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ANALYSIS OF DOUBLE SHELL DOMES IN IRANIAN ARCHITECTURE

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ABSTRACT

Dome in mosques has an indispensable relationship with other elements that gives meaning to the function and shape of Iranian mosques, but it includes solely secrets, said and unsaid materials that have put independently various issues in front of researchers. The research method of this paper has been a library method and collection tool has been articles published in scientific and research publications. This paper intends to review generalities on Iranian domes, structure of Iranian domes, double shell domes and brick domes and finally by the study of all these cases in the case sample (Sultaniye dome), it examines the form of the Sultaniye dome, one of the works remained since the Ilkhanid era in Zanjan, and tries to make clear the formation of its dome design by geometric analysis. Finally, it can be concluded that the dome as the identity of Iranian mosques has taken root in the people's beliefs.

Keywords: Arc, double shell, Sultaniye dome, structure

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Introduction

After arrival of Mongols in Iran and selection of Sultaniye as the capital city by the most powerful Ilkhanid king, the city flourished and enjoyed especial reputation. The building of Sultaniye was built during the reign of Öljaitü (Sultan Muhammad Hudabende) in 10 years. This building in the Southeast of Zanjan, in the current city of Sultaniye, is one of the most valuable mausoleums of the world. This building is considered as the world's third magnificent dome building (Hamzeloo 2009:33). It is one of the most beautiful and magnificent monuments of the Ilkhanid era, a dome that has been built by quite innovative forms with a zigzag (ogee) design. This dome is a continuous double shell dome so that the two shells are parallel to each other. It is the largest dome of the Iranian architecture and has been built without any buttresses or pinnacle or dragged. Double- shell system of the dome with two parallel and separated layers which are related to each other only by the brick buttresses between them, a dome that its inside is completely covered with various inscriptions which have been drawn by the paint on the plaster and include a single form are the exclusive properties of the Sultaniye dome. Accuracy and skill of the architects of the Sultaniye citadel can be seen in all parts of the building (Asgharyan Jeddi 2012:78). Only two brims of decorations can be seen in Sultaniye dome: the first brim is related to the original decorations of the dome and the second brim is concerned with stucco on the decorations, considering that hexagon tile has been used in the lower part of the dome (from the floor to 3m high) and both have been carried out simultaneously. Stucco on the original decorations belongs to the Safavid era (Ghouchani 2002:95). Stucco on the original decorations of the dome has been accomplished at the Öljaitü time itself. All over the internal and external façade of the building includes very beautiful and exquisite brick decorations, stucco, painting, inscriptions and murals, which tile work and tile and plaster inscriptions have been used mostly on the external façade and in its inside, mosaic faiences catch the eye in some porticos. Engravings and gildings can be seen on the building entrance (Hamzeloo 2009:49). The Sultaniye dome first has included four large and four small entrances, Eight sides of the building interior are in the ground floor in the form of eight porticos (four large and four small porticos) with eight minarets, and eight porticos themselves remind us eight paradise which pious doors of the building consist of three floors and three parts, dome chamber, tomb, cellar (Hamzehloo 2009:51), and this research aims at studying Sultaniye dome in terms of structure.

