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Research Article

Dome System in Sinan's Mosques

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Abstract

The Great Sinan, who was the chief architect during the three sultans of the Ottoman Empire (Sultan Suleyman the Magnificent, Sultan Selim II and Sultan Murat III); produced many works with different typological features such as mosques, madrasahs, primary schools, hospitals, palaces, aqueducts. Among these works, the mosque is the type of building that Sinan worked on the most. The structural system of Sinan mosques consists of the dome, dome transition elements (pendentive, squinch), arches and load-bearing walls. However, Architect Sinan applied multi-support systems with four, six and eight supports in terms of load-bearing system. The aim of this article is to relate some examples of square, hexagonal and octagonal supported support systems (Süleymaniye, Kadırga Sokullu Mehmet Pasha and Edirne Selimiye mosques) applied by Architect Sinan to the dome system. In the article, first of all, the literature research, the dome system in general and the dome technique used by Sinan were explained, then the dome of the mosque examples specified in different support systems were presented.

Keywords: Architect Sinan, Dome, Dome Transition Elements, Square, Hexagonal and Octagonal Support System.

Sinan'ın Camilerinde Kubbe Sistemi

Öz

Osmanlı İmparatorluğunun üç padişah devrinde (Kanuni Sultan Süleyman, Sultan II. Selim ve Sultan III. Murat) baş mimar olan Koca Sinan; başta cami olmak üzere medrese, sıbyan mektebi, darrüşifa, saray, su kemeri gibi farklı tipoloji özelliklerine sahip çok sayıda eserler vermiştir. Bu eserler içerisinde cami, Sinan'ın en çok üzerinde çalıştığı yapı türüdür. Sinan camilerinin strüktür sistemi kubbe, kubbe geçiş elemanları (pandantif, tromp), kemerler ve taşıyıcı duvarlardan oluşmaktadır. Ancak Mimar Sinan taşıyıcı sistem bakımından dört, altı ve sekiz destekli çoklu mesnet sistemi uygulamıştır. Bu makalenin amacı, Mimar Sinan'ın camilerde uyguladığı kare, altıgen ve sekizgen destekli mesnet sistemlerinden bazı örnekleri (Süleymaniye, Kadırga Sokullu Mehmet Paşa ve Edirne Selimiye camileri) kubbe sistemi ile ilişkilendirmektir. Makalede önce, literatür araştırması, genel olarak kubbe sistemi ve Sinan'ın kullandığı kubbe tekniği açıklanmış, sonra ise farklı mesnet sistemlerinde belirtilen cami örneklerinin kubbesi sunulmuştur.

Anahtar Kelimeler: Mimar Sinan, Kubbe, Kubbe Geçiş Elemanları, Kare, Altıgen ve Sekizgen Destekli Mesnet Sistemi.

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1. Introduction

Architect Sinan, who lived during the period when the Ottoman Empire had the largest lands, was appointed as the chief architect in 1539, upon the death of Alaeddin, who was known as the Chief Architect Acem Ali. He served as chief architect during Sultan Suleyman the Magnificent, Sultan Selim II and Sultan Murat III. He played a major role in designing and implementing architectural masterpieces that symbolized the power of the empire. Although, Sinan built many mosques during the Ottoman period, he produced many works such as small mosques, madrasahs, tombs, soup kitchens, hospitals, waterways, bridges, caravanserais, palaces, cellars and baths (Benian, 2011).

During the Ottoman period, many buildings with different typologies were built to meet the needs of the society. However, mosques, which are an indicator of the economic power of the state, as well as other types of buildings, came to the fore at that time. When the Ottoman mosques are examined, there is a development process in terms of architecture. It is seen that this process has reached its climax with the contributions of Architect Sinan. Sinan, who lived during the heyday of the Ottoman Empire in the 16th century, is the greatest master builder of Ottoman art (Benian, 2011). In the "agricultural order" architecture, where there are very limited conditions compared to today's technical possibilities, Sinan has become universal with his masterful solutions to the dome architecture and has made a great contribution to architecture (Benian, 2011).

