

The methodology of Iranian curved arches (Sagh) based on their geometry

Afroz Rahimi Ariaei¹, Zahra Sadat Etezadi*²

¹Academic member, Isfahan Sepehr Institute of Higher Education, PhD student of architecture, Architecture faculty, Islamic Azad University of Sharekord

²* BA student, Interior architecture, Isfahan Sepehr Institute of Higher Education and the corresponding author

Received: March 8, 2015

Accepted: May 10, 2015

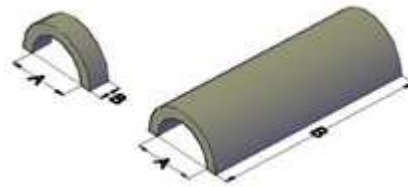
ABSTRACT

The architecture of each county is a display of its culture. So Iran's architecture is the mirror of Iranian cultures; the characteristics of Iranian culture could be found in its architecture and vice versa. In the meantime, arches are one of the apparent expressions of the link between architecture and culture. Iranian coverings, over the ages, have developed due to time requirements and innovative needs; generally speaking, coverings have two types of flat and curved (sagh). The diversity in the geometry of Iranian arches is the result of Iranian architects' efforts based on the antecedent's experiences and their own modern technical achievements. Relying on this reach background, by reclamation and innovation, we could prevent loosing and destruction of this art. Vaults that are made with wishbone arches would increase the height of the monument and have more static stability compared to other vaults. The present study is an effort to assess the typology of Iranian curved coverings (except for domes) based on their evolutionary history, geometry, and shape. This study was a historical, descriptive and analytic study on the basis of two methods of field and library study. Results showed that there was a significant, strong and direct relation between the culture, experiences and creativity of Iranian craftsmen and the diversity of arch's shapes. At the end, in addition to assessing the styles of Iranian curved arches, some recommendations for further studies would also be provided.

KEYWORDS: Methodology, Iranian coverings, Curved arch (sagh), Geometry, Iranian architecture.

1- INTRODUCTION

Architecture is a process combined with science, art, propensity, style, belief, faith and special skills which has been shaped through time based on culture and civilization and is the expressive language of its era [1]. Iranian coverings, over the ages, have developed due to time requirements and innovative needs: generally speaking, coverings have two types of flat and curved (sagh) (27). Tagh (vault) is an Arabic word and its Pahlavi equivalent is Tak (vault) [2]. Generally, vault is the covering between two walls and the shape that vault would follow based on its composition is called arch. Therefore in another definition a vault could be defined as the continuation of the arch; in fact if the depth of the monument would be more than its opening it would be called a vault and otherwise would be arch (Figure 1).



Arch = $B > A$ & Vault = $B < A$

Figure (1): Comparison of vault and arch (authors)

The simplest definition of arch according to architectural terms is that a vault is the movement of one or more arches in one or more axis that is between two walls or at least four load bearing pillars. It must be mentioned that Ghiyas-ud-din Jamshid Kashanihas used the term "azaj" instead of tagh (vault) (Azaj is the Arabic form of azag which means curved branch) and vault instead of arch (same). Based on another definition, by expanding an arc in space or three dimensions, a vault would be created [4]. In terms of form, a flat covering is a plane surface and since

* **Corresponding Author:** Zahra Sadat Etezadi, BA student, Interior architecture, Isfahan Sepehr Institute of Higher Education (zahra_1271641517@yahoo.com)

in this kind of covering the resultant forces on the vault are completely vertical, vault's stagnation against them requires usage of opposing load bearing shafts[5].

“To build a structure means to solve its technical stagnations issues using existing materials and considering the desired limits of performance and also considering a shape that could define its adjunction with its environment.” [4]. The aim of this article is to define the methodology, introduction, historiography and documentation of Iranian curved vaults from different aspects; since studying all of these subjects require more time, here just the methodology of domes has been studied and other matters could be the subject for further studies. Using targeted methods to study these factors and in fact the methodology of vaults, besides revealing the hidden value of these monuments, would be effective in recognition of its production process and its history and also in finding appropriate manners for preservation and restoration of historical and cultural heritage. However the architecture of our country is so rich in valuable experiments and achievements, that it needs recognition and representation to the Iranian and universal architectural community. Data extraction and typology of vaults are some of the important results of this study. Also providing recommendations for further studies is another achievement of this study.

1-1- Research Methods

This is an interpretive-historical and comparative study. Therefore at the beginning information about prototypes were defined through “direct field observation”, “interviewing masters of restoration of historical structures” and “library research”. Then structural form of vaults was modelled using three-dimensional software. Finally, by comparing and analyzing the results, the border differences in shape and history of each covering with others led to finalized typology of vaults.

1-2- Literature

Coverings, due to their importance, have attracted the attention of many researchers. Most of the researchers who have studied vault-related issues usually have studied its form and method of construction from different aspects [6,4, 5,7]. Some researchers such as Godard 1936, Dietrich Huff 1997 and Rolan Besenval 1984 had a form aspect toward the structure of Iranian vaults. Also some researchers have analyzed its stagnation [8,9]. In few references, other than mentioned subjects, vaults' constituent elements have also been reviewed[10, 7,11,12]. Although researchers have approached this subject from different aspects, but there are some common grounds to their results. As it is obvious from studies' backgrounds, most of the researchers on Iranian coverings were conducted based on their own goals to categorize these monuments; therefore, this study has tried to combine the methods of previous studies to provide a comprehensive categorization.

2- Types of Iranian Coverings

In a general categorization, vaults could be divided into two groups of flat and curved [13] that would be reviewed next.

2-1- Flat Covering

In terms of shape, flat covering is a slick surface and since in this kind of covering the resultant forces on the surface are completely vertical, vault's stagnation against them requires usage of opposing load bearing shafts. Before using iron in architecture, usually timber was used. Since in Iran available woods for structures are rare, flat coverings have always been problematic. What made it impossible in some places to use wood was termite. Throughout the history of Iranian architecture, alongside curved coverings (sagh), flat coverings were used for small openings [5].

2-2- Sagh Covering (curved)

The terms sagh or azagh or azag are called azaj in Arabic. Azagh is usually referred to branches of vine, palm, eglantine and jasmine which have an arcuate and curved shape. For referring to vault usually the term azag is used. Curved (sagh) covering is actually a cover that in terms of shape follows an arch. Choosing the right arch to bear the loads exerted on vaults and domes in Iranian architecture has been based on constructional and static logic of structures that were the results of years of experiences and practical skills of masters. Due to the familiarity of the people of desert areas with high resistance of oval arches, in those areas and also areas that used aqueduct for irrigation, to prevent falling of the aqueduct, they used to install large conduits inside them (which in local languages were called Gool or Gom) and they had an arc-shaped oval section. Sometimes, due to the wide openings of aqueducts, conduits were built in three pieces where each piece was a part of the arc-shaped oval. It must be noted

that, since in Iran load bearing formats are not used for formation of vaults, a semicircle shape is not appropriate for vaults and arches considering its stagnation and it could break in different places, if used [13].

