Cenabı Ahmet Pasha mosque. Eng Fail Anal 57:389–398. https://doi.org/10.1016/j.engfailanal.2015.08.015

Krentowski JR, Knyziak P, Pawłowicz JA, Gavardashvili G (2023) Historical masonry buildings' condition assessment by non-destructive and destructive testing. Eng Fail Anal 146:107122. https://doi.org/10.1016/j.engfailanal.2023.107122

Lourenço PB, Trujillo A, Mendes N, Ramos LF (2012) Seismic performance of the St. George of the Latins church: lessons learned from studying masonry ruins. Eng Struct 40:501–518. https://doi.org/10.1016/j.engstruct.2012.03.003

Meftah SA, Aldosari SM, Tounsi A et al (2024) Simplified homogenization technique for nonlinear finite element analysis of in-plane loaded masonry walls. Eng Struct Volume 306:117822. https://doi.org/10.1016/j.engstruct.2024.117822

Mendes N, Zanotti S, Lemos JV (2020) Seismic performance of historical buildings based on discrete element method: an Adobe church. J Earthq Eng 24 – 8. https://doi.org/10.1080/13632469.2018.1463879

Minghini F, Bertolesi E, Del Grosso A, Milani G, Tralli A (2016) Modal pushover and response history analyses of a masonry chimney before and after shortening. Eng Struct. 2016;110:307–24

Murano A, Mehrotra A, Ortega J et al (2023) Comparison of different numerical modelling approaches for the assessment of the out-of-plane behaviour of two-leaf stone masonry walls. Eng Struct 291:116466. https://doi.org/10.1016/j.engstruct.2023.116466

Onat O, Toy AT, Özdemir E (2023) Block masonry equation-based model updating of a masonry minaret and seismic performance evaluation. J Civ Struct Heal Monit. https://doi.org/10.1007/S13349-023-00703-7

Ozden S, Gündogdu E, Bekler T (2015) Interactions between Eurasian/African and Arabian plates: Eskisehir Fault, NW Turkey. J Afr Earth Sci 111:349–362. https://doi.org/10.1016/j.jafrearsci.2015.08.014

Özmen C, Ünay Aİ (2007) Commonly encountered seismic design faults due to the architectural design of residential buildings in Turkey. Build Environ. https://doi.org/10.1016/j.buildenv.2005.09.029

Öztürk ÇO, Çetin SY, Sayin E (2023) Dynamic analysis of historical Sultan Hamit masonry arch bridges. DUJE (Dicle Univ J Engineering) 14(3):499–506

Palhares RA, Medeiros KAS, Parsekian GA et al (2023) A macro-modeling approach for non-linear analysis of multi-story perforated masonry walls with Grout and reinforcement concentrated at their pier ends. J Building Eng 73:106785. https://doi.org/10.1016/j.jobe.2023.106785

Pohle F, Jäger W (2003) Material properties of historical masonry of the Frauenkirche and the masonry guideline for reconstruction. Constr Building Mater 17:651–667. https://doi.org/10.1016/S0950-0618(03)00062-X

Portioli F, Mammana O, Landolfo R et al (2011) Seismic retrofitting of Mustafa Pasha mosque in Skopje: finite element analysis. J Earthq Eng 15:620–639. https://doi.org/10.1080/13632469.2010.532580

RETMC (2024) Boğaziçi University Kandilli Observatory Earthquake and Research Institute Regional Earthquake - Tsunami Monitoring Center. http://www.koeri.boun.edu.tr/sismo/2/deprem-verileri/sayisal-veriler/

SAP (2000) Structural and earthquake engineering software. Computer and Structures Inc

SAP 2000 (2024) Structural and Earthquake Engineering Software website https://wiki.csiamerica.com/display/kb/Solid. https://wiki.csiamerica.com/display/kb/Shell

Schiavoni M, Giordano E, Roscini F, Clementi F (2023) Numerical modeling of a Majestic masonry structure: A comparison of advanced techniques. Eng Fail Anal 149:107293. https://doi.org/10.1016/j.engfailanal.2023.107293

