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Forms and Vertical and Lateral Load Capacities of Columns in Mimar Sinan's Mosques

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Abstract
Along with the walls, columns are the main load-bearing elements in carrying vertical and horizontal loads in most historic masonry buildings. When the mosques of Mimar Sinan, the great Ottoman architect, are examined, it is seen that there is a wide variety in column forms. In this study, the column forms in Sinan's a few mosques were investigated, their geometric dimensions were measured, and the vertical and lateral load carrying capacities of them were determined. The columns examined are the columns of Sinan Pasha, Kılıç Ali Pasha, Üsküdar Mihrimah Sultan, Selimiye, Şehzade and Süleymaniye mosques. Initially, the vertical capacities of the columns were calculated with both the classical stress equation and the Abaqus program, and very close results were obtained with the two calculation methods. Then, lateral load carrying capacities were calculated only by using of the Abaqus software. It has been once again seen and emphasized that height is also important, together with other relevant factors, on the lateral load capacities of the columns.

1. Introduction

There are many great architects and engineers in the history of world architecture and engineering. One of these names is undoubtedly Mimar Sinan, who was the chief architect of the Ottoman Empire for fifty years between 1538 and 1588. Most of the great Ottoman structures of the second half of the 16th century are the work of Sinan. He, along with his assistants, designed and oversaw the construction of buildings, bridges, aqueducts etc. throughout the empire [1]. The great architect died in 1588, when he was about a hundred years old, leaving behind an unprecedented number and quality of works [2].

Nearly 400 of Sinan's works have survived to the present day. Mosques are undoubtedly among his most striking works with their magnificence. Sinan's mosques have been the subject of numerous studies for today's architects and engineers. The examinations, measurements and analyses made within the scope of this study are on the columns of some mosques of the great architect.

As it is known, columns in historical masonry buildings can be divided into two groups as 'pillars' and 'piers'. Pillars are formed either from a single specially shaped stone or from several specially shaped stones. Piers, on the other hand, are formed by laying a large number of stones or bricks (sometimes both together) with a mortar. The main piers of some large mosques are gigantic and are called as 'elephant leg'. For example, the piers of the Süleymaniye and Sultan Ahmet mosques are like this. Columns within the scope of this study are "piers" only, and hereinafter referred to as "columns"

2. Some related previous works

The load-bearing elements of historical masonry mosques and similar structures are walls, columns,

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buttresses, arches, domes and foundations. Columns are of vital importance in carrying vertical and horizontal loads together with the walls. It is seen that many studies have been performed in the technical literature on these elements. Yokel [3] investigated the stability and load bearing capacity of rectangular cross-sectional elements made of no-tension material under the effect of eccentric vertical load. Frisch-Fay [4] studied the stability of eccentrically loaded masonry rectangular columns analytically and using the matrix-displacement approach. Ahunbay [5] discussed the construction techniques and materials used in Mimar Sinan structures.

La Mendola and Papia [6] investigated the stability of masonry piers numerically by considering both their own weight and the effect of eccentric vertical load. De Falco and Lucchesi [7] extended Yokel' s [3] work to the stability analysis of columns made of materials that do not have tensile strength but also have limited compressive strength and deformation capacity. Arıoğlu and Arıoğlu [8] conducted a comprehensive study on the physical and mechanical properties of a limestone (Küfeki stone) that Mimar Sinan used extensively in his structures. Gurel et al. [9] investigated the lateral stiffness of masonry rectangular columns using a numerical model capable of capturing the cracking and second-order effects. Gurel et al. [10] tried to determine the lateral load capacity of cylindrical masonry columns for seismic transverse forces. In his PhD thesis, Şeker [11] examined the behavior of Mimar Sinan mosques under static and dynamic loads. In this context, he discussed the mosque construction techniques, materials used and their properties, and finally performed static and dynamic analyses on three-dimensional models of Sinan's 28 mosques. Gurel [12] studied the stability of slender circular masonry columns under their own weight and eccentric vertical load. Crespi et al. [13] performed seismic assessment of the Santa Maria di Collemaggio Basilica in L'Aquila (Italy) focusing the attention on the behavior of the octagonal stone columns of the naves. Çaktı et al. [14] studied the seismic behaviour of the Mihrimah Sultan Mosque in Edirnekapı, one of the most elegant works of the Sinan. Broseghini et al. [15] analysed several aspects of the instability of homogeneous masonry circular columns loaded with a vertical eccentric load.

