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NEW INSIGHTS ON ARTISANS OF TĀJ

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New insights on the artisans who were involved in the actual construction of the world architectural wonder, the Tāj Mahal, has been obtained based on analysis of dimensions of significant geometric patterns on the floor at different locations in the complex. The artisans were well versed in the traditional building concepts of the subcontinent as confirmed by use of traditional measurement units of the subcontinent to measure out the designs. The wonderfully engineered construction of Tāj was possible due to the technical abilities and skill of native Indian artisans, as confirmed by their adherence to the traditional measurement units of the subcontinent.

Key words: *Aṅgulam, Arthaśāstra,* Artisans, Engineering materials, Tāj Mahal, Techniques, *Vitasti*

INTRODUCTION

The Tāj Mahal is an architectural world wonder, which required stupendous engineering skills to construct. There are several publications detailing with various aspects of the Tāj. The recent book by Koch[1] is very comprehensive and provides a balanced view of the present state of understanding.

The engineering of the Tāj can be conveniently viewed under materials and methods categories. By methods is meant the techniques employed by the architects to design the complex, and the artisans and workmen to construct the monuments. It has been shown recently that the team of architects who designed the Tāj complex were well versed in the civil engineering tradition of the subcontinent[2]. This was verified by analyzing the modular plan of Tāj in terms of measures listed in Kauṭilya's *Arthaśāstra,* with the *aṅgulam* considered constant at 1.763 cm[3-6]. Specifically, the modular plan was understood in terms of *vitasti*

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(= 12 *aṅgulam*). The terrace and the garden sections of the complex were designed on a grid pattern of 90 *vitasti* to the side, while the forecourt and *caravanserai* sections were planned on a grid pattern of 60 *vitasti* to the side[5,6]. These studies also confirmed that the architecture of the Tāj Mahal was essentially based on the traditional Indian concepts of civil engineering, specifically the avoidance of construction at significant intersection points in the modular plan[5].

It will be also useful to obtain confirmation of the Indian effort in the construction of the Tāj. In this communication, attention will be focused on the artisans who laboured to create the world wonder. New insights will be obtained by analyzing the measurement units used in creating some of the intricate design patterns on the floor, seen at different locations in the Tāj complex. However, before delving on the artisans, the engineering materials and techniques used in construction of the Tāj will be briefly highlighted. This is important because, as Lall[7] rightly notes, "the construction of the Tāj is clearly an engineering achievement of stupendous magnitude, even in the context of present-day knowledge."

Engineering Materials

The engineering materials used in the construction of Tāj Mahal are bricks, stone, clay, mortar, plaster, wood, metals and precious stones. Abul Fazl has given a detailed account of construction materials (*masalih imārat*) in the *Ā'īn-i-Akbarī*[8]. The bulk of the structures was constructed using bricks and mortar. Sandstone, slate and marble are the three kinds of stones used for a variety of purposes. Mortar was used for bonding purposes. Polished plaster was used for surface finishing purposes. Wood was extensively used in the foundation while a large number of iron clamps were used to join the stones in place. Semi precious stones served as materials for the intricate inlay work, noticed prominently in the Tāj Mahal mausoleum.

Bricks

A large amount of bricks was used in the construction. They were used for forming the bulk of the buildings as well as for scaffolding purposes. In the Mughal period, bricks were called *ajur* or *khisht.* The traditional Indian bricks were of standard sizes, depending on the time period of history. During the time of Shāhjahān, the standard bricks measured 18-19 cm in length, 11-12.5 cm in breadth and 2-3 cm in thickness[1]. Interestingly, this kind of bricks was traditionally

called *lakhauri* brick, probably interpreted to derive from the traditional Indian term for the number 100,000 or *lakh*[1]. Koch[1] believes that the large number of depressions, which are found in the near vicinity of the Tāj complex, indicate that the bricks were locally made. Alternatively, it may have been transported from nearby.

Three kinds of bricks were used in this period: *pukhta* (the baked), *nim pukhta* (half baked) and *kham* (unbaked)[8]. The baked brick exhibited superior properties and were more expensive. It is certain that baked bricks must have been used in the Tāj.

Stones

The significant stones (*saṅg*) used were sandstone and marble. Different kinds of sandstones were known by different names. Red sandstone was called *saṅg sūrkh*, black slate as *saṅg siyāh*, yellow sandstone as *saṅg zard*, while white marble was known as *saṅg marmar*. Several possibilities opened up in the manner these stones were placed in the structure. Colour contrast in engineering structures was skillfully exploited in the hierarchical colour schemes in several Islamic buildings of the Indian subcontinent. The colour contrast was primarily emphasized and achieved by the use of different types of stone. This kind of idea is also noted in the Alai Darwāzā in the Qutub complex at New Delhi[9] and Humāyūn's tomb in New Delhi[10]. The idea of assigning color of stones based on architectural hierarchy is an ancient Indian idea[11].

The skillful use of (red) sandstone and (white) marble reached its peak in the construction of the Tāj complex. The hierarchy of each building in the complex is indicated by the amount of marble used. For example, the Tāj Mahal mausoleum is the only building in the entire complex that is faced with white marble. The other architectural structures in the complex are faced with red sandstone, with some special designs or special features (like domes) in these subsidiary structures highlighted by marble.

The colour of sandstone used in the Tāj Mahal complex is soft reddish to yellowish. The sandstone came from quarries nearby, in the region of Fatehpur Sikri[1], Rupbas[1] and Tantpur[10]. The sandstone was worked with great skill by the Indian stone cutters. Such was the fame of the Indian artists in stone that Ākbar's historian Abu'l Fazl acknowledged by stating that that "clever workmen chisel it more skillfully than any turner could do with wood"[12].

The majority of white marble came from the famous quarries of Makrana, near Jodhpur, in Rajasthan, which is located more than 400 km away by road from Agra. Historical records confirm that the marble was purchased from the Rajputs, under whose territory Makrana fell[1]. The choice of Makrana marble was due to its aesthetic appeal and engineering properties. The streaks of grey and black in Makrana marble lend a pleasing appeal to its colour[13]. Notably, it possesses several useful engineering properties. It is hard but still easy to work with. It is capable of taking a fine polish. More important, it is translucent in nature which results in interesting colouring effects due to changes in the atmospheric conditions. Dube has related some of these effects to the grain structure of Makrana marble[14]. Other sources of white marble are Dedikar in Alwar, Phinsalana and Mandla in Jaipur, and Kharwa in Ajmer[10]. Jaisalmer marble was known for its yellow texture while an exquisite green variety was found in the Saurashtra region. Black marble came from Jaipur.

