



## Research Article

# Investigation of structural performances of historical building elements made with local materials using the finite element method

Saeid Zardari <sup>a</sup> , İzzettin Kutlu <sup>b,\*</sup> , Aslan Nayeb <sup>c</sup> 

<sup>a</sup> Department of Civil Engineering, İstanbul Okan University, 34947 İstanbul, Türkiye

<sup>b</sup> Department of Architecture, Mardin Artuklu University, 47060 Mardin, Türkiye

<sup>c</sup> Department of Interior Architecture, Yeditepe University, 34755 İstanbul, Türkiye

## ABSTRACT

The structural performance of the materials used in historical buildings can be damaged, usually due to natural events or human-induced interference. Historical buildings in the Southeastern Anatolia Region were generally built with local materials such as stone and brick. This situation should be seen as a factor that may cause severe structural damage in buildings located on a regionally active fault line. Within the scope of the study, the materials used in the region were discussed, and a numerical model representing the behavior of the materials against an earthquake that could occur on the fault line was used. Stone, brick and concrete material definitions were made for the prototype of the arch form modeled with SAP2000, and time-history analyses were carried out separately for each material. Concrete material behaviors, frequently used in buildings constructed today, are also included in the analysis for comparison. As a result of the study, it has been observed that local materials do not have sufficient tensile strength against earthquakes compared to concrete materials and that the structures may face the risk of collapse in case of seismic movements in the region.

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## 1. Introduction

The geographical expanse of Türkiye is situated within an active seismic belt, and historical records underscore the occurrence of numerous earthquakes in these regions throughout human history. Considering all disasters in Turkey, it is evident that natural disasters, particularly earthquakes, have a significant impact (Birinci 2023). An investigation conducted by the Turkish Statistical Institute reveals that a substantial 92.3% of the nation's territory is susceptible to seismic activity (Önal and Koçak 2005; Sayıl and Osmaşahin 2008; Öztürk 2020; Doğangün et al. 2021; Medved et al. 2021). Therefore, Türkiye consistently faces the imminent threat of earthquakes. In the pursuit of safeguarding structures against seismic impacts and enhancing their structural resilience, a paramount prerequisite involves the meticulous identification of their existing structural

condition. Empirical studies have revealed that historical structures exhibit a more complex response to seismic forces when compared to contemporary buildings. Furthermore, these architectural structures demonstrate different sensitivities to seismic influences depending on the temporal context of their construction and how they have been used over time (Sezen et al. 2008; Al-Nammari and Lindell 2009; Şeker 2011; Di Ludovico et al. 2017).

Historical buildings, having survived the passage of numerous years, have been exposed to seismic activity and various external forces. Thus, the structures of historical buildings that are adversely affected by earthquakes sometimes collapse and sometimes become unusable (Camuffo et al. 2004; Sezen et al. 2008; Korkanç and Savran, 2015; Corradi et al. 2023). It is essential to identify the weak points of buildings that can be damaged in an earthquake so that historical buildings are

\* Corresponding author. Tel.: +90-482-212-8980 ; E-mail address: izzettinkutlu@artuklu.edu.tr (İ. Kutlu)

minimally damaged, especially not destroyed, by earthquakes. Preserving the cultural heritage and architectural integrity of these historical structures is of paramount importance, as they represent tangible links to the past and serve as invaluable repositories of a community's identity and traditions (Örmecioglu 2010; Ahunbay 1996; Ertaş and Bekar 2021). Therefore, it is essential to conduct seismic analyses of historical buildings that provide insights that can inform interventions aimed at preserving structural integrity without causing damage (Çırak 2011; Lacanna et al. 2020; Eriçok 2022). A large number of studies are available in the literature report applications of ambient vibration testing and operational modal analysis with multiple goals, such as damage assessment (Betti et al. 2015; Clementi et al. 2017; Alkayem et al. 2018), seismic vulnerability assessment (Bartoli et al. 2015; Erdogan 2017; İlerisoy and Soyluk), structural health assessment and monitoring (Castellazzi et al. 2012; Ramos et al. 2013; Bassoli et al. 2018), modal updating and identification (Aoki et al. 2008; Chiorino et al. 2011; Torres et al. 2017; Girardi et al. 2019; Pavlovic et al. 2019; Mertol 2023). Concurrently with the advancement of computer technology, the formulation of models for historic buildings and their structural analysis using the finite element method is progressively becoming widespread (Kutlu and Soyluk 2024).

Preserving historical buildings for future generations necessitates an initial step of comprehensive documentation. Documenting cultural assets in their current state or original form, utilizing data derived from their existing conditions, holds paramount significance (Styliadis 2007; Kutlu et al. 2023). This meticulous documentation process captures the present state and proves instrumental in discerning damages that have transpired or are likely to occur in the future. Such a proactive approach facilitates a more informed and effective strategy for preserving cultural heritage, ensuring its integrity is passed on to future generations (Durduvan 2003; Donato and Giuffrida 2019). Developing conservation strategies and documentation is essential for analyzing historical buildings. Indeed, the analysis of a historical building becomes an unreliable exercise in the absence of detailed documentation. Documentation is the foundational basis, providing the essential data and details for a comprehensive structural analysis. However, documentation of historical buildings can be time-consuming. During this process, prototypes of undocumented buildings can be built, and preliminary information can be obtained. Prototypes do not contain precise information, but they can provide quick information. These models function as experimental representations, allowing for basic observations and assessments of structural behavior.