It is seen that, in the technical literature, various studies have been carried out on masonry columns, and Mimar Sinan mosques have been examined in terms of some technical and material properties. However, no special study was found about the forms and load capacities of columns in Sinan's mosques. In the context of this study, the columns in Mimar Sinan's some mosques were examined in situ, their geometric dimensions were measured, and their vertical and horizontal load carrying capacities were determined. Thus, some more information was obtained about the columns, one of the most vital elements, in the buildings of the great architect.

3. Materials and Method

When his works are examined, it is immediately seen that Sinan added something "different" to each of his designs. Namely, "innovation" is one of the most outstanding features of the master architect. This search for innovation is also evident in the columns of his building-type structures such as mosques. The authors examined many mosques of the Mimar Sinan on site and clearly observed this fact. It has been observed that there are many different column types, from classical rectangular and circular columns to hexagonal and octagonal columns, and to the columns with special geometric shaped cross-sections having protrusions to provide supports to the arches. Here, the columns of only six mosques are considered. These mosques are Sinan Pasha (Beşiktaş), Kılıç Ali Pasha, Mihrimah Sultan (Üsküdar), Selimiye, Şehzade and Süleymaniye mosques. Column dimensions of the buildings were determined by the authors by in situ measurements. Figure 1 presents a general view of the columns, their cross-sectional shapes and dimensions.

Although this study is on column forms in Sinan mosques, it should be noted that determining how form affects the vertical and horizontal capacities of columns is not the main purpose of this first study on the subject. This issue can be explored in another study in the future.

The materials used in the construction of Mimar Sinan mosques are as important as their rational and innovative designs. When looked at the materials used by Sinan in his buildings, it is seen that he used stone, brick and wood as the main materials, Khorasan mortar and lime as the binder, as well as nails, clamps and tenons of various sizes. His buildings are completely stone or stone-brick mixed structures. Among the mosques we examined, it is seen that Marmara marble had been used in the columns of Kılıç Ali Pasha Mosque and limestone (Küfeki) had been used in the columns of all other mosques. As the mortar, generally Khorasan mortar had been used in all mosques.

It is known that masonry structures can be modeled by detailed micro modeling, simplified micro modeling or macro modeling technique. The details of these techniques will not be discussed here, as they are included in relevant studies. In this study, macro modeling technique (homogeneous material approach) has been preferred. According to this approach, masonry texture is considered as a homogeneous continuum that incorporates the properties of the masonry units and the mortar. By adopting this approach, the compressive strength values were calculated with the $f_c = 0.45 f_s^{\,0.7} f_m^{\,0.3}$ expression, [16]. In the expression, f_s and f_m indicate the compressive strength of the stone and mortar. The characteristic values provided by this equation have been multiplied by a factor of 1.2 to obtain the average values. While determining the elastic modulus, E, of the homogeneous texture, the formula $E = 750f_c$ has been used, [17]. The Poisson's ratio, ν, has been taken as 0.20, which is commonly used for brittle materials. The physical and mechanical properties of the materials (Küfeki stone, Marmara marble and Khorosan mortar) of the columns have been taken from the studies of Şeker [11], Korkmaz [18], Arioğlu and Arioğlu [8]. The f_c and E values for the columns have been obtained by the two expressions given above and are presented in Table 1. The tensile strength value, f_t, for the material of all columns has been taken simply as 1 MPa. The columns have been modeled and analyzed in the Abaqus [19]. The Concrete Damaged Plasticity model in the program has been used to consider degradation in modulus of elasticity of the material due to damage. Stress-strain relations for the texture of the columns were obtained using the diagrams proposed by Hognestad [20] in compression and by Massicotte et al. [21] in tension, Fig. 2. Damaged plasticity parameters used in the analyses were taken from Abaqus's user manuel and the related study of the Valente and Milani [22], (Table 2).