The main building element used by Sinan, who built mosques in different parts of the empire, is the dome. Other structural elements are dome transition elements (pendentive, squinch), arches and load-bearing walls. The dome, which is the main element that also determines the plan in his mosques, is both a load-bearing element and an architecturl element that dominates the outer of the building. The dome, located at the central point of the building, which also determines the urban silhouette of the cities in which it is located, is also an image in Sinan mosques (Erarslan, 2020). In his mosques, which are an important part of the architectural landscape, Sinan gave a new identity to the domed building tradition and developed an architectural style (Özer, 1987). It can be said that the domed structure has matured and gained a new meaning in the hands of Sinan.

The dome, which is a structural and symbolic cover, is the main architectural element in Sinan's buildings. The dome compositions that Sinan used in his mosques, where he made various experiments, are at the same time a form of space and mass (Necipoğlu, 2005). The homogeneity and formal simplicity of the dome contribute to the basic volumetric effect of space in his structures (Kuban, 1988).

In his mosques, Architect Sinan used dome variations of different scales and places of use. Each mosque, which has different structure and functional uses, has handled the dome and therefore the space differently (Erarslan, 2020). In this system, the dome was handled with a formalist attitude, which also determines the plan. Structural principles predominate in this design (Erzen, 1988).

The core of the space in Sinan mosques consists of a domed baldachin. Baldachin space is a space setup formed by the dome covering the space, sitting on different numbers and variety of bearing sitting on different numbers and variety of bearing. The plan and space developed around the baldachin. Architect Sinan made many different structural experiments in mosques. He used multiple support systems such as four, six and eight supports in the dome system (Erarslan, 2020).

Similar studies in the literature are presented below:

Tuluk, 2006; the study includes the 15th century and 17th century where the domed middle space is expanding to the sides of the domed midwear in his article "Variations on The Square Based Baldachin Ottoman Mosques for The Concept of Space (15th and 17th Centuries)". At these historical intervals, he has created the plan schemes that encompass the square based baldachin. He categorized part of the structures that the main dome is partially on the wall and representing the passage of the baldachin.

Bilgin, 2006; "Structural Analysis of Domed Roof Systems in Architect Sinan’s Works " has analyzed the dome of Architect Sinan mosques supported by the quadrilateral, hexagonal and octagonal support system under their self-weights with the "SAP2000" structural analysis program based on finite elements method. All models were established for above the levels where the arches are seated in the columns. The reason for this is to prevent confusion that may occur. As a result of the solution, he determined the mutual structural interaction of the main dome, the arch, half dome and pendants and revise the structural behavior of each system numerically.

Alioğlu and Köroğlu, 2010; “Modular System in Mimar Sinan’s Mosques” in their study examined the relationship between the modular system and the mosque load-bearing system. The modular system was addressed from the architect Sinan period mosques, the Square Baldachin Scheme (Üsküdar Mihrimah Sultan, Süleymaniye and Kılıç Ali Pasha Mosque) and the presence of the modular system was questioned as a result of analytical studies.

Erarslan, 2018; it has examined the relationships between the load-bearing form, covering and spatial aspects of Architect Sinan’s hexagonal baldachin system, as seen in the main spaces and adjacent areas of his Beşiktaş Sinan Pasha, Topkapı Kara Ahmet Pasha, Babaeski Semiz Ali Pasha, Fındıklı Molla Çelebi, Kazasker Ivaz Efendi, Kadırga Sokullu Mehmet Pasha and Üsküdar (Nurbanu) Atik Valide mosques in the article “The Support, Cover and Spatial Relationship in the Architect Sinan’s Mosques with the Hexagonal Baldachin System”.

Erarslan, 2020; five mosques of Architect Sinan’s square baldachin, single-dome mosques (Edirnekapı Mihrimah Sultan, Eyüp Zal Mahmut Pasha, Lüleburgaz, Sokullu Mehmet Pasha, Fatih Bali Pasha and Manisa Muradiye) has been selected in his article “Different Space Organization in The Square Baldachin Single-Domed Mosques Of Architect Sinan”. It is in an effort to offer an analysis on the organization of the domed principal and auxiliary spaces in these structures.

