BEHAVIOR OF IRANIAN ARCHES IN EARTHQUAKE

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ABSTRACT

Vernacular Architect has formed by available tools and geographic-continental conditions in each region, and most of them have been expanded in the same direction. A large part of Iran's architecture was constituted by earthen architecture and the use of adobe and brick or coincident structure is obvious in most of them. Along with these issues, attention of architects due to multiple earthquakes in Iran, is obvious in traditional structure. Including, earthquake-resistant design and construction of the arches, which are often have a high stability against earthquakes. In some countries, various studies have been done on adobe structures, Such as the Getty Research Institute in America. Considering that I've translated this reports and books, and the differences between Iranian adobe structures and California region, so these reports are inapplicable in Iran. In this research we study a few specific arches in Iranian architecture, they're called Kanche-poush, Kolombo and Kajaveh. These arches, due to their high resistance to earthquake, have been used in most important architectural monuments in Iran. In this article we consider technical issues and state of arches in different forces, such as earthquake. The results of this research can help to design and restoration of vaulted structures in Iranian architecture and other countries that use the same structures.

Keywords: Abode arches, Brick, Earthquake, Reinforced arch

1. INTRODUCTION

Development of science and increasing of knowledge level is a co-relation link. If in this relation one of them be impaired, the progression in human life wouldn’t be achievable. On the other hand, the development speed increases every day and takes a progressive trend. In past, acquiring more knowledge had been experimentally which is clearly visible in the architecture extent, so that a building form or a structural component were in use for years and centuries, and during all this years, experiences of architects which gained from their constructions transferred to the next generations. Achaemenian with their high economic power were able to have artists, tools and materials and therefore they left a legacy of architecture which could teach the next empires that economy and investment always make the improvement possible. But with the overthrow of the Achaemenian, their architectural heritage left for Parthian and Sassanian that contrary to the Achaemenid era, these two empires had no great economic power. So they took another way and instead of economic power, invested on their intellectual and scientific strength. They established and optimized a new architectural systems based on arch and dome which trough it they could be self sufficiency in construction practices and eliminate dependence on outsider artists and materials. In a short time that the three most important monuments (Firooz Abad Fire-temple, Ghale Dokhtar-e Firooz Abad and Sarvestan Palace) were built, one can find the importance and grandeur of this construction style. This procedure was followed after Islam until architects were attempting to complete and fix the defects of previous periods and in this regard several vaults built in Iran that even today some of them are strongest and most stable structures of Iranian architecture. (Figures 1-3)

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2 Girl Castle in Firooz Abad
2. IRANIAN VAULTS

The curve covers not only in Iran but also in most countries of the world were commonplace. In Iran, the traditional architecture, especially in areas that lack wood locally, obsesses with arch and dome. Limited access to different buildings materials, and economic and political condition in Iran, was caused to focus on the architecture developing by using indigenous technologies. Therefore the vaults in Iranian architecture were varied and different forms found, so that the vaults based on the ground and building location, resistance required, the building plan, importance and value of building and other factors were designed and built. The same applies creates a different sort of vaults that include decoration vaults to structural vaults.

Iran is located on seismic belt and most of its cities are on the belt and this is what makes the architects always thought about the performance of building, especially vaults, against earthquake. Sometimes using special forms of vault was performed and sometimes by using auxiliary elements such as buttresses would guarantee the stability of the vaults. But in cities or villages fabrics that possible not to use elements and equipments for structural support, architects tried to optimize the behavior of vaults against lateral forces and pressures.

Using the precision divisions so that the forces to be pass uniformly to the piers, creating slope and special form of vaults so that forces are transferred completely and accurately and even carefully to structural details such as slope and angle of adobe-layer (brick-layer) courses or distance between courses and thickness of mortar between the bricks, all helped to established vaults be stable.

But between these, two factors play a larger role in the stability of the vaults. First, shape of arch that vault was built based on and second, shape of volume of vault, especially in the vaults that did not followed the form of an arch, such as Kolombo vault.

