

The structural development of masonry domes in India

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This paper researches the origins, structural development and construction of masonry domes in India. It investigates where the structural engineering knowledge of the original builders came from and how successfully that knowledge was applied. We will also look at the choices that had to be made with materials and methods of construction.

The period under review covers Islamic rule over northern and central India from the late 12th century to the mid 18th century. New types of buildings and structural forms came with the new rulers in particular, for this study, the domed tomb. How Hindu masons, experienced only in trabeate construction, responded to these new structural forms is a key part the synthesis of styles that created a wholly new and original architecture.

The choice here of a particular building has been made on the basis of it marking an important structural development in terms of form, scale or technical achievement. Many of the key buildings in the evolution and development of domes are in Delhi and I have concentrated on these along with the monuments in Agra and Bijapur.

Apart from the buildings themselves, the other sources of information are discussions with Indian architects and engineers and study of 16th century paintings. Where no information is available, such as to how the domes were constructed, assumptions have been made based on comparisons with the building of modern masonry structures in India,

which still generally relies on non-mechanised methods of building and documented practice in Europe during the period under study.

ISLAMIC PROTOTYPES

In Syria the classical Roman temples and mausolea became the model for builders who created churches or memorials to house the body or relics of Christian saints or biblical character, or to mark a particular event (Hillenbrand 1984, 254). These were generally small in scale and used a variety of plan-forms; square, cruciform, polygonal or circular. The small size meant that the structural stability of the dome could be achieved by copying existing buildings.

At the centre of Byzantine in Istanbul the understanding of structures continued to develop and led to buildings such as the Church of Hagia Sophia. Built between 532 and 537, this has a shallow brick dome, approximately 32 metres in diameter. Its builders understood the need to resist the outward thrusts from the dome and used iron cramps between the marble blocks that form the cornice to create a continuous tension ring at the springing point of the dome (Mainstone [1975] 1988, 123). One potential source of this understanding was the continuation of the tradition of building masonry domes that had existed under the Romans. The other reference was translations of the scientific writings of Euclid,

Ptolemy and others, and the Roman architect Vitruvius. These, along with Arabic works on geometry and algebra, were later translated into Latin in the 11th and 12th centuries to form part of the basis of knowledge of the Middle Age cathedral builders in Europe (Gimpel 1993, 100).

The symbolic importance of the dome in Islam was established in the building of the Dome of the Rock in Jerusalem. Completed in 691, the dome is about 20 metres in diameter, and consists of two hemispherical wooden frames supported on a circular colonnade of masonry piers and columns surrounded by two octagonal ambulatories (Eltinghausen and Graber 1987, 28).

With the spread of Islam by nomadic tribes in central and west Asia, these Christian prototypes became mixed with their own indigenous portable structures to produce new building types. The pre-Islamic burial practices of these tribes probably developed out of traditional customs where the deceased was covered with a tent (Mark 1995, 12). Once they had adopted Islam their burial practices were developed to produce masonry mausolea, in line with passages from The Koran, such as Sutha 18, The Cave. This tells of seven youths who are guided by Allah away from a city to a refuge in a cave. After their death the people argued among themselves, «and those that were to win said: "Let us build a place of worship over them."» (Dawood [1956] 1997, 205). The symbolism of the domed temples and churches of the Romans and Christians were obvious models for Islamic tombs and is alluded to in the description of heaven, in Sutha 21:25, spread «like a canopy». (Dawood 1997, 229)

The earliest surviving Islamic tomb is that of Qubbat-al Sulaibiya at Samarra, built circa 892. (Michell [1995] 1996, 250). This is octagonal on plan with a double-height central chamber that was originally covered with a dome raised on a drum. Another important tomb is the early 10th century Tomb of Isma'il the Samanid in Bukhara (Tadgell 1990, 154). It is square on plan with slightly tapering brick walls with a seven metre diameter dome supported across each of the corners by brick squinch arches buttressed by a radial half-arch.

A structural form that was to have a significant influence in India is the double-dome. The earliest known masonry double domes are a pair of 11th century tombs at Kharragan (Eltinghausen and

Graber 1987, 269). In Iran the double dome reached its apogee in the Mausoleum of Oljeitu at Sultaniya. Built between 1304 and 1315, the inner of the two interconnected brick domes has an internal diameter of 26 metres (Hillenbrand 1984, 199; Maidstone 1998, 124).

In Iran the emphasis on height led to tomb towers like that at Gunbad-i Qabus built in 1007 which reached over 51 metres above the ground and is capped with a conical roof, based in form on the tents used by the nomadic Seljuks then ruling from Iran to the eastern Mediterranean (Michell 1996, 253). In 14th and 15th century Samarkand the desire among the rulers and noblemen to build higher tombs for themselves led to domes on the top of elongated, cylindrical, masonry drums, with a dome at the base of the tower to maintain the internal proportions. The Gur-i Amir was built circa 1404 for Timur, a descendent of the Mongol chieftain Genghis Khan (Hillenbrand 1984, 214). This used a framework of timber built off the internal dome that served to help construct and provide permanent support to the outer, bulbous dome.

