The Decorative Bell Capital of the Delhi Iron Pillar

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Figure 1. The Delhi iron pillar located at the Qutub Minar complex in New Delhi.

The design and construction of the decorative bell capital of the 1,600 year old Delhi iron pillar attests to the high degree of skill of the ancient Indian blacksmiths in working iron. Detailed visual observations clearly establish that the decorative bell capital is not a single piece of metal, but is composed of separate pieces that have been individually constructed by forge welding. A critical analysis of the fitting methodology of the Delhi iron pillar's decorative top indicates that the individual pieces were fit around a cylindrical hollow iron shaft, which was connected to the main body of the pillar by means of an insert.

Over the last 30 years, there has been a discernible increase in the number of scholars who have focused their research on early industrial organizations, a field of study that has come to be known as **Archaeotechnology**. Archaeologists have conducted fieldwork geared to the study of ancient technologies in a cultural context and have drawn on the laboratory analyses developed by materials scientists as one portion of their interpretive program. Papers for this bimonthly department are solicited and reviewed by **Robert M. Ehrenreich** of the National Materials Advisory Board of the National Research Council.

Author's Note: According to the Gupta period *Sulba Sutras* (a compendium of rules concerning measurements), the ancient Indian measure of length, omitting microscopic measurements, was the angulam, which measured one inch. This was divided into eight yavas. For greater lengths, 12 angulas equaled one vitasti (12 inches or one foot), and two vitastis equaled one hasta or aratni. Further, four hastas resulted in one danda. In this article, the ancient Indian length measures are used in the figures. For ease of reading, U.S. standard measurements are used in the text.

INTRODUCTION

The iron pillar currently situated in the Quwwat-ul-Islam mosque (Figure 1) near the Qutub Minar at New Delhi, India, has attracted the attention of metallurgists and archaeologists for its excellent corrosion resistance. Several theories have been proposed to explain its superior corrosion resistance and can be broadly classified into two categories: environmental[1–3] and material.[4–7] The proponents of the environment theory state that the mild climate of Delhi is responsible for the corrosion resistance of the Delhi iron pillar, since the relative humidity does not exceed 70 percent for significant periods of time in the year,[3] resulting in very mild corrosion of the pillar. On the other hand, several investigators have stressed the importance of the construction material as the primary cause for the pillar's corrosion resistance. The factors proposed in this regard are the relatively pure composition of the iron used,[4] the presence of phosphorus and the absence of S/Mn in the iron,[5] its slag-enveloped metal grain structure,[3] and passivity enhancement in the presence of slag particles.[6,7] Other theories to explain the corrosion resistance are also found in the literature, such as the mass metal effect,[3] initial exposure to an alkaline and ammonical environment,[2] and surface coatings both after manufacture (treating the surface with steam[8] and slag coating[9]) and during use (clarified butter coating).[3] The importance of the construction material as a factor in determining the corrosion resistance of ancient Indian iron is attested by the presence of ancient massive iron objects located in areas where the relative humidity is high for significant periods of the year (for example, the iron pillar at Dhar in Madhya Pradesh, the iron beams in the Konarak temple in coastal Orissa, and the iron pillar at the Mookambika Temple at Kollur situated in the Kodachadri Hills on the western coast).

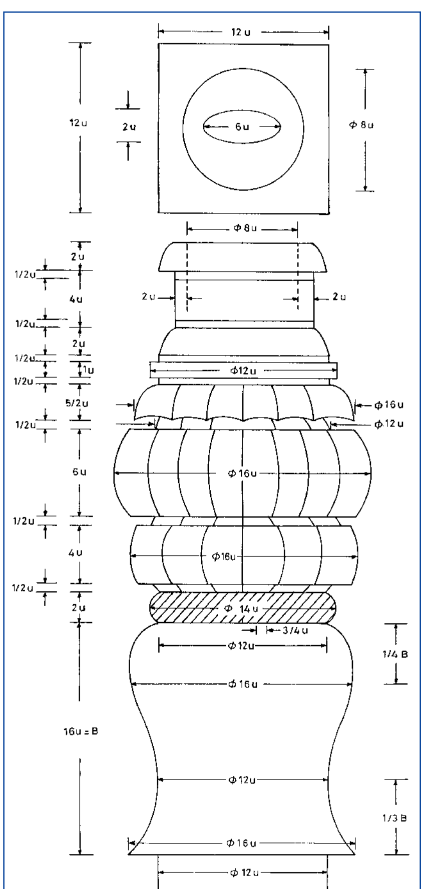


Figure 2. The dimensions of the decorative capital's components.

There are several studies reported in the literature on the Delhi iron pillar's corrosion resistance; however, the construction and manufacturing methods of the decorative top capital of the pillar have not yet been addressed, most probably because of the inaccessible nature of the pillar top. This article, which is based on an investigation conducted with the assistance of the Archaeological Survey of India, elucidates the construction details of the Delhi iron pillar's decorative capital and provides insights into its fabrication method.

The skill of the ancient Indian blacksmiths in the art of working iron is also highlighted. The construction of such a large mass (weighing about six tons) is an engineering marvel considering the time period (around 400)[6] in which it was constructed. The construction of the pillar's top indicates a high degree of sophistication achieved by the ancient metallurgists in planning, executing, and constructing large iron objects.

THE PILLAR CAPITAL

Dimensions

The total length of the pillar is 23 ft 6 in., including the decorated capital (3 ft. 5 in tall). