A Study on the Formation of the North Dome of Masjid-i-Jami Isfahan

by

Marjan Ghannad, B.Arch.

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Abstract

This thesis is an attempt to explore the underlying construction techniques, structural concepts and geometric principles, in one of the celebrated examples of traditional Islamic architecture: the North dome of Masjid-i-Jami of Isfahan, Iran.

On this basis, the construction of the North dome is studied in relationship to the mosque complex, the social conditions and also the architectural characteristic of that period. Second, the North dome is examined based on its unique structural traits and the mathematical relationships which exists within it. Third, the geometrical principles that are used in the construction of the North dome are discussed; and graphically, the geometric patterns of the interior surfaces are explored. Finally, a hypothesis is proposed on the possible techniques for the construction of the North dome. In conclusion, each of theses qualities distinctively demonstrate a unique architectural feature in this building by means of which this architectural masterpiece has come together.

Acknowledgments

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Last but most emphatically not least, I would like to thank the Ministry of Cultural Heritage in Iran for providing us the drawings of Masjid-i-Jami. Also I would like to thank the maintenance workers of Masjid-i-Jami for their hospitality and kind effort in providing us the facilities we required to take measurements and photographs of the mosque.

Unless otherwise stated all the photographs and the drawings are done by Marjan Ghannad.

Glossary of Arabic and Persian words and terms

Word	*Arabic / Persian*	*Brief Definition*
Al-i-Buyid	آل‌بویه	ruling dynasty of Persia from 945 - 998 A.D.
Alam	عالم	the world
Allah	الله	the Almighty God
Asma-ul-Husna	اسماء الحسنی	the beautiful Names of God
Atigh	عتیق	old, ancient
Chahar-taq	چهارطاق	domed roof on top of four piers of a square base
Darvish	درویش	Sufi, humble person
Gaznavids	غزنویان	ruling dynasty of Persia from 998 - 1030 A.D.
Ghayb	غیب	hidden
Ghunbad	گنبد	dome
Goshwareh	گوشواره	technique used to transform a square chamber into an octagon onto which a dome could be placed
Ilm al-Jafr	علم الجفر	science of numerology
Isfahan	اصفهان	a city in central Iran
Iwan	ایوان	a recessed section along a continuous wall
Jami	جامع	congregational
Jom'a	جمعه	Friday, the Islamic holy day
Ka'ba	کعبه	sacred structure towards which all Muslims orient themselves during their prayers
Khaghi	خاگی	egg shaped
Khaki	خاکی	earthly
Kharka	خرقه	a robe, usually worn by the Dervish
Kitab-khaneh	کتابخانه	library
Kufic	کوفی	early Arabic script
Makkah	مکه	holy city of Muslims which houses the holy Ka'ba

Word	***Arabic / Persian***	***Brief Definition***
Malek	ملك	king, ruler
Masjid	مسجد	a mosque, a Muslim place of worship
Mihrab	محراب	a recess in the Qibla wall of a mosque indicating the direction of prayer
Muhandis	مهندس	engineer, architect
Muqarnas	مقرنس	vaulted structure on a curved surface
Qibla	قبله	orientation of Muslim prayers, towards Makkah
Quran	قرآن	the holy book of Muslims
Saheb	صآحب	master, owner
Sailjuqs	سلجوقيان	ruling dynasty of Persia from 1040 - 1194 A.D.
Shagird	شاگرد	student
Shagool	شاقول	traditional construction tool, consisting of a weight suspended from a string, used to define the vertical direction
Shahadah	شهادة	visible
Sofeh	صفه	platform
Sultan	سلطان	king, ruler
Ustad	أستاد	teacher, professor
Zorastrianism	زرتشت	prominent religion of Persia before Islam

Introduction

Traditional Islamic architecture has been studied from many different perspectives. In some studies the formation of Islamic architecture has been carried out within the context of history through examining the role that historical events might have played in creating this tradition. By carving into the remnant memories of the (available) past, a set of relationships have thus been drawn between traditional architectural design and its social condition. Almost at the other end of this spectrum, there are studies that have characterized Islamic architecture through their pursuit of symbolic meanings for its different forms. Only rarely has Islamic architecture been examined as 'the act of construction', structural strategy and the role of geometry in the service of both construction and structure.

To understand the construction process that forms an Islamic building, it is important to place it within the context of society and consider the learning and inclinations of people among whom such skills are developed. A case can be made that the traditional Islamic architecture was shaped by craftsmen who were geometers, mathematicians, artisans and philosophers as well as 'builders' of these structures.

> "A typical product of [traditional] society's educational system is the architect, planner, who is given the title "*Muhandis*"; he who geometricizes and who thereby embodies in his name the fundamental emphasis of the system."[1]

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[1] N.Ardalan and L.Bakhtiar, "The Sense of Unity", page 9, 1973.

A traditional artist *(Muhandis)* uses the principles of geometry to 'construct' his art. Whether it is to weave a carpet or to construct a building, the arrangements have come together by the very same principles and yet are unique in form. From a carved wooden door in a simple house to an elaborate ceiling in a Sultan's palace, from an elegant structure of a Grand Mosque to the intricate fabric of a city, the construction strategies might individually vary, but collectively, they carry the same underlying ideas and geometric principles.

In this regard, to study any form of Islamic architecture we are confronted with questions such as how these constructions are built, strategized and finally realized. How are geometric principles applied? What role does geometry play in transforming an idea into a constructed form? What materials and techniques were applied to construct these forms?

To cope with such questions a systematic approach is needed. One such approach is presented in this thesis through exploration of the underlying construction techniques, structural concepts and geometric principles, in one of the most celebrated examples of traditional Islamic architecture: the North dome of Masjid-i-Jami of Isfahan, Iran.[2]

Masjid-i-Jami is the first and thus the oldest congregational mosque for the city of Isfahan in Iran. This remarkable structure has survived for over one thousand years and is still

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[2] The word *masjid* literary means mosque and *Masjid-i-Jami* is a term used for the major mosque in any Islamic city. *Masjid-i-Jami* of Isfahan is also known as *Masjid-i-Jom'a* which means Friday Mosque. There are other names also associated with this mosque such as *Masjid-i-Jami-i-Atigh* which literary means the Old Congregation Mosque. This name was possibly given in later years, after the city was developed and other Mosques were built.

being used with its original purpose. As Oleg Grabar remarks, a work of architecture with such quality has a contemporary meaning that reflects on some of our contemporary ideologies.[3] In this regard, the value of a building that is permanently alive and functional transcends the frozen concepts of a historical monument and becomes a living phenomenon. In this sense, the Mosque embodies many distinct qualities and can be studied from various perspectives.

Particular to this thesis is a part of this mosque known as Gunbad-i-Kharka[4], or the North dome. This part of the mosque is selected for study on the basis of its construction. In the forthcoming discussion, a systematic framework is presented that is based on four criteria which constructively affect the formation of the North dome. These criteria are as follows:

First, the construction of the North dome is studied in relationship to the mosque complex, the social conditions and also the architectural characteristic of that period. Second, the North dome is examined based on its unique structural traits and the mathematical relations which exist within it. Third, the geometrical principles that are used in the construction of the North dome are discussed; and graphically, the geometric patterns of the interior surfaces are explored. Finally, a hypothesis is proposed on the possible techniques for the construction of the North dome.

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[3] Oleg Grabar, The Great Mosque of Isfahan, London, 1990, pp. 13.

[4] *Gunbad* means 'dome' in Persian and *Kharka* is the name that is given to this dome, (please refer to the glossary of words).

Each of these qualities, distinctively demonstrate a unique architectural feature of the North dome. Nevertheless, the arrangement of this form has collectively come together based on a harmonious combination of the mathematical relationships of structure, structural mechanics underlying the principles of geometry and the strategic crafts of construction. In this regard, the North dome is an architectural manifold that can be fully appreciated only if all its architectural features are considered collectively and in relationship to one another. .

Chapter 1- Historical Background

Saljuq Architecture

Historically, Masjid-i-Jami was mainly constructed during the period known as the Saljuq dynasty in Iran. Saljuqs were Sunni Muslims of Persian-Turkic origins, who defeated the former ruling class, Gaznavids in 1040 A.D. and then ruled until the mid-twelfth century.

The Saljuqs came to power at the time when the Persian civilization after four centuries of Islamic rule had become intellectually quite advanced.[5] It was during this era of learning and knowledge when various libraries, *kitab-khaneh*, literally meaning 'abodes of books' were established everywhere. These libraries were open to the public and therefore, learning was a common value shared by citizens. From this there emerged a series of scholars, scientists, designers and artists who effected considerable achievements in many fields of science and arts.[6]

Saljuqs were the first authority in 'Islamic Iran' who produced a body of built work that was unique enough to become known as a category i.e. *Saljuq Architecture*. Until then the architecture of Muslims in Iran had as such no identifying form of its own. Instead, it was

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[5] Islamic religion was established around 600 A.D.

[6] Among all the scholars of this period we can name three who are known worldwide. First, *Nizam al-Mulk*, the wise minister of Saljuq's Sultan *(Malik-Shah)* whose name is written on one of the calligraphic panels in the south dome of Jami Mosque. Second, *Al-Gazali* (1038-1111), the great theologian, philosopher and the man of great power whose books are known and studied by other great scholars; and lastly, *Omar Khayyam*, the great Persian poet, philosopher and mathematician.

a combination of techniques from pre-Islamic Persian architecture and ideas that were borrowed from other Muslim lands. It was under the great empire of Saljuqs that some innovative features of architectural design were introduced and developed. Here we briefly present some of these traits.

Architecturally, the foremost characteristic of the Saljuq buildings was a very refined sense of masonry, especially in brick structures and patterns. Although many examples of brick construction existed before, Saljuqs carried this material and its techniques to near perfection. They mastered techniques to employ brick as the main material for construction as well as for ornamentation. The uncovered brick was applied to display pure structural elements, while it was also artistically combined with ornaments. The balanced coordination of structure and ornament in their brickwork lent a uniquely honest and characteristically expressive personality to their architecture.

Saljuq brickwork can be described as a combination of inspiration and craftsmanship. The surviving structures of this period are a testament to the craftsmen and builders, whom with their extensive knowledge made countless geometric forms in brick. Some of these executed patterns were combined with richly inventive carved stucco and terracotta.[7] Others were elaborated forms shaping structural elements.

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[7] "Terracotta literary means 'baked earth': clay molded and kiln-fired to make a hard compact material used for bricks, roof-tiling, cladding and ornament .... Sometimes it is left in its raw brownish-red, sometimes coloured with paint to be distinguished from glazed bricks .... It was used in Islamic buildings incorporated in brickwork .... It was also used in Medieval Europe where brick was the building material". Taken From *Penguin References, Architecture and landscape Architecture Dictionary, 1999.*

Another Iranian invention which flourished during the Saljuq period was a technique to transform a square chamber into an octagon on which a dome could be placed. This resolution, commonly known as squinch, is called *Goshwareh* گوشواره in Persian, which literarily means "overturned or transformed corner". It was a method used prior to the Saljuqs in Iran and Central Asia, but it were the Saljuqs who perfected the construction and raised it from a mere solution to a problem of geometric transition to an artistic device of high order.

This invention soon became the basis for one of the most significant structural elements named *Muqarnas* مقرنس. In later periods, the Muqarnas vault system evolved to not only enhance structural support for squinches but also to impart a characteristic expression to them. Structurally, the process of making a squinch involves mechanical techniques, geometrical transformations and mathematical analysis. Saljuqs, by their very careful observation, were able to bring these three elements together to achieve what could genuinely be called an "architectural alchemy".

Builders of this period also made major contributions to another structural problem. Domed structures have been a unique characteristic of Persian architecture even in pre-Islamic periods.[8] Saljuqs, however, managed to acquire mechanical efficiency in their dome usage that was hitherto unknown. Saljuq builders developed techniques that reduced the mass of

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[8] Historically, domes were used in Persian Fire temples before Islam and they were extensively used in shrines, tombs and mosques architecture after Islam.

their dome, while achieving geometrically defined outlines and pleasing proportions. By using mathematical and geometrical principles these builders were able to achieve their goal. (This idea will be discussed in great detail in the next chapter).

Masjid-i-Jami of Isfahan

The magnificence of Saljuq architecture is best exemplified by the Great Mosque of Isfahan, commonly referred to as Masjid-i-Jami. Powerful in presence and structurally sophisticated, this is the first grand mosque established in Isfahan . (Fig. 1.1) There exist many features in this building that place it uniquely, not only within the context of Persian-Islamic architecture of the Saljuqs, but also within the Islamic world. This overwhelming monument stands as a record of over one thousands years of architectural innovation and still continues to provide its original function.

This Mosque is not purely a Saljuq's structure; however, those portions which date from Saljuq time are the chief glories of this monument. The original layout of this Mosque can be traced back to the Al-I-Buyid period around 900 A.D.[9] This layout was based on early Islamic Mosque architecture, known as a hypostyle mosque of Arabic origin.[10] This mosque consisted of a rectangular courtyard with colonnades laid on a grid pattern, around the four

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[9] Based on a study done by IsMEO (Istituto Italiano Per Il Medio Ed Estremo Oriente), under the supervision of Eugenio Galdieri, 1972-1979.

[10] For references on Arabic hypostyle mosques the suggested readings are as follows: Oleg Grabar, "The Formation of Islamic Art"; Hassan Khan "Modern Mosques" Vol.1; Robert Hillenbrand" Islamic Architecture"; and Nader Ardalan "Symbolism and meaning" a paper presented in Agha Khan.

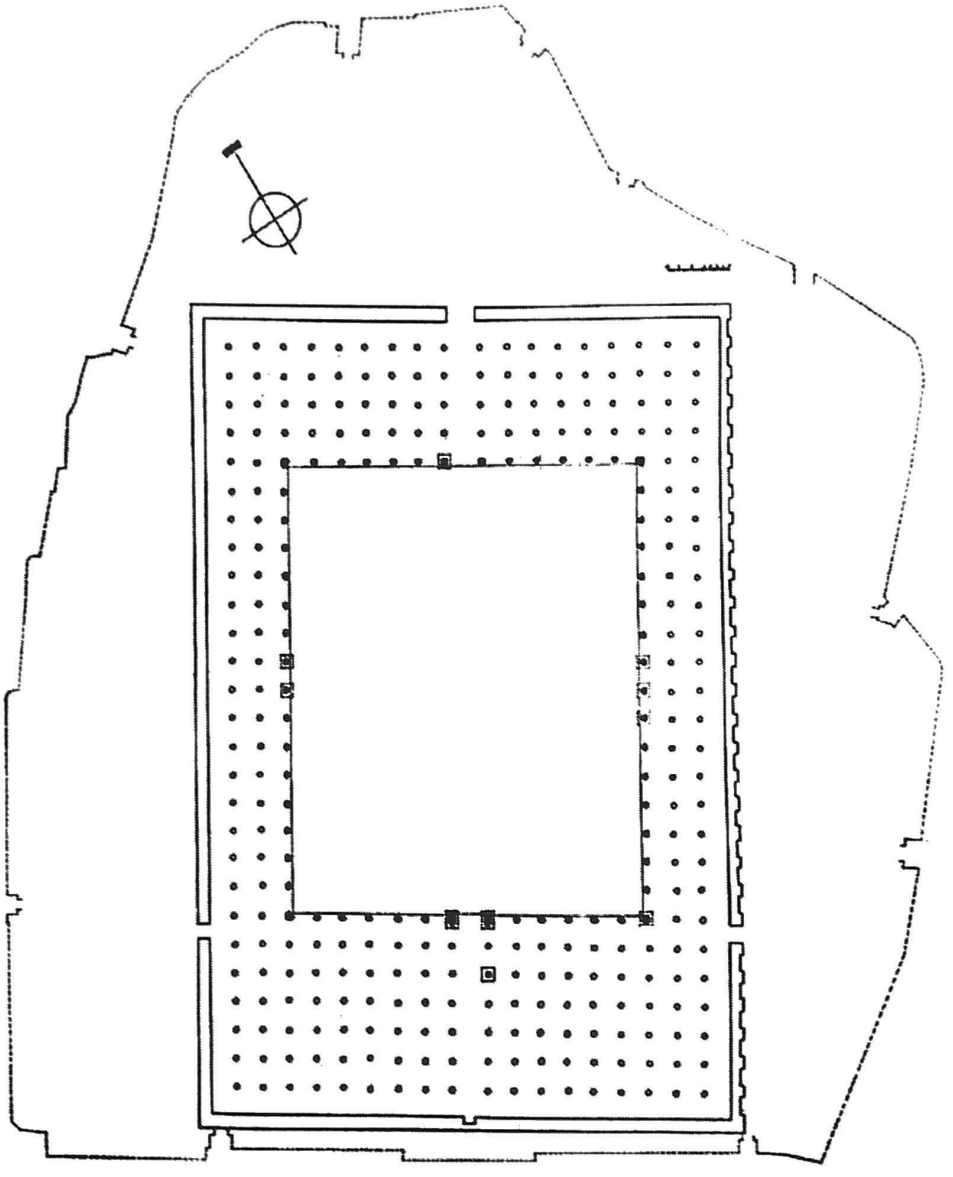
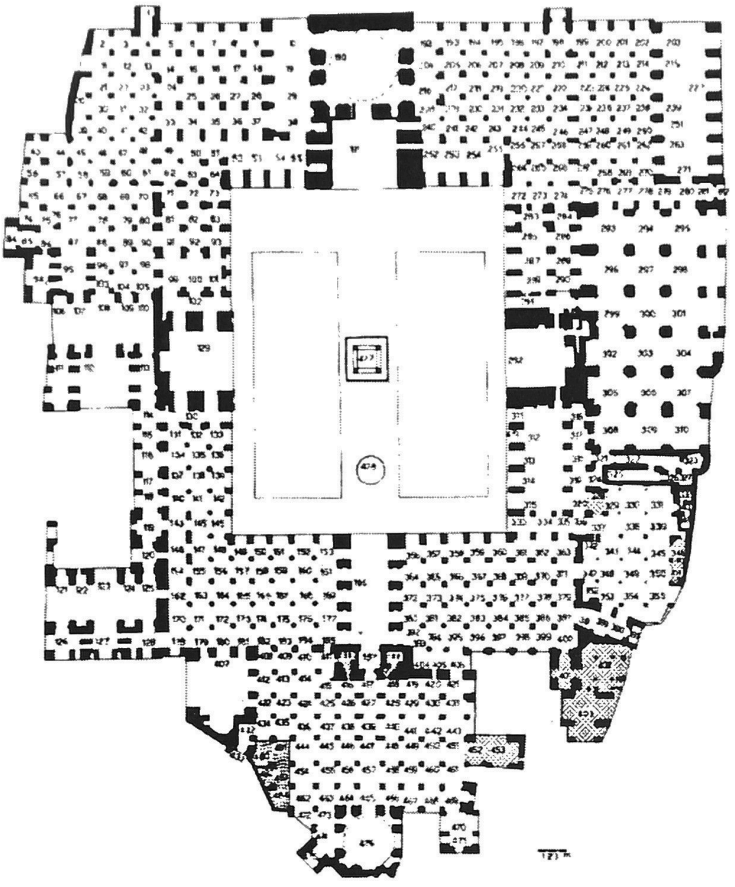
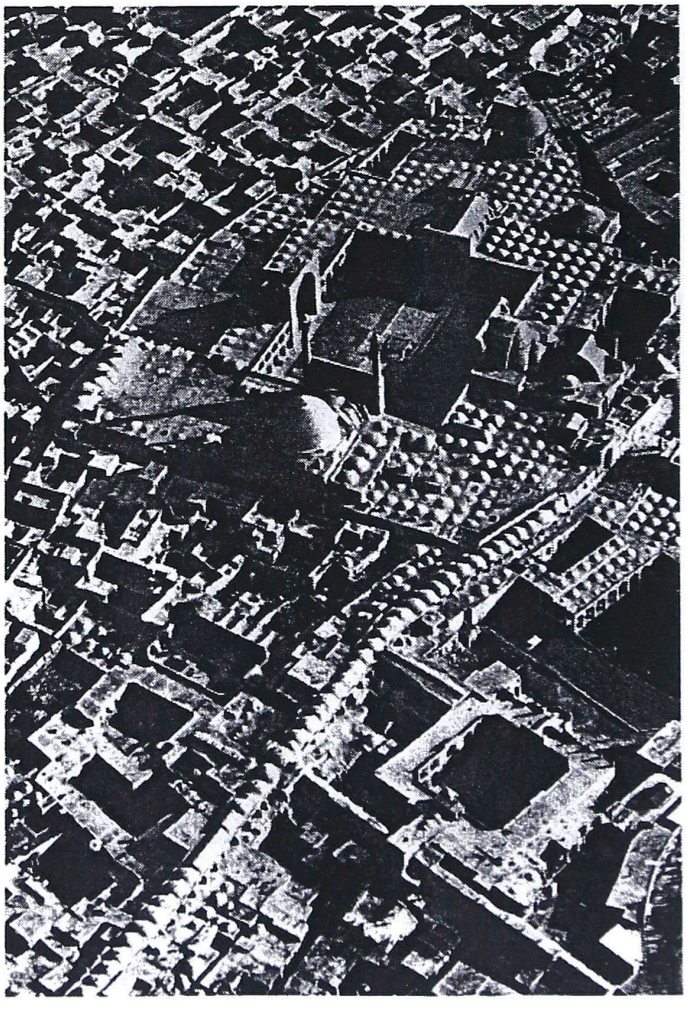


Fig. 1.1 Plan of Masjid-i-Jami in Al-i-Buyid period



Fig, 1.2. The plan of Masjid-i-Jami during the Saljuq period
(Drawn by Eric Schroeder)



sides of the main court. The construction was done with unfired mud-brick forming massive walls with a covered roof. (Fig. 1.2)

During the Saljuq dynasty, after Isfahan was selected as the Capital of Iran, the grand mosque of the city was built on top of the remaining structure of Buyid's Mosque.[11] It seems that by this time much rebuilding was needed, since the original material had not survived and could no longer endure the new construction. The reconstruction of Masjid-i-Jami in the Saljuq period is a turning point, considering that both the layout and the construction material had been modified from its original setting. The Jami Mosque that we see today is mainly the surviving structure from the Saljuq period.

The Saljuq mosque of the 11th and 12th centuries is one of the first examples of a completely evolved form of Persian Mosque. The plan of this mosque which defines the *Qibla* قبله orientation is laid towards *Makkah*, and also is laid along a North-South axis of the city.[12] The construction consists of a courtyard surrounded by arcades and four *iwans* [13] making four axial orientations. Each iwan carries its unique design composed of distinct decorative panels and Muqarnas work. Although the present design for each iwan is not purely Saljuq, the basic plan with four iwans was formalized during the Saljuq period Each

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[11] The situation of building from this period is not known, however, based on the research by IsMEO, it is believed that only the southern and eastern sections of the Mosque remain from this time.

[12] The plan of Masjid-i-Jami is laid along with the Qibla Orientation. The Qibla orientation has an angle of 44.70 degree with the main north-south axis of the city. Although each of the four sides of the Mosque are named in association with the main axis coordinates of the city, the orientation of Qibla is not aligned with the north-south axis. For calculation of the Qibla orientation in Isfahan please refer to *Appendix I.*

[13] *iwan* ایوان is a Persian term that in traditional Islamic architecture defines a recessed section along a continuous wall. Usually iwan appears as a recessed section in the middle of each of the four walls that surround a courtyard.

of the iwans is given a name. The South iwan is known as *sofe-e saheb* صفه صاحب, "the high space of Master"; the East iwan is called *sofe-e ustad* صفه أستاد, "the high space of Teacher"; and the West iwan is called *sofe-e shagird* صفه شاگرد, "the high space of Student"; and finally the North iwan is called *sofe-e darvish* صفه درویش [14], "the high space of Spiritual Servant".[15] (Fig. 1.3)

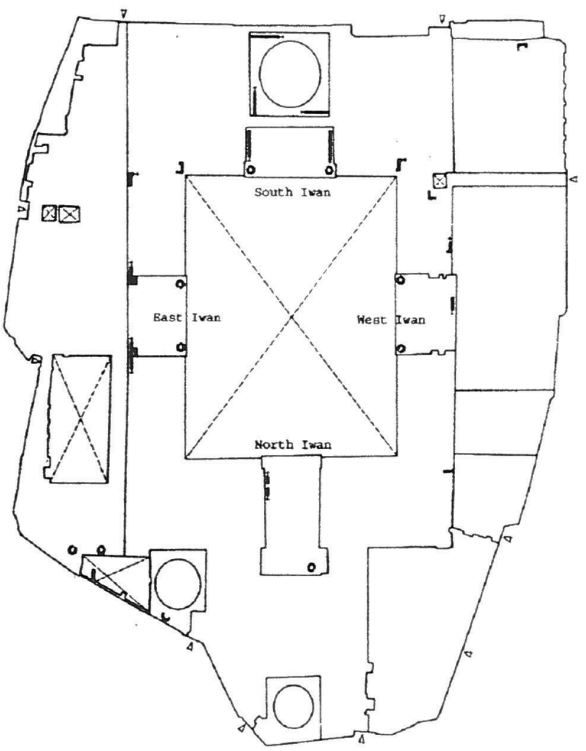

Fig. 1.3 Four Iwans of Masjid-i-Jami
(Mage is taken from a publicatin by Ministry of Culture in Iran based on a work by R.Galdieri f rom IsMEO)

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[14] *Darvish* is a term that can not be easily translated in English. One of the appropriate meanings of *Darvish* is the person who is a spiritual servant of God who is rich in heart and spiritual qualities and have little desire for this earthly world and "dedicates himself to the station of the threshold of the Master". In *Gunbad-i-Kharka* گنبدخرقه the word *Kharka* might refer to the robe that Darvish wears.

[15] It is interesting to remark that with the given name to each iwan there exists a dual relationship between each of the two opposite planes. Master vs.. Sufi, Teacher vs. Student. One can suggest that such a relationship also exists between the two domed structures, located against one another.

There exists two domed chambers along a "north-south" axis i.e. the Qibla orientation. One is located between the South iwan and the *mihrab*, and is known as *Gunbad-i-Nizam al-Mulk*. [16] The construction of the South dome was done in about 1070-1071 A.D. [17] The south dome is a square room of about 16 meters (50 ft.) per side and nearly 30 meters (90 ft.) high. This spacious place supports a huge dome of about 50 feet in diameter that rests on four tri-lobed squinches on each side. The squinches are supported by huge cylindrical columns. These columns were possibly constructed at an earlier date than the dome was constructed. The structure is surrounded by arcades and corridors that are covered by one of the largest variety of geometric patterns and brick masonry solutions of vaulting known to be in a single place. (Fig. 1.4)

Fig. 1.4. South dome interior space

In the opposite direction from the South dome, along the central north-south axis, there exists another dome structure, smaller, yet more elegant than the south dome. This dome, which is the primary subject of this study, is located on the north side and is known as

[16] Nizam al-Mulk was the minister at the time during the reign of Malik Shah, who ordered the construction of this chamber.

[17] Since the name of a famous Saljuq ruler, *Malikshah-i-Saljiq*, is inscribed on one of the calligraphic panels in the dome chamber, Sheila Blair had narrowed the possible date of construction to 1072-93 and has proposed the more specific dates of 1086-1088. *Blair, Iranian Inscriptions.*

Gunbad-i-Kharka گنبد خرگه or *Gunbad-i-Khaki* گنبد خاکی (the earthly dome),[18] and is also known as Gunbad-*i-Taj-ul-mulk.*[19] Aesthetically, it is a magnificent work of art and is one of the most important units in the Jami Mosque. This structure is the only part of the mosque which has the exact date of its construction written on the rim of its dome-dated 1088 A.D. The construction of the North Dome started one year after the South Dome.[20]

The construction of the North dome creates a paradox for anyone studying the Jami Mosque. Traditionally, it is not common to have two distinct domed structures in one unified mosque. In a layout such as the Jami mosque where a grand dome exists aligned with Qibla and is closer to the Mihrab, it seems unnecessary to have another dome further back on the opposite side of the axis.[21] Why was the North Dome constructed and what was its original function? There exists no specific answer to these questions, however, throughout the history a few possibilities are speculated that suggest the function of this structure. Some believe that this dome was constructed as a library for the mosque. Although, the dome's location close to a major public entrance makes this theory a weak assumption. Some say it was a quiet place of meditation for either the King or the Queen. The problem with this theory is that normally, the seat of the rulers are respectfully placed close to the Qibla wall, which is located

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[18] Kharka+Kharga means a robe that is worn by Darvish and Gunbad-i-Kharka is one of the names given to the North dome. Another name that locally is given to this dome is *Gunbad-i-khaghi* , meaning an egg form dome. *Khaghi =Khaghineh* (a dish that is made with egg).

[19] The North dome was built on the order of Taj-ul-mulk, one of the ministers of Malek Shah. His full name in Persian is inscribed on a frieze of calligraphy around the rim of the dome. For further explanation please refer to chapter III, the Geometrical Significance of the North dome.

[20] If the construction of the North dome had started one year after the South dome, then, the building had been under construction for about seventeen years. (1071-1088 A.D.)

[21] In most of the mosques of traditional Islamic architecture, the opposite side of Mihrab (Qibla wall) is marked by a small tower, or in some cases a Minaret. Such examples are as follows: The Mosque of Baibars in Cairo; the Great Mosque of Samara; and Qarawiyin in Fez.

at the south end of the Jami Mosque, but the North dome is on the opposite side. Also there is a possibility that it was used as an astronomical observation site by some great scholars. Despite all these speculations, there is no definite answer to our question.

Structurally, in many architecture books the North dome is introduced as one of the best masonry domed structures ever built.[22] The proportions of this dome, as explained later, are based on the Golden ratio $[(1+\sqrt{5})/2]$ and the dome's characteristic profile has become synonymous with Saljuq form. Over 900 years of history[23] has proven that the structure of the North dome is the only segment of the Jami mosque that has survived earthquakes, fires and civil wars with no considerable damage. It is indeed a very important monument of Islamic, Persian, and more specifically, Saljuq architecture. It is hoped that this study will make a contribution towards more precise understanding of this masterpiece.

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[22] Such as papers and books written by E. Schroder, A. Pope, U. Galdieri, O. Grabar.

[23] The construction of the North dome is between 1071-88 A.D., and therefore it gives us a total of 929 years since the date of construction.

Chapter 2- Structural Significance of the North Dome

In chapter 1, important features of Saljuq architecture were introduced and the basic layout of the Great Mosque of Isfahan was briefly reviewed. Of this vast architectural complex, only the North dome, or Gunbad-i-Kharka, is the main subject of this thesis. This dome, with its rich architectural formation, embodies major characteristics of the Saljuq architecture. In this chapter, the general layout of the North dome is described and then the structural characteristics of this monument are examined.

The General Layout

The North dome has two very distinct qualities when it is approached from the outside, or experienced from the inside. (Fig. 2.1) Like many other forms in Islamic architecture, the outside volume is relatively plain and silent, whereas, the inside space is extensively detailed and expressive.

