

RESEARCH ARTICLE

Seismic evaluation of historical Pertev Pasha Mansion under February 6 Kahramanmaraş (Pazarcık) Earthquake (Mw 7.7)

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Abstract

Historical masonry structures with aesthetic aspects play an important role in cultural heritage. However, such structures are vulnerable to seismic effects. Therefore, periodic maintenance and structural evaluations are required for these structures. In this study, a historical masonry building called the Pertev Pasha Mansion, located in Trabzon, Turkey, was selected for the evaluation. The building was demolished in the last few years and has been planned to be rebuilt in its original form. In the study, the finite element model of the building was created based on reconstruction drawings. Modal analysis was performed to obtain the frequencies and mode shapes of the building. Finally, seismic analyses were conducted based on the February 6 Kahramanmaraş earthquakes for two different acceleration records that were collected from different stations, one near the epicenter (Pazarcık station) of the earthquake and the other near the building (Ortahisar station). From the results of the modal analysis, the frequency and mode shapes of the structure were obtained. The displacement and stress results were obtained from the seismic analysis and presented with contour diagrams. At the end of the study, a general evaluation considering the novel Turkish guidelines for historic structures was conducted. According to the results of the seismic analysis performed using the Pazarcık station data, the drift ratio values of the structure exceeded 0.7%, which corresponds to the Collapse Prevention (CP) performance level. However, according to the seismic analysis results obtained using Ortahisar station data, the maximum drift ratio of the structure was 0.001%, corresponding to the Limited Damage (LD) performance level. Consequently, if the building had been built close to the center of the earthquake, it was likely to collapse, but it was estimated that it would have received limited damage because its current location was far from the center of the earthquake.

1. Introduction

Historic masonry structures constitute a significant part of global cultural and historical heritage. These structures play a significant role in the cultural legacy of society. They constitute the cornerstone of tourism appeal by drawing visitors from distant and wide areas. Despite withstanding the test of time for centuries, these architectural gems remain susceptible to both human-induced actions and natural calamities, with

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seismic events posing a particularly grave threat [1,2]. Consequently, the preservation and regular upkeep of these structures are imperative.

Historic masonry structures are important architectural examples constructed by skillfully assembling natural materials, such as stone, brick, and wood, which have been used for centuries. The preservation and sustainability of historic masonry structures pose significant challenges to engineering and architecture. Therefore, it should be emphasized that numerical analyses play a crucial role in the preservation, restoration, and strengthening of historic masonry structures.

Understanding the durability of historic masonry structures and guiding preservation efforts relies heavily on numerical analyses. Numerical analyses involve the application of mathematical and computer-based methods to evaluate the load-carrying capacity, stress distribution, deformation, and other important mechanical properties of structures. These analyses were used to identify potential issues and provide solutions for strengthening or restoring historical buildings.

Numerical analyses of historical masonry structures may encounter specific challenges. First, the material properties and construction techniques of these structures are often more complex than those of modern buildings. The heterogeneous nature of materials such as stones and bricks is one factor that complicates the analyses. Moreover, deformations over time, material decay, and natural disasters can affect the accuracy of numerical analyses. Therefore, it is crucial to consider and accurately model these factors during analytical processes. The preservation and restoration of historic masonry structures have become more scientific and data-driven with the application of numerical analysis. These analyses assist engineering and architectural teams in understanding the mechanical behavior of these structures and contribute to determining appropriate strengthening and restoration strategies. Many studies have been conducted to numerically determine the structural behavior of historical structures, such as buildings [3-6], mosques [7-9], churches [10-13], masonry bridges [14-15], minarets, and towers [16-19] etc. Numerical studies have shown that the evaluation of the structural behavior of historical masonry structures is prevalent and effective.

Earthquakes are the primary cause of the damage or total collapse of numerous historical structures, particularly in regions prone to intense seismic activity, such as Turkey. The frequent occurrence of earthquakes in such areas has caused extensive damage to historical edifices over time. For instance, the devastating Kahramanmaraş earthquakes in February 2023, which shook 11 Turkish cities and triggered hundreds of subsequent tremors, resulted in severe damage and the outright destruction of numerous historical masonry buildings. Pazarcık and Elbistan earthquakes with magnitudes of 7.7 (Mw) and 7.6 (Mw), which occurred on the same day, caused an incredibly large seismic energy discharge in the region and caused great destruction. Since the depths of both earthquakes were very shallow (8.6 km, 7 km), the intensity of the earthquakes also increased. Many historical buildings built in the region were heavily damaged or destroyed due to these earthquakes. Examining the seismic behavior of historical masonry buildings and investigating the effectiveness of reinforcement applications are very popular topics in the literature. Many studies have been conducted in the literature on these issues [20-24].

In this study, the seismic behaviors of a historical masonry building, both close to and far from the earthquake epicenter, were examined with using Pazarcık earthquake records. The building that called Pertev Pasha Mansion is located in the city of Trabzon. No precise information is available on the historical background of the structure. The building has an approximate floor area of 240 m² and a base plan of 15×16 m. The structure comprised a basement, ground floor, first floor, and an attic. It is rectangular in shape, oriented along the east-west axis, and constructed with a stone masonry load-bearing system. The floors of the building were made of wooden decking on all levels, whereas in the basement and ground floor sections with balconies, a floor arch system was constructed. The building height, starting from the basement, was approximately 16.3 m. A view of the building is shown in Fig. 1.



