A Double Dome Through the Ages: Building Technology and Performance of Esfahan Shah Mosque's Dome

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Building Technology and Performance of Esfahan Shah Mosque's Dome

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Abstract. On 7th May 1611, the construction of Esfahan Shah mosque started to be a part of the re-modeling of Safavid capital, a building that adopts a glazed bulbous double dome as a hybrid structure of brick and wooden elements. This paper aims to present building techniques, construction process and conservation works of this complex dome through historical evidence and onsite surveying. For these purposes, following a brief history of the building, the paper explores the geometry, morphology and construction sequences. It subsequently addresses the conservation during the last century from *Salnameh* (1934–36) up to current intervention and their consequences. The paper necessarily illustrates cracks pattern, not only to recognize its causes via their type and geometry but also to address historical performance and structural capacity. According to the objectives, the study of the Shah dome plays an important role to better understand other similar cases. This paper concludes that structural analysis and future conservation could benefit from the achievements derived from historical research, which also allow further understanding of construction techniques.

Keywords: Shah mosque's double dome · Radial walls · Hybrid structure Construction techniques · Building performance · I-beams strengthening Crack pattern

1 Introduction

A monument is a historical phenomenon, which breathes. It can be read by effects linked to history. Esfahan Shah Mosque, Jame Abbasi, is the highest hybrid double dome (HDD) in Iran, which needs to be analyzed by re-considering historical effects. Many factors may have had influence on the 'structural response' and 'existing damage' [1], such as building process, structural strengthening, and natural disasters. For this purpose, the current research attempts to recognize the HDD of the Shah Mosque to obtain an integrated study on geometrical capacities, construction and consolidation technique's effects on the structural system. The investigation follows two main approaches to understand the dome. Firstly, the geometry data and construction

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sequence are crucial issues, as the future analysis of this structure would principally depend on these features [2]. Secondly, constructive deformation might had happened due to the deflection of the formwork and shoring besides deformations of structural members during intermediate and incomplete configuration of the dome [1]. These assumptions lead to a discussion on deformation during the building process as well as to distinguish structural and non-structural members of this hybrid dome. Finally, the damage and crack pattern distribution is provided to understand the structural performance of the dome [3].

2 History of Planning for Shah Mosque

After 21 years of the initial efforts for urban development of Esfahan around 1590, as it became officially the Safavid capital in 1598, work on the congregation mosque began on the southern edge of the Naghsh-e Jahan *Meidan* [4, 5], (see Fig. 1). Following urban planning based on paradigms of *meidan, bazar*, and *chahar-bagh* (1590–1603), to achieve commercial success in the gigantic '*du-ruyah'* bazar around the *meidan* with the length of almost 524 m, the state decided to construct the Shah mosque for rearranging the city's traffic pattern, in order to bring more clientele into the new market area in later steps of development (1611–1619) [4–6]. This was also a reminiscence of Saljuq-i Jame mosque in old *meidan* wherein the state's first plan for urban regeneration failed to reach consensus of local merchants and politicians [6]. Construction of such a lofty structure with the double dome (height of 53 m), might be the crucial reason for doubling the height of the perimeter wall of the *meidan* after 1611, which corresponds to Galdieri's archeological evidence [7], a dynamic process in Safavid urban development that serves as a mutual reflection on the mosque setting back. Private land of 18 000 m^2 was purchased and officially filed as public property of the mosque, including 'a large khan' [5] and houses belonged to different social classes [8]. In Shah Abbas justice city, 'property acquisition' of public buildings constituted a promising feature to ensure building's maintenance. A legal instrument entitled *Waqfnameh* donated by *Allah Beg* according to the inscription on the mosque was prepared, as an endowment of 14 properties. The teamwork resulted in the collaborations of planner Badi al-Zaman, who managed the social condition of land transformation peacefully, architect-engineer Ali Akbar Esfahani, and contractor Allah Beg along with various artisans. "On Friday 29 April 1611, the Shah funded 2,000 *tomans* for the construction tools and materials which he wanted to be in hand when work began on the building" [8]. Further to the use of brick as a main material, the discovery of a marble quarry in the vicinity of Esfahan provided the usage of the stone for covering only the inner walls, a local but scarce material [5].