This means that it would break toward outside at the Shokrgah point (the point where it has a degree of 22.5 degrees with horizon), toward inside at the Ivargah point (the point where it has a degree of 67.5 degrees with horizon) and at the peak point it would change shape. In order to prevent the above mentioned break downs, Iranian architects would turn the arc toward inside from Pakar to Shokrgah (meaning that they would reduce the radius of the arc and bring it closer to the center) and increase the radius at the Ivargah point where the break would be toward inside therefore the arc would be toward outside; so the arc would be restrained at the peak point where it changes shape. Hence the peak would be lower and the rising would be less than half of the opening. Finally the created arch is one of the most common arches of Iranian architecture named Panj O Haft. This arch is load bearing and could sustain the pressures exerted on it [13].

2-2-1: Types of Curved Coverings Based on Their Arches

Curved coverings are generally divided into two categories: rounded (oval) and pointed. Pointed arch, as it is clear by its name, has a pointed peak and is created from intersection of two curved arcs; it is also called a wishbone arch. The peak of rounded arch is crescent-shaped and is a partial oval. Both of these arches have a longstanding history in Iran and their best examples could be seen in Chogha Zanbil temple (1350 BC). Although, other than Chogha Zanbil, Wishbone arches could also be seen in Nooshijan Hills (Median Empire), Doroudzan Dam (Achaemenid Empire) and Kasra Arch (Sasanian Empire) and other structures before the Islamic era, but most of the arches of that time were rounded and even in the first centuries after Islam most of the arches were rounded; then gradually they changed into pointed arches (same).

The main reason for using wishbone arches was that rounded coverings would increase the height of the structure and since in Islamic art the goal was to reduce the magnitude of the structure, especially reducing the height, wishbone arches were used instead to give the structures more human scales. The best example for this gradual transition are the differences between Damghan's Tarikhaneh building (2nd Hijri century) and Fahraj Mosque (1st Hijri century) that were built within less than a century from each other. In the Fahraj Mosque all of the coverings are rounded but in the Tarikhaneh some have turned into pointed arches. Pointed arches in Iranian architecture are: Chamaneh arch, Sarvak, Steep Panj O Haft, Slow Panj O Haft, Kofte Panj O Haft, Kelil Arch (Parthian and Azeri), Kelil Komshi Arch, Steep Three Piece Arch, Slow Three Part Arch, Steep Goat's Horn Arch, Slow Goat's Horn Arch, Steep Shamrock Arch, Slow Shamrock Arch, Pa Tu Pa Arch... and rounded arches are: Sharp or Jar Rounded Arch, Steep Rounded Arch (Bayes or Steep Huluchin), Slow Rounded Arch (Bayes or Slow Huluchin), Kofte Rounded Arch [13, 10].

3- Types of Iranian Vaults Based on Their Evolutionary History

Based on the revolutionary history, Iranian vaults could be divided into two categories of before and after Islam.

3-1 Before Islam: Before the first millennium BC vaults were existed in the Chogha Zanbil. Also there are some evidences of vaults in Nooshijan and the Persepolis. Before Islam, Iranian vault building has been started from the Parthian Empire. Different types of arches along with vaults and domes were abundant during Parthian and Sasanian Empires and they were the inventors of some structural parts and administrative procedures [10].

3-2 After Islam: During this era using vaults and domes were so frequent that they became a part of Iranian architectural culture. During the first 4 centuries after Islam new methods of vaulting including Tagh Bandi, Potkane and Kar Bandi were invented (same: 131).

4- Types of Vaults Based On Tension Distribution and Geometrical Form

Based on the method of tension distribution on the environmental piers (bearings) of the covering space and geometrical form, vaults are divided into two groups of wide-shaped vaults (open) and close-shaped vault.

4-1 Wide-Shaped Vaults (Open)

This vault is created by the movement of a generative cross-section along a horizontal axis. The produced surface is a half-cylindrical shape that would be based on two parallel bearing lines [6]. The cross-section of this vault that is called barrel or cradle could be one of the sections of Iranian vaults. This type of vault is appropriate for place where they have one spatial axis; in fact they usually are used for rectangular spaces such as hallways, corridors and porches [13].

4-2 Close-Shaped Vaults

Based on their creation style, these vaults are divided into two groups: 1- circular shapes with short rises that are in fact the Colombos, and 2- combined vaults which their geometrical method of creation have led to multiple methods of transition and space covering.

4-2-1 Circular Vaults

This type of vault is created by rotation of a generative cross-section around a vertical axis. When the generative cross-section is a semi-circle the produced shape would be a hemisphere. This type of vault could also be created using a parabolic or oval cross-section. Circular vaults need interface elements (corner building) to adjust to square grounds [6].

4-2-2 Combined Closed Vaults

Unlike circular closed vaults that are produced by rotation of a generative cross-section and therefore lead to a determined curvature throughout the vertical space, closed vaults do not provide such identical and steady curvature. Where circular vaults are usually used for covering square or circular spaces, combined closed vaults are used for covering rectangular spaces. For square surfaces, these vaults would cross the edges in two symmetric sides and would define the two surfaces that include diameters.

5- Types of Vaults Based On Their Geometric Form

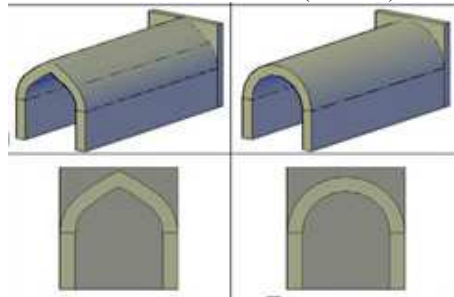
- 1- Simple vaults: BarrelVault, Tarbin, Groin, Colombo Type One, Colombo Type Two and Palanquin
- 2- Complex vaults: KhanchePoush, Arch Beam, Potkane, KarBandi[10].

5-1 Simple Vaults

5-1-1 Barrel Vault

It is produced by the movement of an arch through a horizontal axis on two equal and parallel walls. The curve of the vault had different shapes regarding the time and place of its construction. These vaults have been used in different places such as canals, hallways and porches. In structures before Islam until the second and third Hijri century oval-shaped curves (Bayes) and from the fourth century pointed arches were used [10]. Arches are constructed through four main administrative methods: barrel (Pari), ledge (Ilami), Chapile (partitioned) and combined (barrel and chapile)[14].

Table 1: Barrel vault (authors)



• Indicator Examples of Barrel Vault

Before Islam: The most ancient found example was in Chogha Zanbil (tomb, administrative method was barrel, Bayes curve (oval) and it was constructed with bricks and plaster mortar) [15]. During the Achaemenid Empire this type of vault was used to cover canals. It has also been used during Parthian Empires such as Al-Hazra. But its usage peaked during Sasanian Empires (Fire Temple of Firooz Abad, Kasra Vault, Sarvestan Palace. All three had Bayes vaults). The Kasra Vault with an opening of about 25.5 m, height of about 30 m and depth of 42.5 m was a great monument and the symbol of the power of Sasanian Empires. Three methods of barrels, ledge (Ilami) and Chapile were used in its construction.