Definition of dome

The dome is a hemispherical or a concave roof, which is usually improvised on circular or square and polygon plans that gets circular with the help of the lug. The dome has a long history which its precedence and evolution is not well known. The dome is an approximately hemispherical construction which is built on an edifice by means of adobe, brick and plaster. For many years, the dome has been an outstanding element in introducing the architecture of this country. Selection of the oval shape instead of a hemispherical form for the underlying dome and use of lower shell has enabled western architectures to create a thin and light and airiness dome, also use of the tromp (which had been common in west previously) had made easier covering of large quadrangle spaces and no longer circularity of the context under the dome was not needed and finally Iranian dome building technique has brought us the method of shell covers in our age, so that previously such masterpieces as Saint-Pierre dome has been generated by Iranian fertile art (Stierlin 2012:123). The history of Architecture has always witnessed the presence of the dome for the cover of penthouses, sacred spaces such as prayer rooms and mosques, palaces and other public and private spaces. Up to now many researches have addressed to introduction, typology and analysis of structural and aesthetic features of the domes (Ashkan and Ahmad 2009:109). The dome and portico are two evident eras of Iranian architecture. The dome is a hemispherical or a concave roof, which are usually improvised on circular or square and polygon plans that get circular with the help of the lug. The dome has a long history which its precedence and evolution is not well known. Domed buildings of West which are perfectly known are significantly different from domed buildings of Iran (Stierlin 2012:234). The dome with traditional structure is one of the important and controversial issues in the field of restoration and consolidation, which different methods have been selected, designed and implemented on the part of architects and structural engineers for its retrofitting in each historical period. The form of the dome is created by the rotation of the vault arc around its symmetry axis. This cover has been used for large spans without column when there has been no suitable flat material with these dimensions. In the history of Iranian architecture, there are samples of the dome with materials of stone, adobe and brick (Muhammadi 2008:180). A hemispherical roof or one resulted from a semidome is called a dome which covers a building whatever it may be. This kind of construction, which is applied to the dome, can take on different forms. Sometimes it is called a semidome such as the circular building of Pantheon in Rome, sometimes it introduces a quasi-spherical flattened semi-circular such as Saint-Pierre dome of Rome; sometimes it demonstrates an almost flat half-round, in this case it is called a short crescent dome. Most of domes gain height on a circular plan, but other kinds of it which have polygon plans can also be seen (Zamani 2013:218).

Dome with pointed clover arch

One of these kinds of domes can be seen in İmamzade İsmail in Isfahan. The external diameter of the drawn dome equals with 17/10 m, its span is 14/50 m and its height to the foot is 9/10, Based on the single shell dome, its thickness has been considered 1/30 m (Muhammadi 2008:180).

Dome with blunt clover arch

Dome of the mosque of Yazd is one of these kinds of domes which have been implemented with blunt clover arch. The span of this dome is 14/50m, its external diameter is 1710m and its external height is 12/50. This dome has been analyzed with 640 elements and 641 nodes under the weight load, most of displacement is related to the dome's crown (Zamani 2013:223).

Dome with horseshoe arch

This kind of arch has been used mostly in pre-Islamic architecture works (in the vaults and domes), especially the works of the Sassanid era. This dome's span is 14/50m, considering its 1/30m thickness, its external diameter is 17/10m and its external height is 11/40m. With 360 elements and 361 nodes, under the weight load, most of displacement takes place in the dome's crown (Zamani 2013:225).

Dome with flat turnip arch

This kind of dome's span is 14/50m which, considering its 1/30m thickness, its external diameter is 17/10m and its external height is about 19/50m. With 450 elements and 451 nodes, this dome has been analyzed under the weight load and most of the displacement is related to the around of the dome's crown (Zamani 2013:227).

Dome with turnip arch

Shah Cheragh shrine of Shiraz is one of the buildings which have a dome with turnip arch. The span planned for this dome is 14/50m and its thickness is 1/30m, external diameter of the dome is 17/10m and its external height is about 19/50m, With 450 elements and 451 nodes, this dome has been analyzed under the weight load and most of the displacement is related to the around of the dome's crown (Zamani 2013:229).

Dome with pointed panj o haft arch

Attar of Nishapur tomb is one of the buildings which their domes have been built by means of this arch. The span of the modeled dome is 14/50m, external diameter of the dome is 17/10m and its external height is about 9/60m, With 360 elements and 361 nodes, this dome has been analyzed under the weight load which most of the displacement is around the dome's crown (Ashkan and Ahmad 2009:62)

Dome with broken blunt arch

The span planned for this dome is 14/50m and its thickness is 1/30m, thereby external diameter of the dome is 17/10m and its external height is about 9/50m, With 360 elements and 361 nodes, this dome has been analyzed under the weight load which most of the displacement is related to the crown (Ashkan and Ahmad 2009:68).

Structural system of Iranian domes

Iranian domes can be divided into single-shell, double-shell and triple-shell domes.

In domes, due to the vertical load on it which is transferred to the legs along the arch, twice ring forces are generated in the horizontal direction.

Background and objective of the double shell domes in Iran

Before construction of double shell domes of Timurid and Safavid eras, simple double shell domes had been built in different parts of Iran and perhaps their constructors aimed at the air flowing between the shells and protection of the internal shell against the moisture and prevention of premature deterioration (Pirnia and Memarian 2004:122).

