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Structure of Soltaniyeh Dome and the Project of the Southern Vault Crack Restoration

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Abstract: Soltaniyeh Dome is one of the most glorious and great architectural monuments of Iran. Although this building had continuously encountered several natural and human made disasters, but still gloriously and steady in plain of Soltaniyeh. The secret of stability in this brick building during past centuries is laid in its structure and materials used for building. The main idea of this study is to investigate the structure of Soltaniyeh dome and also finding a suitable way for restoring southern vault crack.

Key words: Structural components; Vault crack; Arches of the building; Material.

INTRODUCTION

The Soltaniyeh Dome monument is located 40 km. far from Zanjan. The plateau in which this structure was laid is about 2000 m above the sea level. This historic building was built during Ilxani Dynasty in about 10 years.

Several restorations in the past and also in recent years were accomplished on this monument and according to investigations the main causes of demolition in this structure are: climate, changes in temperature, earthquakes and existing pressures in the point of support, vaults, domes, and finally settlement.

Fig. 1: The Soltaniyeh Dome.

Skeletal Description:

This dome was constructed on an octagon platform with the diameter of 25.5 m and height of 48.5 m. The skeleton of the building is composed of a very large interdepleted bonded double-shell dome which is placed on several Patgheneh in order to change the shape of platform to a circle. These Patghanehes are laid on two different series of load-bearing arches and these, in turn, are placed on a base composed of eight large bricky bearer pillars.

Each side-length of this octagon is about 10 m and the surface area of the bearer pillars is about 50 m2. This building has eight Iwans or veranda toward every geographical direction. The iwans toward the non-cardinal points are decorated with honeycomb but on the contrary, the iwans toward the main geographical directions have no honeycomb work.

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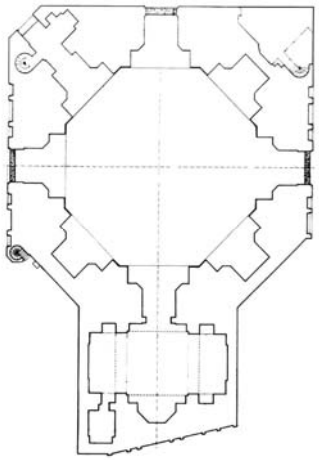

Fig. 2: The Soltaniyeh Dome plan from the height of 11.5 m.

On one hand these so-called iwans had led to diminishing the mass of thick walls on the top and on the other hand, they resulted in creation of a kind of mobility and variety in its height and therefore they could hold different decorative forms toward various axis of the building. Light-sashes are being devised in some iwans of the first floor.

In addition to internal iwans, a set of external iwans are shown as a horizontal strip in the plan that each iwans is divided by small pillars to three sections. Each section is composed of an arch whose fascia ends to an elegant tiling. The great brick dome is placed on top of these iwans and eight lofty minarets are surrounding it.

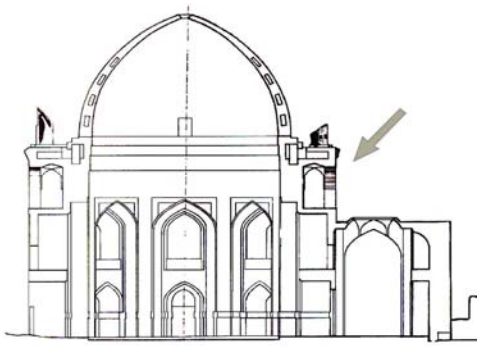

Fig. 3: North-South cross-section of Soltaniyeh Dome.

Structural Components:

Foundation:

Natural terrain of Soltaniyeh is composed of mixed materials including limestones and clay that has some components with various grading (max 20 cm). As the result, it is a solid and very compacted ground which has undergone its final settlement. Hence, the surface water could not harm the structure. This layer is in the beneath of current foundation of the dome in depth of about 1.5 to 2 m.