This article investigates the use of the square, hexagonal and octagonal supported support systems and dome systems applied in Architect Sinan's mosques. As sample structures, Süleymaniye, Kadırga Sokullu Mehmet Pasha and Selimiye mosques were discussed, which is connected to the square, hexagonal and octagonal supported support systems.

2. Material and Method

2.1. The Dome System

The dome is achieved by spinning around the symmetry axis of a vault. The elements carrying the forces on positive double curvature surfaces are shells. The squinch, pendant and turkish triangle are the most common forms used as a transition element in the domed space cover.

The load of the dome transfers the vertical components of the support loads to the vault through the dome legs. The lateral components of the domes are taken with half vaults or buttresses placed in steep direction to the vault plane. The impulses in the vault plane of vertical loads are taken with tenters (Mahrebel, 2006).

In general, domes have static features of the arch. Dome requires a continuous bearing surface element in their support. Therefore, the dome is required to sit in a circular support. In the circular planned structures, it is possible to communicate the loads from the dome to the flat walls, to ensure the passage of the circle with the passage elements. These are pendant, squinch and turkish triangles (Armağan, 2012). The dome and passage elements are shown in Figure 1.

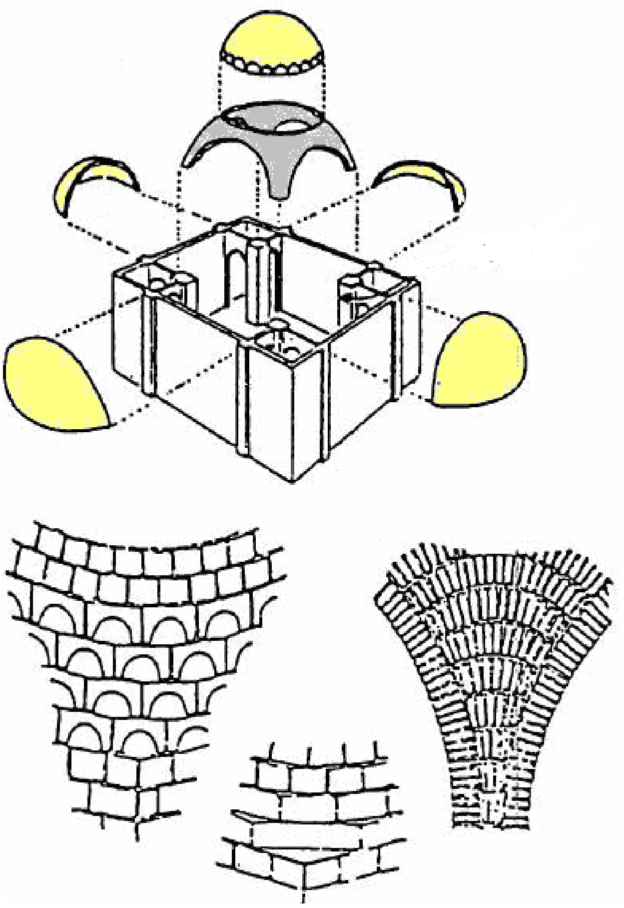

Figure 1. Dome detail with passage elements (Kara, 2009)

Dome is various in terms of construction. It is made as single section and double section. As a static calculation, a sphere from the wall resting on the tambour is part of it. Like walls, domes also show strength under compression. The construction technique is based on the assumption that the dome wall will remain under constant compression. The wall part where the dome sits is called the tambour. The tambour is an important element that maintains the compression of the wall (Kara, 2009).

The load of the dome is transmitted from the dome legs to the arches resting on the vertical legs. The dome legs transmit the vertical components of the support loads to the arches. It transmits the lateral components to the semi-domes and buttresses placed perpendicular to the arch planes. The thrust forces caused by the loads transmitted to the arches from the dome in the arch plane can be taken with tensioners, as well as they are dropped into the core area of the legs by means of weight masses used as extensions of the legs (Kara, 2009). The load distribution of a dome is shown in Figure 2.