Şengör AMC (1979) The North Anatolian transform fault: its age, offset and tectonic significance. J Geol Soc Lond 136:269e282

Şentürk I, Ergün M, Artar M (2022) Seismic behavior assessment of historical Alaeddin Bey mosque and strengthening suggestions by CFRP fabric and steel plate. Eng Fail Anal 137:106242. https://doi.org/10.1016/j.engfailanal.2022.106242

Sezen H, Doğangün A (2013) Sismic performane of historical and monumental structures. Chapter: earthquake engineering. Intechopen. https://doi.org/10.5772/51338

Silva LC, Mendes N, Lourenço PB, Ingham J (2018) Seismic structural assessment of the Christchurch Catholic Basilica. New Z Struct 15:115–130. https://doi.org/10.1016/j.istruc.2018.06.004

Szabó S, Funari MF, Pulatsu B et al (2023) Macro vs Micro limit analysis models for the seismic assessment of in-plane masonry walls made with quasi-periodic bond types. Procedia Struct Integr 44:1340–1347. https://doi.org/10.1016/j.prostr.2023.01.172

Tapan M, Comert M, Demir C et al (2013) Failures of structures during the October 23, 2011 Tabanlı (Van) and November 9, 2011 Edremit (Van) earthquakes in Turkey. Eng Fail Anal 34:606–628. https://doi.org/10.1016/j.engfailanal.2013.02.013

TRSBO (2023) Kahramanmaraş ve Hatay depremleri report. Presidency of the Republic of Turkey. Presidency of Strategy and Budget Office

Türkiye Building Earthquake Code Report-2018

Valente M (2021) Seismic vulnerability assessment and earthquake response of slender historical masonry bell towers in south-East Lombardia. Eng Fail Anal 129:105656. https://doi.org/10.1016/j.engfailanal.2021.105656

Valente M (2022) Seismic behavior and damage assessment of two historical fortified masonry palaces with corner towers. Eng Fail Anal 134:106003. https://doi.org/10.1016/j.engfailanal.2021.106003

Valente M (2023) Earthquake response and damage patterns assessment of two historical masonry churches with bell tower. Eng Fail Anal 151:107418. https://doi.org/10.1016/j.engfailanal.2023.107418

Valente M, Milani G (2016a) Seismic assessment of historical masonry towers by means of simplified approaches and standard FEM. Constr Build Mater 108:74–104. https://doi.org/10.1016/j.conbuildmat.2016.01.025

Valente M, Milani G (2016b) Non-linear dynamic and static analyses on eight historical masonry towers in the North-East of Italy. Eng. Struct. 2016;114:241–70

Valente M, Milani G (2018) Seismic response and damage patterns of masonry churches: seven case studies in Ferrara. Italy Eng Struct 177:809–835. https://doi.org/10.1016/j.engstruct.2018.08.071

Valente M, Milani G (2019) Damage assessment and collapse investigation of three historical masonry palaces under seismic actions. Eng Fail Anal 98:10–37. https://doi.org/10.1016/j.engfailanal.2019.01.066

Wonganan N, Athisakul C, Mahasuwanchai P et al (2021) Ancient materials and substitution materials used in Thai historical masonry structure preservation. J Renew Mater 9(2):179–204. https://doi.org/10.32604/jrm.2021.013134

Yalçın H, Gülen L, Utkucu M (2013) Türkiye ve Yakın Çevresinin aktif Fayları veri Bankası ve deprem Tehlikesinin Araştırılması. Yerbilimleri 34(3):133–160

Yazgan İO, Ünay Aİ (2019) Bursa, Yenişehir Sinan Paşa Külliyesi İmaretinin Sayisal Modellenmesi Ve Yapisal Analizi. Ömer Halisdemir Üniversitesi Mühendislik Bilimleri Dergisi, Cilt 8, Sayı 2, 1193–1203. https://doi.org/10.28948/ngumuh.598235

Yazgan İO, Ünay Aİ (2023) Construction knowhow and conditions due to structural and architectural restoration of a historical town center inn. Selcuk Univ J Eng Sci 22(03):124–130