The scene under the single shell dome of Sultaniye tomb, which is about 50m distant from the viewer, manifests itself better. Another shell has been built on the first shell and some air vents have been created in it to flow the air between two shells, then the internal shell remains safe and dry.

In double or triple shell domes, generally due to static reasons in the upper shell (head piece) and spatial sense, to reduce the height in the lower shell (parietal), each of the domes is built with a different arch. Most of the multifold domes have three separated shell (Pirnia and Memarian 2004:123).

High double shell dome

This dome, which in the form of discrete double shell has 10 , involves a 14/50m span and its height is about 18/40m, the thickness of the shells begins with 85cm and ends with 40cm in the crown, with 14320 elements and 6291 nodes, this dome has been analyzed under the weight load which most of the displacement in the crown of the outer shell (Mainstone 2001:138). In construction of double shell domes, decorative purposes and beauty seeking have been effective because:

Firstly, construction of this shell gives more grandeur to the building and grandeur is one of the important factors of beauty. This term describes a type of special strict beauty which is felt by organisms or objects that have the grandeur and glory and attraction, As beautiful feeling is linked with enchanting, grand feeling is also linked with sublime and great.

Secondly, curved lines of dome are graceful and pleasant and like vertical lines lead the view to upwards on one hand and like horizontal lines are comforting on the other hand. Of course, this feeling applies to the simple domes too, but in the decorative domes, the characteristics of colors strengthen lines character and give more pleasure to the viewer.

Thirdly, the outer cover of the dome is a good surface for artistic performance of the masters of brick cutting and tile work and muqarnas, writers of masonry and Naskh scripts and other decorative elements such as lattices, arabesques, flowers and ornamental plants induce better the feeling of beauty, and no decorative context can manifest motifs, scripts and other elements and can display them to the viewers better than domes.

Fourthly, the outer shell causes that the inner shell is located in lower height and increases its visibility, for example decorations under the double shell dome of the central hall of the Isfahan Shah Mosque which has 36m height manifest themselves more and better than the scene under the single shell Sultaniye dome which is about 50m distant from the viewer (Mainstone 2001:141).

Double shell domes have two separate shells and inner shell is mostly circular and outer shell is often circular, conical, pyramidal or oval. About the philosophy of putting two shells in the buildings also it has been said that, maybe to prevent moisture and rain and snow penetration to inner layer of the building, another shell with proper distance was placed.

Study of the behavior of brick domes

Although it seems that the theory of shell roofs is associated with reinforced concrete shells and is considered to be related to brick domes, but based on the stresses which are created in the brick domes and cause cracks in the lower part, can be concluded that the brick domes have bidirectional curvature cannot tolerate bending because they have been built with masonry material and they can only tolerate pressure. So a close connection between the functions of the brick domes forms and the theory of concrete shell roofs can be found (O' kane 2020).

Types of Iranian brick domes

Historical studies show that over the centuries, Iranian architects to achieve a stable structure, with knowledge about static issues of the dome and regarding three above conditions, by enjoying a variety of arches, have created a wide variety of the domes. Variation has been due to difference of historical periods, change of the spaces span, the manner of transportation from square to circle (corner- making), change of thickness and use of two inner and outer shells and which has moved in a historical trend towards optimizing the structure (Curatola and Scarcia 2007:54).

Ilkhanid architecture can be considered a continuation of Seljuk architecture, which has inherited some plans and techniques from it and it has not generated any new style in the architecture in term of aesthetics. Emphasizing on the vertical and not too heavy elements by the use of windows and construction of surfaces with the niches and shapes are some of the features of the architecture (Ardelan and Bakhtiyari 2000:119)

Sultaniye dome is one of the architectural works of the era. A dome that has been built by the perfectly initiative forms with a zigzag (ogee) design. This dome is a continuous double shell dome, So that the two shells are placed parallel to each other. The dome is the largest dome of Iranian architecture and has been built without any buttress, pinnacle or dragged. Double-layer system of the dome with two parallel and separated layers which are connected to each other only by brick buttresses and have a single form are unique characteristics of the Sultaniye dome (Figure 1.).