According to investigations, the foundation depth of Soltaniyeh Dome in compare with its magnificence and height is very low and inconsiderable. The foundation depth of this building in most parts, except in the north side which reaches to about 1.5 m, is not more than 50- 60 cm.

The material used in foundation is composed of crushed stones with the size of 20- 25 cm and semi-ground gypsum mortar. It is noteworthy that in Zanjan region and in Ilxani era, the semi-ground gypsum was frequently employed in the buildings. Since the best type of gypsum was excavated from mines in Azerbaijan region (Takht-e-Soleyman region in close distance from Zanjan), the best quality semi-ground gypsum had been produced in Iran.

The semi-ground gypsum was produced as follows. The gypsum excavated from mines of the region was heated in low temperature (about 200oC) and technically changed into hollow gypsum. Then the gypsum was pounded using wooden mallet and get ready for use. The difference between normal and semi-ground gypsum is that the normal one is changed into gypsum powder but semi-ground gypsum is granular that by absorbing

moisture, these small grains get hardened and very resistant. Thus it is more resistant against moisture and therefore as the result of this and also its abundance in the region, this kind of gypsum was used very frequently.

With respect to examinations conducted by Professor Paolesy (1961) on this building, the foundation settlement had been monotonous and integrated and only about 8 cm and considering the dimension and magnificence of the structure, this amount is completely negligible. According to same investigation, there is no need to apply reinforcement in the foundation and ground below except in some points including the underneath of the pillars of Torbat-Khaneh (a room in which the soil of Imam Ali sanctuary is kept) and the reinforcement in those sections was accomplished as follows:

At the beginning, the foundation get rinsed with plenty of water so that the lime mortar with no cohesion which is made in the soil could be removed and then using injection system with low pressure, the cement mortar would replace it in such a way that all spots evacuated from lime get totally filled by cement .

Slight settlement of the building might resulted from several reasons but certainly the most important one, however, is the existence of pillars made from homogenous materials (brick) that covers an area of 50m2 and transfer the loads uniformly to the foundation. Note that in order to uniformize the surface above foundation and also to reduce ascending moisture, large stone blocks were applied so that the load of pillars is transferred to the foundation through these blocks. Another reason for this slight settlement is the ground below the structure which had already undergone its settlement.

Walls:

In this huge and glorious structure, considering the iwans in every side, as a rule eight pillars had been created that would transfer the load uniformly to the ground. Based on so-called investigations by Paeolesy (1961), these pillars are completely monolithic and made from brick. The investigation was performed on two out of eight pillars, one in north and next to extension mosque and other in east and adjacent to old mosque.

Previous to this investigation and with regard to gigantic size of the pillars it was taken for granted that the pillars are not constructed monolithically from bricks and instead they are made from stone blocks and lime and just surrounded by a layer of bricks, but the results proved the monolithic nature of these pillars.

Porches:

As we knew, the doctrine of architecture in Ilxani era was based on tendency toward magnificence and in order to achieve this, they had taken the advantages of thickening the pillars. The unsuccessful example of this tendency was the monument of Shanb-Gazan-Xaan in Tabriz-Iran which could not stay steady and had been demolished. The Soltaniyeh Dome is not an exemption and so has thick and very tall pillars.

However, the most genius and talented architects of that era who had a complete awareness of architecture and static, in order to lighten the structure and also to lessen loads on the foundation, had utilized a kind lightening method which is led to creation of porches. Existence of these porches in addition to facilitating the accessibility and beautification, had led to lightening of the structure. Also, there are some cabins in the first floor that, similar to porches, had resulted in lightening of structure and economizing the material employment. Moreover, these porches play another structural role that is preventing the probable movements and swirls in lower parts of pillars. Usually walls in the height of $1/3$, are encounter with the danger of refraction as the result of lateral forces and so the porches of the first floor were constructed to prevent swirling of the pillars of iwans; and in order to be able to do so, most probably in the back of groins beneath porches (and along the Chokkeh of first floor vault) several rows of have been incorporated which halt drifts and if pillars leant toward any side or swirled then the bond timber of adjacent groin would halt its drift.

