Acta Scientiarum

http://periodicos.uem.br/ojs/acta
ISSN on-line: 1807-8664
Doi: 10.4025/actascitechnol.v47i1.70881

CIVIL ENGINEERING

A simplified analytical modeling approach for the structural analysis of massive masonry structures

Ali İhsan Ünay[1], İzzettin Kutlu[2*] and Asena Soyluk[1]

[1]Department of Architecture, Faculty of Architecture, Gazi University, Ankara, Türkiye. [2]Department of Architecture, Faculty of Engineering-Architecture, Mardin Artuklu University, Mardin, Türkiye. *Author for correspondence. E-mail: izzettinkutlu@artuklu.edu.tr

ABSTRACT. This paper, presents a simplified analytical modeling approach to determine the structural behavior of historical buildings. Analytical modeling is a digital tool for determining the behavior of masonry buildings under the influence of dynamic and static loads. In the analytical modeling process, different types of elements are involved to represent buildings. Due to the complex geometrical features of historical buildings, it is significant to the preference for convenient elements. Mardin Great Mosque was discussed and analyzed for the selection of convenient element preferences. Three different mosque models were built and analyzed by using three different element types (frame, shell, solid). In the findings of the paper, the values at the same points on the models were compared. When the first natural vibration period was examined, the first model is 0.76sec, the second model is 0.76sec, and the third model is 0.71sec. In addition, considering the base shear under dead load, 98.35% similarity was observed. As a consequence of the geometrical features of historical buildings, inappropriate definitions and inconvenient element preferences emerge the results questionable. Therefore, to be able to manage the analytical modeling process effectively requires accurate and appropriate definitions of the elements to be preferred.

Keywords: Analytical model; finite element analysis; mardin; masonry structures; structural behavior.

Received on January 1, 2024.
Accepted on April 11, 2024.

Introduction

Analytical modeling of the transition zones of large-section masonry walls, vaults, arches and domes requires careful and precise effort. In the last 20 years, the variety and number of finite element analysis software have increased and the speed and capacities of numerical analysis have improved considerably. This advanced software provides well-suited modeling for contemporary architectural and engineering design projects and construction works. However, numerical modeling of historical masonry buildings, each of which has its own unique geometrical and constructional features, needs more sensibility and attention. A quick and simply understandable structural analysis method will enable appropriate decisions to be taken during the preparation of architectural restoration projects and the planning of repair and strengthening of historical masonry structures.

Both numerical and experimental studies are conducted to evaluate the structural behavior of historical masonry structures. Finite element analysis is frequently used as an efficient tool to assess historical structures (Motsa et al., 2020; Aktaş & Turer, 2015; Betti & Vignoli, 2008; Tsutsumoto et al., 2019). Nowadays, finite elements analysis is an essential structural analysis tool and its use is increasing with the development of computer technology. It accelerated with partial differential equation solutions by Courant in 1943, and with the development of computer technology in the 1950s, the finite element model became close to current use (Wait & Mitchell, 1985). This method enables both 3D static and dynamic building analysis. It is an a structural analysis method in which linear and non-linear analyzes can be conducted and the results can be displayed numerically (Bernardeschi et al., 2004; Cordoví et al., 2024; Lucchesi et al., 1994; Alfano et al., 2000; Sadeghi Movahhed et al., 2023). Linear analysis can be performed to get a quick idea about the structural behavior. With linear analyzes, similar results can be obtained to real behavior. However, for a more detailed analysis result, both mechanical experiments and nonlinear analyzes should be applied (Ünay, 2002). In general, it is a numerical computation method for obtaining valuable results for problems in structural engineering (Hutton, 2003).

Finite element analysis is commonly used to assess the structural behavior of historical buildings. In this context, various difficulties can be emerged depending on a number of parameters:

- Lack of knowledge of the complex geometrical properties of buildings (Betti & Vignoli, 2011; Mele et al., 2003; Pesci et al., 2013; Augusti et al., 2001),
- Insufficient knowledge about cross-sections of structural elements (Betti & Vignoli, 2011; Mele et al., 2003),
- The use of many different building materials in the construction, the non-linear elastic behavior of the material and the difficulty of determining the mechanical properties of these materials (Betti & Galano, 2012).
- Inability to detect mechanical and physical changes of the structure over time (Reyes et al., 2008; Casarin & Modena, 2008) such as these reasons make it difficult to analyze the structural system of historical buildings. In addition, the fact that some restorations and damages implemented in the building are not precisely known can also affect the accuracy of the process (Ünay, 2002; Peña et al., 2010; Lourenço, 2001).

Although there have been great developments in the determination of the structural performance of historical buildings in recent years, the most important and time-consuming stage is still the process of modeling with finite elements (Betti & Vignoli, 2008; Can et al., 2012; Kutlu & Soyluk, 2024). The complex geometrical features of historical buildings complicate the uniform model production process. As a result, each building requires a unique model. In the solution of structural problems, the idealization of the structural systems is the basis of the finite element method (Peña et al., 2010; Armstrong, 1994; Lourenço, 2002). In the finite element method, there are many studies that use linear or nonlinear types of analysis. Mele and Duca (1999), analyzed the seismic behavior of a masonry church building. Elastic analysis results and the final capacity of 2D elements were compared in the model created using shell and frame elements. Bilgin (2006), modeled the domes of Mimar Sinan mosques supported by rectangular, hexagonal and octagonal structural systems with shell elements and analyzed them with a structural analysis program based on the finite element method. Küçükdoğan et al. (2010), evaluated the seismic resistance of the Stoudios monastery against future effects in a study prepared for the structural evaluation of Istanbul's historical buildings. Analyzes were applied to the models created with shell elements in the Sap2000 program. İlerisoy and Soyluk (2013), analyzed the structural behavior of a historical masonry clock tower in Dolmabahçe Palace with dynamic analyses. Çarhoğlu et al. (2014), investigated the behavior of the kumbet in Kars under different earthquake loads. Shell and solid elements are used together in the model. Korkmaz et al. (2014), examined the behavior of the Rize Kurşunlu Mosque under the influence of earthquakes through the model created with shell elements. Stavroulaki et al. (2018), a finite element method analysis was carried out using solid elements, considering the structural behavior of a masonry castle (Frangokastello) in Greece. Türer et al. (2012), conducted a dynamic finite element analysis on the Nemrut monuments to investigate the effects of snow, wind, vandalism and explosion. Brencich and Sabia (2008), produced a finite element model of the Tanaro Bridge in Italy. The natural frequencies, mode shapes and damping ratios of the bridge were included in the study. According to Karaton et al. (2017), a model of the Malabadi bridge was created using solid elements and the structural behavior of the bridge was determined by performing the analysis. Güncü et al. (2024) modeled the historical Çadırcı Hamam in Erzincan in two different types of 3D models with shell and solid elements and obtained similar results in the analysis. These studies indicate that numerical modelling is applicable for different types of structures. Moreover, it can be stated that finite element modelling is also open to improvement for the analysis of historical buildings since these studies were performed using different modelling techniques.