In structural terms the raising of the outer dome on an elongated drum increases the risk of movements in the drum. To resist these outward forces from

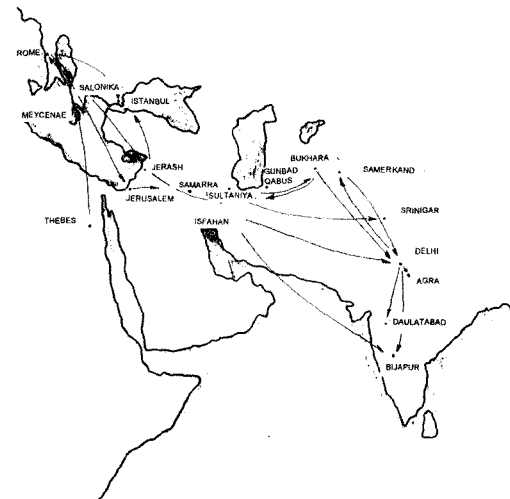


Figure 1
The principal routes for the movement of structural influences on domes in India

causing cracks required the introduction of a material capable of resisting tensile forces (Lewcock 1996, 143). There are references to the use of timber reinforcement rings at the base of the dome, or iron cramps set into stones so that a continuous ring, or reinforced stone chain is formed. For the Gur-i Amir, a cross section through the two domes shows radial tie bars built into the wall at the base of the outer dome (Cresswell 1914, 94). This is a sophisticated use of materials, but this system is not mentioned in any reference to double domes in India.

WHO WERE THE DESIGNERS?

From looking at the masonry domed buildings we can see that they were built with durable materials, we can deduce that the designers and builders knew how to use these materials and that they had an understanding of the importance of proportion and geometry to produce a structure that could support all the loads. There is, however, hardly any information on those involved.

The titles of people engaged in the design and construction have been given a number of different translations. One source says «darogha “imarat”» translates as chief architect, another, in relation to the title for Mir Abdul Karim at the Taj Mahal, calls him the Superintendent of Buildings (Qaisar 1988, 10; Begley 1989, 227).

Qaisar considers the roles of people involved in the construction of a building. From his description the architect/engineer [me'mar/muhandis] was involved in choosing the site and then prepared a tarah, or plan, of the proposed building for the client. More than one design could be presented and for part of Lahore Fort a tarah prepared by the me'mar was chosen by Shah Jahan and «was handed over to muhandis to carry out the work accordingly» (Qaisar 1988, 37).

The documentation on the building of the Taj Mahal offers a rare, but limited, glimpse of those involved in its building. Ustad Ahmad is described by his son as having «followed the profession of Science» and was «Chief Architect [me'mar-i-kull] in this court», i.e. of the emperor Shah Jahan (Begley 1989, 267 & 290). As well as being an architect, Ahmad was recognised as an outstanding astronomer, engineer and mathematician. Mukarramat Khan «Minister of Royal Works» to Shah Jahan is

described as an administrator, not an architect, (Begley 1989, 282) but it is likely that his understanding of mathematics and practical matters would have led him to be involved in aspects of the design and construction. Mir Abdul Karim had been chief architect for Shah Jahan's father, Jahangir. Within a few months of Mumtaz Mahal's death he was transferred from Lahore to Agra to become Superintendent of Buildings. This suggests a specific role, equivalent to a modern-day project manager, appointed by the client to oversee the works which Tavernier said involved twenty thousand men over 22 years (Begley 1989, 227).

BUILDING MATERIALS

The main materials used in the construction of the structure of the domes were stone, brick and mortar, with ironwork for dowels and cramps. Timber and bamboo was used for the scaffold and centring that provided the temporary support to the dome during the construction.

Stone

Stone was widely used as a building material in pre-Islamic Indian buildings. The first Islamic buildings at the Qutb site in Delhi were constructed by captured masons using stones from the remains of the twenty-seven demolished Hindu and Jain temples. New stonework was used for the extension to the mosque, shaped into rectangular blocks and laid horizontally with the corbelled edges cut back to form the arch-shaped openings.

A masonry building could be constructed more quickly and cheaply if undressed stonework was used on one or both faces. The walls, arches and half-domes that remain at the late 13th century tomb of Balban use coarsely cut stones that would have needed an applied finish. Two centuries later the prolific building of tombs during the Lodi dynasty would have put great demands on the availability of skilled masons and of good quality stone. Instead, many of the tombs from the mid-15th century to the early 16th century are built from roughly dressed stonework with a rendered internal and external finish.

