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SPATIAL INVESTIGATION AND STRUCTURAL ANALYSIS OF THE NARTHEX IN OTTOMAN MOSQUES: THE CASE OF EDIRNE SELIMIYE MOSQUE

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Abstract
Introduction. Anatolia has been home to numerous civilizations throughout history. Many civilizations, from antiquity to the present day, have created various kinds of works. Among these works, mosques offer strong spatial and structural paradigms within the complex group of buildings constructed by the Ottomans. **Methods.** In this research, the spatial character of the main entrance of Mimar Sinan's work Edirne Selimiye Mosque, which consists of colonnades that are referred to as the narthex, will be analyzed with semiotic methods and theoretical with architectural background. The second objective is to determine the spatial character as well as, the size (height and span), geometric typology of the columns and material parameters and to investigate the static and dynamic responses to the earthquake factor. In this process, two different parallel models were created for the structural analysis, in addition to the existing narthex of Selimiye, and these three models were analyzed using the finite element method in the ANSYS Workbench environment. **Results.** Based on the results obtained, the spatial, geometric and structural aspects and requirements of the building are evaluated and structural strategies are proposed.

Keywords: spatial character; semiotic; structural analyses; mosque; narthex; pushdown; pushover analyses.

Introduction

Historical Background

The Ottoman Empire (1299–1922) produced a diverse range of religious, civil, cultural, and military architectural works in the region that constitutes modern-day Turkey. Among this rich architectural output, Ottoman mosques stand out as monumental, complex religious structures. They emphasize proportion, symmetry, and spatial continuity with a dome cladding system in conjunction with a central plan scheme, combining static balance and acoustic features with comprehensive engineering techniques to provide both functionality and aesthetics (Kuran, 2018; Goodwin, 2003; Freely, 2011).

Generally, an Ottoman mosque is surrounded by an outer courtyard that separates the building from the crowds of the city and protects it from possible fire risks. Mosques are built according to the direction of the qibla, which in Turkey's geography lies between south and east. For this reason, the main entrance doors of all mosques are located on the northwest wall, ensuring that the entrance always faces Mecca. The inner courtyard, which is accessed through a large crown gate, is surrounded by a gallery of columns called the "portico". The space between the row of columns at the entrance façade of the inner courtyard to the mosque and the mosque's body wall is known as the "final gathering place/last place of congregation/narthex/last prayer hall, etc". This narthex is a space architecturally identified with the concept of the mosque. Historically, it has functioned as a transitional area between the interior and exterior of the mosque (Eyice, 1993). It was built to provide shelter from the sun and rain for those who arrive late for worship or who want to pray in a clean space next to the mosque when there is no more space inside. It also serves as a preparatory and semi-open space, preventing direct access to the mosque and reinforcing the communal nature of Islamic worship.

The developmental phases of the narthex in Ottoman mosques can be traced back to Byzantine and early Islamic architectural traditions. Before the Ottoman Empire, under the influence of the Great Seljuks and the Anatolian Seljuks, the open portico system was introduced, and this feature gradually became characteristic of Ottoman mosque design (Necipoğlu, 2005). Over time, structural developments in building techniques, the adoption of mathematical and geometric constructions, and the availability of different materials transformed the simple and linear design of the narthex into a more complex and rich space (Katoğlu, 1966; Kocaman and Gürbüz, 2023; Kuban, 2010). Researchers of Anatolian-Turkish architectural history suggest

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that single-room, single-domed masjids and small mosques with narthexes were built from the 14th century onwards. These types of mosques essentially consist of a square floor plan, four main walls, a main dome covering the walls, and a narthex. So, the narthex, in particular, was incorporated into traditional mosque architecture in the 14th century (during the time of the principalities) (Ettinghausen, 2001; Katoğlu, 1966).

In the classical Ottoman period, narthex developed under the influence of well-known architects such as Architect Sinan. Sinan's works emphasize that narthexes are compatible with the general composition of the mosque and feature moderate and aesthetically balanced design elements (Necipoğlu, 2007). Examples such as the Süleymaniye Mosque in Istanbul and the Selimiye Mosque in Edirne demonstrate that material alternatives, structural order, and geometric sensitivity were used to develop the specific spatial experience of the narthex. The colonnaded courtyard, the prayer hall, and the narthex of the Selimiye Mosque in Edirne, which is one of the qualified buildings of the Ottoman period and Architect Sinan, are spatially defined in Fig. 1.

The Selimiye Mosque in Edirne is one of the most remarkable monuments by Architect Sinan It reflects the basic principles of classical Ottoman architecture in terms of both structure and aesthetics (Kuban, 2007). Construction of the Selimiye Mosque began in the 16th century, in 1568, and the mosque was completed and opened for worship in 1575. It was built during the reign of Selim II, the son of Suleiman the Magnificent (Yaşaroğlu, 2021; Sönmez and Sönmez, 1996).

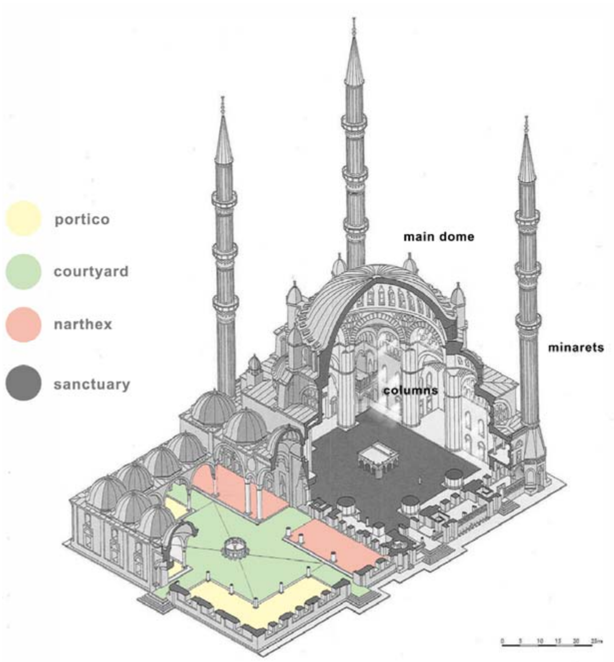


Fig. 1. Definition of the courtyard, the narthex, the portico and the sanctuary/harim in the axonometric perspective of the Edirne Selimiye Mosque (Kuban, 2010; the image, taken from the given source, was redesigned by the corresponding author)

The Selimiye Mosque was built in the center of the city, on Kavak Square. After the construction of the mosque, other buildings such as schools, madrasas, fountains, and arastas, which can be found in classical Ottoman mosques and complexes, were built around the colonnaded courtyard (Rifat, 1989).

The narthexes are divided into different typologies such as single-row porticoes, double-row porticoes, and central domes. In classical Ottoman architecture, porticoes are an important design element, with examples like flat, horseshoe, and Bursa arches. Although these models are similar in function to the narthexes of Ottoman mosques, they differ in their arch shapes (Necipoğlu, 2005; Blair and Bloom, 1994). The narthex of the Selimiye Mosque represents one of the most advanced examples of classical Ottoman porticoes. It features large spans, elongated dimensions, well-proportioned arches, and a centrally arranged dome, distinguishing it structurally from the other models examined in Analyze Chapter. Having established the historical context and the significance of the narthex in Ottoman mosque architecture, the following section outlines the aim and methodology employed in this research.

Aim and Methodology

The conservation of monumental religious buildings from disasters, especially earthquakes, is a common goal of all societies. This requires the analysis of the spatial and structural characteristics of these buildings and the evaluation of their behavior, especially under dynamic loads (Sözen, 2024). The conservation of these buildings enables not only the enhancement of the tourism potential of countries and their sustainability but also the transmission of cultural heritage to future generations. With this in mind, the scope of the study is further clarified using the mind maps (Fig. 2).

A review of existing literature consistently shows that non-linear analysis methods are widely employed to evaluate the seismic behavior of historic buildings. For instance, a study on Turkey's Çilehane complex in Amasya (Sözen, 2024) used finite element analysis to reveal that the building's horizontal bearing capacity was only 30 % of its total load, predicting severe damage in the event of an earthquake. Similarly, research on a stone tower in Italy (Scamardo et al., 2022) evaluated various finite element modeling techniques, achieving a balance between computational efficiency and reliable results with a shell model. Additionally, an analysis of a clock tower in Sungurlu, Turkey (Gökdemir and Baki, 2024), utilizing SAP2000 software, determined that deformation, stress, velocity, and acceleration parameters were within safe limits. In all these types of research, the current condition of historical buildings with regard to earthquakes is analyzed in different contexts with different concepts. Together, these studies emphasize the need for regular maintenance and appropriate technical interventions to preserve and strengthen historical buildings.