Fig. 1. Views of Pertev Pasha Mansion

Within the scope of this study, a 3D finite element model of the structure was created, and modal and earthquake analyses were performed. In the earthquake analyses, accelerations obtained from both the most effective station of the earthquake and stations close to the area where the structure was located were used. Based on these analyses, a general structural evaluation was performed.

2. Finite element analyses of the mansion

Finite element (FE) models of the building were created using the ANSYS software [25]. Within the finite element representation of the structure, the SOLID186 solid element was employed. This element has 20 nodes with three degrees of freedom per node. It exhibits versatile characteristics, including plasticity, elasticity, creep, stress stiffening, large deflection, and substantial strain. Moreover, it offers options for tetrahedral, pyramid, or prism meshing, thereby facilitating the modeling process [25]. In this model, the foundation support was assumed to be fixed. Certain portions of the model were considered fully bonded. The masonry components were represented using a macromodeling technique. The finite element model of the building is shown in Fig. 2. The FE model of the building consists of 96310 finite element and 187351 nodes. The FE model of the structure comprised five distinct structural elements: masonry body walls, inner slender walls, wooden floor, floor arch system, and reinforced concrete (RC) components. No experimental research has been conducted to determine the material properties, relying on literature-based assumptions. Different material properties were used for masonry units in the literature [13,25–27]. According to the literature, different elastic modulus of the masonry units that range from $1.0\text{E}9 \text{ N/m}^2$ to $5.0\text{E}9 \text{ N/m}^2$ and different density values that range from 1600 kg/m^3 to 2300 kg/m^3 were generally used in the analysis. Thus, in this study, the material properties of masonry elements were chosen in these ranges. Additionally, no study

has been found to determine the material properties of wooden floors and floor arch systems. Equivalent stiffness was assigned to these elements to ensure lateral load transfer. The material properties selected for this model are listed in Table 1.

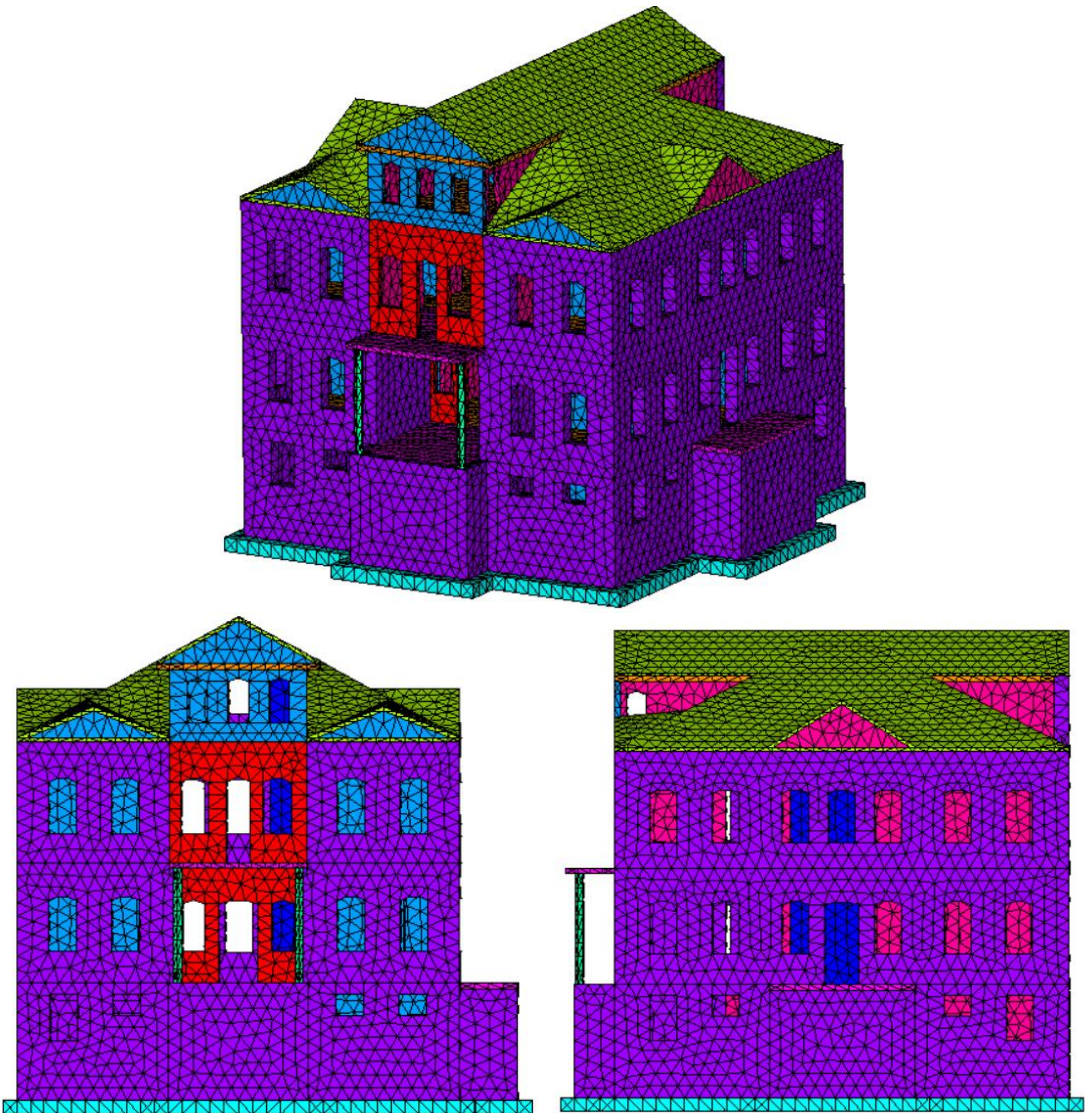


Fig. 2. Views of the finite element (FE) model of the building

Table 1. Linear material properties of the building

Elements	Material Properties		
	Modulus of Elasticity (N/m ²)	Poisson Ratio (-)	Density (kg/m ³)
Outer walls	1.50E9	0.20	1900
Inner walls	2.00E9	0.20	1800
RC parts	2.00E10	0.20	2500

2.1. Modal analysis of the mansion

The numerical dynamic characteristics of the building were obtained using finite element modal analysis. The first three frequencies were obtained in the range of 4.57–6.46 Hz. The mode shapes of the building were obtained in transverse, longitudinal, and torsional modes. The mode shapes and natural frequencies of the buildings are shown in Fig. 3.

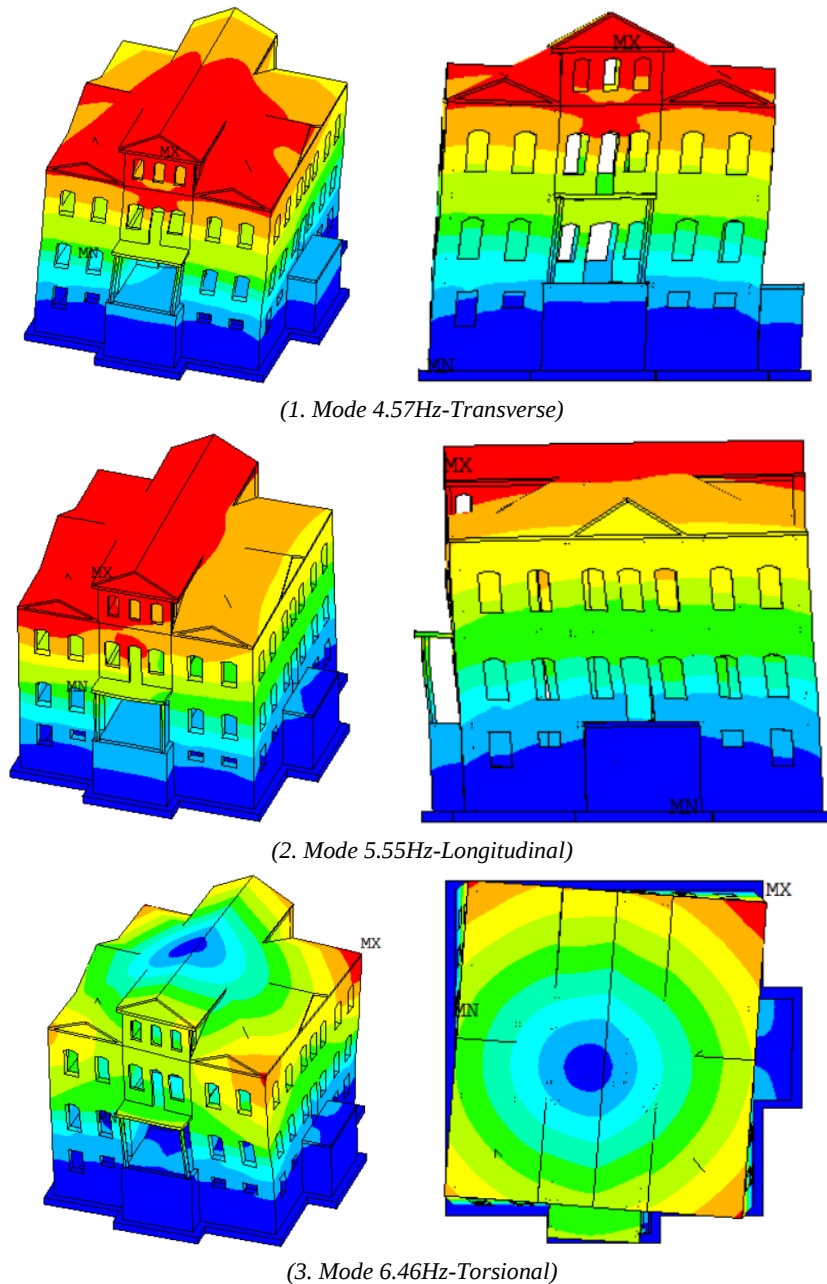


Fig. 3. The numerical mode shapes of the mansion

2.2. Seismic analyses of the mansion

Turkey has been exposed to major earthquakes throughout its history owing to its geographical location and the effects of its active tectonic plates. Turkey is located between the Eurasian, African, and Arabian Plates and has a complex tectonic structure (Fig. 4). The Anatolian Plate, where most of Anatolia is located, is a small part of the Eurasian Plate. Turkey has many important active fault lines, such as the North, East, and West Anatolian faults. Therefore, almost every region in the country is at risk of earthquakes. In particular, the earthquakes that occurred on the East Anatolian Fault on February 6, 2023, centered in Kahramanmaraş, were recorded as the largest earthquakes in recent history. These earthquakes caused shock destruction in the region, and many buildings and historical structures were damaged.