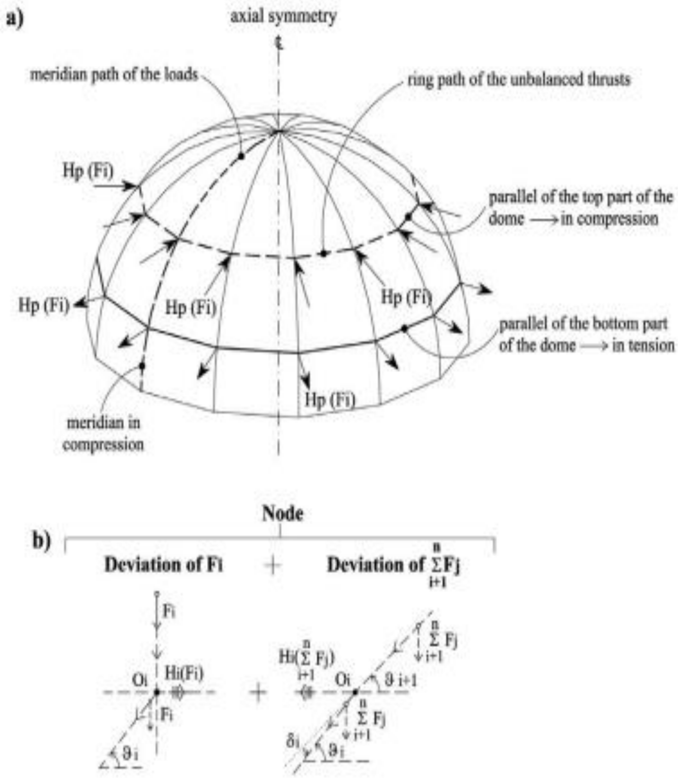

Figure 2. The load distribution in a dome (Palmisano, 2013)

The most important problem of domes is to support the inclined support forces that occur on their circular supports. At the supports, the force vector from the dome creates shear stress in horizontal. Horizontal shear force on tambour length creates tension force. The existence of tensile forces causes creep problem in the tambour. The greater the angle that the dome support force vector makes with the vertical, the more difficult it is to generate the stabilizing reaction force. The dome is directed to the direction of the support force vector, by using vertical gravity towers or by making supports and it is located in the building bearing plan (Armağan, 2012).

The dome is a global space system in terms of structure. The center of gravity is a point in space. The vertical diaphragm frames carrying the dome do not pass through the center of gravity of the dome. Although the frequency and acceleration values of building earthquake vibrations are the same as the dome at the beginning, they immediately change after the second period of the earthquake. The variation of earthquake structure frequency and acceleration values in the dome causes torsion (Armağan, 2012).

2.2. Sinan's Dome Technique

In Ottoman mosque architecture, the dome was accepted as the criterion of design, and at the same time, it was the starting point that directed the shaping of the building. In this context, it can be said that domes played the biggest role in the design of monumental mosques. In this regard, Architect Sinan was able to produce solutions that would leave the previous examples behind and make him reach his greatest desire. Thus, it has succeeded in bringing unique works to the history of world architecture (Benian, 2011).

Architect Sinan tried some formal arrangements in a way that would not spoil the geometric purity of the spherical half dome, and continued his work by increasing the aesthetic quality of these trials throughout his life. In his architecture, the dome formed the center of gravity of the structure, and the building structure was shaped in line with the support of the dome. The dome, which is the dominant element of the building, especially in monumental mosques, was not detached from the structure, but integrated with the building (Benian, 2011).

Considering the superstructure of Sinan's buildings centered around the main dome, the loads of the dome can be defined by passing through the various structural levels by means of supporting elements and auxiliary elements at the lower level. In addition, the support structural system from which the forces from the dome are transmitted can be explained. Sinan used three types dome support system in his works: square, hexagonal and octagonal (Bilgin, 2006).