The research by Kocaman and Gürbüz examines the collapse mechanisms under earthquake action in the narthexes of Cenabi Ahmet Paşa (Ankara / Turkey), Lala Mustafa Paşa (Erzurum / Turkey), and Şerafettin (Konya / Turkey) mosques (Kocaman and Gürbüz, 2023). Apart from this study, no comprehensive analysis of the planning principles, geometric typology, and structural durability effects of the narthex of mosques was found in the related literature. Considering all this research, it is assumed that the idea of considering both spatial character and structural analysis together with an architectural perspective can lead to better results. In light of this information, the character of the space for the narthex, the planning principles, the size, the typology of the columns, and the structural response to earthquake factors can be examined in detail with analysis using the Edirne Selimiye Mosque, built by Architect Sinan. Thus, this study, which focuses on the spatial and structural analysis of the narthex sections of historical masonry mosques, fills an important gap in the literature, demonstrates the close relationship between architecture and structural engineering principles, and contributes to conservation processes.

Spatial Characteristics and Significance of Edirne Selimiye Mosque Narthex

The space, which has various names such as the Last Congregation Place or Narthex, has become an important architectural element in terms of spatial, historical, cultural, and symbolic aspects in Ottoman mosques (Bonner, 2016; Blair and Bloom 1994). It serves as a transitional space between the main sacred / sanctuary / worship space (the harim) and the external environment (Eyice, 1993). This space fulfills the symbolic, functional, and social needs of Islamic worship in terms of spatial and architectural aspects. Historically, this space reached its highest quality during the Classic Ottoman period, evolving in response to the multi-layered dynamics of the interaction of culture, material, and geometry at the intersection of religion and architecture, and continues to evolve today. Although regional differences are noticeable over time, structural arrangements can be recognized that always reflect their particular function (Sönmezer, 2002). In addition to its practical function, the narthex also has a symbolic and cultural significance. It represents a transitional area between the world and the sacred. This situation is emphasized by architectural elements such as inscriptions, domes, and muqarnas that adorn the narthex and lead the faithful into the sacred interior (harim) (Erzen, 2011; Kuban, 2010).

Architectural Planning and Principles

The narthex is usually located on the northwest side of the mosque, directly in front of the main prayer

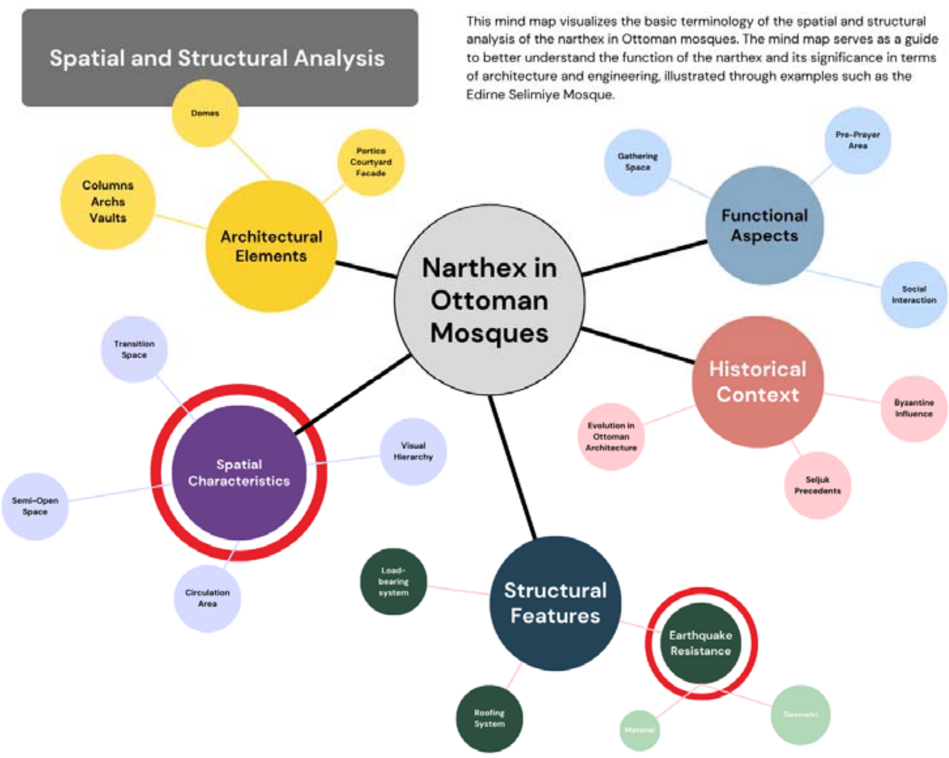


Fig. 2. Classifications and analysis scope of the research with mind map

area, the harim. This space consists of a series of mostly open or semi-open vestibules supported by arches and columns (Goodwin, 2003; Frishman and Khan, 2002). When examining the planning system of the narthex, it becomes clear that the geometric order applied is related to the proportion and modular system used in the other rooms of the mosque. While spatial units covered with more than one dome are generally built with a symmetrical and modular planning system (Orbeyi, 2016), this order can be read as a linear and rectilinear planning system in smaller mosques (Hakim, 2008). The spatial organization of the narthex is fundamentally shaped by linear arrangements aligned with the qibla direction, a central plan scheme, and geometric principles. This design strategy aims to guide worshipper movement and enhance their spatial experience (Hill, 1993). Historical mosque architecture frequently incorporates geometric and mathematical arrangements, reflecting a blend of engineering acumen and contemporary aesthetic sensibilities. Specifically, the porch systems prevalent in Ottoman and Seljuk architecture, including the narthex, were constructed using precise mathematical ratios and geometric systems to ensure static equilibrium. The geometric and mathematical parameters (spatial order) employed in narthex planning are crucial for achieving a monumental form and increasing structural permanence. Ottoman architects, particularly Architect Sinan, emphasized the aesthetic, structural, and functional qualities of these spaces through a focus on proportions, symmetry, and modular design (Aksoy, 2015; Orbeyi, 2012). For instance, the meticulously calculated geometry dictates the arch openings and column spacing within the column rows that define the narthex. In domed spaces, the golden ratio and circular geometry significantly enhance aesthetics, structural openings, and the sense of spatial balance. Furthermore, these mathematical and geometric principles augment the durability of load-bearing elements (Sutton, 2007; Wichmann and Wade, 2017). Emerging in Islamic architecture during the 14th century, the narthex (Fig. 3) achieved its most refined form and function in the Selimiye Mosque, which Sinan considered his masterpiece (Petersen, 1996; Yaşaroğlu, 2021).

The narthex of the Selimiye Mosque was designed as an important part of the overall architectural character of the mosque. It is an assembly that gains importance with its functional, aesthetic, symbolic, and structural features together with the other spaces of the mosque. Surrounded by porticoes, this group of buildings is supported by six marble columns resting on five different arches. The narthex is larger and longer than the porticoes of the inner courtyard, a situation that is in structural harmony (Fig. 4) with the main outer wall of the mosque. The barrel arch in the middle (Arch 4) has a larger opening space than the others.

On either side of the wide-open central arch are two different pointed arches (Arch 3 and Arch 5) with narrower and shorter openings. Next to the pointed arches are symmetrical barrel arches (Arch 2 and Arch 6), which are similar to the central arch (Kuban, 2017). The arches at the very beginning are arranged to form the area where the other colonnades converge in the mosque's courtyard (Fig. 4).

The muqarnas decorations on column capitals function as both aesthetic and structural components, embodying the abstract qualities of Islamic art alongside harmonious rhythmic and geometric patterns (Necipoğlu, 2005). The narthex ceiling features a dome cladding system with an exterior plaster enriched by hand-drawn decorations that blend vegetal and geometric motifs characteristic of Ottoman architecture. The vestibule floor is composed of diverse stone materials, textures, and colors, incorporating geometric mosaic techniques (Goodwin, 2003).

This harmonious design in the entrance area creates a striking aesthetic order, making the spiritual essence of Ottoman and Islamic aesthetics palpable within the space. Furthermore, the narthex adheres to the principles of symmetry and proportion, a consistent aesthetic throughout the Selimiye Mosque. The rhythmic arrangement of columned spaces and arches defines the building's overall composition, particularly its entrance. This classical horizontal and vertical order, typical of Ottoman architecture, contributes to the space's monumental harmony (Kuban, 2007; Hillenbrand, 2021).