Even today hundreds of quarries in the Makrana region supply an enormous amount of marble to the rest of the country. Koch, noting the modern method at Makrana[1], comments that "canyon-like trenches, some as deep as 60-65 meters, are cut down from the surface into the bed of marble; blocks are cut manually with hammers, chisels and wedges, and by drilling with steel rods, and then hauled up by cranes." It would have been challenging to accomplish all these tasks manually as it was done in the past. However, it is reasonable to conclude that the Indian mining and mechanical engineers, from times ancient, successfully solved problems related to handling and moving large blocks of material (by using mechanical systems like pulleys to lift large objects). A good example is the technology used in the fabrication of the massive Aśokān pillars and in transporting them across large distances[15]. Interestingly, a detailed drawing in the manuscript copy of *Sirat-i-Firozshāhi* dating to approximately 1593 AD of a text composed in 1370 AD clearly shows the mechanical device used to manipulate a massive Aśokān pillar to load it on to a boat. The pillar was transported by river from Topra to Delhi during the time of Fīroz Shāh Tuglaq (1351-1388 AD).

The massive sandstone and marble blocks were transported to the construction site on carts drawn by bullocks or buffaloes. The comments of the Spanish Augustinian monk Sebastian Manrique, who saw the construction of Tāj Mahal in 1640-41, is very revealing: "Some of these blocks, which I met on the way. . . were of such unusual size and length that they drew the sweat of many powerful teams of oxen and of fierce-looking, big-horned buffaloes, which were

dragging enormous, strongly made wagons, in teams of twenty or thirty animals."[16] A possible way in which this must have been accomplished can be understood from a painting in *Ākbarnāmā*, which shows a massive cannon being transported uphill by a team of powerful oxen[17]. It is certain a similar arrangement must have been used for carting large stone blocks to the Tāj site.

Once the blocks were received at the construction site, they were sectioned with the help of iron wedges and sledgehammers. The graphic scenes depicted in two miniature paintings in the *Ākbarnāmā*, showing the construction of Agra fort[18,19], provide an idea of workers and construction methodologies of the Mughal period. A large stone block is seen arriving at the construction site on a two-bullock driven cart in the right bottom of Fig. 1b. In the bottom left of Fig. 1a and also Fig. 1b, stone masons can be seen splitting a block of sandstone by cleaving them, like logs, with iron wedges. Another method to section sandstone and marble was with the aid of metal saws. This was time consuming, but presumably resulted in surfaces with a better finish. The method by which the smaller blocks of stone were carried around can also be noted in the miniature painting of Fig 1a. Workmen are seen carrying a long heavy block of stone on a timber ramp (see middle left of the picture). They are doing this by means of rope slings attached to thick bamboo poles. They are seen supporting themselves using a walking stick in one of their hands. Below the ramp, workers can be seen levering a block of stone with a stick. There are many more fine details that can be observed from these pictures, like for example the dressing style, etc., which is beyond the scope of the present article.

In all these operations, it is important to note that the stone had to be cut in the right direction, right from the time it is quarried. The grain structure of the stone is a very important consideration. The cut is usually made such that the stone will cleave easily along the cutting plane. When the stone is laid later, this cutting plane had to be placed horizontal. Otherwise, the sand stone will start cracking under load. The stones that are laid such that the grains are aligned vertically are called "edge-bedded"[1]. Sandstone is softer compared to marble. Therefore, it is more important in case of sandstone to be careful about laying the grains horizontal in the structure. That such care has been taken in the construction of most sandstone buildings of the subcontinent shows the familiarity of the artisans with the engineering concept of material anisotropy (i.e. directional nature of properties). In the few cases where this was not followed, the splitting of sandstone into layers or flakes can be noted.

Fig. 1. (a) and (b) Miniature paintings from *Ākbarnāmā* showing the construction of Agra fort[18,19].

Mortar

There is a long history of use of mortars in the Indian subcontinent[20]. Attention will be focused here on the mortars of the Mughal period only. Qaisar has provided evidence for historical Mughal mortars and plasters, but he has not connected it with actual buildings and locations[21]. This requires the help of trained civil engineers to identify the location and materials engineers to analyze the composition of different types of Mughal plasters.

The common variety of mortar was a paste of earthern clay in water, called *gilābā*[21]. This mortar was made stronger by adding straw (*bhus*)[8]. This was primarily used for plastering. The mortar used for binding purposes contained lime (referred to as *chunām*, *ahaq* or *qalāi*, based on the use) and this was known as *rekta*[11].

There were three sources of lime: limestone, gravel and marine shells. For use in mortars, limestone and gravel were burnt in kilns to prepare the hydrate.

It was added with cementing agents (resins, gelatins and glutens) depending on use. Fazl mentions the additives are pulverized brick (*sūrkhī*), jute fibers (*san*), gum (*samgh*) and reed glue (*śirish-i-kāhi*)[8]. The use of organic additives like curd (for soft finishing), *urad dāl* (as a plasticizer), *gond* (gum preferably of babbool or neem, used as retarder), jaggery (for hardening) is also known[20].

Research work done by the Archaeological Suvey of India on the mortar of the *Śiś Mahal* in the Agra fort has given some insights on the type of mortar used in Mughal constructions. The ingredients of this *cunām* was "1 part burnt lime, 1 part ground shells, calciferous stone or marble dust, 1/8 part gum from the *bābul* or *neem* tree (*Azadiracta indica*), 1/8 part sugar mixed with the juice of the fruit of the bael (*bel*) tree (*Aegle marmelos*), and a little white of egg. The mixture was strengthened with plant fibers and applied to the brick walls as a coating; when it was dry, it was polished with a shell (*kaurī*) and chalk powder."[1]

Plaster

Two kinds of plastering were in vogue during the Mughal period[10]. *Aṣṭarkāri* was basic plastering using lime, hemp, pulverized brick and binding materials. *Sandalkāri* was special whitewashing of plaster to impart luster and smoothness. In addition, plaster was used for creating stucco work, known as *qalibkāri.*

Polished plaster lent a white shining appearance to buildings and was a less expensive alternative to marble facing. This kind of fine plaster work for the walls and floors were also noted in the earliest Islamic structures in the Indian subcontinent (Sultanate period), based on excavations done in the Lāl Koṭ area[22].

Careful research work needs to be performed on the polished plaster used in Tāj complex because historical records of Shāhjahān period mention that the *cunām* was also strengthened with addition of small calciferous stones from Gujarat called *saṅg-i patiāli* ("stone from Patiali") or *saṅg-i māhtābi* ("moonlight stone")[23,24]. The advantage of this stone was that it was white in colour and soft in nature, such that it "could be polished so highly that it reflected all things opposite it like marble."[23]. The mechanical strength offered by the stones to plaster is an advantage. From a materials engineering perspective, this kind of plaster can be considered a composite material, defined as a material composed of more than one kind of material.

