Original Article
ISSN (Online): 2582-7472

ShodhKosh: Journal of Visual and Performing Arts
June 2024 5(6), 2746–2759

GEOMETRIC PATTERNS IN MUGHAL ARCHITECTURE: UNDER A QUANTITATIVE LENS

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DOI
10.29121/shodhkosh.v5.i6.2024.2699

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

ABSTRACT

Geometric designs, a prominent characteristic of Islamic art, were modified to surpass limitations on portraying human or animal subjects, thereby functioning as a universally applicable means of creative representation. The study aims to examine the geometric patterns found in Mughal architecture, with a specific emphasis on their dual function as both decorative and symbolic components. The study analyses two notable architectural projects, Humayun's Tomb and the Tomb of Itmad-Ud-Daulah, emphasising the Mughals' sophisticated use of geometry, which demonstrates their mathematical expertise, cultural values, and scientific accomplishments. This study utilises a quantitative methodology to examine the patterns, assess the degrees of pattern formation, the recognition of fundamental forms and their variations, and the ratios of solid contents to voids in Jalis.

The results demonstrate that Mughal architecture is characterised by its intricate geometric patterns, which are carefully implemented on many architectural components, such as floors, walls, and screens. These patterns serve to not only improve the visual attractiveness but also represent the intellectual and spiritual principles of the Mughal Empire, showcasing a seamless integration of creative ingenuity and mathematical precision. Through an analysis of the conversion of basic shapes into complex patterns, this work offers fresh perspectives on the technical basis of Mughal architectural traditions. The present study enhances our comprehension of Mughal architecture by presenting it as a profound manifestation of creative and scientific brilliance during a historically momentous period in India.

Keywords: Mughal Architecture, Geometrical Patterns, Ornamentation, Islamic Art

1. INTRODUCTION

The architecture of the Mughal Empire, specifically, embodies a remarkable amalgamation of Persian, Islamic, and Indian elements, highlighted by the prominent use of geometric patterns that define its distinctive visual style. In addition to their beautiful nature, these patterns represent the mathematical accuracy, cultural principles, and scientific progress of the Mughal period. The Mughal buildings prominently showcase ornamentation, a core characteristic of Islamic art, which includes a wide range of decorative elements such as geometric patterns, calligraphy, arabesques, and sometimes, animal images. The amalgamation of artistic and scientific concepts exemplifies a wider cultural phenomenon in which art serves as a vehicle for intellectual and spiritual manifestation.

The Mughal era, established between 1526 and 1857, is commonly seen as the highest point of achievement in Islamic art and architecture in India. The architectural wonders of the empire, including the Taj Mahal, Humayun's Tomb, and the Tomb of Itmad-Ud-Daulah, demonstrate an unmatched expertise in geometry, symmetry, and proportion. The architectural designs of these buildings incorporate geometric patterns that not only function as decorative features but also represent the Mughals' profound involvement with mathematical understanding and creative creation. The meticulous application of polygons, star motifs, and radial symmetry demonstrates a refined comprehension of geometric concepts that was essential to Mughal architectural style.

Through the statistical assessment of pattern generation levels, solid-void ratios in Jalis (perforated screens), and the conversion of simple forms into intricate designs, this research aims to offer a thorough comprehension of the dual role of geometric patterns as ornamental and symbolic components in Mughal architecture. This methodology not only emphasises the artistic and cultural importance of these patterns but also provides fresh perspectives on the technical foundations of Mughal architectural methods, therefore enriching our understanding of this extraordinary historical era.

2. GEOMETRICAL PATTERNS IN ISLAMIC ART

Geometry is of great importance in Islam, as geometric patterns were transformed into an art form and ornamental elements to overcome limitations in employing human or natural figures. It is regarded as one of the three categories of embellishments in Islamic art, namely non-figural, that also encompass calligraphy and vegetal designs. Geometry holds a revered status as a sacred art form, whereas calligraphy is regarded as the central component of Islamic painting and decoration. Geometric patterns have been employed and developed, adapting to the era and geographical location, for centuries. These designs not only demonstrate the artistic sensibility of the artisans, but also depict the exceptional proficiency and comprehension of geometry in Islam. Irrespective of their intricacy and complexity, these designs are substantiated by the presence of basic grids. Exemplifying the scientific progress and innovations of the Islamic Golden Age, these intricate mathematical frameworks were constructed solely using a pair of compasses and a ruler.

Geometry holds paramount significance in Islamic art. Star shapes and polygons are prevalent in nearly all forms of art and serve as a significant source of architectural ornamentation. Geometric forms have great versatility and can achieve a high degree of complexity. Starting from basic polygons and rectangles employed as framing elements, to intricate interweaving of stars and irregular polygons. The fundamental shapes, known as "repeat units," from which the more intricate patterns are formed include: circles and interlaced circles; squares or polygons with four sides; the star pattern, which is ultimately originated from squares and triangles inscribed within a circle; multisided polygons. The majority of Islamic geometrical patterns are derived from polygons. When the vertices of these constructive polygons are linked, they form the fundamental Islamic patterns known as star-polygons. This fact underpins the classification of patterns; for instance, all patterns derived from an octagon transform into an octagonal star and are categorized as 8-point geometrical patterns, referred to as an 8-point star. When the two adjacent rays of the star are parallel, resulting in a shape resembling rosette leaves, it is classified as an 8-fold rosette (Abdullahi & Embi, 2013).

3. EVOLUTION OF GEOMETRIC PATTERNS ACROSS VARIOUS ISLAMIC DYNASTIES

Analysis and comprehension of the development of Islamic geometric patterns have been achieved via the examination of the extant architectural structures of the Muslim dynasties. The dominant dynasties that significantly influenced the evolution and formation of Islamic art and architecture are Ancient Umayyad Dynasty reigning from 661 to 750 CE, Abbasid Dynasty reigning from 750-1258 CE, Seljuk Dynasty reigning from 1038 to 1194 CE, Fatimid Dynasty reigning from 909 to 1171 CE, Mamluk Dynasty reigning from 1250 to 1517 CE, Sultanate of the Ottoman Empire reigning from 1290 to 1923 CE, Empire of Safavid reigning from1501-1736 CE and Empire of Mughal reigning from 1526-1858 CE. The Umayyad Caliphs founded the first Arab monarchy within the region of present-day Syria. The architectural style of the Umayyad dynasty was derived from the traditions and decorative elements of the Byzantine and Sassanian empires, particularly in the mosques and palaces. The use of floral motifs and ornamentation became prevalent in Islamic architecture by the late 7th century. Among the earliest and most renowned structures from their kingdom is The Dome of the Rock in Jerusalem, dating back to the late 600s CE. The facade and outside of the building are adorned with mosaics, while the interior surfaces exhibit swirling patterns with botanical motifs, fashioned from gold tesserae, which are small blocks used for mosaic production. Another example is The Great Mosque of Damascus, which features floral decorations influenced by the scenery of Damascus City.

