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The Quality of Light-Openings in the Iranian Brick Domes (with the Structural Approach)

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ABSTRACT

Paying attention to light is considered as one of the most prominent features of Iranian traditional architecture, which influenced most of its structural and conceptual patterns. The construction of light-openings in the buildings such as masjids, bazaars, madrasas, and caravanserais, as the Iranian outstanding monuments, proves the point. The Iranian master-mimars' strategies to create the light-openings in the domes has been taken into consideration through this study. To this end, the light-openings' exact location, according to the domes' structural properties have been taken into analysis. Next, based on the foursome classification of the domes, the research theoretical framework has been determined, and through applying the case-study and the combined research methods, the case-studies have been studied meticulously. According to the achieved results, the light-openings of the Iranian brick domes have been located at four distinguished areas, including: 1- the dome's top, 2- the dome's curve, 3- the dome's shekargah and 4- the dome's drum. Moreover, because of the structural limitations of each type of dome, the constructional techniques have played the pivotal role at locating the light-openings in the domes.

Introduction

Light has got the prominent significance in the Iranian beliefs throughout the history. The insistence on the sanctity of daylight originates from the religious doctrines of pre-Islamic era (Zoroastrian beliefs) which was emphasized in the Islamic era and especially in the Islamic Sufism.

It has been for centuries that the mystics have praised the light as a spiritual essence in their writings or poems. The light's consideration in Zoroastrianism sounds clear in Ashvzrtsht's statement: "Because God or Total Light is hidden form the head-eyes, we should notice the concrete light to incline our spiritual conscience to the spiritual light or Ahura Mazda" (Avshydry, 2000, 25). Light has got the special importance in Quranic verses too:"God is Light of heavens and earth (Quran, Noor, 35).Moreover, Prophet Mohammad has added a cosmological aspect to the mentioned verse: "The first creature of God was Light" (Nasr, 2010, 62). A special branch of philosophy called "School of Illumination", which is based on the light analogy, has been founded by Shahab al-Din Suhravardi and been expanded by Ghotb al-Din Shirazi, Mulla Sadra and others. According to Suhravardi, Iranian and Arabic literature and even everyday dialects are full of descriptions, assuming the light identical with the spirit exhilaration and the proper function of reason, which all are based on the analogy of light with the truth and happiness. Such an analogy has been established in the Islamic customs or traditions; although, some of the older religious rituals, especially Mazdaism had acknowledged it, too (Nasr, 2010, 64). In "Hikmat al-ishraq", he writes: "Everything in the world is from Devine Essence and the beauty or virtue is the God's gift because of his forgiveness, and the perception of this philosophy is the main principle of the human salvation (Ardalan, Bakhtiar, 2001, 47).

By the same token, since no sign like the light does symbolize or manifest Divine Unity, the Islamic artists have strived to use the light in their works to make them much closer to the source of spirituality (Burckhardt, 1986, 47). The Islamic architecture's atmosphere, as one of the prominent emanations of the artistic truth through the materialistic object (Mahdavinejad, 2004, 58), is saturated with the visual and spiritual effects of light; such effects have been applied by the Iranian master-mimars at all parts of a building and especially at a dome.

One of the main characteristics of the Islamic architecture is a dome, full of the vibrant arabesque designs on its inner or outer surface, which covers the maximum volume with the minimum surface area. Moreover, the domical forms have always been the sign of celestial or metaphysical powers; the spherical shape of sky or planets has strengthened such perceptions. Hence, the mechanical requirements along with the symbolic values of the domical forms have caused the crucial position for the domes, in the technical history of Iranian architecture. So, through the design or construction process of a dome as a hemisphere- like shape, both the formal or conceptual issues have been taken into consideration (Memarian, 1988, 107).

The Islamic architecture to achieve the aesthetic purposes and to approach the Divine mysteries has strived to overcome the structural limitations and apply the strategies for the construction of light-openings in the domes. In the early years of the domes' construction in Sassanid era or the early Islamic era, only the oculus was used for leading the light to the inner space of a building, but after achieving the more developed structural techniques to distribute the structural forces or tensions, the Master-mimars adopted the optimal forms or the structural methods to create the light-openings in the dome's drum area (Nemat gorgani, 2003, 35).

The study is to analyze the various locations of the light-openings in the different types of Iranian brick domes to recognize the Islamic Master-mimars' strategies to overcome the structural limitations for the light-openings' construction.

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Typology of Iranian Brick Domes. Taking an overall look at the various types of curved Naar (1) domes, such domes would be classified in two main categories: 1- the domes in which the whole shell is load-bearing and no other part is involved in the process of load transferring to the bearing-walls or piers. 2- The domes in which the ribs, instead of the shells are involved in the process of load-transition. The first category includes three types:

The Single-Shell Domes

This type of domes is older than other types and can be considered as the traditional origin of other types (Memarian, 1988, 122). In such domes, the whole shell is involved in the load-transition process. The shell thickness is decreased from the base to the top of the dome by removing just one brick at the angles of 22.5° and 67.5°.