In this study, a comparison of the effectiveness of the elements used in the finite element modeling was implemented the Mardin Great Mosque (MGM) in the city of Mardin, which has an important cultural heritage in Turkey. The dimensions of the building were determined from the photogrammetric model developed within the scope of the study. In general, frame, shell and solid elements are used in the models to evaluate the structural behavior of historical buildings. The difference between these elements is the degrees of freedom. The number of displacements that can be made by the nodes of the element is defined as the degree of freedom of the element (Szabó & Babuška, 2021). As the number of nodes increases, the number of equations the program will solve increases. Solid elements are three-dimensional and have more nodes than frame and shell elements. Therefore, the analysis process is slower and more time is needed in models using solid elements. In the finite element model, optimal element selections are required for the correct representation of historical building elements. The displacement, acceleration and stress values of the structural system mathematical analyses used with frame, shell and solid elements through the numerical model of the Great Mosque of Mardin were determined. As a result, similar values emerged in the analysis of the same model created using 3 different elements (solid, frame and shell). With correct element definitions, the numerical model showed close behavior. One of the most important situations in the modeling process is to assign the correct definitions for the elements. In this context, an important expansion has been realized in the study that facilitates the structural modeling process.

Material and methods

Measurement, documentation and analytical modeling techniques

Documentation, in its most general sense, is the physical description of the structures (Korumaz et al., 2011). During the documentation period, the necessary information about the buildings can be obtained from old photographs, old maps, old drawings and projects, general and private archives, paintings, engravings, archaeological data and travel notes (Kuban, 2000; Bedate et al., 2004). Documentation is a holistic, inclusive and lengthy process. Documentation is an extensive set of activities that includes research, examination, observation, elaboration, definition, terminology and other data acquisition. The geometry of the building or complex of buildings is not the only parameter to be recorded in the documentation. All the features should be considered such as social, historical, acoustic, and architectural, which provide the building unique and special (D'Ayala & Smars, 2003; Bekar et al., 2023). Documentation studies in the process should include the features that determine the morphology of the building, its current situation and interventions over time (Halaç & Öğülmüş, 2021). In cultural heritage areas, very sensitive documentation can be done by using traditional terrestrial measurement methods. However, the documentation studies conducted with traditional terrestrial measurement methods can take a lot of time and require more labor during the work. Considering the use of tools and equipment, it is generally an expensive process (Westoby et al., 2012). In addition, in studies conducted with these methods, the possibility of damaging the heritage increases due to the physical contact with the study areas (Makineci & Karasaka, 2021). For these reasons, with the developing technology, advanced technology documentation methods come to the fore in the documentation of cultural heritage.

Computer-based methods, and especially digital photogrammetry are recommended as a method that allows us to detect, measure and monitor the temporal development of some structural problems (Arias et al., 2005; Zhao et al., 2023). Photogrammetry is the science of obtaining, measuring and interpreting reliable information about the properties of surfaces and objects without physical contact (Selvaggi et al., 2018). The analytical modeling process is also related to the measurement and documentation techniques of structures. Analytical models of structures can be produced with the data obtained during the measurement and documentation process. Therefore, the practical, reasonable and accurate documentation process will also contribute significantly to the analytical modeling process. Since masonry buildings have a heterogeneous feature, various assumptions can be accepted in the analytical modeling process and various strategies are used according to these assumptions. The structure to be modeled is idealized in different ways *from linear elements, two-dimensional elements (shell), or completely three-dimensional elements (solid).*

The great mosque of mardin and its history

The Great Mosque of Mardin (Mardin Ulu Mosque) is located in the Artuklu district of Mardin province, within the dense historical heritage and in the urban conservation site. It was built on the slopes of Mardin Mountain towards the south of First Street, which divides Mardin from east to west and is the most important street in the city. The mosque is located close to the center of the historical city of Mardin. It is one of the largest and most visited mosques in the region by tourists. According to the written inscription on the base of the mosque minaret, it was built between 1176-1186 (Çağlayan, 2017). There are 12 different inscriptions in the mosque and it has been determined that the earliest inscription belongs to the Artuqid Period (Altun, 1978; Erdal, 2017).

The mosque, which measures approximately 55 x 40 m in the east-west direction, has a rectangular plan, a single dome in front of the mihrab, a courtyard and a single minaret (Figure 1; Altun, 1971). The rectangular planned mosque consists of three main spaces: (1) a sanctuary at the south, (2) a courtyard in the middle and (3) a portico section at the north.

Mardin Great Mosque was constructed entirely of yellow limestone obtained in the region. These stones were obtained from the quarries located on the southern slopes of the Mardin urban site (Çağlayan, 2018). The rectangular planned sanctuary of the mosque is covered by the dome in front of the mihrab and barrel vaults. The fluted dome is the most unique part of the mosque and the most original part of the Artuqid period. The diameter of the original dome is 8.34 m from the inside and 8.90 m from the outside, and it is thought to be double-walled.

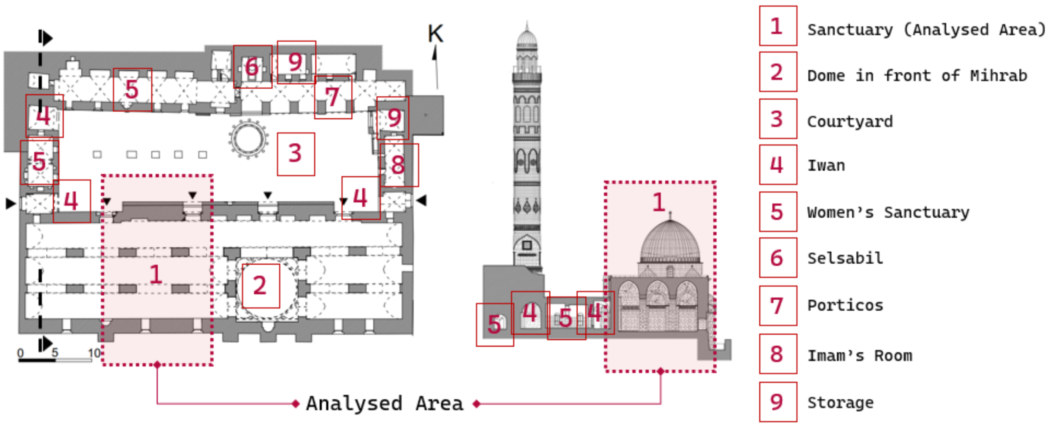


Figure 1. Mardin Great Mosque, spatial and section features.

Within the scope of the study, a photogrammetric model was built in order to create digital documentation of the 2022 data of Mardin Great Mosque and to provide surveys in the analytical modeling process of this study (Figure 2). Photogrammetry is the technique of measuring objects and the metric interpretation of image data. The process is conducted with the special modeling algorithm of the software used. Based on these techniques, 3D models are built from the photographic surface (Yilmaz et al., 2007; Şimşek & Işıker, 2024). In addition to the surveys, it was also aimed to document the current state of the mosque in digital media. During the digital documentation process, 1766 photographs were used. The photographs were added and aligned to the three-dimensional photogrammetric modeling program (Metashape by Agisoft). These photos were taken via a smartphone (iPhone 13 Pro Max) and have a size of 3024 x 4032 pixels and a horizontal and vertical resolution of 72 dpi (dots per inch).

