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The Space-Structure Relation in Sinan's Works

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ABSTRACT: Sinan is one of the outstanding architects of the Islamic world. He is focused on centralizing the space of such structures of the mosques and tombs. As a tireless researcher he began from a square based dome added half domes to it. Later he tried hexagonal based dome several times improving the scheme. Passing into octagonal based dome he managed to create the magnificent Selimiye. This scheme gave him confidence to surpass St. Sofia. In his time the masonry system transformed as if into a carcass system. Domes, semi-domes, arches, piers and buttresses turned into a space element slipping off a rough member of bearing. The reflection of the buttresses that supporting the piers, brought a new appearance to the elevation of the mosques. While assembling the spaces into a pyramidal shape he changed the silhouette and

1 INTRODUCTION

Sinan was an architect whose name came to represent the essence of Ottoman architecture at the 16^{th} century when the Ottoman Empire was at its zenith, both in terms of political power and artistic production.

According to the sources available on Sinan's works, he built 477 buildings. It may perhaps be safer to say that these works were built or renovated during his lifetime. A study of the life of Sinan reveals the story of a true creator, never satisfied with his achievements, constantly in search of new ideas and restlessly trying out innovative features. Sinan was already a mature person when he was appointed Chief Architect in his mid-forties, yet he was still to live through some fifty years of creative adventures, leading Turkish architecture to new heights.

2 THE SPACE-STRUCTURE RELATION IN SINAN'S WORKS

As he designed domes and semi-domes to cover buildings with structures ranging from his initially basic square to the later hexagonal and octagonal ones, Sinan had to deal with structural problems related to the size of the space involved. With dome diameters ranging from 10 to 30 metres, such structures were directly related with problems of spatial organisation. Let us then study the relation between space and structure in some of the important works that contributed to the process leading to the construction of the Edirne Selimiye Mosque.

2.1 The Süleymaniye

In terms of space and structure, this is certainly Sinan's most complex building following the scheme of Saint Sophia. Much of this complexity was no doubt inherited from Saint Sophia. Still, with some thousand years separating the two works, Sinan seems to have sorted out quite a number of problems. The problem caused by the longitudinal effect of the basilica appears to have been diminished with the easier passage to the aisles made possible by the arches. The side naves also receive more light, thanks to the numerous rows of window openings, which also enhances this passage. The dome, which is 26 m in diameter, rests through the mediation of pendentives on four gigantic arches that have a 23 m span, their size reaching 2.65 x 1.80 m at the front and back of the dome and 5.60 x 2.90 m on the sides. Different cross-sections of these suspended arches serve to counterbalance the different thrusts created. On the two sides that have no semi-domes, the arches are filled in with very thin (100 cm) curtain walls, pierced with windows, thus increasing transparency effect.

The gigantic props we see in the section view support the 23 m high pillars are very skilfully hidden within the side nave. The distribution of the other loads is achieved through the semi-domes and the exedras. Indentations and slants give a finer appearance to the main pillars, which measure 7.20 x 7.20 m in width. Seen from the outside, the building appears to be contained within a pyramid lying on four walls. The spreading out effect achieved from the main dome down to the bottom through semi-domes, cupolas and graded buttresses serves not only to diffuse the burden but also to rest the eye. Towards the kiblah, the semi-dome supports the dome while the buttresses protruding from the mihrab façade in turn support the semi-dome. On the entrance side, the semi-dome rests on pillars that remain inside the mosque, with the muezzin loges very skilfully nested between them. Fig.1.

In the Süleymaniye, as had been the case in the Şehzade, Sinan manages to conceal the external buttresses with external sofas or halls, giving the façade a human dimension. Indeed, together with the columns, arches, windows and eaves, they give the visitor the impression of the veranda of some traditional house. The final balance is achieved through the manipulation of the size of the suspended arches. Both the dome and the suspended arches are designed to resist the effects of earthquakes (Çamlıbel 1998).