The Continues Double-Shell Domes

Such domes are composed of two inside and outside shells that vary in form. These two shells are attached to each other to Shekargah (2) area (the angle of 22.5°) and from this area onward would become detached gradually (Pirnia, 1991, 64). The dome of Ardestan Jameh Mosque (555 AH) is one of the oldest continuous double-Shell domes. Moreover, the dome of Seyyed Roknodin Mausoleum in eighth century AH has been constructed according to this method (Pirnia, 1991, 64).

2.3: The Discontinuous Double-Shell Domes: such domes are consisted of two completely separate shells, which are connected to each other by means of the components called Khashkhashi (3). Other features of such domes are their long Arbaneh (4) and short Gerive (5) drums (Memarian, 1988, 239). Imam Reza Shrine in Mashhad and Shah (Imam) Mousque in Isfahan are the main examples of the discontinuous double-shell domes (Pirnia, 1991, 79).

Tarkin (6) Domes or the Ribbed Domes

Tarkin domes are consisted of several sectors with a plaster rib between each two sectors which turns to a load-bearing rib at the construction process (Memarian, 1988, 185). The load-transition process is done through such ribs and the middle sectors are not involved in the process.

Research Mechanism

Research Questions: which are the structural methods of the light-openings' construction in the Iranian domes? Which are the applied strategies to overcome the structural limitations?

Research method: based on the discussed foursome classification of domes, the research theoretical framework is determined, and then through applying the case-study and the combined research method, the case-studies would be analyzed meticulously.

Research Case-studies: considering the foursome types of the curved (Naar) domes, five cases from among all the single-shell domes and three cases from among the other three types have been selected as the case-studies.

The Structural properties of the Domes

Overall, the domes' static features can be classified in two special categories: 1- the common features among all the domes and 2- the features of every single dome that during the design or construction process should be taken in to consideration such as the functional features to achieve the optimal results without any structural defect. The common features among all the domes include the issues like the control of structural bendings, the prevention of tensile stresses or the piers' drifts. The structural action of a dome which is under the vertical forces (such as the dead loads) is dependent to the dome's geometric features. In such domes which are symmetrical to their axis, the meridional lines and the lines perpendicular to the meridians (hoop lines) are considered as the main lines for the main stresses (Salvadori, 2003, 254). The role of such lines on the dome's funicular action is dependent to the meridians' reforms. In a low rise dome, the meridians which are exposed to the compressive forces would become shortened and inclined toward inside (Figure1). In this case, the lines' resistance against the compressive forces because of the high compressive strength of the masonry materials like break or adobe would reduce the meridians' movements considerably. Therefore, in the low rise domes, the compressive stresses would be produced in the meridians' direction and also in direction of the hoop lines. So, such domes can be built by the materials which are non-resistant against the tensile stresses like the brick or the masonry materials (Salvadori, 2003, 256). Moreover, resolving the tensile stresses in such domes along with their low rise, would lead to the drift forces (Cowan, 1977, 4) and to neutralize the horizontal drift forces, the buttresses would be used or the domes' lower parts would be thickened (Figure 2).

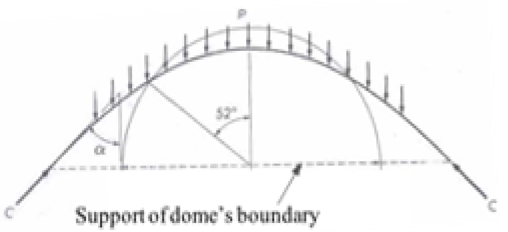

Figure 1. Deformation of a dome with high-rise (Reference: Salvadori, 2003, 256)

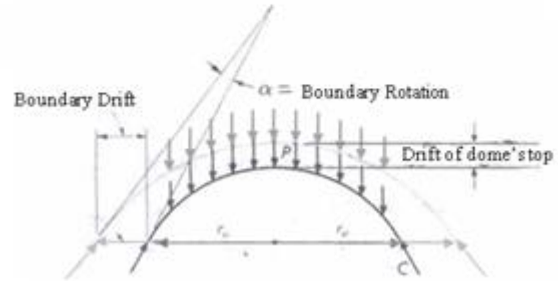

Figure 2. Deformation of a dome with low-rise (Reference: Salvadori, 2003, 256)

In the load-bearing high rise domes, the domes' upper hoop lines being under compression would be shortened, whereas the domes' lower hoop lines under the tensile stresses would become longer (Salvadori, 2003, 257). In the semicircular domes, the forces below the angle of 38° to the horizontal, act as the tensile forces and the forces above the angle of 38° to the horizontal, act as the compressive forces. Such force distribution happens in the domes that just bear the dead loads (Moore, 2006, 223), (Figure 3).