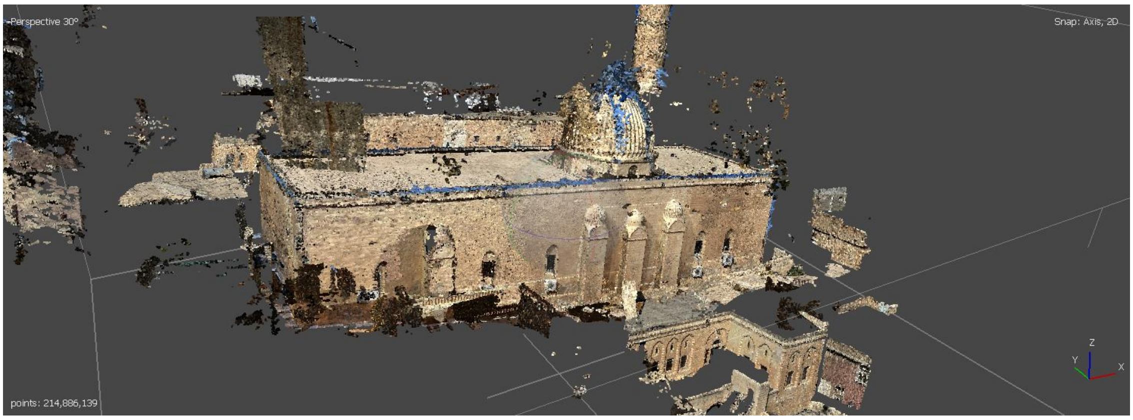


Figure 2. Mardin Great Mosque, 3D dense point cloud obtained from Metashape.

Analytical modelling and simplified structural analysis of the sample structure

Serious problems arise when the large stone masonry columns of the inner arches of the Great Mosque of Mardin integrated with the vaults are modeled with general shell elements. Since the nodes must be on the central axis of the shell elements, eccentricities occur at the intersection, which destabilizes the model due to the irregular geometry of the structure. In such a case, the most accurate modeling option is to use 3D solid elements instead of general shell elements. However, when the structural elements of historical masonry buildings are modeled with 3D solid elements, the parts that remain in the interior and are actively bearing, which cannot be seen and whose cross-section dimensions cannot be determined exactly, cause inaccurate results. For the analytical modeling of connection regions with complex geometric dimensions and shapes, the use of frame elements as transition members can be applied as a simplified modeling approach, provided that they do not contradict the basic modeling and analysis principles of finite element analysis software.

This simplified numerical modeling approach has been tested with the analyzes implemented with three different partial models considering a specific interior space of the Mardin Great Mosque, which includes the vaults, arches and arch piers. As shown in Figure 3(A), vault-arch-arch pillar intersections are entirely modeled with general shell elements. In Figure 3(B), piers of the arches in the same zone are modeled with frame elements, taking into account the varying section size. The third numerical model in Figure 3(C), describes the part of the structure that was then modeled by solid elements to compare with the results obtained in the first two model approaches. The analysis results performed with these three models are compared in terms of displacements, base shears, stresses and moments.

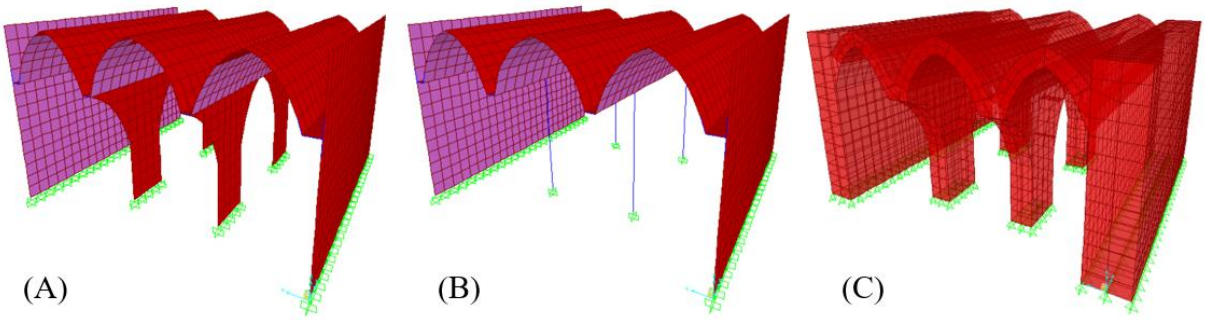


Figure 3. Numerical models, A) MGM-162 with all shell elements, B) MGM-164 with frame and shell elements, C) MGM-166 with 3D solid elements.

The parts of the historical masonry buildings where the most severe damage can emerge even in a moderate earthquake are the structural elements of that building such as arches, vaults, columns and wide facades (Şeker & Şahin, 2023). In order to make a realistic prediction for seismic risks on these structural elements, dynamic and static analyses should be applied. For this realistic prediction, the material properties and element features specified in Table 1 were assigned for the models built in the study. During the assignment on Sap2000, ‘other’ was introduced and the material properties listed in Table 1 were directly entered.

Table 1. Material properties and element features of the finite element models (Ünay, 2002; Altunışık et al., 2016; Can et al., 2012).

Model	Element Type	Element Features	Modulus of elasticity E [kN m^{-2}]	Unit weight [kN/m3]	Poisson Rate
First Model	Masonry walls and vaults (with mortar)	The north wall was modeled with 200 cm thick shell elements, the south wall with 150 cm thick shell elements, the arches and columns with 115 cm thick shell elements and the vaults with 70 cm thick shell elements	450.000,00	24,00	0.2
Second Model	Masonry walls and vaults (with mortar)		450.000,00	24,00	0.2
Third Model	Masonry walls and vaults (with mortar)		450.000,00	24,00	0.2

The First Model (MGM-162)

If a typical connection method is used at the intersections of the vaults with the outer walls and arches, according to the analytical modeling theory based on the nodes the central axes will bond in a very different way regarding the present state of the structure. In the case of walls with different thicknesses or very thick walls as in the Great Mosque of Mardin, an eccentricity that cannot be neglected occurs as seen in Figure 4. The second order moments resulting from this condition raise a critical question about the accuracy of the results achieved. As shown in Figure 4, a reasonable solution can be applied to overcome this problem. Assuming that the shear surface at the intersection of the 200 cm-thick wall with the vault is very rigid, 1 cm thick shell elements with material properties that are weightless and massless but with a very large modulus of elasticity are placed here. However, there is no specific mathematical theory in determining the stiffness based on the modulus of elasticity according to the software used to solve the equations and the configuration of the hardware used. Therefore, in this simplified analysis approach, before the model of the whole structure is prepared, the modulus of elasticity, which will provide high stiffness, should be tested on a small model where the analysis results can be compared more easily. As stated above, taking the modulus of elasticity “E=1.0x109”kN/m2 (“E=1.0x106 MPa) for the definition of a rigid element depending on the software and hardware will not cause ambiguous results. The applied method is actually introduced in several structural analysis software in the modeling of contemporary structural systems, with some special elements such as “LINK” elements or modeling options such as the “rigid end” definition. However, as in the case of the Great Mosque of Mardin, these options are not used effectively in the analytical modeling of historical buildings with unusual and complex cross-sectional properties. When frame elements are also used in the simplified analytical modeling approach, frame elements defined as having higher stiffness in terms of material properties can be used to provide a rigid zone in the connections, similar to the rigid shell element. Based on this assumption, 2 cm diameter circular frame elements were installed to form a rigid grid along the edges of the shell elements in the connection.