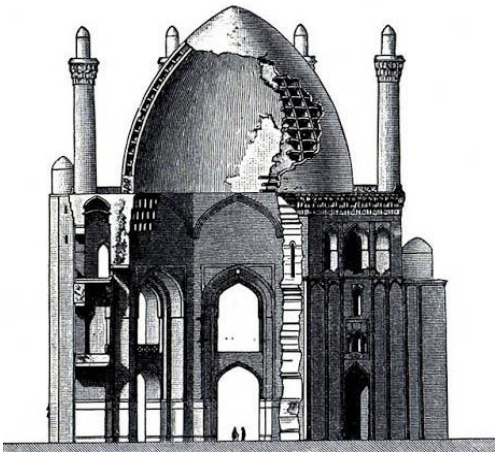

Figure 1. Sections of double shell Sultaniye dome (Vasseghi and et al. 2007:71)

Historical background of Sultaniye Dome

Sultaniye city has been taken into consideration from the earliest times including before the Mongol Ilkhanid era and archaeological evidences suggest that the Sultaniye plains had been inhabited since the fifth millennium BC and the pottery obtained from the Noor hill in the southeast of the old city of Sultaniye illuminates this fact (Figure 2.).

This kind of construction, which is applied to the dome, can take on different forms. Sometimes it is called a semidome such as the circular building of Pantheon in Rome; sometimes it introduces a quasi-spherical flattened semi-circular such as Saint-Pierre dome of Rome; sometimes it demonstrates an almost flat half-round, in this case it is called a short crescent dome. Most of domes gain height on a circular plan, but other kinds of it which have polygon plans can also be seen, some others have a quadrangular base (Ghouchani 2002:97).

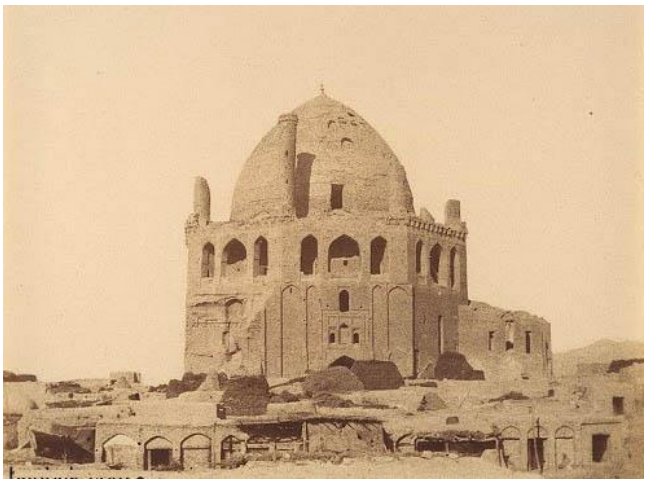

Figure 2. Old photo of the Sultaniye dome (Vasseghi and et al. 2007:54)

Sultaniye dome is a building full of emotion and spirituality that has turned into a symbol of the depth of Iranian culture in the history of the country. Although home styles and trends are clearly evident in the creation of this monument, it is not consistent with any of Iranian tombs before it in terms of the combination of space with the architecture and this issue results from the composition of very complex and labyrinthine cellars and existence of various cubic units that have no spatial connection with each other (Asgharyan Jeddi 2012:102). The dome of this monument, according to high knowledge in the field of implementation and proportions, observance of all angles and lines, architectural system, static and complete harmony with other structural elements of the Sultaniye complex, emerged very cleverly which includes detailed calculations of the architects in the design area and determination of the spatial location of the work from the soil strength perspective (Figure 3).

In creating such a unique building, manufacturers of the Sultaniye dome have brought creativity to such an extent that it is now among the world's unique works. Sultaniye dome located in the city of Sultaniye in Zanjan province, is one of the masterpieces of Islamic architecture. This dome is considered a unique example and a turning point in Islamic architecture in terms of volume, architectural style, spaces' relationship, and the proportions of the various components, static issues and resistance of the building, and aesthetics and decorations. Many historical texts and travel accounts refer to the grandeur of this magnificent building and many western orientalists and archaeologists have also emphasized its tremendous importance (Hamzeloo 2009:103).

Figure 3. Surrounding area of the Sultaniye dome (Hamzeloo 2009:105)

This historical and famous building is one of the magnificent and grand monuments in the architecture of the Islam world. The building, at the Southeast of Zanjan in the current Sultaniye city, is one of the most valuable and important tomb monuments of the world, After the Hagia Sophia dome in Turkey and Saint Mark church in Italy, this building is considered as the world's third massive dome building (Ghouchani 2002:99).