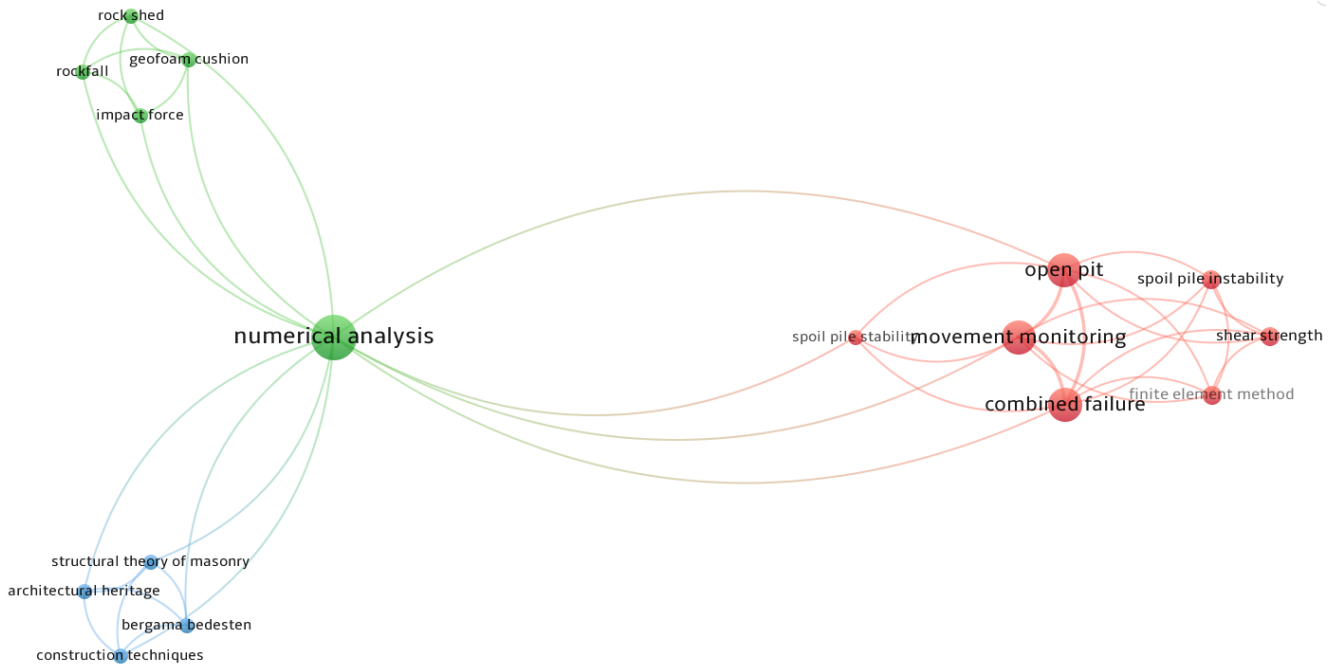
Natural stones have been esteemed for their enduring qualities and have been integral to architectural endeavors across centuries (Winkler 1997; Pereira and Marker 2016; Marzo and Neves 2020). Their incorporation into construction practices has encompassed a broad spectrum of applications, with natural stone serving as foundational elements and aesthetic enhancements alike. Notably, historical edifices stand as testaments to the extensive utilization of natural stone, where it has been employed as blocks in columns, integral components of

load-bearing walls, external cladding material on facades, and flooring substrate (Kılıç 2009). The multifaceted roles that natural stones play underscore the necessity for a comprehensive assessment of their resilience against environmental factors, an examination of their technical attributes, and the formulation of judicious decisions informed by empirical data. The durability of natural stones is of paramount importance in architectural endeavors. Through the ages, architects and builders have relied on the robustness of natural stone to ensure the longevity and structural integrity of their constructions. Winkler (1997) underscores the enduring nature of natural stones, highlighting their ability to withstand the passage of time and resist deterioration caused by external forces. Moreover, Pereira and Marker (2016) emphasize the role of natural stones as a sustainable building material, owing to their innate durability and longevity, which contribute to reduced maintenance requirements and prolonged structural stability. In addition to their durability, natural stones possess a diverse array of technical properties that render them suitable for a multitude of architectural applications. Marzo and Neves (2020) delve into the intricacies of these properties, including compressive strength, porosity, thermal conductivity, and weathering resistance. Understanding these technical characteristics is imperative for architects and engineers, as it facilitates informed decision-making during the design and construction phases. For instance, the compressive strength of natural stone dictates its suitability for load-bearing applications, while its porosity influences its susceptibility to water ingress and subsequent deterioration. Wonganan et al. (2021) presents the physical and engineering properties of historical building materials and substitution materials used for the preservation of historical structures in Thailand. Eslami et al. (2012) conducted a comprehensive research study on the seismic behavior of a masonry vault structure in a historical building located in the city of Yazd. Yıldızlar et al. (2019) provides a detailed explanation of the restoration works conducted on a historical masonry building, used as a hospital building in the 1840s but now serving as the Faculty of Political Sciences of İstanbul University, based on its original geometrical and material characteristics.

Türkiye has a rich and ancient history, with numerous empires leaving deep traces and significant historical heritage across the country (Karalar and Çavuşlu 2021). Anatolia has a very diverse geography in terms of natural stone. The use of these stones in architecture is quite commonly observed. However, this region is also exposed to destructive effects such as earthquakes. Türkiye, situated in a region of high seismic activity, has experienced significant consequences due to earthquakes occurring in various fault systems throughout its history (Pampal 1999; Dal Zilio and Ampuero 2023). Structural analyses are quite critical for a region that is under the earthquake effect to this extreme. This study examines the relationships established through the keywords in research literature that contains the terms "finite element analysis" and "Anatolia". The objective is to identify the common words used in this field and gain insights into the methodologies, aims and findings of the

relevant studies. The research process was conducted using the Web of Science (WoS) online database, which is utilized to monitor, analyze and access scientific research and academic publications. Specifically, the studies that have employed both "finite element analysis AND Anatolia" in their content were searched and analyzed. Accordingly, 21 studies were found in the WoS da-

tabase. The VOSviewer (visualizing scientific landscapes) program was used to create bibliometric networks among these studies and visualize the keyword occurrences. The keywords that appeared at least once in the studies were shown in the program. Notably, the studies were highly related to the keywords "rock, numerical analysis, movement monitoring" (Fig. 1).