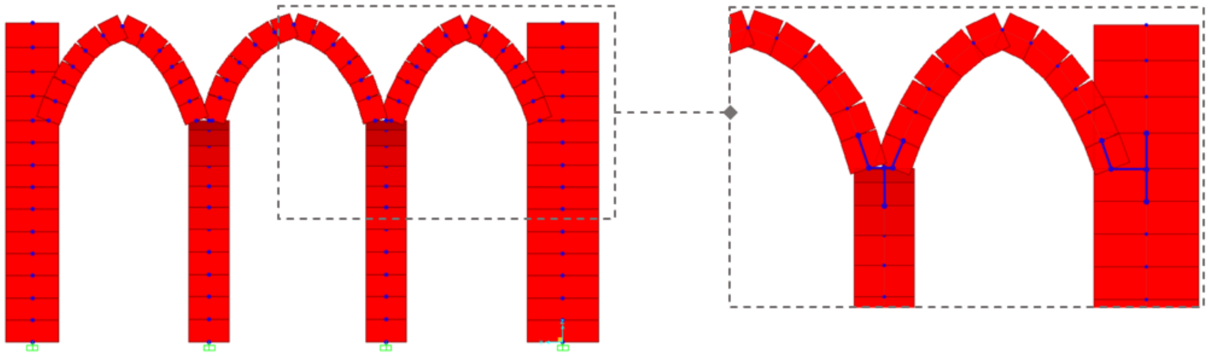


Figure 4. Eccentricity when the analytical model is based on nodal points relative to the central axes of the shell elements and the use of rigid elements to overcome the eccentricity problem.

The Second Model (MGM-164)

In order to ensure the integrity of the finite element model, it is common practice to use shell elements in the modeling of pillars in some masonry structures where the arch piers turn into columns. In such cases, some difficulties arise in the evaluation of analysis results in pillars modeled with shell elements. In many cases, eccentricity incompatibility occurs in analytical modeling due to the fact that the central axes of the elements do not coincide when the pillars are joined with structural elements such as vaults, pendentives, semi-domes and domes. Although the use of frame elements seems to be a practical solution in such cases, it causes significant modeling problems such as the non-coincidence of axes and inappropriate rigid zone definition. In the second phase of the analytical model of comparative analyses, the interior arches and arch piers and abutments of the Great Mosque of Mardin are modeled with frame elements with varying sizes in 10 levels, depending on their cross-sectional dimension. As shown in Figure 5, arches and arch piers are formed by frame elements with the same mass and weight as the shell elements applied in the first model (MGM-162), with a thickness of 115 cm, which can be fitted to the thickness of the arch and arch piers, and with dimensions varying according to the shape of the arch. The "extruded" view, a feature of the Sap2000 program, was confirmed to be applicable to the actual arch dimensions of the frame elements with the features specified. The part of the frame elements representing the arch and the arch abutments from the axis of the columns to the apex of the arch is integrated into the vaults with the "rigid grid-frame" and "rigid plate" elements described in the previous paragraph. Thus, the rigid zone at the connection of arches, vaults and pillars is defined in accordance with the general formulation of finite element analysis equations.

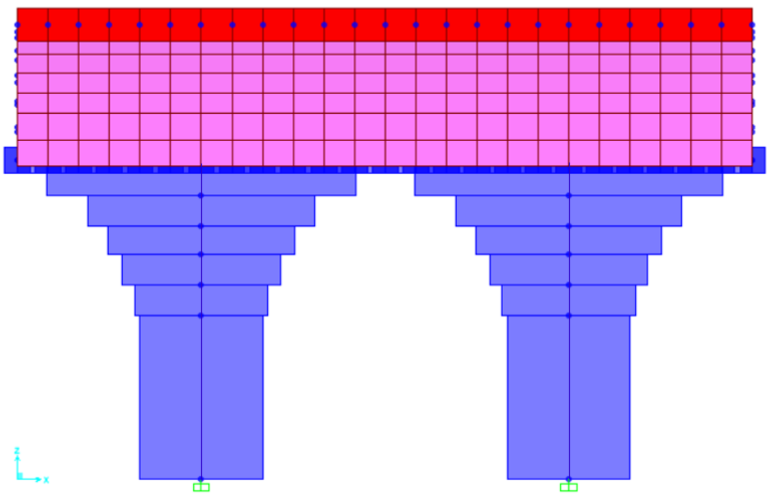


Figure 5. Frame elements with varying sizes to define the mass and rigidity of the arch piers.

The third model (MGM-166)

In order to compare the analysis results of the first analytical model formed with shell elements and the second analytical model assembled with shell elements + frame elements, a third analytical model was generated for the same part of the structure with 3D Solid elements and analyzed under the same load cases. The results of this structural analysis, which is assumed to be performed with the most realistic model, were compared with the results of the analysis carried out with the other two models in terms of the base shear, periods of modal analysis, displacements and stresses.

The material properties, support conditions and load cases considered in these three modeling approaches are as follows;

- The modulus of elasticity of the masonry stone wall is assumed to be E=450 MPa, a value widely accepted for similar structures in the scientific literature.[21,56]
- The material properties of the rigid elements were accepted as E=1.0x106 MPa as a result of trial-and-error analyses on various simple models, according to the capability of the software and hardware used, so as not to create instability in the analyses.
- While the supports of shell elements and frame elements are defined as fixed supports, the supports of 3D solid elements are defined as hinged supports.
- Although seismic analysis will not be performed, modal analysis was performed to examine the first five modes to monitor the general geometric shapes of these three numerical models.

The following load cases are applied respectively;

- First, gravity loads in the vertical direction (Dead Loads), in which the self-weight of the structural elements whose cross-sectional dimensions are defined in a way that fully takes into account the weight of the structure in the numerical models.
- Then, as the second and the third loads cases, %40 of the mass of all shell and 3D solid elements except the arches and the arch abutments were applied as horizontal gravity loads in the global X and Y axes.
- Since the arch and arch abutments are modeled with frame elements in the MGM-164 model, it is not possible to load %40 of the weight as horizontal gravity load on the frame elements under the same conditions as in the shell and 3D solid elements in all analysis software; these elements are exempted from horizontal loading.