According to official records, an earthquake with a depth of 8.6 km and a magnitude of 7.7 (M_w) occurred on February 6, 2023, with the epicenter in the Pazarcık district of Kahramanmaraş. On the same day, another earthquake occurred in the Elbistan district of Kahramanmaraş, with a depth of 7 km and a magnitude of 7.6 (M_w). While these earthquakes have been experienced in many regions of Turkey, they have caused destruction, loss of life, and economic losses over a wide area. Nearly 3000 aftershocks occurred during the first months after the earthquakes [29-31]. The earthquakes that occurred on February 6 and the aftershocks are shown in Fig. 5.

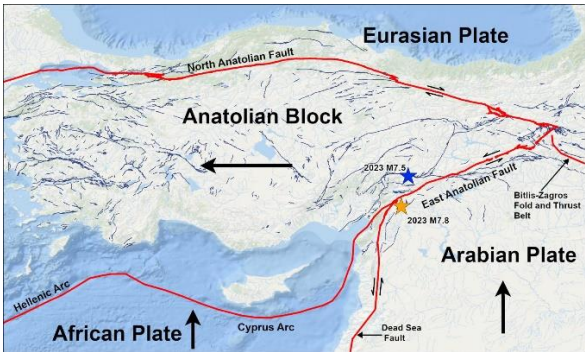


Fig. 4. Tectonic map of Turkey [28]

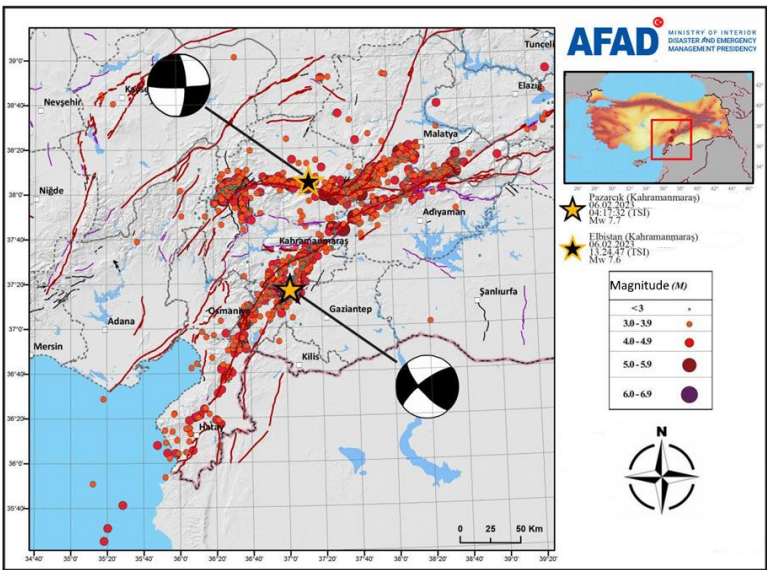
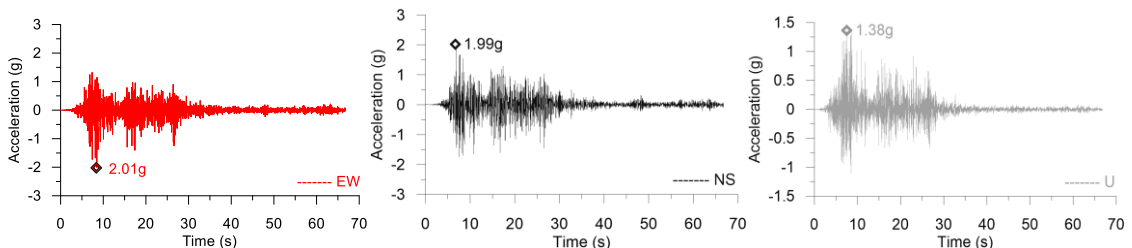


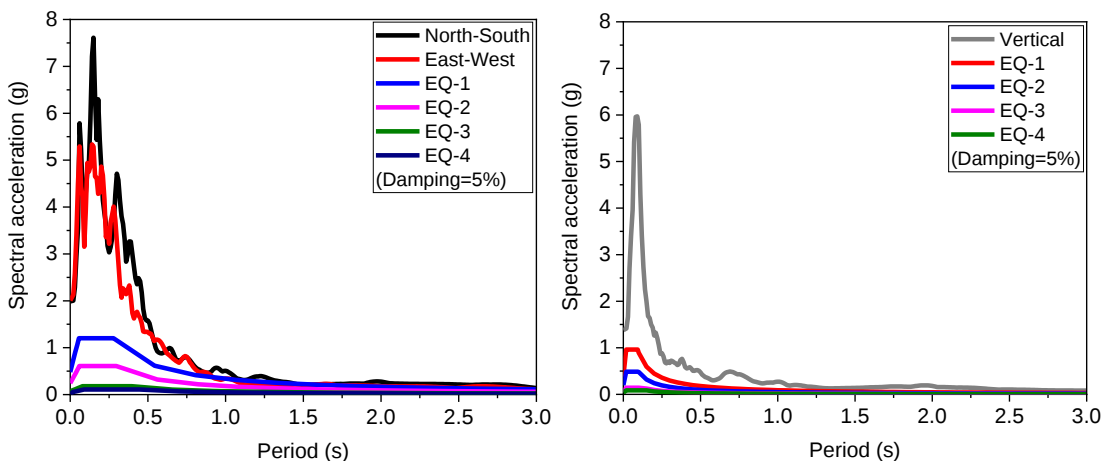
Fig. 5. Location of Pazarcık (Mw 7.7) and Elbistan (Mw 7.6) (Kahramanmaraş) earthquakes and aftershock activity map (adapted from [29])