Construction of the building is considered a turning point in the history of Iranian architecture. The dome is located in a campus or citadel which its area is thirteen acres. This grand dome-shaped building has a span with 25/5 m diameter and a height of about 46m, it is an octagonal building which the length of each side is 17m and has eight legs that the area of each leg is 50 m^2, Inside the building, in the ground floor, eight porticos can be seen in its eight sides. Accuracy and skill of the Sultaniye dome's architects can be seen in all components of the building. It obtained a stable regularity in the Sassanid era and was used in the Islamic era and reached a great degree of evolution in the ancient Sultaniye city (Vasseghi *et al.* 2007:221).

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Concrete coiling of Sultaniye dome

The dome of the Öljaitü tomb in Sultaniye is one of the clover domes with oval cross section which has been constructed in the double shell. Height of the dome is 48/50m and the curve of the dome arch is more in its inside than outside.

Brickwork in Sultaniye dome

Brickwork in the Sultaniye dome has been done in two ways, first, as previous eras, decorative brick facade has associated with laying main bricks of the building like the skeleton of the building itself. Second, after construction of the skeleton by brickwork, a decorative shell of brick has been added over the building as an outer shell and this method has been used in all internal porticos under the dome and in all buttresses of the porticos in the first layer of the decorations.Unlike brick facade of the past eras, typical brickwork has been used in the external facade of the dome (Khaghani 2012:119).

On the lateral rims or buttresses of the northern entrance portico, this brickwork has been built by the combination of brick and tile with a cross pattern which can be seen in other places of the dome. In painted geometric dead walls of the 24-fold vaults made of brick and tile decorations with geometric and spherical motifs which are extremely nice in terms of the color and design, decorative brick work can be seen which has been damaged intensively today in the external facade (Figure 4).

Figure 4. typical brickwork in Sultaniye (Khaghani 2012:127)

Generalities about the building foundation

The ground of the building is composed of compacted layers of sand and clay with an approximate depth of 10 meters. The building is established on the legs composed of eight large brick load bearing piers which form a regular octagon in the plan. Length of each side of the octagon is 17m and the area of each load bearing pier is $50m^2$, load of these piers and generally load of the whole building are exerted on the foundations with 2m diameter, which have been created as general radial (Khaghani 2012:217).

The foundations of the massive building are very small and shallow. This is due to the excellent resistance of the earth, a point which has been considered by the manufacturers of the work. Only in the north of the building foundations is about 1/50m lower than the natural ground level, but in other part the depth of foundations are not more than 50-60 cm. Given foundations have been made of regular stone blocks with dimensions of 20-25cm and gypsum and lime mortars (Curatola and Scarcia 2007:41).

Skeleton and static issues of the whole building

It should be said that the issues related to the building static in the Iranian architecture have been solved and demonstrated by scientific experience for Iranian architect from a long time ago, and they have evolved during the time. It should be considered that in the Sultaniye dome, despite lack of implementation facilities, since the static design of the building was scientific, the dome of the building has resisted against the worst weather conditions over 600 years. It must be noted that Sultaniye is one of the coldest and snowiest places in Iran. Here it should also be remembered that issues said about the static aspects of the building in this text cannot be faultless and extensive researches should be done in this area by means of necessary facilities (Mainstone 2001:127).

Vertical forces

It is obvious that vertical forces do not cause much problem, but can be neutralized by the legs through the ground reaction force, an issue that ancient architects solved it is easily based on their extensive experience by building thick and sturdy legs. They solved the drawbacks that have been proposed about the vertical forces by the following methods:

The pressure on brick and mortar

Each brick can only tolerate the weight of the legal materials in the wall, everything that is underside should tolerate more pressure and this formula shows that pressure on the brick and mortar is a function of the wall height. Everything which is in low height, the pressure on it is higher. It should keep in mind that in some cases the pressure on the lower bricks of the Sultaniye is greater than 60 kg/cm. Where the brick and mortar tolerance has been low because of bad materials, can be witness samples of crushed bricks. Hence, the materials used in construction of bricks and mortar among them and their composition should be studied (Asgharyan Jeddi 2012:135).