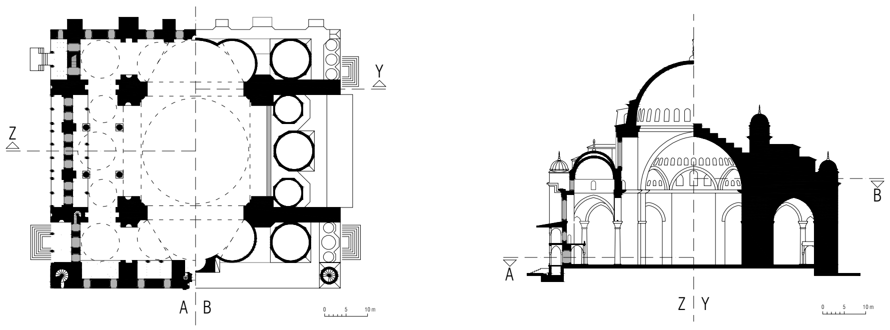

Figure 1 : The Süleymaniye Mosque. Plan and section.

2.2 The Molla Çelebi and Kadırga Sokollu

The barest or most uncluttered implementation of the hexagonal structure is the Kadırga Sokollu. Fig.3. The Molla Çelebi, on the other hand, constitutes an important stage in Sinan's experimental journey, see Fig.2.

In the Molla Çelebi, the structure is as bare as the space. In the hexagonal model, the span of the arches that support the dome is smaller than in the square model, which ensures more stability and security. Two of the six arches that support the 12 m wide dome rest on the walls erected on both sides of the mihrab, two on the buttresses hidden in each of the sidewalls and two on the props that stand independent along the entrance façade. As one enters the mosque, the bareness of the structure creates a powerful effect of clear open space. The salient mihrab helps to counter the load pressure bearing in its direction, while the reduced size of the supporting elements help reduce the construction costs.

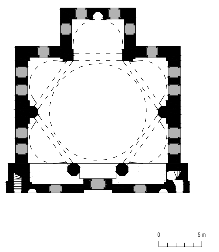

Figure 2 : Molla Çelebi Mosque

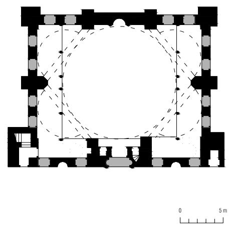

Figure 3 : Kadırga Sokollu Mosque

2.3 The Edirnekapı Mihrimah

Sinan's return to the square based dome was to be magnificent. As you enter the mosque's interior, you are wrapped with the bareness of the four arches that support the dome. Windows pierce the walls that are supposed to fill the space inside the arches, giving them a lacework appearance rather than that of a solid wall. The 19 m wide dome seems to rise from the pointed extremities of its four sustaining pendentives. This luminous crystal-like interior is as bewildering as impressive. You feel as if you were standing under a slender concrete shell. The ease with which the pendentives ensure the visual transition from the dome to the square supporting structure certainly plays an important role in obtaining this impression. In hexagonal and octagonal plans, the semi-domes and the squinches do not achieve the same smoothness. The effect of the four gigantic suspended arches is moreover truly splendid. In hexagonal and octagonal structures, the arches are quite reduced in dimension and their impact diminishes in the same measure. Indeed, it seems the reduced arches sacrifice themselves in order to enhance the dome. In the Mihrimah, the walls inside the arches are now reduced to screens. Because they are situated closer towards the interior side of the arches, the thickness of the arches (3.60 and 4.30 m) is not noticeable from the inside. The dimensions of the arches are 3.60 x 2.40 m in the kiblah direction and 4.20 x 2.40 m in the opposite direction.

At the lower level, Sinan has added naves on both sides, thus widening the interior space while strengthening the lateral supporting structure. The supporting pillars reach the external corners of the mosque and are thus not noticed from the interior. Fig.4.

The audacious plan has its weak points however. The dome collapsed twice during the 1719 and 1894 earthquakes, when the whole building was seriously damaged. Çamlıbel has calculated that an earthquake would affect the stability of the suspended arches (Çamlıbel 1998). The crack on the arch situated near the mihrab can still be seen today. The arch on the entrance side must have suffered even greater damage if we consider that it has been reinforced with two extra props. This audacious design constitutes a step forward in the square plan concept Sinan had already so much experimented with. His previous experiences must have made him hope he would succeed with this design and encouraged him to take the risk. In designing the Selimiye, he would prefer to use the safer octagonal structure, with which he felt more comfortable.