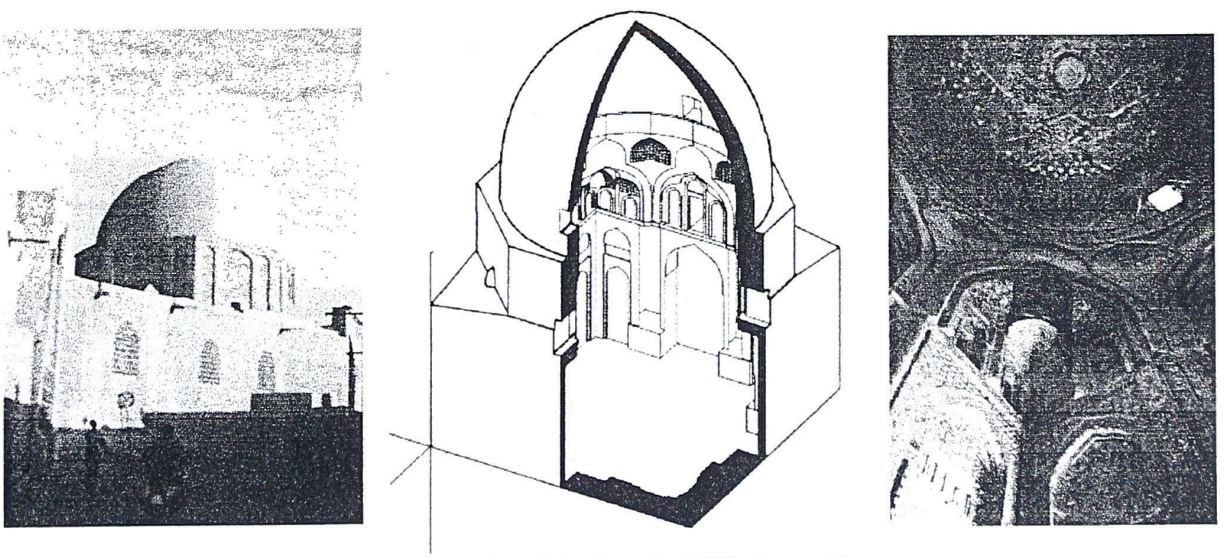


Fig. 1.1. Left, North dome's exterior; Middle, Axonometric cut-out; Right, North dome's interior space

Along a vertical section, Gunbad-i-Kharka can be divided into three major parts. (Fig. 2.2) The first part is a square chamber, located in the lower section of this structure. As it is shown in the plan (Fig. 2.3), this volume is completely enclosed from the north and the west walls and has openings in the south and the east walls. Of five entrances to this dome, three are located in the south wall and the other two are located in the east wall. These openings connect the dome's interior space to other sections of the Mosque. (Fig. 2.4)[24] The interior space of this chamber is signified by a series of arches that visually lift the structure upwards and give a lighter feeling to the interior space. Each side of the square chamber is characterized by three major arches, wherein the middle arch has a wider span than the other two and visually dominates the space. (Fig. 2.5)

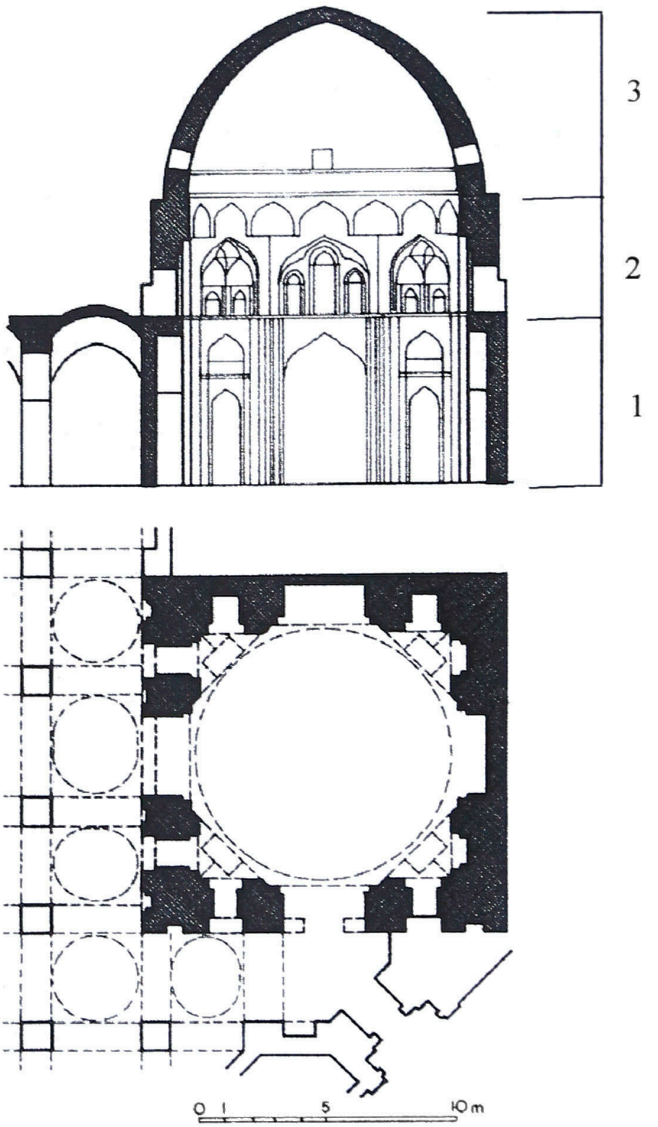
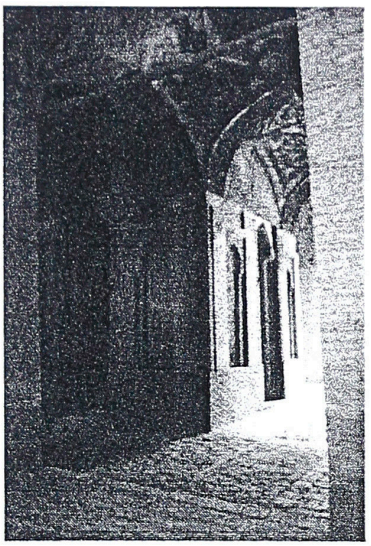
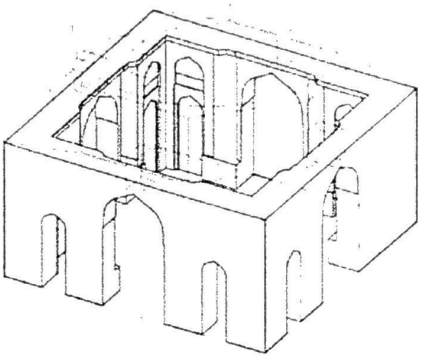


Fig. 2.2 & 2.3 Plan and Section of the North dome
(From J.Hoang, Islamic architecture, New York, 1975.)

[24] Based on the research by IsMEO, it has been discovered that these five openings have always been the only entrances to the dome-chamber and as a result, the other two sides (the north wall and the east wall) have always been completely covered with brick walls.





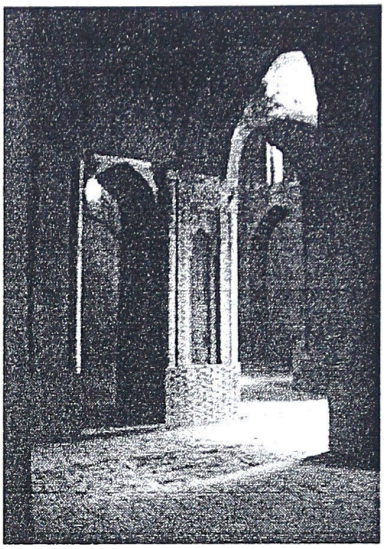


Fig. 2.4. The square chamber of the North dome and entrances

The second(middle) part of the structure is a section that stands between the lower square chamber and the dome itself. This section is the result of a series of geometrical transformations that start from a square base, then form an octagon (eight sided polygon) and by the time they meet the circular base of the dome, form a hexadecagon (sixteen sided polygon). This middle section is considered 'the zone of transition' which in itself is an innovative design. (Fig. 2.5)

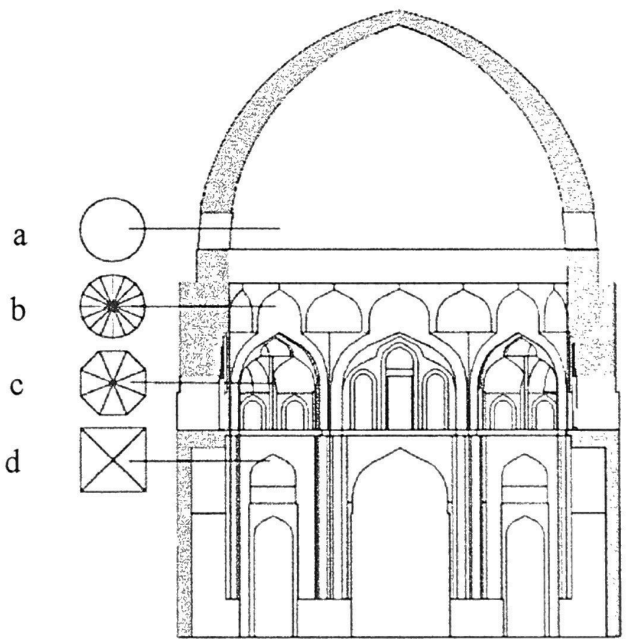


Fig. 2.5 Transformation from a square form to a circular dome in the Zone of transition

In the zone of transition, the octagonal volume is formed by eight large arches of equal profile in each plane. Four of these arches are aligned with the planes of the square chamber (below) and each has a window to the outside. The other four arches are located at 135 degree angles forming the other four sides of the octagon. These arches frame four squinch structures in each corner. These squinches are the basic structure that transform the square base to the circular dome. (Fig. 2.6 & 2.7)

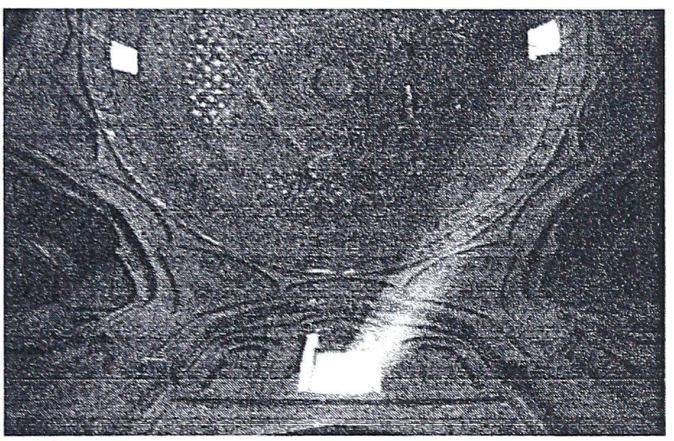


Fig. 2.6. View of the North dome from the zone of transition to the dome

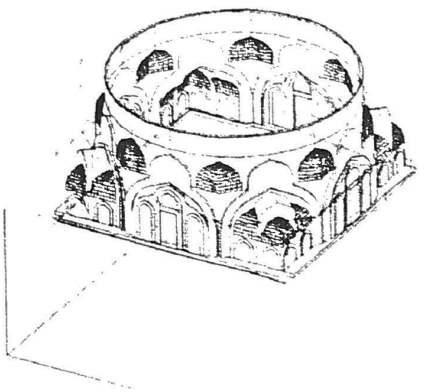
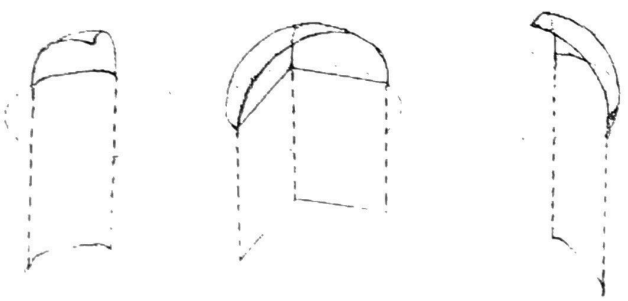


Fig. 2.7. Axonometric view of the zone of transition

The north dome squinch, when viewed from the front, has a trefoiled or three-lobed arch. The profile of the side lobes revolves around its peak with a linear base. The middle lobe, on the other hand, revolves 180 degrees around its peak, with two perpendicular lines forming its base. The result of this arrangement is a unique structure that brings surfaces and revolved forms together in a geometrical space. (Fig. 2.8)



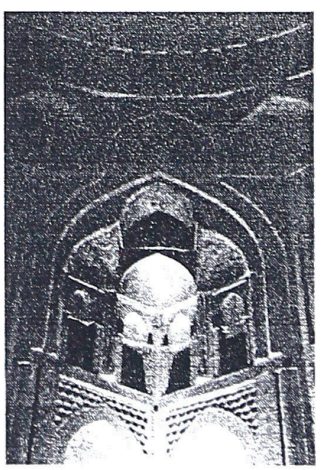


Fig. 2.8. Left, Analytical study of the three-lobed arches in corner squinches; Right, image of a corner squinch.

Between these arches an element emerges to allow the smooth transition from the octagon up to the round dome. "This element is a narrow reveal or pair of plains at an angle of 135 degrees, determining the corners of the octagon"[25]. With such an open angle, this element can be perceived as if it were a flat surface. Above the great arches of the octagon this element expands like a flower and comes to an end at an altitude where the octagon ends and a hexadecagon starts. At this point, a ring of sixteen arches is repeated around which the circular rim of the dome is placed. Eight of these smaller arches are placed on top of the octagon's greater arches and the other eight fill the space in between each pair. (Fig. 2.9 & 2.10)

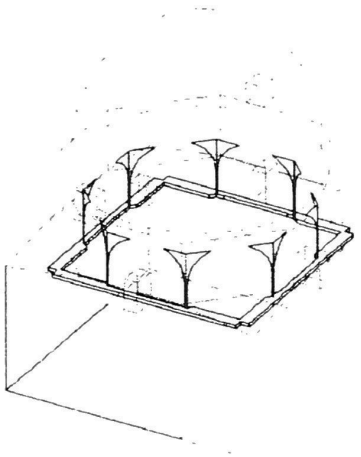
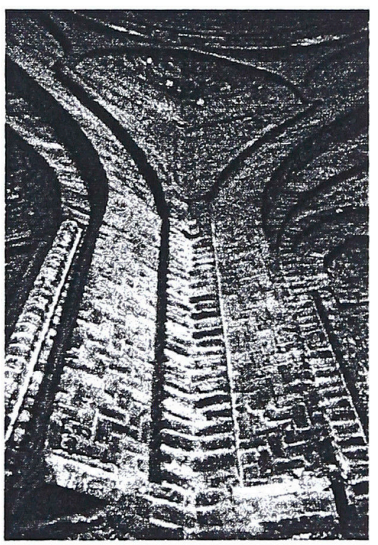


Fig. 2.9. Structural element above the octagon's vertices



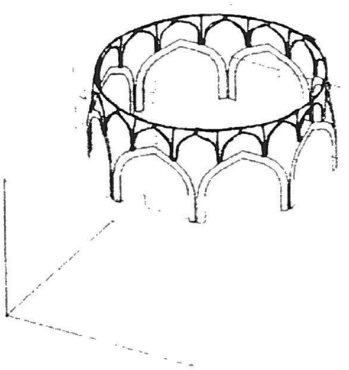


Fig. 2.10. Eight and sixteen arched forms in the zone of transition

The same narrow pair of planes that were revealed in the octagon are repeated again in the hexadecagon. This time a ring of sixteen pairs is repeated in between each of the sixteen smaller arches. Similarly, these sixteen pairs open up to define the edge of the hexadecagon where the rim of the dome is placed. (Fig. 2.11)

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[25] Eric Schroeder, A survey of Persian Art, Vol.II, Arthur Upham Pope, 1939, Pages 1000-1007.

Structural Remarks

The design of the North dome, more so than any of its contemporary buildings, ties form and structure harmoniously together.[26] While it may be generally assumed that 'structure limits form', if one looks at Masjid-i-Jami's North dome, structure opens up new possibilities of expression. "Beauty of form and mechanical perfection of structure are by no means identical terms"[27]. But in this building these two elements are well combined in a perfectly balanced form and therefore, the unity is silently achieved. On this basis there exist three distinct qualities in the structure of the North Dome that form the uniqueness of this structure. These structural traits are as follows:

a) Independent Construction

The first structural characteristic of the North Dome is the independence of its construction from the rest of the mosque.(Fig. 2.13) Visually, the North Dome is surrounded by a series of arcades in the south and the east walls. This structure ties with the rest of the mosque at the level where the square chamber ends and the zone of transition starts. However, based on thorough research by IsMEO[28], this

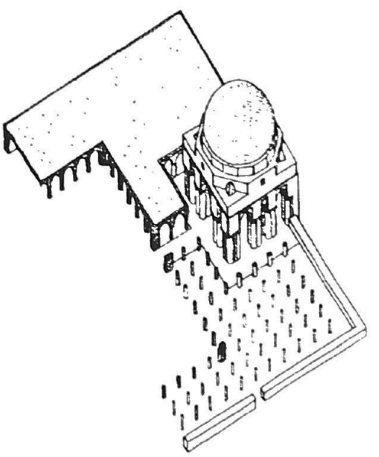

Fig. 2.13. The independent structure of the North dome is the similar to the structure of the South dome. (From E. Galdieri "Masjid-i-Jami, IsMEO Research".)

[26] Of contemporary examples, there are Yazd- Shrine of Davazdah Imam, Isfahan-Mausoleum of Khwaja Sa'd, Kirman-Jabal-i-Sang, Qazvin-Masjid-i-Haydariya, Isfahan-The South Dome of Jami Mosque.

[27] A.Pope, "Persian Architecture".

[28] IsMEO, "*Istitiuto Italiano per il Medio ed Estremo Oriente*", is a restoration organization from Italy, that worked on Masjid-i-Jami for eight years (1971-1979) under the supervision of Eugeino Galdieri. Three volumes of their restoration work has been published in Italian and translated in English and Persian.

connection has no effect on its structural support. The basic structure of the North Dome is based on a form known as *chahar-taq*[29] چهارطاق in Persian architecture. This form consists of a domed roof on top of a square base with four load bearing columns in each corner. This unique structure was originally developed in pre-Islamic Zoroastrian fire-houses and in later periods, was adopted as the basic form in Islamic tombs. The early squinch structures were also developed based on the structural necessities of the *chahar-taq* form[28]. (Fig. 2.14)

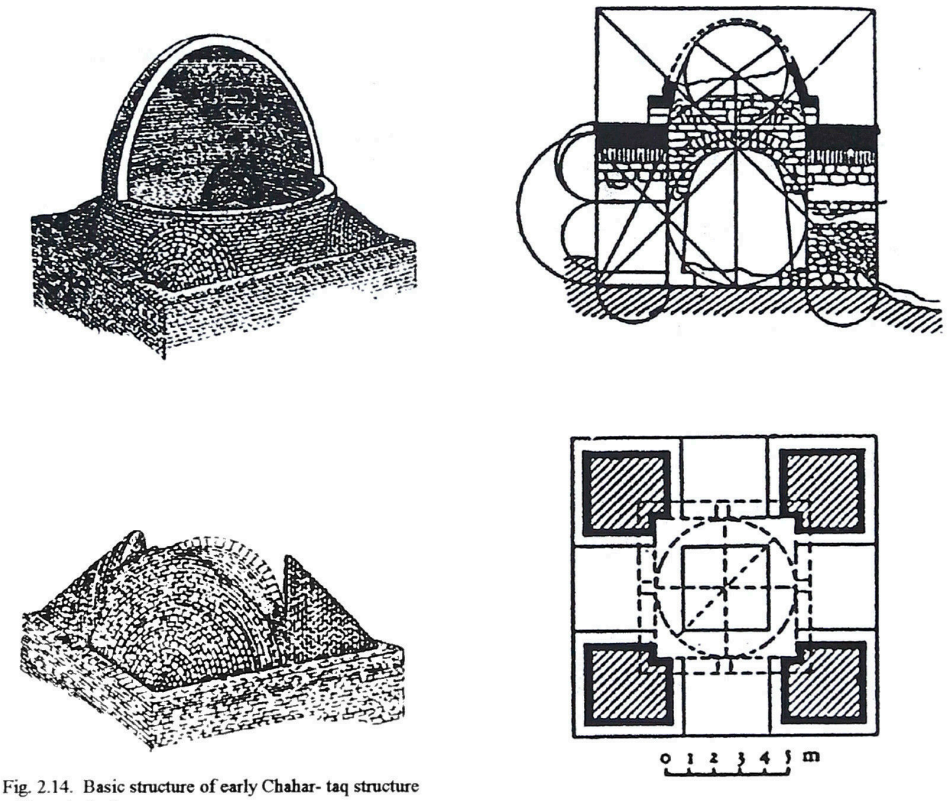

Fig. 2.14. Basic structure of early Chahar- taq structure with squinch forms.
(From G. Mimarian "Domed structures in Persian Islamic Architecture".)

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[29] The word *'chahar-taq'* is a Persian word. *'Chahar '* means four and *'Taq'* means cover or curved ceiling. Another meaning for *chahar-taq'* is a room that is built on top of four columns, *Burhan-i-ghatiq*.

[28] The research done by IsMEO shows that in the north dome, there exists a possibility that this structure was at one time part of a larger complex. In pictures taken from the existing roof top, it seems that in the south and the east the geometrical design was continued to the outside. This continued geometry is now interrupted by the roof of the surrounding structures. However, no trace of such structure exists to verify this theory. Even if such a structure existed, it only confirms that the north dome is a complete structure unto itself that has been able to survive without attached buildings.

b) Mathematics of Proportions

In the floor plan, the North Dome can be divided accurately into three equal sections along the edges of the square base. By this division a nine square grid will be formed which in itself has an important significance in Islamic geometry and mathematics.[29] The division of nine square units is such that the middle arches on each side are aligned with the middle section, and the two smaller arches are aligned with the corner sections. (Fig. 2.15)

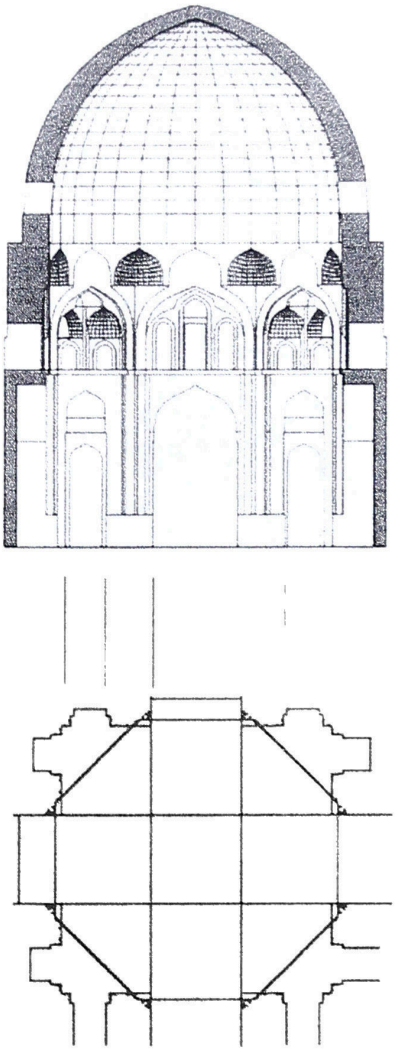

Fig. 2.15. The formation of nine square grid in the Square plan of the North dome

The mathematical proportion of the North dome is more complicated in its vertical section. Once again, this structure can be divided into three parts. The lower part is the square chamber, the middle part is the zone of transition, and finally, the upper part is the dome itself. (Fig. 2.2)

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[29] The magic Square is a well known mathematical problem that is based on nine square grid. Also, in Islamic geometry the close packing of nine square units is used as the base for many geometrical patterns. Similarly, this form has been used for the basic layout in some of the forms of Islamic architecture. References: J. Berggren, "Episodes in the Mathematics of Medieval Islam". N. Ardalan, "Sense of Unity". G. Haider, "Islamic Architecture and Cities".

Some of the mathematical/geometrical relationships found in the North Dome are as follows;[30]

1) Mathematically it is proven that the total inner height, from the inner apex of the dome to the ground, is twice the length of the base. (Fig. 2.16)

2) The total inner height is divided into two parts by means of the "Golden Section", whereby the smaller portion of the ratio starts from the ground up to the line defining the beginning of the zone of transition.[31] (Fig. 2.16)

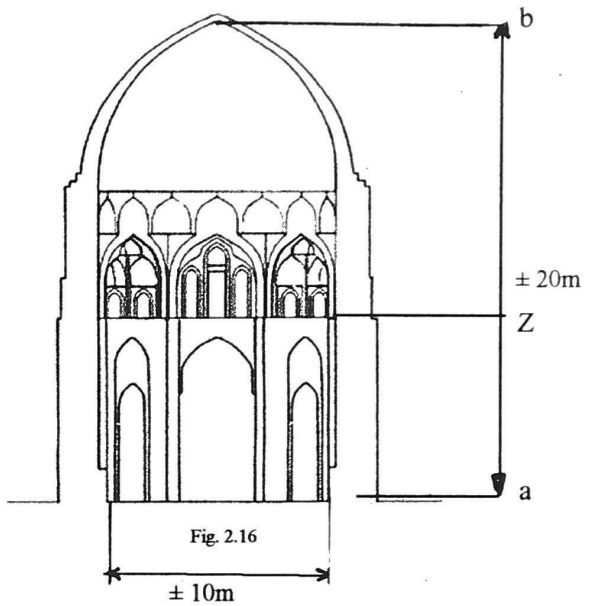
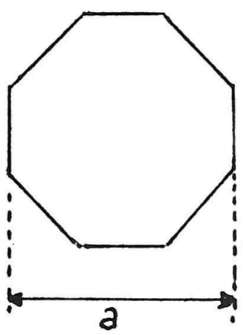


Fig. 2.16

3) The height, from the beginning of the zone of transition to the rim of the dome, is half the width of the octagon. (Fig. 2.17)



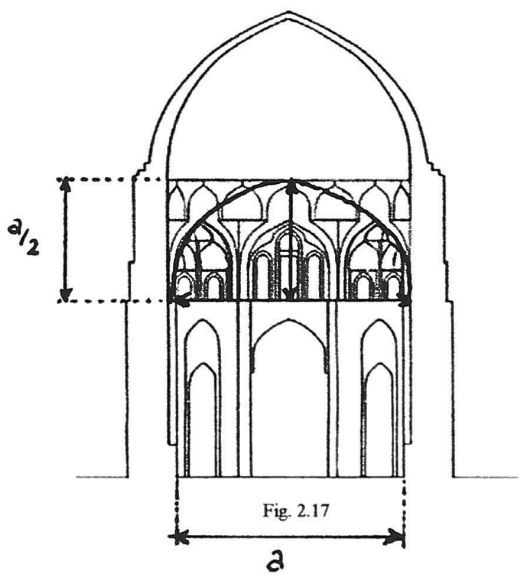


Fig. 2.17

[30] The basic ideas on the mathematical proportions of the north dome are based on a detailed study done by Mr. Eric Schroeder and published in "a Survey of Persian Art" by Mr. Pope published in 1939.

[31] For more information on the golden ratio and how it is geometrically determined, please see *Appendix(II)*.

4) The peak of the lower middle arch is defined by dividing the total height from the base to the peak of the octagon arch, by means of the "Golden Section", leaving the bigger section of the ratio in the lower part The peak of the lower middle arch is also the centroid of a grand equilateral triangle, whose apex is the inner peak of the dome. (Fig. 2.18)

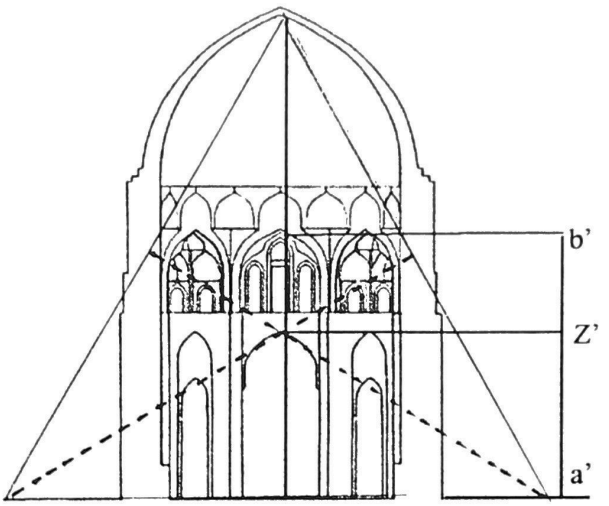


Fig. 2. 18

5) The peak of an octagonal arch in the zone of transition is determined by an equilateral triangle whose base coincides with the side of the octagon, and its top vertex, if extrapolated from its base, will coincide with the peak of the octagonal arch. (Fig. 2.19)

6) An equilateral triangle which is set on the ground, with its apex at the peak of the lower middle arch provides the vertical axis for each of the lower side arches. (Fig. 2.19)

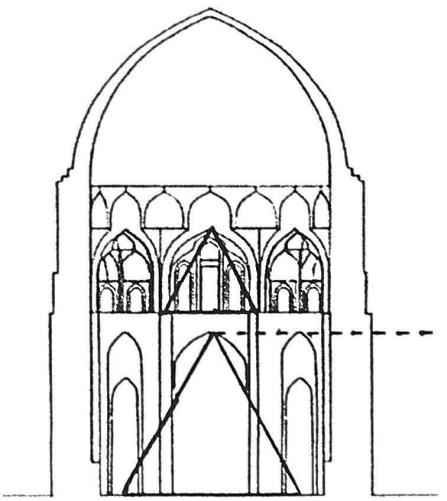


Fig. 2. 19

7) Along the angles of the grand equilateral triangle a series of parallelograms are set, with sides equal to a quarter of the side length of the triangle itself. In the lower section, the

parallelogram determines the height of the lower side-arches. In the upper section, the parallelogram determines the height of windows for the grand octagon's arch. (Fig. 2.20)

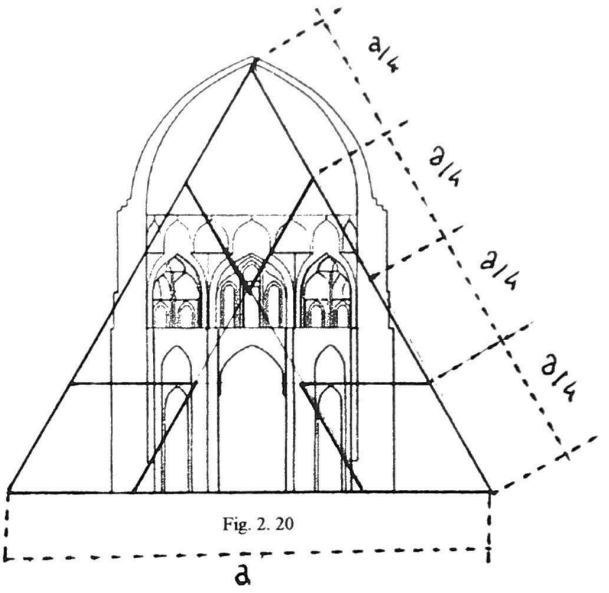


Fig. 2. 20

The general mathematical proportions of the building are also used in some of the motifs of the brick decoration in the interior space. Forms such as triangles, lozenges, squares and pentagons[32] are repeatedly applied in different parts of the interior space. Thus, the brick decoration is a key to the whole system of geometrical adjustments and mathematical relations of the building's structure. (Fig. 2.21)

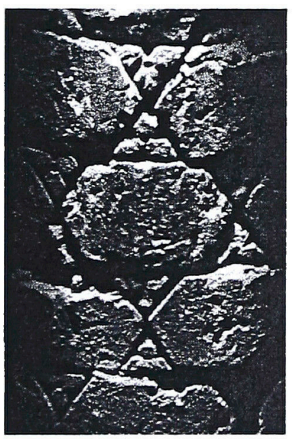


Fig. 2.21a. Hexagonal brickwork on one of the columns

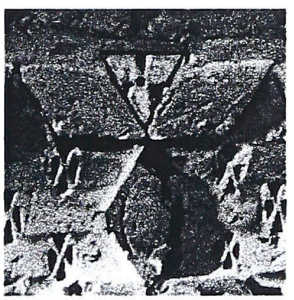


Fig. 2.21b. Details of a triangular-lozenge pattern on the wall

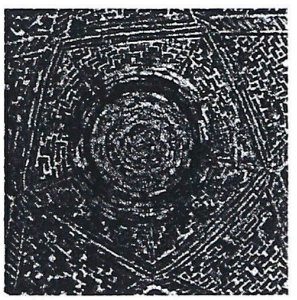


Fig. 2.21c. Pentagonal pattern on the center of the dome's interior surface.

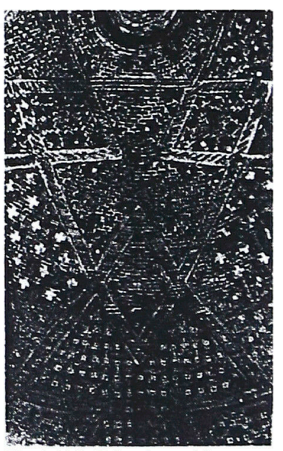


Fig. 2.21d. Triangles and lozenges on the dome's interior surface.

[32] The main pentagon form is generated on the interior surface of the dome's curvature. "This pentagon is generated between the sides of five equilateral triangles and the produced arms of the re-entrant angles. Based on the property of pentagon a perpendicular from the apex to the base is divided at its golden section by a line joining the remaining angles". E. Schroeder, "A survey of Persian Art".

c) The 'Ideal Dome' Structure

The third structural characteristic of the north dome is the result of a revolutionary technique that was achieved by Persian dome builders during the Saljuq period who may be "..... considered as the greatest masters of this noble form which the world had hitherto produced."[34] It is a large claim, but made in recognition of the fact that in the eleventh century, Saljuq dome builders were able to bring together mechanical techniques with geometrical principles that had not been achieved before. As a result of a balanced coordination between mechanics and structures, they were able to build domed structures that literally were "as light as possible".

Theoretically, a light dome structure challenges two structural factors that are of concern for any non-linear curved construction. First, the curvature that forms a dome's arch must give maximum strength, while maintaining the lightest structural form. Second, the structural support that upholds a dome should maintain the minimum thickness while containing the lateral thrust of a dome within.

The North dome of Masjid-i-Jami is the acclaimed structure of the Saljuq period. The general proportions of the north dome, however minutely adjusted to the mathematical form, are governed by the need of construction. This building combines the pleasing mathematical / geometrical proportions with the lightest structural form, and structurally suggests a good

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[34] E. Schroeder, "A Survey of Persian Art", Vol. II, Page 1008.

example for a perfect domed construction. [35] In the forthcoming discussion, the structure of the north dome will be analytically studied based on the theoretical 'ideal dome'.[36]

1) The traditional dome builders have always faced the challenge of constructing a stable structural support for domes. The earlier Persian domes were built on massive walls, relying on strength-by-weight proportions. It was not until the Saljuq period that advanced computational methods were developed. Based on these methods a series of geometrical rules were applied that would allow the builders to determine the exact thickness for load bearing piers.

