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Geometric Proportions in the Structure of Mazey Arches in the Sasanian Period Vaults

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Abstract: *The Sasanian period of architecture is regarded as one of the most brilliant artistic and engineering construction periods in pre-Islamic Iranian history. This era, which began in the 3rd century CE, not only inherited the engineering knowledge of its predecessors, such as the Achaemenids and Parthians, but also introduced significant innovations in spatial and structural design. One of the most prominent architectural features of the Sasanian period is the use of massive and tall vaulted arches with semi-circular arches, allowing architects to create vast spaces without columns. The design of these arches, especially in large iwans and massive domes, required mastery of geometric and mathematical principles. The main objective of this research is to identify the arches used in Sasanian-period vaults to uncover the hidden geometry in the design and construction of these structures. This study employs a descriptive-analytical method with an emphasis on the application of geometry in architecture to examine the arches used in buildings from this period. The results indicate that the arches employed during this period are of the "mazey" type, utilizing geometric ratios of 2:1, 3:2, and 4:3 in their plan designs. Additionally, circular geometry and geometric curvature principles were applied in the design of these arches to optimize load distribution. Therefore, these structures are not only regarded as a technical achievement but also demonstrate a visual representation of order, symmetry, and balance through the use of precise geometric proportions. Ultimately, it can be stated that Sasanian period architecture extensively utilized geometry in the design and construction of buildings, particularly concerning ratios, scales, and complex structures, with engineers and architects possessing complete mastery of geometric principles to achieve stability and beauty in their constructions.*

Keywords: Iran, Architecture, Arch, Mazey, Golden Ratios, Geometry, Sasanian

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Introduction

Proportions are a mathematical concept that addresses the relationship between components and the whole, contributing to visual beauty in architecture. Proportions can arise either through intuition and insight or through the application of mathematical ratios. Humans have long sought to discover these proportions to satisfy their curiosity and to incorporate them into their works. Thus, they have understood the relationship between sizes and shapes, using geometry as a suitable tool for organizing architecture and establishing conscious relationships between elements, enabling them to utilize the integrity of space as a creative and purposeful composition. Historically, proportions have played a significant role in both Iranian and global architecture, with architects employing not only mathematics but also geometry. In this way, the system of proportions is a collection of fixed visual ratios between components and the whole,[1] and geometry serves as a suitable tool for organizing architecture and establishing conscious relationships among building components to create a unified space despite its complexity.[2] One of the frequently recurring structures in Sasanian period architecture is the vault. A vault refers to a ceiling that rests on two bases aligned at the same level and parallel to each other, consisting of five parts: two circular arcs, two curved sections, and a connecting piece that completes the vault.[3] Thus, it can be said that the vault covers the space between two walls, and the shape that the vault takes in terms of composition is called an arch. Vaults and arches were used to cover iwans, corridors, alcoves, and domes, allowing architects to create large spans without the need for columns. The origins of this covering date back to the Parthian period. In this period, to demonstrate the grandeur of the building, they used a portico with a barrel vault, which is a prominent feature of Parthian architecture, and this structure was completed and reached its peak during the Sasanian period. Researchers who have studied the vaults of the Sasanian period and the application of geometry in the buildings of this period include André Godard, who dedicated a section of his book "The Works of Iran" to introducing the Iranian vault and discussed the techniques of vault construction.[4] Golombek and Wilber also examined vaults and arches.[5] Pirnia have conducted research in this field, addressing technical aspects and drawing methods.[6] Zomoroshidi, in his book *Vault and Arch in Iranian Architecture*, initially discusses traditional architecture and then explores the use of arches and their execution in Islamic period works and some contemporary

[1] Donals & Willber, 1955; Pirbabaei, Medghalichi & Mirahmadi, 2023: 46.
[2] Najafgholi Pourkalantari, Etesam & Habib, 2017: 478; Mansouri, Habib & Shahcheraghi, 2023: 6.
[3] Kashani, 2021: 27.
[4] Godard, 1936.
[5] Golombek & Wilber, 1995.
[6] Pirnia, 1994, 1999.