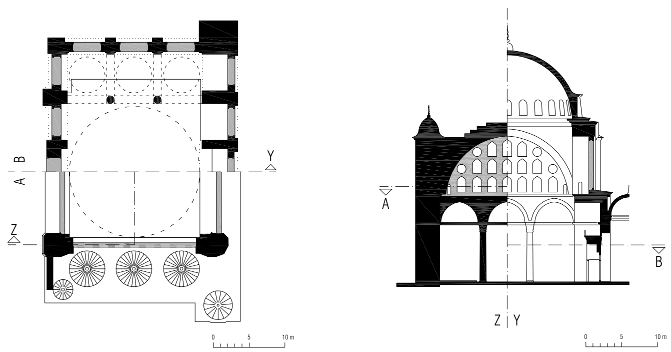

Figure 4 : The Edirnekapı Mihrimah Mosque. Plan and section.

2.3.1 The Selimiye

The main objective in the Selimiye is an uncluttered bare interior space. From the first stage of the designing process, the obsession with Saint Sophia seems to be overcome. We can gather that with his empirical knowledge of structure and the rich experience he had gathered Sinan was ready to create new sustaining structures. After his Edirnekapı Mihrimah adventure, he chose the more reliable octagonal system for the Edirne Selimiye. As we have seen, in the octagonal plan, the arch spans are reduced. Moreover, the increased number of props also reinforces the building's resistance to potential earthquakes. In short, a dome supported by eight props is much safer than one sustained by four props, see Fig.5.

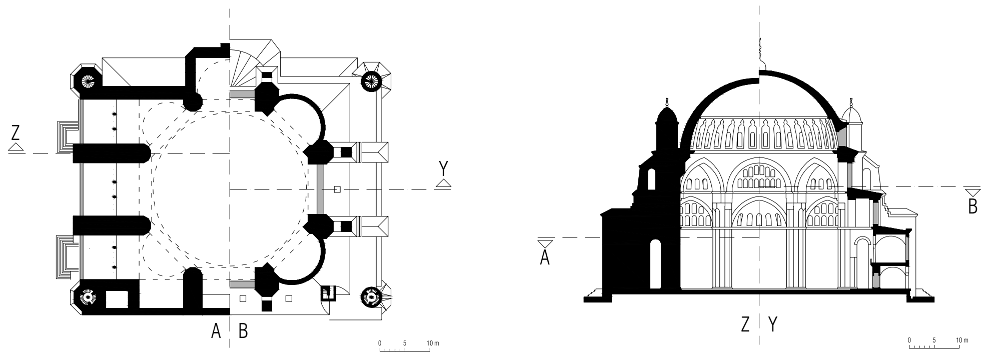

Figure 5 : The Selimiye Mosque. Plan and section.

The octagonal frame rests on the sidewalls surrounding the mihrab on the kiblah front, on the two other fronts on large buttresses (4 x 16 m together with the pillars) and large pillars on the entrance front. It is held laterally at two levels by arches. Walls or buttresses thus support the main pillars. The minarets, situated on four corners of the mosque, can be said to anchor the system to the ground with their weight. Each bearing element has its own logic function but maintains a balanced relation with the others. Here none of the elements gain sufficient importance to enter in competition with the dome, as would be the case with suspended arches in a square based system, so that it is left to dominate the whole interior space. Finally, the light penetrating from eight sides defines the visual balance of the space.

Seen from the exterior, the building takes the appearance of pyramidal structure resting on the main walls, but here these walls rise before us with a simple elegance, divided by buttresses and small arches, and pierced with windows at regular distance. Thanks to the octagonal structure, the size of the elements can be kept smaller and the proportions more humane than in the Süleymaniye. The alternate tones of the reddish arches and props create a warm atmosphere. With their recessed lower walls, the façades seems to rise over some sort of cloud. Thus, the relieved mass, with the minarets on its four corners, seems to hang from the sky.

3 THE BEARING SYSTEM

The most important bearing systems were developed in the mosques involving the widest spans. The bearing system is inseparable from the interior space. Designing the space implies conceiving how it will be structured and how it will be covered. In Sinan's mosques, the bearing system is particularly clear and rational. The outer shell and the interior space reflect each other. The bearing elements do not turn into meaningless forms on the outer façade, neither are they used for mere decoration. Sinan of course used forms from buildings erected before him, but he managed to develop new compositions and variations out of these elements. Domes, semi-domes and squinches usually cover the interior space. At times, mirror, but also cloister, trough and cross vaults are used.