The form by which the tensile forces in a dome can be removed and the horizontal drifts be prevented, is called the "funicular curve" form. When a funicular curve structure bears the loads, it changes to a form to convert the inner stresses to the direct compression and tension. Such form in Iranian architecture is known as the oval form or the egg form.

Because a dome is constructed through the rotation of an arch around an axis (Moore, 2006, 307), to study and analyze the domes, the arches' actions should be taken in to consideration. The arch with the funicular curve form only bears the axis compression and not any bending forces (Moore, 2006, 183). The funicular curve form of an arch overlaps its drift line (the collection of the resultants of the drift force and the weight of every single part of an arch) (Figure 4). To the full removal of an arch's bending, the arch's drift line and its axis should overlap, although the arches with the compressive masonry materials can bear a small diversion from the drift line without any tension splits. If the drift line be located in the middle one-third of an arch, only the compressive forces would remain without any tensile forces (Moore, 2006, 186). To create an opening on a dome's surface, paying attention to the distribution of tensile and compressive forces is so important. The Construction of openings at the lower parts of a dome, which are under the tensile forces, may cause the cracks and finally the dome's collapse. But, at the parts of a dome, which are under the compressive forces, the light-openings can be constructed without any limitation

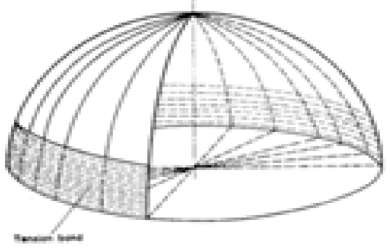

Figure 3. The semicircular domes' hoop lines and the tensile stresses area (Reference: Cowan, 1977, 4)

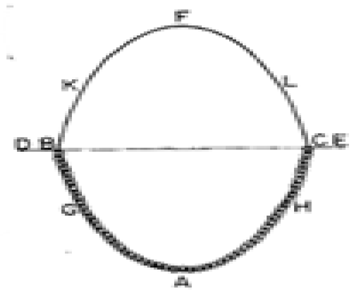

Figure 4. The dome's funicular form, overlapping its catenary form (Reference: Cowan, 1977, 4)

The Case-Studies

The Single-Shell Domes

Haj Safar Ali Timcheh of Tabriz: Haj Safar Ali Timcheh has been located in New Bazaar of Tabriz (after Safavid dynasty) which has been consisted of two parts: the corridor and the central space. The central space is a prayer hall with a base, composed of a central octagon which is surrounded by four semi-octagons. Its dome with the height of about 16 meters and a span of 9 meters diameter (Haji Ghasemi, 1996, 124) is a kind of single-shell dome with the openings at two levels (Figure 5: A1 & A2).

Amir Timcheh in Tabriz Bazaar: Amir Complex, constructed in Fath Ali Shah Qajar era, has been located in the southern part of Tabriz. The central dome's span is about 10.5 meters diameter and its height is about 17.5 meters (Haji Ghasemi, 1996, 156). The dome is composed of one shell, resting upon a ribbed base (Figure 5: B1 & B2).

Taj Al-Mulk Dome of Jameh Mosque of Isfahan: Taj al-Mulk dome is suited behind the north iwan of Jameh Mosque of Isfahan, known as Sofeye Darwish and along the northern axis of mosque. It has been constructed under the command of Tarkan Khatoon (wife of Malik Shah) in 481 AH. The dome with a span of 10.5 meters diameter rises 19.5 meters above the ground (Pirnia, 2007, 182). It has got the relatively high rise and its height from the spring to the crown is about 7 meters. There are two light-openings at the dome's structure and twelve ones at the wall of prayer hall (Memarian, 1988, 125). According to the accomplished researches, the form of dome completely matches its funicular curve form (Farshad, 1977, 84), (Figure 5: C1 & C2).

Imam (Shah) Mosque of Semnan: this mosque has been constructed in the first half of thirteenth century AH under the command of Fath Ali Shah Qajar. The construction process completed in 1242 (Haji Ghasemi, 1996, 96). In Shah Mosque of Semnan, there are eight light-openings around the dome with a lantern at the top (Figure 5: D1 & D2).

Sheikh Lotf Allah Mosque of Isfahan: the Mosque has been constructed from the years 1012 to 1028 AH. Its master-mimar is Mohammad Reza Isfahani (Pirnia, 2007, 298). The dome of mosque has been raised upon a wall with a thickness of about three meters and a span of 19 meters diameter. Its vertical section with the low rise has got the elliptical shape (Memarian, 1988, 127). The dome has been surrounded with sixteen light-openings (Figure 5: E1 & E2).

The Continuous Double-Shell Domes

Kabod Mosque of Tabriz: Kabod Mosque, known as the Turquoise of Islam in its own time has been constructed in 870 AH (Pirnia, 2007: 266). The mosque without any yard is a kind of outward-oriented architecture. Its original dome was destroyed by an earthquake and reconstructed by Ostad Reza, as one of the most famous master-mimars of Tabriz, according to the remains of the old dome. The curve form of the dome's inside shell is Shabdari[7] form with the angles less than 90 degrees. The dome has got four light-openings in its lower part (Figure 6: A1 & A2).