When the first natural vibration period was examined, it was observed that the first model is 0.76sec, the second model is 0.76sec, and the third model is 0.71sec. In all three models, mode 1 was caused participation proportion in the Y direction, mode 2 was compression and mode 3 caused bending (Table 2). As seen in Table 3, the periods were calculated almost the same for the first five modes, according to the analyzes performed with all three models. On the other hand, as a result of vertical load and horizontal loads in x and y directions, base shear and displacements at randomly selected points were calculated the same in all three models. When the base shear was evaluated, the same values were determined for MGM-162 and MGM-164, while there is a 98% similarity for MGM-166. Although the displacements in the MGM-166 model, which is modeled with 3D solid elements, differ by %10 - %20 at some points compared to the results of the other two models, it can be said that this is due to the qualities of the numerical model created with 3D solid elements, which is a completely different modeling feature. In MGM-162 and MGM-164 models, while the stresses were calculated in equal values, some small differences were observed in the model prepared with solid elements due to the element type used. This difference appeared mostly at the intersection of the vaults and the walls.

Table 2. Mode shape 1 of the models - Translation in Y direction.

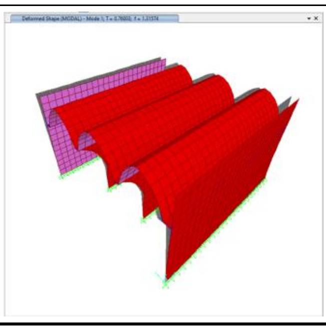
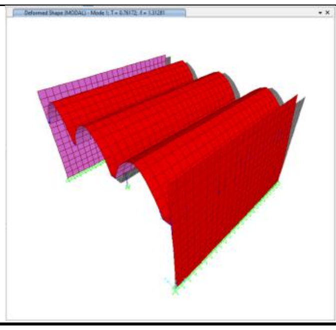
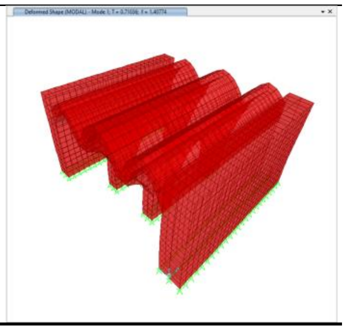
Model Type	First Model MGM-162	Second Model MGM-164	Third Model MGM-166
Mode Shape 1 - Translation in Y direction			

Table 3. Summary of the results structural analysis of the three models.

Analysis Case		Units	First Model MGM-162	Second Model MGM-164	Third Model MGM-166
Modal analysis for the first five natural periods	T1	second	0.7601	0.7617	0.7112
	T2	second	0.4618	0.4623	0.3601
	T3	second	0.3349	0.3396	0.3506
	T4	second	0.2738	0.2757	0.2492
	T5	second	0.2408	0.2416	0.2150
Base Shear	DEAD LOAD	kN	18289.90	18299.61	17904.91
	Fx (HRZTL-X)	kN	-6437.05	-6437.05	-6283.05
	Fy (HRZTL-Y)	kN	-6437.05	-6437.05	-6283.05
Displacements (At Crown of the vault)	Δx	mm	8.61	8.92	5.93
	Δy	mm	59.77	59.69	51.63
	Δz	mm	-6.91	-7.02	-7.03
Stresses at uppermost fiber of the vault at location A	DL S22	kN m^{-2}	-95.65	-95.29	-34
	DL S11	kN m^{-2}	-2.53	-2.53	-1.58
	HRZTL-X S22	kN m^{-2}	-35.05	35.67	15.82
	HRZTL-X S11	kN m^{-2}	0.86	0.84	0.21
	HRZTL-Y S22	kN m^{-2}	-442.84	-446.67	-382.24
	HRZTL-Y S11	kN m^{-2}	-20.52	-20.31	-13.33

Results and discussion

With these comparative analyses, it has been determined that the frame elements, which are relatively more practical in interpreting the results of analysis, can be used without any problems in spatial structures that cause some uncertainties when modeled with general shell elements. Historical masonry buildings usually have unique structural characteristics. Therefore, each case is subject to individual study.

In the case of the Great Mosque of Mardin, the structural assessment of displacements and stresses in the vaults is more important, while the evaluation of shear stresses and shear forces is significant in stone walls and arch abutments. Discretization of structural elements such as columns and slender pillars with general shell elements or 3D solid elements often causes a compatibility problem in the analytical model. Therefore, this simplified analysis approach proposed for the analytical modeling of historical masonry buildings, which includes the use of frame elements with shell elements, showed reliable results in the structural analysis carried out with the partial numerical model of the Great Mosque of Mardin.

The results of the analysis of the numerical model consisting of shell elements (MGM-162) and the results of the analysis (MGM-164), in which arch abutments and pillars are modeled with frame elements, were compared at the selected points where the vaults and arch abutments meet. As a result of the structural analysis carried out with these two numerical modeling approaches, identical results were achieved at almost the corresponding points in terms of displacements and stresses. In Figure 6(A), Figure 6(B) and Figure 7, the variation of displacements along the vault curve in the direction of the global Z axis as a result of vertical load analysis, and in the direction of global X and global Y axes as a result of horizontal load analysis are shown, respectively. When these figures were examined, it was determined that the displacements in the Z and Y directions produced the same results, while a 96% similarity was observed due to horizontal loads in the direction of global X-axis. In Figure 8 and Figure 9, since it is relatively apprehended and simple to evaluate, as it is due to the geometry of the vault the stresses calculated according to vertical and horizontal loads at the outermost fiber of the vaults in the direction of the meridians are compared. At the mid-vault corner end point of the models, MGM-162 had a stress of -106.17 kN while MGM-164 had a stress of -103.63 kN. At the midpoint of the vault top in the south direction, MGM-162 had a stress of -53.67 kN and MGM-164 had a stress of -53.91 kN.

The graphs in Figure 10(A) and Figure 10(B) show, more or less the same stress values were calculated at selected points. Consistent with the results of these comparative analyzes, computations that are more reliable can be made by appropriately defining the rigid connectors where it is more appropriate to use in historical masonry buildings with complex geometry and disproportionate member cross-sections. Considering these figures, it is clear that the stress values are almost 100% similar. At the lower end point of the vault in the south direction, the vertical load analysis revealed a stress of -6.61 kN in the MGM-162 model and -6.81 kN in the MGM-164 model.

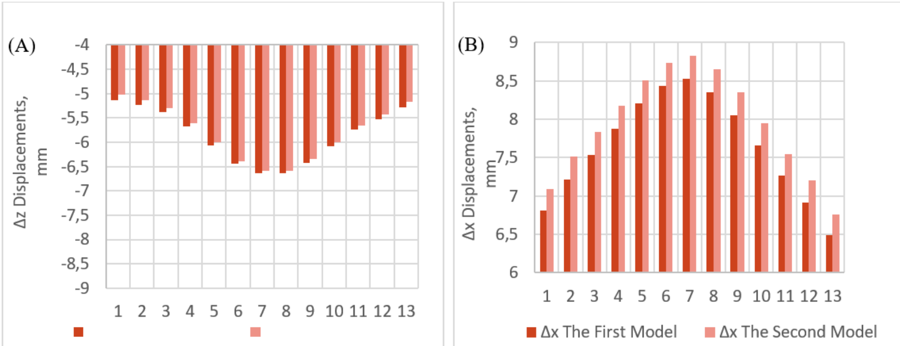


Figure 6. The variation of displacements – A) Δz displacements over the vault due to vertical loads, B) Δx displacements over the vault due to horizontal loads in the direction of global X-axis.