Static analyses have been performed in the Abaqus program to determine both the vertical and horizontal load capacities of the columns. Vertical load capacities were also determined using the classical $\sigma = N/A$ expression in Strength of Materials. The "displacement control method" was used to determine the vertical load capacities of the columns with the Abaqus program. As for the horizontal load capacities, they were determined by applying firstly a vertical load equal to their own weight to the columns, and then imposing horizontal displacement using again the displacement control method. The C3D8R finite element type has been used in the finite element models of the columns. Finite element models of the columns are given in Fig. 3. All freedoms of all nodes at the base cross-sections of the columns were restrained, i.e. the columns were taken as fixed at their bases.

4. Analyses, obtained results and discussions

In this part of the study, the vertical and lateral load carrying capacities of the columns have been calculated. The values of the vertical capacities obtained from the classical formula and the Abaqus are presented in Table 3. The results are quite close to each other. Compared to the formula, the program gave higher capacity values for the columns, except the Kılıç Ali Paşa Mosque column. It is rather normal to have some difference between the formula and the Abaqus results. Because, the formula is based on simply not exceeding the strength without any damage to the columns, whereas Abaqus, by considering many parameters, takes into account the damage to the columns as the calculation progresses. On the other hand, it is needless to say that, the vertical capacity increases from the columns with small cross-sectional area to the larger ones. With a value of approximately 460000 kN, column of the Süleymaniye Mosque has the highest vertical load capacity.

In the analyses with the Abaqus program, vertical displacement was imposed to the upper cross-sections of the columns and the total axial (vertical) reaction forces were calculated at the nodes in the base sections of the columns. Vertical displacement - base axial reaction graphs obtained with the program are given in Fig. 4.