Following the decline of the Umayyad Empire, the Abbasid Empire advanced. Popularity of architectural ornamentation increased as new techniques and more abstract designs were embraced. Elaborate use was made of frescos, wood and stone sculptures, brick works, stucco, and terracotta (Sheila S. Blair and Jonathan M. Bloom, 1996). The Great Mosque of Kairouan in Tunisia, constructed in 670 CE and reconstructed in 836 CE, features simple geometric configurations adorned with floral and vegetal motifs. This architectural masterpiece stands as one of the earliest instances of geometrical patterns in Islamic design. The geometrical forms were first employed on surfaces from the late 8th century, but solely as separate decorative components. Under the Seljuk Empire, the Islamic world primarily concentrated on the construction of tombs and madrasas. The artistic movement of the Seljuks revolutionized geometric ornamentation and created intricate patterns. During the Seljuk era, there was documented use of 10-point geometrical patterns, abstract 6-point and 8-point patterns, as well as unconventional designs composed of non-constructible polygons such as 7, 9, 11, and 13-point geometrical patterns.

The six-point stars of the Fatimid Dynasty, like those of the Seljuks, were equally popular in their architectural works. However, they were more isolated or sculptural in nature, as they did not adorn the entire shape or surface and were always orientated towards a focal point. An outstanding achievement of the Fatimid dynasty that is renowned to this day is The Al-Azhar Mosque and madrasa (970-2 CE and later), adorned with intricate stuccowork including floral and geometric decorative motifs (Reki & Arslan Selçuk, 2018). The Mamluks period is traditionally regarded as the second artistic trend following the Seljuk era. Their architectural decoration consisting of geometrical motifs was primarily intended as prominent focal points rather than being intertwined. An exceptional characteristic of the decoration during their era was the presence of 16-point geometrical designs.

The Ottoman Empire emerged as the foremost practitioners of construction. Their composition was shaped by the artistic style of the Seljuks, with certain influences from the Mamluks. The Ottomans' works predominantly feature floral and vegetal motifs, with geometrical embellishment confined to doors and Minbar panels exclusively. Among the craftsmen and architects of the Ottoman Empire, the most common geometrical patterns were 8 and 16 points, as well as 5, 6, 10, and 12-point layouts. The doors and gateways of the Sehzade Complex (1544-8 CE) are adorned with 6 and 10-point geometric motifs. Additionally, the stone minbar incorporates carved 9-10 point and 12-point geometric motifs. This structure is a highly important architectural masterpiece from the time period, created by the renowned Master Architect of the Ottoman Empire, Mimar Sinan. Within the context of ecclesiastical architecture, these geometric patterns were combined with calligraphic inscriptions. Within Safavid architecture, the utilization of mixed patterns was somewhat limited.

The Great Mughals made significant contributions to geometric patterns. They governed as a diverse empire and derived inspiration from magnificent works of art and architecture, including those from early Islamic, Hindu, and Persian styles, so displaying their multi-cultural orientation. This enhanced their sensibility, imparting to them the importance of geometry in building as a universally understood means of expressing unity and symmetry. Their initial architectural manifestation featuring floral embellishment (tiles and paintings) may be observed in Sher- Shah Mausoleum (1540-5 CE) (Reki & Arslan Selçuk, 2018). Subsequently, in Delhi, the Mausoleum of Humayun showcases the utilization of several materials and methods. The juxtaposition of white marble frames with a contrasting red sandstone construction has distinguished this edifice as unique. Decorative 6 point and 8 point geometrical designs are incorporated into floor patterns and elegantly crafted into window grills (screens or jali) and balcony railings.

The Red Fort of Agra (1564-80 CE) also exhibits similar usage of materials and patterns, as well as a few geometrical designs consisting of 10 and 12 points. By the conclusion of this period, several instances of 10-point geometric motifs are noted, such as in the Friday Mosque of Fatehpur Sikri (1571-96 CE), where one of the earliest instances of a 14-point pattern on the piers of the main dome is also evident. The designers deliberately minimized intricate geometric patterns in their creations and instead emphasized proportions and angles during the design process. The most exceptional samples from this era, showcasing designs with 6, 8, 10, and 12-point patterns on sandstone and marble inlay work, are Akbar The-Great's Tomb (1602-12 CE) and the Tomb of Itmad-ud-Daulah in Agra. The Great Taj Mahal and Lahore Fort are representative examples of the most remarkable Mughal Complex, showcasing unparalleled geometric patterns and embellishments. Profound artistry is evident in the screens, windows, floor finishing, fountains in the courtyard, mosaics, and railings.

Geometry is the fundamental unit and division used in architectural design and transformation (Khan et al., 2024). They further elaborated that transitions and element design may both benefit from the usage of geometry. Also mentioning (Al-Mosawi, 2016), the use of various geometrical shapes, their combinations and transformations, height/depth of their transitions, and the number of transitions occurred in an element, can all be learnt from Mughal architectural practices, which were regarded as the pinnacle of architectural design.

4. GEOMETRIC PATTERNS IN JALI DESIGN

Jali is an Urdu term that refers to a net or a fine web. A decorative perforated screen is an element prevalent in Indian, Indo-Islamic, and Islamic architectural styles. As a shading device, it is a little egg crate that combines horizontal and vertical shading techniques. Although the structure seems to be two-dimensional, its thickness and interconnected balusters create numerous little devices that resemble a substantial overhang or vertical fin. Jalis, sometimes known as screens, have been a prominent architectural element for several decades. Historically, these structures served not only as decorative elements in architectural architecture but also as crucial components in addressing the natural circumstances related to ventilation and illumination in buildings (Kamath & Daketi, 2016). These passive cooling and lighting screens have been incorporated into various design and architectural approaches in different regional contexts, leading to diverse material and design applications. Screens have been effectively used and integrated into the construction techniques in most places with hot climatic conditions for many years. Jalis are characterized by their repetition, infinity, and symmetry. Moreover, Kamath and Daketi (2016) enumerate the primary characteristics of a jali as follows: The jalis generally have a geometric structure, characterized by the repetition of modules. Typically, intricate designs are created on grids. The modular composition typically comprises squares, triangles, or hexagons. The recurring nature of the patterns creates an appearance of continuity that extends beyond the actual boundaries of the frames, therefore complicating the identification of the distinct starting and stopping points of the overall patterns. The deliberate repetition serves as a metaphor of the boundless essence of God. It is the case because Muslims hold the belief that humans are unable to conceive of a suitable dwelling for God.

5. MUGHAL ARCHITECTURE: THE ZENITH OF ISLAMIC ARCHITECTURE IN INDIA

Mughal architecture epitomises the highest point of Islamic art and architecture in India, artfully combining Persian, Islamic, and native Indian elements to produce a distinctive and long-lasting style. The Mughals celebrated their Timurid heritage through various means, including painted genealogies, dynastic portraits, and calligraphic inscriptions. They looked to the Timurids as a source of inspiration and sought to honor their legacy through their own artistic and architectural endeavors (Khan & Ameen, 2024). Covering the period from the early 16th to the mid-18th century, the Mughal era was characterised by a sequence of impressive architectural accomplishments that serve as evidence of the dynasty's creative vision, technical expertise, and cultural amalgamation. This era saw the erection of renowned edifices such as the Taj Mahal, Humayun's Tomb, and the Red Fort, renowned not just for their immense size but also for their meticulous artistry, balanced proportions, and inventive spatial design.