There are indications that other ingredients may also have been used in Shāhjahāni plaster. Lāhori noted that Shāhjahāni plaster "is better than marble-dust plaster in polish and purity."[24] The statement of Lāhori regarding plaster, namely "*cunā-az saṅg-i marmar*" has also been interpreted to mean shell plaster by Nūr Bakhsh[25].

Some details about Mughal plaster finishing process can also be gleaned from the invaluable account left behind by Francisco Pelsaert[26], who was the senior functionary in the Dutch East India Company from 1621 to 1627. The observant Dutch trader noted[26] that Mughal plaster was "very noteworthy, and far superior to anything in our country. They use unslaked lime, which is mixed with milk, gum, and sugar into a thin paste. When the walls have been plastered with lime, they apply this paste, rubbing it with well-designed trowels until it is smooth; then they polish it steadily with agates, perhaps for a whole day, until it is dry and hard, and shines like alabaster, or can even be used as a looking–glass." Another early observer, an artist called William Hodges, admired Indian *cunām* for its affinity to marble[27].

In the Tāj Mahal, where marble was not used (like in ambulatory rooms and subsidiary rooms), the walls and vaults were faced with stucco plaster. Moreover, at several locations, blind arch designs were achieved on the walls using plaster relief. Stucco is the paste of lime plaster with binders. This was used for shaping underside of architectural features. The smooth surface was also useful for executing colourful decorative paintings. This technique was called *qalibkāri* because the shapes were pressed into the wet plaster with moulds. The term indicates that, originally, the pattern may have been applied by means of moulds, presumably of wood[28]. Plaster *qalibkāri* work was used as decorative work applied to the facing of faults or the curved part of covered ceilings. This has been discussed in great detail, elsewhere[28].

Precious Stones

Precious stones formed another important part of the materials used in the construction of the Tāj Mahal. Their purpose was decorative rather than, strictly, engineering. Nevertheless, a brief discussion on precious stone is not out of order here. The precious and semi-precious stones were very important in the marble inlay work at Tāj[1,29]. This inlay method is called *parcinkāri* and it will be described in a more detail later.

The stones have been much vandalized in the history of the Tāj. For example, at the end of the nineteenth century, Lord Curzon wrote with sarcasm[30] that "it was not an uncommon thing for the (British) revelers to arm themselves with hammer and chisel, with which they whiled away the afternoon by chipping out fragments of agate and carnelian from the cenotaphs of the Emperor and his lamented Queen." Voysey[31] investigated the stones and identified lapis lazuli or *lajward* (blue), chalcedonic quartzes such as jasper (reddish), heliotrope or bloodstone (dark green spotted with red), agate (brownish red), chalcedony, carnelian or '*aqiq* (brownish red), *sard* (brown cornelian), plasma (a slightly translucent variety of quartz, either green, grey or blue), chlorite (green), jade (nephrite or jadeite), clay slate, yellow and striped marble, and yellow and a variety of limestones. These stones are available in the Indian subcontinent and its neighborhood.

Wood

Due to the luxuriant growth in India, a wide variety of woods were known. More than seventy two varieties of wood were available to the builders of Ākbar[21]. Wood was used in the foundations laid by the riverside, details of which are presented later. Another important use of wood, which was important during the construction, was for the purpose of scaffolding as well as for ramps for work-persons. The use of wooden scaffolding can be noted in Fig. 1a while the different types of wooden ramps can be seen in Figs. 1a and 1b. Wooden scaffolding was particularly important for high rise multistoried structures of the Mughal period. This was termed *pan* in Hindi and *chob bast* and *chob band* in Persian[21]. While the scaffolding on the external face of the Tāj must have been primarily of wood, the scaffolding for the inner interior walls and dome of the Tāj must have utilized both bricks and wooden scaffolding. This is evident from the scaffolding in the interior of the dome of the gate in the Mughal miniature painting of Fig. 1a.

Metals

Different kinds of metals were used in the construction of Tāj. While some are readily noticeable, others are not.

A large number of iron clamps were used to hold the stones together. This is not readily noticeable, but going by the number of stones used, it is easy to

estimate a large number of iron clamps were used in the construction of the Tāj. These were known as *ahan jamā*[8]. Due to corrosion of the iron clamps and corresponding expansion caused by the corrosion product, cracking of marble has been noted in some locations of the Tāj. Conservation measures to rectify this problem include replacement of corroded iron clamps with stainless steel, copper or titanium clamps. The best option (and the costliest) is titanium clamps.

The entrance to the *Cārbāgh* garden is through the main gate set in the back of the fore court. The entrance of this gate is now covered with a impressive wooden gate sheathed in bronze plates. There are interesting patterns of cartouches in relief. Originally, the door was supposed to have been made of silver, which was supposedly removed by Suraj Mal when he took Agra in 1761. Interestingly, this is not mentioned in any contemporary record by in a manuscript[32] of the late nineteenth century, a time period when much misinformation (especially in matters related to Indian culture and history) was sponsored and spread by the ruling British.

A large bronze lamp hangs from the middle of the dome of this gate. This was presented by Curzon (who was Governor General and Viceroy between 1898 and 1905). He got this made in Mayo School of Art in Lahore. After being exhibited in England, it was set up in 16 Feb 1909, after Curzon left India. From the central dome of the Tāj mausoleum hangs a vase-shaped bronze lamp inlaid with gold and silver, which was also a gift from Curzon. Interestingly, he is supposed to have got the design for this lamp from a book on the Islamic monuments of Agra that he had found. He had this lamp made in Cairo. The original design and exact shape of the object that was suspended from the apex of the dome is not known. Contemporary records[33,34] mention, in the original condition, there were orbs (*kaukābā*) and hanging lamps (*qindil*) of gold with enamel work suspended in the interior.

On the top of all the domed structures is the crowning element formed of copper. On top of the main dome of the Tāj, the crowning element is made of lotus leaves, which is a standard feature of Indian Islamic architecture. The finial (*kalaśa*) rises from this and made of superimposed bulbs topped by a crescent. This pinnacle was re-gilded in 1874.

The fountain system of the central tank consisted of copper vessels connected through copper pipes with the main supply pipe.

The central cenotaphs of Mumtāz and Shāhjahān are now surrounded by a perforated marble screen (*mahjar-i-mushabak*) with its spectacular design of flowers and plants inlaid with semi-precious stones. This was set up in 1643 to replace the original one that was made of enameled gold. Lāhori[33] mentions that this golden screen was made by the superintendent of imperial goldsmiths, the goldsmith and poet Bibādal Khān, on the occasion of the second anniversary of Mumtaz Mahal's death in 1633. The screen was made of pure gold and decorated with inscriptions and floral designs in enamel work. Plus, golden globes and lamps were also hung around the screen. The golden screen weighted 40000 *tolas* and cost six lakhs of rupees, as per Lāhori[33], which was almost 12 percent of the cost of the entire mausoleum complex. This screen was placed around the tomb on the upper cenotaph, which had already come up on the platform. Peter Mundy[35] observed in 1633 that "there is already(e) about her Tomb(e) a rail(e) of gold." The gold screen was very expensive and deemed too precious. It was replaced by the marble screen, which cost 50000 rupees and took ten years to make[33].

Engineering Techniques

There is very little written evidence about the actual construction of the Tāj Mahal. No architectural drawings are preserved and therefore nothing is really known about how the Tāj was constructed. The only inscriptional evidences for possible design of the Tāj are the few incised patterns on stone slabs re-used in buildings. The engineering techniques that were employed in building the Tāj have to be gleaned from actual material evidences, namely the Tāj itself.

Foundation

The foundation is basic to the structure and an important component. Based on historical records, we know that the head of the architects, with his assistants, would first chalk out the plan on the ground and then diggers (*beldār*) would excavate the foundations[36]. It would have been fairly easy to lay the foundation on hard ground. However, the challenge was to secure the foundations of the Tāj Mahal on the sands of the riverbank of Yamuna. This must have posed a technical problem, but it appears that time-tested solutions were available since structures were routinely constructed near river banks of the Indian subcontinent, through the ages. In fact, the defining cultural idiom of the civilization of the Indian subcontinent is the close association of urban centers with large

sources of fresh water bodies, especially rivers. The long continuity of this tradition from the Harappan Civilization to pre-modern times (i.e. before the introduction of railways) must be specially noted.

There was a great technical challenge in securing the foundations of the riverfront terrace in the unstable sands of the riverbank. It had to be strong in order to take the support of the large structure (about 68 meters high) of the Tāj Mahal.

Not much can be gleaned from the description of Lāhori[33], who informs that the foundations were "built of stone *(saṅg)* and [watertight] mortar or cement (*saruj*)." Qaisar informs that *saruj* was a special mortar for waterproof construction and was made of lime, wood ash and sand[21]. Lahori further adds that on these foundations was built a terrace *(chabutra)* of brick (*ajur*) and mortar *(āhak)*, and on this platform the main buildings were placed. Its exterior (*ru-yi kar*), especially the front to the river, was artistically faced with red sandstone[33].

Valuable insights on the foundation technology can be obtained from the poem by Kalim[37], who was not an engineer but a writer.

Since there is sand where there is a river, it is difficult
to lay down foundations:
As sand is removed, it fills in again.
They make a well (*chah*) to manage the work, from wood,
and set it firmly into the sand.
Then they take out the sand from inside it, until solid earth
comes from its depth.
In this well stone and iron are buried until they reach
the level of the surface.
Then another well beside it is emptied of sand and filled
in the same way, so that the building may be erected.
With this good method and powerful concept they raise
a mountain from the ground.

This clearly indicates that the foundation was secured using a double-well construction, with each cased in wood and filled with rubble and iron, bound with special water tight mortar or cement.

Excavations were conducted in the 1950s by the ASI on the foundations of the Tāj Mahal. The excavations revealed wells filled with rubble, which were

located at a distance centre-to-centre of 376 cm[38,39]. (This distance equals approximately 2 *dhanus* as per the traditional Indian units[3-6]) The strong foundation of the Tāj Mahal has to be appreciated because it has been able to withstand great floods that have visited Tāj Mahal since its inception. It is also clear that the designers and constructors of the Tāj had a good idea of the flood pattern of the Yamuna when the height of the terrace was planned.

The riverfront architecture of Agra of the Mughal period has been elaborated in great detail by Koch[40], from which it can be noted that there were numerous riverfront buildings in Agra during the Mughal period. Koch notes that "foundation wells of this type can be seen exposed in the riverbed in front of several of the gardens on the left bank of the Yamuna - the garden of Jahānārā /*Zahārā Bāgh*, the *Cini-kā Rauza*, and the garden of Khwāja Muhammad Zakārya or Wazir Khān."

Walls

All buildings of the Tāj complex are built of brick. In particular, the walls of the mausoleum are very thick, as much as several meters at some locations. Koch[1] notes that in a typical Shāhjahāni structure, the bricks are laid in horizontal courses composed largely of stretchers, but alternating at times with headers, in a thick bed of mortar made with *kankar*, a nodular limestone[1,8]. Vaulted structures were constructed using concentric rings of brick courses, which were set in an even thicker bed of lime mortar. It was important that the masonry to support the curvature of the partly spherical shell of the inner dome and the high bulbous dome above it. There are no stiffening walls between these two structures and therefore it was more important that the masonry was of good strength. The structure of the outer dome is reinforced by a continuous series of relieving arches integrated in the brickwork of the drum[41].

The brick masonry was then faced with marble or sandstone slabs, which were firmly locked together with iron dowels and clamps. All the important domes in the Tāj complex are faced on the outside with white marble. In the special case of the Tāj mausoleum, the main inner dome of the tomb chamber is also faced with marble, while the inner domes of the side rooms and the rooms of the upper storey are covered with white plaster.

The supporting walls in the entire complex are faced with red sandstone. This is a typical feature of Mughal walls. Based on her field studies, Koch has

identified a typical construction technique for the walls, which she calls "Mughal bond"[1]. As per this method, "long sandstone slabs, of size 125-200 cm in length, 60-80 cm in width and 10-15 cm in thickness, were laid alternately horizontally and vertically in a fixed pattern. The alternate vertical slabs were placed at right angles through the thickness of the wall and, with the horizontal slabs, formed a permanent framework that was filled with rubble or bricks set in mortar."[1].

Tavernier[42] noted that all the scaffolding of the Tāj Mahal, including the centering for the vaults, was made of brick. They were apparently removed after completion of the structural work. This is supposed to have added greatly to the building costs. In this regard, the miniature painting in Fig. 1 shows the possible method in which the scaffolding of wood was raised using bricks[19]. This must have been the scheme witnessed by Tavernier. This kind of scaffolding must have been important especially for working on the inner portions of the structure. For work on the outer structure, it would have been easily performed by the traditional method of bamboo scaffolding, which is widely used all over India even today. The material had to be heaved up and for this the use of wooden ramps is easy to envisage, as can be gleaned from the miniature painting of Fig 1a[19]. Interestingly, Koch[1] noted that the craftsmen working on the restoration of the Tāj Mahal even today employ similar techniques, which do not seem to have changed much since Mughal times.

Decoration

Several techniques were employed for decorating the surface. This involved the artistic work of several kinds of artisans. Some notable decorative techniques will be highlighted.

Stone carving

The stone carving work in Tāj is truly incredible. The work of the stone carver covered a wide range of work and materials. The carving included fairly simple ones in sandstone and the carving of simple mouldings. The more challenging was the exquisite depiction of flowering plants in sandstone and marble on the dados of the mausoleum and flanking buildings.