To determine mathematically the thickness of the load bearing piers in the North dome, the inner arch of the dome is first drawn. Then the diameter of the great circle of the dome is divided into two equal parts. A circle is drawn so that its center is on the rim of the dome (point *d*) and its diameter is the dome's great circle. From this circle a diameter is drawn such that at one end it meets

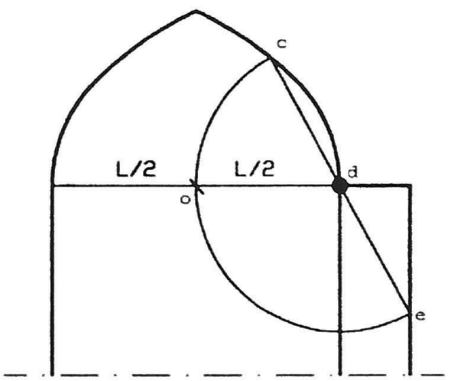

Fig. 2.22. Calculation of wall thickness (From K. Afshar Naderi "Mimar magazine", Tehran, Iran).

[35] E.Schroeder in his chapter on Saljuq architecture in"*A survey of Persian Art*" describes the quality of the north dome as follows "Quite early in this period (referring to the Saljuq period) there emerges in Central Persia a dome which approximates with almost inexplicable closeness to the "ideal" dome which could only be prescribed after the advance of mechanical science under Newton. It was a dome of steeper pitch than any that the Roman or the Eastern world had hitherto seen".

[36] Most of the ideas presented here in respect to the definition of an Ideal Dome are based on the paper *"On the Mathematical Theory of Domes"* by Mr. E.B. Denison. This paper was submitted to the *Royal Institute of British Architects* in 1871.

the dome's inner arch (point *c*) and at the other end cuts across the circle somewhere outside the dome (point *e*). This very point determines the thickness of the piers. In general, depending on the dome's curvature, the thickness of the load bearing pier varies for each dome. Thus, the greater the angle of inclination the lesser the wall's thickness. (Fig. 2.22)

Historically, a similar computational method to the Saljuq's was a method that was developed by European builders for Gothic churches in the twelfth century.[37] In this method, to determine the thickness for the load bearing piers, instead of dividing the great circle, the dome's inner arch is divided into three parts. A semi-circle is then drawn on the dome's rim with a radius equal to the length of the "tripartite division". Based on this division, the required thickness for the load bearing piers is calculated. (Fig. 2.23)

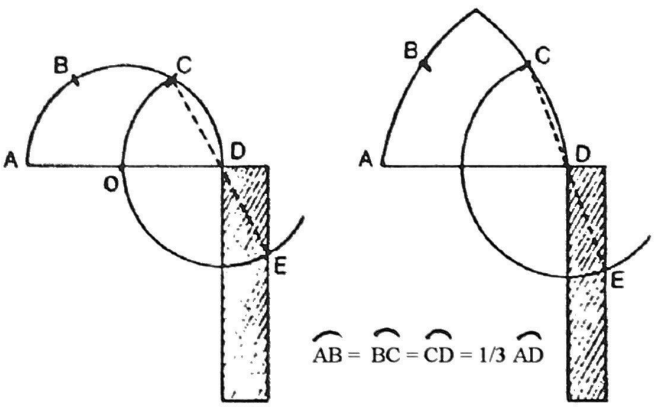

Fig. 2.23. European computation method for wall thickness of semi-circular domed structures and pointed domed structures.(From K. Afshar Naderi "Mimar magazine", Tehran, Iran).

Comparing these two methods, both give the same thickness of the load bearing piers for semi-circular domes. Nevertheless, in case of a pointed domed, the Iranian method has an advantage over the European one. Whereby, the former results in much thinner load

[37] K. Afshar Naderi, "A structure Computational Method of the Saljuq Era", Mimar Architecture Magazine, E. Schroeder, "A survey of Persian Art", Vol.II and B. Denison "On the Mathematical Theories of Domes".

bearing piers than the latter. (Fig. 2.24)

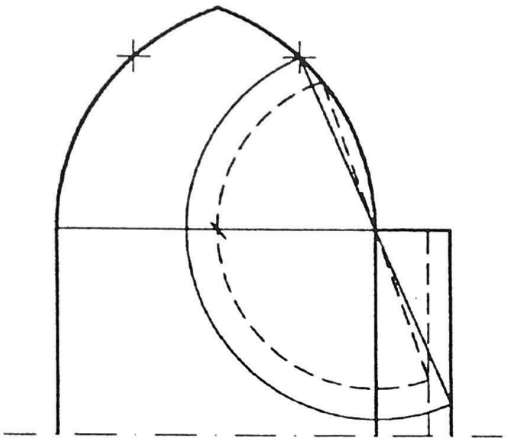

Fig. 2. 24. Comparison of Saljuq and European method of computation for the wall thickness. (From K. Afshar Naderi "Mimar magazine", Tehran, Iran).

2) In the North Dome the total load of the dome and the four squinch arches are concentrated in each vertex of the octagon. Each vertex rests on a column, thereby transforming the load to eight piers in the square chamber. This innovation has enabled the designers to distribute the dome's load among specific points and relieve the walls of carrying the total load. Where there is no load, the wall is cut and an opening is inserted. Aesthetically, this structural technique is used to create both a lighter structure and enhance the quality of design.

3) E.B. Denison has claimed a mathematical proof that a pointed dome is more stable than a hemispherical dome. [38] Comparing a pointed dome with a hemispherical dome, the angle of inclination at each point of the arch in a pointed dome is greater than the angle of inclination in each hemispherical dome. In addition, the radial force towards the centre in

[38] Edmound Beckett Denison. "On the Mathematical Theory of Domes". Royal Institute of British Architects. 1871.

a hemispherical dome is more than the radial force in the pointed dome, and therefore, F1>F2. As a result, a hemispherical dome has thicker load bearing piers compared to a pointed dome. We know that the North dome is a pointed dome and therefore, has better structural qualities than a hemispherical dome.(Fig. 2.26)

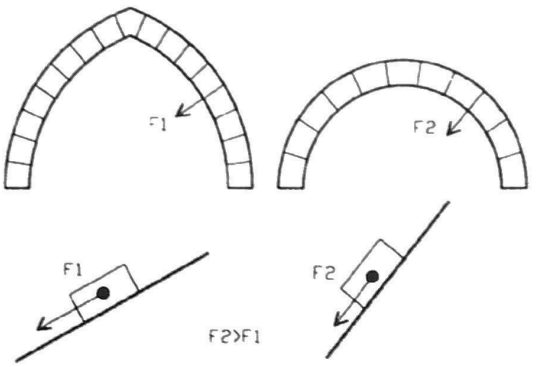

Fig.2.26. Comparison of forces in a pointed dome and a hemispherical dome.(From K. Afshar Naderi "Mimar magazine", Tehran, Iran).

4) The north dome is considered an ideal dome because the destructive lateral thrust which endangers hemispherical domes at a point 30 or 40 degrees above the horizontal has been brought down much lower and closer to the drum. As a result, a strong shell is produced which can transmit a considerable thrust to its base. By taking the thrust straight to the ground, the dome has always been able to survive even when confronted with massive earthquakes. This simple, logical solution is almost perfect. By this method the angle of inclination is placed within the recommended thickness of the walls. This angle is the critical factor for supporting the dome's weight. As a result the mass is reduced to a minimum, yet the angle is contained within the load bearing piers. (Fig. 2.27 & 2. 28)

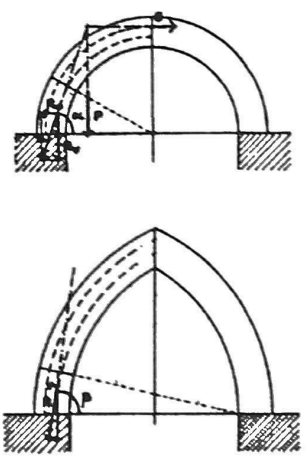

Fig. 2. 27. Distribution of lateral thrust in hemispherical and pointed domes. (From G.Mimarian, "Domed structures in Persian Islamic architecture").

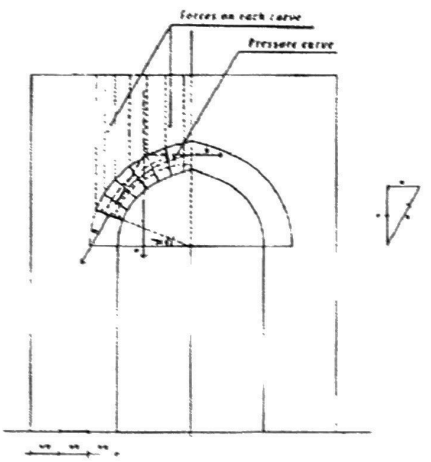

Fig. 2.28. Distribution of forces to the pointed dome's load bearing wall.(From G.Mimarian, "Domed structures in Persian Islamic architecture")

5) The stability of a dome relies on the fact that its lateral thrust is placed within the drum's thickness. If the lateral thrust of the dome falls outside of the drum, the forces that are in compression will act in tension and instead of holding the structure together will pull it outwards. It is suggested that the drum of the ideal dome contain an inclination of 5 to 1 to meet the lateral thrust of the dome. In the north dome the inclination contained in the walls is 4 ½ to 1. (Fig. 2.28)

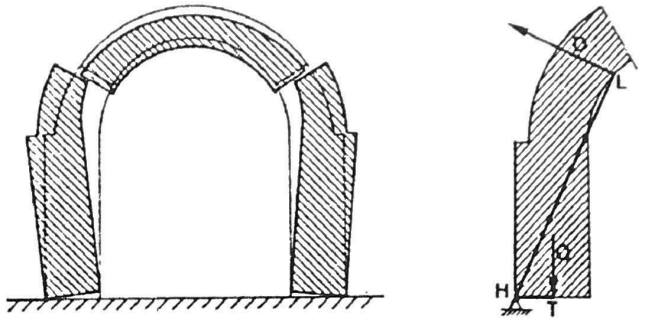

Fig. 2.28. Stability of a dome in relationship to its lateral thrust.(From G.Mimarian, "Domed structures in Persian Islamic architecture")

6) The ideal dome will gradually be lighter so that the shell at the peak will be half as thick as that at the base. In the case of the North dome the thickness of the shell at the peak is exactly half of the thickness at the base. [39] (Fig. 2.32)

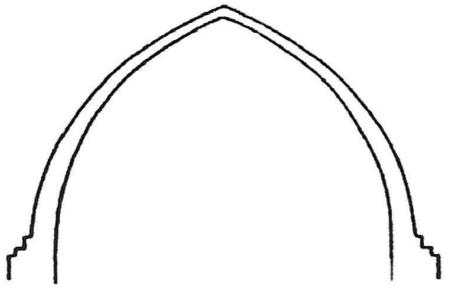
Fig. 2.32 This diagram shows how the thickness of the shell in North dome gradually reduces as it gets closer to the peak

From these technical/structural elaborations it is claimed that the structural formation of the North Dome has achieved theoretical near proportions and performance. In return, the structural complexity of the North Dome explains the nature and extent of innovation evolved throughout its construction.

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[39] B. Denison has claimed that at the peak of the ideal dome, the thickness of the shell must be about 1/46 or greater, form the outer diameter at the base. E. Schroeder has proven that this thickness for the North dome is 1/42 of the outer diameter, and therefore, it meets the requirement of an ideal dome structure.

Chapter 3- Geometrical Significance of the North dome

"Conditions are not invariable; terms are not final. Thus the wise man looks into space, and does not regard the small as too little, nor the great as too much; for he knows that there is no limit to dimension."[40]

As mentioned, by the 11th century, the Islamic cultural life and thought had reached the point where it was highly advanced both aesthetically and intellectually. This advancement was truly the product of the new faith (Islamic religion), whereby acquiring knowledge was ranked second after prayer and therefore, learning was regarded as one of the most sacred acts for a pious Muslim . In this respect, "nature was to be studied in her mode of operation and not merely in her manifested form" [41] and various sciences and arts were to be admired as a means for better understanding of the universe which includes both the world that is known to us *(alam al-shahadah)* عالم الشهادة and the one that is invisible *(alam al-ghayb)* عالم الغيب.

Likewise, this unique approach influenced the attributes of architecture as much as it affected other fields of science and art. In this regard, Islamic architecture became an abode to embody the sacred art, and Islamic geometry became its instrument to give it a physical form. For Muslims who were impressed by the Pythagorean concept of space on the one

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[40] Chuang Tzu, ch. XVII (4th century), from *"Order in Space"* by Keith Critchlow.

[41] Ardalan & Bakhtiar, *"The Sense of Unity"*, The Sufi Tradition in Persian Architecture.

hand and Divine creation on the other hand, the Islamic concept of geometry was an instrument to establish a sense of sacredness in art and architecture.[42]

On this basis, the structure of the North dome was formed using geometric order(s) in different levels of construction.

In the first level, geometry is incorporated to form the basic structure. The plan starts as a perfect square and along a vertical axis, it gradually transforms into an octagon (eight sided polygon), and then into a hexadecagon (sixteen sided polygon) until it meets the circular rim of the dome. Throughout this transformation, corner squinches have developed which have their unique geometric form.[43] The geometrical structure of the North dome, although externally solid and plain, internally creates a unique geometric space. This space visually provides other geometric attributes such as symmetry, structural balance and harmony.

In the second level, the geometric order of the North dome is based on a precise mathematical proportion. The square base is divisible into a close pack of nine square units, such that each of the arches of the square chamber are proportionally aligned with this division. Similarly, in section, the main structure is carefully proportioned based on the mathematical laws of the Golden ratio. This division has been further carried out to another

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[42] Geometry by its very nature resides between the world of science and art. Driven as a branch of mathematics, geometry is based on theoretical science and deals with the properties and relations of lines, angles, surfaces and solids. Geometry also belongs to the world of art and imagination where theses properties can be formed in endless arrangements.

[43] The geometric form of squinch was extensively discussed in the previous chapter.

level, where forms such as an equilateral triangle, a lozenge, and a pentagon create a greater geometric relationship between different sections of the structure.

This deliberate use of mathematical relations is an attempt to create a dialogue between natural forms and man-made architecture. To a Muslim believer, the creation of the world is based on the multiplication of natural phenomenon. God, who is 'One', is the beginning of everything and therefore, under His command creation starts from 'two' and is carried to infinite numbers. The generation of numbers in mathematics is similar to the basic rules of creation. In this respect, numbers are closely bound to nature. Using this analogy, since form is quantifiable through mathematics, then, geometric forms are related to nature via the abstract language of mathematics. Based on this indirect relationship, the use of geometry as "the expression of personality of numbers" permits further exploration into the process of nature.[44]

At the third level, the geometric forms reveal a symbolic meaning beyond their physical application. On this basis, geometry bridges the gap between conception and perception, such that it transforms an intangible idea into a tangible form. Much literature has been written in respect to this geometric trait. One work in particular that is presented here corresponds

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[44] In the Islamic philosophy, a branch of science known as the science of numerology is developed which deals with the numerical symbolism of letter, *'ilm al jafr'* علم الجفر. On this basis, the creation of world, or the manifestation of existence is compared to the generation of numbers and therefore, numbers are closely bound to nature. Geometry is driven from mathematics. Number 1 symbolizes a point, 2 symbolizes a line, 3 symbolizes a surface, and 4 symbolizes the first solid form which is the first 'platonic solid' known as Tetrahedron.

closely to the structure of the North dome:

"Various geometric forms have specific symbolic meaning which relates the outward forms to inner meaning and architectural utility to spiritual significance. The dome, while creating a ceiling which protects from both heat and cold, is also the symbol of the heavenly vault and its centre the *axis mundi* which relates all levels of cosmic existence to the One. The octagonal base [refer to the zone of transition] symbolizes the Throne and Pedestal and also the angelic world. The square base [corresponds] to the corporeal world on the earth. The vault structure [of squinch] represents reflection here below the supernatural archetypes, the descent of the heavenly abode towards the earth and the crystallization of the celestial substance or ether in terrestrial forms... [theses geometric] forms create a sacred quality and signify realities beyond the earthly realm." [45]

Lastly, geometry serves a decorative function, as it covers the entire surface of the North dome with aesthetically pleasing patterns. Historically, the art of decoration on the surface of Islamic buildings started in the early periods of the Islamic architecture. For a Muslim artist, ornamentation was not a mere representation of living forms, instead, it was a symbolic language with cosmic references. This language was expressed by means of geometric patterns, arabesque forms and calligraphic panels filling the surfaces of walls, ceilings and sometimes even floors. [46]

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[45] Nasr S. H. , "Islamic art and Spirituality". Pages 49-50

[46] A good example of the use of geometric patterns on the floor is the courtyard of Sultan Hassan Mosque and Madrasa in Cairo.

1) Geometric patterns:

The main geometric patterns were created by bricks that are molded in various forms.[47] These bricks have distinct geometrical arrangements in different sections of the building. Some of the brickwork is purely decorative, while other brickwork participates in the structural stability of the building. Both structural and non-structural bricks are harmoniously combined in such a way that they cannot be easily identified from each other. The final decorative design to the interior surface is given by carved terracotta ornaments and plaster inlays. Both of these materials are capable of producing small decorative forms that are visually organic to the brickwork and easily combine with it. (Fig. 3.1)

Fig. 3.1a. Plaster inlays and brick-plaster plugs on columns.

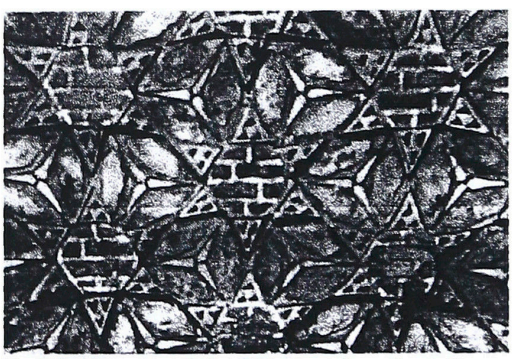

Fig. 3.1b. Terracotta and plaster inlays on a decorative surface.

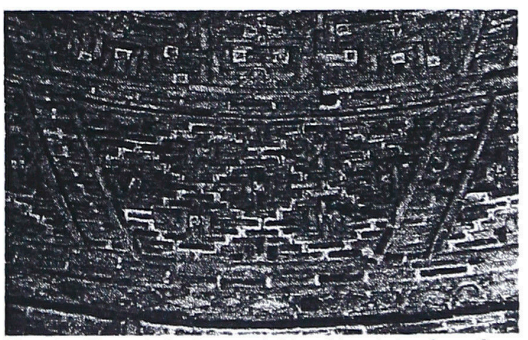

Fig. 3.1c. Plaster design between bricks of dome's interior surface.

[47] The brick construction is extensively explained in the next chapter.

Geometric patterns on the interior surface of the North dome are developed from the repetition of a geometric form (which can be a polygon or a combination of different polygons) in and around a circle. [48] In this respect, the circumference of a circle can be divided into 3,4,5,6,... equal sections and various geometric forms can generate from this circle based on such divisions. To further explore how a geometric pattern develops by applying simple geometric rules, two examples of geometric patterns on the interior surface of the North dome are presented here. In the first example, the basic form of the geometric pattern is generated from the combination of a regular hexagon (a six sided polygon) that is surrounded by six triangles (three sided polygons) within a circle. Considering that this combination is formed within a circle it can be repeated in infinite numbers by close packing of these circles. (Fig. 3.2a)

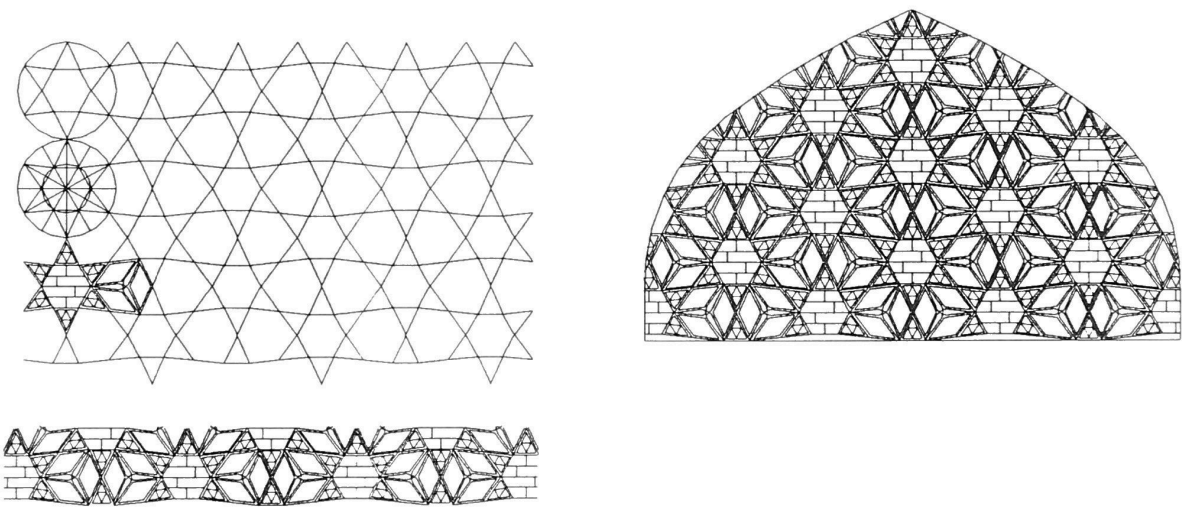

Fig. 3.2a The geometric patterns on one of the arches of the North dome generated from hexagons and triangles

[48]The main regular polygons that are recognizable on the surface of the North dome are triangles, squares, pentagons, hexagons, octagons and dodecagons. Only three of theses geometric forms (triangle, square and hexagon) can fill a surface with close packing of themselves, since multiples of their vertices add up to 360 degrees. Nevertheless , different polygons can combine with each other and generate a system of closed patterns with infinite numbers and arrangements.

Another geometric pattern that is presented here is created by dividing the circumference of a circle into ten equal sections. Based on these ten divisions a geometric pattern is developed that in process forms a star-like, dodecagonal (a ten sided polygonal) pattern. (Fig. 3.2b) Five of these shapes are placed adjacent to one another in such a way as to resemble the close packing of pentagons (five sided polygons). Based on similar division to what is presented here the entire surface of the North dome is decorated with numerous geometric patterns. .[49]

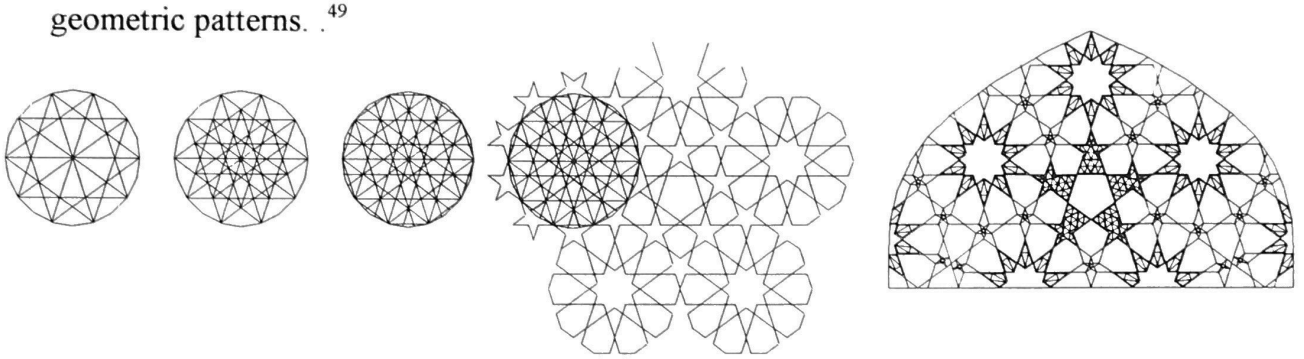

Fig. 3.2b The process of creating a star-like, dodecagonal geometric form in one of the arches of the North dome

2) Calligraphy:

In addition to the surface patterns, brickwork in the North dome also forms a series of calligraphic panels. Historically, calligraphy has been vastly used on the interior and exterior facades of Islamic buildings, particularly for the religious architecture such as mosques and tombs. Most of the calligraphy writings are the selected verses from the Quran

[49] During a field trip to Isfahan in the summer of 1999, the geometric patterns of the interior surface was carefully studied. A series of sketches from this trip is gathered and presented in Appendix(III).

and they are used to highlight particular concepts. Calligraphy in this sense is a direct expression of the Divine; by means of its carefully orchestrated use the building virtually becomes "the Word of God".[50]

Besides its spiritual message, the Arabic calligraphy by its very nature is also well adapted to decorative developments. Due to its unique writing principles, it is compatible with the geometric patterns.[51] Arabic letters are formed based on the combination of verticals and horizontals in a continuous design and so lend themselves to abstract decoration. "The verticals provide structure and rhythm, the horizontals impart balance and continuity. [Moreover], the necessity of joining certain letters promotes the tendency towards the creation of complex traceries".[52] (Fig. 3.3)

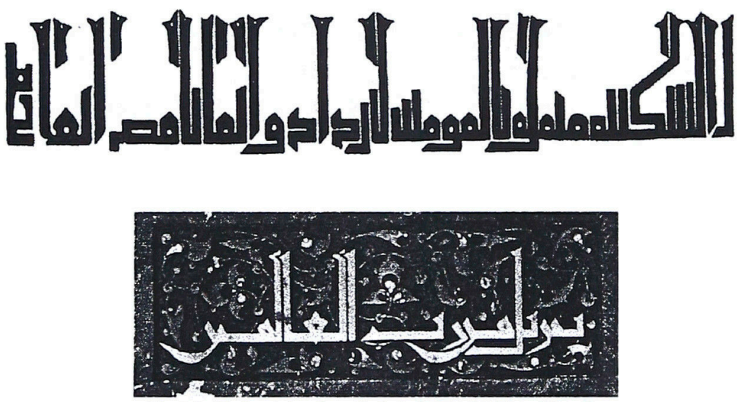

Fig. 3.3. Horizontal and vertical strokes in Arabic calligraphy
(From A.U. Pope, "A survey of Persian Architecture", 1939).

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[50] E.Dood & S.Khairallah, "The Image of the Word", Vol. I and II, 1981.

[51] A good Arabic writing can resemble a good architectural work. The following quote describes a balanced calligraphic work:

"A great scribe was asked: 'When is writing worthy to be called beautiful?' He replied: 'If its parts are well proportioned and its *alifs* (equivalent to letter '*a*') and *lams* (equivalent to letter '*l*') are long; its lines are straight and the descending strokes balance the ascending. its *ayns* (equivalent to letter '*a*' *or* '*e*') are open and its *ras* (equivalent to letter '*r*') do not resemble its *nuns* (equivalent to letter '*n*'); the paper is Lustrous, the ink dense, and its type does not vary; it is ready of visual apprehension and mental comprehension; its spaces are measured, its connectives are contracted, and its fine script is in proportion to its heavy script." Form "The Survey of Persian Art". Calligraphy; An Outline History, Page 1720.

[52] A.U. Pope, "Calligraphy; An Outline History, A survey of Persian Art".

The very structure of Arabic calligraphy also provides a cosmological symbolism based on the composition of horizontal and vertical strokes. "The verticals, like the warp of a carpet, provide an ontological relationship as well as structure for design, while the horizontals, like the weft, correspond to the creation that develops the balance and flow of the basic conception. It is through the harmonious weaving of the horizontal and the vertical that unity is achieved."[53]

The styles of Arabic calligraphy have been modified throughout time, however, the basic principles have remained practically unchanged. The calligraphic style that is used for the North dome is known as Kufic. This style is one of the first Arabic scripts that was developed by Muslims during the early periods of Islam.[54] Compared to other styles, Kufic calligraphy has a unique geometry and proportions and therefore, can be composed in various scales and be adjusted with geometric patterns.

In the North dome of Masjid-i-Jami, four traceries of Kufic calligraphy are applied in different sections. One calligraphic panel is located beneath the main arch-entrance of the south wall. (Fig. 3.4)

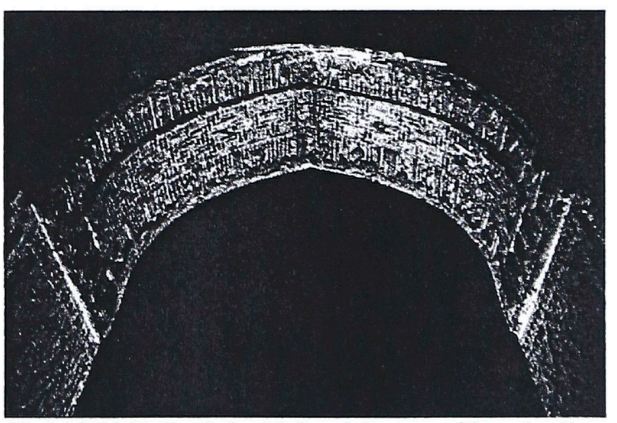

Fig. 3.4. Band of calligraphy beneath the arched entrance of the south wall.

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[53] ____ ibid ____

[54] Two other Arabic styles are identified before Kufic, and are known as Madani and Makki. Each of these two have survived for a short time and were developed to the Kufic style.

The script of this panel is translated as follows:

بسم ألله الرحمن الرحيم _ قل اللهم ملك الملك تؤتي الملك من تشآء و تنزع الملك ممن تشآء و تعز من تشآء و تذل من تشآء بيدك الخير إنك على كل شئء قدير۞ تولج اليل فى النهار و تولج النهار فى أليل و تخرج ألحى من ألميت من ألحى و ترزق من تشآء بغير حساب ۞

'In the Name of God, Most Gracious, Most Merciful_ Say: "O Allah! Lord of Power, Thou givest Power to whom Thou pleasest, and Thou strippest off power from whom Thou pleasest, Thou enduest with honour whom Thou pleasest, and Thou bringest low whom Thou pleasest. In Thy hand is all Good. Verily over all things Thou hast power. Thou causest the night to gain on the day and Thou caused the day to gain on the night. Thou bringest the living out of the dead and Thou bringest the dead out of the living and Thou givest sustenance to whom Thou pleasest without measure" (3:26 & 3:27)[55]

The second writing is a frieze of calligraphy around the rim of the dome. This writing starts somewhere around the south-west area of the rim and continues counter clockwise around the rim of the dome. (Fig. 3.5) The calligraphy of this section is translated as follows:

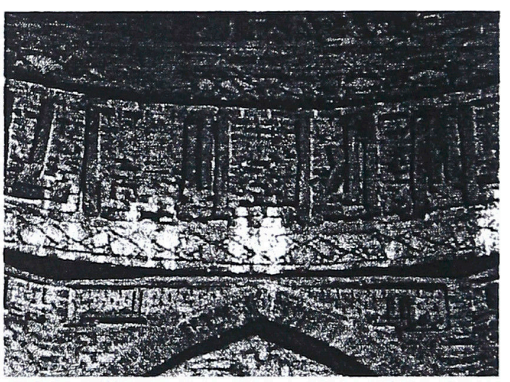

Fig. 3.5. A section of calligraphy band between the rim of the dome and the hexadecagon section.

بسم ألله الرحمن الرحيم _ إن ربكم ألله ألذى خلق السموت و ألارض في ستة ايام ثم استوى على العرش يغشى اليل النهار يطلبه حثيثا و الشمس و القمر و النجوم مسخرت بامره ألا له الخلق و آلأمر تبارك ألله رب العلمين۞

' In the Name of God, Most Gracious, Most Merciful_ Your Guardian Lord is Allah, Who created the heavens and the earth in six days, then He settled Himself on the Throne. He draweth the night as a veil over the day, each seeking the other in rapid succession and the sun, the moon and the stars all are subservient by His command. Verily, His are the Creation and the command Blessed. Be Allah, the cherisher and sustainer of the worlds ....."(7:54)

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[55] All the Quranic translations are taken from Yusuf Ali's translation of The Holy Quran, 1939.

The writing continues by inscribing the name of *Taj-ul-Mulk* who was one of the ministers of Malek-Shah-i-Saljuq and the patron of the North dome.[56] The text ends by indicating the construction date. This text is translated as following:

. . . . . أمر ببناء هذه القبه ابو الغنائم المرزبان بن خسرو فيروز ختم ألله له با لخير في شهور سنة احدى و ثمانين و اربع مآئه.

....Who ordered to build this dome is Abu-Ghana'em al-marzban ibn-i-khusro Firuz, may God seal for him with blessings. In the month of the year 481 (A.H.).

Beneath the rim of the dome, another set of calligraphic writing appears where it fills the surface of the hexadecagon. In this section, each edge of the hexadecagon is divided into two parts such that an arch form is placed in the middle. (Fig. 3.6)

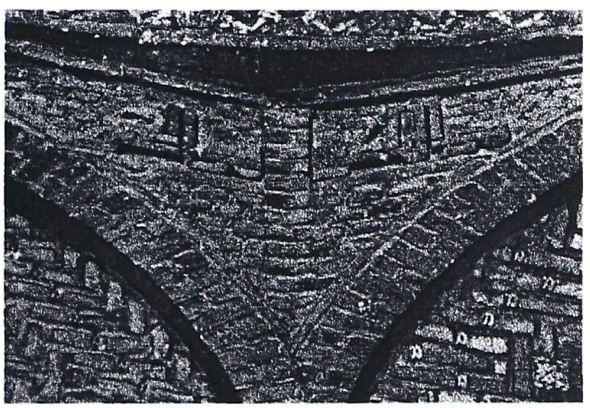


Fig. 3.6. A section of the calligraphy work on the hexadecagonal surface between two of the arches. Two names of God's Beautiful names are inscribed in this example. On the left is written هوالحى The Ever Lasting and on the right is written هوالناصر The Assister.

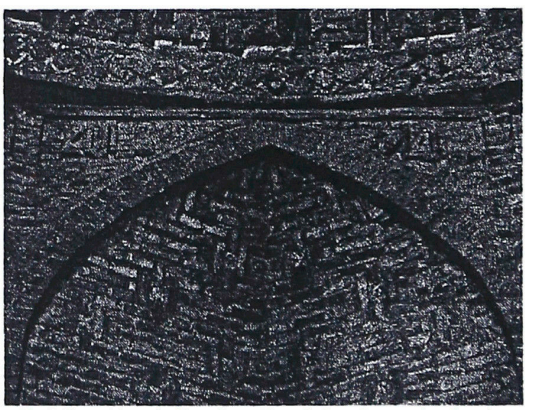


Fig. 3.6b a section of calligraphy work on the hexadecagonal surface that frames one arch

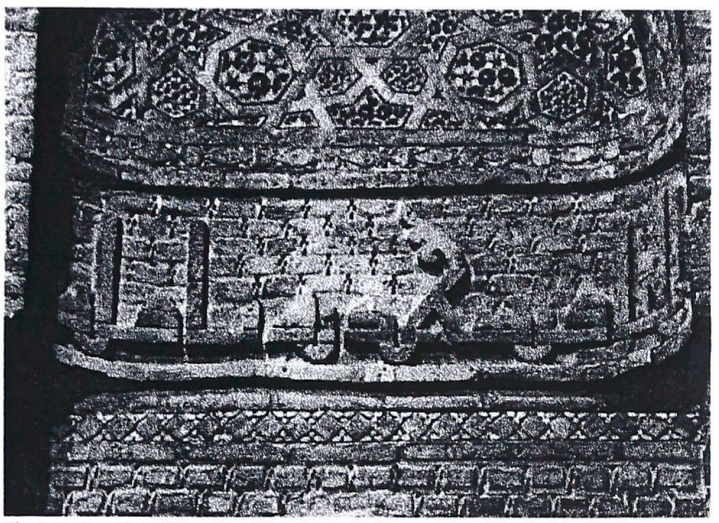
[56] Despite the common use of Arabic names in the court of Saljuq's, Taj-ul-Mulk has used his full Persian name on the script of the North dome calligraphy. The reason is not known.

This division creates 32 small panels upon each of which a piece of writing is placed. The writing of this section are 32, *Asthma-ul-Husna'*, "beautiful names" of God , [57] which are of special significance in Islam because of their meaning as well as the grace associated with their presence and invocation. The 32 names of God inscribed in the hexadecagonal walls of the North dome are as follows:

He is the Most High,	هو ألاعلى	He is the Sacred,	هو الديان
He is the Self-Sufficient,	هو الغنى	He is the Wise,	هو الحكيم
He is the Truth,	هو الحق	He is the God,	هوألله
He is the Gracious,	هو الرحمن	He is the Glorious,	هو المجيد
He is the Sovereign,	هو الملك	He is the Ever Living,	هو الحى
He is the Source of Peace,	هو السلام	He is the Giver of Faith,	هو المؤمن
He is the Overall Controller,	هو المهيمن	He is the Almighty,	هو العزيز
He is the Generous,	هو الكريم	He is the Saviour,	هو المنجى
He is the Creator,	هو الخالق	He is the Everlasting,	هو الباقى
He is the Single,	هو الفرد	He is the One Who Shapes,	هو المصور
He is the Eternal Cause of All Being,	هو الصمد	He is the One,	هو الواحد
He is the First,	هو الاول	He is the Last,	هو الاخر
He is the Truthful,	هو الصادق	He is the Assister,	هو الناصر
He is the Aware,	هو الخبير	He is the Forgiving,	هو الغفور
He is the All-Seeing,	هو البصير	He is the Sublime,	هو العالى
He is the Able,	هو القادر	He is the Supreme,	هو العلى

[57] In Islamic religion, ninety-nine names are God's attributions, thirty-two of which are written on the hexadecagon surface of the North dome. One cannot help wondering about the criteria that led to the selection of these in comparison with sixty-seven other names.

The last calligraphic work is written in the lower section of eight corner arches of the Square chamber. The writing for this section starts from the south-west corner. Each arch contains a segment of the verse and then it is carried to the next arch. (Fig. 3.7) This process continues until the verse is completed.



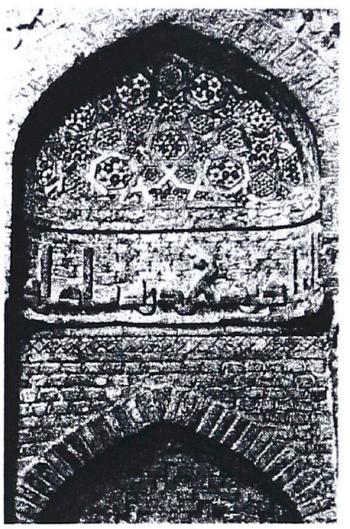


Fig. 3.7. A section of Quranic calligraphy on the lower arches of the Square chamber.

The following verses are written on this section:

بسم ألله الرحمن الرحيم _ أقم ألصلوة لدلوك الشمس إلى غسق اليل و قرءان الفجر كان مشهودا ☼ و من اليل

فتهجد به نافلة لك عسى أن يبعثك ربك مقاما محمودا ☼

> " In the Name of God, Most Gracious, Most Merciful_ Establish regular prayers at the sun's decline till the darkness of the night and the recital of Quran in morning prayer for the recital of dawn is witnessed. And as for the night keep awake a part of it as an additional prayer for thee, soon will thy Lord raise thee to a station of praise and glory". (17:78 and 17:79)[58]

[58] It is important to note that these verses and the beautiful names of God are carefully selected for this monument. On one hand, the divine omnipotence and human highest level of submission are clearly emphasized. On the other hand some of the selected verses convey a strong cosmological reference to the creation of the universe and the inter-play of day and night. Although the choice of this selection is not known, one cannot deny the compatibility of the selection of these verses with such powerful architectural form.

Chapter 4- Construction of the North Dome

Up to this point, the North dome of Masjid-i-Jami has been studied from three different perspectives. First, the North dome was placed within the context of history and its formation was examined against the architectural traits of the Saljuq period. Second, the structural characteristics of this dome were studied and third, the geometric attributes of the North dome were explored. Although, each of these characteristics distinctively demonstrates a unique architectural feature on their own, collectively, the dome's arrangement must be studied from a fourth perspective, that is its method of construction, where the outlooks mentioned will come together. Construction is determined by the constraints of history, structure of the building and its intricate geometry.

The construction of the North dome is directly related to the building methods that were used by Saljuq builders. Thus, to understand the techniques applied to this dome, it is necessary to look into the construction methods from this period. It is important to state that the information about the traditional construction of Islamic architecture in general and that of the Saljuqs in particular has not been documented well and is not available. There exist few studies that go beyond illustrating geometrical rules to actually describing construction methods.

As a result, the information available for this research is limited to a few sources;

a) Excavation and restoration work done on Masjid-i-Jami by IsMEO between 1971-1979.

b) Techniques that have been carried out by generations of craftsmen and builders and that are still in use by local builders.

c) Personal observations during a field trip to Isfahan in 1999.

The study of construction strategies that is presented here is only a hypothesis based on the limited sources mentioned. This chapter speculates on the construction order of the North dome to develop some kind of comprehensive understanding of how this structure was built. In this process a series of construction techniques will be proposed. Based on these techniques we aim to re-establish a framework that could have evolved during the construction of the North dome. We also look into tools applied to achieve the exact measurements for such well proportioned geometrical forms. i.e. how the geometry of pentagons and stars were laid on the interior surface of the dome's curvature.

The Construction Materials

As mentioned, brick was an accepted building material for most of the Saljuq architecture. Burnt clay brick originated in Persia in the third millennium B.C.[59] When Persian craftsmen first used brick, new possibilities of construction were discovered and soon

[59] Arthur Upham Pope, "Persian Architecture" and Hossain Zomorshidi, "Traditional Construction Material in Persian Architecture"

the builders had good reasons to prefer brick over other materials.

The advantages of brick were obvious and substantial. In comparison with stone, brick was less expensive and in comparison with wood more enduring. More importantly, considering that arid and hot climate covers major parts of the region under the study, [60] brick is most abundant. Brick also allows rapid construction. Because of its superior "elasticity", it is capable of forming in different ways. "This elasticity is a necessary consequence of the smallness of the units of composition which permits adjustments individually minute and invisible, but cumulatively demonstrative and emphatic."[61] Structurally, each brick unit demonstrates physical forces and aesthetically, it can be molded in different forms. Brick with its unique qualities opened a field of exploration for Persian builders for many centuries.

Although brick had been used for centuries before the Saljuqs, with Saljuq architects brickwork was carried to unprecedented perfection both aesthetically and constructionally. The builders of the Saljuq era explored the possibilities of applying brick in a "pure style" in such a way as to exclude all other major materials of construction. Brick was used both as the structure for buildings as well as ornamentations. By this application, they explored fully

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[60] The central part of Iran to the east is all dry and has an arid climate (Isfahan geographically is located in central Iran). Towards the south, the weather progresses to a more humid and hot climate. Along the Caspian Sea towards the north, is the only area with moderate climate and therefore, there exists numerous trees and plants in this region. As a result of an expanded hot and arid climate, most of the land is covered with different types of earth and sand. In this respect, the essential material for making brick is easily available to the builders of this region.

[61] Schroeder, "a Survey of Persian Art", the architecture of Saljuq period, A.Pope, 1939.

all aspects of this material. The North dome of Masjid-i-Jami is a prime example of exposed brickwork and brick construction during the Saljuq era. "Here the beauty of the exposed form is supreme and the ornament one with the substance of the structure and inherent in the material"[62] (Fig. 4.1)

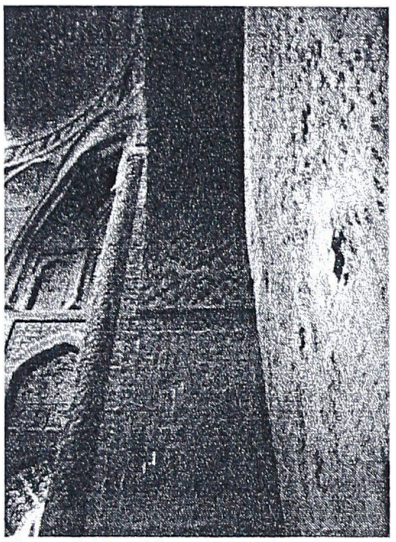
Fig. 4.1a brickwork beneath the arch surface.

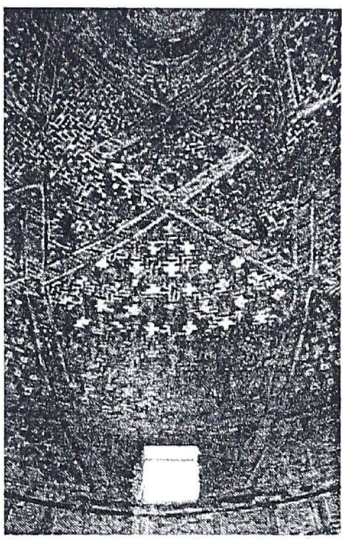
Fig. 4.1b brickwork on the dome's interior surface

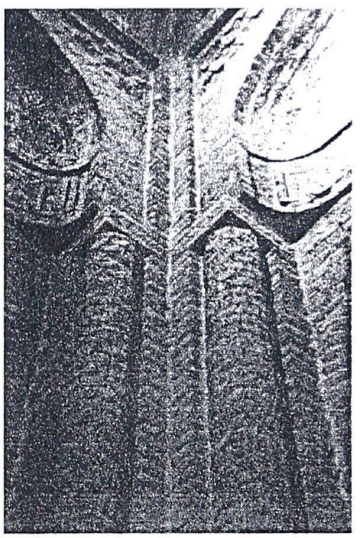
Fig. 4.1.c brickwork on the columns

In the North dome two sizes of brick are used. The interior of the dome consist of bricks 8-3/4 X 8-3/4 X 1-1/2 inches (22 X 22 X 4 - 4.5 cm). On the exterior of the North dome bricks are 8-3/4 X 9 X 2 inches (22 X 23 X 4.75 - 5.25 cm).

In traditional architecture of Iran, the brick was made by combining about 75 % clay with 25 % soft sand. Then it was mixed with water to create the unbaked brick composite. This composite was then poured into a wooden mold of desired dimensions and after it had dried enough to contain the form, it was heated for about twenty days [63]. (Fig. 4.2) The

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[62] _____ ibid _____

[63] The traditional brick-kilns were heated up to 900 degree Celsius. Depending on the number of bricks that were fired at the same time, the brick-kiln was heated constantly from seventeen to twenty one days . Hossain Zomorshidi, *Iranian Architecture, "Traditional Construction Material"*, Page 34.

traditional brick-kilns were usually built under the ground or on the ground level.[64] Heavy timbers were used as fuel for these kilns and unbaked bricks were placed in kilns at different levels.

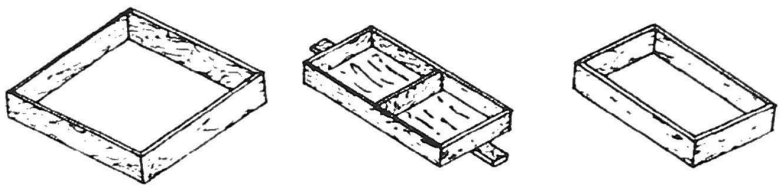

Fig. 4.2. Wooden molds, (Form H. Zomorshidi, "Traditional construction Materials in Iran",1999.)

After the brick was baked it would turn different colours depending on where it was placed in the brick-kiln. The first layer of brick exposed to the direct heat would turn green.[65] The next layer of brick would be green-yellow. The third layer would be yellow; the fourth layer red-pink; and finally some bricks would remain half-baked. The green brick was used for the main structural support and floors of buildings. The green-yellow brick was used for walls and panels that could hold the load to some extent. The red-pink brick was used for walls with no effective load-bearing structure, and finally, half-baked bricks were re-heated again.

This approach shows that the Saljuq builders did not only mold bricks in various sizes and forms, but also used them selectively according to their respective structural strength needed in different sections of the buildings. After the brick was made, other tools were used to cut and shape each brick unit. Tools such as chisels and sanders were used to enhance the smoothness and give the desired form to each brick unit. Wooden triangles and other tools

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[64] A drawing of brick-kiln is shown in Appendix (IV).

[65] These colours are not obviously pure colours. i.e. the green is not pure green, it is a mixture of brownish green colour.

were applied to measure and scour bricks. (Fig. 4.3) Using this process, the builders were able to form and combine different shapes of brick in various sections of buildings.

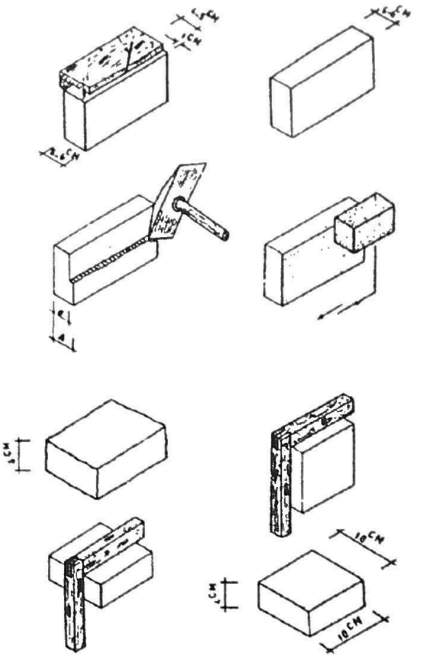


Fig. 4.3. The traditional tools that were used to form bricks (Form H. Zomorshidi, "Traditional construction Materials in Iran",1999.)

Bricks used in the North dome illustrate all the techniques mentioned. The final touch to the interior surface of the brick structure was given by using terracotta and white plaster. These two elements were subtly used to add more design and elaboration where the brick could no longer do the job. "Terracotta is clay either modelled or moulded and baked. This material has been used from the end of the tenth century either as sections or plaques or as a subsidiary filling and enrichment in a brick or stucco framework."[66] In the North dome terracotta is used on different surfaces with numerous geometrical patterns. This material offered several advantages to the design. Being approximately the same colour and texture as brick, terracotta harmonized well where the brick was not surfaced. The carved terracotta fillings inserted in the geometrical frameworks gave a rich texture to the whole interior space of the North dome. (Fig. 4.4)

Besides terracotta, plaster was also applied in some sections of the design. Along architectural lines, in the space between bricks, plaster was applied using finely carved and

[66] E.Schroeder, "A survey of Persian Art", Saljuq Period.

embedded patterns to both accentuate the design detail and to hold the brick together. (Fig. 4.5)

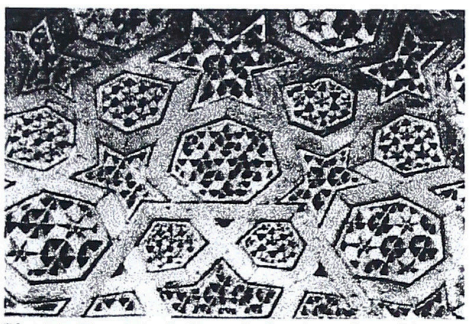


Fig. 4.4a. Terracotta design on the interior surface of the North dome.

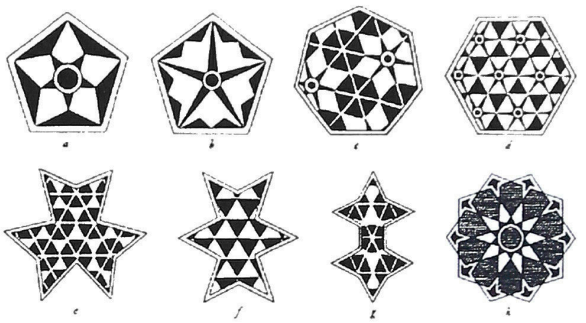


Fig. 4.4b. Various terracotta design in the North dome, drawing by E.Schroeder.

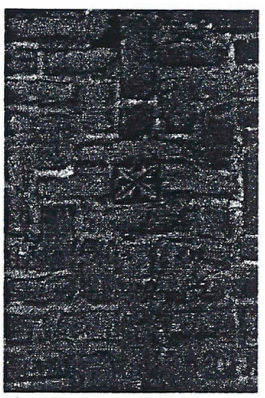


Fig. 4.5a. Plaster-brick plugs on the interior surface of the North dome.

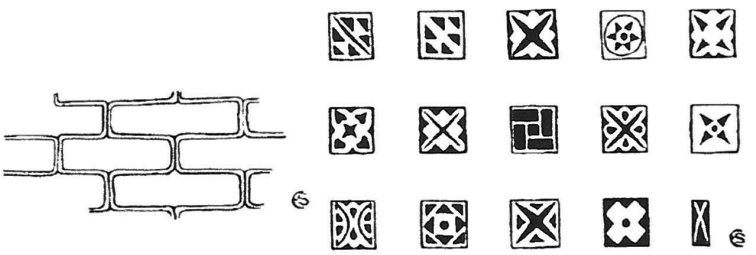


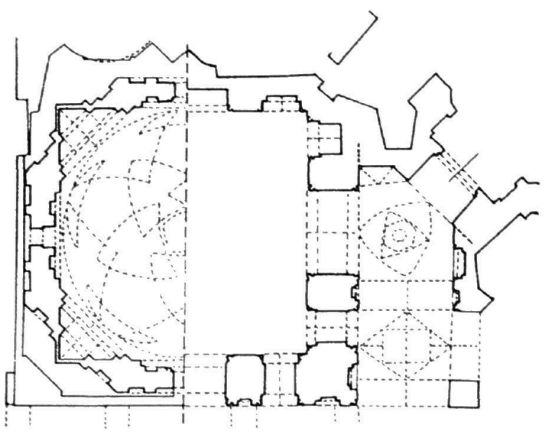
Fig. 4.5b. Various plaster-brick plug designs in the North dome, drawn by E.Schroeder.

The General Construction Layout

The construction of the North dome is an interweaving of various brick forms in a harmonious setting. From the base to the dome's top, from the inner surface to the exposed form outside, layers of brick are put next to one another in different directions to establish this form. Although visually the brickwork is unified, it structurally plays different roles in each section. In some parts where the structural load is concentrated, the brick of higher quality

is used in higher density. Where the construction is lighter, the brick is applied with more elaboration and detail. Also, the brickwork on the dome's inner surface is smaller and uses more design varieties, whereas on the exterior surface the brickwork is laid using a much simpler design.

The construction starts by defining the locations of the structural foundations on the ground. Based on the excavation work by ISMEO, most of the structural foundation in various parts of Masjid-i-Jami is buried about one meter below ground.[67] Because the dome's structure starts from a square base, the main structural load is concentrated on 12 load bearing piers, four of which are located at each corner of the square, forming heavy piers of approximately 2.5 X 2.5 meters. The other eight structural supports are piers (1.5 X 2 meters), that in pairs are situated between the corner points. (Fig. 4.6)



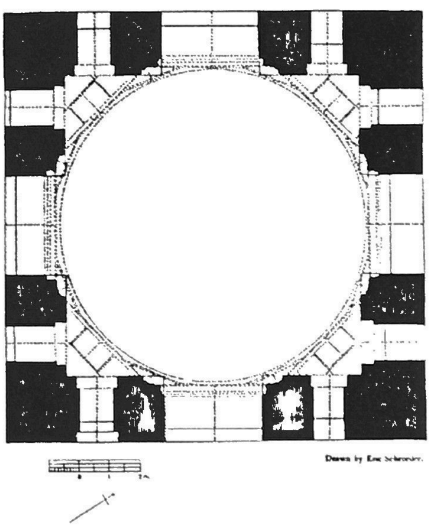


Fig.4.6. Left, Plan of the North dome in connection to the east entrance right, Plan of the North dome with 12 load bearing piers. (Left dreawing is taken from "The Great Mosque of Isfahan" by O. Grabar, Right drawing is taken from "A survey of Persian Art" by A. U. Pope.)

[67] Two issues need to be discussed here. First, the foundation depth mentioned is not specific to the North dome and it is not certain if 100 cm foundation depth is truly applicable for the North dome. Second, during a series of excavation work by ISMEO, it is also shown that the exact original floor of the Mosque is not defined, however, in case of the North dome, it seems certain that the existing ground floor is the same as the original.

After filling the structural foundation, the next challenge for the traditional builders was to achieve the desired geometrical accuracy for the form. To this end, as the structure grows, a set of wooden scaffolds are applied in the desired locations to both enable the builders to reach the higher levels of construction and also provide the main geometrical guideline for the work. The end of these beams were placed inside the structure and therefore, the brickwork was laid around them. (Fig. 4.7)

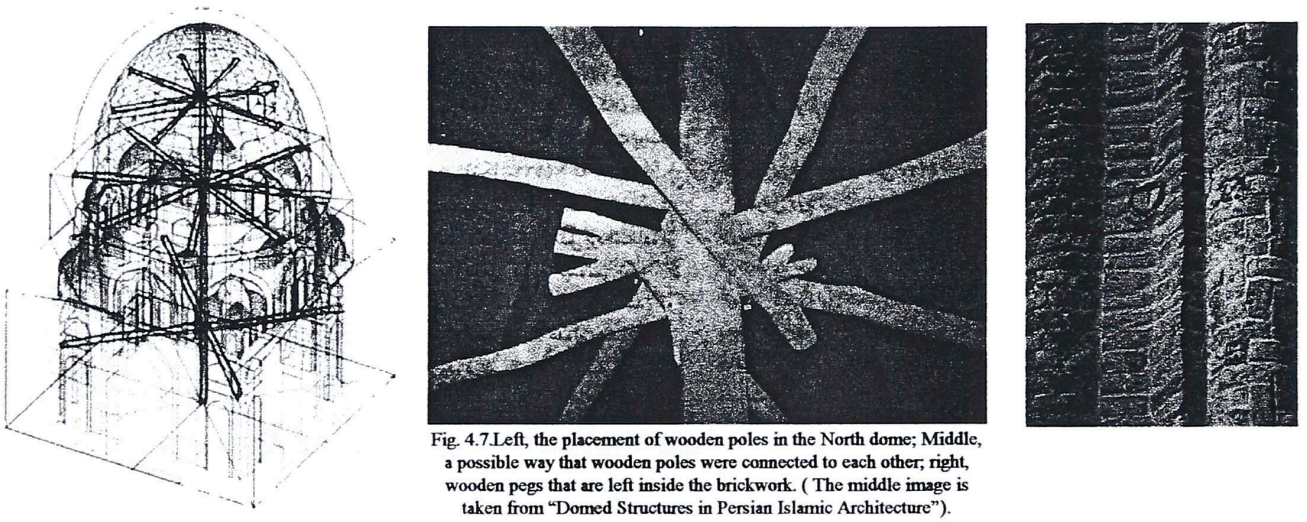


Fig. 4.7.Left, the placement of wooden poles in the North dome; Middle, a possible way that wooden poles were connected to each other; right, wooden pegs that are left inside the brickwork. (The middle image is taken from "Domed Structures in Persian Islamic Architecture").

The wooden beams were stretched along the vertices of the octagon at eight points at each level. The distance between any two levels was about 80 inches. This height was comfortable enough for an average person of 70 inches height to stand. These levels were carried up to the point where the dome ends. Besides the wooden scaffolds that were assembled for the main construction, the builders also used other poles and beams in different sections of design to construct other geometrical forms such as squinches, arches and dome. At the end of the construction these beams were cut from the structure, leaving a segment inside. (Fig. 4.7) Even today, some of these wooden pegs are still clearly visible in different

sections of the structure. It has been said that the builders kept these wooden pieces inside since it prevented the breakage of the brick due to pressure from the upper layer. As a result, the wooden pegs act like a cushion in reducing pressure and protecting lower sections. [68]

Now that the general construction strategy has been introduced, we can look at the structure of the three main parts of the dome we used in exploring its structure and geometry: the square base, the zone of transition and the dome. Based on this division, the construction techniques and brickwork in each section will be further examined. [69]

The Construction layout for the Square Chamber

Above the ground level, the first layers of structural brick is laid over the load bearing piers. This brickwork is carried harmoniously around the square base to a height of about 100 cm. The brickwork in this section has a much simpler layout compared to the rest of the structure. As the structure proceeds in successive zones, the brickwork embodies more daring elaboration and design detail. The following drawings show the construction of the brickwork in the lower section of the square chamber. (Fig. 4.8)

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[68] *Golam-Hossain Mimarian "Curved Structures in Islamic Architecture of Iran".*

[69] It is necessary to mention that this division by no means indicates the independency of construction for each part. The North dome construction is a unified and continuous structure and the construction of each section is dependent on the rest of the setting.

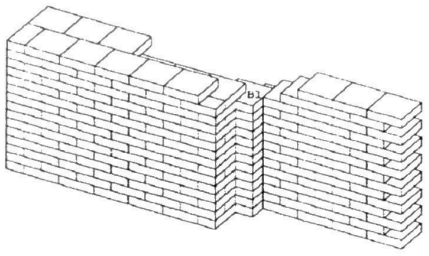


Fig. 4.8a brick work on the lower section of the square chamber, front view.

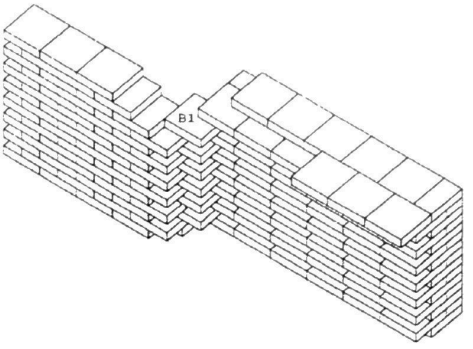


Fig. 4.8a brick work on the lower section of the square chamber, back view.

From this level up to the edge where the zone of transition begins, each wall of the Square chamber is divided into three deeply recessed panels. Each panels is strongly defined by an arch in its centre. The middle panel is wider and has a larger arch. The side panels, however, are smaller and each holds two smaller arches. As mentioned, the entrances to the domed chamber are punctured through five of the arches along the south and the east walls. Where no openings exist these walls are filled with brickwork design.[70] (Fig. 4.9 / 2.4)

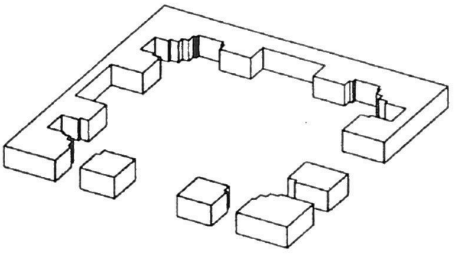


Fig. 4.9a The lower section of the square chamber

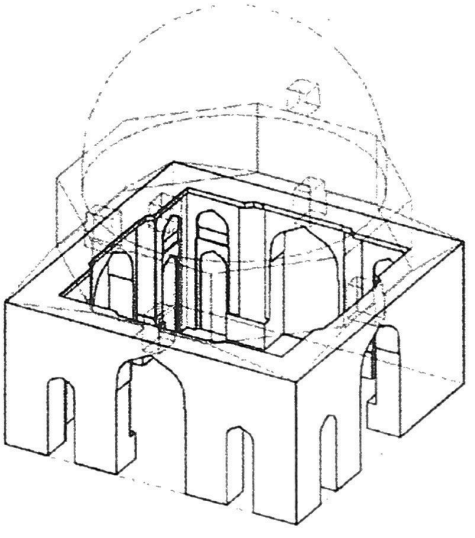


Fig. 4.9b The square chamber with openings

In addition to the arches, the recessed panels are also defined by clusters of slender

[70] The geometry and brickwork of these panels are explored in detail in chapter IV on "The Geometrical Significance of the North Dome".

columns that are formed above the load bearing piers. These columns stand in between the recessed panels and along with the arches visually raise the square chamber to the successive zones. Both the arches and the round columns participate as the structural support and ornamentation. In the forthcoming discussion the construction technique(s) for each of these elements will be studied.

a) brick construction for arches

Traditionally, two techniques were commonly used for the construction of brick arches. In the first technique, the arch form is first plaster molded in the desired curvature. Then this plaster cast is used as a guideline to lay brick units as they follow the interior curvature of the arch. In this method bricks are laid such that the wider face of the brick is parallel to the arch and therefore, has lower structural efficiency (stability and Strength). (Fig. 4.10)

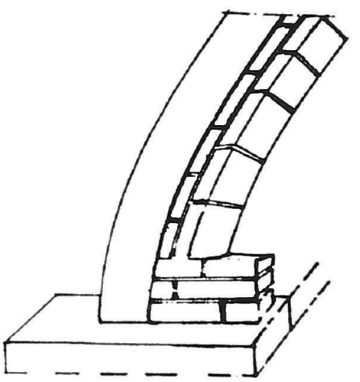


Fig. 4.10a. First construction method (Both Images are from "The Domed Structures in Persian Islamic Architecture" by G. Memarian.)

The second technique is more complicated than the first and has more structural stability. Using this method, two sets of arch forms are made with the desirable curvature and then are placed parallel to each other over the base. Then layers of brick fill the space between these two arches. The construction starts from haunch of the arch and moves to the crown. The bricks

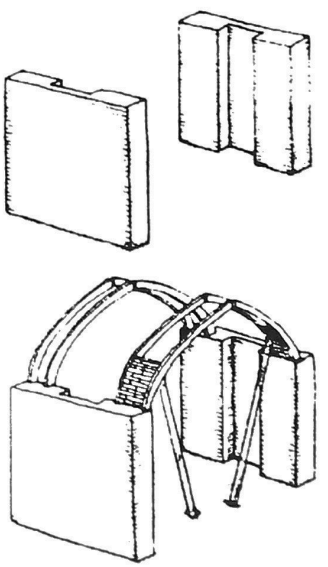
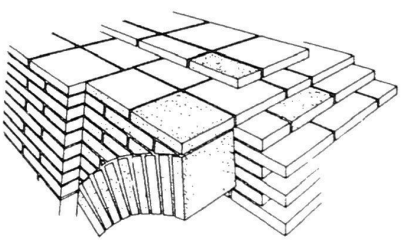


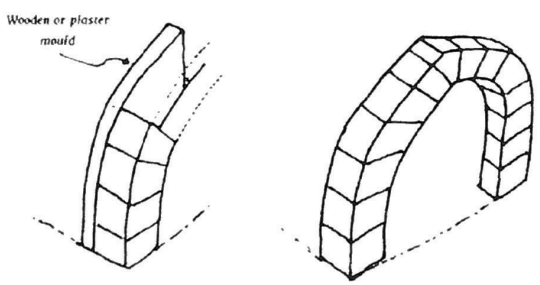
Fig. 4.10b. Second construction method

are laid such that their wider surface is perpendicular to the arch form, and therefore, this technique leads to higher structural efficiency (stability and strength).[71] (Fig. 4.10)

In the square chamber of the North dome, the three arch forms are constructed with similar principles as the two techniques mentioned. However, with respect to the complexities of their brickwork, these techniques are skillfully adjusted to suit more advanced arch design. The construction method for each of the three arches is as follows:

The first arch form is located in the lower section of the two smaller panels on each wall. The construction of this arch employs the second technique we have mentioned. In this case a single brick is laid along the arch curvature. Similar to the second method, the construction starts from the lowest section of the arch and moves to the higher sections up to the point where the last two bricks meet. At this point the final brick is shaped so that it perfectly defines the peak point of the arch. (Fig. 4.11)





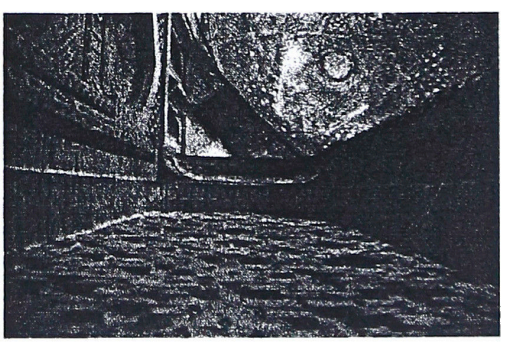


Fig. 4.11. Left, The construction method for the lower arch of the square chamber; right, view from underneath the lower arch.
(The right image on the top is from "Masjid-i-Jami of Isfahan" by E. Galdieri, 1991.)