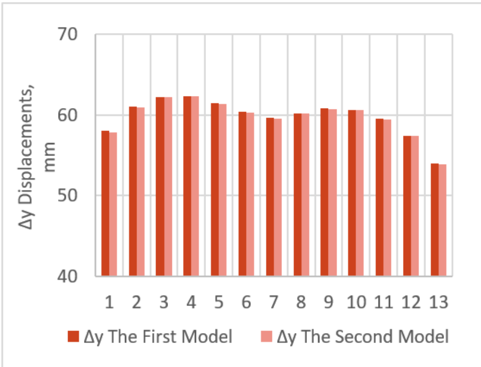


Figure 7. Variation of Δy displacements over the vault curve due to horizontal loads in the direction of global Y-axis.

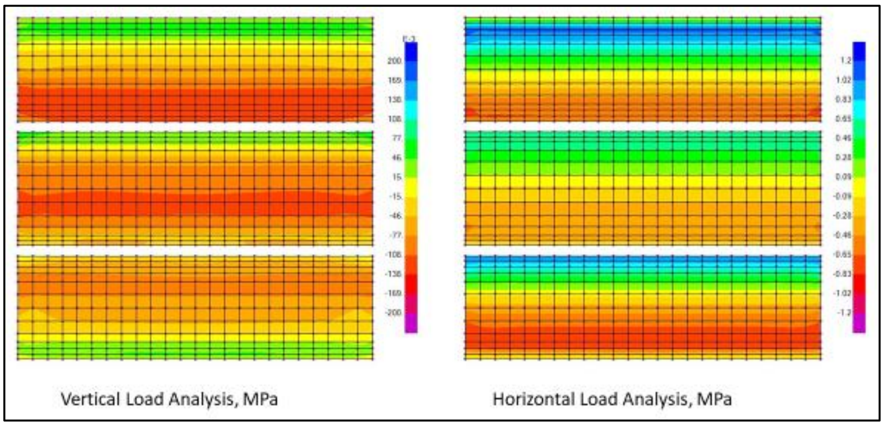


Figure 8. Variation of stress in the meridional direction of the vaults due to vertical and horizontal loadings in the First Model (MGM-162).

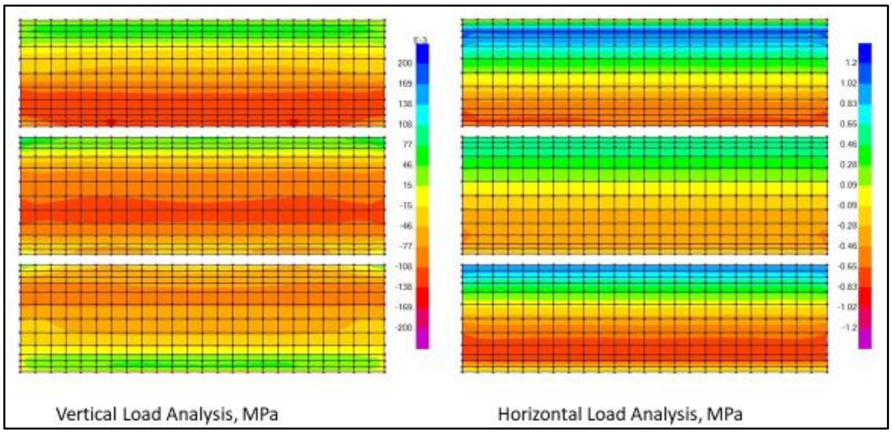


Figure 9. Variation of stress in the meridional direction of the vaults due to vertical and horizontal loadings in the Second Model (MGM-164).

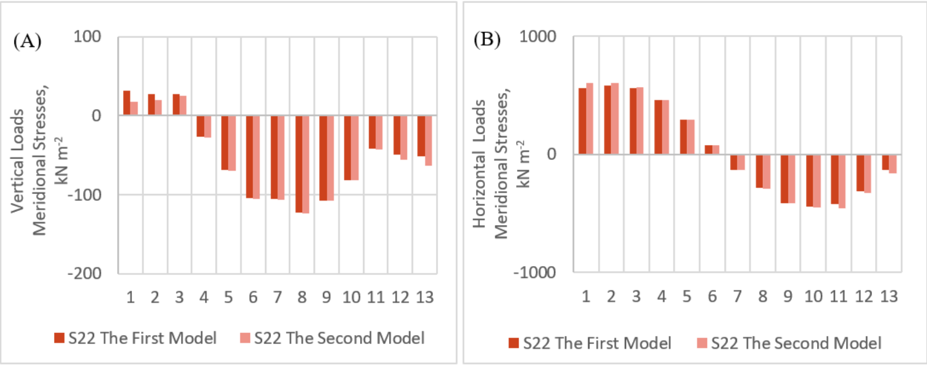


Figure 10. The variation of stress in the meridional direction of the vaults – A) Due to vertical and horizontal loadings in the First Model (MGM-162), B) Due to vertical and horizontal loadings in the Second Model (MGM-162).

Conclusion

Constantly developing analytical modeling and structural analysis methods based on the complex material properties of masonry are being tested. Usually, in masonry buildings where the load bearing cross-sections cannot be fully identified by external observations and measurements, modest errors that are ignored due to the synchronized transfer of numerical data provided by the surface geometry of the building to structural analysis software may cause much more important errors than predicted. The synchronized transmission of data about the visible dimensions of the structure provides full assurance about the overall geometry of the structure. Researchers generally focus on structural analysis methods based on the material model and mathematical formulation, without questioning the configuration of the invisible main structural system of the building. Since the analysis results are in terms of displacements, forces and stresses, no matter how precise the analysis methods are, incomplete and inaccurate data transfer due to geometric dimensions make the results questionable.

Photogrammetry, which has been integrated into the documentation process of historical buildings in recent years, can also provide data for the finite element model. Especially, the build of a digital 3D photogrammetric model reduces the need for field studies. The required measurements can be easily obtained from the 3D model. In addition to measurements, direct data transfer via photogrammetric models is also possible. The suitability and idealization of the data transferred to the structural analysis program to represent the real state of the building must be checked. Otherwise, data transfers will not make the process easier and may lead to complicated and inaccurate results. Unquestioned confidence in the material model and analysis methods leads to misinterpretation of the structural behavior and current structural capacity of the building.

References

Aktaş, D. Y., & Turer, A. (2015). Seismic evaluation and strengthening of Nemrut monuments. *Journal of Cultural Heritage*, *16*(3), 381-385. https://doi.org/10.1016/j.culher.2014.06.009

Alfano, G., Rosati, L., & Valoroso, N. (2000). A numerical strategy for finite element analysis of no tension materials. *International Journal for Numerical Methods in Engineering*, *48*(3), 317-350. https://doi.org/10.1002/(SICI)1097-0207(20000530)48:3<317::AID-NME868>3.0.CO;2-C

Altun, A. (1971). *Mardin'de Türk Devri Mimarisi (Turkish Era Architecture in Mardin)*. Gün Publishing.