Regarding the investigations, the second floor porch or outer porch in addition to lightening and beautification leads to reduction of drift, as well. It is noteworthy that drifts of vault and groin of porch are halted by wooden ties placed beneath the vault and load-uniforming woods incorporated in behind of the vault. Recently the tie woods had been removed from the structure and this resulted in creation of fractures in ridge of vault and groins. In behind of the vault and groins a series of palpate uniforming woods were applied which could engaged perfectly with surrounding materials and because of these branchlets, they barely may move and play the role of tie, as well.

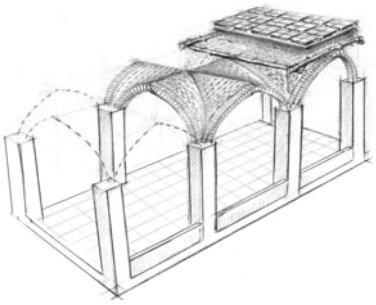

Fig. 4: Bond timber of second floor porch.

Fig. 5: Palpate woods of bond timber.

Minarets:

In historical monuments different methods were applied in order to reduce drifts which include using bond timber or guarding wall and thickening the walls. With respect to previous knowledge about Shanb-Gazan-Xaan, in this structure the architect in addition to thickening of the walls, had employed minarets to reduce slope angle of the dome that along with decorative aspects and beautification of the view, were devised to invert drift to weight so that every eight edges of the structure get immune to danger of joint movement. Of course, the role of stairways in this building should not be underestimated, since the stairs join the different floors together and also they have structural role similar to minarets and led to halt of drifts.

Arches of the Building:

According to studies, the type of arch used in vaults and groins of the structure is Shabdary-e-kond. In order to install the groins of the structure, at first the wall was constructed up to Pakaar (foot) of arch and then the double vault was built up to Shekargaah and then the floor vault was used to complete the arch.

In implementing the floor vault there is no need for moulding. If there was a wall behind the vault, the desired arch type is drawn on the wall and the brick work is done on the pattern using browning plaster. To do so, during the brick work the foreman plasterer puts mortar on the rows of arches and then places a brick on the mortar, meanwhile he has a plasterer mate who holds the brick until the mortar hardens and gets able to bear its weight. Usually in order to construct a double vault, the foreman starts brick work from both sides until reaching to the ridge.

Unlike the floor vault, however, moulding is necessary for constructing the double vault because it is constructed on the horizontal plane. Double and floor vaults are resistant to shearing and drift forces, respectively and combining those together results in a reasonably strong groin arch.

In the vault ridges of this building, application of the trapezoid bricks had led to enclosure of ridge top. Following the installation of groins and in order to reinforce the arches, three rows of Palaneh had been employed in the backside of all sections (Pirnia, 2002).

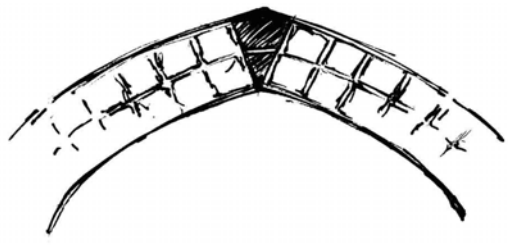

Fig. 6: Trapezoid bricks in ridge top.

Wood in Soltaniyeh Dome:

Wood and cane are considered as the most primeval types of materials for making building. They were prevalently utilized because of their availability, lightness, suitable compressive, tensile and shearing strengths, simple joints and fast installation. These specifications had enhanced the significance of wood among other construction materials and more specifically its application in the ceiling of the structure.

It is noteworthy that scarcity of wood in one hand and its vulnerability against termite, moisture and some other harmful factors on the other hand are logically resulted in limited utilization of wood in the buildings of central Iran.