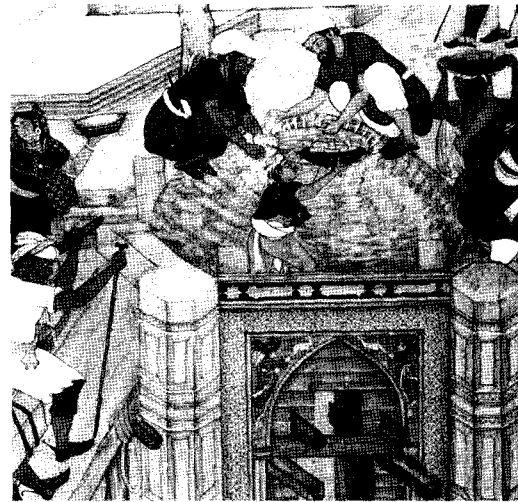
Dressed stonework was used externally and internally for most of the important buildings, such as the surviving walls of Iltutmish's tomb, built circa 1235. Here the stone outer and inner faces of the walls were bonded together with a core of roughly cut stones or broken bricks (Brown 1997, 17). This allowed the use cheaper materials and labour for the unseen parts of the structure.

Where the stonework forms the exposed faces of a dome, it needs to be carefully cut in all three dimensions to form the voussoir blocks. This requires an understanding of three-dimensional geometry by the masons, with the sides and exposed face(s) cut to the correct profile for the size of the dome. The first use of a dressed stone dome in India is for the Alai Darwaza in 1311. It is likely that the masons who had this knowledge came from the break up of the Seljuk empire to the west caused by the «total war» raged by Genghis Khan and his decedents in the 13th century (Hillenbrand 1999, 96).

Brick

The use of brickwork is mentioned during the 14th century building works at Hauz Khas and was widely used for smaller arches and domes from the 16th century (Rani 1991, 89). Examples can be seen at the tomb of Humayun or the 18th century tomb of Safdar Jang. The bricks are all rectangular in shape with tapered mortar joints used to form the required curvature.

Three types of bricks are mentioned in the 16th century; baked, half-baked and unbaked (Qaisar 1988, 16). The lesser quality bricks may have been used for the temporary centering seen in the Akbarnama. Nath refers to a standard Mughal brick size of $8'' \times 7 \frac{1}{2}'' \times 1 \frac{3}{4}''$, but that the Taj Mahal was built using a thinner size, $7'' \times 4 \frac{1}{2}'' \times 1''$ «... to allow the mortar to occupy a greater part of the volume» (Nath 1972, 79). It is not clear what is the basis of this comment since, structurally, the greater use of mortar increases the risk of cracks developing as the mortar dries and shrinks. Nath also mentions that the bricks for the foundations, which extend well below the level of the adjacent River Yamuna, were dipped into liquid fat to «make them waterproof» (Nath 1972, 79).



Picture 1
Building Agra Fort

Mortar

Hindu architecture of the pre-Islamic period appears to have used mortar as little as possible (Qaisar 1988, 18) and the stonework in the first building at Qutb is also dry bedded. By the early 13th century the buildings made use of rekhta, meaning either mortar or plaster, in the construction (Qaisar 1988, 19). Mortars made use of lime mixed with a range of additives to improve its workability, durability and setting properties. These included jaggery, a fermented nut whose use has been revived in recent years for conservation work, and surkhi —or crushed brick— as an artificial pozzolana.

Iron

The structural use of iron in masonry was fundamental in restraining the high outward forces generated in the larger domes. The use of iron cramps between stones was already known in pre-Muslim India, and cramps between adjacent stones were used to create what we today call hoop reinforcement in order to restrain the base of domes (Qaisar 1988, 22). Iron dowels were used to connect vertical elements

such as the individual stones within columns, and cramps employed to secure the facing stones back to the core of the wall, such as at Humayun's Tomb and the Taj Mahal.

Timber and Bamboo

This was used to form access ramps from ground level to the level of construction, and to provide temporary support to the centering. There is no evidence of timber being used as part of the permanent structure.

METHODS OF CONSTRUCTION

One of the best sources of information about how arches and domes were built is the Akbarnama, or Life of Akbar, a series of paintings from the late 16th century that chronicle the life of the third Mughal emperor.¹ None of the buildings in the Akbarnama, or other contemporary paintings, have been specifically identified but they do show the organisation of the site, the works of different trades and their methods of working.

There is little evidence of off-site working or pre-fabrication. Large sections of stone were brought to site where they were split to the required size using driven iron wedges. The larger stones were then secured with ropes and manhandled using temporary timber ramps to where the masons were working. This method is clearly limited by what it is physically possible to carry. In one illustration four men are carrying a block of stone about 1500 mm long \times 300 mm square in section, a load of about 100 kgs per man.

Some illustrations tell us about actual methods of construction. An arch to a gateway is shown with two piers of bricks and a timber lintel to support the centering used to construct the structural arch. The lintel allows access through the gate while it is being built. Above the gate a small brick dome is being constructed with the bricks laid in concentric rings to eliminate the need for centering. Examples of this type of construction can be seen at Humayun's Tomb and Safdar Jang's Tomb.

For larger domes, where the thickness of the structure is greater a different approach is required.

The dome of the Gol Gumbad in Bijapur is one of the largest masonry domes in the world with an internal diameter of 41.15 m that is 2.6 metres wide at the base. The dome is built off eight intersecting arches that span across the corners of the square to support the dome and rise to 37m above the crypt floor level (Reuban 1947, 39–47).

There are no large forests around Bijapur, so the large quantity of timber required for the centering to support the arches during the construction would have been difficult and expensive to procure. An alternative is to use brick centering as the temporary support to the arches. Once the permanent arches and pendentives were in place the vertical base of the dome could be formed. This helped to tie the top of the arches together and provided the dead load to the top of the walls to reduce the outward thrusts from the arches so that the brick centering could be removed. It is possible that this removed material was used in the construction of the upper part of the dome that could have been built off temporary formwork supported on the balcony around the base of the dome.

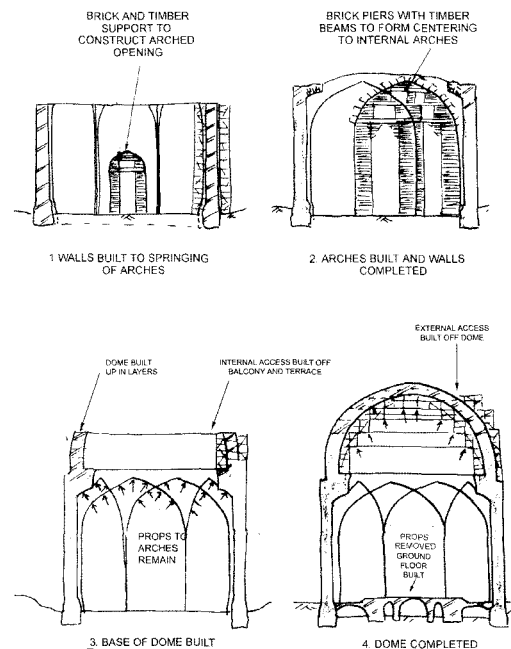


Figure 2
The Assumed Sequence of Construction of the Gol Gumbad

At the Taj Mahal Tavernier reported that «It is said that the scaffolding . . . for the want of wood . . . had to be made of brick» (Begley 1989, 298). Given the scale and geometry of the building it is very unlikely that brickwork alone would have been used for temporary support during the construction. Scaffolding was used for a variety of purposes and timber or bamboo scaffolding would have been used externally to provide access to place the marble cladding. It could also have provided the temporary support to the structure during construction and it may be that a combination of brick piers and wooden scaffolding was used. Once the inner dome was formed it could be used to support the wooden framework needed to create the outer dome.

MASONRY DOMES IN INDIA

The first key buildings date from the end of the 12th century with the capture of Delhi in 1192 by the forces of the Afghan Turk, Muhammad of Ghor (Sharma 1990, 52). The leader of the invading army, Qutb-ud-Din Aybak, was placed in charge of the conquered areas and established Delhi as his capital. In the same year a mosque was built, later to be called the Quwwat-al-Islam or Might of Islam which, as we have seen, used stonework from destroyed Hindu and Jain temples; re-laid by indigenous masons following their traditional technique of beam and post construction.

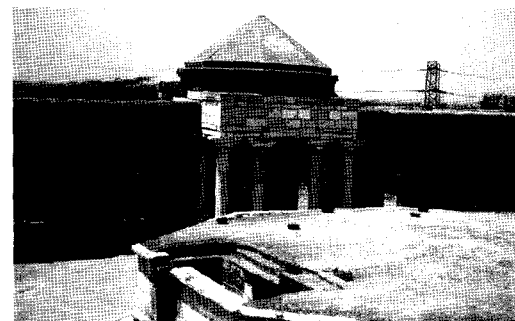
About eight kilometres from the mosque is Sultan Ghari's tomb. This is the first major Islamic tomb in India, built by Iltutmish for his son and heir Nasir-ud-Din who died in 1229 (Sharma 68). This is set within a walled enclosure with the tomb chamber in the centre of the compound below an octagonal plinth. The original roof to the chamber has been replaced by a flat surface, but it may have been similar in form to the trabeate construction of the square pyramidal roofs on the outer walls.

The first use of true arches is the tomb of Sultan Balban, who died in 1287, and two smaller adjacent tombs, about 500 m southeast of the mosque (Rani 1999, 6). The main tomb is about 11.5 m square with its walls constructed in roughly coursed stone bound in a mortar. The arches are either made in the same roughly cut blocks or with dressed stonework. On the west wall of the main building, in the direction of



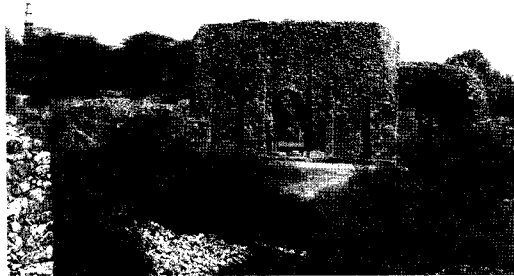
Picture 2
Remains of the Quwwat-al-Islam Mosque, Delhi

Mecca, is the remains of a half-domed prayer niche. The roof of the tomb to the south, known as that of Khan Shahid is similar in outline to the roofs on the tomb of Sultan Ghari but its structure relies on



Picture 3
Courtyard of Sultan Ghari's Tomb, Delhi

arching action to create a small dome with the external finish built up in render. These structures stand apart from the general developments in arcuate construction. Similarities in the three buildings suggest that the same masons were employed, and perhaps after their patron died they moved elsewhere. As the tombs lie outside of the mosque complex and the structures, when completed, were covered with a rendered finish the use of arcuate construction was not adopted by other masons.

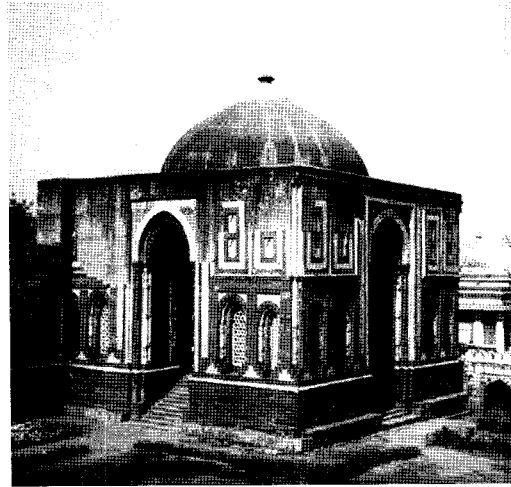


Picture 4
Remains of Balban's Tomb, Delhi

The Alai Darwaza, completed in 1311 as the south gate to the Quwwat-al-Islam mosque is the first building to use and express true arches and the central dome. The arches are formed from stone voussoirs and similar arches are used internally to form the transition from a square to an octagonal plan. The final transition to a 16-sided polygon at the base of the dome is by small, corbelled brackets.

The dome for the tomb that Ghiyas-ud-Din Tughluq built for himself before his death in 1325 rises clear above the massive sloping walls. Internally the dome has alternate rings of shallow and deep stones, with the shallow layers bonded into the core of the dome to produce a more robust structure. Within the same compound is the tomb of Zafar Khan, built by his father Ghiyas-ud-Din, notable for its octagonal shaped chamber and ambulatory.

Ghiyas-ud-Din was succeeded by his son Muhammad Tughluq who in 1328–29 moved his capital to Daulatabad, 960 kms to the south of Delhi,



Picture 5
Alai Dawaza, Delhi

to consolidate his authority in the Deccan, only to return soon after (Brown [1956] 1997, 22). A consequence of this move was the dispersal from the Delhi region of the skilled masons and artisans. This loss had an impact on the construction of buildings under the next ruler, Firoz Shah Tughluq. In place of carefully cut stones that formed both the structure and finishes, the buildings from the late 14th century used roughly shaped stones for the arches and the domes, which were then covered with render. This can be seen at the Khirki Masjid, built circa 1375 and the tomb of Firoz Shah, who died in 1388.

The reduction in masonry skills would have been accompanied by a loss in the understanding of how to structure the buildings. In its place the builders would have simply copied what had been built before. As structures they have survived due to the massiveness of the walls that support the vertical and horizontal loads from the dome. One building of this period that is stylistically important is the tomb of Khan-i-Jahan Tilangani, the prime minister of Firoz Shah. Built circa 1368, this, despite the tomb of Zafar Khan mentioned above, is generally referred to as the first octagonal tomb in Delhi with the domed central chamber surrounded by an ambulatory verandah with three arched openings on each facet (Rani 1991, 51; Tadgell [1990] 1995, 170).