After Islam: After Islam for about three centuries structures were built smaller sizes (Fahraj and Tabriz Grand Mosques). During the 5th and 6th centuries Barrel vaults were used in some great monuments (SofeDarvish of the Grand Mosque of Isfahan and the main porch of the Grand Mosque of Ardestan). In the 8th century the Alishah Mosque of Tabriz (722 Hijri) had the greatest Barrel vault of Iran with an opening of about 30 m, height of about 40 m and porch depth of about 65 m. This monument was ruined after a while. Due to its simple administration, this type of vault has been frequently used in local architectures especially in desert houses [10]. (Table 2)

Table (2): Indicator examples of barrel vault (authors)



5-1-2 Tarbin Vault (GardePoush)

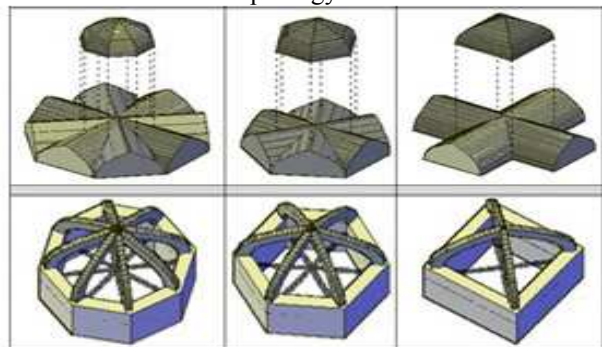
Patch or slice in vaults is a part of the whole that would create a covering by putting some of them together. To have a better understanding of this type of vault assume that two barrel vaults are collided by 90 degrees; their intersection would produce a Tarbin or Groinvault [10].

- Types of tarbin vault: These vaults are constructed in four, six and eight patch types (Table 3). This vault would be constructed on two types of bases; foursquare to octagonal base and circular base which this type of vault would be somehow similar to “Colombo vault with arch beam”. In general some of the characteristics of tarbin vaults are similar to characteristics of tarbin domes [10]. The history of principal and technical GardePoush vaults with more than three corner buildings and pendentives that starts with a curved rotation around two horizontal and vertical axis goes back to the Sasanian Empires; examples of this pendentive exist in Firooz Abad palaces, Sarvestan Palaces... and during Islamic era it was used in adobe and brick structures [7].

- Morphology of tarbin Vaults: These vaults could be categorized as simple tarbin vaults and tarbin vault with arch beam. Simple tarbin vault is a vault that is like a line from within the distance of two patches and they could be constructed on square or rectangular bases. Tarbin vaults with arch beam are arches as thick as one or more bricks. They vary from 2 to 4 arch beams. Arch beams would be placed on the diameter of the vault and also on two edges of the vault’s base (Table 3).

- Applications: These vaults were mostly used for springs of mosque’s seraglio. Sometimes they were used for small rooms of cottages. Generally this type of vault has not been used for important spaces (same).

Table 3. Morphology of tarbin vaults



- Indicator Examples of Tarbin Vault**

Before Islam: The most ancient tarbin dome is The ChaharTaghi of Niasarwith eight patches (220 AD). Some researchers believed that squinch that is produced from the combination of two patches inspired architects to build this dome [1, 7].

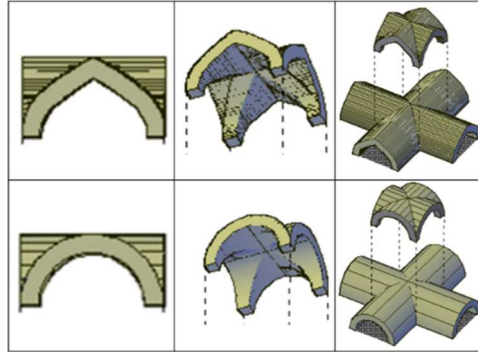
After Islam: This type of vault was so common during the 5th and 6th centuries but researchers believe that foundation of its shapes was done during Buyid dynasty; during this era potkane vaults were created based on small

patches or taseh. Brick tarbin vaults over huge spaces could be seen at the late 5th and 6th centuries in monuments such as The Grand Mosque of Isfahan and Ardestan[1, 7].

5-1-3 Groin Vault

This type of vault is created from four pieces and it is similar to a four piece vault in its plan but it looks different in section and three views. This vault similar to the four piece vault is created by crossing two barrel vaults but the difference is that in tarbin vaults we considered the intersection but in groin vaults we assume their intersection with the square base[1]. This type of vault emphasis on chaharsuand one of its important features is that by putting them together, they could cover a wide space. In some examples of this vault Iranian architects have reduced its rise and put a flat surface on it to use it as a second floor [5]. (Table 4)

Table 4:Morphology of groin vault

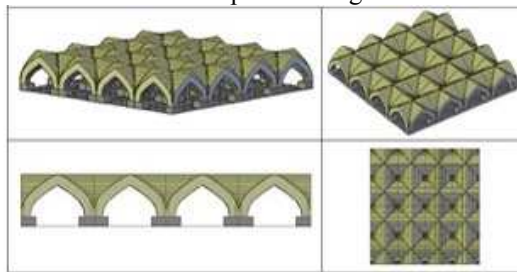


• **Indicator Examples of Groin Vaults**

Some of the Western researchers believe that Iranian groin vaults are rooted in Western [16]. In the existing architectural works after Islam this type of vault was first used in The Grand Mosque of Shiraz (281 Hijri/894 AD) [14,]; this date is about 200 years prior to the creation of Gothic architecture. Afterward it was used in The Grand Mosque of Isfahan and Iranian researchers do not believe that it has been an imitation of Gothic architecture. One of the Iranian monuments with multiple groin vaults is The Grand Mosque of Varamin[1].

Groin vaults could be divided into two groups based on their foundation. One group is based on thick piers like seraglio of The Grand Mosque of Natanz (700 to 720 Hijri) and the second group (tent) is based on four short pillars that could be seen in some monuments from Ilkhanate, Timurid and Safaviddynasties. Some of its examples are seraglio of The New Mosque of Sheikh Jam of Khorasan (848 Hijri/1444 AD) and seraglio of Beit-O-Sheta of The Grand Mosque of Isfahan. Since winter seraglios are used in cold weather, they must have low ceilings and the least possible windows; groin vaults start at the height of half a meter without the need for four pillars. Some researchers believe that this type of vault belonged to the Safavid dynasty [17]. But there are evidences that this vault was used during Ilkhanate and Temurid dynasties too. Winter seraglio of Imam and Sheikh Lotfollah Mosques (11thHijri century) are of this type too; during this era southern seraglio of The Grand Mosque of Ardestan was built with kelil curve [18]. Another reason for building these tent vaults are their resistance against exerted loads. (Table 5)