3.1 The Dome

The dome is the uppermost element. It is a portion of a sphere ending with a circular base, which is usually placed over a cylindrical drum. In order to counterbalance the lateral thrust exercised by the dome, the thickness of the drum is slightly greater than that of the dome. Lateral stress is also transferred downwards through exterior props that often take the shape of buttressed arches. This also contributes to the visual integration of the dome with the lower part of the building. Most often, the drum is visible from the exterior is not noticeable from the interior, where it is integrated to the slope of the dome. It is also pierced all around with apertures, which, except in small mosques, form a quasi-rhythmic sequence of filled and open windows. The higher the number of dome bearing elements, drum, pillars, props, arch buttresses and other transitional elements, the easier it will be to transfer horizontal loads to the lower part of the building. In the lower part, walls-pilasters-buttresses or arch-pillar-buttresses combinations transfer the load of the dome, semi-domes and vaults.

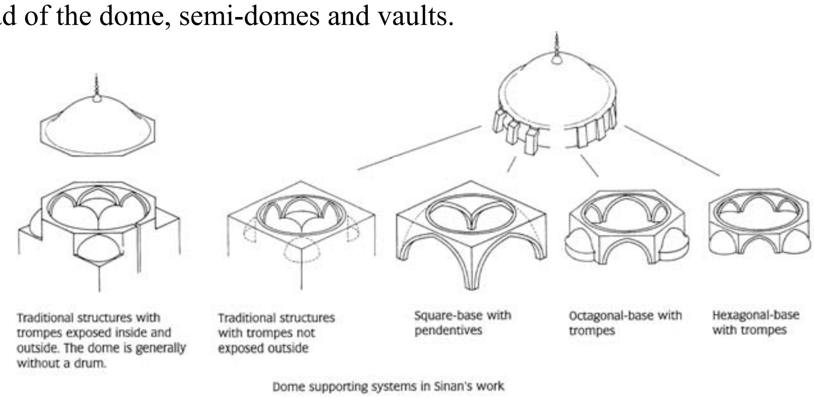

Figure 6 : Dome supporting systems in Sinan's works

As indicated in the below Table 1, the dome measures between 11 and 15 m in diameter in a majority of Sinan's mosques. The smaller dome height/dome diameter is, the more difficult it is to counterbalance the lateral stress it exercises. A shallow dome has thus always been considered as a sign of the architect's mastership, see Table 2.

Table 1 : Dome diameters in a few of Sinan's mosques

Mosque	Number of support elements	Dome diameter* (m)			
		Yorulmaz 1986	Çamlıbel 1998	Kuran 1986	Ülgen** 1989
Üsküdar Mihrimah	4	11.07	11.85	-	11.10
Kara Ahmet Paşa	6	12.00	11.80	-	12.90
Molla Çelebi	6	12.08	-	11.80	11.80
Kadırga Sokollu	6	12.76	12.70	13.00	13.30
Rüstem Paşa	8	15.54	14.80	15.20	15.65
Şehzade	4	18.42	19.50	-	-
Edirnekapı Mihri-mah	4	19.30	19.46	20.25	19.35
Süleymaniye	4	26.10	27.25	26.20	27.80
Edirne Selimiye	8	30.75	31.50	31.22	-

* Each source gives different figures for dome spans.

** Measurements are from the drawings.

The higher the dome is situated, the more difficult it is to transmit horizontal thrusts down the rest of the building, which will require thicker walls or larger props. Çamlıbel considers the compression zone of the dome - the part remaining above an angle of 103 degrees formed from a starting point situated at the centre of the dome base circumference – to be safe if this part of the dome is thick enough, see Table 3.

Table 2 : Dome depression in a few of Sinan's works

Building	Dome depression (Dome height/dome diameter)*
Ayasofya	0.290 - 0.310
Kılıç Ali Paşa	0.300
Hadım İbrahim Paşa	0.308
Zal Mahmut Paşa	0.312
Selimiye	0.327
Kara Ahmet Paşa	0.333
Edirnekapı Mihrimah	0.333
Azapkapı Sokollu	0.342
Süleymaniye	0.347
Şehzade	0.366
Üsküdar Mihrimah	0.385
Rüstem Paşa	0.387
Kadırga Sokollu	0.390
Küçük Ayasofya (Sergius-Bacchus)	0.423

* Data obtained from Çamlıbel 1998.