Semiotic Analyses of the Narthex Space

A semiotic approach provides a valuable framework for analyzing the spatial characteristics of the Selimiye Mosque's narthex and entrance. This perspective allows for an examination of the space's structural codes, symbolic meanings, and its semantic relationship with the user, drawing upon theories from scholars like Umberto Eco and Charles Sanders Peirce. Semiotics views space as a "meaning-producing system".

Charles Sanders Peirce's semiotic theory, in particular, classifies signs into three categories based on their meaning-production: Icon, Index, and Symbol. An icon establishes a relationship of similarity between the signifier and the signified; for instance, the dome of the Selimiye Mosque serves as an iconic sign emphasizing eternity, unity, and heaven (Peirce, 1931-1958). An index indicates a concrete causal relationship between the signifier and signified; the minarets of the Selimiye Mosque, directly linked to the call to prayer, function as indexical signs (Peirce, 1991). A symbol is a signifier where the connection between signifier and signified is defined by tradition and culture; a divine word in calligraphy, for example,

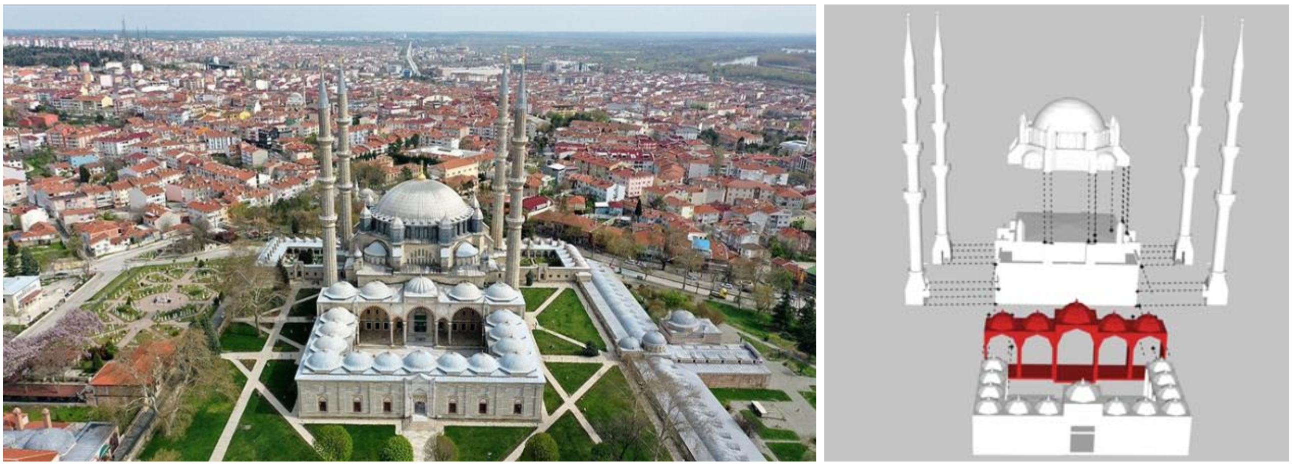


Fig. 3. Front view of the Selimiye Mosque in Edirne and model of the mosque parts and the narthex (TRT News, 2025; revised and remodeled by the corresponding author)

can be interpreted as a symbolic sign representing God in Islamic culture (Eco, 1976).

This classification offers a clear methodology for analyzing how historical spaces and architectural elements generate meaning. Applying this method to the Selimiye Mosque's narthex can elucidate its meaning-making processes. Two primary semiotic approaches are relevant here: analyzing the space's meaning production through Saussurean semiotics (signifier-signified) or Peircean semiotics (sign-interpreter-objective meaning) (Table 1).

Structural Analyses of Edirne Selimiye Mosque Narthex

Material

The structure discussed in this article is the portico of the narthex of the mosque. This section comprises 3 large and 2 smaller pointed arch systems in the lower sections, which can be seen from the front facade. The main beams are monolithic marble columns. Therefore, these columns were assigned the material property stone found in the ANSYS library and the arched portico walls in the upper

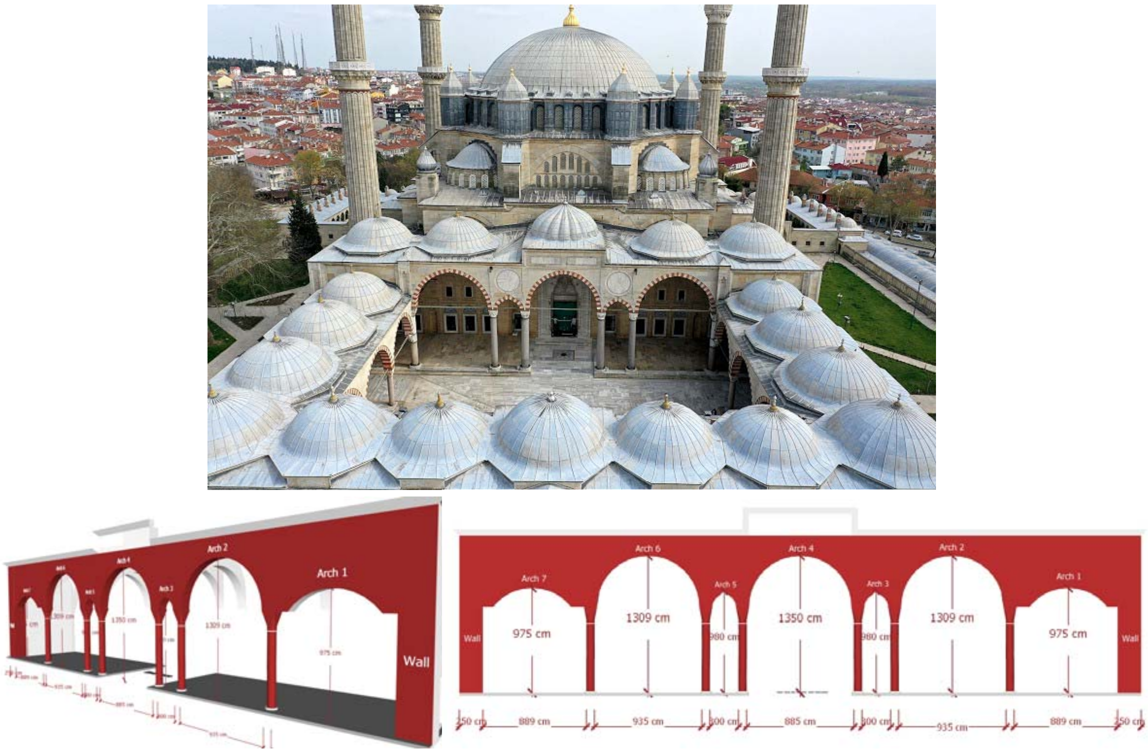


Fig. 4. Model and dimensions of the narthex of the Selimiye Mosque in Edirne (Baran, 2021; models created by the corresponding author)

section were assigned the material property Drucker-Prager (Drucker and Prager, 1952), also found in the ANSYS library, taking into account the compressive and tensile strengths. To determine the engineering properties of masonry building materials, the average values for the mechanical properties of the masonry material given in the Earthquake Risk Management Guide for Historical Buildings (TYDRYK, 2017) were used. As a result of the static and dynamic analyses carried out using these material properties used in the study, inelastic permanent deformations and stresses could be determined. The material values used in the analyses are listed in Table 2 (TYDRYK, 2017).

Method

In the first phase, the models to be investigated were defined. Within the framework of the article, arcade models were to be created for the meeting place, consisting of arches with three different geometries, and their comparative analyses were to be carried out. The arcade model of Selimiye Mosque was selected as the main model and the other two models were created with the same opening, height and width but depending on different arch typologies. The model for the meeting room, which we refer to as Model 1, consists of five equal openings, all of which are round arch arcades. Model 2 consists of five equally sized openings with a pointed arch in the middle and round arch arcades on the sides. In Model 3, the final meeting place of the Selimiye Mosque was recreated (Fig. 1). By comparing the three different models, conclusions were to be drawn about the differences in the structural behavior of the model of the narthex used by Architect Sinan in the Selimiye Mosque.