Seyed Rokn-al din Mausoleum of Yazd: the mausoleum has been constructed from the years 491 to 493 AH near Jameh Mosque of Yazd (Pirnia, 2007, 238). The dome's inside shell has got the oval form and the span of about 12 meters diameter (Memarian, 1988: 163) and is detached from the outside shell at Shekargah area (Figure 6: B1 & B2).

Barsian Mosque of Isfahan: Barsian Mosque as an old Seljuk mosque completed from the years 491 to 493. The inside shell with a spam of about 10 meters diameter is a kind of ribbed one. The inside shell rises 19 meters and the outside shell rises 21 meters above the ground. The dome's thickness at the spring area is about 1 meter (Memarian, 1988: 186) which is reduced to the dome's crown (Figure 6: C1 & C2).

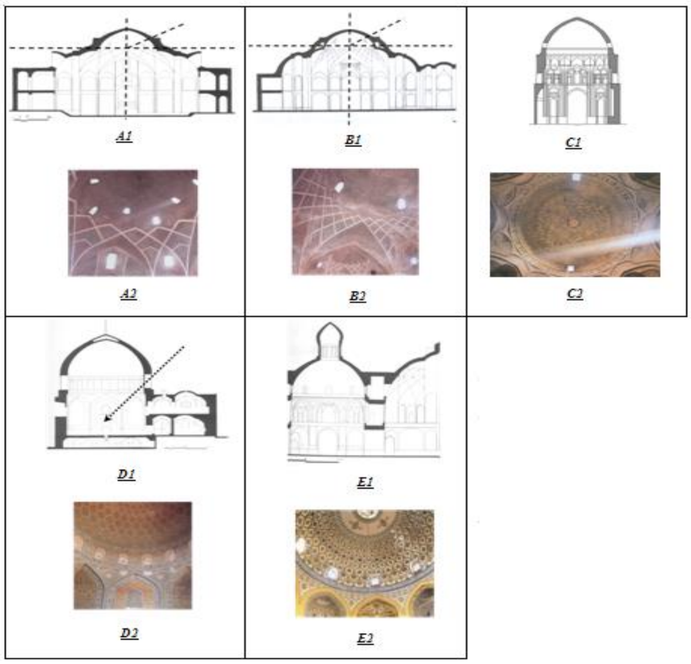

Figure 5. The single-shell domes and the location of their light-openings

A1. A section of Haj Safar Ali Timcheh and the location of its light-openings to shekargah (R: Haji Ghasemi, 1996, 126) A2. An image of the dome's interior space (R: Haji Ghasemi, 1996, 124).
B1. A section of Amir Timcheh and the location of light-openings to Shekargah
(R: Haji Ghasemi, 1996, 159)
B2. An image of the dome's interior space (R: Haji Ghasemi, 1996, 163).
C1. A section of Taj Al-Mulk Dome of Jameh Mosque of Isfahan
(R: Ashkan, 2009, 103)
C2. An image of the dome's interior space (R: Haji Ghasemi, 1996, 63).
D1. A section of Imam Mosque of Semnan (R: Haji Ghasemi, 1996, 102).
D2. An image of the dome's interior space (R: Haji Ghasemi, 1996, 101).
E1. A section of Sheikh Lotf Allah Mosque (R: Haji Ghasemi, 1996, 12).
E2. An image of the dome's interior space (R: Haji Ghasemi, 1996, 12).

The Discontinuous Double-Shell Domes

Imam (Shah) Mosque of Isfahan: the construction process started at 1020 AH by one of the brilliant Iranian master-mimars, Ali Akbar Isfahani. The mosque's big dome is the discontinuous double-shell one with the inside shell's span of about 20 meters (Pirnia, 2007, 291). The inside shell rises 25 meters above the ground and its thickness at the spring area is about 2.1 meters (Memarian, 1988, 258), (Figure 7: A1 & A2).

Agha Bozorg Mosque of Isfahan: Agha Bozorg Mosque with the beautiful discontinuous double-shell dome was built in 1268 AH in Qajar era. The inside shell with the low rise and the span of 10.3 meters diameter raises about 18 meters above the ground. According to Memarian (1988, 261), the outside shell with the low rise has risen upon a drum with the height of 4 meters and the thickness of 1.5 meters (Figure 7: B1 & B2).