Inlay

Inlay work was termed *parchin kāri* in the Mughal period. There are two kinds of inlay work noticed in the Tāj complex.

Simple stone inlay work involved the inlay of one stone of certain shape into a hollow in the stone of another color. This theme has been used in some parts of the Tāj complex. This basic idea has been in use over a long period of time in the subcontinent, since the region abounded in attractive stones.

The highly specialized form was inlay of hard or semi-precious stones into marble. It involved the inlaying of many stones and not just one single stone. This kind of work was known in Europe as *pietra dura,* which is short for *commesso di pietre dure* (composition of hard stones)[43]. Whether this technique was originally Indian or European can be debated, as usually Western scholars do not want to attribute any craft or art of merit (and also science and engineering) as originating from India (and of course focus primarily on the Eurocentric origin of all knowledge), but there is no denying the fact that this craft found its most beautiful expression in the Indian subcontinent.

The engineering knowledge and practical skill required for *parchin kāri* was considerable. The stone had to be sawed into small thin pieces of various shapes and sizes using bow saws with abrasives. The stones used are agate, jasper and heliotrope (bloodstone). The pieces are then inlaid on marble in such a fashion that the natural look of the desired image is obtained with a combination of colors. Technique wise, the stones are fixed in the cavity with glue and polished. The end result is that the joints became invisible[44]. It is important that the cutting of stones had to be performed with great skill, since complex shapes had to be crafted.

Mosaic

Another typical decorative feature of the Tāj complex is the intricate mosaic work. The technique of mosaic making involved sketching of design on the desired background, selecting the color and material for different parts of the pattern and then setting them with liquid plaster. The medium used was generally red sandstone and marble. In one manner, this was a precursor to the work wonderful *parcin kāri* decorations seen in the Tāj.

The fine mosaic work on floor (and also the inlay work) required expertise in polishing or *mohrā kashi*[45]. This was achieved with abrasive stones, traditionally used for shining, polishing and smoothening of surfaces.

One may briefly digress here to understand another typical decorative technique used in the Mughal period and earlier Islamic period, namely glazed

tiles. They were commonly used in Central Asian buildings. In this process, the surface of the tile was fused with carbonate salt of copper and silica. On heating, the pres of the tiles were filled and a glaze was imparted to the surface. This resulted in waterproof non-porous surfaces, suitable for both decoration and protection. Gazed tiles have not been used to decorate the surface of Tāj. The *Chini-kā-Rauza* (Chinese Tomb) at Agra is faced with a mosaic of glazed tiles and an excellent example of use of this technique in decorating an important architectural structure of Agra[40].

ARTISANS

Having understood the important engineering materials and construction methodologies employed in the Tāj, it will be enlightening to turn attention on the persons involved in constructing the monument.

The team of workers can be conveniently classes as *muhandis* (engineers), *mimar* (architects) and *banna* (builders)[21]. New insights on architects of Tāj have been presented in detail elsewhere[2]. The present focus will be on the engineers (i.e. supervisors) and artisans.

Supervisors

The engineers were consultants who maintained the norms of construction and supervised the building activities. They were known as *naksh nigārs* or *mīr bāhār*. They were supervisors and along with the architects formed one class while the artisans and worker the second level[21]. The supervising engineers like *mīr bāhār* were entrusted with development of agriculture, gardening and digging of canals and streams[10]. It is of interest to note that no engineer or architect, assuming that they belonged to the higher social order, were conferred with any *mansab*[46], which was a measure of social recognition and prestige during the Mughal period[47].

The artisans and workers worked under the supervision of senior functionaries called *shāhnā cālak*[21]. They must have been technical superintendents supervising the actual work, but reporting to the engineers.

Another class of supervisors included persons responsible for commercial activities. Historical records mention the supervisory position of *mīr imārat*, assisted by a *mālik ghāzi* as overseer (*shāhnā*)[10]. The *mīr imārat* were supposed

to be well versed in accountancy, know the prevailing wages, and assess and procure building materials[21]. This was clearly an administrative post. Nevertheless, the massive use of construction materials must have required a scientific inventory keeping. It must be realized that apart from the actual process of physical construction, the logistics of handling the personnel and the material must have been important and stupendous. A large amount of material had to be handled, for example huge amounts of bricks, thousands of cartloads of stone, marble and *cunām*. Therefore, the planning of the entire logistics itself deserves praise. It has been observed that the major construction was essentially completed in twelve years from 1631 till 1643, with decoration work continuing for another five years[1]. Therefore, the use of technology to move large amount of material and undertake the massive construction, in a relatively short period of time, must be appreciated.

There were different kinds of skilled craftsmen, with specific work functions and skill sets. Some of the important ones are discussed below:

Masons

The bricklayers were called *rāj*[21]. They used a commonly used tool *basoli* to cut the bricks to proper shape while laying. The trowel (*kirnī*) was another important tool used in construction. The brick layers at work can be noted in Fig. 1a and 1b. Mortar is being prepared in Fig. 1b under supervision and later carried to the top of the walls using wooden ramps. The mortar maker was known as *gil-kār*. The mortar is being carried both on a large basket that is held with a pole and supported by two men, as well as by individual persons using small baskets (see Fig. 1b).

Stonemasons

Stonemasons were called *saṅgtarāś*. They undertook four kinds of specialized work like quarrying, plain cutting, embossing and tracing, and inlaying. *Saṅgbār* was a worker in quarry, *naqqār* was the embosser and tracer, and inlayers were called as *saḍkār* and *parcinkār*[8,33].

Such was the fame of the Indian stonecutters that Akbar's historian Abu'l Fazl confirms that "clever workmen chisel it more skillfully than any turner could do with wood"[12].