Table 5:The expansion of groin vaults

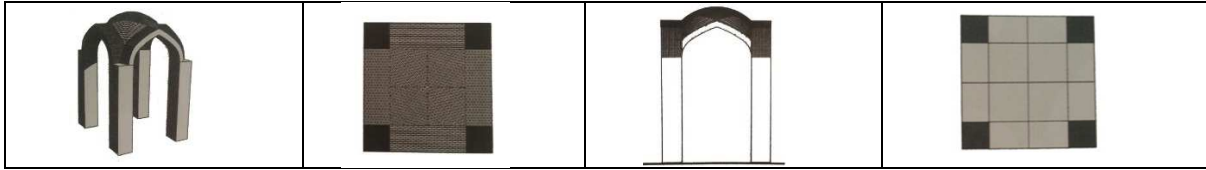


5-1-4 Colombo Vault

Colombo vaults are strong vaults that have stayed still in abandoned caravansaries in deserts for centuries; master Pirnia believe them to be one of the toughest vaults of Iranian architecture[5]. Geometrically, Colombo vault

is a hemisphere that its circular base would be settled on four hangers. Colombo vault could be set on a square or a close to a square rectangle. In other words one of the main features of Colombo vaults is that the extension of its openings is equal in both sides. Colombo vault could also be places on an octagonal base and be called a small dome. The main characteristic of this vault is that its rounded base could be seen from beneath [1].

Table 6: Morphology of Colombo vaults



• **Morphology and Administration of Colombo Vault**

Implementation of colombo have three parts: 1- Pendentives: the pendentives of colombo vaults are the same as other pendentives and no differences could be observed in them. 2- Skullcap: it is a hemispherical bulk that would be places on the pendentives. 3- Corner building: it is the gap between the corners of the pendentives and the skullcap [1].

5-1-5 Colombo Vault Type Two (four laps)

This vault is one of the most important Iranian vaults and belongs to the Sasanian Empires. Its difference with colombo vault type one is shortly mentioned in the next table. (Table 7)

Table 7 :Colombo Vault form between type 1 and type Colombo (four away) (Source: the authors, Pictures Memarian 0.1391)

| | Colombo type 1 | Colombo type 2 |
|----------------------------|-----------------------------------|----------------------|
| Differences in form | Yes | Yes |
| Pendentives | Yes | Yes |
| Skullcap | Circular base | Square base |
| Corner building | Store | Four curved diamonds |
| | Broken store | |
| | Combination (store and octagonal) | |
| | Narrow foot | |
| | Stellar KarBandi | |
| | Other methods | |

5-1-6 Palanquin Vault

If we expand the Chahar Dari vault (envelope four patch) from both sides a palanquin vault would be produced. Its executive history returns to the Safavid dynasty [7]. One of the main characteristics of palanquin vault is that the depth of its opening is about 3 to 4 times more than its width. Therefore the intensity of forces and tension is more longitudinally than the transverse direct. Hence, unlike colombo vault, the thickness and structural role of pendentives are nor equal here. The pendentives on the longitudinal sides bear the main load and are thicker and the pendentives on the transverse sides bear less load and have less width; this is the main structural feature of this vault and what distinguishes it from colombo vault [1]. Palanquin vault is the resultant of the movement of a curve on two main pendentives. In this vault the bigger pendentive is pointed and the moving curve could be pointed or not (same: 226).

There are two ways to create a vault between two pendentives:

- a) Two pendentives and a vault between them would create a barrel vault and pendentives are just seen as juts. The main curve of barrel vault is parallel to the main bigger pendentives.
- b) The vault's curve is parallel with the smaller transverse pendentives and the pillars of arches of the medial vault are settled on the main pendentives (the palanquin vault).

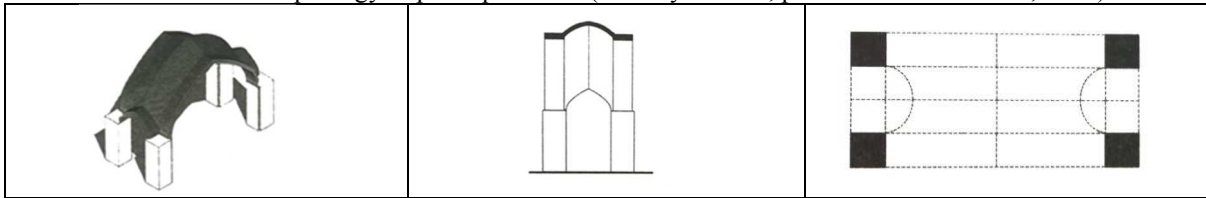
These vaults have two structural limitations:

- 1- They would create a huge Buoyancy at their own Pakar
- 2- Thrust would exist at any point of the Pakar of the barrel vault

Smaller palanquin vaults are fast to construct. Speed in implementation and simplicity have made this vault so common in local architecture especially in houses on the ledge of the desert. Palanquin vault is very common in Zavarehand have been used as covering for SofeKhanes of Dezfouli and Shooshtari. One of its indicator examples is The Grand Mosque of Tabriz [1]. Generally envelope four patch vaults were used for spaces in rural and traditional

residential buildings that had limited size; but palanquin vault has a high rise and it has been used for constructing wide openings like bazaars [1] (Table 8).

Table 8: Morphology of palanquin vault (table by authors, picture from Memarian, 2012)



- **Types of palanquin vaults**

1- The common palanquin vault includes two main longitudinal and two small pendentives. Between these four a joined room would be constructed. So no dissociation in vault between pendentives would be seen from the inside.

2- A discrete surface exists between two main pendentives and it is due to a ventricular element such as working with arch beams. Some examples of this vault are seen in the Southeast seraglio of The Grand Mosque of Isfahan [1]. The great Shah Abbasi seraglio of The Grand Mosque of Isfahan includes seven openings of great palanquin vaults. Galdieri believed that formerly, instead of each palanquin vault, there were three openings of colombo vault and each palanquin vault is created by eliminating three openings (same: 236).

- **Vault's Template**

The administrative method for this vault is to use four templates in direct inclined lines for four sides of palanquin vault that would be settled on four corners and intersection of rows from Pakar to the point; two arcs of pendentives would pass through the scapula. Then each side of the vault would be covered like direct rows but at the conflux intersection of rows and by considering the junctions (Zamarshidi, 2003: 120).