Picture 6
Khirki Masjid, Delhi

The building skills that were re-learned during the second half of the 14th century were lost again following the invasion of Delhi in 1398 by the army of Timur (Rani 1991, 116). A grandson of Genghis Khan, he sacked Delhi and took artists and craftsmen back to build in his capital, Samarkand (Brown [1956] 1997, 25). The Tughluq dynasty ended soon after and this was followed in 1414 by the Sayyids, and from 1451 to 1526 by the Lodis. There are no significant differences, or major structural developments in the buildings of these two dynasties. Instead, there was a great proliferation of tomb building that reflected the Lodi's Afghan origins where a brotherhood of nobles was commonplace and the king was first among equals rather than the absolute ruler. There was however a hierarchy in

terms of plan-form, with octagons for royal tombs, and square for nobles and others of high rank.²

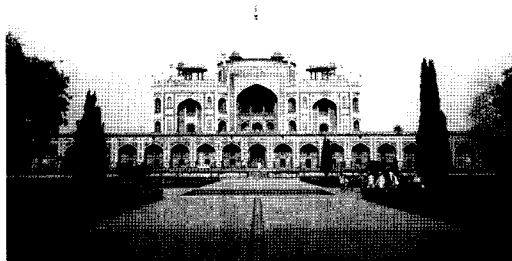
One structural question from this period concerns the introduction of the double dome. The tomb of Sikander Lodi, built 1517–18, is referred to as the first double-dome in India, but the section through the building from Tadgell shows only a single dome (Brown 27; Tadgell 162). The interior of the tomb is dimly lit (some doors have been infilled with brick) but the dome does spring from a level where externally the sides of the dome are vertical. There is also what appears to be a partly blocked opening on this vertical face that is not apparent internally. Presumably this opening provides access to the small void between the two domes.

Whether Sikander Lodi's tomb was the first double dome in India is less certain. The tomb built by Zainul-Abidin c.1465 for his mother at Zaina Kadal in Srinigar in Kashmir is a brick structure with double domes over the central and perimeter chambers (Agrawal 1988, 168). In Delhi, Sabz Burj has a shallow inner dome and an outer dome raised on an extended drum in the style of the early 15th century tombs at Samarkand. Written sources place this in the early Mughal period of 1530–40 (Koch 1991, 36), but it may be over one century earlier.³

The Lodi period ended following defeat by Babur, the first Mughal emperor. Babur was descended through his father from Timur and through his mother from Genghis Khan (Koch 1991, 10). He died in 1531 and was buried in a simple grave in Kabul. His son, Humayun, ruled between 1531–40 and 1545–56 and his tomb is the first major Mughal building. It was built between 1562 and 1571 early in the reign of his son, Akbar, to a design by Mirak Mirza Ghiyas, an architect from Persia (Brown [1956] 1997, 90). This has a double dome above an octagonal central chamber that is about 15m from side to side. At roof level the small domed kiosks, or «chattri», are constructed in brick and clad externally in stone and rendered on the underside.

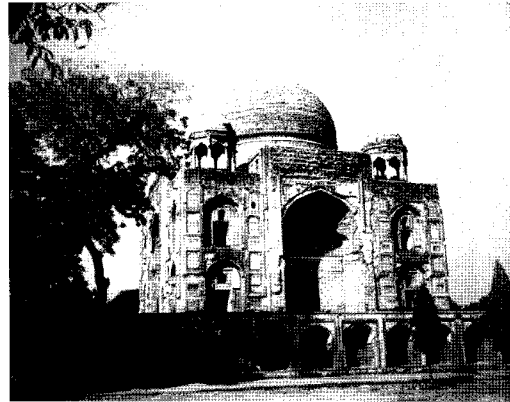
It is likely that the main structure of the tomb was also built from brickwork that was then clad with sandstone and marble. The outer surface of the dome has alternate layers of wide and narrow blocks of marble to help bond the cladding to the structural core. The use of iron cramps to tie the facing stone to the core of the wall can be deduced from the characteristic corrosion-related damage at the corner

of a number of stones above the entrance portal. There must also be a system of ties around the base of the outer dome to resist the outward forces acting on the top of the drum. It may be that the stones in the horizontal band of marble at the top of the drum are connected by iron cramps to form a continuous tension ring.

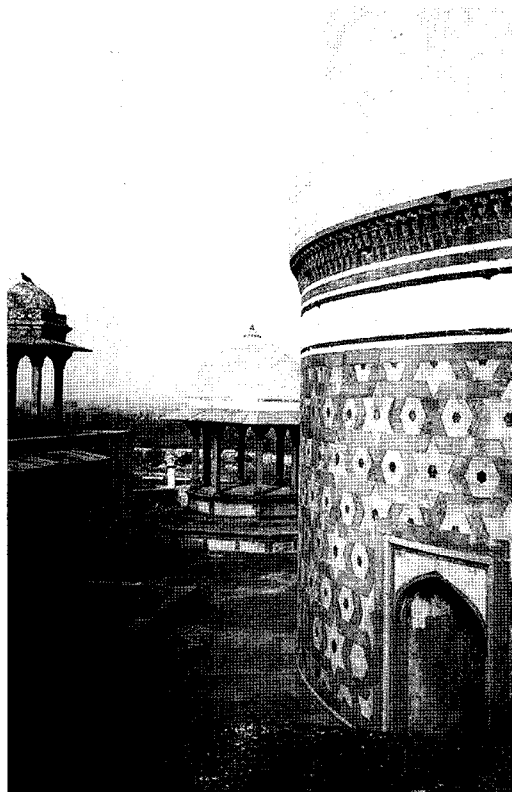


Picture 7
Humayun's Tomb, Delhi

In the same part of Delhi is the tomb of Khan-i-Khanan who died in 1627, the same year as the following emperor, Jahangir. The stripping of large amounts of the sandstone and marble in the 18th century to clad Safdar Jang's tomb has revealed a brick structure with a brick double-dome.

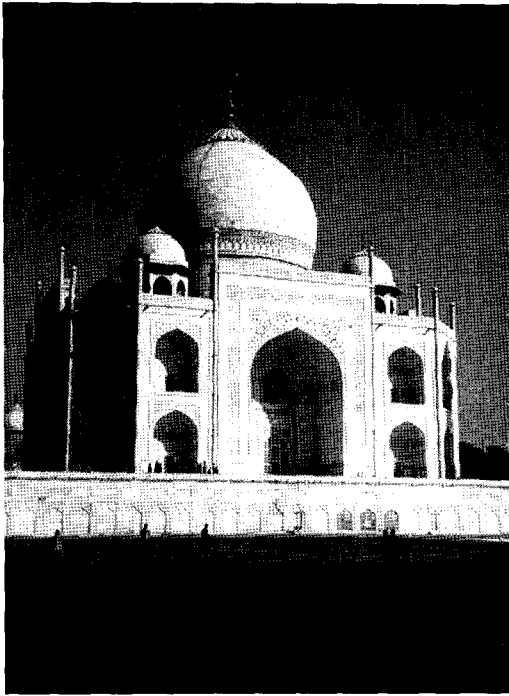


Picture 8
Tomb of Khan-i-Khanan, Delhi



The Taj Mahal at Agra is also a brick structure clad mainly in marble, with sandstone to the half-hidden areas at roof level. Work began in 1632, the year after the death of Mumtaz Mahal, a wife of the emperor Shah Jahan. Much of the tomb was complete four years later and by 1643 the entire complex of buildings and gardens was virtually finished (Asher 1992, 212). It is founded on a series of brick wells that were filled with rubble bound in a lime mortar. The areas between the wells were then dug out and filled with stone and mortar (Nath 1972, 79). These footings pass through approximately 19m of soft alluvial deposits to bear onto a seven metre thick layer of sandstone overlaying clay. The internal dome is 22 metres in diameter and three metres thick. Above this the five metre thick walls to the drum support the outer dome that encloses a void over 30 m high. A summary of how the Taj Mahal works as a structure is shown below.

In Bijapur, the tomb Muhammad Adil Shah built for himself before he died in 1656 is now referred to as the Gol Gumbad, or Round Dome. This has one of



Picture 9
Taj Mahal, Agra

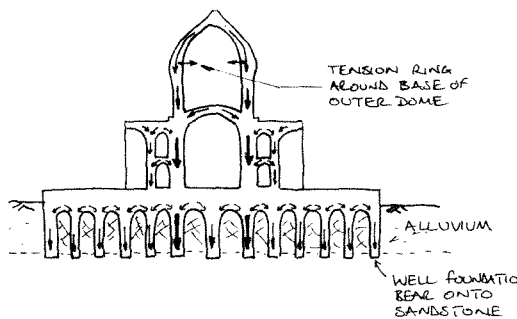
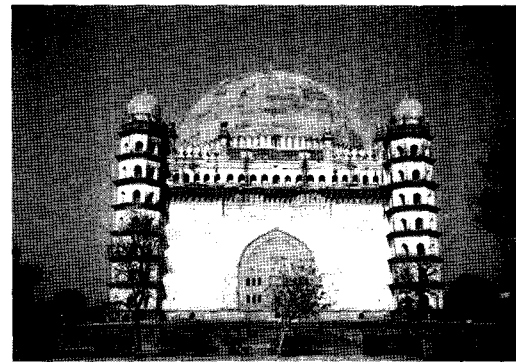


Figure 3
Structural Summary of the Taj Mahal

the largest masonry domes in the world with an internal diameter of 41.15 metres that rises to 54.25 metres above the floor. The base of the dome is approximately 2.6 metres thick.