The stonemasons of the Tāj Mahal made their contribution known through numerous marks, found around the complex. These marks have been presented in Fig. 2. Most of these are "scratched into the paving of the garden walkways and the slabs facing the walls of the buildings; some appear on the façade of the riverfront terrace."[1] A wide variety and shapes were noted by Koch, like "graphic symbols such as stars, *swastikas*, fishes, flowers and intersecting figures, and numerals." One also frequently comes across incised names, "largely Hindu but

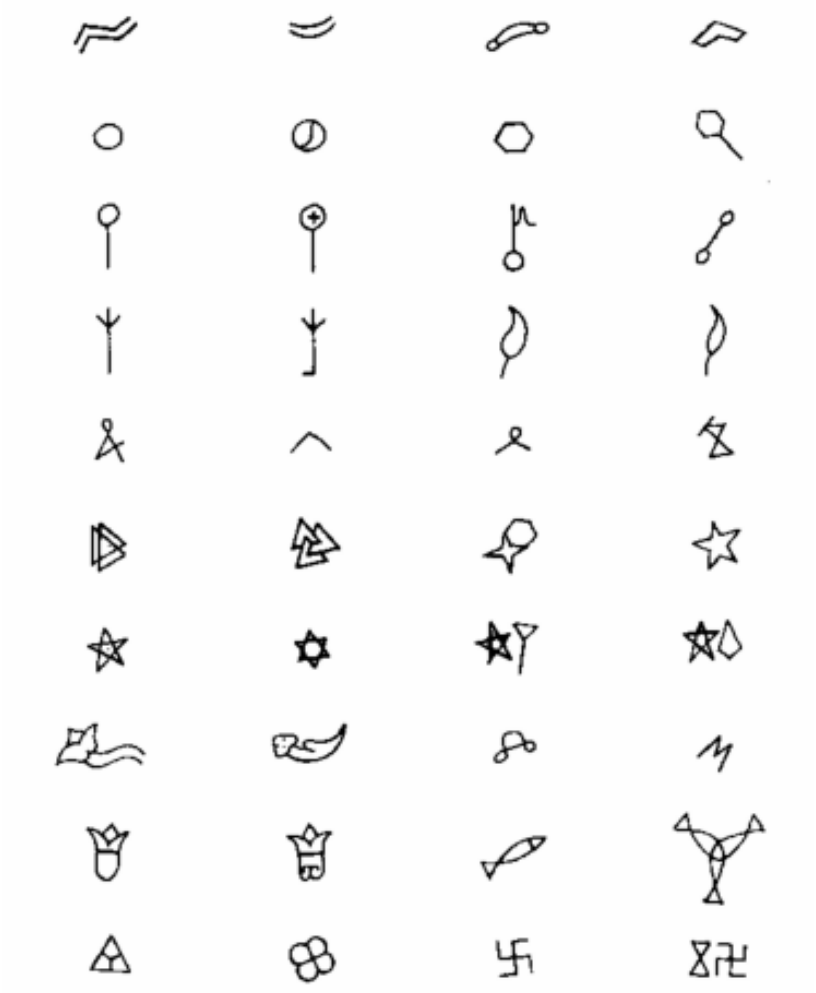


Fig. 2. Some artisans- marks noted at different locations in the Tāj complex[1].

also Muslim, respectively in Devanāgari and in Arabic (Persian) letters."[1]. This could also be due to visitors from later period and not necessarily the original craftsmen. Koch remarks that the masons' marks have been largely ignored by scholars and are still not sufficiently understood[48-51]. There are several dangers in their interpretation as scholars tend to relate mason's mark to indicate the architect of the Tāj Mahal[51]. It is interesting to note that these marks are not exclusive to the Tāj and that the same marks appear on contemporary or earlier Mughal buildings, which has been interpreted to denote the contribution of groups of hereditary stonemasons[1]. This is likely as Abul Fazl mentions that the stone masons were paid by the linear measure of stone cut[12].

Stonecarvers

They are called, in modern usage, as *munabbatkār* and also *sangtarāś*. They played a major role in the construction of the Tāj[21]. They were responsible for carving relatively simple designs to the most exquisite screens (*jālis*) and relief of plants and flowers on the walls of the monument. The careful attention to material grading, form and colors is also evident in the minute details of the exquisite marble work of dado flowers and intricate inlay decorative work.

Inlay workers

The craftsmen employed to do the stone inlay work were called *parcinkār*. The stone inlay technique appears to have been mastered to such perfection by the stone workers of Shāhjahān that "in its complexity, subtlety and elegance their *pietra dura* work far surpasses that of the Italian artists."[1] One may see the most exquisite inlay work in the cenotaphs and the surrounding screen in the tomb chamber at the very heart of the Tāj Mahal. Voysey who scientifically studied the stones in 1825[31] noted that "a single flower in the screen around the tombs, or sarcophagi, contains a hundred stones, each cut to the exact shape necessary, and highly polished; and in the interior alone of the building there are several hundred flowers, each containing a like number of stones."

Shāhjahān's love for gems was legendary. Of more importance was the fact that he was the richest person in the world at that point in time. It is no wonder that the observant François Bernier noted of the Tāj Mahal in 1659 that "Everywhere are seen the jasper, and *jachen* [*yashm*] or jade, as well as other stones similar to those that enrich the walls of the Grand Duke's chapel at Florence,

and several more of great value and rarity, set in an endless variety of modes, mixed and enchased in the slabs of marble which face the body of the wall."[52] This wonderful effect was made possible by the tireless and skilled *parcinkāri* artisans.

Other Artisans

Several other classes of workers were employed in Mughal constructions. These included sawyers (*arrakāsh*), carpenters (*darudgār*), mortar and lime makers (*gil-kār* and *cuna-kār*), water carrier (*abkāsh*), well cleaners (*goṭ khur*) and laborers (*mazdur*)[10]. Every person had a role to play in the over scheme of construction. Notice the depiction of the water carrier pouring out water in Fig. 1a, while Fig 1b shows the carrier filling water from the river.

The above review has shown that a large number of artists were involved in creating the world wonder, Tāj. The actual number of people involved in its construction is not clear. Usually, the record is from European observers, whose numbers are unsubstantiated. Jean-Baptiste Tavernier[42] was a jeweller who visited Agra in 1640-41 and again in 1665. He claimed that "twenty thousand men worked unceasingly" on the tomb for twenty-two years. On the other hand, Manrique notes that a thousand men were employed on it everyday[16].

Surprisingly, the craftsmen of the Tāj Mahal are not named in the histories of Shāhjahān. The only note that Lāhori makes is that only the best artisans came from all over India. He notes that "from all sides and parts of the imperial territories were assembled troop after troop of [skilled] men, stonecutters *(sangtarāś)* of smooth work, inlayers *(parcinkār),* and those who do carving in relief (*munabbatkār*), each one an expert in his craft, who started the work together with the other laborers."[33]

Shāhjahān's biographer specifically mentions that they were native Indians and came from different parts of the land. A novel method will be now utilized to gain insights on these skilled artisans of Tāj.

Analysis of Mosaic and Floor Patterns

The distinguishing feature of the arts of three great Islamic empires - the Ottomans, The Safavids and the Mughals - is the use of intricate geometric patterns in their architecture. This was known as *girih bandi* which loosely

translated as geometric ornament[1]. This aspect finds great expression in architecture of the Tāj complex. Some aspects of Shāhjahāni architecture have been discussed in detail elsewhere[53]. One of the dominant principles of Shāhjahāni architecture is the geometric planning. This was achieved at the macro level by using a modular plan for the overall design of the complex. New insights have been obtained on the modular planning of the Tāj and it confirmed that the design of the Tāj was based on traditional Indian civil engineering principles[5,6].

