

Comparative Analysis of Geometric Characteristics and Construction Techniques of Double-Shell Domes in Holy Shrines

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Article Info	Abstract
Received 13/04/2026	Holy shrines are a common architectural type in many Islamic countries, and they have been distinguished from other styles of Islamic architecture due to their function as a shrine that carries high symbolism for an influential Islamic figure. Domes are regarded as one of the most prominent architectural elements in these shrines, appearing in diverse forms and classifications across the regions of the Islamic world. The research aims to investigate the geometric characteristics and structural techniques of discontinuous double-shell domes in holy shrines in Iraq and Iran, the majority of which date back to the Jalayirid and Safavid periods, in order to develop a framework for identifying these domes. Following a study of the primary components of the selected models, the research established a framework through which these domes can be distinguished at the formal, structural, and decorative levels. Furthermore, the results indicated that the dome of Imam Rida is characterized by geometric and structural characteristics that distinguish it from the domes of Iraq.
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1. Introduction

The dome is an architectural structural element that has been used across various civilizations due to its great importance in covering large spaces and its profound symbolism [1]. Domes developed significantly during the Islamic civilization, roofing palaces, mosques, shrines, khans, and other buildings across diverse Islamic architectural styles [2], [3]. Thus, the dome stands out as a prominent element in Islamic architecture that requires detailed study.

The development of domes in holy shrines began noticeably during Jalayirid rule, and continued to evolve throughout the Safavid and Ottoman periods up to the present day [4]. Although numerous studies have addressed holy shrines from various aspects, they have not comprehensively investigated the historical domes of holy shrines in Iraq, particularly double-shell domes. This indicates a clear research gap that necessitates a study investigating the geometric characteristics and construction techniques to develop a deeper understanding of this type of dome, which constitutes the objective of this research. To achieve the research objective, a comparative analytical approach was adopted, represented in two axes:

The theoretical axis: Represents the collection of quantitative and qualitative data to expand the theoretical foundation of the study.

The practical axis: Through which the selected case studies are examined: the dome of Imam Hussein, the dome of Abbas ibn Ali, the dome of the two Kadhimiya Imams, and the dome of Imam Ali (peace be upon them) in Iraq, as well as the dome of Imam Rida (peace be upon him) in Iran, by applying the derived theoretical framework to them.

The research utilized several tools that facilitated data collection, comparison, and discussion, including: previous literature, field visits, interviews, and engineering software.

2. Previous Studies on Double-Shell Domes and Shrine Architecture

Studies that have dealt with double-shell domes and the architecture of holy shrines are classified into two categories based on their methodologies: descriptive studies, which focus on historical information and formal characteristics; and analytical studies, which have dealt with the geometric

characteristics, structural behavior, and construction techniques of domes.

2.1. Descriptive Studies

These studies dealt in a general descriptive manner with historical aspects related to the holy shrines, with a brief description of their general plans and their most prominent elements, such as studies [5] that dealt with the most important developments witnessed by Al-Ha'ir al-Husseini, including the element of the dome during the accession of the Abbasid caliphs to power and those who came after them, while the study [2] examined the emergence of holy shrine cities and their architecture and referred with a descriptive approach to their architectural elements, including the dome. Maher's study addressed the history of the scene of Imam Ali and its architectural description, and pointed to the stages of development of the current dome and its external and internal finishes [6].

Al-Fartoosi [7] provided a comprehensive architectural and cultural history of the golden dome over the holy shrine of Imam Ali (pbuh) in Najaf. Chronologically organized, the text traces the evolution of seven historical domes commissioned by different rulers, starting from the Abbasid Caliph Harun al-Rashid through the Safavid and Ottoman eras, while also addressing the dome's design, gilding process, and maintenance.

Memarian [8] dealt with building domes and classified them according to their shapes, the number of shells, as well as the methods of their construction, but it was limited to the study of Iranian domes and did not refer to Iraqi domes.

2.2. Analytical Studies

Analytical studies of domes have varied, including the study by Al-Kaflawi [9], which classified the domes of holy shrines according to the arch that forms them, and concluded that all the arches used in forming the domes of holy shrines are adjacent pointed arches. Jaafar [10] dealt with the domes of the holy shrines in Iraq using a survey method and pointed out that they are bulbous in shape but not identical, and that there is a difference in proportions on the one hand and the nature of the curve of the dome on the other hand. The study came up with a dome model that represents the general average of these domes. The study dealt only with the external shape of the dome body (outer shell) and did not study the rest of the parts that make up the dome and its design and structural characteristics [10]. While some studies have focused on the supporting elements (Khashkhashis) used in the support of the double domes [11] and briefly referred to some of the domes of the holy shrines.

Hejazi and Pourabedin [12] dealt with the structural performance of disconnected double shell domes made of Persian bricks against earthquakes. Different shapes of upper and lower domes were studied. The study dealt with Iranian domes and was limited to the structural aspects only.

In their 2016 study, Wahdattalab and Rezaiezhadeh examine the morphological characteristics and aesthetic proportions of heritage domes, analyzing their spatial and geometric distribution patterns across the central Iranian plateau. This

study highlights the relationship between dome diameter and height, linking it to the visual and structural identity of Islamic architecture in the region. It provides an analytical framework for the historical development of forms and transition zones [13]. In their 2010 study, Ashkan and Ahmad classified double-shell domes based on their geometry and structural behavior, focusing on load transfer. They developed a mathematical framework to examine the transition zone from square to circle and the geometric proportions of domes in Islamic architecture across different periods [14].

A critical review of previous studies revealed the following:

- A lack of specialized research on double-shell domes in holy shrines in Iraq, with most studies relying solely on descriptive approaches.
- Some studies addressed the geometric features of these domes but failed to provide precise and comprehensive data on the relationship between their geometric characteristics and construction techniques.