Altun, A. (1978). *Anadolu'da Artuklu devri Türk mimarisi'nin gelişmesi (Development of Turkish architecture of the Artuqid period in Anatolia)*. Republic of Türkiye Ministry of Culture and Tourism.

Altunışık, A. C., Bayraktar, A., & Genç, A. F. (2016). A study on seismic behaviour of masonry mosques after restoration. *Earthquakes and Structures*, *10*(6), 1331-1346. https://doi.org/10.12989/eas.2016.10.6.1331

Arias, P., Herraez, J., Lorenzo, H., & Ordonez, C. (2005). Control of structural problems in cultural heritage monuments using close-range photogrammetry and computer methods. *Computers & Structures*, *83*(21-22), 1754-1766. https://doi.org/10.1016/j.compstruc.2005.02.018

Armstrong, C. G. (1994). Modelling requirements for finite-element analysis. *Computer-aided Design*, *26*(7), 573-578. https://doi.org/10.1016/0010-4485(94)90088-4

Augusti, G., Ciampoli, M., & Giovenale, P. (2001). Seismic vulnerability of monumental buildings. *Structural Safety*, *23*(3), 253-274. https://doi.org/10.1016/S0167-4730(01)00018-2

Bedate, A., Herrero, L. C., & Sanz, J. Á. (2004). Economic valuation of the cultural heritage: application to four case studies in Spain. *Journal of Cultural Heritage*, *5*(1), 101-111. https://doi.org/10.1016/j.culher.2003.04.002

Bekar, İ., Kutlu, I., & Ergün, R. (2023). Importance performance analysis for sustainability of reused historical building: Mardin Sabanci City Museum and art gallery. *Open House International*, *49*(3). https://doi.org/10.1108/OHI-04-2023-0080

Bernardeschi, K., Padovani, C., & Pasquinelli, G. (2004). Numerical modelling of the structural behaviour of Buti's bell tower. *Journal of Cultural Heritage*, *5*(4), 371-378. https://doi.org/10.1016/j.culher.2004.01.004

Betti, M., & Vignoli, A. (2008). Assessment of seismic resistance of a basilica-type church under earthquake loading: Modelling and analysis. *Advances in Engineering Software*, *39*(4), 258-283. https://doi.org/10.1016/j.advengsoft.2007.01.004

Betti, M., & Vignoli, A. (2011). Numerical assessment of the static and seismic behaviour of the basilica of Santa Maria all'Impruneta (Italy). *Construction and Building Materials*, *25*(12), 4308-4324. https://doi.org/10.1016/j.conbuildmat.2010.12.028

Betti, M., & Galano, L. (2012). Seismic analysis of historic masonry buildings: the vicarious palace in Pescia (Italy). *Buildings*, *2*(2), 63-82. https://doi.org/10.3390/buildings2020063

Bilgin, H. (2006). Mimar Sinan yapılarında kubbeli örtü sistemlerinin yapısal analizi (Structural Analysis of Domed Roof Systems in Architect Sinan's Works). *Selcuk University Journal of Engineering, Science and Technology*, *21*(3-4), 119-128.

Brencich, A., & Sabia, D. (2008). Experimental identification of a multi-span masonry bridge: The Tanaro Bridge. *Construction and Building Materials*, *22*(10), 2087-2099. https://doi.org/10.1016/j.conbuildmat.2007.07.031

Can, H., Kubın, J., & Ünay, A. İ. (2012). Düzensiz geometrik şekile sahip tarihi yığma binaların sismik davranışı (Seismic behavior of historical masonry buildings with irregular geometry). *Journal of the Faculty of Engineering and Architecture of Gazi University*, *27*(3), 679-686.

Casarin, F., & Modena, C. (2008). Seismic assessment of complex historical buildings: application to Reggio Emilia Cathedral, Italy. *International Journal of Architectural Heritage, 2*(3), 304-327. https://doi.org/10.1080/15583050802063659

Cordoví, Y. C. S., Deulofeu, E. R. Á., Quintana, I. V., Téllez, M. C., & Nuñez, R. P. (2024). Seismic behavior of large concrete panel prefabricated structures in relation to structural joints. *Acta Scientiarum. Technology, 46*(1). https://doi.org/10.4025/actascitechnol.v46i1.64476

Çağlayan, M. (2017). *Mardin ortaçağ anıtları ve yapım teknikleri (Mardin Medieval Monuments and Construction Techniques)*. Hiperlink Publishing.

Çağlayan, M. (2018). Ortaçağ'dan günümüze bir anıt: Mardin Ulu Camii (A monument from medieval to present: Mardin Ulu Cami - Grand Mosque). *Restorasyon ve Konservasyon Çalışmaları Dergisi*, *1*(21), 29-40.

Çarhoğlu, A. İ., Zabin, P., & Korkmaz, K. A. (2014). Kars Kümbet Camisinin deprem davranışının incelenmesi (Investigation of earthquake behaviour of Kars Kümbet Mosque). *Gazi University Journal of Science Part C: Design and Technology*, *2*(1), 189-196.

D'Ayala, D., & Smars, P. (2003). *Minimum requirement for metric use of non-metric photographic documentation*, University of Bath Report. https://www.researchgate.net/publication/321758681_Minimum_requirement_for_metric_use_of_non-metric_photographic_documentation_Report_for_English_Heritage (Available at 25.12.2023)

Erdal, Z. (2017). Mardin Ulu Cami üzerine yeni görüşler (New opinions on the Great Mosque of Mardin). *The Journal of Social Sciences Institute*, *17*(2), 433-447.

Güncü, A., Soyluk, A., Çelik, A., & Mutlu, E. O. (2024). Investigation of the Earthquake Behavior of Historical Erzincan Çadırcı Bath and the Reasons for Its Persistence Until Today. *Politeknik Dergisi*, *27*(6) 2069-2078. https://doi.org/10.2339/politeknik.1407217

Halaç, H. H., & Öğülmüş, V. (2021). Kültürel Miras Verilerinin Dijital Olarak Depolanması: Openheritage3d Örneği (Digital Storage Of Cultural Heritage Data: Openheritage3d Example). *Turkish Online Journal of Design Art and Communication*, *11*(2), 521-540.

Hutton, D. V. (2003). *Fundamentals of finite element analysis*. McGraw-Hill Education.

İlerisoy, Z. Y., & Soyluk, A. (2013). Dynamic analysis of Dolmabahce masonary clock tower. *Gradevinar*, *65*(4), 345-352. https://doi.org/10.14256/JCE.885.2012

Karaton, M., Aksoy, H. S., Sayın, E., & Calayır, Y. (2017). Nonlinear seismic performance of a 12th century historical masonry bridge under different earthquake levels. *Engineering Failure Analysis*, *79*, 408-421. https://doi.org/10.1016/j.engfailanal.2017.05.017

Korkmaz, K. A., Zabin, P., Çarhoğlu, A. İ., & Nuhoğlu, A. (2014). Rize Merkez Kurşunlu Camisi'nin deprem davranışının incelenmesi (Investigation of seismic behavior of Rize Kursunlu Mosque). *Sakarya University Journal of Science*, *18*(3), 149-156.