Table 3 : Spherical sector angles in some of Sinan's mosques *

Mosque	Spherical sector angles (degree)
Kılıç Ali Paşa	110
Selimiye	130
Süleymaniye	134
Şehzade	140
Üsküdar Mihrimah	142

*Data obtained from Çamlıbel 1998.

However, because the part of the dome below the angle thus formed remains within the tension zone, it will present a certain danger for the masonry (which may not be able to resist tensions), causing the appearance of radial cracks. In order to counteract this, the thickness of the support of the dome would be doubled compared to that of the top part, or surrounded by iron belts/rings in order to keep the dome base from spreading out. Some of these iron belts measured between 10-7 x 7-5 cm, passing above or across the windows, see Fig.7.

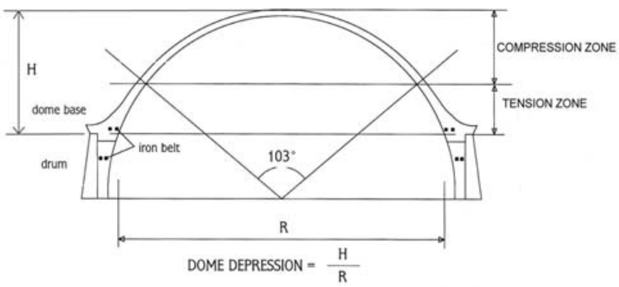

Figure 7 : Typical dome section showing compression and tension zones, and iron belts.

3.2 The Semi-dome

The semi-dome functions as a sheltering element but also as one of the dome bearing elements. Like the arches, pillars and other props, it transfers the lateral thrust of the dome towards the outer walls, the thickness of which is calculated so as to in turn transfer this load to the ground. As for the pillars, they can now be all the more slender since they practically only have vertical thrusts to bear.

3.2.1 Transitional Elements

The dome usually covers a square, sometimes a hexagonal or octagonal prism, see Fig. 6. The development of the polygon based dome plan in Islamic architecture owes much to Sinan (Kuban 1958). The transition from the square or polygonal structure to the dome circumference is provided through transitional elements. These elements will be either squinches or pendentives. Windows are placed at the bottom of the semi-domes and squinches. If the span is very wide, it is reinforced with iron beams.

In Sinan's works, this elaborate gradual rise from the external main walls up to the main dome is an important development which reinforces the relation between wall and dome from a structural point of view, and the link between prism and semi or quarter sphere from a visual point of view. On the exterior, the whole upper structure spreads out like a pyramid until it reaches the outer walls; from the main dome flanked with its flying buttresses, the top part of the arches supporting it - which are often graded (Süleymaniye, Edirnekapı Mihrimah, Lüleburgaz Sokollu) - and the stabilising turrets, down through the squinches and semi-domes, all the way to the cupolas capping the aisles and latecomers porch. This gradation has the effect of emphasising the dominance of the dome without exaggerating it. Prisms, cylinders, and semi and quarter spheres fuse together in harmonious rhythm and symmetry. Loads are easily distributed onto the ground, without tiring the eye or confusing the mind.

3.2.2 Suspended Arches

Suspended arches transfer the load they receive from the dome, pendentives and walls above them to vertical bearing elements below, see Table 4. We must consider them as forming a whole with their neighbouring walls. In Sinan's works, the dome lies on a prism formed by arches. The number of these arches can vary from four, six to eight. Some semi-domes and vaults seem to act like buttresses supporting the arches. Large arches have their bay filled in with a windowed wall, so that light can penetrate the interior. The Edirnekapı Mihrimah offers the most impressive example of the use of such windowed walls, followed by the Süleymaniye and the Selimiye. As the span of the arch increases so does its cross-section or soffit.