Based on the knowledge gaps highlighted in the literature, the research problem is defined.

2.3. Research Problem

The need to establish a comparative analytical framework to characterize and classify the geometric characteristics and construction techniques of discontinuous double-shell domes in the holy shrines of Iraq and Iran.

To achieve a comprehensive study of these domes, the research addresses the following questions:

- What is discontinuous double-shell domes, and what is their historical context within holy shrines?
- How do these domes compare and contrast in terms of their geometric characteristics and construction techniques across the selected regions?

3. Research Methodology

3.1. Data Collection & Field Survey

Following the completion of desk studies, detailed field surveys were conducted, establishing the geographical scope of the research, which focuses on the discontinuous (detached) double-shell domes of the holy shrines. In-depth interviews were held with the relevant authorities represented by the engineering project departments of the holy shrines and the Shia Waqf Directorates to gather survey data and obtain the available architectural drawings of the selected case studies. During the field surveys, the geometric dimensions of the domes (diameter and height) were measured using various surveying instruments. Additionally, numerous photographs of the domes' interior and exterior profiles were captured to analyze the inner and outer curves, the construction and finishing materials used, the structural transition zones (from square to circle), and the supporting structural elements, such as drums and radial stiffeners (Khashkhashis). Architectural software (AutoCAD and 3ds Max) was used to document the results and create models. After comparing and analyzing the acquired data, a comprehensive framework was developed that classifies the

domes of holy shrines in Iraq and Iran based on their geometric characteristics and construction techniques.

3.2. Evaluation Parameters

Two categories of descriptive criteria were followed to compare the selected domes:

Geometric Characteristics: This section deals with the formal and dimensional characteristics of the selected domes. It includes measuring the geometric dimensions in terms of diameters and heights, the height-to-diameter (H/D) ratio, and the number of curvature centers forming the dome's arch. Additionally, it addresses the geometry of the drum and its openings, as well as the springing point location of the inner shell relative to the drum.

Construction Characteristics: This category focuses on the type of materials used in the construction and finishing of the selected domes, the type and structure of the transition zone (from square to circle), and the classification of the radial stiffeners (Khashkhashis) in terms of their types, quantities, and dimensions (where available).

4. Theoretical Framework

4.1. Domes Classification

In previous studies, researchers classified domes into two types according to their shapes, where domes take an arched shape in space. Based on the shape of this arch, domes can be classified. The other classification depends on the number of shells that make up the dome [8].

Domes are divided into three types according to the type of shells:

- Fully connected two-shell domes
- Double-shelled domes connected between the spaces
- Domes with fully separated shells [15].

This classification provides a suitable basis for the architectural distinction of domes and can be used with some modifications to enhance their structural roles. Domes with two completely disconnected shells are divided into two groups: domes (Nar) and domes (Rak), according to the Persian language. Rak domes have a curved inner shell, and the outer shell is cone-shaped. Nar domes have two disconnected shells with curved shapes as shown in Fig.1 [8], [14].

This research focuses on disconnected double-shell domes in the holy shrines of Iraq and Iran.

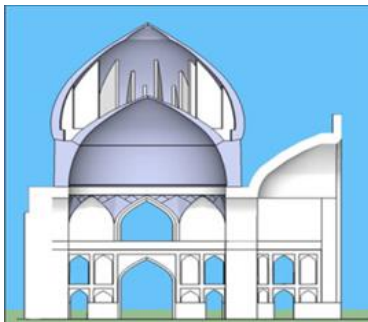


Figure 1. Shows a disconnected double-shell dome (Nar) [16].

4.2. Dome Parts and Structural Elements

Through the formal analysis of the dome, we can identify its primary constituent structural components, similar to other vertically oriented architectural elements, which are categorized as follows (Fig. 2):

The basic plan of the dome: Defines the foundational geometry of the structure.

The walls or columns that carry the dome: Take their shape according to the basic plan, and if square, they form a cubic structure that extends under the octagonal base [17].

Transition zone: Represents the area of transformation from a usually square layout to the circular shape on which the dome sits. It is an important structural part commonly used in the Islamic world, comprising several types: pendentives and squinches, whose origins trace back to Sasanian architecture, achieving maximum stages of development in Islamic architecture, including muqarnas, or hybrid configurations combining multiple types [18], [12].

Base: Covers the transition area, connecting the dome to the roof of the building, upon which the outer shell of the dome sits. The base exhibits various forms, including cylindrical, ribbed, or octagonal, and its height varies according to functional type, model, or region [16].

Drum: The drum is considered the supporting part of the shell, positioned above the base to connect with the body of the dome [1]. It may be omitted in some domes so that the body connects directly to the base, or its height may be significantly elevated to form a large percentage of the overall dome profile, as in the dome of Imam Rida (peace be upon him). Drums often include window openings [19]. The choice of shell type depends largely on the thickness and height of the drum, as these characteristics affect the building's ability to withstand gravity loads [14].

Dome Body: As the primary volumetric component of the structure, the dome body (known as Nar) is formed into various profiles according to the number of curvature centers, which differ across regions, historical periods, and functional typologies [19]. The body of the dome in the double-shell domes under study consists of two shells:

A. The inner shell of the dome: Typically featuring a stepped and rough upper face, it exhibits structural behavior similar to that of single-shell domes [18]. Due to increased tension in double-shell configurations, it is necessary to use more resistant arches to build this shell, with parabolic or pointed profiles typically utilized. The inner shell may spring from the bottom, middle, or upper part of the drum, resulting in various structural details, as shown in Fig. 3 [8].