Within the scope of the study, data from the Pazarcık station (Station Code: 4614), where the greatest ground acceleration of the Pazarcık-centered earthquake ($M_w = 7.7$) was measured, and Ortahisar station (Station Code: 6101), which is close to the location of the building, were used for the seismic analysis of the historical building. Figures 6 and 7 present the acceleration records and response spectra of both stations corresponding to the Kahramanmaraş-Pazarcık earthquake for TBEC (2018) [32]. EQ-1, EQ-2, EQ-3, and EQ-4 are earthquake levels that correspond to earthquake ground motions of 2%, 10%, 50%, and 68% probability of exceedances within 50 years. As can be seen in Figs 6 and 7, the acceleration values obtained from the station close to the center of the earthquake were quite high. However, the data obtained from the Ortahisar station, which is far from the earthquake center, was quite low. The spectral accelerations obtained from Pazarcık station were well above the spectral values obtained from the earthquake hazard maps for the region where the building is located. The spectral acceleration values obtained from the Ortahisar station did not exceed those of the region where the building was located.

Numerical seismic analyses (time histories) were performed using acceleration values obtained from the Pazarcık and Ortahisar stations. The displacement values obtained from the analysis are shown in Fig. 8. As can be seen from Fig. 8, the maximum displacements were obtained at the top of the structure at 100 mm for Pazarcık station and 0.15 mm for Ortahisar station.

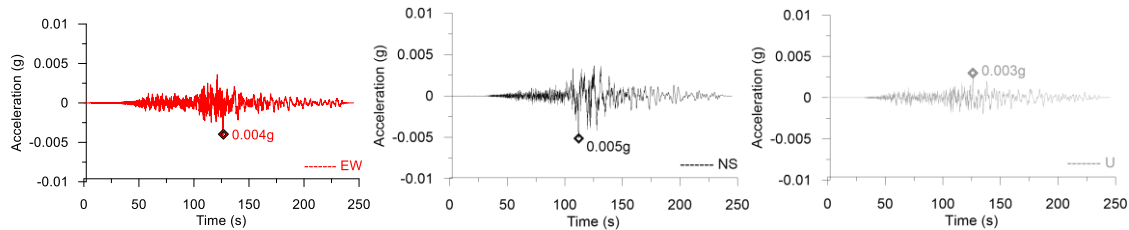


Acceleration graphs obtained from Pazarcık station (Pazarcık earthquake)

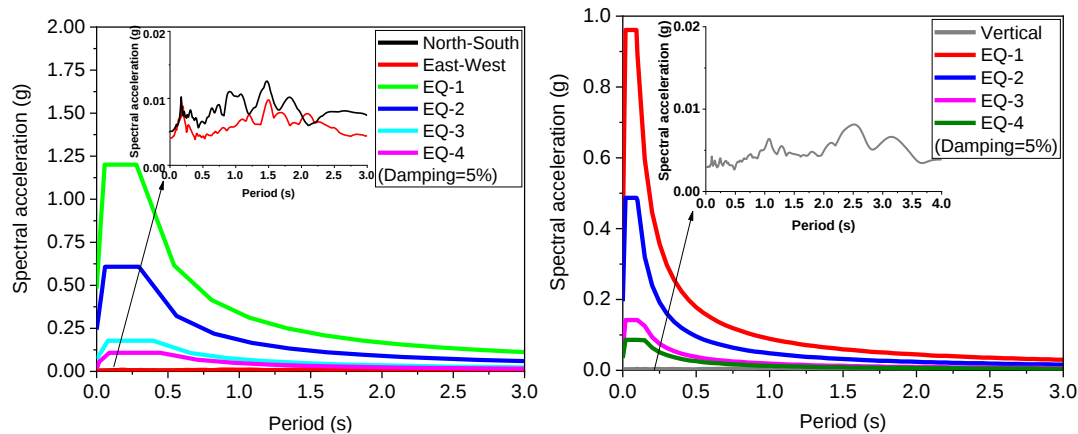


Comparison of Pazarcık Earthquake (Pazarcık station) spectrum values with Pertev Pasha Mansion earthquake spectra

Fig. 6. Acceleration records obtained from Pazarcık station and comparison between spectral values of Pazarcık station and spectrum values obtained from earthquake hazard maps for Pertev Pasha Mansion

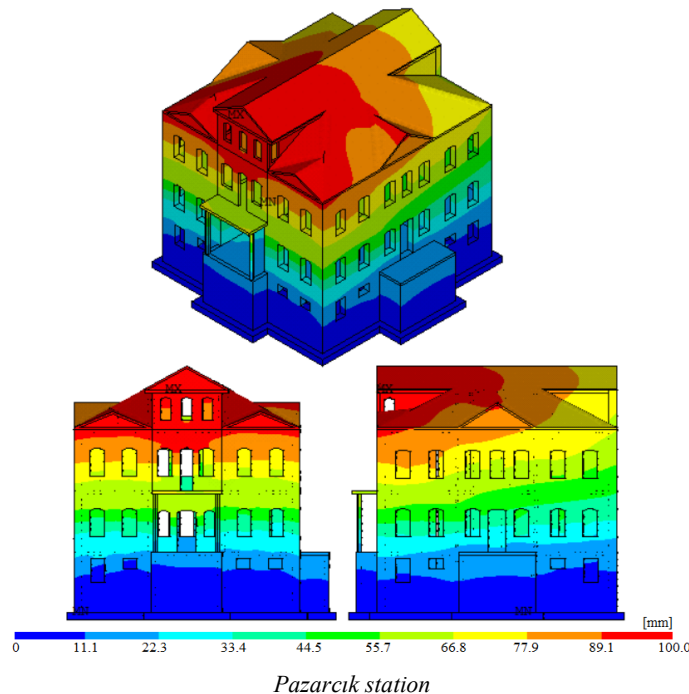


Acceleration graphs obtained from Ortahisar station (Pazarcık earthquake)