Wooden Scaffold:

From among the facilitating roles of wood is its application as scaffold. Scaffolds of Soltaniyeh Dome were installed as follows. After constructing the wall for about 1.5 m, woods with length of possibly 50 – 60 cm were placed horizontally in the wall and then as many as needed flat timber were placed on these wooden scaffolds. The space between each row of timbers equals to the height of a man.

This operation continued up to the top of dome and after the accomplishment of the final stage of beautification works, the horizontal woods were cut and replaced by decorative objects from top to floor.

Structural Woods:

In Soltaniyeh structure, all walls and pillars were constructed in an integratedly and none of them, except for Torbat-Khaneh, were built separately or as an extension. The dome was built on the pillars which are placed integratedly on the foundation. In order to construct the dome, the architect had taken the advantage of two primary and secondary vaults. The first vault which considered as the secondary did not disturb the integrity and unity of the wall. Along with the construction of second vault (primary vault), however, these unity is gradually diminished and hence the load is transferred to secondary arch. To solve this problem, about two or three rows below the Pakaar of primary vault and about 1.5 m above the ridge of secondary vault, five rows of bond timbers with the diameter of 16 cm were placed in the vault (Moradi, 1994)

Fig. 7: Five rows of bond timber in Pakaar of primary vault.

In order to install the bonds, the first one were placed in the depth of 16 cm of the wall (toward inside) and then the next bonds were placed with the distance of 2 cm from each other. These bond timbers are probably built in five rows. However, using the Soundage method in cracks of southern vault, three rows of these bond timbers had been observed and the existence of two other rows seems to be more probable.

For joining bonds together, they were connected from beginning, middle and ending parts to each other by means of wooden timbers. This timber was placed above the bond and fastened to the underneath bonds using spikes. This caused that the bonds would not swirl and the space between them would be preserved.

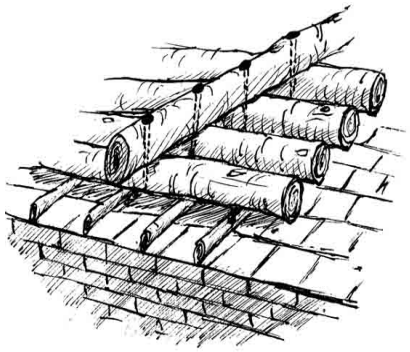

Fig. 8: Joining bonds together using spikes.

The so-called bonds were implemented in five rows and they existed in Pakaar of all primary vaults of iwans. The length of each bond is 10.5 m. Therefore there are 40 timber bonds in this section that in every iwans about 52.5 m of wood were employed and totally 420 m of wooden bonds with the diameter of 15 cm were utilized in Pakaar of primary vault.

Beside, the timber bonds were utilized in structure of outer porches, as well. To do so, two timbers were placed perpendicular to structure and two other timbers were set over them as a bond. These bonds fixed to the surrounding walls using their wooden branchlets because these branchlets prevents the movement of timbers.

Dome:

Soltaniyeh Dome is an interdepleted bonded double-shell dome and its outer and inner shell types are from the Shabdary-e-Tond arch and the Gous-e-Mazedar (Bastoo arch), respectively.

This dome was constructed on an octagon platform and in order to transform the shape of platform to circle, several Patghenehes were implemented which play a structural role. In Persian architecture, for transforming the quadrangle shape of ground to circle shape of dome, the architects usually had utilized Karbandy, Filpoosh, and Patgheneh, and so changed the platform model into eight-, sixteen-, thirty two, and sixty four-sides shapes.

This structure is also placed on an octagon platform that had changed into a 16-sides configuration by means of several Patghenehes in every angle of the structure and then the dome was constructed on it.

It is noteworthy that in most Persian monuments, the architects took the advantages of the double-shellness of bonded dome (two separated shells) in order to lessen inner height of building, humanizing the indoor space, and of course to increase the outer height of building. In this building, however, both shells were constructed parallel and bonded together so that they could not carry out the role of lessening the inner height of building. Hence, the logic behind the double-shellness of the dome could be as follows:

1- To prevent thermal exchanges
2- To restrain and counteract the weight load of tills and its mortar on inner shell.