5-2 Complex Vaults

5-2-1 KhanchePoush Vault (cradle cap)

KhanchePoush vault (cradle) belongs to the Sasanian era. This covering was used frequently in “once was there Arg-e-Bam” [7]. This vault includes these four parts:

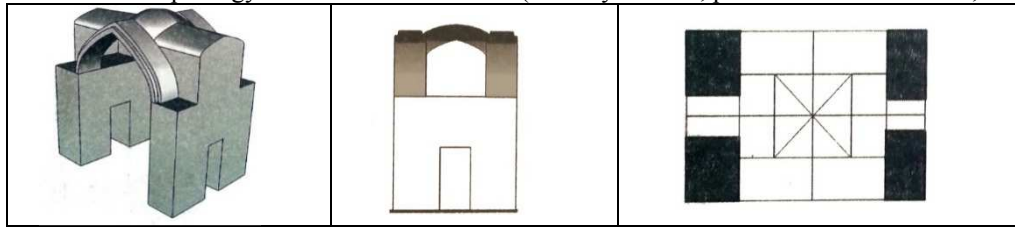
1- Pendentives 2- The wall on the pendentive 3- Barrel vault 4- Medial square-shaped vault

Applying this implementation in KhanchePoush vault would lead to a distinctive feature. By applying two walls on pendentives and putting the barrel vault on them, the width of the room on Pakar would bear no load. Therefore different types of windows could be used as skylight; palanquin vaults do not have this ability. Another difference between this vault and palanquin vault is the method of settlement of barrel vault on pendentives. In KhanchePoush vault on the two main pendentives and the first load bearer a horizontal wall would be placed until it is close to the peak point of the main pendentive, then a barrel vault would be placed on it. But in palanquin vaults a small semi-barrel vault would move parallel to the small pendentive and on the big pendentive toward their peak points [1]. (Table 9)

Cradle vaults that are also known as barrel vault are used in covering rural residential buildings that are usually made with adobe and rarely with brick [7]. Barrel vault and medial vault have variety in their shapes. Barrel vault is between two pendentives in both rounded (without a point) and pointed arches. Pointed examples of barrel vaults could be seen in The Grand Mosque of Isfahan and Mozafarieh School and its rounded example is the mosque of PaderakhtMohammadiyeh district in Naein[13]. Another part of KhanchePoush vault is medial vault that could be seen in The Grand Mosque of Yazd and Mozafary School of The Grand Mosque of Isfahan. In The Grand Mosque of Ghaen and Yazd colombo vaults settled on octagonal bases could be seen [1]. (Table 9)

KhanchePoush vault is common in Naein and Meibod cities for covering small local mosques. In these cities the total space of the mosque is a simple elongated space that is covered with a marquee of KhanchePoush vault. Naein's PaderakhtMasjedSeyed is one of these examples. The building is expanded from east to west and the altar is placed in a small pier beneath two pendentives of the vault [1].

Table 9: Morphology of KhanchePoush vault (table by authors, pictures from Memarian, 2012)



- Features of KhanchePoush Vault: It is appropriate for stretched spaces and could provide skylight on both sides of the vault. Also fast administration is another ability of this vault [1, 7].

- Iranian Art and Architecture in Europe: Girshman, French archeologist contemporaneous with Andre Godard, believed that Saint Germain des Pres in France has been designed like a fire temple and its walls are decorated with plasters that are similar to the shape of Tree of Life in Taq-e-Bostan. He did not believe that this example was an exception and mentioned other examples including the Bic Church. Girshman said “the bent index finger of the hand that was the symbol of respect for grandees during Sasanian Empire has been engraved without even realizing its true meaning”[19]. He said about Sasanian art: “The stronger the art, the further its effect would reach and its durability would be more secure –even in other countries. The Sasanian art had this destiny and was expanded from China to Atlantic Ocean. It had a great impact especially in West where its inspirational role on the medieval art is so obvious” [19, 1].

- KhanchePoush vault of Ivan-e-Karkheh: Ivan-e Karkheh is a monument from the Sasanian era in the 4th century AD. Its marquee cover was a KhanchePoush vault and it was first represented to the world by Madam Dieulafoyin her book. Andre Godard for proving that KhanchePoush vault was French has searched its roots in the Middle East:

- 1- The first samples were observed in Jerusalem and Hawran.
- 2- Afterward other samples were discovered in Syria that had two main pendentives and was covered with a flat stone.
- 3- During Parthian dynasty this technique traveled from Syria to Mesopotamia and was used in construction of Al-Hazra palace.
- 4- It went from Mesopotamia to Assyria and implanted with brick coverage.
- 5- Then the method of Mesopotamia was used in Ivan-e-Karkheh.
- 6- After Islam it was used in different places, such as Okheidar, The Grand Mosque of Shiraz andKhan-e-Artame and in all of these examples the imitative aspect is noticeable [20].

- Ivan-e-Karkheh: Some of the great Iranian archeologists describe this monument as follows :”Twenty kilometers northwest of the ruins of Susa and almost at the same distance in the southwest of Dezfool the remainings of a great palace from Sasanian dynastyare visible on the right side of the Karkheh river... Regarding its brick crescent vault and other features of the building, it could be assumed that it was once a glorious chamber...” [21]. Characteristics of the components of monument’s walls that were presented in 2015 are as follows:

- The width of the remaining wall’s foundation of the east side: 2.35 m
- The length of the remaining broken (ruined) wall: 18 m
- The foundation’s width of the monument’s northern pier from west: 2 m
- The width of the remaining wall at the north of the monument: 5.35 m
- The thickness of the original bricks: 6-8 cm (32 * 32 * 6-8)
- A remaining half-arch: 1.60 m
- Five square-shaped tamche: 1 * 2.30 m (that were Ivan’s skylight under the vault) [22].

Iranian architects considered KhanchePoush vault as at least one of the top ten Iranian vaults and their minds were more developed than just simple vaults and Mogharnas, YazdiBandi and KarBandi for them were mind games yet their designs and implementations showed ingenuity and creativity of Iranian architects [1].

5-2-2 Vaults with Arch Beams

Vault is a curved structural part that is used to cover a space and in simple words arch beam is an arch and bearing arc. When this arch is placed on a port, or even a space, and is combined with other arches and the combination covers a space, a structure would be produced that cannot be called a complete vault;

because the gaps between arches are still empty. After filling the gaps with brick covering, the vault would be complete and it would be called a vault with arch beams [1].

Table 10: Morphology of vaults with arch beams (table by authors, pictures from Memarian, 2012)



- Administration of Vaults with Arch Beams: In above mentioned vaults due to accurate consideration of building continuity and their architectural shape, construction starts from all four sides at the same time. But it is not the same for vaults with arch beams. First arch beams that are the bearing frame would be administered and the interval coverings would be installed in the vaults [1].
- Stagnation Ability: Vaults like colombo, groin, tarbin, palanquin and barrel follow a continuous transmission of symmetrical forces on their own supports. Vaults with arch beams break this regulation. By creating an arch beam an arch is produced. The arch would transmit the force to its two points of support. Therefore total arch beams (load bearing arches) would transmit the forces to different points on the vault's support. In this system transmission of force to supports is point wise not surface wise (same: 270).
- Spatial Ability: When the vault has shape diversity it could be extended to vertical and even horizontal surfaces. In this case, following the lines of arch beams, we could frame and shelf the body of the space and change the uniformity of the continuous walls. Another important feature is the ability to transmit light to the space. In vaults with arch beams, skylights could be installed in gaps between two arch beams. In The Grand Mosque of Isfahan 12 skylights are installed in a vault with arch beams [1].
- Shaping Ability: Combination of arch beams like working with KarBandi would allow us to create diverse polyhedral shapes to cover the body. It might be one of the reasons for popularity of vaults with arch beams, KarBandi and Potkane. This ability allows the architect to design his marquee like sky. In this sky sometimes moving toward a point that indicates unity of God and the sources of all lights could be clearly observed [1].
- Shape System of Vaults with Arch Beams: The geometry of vaults with arch beams could be divided into three main groups:
 - 1- Vaults with paired parallel arch beams where each pair cross the other horizontally.
 - 2- Vaults with paired parallel arch beams where each pair cross the other as a combination of horizontally and oblique.
 - 3- Vaults with radial arch beams (same: 280)
- Vault with arch beams and tarbin dome with arch beams: Tarbin domes with arch beams are the larger kind of vault with arch beams, type three. Both of these coverings have circular bases. The line of arch beams would move from the base to the peak of the vault. The thickness of arch beams could be seen with some bricks. If the size of vaults with arch beams would be doubled or triple, something like the tarbin dome with arch beams of The Grand Mosque of Isfahan would be produced.
- Administrative Method of Vault with Arch Beams: First a plaster doublet would be placed on the Pakar of the vault. This is the case where the plaster doublet must be hidden inside arch beams. If the plaster doublet must be removed at the end of the work, it would be installed on the interior edge of the vault's base. On this plaster doublet an arch with thickness of one brick would be placed. This brick arch would be the foundation for administration of arch beams. By adding more rows on and beside this arch it would be strengthened and finally a load bearing arch beam would be produced. This simple administration is specific for Iranian architects [1].
- Historical Examples:
 - 960-990 AD: Existence of arch beams in Islamic monuments of Spain
 - 1150 AD: Existence of arch beams in groin vaults of Gothic