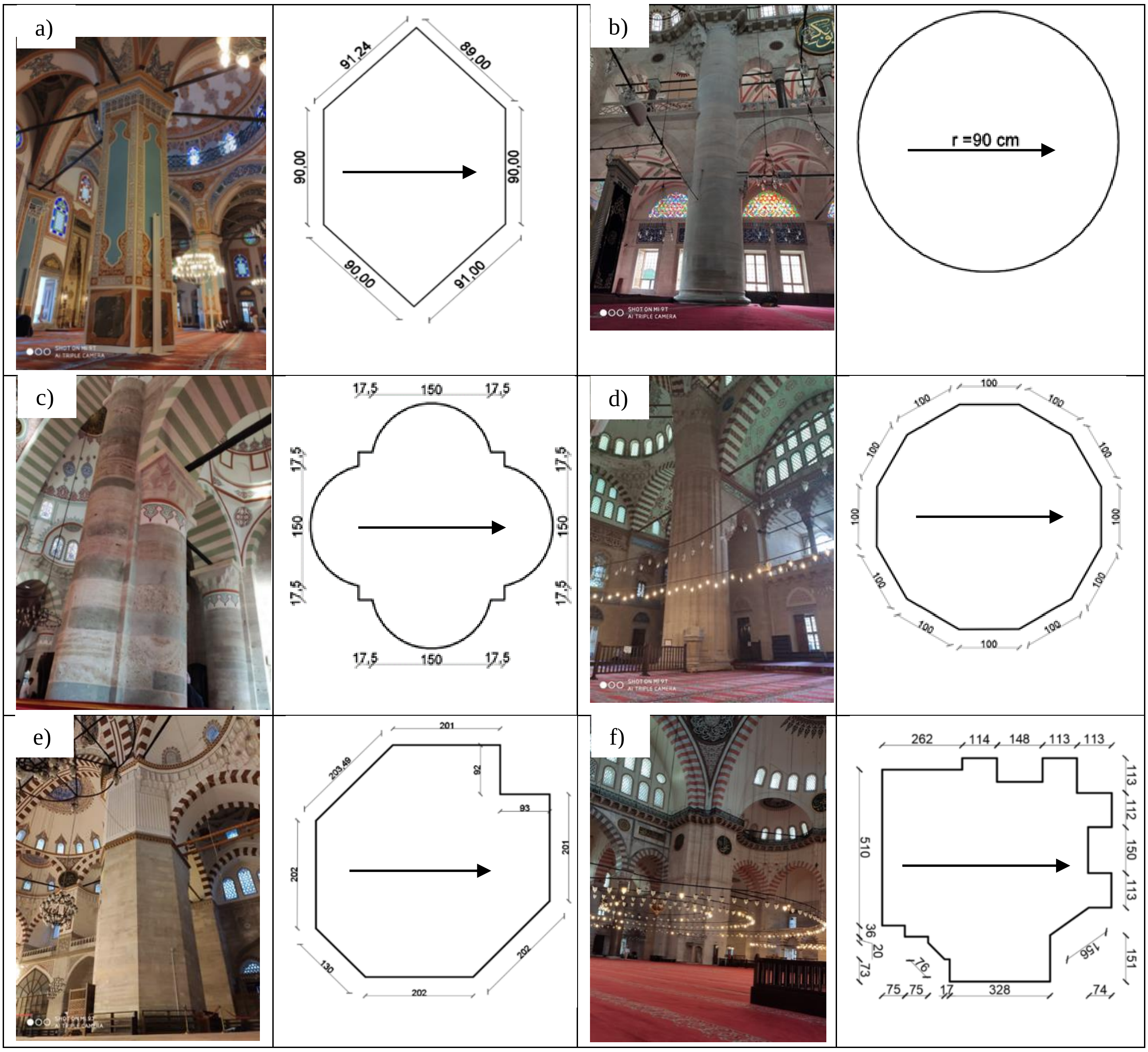


Figure 1. Columns, their sections and dimensions in the examined mosques of Mimar Sinan: a) Sinan Pasha Mosque, b) Kılıç Ali Pasha Mosque, c) Mihrimah Sultan Mosque (Üsküdar), d) Selimiye Mosque, e) Şehzade Mosque, f) Süleymaniye Mosque (dimensions are in cm and drawings are not to scale)

Table 1. Material properties used in calculations for the columns

Material	Unit weight, γ (kN/m^3)	Modulus of elasticity, E (MPa)	Compressive strength, f_c (MPa)	Tensile strength, f_t (MPa)	Poisson's ratio, ν
Küfeki stone + Khorasan mortar	19.7	8630	11.5	1	0.20
M. marble + Khorasan mortar	26.5	10656	14.25	1	0.20

From the graphs, the behavior of the columns under increasing axial displacement, hence increasing axial load, can be clearly seen. With the analyses made with Abaqus, it is as if axial loading tests were performed on the columns in the laboratory. In this way, resistance to the increased load, reaching the maximum resistance, then decrease in resistance with increasing damage in the body, and eventually the complete crushing of the columns could be observed. This is just one of the numerous examples that illustrate the possibilities that an advanced software like Abaqus provides for engineers.

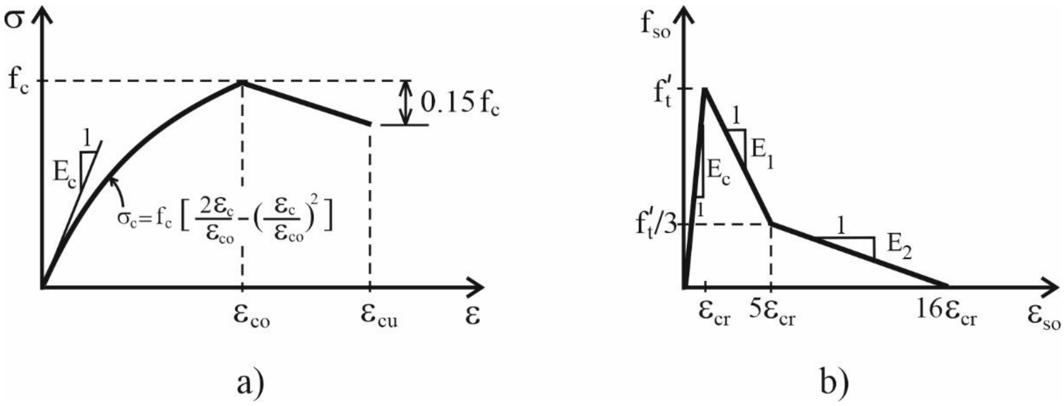


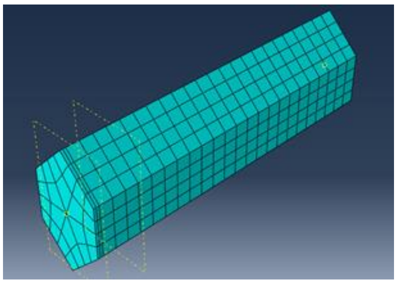
Figure 2. Stress-strain diagrams for the texture of the columns: a) in compression (Hognestad [20]), b) in tension (Massicotte et al. [21])