Korumaz, A. G., Dülgerler, O. N., & Yakar, M. (2011). Kültürel mirasın belgelenmesinde dijital yaklaşımlar (Digital techniques in cultural heritage documentation). *Selcuk University Journal of Engineering, Science and Technology*, *26*(3), 67-83.

Kuban, D. (2000). *Tarihi çevre koruma ve onarımın mimarlık boyutu kuram ve uygulama (Architectural aspects of historical heritage conservation and restoration theory and practice)*. YEM Publishing.

Kutlu, I., & Soyluk, A. (2024). A comparative approach to using photogrammetry in the structural analysis of historical buildings. *Ain Shams Engineering Journal, 15*(1), 102298. https://doi.org/10.1016/j.asej.2023.102298

Küçükdoğan, B., Kubin, J., & Ünay, A. İ. (2010). Seismic assessment of monastery of stoudios (Imrahor Mosque) in İstanbul. *In Advanced Materials Research*, *133-134,* 721-726. https://doi.org/10.4028/www.scientific.net/AMR.133-134.721

Lourenço, P. B. (2001). Analysis of historical constructions: from thrust-lines to advanced simulations. *Historical Constructions*, 91-116.

Lourenço, P. B. (2002). Computations on historic masonry structures. *Progress in Structural Engineering and Materials*, *4*(3), 301-319. https://doi.org/10.1002/pse.120

Lucchesi, M., Padovani, C., & Pagni. A. (1994). A numerical method for solving equilibrium problems of masonry-like solids. *Meccanica*, *29*(2), 175-193. https://doi.org/10.1007/BF01007500

Makineci, H. B., & Karasaka, L. (2021). Investigation of 3D models acquired with UAV oblique images. Turkish Journal of Geosciences, *2*(2), 13-20. https://doi.org/10.48053/turkgeo.980559

Mele, E., & De Luca, A. (1999). *Behaviour and modelling of masonry church buildings in seismic regions*. WIT Transactions on The Built Environment.

Mele, E., De Luca, A., & Giordano, A. (2003). Modelling and analysis of a basilica under earthquake loading. *Journal of Cultural Heritage*, *4*(4), 355-367. https://doi.org/10.1016/j.culher.2003.03.002

Motsa, S. M., Drosopoulos, G. A., Stavroulaki, M. E., Maravelakis, E., Borg, P. R., Galea, P., d'Amico, S., & Stavroulakis, G, E. (2020). Structural investigation of Mnajdra megalithic monument in Malta. *Journal of Cultural Heritage*, *41*, 96-105. https://doi.org/10.1016/j.culher.2019.07.004

Peña, F., Lourenço, P. B., Mendes, N., & Oliveira, D. V. (2010). Numerical models for the seismic assessment of an old masonry tower. *Engineering Structures*, *32*(5), 1466-1478. https://doi.org/10.1016/j.engstruct.2010.01.027

Pesci, A., Teza, G., Bonali, E., Casula, G., & Boschi, E. (2013). A laser scanning-based method for fast estimation of seismic-induced building deformations. *ISPRS Journal of Photogrammetry and Remote Sensing*, *79*,185-198. https://doi.org/10.1016/j.isprsjprs.2013.02.021

Reyes, E., Casati, M. J., & Gálvez, J. C. (2008). Cohesive crack model for mixed mode fracture of brick masonry. *International Journal of Fracture*, *151*(1), 29-55. https://doi.org/10.1007/s10704-008-9243-1

Sadeghi Movahhed, A., Shirkhani, A., Zardari, S., Noroozinejad Farsangi, E., & Karimi Pour, A. (2023). Effective range of base isolation design parameters to improve structural performance under far and near-fault earthquakes. *Advances in Structural Engineering*, *26*(1), 52-71. https://doi.org/10.1177/13694332221119870

Selvaggi, I., Dellapasqua, M., Franci, F., Spangher, A., Visintini, D., & Bitelli, G. (2018). 3D comparison towards a comprehensive analysis of a building in cultural heritage. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*(8), 1061-1066.

Stavroulaki, M. E., Drosopoulos, G. A., Tavlopoulou, E., Skoutelis, N., & Stavroulakis, G. E. (2018). Investigation of the structural behaviour of a masonry castle by considering the actual damage.

International Journal of Masonry Research and Innovation, *3*(1), 1-33. https://doi.org/10.1504/IJMRI.2018.089046

Szabó, B., & Babuška, I. (2021). *Finite Element Analysis: Method, Verification and Validation*. John Wiley & Sons, Inc.

Şeker, S., & Sahin, H. (2023). Numerical Investigation of A Historic Masonry Minaret Subjected To Seismic Excitation. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, *48*, 2249-2262. https://doi.org/10.1007/s40996-023-01285-6

Şimşek, D., & Işıker, F. (2024). Bir Erken Cumhuriyet Dönemi Yapısı: İzzetpaşa Karakolu ve Dijital Belgeleme Süreci (An Early Republican Period Building: Izzetpasa Gendarmery Station and Digital Documentation Process). *Modular Journal*, 7(1-2), 11-29. https://doi.org/10.59389/modular.1587780

Tsutsumoto, N. Y., Fazzan, J. V., Melges, J. L. P., Fioriti, C. F., Tashima, M. M., & Akasaki, J. L. (2019). Structural behavior of reinforced concrete beams strengthened with bamboo splints. *Acta Scientiarum. Technology, 41*, e36989. https://doi.org/10.4025/actascitechnol.v41i1.36989

Türer, A., Aktaş Erdem, Y. D., & Güçhan, N. Ş. (2012). Reverse-engineering evaluation and monitoring of Nemrut monuments. *International Journal of Architectural Heritage*, *6*(4), 373-395. https://doi.org/10.1080/15583058.2011.561906

Ünay, A. İ. (2002). *Tarihi yapıların depreme dayanımı (Earthquake behaviour of historical buildings)*. ODTÜ Publishing.

Wait, R., & Mitchell, A. R. (1985). *Finite element analysis and applications*. John Wiley and Sons Incorporated.

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J., & Reynolds, J. M. (2012). Structure-from-Motion'photogrammetry: A low-cost, effective tool for geoscience applications, *Geomorphology*, *179*, 300-314. https://doi.org/10.1016/j.geomorph.2012.08.021

Yilmaz, H. M., Yakar, M., Gulec, S. A., & Dulgerler, O. N. (2007). Importance of digital close-range photogrammetry in documentation of cultural heritage. *Journal of Cultural Heritage*, *8*(4), 428-433. https://doi.org/10.1016/j.culher.2007.07.004

Zhao, D., Liu, C., Zhang, X., Zhai, X., Deng, Y., Chen, H., Hu, J., Liu, D., & Luo, P. (2023). 3D Digital Modeling as a Sustainable Conservation and Revitalization Path for the Cultural Heritage of Han Dynasty Stone Reliefs. Sustainability, *15*(16), 12487. https://doi.org/10.3390/su151612487