Jameh Mosque of Yazd: the constructing process started at 724 AH. Its dome with an oval form is a discontinuous double-shell dome. The inside shell with the spam of about 15 meters diameter has risen 24 meters above the ground. Two shells are attached to each other by 12 bearing-walls (Memarian, 1988, 245). The form of inside shell is Naar, whereas the form of outside shell is a low-rise Shabdari (7) (Pirnia, 2007, 243) with 4 light-openings (Figure 7: C1 & C2)

The Domes with the Bearing-Ribs

Timche Malek of Tabriz Bazaar: Timche Malek is considered as one of the Qajar beautiful Timches in Tabriz Bazaar. Its dome with the spam of 9.5 meters diameter rises 14 meters above the ground (Haji Ghasemi, 1996, 136). The domical ribs, instead of attaching to a Shamseh(8)form at the top of the dome, all reach to the same point. Therefore, such domes have got no middle oculus and instead have got several surrounding openings. (Figure 8: A1 & A2)

Haj Sheikh Kazem Timcheh of Tabriz Bazaar: this complex has been located at the intersection of the shoemakers' corridor and the New Corridor. The main Timche of this complex is composed of a central octagon, surrounded by four semi-octagons. The dome's ribbed structure, consisted of a high central domical vault and four lower surrounding semi-vaults is coordinated with such geometric plan (Haji Ghasemi, 1996, 118) (Figure8: B1 & B2).

Ardestan Jameh Mosque: some parts of Ardestan Jameh Mosque have been constructed according to Khorasan (9) Style, as one of the Iranian traditional architecture styles (1^{th} AH – 4^{th} AH) and some other parts such as the southern iwan and the prayer hall have been constructed according to Razi (10) Style (4^{th} AH – 6^{th} AH). The inside shell of its continuous double-shell dome is a ribbed one, but the outside shell is a high rise Shabdari (Pirnia, 2007, 197). The dome's thickness at the spring area is about 80 centimeters. The inside shell's span is about 10 meters (Memarian, 1988, 187) surrounded by four light-openings

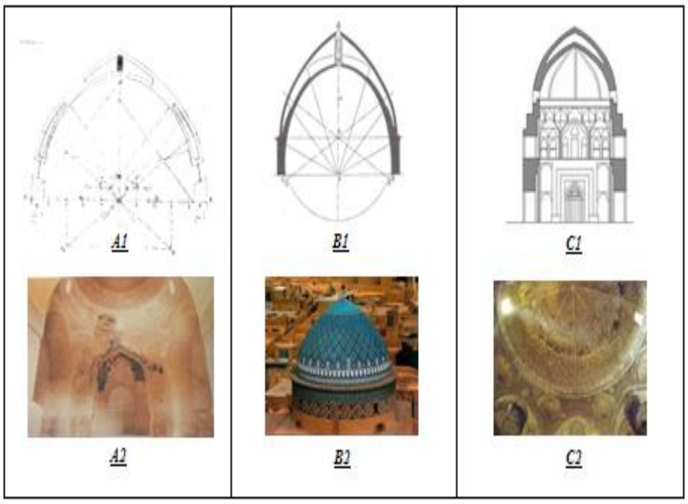

Figure 6. The continuous double-shell domes and the location of their light-openings

A1. The section of Kabod Mosque of Tabriz and the construction of the light-openings at the continuous area of two shells (Pirnia, 1991, 66)
A2. An image of the dome's interior space (R: Haji Ghasemi, 1996, 61)
B1. The section of Seyed Rokn-al din Mausoleum of Yazd (Pirnia, 2007, 238) B2. An image of the dome's exterior (www.mahoor.org)
C1. The section of Barsian Mosque of Isfahan (Ashkan, 2009, 105) C. An image of the dome's interior space (www.shw.kousha.photopages.com)

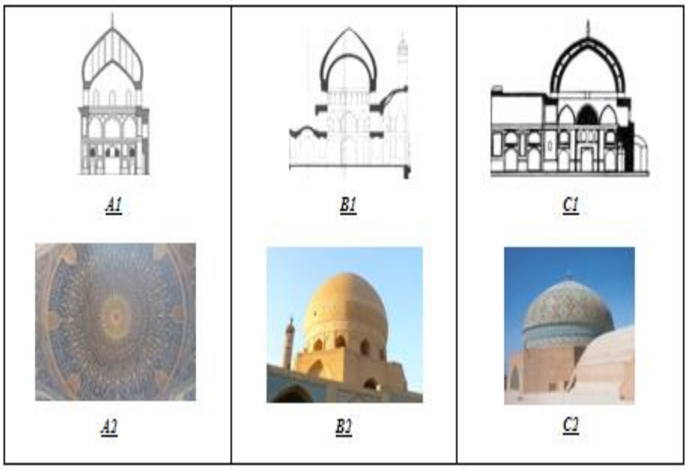

Figure 7. The discontinuous double-shell domes and the location of their light-openings

A1. The section of Imam (Shah) Mosque of Isfahan (R: Ashkan, 2009, 109) A2. The dome's interior space (R: Haji Ghasemi, 1996, 25)
B1. The section of Agha Bozorg Mosque of Isfahan (R: Haji Ghasemi, 1996, 157) B2. An image of the dome's exterior (R: the authors)
C1: the section of Jameh Mosque of Yazd (R: Pirnia, 2007, 234)
C2. An image of the exterior (R: Haji Ghasemi, 1996, 171)