Sinan used the dome in mosques, madrasas, baths and tombs structures with different construction techniques. This structural element carries its loads with the help of internal forces that spread uniformly throughout its thickness and act parallel to the average surface. Nowaday, it can be calculated theoretically and numerically the effect of loads on the dome and the internal forces with the help of shell theory (Bilgin, 2006).

The ratio of the dome height to its circular diameter is called flatness. The angle of the support force vector with the vertical increases as the flatness ratio decreases and the horizontal load value increases. As the flatness increases, the dome load increases and the angle of the force vector with the vertical decreases. In addition, the horizontal support load value decreases. Sinan's domes are among the flattest domes in history (Armağan, 2012). the dome flatness rates of Sinan structures are given in Table 1. In general, the dome flatness ratio of the Sinan period buildings varies between 0.30 and 0.448 (Çamlıbel, 1998). However, the dome flatness ratio in the mosque structure of the Haseki Complex, which is Sinan's first work in Istanbul, is around 0.480 (Şahin, 2021).

Sinan made structural changes to the dome tambour. The masonry of the dome walls starts with arches on the tambour. One-third of the dome wall height has turned into a tambour. The tambour is built as a zero joint stone wall. A separate load-bearing system is formed on the tambour. The plates form formed from one third of the height is in the form of a continuation of the dome wall. The tambour has been enlarged and raised. Forming the leg part in the form of the wall of the dome is important for the transfer of vertical and horizontal loads to the substrate. The leg part was the continuation of the dome. However, the vault system in its structure is for carrying the torsional moment. Torsions in the dome create horizontal shear stresses on the walls close to the tambour. Shear stresses create permanent deformations in the wall of the dome. Permanent deformations cause dispersion in recurrent loads. The flexible structure of the vault system is made to prevent permanent deformations in the repeated effects of torsion (Armağan, 2012).

Table 1. The dome flatness rates in some structures belonging to Architect Sinan (Çamlıbel, 1998; Şahin, 2021)

Structure	The Dome Flatness Ratio
Süleymaniye Mosque	0.347
Üsküdar Mihrimah Mosque	0.385
Edirnekapı Mihrimah Mosque	0.333
Şehzade Mosque	0.366
Azapkapı Sokullu Mehmet Pasha Mosque	0.342
Edirne Selimiye Mosque	0.327
Haseki Sultan Mosque	0.480

3. Structural and Geometric Features of Architect Sinan Mosques

3.1. Square Support System: Süleymaniye Mosque

Architect Sinan built Süleymaniye Mosque in the name of Suleyman the Magnificent between 1550 and 1557. In this structure, he tried the dome and two half-domed plan scheme applied in Beyazıt Mosque. In Süleymaniye, he succeeded in creating a stronger interior place effect by using the technology of his age. Examining Hagia Sophia and Bayezid Mosque, Sinan sought the most suitable ratios for his new work. At the same time, the interior space and exterior mass effect were considered together. In Süleymaniye, the large dome was supported by two semi-domes in the direction of the entrance and the mihrab, resting on four large load-bearing pillars, and the half-domes were enlarged with two quarter-domes. The side sections were also covered with five domes, but instead of the monotony of equal domes, one big and one small dome created a different effect. Therefore, the dome in the middle is kept the same width as the domes in the corners, and the side sections are combined with the interior place (Benian, 2011). The dome of Süleymaniye mosque is showed in Figure 3. The plan schemes of the Süleymaniye mosque are given in Figure 4.

Figure 3. View of the dome of Süleymaniye mosque (Benian, 2011)

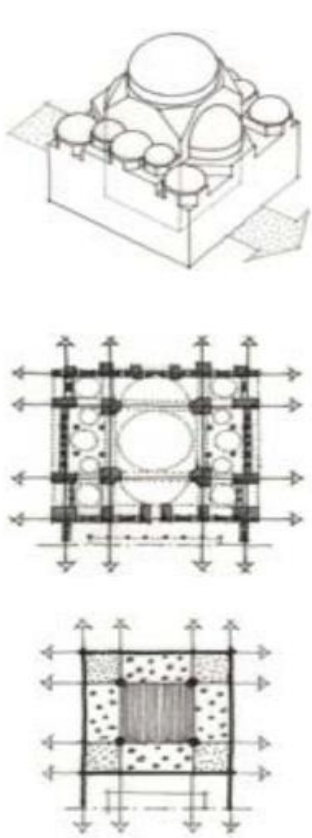

Figure 4. The plan schemes of the Süleymaniye mosque (Tuluk, 2006)