**Fig. 1.** Bibliometric analysis performed with the expression "finite element analysis and Anatolia".

Masonry structures are some of the oldest building types used throughout history. Consequently, many masonry structures hold historical significance and are still in use today (Akin and Alagöz 2024). The structural integrity of masonry systems, prevalent in historical buildings across Anatolia and particularly in the Southeastern Anatolia Region, becomes crucial in mitigating the impact of seismic events. Failure of these materials to withstand horizontal ground movements during earthquakes can lead to severe damage or collapse of historic structures. Therefore, there is a pressing need to investigate the earthquake resilience of buildings constructed with traditional materials such as stone and brick, comparing their performance to modern building materials like concrete. The primary objective of this study is to analyze the seismic behavior of structures composed of traditional materials prevalent in Anatolian historical buildings, with a particular focus on the Southeastern Anatolia Region. Mechanical properties of stone and brick, commonly utilized in these constructions, was examined in relation to their earthquake resistance. Furthermore, this research aims to juxtapose their performance against that of concrete, a staple material in contemporary construction practices. To achieve these objectives, a curvilinear structural element model, representative of arches commonly found in historical buildings, was employed. Ground motion data from four significant earthquakes in Türkiye was applied to the model, simulating seismic forces experienced by struc-

tures in the region. By subjecting these models to realistic earthquake scenarios, the study seeks to elucidate the seismic response of historical buildings along the Eastern Anatolian Fault Line. The findings of this research endeavor were expected to yield valuable insights into the seismic performance of traditional building materials prevalent in Anatolia. By discerning the strengths and limitations of stone, brick, and concrete in withstanding seismic forces, architects, engineers, and policymakers can formulate informed strategies for the preservation and retrofitting of historical structures. Ultimately, the study aims to contribute to the development of seismic-resilient building practices, safeguarding Anatolia's rich architectural heritage for future generations.

## 2. Materials and Method

The study used the finite element method to determine the changing seismic performance of local materials and compare them with concrete. Finite elements analysis, a contemporary numerical modeling method that has increased in use with the development of computer technology in recent years, is one of the most crucial modeling methods today. It is an analysis method that allows 3-dimensional static and dynamic analysis of structures; linear and non-linear analyses can be made, and the results can be displayed numerically or graphically (İmamoğlu and Çetin 2007; Demirtaş and Erkm

2019). The finite element method of the study consists of three stages. In the first stage, the arch, whose dimensions were defined above, was modeled with the SAP2000 (Structural Analysis Program) program. In the second stage, the properties of three different materials, stone, brick, and concrete, were defined on the model created in the program. In the third stage, four ground motion records accessed on the PEER Berkeley website were applied to the arch form for each material value entered to determine the earthquake performances (Dabanlı 2008). The analysis results obtained after these stages were evaluated.

In the study, the curvilinear structural element, the arch, frequently used to pass any opening in historical buildings, is discussed, and we aim to determine the changes to be seen in the earthquake performance of the arch form with different materials. In this context, a prototype three-span arch form was created, and the material properties of the arch were defined as stone and brick materials, primarily used in the Southeastern Anatolia Region. The region is under the influence of the active East Anatolian Fault System, which poses a danger to the historical structures in the region today. Despite the intense earthquake movements on the fault in recent years, the Eastern Anatolian Fault System is thought to be in a position to cause destructive earthquakes in the next century due to the seismic gaps on the fault (Hutton 2003; Pacific Earthquake Engineering Research Center). Therefore, the studies to be carried out for the historic structures within the affected region are of great importance. Within the scope of the study, the local materials frequently encountered in the region, stone and brick, were discussed. In addition, concrete material properties are defined on the prototype arch to compare with concrete, which is one of the important building materials today. Previous experimental studies on materials from the literature were used to determine material properties. Altunışık et al. (2016) investigated the seismic behavior of the Kaya Çelebi Mosque located in Türkiye, which has been undergoing a restoration process since the 2011 Van earthquake. In their study, the researchers addressed the material mechanical properties of the historical structure. Ünay (2002), on the other hand, presented approaches regarding the general material properties of historical structures. Based on the findings of these two studies, average material mechanical properties were determined for a prototype model, and detailed information was included in the modeling process.

### **2.1. Local materials used in Southeast Anatolia**

Anatolia, positioned at the crossroads of Asia and Europe, has served as a fertile ground for the emergence of numerous civilizations since ancient times. The rich cultural legacy left behind by these civilizations not only provides valuable insights into Anatolia's past but also sheds light on various aspects of its present-day socio-economic, cultural, and architectural landscape. Preservation efforts aimed at safeguarding Anatolia's cultural assets, spread across its seven distinct regions, play a crucial role in ensuring the transmission of this histori-

cal wealth to future generations. Among these regions, the Southeastern Anatolia Region stands out for its unique cultural heritage, shaped by the convergence of diverse civilizations over millennia. Local materials, particularly stone and brick, have played a central role in shaping the architectural identity of this region. Their abundant use in the construction of historical structures not only reflects the region's indigenous building traditions but also embodies its resilience and adaptability in the face of changing socio-political landscapes. The conservation of cultural assets in the Southeastern Anatolia Region holds profound significance, not only from a historical perspective but also in terms of fostering local identity, promoting tourism, and stimulating economic development. By preserving and showcasing the architectural marvels crafted from indigenous materials like stone and brick, the region can capitalize on its cultural heritage as a catalyst for sustainable growth and community empowerment. In essence, the discussion of local materials such as stone and brick within the context of the Southeastern Anatolia Region underscores the region's pivotal role in Anatolia's cultural narrative. By nurturing and protecting these invaluable cultural assets, Anatolia can continue to serve as a beacon of cultural heritage, inspiring curiosity, fostering understanding, and bridging the past with the present for generations to come.