An eminent feature of Mughal architecture is its intricate embellishment, distinguished by geometric designs, floral themes, calligraphy, and intricate carving. The Mughals admired and emulated Timurid architectural styles, incorporating elements such as geometric patterns, dome and vault technology, use of minarets (started from Jahangir and Shahjahan period) and decorative motifs into their structures (Khan & Ameen, 2024). The architectural design frequently showcases imposing domes, slim minarets, spacious courtyards, and sophisticated gardens, which embody a harmonious blend of strength and elegance. The Mughals demonstrated exceptional skill in combining landscape and architecture, exemplified by the Charbagh garden system, which represented paradise and was carefully designed to enhance the architectural structure. The amalgamation of natural and constructed surroundings resulted in settings that served not only practical purposes but also held profound symbolic significance, representing spiritual principles and the Mughal emperors' pursuit of everlasting heritage.

In Mughal architecture, geometric patterns were of paramount importance, fulfilling both ornamental and structural functions. (Khushboo & Khan, 2024) identifies the significance of geometrical ornamentation as: Reflection of divine order, Aesthetic appeal, Symbolism and meaning, Cultural synthesis, Architectural harmony and Preservation of craftsmanship. Further, identifying the techniques of geometrical ornamentation, (Khushboo & Khan, 2024) elaborated the following techniques: Tessellations, Interlocking patterns, Symmetry, Inlay work, Geometric carving and Jali (lattice) work. The architecture of the Mughal Empire in India represents the pinnacle of Islamic architecture, encompassing visual elegance, technical ingenuity, and cultural importance. It epitomises a synthesis of several architectural styles that surpassed geographical limits, making a lasting impact on the architectural panorama of India. The enduring influence of Mughal architecture continues to evoke a sense of wonder and respect, acting as a potent reflection of a period when art, science, and spirituality were interconnected to produce some of the most splendid edifices ever witnessed.

6. METHODOLOGY

The aim of this research is to analyze and quantitatively evaluate geometrical patterns as elements of surface decoration and ornamentation in Mughal architecture. This aim was fulfilled by the following objectives: to study the references of and identify different types of geometrical patterns used in Mughal Architecture, to explore the quantitative methods to evaluate the presence of geometrical patterns as elements of surface decoration and ornamentation and to evaluate geometrical patterns in a quantitative way by the means of levels of pattern generation.

To conduct this research, Humayun's Tomb and Tomb of Itmad-Ud-Daulah were selected for the study. Humayun's Tomb remains as the inaugural garden-tomb constructed in the Indian subcontinent, and is widely regarded as a significant milestone in the evolution of Mughal architectural style. Tomb of Itmad-Ud-Daulah was the first Mughal tomb constructed exclusively from marble and finished with pietra dura, a semi-precious stone embellishment. The mausoleum signifies the shift from the red sandstone tomb of Akbar to the predominantly white marble Taj Mahal. The facades of Humayun's Tomb and the Tomb of Itmad-Ud-Daulah were examined to study the use of geometrical patterns as a kind of surface ornamentation. The study focused on Jalis analysis as there were no prominent geometrical patterns present on the facades of Humayun's Tomb. Visual documentation of the patterns was carried out.

After the visual documentation, the patterns observed were reconstructed on AutoCAD and various parameters for the quantitative evaluation were checked upon. The key parameters identified for the case study to formulate a quantitative framework:

- Levels of Pattern generation: How many different levels are there in which the said pattern has been derived from the basic shape.
- Identification of basic shape: Shape that has been tweaked beautifully to transform into the pattern.
- Identification of derivatives using the basic shape: Derivatives that are used as repeated units along with basic shapes to make the said pattern.
- Solid-void ratio calculation for Jalis: The ratio of solid and void in one unit of a pattern being repeated in the jali.

7. DATA ANALYSIS

7.1. HUMAYUN'S TOMB

The Humayun's tomb is the burial site of the Mughal Emperor Humayun in Delhi, India. It was constructed by Akbar and architecturally planned by Mirak Mirza Ghiyas, a Persian architect. The Tomb is situated on a platform measuring 120 square metres and its height is 47 metres. Constructed using rubble masonry, this building is the prime illustration of the extensive use of red sandstone and white marble. Two gates mark the end of the central walkways. The structure features two double-storey entrances: the West gate, currently in use, and the South gate, operational during the Mughal period. Positioned at the heart of the eastern wall is a baradari, which is a pavilion with twelve doors. Geometric patterns are present on the floor and in the Jalis decoration of Humayun's tomb. The multitude of jali patterns contribute to the well-illuminated rooms. These structures function as lattice screens via which sunlight penetrates the interiors. 4 different geometrical patterns in Jali were identified as shown in the figure 1- 4 below. 2 different geometrical patterns were identified on the floor as shown in figure 5-6.