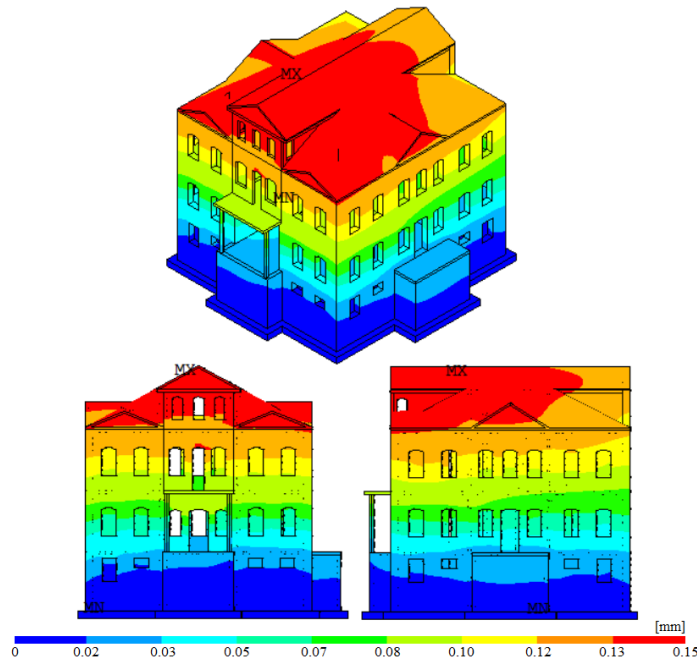


Comparison of the Pazarcık Earthquake (Ortahisar station) spectrum values with the Pertev Pasha Mansion earthquake spectra

Fig. 7. Acceleration records obtained from Ortahisar station and comparison between spectral values of Ortahisar station and spectrum values obtained from earthquake hazard maps for Pertev Pasha Mansion



Pazarcık station
Fig. 8. Maximum displacement contour diagrams for each analysis



Ortahisar station

Fig. 8. Continued

The tensile stress contour diagrams obtained by applying the analyses are shown in Fig. 9. The maximum tensile stress value obtained from the analysis with Pazarcık station accelerations was 21.4 MPa at the corner points of the windows. Similarly, a maximum stress value of 0.032 MPa was obtained at the window corner points as a result of the acceleration and growth analysis at the Ortahisar station. In both analyses, tensile stresses were concentrated at the corner points of the wall openings in the lower floors. As expected in seismic analyses, tensile stresses in masonry walls occur diagonally. For this reason, diagonal cracks are commonly observed in masonry walls after an earthquake.

The compressive stress contour diagrams obtained according to the analysis results are presented in Fig. 10. The compressive stress values obtained from the analysis performed on Pazarcık station accelerations were maximum at 21.6 MPa at the corner points of the window opening. Similarly, as a result of the analysis conducted with the Ortahisar station accelerations, the maximum stresses were obtained at 0.034 MPa at the window corner points. As a result of the analysis carried out with Pazarcık station data, the resulting compressive and tensile stresses were well above the strength values of unreinforced masonry walls. The compressive and tensile stresses resulting from the analysis carried out with Ortahisar station data are at a level that will cause very limited damage to the masonry walls.

3. Structural evaluation of the mansion

To evaluate the results of the seismic analyses, the Earthquake Risk Management Guide for Historical Structures [27], published in Turkey, was used. These guidelines aim to evaluate the seismic performance levels of historical masonry structures (Fig. 11). The guidelines delineate three performance levels concerning the conditions of historical buildings: (1) Limited Damage Level (LD), (2) Controlled Damage Level (CD), and (3) Collapse Prevention Level (CP). Within the LD category, the building was assumed to be nearly within or slightly above the elastic range, showing minor cracks in its structural elements. CD represents the stage prior to collapse, indicating situations in which a building can be reinforced and utilized

without requiring extensive interventions. The CP represents the final stage before potential collapse. Table 2 lists the target performance levels and their limits.