Stones represent mineral formations resulting from the intricate interplay of elements within the atom-molecule-element chain, culminating in the creation of minerals, which subsequently aggregate to form stones (Yüzer et al. 2016). These mineral compositions, shaped by geological processes over eons, have been integral to human existence since antiquity, enduring through the passage of time and the advancements of technology. Despite the evolution of civilization and the advent of modern materials, natural stones persist as essential elements in various facets of human life. Türkiye stands out as a fortunate nation endowed with abundant natural stone resources, boasting remarkable reserves and diversity (Taşlıgıl and Şahin 2016). This geological wealth spans a spectrum of stone types, including marble, granite, limestone, travertine, and many others, each characterized by distinct aesthetic, structural, and functional properties. The country's geological diversity, coupled with its strategic location bridging continents, positions Türkiye as a global hub for natural stone extraction, processing, and trade.

Türkiye has proven itself in this market, especially in production and export in recent years. At the same time, Türkiye has a special place in the sector with its unique stones and geographical location (Erkanol and Aydındağ 2013). In addition to all these positive aspects, unfortunately, there are still many shortcomings. Historical buildings, in which Türkiye's natural stone existence is shaped as a cultural and architectural heritage, are faced with many dangers today. When stone structures are examined, we can see that weathering occurs for many reasons. Stones are often exposed to deterioration due to environmental and time-dependent factors. Natural stones weaken over time with these effects and lose their physical-mechanical properties (Hasbay and Hattap

2017). It is essential to know the factors that cause deterioration in stones, to take precautions accordingly to prevent the deterioration of stones and to transfer the structures from generation to generation.

Natural stones, commonly used in some cities consisting of common areas where people live together, give this city a separate visual identity. For example, 'Bakirkoy Küfeki Stones and Marmara Island marbles' used in historical buildings in İstanbul, 'andesites' in early republican period buildings in Ankara, 'basalts' in Diyarbakir, and easily processed 'limestones' in Urfa and Mardin can be shown among them (Yüzer et al. 2016; Kazancı and Gürbüz 2017). Another material used in the region is clay, the raw material of brick. It is possible to divide the materials made of clay into two as baked and unbaked. The leading unbaked material is mud-brick. Bricks and tiles can be given as examples of baked materials. The production method of brick and tile is the same, only the molding systems are different (Şimşek 2003). Regional conditions are important in the use of brick. Therefore, structures made of stone draw atten-

tion due to the density of stone resources in Anatolia, Caucasus, Crete, and Cyprus. Due to the limited availability of stone in Mesopotamia, Iran, Central Asia, and Egypt, it was replaced by brick. In these regions, stone was only used to reinforce the brickwork (Bakirer 1981; Eroğlu and Akyol 2017).

## 2.2. Modeling of materials using the prototype finite element method

In the study, the arch, one of the most important elements of historical buildings, is handled as four spans. The external dimensions of the created model are 15.0 x 1.0, the arch height is 4 meters, and the total height is 5 meters. The arch piers are arranged as 1 m each, the middle openings 3 m, and the openings at the corners 2 m (Fig. 2). The study's primary purpose is to identify the differences between the materials. For this reason, this data was not included in the analysis process, so that the results obtained from the created model would be independent of the region and soil characteristics.