While floral decorations were the main kind of ornament for buildings in seventeenth century India[54], typical geometrical patterns were used in less prominent places. In the Tāj Mahal complex, they were relegated to the floors and *jālis* (screens). The symmetry and modular planning is also evident in these geometric patterns. The floor patterns are differentiated in complexity and technique, and also underlined the hierarchical importance of the area or building where they occurred.

Of particular interest are the geometric patterns created on the floors. They are quite intricate and crafted with great skill. For example, the floor of the central tomb chamber of the mausoleum is paved in a geometric pattern that consists of octagonal stars that alternate with pointed cruciform shapes. This design has been created by inlaying black marble in white marble.

The designs of the decorative floor patterns at some prominent places in the Tāj complex will be now understood, with particular emphasis on the measurement unit based on which they were conceived and constructed. The original measurement of these patterns is given in inches by Koch[55]. These patterns will be analyzed in terms of *vitasti* unit of *Arthaśāstra*, which is 21.156 cm (= 12 x 1.763 cm per *aṅgulam*).

Fig. 3 shows a common geometric pattern that is noted at different locations, namely on the platform in front of the great gate on the garden side, platform of the southern galleries, and platform of the riverfront terrace. The design is in red and buff sandstone. In this figure, the length of each star is 3V. The good match between the predicted measure of 63.5 cm and the actual measured (published) value of 64 is noteworthy. This match confirms the fact that units based on *Arthaśāstra* were used to design the mosaic patterns.

Fig. 4 shows the geometric pattern seen on all the walkways of the garden. The material of construction is red sandstone. The symmetrical placement

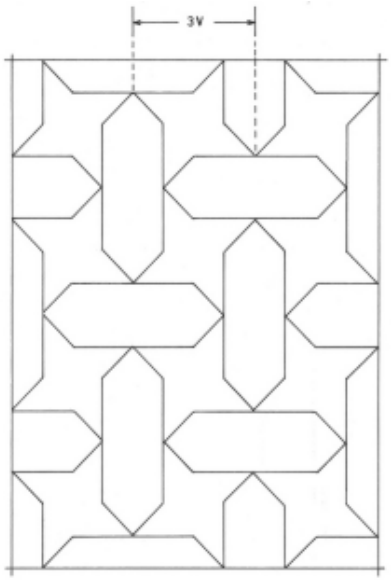


Fig. 3. Geometric pattern that is noted at three locations in the Tāj complex, namely on the platform in front of the great gate on the garden side and of the southern galleries, and platform of the riverfront terrace. The design is in red and buff sandstone.

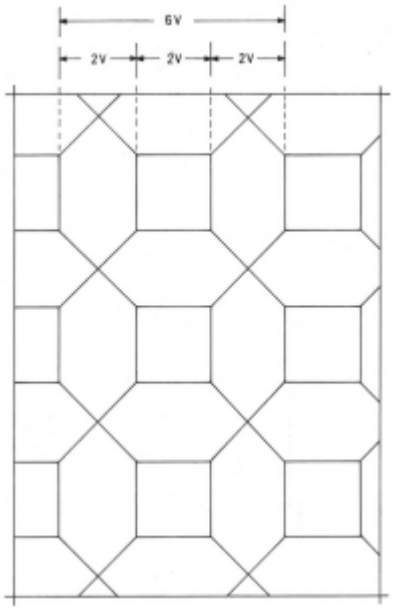
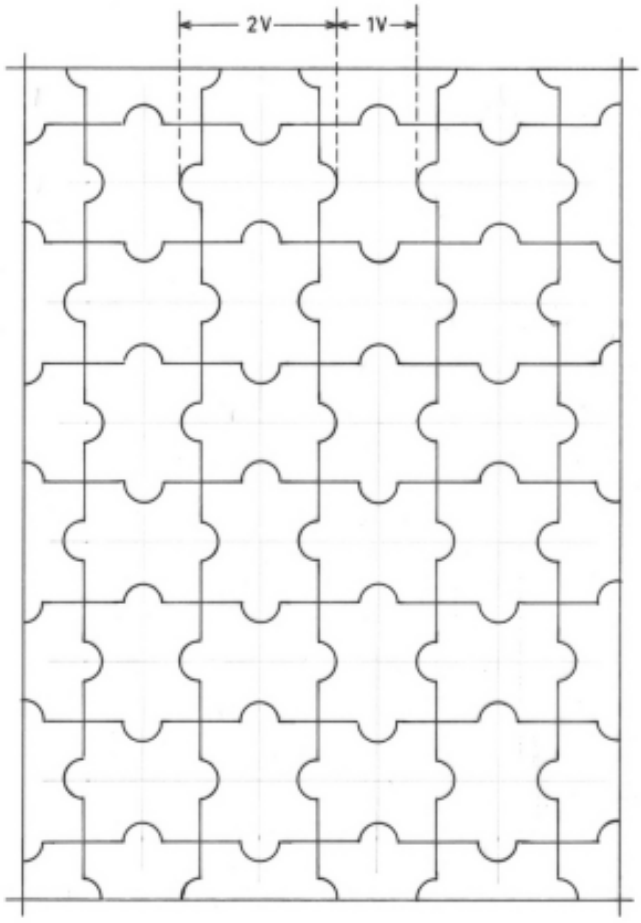


Fig. 4. Geometric pattern on all the walkways of the garden made in red sandstone.

of 6V patterns divided into 2V segments can be noted. The predicted measure is 126.9 cm while the average actual measure is 124.5, which indicates the match is good.

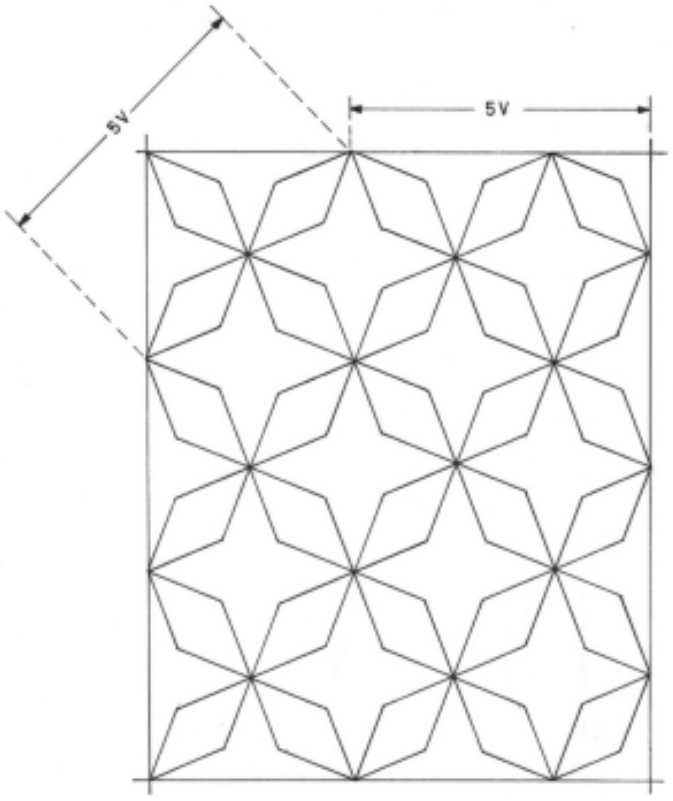
The geometric pattern on platforms in front of the garden wall pavilions is analyzed in Fig. 5, where the symmetrical elements of 1V and 2V segments are indicated. The construction is in white marble and red sandstone. The three domes of the mosque sit on drums decorated with a striking interlocking pattern of red and white inlay pattern, which is a variation of this pattern.