Table 4 : Span& voussoir sizes of suspended arches in a few mosques*

<table>
<tr><th rowspan="2">Mosque</th><th rowspan="2">Number of pillars</th><th colspan="3">Arch span (m)</th><th colspan="2">Arch voussoir sizes b x h (m)</th></tr>
<tr><th>Kiblah direction</th><th></th><th>Opposite direction</th><th>Kiblah direction</th><th>Opposite direction</th></tr>
<tr><td>Azapkapı Sokollu</td><td>8</td><td colspan="3">4.15</td><td colspan="2">0.80 x 1.17</td></tr>
<tr><td>Kara Ahmet Paşa</td><td>6</td><td colspan="3">5.15</td><td colspan="2">1.40 x 1.15</td></tr>
<tr><td>Rüstem Paşa</td><td>8</td><td>4.90</td><td>6.32</td><td>6.70</td><td colspan="2">1.65 x 1.55</td></tr>
<tr><td>Kadırga Sokollu</td><td>6</td><td colspan="3">7.02</td><td colspan="2">0.90 x 1.90</td></tr>
<tr><td>Üsküdar Mihrimah</td><td>4</td><td>9.40</td><td></td><td>9.40</td><td>1.60 x 1.80</td><td>1.60 x 1.80</td></tr>
<tr><td>Edirne Selimiye</td><td>8</td><td colspan="3">9.68</td><td colspan="2">2.35 x 2.60 - 3.87 X 2.60</td></tr>
<tr><td>Edirnekapı Mihrimah</td><td>4</td><td colspan="3">19.60</td><td>3.60 x 2.40</td><td>4.30 x 2.40</td></tr>
<tr><td>Şehzade</td><td>4</td><td>17.25</td><td></td><td>17.25</td><td>1.45 x 2.38</td><td>2.12 x 2.38</td></tr>
<tr><td>Süleymaniye</td><td>4</td><td>22.58</td><td></td><td>23.30</td><td>5.60 x 2.88</td><td>2.65 x 1.80</td></tr>
</table>

*Figures are taken from Çamlıbel 1998 and presented in table form.

In some cases, arches are interconnected with iron tie beams at springing line level. This compensates some of the thrust they bear, making it possible to diminish the size of their pillars. On the exterior of the building, arches are wilfully made particularly apparent, which rhythmically enhances the general modular system. Sinan mostly uses pointed arches in his works. These are double centred or double centred tangent arches, their centre situated at a distance corresponding to three fifths of their span at springing line level.

4 VERTICAL SUPPORT ELEMENTS

4.1 Walls and Supports (Buttresses)

Only in mosques with narrow spanned domes do we see Sinan use the walls alone to support the dome, and even here, the presence of arches can be traced on the inner wall surfaces. While the general bearing system consists of a masonry wall structure, the load distribution is quite clearly defined, from the covering elements downwards. This definition implies what may be called a "masonry carcass" system, in which the load of the dome is transmitted to the large arches rising from their pillars and from there to the pillars themselves as well as to other pilasters and buttresses. In many cases, such a system practically eliminates the need for bearing walls.

Especially where they serve to bear the arches, walls are reinforced by pilasters. Props can also be internal or external or situated on both sides, sometimes linked to each other by arches. Mihrab protrusions reinforce the pillars on which the arches are based, as do the external graded buttresses, which are more or less hidden within the galleries and porticoes. From the Şehzade onward, Sinan brilliantly manages to cloak the buttresses with the galleries and arcades he designs on the lateral façades (also on the mihrab façade in the Selimiye). In the Selimiye, the stairs too are situated inside the buttresses.

The walls erected within the bays of the arches or between the buttresses are usually pierced with numerous windows, their function being practically reduced to that of partition walls. Sinan was particularly skilful at composing the window layout between the arches. Such walls were also very skilfully used to hide the thickness of arches or buttresses.

4.2 Pillars and Columns

In Sinan's mosques, the suspended arches on which the dome rests are most often born by pillars. In order to bear the thrust of the suspended arches, these pillars must be both broad and heavy. For this purpose, they are prolonged way above the level of the arches, thus forming the stabilising turrets or weight towers, which increase the vertical (as opposed to the horizontal) pressure. In polygon based mosques especially, pillars that are close to a wall are reinforced by special arches linking them to the said wall, its pilasters or buttresses. As their numbers increases, pillars get slimmer. Only in a few buildings (The Kara Ahmet Paşa and Atik Valide mosques, and the Kanuni and Selim II tombs), are domes supported by columns. The larger polygon shaped pillars (7.5 x 7.5 m at the Süleymaniye) may be profiled or have their corners indented, or have a mihrab niche lodged into them, in order to be given a slenderer appearance.

5 CONCLUSIONS

Sinan beginning with a simple traditional dome, created complex dome structures in mosques. As the size and complexity rise he tried new structural supports with the harmony of architectural space.

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