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Seismic Behavior Analysis of a 14th Century Anatolian Seljuk Kumbet

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Abstract: The preservation of cultural heritage and the seismic resilience of historic buildings are crucial for maintaining social identity, particularly in earthquake-prone regions. This study focuses on the modeling of Sırçalı Kumbet, a Seljuk monument built in the 14th century in Kayseri province, located in the Central Anatolia region of Turkey, using survey drawings and analysis using the finite element method (FEM) to evaluate its seismic performance. The analysis indicates that linear elastic calculation methods can serve as an initial approach for evaluating such geometrically complex structures. The findings demonstrate that Sırçalı Kumbet exhibits substantial structural rigidity, reducing deformation and enhancing resistance to material fatigue during seismic events. Displacement and stress analyses under G+EQx and G+EQy loading conditions reveal that tensile and compressive stresses remain within acceptable limits, with localized exceedances occurring at specific points, such as cavity corners and wall bases. While these localized stresses are manageable, they highlight areas that require continuous monitoring and potential reinforcement to ensure long-term stability. Additionally, the study suggests that the integration of regular maintenance and targeted reinforcement measures can further improve the monument's durability and minimize potential damage. This research underscores the essential role of the FEM in bridging the gap between cultural heritage conservation and seismic resilience. It provides a methodological framework for integrating architectural, restoration, and engineering expertise into comprehensive conservation strategies. Future studies should expand this approach to include various building types and material properties to enhance the development of preservation strategies.

Keywords: finite element method; Seljuk building; Sırçalı kumbet; seismic behavior; earthquake; cultural heritage conservation

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1. Introduction

Earthquakes, which result from active fault lines in countries located within seismic zones, inevitably cause significant damage to many structures, sometimes even leading to destruction and loss of life. For this reason, the concept of earthquake-resistant building design has become a global necessity and is a focal point for many researchers [1]. Additionally, understanding the seismic behavior of structures during potential earthquakes is crucial for ensuring their durability in such events [2]. The increasing urbanization and population density in seismically active regions make accurate assessment of structural seismic performance essential to maintain resilience over the lifetime of buildings [3]. Seismic hazard assessment and analysis of local seismic responses are critical starting points in structural design processes [4]. This knowledge is especially vital in cultural heritage structures, where understanding seismic behavior supports conservation efforts and guides future research [5].

The preservation of historic buildings is crucial for maintaining cultural heritage and strengthening social identity. These structures showcase the architectural, artistic, and engineering achievements of the past, offering valuable insights into historical events and social changes. As Ashworth and Tunbridge (1999) emphasize, heritage sites significantly contribute to a community's sense of place and belonging [6]. By serving as centers for social interaction, they support collective memory and reinforce local identity. The loss of such structures can disrupt the connection with the past, leading to a diminished sense of community cohesion.

The preservation of cultural heritage and its transmission to future generations is a significant issue that intersects various disciplines such as engineering, architecture, art history, and archaeology. With the widespread use of computer technology, structural engineering calculation methods now enable faster and more accurate results. Numerous software programs have been developed to support the design and analysis processes of modern engineering projects, facilitating data transfer and integration of results into projects. However, historical structures that have survived to the present day are often examples such as temples, palaces, bridges, and castles—prestigious symbols of their time—and their structural systems differ from those of modern buildings. For this reason, finite element analysis (FEA) is the most suitable method for the structural analysis of historical structures [7,8]. This method is crucial for understanding the behavior of these structures with complex geometries and evaluating their current condition. Additionally, finite element analysis can be employed to enhance the durability and safety of historical structures by considering their material properties and the loading conditions to which they are exposed.

The protection of cultural heritage in the context of earthquakes is essential to ensure the resilience of historical buildings to seismic events and to enable the transfer of these valuable structures to future generations. Understanding how these buildings will respond to earthquakes is critical for developing effective preservation strategies. The finite element method (FEM) plays a pivotal role in this analysis by allowing for detailed simulations of structural responses under seismic loads. Moreover, accurately assessing the earthquake performance of historic buildings is crucial not only for their preservation but also for securing their legacy. Modeling the seismic response of historic structures precisely is vital for formulating robust conservation strategies.

Finite element modeling (FEM) plays a crucial role in the analysis and conservation of cultural heritage structures, enabling accurate simulations of structural behavior, stress analysis, and dynamic responses [9,10]. Historical masonry structures, which constitute a significant part of cultural heritage, exhibit unique responses to horizontal loads, requiring specific models and procedures for seismic assessment. A commonly used preliminary method is the macro-element approach, which divides the structure into separate components and considers various collapse mechanisms [11]. Simplified safety indexes, based on geometrical methods, offer practical initial insights into seismic vulnerability and help prioritize structures for more detailed analysis and interventions in earthquake-prone regions. Advanced computational methods, such as finite element (FE) modeling and non-linear dynamic analyses (NLDAs), provide detailed evaluations of structural behavior, energy dissipation, and damage patterns, supporting effective strengthening designs. However, these methods demand substantial computational effort and expertise [12]. Traditional CAD-based FEM approaches, when applied to heritage artifacts with time-varying characteristics, have the potential to introduce inaccuracies. To address this issue, researchers have developed methods to create FEM-ready models from high-resolution 3D scans [10,13]. These methods involve retopology procedures to simplify complex geometries while maintaining accuracy and converting them to NURBS surfaces to ensure compatibility with FEM software [13,14]. NURBS curves are a highly flexible mathematical representation frequently preferred in computer numerically controlled (CNC) processing [15]. By providing an accurate and consistent framework for both analytical and freeform curves, they offer a higher level of design flexibility compared to Bezier and B-spline curves [16]. In

addition, integrating geomatics techniques, such as photogrammetry, with FEM analysis has proven effective in assessing the structural stability of complex heritage structures, such as sculptures [14]. This approach enhances conservation efforts and supports proactive strategies for preserving various heritage objects [9].