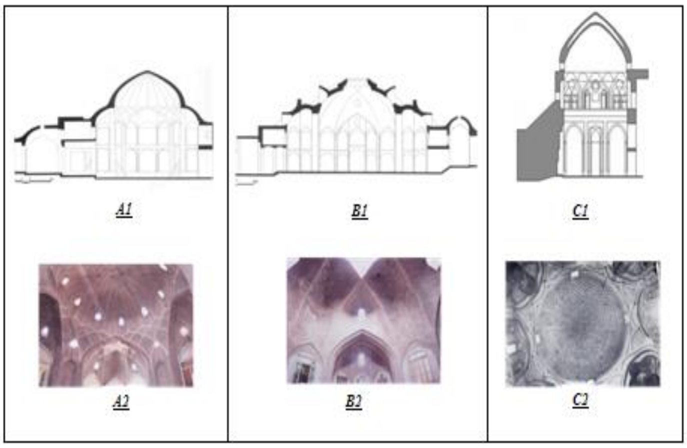

Figure 8. The Domes with the Bearing-Ribs and the location of their light-openings

A1. The section of Timche Malek (R: Haji Ghasemi, 1996, 139)
A2. The dome's interior space (R: Haji Ghasemi, 1996, 137)
B1. The section of Haj Sheikh Kazem Timcheh (R: Haji Ghasemi, 1996, 122)B2. The dome's interior space (R: Haji Ghasemi, 1996, 122)
C1. The section of Ardestan Jameh Mosque (R: Ashkan,, 2009, 105) C2. The dome's interior space (Memarian, 1988, 202)

The case-Study Analyses

The Number and Location of the Light-Openings

In order to analyze the light-openings of the Iranian brick domes, fourteen domical buildings from among all the traditional domical buildings were selected considering their types (single-shell, discontinuous double-shell, …). Then, the number and location of all the light-openings of every single dome were determined. In this way, the structural limitations of each type of dome for the construction of the light-openings at the different parts would be clear. Through the comparison of the domes' types, the domes' numbers and the domes' locations, the research questions would be answered. According to table 1, the light-openings have been located at 4 points: 1- The dome's top, 2- the dome's curve, 3- the dome's shekargah, 4- the dome's drum (Figure 9). The drum of a dome is a vertical component under its main structure, detached from the whole part and free from the tension and drift stresses. Such component in the Iranian- Islamic architecture is called Chanbareh (11) and in the double-shell domes is longer than the single-shell domes. The longer drum of the double-shell domes is called Gerive and the shorter drum is called Arbaneh in the Islamic-Iranian architecture (Figure 9).

Shekargah as the significant component of a dome with an angle of 22.5° to the horizon is exposed to the tensile forces. The Iranian master-mimars took this part thicker than other parts of a dome. The construction of the light-openings at this part, because of the tensile stresses, has got the special importance in the Iranian architecture (Figure 10).

The dome's top and the dome's curve are exposed to the compressive stresses; but in general, the Iranian master-mimars for the construction of the light-openings at these parts have been encountered the less structural limitations. The construction of the light-openings at the dome's top for getting the natural light and ventilation has been common for a long time in the Islamic-Iranian architecture, because the compressive stresses of this part have been borne well by the use of building materials like brick (Figure 11 & 12).

Although in general speaking, the light-openings can be constructed in all the mentioned points, but there are the structural limitations for some types of domes. The structural limitations, considering the studied case-studies include the following items:

According to Table 2, there is no location limitation in the single-shell domes and the domes with the bearing-ribs. The lack of the structural limitation in the single-shell domes is because of the connection of the four discussed areas with the outdoor; so the light-openings can lead the fresh air and light to the indoor, easily; Whereas, in order to create a light-opening in the shekargah area, because of the pre-mentioned structural properties, the special arrangements should be applied to control and reduce the tensile stresses.

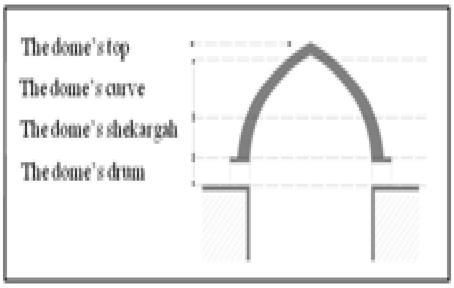

Figure 9. The different areas to locate the light-openings in the Iranian domes

The light-opening in the drum area
(Reference: the authors)

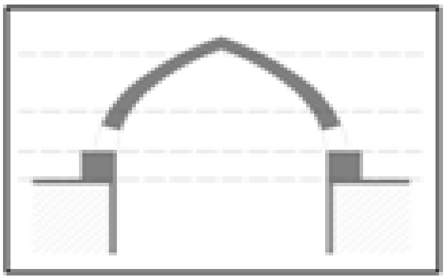

Figure 10.The light-opening in the Shekargah area (Reference: the authors)

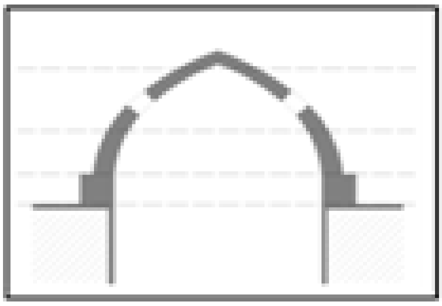

Figure 11. The light-opening in the curve area (Reference: the authors)

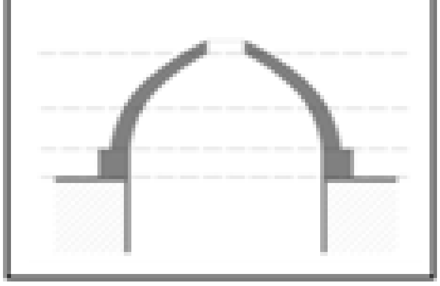

Figure 12. The light-opening in the top area (Reference: the authors)

Table 1. The Number and Location of the Light-Openings in the case-studies (Reference: the authors)

NO	The name of building & site	Type of dome	The number of light-openings	The Location of light-openings
1	Amir Complex in Tabriz Bazaar	SS	4	
2	Haj Safar Ali Timcheh of Tabriz	SS	8	⊖ ⊕
3	Taj Al-Mulk Dome of Jameh Mosque of Isfahan	SS	2	⊕
4	Imam (Shah) Mosque of Semnan	SS	9	○ ●
5	Sheikh Lotf Allah Mosque of Isfahan	SS	16	●
6	Kabod Mosque of Tabriz	CDS	4	⊕
7	Seyed Rokn-al din Mausoleum of Yazd	CDS	4	●
8	Barsian Mosque of Isfahan	CDS	2	⊕⊕
9	Imam (Shah) Mosque of Isfahan	DDS	8	●
10	Agha Bozorg Mosque of Isfahan	DDS	12	●
11	Jameh Mosque of Yazd	DDS	4	●
12	Timche Malek of Tabriz Bazaar	BR	10	⊕
13	*Haj Sheikh Kazem Timche in Tabriz Bazaar*	BR	5	○ ⊕
14	Ardestan Jameh Mosque	BR	4	⊕

key			
SS	The Single-Shell Domes	○	The dome's top
CDS	The Continuous Double-Shell Dome	⊖	The dome's curve
DDS	The Discontinuous Double-Shell Domes	⊕	The dome's shekargah
BR	The Domes with the Bearing-Ribs	●	The dome's drum

Table 2. The limitations or possibilities of the light-openings' construction in the different types of domes

Type of dome	The Single-Shell Domes	The Continuous Double-Shell Dome	The Discontinuous Double-Shell Domes	The Domes with the Bearing-Ribs
The location of light-openings	○	⊕	●	○
	⊖	●	–	⊖
	⊕	–	–	⊕
	●	–	–	●

key	
○	The dome's top
⊖	The dome's curve
⊕	The dome's *Shekargah*
●	The dome's drum

The Strategies to Reduce the Tensile Stresses in Single-Shell Domes

Thickening the Shekargah Area: thickening the Shekargah area to reduce the tensile stresses has been caused by the use of heavier materials. Such strategy has been applied in Haj Safar Ali Timcheh of Tabriz and Imam (Shah) Mosque of Semnan. The dome of Haj Safar Ali Timche of Tabriz has got four light-openings at Shekargah area and four ones at the dome's curve area. Because of the compressive stresses at the dome's curve area, the construction of the light-openings with the limited number and size does not cause any serious structural problem. But the construction of the light-openings at shekargah area may cause the crack or collapse of the dome which can be prevented by thickening this area (Figure13).

Using the Buttress: the transition of the tensile forces by using the buttress at shekargah area is seen in the dome of Amir Timcheh in Tabriz Bazaar. Because of the dome's low rise,

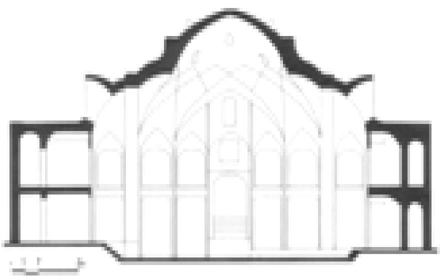

Figure 13. Thickening the area, bearing the tensile-stresses in the dome of Haj Safar Ali Timcheh of Tabriz (Reference: Haji Ghasemi, 1996, 126)

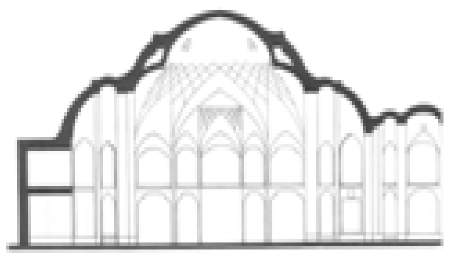

Figure 14. Using the buttress at the shekargah area of Amir Timcheh in Tabriz (Reference: Haji Ghasemi, 1996, 159)

there are less tensile forces, but the drift forces can cause the structural problems that have been controlled by using the buttresses (Figure 14).