[71] Golam-Hossain Mimarian "Curved Structures in Islamic Architecture of Iran".

The second arch form is located in the upper section of the two smaller panels on each wall. This arch has more elaborated brickwork than the first arch and constructively combines both techniques mentioned. A suggested process of construction is as follows: Using the first technique, bricks fill the outer diameter of the arch. Then the second technique is applied to fill the inner diameter of the arch with bricks. In the inner part bricks are smaller and are combined with unique geometric composition. (Fig. 4.12)

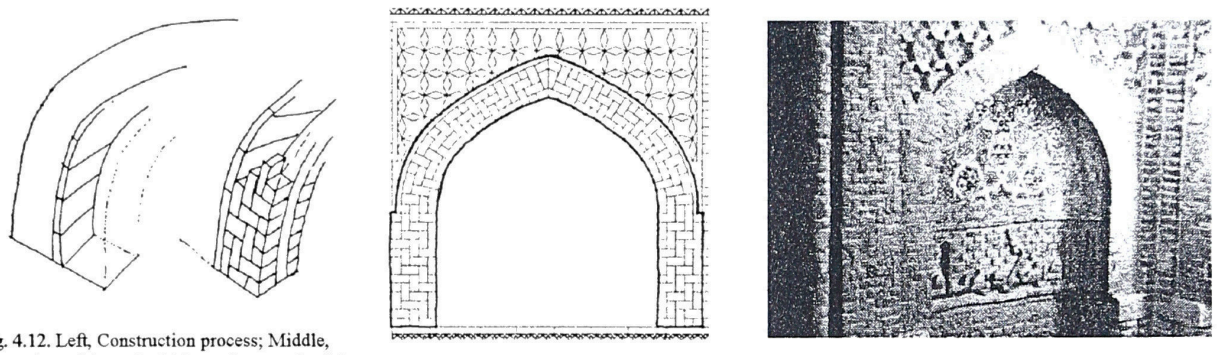


Fig. 4.12. Left, Construction process; Middle, Front view of the arch; Right, a photograph of the arch.

The third arch form is located in the middle panel on each wall which has a wider span compared to the other two arches. The span of each arch in the middle panel is about 300 cm. The most intricate arch form of this set is the arch gate that is placed on the centre of the south wall. As shown in (Fig. 4.13), this arch has a deep recess of about 90 cm and is filled with both geometrical brick patterns and calligraphic work.

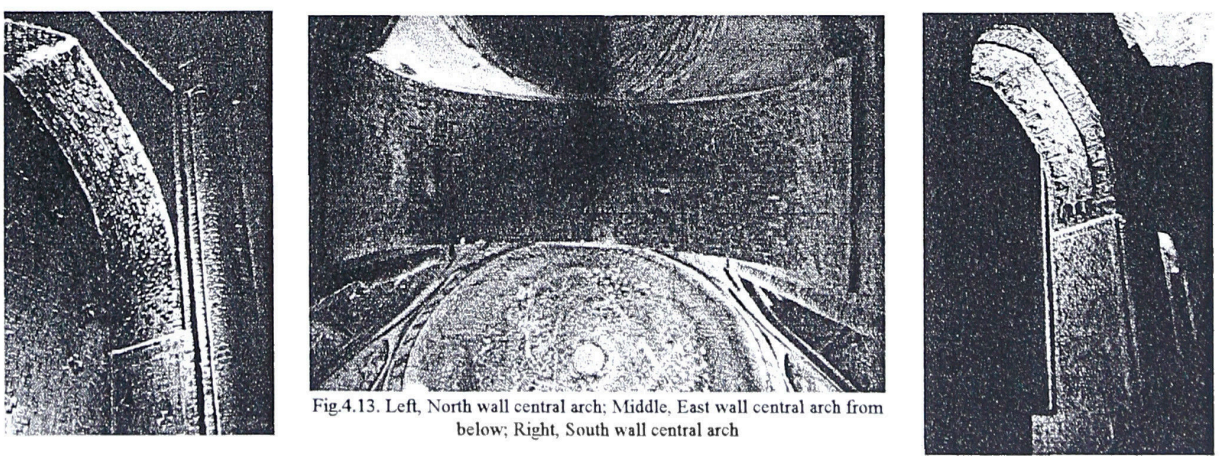
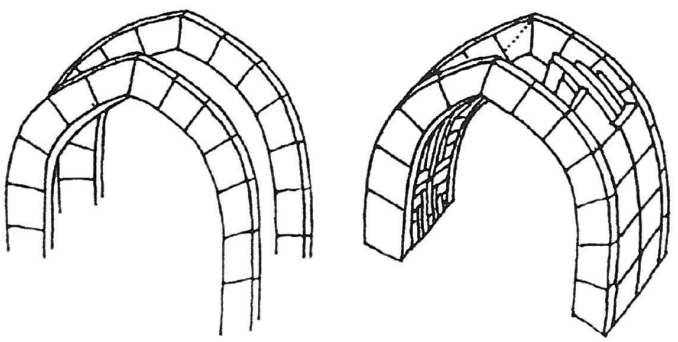


Fig.4.13. Left, North wall central arch; Middle, East wall central arch from below; Right, South wall central arch

In this section, a possible construction technique for the arch that is located in the central panel of the south wall, is discussed. Considering the deep recess of this arch, the construction starts from the central section and moves to the outer layers in both directions until it meets the exterior layer of brick on the surface. Using the second technique, two wooden or plaster arch molds are placed about 30 cm apart. Then a set of brick units fills the space in-between. The brick units are carefully made and are placed with defined geometrical patterns in both directions. Since the span of the arch is reasonably wide, two poles are placed in critical structural locations to support the structure during construction. After the middle section is filled with brick, the construction is carried to the sides following the same technique. Once the main structural bricks of the arch are placed, the exterior surface is covered with decorative brickwork forming a calligraphic panel with geometrical design. (Fig. 4.14)



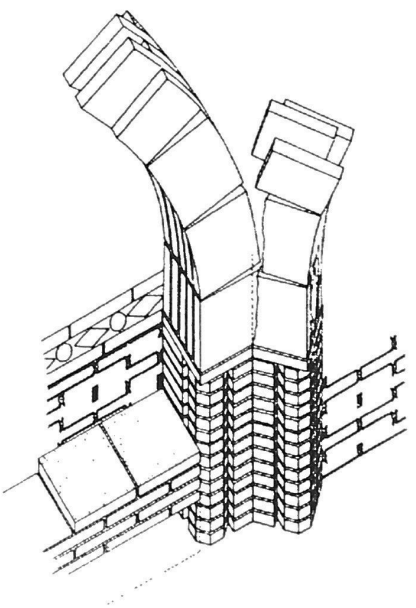
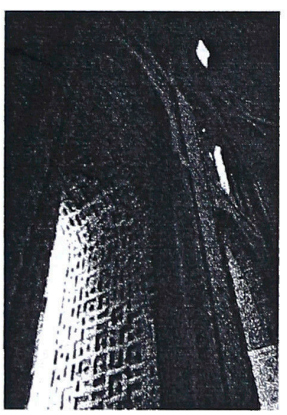
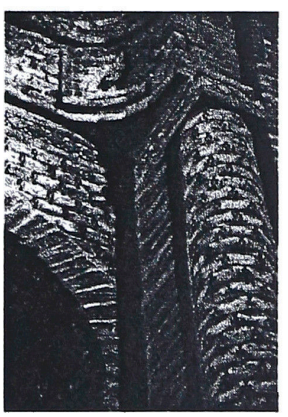


Fig. 4.14. Brickwork construction for the central arches
The right image on the top is from "Masjid-i-Jami of Isfahan" by E. Galdieri, 1991.)

b) brick construction on columns

The round, clustered columns on the sides of the recessed panels are one of the most appealing elements in this chamber. The slender and narrow form of these columns visually lifts the structure upwards. These columns start above the lower section of the load-bearing piers and cover the interior facade of the load-bearing structure right up to the point where the zone of transition begins. (Fig. 4.15) As shown in the plan (Fig. 4.16), each of these columns is attached to the rest of the structure behind such that only a portion of their round form is visible. The brickwork behind each column is structural and therefore, is part of the load-bearing structure that carries the load from the upper sections to the ground. The following diagram shows how the brickwork behind each column is interlocked to enhance the stability of the structure. (Fig. 4.17)





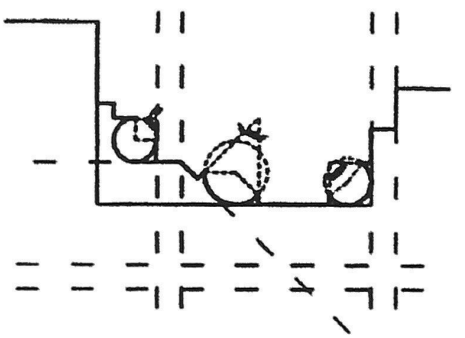


Fig.4.15 in left shows the round brick columns with geometric design; right, Fig. 4.16. On top is the sectional plan for connection of brick columns to the wall.

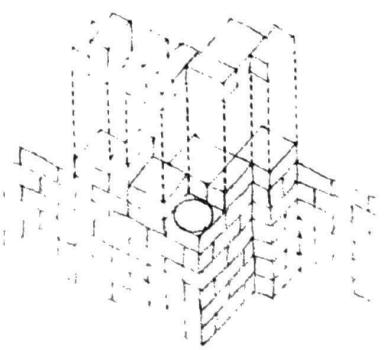


Fig. 4.17 The interlocking of bricks behind the round columns

Based on a careful observation, the brickwork in the Square chamber of the North dome can be classified in four different categories:

1) The first brickwork is the main structural brick used for the load bearing piers (12 locations in plan) that carries the load from the structures above (i.e. the zone of transition and the dome) to the ground.

2) The second brickwork covers the surfaces of wall panels and arch forms on all four sides of the square chamber. This brickwork carries a reasonable load and geometrically has different patterns on each wall.

3) The third brickwork forms the round columns that covers the front facade above the load bearing piers. These columns are more a geometric outcome and are not to be considered as one of the main structural supports for the building.

4) The last set of brickwork appears at the level of the calligraphy panels. In this section, brickwork has more of a decorative function than a structural support.

The Construction Layout for the Zone of Transition

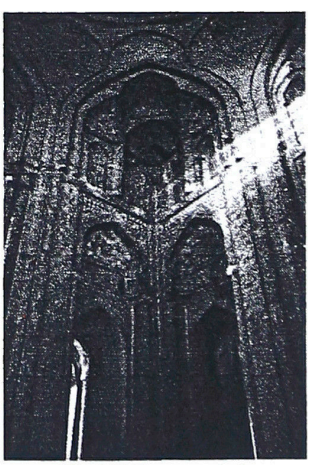


Fig. 4.18 Corner squinch

Previously, the complete form of the zone of transition with its unique structural characteristics was discussed. The main element of this section was introduced as the squinch structure, located in each of the four corners of the octagon. (Fig. 4.18) The squinch is an

important structural element that stands between the square base and the circular rim of the dome. In this section an attempt is made to explore the construction of the squinch structure.

Geometry: First, it is important to understand the geometrical components of this form. Conceptually, the squinch structure is an elaborated form carved-out from a triangular base prism that sits on each of the four corner of the square base. (Fig. 4.19) Each prism can be divided vertically into two sections. In the lower section, the edges along the corner of the square base are elevated to a certain height and they form four small arches on the interior surface. (Fig. 4.20) From the outside, the lower section of the prism defines the edge where the square base ends and the octagonal form begins. (Fig. 4.21)

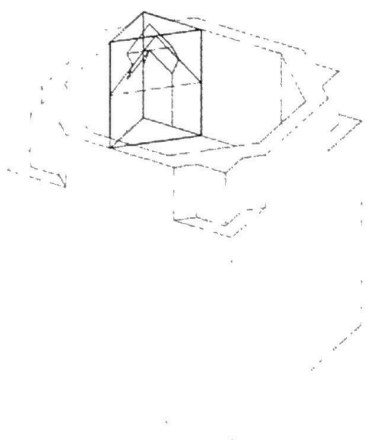


Fig.4.19. Conceptual prism in each of the four corners

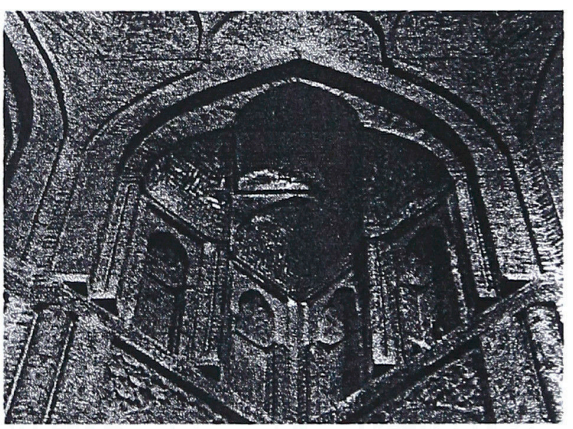


Fig. 4.20 Above, squinch form; Bellow, smaller arches in lower section

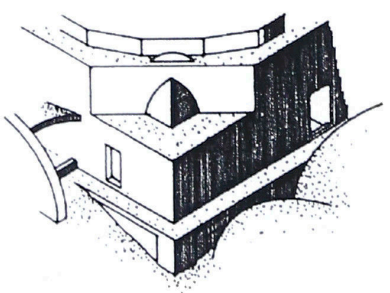
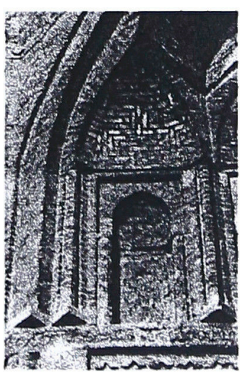
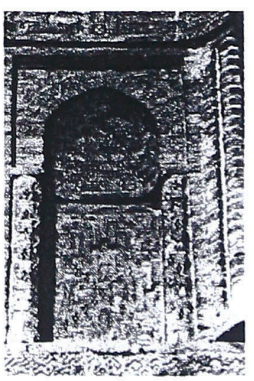


Fig. 4.21 Corner squinch view from the exterior of the North dome. (From "Masjid-i-Jami of Isfahan by E. Galdieri, 1991.)





In the upper section of the prism, the perpendicular plains from the lower section gradually merge until they meet in a line on top. In this process, a series of trefoil lobes are formed such that each reduces the surface by transforming a line to a point and creating a curved form in space. The geometrical analysis of this transformation is shown in the following diagram. (Fig. 4.22)

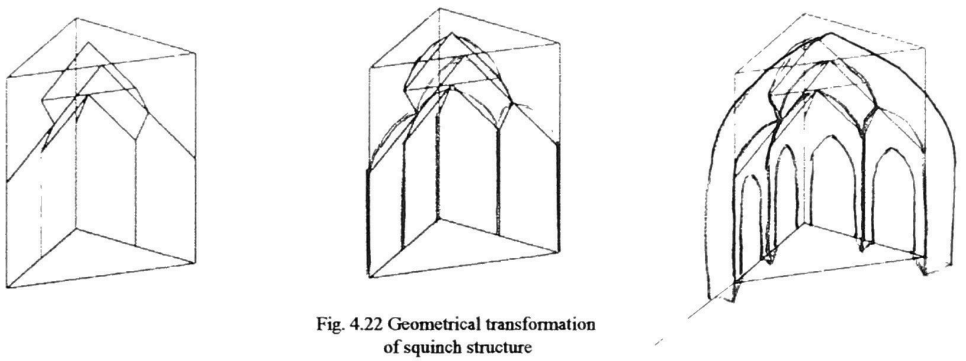


Fig. 4.22 Geometrical transformation of squinch structure

Construction: Based on this geometrical transformation the construction of the squinch starts from the corners of the square base. The construction continues vertically up to the point where the trefoiled forms begin. At this point the bricks are placed such that as they move upwards they also form a curved surface towards the interior. On this basis the construction continues until the squinch form is completed and as a result, the two perpendicular planes of the square base are transformed along a vertical axis to a plane of the octagon. (Fig. 4.23)

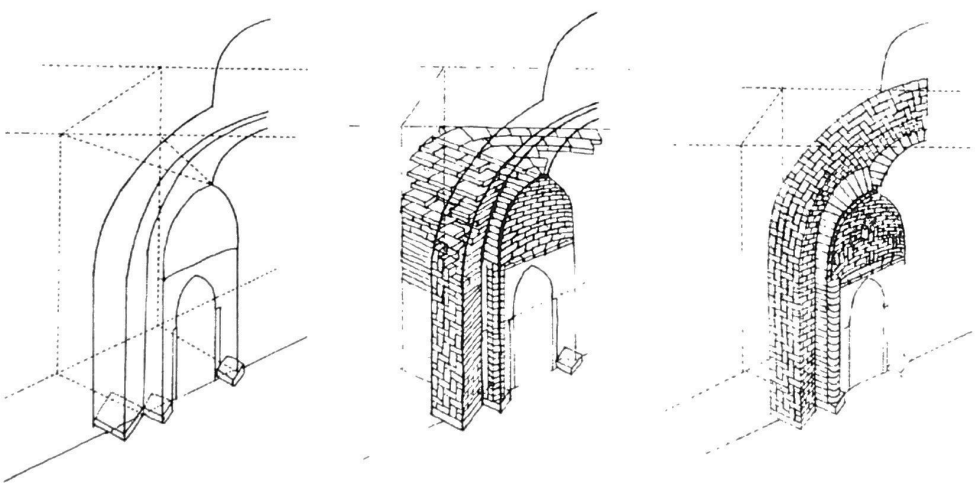


Fig. 4.23a The brickwork from inner structure to the outer surface in a corner squinch form

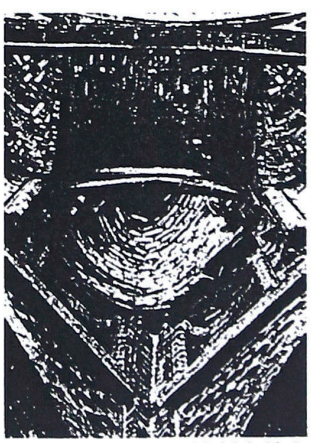


Fig. 4.23b The structural brick behind the exterior brickwork

After the main structural brickwork is completed, the interior surface is covered with a layer of elaborated brickwork combined with plaster inlays and brick plugs. In this process, each of the brick units are finely cut and shaped in their unique form and are placed in their specific location. (Fig. 4.24) On the lower section of the squinch, the brickwork is finely elaborated with small hexagonal columns and arches. On the upper section, the trefoiled lobes are framed with a half arch brickwork and then they are filled with brick patterns on the curved surface. (Fig. 4.25 & 4.26)

Fig. 4.24 Brickwork on the surface of squinch structure

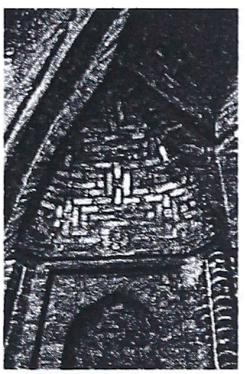


Fig. 4.25 brickwork on the trifoiled squinch

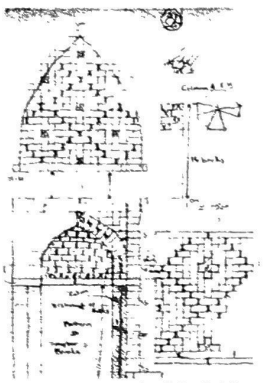


Fig. 4.26. Sketch of the brick patterns on the surface of squinch

The final geometrical form is an arch that stands on the interior facade framing the squinch structure. This arch sits at the edge on the corner of the square base at a 45 degree angle, where it defines the interior surface of the octagon. A brick unit lying on the same angle of the arch connects the lowest section of the arch to the base while it stresses the angular transformation with a subtle design element. (Fig. 4.27)

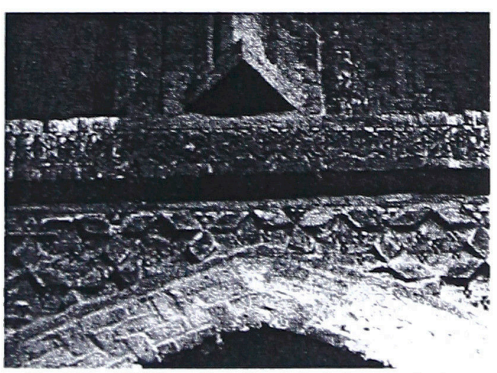


Fig. 4.27a Middle section of squinch, in between the two small arches

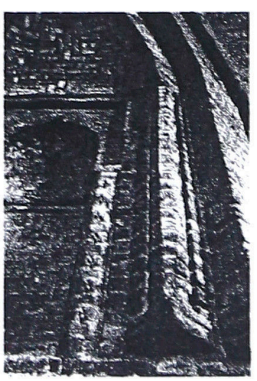


Fig. 4.27b Corner of the squinch with brick unit

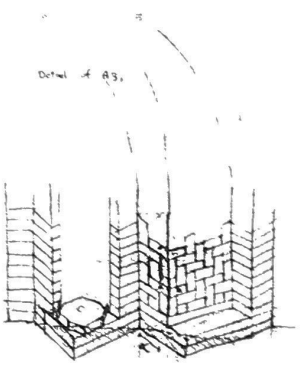


Fig. 4.27c Sketch of the squinch corner with brick patterns

The Construction Strategy for the Dome Structure

The construction of the dome starts above the zone of transition. The dome structure sits on a circular drum with a diameter of 14 meters and a total height of 7.5 meters. Although this dome is not volumetrically a large structure, it has a unique geometric design on the interior surface that captures the eyes of visitors as they walk into the space. (Fig. 4.28)

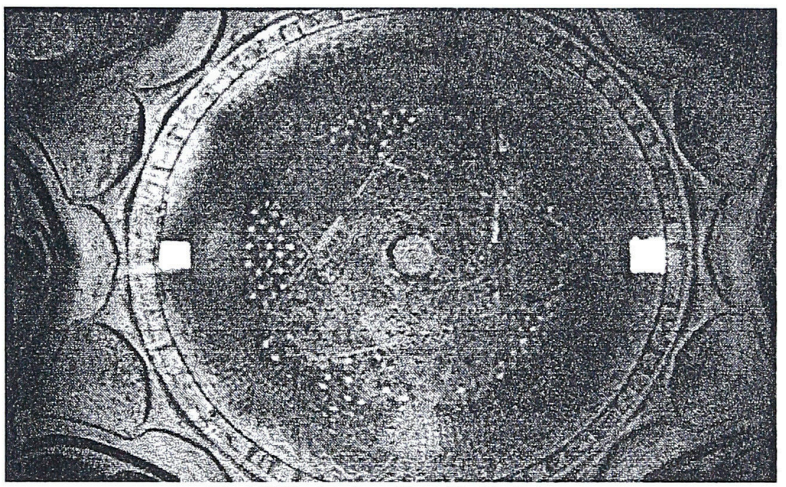


Fig. 4.28 The interior ceiling of the North dome

In this respect, two issues are discussed here in relation to the construction of the dome. One is the method of construction for the structure of the dome and the other is the possible method of construction for the magnificent brick design on the inner surface.

1) In traditional Islamic architecture dome structures are classified in various categories.[72]

[72] In Islamic architecture of Iran we can generally classify domed structure in four different categories. Single shell dome; double shell dome (this type of domed construction comes in various forms); ribbed structure dome; and triple shell dome. *Golam-Hossain Mimarian "Curved Structures in Islamic Architecture of Iran".*

Depending on the size, shape, materials and also the advancement of techniques, the domed construction is performed differently. The North dome of Masjid-i-Jami is one of the earliest types of domed structures and is known as a 'single-shell dome'. Traditionally, the brick setting for this type of dome is based on two different construction techniques. In the first technique the bricks are laid parallel with the horizontal surface. In the second method, the bricks are laid at an angle that leans towards the centre of the dome's circular base. (Fig. 4.29)

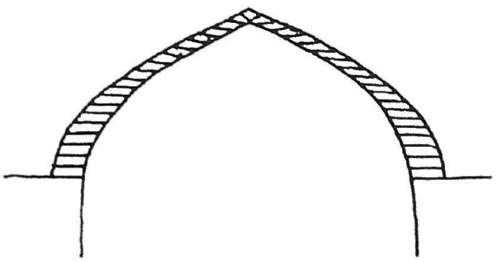


Fig. 4.29a Bricks are laid parallel to the horizontal surface

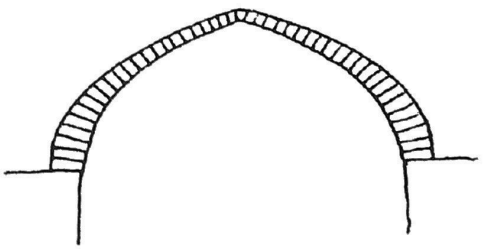


Fig. 4.29b Bricks are laid perpendicular to the curvature of the arch

Two layers of brick are employed for the construction of the shell of the dome. The brick on the exterior shell is laid based on the first method, and the brickwork on the interior shell incorporates the second method of construction. (Fig. 4.30)

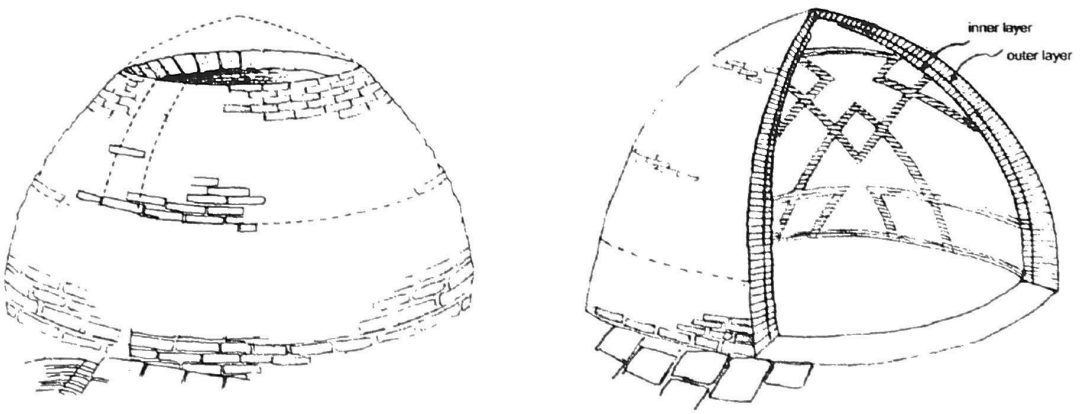
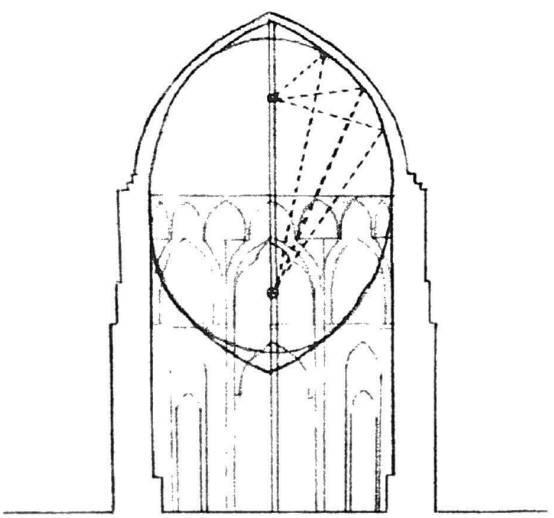
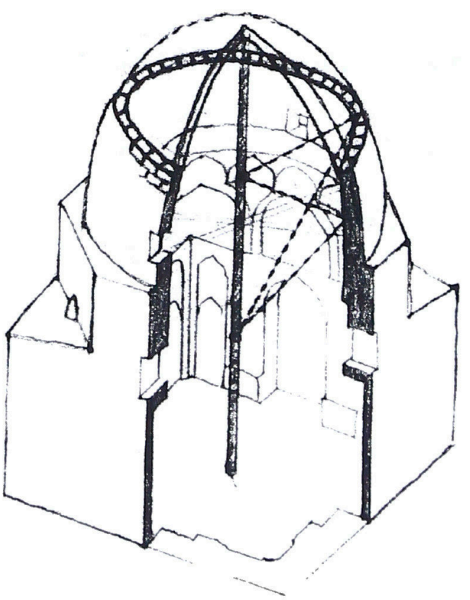


Fig. 4.30 The construction of the dome with two layers of bricks

Technically, the construction starts from the drum, which is the base of the dome. As the structure rises, each circular section reduces until the peak of the dome, where the brick structure merges to one point. To achieve the exact curvature for the dome, the skilled Saljuq builders did not use templates. Instead, the following technique was ingeniously applied:

First a wooden pole was placed vertically in the centre of the square room, such that at the ground it was fixed to the centre of the square room, and at the other end it was aligned with the peak of the dome. This pole was fastened and supported by a series of wooden beams to the corners of the structure in different sections. Two points were carefully selected on this pole, such that they were the focal point for an elliptical curvature that geometrically formed the interior surface of the dome. These two points were marked on the pole with a chain connecting the two. The length of the chain, which is the sum total of the "focal radii" of the ellipse, is such that it perfectly sits on each point of the dome's interior surface when fully extended. (Fig. 4.31) Using this chain the builders were able to place each brick unit at its proper location along the elliptical curvature of the dome.





2) After finishing the exterior brick construction, the second layer of brickwork was placed on the interior surface. The inner surface has a beautiful star-like geometrical design that generates from the rotation of a curved triangle five times around the peak of the dome. (Fig. 4.32) In this process, five triangles are formed so that each is interlocked to the neighbouring form. From the intersection of the five triangles a series of curved pentagons and lozenge forms are generated that all together form an appealing geometric design on the dome's interior surface.

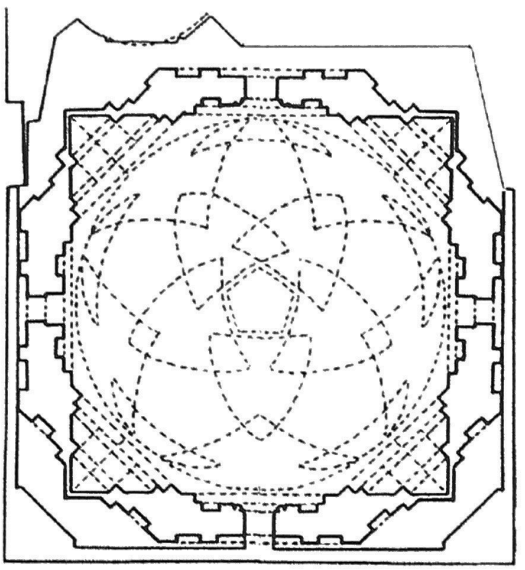


Fig. 4.32 Reflected ceiling plan with its geometric patterns
(This image has been modified from its original drawing which is taken from "The great Mosque of Isfahan" by Oleg Grabar)

Constructively, this intricate geometry is one of the most challenging sections of the brickwork in the North dome. On this basis, we are confronted with questions such as how this geometric pattern was constructively formed. How was the brickwork technically laid on the interior surface of the dome? Lastly, was this geometric pattern effective for the structural stability of the dome?