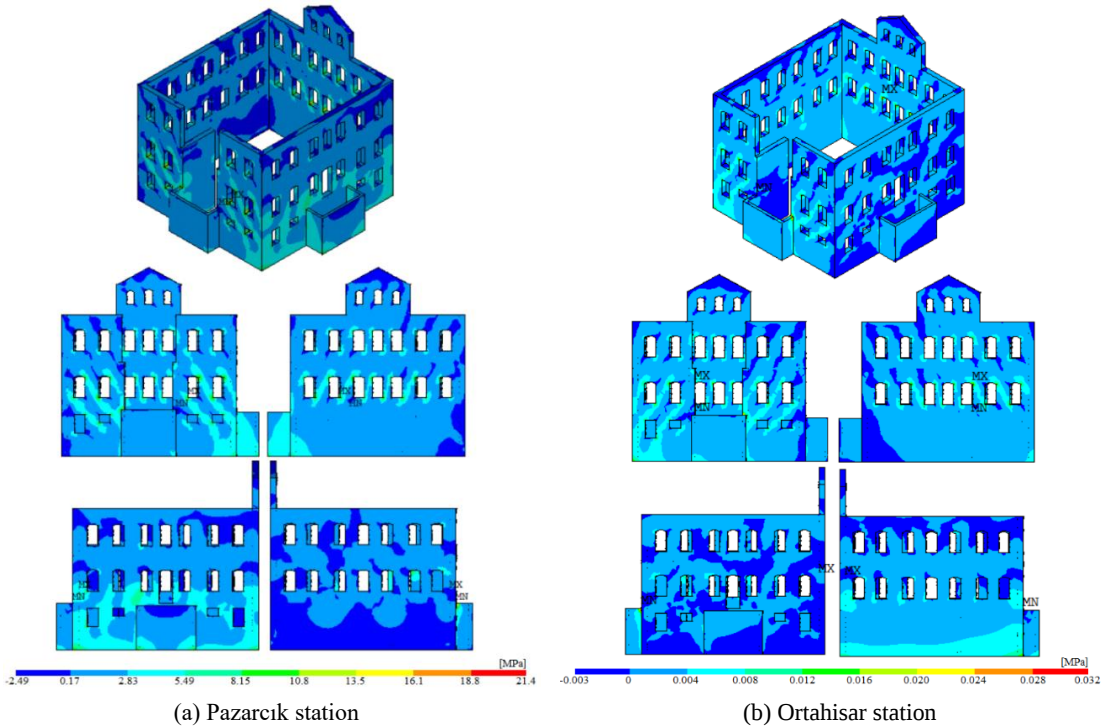


Fig. 9. Maximum principal stress contour diagrams for both analyses (Tensile stress)

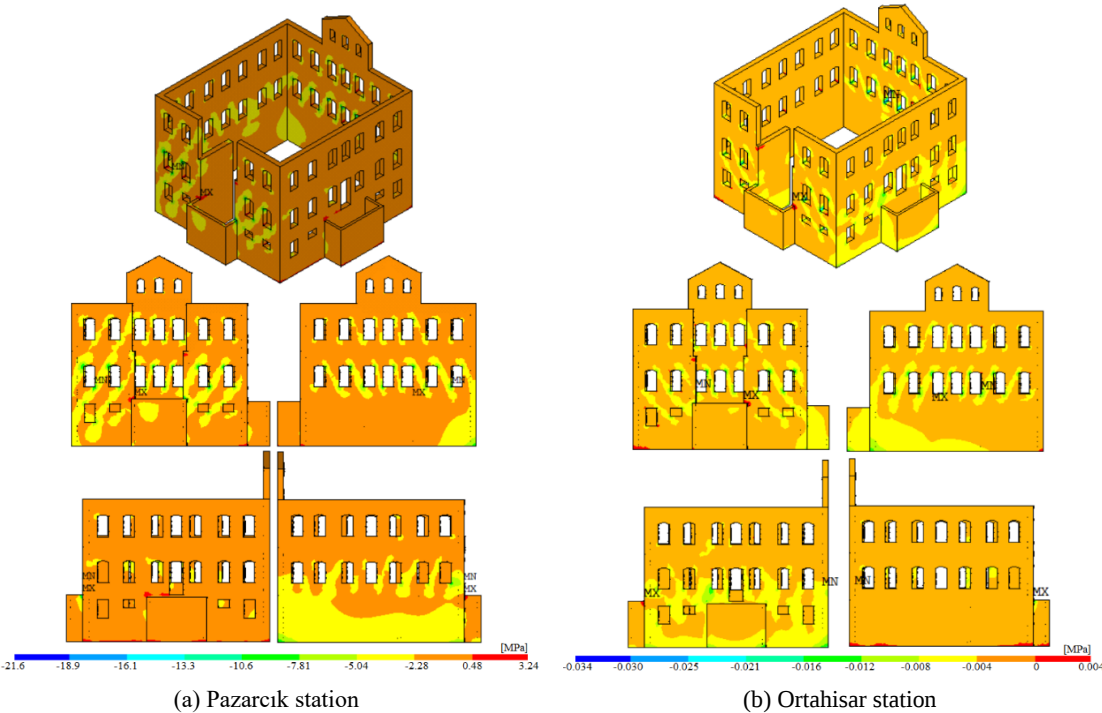


Fig. 10. Minimum principal stress contour diagram for both analyses (Compressive stress)