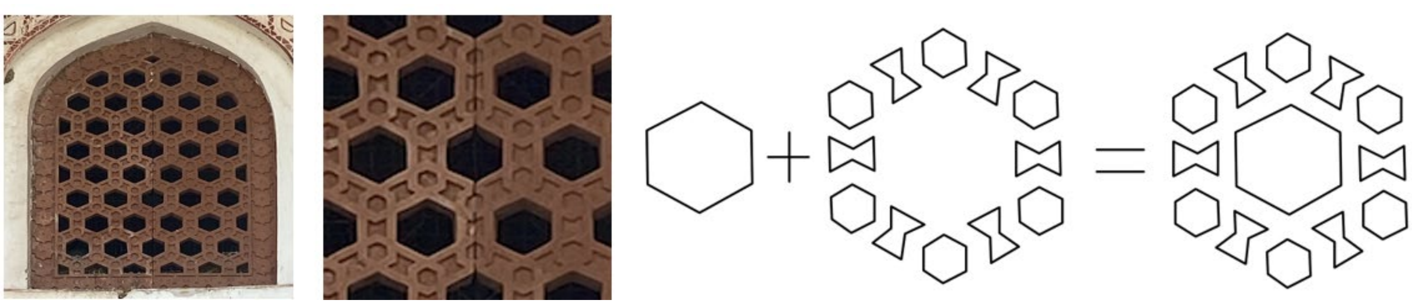

Figure 1: Niche Jali 1 at lower level, Source: Author

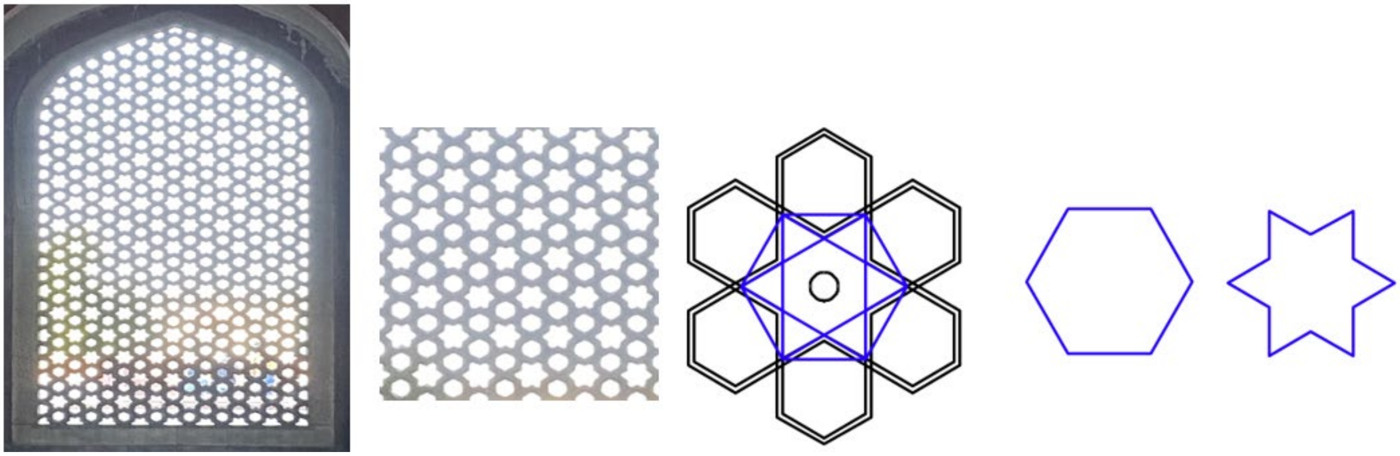

Figure 2: Jali 2 in the recessed arch niche at the upper level, Source: Author

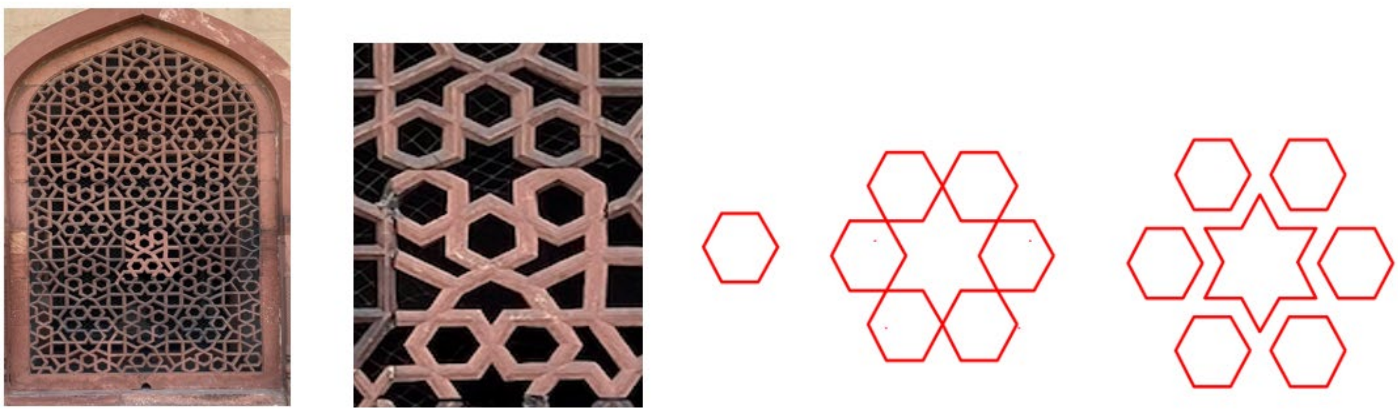

Figure 3: Jali 3 in the outer facade of Upper Level, Source: Author

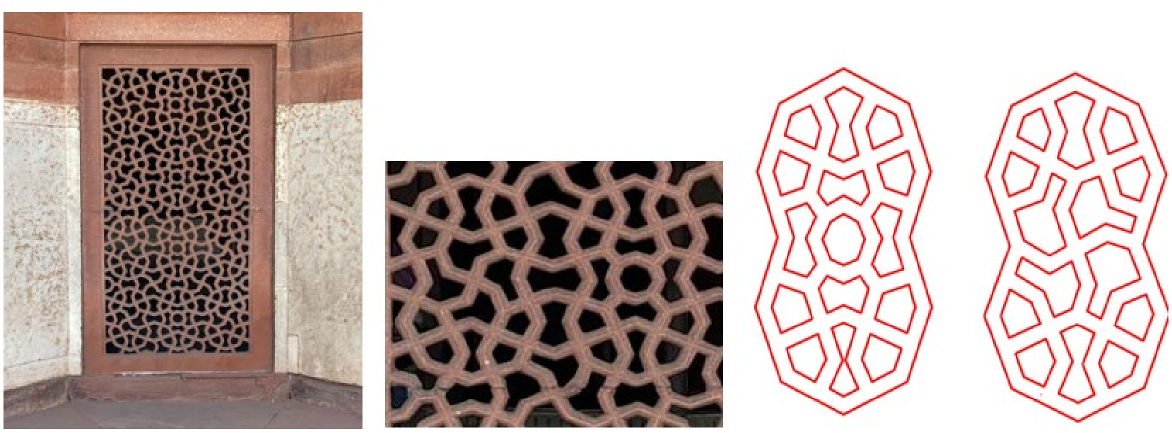

Figure 4: Jali 4 in the outer facade of Upper Level, Source: Author

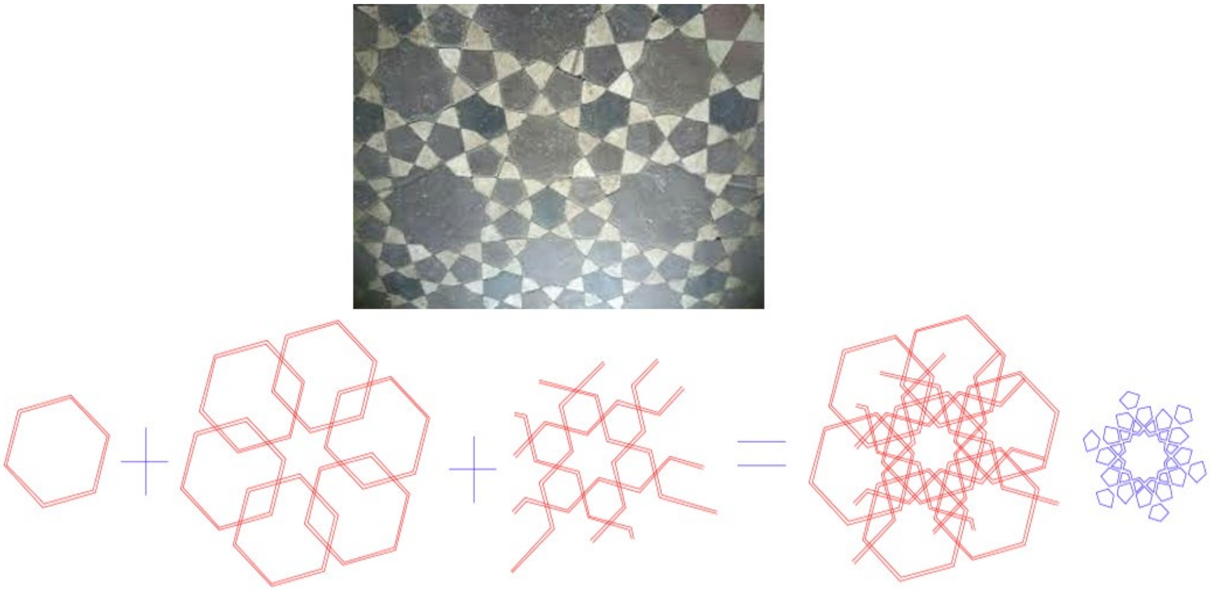

Figure 5: Floor Pattern 1, Source: Author

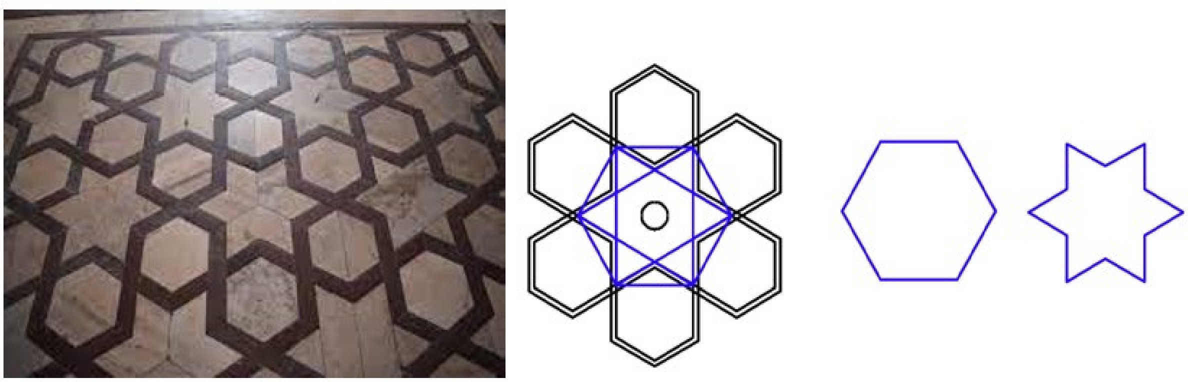

Figure 6: Floor Pattern 2, Source: Author

7.2. TOMB OF ITMAD – UD – DAULAH, AGRA

The Tomb of Itmad-Ud-Daulah should not be regarded as merely another example of Mughal architecture, but rather as one of the most exquisite and intricately designed garden tombs in the whole repertoire of Islamic architecture. Traditionally regarded as the burial site of Mirza Ghiyas Beg Tehrani, a distinguished Iranian noble and Mughal courtier of the highest rank in the empire, as well as the minister of Treasury and prime minister of the State, Itmad-Ud-Daulah, and his consort Asmat Begum, it is also considered the tomb of his nearly entire family, including notable members of the Mughal court. The architecture of this building is characterized by its polychrome rich ornamentation, which includes detailed floral patterns, stylized arabesques, abstract geometrical patterns, mosaic kaleidoscope techniques, and exquisite façade carving (incised and bas-relief) that resembles the finest lace embroidery work. These works are further enhanced by extravagant ornamentation using semi-precious and rare stones inlay. For our study, the presence of geometrical patterns is studied on the façade of the walls, minarets and jali. 9 different wall geometric patterns were identified as shown below in figure 7 - 15. Three different jali geometric patterns were identified for the research as shown in figure 16 – 18.