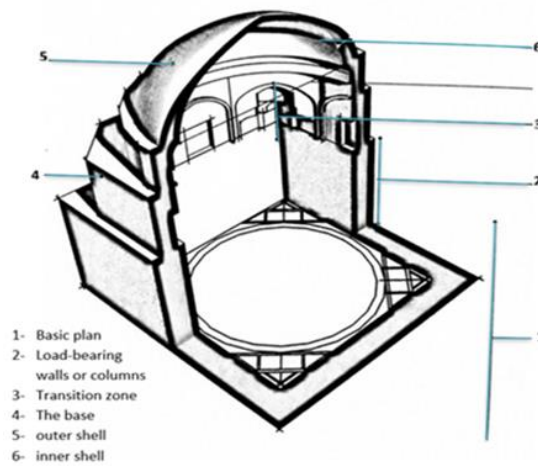


Figure 2. Components of double-shell domes, from the load-bearing walls to the outer shell.

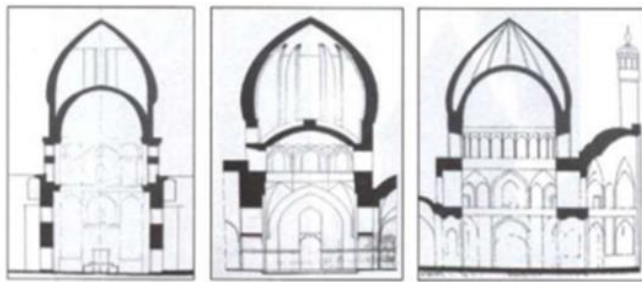


Figure 3. Different positions of the inner shell in relation to the drum. (Left to Right:) Inner shell under the drum, Inner shell between the Drum, Inner shell top of the drum [12].

B. The outer shell of the dome, which is placed on the inner shell, plays an important role in the urban landscape, and can be created from different types of load-bearing arches [18].

- **Stiffeners (Khashkhashis):** Stiffeners are thin brick walls that are used between the two shells of double shell domes [18]. Stiffeners are built simultaneously with the outer shell and are connected to it with an in-and-out joint. This adds stability to the stiffeners under bending stress and prevents them from separating from the shell. The shell section is larger where the stiffeners connect, which prevents outward movement in the shell and the drum. Moreover, vertical forces from the stiffener's weight result in a steeper slope in the diagram of tensional stresses through the middle one-third of the shell [12]; see Fig. 4.

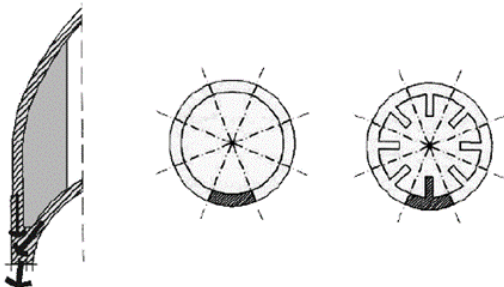


Figure 4. Structural role of stiffeners in discontinuous double shell domes [16].

5. Selected Case Studies

The selected case studies represent the empirical foundation of this research. This section is limited to presenting a concise and standardized profile for each case, arranged in chronological order.

5.1. The Dome of Imam Hussein Holy Shrine

Located in the city of Karbala, the Holy Shrine of Imam Hussein (pbuH) is one of the most prominent historical and religious landmarks in Iraq and the Islamic world [20]. The current layout and architectural form of the shrine largely date back to the reconstruction and restoration works initiated by Sultan Uways al-Jalayiri in 767 AH (1366 AD), and completed by his sons, Sultan Ahmad and Sultan Hussein, in 786 AH (1384 AD) [5]. Since then, the shrine has undergone successive preservation, expansion, and restoration campaigns that have maintained its architectural authenticity and religious significance. The shrine is distinguished by its golden double-shell (discontinuous) dome, the monument's most prominent architectural and structural feature [21]. Fig. 5 shows a photo of the interior and Exterior Views of the Imam Hussein Dome.



Figure 5. Imam Hussein Dome: Interior and Exterior Views.

5.2. The Dome of Al-Abbas Holy Shrine

Located near the Holy Shrine of Imam Hussein in the center of Karbala, the Holy Shrine of Al-Abbas (pbuh) is a significant architectural landmark [22]. Although the earliest documented structure built over this tomb dates back to the Buyid era in 372 AH (983 AD), the current architectural form of the shrine was largely established during the Jalayirid period through successive construction campaigns carried out between 740 AH and 790 AH [23]. These works began under Sheikh Hassan al-Jalayiri and continued during the reigns of Sultan Uways, Sultan Hussein, and Sultan Ahmad Bahadur Khan, who completed the main structure of the shrine [24]. The shrine underwent several restoration and preservation campaigns throughout the Ottoman, Safavid, and Qajar eras up to the present day [9]. Architecturally, the shrine is distinguished by its prominent pointed double-shell (discontinuous) dome, which serves as its primary architectural landmark. Fig. 6 shows the interior and exterior views of Al-Abbas Dome.

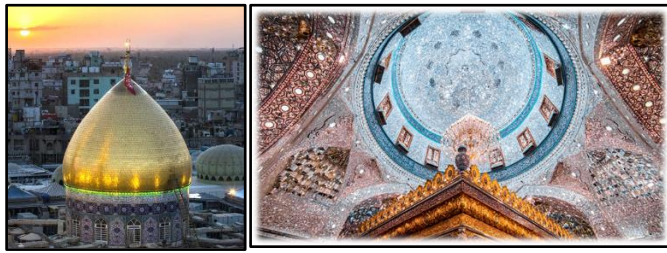


Figure 6. Al-Abbas Dome: Interior and Exterior Views.