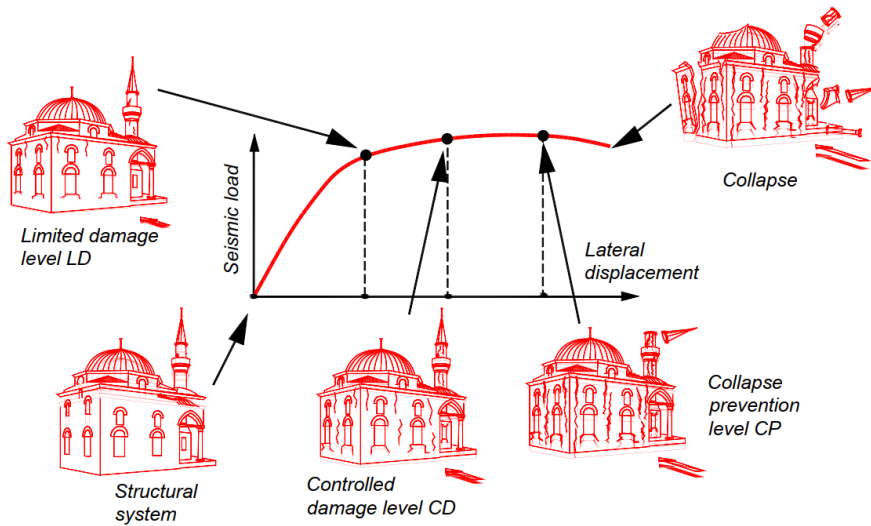


Fig. 11. Schematic view of performance levels for historical structures [27]

Table 2. Performance levels and limits for historical masonry structures [27]

Performance Level	Methods of Analysis / Limits
	<u>Linear analysis is employed</u>
Limited Damage Level (LD)	➤ Ultimate stresses of the material or ultimate strength of the structural element and joints are not exceeded ➤ Drifts do not exceed 0.3%
	<u>Linear analysis is employed</u>
Controlled Damage Level (CD)	➤ Ultimate stresses of the material or ultimate strength of the structural element and joints are not exceeded when the structure is subjected to vertical and earthquake loads reduced by $R_a \leq 3$ ➤ Drifts do not exceed 0.7%
	<u>Nonlinear analysis is employed</u>
	➤ Ultimate strains of the material are not exceeded ➤ Drifts do not exceed 0.7%
	<u>Linear analysis is employed</u>
Collapse Prevention Level (CP)	➤ Ultimate stresses of the material or ultimate strength of the structural element and joints can be exceeded by a certain ratio (i.e. 50%), when the structure is subjected to vertical and earthquake loads reduced by $R_a \leq 3$ ➤ Drifts do not exceed 1.0%
	<u>Nonlinear analysis is employed</u>
	➤ Ultimate strains of the material can be exceeded by a certain ratio (i.e., 20%), ➤ Drifts do not exceed 1.0%

The maximum drift ratios obtained according to the seismic analysis results of the Pertev Pasha Mansion are presented in Table 3. The calculations were performed based on the height of the mansion from the soil (14 m). According to the results of the seismic analysis performed using the Pazarcık station data, the drift ratio values of the structure exceeded 0.7%, which corresponds to a CP performance level. However, according to the seismic analysis results obtained using Ortahisar station data, the maximum drift ratio of the structure was 0.001%, which corresponds to an LD performance level.

Table 3. Drift ratio values for seismic analyses

Parameter	Analyses with Pazarcık Station Data	Analyses with Ortahisar Station Data
Drift Ratio (%)	0.71	0.001
Performance Level	CP	LD

When the tensile stresses obtained from the analysis using Pazarcık station data were examined, values such as 21.4 MPa were obtained, which are quite high for masonry walls. Based on these values, partial or complete structural collapse may occur under such an earthquake. However, when the tensile stresses obtained from the analysis using Ortahisar station data were examined, values such as 0.032 MPa were obtained, which are quite low for masonry walls. Based on these results, the damage to the structure would be minimal. From the data analysis of the Pazarcık station, compressive stresses reached notably high values, such as 21.6 MPa, which are considerably elevated for a masonry wall. These findings suggest the likelihood of a partial or complete structural collapse during a seismic event of such magnitude. Conversely, the analysis using data from the Ortahisar station yielded significantly lower compressive stress values, such as 0.04 MPa, which were considerably lower for a masonry wall. Consequently, these results indicate that potential damage to the structure is minimal.

4. Conclusions

This study examines the seismic behavior of the historical Pertev Pasha mansion located in Trabzon province based on the Kahramanmaraş-Pazarcık earthquake. Analyses were performed using data from the Pazarcık station, where the highest acceleration values of the Pazarcık earthquake were recorded, and data from the Ortahisar station, which is close to the area where the structure is located. Modal analysis of the structure was also performed. The following conclusions have been drawn for this study:

- The first three natural frequencies were obtained as 4.57Hz, 5.55Hz, and 6.46Hz respectively. The mode shapes of the building were obtained in transverse, longitudinal, and torsional modes.
- According to the results of the seismic analysis performed using the Pazarcık station data, the drift ratio values of the structure exceeded 0.7%, which corresponds to a CP performance level. However, according to the seismic analysis results obtained using Ortahisar station data, the maximum drift ratio of the structure was 0.001%, which corresponds to an LD performance level.
- In both analyses, tensile and compressive stresses were concentrated at the corner points of the wall openings in the lower floors. As expected in seismic analyses, stresses in masonry walls occur diagonally. This case demonstrated the potential for diagonal crack damage in real earthquake scenarios.
- The displacement and stress values obtained from the seismic analysis of the structure indicated that it would likely undergo severe damage and collapse if located close to the earthquake zone. However, at its current location, it is estimated that the structure will receive minimal damage.

Even for the same earthquake, substantial discrepancies can be observed between records obtained from different stations due to their varying distances from the epicenter. This finding emphasizes the crucial influence of station location on the captured seismic data, highlighting the importance of carefully selecting data for accurate and reliable numerical analyses of buildings' seismic response, especially for historical structures.

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Conflict of interests

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Data availability statement

No new data were created or analyzed in this study.

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