For the structural analysis, three distinct models were systematically developed: two representing alternative narthex configurations and one accurately replicating the actual narthex of the Edirne Selimiye

Table 1. **Analysis of the narthex space with architectural data and semiotic methods**

Architectural Elements	Indicator Type (Icon/Index/Symbol)	Indicator	Meaning/Interpretation
Cloister/ Courtyard	Symbol & Icon	Transition Area (Threshold)	A transitional area between the secular and the sacred space, a preparatory area before worship.
Domes and Columns	Index & Symbol	Divine power and unity	It can be associated with heaven and symbolizes centrality and eternity. It can refer to the representation of divine qualities, the connection to heaven, centrality and order. It also emphasizes the monumentality of the building, its continuity and the sense of unity that brings the community together.
Muqarnas and Decorations	Icon & Symbol	Monumentality	It can be interpreted as an architectural visualisation of architectural order, eternity, aesthetics and divine knowledge.
Door and Arch Opening Spaces	Symbol	Opening / Door / Transition Symbolism	It stands for transition and continuity and is part of the rhythmic and symmetrical repetition in Ottoman and Islamic architecture.
Traditional Calligraphy / Hand-drawn Ornaments	Symbol	Quotations from the holy book quran	It emphasizes holiness by conveying divine messages.
Main prayer areas	Index	Entrance area to the main place of worship under the portico	The process of preparing the congregation for worship, the organization of the functional areas of the mosque, the social area that allows the congregation to come together, the sense of community and togetherness.
Lighting and Shading and Visual Hierarchy	Index & Icon	Orientation, Spiritual Feelings	The flow of movement and physical experience, the purpose of the worship area, the sense of depth, the separation of the original space and the interior and exterior spaces, the emphasis on symmetry, proportion and monumentality are palpable.

Table 2. **Material Properties used in the structure**

Structure Part	Compressive Strength (MPa)	Tensile Strength (MPa)	Unit weight (kg/m³)	Poisson ratio	Elasticity Modulus (MPa)
Main Bearing Columns	34	3,4	2500	0,23	34000
Upper part with Arches	1,75	0,175	2100	0,2	1750

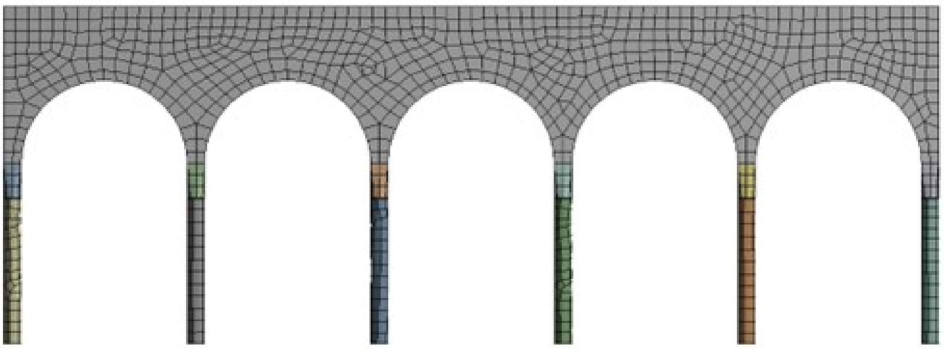
Mosque as implemented by Architect Sinan. After detailed examination of these three models, their results were collectively evaluated, focusing on stress distribution and identifying critical areas where stresses were observed. Equal analytical procedures were applied to all models to ensure a consistent comparative assessment.

The final models of the meeting room with 3 different geometries were created in a 3D computer environment. The most important parts of the model are the supporting columns, the column capitals, the upper row of arches, and the walls of the portico. These three-dimensional models, created in the ANSYS Workbench environment, were discretized into solid elements using the finite element method. A mesh size of 150 mm was used for this solid mesh, enabling the desired analyses to be carried out on the models. As part of the analyses, the columns, which are the main beams of the models, were assumed to have fixed (encastre) support conditions at their base, firmly connecting them to the ground at the support points. Horizontal and vertical loads were applied to the models after assigning material properties to the respective model parts. The material model used for these analyses was as described in the “Material” section of this article. In this way, an attempt was made to determine the horizontal and vertical load-bearing capacities of the relevant models within the framework of the relevant regulations (TYDRYK, 2017). The finite element models of the relevant structures are shown in Fig. 5.

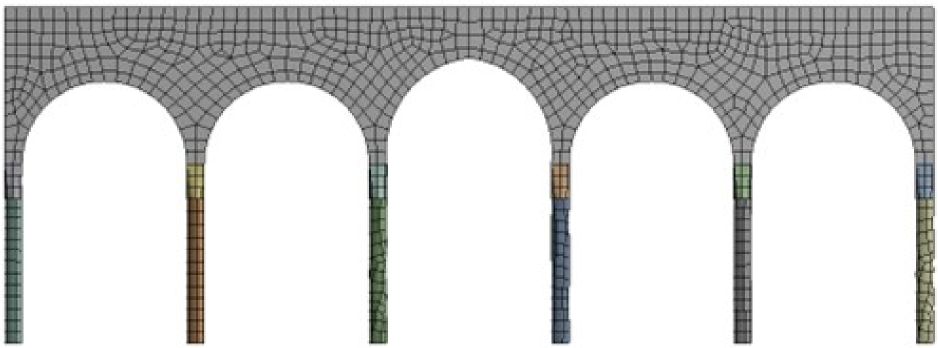
Results

Analyses

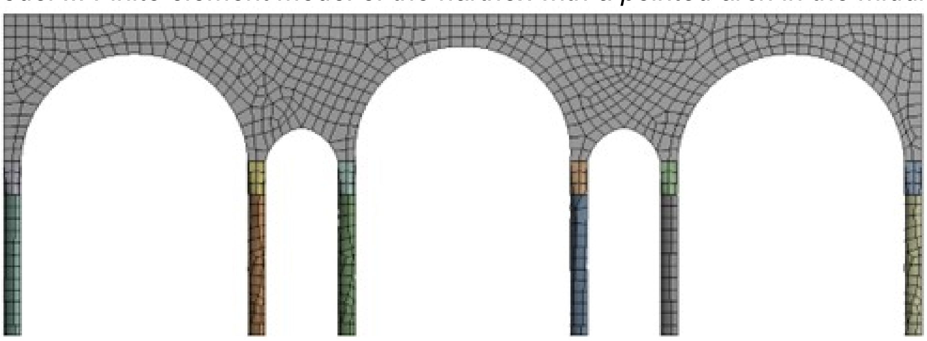
The three-dimensional finite element models created in a computer environment were subjected to static and dynamic analysis. In this way, an attempt was made to determine the reactions and



Model I: Finite element model of the round-arched narthex



Model II: Finite element model of the narthex with a pointed arch in the middle



Model III: Exist finite element model of the narthex of the Selimiye Mosque

Fig. 5. Three types of finite element models of the narthexes

capacities of the models in question to different types of loads.

Pushdown Analyses

In this section, the models were subjected to compressive stresses in the vertical direction from their upper edge and the analyses were carried out by increasing the applied load values. As a result of the analyses, stress, displacement and plastic deformation values were determined and the results are shown in the figures as a colour scale for each model.

Pushdown Analyses for Model I

Increasing compressive stresses were applied vertically to Model I, which consists of round arch portals with 5 identical openings; the direction of loading is shown in Fig. 6.

The displacement values (mm) and the distribution in the horizontal direction (X-axis) resulting from the compressive stresses applied vertically to Model I are shown in Fig. 7. The maximum displacement values in Model I, which consists of circular arch portals with 5 equal openings, reached a maximum value of 3.74 mm at the column heads, which are the support points at the stirrup points of the arches at both ends. It can be seen that the displacements in the other arches have lower values in the middle openings.

The vertical (Z-axis) displacement values (mm) and the distribution resulting from the compressive stresses applied vertically to Model I are shown in Fig. 8. The maximum vertical displacement values reached a maximum value of 3.56 mm around the keystone at the centres of the arches at both ends. In the other arches in the middle spans, the displacements were 2.74 mm and 1.92 mm in the keystone of the arch in the middle. In the columns supporting the porticoes, the minimum value of the displacement was 0.11 mm.

The distribution of plastic deformations occurring after the vertical loading of Model I is shown in Fig. 9. It can be observed that the maximum plastic deformations occur at the centres of the initial and final arches (0.00069) and are distributed over a larger area over time. It is predicted that deformations are observed at the key points and column heads of these arches when the load applied in the vertical direction is increased.