3. IRANIAN VAULTS STRUCTURE

Each vault apart from its volume shape relies on other several factors. Kind of base arch, load bearing ribs and piers. In another words operation of power transmission according to vault form and size, initially transferred to ribs and then are transferred through ribs to the piers. In this structure, the shape vault can be followed by a basic and specified form of Iranian arches or vault volume be entered to elements such as load bearing ribs that they followed by load bearing arches. Therefore the role of load bearing arches is very important and effective in the transmission of forces.

Iranian primary vaults that said "Ahang vault"\(^3\), was constructed on two parallel piers and would lean on one or two support that due to technical limitations and also increase likelihood of damage and increase

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\(^3\) Tunnel vault
harmful forces along the vault, if the vault was performed in large scale, it was always had a risk and architect was have to compensate this weakness with the diagonal courses and lean on them to the thick support pier or it was put on a thick pier that vault was placed on it. But with the innovation were done in the field of vault building, were using of the elements that were called "Tavizeh".4

The rib was vault sections that their opening was more than their deep. Therefore put on the rib name of "vault strip". This vault strips divided a place which was supposed to built a vault into several sections and put the vaults in between. Therefore first step in optimizing the vaults by doing this was done. This factor would caused weakness of vault building does not destruction of the whole cover, even weaker vault among the ribs destroyed and other vaults remains with ribs.

After inventing rib, for filling between them, emerged other type of vaults that two of them named "Kolombo" and "Kajaveh" due to the properties that had a remarkably stability, therefore vault and the rib that was performed by using Kolombo and Kajaveh, quickly become one of the most widely consumed type of coverage, so that in most residential and public buildings we can see the use of these two types of vaults.

The other type of Iranian sustainable vault is "4 Bakhsh vault"5 that this vault built between bearing ribs and because of its spatial structure do accurate segmentation of transferring loads. So that the first loads divided to 4 parts and then each section loads transferred to the 4 pillar and finally transferred to the ground. Other loads also received by 4 lateral ribs (between each two columns) and transferred to ground.

Another feature that has been able to give more stability and consistency to the Iranian vault and dome based architecture, is it continuity and interconnectedness, so that the sometimes several homes have a connection to one another in one urban fabric and the common elements behave as a backup to each other. Even this can be seen in homes located on both sides of alleys that caused the formation of elements in the historic fabric that called "Sabat"6.

4. EARTHQUAKE RESISTANT VAULTS

As mentioned earlier, Iranian vaults are have a different physical structure and among them 3 type of vaults more than other vaults are notable in terms of earthquake-resistant. These vaults are selected through 5 years researching in the field of Iranian architecture and review examples of the historical fabrics that earthquake occurred in there and so by professional work in the restoration of historical monuments that done by the author. Technical reason for selection them as a stable vaults against earthquake is called in continues when reviewing any vault. Mentioned vaults are allocated to large amount of vaults that built in Iran that even in the some cases by using special techniques and methods they have changed and optimized according to place of built.

One of the problems that obstacle in the analyzing these type of vaults in terms of structurally and their earthquake resistance is impossibility of using simulation software in the field of buildings structural analyzing. The specific form that exists in the various Iranian vaults, have made partly impossible for drawings and calculations methods with existing software and unfortunately, native software have not been written for this issue. Therefore, most reviews and analyzes have been based on objective observations, case studies analyzing, matching samples with each other and understand the curved structural behavior in the specific situations such as earthquakes.

4.1. Kajaveh Vault

The vault is usually performed in a rectangular plan. After the bearing ribs have been implemented (Given that the plan is rectangular, two of the four ribs will be smaller), bricklaying started from two sides in line with the smaller ribs and come together at the top of the larger rips. Kajaveh vault has slop from both side and has a curved form that it is similar to the tent (Figure 4).

According to the definition and its spatial form, the forces moved as a specific way from the tip of the vault and transmitted to the ground. Kajaveh vault is composed of 4 parts that are placed as symmetrically against another (This situation can be seen in the reverse plan of this vault) (Figure 5). This vault of each side relies on four ribs. Small sides rely on two small ribs and large sides rely on two large ribs. Therefore all aide of vault are completely enclosed between four ribs and can move all forces were generated in the vault.