Prior to answering these questions, it is important to understand the geometric

formation of the dome's interior surface pattern. Conceptually, this form starts with two parallel diagonal cuts on the dome's curved surface. As a result of this imaginary cut, two parallel elliptical lines are generated on the dome's curvature. If these two elliptical lines are rotated five times around the rim of the dome, we can see the geometric pattern that forms the interior surface of the dome. (Fig. 4.33)

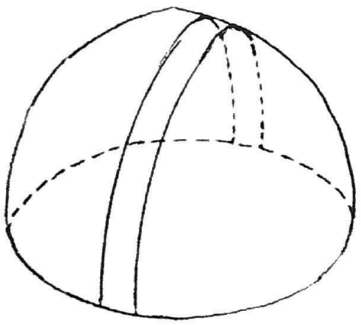


Fig. 4.33a Two parallel elliptical lines cutting the curvature of the dome in angle

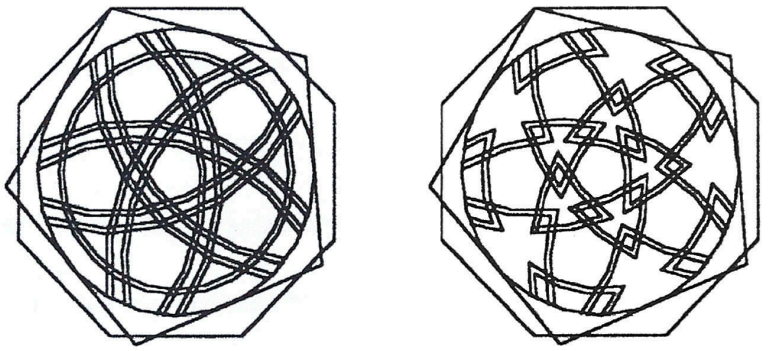


Fig. 4.33b The basic elliptical curved lines in reflected plan of the dome as they transform into the star-like geometric pattern

Based on the foregoing description, two construction methods are suggested as to how this geometrical pattern is laid on the surface of the dome. Using the first method, assuming that the geometrical curvature of the dome was known, the builders could then precisely calculate the mathematical properties for each of the two elliptical lines. Based on this calculation, every point on these curved lines could be easily identified in relation to the dome's peak point (centre) and its circular base (similar to knitting a jacket with patterns assigned for each knot). On this basis, during construction the builders knew what pattern and geometry each brick had, in relation to its specific location on the curvature of the dome.

In the second technique, the builders could have easily projected a two dimensional pentagonal star pattern on the floor and then by using a traditional tool, a plumb attached to a rope, known as *Shagool* in Persian, project the pattern above to the three dimensional surface of the dome.

Based on either of these methods, the builders could identify the main curved lines on the interior surface of the dome. After these lines were defined, the rest of the geometry entailed filling the space between them and giving a unique geometric pattern to each segment of the curved surface. The brickwork on the dome's interior surface is clearly distinguishable from the elliptical curved lines and the curved surfaces between these lines. (Fig. 4.34)

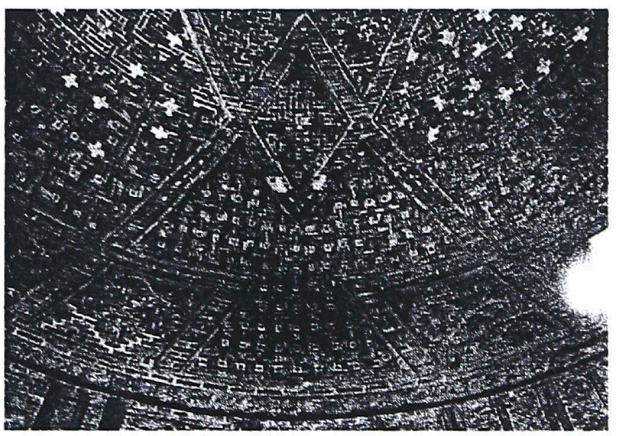
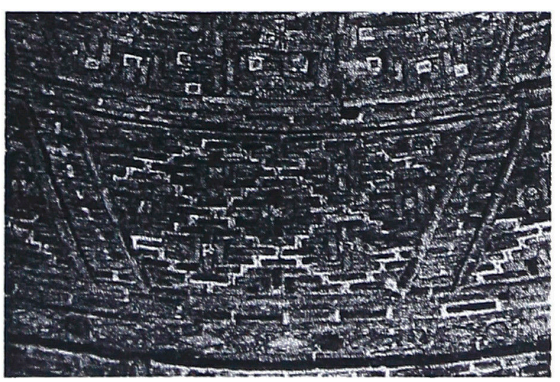
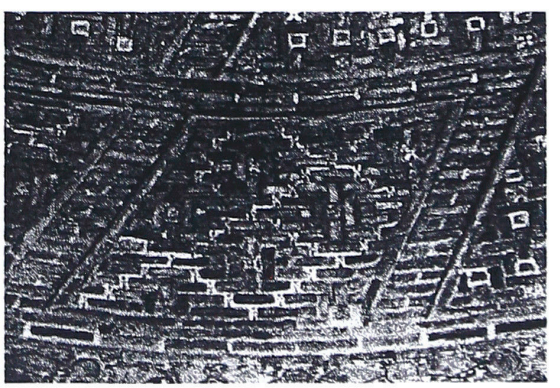


Fig. 4.34, Brickwork in between the curved patterns





As explained earlier, the dome structure consists of two layers of brickwork. One layer covers the exterior of the dome and the second layer covers the interior surface. It is debatable whether the brick design of the interior surface has any structural role to play in the mechanics of the dome or if it is only used as the interior decoration. Here we propose that the second layer of brick undoubtedly reinforces the structure. However, the brick's geometric pattern has no effect on the structural stability of the dome and it only serves as ornamentation for the interior surface of the dome.

Conclusion

The North dome of Masjid-i-Jami of Isfahan, powerful in presence, quietly occupies one of the most secluded areas of the mosque. In its silent presence, it narrates a story about an architecture that modestly glorifies both its creators, and in turn, their Creator. This architecture is shaped by artists/architects who are not only 'builders', but also 'believers', constructing a building that spiritually serves as a house for God. Although its exact architectural function is unknown to us (other than the fact that it is part of the Jami Mosque), its intellectual, artistic and spiritual message is clearly readable in each of its design features.

In its structural design, by employing mathematical relations that are driven from an idealized nature, i.e. the Golden ratio, this elegant form creates a connection between natural and man-made structures. Also, based on these relations, a "perfect" form is constructed that not only structurally speaks of harmony and balance, but also speaks of formal perfection and timelessness, which is comparable to the ever lasting faith in a believer's heart. This structure has survived for more than nine hundred years in an earthquake zone and is unchanged from its original form.

In its geometric design, the North dome introduces a unique relationship between structural form and ornamentation. In one instance, geometry is used to create a two-dimensional surface pattern. In another instance, by elevating a surface into a three-dimensional structure, creates a space. When entering the space of the North dome, one

experiences the main structural geometry. Gradually, countless geometric patterns appear. Looking further, one discovers more detailed forms that were otherwise hidden. The geometric design is enhanced as the structure rises through successively elevating zones. This quality invites the observer to raise eyes upwards to the point where the dome is placed. The star-like design of the dome is significantly comparable to the heavenly sky; by means of which, one can be connected to the spiritual realm. In this sense, geometry becomes an abstract cosmological language that is revealed in both structural and aesthetic forms to create a rapport between architectural form and the universe.

In its construction, each of the brick units is an individual character that collectively forms the total design. Each brick unit is uniquely placed in its assigned location. Some bricks are purely structural and have a simple form. Others are purely decorative and are fashioned with elaborated geometric designs. Similarly, there are bricks that plainly cover the floor, while others with intricate design cover the curved surface of the dome. Finally, brickwork is also used for the Kufic calligraphy on various panels, where it becomes a calligraphic stroke to celebrate God's Word.

A great work of art like the North dome is a lesson for us to see how architecture tells a story and conveys a message by incorporating different design components, from structure to geometry and construction. By these means it collectively brings a form into life that geometrically speaks of harmony, structurally speaks of knowledge, aesthetically speaks of art and above all, silently speaks of faith and subtly glorifies the Unseen. Lastly. The space inside the North dome is a cut out from the material world around and is filled with a

comforting silence that can only be captured through "the loud flight of agitated pigeons leaving a profound silence [behind]". This space silently speaks of many qualities that simply can not be captured in a work like the one that was presented here. However, it is hoped that this humble effort will open new possibilities for further explorations, in pursuit of many issues that have developed based on this study.

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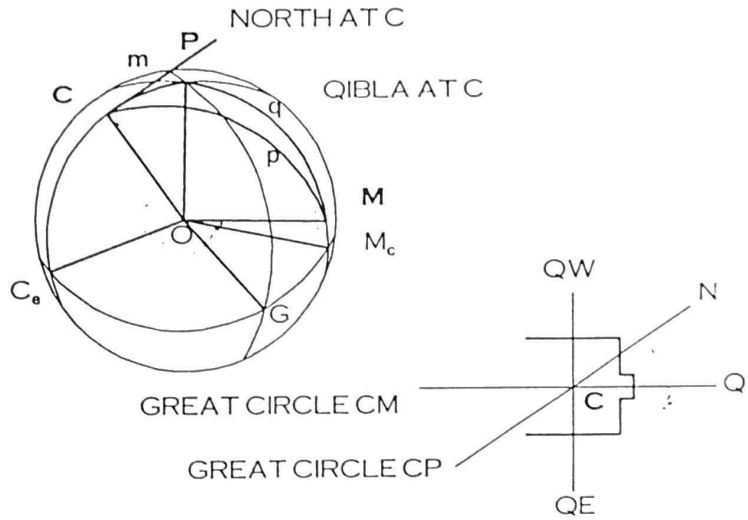
Appendix I

The calculation of Qibla orientation for the city of Isfahan: [1]

The following equation and figure is applicable for the cities in the Northern hemisphere. The city of Isfahan is located in the northern hemisphere east of Makkah.



C = City whose Qibla is to be calculated

C'= Geometric location of city meridian on equator

M = Makkah, location of Kaa'ba

M'= Geometric location of Makkah meridian on equator

p = Geometric north pole of earth sphere

O = Geometric center of earth sphere

G = 0° meridian at equator

q = Angle COP (known as 90°- latitude of Makkah)

m = Angle POM (known as 90°- latitude of city C)

p = Angle COM

p = Angle C'OM'

Q = Qibla orientation at C, angle between diametric planes CPO and CMO

Two equations are presented here, using equation 1, the unknown angle of p will be solved and then by using this angle in equation 2 the angle Q which is the Qibla orientation will be solved.

Equation 1: $\cos p = \cos q \cos m + \sin q \sin m \cos p$

Equation 2: $\sin Q = \sin q \sin p / \sin p$

[1]This calculation is based on equations from "Graphics Standards". These equations are developed by G. Haider.

Latitude and Longitude for the city of Isfahan are as follows:	Latitude	32° 40′ N
	Longitude	51° 38′ E

Latitude and Longitude for the city of Mekkah are as follows:	Latitude	21° 30′ N
	Longitude	40° 20′ E

therefore, in the first equation we have:

$$\cos p = \cos(90 - 21.5)\cos(90 - 32.67) + \sin(90 - 21.5)\sin(90 - 32.67)\cos(50.63 - 40.33)$$

$$\cos p = \cos(68.5)\cos(57.33) + \sin(68.5)\sin(57.33)\cos(11.3)$$

$$\cos p = 0.197837227 + 0.768036516 = 0.965873$$

$$\Rightarrow p = 15.01°$$

using p in equation 2 we have:

$$\sin Q = \sin(68.5)\sin(11.3) / \sin(15.0)$$

$$\sin Q = 0.70394$$

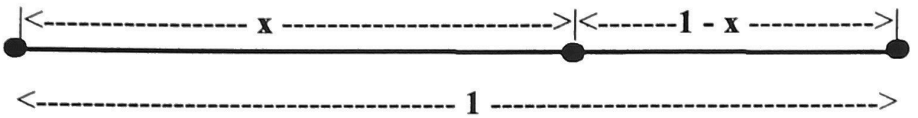
$$\Rightarrow Q = 44.7439°$$

As a result the Qibla orientation for the city of Isfahan is about 45° south-west from the north-south axis of the city.

Appendix II

The Golden Ratio

Mathematical Definition: The Golden Ratio is produced by that point on a line segment which divides the line segment into two portions such that the ratio of the length of the larger segment to the smaller segment is equal to the ratio of the length of the whole line to the larger segment.



Thus, the definition of the Golden Ratio can be translated to this algebraic equation:

$$\text{Golden Ratio} = (x)/(1 - x) = (1)/(x)$$

Solving this equation for x gives:

$$x^2 = 1 - x$$

$$x^2 + x - 1 = 0$$

Using the quadratic equation and taking the positive root only:

$$x = (-1 + \sqrt{5})/2$$
$$\approx 0.61803\ldots$$

Therefore the value of the Golden Ratio is:

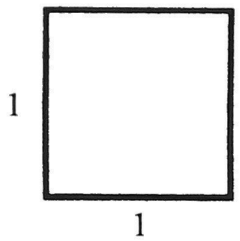
$$\text{Golden Ratio} = 1/x$$

$$= 2/(-1 + \sqrt{5})$$

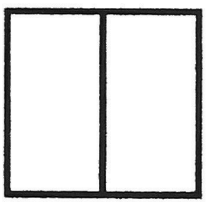
$$= (1 + \sqrt{5})/2 \quad \text{(after rationalizing the denominator)}$$

$$\approx 1.61803\ldots \quad \text{(approximate numeric value)}$$

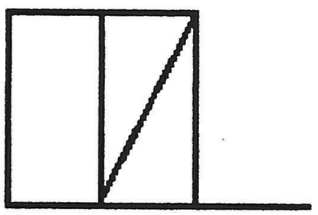
A Geometric Construction of the Golden Ratio: Here are instructions for constructing the Golden Ratio, that is a line segment which is exactly $(1 + \sqrt{5}) / 2 \approx 1.61803\ldots$ units long, using only traditional tools, a ruler and a compass.



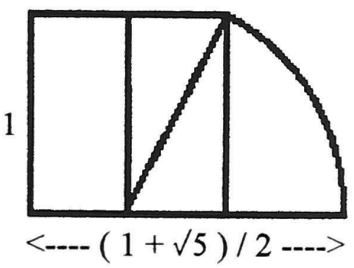
Construct a square with side length of 1.



Bisect the square.



Draw a line from one end of the bisecting line to one of the opposite corners. Extend the baseline of the corner.

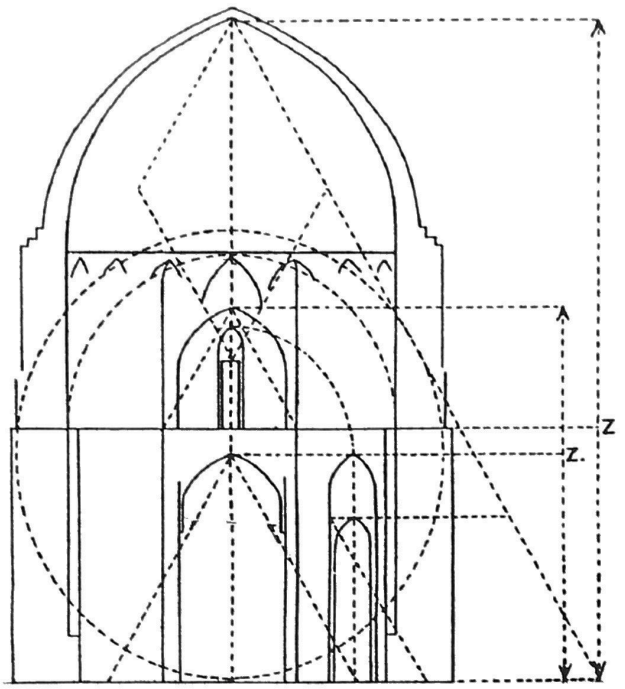


Using the diagonal line as a radius, drop an arc from the corner of the square down to the baseline.

The total length formed along the base of this figure is the Golden Ratio $= (1 + \sqrt{5}) / 2$.

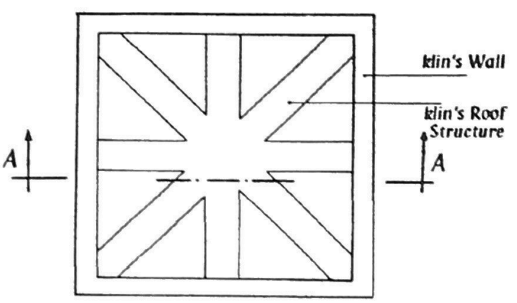
Majid Moghadam, May 2000

Appendix II, Continued

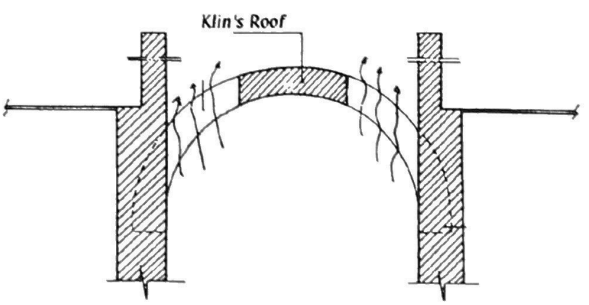


A drawing by Eric Schroeder that shows the geometrical relationships in the North dome of Masjid-i-Jami. The construction of the North dome employes the properties of Golden ratio and other geometric relationships.

Appendix IV



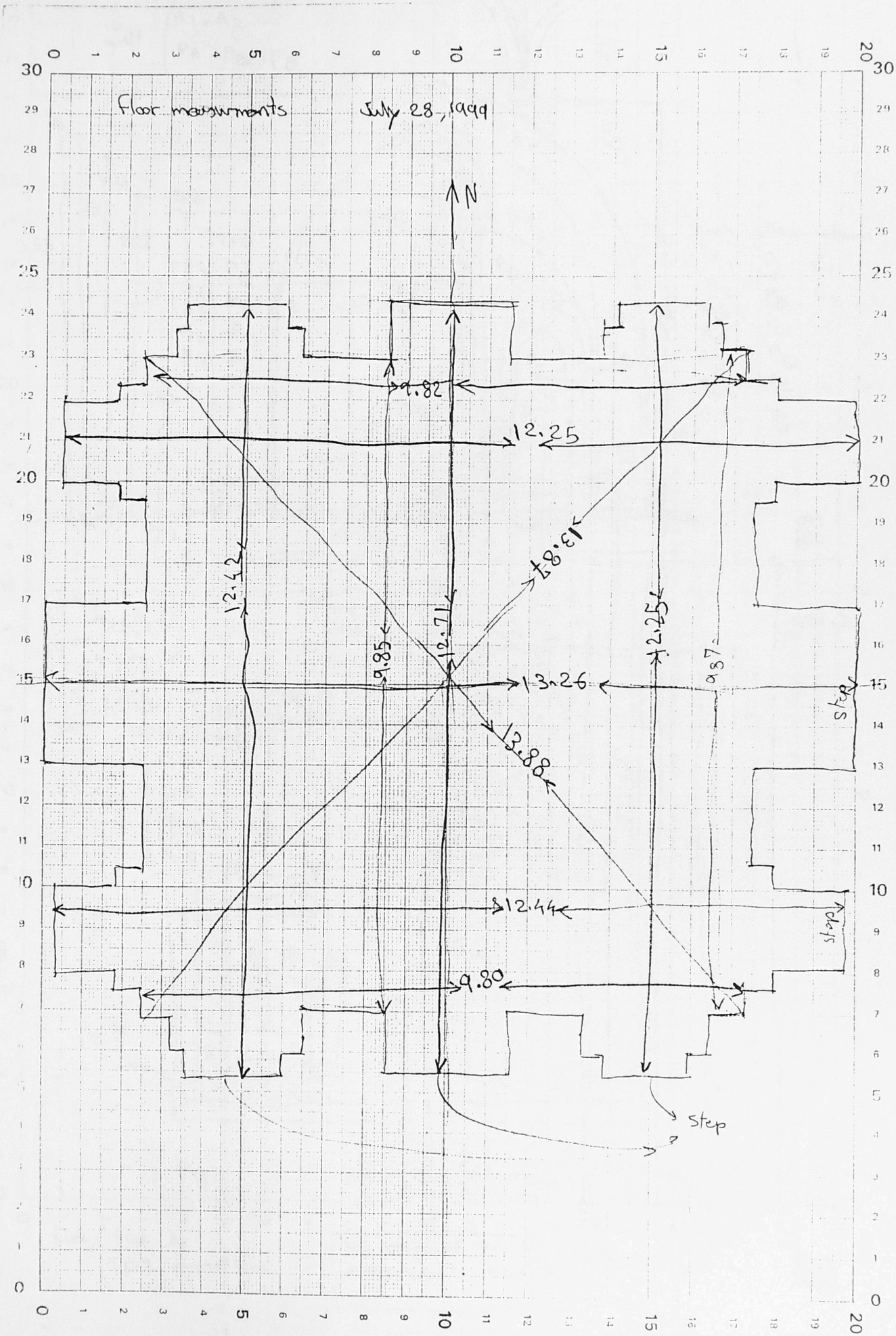
Klin's Plan & Section

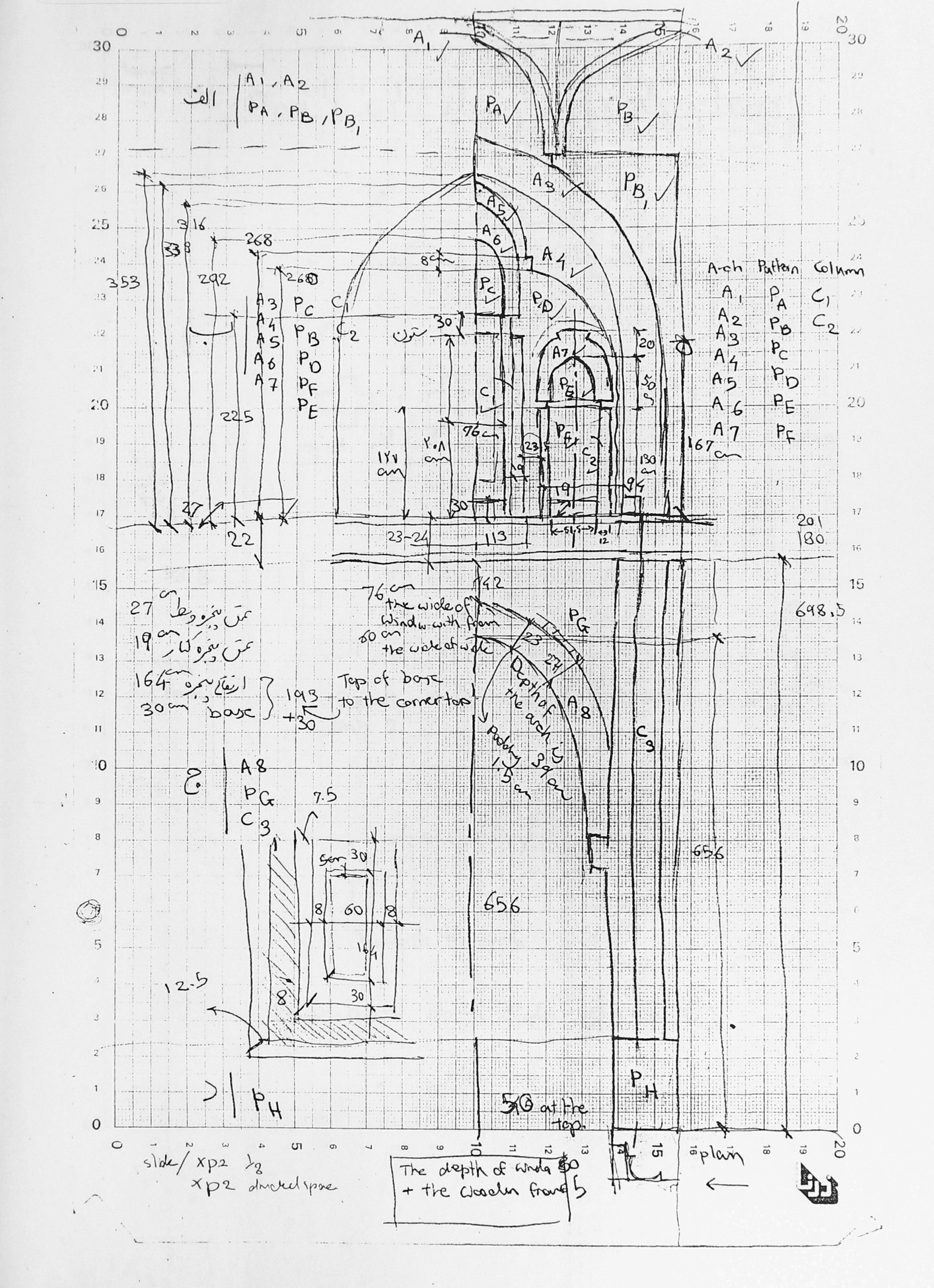


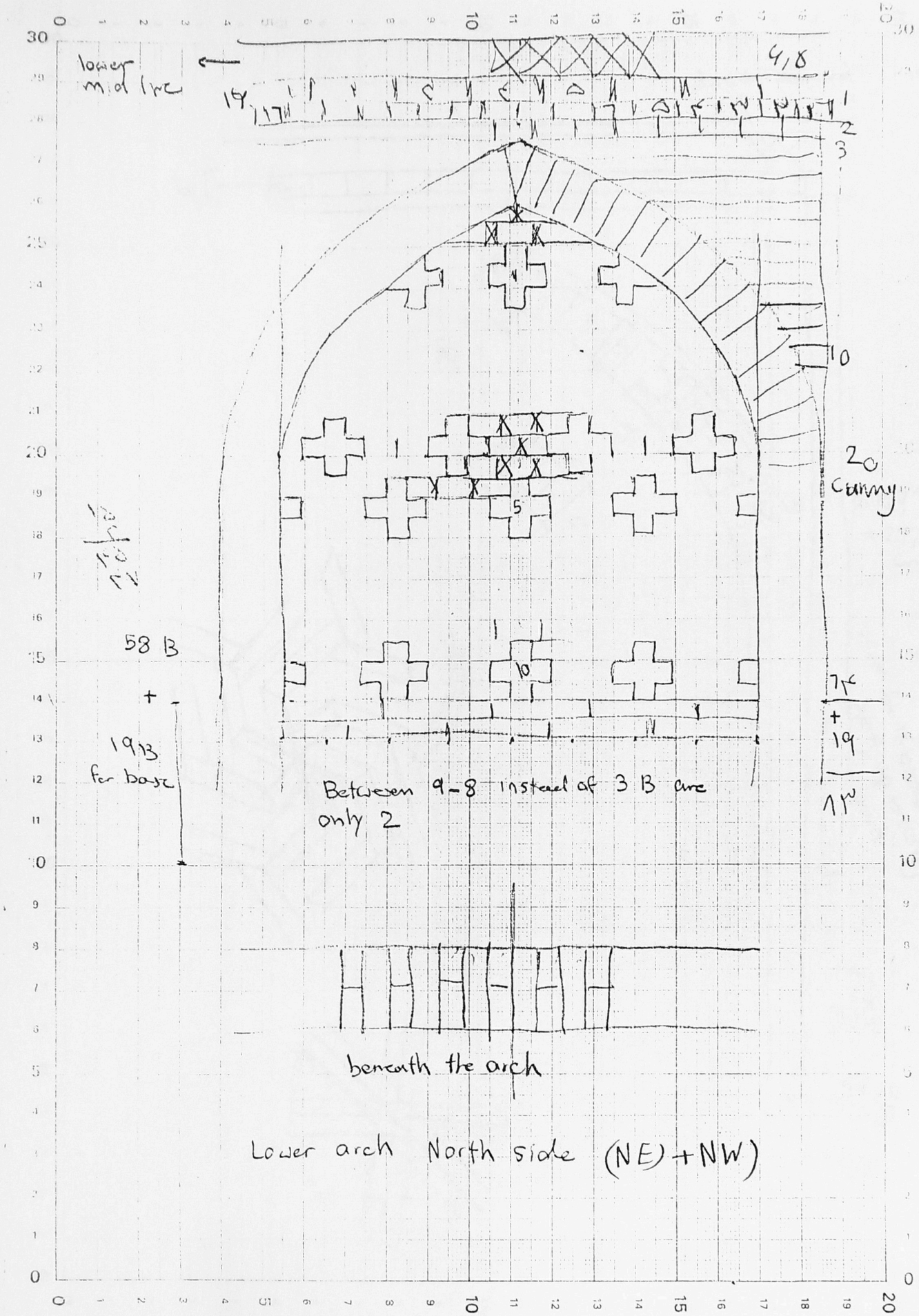
The structure of a traditional brick klin

Appendix III

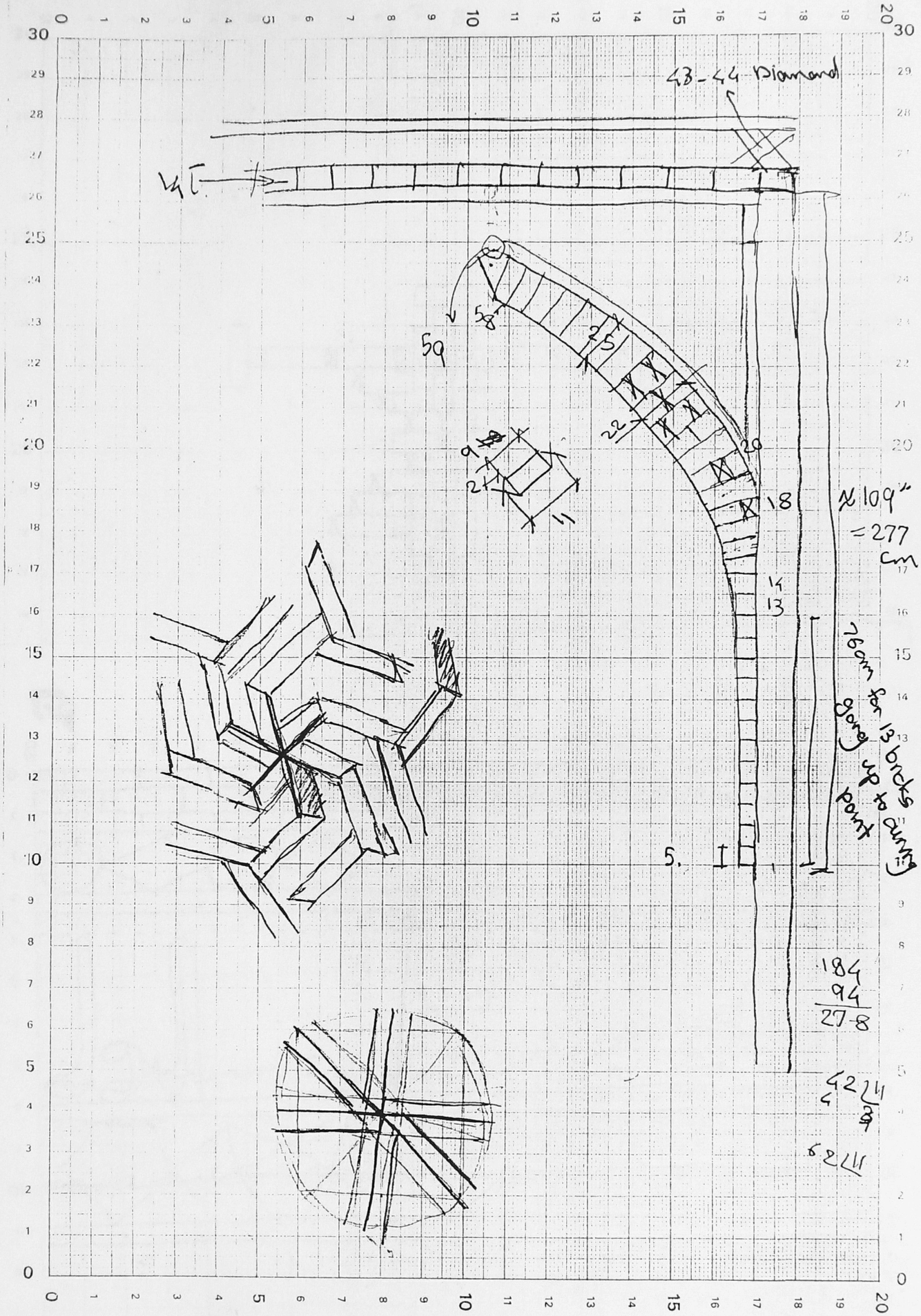
Sketches from the Field Study of the North dome of Masjid-i-Jami