Fig. 1. Naghsh-e Jahan Meidan 1703, by G. Hofsted van Essen, Leiden University Library

3 Geometry and Morphology of the Dome

3.1 Hybrid Double Dome (HDD)

HDD is a composite structure of brick double dome with radial stiffener walls, wooden ties and struts arranged in radial, circumferential or diagonal positions adopted in the building construction and the structural system. This type of dome had appeared since the 15th century in Persian region, which reached the most advanced application in the Esfahan Chahar Bagh Madrasah (1710), (see Fig. 2).

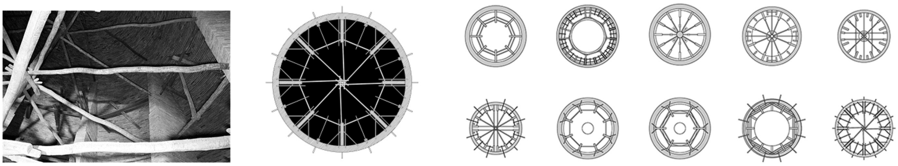

Fig. 2. Esfahan Chahar Bagh HDD: Space in-between of the domes (left) and plan (center), IES Studio, 2016; Different types of Persian HDD, ICHTO archive, Hillenbrand 1994, Prinia 1991, Memarian 1988, IEStudio 2017 (right)

3.2 Building Components

3.2.1 Domes

The domes of Shah mosque are erected on top of each other, which reach 38 m (inner dome) and 52 m (outer dome) in height, covered by faience tiles outwards. A square base of 22.65 m serves as a support for the HDD, which transition into the circular base by squinches. The space between the two shells provides not only a spatial structure but also works as insulation, absorbing radiant heat [9]. The inner dome, *Ahiyaneh*, means the parietal bone of the skull [10] and is a pointed dome with 8 openings, which provides a support to the outer dome, radial walls and wooden elements. The geometry follows the rotated arch type II described by *Jamshid al-Kashani* in 15th century [11], (see Fig. 3). He offers tables for definition of geometrical properties of the arches such as length of intrados, area of the façade, rise of intrados, height of convexity and empty area underneath the arch. These play a crucial role in construction and estimation of the required building materials and scaffolding [11, 12].

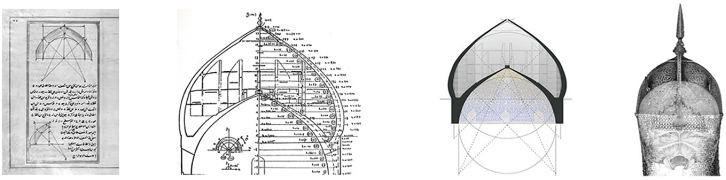

Fig. 3. From left to right geometry of arch type II in the *Meftah al Hesab* by *al-Kashani*, 1427, National Library Egypt; a survey on Shah HDD by IsMEO, 1960s; Shah domes' geometry, IEStudio, 2016; superimposition of Safavid *Khud* on *Ahiyaneh*

The bulbous outer dome, *Khud*, which means battle helmet [10], is seated on 32 radial walls and a platform, *Geriv* or raised 7 m high from the springing point of the inner dome. The integration of drum into the inner dome creates an optimized form in order to absorb the horizontal thrust. Consequently, the outer dome becomes more stable against lateral forces when compared to a single tall drum (see Fig. 4).