Süleymaniye Mosque is one of the buildings with the most advanced types of baldachin variations, with the middle space expanding to four directions and the corner spaces joining the main space. The finite element model of the mosque is indicated in Figure 5. The geometric properties of domed roof systems of Süleymaniye mosque, which has a square-supported support system, are given in Table 2.

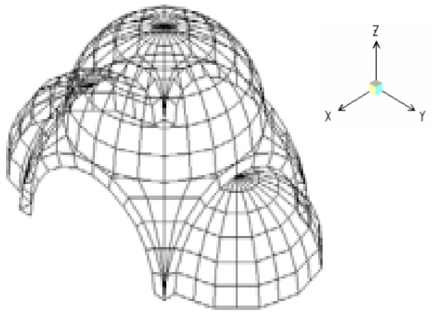

Figure 5. Finite element model in a square-supported support (Bilgin, 2006)

Table 2. Geometric features of domed roof systems supported with square support system in Süleymaniye mosque (Çamlıbel, 1998)

Main Dome Diameter (m)	**Vault Thickness/ Without Semi-Dome (m)**	**Vault Thickness/ Semi-Domed (m)**	**Average Main Dome Thickness (m)**
26.0	3.95	2.65	0.60

3.2. Hexagonal Support System: Kadırga Sokullu Mehmet Pasha Mosque

Architect Sinan applied a different structure program in the hexagonal baldachin in the Grand Vizier Sokullu Mehmet Pasha Mosque, one of the important grand viziers of the Kanuni Period, in Kadırga. The structure is the most mature of Sinan's hexagonal experiments and the mosque was built near the palaces of Sokullu in Kadırga. The building, which was built on the ruins of the famous Byzantine Great Palace in 1571, is on a hill extending in the east-west direction. It is also located on a hilly land in the oldest center of the city. In the complex, which consists of a mosque, a madrasa and a lodge, Sinan placed the complex structures at different levels by using the terracing method, which is the most effective method he applied in terms of urban space organization in the problematic land. The building, which shows Sinan's mastery in establishing the building-land relationship, has a perfect spatial integrity in terms of hexagonal domed design. The hexagonal system in the prayer area (harim) of the rectangular planned structure that develops transversely is completely integrated with the volume (Kuban, 2007). Sinan builds the hexagonal substructure in the building with six pillars that he connects with the walls in all directions. The plan scheme of the mosque is given in Figure 6.

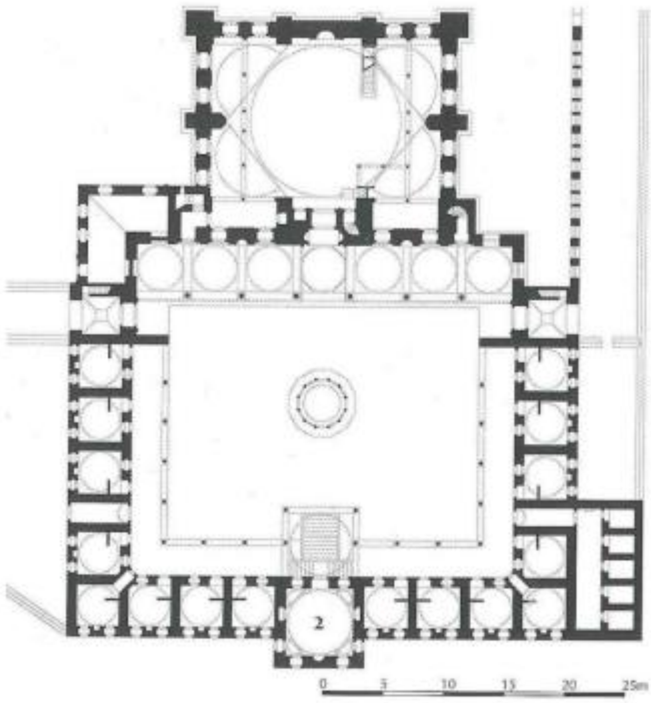

Figure 6. Plan scheme of Kadırga Sokullu Mehmet Pasha Mosque (Kuban, 2007)