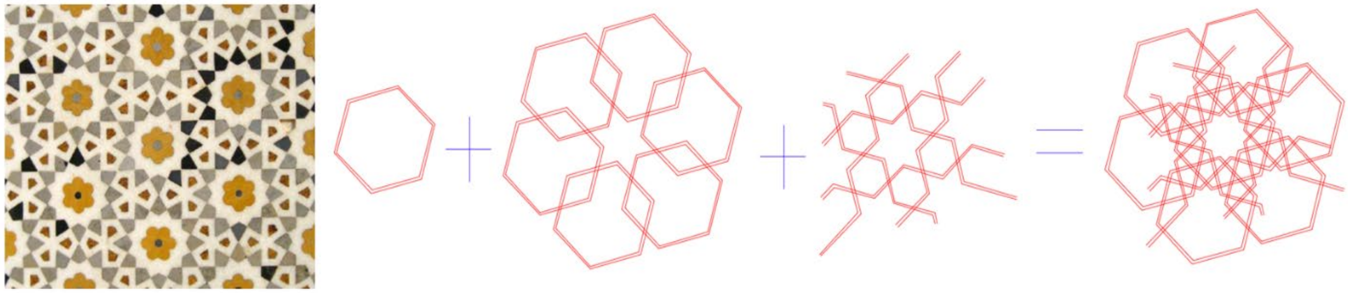

Figure 7: Pattern 1- Ground floor archway, Source: Author

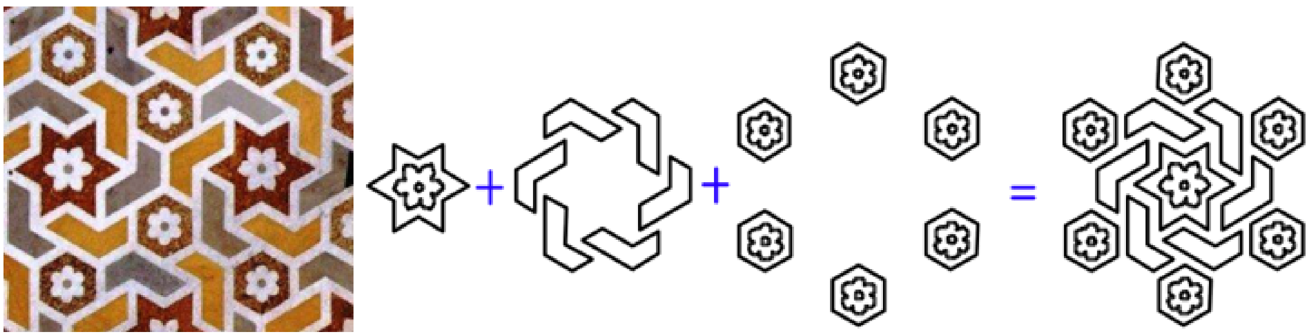

Figure 8: Pattern 2 – Ground floor wall, Source: Author

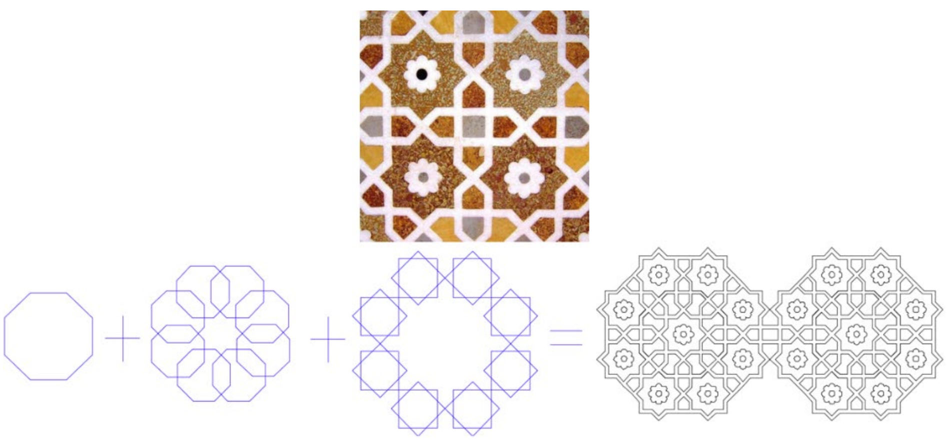

Figure 9: Pattern 3 - Ground floor tower, Source: Author

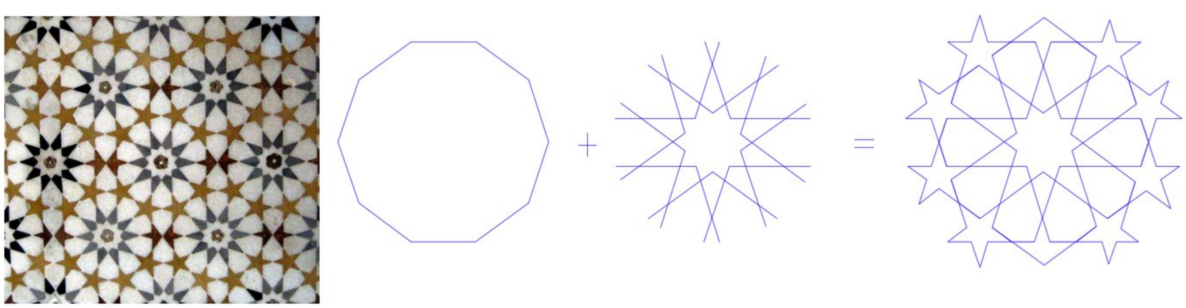

Figure 10: Pattern 4 - Ground floor wall, Source: Author

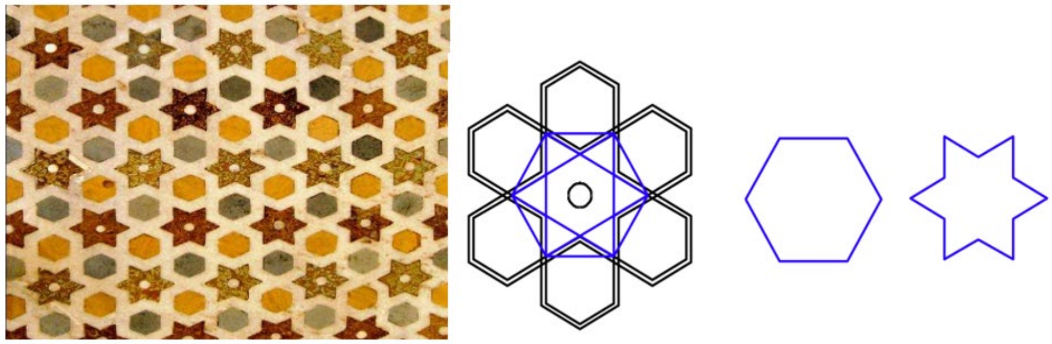

Figure 11: Pattern 5 - Ground floor niche, Source: Author

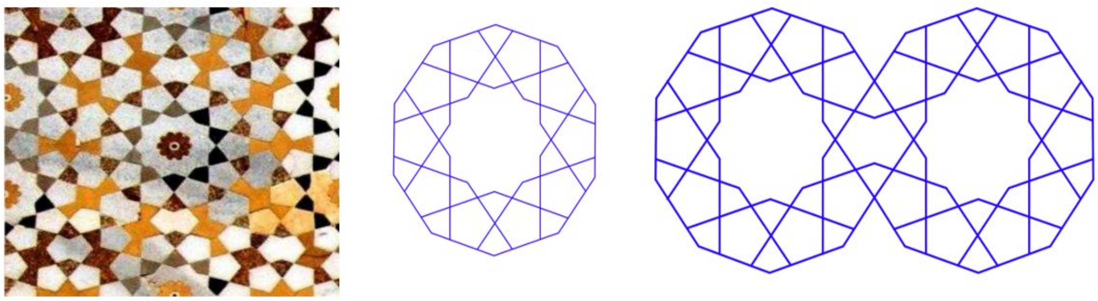

Figure 12: Pattern 6 - Ground floor wall, Source: Author

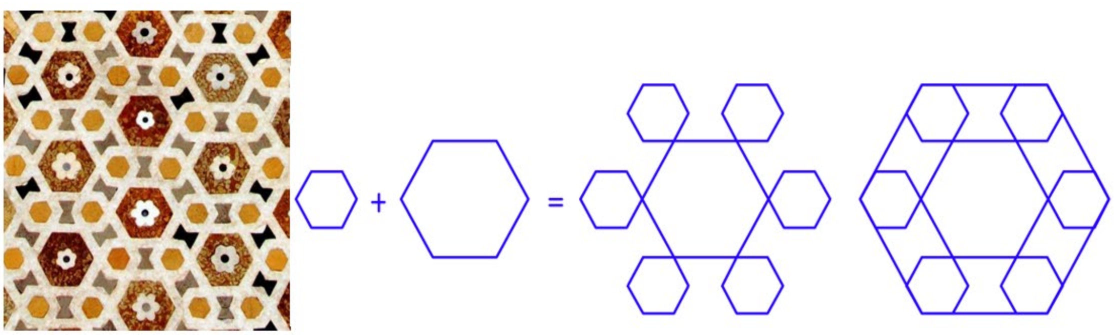

Figure 13: Pattern 7 - Ground floor tower, Source: Author

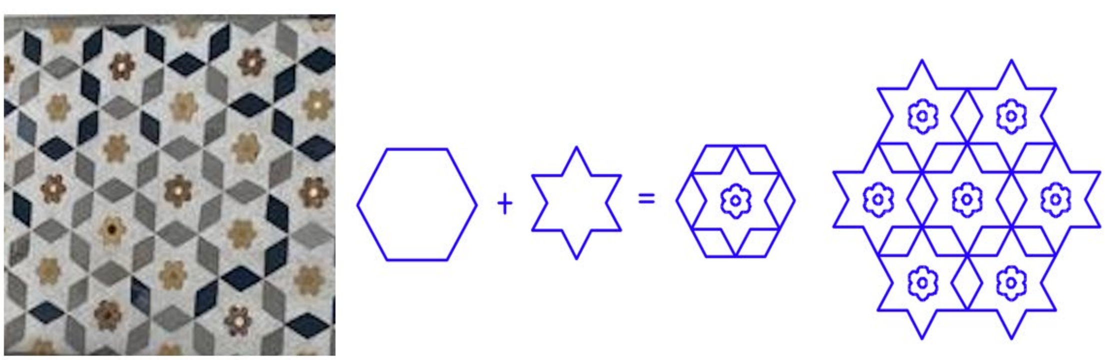

Figure 14: Pattern 8 - Ground floor tower, Source: Author

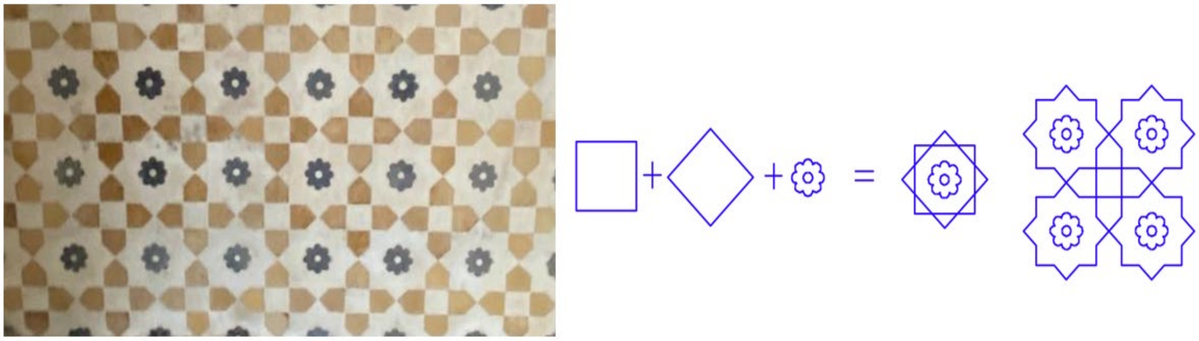

Figure 15: Pattern 9 - Ground floor tower, Source: Author

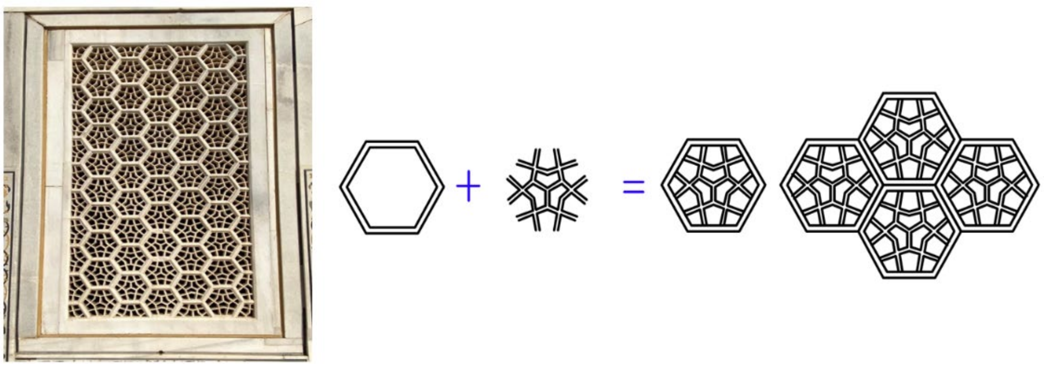

Figure 16: Jali pattern 1, Source: Author

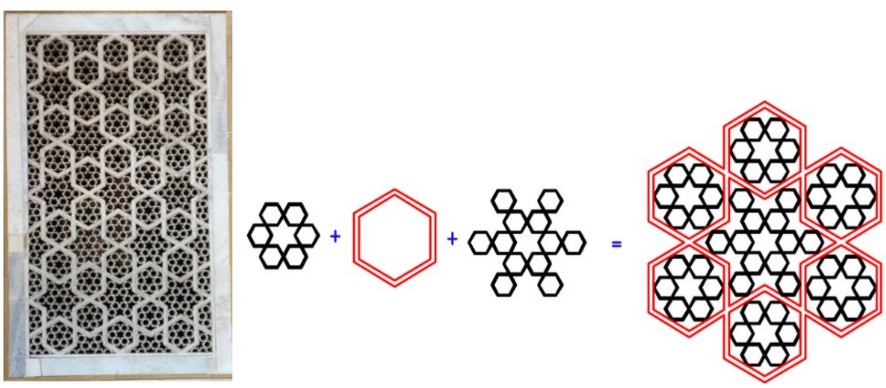

Figure 17: Jali pattern 2, Source: Author

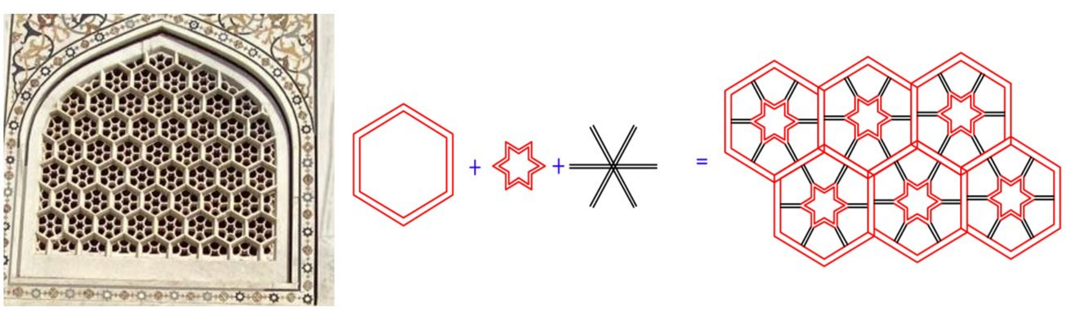

Figure 18: Jali pattern 3, Source: Author

8. FINDINGS

Islamic geometrical patterns mostly originate from polygons, through which the interconnection of vertices of these polygons gives rise to the basic Islamic patterns referred to as star-polygons. It is this feature that forms the basis for categorizing patterns. Patterns originating from an octagon will undergo a transformation into an octagon star, thereby being classified as 8-point geometrical patterns. This specific configuration is commonly known as an 8-point star. Conversely, designs in which the two neighboring rays of the star are directly parallel, forming a shape similar to rosette leaves, are categorized as 8-fold rosettes. A research of the literature has shown that both Humayun's Tomb and Tomb of Itmad-Ud-Daulah prominently display geometrical patterns as surface decorations and decorative elements. These buildings are broadly recognized as exemplary specimens of Mughal architecture. The key parameters identified for the case study to formulate a quantitative framework:

- Levels of Pattern generation
- Identification of basic shape
- Identification of derivatives using the basic shape
- Solid-void ratio calculation for Jalis