3.2.2 Walls

The existence of this delicate HDD depends on optimized radial walls called *Khashkhashi*, which have an essential role in subtlety, stability and construction of Persian bulbous dome. A spatial syntax of brick stiffener walls reaches upward from the springing point of the outer dome, (see Fig. 5). These walls contain 9 (RW1), 8 (RW2), and 15 (RW3), with thickness of 40 cm and height of 12.6 m, 10.6 m and 7.6 m, respectively. The walls follow the domes' curvature and pursue a possible optimized form, e.g. RW1 and RW2 set back from the center to be located at the top of the drum. To retain horizontal thrust the walls are interlocked to the outer dome and embedded wooden elements join them to the inner dome. Therefore, the structural role of the integrated walls into the domes cannot be ignored. Choisy (1899) and Saladin (1907) present mechanical advantages of these walls changing the center of gravity (see Fig. 5, right) [13, 14]. Yet, this structural composition keeps the thrust line of the outer dome within the walls as every 11° in plan, stiffeners are repeated.

3.2.3 Wooden Elements

Due to the construction process and structural reasons, wooden members of HDD are either exposed or embedded, in both circumferential and radial arrangements. Three encircling wooden ties system on the extrados of the outer dome are laid under the layer of the faience tiles (Fig. 7). These wooden chains locked together might have been inserted during the construction to balance the horizontal thrusts of the bulbous dome. There are 42 circumferential elements serving as scaffolding, connecting the walls in three levels, which are not anchored. The radial types appear in either the diagonal elements (RT2), which are structural, or the other elements fixed in the outer

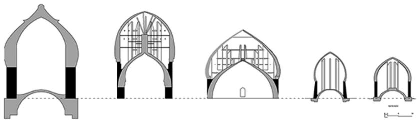

Fig. 4. Compression study of different height of drums in stability of double dome: from left to right: *Taj Mahal*, *Gur-e Amir, Shah mosque, Darb-e Emam, and Khaje rabi tomb*

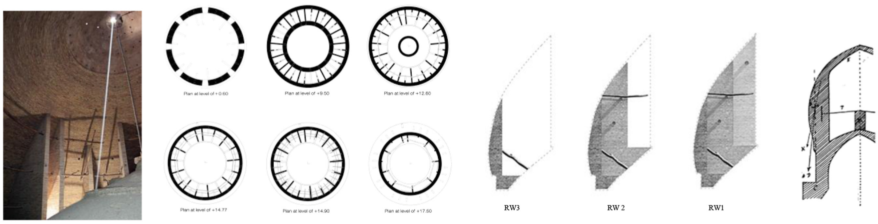

Fig. 5. From left to right: Space in-between of the domes, 2016; Walls and timber elements' arrangement in Shah HDD in sequential sections; three types of radial walls with wooden elements; center of gravity changed, Gur-e Amir double dome, Saladin, 1907

dome (inside for scaffolding and outside to improve the tiles connection mostly in the lower portion of the dome). The 15 diagonal elements connect the RW3 into the inner dome, while other embedded tree branches connect RW1 and RW2 to the inner dome. Moreover the 8 embedded elements in RW1 were used to establish the *shahang,* a vertical column of the scaffolding also for building guidance.

4 Building Techniques and Construction Process

Persian brick domes are constructed without centering, based on special techniques subtly reflected in the structure assemblage. This feature results in a juxtaposition of the masonry and wooden elements, and a techno-poetic fulcrum, namely the *Shahang-Hanjar* technique. This contains a vertical wooden column established in the center of the dome with radial timbers fixed to the structure and an *Ardakan* chain radially adjusted [15]. This simple system plays both roles of scaffolding and building guidance. The outer dome and walls, which correspond to this 'productive machine' for the structure, are simultaneously erected.

The inner dome was built up to the start point of its new curvature profile, in which the diagonal wooden components have been integrated with radial walls. In the lower portion of the outer dome, three wooden tie-rods and 15 diagonal ties were applied to retain the horizontal thrust as well as any probable deformations in the incomplete configuration. Following the completion of the inner dome, the *Shahang* was established on the crown and connected to the largest walls (RW1) by 8 temporary radial timbers. Therefore the role of circumferential (CT1, 2 and 3) and radial wooden elements (RT1) becomes indispensable for the building process. Furthermore, there are some elements' removal: traces of cutting the *shahang* and eight radial timbers along with the upper part, are identified via holes in the shell (see Fig. 5 left and 6d). Finally the gleaming dome generates through a prefabrication technique of tiles on the ground in an additive method (see Fig. 7).