1vitasti (V) = 12 aṅgulams = 12 × 1.763 cm

Fig. 5. Geometric pattern on platforms in front of the garden wall pavilions in white marble and red sandstone.

Fig. 6 shows the geometric pattern around the platform of the mausoleum in white marble and red sandstone. The unit of 1V is indicated. Fig. 7 shows the geometric pattern on platforms in front of the mosque and *Mihmān Khānā* (assembly hall) in red and buff sandstone. The units of 1V and 4V are indicated. Fig. 8 shows the geometric pattern on platforms of tanks in front of the mosque and *Mihmān Khānā* in red and buff sandstone. The symmetry in the unit of 2V segments can be noted. The geometric pattern on the tomb chamber in the mausoleum and octagonal corner chambers is depicted in Fig. 9. The star and cross pattern is made by black marble that is inlaid in white marble. One 2V segment is marked.



1vitasti (V) = 12 aṅgulams = 12 × 1.763 cm

Fig. 6. Geometric pattern around the platform of the mausoleum in white marble and red sandstone.

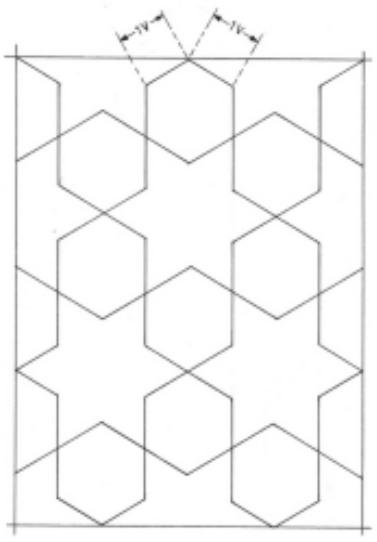


Fig. 7. Geometric pattern on platforms in front of the mosque and *Mihmān Khānā* (assembly hall) in red and buff sandstone.

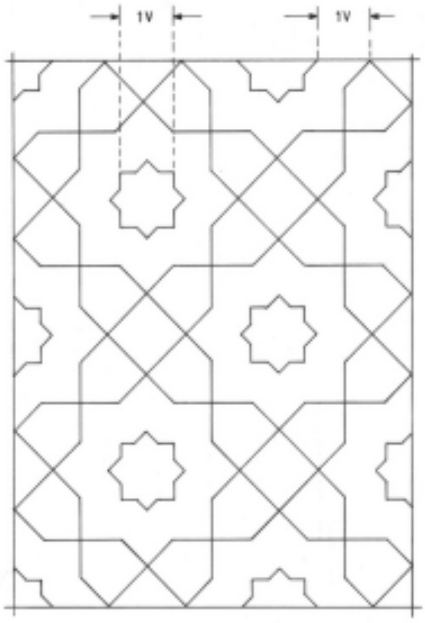
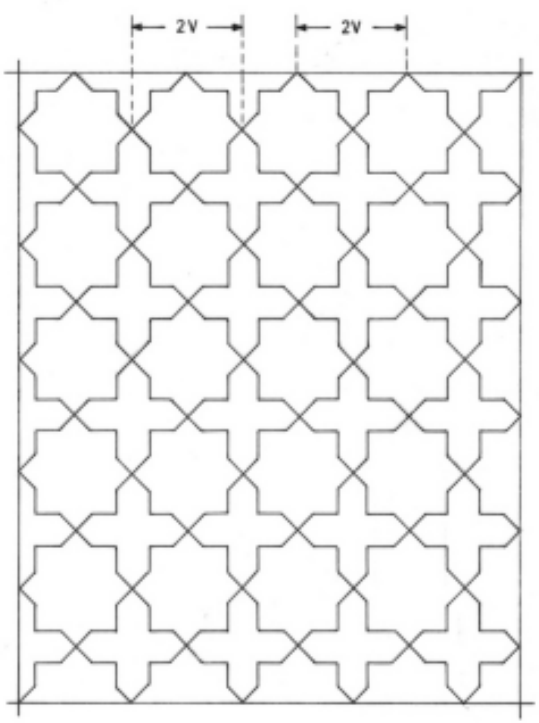


Fig. 8. Geometric pattern on platforms of tanks in front of the mosque and *Mihmān Khānā* in red and buff sandstone.



1vitasti (V) = 12 aṅgulams = 12 × 1.763 cm

Fig. 9. Geometric pattern on the tomb chamber in the mausoleum and octagonal corner chambers. The star and cross pattern is made by black marble that is inlaid in white marble.

ORIGIN OF ARTISANS

The above analysis has cleared the confusion regarding the artisans who helped create the world wonder Tāj complex. Going by the traditional measurement units used for designing minute elements, like the patterns on the floor, it is clear that the artisans who constructed the entire complex were well versed in the traditional building concepts of the subcontinent. The present communication has further confirmed that the construction of the Tāj Mahal is primary based on the civil engineering traditions of the subcontinent. Therefore, it is reasonable to conclude that the construction of the Tāj Mahal was executed by persons trained in traditional building concepts of the subcontinent.

The foreign element in the engineering is not significant. While the supervision and superintendence may have been of people of foreign origin, the current study

proves that the actual engineering of the complex was the accomplishment of the genius of local Indian talent. A complimentary study has established the architecture of the Tāj was based on traditional Indian concepts of modular planning and construction[2]. These studies, together, prove that the ultimate realization of the wonderfully engineered construction of Tāj was possible due to the engineering abilities and skill of native architects and artisans, as confirmed by their adherence to the traditional measurement units of the subcontinent.

CONCLUSIONS

New insights on the artisans who were directly involved in the construction of the world architectural wonder, the Tāj Mahal, has been obtained based on analysis of dimensions of significant geometric patterns on the floor at different locations in the complex. The use of traditional measurement units of the subcontinent to measure out these designs provides firm confirmation that the artisans involved in constructing the world wonder were native to India since they were well versed in the construction methodologies of the Indian subcontinent.

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