Table 2. Damaged plasticity parameters used in the analyses, [22]

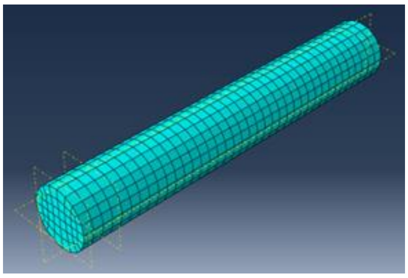
Dilatation angle	Strength ratio	Eccentricity	*K* par.	Viscosity par.
10º	1.16	0.1	0.667	0.002

Table 3. Geometric properties of the columns and the vertical load carrying capacities obtained for them

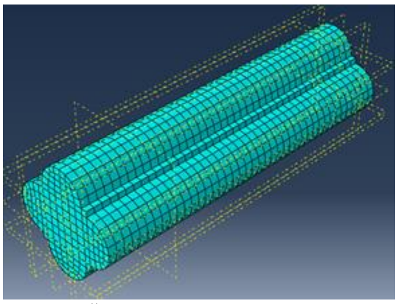
Mosque	Column height, *h*(m)	Cross-sect. area, *A* (m^2)	N_{max}, Class. cal. (kN)	N_{max}, Abaqus (kN)
Sinan Pasha	5.8	1.93	22200	24891
Kılıc Ali Pasha	11.3	2.46	35600	34331
Mihrimah Sultan	10.3	6.84	78700	79900
Selimiye	19.2	10.87	125000	135606
Şehzade	15.2	15.39	177000	190007
Süleymaniye	18.65	36	414000	458734



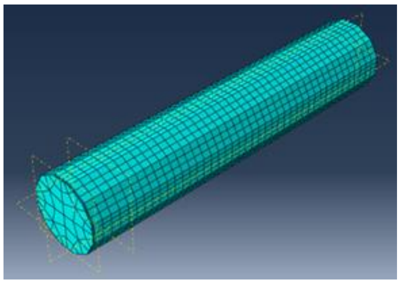
a) Column of Sinan Pasha Mosque,
Number of elements: 600
Number of nodes: 962



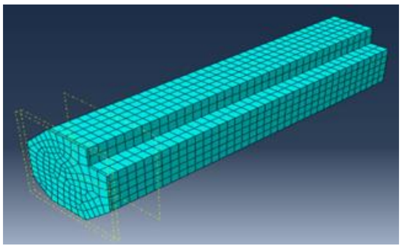
b) Column of Kılıç Ali Pasha Mosque,
Number of elements: 1672,
Number of nodes: 2145



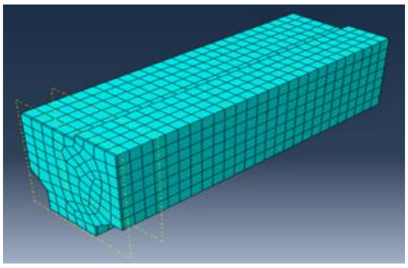
c) Column of Üsküdar Mihrimah Sultan Mosque,
Number of elements: 6232
Number of nodes: 7434



d) Column of Selimiye Mosque,
Number of elements: 1760
Number of nodes: 2745



e) Column of Şehzade Mosque,
Number of elements: 4797
Number of nodes: 5720



f) Column of Süleymaniye Mosque,
Number of elements: 2241
Number of nodes: 2856

Figure 3. Finite element meshes of the columns

When an approximate superstructure weight is calculated for any of the mosques, taking into account the dome, main arches, pendentives and weight towers (if any), and the force per column is determined (see reference [10]), it is seen that the value obtained is well below the capacity of the column. It is well known that this is the case in the vast majority of historical buildings, that is, the load-bearing elements in these buildings had been “overdesigned” against vertical loads. Here, we saw that Sinan also adhered to the tradition and designed and built the columns in his mosques in a rather safe way against vertical loads. The fact that he was the chief architect in the most powerful period of the Ottoman Empire is undoubtedly another important factor that enabled Sinan to be more generous in his designs.