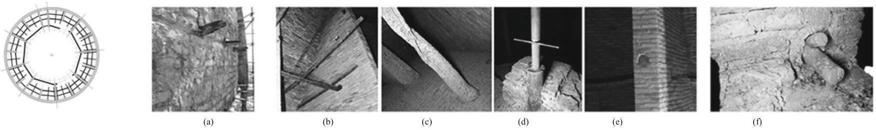

Fig. 6. Wooden elements of Shah HDD: radial timbers on the extrados of the outer dome, Photo: Pakdel, 2015 (a); RT1 and CT1 (b); diagonal RT2 (c); traces of cutting the *shahang* (d) and its radial timbers (e); natural anchored joint, *Chahar Bagh* HDD (f)

5 Conservation History of Shah Mosque's Dome

During the recent centuries, there have been several restorations on Shah Mosque mainly repairing mosaic faience from time to time [16] and strengthening of the structure. The earlier evidence refers to the 1844 earthquake, when Mohammad Shah Qajar called to repair the cladding with tiles, upon the south *Eyvan*'s cracks in the dome, superficially healed by stucco in 1845. Subsequently, tiles were mostly collapsed in 3rd February 1932 [17]. In fact, the cracks had become deeper due to weather erosion during the years [18]. Moreover, each minaret was displaced about 0.5 m from its original position [19]. This disaster caused public critics due to the seized mosque's endowments as financial source for the maintenance of the building [20]. The *Salnameh* also points out a deep crack and the strengthening of south *eyvan* in 1932 supported by charity funds, almost 110,000 Rials were provided by Esfahan Municipality, Ministries of Education and Finance between 1932 and 1933 [21], (see Figs. 8 and 9). One of the foremost parts of the text underscores the Ministry of Education's conservative motto, "no alteration is made to the original thing" [21, 22]. This was a milestone in modern conservation of the Shah mosque.

Hossein Moarefi, as the maestro in restoration, proposed a techno-poetic solution for the complex masonry elements of Shah Mosque through his impressive lecture among Esfahan's artisans in 1932 with direction of Andre Godard. Based on his experimental exploration on the site, he claimed that acceleration of building process, due to number and time limitation of Safavid projects, could be the main reasons of the structural weakness in some parts [19]. However, he did not neglect the role of earthquake of 1844 in structural performance of the monument. His proposal for the South *Eyvan* and dome included: 1. preparing a wooden scaffolding with 32 m height; 2. collecting and coding all the remained tiles; 3. restraining the two Minarets by a steel cable to avoid their displacement; 4. stabilizing the *Eyvan* with a net of three steel I-beams 40 in the right and two others in the left side; 5. re-assembling old tiles with pins and new ones without pins [19–21]; 6. applying steel tie-rod on the extrados of the outer dome in the position of the middle encircling wooden ties system. The concept of the intervention could be observed in the connection between cables and I-beams, as an integrated net, which eliminated the extensive cracks and stopped movement of the Minarets [23]. Another steel profile ring was applied on the extrados of the outer dome in 2015, even if its necessity and consequences should be discussed and monitored.

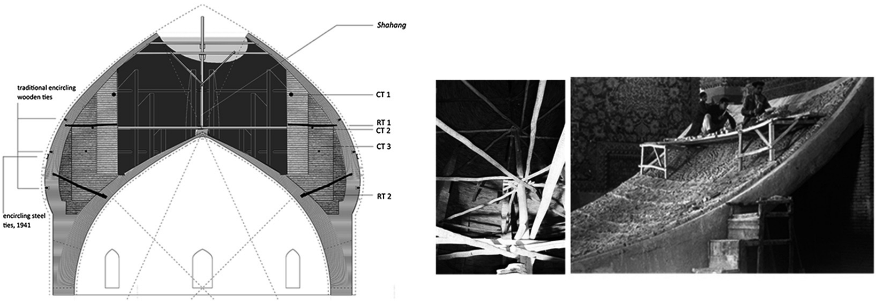

Fig. 7. The final construction sequence of Shah HDD (left); *Shahang* of Chahar-Bagh HDD, 2016 (center); Tile prefabricating technique: facing down the glazed tiles on the 1/16 portion of outer dome template through the subtractive and additive methods, Shah mosque, photo by H. Nyman, 1937, Fine Arts Library, Harvard University (right)

Fig. 8. From left to right: Hossein Moarefi portrait, Moarefi family collection; I-beam net strengthening of south *eyvan*, IEStudio 2016; the I-beams laid on the curvature of the vault and twisted nearby pinned support, IEStudio 2016.

Fig. 9. From left to right: wooden scaffolding for *eyvan* restoration, photo by Robert Byron, 1933, Courtauld Institute of Art Source Fine Arts Library, Harvard; Aerial view of Shah mosque shows the strengthening that had been applied, 6 July 1937, The Oriental Institute, The University of Chicago; dome strengthening of 1941 by the encircling steel ties system, 2018

6 Discussion and Analysis of Crack Pattern

Understanding the structural performance of a historic masonry benefits from mapping damage and crack pattern distribution [3], which is also essential for the safety of the building [24]. The cracks are observed to categorize their width and location. The intrados of the outer dome exhibits several serious cracks. Vertical cracks separating the outer dome from the radial walls axes 3, 3a, 6a, 7b are also present, which are even seen under the tile-layer of the extrados. Yet, significant cracks between axes 8b and 1b are towards the strengthened *Eyvan* (see Fig. 10). Furthermore, several thin cracks appear between the top of the RW1 and RW2. As cracks are not symmetrical, they are not likely to have occurred during the construction process. Due to the largest horizontal thrust of the dome, the connection between the walls and outer dome requires improvement. However the crack pattern should be monitored during time to better understanding structural behavior. Needless to say, a finite element analysis and thermal analysis are recommended.

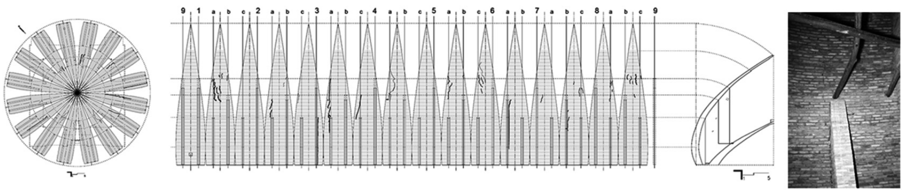

Fig. 10. Crack pattern, 24 August 2016

7 Conclusion

From historical studies, the economic, social, and aesthetic reasons required a large bulbous dome in Naghsh-e Jahan *meidan*, which had to be optimized and hybridized by walls and wooden timbers. Time limitations of initial construction, earthquake of 1844, and modern strengthening of 1932 are the main historical effects. Their consequences should be monitored for any structural analysis and conservation. Economically *Waqfnamehs* of Shah mosque have guaranteed the monument maintenance through the ages, an urban policy that could be a conservative solution for other cases. Technically speaking, building the HDD was impossible without walls retaining the horizontal thrust along with the diagonal and encircling wooden ties system which also play an indispensable role in the building process and in improving the connections. The construction process study indicates no relevant deformation of the components during the intermediate and incomplete configuration of the dome. However, a detailed structural analysis is highly recommended and non-destructive testing could lay the basis for future work. From the strengthening viewpoint, historical performance of the South *eyvan* might have effects on the crack distribution of the dome close to that element. Moreover, walls' connections with the outer dome should be improved. The advanced case of *Chahar-bagh* HDD as a more durable hybrid structure could be an archetype for sustainable consolidation plan with minimum of intervention. Wooden system of this case could inspire a net of lightweight ties and struts for masonry consolidation.

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