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4 Rib
5 Quadripartite vault
6 Archway
But Iranian architects with a special bricklayer that are doing, provide great help to transporting forces to the fourth rips and at the same time, this work cause removed all forces of the vault. According to bricklayer plan (Figure 6) brick courses are arranged such a way that forces received from middle section (Intersects the two central axis) and are transferred to the four corners that it is the confluence of two small and big ribs. This issue causes forces transferred exactly to the location of the piers and the ribs received only part of the forces and then transfer to the ground (Figure 7). In other words small and large ribs received the part of the forces that by the shape of vault can't reach to the base and transmits to the ground. In this situation, the vault is perfectly in balance with all thrust and compressive forces. But as soon as other forces enters or the bottom structure balance get falls, more forces enters to ribs but because the ribs made of bearing arches, have ability to withstand forces and more forces will not cause them into destruction.

Studies show that that this vault in the proper implementation and bracing forces, is resist to 6 Richter earthquake that in the Bam earthquake and recent earthquake in Damgan (2011) it is visible. In some special cases, this type of vaults can also have a high resistance.

One of the features that make this vault is resistance against earthquake is volume dividing into 4 parts and the transfer of forces to foundation. The shape of Kajaveh vault is based on small ribs along and in line with large ribs, in another word the vault is composed of two form of bearing ribs. If preparing multiple cross sections of the vault, will always have the shape of small ribs (Figure 8) and If preparing longitudinal section of the vault will be shape of larger arch ribs. Based on this, this vault in cross sections and longitudinal sections has a stability form relying on the shape of bearing arches.
Studies and experiences show that Kajaveh vaults that it are implemented side by side with a common ribs have a good stability and even sometimes the destruction a Kajaveh vault is not damaging to its adjacent vault. This issue is indicates sole behavior of each vault in a series. For example it is possible to covered one space with four Kajaveh vault and during an earthquake only one of them destroyed and side vaults stay safely. In this case will remain intact \( \frac{3}{4} \) roof cover and this is a unique feature that have a vaults placed between groined vault system.

According to Figure 9, this vault in the points of A, B, C, and D have a maximum force and in E point have a minimum force. Low force rate in the E point allows that can use a hole in this point and in spaces that need to light and ventilation using this feature.

Building another floor on this vault it does not reduce the strength of its bearing because entered forces to the top of vault is transferable to the base by the shape of vault volume and usually in this situation architects use the ribs with high thickness to enhance the groined vault bearing system.

4.2. Kolombo Vault

The shape volume of his type vault is kind of dome and often known as the "Kolombo Dome" but the main difference with the dome that it is placed in the vault category is how to transfer forces. Iranian dome is a structural that it sits on four bearing wall, but Kolombo vault instead of four bearing wall sits on 4 pillar or 4 ribs. This will cause instead of using squinch (in the dome building is used) is used of elements called "Domgazeh". Domgazeh takes a great help in the transfer all existing forces on the four pillars. Domgazeh is inverted triangle form that from one side connected to vault and from two sides connected to ribs (Figure 12).
Because the Kolombo vault is a perfectly circular shape, usually be made in the square plan. Although some of it is built in the rectangular plan, but the stable form of this type of vault, it is a vault that it will implemented on the square plan. This vault built on four ribs which are the same size and shape (Based on the type of arch). If the arches are not the same causes the vault to be unstable and fall. Kolombo vault is built brick (or adobe) courses that it parallel to the ground and each course support is bottom course. For this reason, vault comes with location plans and dimensions and its height also follow from this and shape has a high bearing capability. The main weakness of Kolombo vault is failure to put a floor on it, because is not ability to withstand compressive loads but can transfer thrust and pressures forces occurring in the vault toward the piers and good inhibited. This vault form and shape is a high capacity to transfer forces so that in the sample was built with a brick or adobe still remain, although with water erosion and loss of multiple layers of brick (adobe) and mortar (Figures 13 and 14).