Within Humayun's Tomb, most of the designs exhibit a fundamental hexagonal shape, which subsequently undergoes two degrees of alteration to produce the intended pattern. The star pattern originates from the polygons. The star pattern generated by the radial repetition of any polygon with N sides is undeniably a prominent ornamental element of the Mughals, both in terms of its frequency and quantity of repetition. The fundamental shapes defined for the creation of geometric patterns are the hexagon and octagon. The geometrical patterns of Humayun's Tomb exhibit predominantly 6-pointed star and 11-pointed star derived forms. Most geometric patterns adhere to the principles of radial repetition and axial symmetry. The solid void ratios of Jalis are as presented in table 1: Jali 1 - 4:1, Jali 2 - 10:7, Jali 3 - 9:11, Jali 4 - 3:2.

Table 1: Quantitative evaluation framework of patterns identified in Humayun's Tomb, New Delhi, Source: Author

Element	Levels of Pattern generation	Relief/Inlay	Basic Shape	Derivatives	Type of repetition	Solid-Void ratio
Jali 1	2	Relief	Hexagon	Module with hexagon and other polygons	Radial repetition of polygons around a hexagon	4:1
Jali 2	1	Relief	Hexagon	6-pointed star	Radial repetition of hexagon making a 6-point star	10:7
Jali 3	2	Relief	Hexagon	6-pointed star, 6 hexagons arranged radially to form foliated module	Radial repetition of hexagon making a 6-point star	9:11
Jali 4	2	Relief	Octagon	Geometrical module forming inverse 8 pattern	Geometrical pattern created from 2 octagons	3:2
Floor Pattern 1	3	Inlay	Hexagon	11-point star, pentagon, diamonds	Radial	-
Floor Pattern 2	1	Inlay	Hexagon	6-pointed star	Radial repetition of hexagon making a 6-point star	-

The panels of walls, towers, and dados of the Tomb of Itmad-ud-Daulah are systematically adorned with a comprehensive network of geometric variations of stars (five-pointed, six-pointed, eight-pointed, ten-pointed, twelve-pointed) and polygons (pentagons, hexagons, octagons, decagons). Stars have been a prominent feature in Islamic art since ancient times, embellishing sacred sites and things with their luminous appearance. Symbolically, spiritual starlight leads a Muslim gracefully through life, which, according to Oriental symbolism, is a voyage across the desert, filled with sorrow for the loss of paradise that can only be restored after death. The Quran serves as another venue where the star cult phenomenon is encountered.