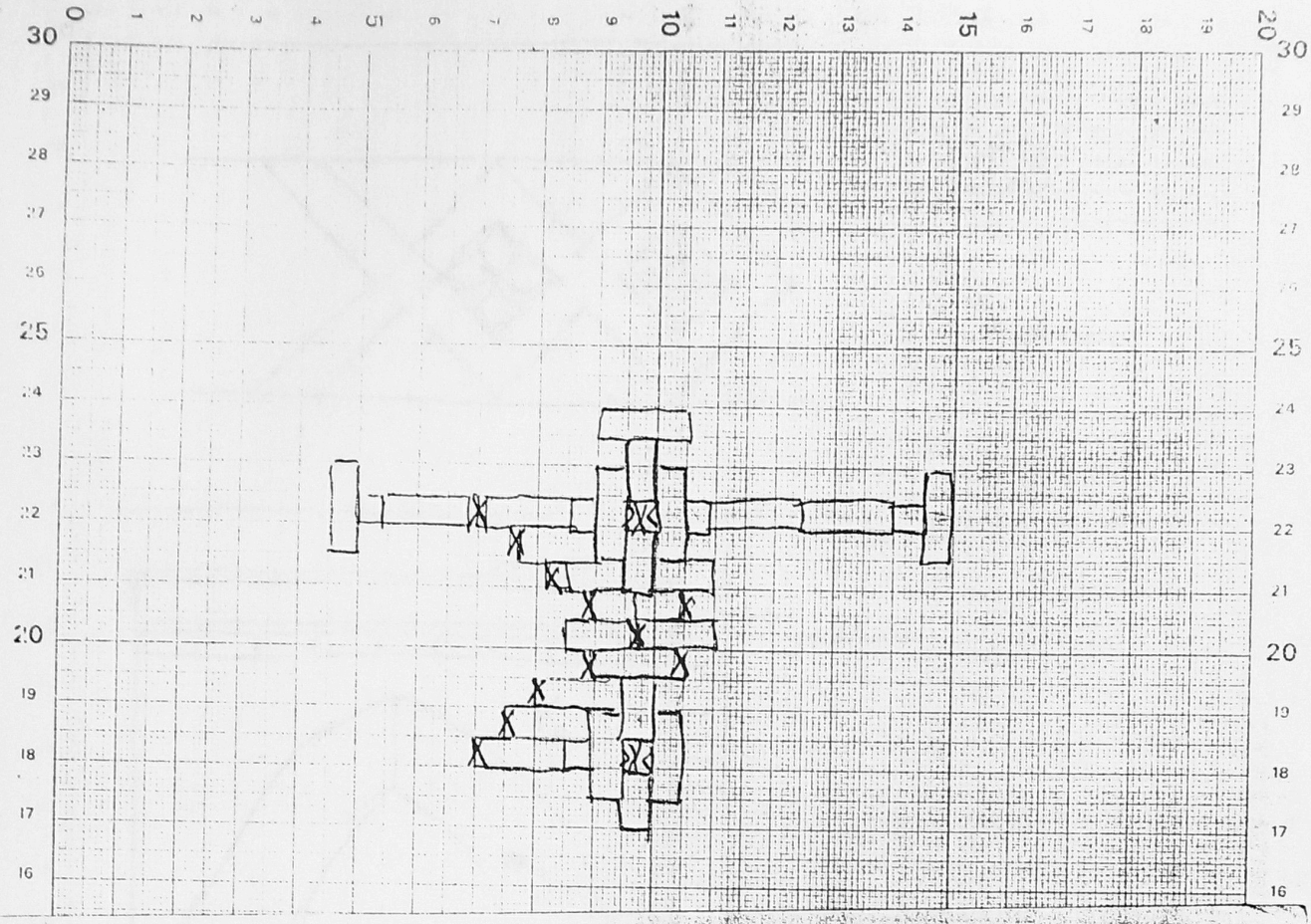

Floor measurments
July 28, 1999
N
9.82
12.25
13.81
12.42
12.71
12.25
9.85
9.87
13.26
13.88
12.44
9.80
step
step
step

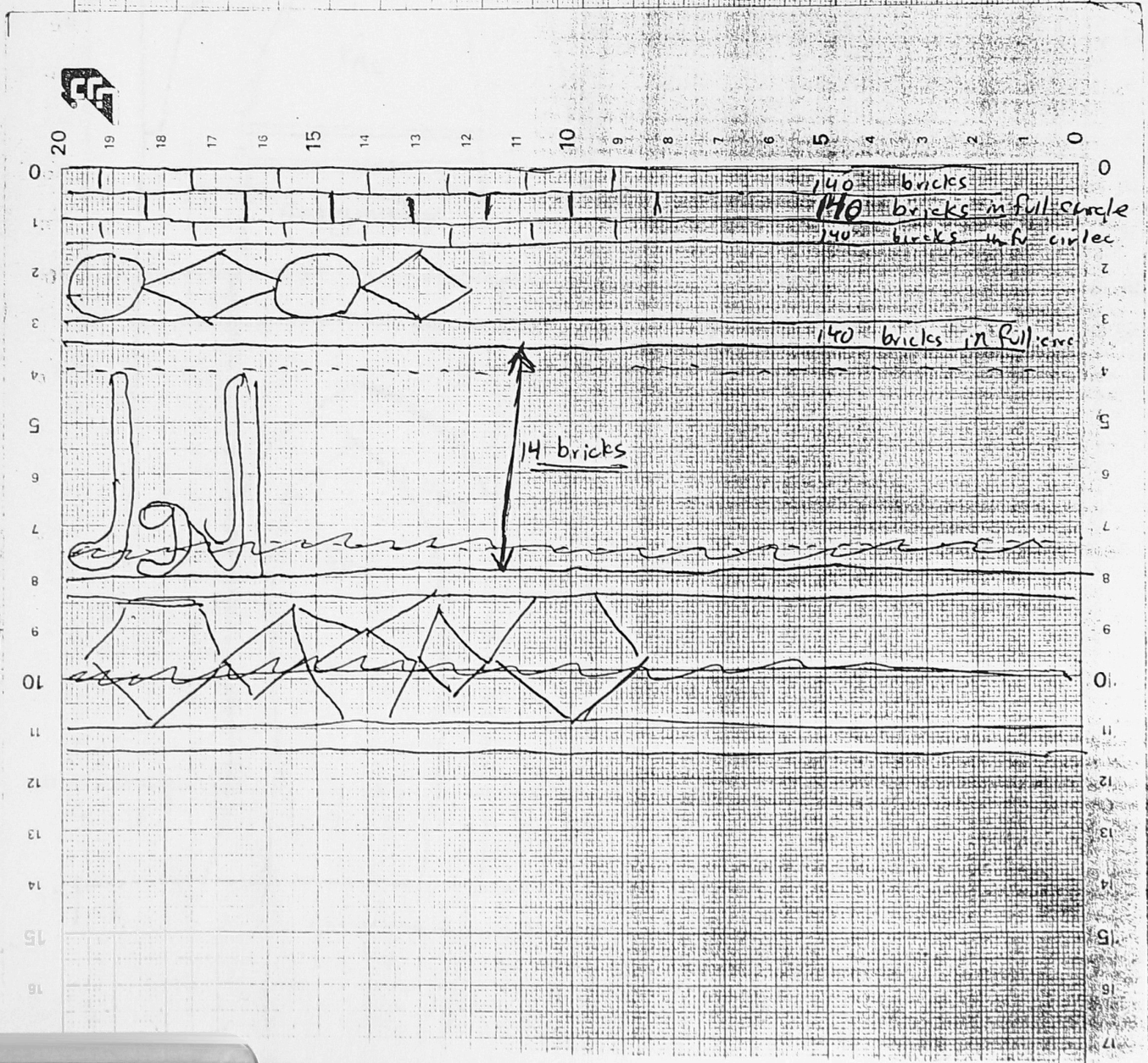

الف
A1, A2
PA, PB, PB1
A1
A2
PA
PB
PB1
A3
A4
A5
A6
A7
PC
PD
PE
PF
C1
C2
C3
PG
A8
PH
Arch Pattern Column
A1 PA C1
A2 PB C2
A3 PC
A4 PD
A5 PE
A6 PF
A7
353
316
338
268
292
268
225
27
22
30
ستون
8cm
96cm
177 cm
208 cm
167 cm
50 cm
20
130 cm
94
19
23
113
23-24
142
201
180
698.5
656
656
27 cm عمق پنجره وطا
19 cm عمق پنجره کنار
164 cm ارتفاع پنجره
30 cm base
193 + 30
Top of base to the corner top
76 cm the wide of window with from
80 cm the wide of wall
Depth of the arch 39 cm
Pocket 1.5 cm
ج
A8
PG
C3
7.5
30
8
60
164
12.5
د
PH
5/8 at the top
slide/ xp2 1/8
xp2 divided space
The depth of wall 80 + the wooden frame 5
plan

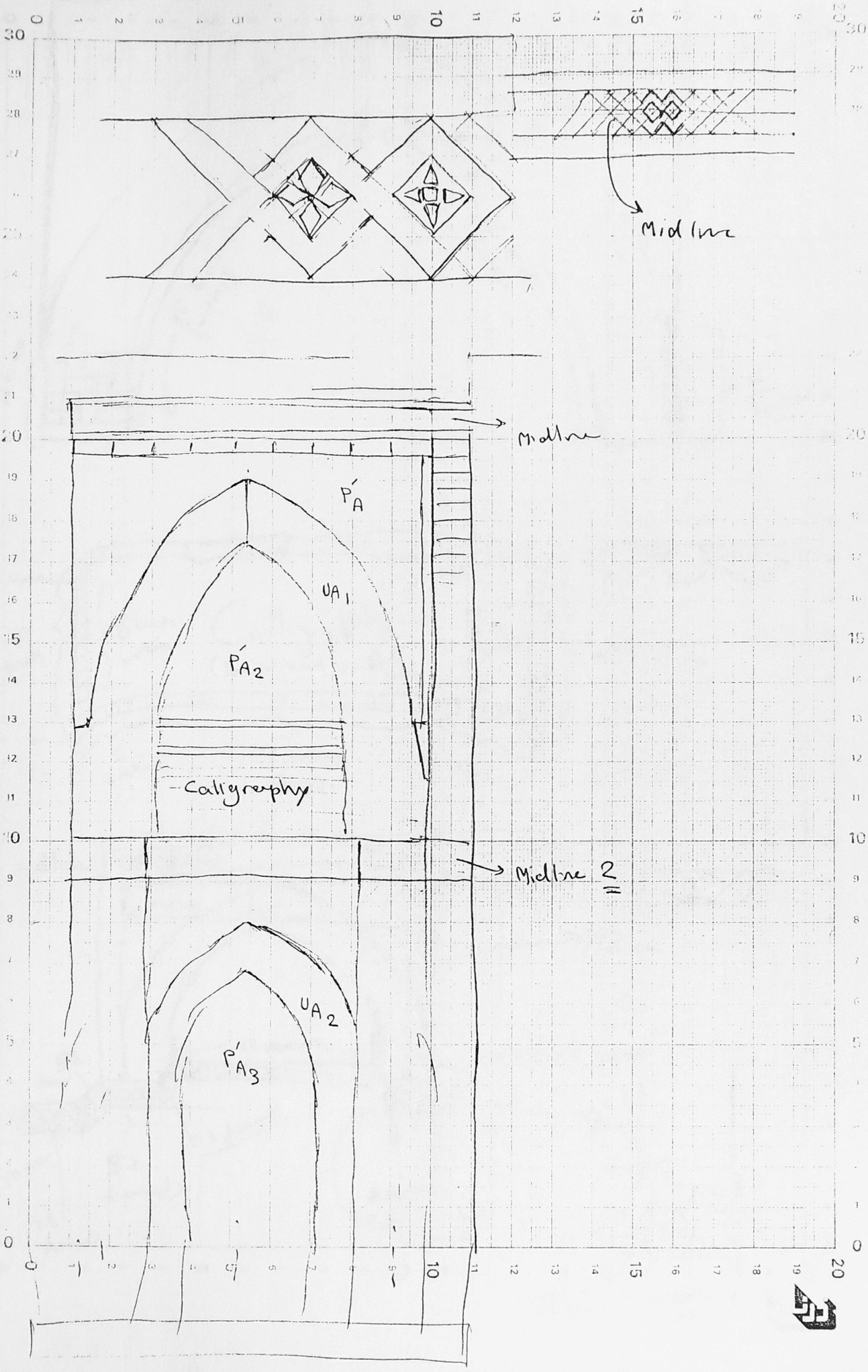


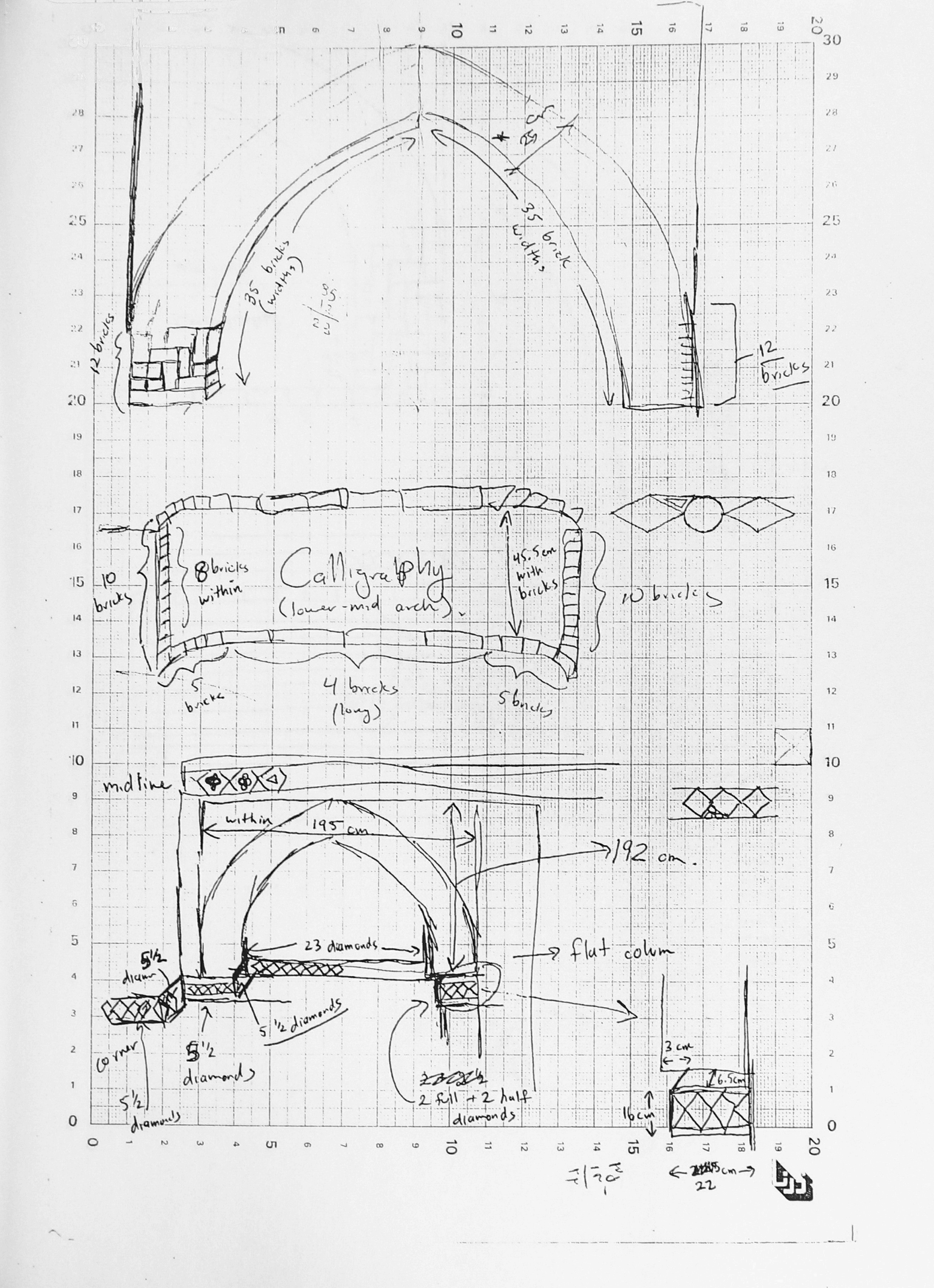
Lower arch North side (NE)+NW)

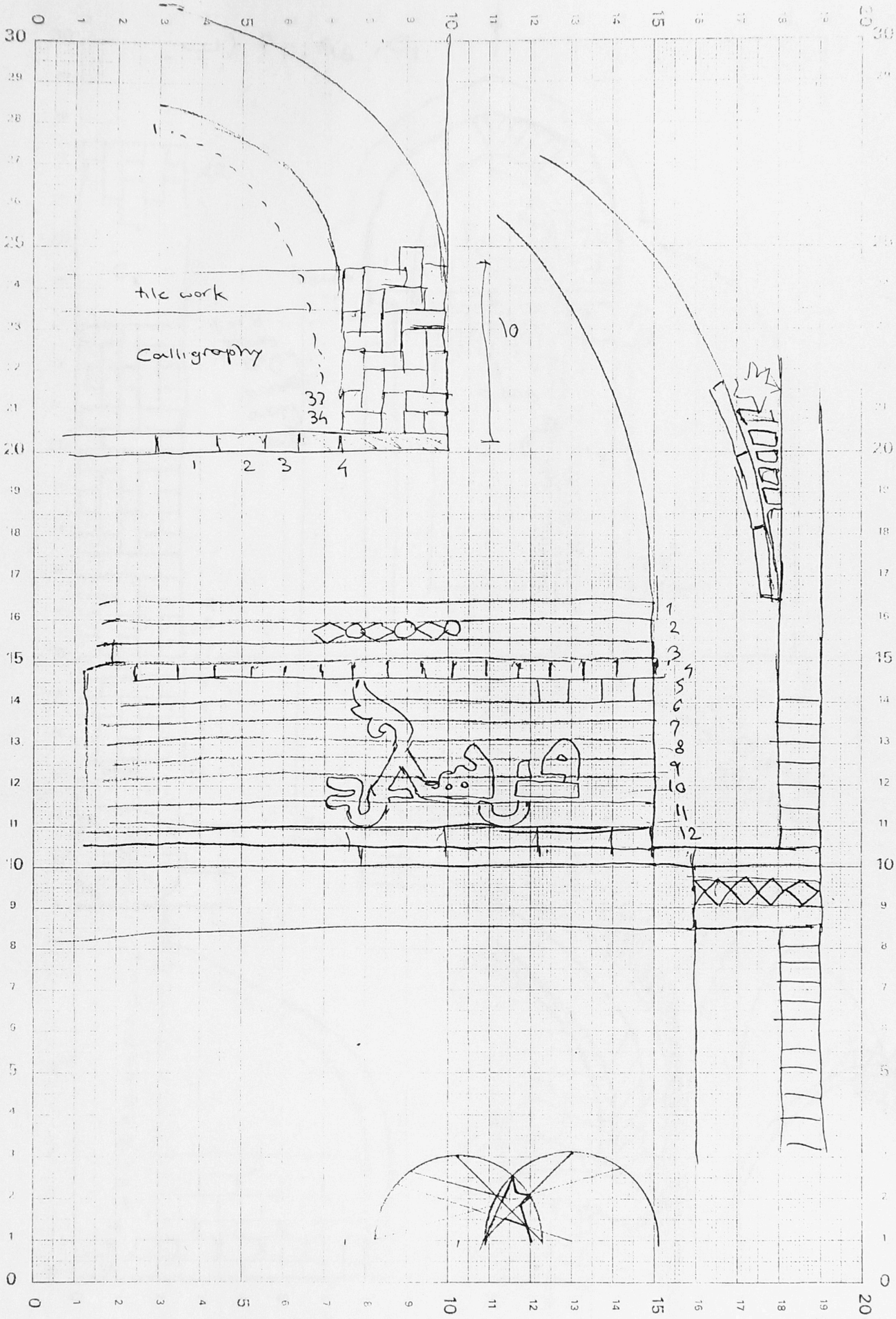

43-44 Diamond
14
59
58
25
22
20
18
14
13
9
21
11
5.
≈ 109"
= 277 cm
76cm for 13 bricks going up to curve point
184
94
278
42 14
9
17 29
62 14

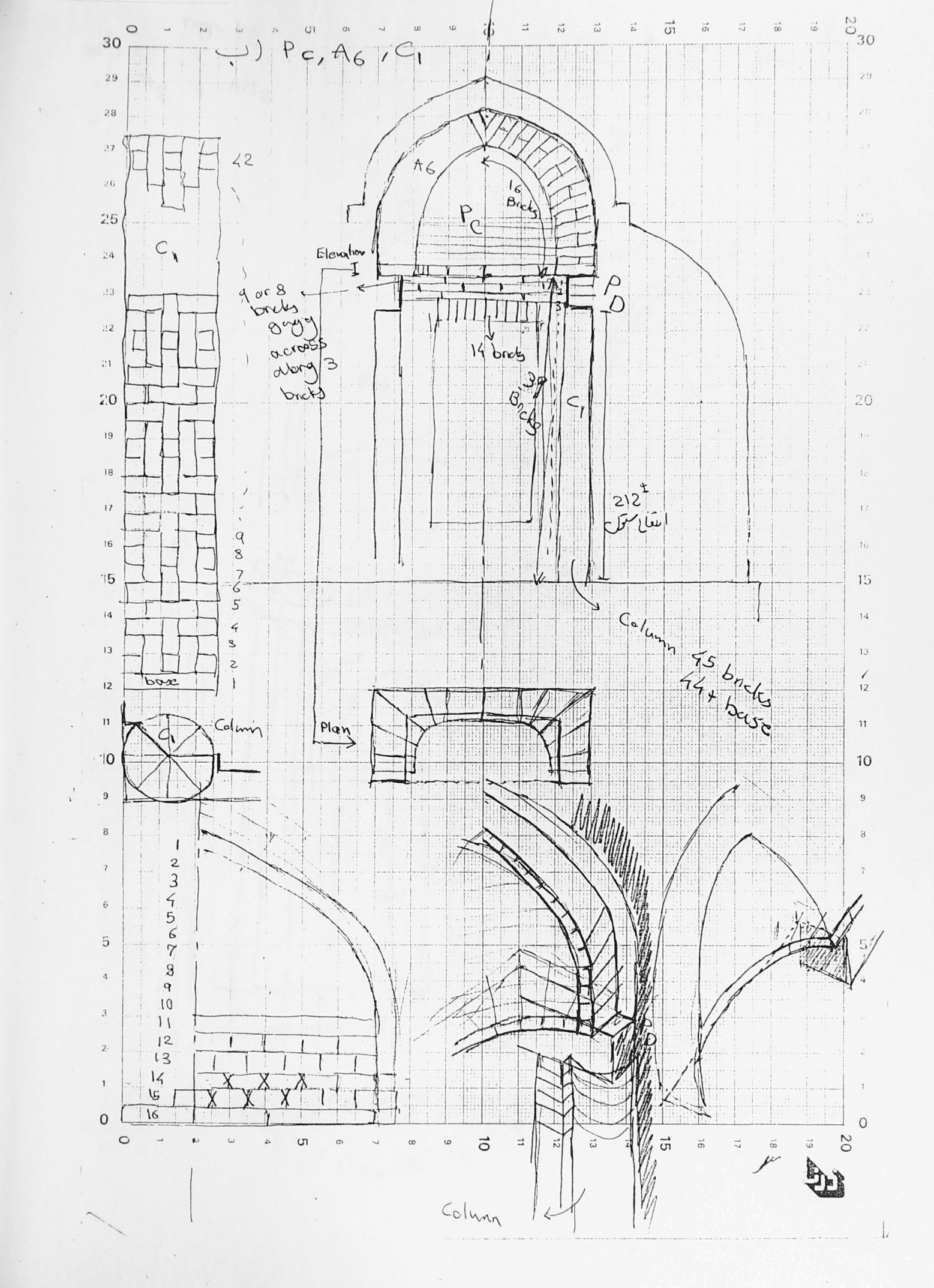



140 bricks
140 bricks in full circle
140 bricks in full circle
140 bricks in full circle
14 bricks

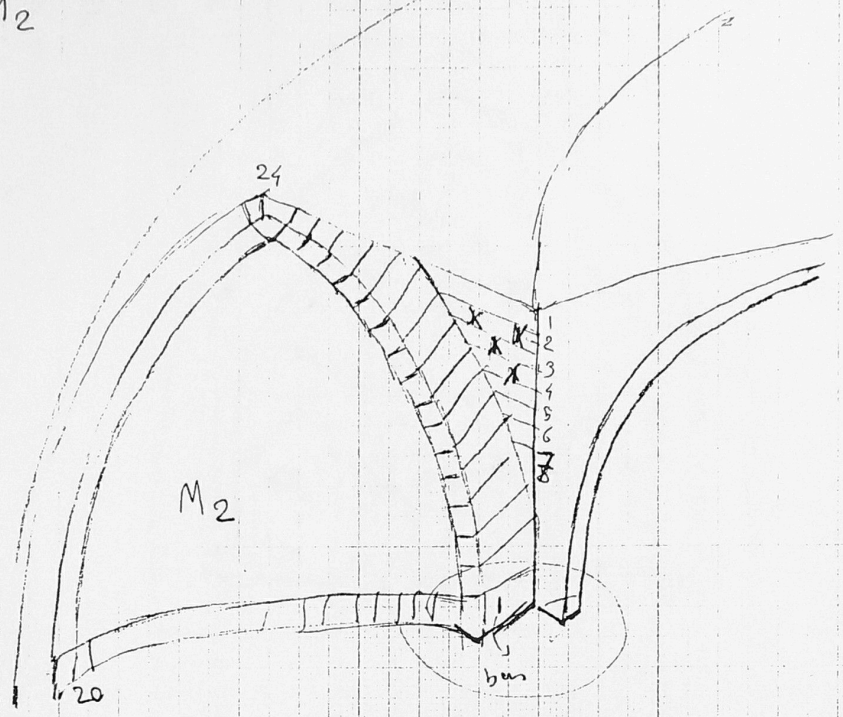

Midline
Midline
P'A
UA1
P'A2
Calligraphy
Midline 2
UA2
P'A3

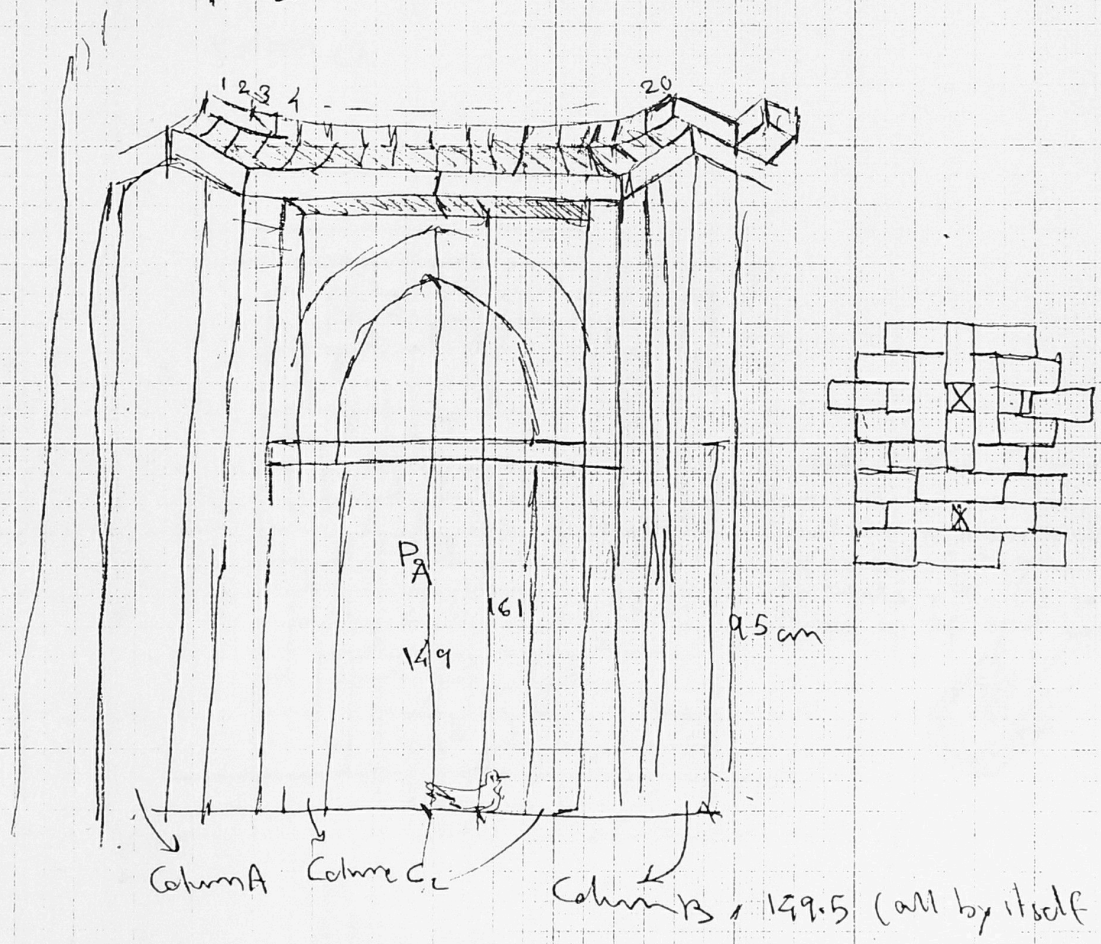

12 bricks
35 bricks (widths)
35 brick widths
12 bricks
10 bricks
8 bricks within
Calligraphy
(lower-mid arch)
45.5 cm with bricks
10 bricks
5 bricks
4 bricks (long)
5 bricks
midline
within
195 cm
192 cm.
23 diamonds
flat colum
5½ diamr
5½ diamonds
corner
5½ diamonds
5½ diamonds
2 full + 2 half diamonds
3 cm
6.5cm
16cm
22

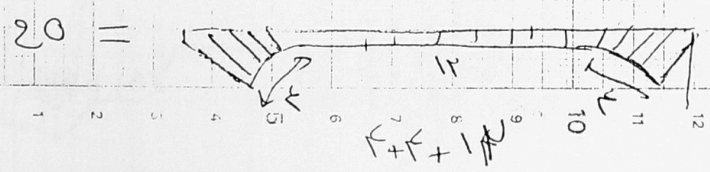

tile work
Calligraphy
10
37
34
1
2
3
4
1
2
3
4
5
6
7
8
9
10
11
12

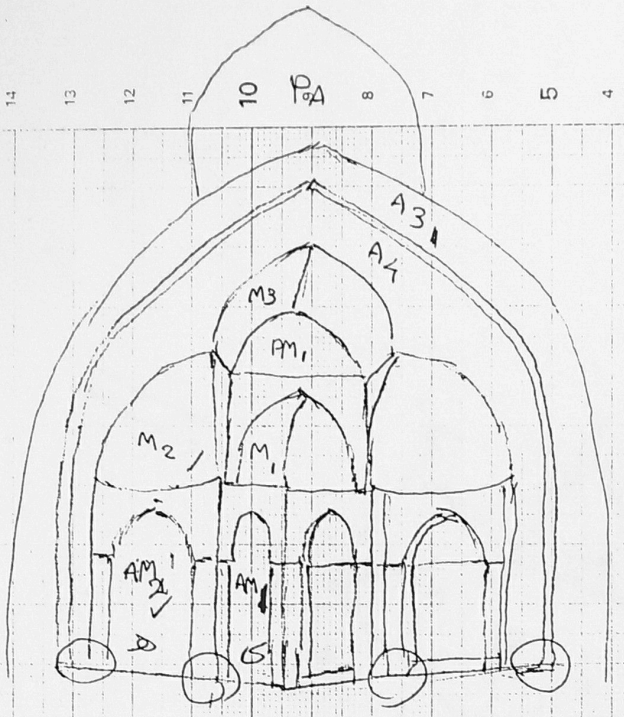

ب) Pc, A6, C1
42
C1
box
Column
C1
Elevation I
9 or 8 bricks gap across along 3 bricks
A6
16 Bricks
Pc
14 bricks
3 Bricks
C1
PD
212 ± انقاع ستوك
Column 45 bricks 44 + base
Plan
PD
Column

M_2 & AM_2

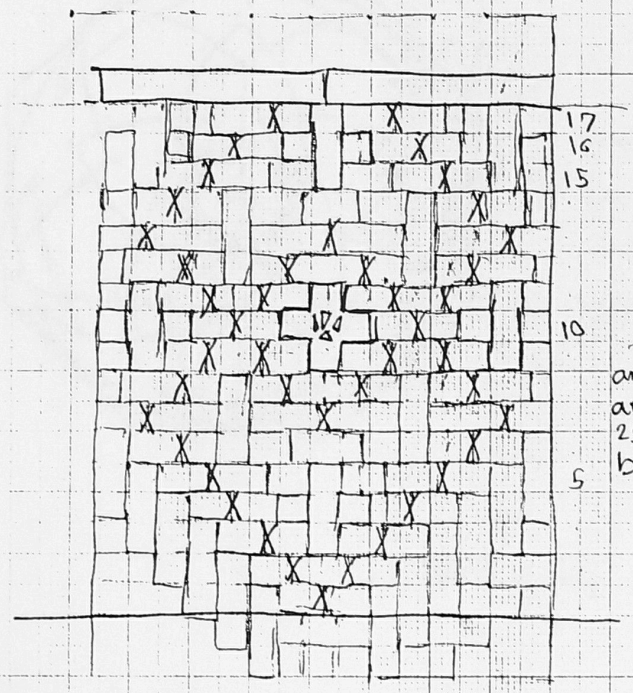

24
1
2
3
4
5
6
7
8
M2
1
20
bus


1 2 3 4
20
PA
161
149
95 cm
Column A
Column C
Column B, 149.5 (all by itself

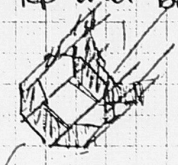

20 =
12
4
4
4+4+12



Pattern 5

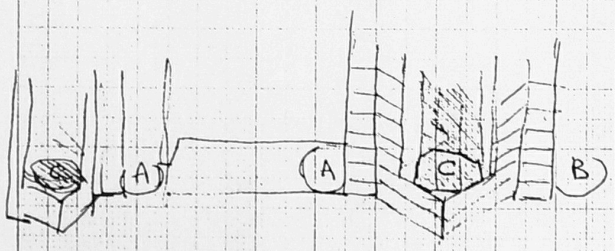


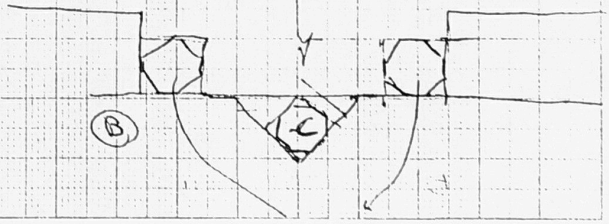
Note that 4 Column two in between AM_2 & AM_1 and two in either side of Arch are solid octagonal bricks 25 bricks + 2 + (1) Solid bases on top and bottom