structures.[7] Hejazi, in an article titled *Geometry in nature and Persian architecture*, discusses the golden proportions found in nature and their application in traditional Iranian architecture.[8] Bamanian (*et al*.)[9] explored the application of geometry and proportions in architecture, examining the concept of geometry in various historical buildings from an aesthetic perspective.[10] Kharazmi (*et al*.), in an article titled *Applied Geometry in the Decorations of Pre-Islamic Iranian Architecture*, discussed the application of geometry in Achaemenid, Parthian, and Sasanian period works, stating that geometry made significant advancements during the Sasanian period.[11] Valibeig (*et al*.) also analyzed the geometric and mathematical features in the structure of five or seven pointed arches in Iranian music vaults.[12] Sodaei and Khosravi, in an article titled *Study of Decorative Plasterwork of the Jahangir Dome and Goryeh with Emphasis on Applied Geometry*, addressed the application of geometry in Sasanian period plasterwork, noting that the motifs used in these decorations were created based on complex and innovative geometric divisions.[13] Given that there has been limited research on Sasanian period arches, it is necessary to examine the arches used in palaces, fire temples, and fortresses of the Sasanian period from a technical perspective. The aim of this research is to identify the used arches in Sasanian period vaults to uncover the hidden geometry in the design and construction of these structures. The research questions are: 1. By investigating the vault in various buildings of the Sassanid period, what type of arch was used to construct them? 2. What proportions were utilized in executing these structures?

Research Methodology

This research was conducted using a descriptive-analytical method with a focus on the application of geometry in pre-Islamic architecture. Initially, information was gathered through field observations and library research. Then, to achieve the theoretical foundations of the research, golden ratios and geometry in architecture were utilized, and geometric drawings were executed based on the geometric shapes from various texts, such as *Iranian Geometry* by Abū al-Wafā' al-Būzjānī,[14] *The Key to Calculation* by Ghiyath al-Din Kashani,[15] and *Arch and Vault* by Zomoroshidi,[16], using

[7] Zomoroshidi, 2008.
[8] Hejazi, 2005.
[9] Bamanian, Akhot & Baghaei, 2011.
[10] Bamanian, Akhot & Baghaei, 2011.
[11] Kharazmi, Afhami & Tavoosi, 2012.
[12] Valibeig, Mehdizadeh & Tehrani, 2012.
[13] Sodaei & Khosravi, 2024.
[14] Abū al-Wafā' al-Būzjānī, 1990.
[15] Kashani, 2021.
[16] Zomoroshidi, 2008.

AutoCAD software. In this way, examples of Sasanian period vaults were placed within geometric models, and the proportions used in them were identified. To investigate the vaults in Sasanian period buildings, efforts were made to select prominent and less damaged structures for analyzing geometric proportions, considering that many buildings from this period have been destroyed.

Discussion

With the rise of the Parthians, significant transformations occurred in Iranian architecture regarding materials, construction methods, and designs. Notably, this included the introduction of tall coverings with spherical and dome-shaped valuts, known as the Parthian style. This method reached its peak during the Sasanian period, where Iranian architects skillfully executed tall iwans with arched shape, examples of which can be found in palaces, religious buildings, fortresses, and military fortifications, which will be introduced below.

Palaces

Palaces are the most prominent remnants of Sasanian period architecture, characterized by a diverse range of designs yet organized with symmetrical axes and elements like iwans and valut. The palace of Ardashir I (r. 224-242 CE) in Firuzabad and the Qal'eh Dokhtar feature reception halls with deep iwans and side rooms positioned in front of the central dome room.[17] Another notable palace from this period is the Palace of Shapur I (r. 242-272 CE) in Bishapur, which is a striking example of early Sasanian period architecture. This palace consists of a large central hall measuring 22 meters on each side, featuring decorative niches topped by a massive dome.[18] During this period, the hallmark of palace architecture was the iwans and dome rooms [Fig. 1]. By the mid-Sasanian period, few palaces remained, with notable remains from this era including the Hajibad noble house in Fars province.[19] The Palace of Khosrow I (r. 531-579 CE) at Takht-e Soleyman and the Taq Kasra in Ctesiphon date back to the late Sasanian period. In this era, the iwans with wide valut and semi-circular coverings became a defining feature of palaces.[20] The main design of palaces during this period typically included a large iwans and a domed room behind it.[21]

[17] Mohammadi *et al*., 2011: 86.
[18] Schippmann, 2005: 129.
[19] Azarnoush, 2008.
[20] Watclin, 1938; Huff, 1986: 332.
[21] Pope, 1933: 75; Kröger, 1982; Huff, 2005: 371-395.

Fig. 1. Entrance iwans of the Palace of Ardashir with semi-circular arches in Firuzabad, Fars (by the Authors).

Religious Buildings

From an architectural perspective, the religious buildings of this period can be divided into three groups: 1. Religious complexes where the central core consists of a domed four-iwan structure with covered corridors around it, featuring spaces for various uses, such as the Fire Temple of Takht-e Soleyman. 2. Independent fire temples that include a domed four-iwan structure with covered corridors, such as the four-iwan in Firuzabad. 3. Independent four-iwan structures which include a domed room with four wide openings, making the interior visible from all sides, like the four-iwan of Negar in Kerman [Fig. 2]. In addition to four-iwans, structures associated with the worship of Anahita have also been discovered, such as the Anahita Temple in Bishapur, which was constructed in a unique style using carved stone.[22]

[22] Khaledian *et al*, 2017: 35-71.

Fig. 2. Four-Iwan of Negar with semi-circular arches in Kerman province (by the Authors).

Fortresses and Military Fortifications

Another segment of the architectural remnants from the Sasanian period includes defensive buildings and installations, such as city walls, various fortresses, and large defensive walls with towers and battlements.[23] These structures have suffered significant destruction. Among these fortresses is the site of Kuh-e Khwaja, which includes diverse spaces for defensive buildings, citadels, and religious structures.[24] Radiocarbon tests on the mortar of the gallery room conducted by Ghanimati date the construction of this site between 80 and 240 CE (late Parthian to early Sasanian periods), while other tested samples indicate dates between 540 and 650 CE (late Sasanian period).[25] Investigation of the structures at Kuh-e Khwaja shows the use of iwans with sleeping semi-circular arches [Fig. 3]. Another fortress from this period is the Qal'eh Dokhtar in Firuzabad, where many parts have been destroyed, but remains of tall iwans with arched vaults can still be observed. Thus, it can be stated that arched shape was one of the hallmark structures in Sasanian period architecture, utilized in both religious and non-religious architecture across various regions, leaving a remarkable legacy in Iranian architecture. The following sections will explore the geometric proportions in the arches of the Sasanian period. In geometric terms, an arch consists of a line or curved shape (arch), and in architectural terminology, it refers to the narrow valut that rests atop a doorway. In terms of curved coverings, they can be divided into two sections: elliptical and pointed arches. The pointed arch, as the name suggests, has a sharp apex formed by the intersection of two curved arches and is also known as a "gabled arch." Morphologically, it encompasses various types

[23] Schippmann, 2005: 133.
[24] Mehrafarin, Mosavi Haji & Bani Jamali, 2011: 43.
[25] Ghanimati, 2000: 137-150.

including scalloped, pointed, goat-horned, three-part, four-part, five-part, and seven-part arches.[26] Curved arches are semi-circular in shape and include circular, egg-shaped, and Haluchin arches, which are commonly referred to as "mazey arches." The mazey arch exhibits continuity at its upper section. Architects employed mathematical and geometric principles to construct these arches, considering the method of bearing compressive forces, which can be categorized into four groups: sharp, tond, kond, and flat [Fig. 4].[27] Considering the mazey and pointed arches and examining the buildings of the Sasanian period, it can be stated that during this time, mazey arches (elliptical) were utilized. The following sections will discuss the execution of these arches.

Fig. 3. Arched shape used in sections of the Kuh-e Khwaja complex in Sistan (by the Authors).

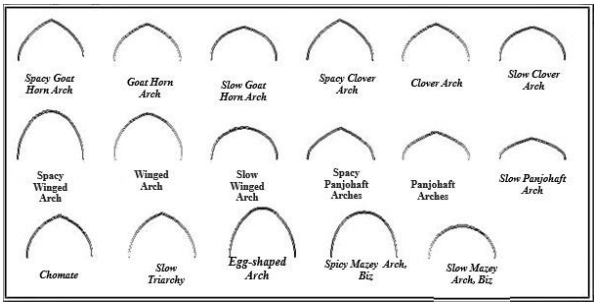

Fig. 4. Types of arches used in Iranian architecture (by the Authors).

Sharp Mazey Arch or Bistu

The sharp mazey arch, also known as "Biz Tiz," is one of the types of elliptical arches in traditional Iranian architecture. To draw this arch, two columns and vertical and horizontal axes are first established. Then, point O2 is determined on the vertical axis at a distance L from the horizontal axis. Next, arcs are drawn from points A and B

[26] Kashani, 2021: 52-73.
[27] Pirnia, 2003; Von Meiss, 2013.

with a radius of BA, intersecting the extensions of O2A and O2A at points k and K'. Finally, an arc is drawn from the center O2 with a radius of O2K, connecting the previous two arcs and completing the arch [Fig. 5]. This process is executed in six stages using AutoCAD. This method is based on an upright elliptical geometry with a focal distance to span ratio of 4:3, providing a high rise and consequently greater load-bearing capacity.[28] By investigating some remnants from the Sasanian period, this type of arch has been used in the Anahita Temple in Bishapur, the corridors of Takht-e Soleyman, and the entrances of the Sarvestan Palace [Fig. 6].

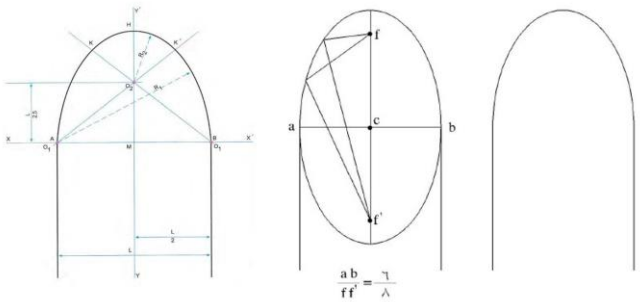

Fig. 5. Left drawing of the sharp mazey arch or Bistu (after Zomoroshidi, 2008: 162, Pl. 220); right drawing by the Authors.

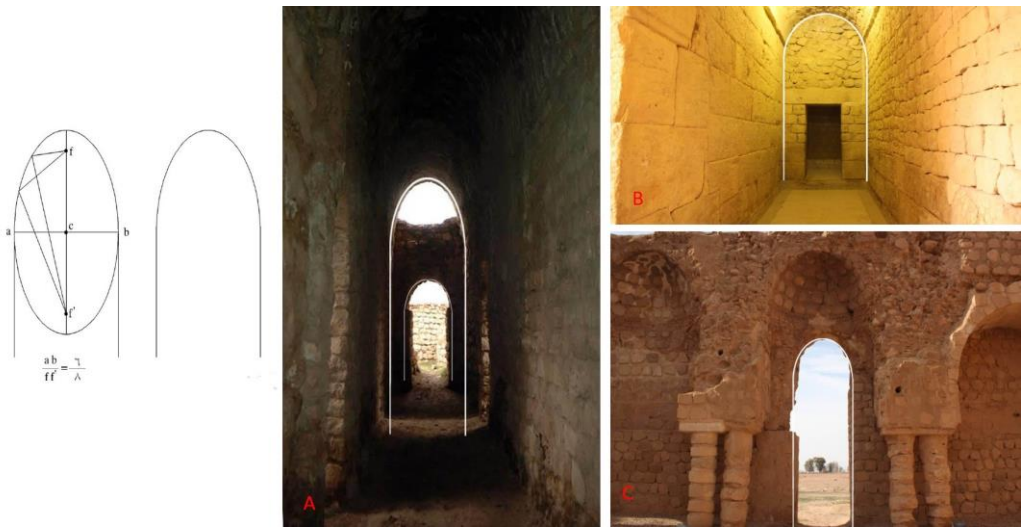

Fig. 6. Entrance corridors of Takht-e Soleyman in Takab (a); Corridor of the Anahita Temple in Bishapur, Fars (b); Sarvestan Palace in Fars (c) (by the Authors).

[28] Zomoroshidi, 2008: 169.

Spicy Mazey Arch, Biz or Haluchin Tond

The spciy mazey arch, also known as “Biz spicy” (Biz Tond) or “Spacy Haluchin” (Haluchin Tond), is another type of elliptical arch in traditional Iranian architecture. This arch has a lower rise and is defined mathematically as an upright ellipse with a focal distance equal to the span. Due to its sufficient rise, this arch possesses significant strength and was widely used during the Sasanian period. The method of drawing it is as follows: two columns are first drawn on the vertical and horizontal axes. Then, line O1k is drawn at a 30-degree angle to the horizontal axis. Next, line O2M is drawn at a 45-degree angle to the horizontal axis, with its intersection with the vertical axis giving the center O3. After that, an arc is drawn between points O1 and k with a radius of O105 from center O1. Then, an arc is drawn from point k to point M with a radius of O2k from center O2. Finally, a third arc is drawn from M to H with a radius of O5M from center O3 [Fig. 7]. This arch has less rise compared to the Bistu arch. This drawing method is based on upright elliptical geometry with a focal distance to span ratio of 1:1, yielding a lower rise and thus providing higher load-bearing capacity.[29]

By investigating the arches of Sasanian period buildings, tond mazey arches have been used in the four-iwan of Negar in Kerman, the four-iwan of Niasar in Kashan, the ruins of the Palace of Khosrow in Qasr-e Shirin, and the Palace of Khosrow in the Fire Temple of Shiz in Takab [Fig. 8].

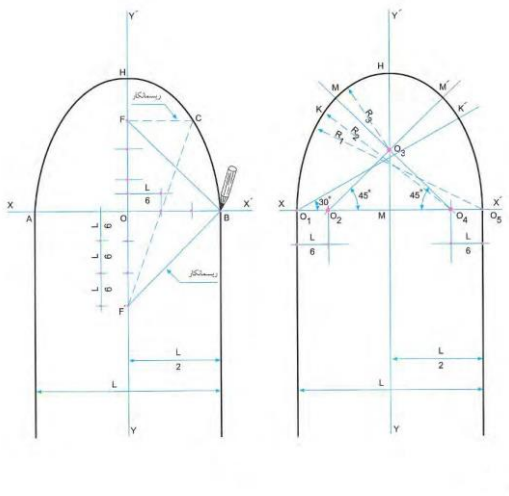

Fig. 7. Method of drawing the tond mazey arch (after Zomoroshidi, 2008: 164, Pl. 243).

[29] Zomoroshidi, 2008: 164.

Fig. 8. Tond mazey arches in the four-iwan of Niasar, ruins of Qal'eh Hazaar in Dareh Shahr, ruins of the Khosrow building in Qasr-e Shirin, and the Palace of Khosrow in the Fire Temple of Shiz in Takab (by the Authors).

Slow Mazey Arch, Biz or Haluchin Kond

This arch is an upright ellipse where its focal distance is equal to half the span, resulting in a shape very close to a circle. This arch, with a rise lower than that of a semi-circular arch and greater than that of a horseshoe arch, exhibits greater resistance to forces. The force in this arch easily transfers from the apex to the shoulders, and by securing the shoulders, the thrust in this arch is reduced. Other factors contributing to the strength of this arch include its significant height and the change in the type of joints and mortar used between courses from wedge-shaped to standard, which somewhat increases the arch's resistance to thrust.[30] To draw this arch, two columns and vertical and horizontal axes are first established. Then, a helper line MK is drawn from point M at a 60-degree angle to the horizontal axis. Center O1 is marked at a distance of L/10 from M on the axis. Next, center O2 is determined at a distance of L/5 from M on the horizontal axis. Then, an arc is drawn from points B and K' with a radius of L 7/10 from center O2. Finally, a secondary arc is drawn from point K to the apex with a radius of O1K from center O1 [Fig. 9]. Studies show that the slow mazey arch has been utilized in the Palace of Ardashir I in Firuzabad and the Taq Khosrow in Taq-e Bostan, Kermanshah [Fig. 10].

[30] Zomoroshidi, 2008: 158-162.

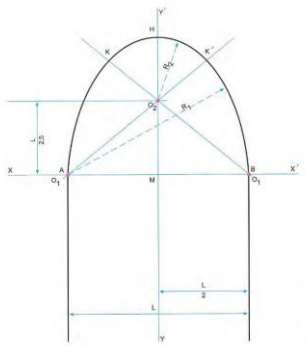

Fig. 9. Drawing of the slow mazey arch (by the Authors).

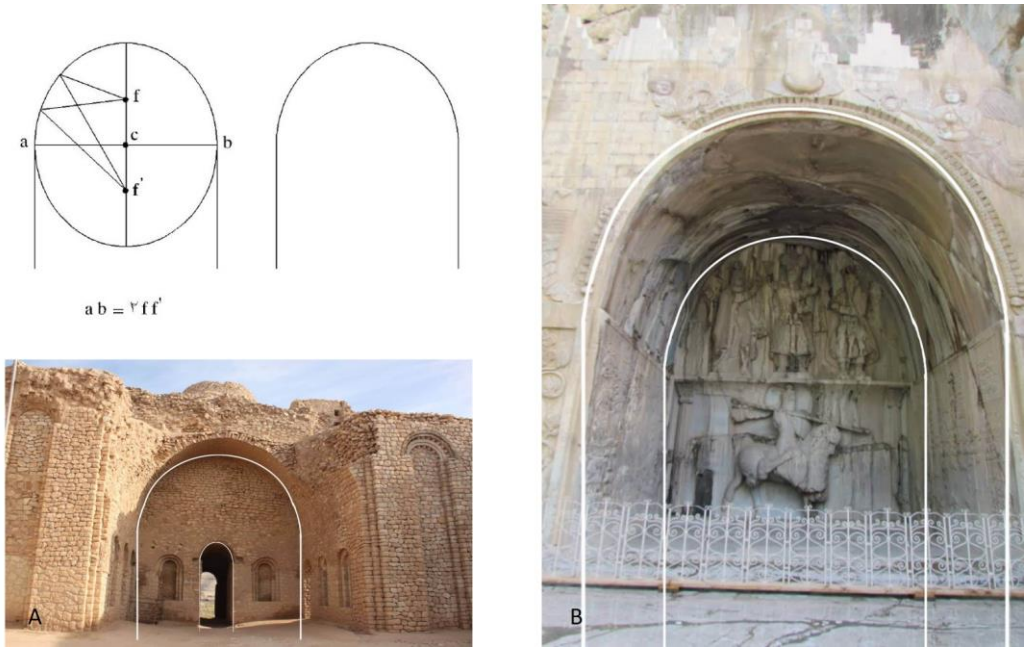

Fig. 10. Slow mazey arch in the Palace of Ardashir in Firuzabad and Taq Khosrow in Taq-e Bostan, Kermanshah (by the Authors).

Egg-shaped Arch

Another type of arch used during the Sasanian period is the egg-shaped arch, which is drawn as follows: first, the columns and vertical and horizontal axes are established. Then, from two points O1 and O4, helper lines O1K and O4K are drawn at a 45-degree angle to the horizontal axis. The intersection of these two helper lines with the vertical axis determines center O2. Finally, the continuation of the arch's curve is drawn using radius O2K from center O2 to complete the arch [Fig. 11]. This arch has been used in

the Taq Kasra. This type of arch consists of various horizontal ellipses and was used in two-story buildings on the lower level. To construct this arch, two columns are first drawn with horizontal and vertical axes. The span is divided into 12 parts, and the axis is bisected based on these divisions. The base of the arch is connected to the apex, and its perpendicular bisector is drawn. The intersection of the perpendicular bisector and the extension of the axis determines the center of the arch. Then, an arc is drawn from the center point with a radius equal to the base of the arch. Kofte arches have been utilized in some structures at Kuh-e Khwaja [Fig. 12].

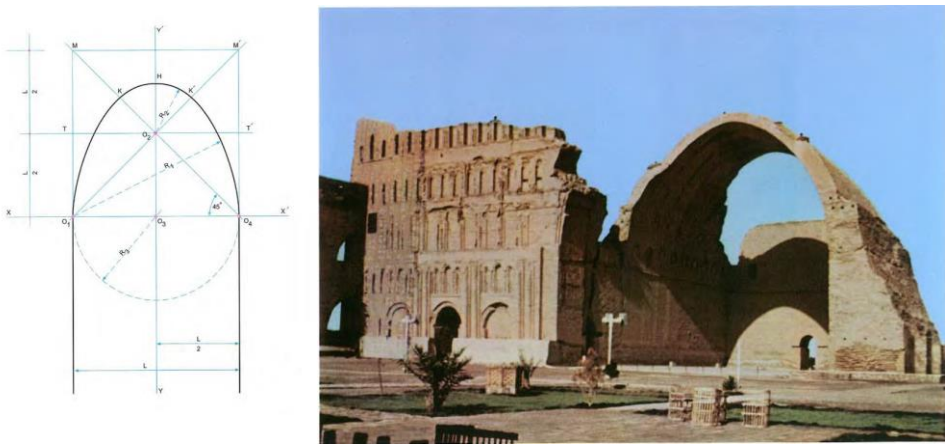

Fig. 11. Method of drawing the egg-shaped arch and its application in Taq Kasra Kofte Arch (after Zomoroshidi, 2008:173, Pl. 252).

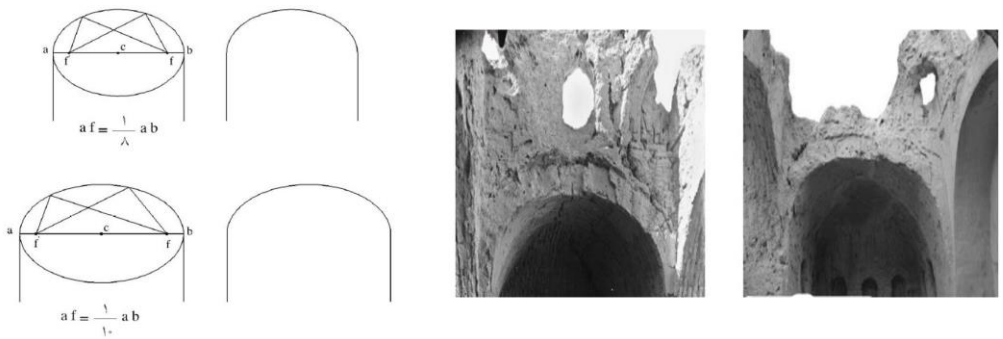

Fig. 12. Kofte arch in Kuh-e Khwaja (by the Authors).

Analysis

Since ancient times, geometry has been used in Iran as a powerful tool in architecture for measuring spatial proportions, creating balance, order, and beauty. Geometry is simple in terms of shape and form but complex in meaning and understanding.[31] The system of proportions includes a set of fixed visual ratios between the components of a building, where all dimensions (length, width, and height) and their combining elements are interdependent.[32] Geometry has been employed not only as a tool for aesthetics but also as an engineering principle for designing structures and ensuring the stability of buildings. Therefore, the science of geometry is considered a fundamental key to establishing a connection between the building and the builder's thought.[33] One of the most prominent features of Sasanian period architecture is the use of arches in building design. Arches not only strengthen the structure but also add a specific beauty and harmony to it. A study of Sasanian period buildings shows that architects utilized mazey arches (elliptical) with golden ratios of 2:1, 3:2, and 4:3 in constructing various structures [Tab. 1]. Thus, based on the basic geometric form, the bases of semi-circular and elliptical arches are repeated along the longitudinal axis, which structurally allows the roof pressure to be uniformly transferred to the side walls. The geometric proportions used to regard the span-to-height ratio of the arch are usually based on specific ratios. This type of arch has been used to optimize load distribution, allowing heavy loads to be effectively distributed and covering larger spaces without the need for columns. For effective execution and force transfer, as well as to increase the stability of the structure, precise geometric proportions were used alongside structural calculations.

Tab. 1. Geometric Proportions in Sasanian Mazey Arches

Geometric and structural features	Height to openings Ratio (H/D)	Focal length to openings ratio (F/D)	Type of Mazey Arches
High height, effective transfer of forces from the point to the shoulders	1:3	4:3	Tiz Mazey Arches (Baste)
Nearly circular shape, high resistance to force, reduced drift by closing and restraining the shoulders	1:2	2:1	Kond Mazey Arches (biz or kond Haluchin)
Combination of tiz and kond arch characteristics – used in medium-sized coatings, good balance between beauty and strength	1:2.5	3:2	Mazey Arches with medium rise

[31] Lawlor, 1983: 15.
[32] Ching, 2023: 304.
[33] Clark & Pause, 2012: 228.

Niarash refers to the knowledge and techniques that examine stability, strength, and the transmission of forces in structures. This concept, which is one of the fundamental principles of traditional Iranian architecture, has played a key role in the design and construction of Sasanian period buildings. Niarash involves understanding the quantity and quality of the forces of building materials and knowledge of stability and construction techniques. In the process of Niarash, an element called Peyman is also utilized. Peyman is a measurement unit that helps architects accurately and harmoniously design the proportions and dimensions of the structure. This method not only facilitates execution but also contributes to creating harmony and beauty in buildings. Thus, architects, considering geometric and Niarash principles, would first design the arch shape based on the desired span and height. Then, using wood or bricks, a temporary mold for the vault, known as "Shamaneh", would be constructed. After this stage, bricklaying begins from both sides of the span, with the bricks arranged radially so that the top of each brick faces the center of the imaginary arc. The mortar used is usually a mixture of clay, lime, or gypsum. In mazey arches, as the bricks rise, each course is laid slightly further inward than the previous course, thereby increasing the rise of the vault until it takes on an arched form. Once the mortar has dried, the mold beneath the vault is gently removed, and after removing the mold, the vault is characterized by a setback known as the shoulder or Hoviyah [Fig. 13]. This type of vault usually consists of a combination of two or more broken arcs. Thus, the weight of the bricks is transferred from the highest point to the lowest point, creating a curved force line that transmits the total forces to the thrust and then to the ground. The applied force is an inclined force that is converted into horizontal and vertical components.[34]

Fig. 13. Execution of Arches in Sasanian period Architecture (by the Authors).

[34] Memarian, 2012.

In mazey arches, since the transfer of forces is lateral, the load-bearing walls or buttresses must be constructed robustly. Sometimes, to prevent lateral thrust, a "buttress vault" has also been used. Technical features of this vault include the ability to create large spans without the use of wooden beams and high resistance to pressure, achieved through the simultaneous use of Niarash and Paimon. Architects utilized Niarash to enhance the stability and resilience of the structure, while Paimon was used to regulate the dimensions and proportions of the arch. This combination reflects the technical knowledge, practical experience, and profound understanding of materials and structural behavior by architects of this era, leading to the creation of buildings that are strong, beautiful, and durable, playing a crucial role in the design and construction of mazey arches. It is noteworthy that in some cases, wooden beams were used for vault construction and force transfer. In these instances, stones and bricks are placed horizontally and stepwise on top of one another, typically protruding about one-third of each upper stone or brick. This method in bricklaying facilitates force transfer, combining vertical and horizontal forces [Fig. 14].[35] This technique was common in western Iran, and evidence of flat-roofed timber structures has been found in the Hajjiabad area.[36]

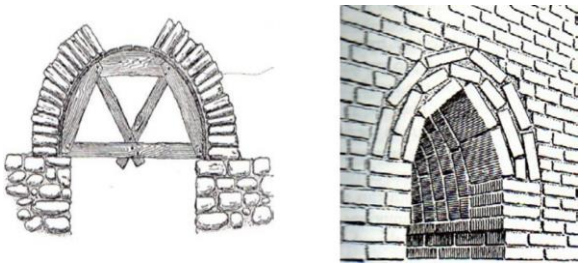

Fig. 14. Method of constructing setback vault with molds (after Reuther, 1938: 499).

It is important to mention that the materials used during this period included stone rubble with clay, lime, mortar, and half-burnt gypsum, which were laid without bonding.[37] Additionally, bricks, clay, and adobe were also utilized.[38] Bricks were employed for constructing arches, domes, and decorations.[39] The use of these materials was common due to the scarcity of timber in Iran. Therefore, an examination of some Sasanian period buildings reveals that during this period, both Niarash and Paimon were employed in the construction of religious and non-religious buildings, as well as mazey arches for erecting domes and vaults, utilizing local materials such as stone rubble with half-burnt gypsum, mortar, and clay.

[35] Reuther, 1938: 493-570.
[36] Azarnoush, 1994: 55, 2008.
[37] Huff, 1986: 329.
[38] Varjavand, 1984: 145; Azarnoush, 1994: 39.
[39] Schippmann, 2005: 129.

Conclusion

The study of Sasanian period buildings indicates that architects of this period constructed vaults and domes with a solid understanding of mathematics and geometry, utilizing mazey arches to cover porticoes and doorways. These arches not only served as structural elements for spanning openings but also showcased a blend of engineering science, aesthetics, and a deep comprehension of geometry. Furthermore, the precise proportions between span, height, and radius of the arch led to the creation of structures that not only possessed strength but also imparted a unique grandeur to the buildings. The construction methods and execution of this type of arch, utilizing local materials like bricks and gypsum mortar along with precise molds, demonstrate the high level of skill and technical knowledge of Sasanian period architects. This type of arch, due to its curvature, facilitated effective force transfer and was favored for its excellent load-bearing capacity and high stability. Therefore, recognizing the paths of force movement, establishing load-bearing structures, the role of Paimon, special usage of materials, and familiarity with geometry were essential for arch construction. Thus, the mazey arches used in both religious and non-religious Sasanian period buildings illustrate that the application of Iranian geometry was not only practically useful in construction but also served to establish order and cohesion among all components of the structure.

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