- 1420 AD: Existence of arch beams in the dome of the Cathedral of Santa Maria del Fiore, Italy
 - 890 AD: Existence of a vault similar to KarBandi in The Grand Mosque of Shiraz
 - 907 AD: Cornering with arch beams in the tomb of Samanid Amir Ismael in Bukhara
 - Around 950-960 AD: Existence of arch beams in bleached cover and spatial radial axis of Neain's Grand Mosque
 - 1072-1075 AD: Construction of the dome of Nizam Al-Mulk by tarbin dome with arch beams and with an opening of 15 m high
 - 110-1150 AD: Existence of vaults with arch beams in southern seraglio of mosques
- Comparing the history of vaults with arch beams in Iran and Western countries obviously shows its longest history in Iran (Memarian, 2012: 280-281).

5-2-3 Potkane Vault

Potkane is one of the most amazing and complex vaults of Iranian architecture. Specialized dictionaries of architecture like Iranian Mehrazi Dictionary (architecture), The Dictionary of Traditional Iranian Architecture (Fallah Far, 2009: 54; Rafei Sereshki, 2003: 124) and encyclopedia of architecture and urbanism, according to the writings of Master Pirnia, have defined Potkane as follows: "Potkane is a shape consisted of some sconces being placed on each other and bulging to shape a corner. Potkane means Kanehor shelf over shelf". He has defined the border between Mogharnas and Potkane through the differences in their administrations and structural behavior and has written: "at the first sight, Potkane is very similar to Mogharnas and could be mistaken with that. The major difference between these two is in their administration. Mogharnas is hanging from the ceiling but Potkane is standing on its own and is not hanging... "[5]. Camellia and David Edwards in their article has named Potkane as "shouldered arch" [23]. Many books and articles have been written about the geometry of Iranian architecture and most of them have reviewed its appearance and geometric patterns. While structural calculations of Iranian architecture use geometry and organism and niresh of architecture are also based on geometry [24]. Andre Godard has indirectly described Potkane. He has mentioned examples of cornering in The Grand Mosques of Isfahan and Bersian, and believed that shelves of Potkane are decorative and "since by destroying the shelves the dome would stand still, transmission of load is only through backrests and the shelves are decorative." [25].

Table 11: Morphology of Potkane shelves (table by authors, pictures from Memarian, 2012)



• History of Formation

One of the most important issues in the history of world architecture has been transmitting square surface to spatial circle. This issue was solved by Iranian architects for the first time. The time of inventing cornering has been estimated to be at the late Ashkani era which was improved during Sasanian era and especially after Islam. Iranian architects of Ashkani era were the firsts to look for a solution to place a circle dome on a square body [1]. Dome house is consisted of three parts of dome, bashan and chapireh. Dome house is the field of the dome and bashan (body) is the part that rises on three sides as a cube (or other regular shapes) and has one or two open sides. And finally Chapireh (accumulated) is the part where the square or rectangle would fade into a circle and places the dome over the bashan [5]. What could be the development of Potkane is squinch cornering. Master Lorzadeh in the book of "resurrection of forgotten arts" defined this matter as follows: "For covering large openings and churches wood was used. Gradually, by using brick, large ceilings of Sasanian and Ashkanian styles were produced. Large meshes were gradually come forward from the corners of arches toward their peaks and change the square into a circle-shape. This implementation was problematic for large openings and was life-threatening. Therefore masters and great architects decided to find another way to change meshes into circles. So they put smaller vaults in between the four vaults and hence changed the square into an octagonal; their works could still be found in some places." [26]. "Squinch is consisted of two diagonal vaults that have crossed each other in a point (more accurately in a

line)... the intersection of two vaults would create this type of cornering.” (Pirnia, 1991: 22) The result of the intersection of these two vaults would produce curved triangular shelves in space that are called taseh[1]. The cornering implemented in the tomb of Samanid Amir Ismael was one of the first samples where a Sasanian course was expanded using arch beams. The next sample was found in Isfahan during Buyid dynasty. At the time of development of The Grand Mosque of Isfahan, Jorjir Mosque (the current Hakim Mosque) was built in 327 Hijri[1]. For the first time during the second half of the 4th Hijri century in The Grand Mosque of Naein, Potkane was developed from a shape at the corner of the space to a covering and the first examples of application of Potkane in vaults were appeared [27]. The most ancient date recorded in this monument has been engraved on its wooden pulpit and belongs to 784 Hijri. But Flary compared the decorations of this mosque with decorations of some monuments from Abbasid dynasty and believed that this mosque was constructed in the second half of the 3rd Hijri century [28].

- Abilities of Potkane: As it has been seen in the tomb of Samanid Amir Ismael and at the facade of Jorjir Mosque, on one hand Potkane is able to cover the corners of the space and on the other hand it could create a covered space in The Grand Mosque of Naein; this ability has created a collection of domical and vaulted coverings in semi-open and closed spaces[1].

- Structural Behavior: Understanding the structural behavior of Potkane is very complicated and vague for most of the people. Islamic architecture had tendency to achieve previous references and information and develop them into Islamic themes and methods. Also in Islamic arts, shapes always have an unclear role and it is not certain whether a shape is just decorative or not and there are so many elements that are a combination of these two cases [23].

In fact when a Muslim architect dominant niresh requirements of the building starts to process and develop the shape of the building. The late Abolghasemi have mentioned this matter “most of the things that are conducted in architecture regarding structure, later, could be considered decorative. Mogharnas is one of the things that is structural but later would be considered decorative. Originally Mogharnas was used for covering and was a part of load bearing structure.” [29]. Regarding their participation in load transfer, Potkane could be divided into two groups of imagery (array) and imagery-structural (combined) [1].