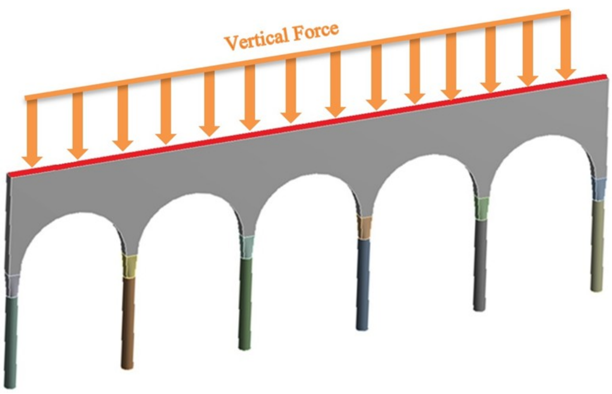


Fig. 6. Loading direction for Model I

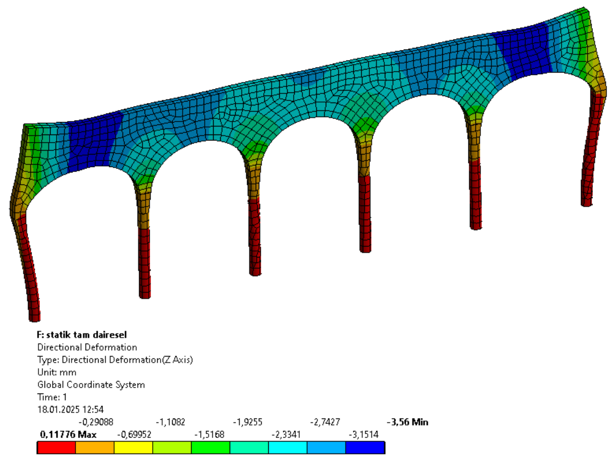


Fig. 8. Vertical Directional Deformation of Model I

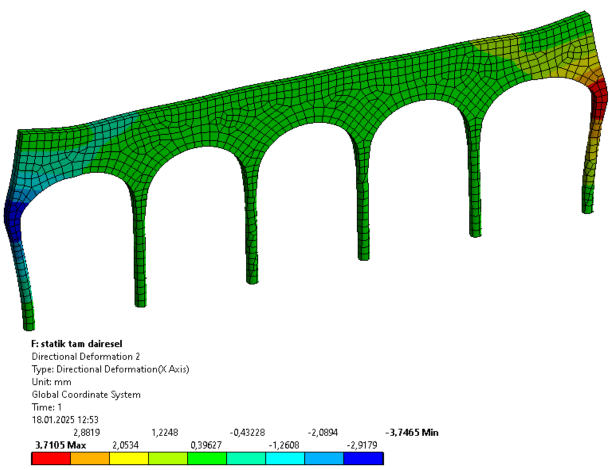


Fig. 7. Horizontal Directional Deformation of Model I

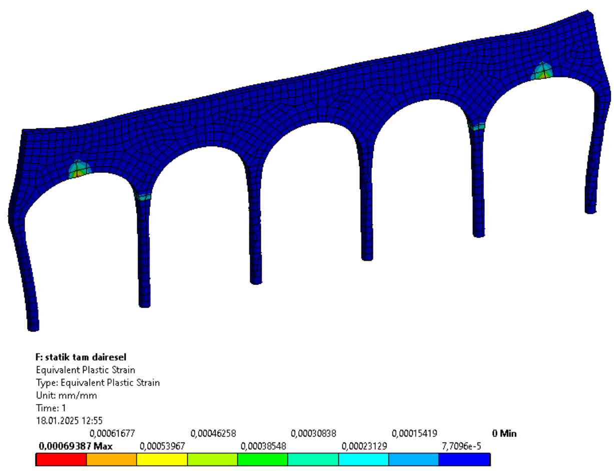


Fig. 9. Plastic Strains distribution of Model I

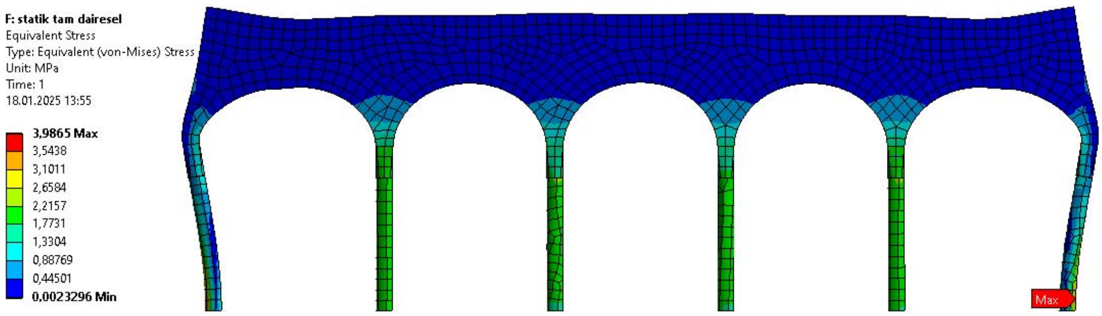


Fig. 10. Equivalent (von-Mises) Stress of Model I

When looking at the comparative stress distribution in Fig. 10, it can be seen that the stresses increase downwards as a result of the vertical loading of Model I. The stresses are particularly concentrated in the columns and reach a maximum value of 3.98 MPa at the bottom of the first and last column. The stresses in the second and fifth columns reach a value of 3.10 MPa and in the middle column a value of 2.21 MPa. The minimum stress in the walls of the column hall above the arches is 0.002 MPa.

Pushdown Analyses for Model II

In Model II, which has five identical openings, a pointed arch in the middle and round arch portals on the sides, compressive stresses were applied by raising them in the vertical direction; the direction of loading is shown in Fig. 11.

The displacement values (mm) and the distribution in the horizontal direction (X-axis) resulting from the compressive stresses applied vertically to Model 2 are shown in Fig. 12. The maximum displacement values in Model II reached a maximum of 3.73 mm at the column heads, which are the support points of the arches at both ends. Displacements of 2.08 mm were recorded at the stirrup points of the arches at the start and end. For the other arches in the middle spans, the displacements are smaller (1.22 mm).

The vertical (Z-axis) displacement values (mm) and the distribution resulting from the compressive stresses applied vertically to Model II are shown in Fig. 13. The maximum vertical displacement values reached a maximum value of 3.70 mm around the centre of the first and last round arch and the keystone of the pointed arch in the middle. It can be seen that the displacements at the centres of the second and fourth round arches are smaller (2.85 mm). The displacements at the column heads, which are the support points of the arches with the columns, are 0.73 mm. For the columns supporting the porticoes, the minimum value of the displacement is 0.11 mm.

The distribution of plastic deformations occurring after the vertical loading of Model II is shown