Finite element modeling (FEM) is a crucial method for analyzing the seismic fragility of historic masonry structures [17–19]. This approach allows both static and dynamic nonlinear analyses, providing valuable insights into structural behavior under earthquake loads [17]. Typically, the process involves using geometric measurements, material tests, and dynamic test results for model calibration [18,19]. FEM analyses can identify critical areas susceptible to damage and support the development of effective retrofitting strategies by evaluating the structure's seismic safety [18,19]. Although this method yields highly accurate results, it requires significant computational power. To address these challenges, equivalent framework methods may be used as alternatives [20]. One of the main limitations of FEM is that the accuracy of its results is highly dependent on precise knowledge of the material properties. In many cases, insufficient data on these properties can lead to significant discrepancies between simulated and actual behavior. For example, in modeling piezoelectric ceramics, a limited understanding of material properties directly affects the reliability of FEM simulations [21]. This highlights the need for comprehensive material characterization to improve the accuracy of FEM analyses. Furthermore, FEM is inherently computationally intensive and requires significant amounts of processing power and memory, especially for large-scale models. This limitation is particularly evident in scenarios involving complex simulations such as structural engineering and heat transfer analysis [22,23]. The process of calibrating FEM models to make them compatible with experimental data can be complex and full of challenges. As mentioned in the context of updating finite element models, parameter estimation techniques should be used to reconcile discrepancies between experimental and numerical modal parameters [24]. This calibration process can be time-consuming and may not always give satisfactory results, especially when experimental data are limited. Furthermore, the high computational cost may limit the practical application of FEM, especially in real-time or iterative design processes. Establishing appropriate boundary conditions is critical for the accuracy of FEM simulations. Incorrect or oversimplified boundary conditions can lead to erroneous results and weaken the reliability of the analysis. In summary, finite element modeling (FEM) is a powerful tool for simulating complex systems; however, some limitations such as simple geometric representations, uncertainties in material properties, high computational costs, difficulties in correctly defining boundary conditions, mesh dependency, calibration requirements, and difficulties in modeling nonlinear behavior must be carefully managed. Addressing these limitations using advanced modeling techniques, more accurate material characterization, and advanced computational methods will maximize the effectiveness and accuracy of FEM in engineering applications. Despite all of these challenges, the detailed numerical analysis possibilities provided by FEM are important for understanding the behavior of complex structures, especially cultural heritage assets exposed to risks such as earthquakes. Consequently, advanced numerical analysis methods such as FEM are essential for both understanding and protecting cultural heritage structures at risk of earthquake damage.

The finite element method has been utilized in studies aimed at assessing the seismic vulnerability of historic buildings in Iloilo City, located in the Western Visayas region of the Philippines. This approach helps identify weaknesses and formulate adaptive reuse strategies [25]. In the study of Çardak Khan in Denizli province, located in the Mediterranean region of Turkey, the modeling of historic masonry structures highlights the importance of understanding structural elements for the longevity and safety of these buildings [26]. The case of Arg-e Bam, severely damaged in the 2003 Bam earthquake in Iran, underscores the challenges faced in preserving historical buildings after disasters [27]. Known as the world's largest adobe structure, this monument illustrates the significance of traditional building techniques in seismic resilience. Additionally, the fragility of cultural heritage extends beyond immediate structural damage; the long-term effects of earthquakes can lead

to deterioration and loss of historical value. For instance, the 2021 Arkalochori earthquake in Greece demonstrated how seismic events threaten the integrity of ancient structures, such as the Heraklion City Wall [20]. Similarly, in Turkey, the 2023 Kahramanmaraş earthquake prompted the use of advanced remote sensing techniques to assess damage to cultural heritage sites and to identify restoration strategies [28]. These studies underscore the need to combine modern technologies with traditional conservation methods to ensure the preservation of historical monuments.

Shehu (2024) investigated the seismic safety of the 12th century bell tower of Portogruaro (Italy). This study evaluated seismic behavior through pushover analysis for different material properties in the tower. Furthermore, material properties simulations based on different scenarios showed that the seismic safety of the tower is highly dependent on the properties of the material used [29]. Pouraminian (2022) investigated the structural behavior of the Gaskar brick minaret in Iran against wind and earthquake loads. In this study, finite element (FE) modeling was used to accurately perform the structural analysis of the minaret, and the wind load and earthquake loads were determined based on national building codes. Material variability was considered through use of Monte Carlo simulations and the seismic safety of the minaret was evaluated through probabilistic analysis. The results show that the minaret is safe against wind loads but has a slight risk of damage in earthquakes [30]. Zucca et al. (2022) investigated the seismic evaluation and retrofitting of a historic building damaged by the 2016 Centro Italia earthquake in Italy. Linear and non-linear analyses using finite element analysis revealed that reinforced plaster and cement-based mortar injections applied to the walls significantly improved the seismic performance of the building [31]. In their study, Uzair et al. (2023) evaluated the seismic performance of the Jesuit College in Dubrovnik, Croatia. In this study, the structural response of the building was investigated with a complex finite element model validated using frequency measurements. The structural analysis was performed using linear static and response spectrum analyses according to Eurocode 8 standards. This evaluation revealed risks such as high shear stress in the weak wall components of the structure and exceeding the elastic stress limit [32]. López-González and García-Valldecabres (2023) developed a new protocol based on the integration of HBIM and GIS for the conservation of cultural heritage and the sustainable management of cultural tourism. This protocol was applied to three monumental buildings in Valencia (Spain), providing efficiency in cultural heritage management and tourism planning. The integrated system aims to synchronize the data of both domains using the combination of HBIM and GIS [33]. El-belkasy and Wahieb (2022) evaluated a proposed project to enhance the sustainability of the historic district in Jeddah, Saudi Arabia. In this project, adaptive reuse of historic buildings and reclaiming the local community were targeted. Using theoretical and analytical approaches, the study authors concluded that adaptive reuse provides sustainability for the district and increases property values [34]. Daly et al. (2022) addressed the threats to marine heritage sites in Asia due to climate change. In this study, it was emphasized that environmental stresses such as coastal erosion, sea level rise, and flooding pose major threats to the conservation of marine heritage sites in Asia. It was also noted that innovative solutions need to be developed for the conservation of these sites [35].

The seismic events in Italy in 2016 underscored the inherent fragility of buildings and the challenges of preservation efforts, particularly in the historic centers of the Marche region [36]. The high density of historic buildings and limited open spaces create an environment that complicates the implementation of effective seismic regulations. This situation necessitates a comprehensive understanding of the structural behavior of these buildings under seismic loads, which advanced computational techniques, such as the finite element method (FEM), make possible. By simulating various earthquake scenarios, engineers can identify vulnerabilities in historic buildings and develop targeted retrofitting strategies.

The finite element method is particularly valuable for analyzing the seismic response of masonry structures, which are prevalent in many historic buildings. Negi's (2018) study demonstrates how virtual reality simulations can enhance understanding of building behav-

ior during earthquakes [37]. Through these realistic simulations, stakeholders can visualize potential damage and develop strategies to mitigate risks. This innovative approach aligns with the need for cost-effective solutions that prioritize safety and preservation, especially in regions with frequent seismic activity.