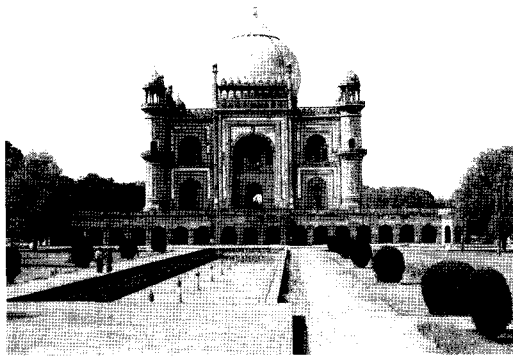


Picture 10
Gol Gumbad, Bijapur

The dome is rendered on both faces. Reuben says he saw it was constructed in brickwork «laid flat in lime mortar . . . joints (that vary) from 25–50 mm thick . . . The bricks are of varying size and do not appear to be very systematically laid» (Reuban 1947, 46). Brown talks of the dome being «constructed in horizontal courses of brick with a substantial layer of mortar between each course, in other words it is a homogeneous shell or monobloc (sic) of concrete reinforced with bricks . . . » (Brown [1956] 1997, 77). It is unlikely that the bricks are laid horizontally throughout the dome, since this would produce a structure that acts more as a series of corbels. Presumably, what both Brown and Reuben saw was towards the base of the dome and that higher up the brick courses are inclined to the inside face so that the layers acted as self-stable compression rings during the construction.

Safdar Jang's tomb in Delhi built 1753–54 was the last major Islamic tomb to be built in India. It is a brick structure that is clad externally in sandstone and marble, and rendered internally. The shallow domes to the chambers around the perimeter of the plinth follow the traditional form of concentric brick rings. The central dome is described as a triple dome, with two «flattish» inner brick domes and an outer bulbous marble dome (Beglar 1874, 76), but no drawings have been found to verify this. It is unlikely that the marble acts alone as a thin shell since its geometry suggests it would collapse under its own self-weight. Instead it seems more likely that the marble is attached to the outer of two brick domes, and there may be a small

domed void between the outer brick dome and the marble lotus leaf finial.



Picture 11
Safdar Jang's Tomb, Delhi

Some Common Structural Problems

The proliferation of dome building from the mid-15th century would have required an increase in the number of masons to build the structures. Inevitably some of these domes were built by masons who copied the form of existing buildings without understanding the structural principles. A common problem with the Lodi-era tombs is an outward spreading of the octagonal verandah at eaves level, caused by the horizontal forces in the arches and vaults that form the verandah roof. These movements can be seen in a circumferential crack at the mid-point of the ceiling and rotation of the outer piers of a number of tombs. This movement probably occurred early in the life of the building as the structure adjusted to reach a state of equilibrium.

There are generally few signs of structural problems resulting from the horizontal forces in the central dome. The early square domes the walls are sufficiently massive to resist these loads and in octagonal tombs the verandah will act as a partial buttress to the central dome. For larger structures, like Humayun's Tomb, the walls of the surrounding chambers resist the forces from the inner dome. The lack of significant vertical cracks at the top of the drum, or radial cracks in the lower part of the dome

suggests that where a dome was raised onto a drum, the need to resist the horizontal forces generated was understood.

Masonry, like all materials will expand and contract with changes in its temperature. A structure composed of small elements of stone or brick in a lime mortar will move as a result of thermal changes, but generally the cracks that result will be spread evenly over the whole of the structure and consequently small in size. A large monolithic structure will tend to produce larger cracks that concentrate along lines of weakness. This seems to have been the cause of the radial cracks to the dome of the Gol Gumbad. It was repaired in 1936–37 by spraying concrete to reinforcement fixed to the outside face to help tie the cracked segments of the dome together (Dikshit 1940, 16).

CONCLUSIONS

The domes of India are a unique synthesis of Islamic and Hindu influences. Their historical, architectural and structural importance is recognised by having the Taj Mahal, Humayun's Tomb and the Qutb Minar complex on the list of World Heritage sites. As important from a construction viewpoint is the Gol Gumbad in Bijapur that in scale ranks alongside the Pantheon and St Peter's Cathedral in Rome, and Santa Maria del Fiore in Florence.

The early buildings were built by Hindu masons using their traditional trabeate methods of construction. The knowledge of how to build true arches and domes, and effect the transition from a square or octagonal chamber to the base of the dome, came with links central Asia. Other design influences such as the plan-form, double domes and the placing of tombs within larger landscapes also came from these areas and Persia.

A number of the less well-known buildings and structures are in a poor condition, either because of neglect or ill-conceived repairs. Often these repairs are carried out with good intentions but without understanding how the structure was originally intended to work, how it may now be working and what, if any, repairs are needed. At present the building conservation movement in India is almost wholly composed of architects. If these domes and other examples of India's built cultural heritage are to

be handed on to future generations it is important that suitably experienced engineers also take an active role in their conservation.

NOTES

1. The Akbarnama in the Victoria and Albert Museum's collection has recently been described in «Painting for the Mughal Emperor: The Art of the Book 1500–1600» by Susan Stronge, V&A Publications, 2000.
2. From «Visions in Marble», lecture by Catherine Asher at the V&A Museum, London, 1997.
3. From a discussion with Dr Agrawal, Director (Museums and Projects) Archaeological Survey of India at New Delhi in April 2000 who gives a date of circa 1426.

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