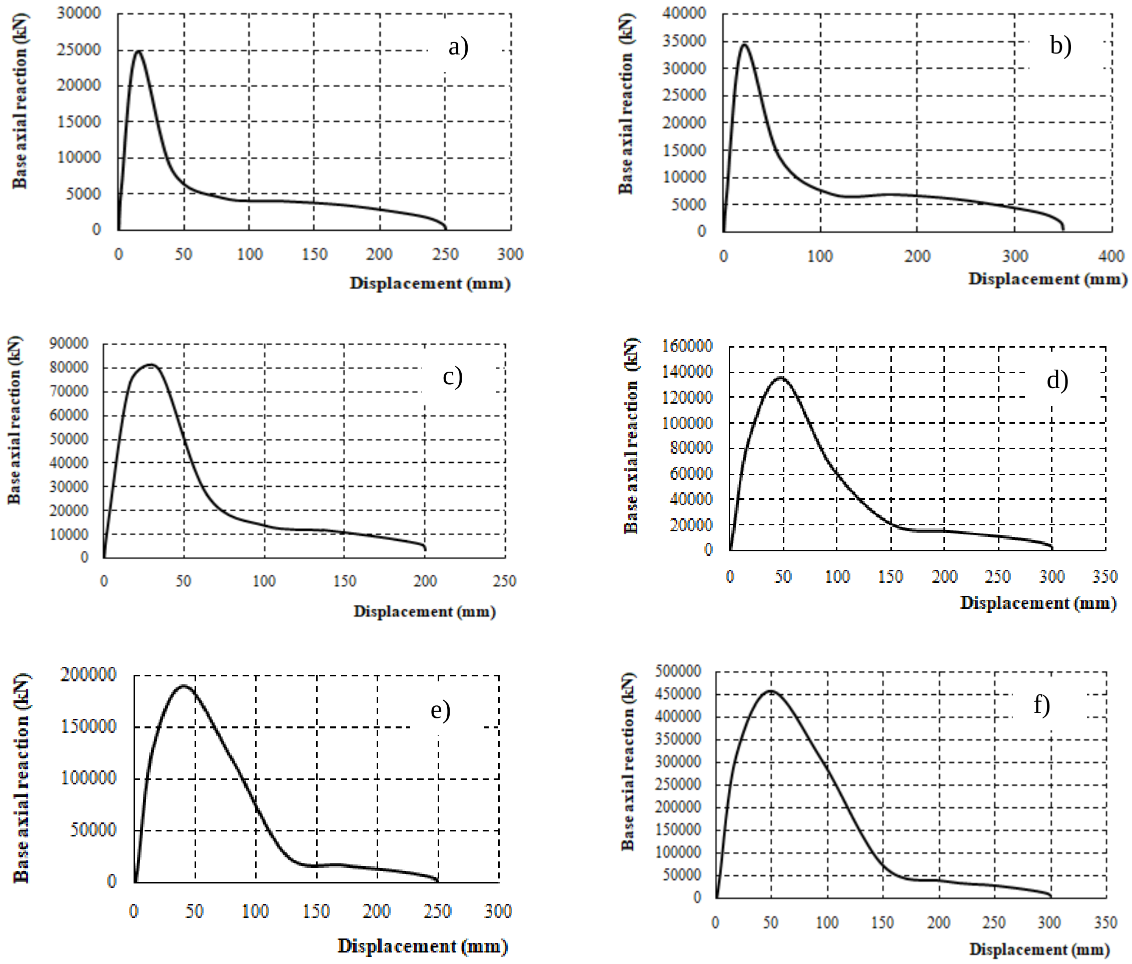


Figure 4. Vertical displacement – base axial reaction graphics for the columns: a) Sinan Pasha Mosque, b) Kılıç Ali Pasha Mosque, c) Üsküdar Mihrimah Sultan Mosque, d) Selimiye Mosque, e) Şehzade Mosque, and f) Süleymaniye Mosque

To determine the horizontal load capacities of the columns, initially an axial load equal to self-weight of the column was applied to the top of each column in the Abaqus program. Then, gradually increasing horizontal displacements were imposed on the upper section of the column and the shear forces at the base cross-section were calculated. The directions in which the horizontal displacement is applied to the columns are indicated in Fig. 1 on the column cross-sections. Top cross-section horizontal displacement versus base shear force relationships obtained in this way are presented in Fig. 5. The values determined for the horizontal load capacities of the columns are given in Table 4. If desired, by considering various values of the axial load applied to the top sections of the columns, it can also be determined how this load affects the horizontal capacities.