Thus after constructing the first shell (inner shell), in a distance equal to 70 – 80 cm some Khashkhashi features were implemented in the form of Sandougeh or caisson on it, which transfer the weight of outer shell to pillars and then the outer shell were built and tile-work had accomplished on it.

Of course this gap between two shells had resulted in immunity of inner shell against moisture and in the case of any moisture infiltration into lower layers, thanks to implementation of caissons, this moisture would easily desorpted from the building. Based on aforementioned research by San Paolesy (1961) on the Dome, he had observed some vertical cracks in dome and therefore he had created a concrete belt in Pakaar (foot) of dome in order to anchor it.

South Vault Crack:

In order to investigate the crack and the causes of its creation, dimension of bricks that used in the southern vault was measured to be equal to 22*22*5 cm.

According to these data, the size of brick in topmost point of crack was 26 cm. Through this measurement it was revealed that the length of crack in its upper most point is equal to 3 cm and the remaining 1 cm was created as the result of erosion.

It was also appeared that the length of the crack in the bottommost point that is to say the ridge of secondary arch is equal to zero. In this stage, horizontal direction of the cracked bricks was measured by means of leveling pipe that revealed that the broken brick was about 2 cm above the bricks of the same row while it ought not to be. In addition, the brick joints of primary arch in west and east sides of the vault faced shrinkage and movement, respectively. Regarding these observation, the chief cause of the crack in southern vault seems to be the drift force. But the question is that what the main reason for this drift force was.

Based on previous investigations on adjacent pillars and studying the report of restoration by Professor San Paolesy (1961), it is found that the main cause of this drift force was the crack of southwest vault. This crack had been restored by Italian board of restoration.

Since in historical monuments and specially in this structure, the forces are run collectively and are in close relation with one another, the drift forces of the arches offset each other in one point and transform into weight forces. The crack leads to disturbance of this balance and possibly following to an earthquake the drift force of southern vault in primary arch got activated and resulted in movement of this force toward the crack and creation of southern vault crack. The direction of this crack is vertical and in the wall between two arches from the Shekarghah section, it had twisted toward the secondary arch.

This twisting of the wall in Shekarghah section had led to creation of a gap on the wall between primary and secondary arches. Taking the existence of timber bond in about 150cm above the ridge of secondary arch into consideration, the wall above the bond had stood still but the underneath wall had moved toward downside. The arch of secondary vault in west side had settled for about 1.5 cm and in one point it had reached to equilibrium and had formed an imaginary arch. In the other word, following to restoration of southwest vault crack, the southern one had arrived in a secondary stability and by implementing a testifier in 1985 it was proved that the crack is not currently active anymore.

South Vault Crack Restoration Plan:

With respect to this fact that the crack of southern vault had been restored in 2001, here only the method of restoration without any details or plan is being presented. In previous sections the process of crack formation was clarified but its restoration method is as follows:

Considering that the existing crack in southern vault is not active and only needs slight restoration. The method implemented, however, for this purpose is as follows:

In underneath of so-called timber bond there is no need for complete splitting of the crack and rebuilding it and on the other hand, this splitting and resetting of bricks may lead to some structural problems because the imaginary arch would diminish and there is the possibility of insufficient brick bonding during the reconstruction of the wall.

Therefore, the probability of forming another crack in that area is very would be very high so in order to repair the crack it would be enough to perform brick bonding of the wall in the face section and only up to one brick width from both side of crack. In addition, about 1.5 m over the ridge of secondary arch, there are ornamental wood works which were implemented in order to create a Gilouyi feature over there. Nowadays, these ornamentations were demolished and in some sections, there are Pakofteh bricks which were also removed because they used to inserted extra-weights over those sections. From the starting point of Gilouyi toward the beneath of the bond timbers, the ornamental wood-works were implemented up to the size of three Pakofteh bricks. In order to reinforce these woods, they are fasten together by means of cruciform high resistant woods and covered by metal gauze or rabitz; then plasterwork or other ornamentations would accomplished on them.