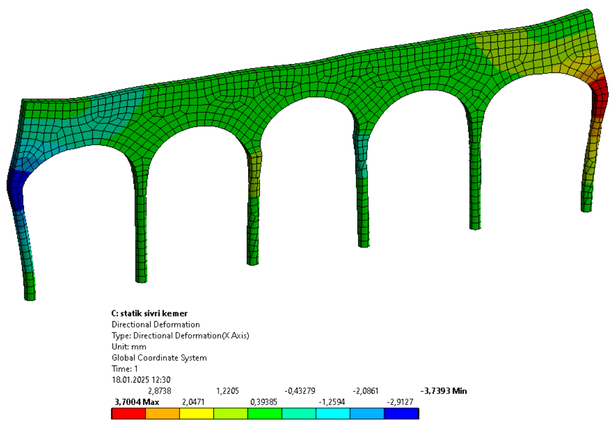


Fig. 12. Horizontal Directional Deformation of Model II

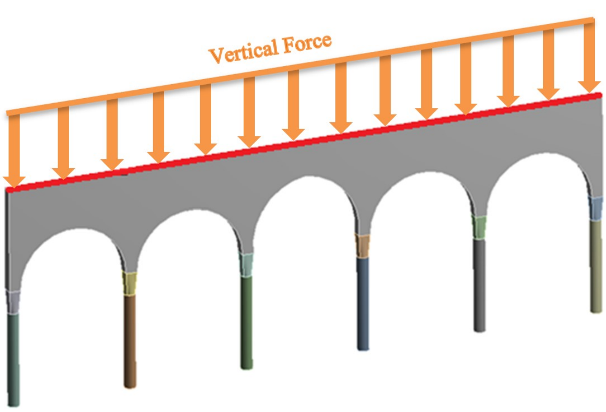


Fig. 11. Loading direction for Model II

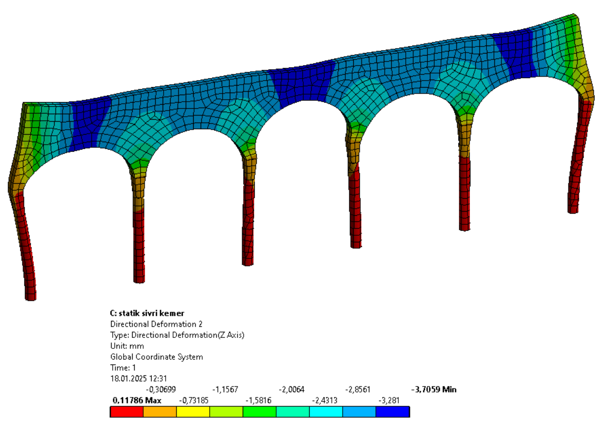


Fig. 13. Vertical Directional Deformation of Model II

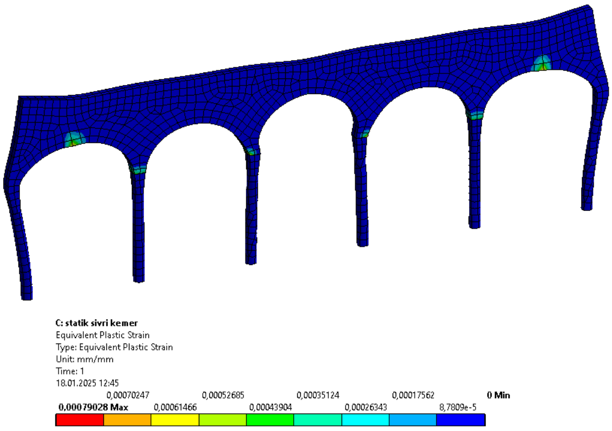


Fig. 14. Plastic Strains distribution of Model II

in Fig. 14. It can be observed that the maximum plastic deformations occur at the centres of the initial and final arches (0.00079). It is predicted that the plastic deformations propagate over time and reach smaller values (0.00043) at the column heads, which are the support points of the arches.

Looking at the comparative stress distribution shown in Fig. 15, it can be seen that the stresses increase downwards as a result of the vertical loading of Model II. The stresses are mainly concentrated at the lower ends of the columns and reach a maximum value of 3.96 MPa at the lower ends of the columns at the beginning and at the end. The stresses in the middle columns reach a value of 2.64 MPa. The stresses in the portico walls above the arches are at a minimum value of 0.001 MPa.

Pushdown Analyses for Model III (Edirne Selimiye Mosque Narthex)

The vertical compressive stresses were increased and applied to Model III, the porch of the Selimiye Mosque, and the direction of loading is shown in Fig. 16.

The horizontal displacement values (mm) and the distribution resulting from the compressive stresses applied vertically to Model III are shown in Fig. 17. The maximum displacement values in Model III reached a maximum value of 49.22 mm at the column heads, which are the support points of the arches at both ends. Displacements of 37.38 mm were recorded at the stirrup points of the arches at the start and end. It can be seen that the displacements in the small arches in the 2nd and 4th openings and in the middle arch are smaller (4.90 mm).

Although the horizontal displacement values seem to be larger in this model than in the other two models, Architect Sinan added another arch at the beginning and end of the colonnades to prevent this large displacement at the narthex of the Selimiye Mosque and connected the structure to the main mass in the other direction.

The vertical (z-axis) displacement values (mm) and the distribution resulting from the compressive stresses applied vertically to Model III are shown in Fig. 18. The maximum vertical displacement values reached a maximum value of 36.44 mm at the centres of the round arches at the beginning and end. It can be seen that the displacements at the central point of the round arch in the middle are smaller (6.07 mm). The vertical displacement value in the columns supporting the arcades is 2.59 mm. At the centres of the small pointed arches in the 2nd and 4th openings, the displacements decrease even more and reach a minimum value of 1.74 mm.

The distribution of the plastic deformations occurring after the vertical loading of Model III is illustrated in Fig. 19. The highest plastic strains are observed at the midpoints of the outermost arches, reaching up to 0.0148. Additionally, plastic deformations of approximately 0.0098 are concentrated around the upper segments of the arch barrels. These deformations gradually propagate over time and reduce to lower magnitudes, reaching about 0.00659 at the column capitals, which serve as the primary support points for the arch system.

Looking at the comparative stress distribution shown in Fig. 20, it can be seen that the stresses increase downwards as a result of the vertical loading of Model III. The stresses are particularly concentrated at the lower ends of the head and tail columns and reach a maximum value of 29.928 MPa. The stresses in the middle columns reach a value of 13.31 MPa. The stresses in the

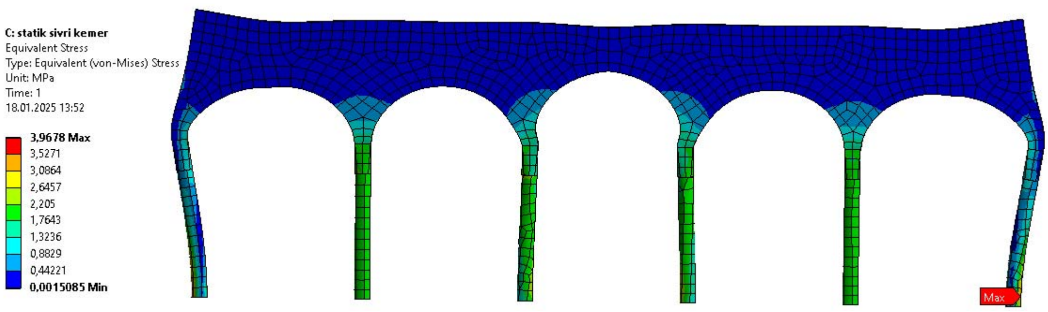


Fig. 15. Equivalent (von-Mises) Stress of Model II

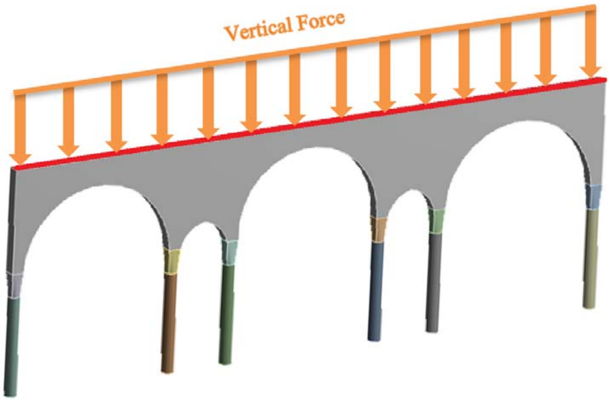


Fig. 16. Loading direction for Model III (Edirne Selimiye Narthex)

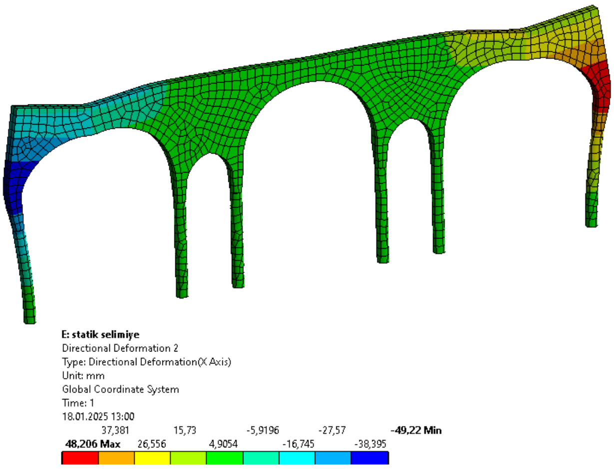


Fig. 17. Horizontal Directional Deformation of Model 3 (Edirne Selimiye Narthex)

portico walls above the arches are at a minimum value of 0.0203 MPa.