The pillars are polygonal on the side walls and the qibla and the entrance are rectangular. The two side pillars on which the 13-meter-diameter and 22.80-meter-high dome sits are outside and protrudes into buttresses (Binan, 2016). Thus, the load-bearing system divides the walls of the building in all directions into three surfaces. The supporting pillars are connected to each other by exedra with windows inside and muqarnas. The middle volume formed under the dome is expanded to the sides by two-storey, narrow, low, high floor and flat ceilinged side galleries (Necipoğlu, 2005). These side mahfils, which provide a homogeneous spatial integrity with the main space, are placed in the depth of the exedra. The ratio and harmony in all elements and units of the building strengthen the spatial and create a balanced and strong central spatial effect.

The finite element model of the mosque is showed in Figure 7. The geometric properties of domed roof systems of Kadırga Sokullu Mehmet Pasha mosque, which has a hexagonal-supported support system, are given in Table 3.

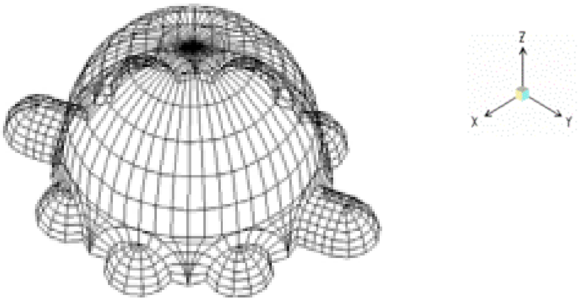

Figure 7. Finite element model in a hexagonal-supported support (Bilgin, 2006)

Table 3. Geometric features of domed roof systems supported with hexagonal support system in Kadırga Sokullu Mehmet Pasha mosque (Çamlıbel, 1998)

Main Dome Diameter (m)	**Vault Thickness/ Without Semi-Dome (m)**	**Vault Thickness/ Semi-Domed (m)**	**Average Main Dome Thickness (m)**
20.60	1.60	1.60	0.45

3.3. Octagonal Support System: Edirne Selimiye Mosque

The octagonal experience of Architect Sinan reached its zenith with the Selimiye Mosque in Edirne, which is considered the masterpiece of the Ottoman Empire and himself. Edirne Selimiye Mosque is the work of Sinan, in which he fully achieved his goal and his desire became reality. Selimiye, which was built between 1568 and 1575 during Sultan Selim II, stands out as an example where the unity of spatial under the dome was completely dissolved. The dome view of Selimiye mosque is shown in Figure 8.

Figure 8. Dome of Edirne Selimiye mosque (Benian, 2011)

In this structure, Sinan succeeded in gathering the congregation under the same dome and crossing a large opening with a single dome. The plan scheme of the mosque includes almost all geometric forms, unlike all the mosque plan schemes we have seen (Figure 9). The dome, which is approximately 43 meters above the ground and 31.5 meters in diameter, was transported with 8 big pillars. An even larger space was created with four exedra oriented towards the corners of the building. The rectangular scheme of the main space on the ground is provided by the lower level mahfil. At the level where the mahfils end, the plan has been transformed into a square. A smooth transition from square to octagon is ensured while preparing the round dome drum with exedra. The circle of the dome drum has reached the zero point with the dome with a diameter of 31.5 meters covering it. Architect Sinan also saved the building from monotony by moving the large dome onto a mobile body, whose change from rectangular to round is provided by smooth transitions, instead of placing it on four cubical inert walls (Benian, 2011).