- * Imagery (Array) Group: In the imagery group, the geometry of Potkane which is rooted in architecture of previous eras would continue as a imagery tradition. Therefore this group’s Potkane, in terms of structure, have no share in load bearing and are considered decorative. In other words in this group Potkane is a tool to shape the interior layer of the space. The first created sample of this type of Potkane is at the top of the southern entrance’s doorway of Gonbad-e-Qabus tower (397 Hijri) in Gorgan. A similar sample in details of works conducted on brick body is a tomb in Varamin. Another samples of Potkane are The Grand Mosque of Yazd, The Grand Mosque of Varamin and the tomb of PirBakran [1].

Other samples of developed imagery potkane could be found as a decorative cover on the old walls of altars. The altar of the eastern porch of The Grand Mosque of Isfahan, the altar of the Eziran Mosque and the altar of The Grand Mosque of Bersianare examples of this group [1].

- * Imagery-Structural Group (Combined): Potkane of this group, other than following the geometrical patterns of Potkane, also have a structural role too and bear the load of forces exerted by other parts and resulted by their own weights. The samples of this group could be found in the following categories:

- 1- Potkane with arch beam and taseh: The grand Mosque of Naein is the most ancient sample of this type. Other samples are The Taj-o-Mulk dome of The Grand Mosque of Isfahan and The Grand Mosque of Varzaneh.

- 2- Potkane with arch beams, taseh and tensile elements: Its samples could be found in western (Master) and Southern Sofe (Lord) and The Grand Mosque of Isfahan [1].

- Potkane as a vault: Early samples of using Potkane as a vault could be found in The Grand Mosque of Naein (The second half of the 4th Hijri century). Other samples of vaulted Potkane could be found in coverings of seraglios of The Grand Mosque of Isfahan. These seraglios along with porches of The Grand Mosque of Isfahan, by having more than 470 vaults, are truly a museum for vaulted coverings. In the south eastern seraglio of The Grand Mosque Isfahan, samples of Potkane coverings for small openings could be seen [1]. A sample of different usage of Potkane could be found in coverings of adjacent rooms of Shagerd Porch (eastern) of The Grand Mosque of Isfahan that Galdieri believed it belonged to the Seljuq dynasty [17]; in fact this covering is a combination of two Potkane that create two complete vaults and four half-vaults. Studying and understanding this covering is the first step for understanding Potkane covering in half-vaults and it could be said that half-vault Potkane is a development of this sample[1]. Galdieri has described the structural behavior of this vault as follows:” on one hand this covering introduces a developed administrative method that was common during Seljuq dynasty and on the other hand it is the indicator of complexity and development of administration during that era... the underlying

ceiling is like a crust that sometimes is the load bearer and sometimes is hanging by itself and even most of the times it is independent from the main upper architectural parts (arch beams). Arch beams, in turn, are leaning over other structural parts and rarely get close to the underlying crust” [17].

- Potkane In Semi-Open Spaces: The most outstanding Potkane were appeared at the late 5th Hijri century as porch coverings. At this point, from a part for cornering, Potkane had become a developed marquee that could cover wide openings. Two supreme examples of this type are the coverings of southern (lord) and western Sofe(master) of The Grand Mosque of Isfahan. High altitude of the covering has made the architect to use such large taseh and therefore create an appropriate covering relative to the space (Memarian, 2012: 327). Many people like Godard wrongly believe that the covering of all three eastern, southern and western porches are Mogharnas and call it pendant [16].

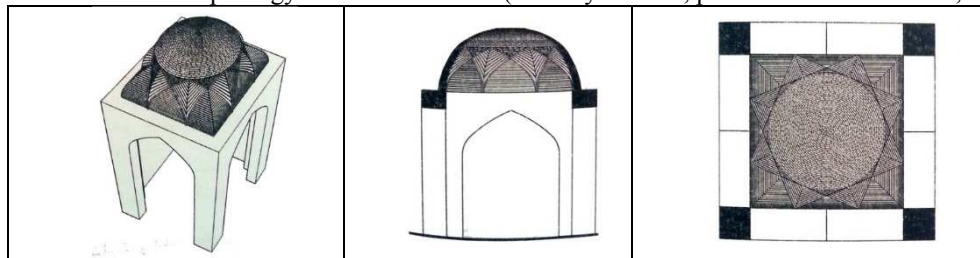
5-2-4 KarBandi Vault

In appearance, work in KarBandi curved lines in different sizes. In terms of vocabulary, attaching these works together is called KarBandi that would become a complete covering by adding a skullcap. Among written references, two valuable works exist about KarBandi. The first is by Master Pirnia and Engineer Bozorgmehri[30] and the other one is by Sherbaf[31] and Memarian, 2012: 337-338 [1] (Table 12).

- **Morphology and administration of KarBandi:**

- 1- ZirHafti, an arch or a perfect arc that is used as the imagery base for creating work.
- 2- Open chest or liliaceous: In formal KarBandi for extending works to shamsch or the central sun in the background of the KarBandi, an intermediate element is required that one foot and two feet works would be settled on it. This element is called liliaceous.
- 3- Narrow feet: In the lower corners of KarBandi a long diamond shaped element with two long sides and two short sides exists.
- 4- Moth or Bergamot: Small diamonds which are symmetrical with respect to the longitudinal axis. Moths could repeat over each other in some orders.
- 5- Samosa: In the gap between two sides of moth and the base of skullcap a triangle would be created that is called samosa.
- 6- Shamsch or central sun: A sun like shape that is created from combination of samosas beneath the skullcap.
- 7- Skullcap: The covering that is placed on the sun of the KarBandi. This cover could be simple or have patches [5, 30].

Table 12: The morphology of KarBandi vault (table by authors, pictures from Memarian, 2012)



- **The Ability of KarBandi Space**

- 1- Totally closed space on square, rectangle, eight Kashkoobi, gemmed, eight and half-eight, corner twist, half-eight, one side gemmed and half eight. Rectangle spaces in different proportions, from square-like rectangles to long rectangles are all covered with KarBandi.
- 2- One side open spaces that exist in porches and balconies. This type of KarBandi is called half-work which is called by the name of its complete type. For example if a half-work KarBandi has 8 moths it is called 16 half-work. Half-works have three types. This categorization is named based on the spatial ratio of sides that are covered [26].
 - Square half-work: The size of the opening is double the size of its depth.
 - Tight half-work: The size of the opening is more than double the size of its depth.
 - Transportation half-work: The size of the opening is half or less than half of the size of its depth [1].