5.3. The Dome of Imam Rida Holy Shrine

The Shrine of Imam Rida (peace be upon him), shown in Fig. 7, is located in the city of Mashhad and is considered one of the most prominent religious and historical landmarks in Iran [25]. Historical sources indicate that the primary load-bearing structure of the shrine, constructed of brick and gypsum mortar, dates back to the 6th century AH (the Seljuk era), when a dome was erected over the holy sanctuary by order of Sultan Sanjar the Seljuk and his vizier, Sharaf al-Din Abu Tahir al-Qumi, following earlier damage to the shrine [26], [27]. Other sources suggest that the present structure of the dome dates back to 761 AH (1360 AD) [8]. During the reign of Shah Abbas I, the outer shell of the dome was gilded with gold-plated copper sheets [11]. The holy shrine and its dome have undergone development, restoration, and structural maintenance through to the present day.



Figure 7. Imam Rida Dome: Interior and Exterior Views.

5.4. The Domes of Al-Kadhimayn Holy Shrine

The Holy Shrine of Al-Kadhimayn is one of the most prominent religious and historical landmarks in Baghdad, shown in Fig. 8 [9]. The shrine's origins date back to the Abbasid era. It subsequently underwent several phases of construction and expansion until its current form was established during the Safavid period [28]. In 914 AH (1508 AD), Shah Ismail I ordered the shrine's reconstruction, replacing the old structure with the present one and adding four minarets and a mosque on the northern side [29]. The shrine has maintained its architectural style through subsequent ongoing restoration efforts. Its most prominent feature is its two identical, double-shelled domes [30].



Figure 8. Al-Kadhimayn Dome: Interior and Exterior Views.

5.5. The Dome of Imam Ali Holy Shrine

The shrine of Imam Ali (peace be upon him) in Najaf, Iraq (Fig. 9), is one of the most prominent religious and historical landmarks in the Islamic world and Iraq [31]. Sources indicate that the shrine's origins date back to the reign of the Abbasid Caliph Harun al-Rashid in 170 AH (786 AD) [7]. Its current form largely dates to the Safavid era during the reign of Shah Abbas I [32]. Architecturally, the shrine is distinguished by its double-shelled (non-connected) dome, making it a prime example of historical architecture in Iraq [33].



Figure 9. Imam Ali Dome: Interior and Exterior Views.

6. Results and Discussion

6.1. Comparative Geometric Analysis

To systematically analyze and compare the selected domes, the geometric evaluation is divided into two main sub-axes to ensure a high-precision comparison of the distinct geometric components:

Dome Shells (Outer and Inner Shells): This axis focuses on morphological curvature, diameters, heights, aspect ratios (H/D), and the geometric layout of arch profiles (number of centers).

The Drum (Supporting Base): This axis focuses on the cylindrical base, its metric/physical dimensions, as well as the geometry and number of window openings.

6.1.1. Analysis of the dome shells

To evaluate the volumetric and geometric properties of the inner and outer dome shells across the studied cases, key parameters including diameters, total height, height-to-diameter ratio (H/D_o), and curvature centers were consolidated as presented in **Table 1**.

Table 1. Comparative geometric characteristics of the inner and outer dome shells (Compiled by the author based on [11], [21][24][31] and field observations).

Case ID	Dome Name	Outer Shell Diameter (D_o) [m]	Inner Shell Diameter (D_i) [m]	Total Height (H_o) [m]	Height-to-Diameter Ratio (H/D_o)	No. of Curvature Centers (Outer)	Profile Type
CS-01	Imam Hussein Dome	13.68	11.00	9.78	0.714	6	Pointed Bulbous
CS-02	Al-Abbas Dome	16.00	13.00	14.35	0.896	7	Pointed Bulbous
CS-03	Imam Rida Dome	13.40	11.00	6.60	0.492	4	Pointed Bulbous
CS-04	Al-Kadhimayn Domes	10.81	6.5	7.5	0.693	5	Pointed Bulbous
CS-05	Imam Ali Dome	16.60	13.5	12.55	0.756	6	Pointed Bulbous

A. Curvature and Proportional Analysis (H/D_o)

Table 1 shows a large variation in the sizes and dimensions of the outer shells of the studied domes. Structural slenderness and overall height are measured using the height-to-diameter index (H/D_o). The analysis of the study models shows that Al-Abba's dome (CS-02) reaches the highest ratio (0.896), producing a prominent pointed shape. Meanwhile, Imam Reza dome (CS-03) recorded the lowest value (0.492), reflecting a wider and lower outer geometry. The other Iraqi cases (CS-01, CS-04, and CS-05) maintained a medium balance, with indices ranging between 0.693 and 0.756.

B. Geometrical Layout Complexity (Curvature Centers)

The results show a clear variation in the number of centers defining the curves of the outer shell, reflecting a distinction in terms of formal aesthetics and structural transition. Morphological analysis shows that Al-Abba's dome (CS-02) reached peak complexity with 7 centers shaping its curvature. This was followed by the domes of Imam Hussein (CS-01) and Imam Ali (CS-05) with 6 centers. Meanwhile, the Imam Reza dome (CS-03) in Iran had the lowest number, with 4 centers forming its curvature, as shown in Fig. 10.

6.1.2. Analysis of the dome drums and openings

For the purpose of evaluating the geometric properties of the drums in the selected case studies, the heights, diameters, and height-to-diameter ratio (H_d/D_d) were measured, as well as the internal shell springing points, opening characteristics, and their numbers. Table 2.

A. Drum Proportions and Spatial Role (h_d/D_d):

The drum acts as a structural mediator between the transition zone and the dome shells. It is evident from Table 2 that the dome of Imam Rida (CS-03) is characterized by the highest drum ratio (0.626) with a height of 8.40 m, creating a lofty

cylindrical base. Meanwhile, the Iraqi models (CS-01, CS-02, and CS-05) show clearly convergent drum ratios, with their percentages confined between 0.337 and 0.423, reflecting an architectural pattern that balances drum height with structural span.

B. Fenestration System and Lighting Dynamics:

A morphological difference was observed in the architectural treatments of the openings, where a system based on the presence of 12 pointed-arch windows distributed evenly around the drum circumference was applied in the domes (CS-01), (CS-02), and (CS-05). Sources indicate that this number is linked to the 12 Infallible Imams in the Shia doctrine [3]. This arrangement achieves a dual purpose: reducing the dead weight of the brick masonry mass at the drum level, and improving natural daylighting inside the sanctuary, as well as enhancing the spiritual connection due to the continuity between the interior and exterior provided by these openings. On the other hand, we observe that both the dome of Imam Rida (CS-03) and the Al-Kadhimayn domes (CS-04) are completely devoid of openings, and the researcher attributes this to the positioning of the inner shell below the drum, which renders the presence of openings useless.

C. Inner Shell Springing Points:

The springing points of the inner shell varied across the selected models. In the holy shrines of Najaf and Karbala (CS-01, CS-02, and CS-05), it was found that the inner shell springs from the top of the drum. This design grants height and spaciousness to the ceiling, while the visible openings on the dome reveal the interior space. However, in the domes of Al-Kadhimiya and Imam Reza (CS-03 and CS-04), the inner shell originates from the bottom of the drum, creating a larger space between the two shells and concealing the volume from the interior space. (Fig.10)

6.1.3. Comparative analysis of double-shell domes: Iraqi vs. Iranian models

The engineering evaluation revealed distinct construction traditions and design philosophies among the selected domes in Iraq and Iran, shaped by local context and architectural style:

- The Iraqi Tradition (The Shrines of Karbala and Najaf):**
 Characterized by a unified formal pattern where the outer pointed-bulbous shell exhibits high slenderness (0.714 - 0.896) generated by a complex geometric layout of (6 - 7) centers. In this school, we notice that the inner shell rests at the top of the drum, contributing to expanding the internal volume of the sanctuary and integrating the drum within the interior space, which functionally and spiritually justifies the presence of pointed-arch openings.

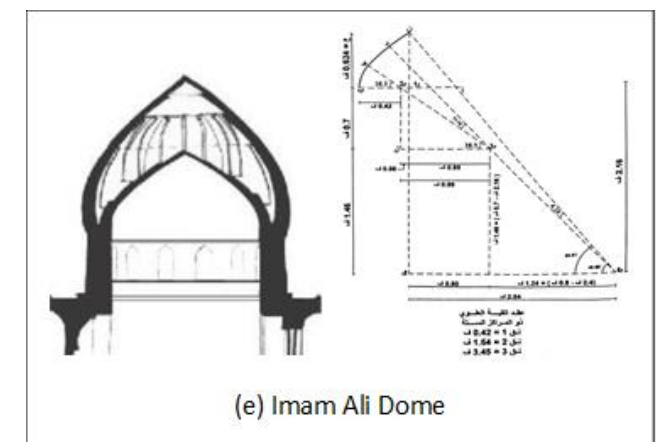
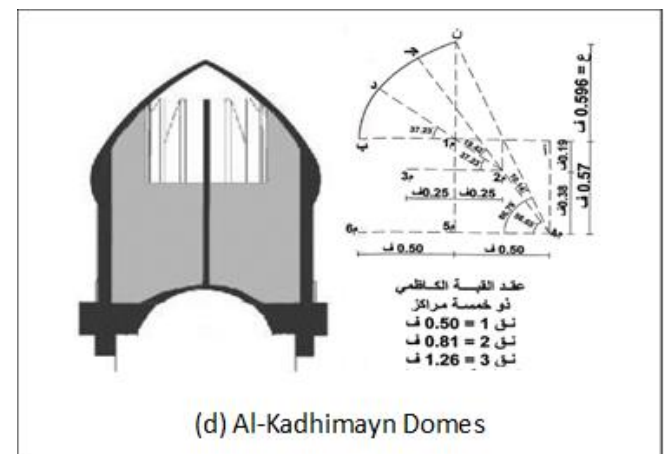
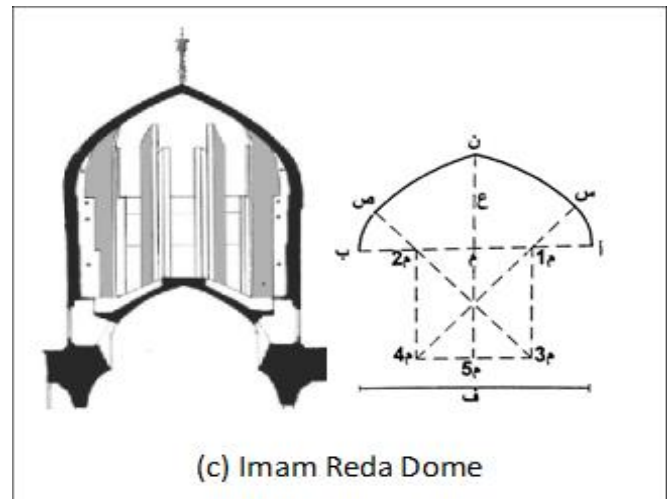
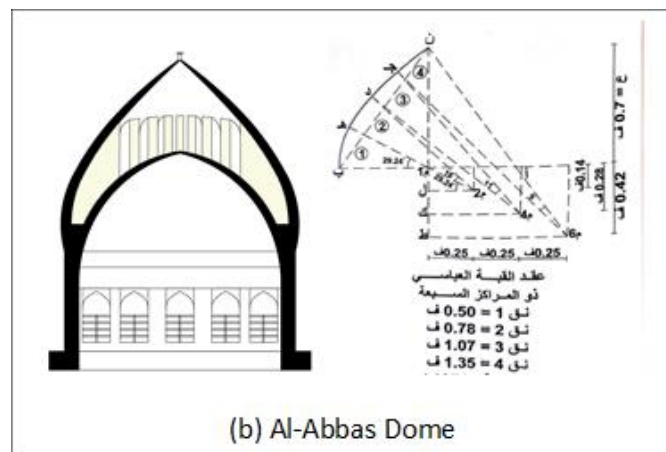
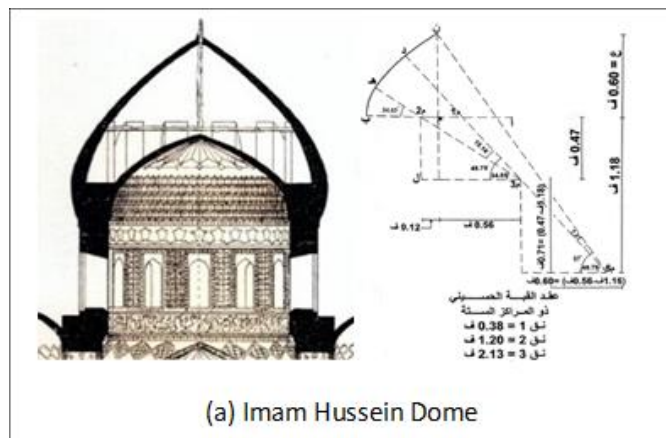


Figure 10. illustrates the geometry of the internal and external shells and the centers of curvature in the domes selected for study.

Table 2. Comparative geometric and structural characteristics of the dome drums (Compiled by the author based on [8] ,[9], [22] and field observations).

Case ID	Dome Name	Drum Diameter (D _d) [m]	Drum Height (h _d) [m]	Height-to-Diameter Ratio (H/D)	No. of Openings	Shape of Openings	Inner Shell Springing Point (Relative to Drum)
CS-01	Imam Hussein Dome	13.00	5.00	0.384	12	Pointed arch window	At the top of the drum
CS-02	Al-Abbas Dome	15.00	6.35	0.423	12	Pointed arch window	At the top of the drum
CS-03	Imam Rida Dome	13.40	8.40	0.626	None	None	At the base of the drum
CS-04	Al-Kadhimayn Domes	10.00	5.00	0.50	None	None	At the base of the drum
CS-05	Imam Ali Dome	16.60	5.6	0.337	12	Pointed arch window	At the top of the drum

- **The Iranian Tradition (The Mashhad Typology):** Prioritizes the external monumental appearance in the urban space by utilizing an excessively high drum (h_d = 8.40 m). We find that the geometry of the outer shell is less complex compared to its counterparts in the Iraqi school, utilizing 4 centers, and is more flattened (H/D_o = 0.492). As for the inner shell, it springs from the base of the drum, separating the internal volume of the drum from the lower sanctuary space and adding it to the interstitial space between the two shells, which explains the drum's lack of openings.
- **The Transitional Hybrid Typology (The Al-Kadhimayn Typology):** Al-Kadhimayn domes (CS-04) represent a hybrid model that beautifully blends geometric aspects. This is embodied through the proportions of its outer shell, which

align with the Iraqi school, while we find that its internal layout logic follows the Iranian traditions, manifested by the springing of its inner shell from the base of the drum and the absence of openings in its drum, documenting a historical cross-regional exchange in building traditions.

6.2. Construction Materials and Structural Techniques

6.2.1. Analysis of construction materials and finishing coverings

This section deals with the building and finishing materials used in the construction of the drums and the external and internal shells of the domes selected for study, providing a knowledge base for understanding their aesthetic and structural foundations, as shown in Table 3.

Table 3. Comparative analysis of construction and finishing materials for the studied domes (Compiled by the author based on [3], [7], [21], [22] and field observations).

Case ID	Dome Name	Core Construction Material	Outer Shell Finishing	Drum Exterior Finishing	Inner Shell Interior Finishing
CS-01	Imam Hussein Dome	Brick and Gypsum Mortar	Gold plating	Gold plating with crowning Qashani calligraphic band	Mirror mosaic with upper & lower calligraphic bands
CS-02	Al-Abbas Dome	Brick and Gypsum Mortar	Gold plating	Qashani tiles with crowning Qashani calligraphic band	Mirror mosaic with upper & lower calligraphic bands
CS-03	Imam Rida Dome	Brick and Gypsum Mortar	Gold plating	Gold plating with crowning Qashani calligraphic band	Mirror mosaic only
CS-04	Al-Kadhimayn Domes	Brick and Gypsum Mortar	Gold plating	Gold plating with crowning Qashani calligraphic band	Mirror mosaic only
CS-05	Imam Ali Dome	Brick and Gypsum Mortar	Gold plating	Gold plating with crowning Qashani calligraphic band	Mirror mosaic with upper & lower calligraphic bands

Regarding the core materials, the primary building media utilized in the execution of all studied domes are brick and gypsum mortar. As for the finishing materials, the outer shell in all domes was finished with gold plating. We find that the

drums of the domes of Imam Ali (CS-05), Imam Hussein (CS-01), Imam Rida (CS-03), and Al-Kadhimayn (CS-04) are gilded with gold, crowned by a Qashani tile band inscribed with Quranic verses, except for the dome of Al-Abbas (CS-02),

where its drum finishing consisted of Qashani tiles along with a calligraphic band crowning the drum as well. As for the interior finishing materials (the inner shell), in both the domes of Imam Hussein and Al-Abbas, they consisted of reflective mirror mosaic accompanied by two calligraphic bands located above and below the openings. In the domes of Imam Rida and Al-Kadhimayn, the interior finishing consisted of reflective mirror mosaic only. Meanwhile, the inner shell of the dome of Imam Ali was executed using Qashani tiles and ceramic mosaics, complemented by two calligraphic bands above and below the windows.

Table 4. Structural typology and geometrical classification of dome transition zones (Compiled by the author based on [8],[9] and field observations).

Case ID	Dome Name	Primary Transition System	Structural & Geometrical Configuration	Figure Reference
CS-01	Imam Hussein Dome	Intersecting Rib Pendentives (Karbandi)	Complex and interlocking pendentive structure	Fig. 11a
CS-02	Al-Abbas Dome	Intersecting Rib Pendentives (Karbandi)	Cross-grid pendentive system	Fig. 11b
CS-03	Imam Rida Dome	Muqarnas Arch System	Distinct regional Muqarnas arch configuration for geometrical transition	Fig. 11c
CS-04	Al-Kadhimayn Domes	Intersecting Rib Pendentives (Karbandi)	Complex and interlocking pendentive structure	Fig. 11d
CS-05	Imam Ali Dome	Intersecting Rib Pendentives (Karbandi)	Cross-grid pendentive system	Fig. 11e

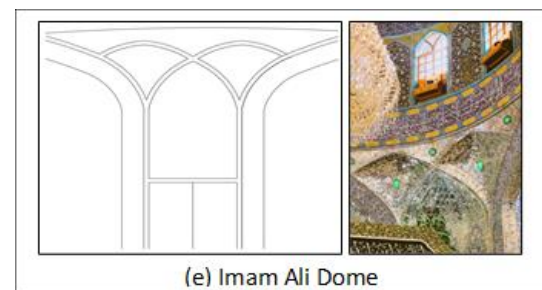
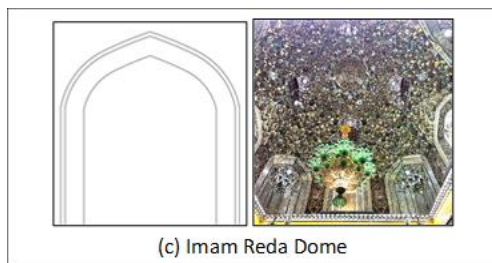
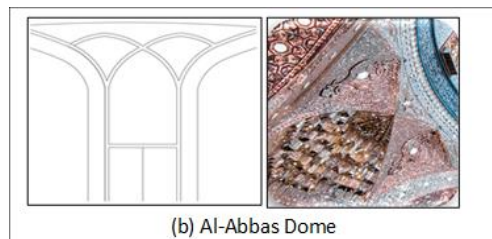
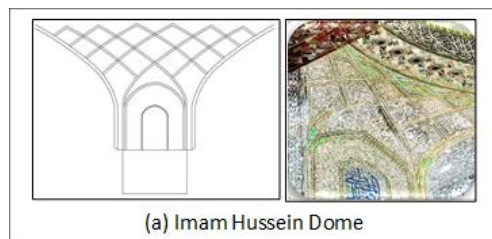


Figure 11. Geometrical layouts and architectural details of the transition zones (Source: Prepared and photographed by the author based on field observations).

We observe the adoption of the intersecting rib pendentive system (Karbandi / Intersecting Rib Pendentives) in the Iraqi domes to achieve the spatial transformation from square to circle; however, they exhibited variations in their constituent frameworks and internal distribution networks. Imam Ali Dome (CS-05) and Al-Abbas Dome (CS-02) share a similar transition technique from square to circle using an intersecting arch system (pendentives), whereas more complex and intertwined arches were used in Imam Hussein Dome (CS-01) and Al-

Kadhimiya Domes (CS-04). As for Imam Reza Dome (CS-03), it is distinguished by utilizing a muqarnas arch system to achieve the transition.

6.2.3. Stiffening Wall System (Khashkhashi)

The Khashkhashi ribs, located between the two shells, act as support walls for the outer shell and help to reduce its buckling. For details on the Khashkhashi ribs, see Table 5, which provides a complete analysis of their dimensions, types, and positions.

Table 5. shows the dimensions, types, numbers, and positions of Khashkhashi ribs in the selected models. (Compiled by the author based on [11][21] [24] and field observations).

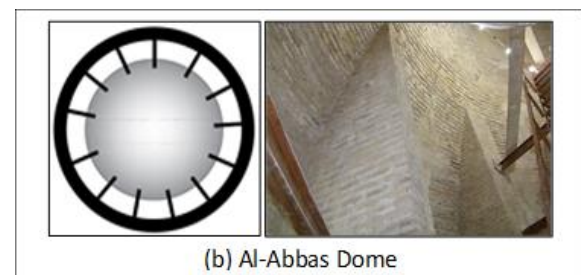
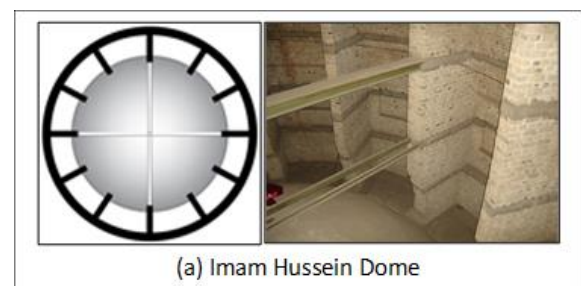
Case ID	Dome Name	Type	No.	Width (m)	Depth (m)	Height (m)	Position (Start)	Position (End)	Figure Reference
CS-01	Imam Hussein Dome	Main	12	0.36	1.20 - 1.45	7.20	Over the drum and inner shell	Above upper breaking point	Fig. 12a
CS-02	Al-Abbas Dome	Main	12	-	-	-	Over the drum and inner shell	Above upper breaking point	Fig. 12b
		Main	8	0.45	1.75	13.0	Drum bottom over inner shell	Above upper breaking point	
CS-03	Imam Rida Dome	Sub 1	9	0.43	1.15	10.0	Drum bottom over inner shell	At upper breaking point	Fig. 12c
		Sub 2	3	0.43	0.60	10.0	Over the drum and inner shell	At upper breaking point	
CS-04	Al-Kadhimayn Domes	Main	4	0.26	4.10	12.0	Over the drum and inner shell	At upper breaking point	Fig. 12d
		Sub	12	0.26	1.35	12.0	Over the drum and inner shell	At upper breaking point	
CS-05	Imam Ali Dome	Main	16	2 bricks	3.0 - 4.0	7.5	Over the drum and inner shell	Above upper breaking point	Fig. 12e
		Sub	16	2 bricks	1.0 - 1.5	5.5	Over the drum and inner shell	Above upper breaking point	

A significant variation in the distribution and quantity of Khashkhashis is observed among the domes. The dome of Imam Ali (CS-05) relies on a dual system consisting of 16 main Khashkhashis, reaching a depth of up to 4 meters and a height of 7.5 meters above the drum and inner shell, along with 16 secondary Khashkhashis. In contrast, 12 main Khashkhashis were used in the dome of Imam Hussein (CS-01) and the dome of Al-Abbas (CS-02) to achieve the required structural coupling. The Al-Kadhimayn domes (CS-04) and the Imam Rida dome (CS-03) display greater complexity in rib partitioning. The Al-Kadhimayn domes are characterized by an arrangement of 4 main Khashkhashis at a height of 12 meters, alongside 12 secondary Khashkhashis of equal height. The Imam Rida dome uniquely features a three-tier arrangement comprising 8 main Khashkhashis, 9 primary secondary Khashkhashis, and 3 tertiary secondary Khashkhashis extending from the base of the drum above the inner shell. Fig. 12 illustrates the Khashkhashi ribs used in the studied domes.

6.2.4. Integrated structural behavior

The results of the comprehensive analysis of construction techniques demonstrate a structural integration among the core building materials (brick and gypsum mortar), the transition zone systems, and the interstitial Khashkhashi networks across the studied domes. Intersecting rib pendentives (Karbandi) and Muqarnas arches provided high flexibility in transferring loads from the square base to the drum, while the Khashkhashis performed the function of connecting the two shells, reducing

the unbraced buckling length of the outer shell, and enabling the interstitial space between the shells to act as a supportive masonry system. The primary building materials, brick and gypsum mortar, contributed significantly to achieving this integrated system due to their high flexibility, which enabled master builders to construct complex interlocking networks.



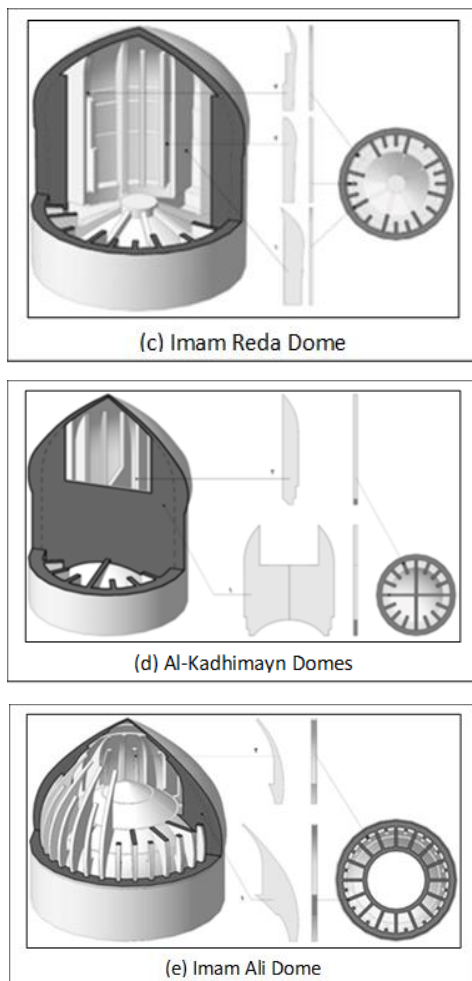


Figure 12. Horizontal and vertical projections and images, illustrating the Khashkhashi ribs used between the two shells of the selected models (Prepared by the author based on [11][21],[22]).

7. Conclusions

The study reveals an integration of structural and functional aspects in the construction of historical double-shell domes. Brick and gypsum mortar were used as the primary building materials in the structures of all the studied models. Khashkhashis (interstitial structural walls) were used as supporting walls between the outer and inner shells to connect them and reduce buckling. The study also showed a clear difference between most Iraqi domes and the dome of Imam Reza. Iraqi domes were characterized by their high slenderness and the complexity of their multi-centered arches (6-7 centers). The inner shells sprung from the top of the drum, allowing for windows to provide natural light and reduce weight. In contrast, the dome of Imam Reza exhibited a lower external form, with its arch relying on only four centers. The drum was long and solid, with the inner shell springing from below, creating a wide interstitial space. Furthermore, the dome of Imam Reza was distinguished by its use of a different structural system for the transition zone, employing muqarnas arches instead of the Pendentives (Karbandi) prevalent in Iraqi models. It was also noted that there was a hybrid Iraqi model between the Iraqi and Iranian schools, which is the Kadhimiya dome, which was

formed from a drum that did not contain windows, and its inner shell was similar to the dome of Imam Reza in terms of springing from the bottom of the drum, while the rest of the characteristics were similar to the Iraqi models.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Ammar Dhumad: Conceptualization, Methodology, Field Data Collection, Formal Geometric and Structural Analysis, Investigation, Visualization, and Writing Original Draft.

Gh. Hossein Memarian: Methodology consultation and Result Validation.

Use of LLM and AI

During the preparation of this work, the authors used AI tools (such as Gemini/ChatGPT) minimally and exclusively to improve the English language and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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Data Availability

The qualitative data, field observations, architectural surveys, and historical records collected and analyzed during this study are available from the corresponding author upon reasonable request.

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