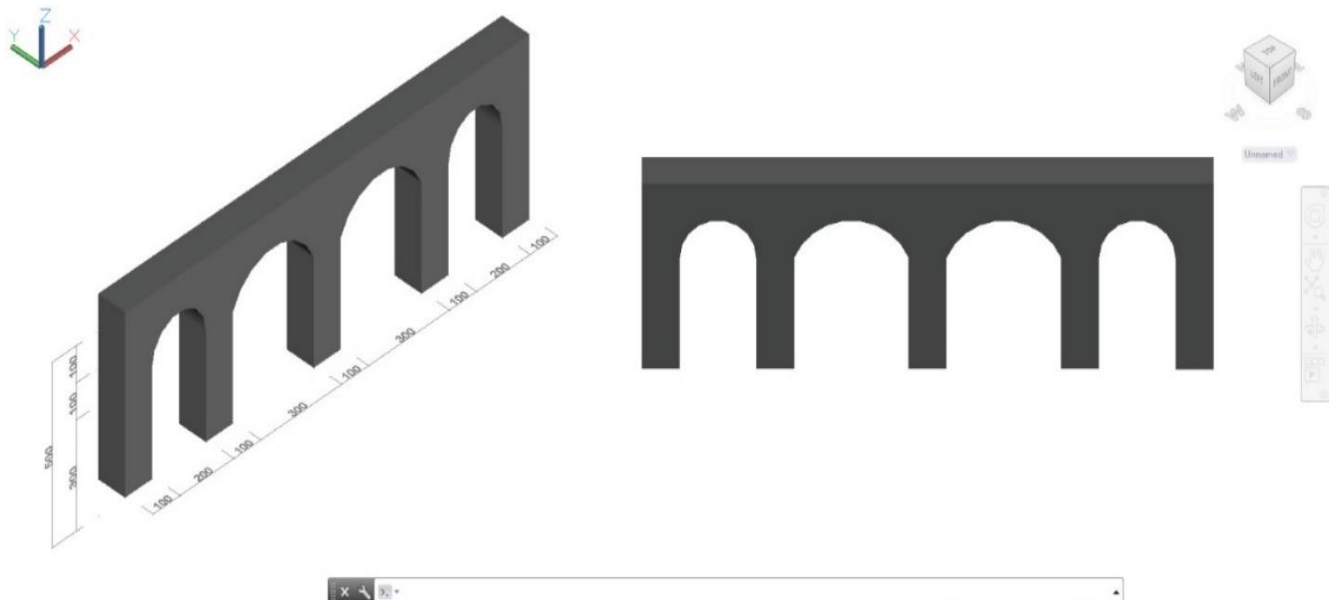


Fig. 2. Prototype model.

The mechanical properties of the materials used in the modeled prototype arch are given Table 1, and for this purpose, a finite element model of the prototype model was created in line with the model preparation features and rules of the SAP2000 software.

Model creation and calculation values are given below:

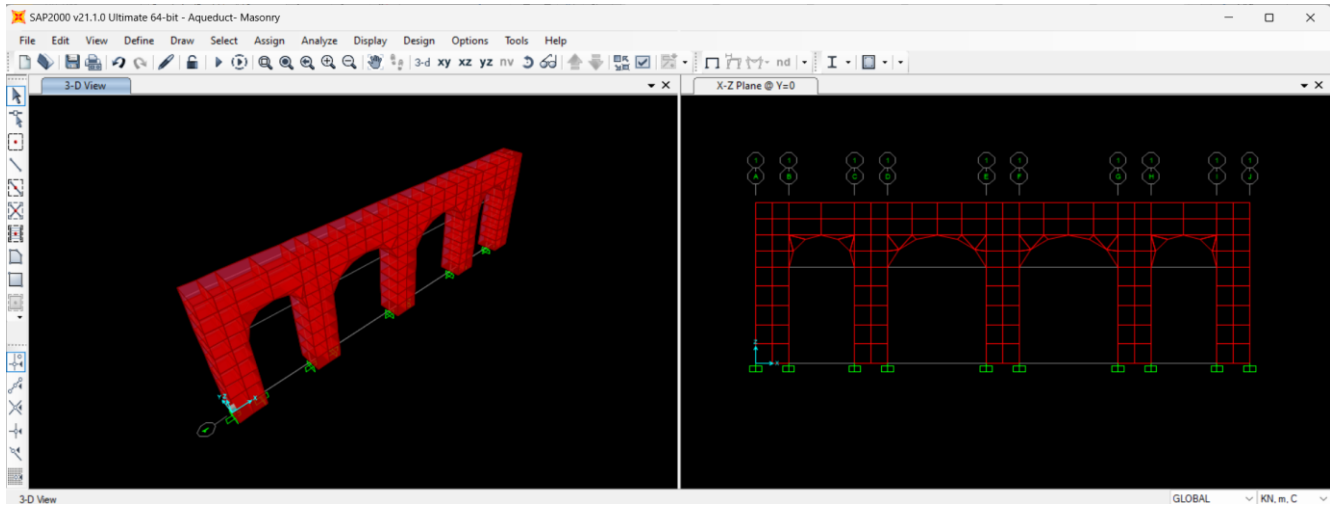
- The building's masonry walls and vault cover were modeled with SHELL elements.
- The relationship of the building with the ground was defined as fixed support.
- The model to be analyzed was prepared with 304 nodes and 95 SHELL elements (Fig. 3).
- Linear elastic calculation methods are also sufficient to comment on the modeled structural elements' general structural and seismic behavior, such as arches. In cases where more detailed results are desired, non-linear methods and experimental studies can also be

evaluated. In the study, it was accepted that the materials defined in the model showed linear elastic behavior together with the mortar.

- The material properties used in the analysis for the masonry prototype model were produced as a result of previous studies for similar structures in the region and are given in Table 1 above.
- In order to interpret the earthquake resistance data obtained as a result of the analysis, the resulting stresses were compared with the safety stresses of the material used in the building. The safety stresses of materials in the literature were used as mentioned (Altunışık et al. 2016; Ünay 2002). C25/30 was used for concrete, and the properties were implemented according to TS 500. The accepted safety stresses for the stone, brick and concrete used in the prototype model were presented in Table 2.

**Table 1.** Mechanical properties of the materials used in the arch during the analysis process and finite element model of prototype building (Altunışık et al. 2016; Ünay 2002).

Structural components	Modulus of elasticity (N/m <sup>2</sup> )	Density (kg/m <sup>3</sup> )	Poisson's ratio
Stone wall (with mortar)	4.50·10 <sup>8</sup>	2400	0.200
Brick	1.20·10 <sup>9</sup>	2400	0.200



**Fig. 3.** Finite element model view of the prototype in SAP2000.

**Table 2.** The accepted safety stresses for the materials used in the prototype model.

Materials	Pressure safety stresses (MPa)	Tension safety stresses (MPa)
Stone wall (with mortar)	0.90	0.135
Brick	2.40	0.360
Concrete	25.0	1.800

With numerical modeling, analyses are prepared to observe the reaction of the whole or some parts of the

structure under different loads or physical effects. This part of the study aims to apply four different ground motion records on the prototype model, the dimensions, and the plan mentioned above and to analyze the response of the structural element to these earthquake loads. Earthquake records were taken from different stations as indicated in Table 3. The first of these records was the earthquake that took place in Erzincan in 1992 with a magnitude of Mw=6.69; the second and third earthquakes occurred in Kocaeli in 1999 with Mw=7.51; the fourth is the earthquake of Mw=7.14, which took place in Düzce in 1999 (Ministry of Interior, Disaster and Emergency Management Presidency, Türkiye).