Comparison of Pushdown Analysis Results

The pushdown analysis results reveal significant differences in the structural performance of the three narthex models under increasing vertical loads (Table 3). Models I and II, which incorporate simple and repetitive arch configurations (either five round arches or a central pointed arch flanked by round arches), exhibited

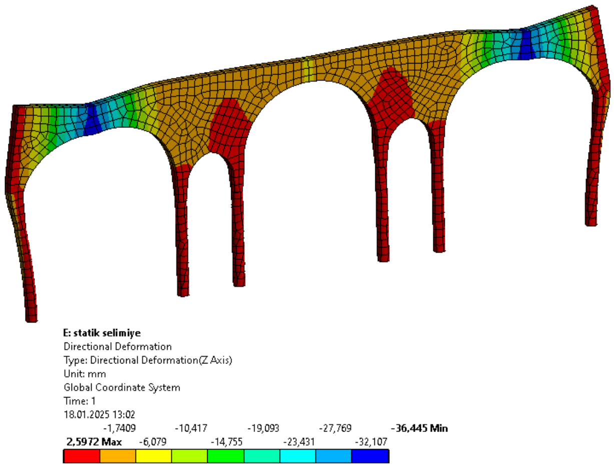


Fig. 18. Vertical Directional Deformation of Model III (Edirne Selimiye Narthex)

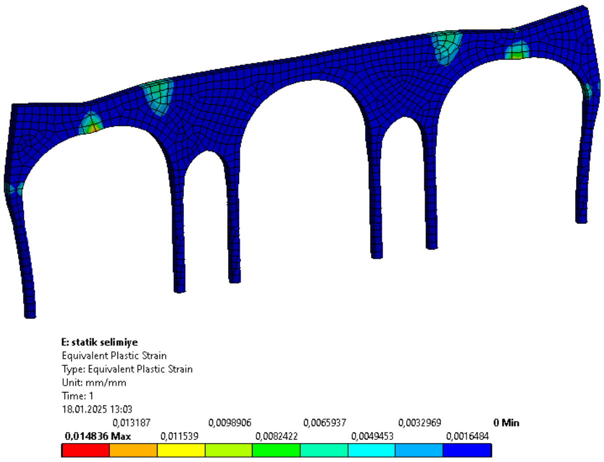


Fig. 19. Plastic Strains distribution of Model III (Edirne Selimiye Narthex)

comparable horizontal and vertical deformations, inelastic strains, and stress concentrations, with maximum horizontal displacements remaining under 4 mm and von Mises stresses below 4 MPa. In contrast, Model III, representing the actual Selimiye Mosque narthex designed by Architect Sinan, demonstrated markedly higher values in all measured parameters. The maximum

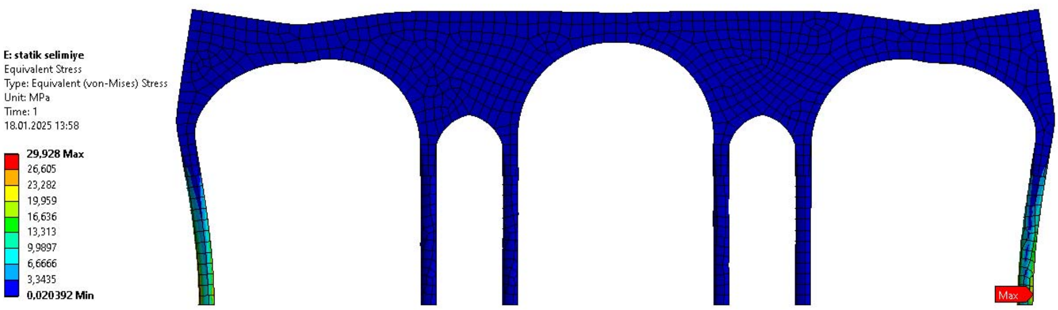


Fig. 20. Equivalent (von-Mises) Stress of Model III (Edirne Selimiye Narthex)

Table 3. **Comparison of Pushdown Analysis Results for Three Narthex Models**

Models	Horizontal Directional Deformation (mm)	Vertical Directional Deformation (mm)	Plastic Strain	Equivalent (von-Mises) Stress (MPa)
Model 1	3.74	3.56	0.00069	3.98
Model 2	3.73	3.70	0.00079	3.96
Model 3	49.22	36.44	0.0148	29.93

horizontal and vertical displacements reached 49.22 mm and 36.44 mm respectively, while the plastic strain and stress values peaked at 0.0148 and 29.93 MPa.

Although Model 3 exhibits higher stress and deformation values compared to the other models, it is observed that these stresses are primarily concentrated at the support points of the first and last columns. Despite the relatively high deformation values recorded in the analysis, the actual structure's revak arches are connected to the massive exterior walls along the X-axis through additional arches, which prevents the occurrence of lateral displacements at the magnitudes predicted by the simulation. This suggests that, in reality, the structure behaves in a more balanced and rigid manner than the analysis model indicates.

These elevated analysis values are directly associated with the more complex geometric configuration and broader spatial span of the Selimiye Mosque's narthex. Nevertheless, Architect Sinan's original design includes a series of structural precautions that go beyond mere aesthetic considerations. These include the addition of extra arches, the integration of the portico system with the surrounding solid walls, the application of confinement (ringing) at column capitals and support points, and the establishment of structural continuity with the main mosque body. Such structural arrangements are believed to facilitate a more balanced distribution of stress and significantly enhance the seismic resilience of the structure.

Pushover Analyses

Pushover analysis is a type of static analysis that examines how far a building can penetrate into the inelastic range before it collapses completely or partially. First, a small horizontal force is applied and the deformations are calculated. A diagram is then drawn up showing the extent of the deformation with gradually increasing forces. This diagram can be used to determine the maximum load that the building can withstand. The collapse mechanism can be investigated using this diagram. At each step of the process, the inelastic shape and displacements in the load-bearing elements and the approximate limits of the collapse mechanism can be checked against the drift ratio limits (TYDRYK, 2017). Based on the results of the non-linear analysis, the ratio of the maximum horizontal displacement (Δ) to the relevant wall height (H) (Δ/H) is calculated as a percentage and compared with the drift ratio limits in (TYDRYK, 2017).

The distributions of the horizontal deformations in the models due to the horizontal load in the pushover analysis before and after are shown in Fig. 21.

The diagram in Fig. 22 shows the horizontal displacements resulting from the gradually increasing forces acting on the models in the pushover analyses. When the horizontal loads on Model 1 were gradually increased and a force of 44.55 tons was applied, the Δ value reached 165.04 mm. When the horizontal loads were gradually increased on Model 2 and 44.55 tons of force was applied, the Δ-value reached 183.46 mm. While the horizontal displacements of Model 1 and Model 2 are approximately the same, the horizontal load of Model 3 increased to 65.34 tons when the same displacement values were reached. It can be concluded that the load capacity of Model 3 is greater than that of the other models.

Conclusions

This article analyzes the spatial and structural qualities of the narthex, one of the most important spatial elements of classical Ottoman architecture, with particular reference to the Edirne Selimiye Mosque by Architect Sinan. The geometric and symmetrical planning principles, structural balance, and aesthetic design approach of historical Ottoman mosques are discussed at the intersection of architecture, engineering, mathematics, and art.

The research results show that Architect Sinan, one of the leading Ottoman architects, used mathematical proportions and modular systems in his works to ensure an optimal static and dynamic balance of space. The arch openings, colonnades, and load-bearing elements used in the vestibules were designed according to specific engineering and architectural principles, not only for aesthetic purposes but also in terms of earthquake resistance, spatial continuity, and functionality in worship. The symmetry, the golden ratio, and the central arrangement — particularly evident in the Selimiye Mosque — demonstrate that this space is not merely an entrance area in classical Ottoman architecture but also a significant transitional / boundary space that defines spatial hierarchy and functional distinctions. The semiotic analyses carried out as part of the study indicate that the narthex of the Selimiye Mosque is not only a physical architectural element but also a ritual and symbolic space. The spatial