![Fig. 13 Bearing parts of Kolombo Vault](image)

![Fig. 14 Forces transferring form](image)

Kolombo vault has the ability to expand in the various plans and mostly used in caravansaries to built "Shotor-khan" (The camels place). Because of this the forces of Kolombo vault are entered into the four columns, with strengthening columns the vault stability also go rise. Also being the four Domgazeh in the four corners will be causes thrust and pressure forces of vault are transmitted to the pier, especially with a bearing ribs, having sufficient thickness and most important of all good interlocking between ribs and vaults. In this type of vault, the bottom space of the vault under the ribs is usable and it specific bearing causes that more space will also be used. Therefore it is used in the non-residential spaces and places that required to high altitude. If the vault is made continuously and side by side is called "Tagh-o Cheshmeht". Using the Tagh-o Cheshme behind the other spaces, causes the other vaults forces are also inhibit (Figure 15). Such a way that it usually built around the buildings with Kolombo vault.

![Fig. 15 Other forces inhibiting by Kolombo vault](image)
4.3. Chahar-bakhsh vault

This vault usually built on square plan and it can be added another floor. To build this vault, top of the four sections is placed the top of the head of ribs (Usually the size of a brick) to resist against the forces. The guide rip also use to build this vault from top of rips are implemented one or two bricks above that to can be resistant against the thrust forces. The bearing arch bricks continue from four sides and in the diameters the plan they interrupt each other.

Implementation of this vault in the square (or sometimes rectangle) plan causes to create symmetrical parts in front of each other. In the square plan each four parts of vault is equal together and the same forces have entered to the fourth column (Figure 18). In the rectangular plan also always have a balance from forces From 4 parts vault to four columns In corners (Combining forces on columns A and B) (Figure 19). Another factor in the stability of this vault, Neutralize forces each of the four sectors against another by exposure and rely on each other. This factor makes two pieces A and B (in Figure 20) to neutralize each other forces and pieces C and D (Same Figure) also neutralize each other forces.

In addition to the above factors, being parallel brick (or adobe) course will help on stability of each of the parts. Because of the this vault is also relying on four ribs, like as Kolombo vault, has the ability to expand and placement Chahar-bakhsh vaults side by side, considering each part have a separate behavior against the various forces provides stable total coverage against earthquakes.

The most important factor of this vault stability is its symmetrical figure and orientation forces based on the vault spatial form toward the four columns in the corners. Therefore it is possible to change forms of bricklayer, so that In Isfahan Great Mosque the vaults performed with a very high diversity in bricklayer plan.

The exact geometry of vault and good connection in brick course and with other pieces, the vault is very resistant to against earthquake. Figure of each piece of vault followed from ribs form. Therefore construction ribs follow by bearing arches takes a very high the total ability of the vault against the forces. Therefore vault cover is composed of four pieces with form of earthquake resistant arches. On the other hand, with jointing 4 pieces together another form of the arch obtained as the diagonal (Figure 21) and if during the Implementation of this vault, diagonal ribs guide to be implemented on the one of the arches Iranian bearing, in addition each fourth piece have a bearing arch, the whole structure of vault also building on the two diagonal arches, therefore will have a very high resistance.
Survey shows another factor that affects in stability of the Chahar-Baksh vault, is height difference between spots A (Confluence of four pieces together in the middle of vault) and spot B (head of ribs) (Figure 22). This causes pressure forces transmitted of the point A to the B and from B point is transferred to the piers by ribs.

5. CONCLUSION

Analytical studies on earthquake resistant three types of vaults and the case studies shows that traditional and local architecture although having weaknesses, compared with modern technologies in structures and materials, have a good behavior during the earthquake and during the structural imbalance. In Bam earthquake the destruction many buildings with modern materials were seen while the samples of adobe structures were standing non-destruction or with less damage.

It seems that using traditional forms in structure that have been retrofit by computer software analyzing still to be used in rural areas or towns with historic areas without damaging the traditional architectural contexts. This subject especially in countries such as Iran that the structure of rural architecture is usually the traditional forms, can offering guidelines about retrofitting them do a lot of help to prevent financial and physical losses and in addition to prevent change the face of traditional fabrics.

It also should not forget that most of traditional architecture elements today will be damage or destroy by earthquake is due to mortar and material weakness not shape or volume of building structure, therefore reinforcing these elements and strengthening and replacement materials can still maintain they stability.