Using the Funicular Forms: using the funicular forms in Taj al-Mulk dome of Jameh Mosque of Isfahan has reduced the tensile stresses. As a result, the light-openings' construction does not cause any serious structural problems.

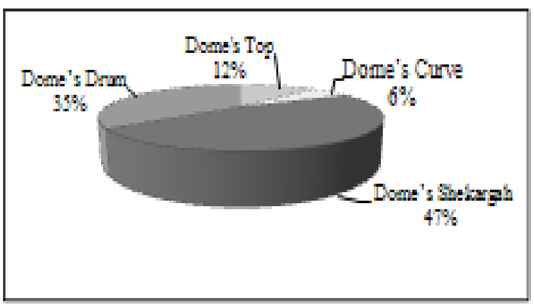

Figure 15. The distribution of the light-openings at the different parts of a dome (Reference: the authors)

According to the accomplished studies, although the single-shell domes have no serious problems with the location of the light-openings, but they have got the more structural limitations comparing with the other types of domes. Moreover, the domes with the bearing-ribs have got the least limitations not only about the location of the light-openings, but also about their structural properties. In the discontinuous double-shell domes, the light-openings can just be located at the drum area, because three other parts have no connection with the outdoor.

The descriptive analysis of the light-openings' numbers (Figure 15) shows that in spite of the less structural limitations at the dome's curve area, but there are the least light-opening at this area, whereas shekargah or drum areas have attracted the Iranian master-mimars' attention more than other parts.

Because of the compressive forces and the thickness of the drum area in the most of Iranian domes, more light-openings have been located at this area. Because of the structural limitations, in spite of applying the strategies for controlling the tensile stresses at shekargah area, there are the limited numbers of domes at this area. However, the dome of Timche Malek of Tabriz Bazaar, as a dome with the bearing-ribs has got no limitations for the light-openings' localization at shekargah area and there are a large number of the light-openings at the sector between two bearing-ribs at shekargah area.

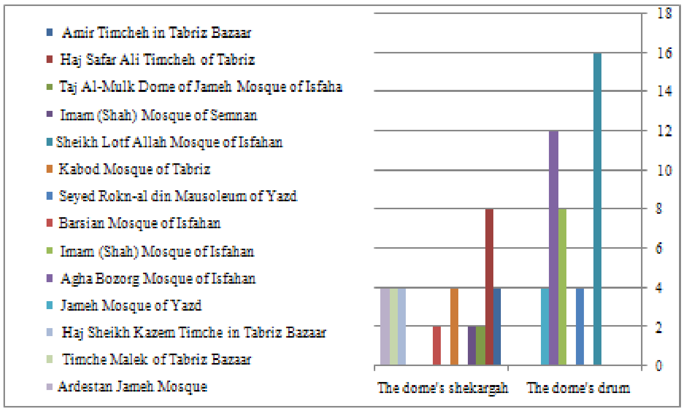

Figure 16. The number comparison of the constructed light-openings at the shekargah area and the drum area in the studied case-studies (Reference: the authors)

Conclusion

The study shows that in the Iranian brick domes, the light-openings have been located at four areas: 1- the dome's shekargah area, 2- the dome's top area, 3- the dome's curve area and 4- the dome's drum area. The least of the light-openings have been located at the curve area. In order to create the domes at shekargah area, the tensile stresses should be controlled; nevertheless there is not the considerable number of domes at such area in the Iranian brick domes. The existence of only four light-openings at this area, in spite of its less structural limitations comparing to other areas can be considered as the subject of the future researches. Moreover, in the domes with the bearing-ribs provided that they have got just one shell, the light-openings can be located at all the four parts.

Notes

1- A name for the Iranian domes with the curve form.

2- The dome's sector with the angle of 22.5° to the horizon.

3- The load-bearing walls of the discontinuous double-shell domes which attach two shells to each other.

4- The cylinder under the discontinuous double-shell domes which is shorter than Gerive.

5- The long cylinder under the discontinuous double-shell domes.
6- The dome with the ribbed load-bearing shells.
7- A kind of arch formed of the intersection of two ovals.
8- The famous geometric form of the Islamic art.
9- The third style of the traditional Iranian architecture (1^{th} AH - 4^{th} AH).
10- The fourth style of the traditional Iranian architecture (4^{th} AH- 6^{th} AH).
11- An octagonal and vertical component of a dome under its main structure.

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