- Types of KarBandi
 - 1- Based on the shape and the space it covers
 - 2- Based on the placement of works in space:
 - Plummet format KarBandi: One of the features of plummet format KarBandi is the size of the diameter of its shamse or central sun. The opening of plummet KarBandi is the size of two peaks facing each other across the work.
 - Thick head format KarBandi: In this format, works place toward the horizontal line in a way that the image of arch's peak and two Pakars are not on a straight line and they create a broken line.
 - 3- **Based on the shape:**
 - Formal: It is applied to KarBandis that perform on rectangular, especially long rectangle surfaces. To do this, a complete formal would be performed in the middle of the background and since the base is long another formal KarBandi would be performed on both sides of the central KarBandi. The result would be a KarBandi covering with half a formal on one side and another half on the other side and one formal KarBandi in the middle [30].
 - Stellar: This type of KarBandi is mostly used in square and close to square bases. Stellar would be performed in continuous and disjoint methods. Its planning method is easier than formals. Disjoint stellar is produced from the movement of a square inside a circle. Continuous stellar is produced by the movement of a line inside a circle. This line would connect the arcs of the circle for example 5 by 5 until it reaches the first point [30].
- Administration of KarBandi:
 - 1) Performing post arch
 - 2) Setting plaster molds (or metal in new works)
 - 3) Performing arch beams
 - 4) Performing secondary arch beams and filling the gaps between arch beams (Pour Nadery, 1996: 26-32)

6- CONCLUSIONS

Iranian architects have always tried to race each other in increasing the opening and height and decreasing the weight of the monument. Sometimes in different historical eras, vaults had special characteristics and became the indicator of that time's architecture. Actually by studying the architecture of each era, along with the innovations of that era, traces of predecessors and a long unity could obviously be found. This feature could rarely be found in contemporary architecture of Iran. According to the present study Iranian vaults could be categorized and evaluated based on different criteria (Table 13).

Table 13. Morphology of KarBandi vault (authors)

| Categorization of Iranian vaults | Flat | |
|--|-------------------------|-------------------|
| | Curved | Rounded |
| Different types of Iranian vault based on their evolutionary history | Before Islam | Pointed |
| | After Islam | |
| Types of vaults based on tension distribution and geometrical form | Widespread vault (Open) | |
| | Closed vault | Rotational vaults |
| Types of vaults based on geometrical form | Simple Vaults | Rotational vaults |
| | | Barrel |
| | | Tarbin |
| | | Groin |
| | | Colombo type one |
| | Complex vaults | Colombo type two |
| | | Palanquin |
| | | KhanchehPoush |
| | | Arch beams |
| | | Potkane |
| | KarBandi | |

Diverse structural forms of Iranian vaults are the result of innovative effort of Iranian architect that has created new and diverse vaults using previous experiences and new and safe techniques. Actually what is created could not

be the results of a delusion or an immediate experience and its durability must have been proved to the architect. Other than cultural, social, political, economic, and environmental matters and the performance and method of the work, other factors like capability, mental state and the taste of the architect are also effective on making a monument unique. For further studies matters like methodology of Iranian domes and the construction method of these valuable elements of Iranian architecture could be considered.

REFERENCES

1. Memarian Gh (2012), *Niaresh in Iranian architecture*, Volume 1 & 2, Tehran: Naghme No Andish.
2. Rafei Sereshki B, Rafei Zadeh N, Ranjbar Kermani AM (2003), *Iranian Mehrazi Dictionary (architecture)*, Building and Housing Research Center.
3. Youschkevitch P. and Rosenfeld. B. A. 1987. "al-Kāshī (al-Kāshānī), Ghiyāth al-Dīn Jamshīd Mas'ūd" *Dictionary of Scientific Biography*.
4. Memarian Gh (1988), *Niaresh of vault structures in Islamic architecture of Iran*, Tehran, Jahade Daneshgahi, Iran Science and Technology University.
5. Pirnia M (1991), *Dome*, Asar Journal no. 20, Cultural Heritage Organization.
6. Besenval R (2000), *Technique of vaults in ancient East*, Trans: Mohsen Habibi, First edition, Volume 1 & 2, Tehran: Cultural Heritage Organization.
7. Zamarshidi H (2003), *Iranian architecture, Construction with traditional materials*, Tehran: Azadeh Publications, 6th edition.
8. Hejazi M (2008), *Isfahan, city of traditional monuments*, Danesh Nama, 16th year, no. 161-162 (3), p 27-52.
9. South, Nanette & Habib Sadid. (2005). *A Finite Element Analysis of the Monolighic Dom*. Publisher: Idaho state university.
10. Memarian Gh (2001), *The neglected discourse and position of Iranian architecture in the history of world architecture*, *Memariva Farhang Quarterly*, no. 11, year 3.
11. Tehrani F (1992), *Beyond the geometry of vault and dome*, *Sofeh*, Second year, no. 6-8, 9 58-
12. Tehrani F, Rasekhi M (2009), *Vault and arc*, *Bulletin of Engineers of Florence*, no. 6, 12-31.
13. Pirnia M (1998), *Arches and vaults*, Asar Journal no. 24, Cultural Heritage Organization.
14. Pirnia M (1974), *Art book of high school*, Architecture section.
15. Negahban A (2003), *Excavations of Haft Tape, fields of Khuzestan*, Cultural Heritage Organization.
16. Godard A (1990), *Iranian vaults*, Tehran: Farhangsara
17. Galdieri A (1991), *Grand Mosque of Isfahan*, Trans: Abdollah Jabal Ameli, Tehran: Cultural Heritage Publications, Volume 3.
18. Pirnia M (2008), *Methodology of Iranian architecture*, Memarian, Gholamhosein, Tehran: Soroushe Danesh.
19. Girshman R (1989), *Iran from the beginning until Islam*, Trans: Mohammad Moein, Tehran, Scientific and Cultural Publishing Company.
20. Godard A (1988), *Iran's art works*, Volume 3, Trans: Abolhasan Sarv Moghadam, Mashhad, Astane Ghodse Razavi.
21. Mostafavi S (1939), *Ivan-e-Karkheh and Grand Mosque of Dezfoul*, *Amoozeshva Parvaresh Journal*, no. 7-8, p 94.
22. Eghtedari A (1974), *Diare Shahre Yaran*, Tehran, National Heritage Association.
23. Edwards c. and David Edwards (1999), *The Evolution of the Shouldered Arch in Medical Islamic Architecture*, *Architectured history Vol.42 PP.68 -95*.
24. Abolghasi L (1987), *Formative norms in Islamic Iranian architecture*, *Iranian architecture during Islamic era*, Compilation: Mostafa Kiani, Tehran, Jahade Daneshgahi.
25. Godard A (1990), *Iranian vaults*, Trans: Kerantollah Afsar, Tehran: Farhangsara.
26. Lorzadeh H (2006), *Resurrection of forgotten arts*, Tehran: Mola.
27. Pirnia M (2003), *Methodology of Iranian architecture*, Tehran, Pajoohande-Memar Publication
28. Flary S (no date), *The mosque of Naein*, Trans: Klor Kalbasi, Asar Journal, 22-23, Galdieri E (1991), *The Grand Mosque of Isfahan*, Volume 3, Trans: Abdollah Jabal Ameli, Isfahan: Cultural Heritage.
29. Abolghasemi, Mohsen, 2005. *A guide to Iran Ancient Languages*, Vol. 2, p 3
30. Bozorgmehri Z (1981), *Geometry in Iranian architecture*, Tehran, National Heritage Association Publication (second edition 1979).
31. Sherbaf A (1983), *Knot and Kar Bandi*, First Volume, Tehran, Publication of National Organization for Protection of Monuments (second edition 1979).