**Table 3.** Characteristics of ground motion records (Peak Ground Acceleration – PGA).

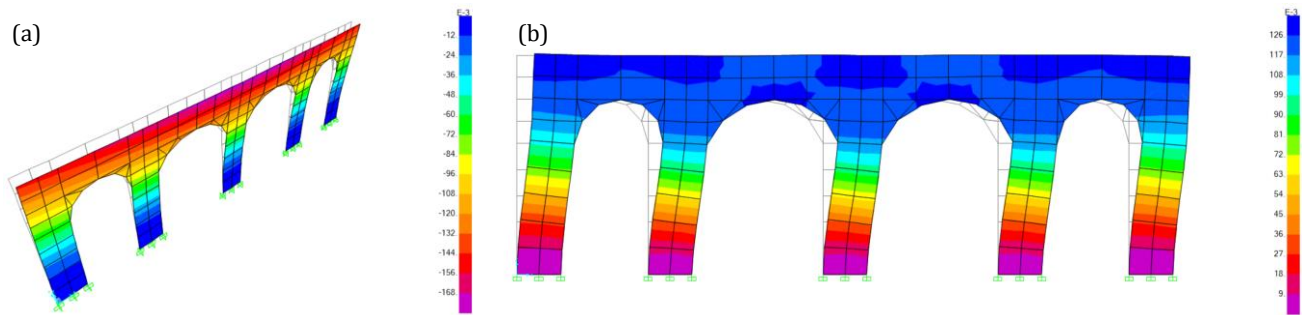
No.	Record ID	Event	Year	Station	Magnitude	Fault distance (km)	PGA-1 <sup>1</sup> (g)	PGA-1 <sup>2</sup> (g)
1	821	Erzincan, Türkiye	1992	Erzincan	6.69	0.00	0.496	0.386
2	1166	Kocaeli, Türkiye	1999	İzmit	7.51	30.73	0.124	0.090
3	1158	Kocaeli, Türkiye	1999	Düzce	7.51	13.60	0.312	0.364
4	1605	Düzce, Türkiye	1999	Düzce	7.14	0.00	0.404	0.515

### 3. Findings

First of all, the behavior under modal analysis was examined to analyze the structure's behavior under dynamic loads, independent from the region and earthquake, only depending on its system. Mode 1 and Mode 3 shapes that dominate in Y and X directions are shown in Fig. 4(a-b), and the period values resulting from the modal analysis are given in Table 4.

**Table 4.** Period values of the dominant Mode 1 and Mode 3 of the prototype model.

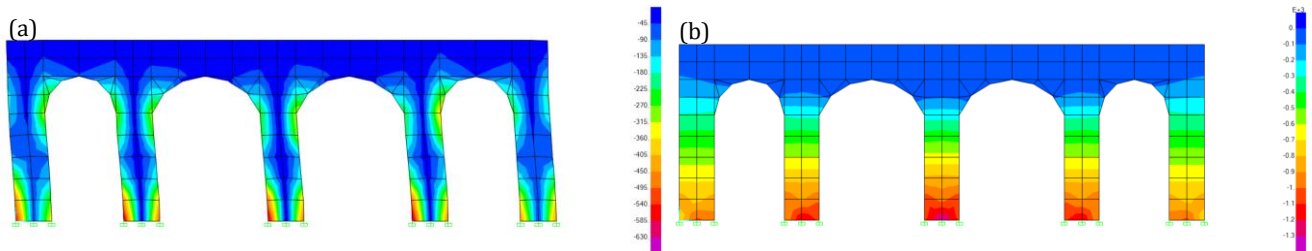
Materials		Mode 1	Mode 2	Mode 3
Stone	T(s)	0.56	0.41	0.26
Brick	T(s)	0.34	0.15	0.15
Concrete	T(s)	0.07	0.032	0.032



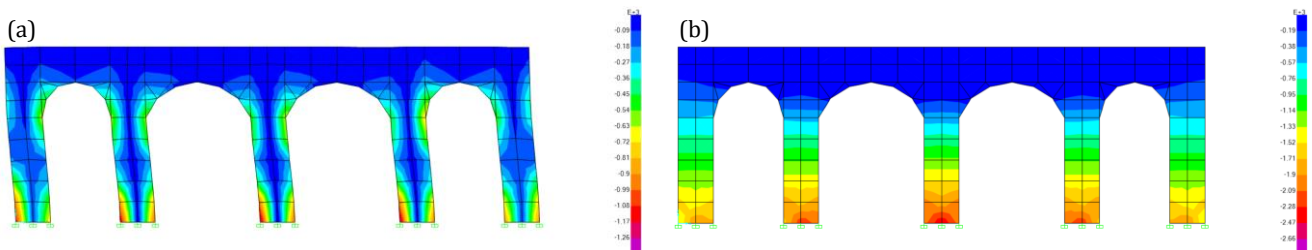
**Fig. 4.** Modal analysis: (a) Mode 1 translation is in the  $Y$  direction; (b) Mode 3 translation is in the  $X$  direction.

Four different ground motion recordings were applied to the arch from which the prototype model was created. For each earthquake record, the behaviors of the arch element, whose stone, brick, and concrete materials were defined, were compared. As the dynamic response of the arch, the displacements and the maximum compressive and tensile stresses in the materials are investigated. When the earthquake acceleration records

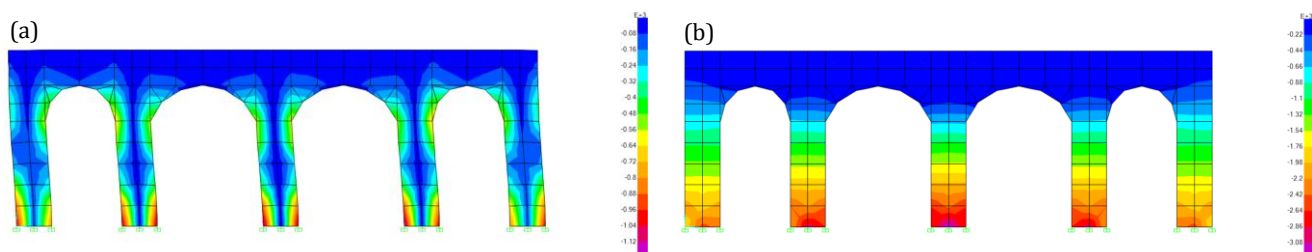
are applied to the model and the stresses occurring in the structure are compared, the most significant stress was obtained from the Erzincan earthquake acceleration record.  $X$  and  $Y$  direction compressive stress values obtained from recordings applied to the prototype arch for all three materials are shown in Figs. 5(a-b), 6(a-b), and 7(a-b). Time-history analysis results are given in Table 5.



**Fig. 5.** Compressive stresses obtained from the Erzincan earthquake analyses for the stone arc: (a)  $X$  direction; (b)  $Y$  direction.



**Fig. 6.** Compressive stresses obtained from the Erzincan earthquake analyses for the brick arc: (a)  $X$  direction; (b)  $Y$  direction.



**Fig. 7.** Compressive stresses obtained from the Erzincan earthquake analyses for the concrete arc: (a)  $X$  direction; (b)  $Y$  direction.

The result of the earthquake code 821 (Erzincan) was applied in the  $X$  direction. The analysis values were provided in the Table 5. For stone material, the maximum compressive stress value is 0.652 MPa, and the maximum tensile stress value is 0.650 MPa. The maximum

compressive stress value for brick material is 1.300 MPa, and the maximum tensile stress value is 1.300 MPa. The maximum compressive stress value for the concrete material was 1.252 MPa, and the maximum tensile stress value was 1.250 MPa.

**Table 5.** Maximum compression stresses and maximum tensile stresses (MPa).

			Stone	Brick	Concrete
Maximum compression stresses	Erzincan 821	Ex	0.652	1.300	1.252
		Ey	1.423	2.544	3.292
	Kocaeli 1166	Ex	0.526	0.475	0.329
		Ey	0.379	0.753	1.029
	Kocaeli 1158	Ex	0.376	0.691	0.770
		Ey	0.489	1.795	3.555
	Düzce 1605	Ex	0.450	1.416	0.906
		Ey	0.654	1.847	5.350
Maximum stresses	Erzincan 821	Ex	0.650	1.300	1.250
		Ey	1.397	2.807	2.138
	Kocaeli 1166	Ex	0.526	0.474	0.329
		Ey	0.330	0.771	0.865
	Kocaeli 1158	Ex	0.375	0.690	0.770
		Ey	0.619	1.609	4.986
	Düzce 1605	Ex	0.450	1.416	0.906
		Ey	1.099	1.408	5.674

Maximum displacements were given in Table 6. In SAP2000, U1 and U2 typically represent the displacement components in the global  $X$  and  $Y$  directions, respectively, for a structural analysis model. When you perform a structural analysis using SAP2000, the software calculates various results to help you understand how the structure behaves under different loading conditions. Displacement results, represented by U1 and U2,

provide information about how much the structure moves or deforms in the  $X$  and  $Y$  directions, respectively, due to applied loads. As can be seen from the results, the maximum displacement for the stone material was 38.9 mm displacement under the effect of the acceleration in the  $Y$  direction of the Erzincan earthquake. This value was determined as 29.3 mm for brick material and 1.33 mm for concrete material.

**Table 6.** Maximum displacements (mm).

	Stone		Brick		Concrete	
	U1	U2	U1	U2	U1	U2
Erzincan - 821	8.27	38.9	6.18	29.30	0.22	1.33
Kocaeli - 1166	6.60	10.3	2.20	8.01	0.061	0.41
Kocaeli - 1158	4.70	17.0	3.28	18.70	0.142	2.02
Düzce -1605	5.70	30.0	6.70	19.40	0.15	2.30

#### 4. Evaluation

Finite element analysis (FEA) was conducted utilizing linear elastic material properties to investigate the behavior of a modeled arch element subjected to four distinct ground motion scenarios. Through meticulous calculations, comprehensive insights were gained into the performance of the arch form constructed from three different materials in response to seismic forces and stress effects anticipated during an earthquake

event. The utilization of FEA enabled the simulation of complex structural behaviors under varying seismic conditions, providing a rigorous assessment of the arch element's response to dynamic loading. By employing linear elastic material properties, the analysis accounted for the linear relationship between stress and strain within the materials, allowing for a precise evaluation of structural performance within the elastic deformation regime. The examination encompassed the evaluation of displacement patterns, stress distributions,

and deformation mechanisms exhibited by the arch element under different ground motion excitations. Through systematic analysis, notable distinctions in the seismic response of the arch form constructed from different materials were elucidated, shedding light on their respective capacities to withstand earthquake-induced forces. The outcomes of the study unveiled critical insights into the seismic resilience of the arch element modeled with various materials, delineating their abilities to resist external loads and endure stress effects arising from seismic activity.

When the compressive stresses in the analysis results are examined, the stone arch element is durable for all three earthquake records, but the maximum compressive stress of the stone was obtained as 1.423 MPa under the effect of the Erzincan earthquake in the *Y* direction. Since the obtained compressive stress is higher than the value of 0.9 MPa, which is accepted in the material properties, the stone material could not show sufficient compressive strength during the Erzincan earthquake. The brick arch element is also durable for all three earthquake records, but the maximum compressive stress of the brick was obtained as 2.544 MPa under the effect of the Erzincan earthquake in the *Y* direction. Since the obtained compressive stress is higher than 2.4 MPa, which is accepted in the material properties, the brick material could not show sufficient compressive strength during the Erzincan earthquake. Concrete material showed sufficient compressive strength against all four earthquake records. Therefore, brick and stone could not show sufficient compressive strength against the *Y* direction effect of the Erzincan record.

When the tensile stresses were examined, the stone and brick arch elements did not show sufficient tensile strength for all four earthquake records. Concrete material showed sufficient tensile strength in the *X* direction earthquake effects but could not show sufficient tensile strength in the *Y* direction effects of the Erzincan, 1158-Kocaeli, and Düzce records. Therefore, it has been observed that the tensile strength of stone and brick materials is insufficient, and concrete has sufficient strength.

## 5. Conclusions

Determining the behavior of the structural elements that make up the historical structures under the influence of earthquakes is very important for protecting these structures. In this study, using the finite element method, an arch model was created in the SAP2000 program, and ground motion records of 4 different earthquakes in our country were examined by applying them to time-history analysis. During the examination, stone and brick, which are frequently encountered as local materials in the historical structures of the Southeast Anatolian Region, which is under the influence of the Eastern Anatolian Fault System, and concrete materials that are frequently used in today's contemporary architecture are defined separately for the arch, after the ground motion records applied to the arch elements that emerged as a result of the material definitions, the displacement

and stress values were discussed. The results were compared according to the material behavior. In the results of four different ground motion records applied separately for each material, generally, the highest stress values were observed in the Erzincan earthquake, with a magnitude of 6.9 in 1992.

When the data was considered numerically;

- It was observed that the compressive stress of the stone arch element exceeded the safety stress only in the *Y* direction effect of the Erzincan earthquake. While the same is true for the brick arch element, the concrete showed sufficient compressive strength against all four earthquake records and did not exceed the safety stress. Therefore, in compressive stresses, it can be concluded that concrete is the safest material against all four records. It is seen that when the stone and brick exceed the safety stress, the concrete does not even reach approximately 20% of its safety strength.
- While stone and brick arch elements could not show sufficient tensile strength for all four earthquake records in both directions, concrete showed sufficient tensile strength in *X* direction records, but it could not show sufficient tensile strength in the Erzincan, 1158 Kocaeli and Düzce records in the *Y* direction. Since concrete cannot show sufficient resistance to tensile strength as a material property, it is reinforced with reinforcements today.
- While it has approximately sufficient strength in the compressive stress of stone and brick, which is frequently used as local material, it has low strength in tensile stress. Tensile strengths may vary depending on the properties of the mortar used as binding material. Therefore, if a mortar with high binding properties is used, an increase in the safety tensile strength can be observed.
- Since stone and brick behave more flexibly than concrete, they showed more displacement under the effect of ground motion records applied. In terms of material properties, concrete has a higher modulus of elasticity and behaves more rigidly than other materials. Therefore, in the analyses made, the concrete showed less displacement. When the periods of the structure in the modes are examined, the lowest period belongs to the concrete structural element, confirming that the concrete has shown a rigid behavior.
- In the event of an earthquake with an earthquake acceleration record similar to the Erzincan earthquake in the Eastern Anatolian Fault System, it can be predicted that the historical buildings with stone and brick arches in the region cannot provide sufficient compressive and tensile strengths where there is a risk of damage.

The evaluation of the obtained results has revealed that the local materials used in the arches, which are commonly found in historical buildings, may not exhibit sufficient resistance against seismic forces compared to contemporary building materials such as concrete. This finding is particularly significant, as historical structures often rely on traditional construction techniques and local materials, which may not have

been designed with modern earthquake engineering principles in mind.

The time-history analyses conducted within the scope of the study provide valuable insights into the dynamic behavior of these historical structures under earthquake loading. These advanced analytical techniques allow for a more comprehensive understanding of the structural response, including the identification of critical failure modes and the quantification of the seismic performance. The results of these analyses can serve as a foundation for future studies, informing the development of more effective seismic assessment and retrofitting strategies for historical buildings. To further expand the knowledge in this field, it is essential to carry out similar studies on a wider range of historical buildings, encompassing different construction materials, structural systems, and architectural styles. This diversity of case studies would enable researchers to identify patterns, correlations, and underlying factors that influence the seismic performance of these structures. Additionally, the integration of advanced computational modeling and experimental validation could provide a more robust and reliable framework for assessing the seismic vulnerability of historical buildings.

Furthermore, future studies may explore the incorporation of traditional construction techniques and local materials into modern seismic design approaches. By understanding the inherent strengths and weaknesses of these traditional systems, researchers can work towards developing innovative retrofitting solutions that preserve the cultural heritage and architectural integrity of historical structures while enhancing their seismic resilience. This multidisciplinary approach, combining historical knowledge, structural engineering principles, and sustainable design, could pave the way for more effective and holistic preservation strategies for our architectural legacy.

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#### Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

#### Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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