The cross-section shape, which does not all that come to the fore when calculating vertical capacities, shows itself in the horizontal capacities. This can be noticed when Fig. 4 and Fig. 5 are compared. Indeed, while the graphs in Fig. 4 are more similar among themselves, the similarity of the graphs in Fig. 5 is less. Of course, the fact that column heights are important when calculating horizontal capacities also has influence on this situation. When Table 3 and Table 4 are examined together, this can be seen immediately. For example, let' s compare the columns of Mihrimah Sultan and Şehzade Mosques. For this comparison to be meaningful, it is worth remembering that identical material properties (Küfeki stone + Khorasan mortar) were taken into account for the two columns, Table 1. The cross-sectional area of the Şehzade Mosque' s column is bigger than that of the Mihrimah Sultan Mosque, and therefore its vertical load capacity is higher, Table 3. However, the column of the Şehzade Mosque has a slightly lower horizontal load capacity due to its greater height, Table 4. This simple comparison shows once again how important the column length is on the lateral load capacities of the columns, a fact well known to structural engineers.

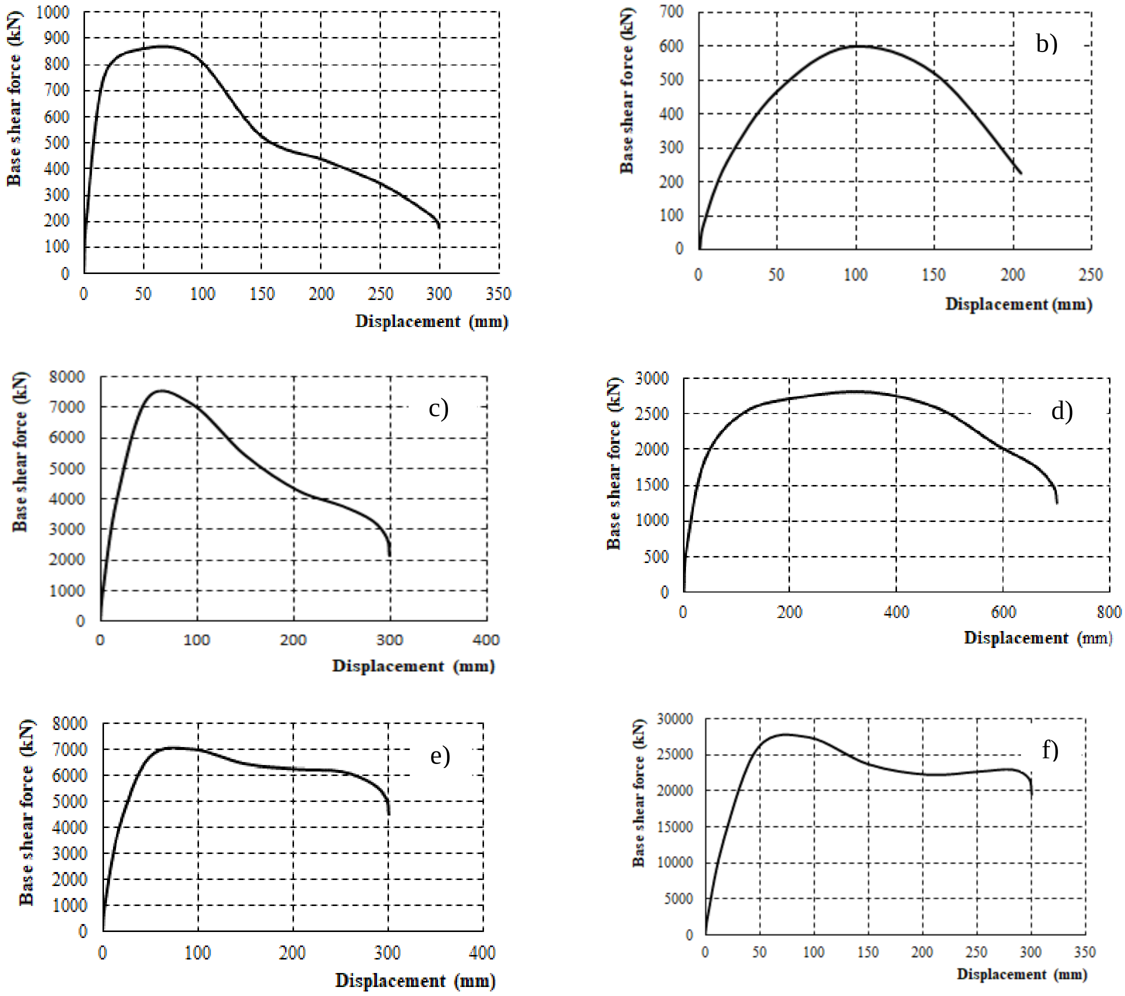


Figure 5. Top section horizontal displacement – base shear force graphics for the columns: a) Sinan Pasha Mosque, b) Kılıç Ali Pasha Mosque, c) Üsküdar Mihrimah Sultan Mosque, d) Selimiye Mosque, e) Şehzade Mosque, and f) Süleymaniye Mosque

Table 4. The results obtained for the horizontal load carrying capacities of the columns

Mosque	H_{max} **(kN)**
Sinan Pasha	857
Kılıç Ali Pasha	600
Mihrimah Sultan	7279
Selimiye	2740
Şehzade	6997
Süleymaniye	27526

If the horizontal load capacities of all columns are compared, it is seen that, despite its great height, the column of the Süleymaniye Mosque is well ahead, as in its vertical load capacity, due to its colossal cross-sectional area. From here, it is seen that, as is the common opinion of all experts on the subject, Sinan designed and built the Süleymaniye in a privileged way in terms of "strength" as well as in other aspects. As for the columns of other mosques, the values obtained show that, they also have lateral load capacities at significant levels. Therefore, it is obvious that, together with the walls, they will provide significant lateral resistance to the buildings they belong to under horizontal effects such as earthquakes and winds.

5. Some further remarks