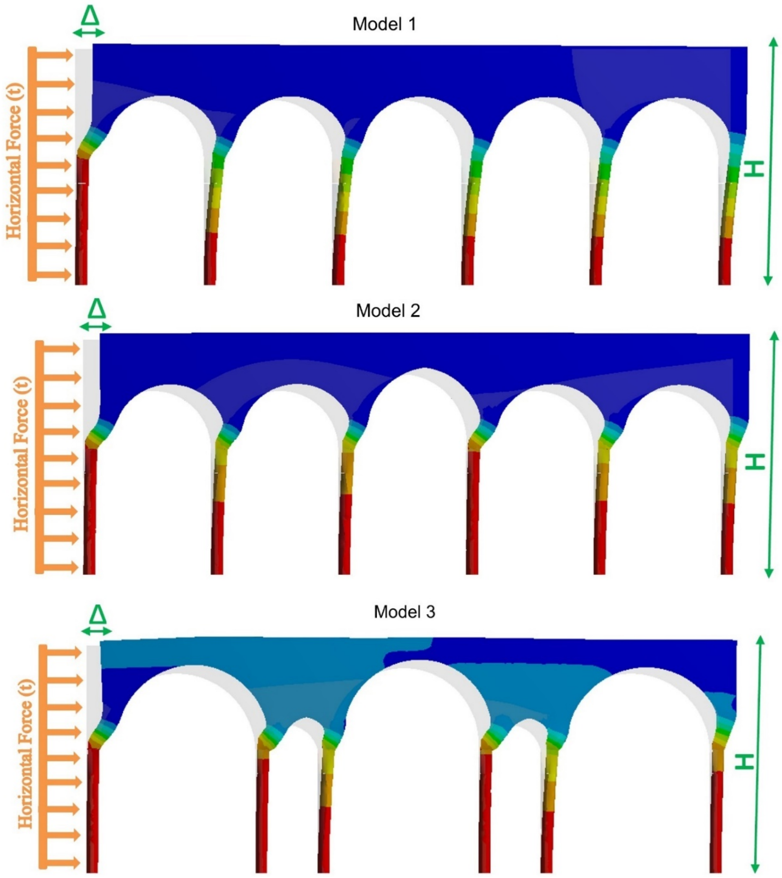


Fig. 21. Models before and after deformations resulting from horizontal loading

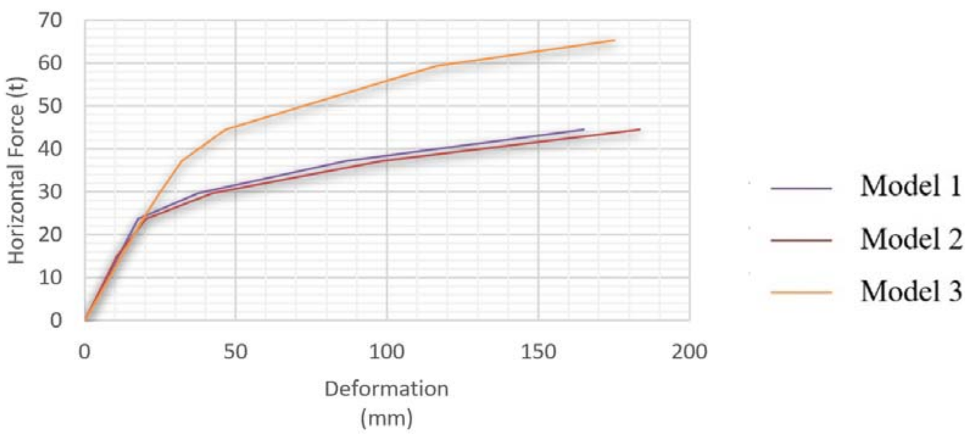


Fig. 22. Force-displacement curves obtained from pushover analyses

organization provides a system that guides the movement of worshippers (user experience) and enriches the spatial experience. It also shows that muqarnas, arch openings, calligraphy, and the use of light are significant not only architecturally but also theologically and sociologically. Also this study primarily aimed to provide a qualitative examination of the structural behavior of the narthex, investigating why this structural system functions as it does, and to highlight the distinguishing features of the Edirne Selimiye Mosque's design.

The architectural studies also demonstrate that the seismic safety and structural durability of an important Ottoman building such as the Edirne Selimiye Mosque are critical aspects to be considered in conservation and restoration efforts. Computer-aided structural analysis, widely used in the literature, offers essential and advanced methods for evaluating the seismic behavior of such structures. In the future, advanced digital simulation techniques, 3D modeling, and structural analysis methods should be utilized more effectively for the conservation of similar historical mosques.

The analyses of the three different narthex models yielded the following structural findings:

• Model 3 (narthex of the Selimiye Mosque) shows the highest values in terms of horizontal displacements and stresses.

• Although the highest values occur in Model 3, Architect Sinan added an additional arch at the beginning and end of the arcades and connected them to the arcades and the main mass in the other direction using buttresses to eliminate this weakness.

• Fig. 18 shows that the load-bearing capacity of Model 3 is greater than that of the other models when reaching the same displacement values.

• When the differences between these three models are evaluated, it becomes clear that the values of the round arch with equal spans and the model with a pointed arch in the middle are approximately the same, indicating that arch geometry has minimal effect on load-bearing capacity; however, Model 3, designed by Architect Sinan, significantly increases the load-bearing capacity.

• Fig. 18 also indicates that Model 3 has a higher energy absorption capacity due to its larger surface area.

• The pushover analyses were performed in the longitudinal direction of the models; the other direction, where the narthex is structurally weaker, was not evaluated. The structure was connected to the main mass in that other direction.

When examining the models in terms of stress distribution, it is observed that the stresses in the arcade systems of Models 1 and 2 are distributed along the main axes of all columns. These stresses are particularly concentrated at the column bases and capitals. It is known that these sections were architecturally built wider than the column diameter and that iron rods were cast in lead at these joint areas, connecting the columns at the support points to the upper arch sections and the stone foundation at ground level. The obtained analysis results demonstrate the importance and necessity of this application. This knowledge and the experience accumulated throughout history were likely passed down to subsequent generations.

To counteract the effects of stress and deformation, it was concluded that the cross-sections at the column capitals and support points should be enlarged. The column bases not only meet technical requirements but also satisfy aesthetic considerations and provide architectural unity. Additionally, it was noted that tension rods were inserted between the two colonnades to balance supports and stresses, which is expected to enhance the structure's durability.

When examining the stress results in the model of the Selimiye Mosque's portico, it is found that significant stresses are only distributed along the main axes of the first and last columns. No noticeable stress values are observed in the middle column bays. These tensile stresses, which could pose a threat to masonry structures, are confined to a limited area and thus reduced to two columns. The fact that these columns are connected to the solid sidewalls through porticoes perpendicular and parallel to their axes seems to have mitigated the negative effects on these columns. This affirms that Sinan demonstrated his engineering mastery not only within the main mosque but also in the design of the narthex.

In this context, it is stated that the Edirne Selimiye Mosque and its architecture are not only aesthetic and cultural heritage but also represent an advanced structural and engineering system. The narthex of the Selimiye Mosque stands as a prominent architectural example that reflects the close relationship between geometry, engineering, and religious practice in classical Ottoman architecture. This study, therefore, contributes to the protection and sustainability of cultural heritage by offering a novel, interdisciplinary perspective on the spatial and structural analysis of Ottoman mosques.

It is anticipated that future studies may deepen the structural analyses of Ottoman mosques through more refined digital modeling and artificial intelligence-based engineering approaches. In this way, it will be possible to preserve this architectural heritage, protect it from high-risk natural disasters such as earthquakes, and develop sustainable conservation strategies.

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ПРОСТРАНСТВЕННОЕ ИССЛЕДОВАНИЕ И СТРУКТУРНЫЙ АНАЛИЗ НАРТЕКСА В ОСМАНСКИХ МЕЧЕТЯХ: ПРИМЕР МЕЧЕТИ ЭДИРНЕ СЕЛИМИЕ

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Аннотация

Введение. Анатолия на протяжении истории была родиной многочисленных цивилизаций. Многие цивилизации, от античности до наших дней, создали различные виды сооружений. Среди этих сооружений мечети представляют собой сильные пространственные и структурные парадигмы в рамках сложной группы зданий, построенных османами. **Методы.** В данном исследовании пространственный характер главного входа в мечеть Эдирне Селимие, построенную Мимаром Синаном, который состоит из колоннад, называемых нартексом, будет проанализирован с помощью семиотических и теоретических методов с учетом архитектурного контекста. Вторая задача — определить пространственные характеристики, а также размеры (высоту и пролет), геометрическую типологию колонн и свойства материалов, а также исследовать статические и динамические реакции на сейсмическое воздействие. В этом процессе были созданы две различные параллельные модели для структурного анализа, в дополнение к существующему нартексу Селимие, и эти три модели были проанализированы с использованием метода конечных элементов в среде ANSYS Workbench. **Результаты.** На основе полученных результатов оцениваются пространственные, геометрические и структурные аспекты и требования к зданию, а также предлагаются конструктивные решения.

Ключевые слова: пространственные характеристики; семиотика; структурный анализ; мечеть; нартекс; продавливание; анализ на предельную прочность.