The study of historical structures, such as the Diyarbakır Çüngüş masonry stone bridge in the Southeastern Anatolia Region of Turkey, highlights the importance of understanding creep behavior and seismic performance [38]. The application of 3D discrete element modeling allows for a detailed analysis of these structures' responses over time, particularly under seismic loads. Such studies are essential for guiding restoration practices and ensuring that historic buildings remain resilient to future earthquakes. The data obtained from these analyses can inform engineers and architects in developing retrofitting techniques that enhance structural resilience while preserving the original design.

The recent earthquakes in Turkey have underscored the urgent need for preserving historic buildings, particularly given their fragility and cultural significance. Protecting these structures not only safeguards architectural heritage but also promotes sustainable practices in urban environments. Many historic buildings in Turkey, especially those with unreinforced stone walls, sustained severe damage during the 2023 earthquakes, highlighting their non-compliance with modern seismic standards [39].

Especially in regions prone to frequent seismic activity, such as Anatolia, earthquakes not only cause physical destruction but also leave deep emotional and psychological impacts on communities. Additionally, the relationship between architectural heritage and collective memory is of great significance. Historic buildings serve as culturally valuable repositories that shape how communities remember their past. Therefore, their conservation and restoration not only preserve the traces of history but also provide a sense of identity and belonging for future generations [40].

The Sırçalı Kumbet, examined in this study, is in Kayseri, in the Central Anatolia region of Turkey. Turkey, situated within the Alpine–Himalayan orogenic belt, is a country with a high seismic risk. However, the Central Anatolia Region, which encompasses Kayseri, is generally regarded as a relatively stable area regarding seismic activity. Nevertheless, significant fault lines that generate destructive earthquakes are present in and around Kayseri [41]. In this region, secondary fault systems and fault zones that subdivide the Anatolian Plate into smaller blocks and contribute to the tectonic evolution of the entire plate are found. Examples include the left-lateral Central Anatolian Fault Zone, the right-lateral strike–slip and normal component Tuz Gölü Fault Zone (TGFZ), the İnönü-Eskişehir Fault System, and the Akşehir Fault Zone. Among these, the Tuz Gölü Fault Zone (TGFZ), which extends approximately 220 km in an NW-SE direction, is considered one of the most significant active tectonic features in Central Anatolia due to its morphotectonic characteristics and ongoing microseismic activity. It has been extensively studied by many researchers [42].

The documented historical earthquakes of Kayseri include those that occurred in 1714, 1717, and 1835. However, it should be noted that the 1714 and 1717 earthquakes may refer to the same event. The 1717 Kayseri earthquake, with an intensity of VIII, was a moderate event that caused severe damage in Erkilet, Molu, Güneşli, and the Kayseri city center. This earthquake resulted in significant loss of life and caused extensive damage to the historic Grand Mosque (Ulu Cami) in the city center. The total reported death toll was 8331. Similarly, the VIII-intensity earthquake in 1835 caused widespread damage in Akçakaya, Talas, Aydınlar, Mimarsinan, Bahçeli, Yeşilyurt, Gezibağları, Gömeç, and Kayseri city center. The reported death toll ranged between 600 and 1064, with surface ruptures also observed. These earthquakes, from 1717 and 1835, have been associated with the Central Anatolian Fault Zone surrounding Kayseri, clearly highlighting the active nature of this fault system. In the instrumental period after 1900, notable earthquakes in Kayseri include a 5.2-magnitude event in 1940 and a 4.7-magnitude event in 1960, as well as numerous other events with magnitudes above 4 [43]. More recently, the 4.6-magnitude earthquake in Sarıoğlan on 2 February 2021 and the Kahramanmaraş-centered earthquake

on 6 February 2023 were felt in Kayseri with intensities ranging from 5 to 6. According to Turkey's Earthquake Hazard Map, Kayseri is classified as a "moderate-risk region", represented by the color yellow (Figure 1).



Figure 1. Location of Kayseri, where Sırçalı Kumbet is located, in Turkey and Earthquake Map of Kayseri [44–46].

This study makes a significant contribution to the field of preservation of historical structures and enhancing their earthquake resilience. Specifically, by examining the structural behavior of the Sırçalı Kumbet, a Seljuk monument from the 14th century, it provides a comprehensive assessment of seismic analysis for historical buildings. The primary aim of the study is to examine the current condition of the Sırçalı Kumbet, evaluate its earthquake performance, and test the effectiveness of proposed strengthening methods. Additionally, the findings aim to develop general principles that can be applied not only to Sırçalı Kumbet but also to other historical buildings with similar characteristics. The research provides an important example of how modern engineering methods can be used to assess the seismic resilience of historical structures and contribute to the development of strengthening strategies.

The research process began with a review of the relevant literature, which examined existing knowledge on the earthquake resilience and preservation of historical buildings. Following this, detailed research on Sırçalı Kumbet led to the creation of its architectural drawings. These drawings were accurately prepared to reflect the geometric properties of the structure, and using these data, a finite element model of the building was developed using SAP2000 software. All of the necessary geometric dimensions and measurements for constructing the mathematical model were derived from pre-existing architectural surveys. The methodology for constructing the model and the subsequent analysis process were described in detail, followed by an evaluation of the building's seismic performance, with the results being analyzed and interpreted.

There are various methods in the literature to assess the seismic resilience of historical structures. However, since these buildings typically have structural systems that differ from modern engineering approaches, traditional analysis methods do not always provide sufficient results. In this context, in recent years, the finite element method (FEM) has become widely used to assess the seismic resilience of historical buildings. However, there is limited research in the existing literature on the FEM analysis of such structures and the integration of the results into long-term preservation strategies. The innovative aspect of this study is not only the FEM analysis of historical buildings with unique and complex geometries, such as the Sırçalı Kumbet, but also the practical suggestions on how the structural performance results can be transformed into strengthening and restoration strategies. At this point, the study emphasizes how FEM can be used not only as a structural analysis tool but also as an effective method for the preservation of cultural heritage. The findings offer important insights into how these structures can be made more resilient to natural disasters like earthquakes. Furthermore, the documentation and digital archiving of such structures are of great importance in preserving the traces of cultural heritage that may be lost due to natural disasters.

Among the contributions of this study are the presentation of new methods and models for improving the seismic resilience of historical buildings, recommendations for their sustainable preservation, and findings that will inform future research. Additionally, it emphasizes the need for increased use of FEM as a potential assessment tool for historical structures. Natural disasters, such as earthquakes, can lead to the destruction of historical buildings, and in such cases, the documentation process becomes crucial to prevent the loss of cultural heritage. This approach offers a comprehensive perspective on both structural analysis and the preservation of cultural heritage, providing lasting data for future restoration projects and allowing for the preservation of cultural memory. The research enables the development of more effective strategies for preserving historical buildings through collaboration across engineering, restoration, and architectural disciplines. Ultimately, the findings establish concrete principles for the preservation and strengthening of both Sırçalı Kumbet and similar structures, offering a framework for ensuring the transmission of cultural heritage to future generations.

2. Historical Sırçalı Kumbet (14th Century Seljuk Architecture)

Gabriel (1954) states that the historical building, which was built in the mid-14th century, is known as Sırçalı Kumbet and is in the garden of Kayseri Technical and Industrial Vocational High School on Talas Road in Melikgazi District of Kayseri Province in the Central Anatolia region of Turkey [47,48] (Figure 2).



Figure 2. Location of Sırçalı Kumbet and visuals from the site [49,50].

As an important part of Kayseri's cultural heritage, Sırçalı Kumbet stands out with its architectural features and historical value. Such structures built during the Seljuk period generally functioned as burial structures and reflected the architectural aesthetics of the period. Sırçalı Kumbet draws attention with the tetrahedral and polyhedral forms used in its architectural design. While these structures bear the unique architectural features of the Seljuk period, they also show similarities with other kumbets in Anatolia [51] (Figure 3). As an important example of Seljuk architecture, it is a part of the city's historical and cultural identity. It enriches Kayseri's cultural heritage and contributes to the city's tourism potential. Preserving Kayseri's historical buildings and passing them on to future generations is critical to the sustainability of this heritage [52].

Sırçalı Kumbet is built on a wide four-cornered pedestal and has a round-planned masjid or cist chamber. The entrance door on the north side is reached by two running stairs. The outer surface of the tomb building is covered with very regular cut stones. This building, which had been in ruins for many years, was restored by the master architect Macit Kural in 1940 and its collapsed upper cover was rearranged as a half dome. The door frame is raised so that it stands out more than the window frames. The entrance of the building, made entirely of stone, features a flattened arch, with stone columns at the corners of the entrance niche. The door pediment has a pointed arch and relief decorations are seen

on both sides of the upper pediment inscription. Contrary to the exterior cylindrical body of the masjid room, the interior walls are quite angular and flat. There are small pantantifs above the corners that provide a transition to the dome pulley [53].



Figure 3. Views of Sırçalı Kumbet and 'Inventory for the Protection of Natural and Cultural Assets' of Sırçalı Kumbet [49].

Sırçalı Kumbet is a cylindrical-shaped historical building with a height of 8 m and a diameter of 5 m. All load-bearing elements and walls of the building were constructed using stone material. The stone material was bonded with lime mortar and soil-based binders. It also has a 1.5 m high pedestal made of stone material. It has three windows of 800 mm × 1000 mm and four skylights of 400 mm × 200 mm. There is a door with a size of 900 mm × 2200 mm. The structure of the building is made of stone material. (Figure 4). Stone has been a valuable building material in architecture throughout history due to its durability, versatility, and aesthetic value [54]. The use of natural stone in architecture has been shaped by factors such as accessibility to local resources, geographical adaptability, durability, and quality [55]. From antiquity to the present day, it has stood out as a long-lasting building material in many structures such as Roman arches, Seljuk kumbets, and Ottoman mosques. However, the stone is susceptible to atmospheric conditions and corrosion and can deteriorate over time, especially in environments affected by urban pollution. Therefore, various conservation strategies have been developed to increase the durability of stone and prevent structural deterioration, and disciplines such as engineering geology and hydrogeology have contributed to restoration efforts [56,57]. Thus, stone is not only an element of the past but also the future as a sustainable and timeless building material.

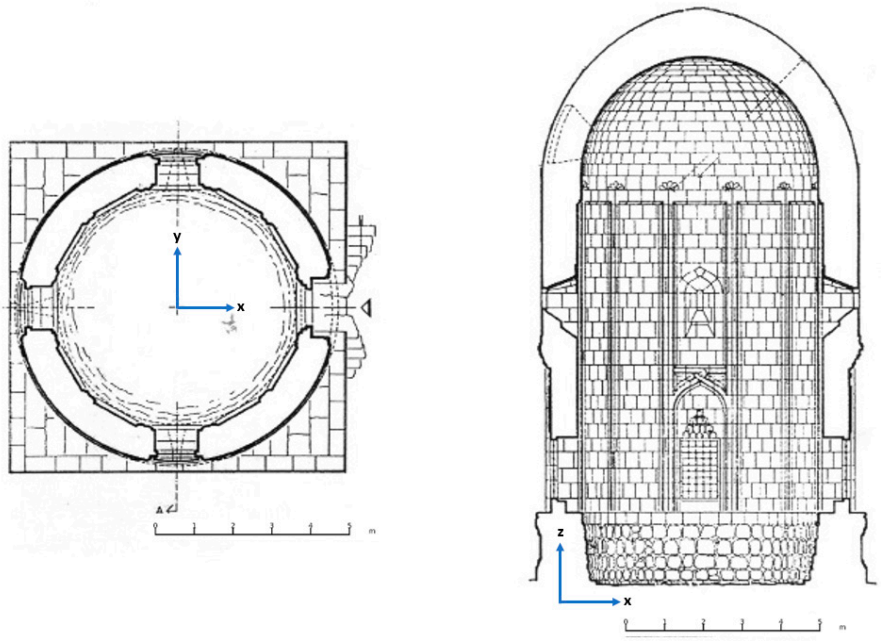


Figure 4. Survey drawings of Sırçalı Kumbet [49].

3. Finite Element Analysis of Sırçalı Kumbet

In this study, the results of the finite element method-based calculation of the historical Sırçalı Kumbet to determine its structural behavior and earthquake resistance to a possible earthquake are presented.

The finite element model of the historical Sırçalı Kumbet was prepared according to the modeling features and rules of the SAP2000 program. All geometric dimensions and measurements required for the creation of the mathematical model of the building were obtained using previously prepared surveys.

Modeling and calculation parameters are presented below:

- The entire structure is suitable to be defined as a 'general shell element' (SHELL). Therefore, it is modeled with SHELL elements.
- The use of shell elements provides numerous mathematical and computational advantages, particularly for thin-walled and homogeneous structures. This approach not only improves computational efficiency but also allows for an accurate representation of critical behaviors in the modeled structure, making it especially suitable given the geometric characteristics of the structure. Moreover, the structure under study—a low-height, homogeneous general shell—reinforces the appropriateness of this method. Shell elements are particularly well-suited for surfaces where one dimension (thickness) is significantly smaller than the other two dimensions. Such surfaces distribute loads along their plane and rely on shell theory to accurately capture bending effects. Considering that the structure under study is simple, low in height, and homogeneous, shell elements are a more effective choice for modeling the behavior of thin-walled structures [58].
- The model that constitutes the basis for the calculations was constructed using 1758 nodes and 1689 SHELL elements.
- The material properties of the structural elements were selected by considering the values recommended for masonry structures in the current Earthquake specifications, by utilizing studies produced because of previous studies for similar structures and published by international peer-reviewed journals and recommended connections in international literature [59].
- Using the macro modeling method, the stone masonry elements and mortar were considered together as a single material. This approach was preferred to simplify the overall behavior of the structure and facilitate the analysis process. Due to the simple geometry and homogeneity of the structure, detailed micro-level analysis was not required.
- Two main loading cases were applied to the prepared calculation model, in which ground motion-induced stresses defined by constant loads and earthquake spectrum were considered. Figure 5 displays the EQ spectrum as a graph with a period range of 0–4 s.
- To facilitate the evaluation of the results, good separate load combinations were defined as G + EQx (Constant loads + earthquake loading in the *x*-axis direction) and G + EQy (Constant loads + earthquake loading in the *y*-axis direction). The constant load is the weight of the structure itself. The 'Equivalent Earthquake Load Method' is explicitly outlined in Section 4.7. 'Linear Earthquake Calculation with the Equivalent Earthquake Load Method' of the Regulation on Buildings to be Built in Seismic Zones in Turkey [59].
- The physical properties and strengths of the materials used in this study were derived from the Turkish Seismic Code-2018.
- Maximum ground acceleration (g) PGA = 0.187, maximum ground velocity (cm/s) PGV = 10.795, short period map spectral acceleration coefficient SS = 0.432, map spectral acceleration coefficient for 1.0 s period S1 = 0.110, short period design spectral acceleration coefficient SDS = 0.562, and design spectral acceleration coefficient for 1.0 s period SD1 = 0.165 [60].

- During the evaluation of the results, no reduction was made in the earthquake effect or constant loads (R = 1).

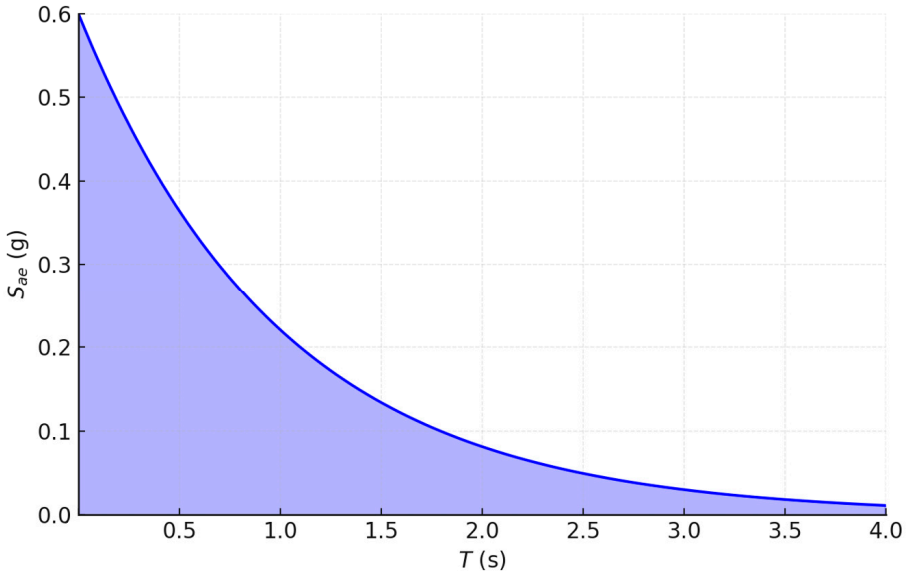


Figure 5. EQ spectrum graph in the 0–4 s period range.

The material properties considered in the finite element model of the historical Sırçalı Kumbet are summarized in Table 1.

Table 1. Material properties of the historical Sırçalı Kumbet in the finite element model.

Type of Element	Modulus of Elasticity E (kN/m^2)	Specific Weight (kN/m^3)	Specific Mass (t/m^3)
Stone Walls—Dome—Pedestal (with mortar)	450,000 (450 MPa)	24	2.45

The finite element model of Sırçalı Kumbet was constructed using 1758 nodes and 1689 SHELL elements (Figure 6).

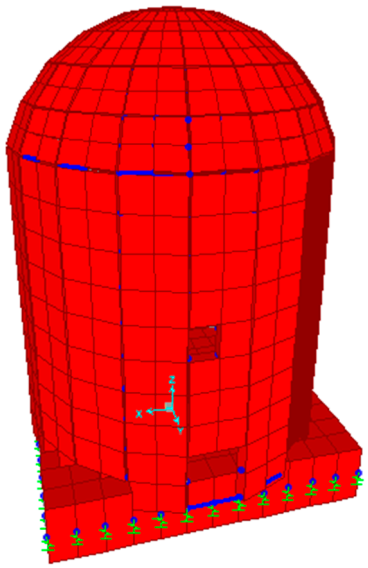
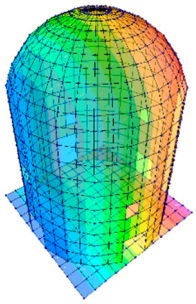
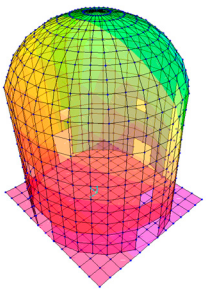
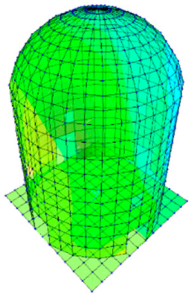
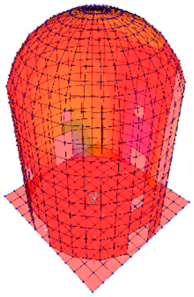


Figure 6. Sırçalı Kumbet finite element model.

The damping ratio was assumed to be 5% as specified in the Turkish Seismic Code-2018 [59]. The mode shapes and periods of Sırçalı Kumbet, which is a finite element model, are given in Table 2.

Mode 1 (T1 = 0.38 s) represents translation in the x-direction, involving 60% of the mass in its oscillation. Mode 2 (T2 = 0.33 s) corresponds to translation in the y-direction, with 57% of the mass participating in its oscillation. Mode 3 (T3 = 0.26 s) represents torsion, involving 57% of the mass in its oscillation. Mode 4 (T4 = 0.18 s) is translation in the x-direction, and the modes repeat after Mode 3.

Table 2. Mode shapes and periods of the historic Sırçalı Kumbet.

Modes and Periods			
Mode 1	**Mode 2**	**Mode 3**	**Mode 4**
			
T1 = 0.38 s	T2 = 0.33 s	T3 = 0.26 s	T4 = 0.18 s

4. Finite Element Calculation of Sırçalı Kumbet

In the current Earthquake Regulation, the compressive safety stress for stone masonry walls is recommended as fm = 0.3 MPa [59]. It is possible to interpret the earthquake resistance of the historical Sırçalı Kumbet by comparing the stresses obtained at the end of the calculation with the safety stresses. No reduction was made in the forces obtained because of the calculation (R = 1). On the contrary, the safety stresses were increased by a factor of 3. Thus, the bearing stress for stone in walls and arches has been accepted as:

$$\text{fm} = 0.3 \times 3 = 0.9 \text{ MPa}, \quad (1)$$

Tensile safety stresses can be accepted as 15% of the value determined as compressive safety stress [61]. In this case, the tensile safety stress for stone in the walls and dome is as follows:

$$\text{fm} = 0.9 \times 0.15 = 0.135 \text{ MPa} \quad (2)$$

The safety comparison stresses for the material groups of the historical Sırçalı Kumbet are given in Table 3.

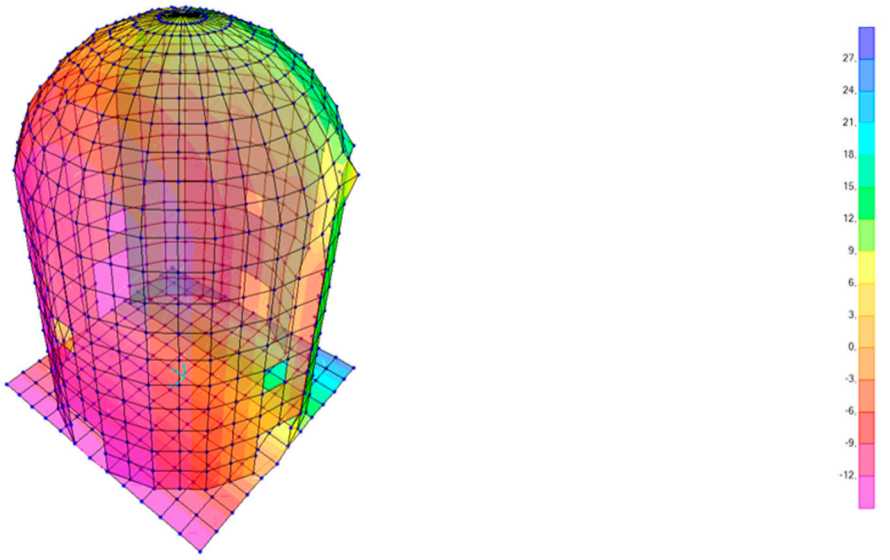
Table 3. Safety comparison stresses for material groups.

Material Type	Compressive Stress (MPa)	Tensile Safety Stress (MPa)
Stone Walls—Dome—Arches	0.9	0.135

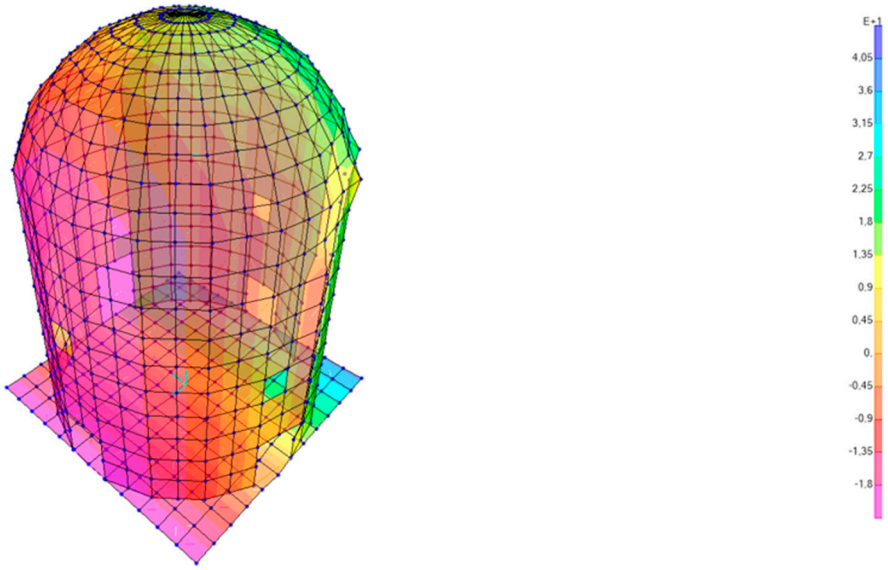
The structural calculation of the model was performed using the SAP2000 finite element program according to the load combinations mentioned above. It is nearly impossible to interpret the translations, forces, and stresses obtained at all nodes and structural elements by examining them individually. Therefore, the interpretation of the calculation results was carried out by considering the most unfavorable values, utilizing the color-coded shape and stress maps produced by the SAP2000 program. Due to its homogeneity,

non-height, and simple geometry, the structure was analyzed only with the equivalent seismic load method.

The characteristic structural elements affecting the behavior of the structure were investigated using the stress maps prepared separately for the G+EQx and G+EQy load combinations, focusing on the S11 stress values, as detailed in the attached figures. The drifts resulting from the G+EQx (Figure 7a) and G+EQy (Figure 7b) loadings are illustrated in Figure 6.



(**a**)



(**b**)

Figure 7. Displacements resulting from G+EQx (MPa) and G+EQy (MPa) loading: (**a**) X-direction (EQx) (mm) displacements; (**b**) Y-direction (EQy) (mm) displacements.

S11 tensile and compressive stresses for G+EQx loading are shown in Figure 8. As a result of G+EQx loading, the maximum tensile stress is 0.07 MPa and the maximum compressive stress is 0.17 MPa.

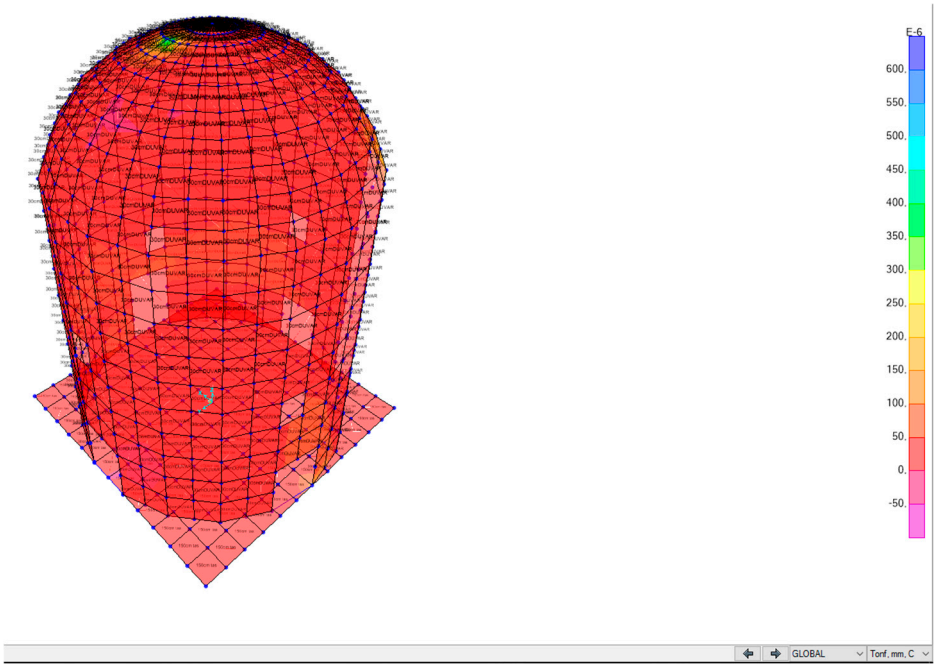


Figure 8. Stress Distributions Resulting from G+EQx (MPa) Loading.

S11 tensile and compressive stresses for G+EQy loading are shown in Figure 9. As a result of G+EQy loading, the maximum tensile stress is 0.03 MPa and the maximum compressive stress is 1.41 MPa.

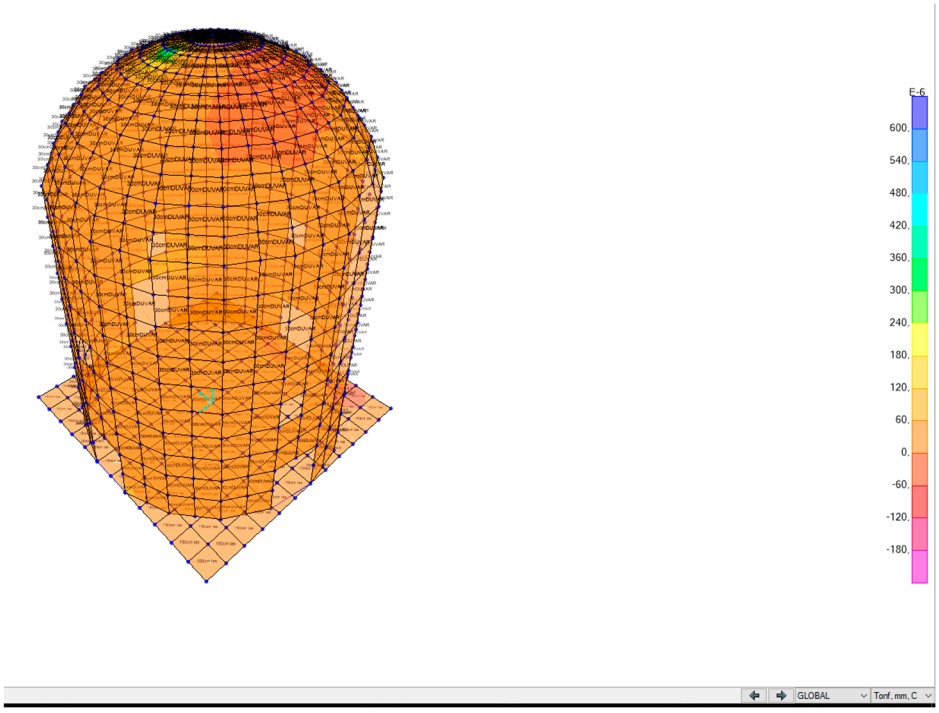


Figure 9. Stress distributions resulting from G+EQy (MPa) loading.

5. Evaluation of Account Results

In this part of the study, the results of the stress calculations based on the finite element method were evaluated to determine the structural behavior of Sırçalı Kumbet in the event of a possible earthquake and to assess its earthquake resistance.

Determining the elastic properties of materials in historical structures is complicated by factors such as time-dependent deterioration, cracks, and insufficient data on structural elements. These challenges necessitate the use of linear inelastic methods for accurate assessments. Such methods are essential for a better understanding of material behavior and for maintaining structural integrity. In this context, experimental studies and simulation techniques facilitate a more accurate determination of material properties.

The preservation of historic buildings is crucial for maintaining cultural heritage and social identity, and these structures must be protected against earthquakes and other risks. Wear and tear over time, along with past damage, can reduce the seismic resilience of these buildings, highlighting the need for intervention [62]. Cracks and seams in historic structures can significantly affect their structural integrity, and assessing these effects requires advanced modeling techniques [63]. Integrating such analyses provides significant advantages not only in preserving existing structures but also in developing new designs. These advantages contribute to the construction of more reliable and durable structures in engineering applications. Finite element modeling (FEM) plays a vital role in simulating the dynamic response of heritage structures and helps identify optimal monitoring strategies [9].

Factors such as the effects of time, cracks, and settlements that have occurred in the structure over the centuries, along with the inability of the survey to fully reflect the internal structure, present significant reasons to avoid extending calculations beyond linear limits. Therefore, considering these situations enables engineering processes to be carried out in a more comprehensive and effective manner.

A stronger justification for the choice of linear-elastic calculations is as follows: Historic buildings have experienced displacement over time since their construction due to ground settlements, and some have undergone repairs or renovations. These circumstances necessitate the application of linear-elastic approaches to understand the static and dynamic behavior of these structures. In this context, analyzing the effects of past interventions alongside the current situation will enable more well-founded decisions in engineering applications.