Creation of slenderness ratio

Since the legs of the dome constructed as piers have high altitude, the issue of slenderness ratio has been very sensitive which ancient architecture solved this problem by creating moment of inertia. This means that if we consider two columns with the same cross-sectional area, one hollow and the other solid, the first column has greater strength against slenderness ratio (such as hand and foot bones that are hollow), but the solid column has less resistance (Muhammadi 2008:42).

Considering above mentioned materials it is clear that in the height of 30 – 40 m, slenderness ratio is an issue which by creating hollow space and increase of the column volume and fixing its area, moment of inertia of the dome will increase and the bending problem of the column can be solved (Ghouchani 2002:107).

Horizontal force and thrust

Considering that the brick functions only for compressive forces and has no resistance against tensile forces, Horizontal forces are the most dangerous issue for the brick buildings which based on horizontal forces are neutralized in the arch.

Static problems of the building components

Study of each component of the building in terms of static aspects is very important and among different issues related to this area we only explain briefly some of them. It should be considered that most of the domes in Iran are double shell. This is done for two reasons: Firstly, creating a sound and temperature insulation by the space between two shells. Secondly, putting the decorations on the lower shell to seem better. But Sultaniye dome has been built by quite specific and innovative method with a zigzag (ogee) design. Outer and inner shells have been built parallel in the Sultaniye dome (Khaghani 2012:243).

Role of the wood in Sultaniye dome

Although wood is not involved apparently in the brick buildings, but we should know that wood has been used in the area of tension or division of compressive force or scaffolding.

Scaffolding

It should be notified that due to low facilities for implantation in the past, Scaffolding was an important issue. More than other parts, this factor had a significant role in building a dome, so that scaffoldings were put into the skeleton and remained until the end of decorations and after the end of the work they were cut and they covered with plaster or other decorations (Nejad Ebrahimi *et al.* 2019:167).

Division of compressive forces in emergency time

Although brick tolerates perfectly compressive forces, however it should be mentioned that when, due to subsidence of the foundation, shear force is produced and cracks are created; if there would be a coil of wood on the wall, before the creation of cracks, shear force changes to compressive force that hence it can be divided into other parts of the wall. If the shear force is created due to the concentrated force or subsidence, or any other cause, and there is no wood coil, the crack will be created. While the coil of wood divides the compression into all levels and avoids the compression on one row of bricks and the shear (O' kane 2020).

Neutralization of tensile forces

Neutralization of tensile forces, which cannot be tolerated by the brick, can be done by wood in arches. For this purpose, when arch has had a high deflection, the problem of thrust has been solved by putting a coil of wood between the two legs (pillars) and the arch span, but when the arch deflection has been low (like porticos of Sultaniye), given coil was embedded at the top of the arch and inside the brickwork volume. A sample of tensile woods embedded inside the building skeleton has been discovered in the porticos of Sultaniye which has been done very scientifically. As can be seen in the map, on each arch, proportional to its width, 2 to 4 rows of wood (cypress) have been embedded, and since wood was not available as tall as the length of the arch span, a coil with the desired length was freely created by tip to tip integration of the woods. In longitudinal integration of two perpendicular chainage which are created to neutralize two perpendicular arches, thinner chainages are embedded on thicker chainage. To secure the wood to the brick, branches of the tree were cut by 5cm to give the dentate form to the wooden beam. Tree branches have a significant role in securing brick to the wood and to protect wood against moisture and termite, thatch was used around the wood by 4 cm diameter and some salt have poured into the thatch (Nejad Ebrahimi *et al.* 2019:189).

Conclusions

Dome as a main organ and an important element in the mosques' architecture, has had different dimensions and with traditional structure is one of the most important and debatable factors in the field of strengthening which different methods have been selected, designed and implemented by architects and structural engineers to retrofit it. In this paper,

it has been briefly mentioned that Iran is not only the origin of the dome emergence, but Persian domes have had a remarkable distinction with domes made in other lands. Prudent determination of the domes various shapes has been discussed and by referring to proportions and structural systems of Sultaniye dome, the thoughts and knowledge of their manufacturers have been emphasized, and it deals with structural features of the dome and finally it is concluded that the structure of Sultaniye dome has been interested fundamentally by the domes artists, architectures and manufacturers.

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