The underneath of bond timbers, however, must be reinforced because they had reached to their secondary tension and their resistance had been decreased significantly. In order to reinforce them, underneath of each bond should be exposed for about 1.5 m from both sides and another timber which is resistant against moisture and termite would be placed there. The new timber and the bond timber should fasten together by hoop irons so that they would lead to integrity and unity of it.

However, in upper side of bond timber the range of possible restoring actions are further, that is the restorer removes ornamental features by common methods and numbers them. Then reinforces their beneath up to underneath of primary vault using bonding and finally retransfers the ornamental features on restored structure.

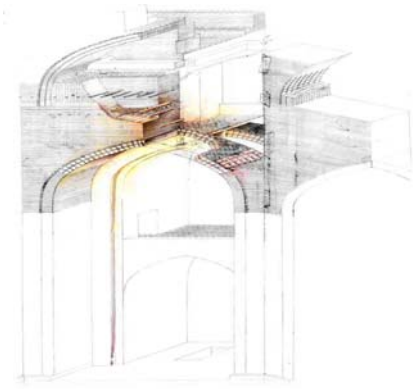

Fig. 9: Sketch of the structure of southern vault- Soltaniyeh Dome.

Conclusion:

With respect to importance of the monument of Soltaniyeh Dome and its specific historical and structural features, it could be stated that all damages and restorations are considered as historical event and they must be documented in a perfect and most accurate manner. In this perspective, the crack of southern vault of Soltaniyeh Dome from depth and structure points of view, however, is regarded as an important damage for the whole building and it may considered a good example for significant pattern of force movement and recognition of damaging factors.

Therefore, it is suggested that in order to restore this crack, at the beginning a comprehensive investigation would be accomplished on it and then for restoration, a method to be applied that a tint of crack remains on the vault. In the other word, along with restoration of crack, it is better to preserve the essence of it. To do so, for example after bonding the crack, we could set the bonding bricks some centimeters behind.

In this method we can clearly present the restoration activities so that the researchers could gain proper and complete information about the building in the future. This was accomplished through restoration of west vault crack. In the other word, since the Soltaniyeh Dome is a typical monument, its cracks ought to be typical, as well.

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Appendix:

Definition for some architecture technical words used in the text:

Bastoo arch: A kind of arch or Mazedar vault with high elevation.

Filpoosh: A well-known type of making corners.

Gilouyi: An ornamental feature strip which is set on the front or above the vaults; a partition between vault and wall.

Gous-e-Mazedar: Ellipsoidal arch or vault.

Implementing testifier: Pasting a piece of chuck or glass or other brittle material on the cracks of building in order to control it in such a way that if it broken, we can find out that the crack is continuing to move or opening up.

Iwan: A semi-opened space between inner and outer spaces of building; a roofed area which faces the yard.

Karbandy: it is made in the junctions of bond-timbers and is an decorative structure.

Khashkhashi: Small walls which are built over the lower arch of interdepleted bonded double-shell dome so that the upper arch would set on them.

Pakofteh bricks: Pasting bricks vertically on the wall in order to filling the gaps.

Palaneh: Several layers of brick work in the form of nogging; thickening the vault by means of several layers brick work.

Patgheneh: Several series of arc-shaped niche which were set on each other and lean forward; A method for making corners; The area where the dome transforms to circle.

Porch: A roofed, semi-opened and prolonged space in the building; a connecting space which usually created in one or several directions.

Shabdari Tond & Shabdari Kond: Some kinds of arch used for building domes.

Shekarghah: A spot in which the arch is launched up to the degree of 22.5o proportionate to horizon.