In terms of calculation technique, ground settlements, partial renewals, and other interventions correspond to initial displacements. When the exact values of these displacements are unknown, it is impossible to perform subsequent calculations with precision. For these reasons, performance under potential earthquake effects is evaluated based on linear calculations.

As a result of the calculations, the following observations were made regarding the behavior of Sırçalı Kumbet in the event of a possible earthquake and the resistance of its structural elements to the effects they are exposed to. These observations are critically important for ensuring the overall stability of the structure and determining the retrofitting requirements.

- It is seen that Sırçalı Kumbet has a rigid structure. This rigidity allows the building to undergo less deformation in the event of an earthquake, while at the same time creating a resistance to material fatigue. Therefore, the quality and durability of the materials used in the design of the building are of great importance.
- The maximum displacement values obtained as a result of the analysis according to the calculation spectrum and earthquake effect are as follows: Under G+EQx loading, the maximum tensile stress was 0.07 MPa and the maximum compressive stress was 0.17 MPa. Under G+EQy loading, the maximum tensile stress was 0.03 MPa and the maximum compressive stress was 1.41 MPa. Displacement values are 27 mm in the x direction and 40 mm in the y direction. At this relative displacement limit, cracks can be expected to occur depending on the material used in the walls; however, it can be said that a complete collapse of the structure is unlikely. These findings reveal that Sırçalı Kumbet exhibits favorable performance in terms of earthquake safety. Furthermore, the additional measures recommended for strengthening the structure will increase its durability in the long term and minimize possible damage.

- When evaluating the seismic performance of the structure, it is important to determine not only the maximum displacement values but also the displacement ratios of all points. The performance of the structural model, formed by the integration of a large number of nodes, can be analyzed by converting the displacements into local stresses. Such an analysis will enhance our understanding of the overall stability and durability of the structure.
- Tensile stresses were exceeded only in small areas at the cavity corners and the bottom corners of the walls. Given the web structure and support conditions of the elements used, the occurrence of such stresses under horizontal loading is acceptable. Nevertheless, monitoring these stresses and implementing reinforcement measures when necessary will help ensure the longevity of the structure.
- When performing the stress calculations, it is essential to consider that the material properties of the elements constituting the structural system of the building are determined in accordance with literature research and the values recommended in current regulations. In this context, it can be noted that material deterioration in certain parts of the structure or losses in the load-bearing elements may impact the overall behavior of the structure. However, since the obtained displacements and stresses are within acceptable limits, it is highly unlikely that a negative situation will arise regarding the earthquake resistance of Sırçalı Kumbet, even under such assumptions. Nevertheless, it is important to continue regular maintenance and monitoring activities to evaluate the long-term performance of the structure.
- As a result of the evaluations conducted according to the accepted calculation principles, it can be concluded that Sırçalı Kumbet will have sufficient resistance to earthquakes. Additionally, regular maintenance and repair processes will help prevent wear and tear that may occur over time.

6. Conclusions

This study has analyzed the seismic performance of the 14th century Sırçalı Kumbet, emphasizing its structural behavior under potential earthquake scenarios through a detailed finite element method (FEM) approach. The findings demonstrate the Kumbet's inherent structural rigidity, which limits deformation and enhances seismic resilience. The study highlights localized stress concentrations at specific structural points, suggesting the need for regular monitoring and targeted reinforcement. Furthermore, it underscores the importance of integrating advanced numerical methods, such as FEM, in cultural heritage conservation, effectively bridging engineering and architectural expertise. The proposed methodology provides a foundation for future studies to extend these principles to similar historical structures, ensuring their preservation and seismic resilience for generations to come.

The following comments can be made from the results obtained in this study in Section 5. 'Evaluation of Account Results':

- Structural Rigidity: The Sırçalı Kumbet exhibits significant structural rigidity, minimizing deformation during seismic events. This rigidity contributes to resistance to material fatigue and underscores the quality and durability of the materials used in its construction.
- Displacement Values: The displacement values observed under seismic loading remained within acceptable limits. Specifically, for the G+EQx loading case, the maximum tensile stress reached 0.07 MPa while the maximum compressive stress was 0.17 MPa. For the G+EQy loading case, the maximum tensile stress was 0.03 MPa, and the maximum compressive stress was 1.41 MPa. While localized cracking may occur, particularly in areas of material weakness, the overall structural integrity of the monument is unlikely to be compromised, as no significant risk of collapse was identified.
- Stress Distribution: Tensile stresses were concentrated at cavity corners and wall bases. Although these were minor localized exceedances, continuous monitoring and timely reinforcements are recommended to ensure long-term stability.

- Material Properties: The determination of material properties, while aligned with literature and current regulations, requires further experimental validation to refine assumptions about structural behavior under prolonged stress conditions. The primary construction material of the Sırçalı Kumbet is stone, historically valued for its durability and aesthetic appeal. However, stone materials are vulnerable to environmental factors such as weathering, atmospheric corrosion, and urban pollution, which may compromise their mechanical properties over time. The study assumes that the stone masonry elements, combined with mortar, act as a homogeneous material. While this simplifies the modeling process, periodic assessments are essential to monitor potential deterioration and better understand the interaction between stone and mortar under dynamic loading conditions.
- Linear Elastic Assumptions: The study justifies the use of linear elastic analysis due to the age, structural modifications, and inherent displacements of the monument over time. While nonlinear methods may offer enhanced insights, they were deemed unnecessary at this stage due to data limitations.
- Recommendations for Maintenance: Regular maintenance and targeted reinforcement strategies are essential for the continued preservation of Sırçalı Kumbet. Proactive measures will help mitigate long-term degradation and enhance its seismic performance.
- Implications for Similar Structures: The methodology and findings can serve as a reference for evaluating other historical masonry structures, promoting resilience through informed engineering and conservation strategies.

Future studies on the seismic performance of historical structures like the Sırçalı Kumbet could focus on integrating advanced nonlinear analysis methods to complement the linear elastic approaches employed in this study. Incorporating experimental data on the material properties of aged stone and mortar would further enhance the accuracy of finite element models, enabling a more detailed understanding of structural behavior under complex loading conditions. Additionally, developing methods for real-time monitoring of stress and displacement in historic buildings could provide valuable insights into their long-term stability. Expanding the scope of research to include comparative analyses of similar Seljuk-era monuments would facilitate the development of generalized preservation strategies. By combining interdisciplinary approaches with cutting-edge technologies, future research can continue to bridge the gap between cultural heritage conservation and modern engineering practices, ensuring the resilience of these invaluable structures to seismic risks.

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