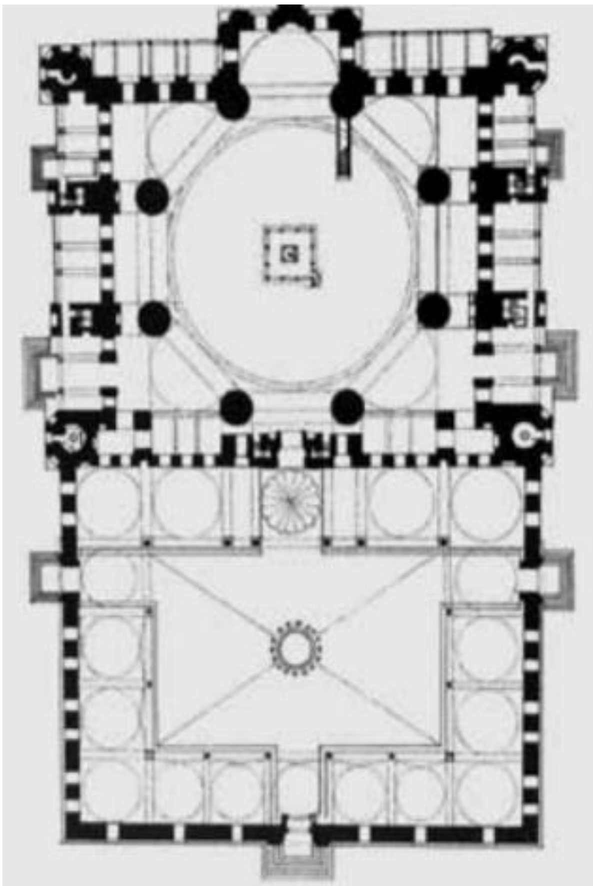

Figure 9. Plan scheme of Edirne Selimiye Mosque (Kuban, 2007)

The gradual rise of all structural elements from the ground to the main dome provides mobility inside the building as well as outside. In addition, the difference in size between the main dome and the semi-domes supporting this dome draws attention to the single dome both inside and outside the building. The minarets placed on the four corners of the main dome and the weight towers on the eight corners also have a great share in this impression (Benian, 2011).

The finite element model of Edirne Selimiye mosque is showed in Figure 10. The geometric properties of domed roof systems of the mosque, which has a octagonal-supported support system, are given in Table 4.

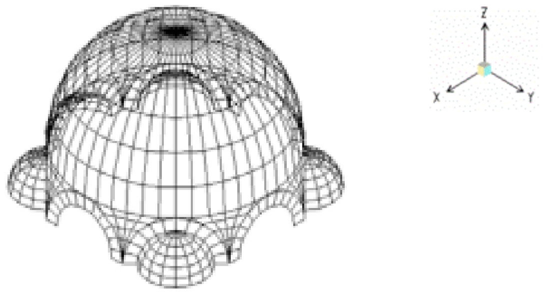

Figure 10. Finite element model in a octagonal-supported support (Bilgin, 2006)

Table 4. Geometric features of domed roof systems supported with octagonal support system in Edirne Selimiye mosque (Çamlıbel, 1998)

Main Dome Diameter (m)	**Vault Thickness/ Without Semi-Dome (m)**	**Vault Thickness/ Semi-Domed (m)**	**Average Main Dome Thickness (m)**
31.50	2.35	2.35	0.60

4. Conclusions

Architect Sinan, who uses the same elements in every building but makes different experiments, shows this feature both in the baldachin setup and the side space organization around it. The search for new forms created by Sinan with existing architectural elements has always continued. It manifests itself in the balance structures between the spatial setup and the main structure, cover elements and mass organization. The relationship between bearing system, cover, main space and side space is designed in harmony in all of his buildings and represents Sinan's creativity.

Sinan's architecture is not a creation out of nothing, on the contrary, the competence and creativity in bringing the existing together astounds. He constructs different constructs in every structure of his observations and experiences. This is especially evident in the octagonal support system dome composition.

The most important physiognomic element used by Sinan, who created a new urban environment with his buildings, to achieve this goal is the domes. He brought new visual dimensions to Turkish mosques and cities with the "Sinan’s idea" that the buildings created with the understanding of plan and mass.

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