Through careful examination of the star motif found at the tomb of Itmad-ud-Daulah, as well as on other Mughal structures, namely at the tombs of Humayun and Akbar, it becomes evident that the star is a prominent and undeniable ornamental element of the Mughals, evident from its frequent and extensive repetition. This feature is not coincidental. Many Mughal structures prominently feature five-pointed, six-pointed, and ten-pointed stars, often positioned at the doorways of buildings, similar to the star motifs seen at the mausoleum of Itmad-ud-Daulah. Although the tomb features five-pointed and ten-pointed star patterns on its East and North walls, corner towers, and balustrade, the dados, niches, and most of the jali screens are adorned with a six-pointed star design. The star motif is thought to have been initially associated with Humayun and then with the entire Mughal dynasty (the six-pointed star alignment corresponds to six Mughal emperors, whether by coincidence or not), perhaps due to their interest in astrology and alchemy or other factors.

Surface decoration and decorations of the Tomb of Itmad-Ud-Daulah are characterized by a significant presence of geometrical patterns and arabesque. Identified fundamental shapes for generating geometric patterns are circle, square, pentagon, hexagon, octagon, and decagon. The geometrical patterns consist of derived shapes for 6-point star, 8-point star, 10-point star, 11-point star, and n-fold rosettes. The majority of geometric patterns adhere to the principles of radial repetition and axial symmetry. The solid void ratios of Jalis are as table 2 shows: Jali 1 - 3:7, Jali 2 - 23:77, and Jali 3 - 17:33.

Table 2: Quantitative evaluation framework of patterns identified in Tomb of Itmad – Ud – Daulah, Agra, Source: Author

Element	Levels of Pattern generation	Relief/Inlay	Basic Shape	Derivatives	Type of repetition	Solid-Void ratio
Pattern 1	3	Inlay – Pietra Dura	Hexagon	11-point star, foliated diamonds and 6 petal flower - narcissus	Radial	NA
Pattern 2	3	Inlay – Pietra Dura	hexagon, circle	6-point star, 6 petal daisy and 6 petal jasmine	Radial	NA
Pattern 3	3	Inlay – Pietra Dura	Octagon, square, circle	8-point star, 8 petal daisy	Radial	NA
Pattern 4	2	Inlay - Pietra Dura	Decagon	10-fold rosette, 10-point star, 5-point star	Radial	NA
Pattern 5	2	Inlay - Pietra Dura	Hexagon, circle	6-pointed star	Radial	NA
Pattern 6	2	Inlay - Pietra Dura	Decagon, Pentagon	10-pointed star, marigold	Radial	NA
Pattern 7	2	Inlay - Pietra Dura	Hexagon	overlapping hexagon, daisy	Overlapping radial patterns	NA
Pattern 8	2	Inlay - Pietra Dura	Hexagon	6-point star, marigold, three petal fractal patterns	Radial	NA
Pattern 9	2	Inlay - Pietra Dura	Square	8-point star, 8 petal daisies	Radial	NA
Jali 1	2	-	Hexagon	6-point star	Radial repetition	3:7
Jali 2	3	-	Hexagon	6-pointed star, 6 hexagons arranged radially to form foliated module	Circular repetition of hexagon making a 6 point star	23:77
Jali 3	3	-	Hexagon	Fragmented pattern is formed by joining medians	Radial repetition	17:33

9. CONCLUSION

One of the most extraordinary accomplishments in the history of Islamic art and architecture is Mughal architecture, which combines Persian, Islamic, and Indian features to produce a unique style that persists to this day. The objective of this study was to investigate the significant influence of geometric patterns in Mughal architecture, with a specific emphasis on two renowned buildings: Humayun's Tomb and the Tomb of Itmad-Ud-Daulah. By conducting an in-depth examination of these patterns, this study emphasizes the Mughals' advanced utilization of geometry not only as an ornamental instrument but also as a means of expressing cultural, spiritual, and theoretical principles. The discoveries demonstrate that geometric patterns in Mughal architecture serve a purpose beyond mere decoration; they are intricately integrated into the buildings as representations of organization, equilibrium, and heavenly excellence. The Mughals employed many geometric shapes, such as polygons, stars, and radial symmetries, to produce visually captivating patterns that convey a feeling of unity and boundlessness. The creation of these patterns was precisely executed by using fundamental geometric concepts, frequently relying on recurring units such as circles, hexagons, and stars, which were thereafter reshaped into increasingly intricate shapes. This technique exemplifies the Mughals' sophisticated comprehension of mathematical principles, which were smoothly incorporated into their construction methods.

An examination of Jalis (perforated screens) in the structures under investigation offers a more profound understanding of the practical and symbolic functions of geometric patterns. Jalis were utilized not just for their visual attractiveness but also for their utilitarian functions, including the regulation of light and ventilation. The quantitative assessment of Jalis, which includes the solid-void ratios, demonstrates the meticulous correlation between form and function in Mughal architectural design. By way of example, the complex latticework facilitated natural cooling and illumination while preserving privacy, hence showcasing the Mughals' clever use of geometric concepts in architectural solutions. The tombs of Humayun and Itmad-Ud-Daulah provide as vivid examples of the Mughals' exceptional building skills. The Jalis and floor designs at Humayun's Tomb conspicuously exhibit geometric patterns, like star polygons and radial symmetry, which emphasize the Mughals' captivation with intricate geometric constructions. By employing hexagons, octagons, and 6- to 11-point stars as fundamental shapes, the dynasty highlights its expertise in pattern creation, which entails extracting complex forms from simple geometric constructions. This exemplifies a wider cultural phenomenon in which art was regarded as a manifestation of intellectual and spiritual concepts, therefore demonstrating the integrated nature of science, art, and religion within Mughal culture.

The Tomb of Itmad-Ud-Daulah, celebrated for its intricate pietra dura inlay craftsmanship, serves as a prime example of the Mughals' expertise in geometric designs. The architectural design incorporates a wide variety of geometric patterns, such as 6-, 8-, and 10-point stars, in addition to floral and arabesque artworks. The methodical organisation of these patterns on walls, towers, and screens serves to establish a visually cohesive impact, therefore strengthening the symbolic concepts of unity and eternity. A prominent feature of Mughal architecture, the star motif had great importance as a symbol of celestial direction and divine order. It was often used as a metaphor for the emperor's authority and cosmic legitimacy.

In general, the research emphasizes that Mughal architecture is not only a matter of aesthetics, but also a deep manifestation of the cultural ethos, intellectual accomplishments, and spiritual ambitions of the empire. The incorporation of geometric patterns into their architectural style exemplifies the Mughals' dedication to converging art and science, resulting in spaces that are both operationally advanced and visually fascinating. The present study enhances our comprehension of Mughal architecture by elucidating the intricate relationship between ornamentation and symbolism, and by emphasising the lasting impact of a style that still evokes awe and reverence within the realm of architecture. The geometric patterns of the Mughals are a remarkable and enduring manifestation of a time when art, mathematics, and spirituality merged to create some of the most renowned buildings globally.

CONFLICT OF INTERESTS

None.

ACKNOWLEDGMENTS

None.

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