In this study, in particular, the column forms, and vertical and lateral load capacities of Mimar Sinan mosques are discussed. As mentioned earlier, there are many other studies on Sinan's mosques. On the other hand, when we look at the literature, it is seen that there are innumerable works about historical structures and historical mosques in general. A few such works are given in [23-29] for the sake of sample. Investigation of historical buildings in every aspect and comprehensively will guide us in understanding these structures better and transferring them to future generations with confidence. Therefore, future studies in this direction will also certainly be valuable.

6. Conclusions

The great Ottoman architect Sinan is one of the most prominent figures in the history of world architecture, “whose works are worth examining elaborately and in all aspects”. Numerous studies (scientific articles, theses, etc.) have been made on his works. This study aimed to determine the vertical and horizontal load capacities of the columns of some mosques of the great architect. Mosques considered are Sinan Pasha, Kılıç Ali Pasha, Üsküdar Mihrimah Sultan, Selimiye, Şehzade and Süleymaniye Mosques. The columns of these structures have different geometric shapes. Their dimensions were measured in situ, and the material properties were taken from studies related to the subject. The vertical load capacities of the columns were determined both with the classical stress expression and with the Abaqus program, and the lateral load capacities were determined only with Abaqus. The vertical load capacities determined by the two methods are rather close. Very high vertical load capacity values were calculated for all columns. It has been determined that the horizontal load capacities are also generally quite good, especially the column of the Süleymaniye Mosque, which has a very large cross-section. Hence, it is understood that Sinan designed and built the columns in his buildings to withstand vertical loads very well and to have substantial resistance to horizontal loads. He almost always kept the outer walls thick in his buildings and did not leave the columns alone against horizontal loads.

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Contribution of the Authors

The article was produced with the joint contributions of the authors.

Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

Research and publication ethics were complied with in the study.

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