$\frac{1}{25}$

2(1+1)





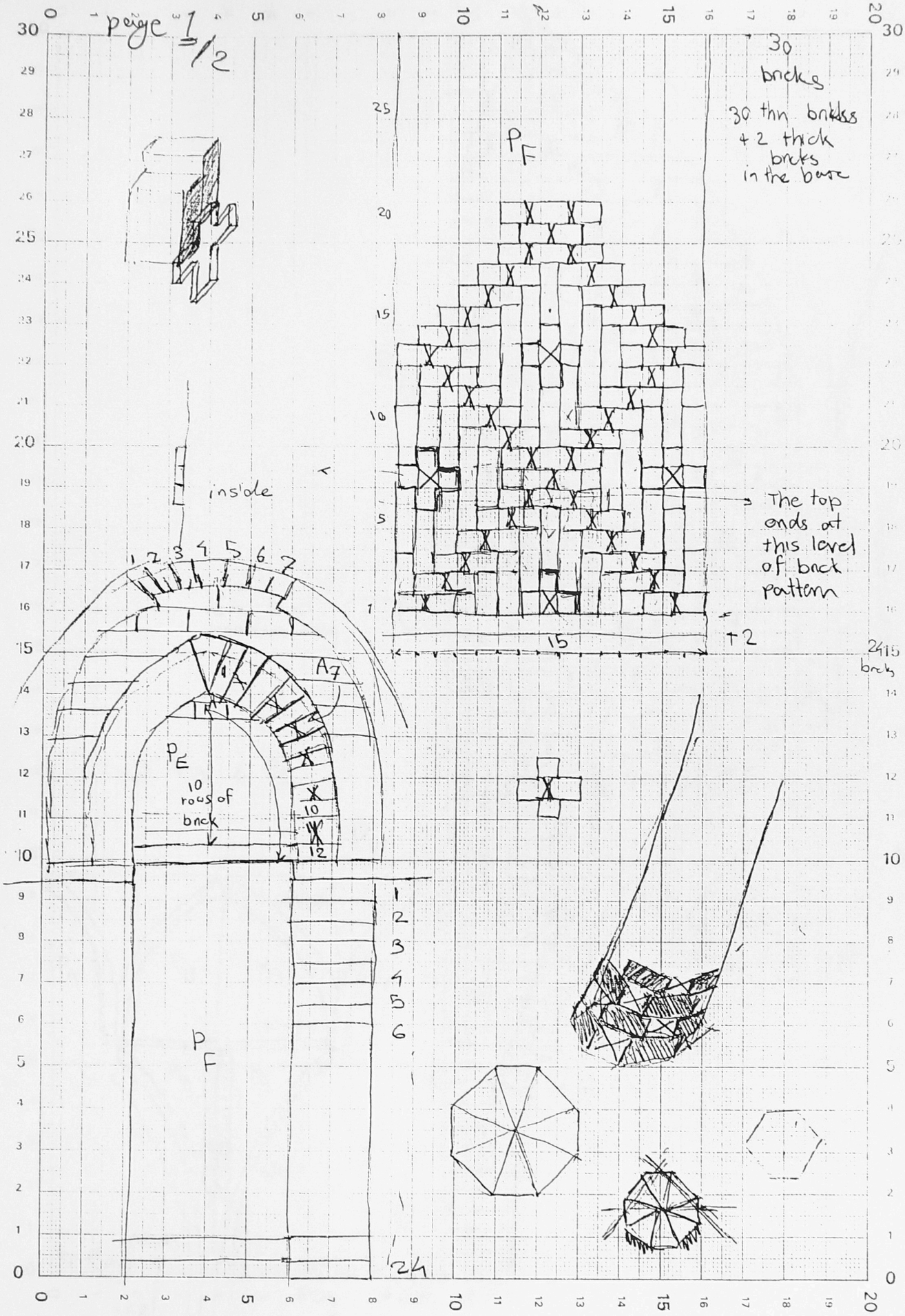
Column A & B

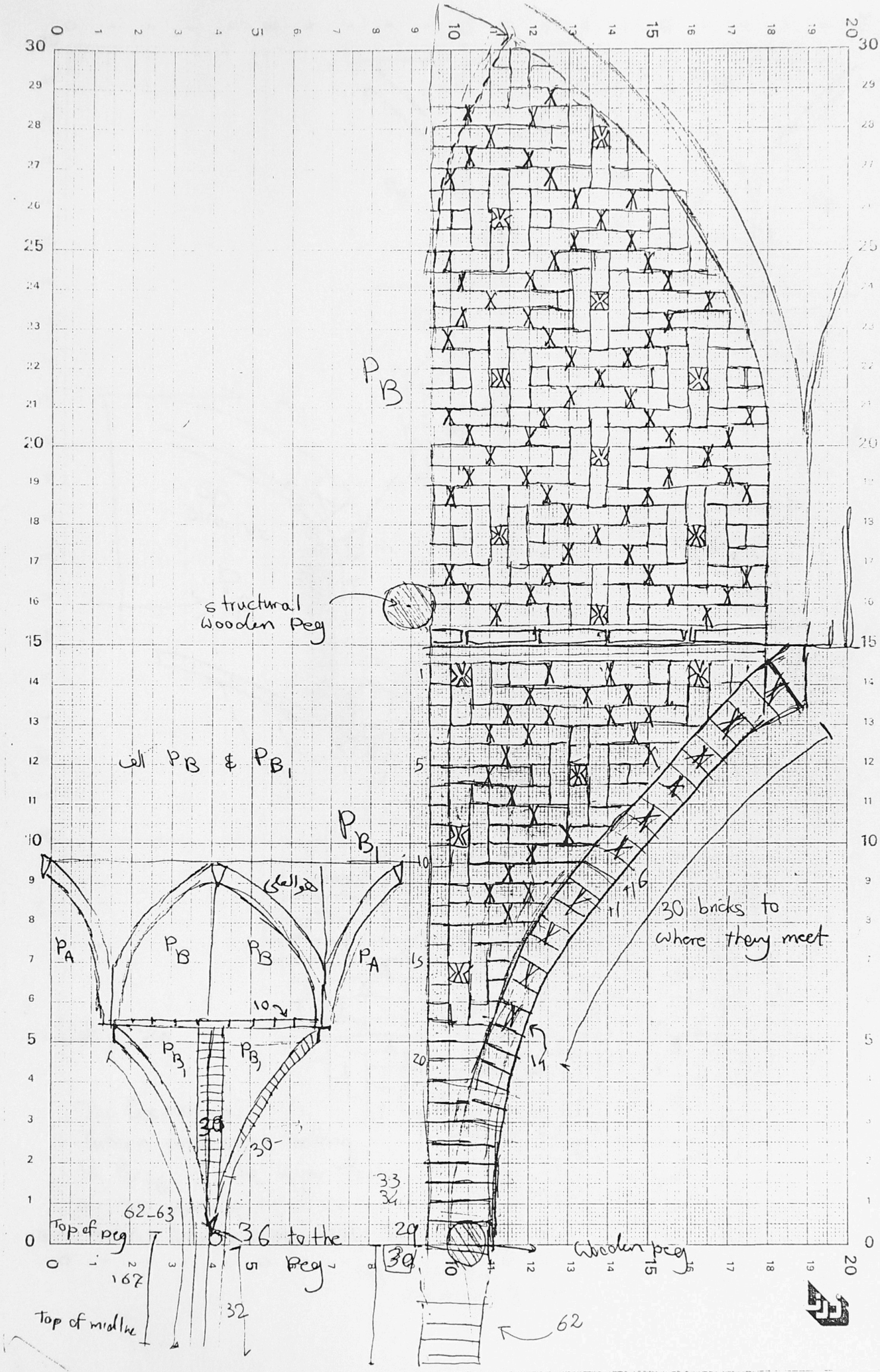
Radiens of 6

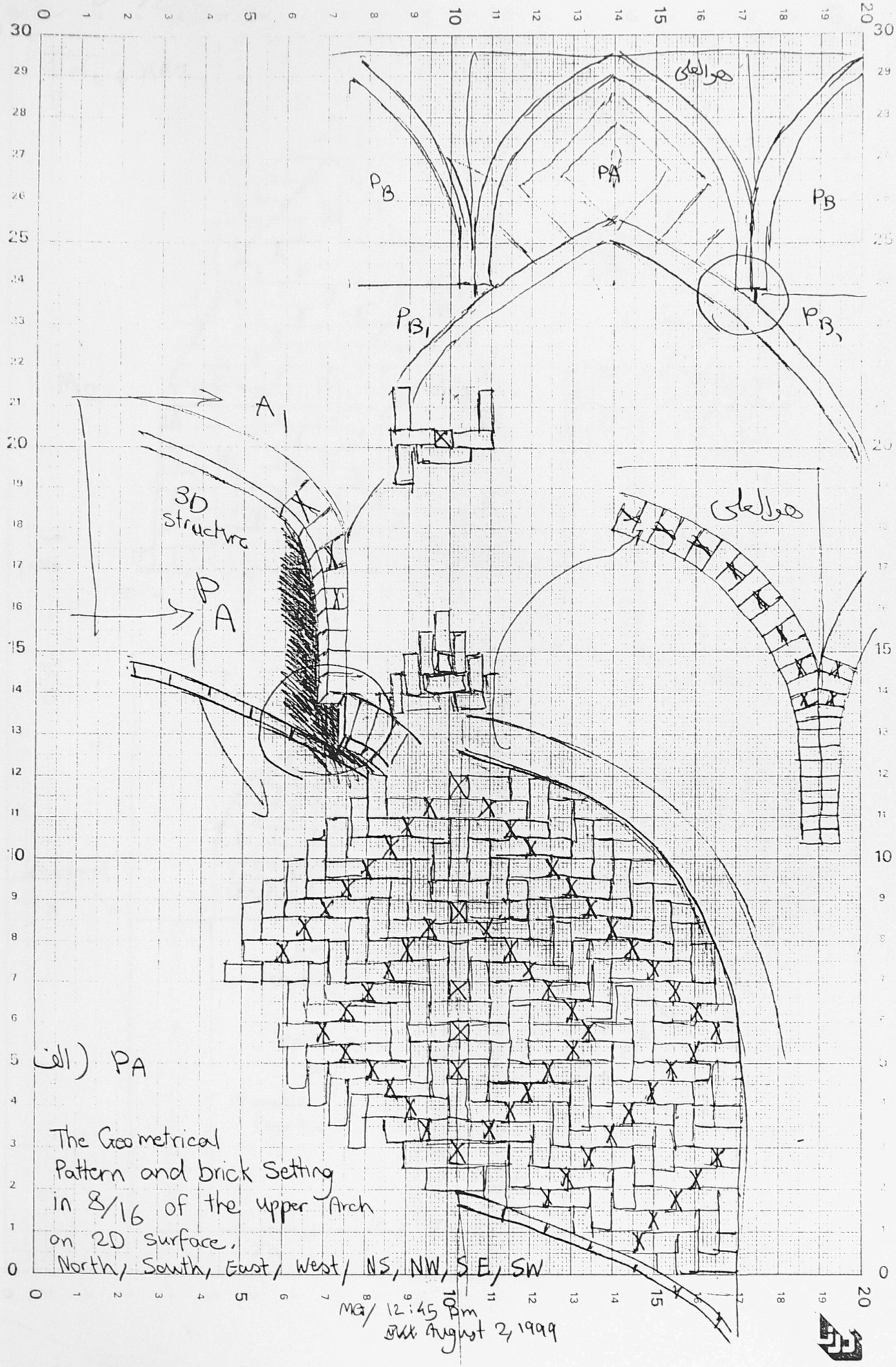
radius (cm)

	#1	#2	#3	avg
1	Book	Bedbow		
2	215 245	236 238	225 220	223
3	287 245	266 262		
4	292	280	305	306
5	361 327	361.5 372	392	
6	421.5	427	416	417
7	479 425	454	459	
8	448	507 503	492 506	

471 ± 2 is the radiens of lower circle

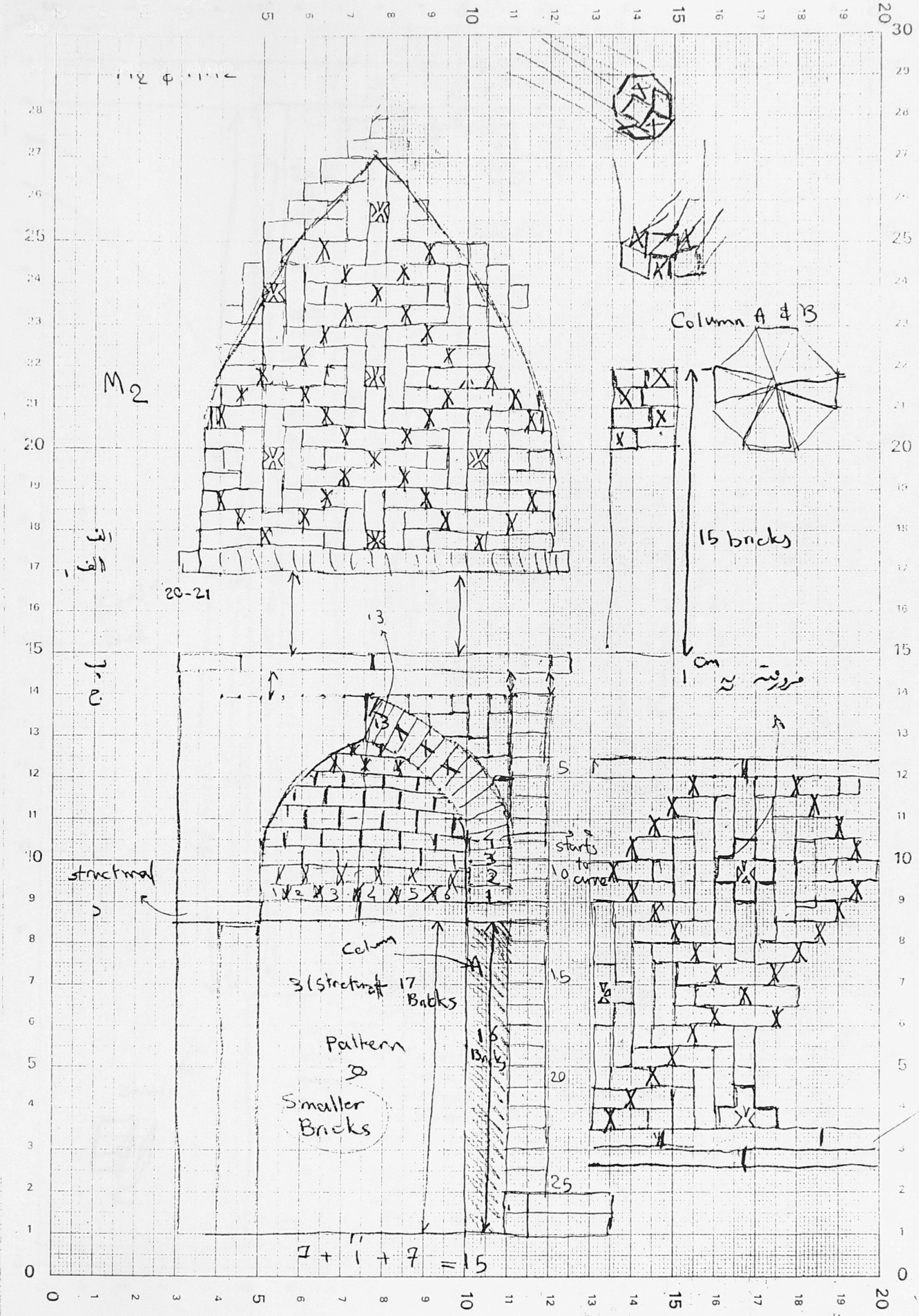

page 1/2
30 bricks
30 thin bricks + 2 thick bricks in the base
P_F
The top ends at this level of brick pattern
15
+2
24 bricks
inside
1 2 3 4 5 6 7
A_7
P_E
10 rows of brick
10
12
1 2 3 4 5 6
P_F
24

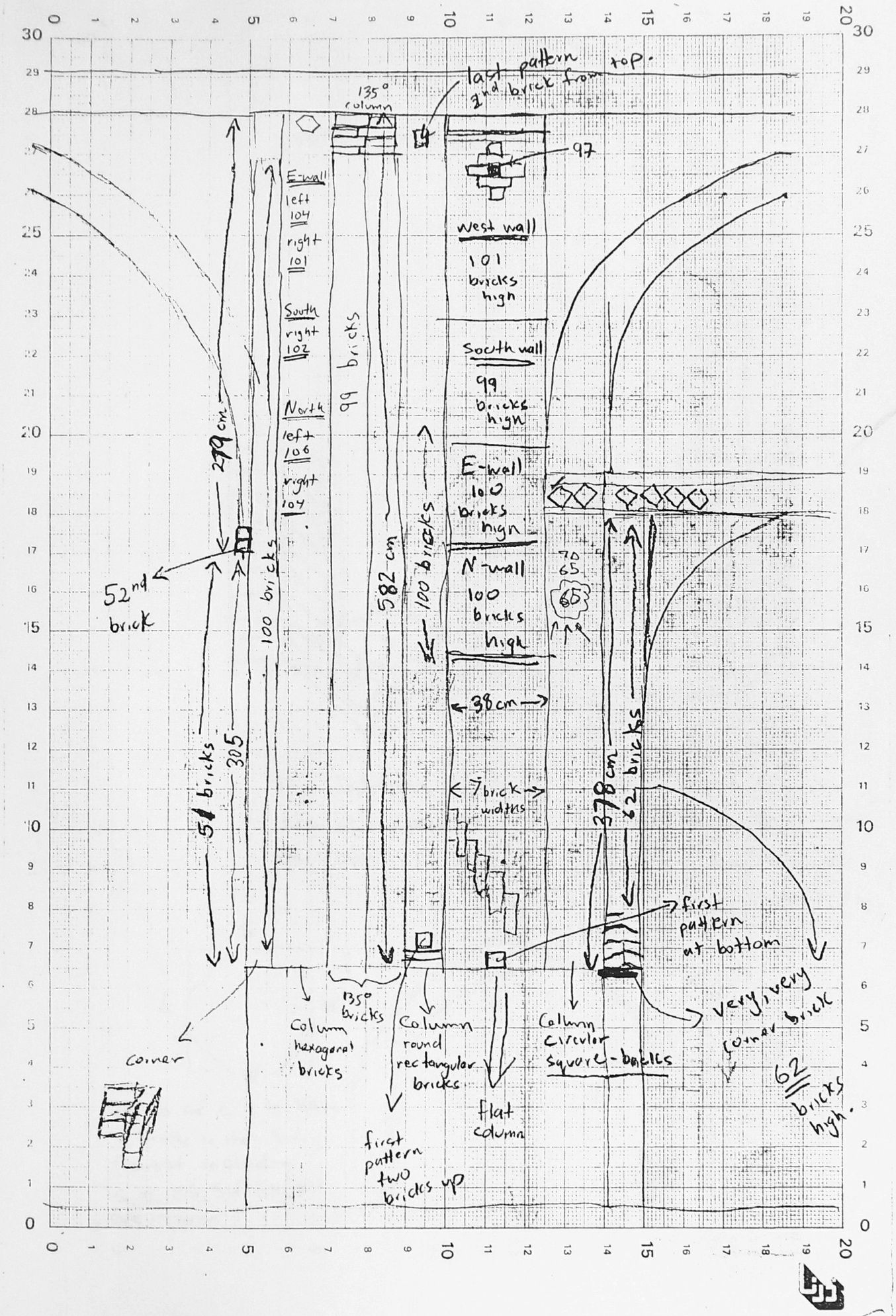

P_B
structural wooden peg
الف P_B & P_{B_1}
P_{B_1}
هو العلى
P_A
P_B
P_B
P_A
P_{B_1}
P_{B_1}
30 bricks to where they meet
Top of peg
62-63
36 to the peg
Wooden peg
Top of midline
62



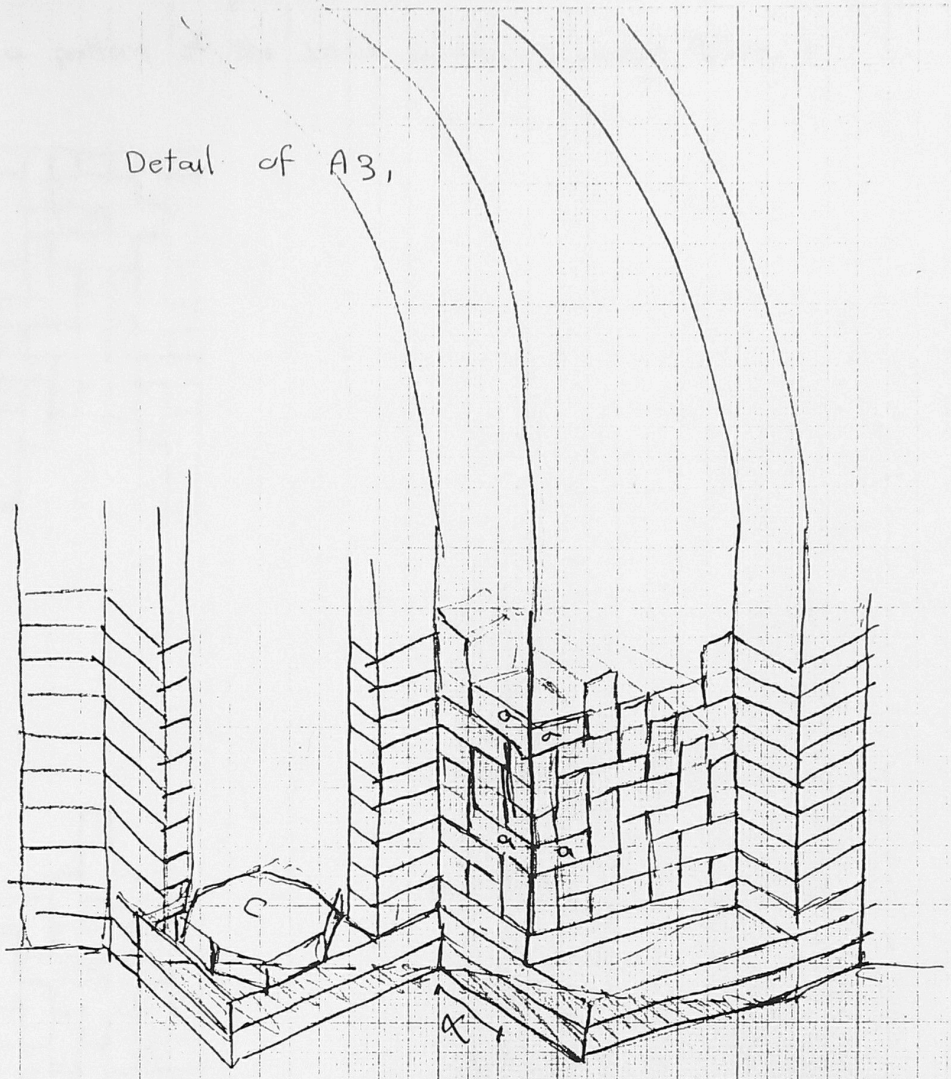
The Geometrical Pattern and brick Setting in 8/16 of the upper Arch on 2D surface, North, South, East, West, NS, NW, SE, SW

MG/ 12:45 pm
August 2, 1999

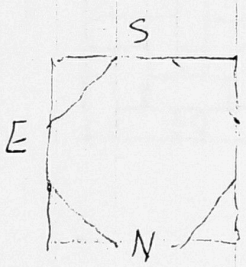

M2
Column A & B
15 bricks
20-21
13
starts to curve
structural
Column
A
3 structural 17 Bricks
Pattern
Smaller Bricks
16 Bricks
7 + 1 + 7 = 15

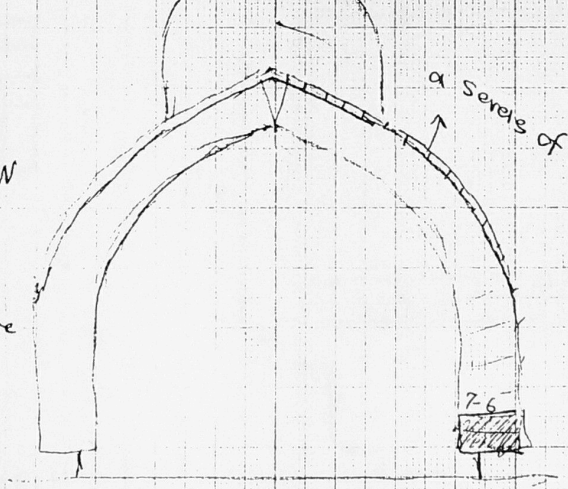

last pattern top.
2nd brick from
135° column
97
E-wall
left 104
right 101
South right 102
North left 106 right 104
99 bricks
West wall
101 bricks high
South wall
99 bricks high
E-wall
100 bricks high
N-wall
100 bricks high
279 cm
52nd brick
100 bricks
582 cm
100 bricks
70
65
65
38 cm
7 brick widths
51 bricks
305
278 cm
62 bricks
first pattern at bottom
very, very corner brick
62 bricks high.
135° bricks
Column hexagonal bricks
Column round rectangular bricks
Column circular square-bricks
flat column
first pattern two bricks up
corner

Detail of A3,



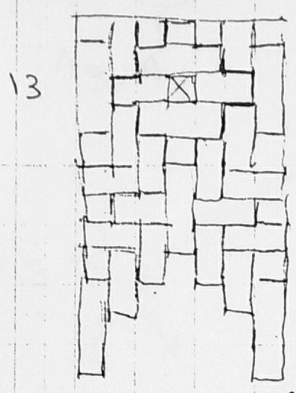
The Difference betwee A3 & A3, is in the α where in A3, there are 3 bricks in one row and in A3 are 4 (See Section A3, A4)

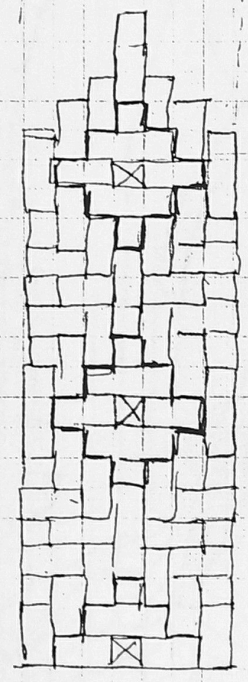


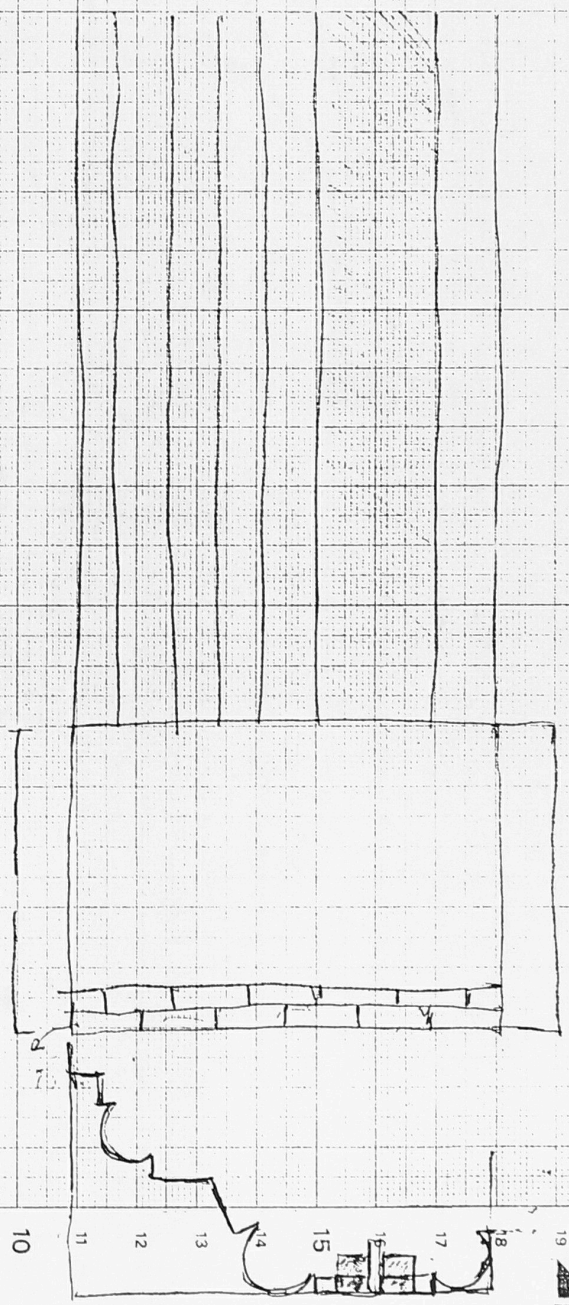


Arches on E & W have 6 bricks in their Sidrg the rest including S, N, ES, SW, EN, NW are seron

a pattern of the brick column (8 existing patterns)



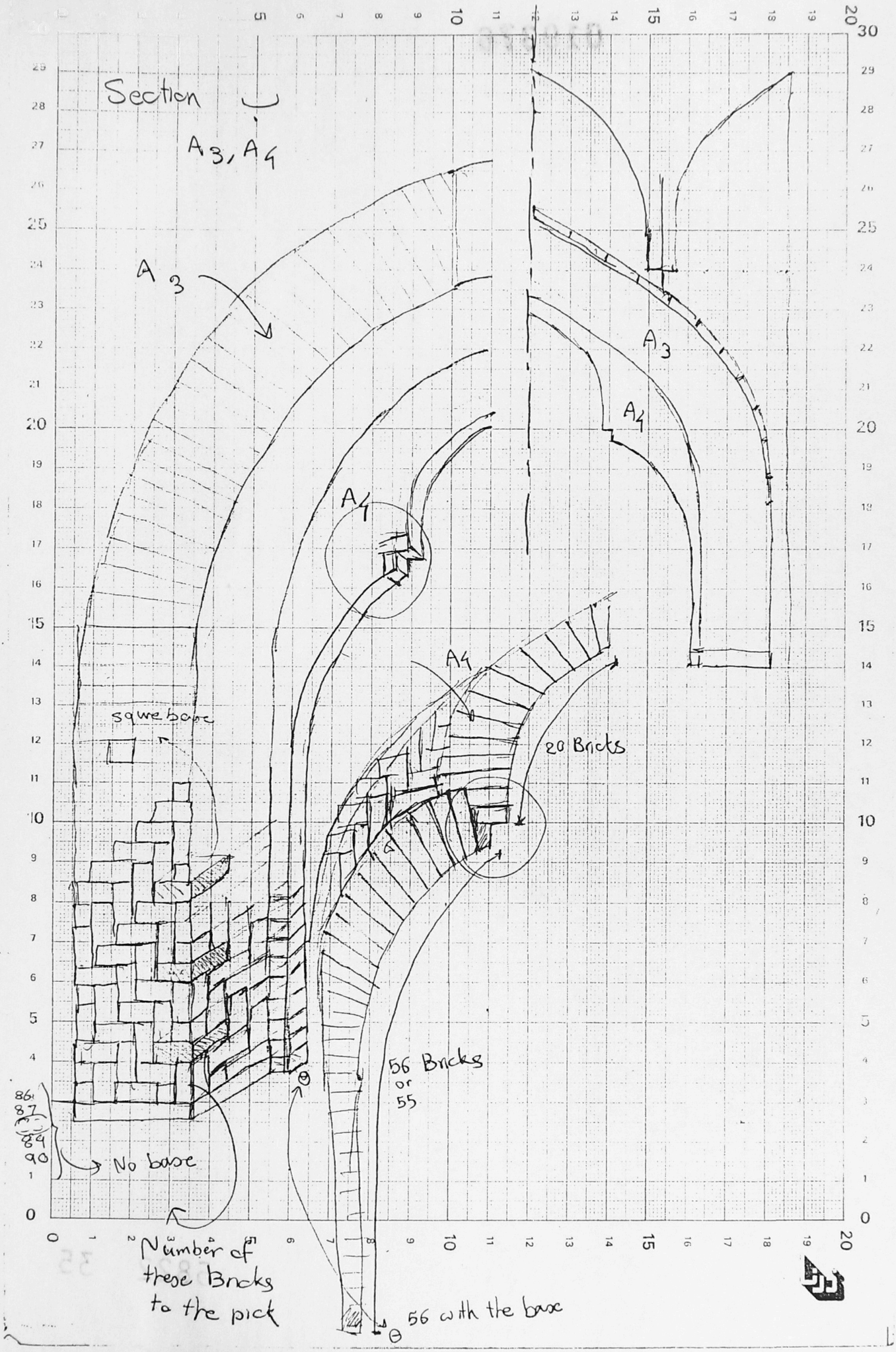




7(12) + 13 + 2

84
15
99

109 $\frac{11}{100}$


Section
A3, A4
A3
A4
A4
A4
A3
A4
squebase
20 Bricks
56 Bricks
or
55
86
87
88
89
90
No base
Number of
these Bricks
to the pick
56 with the base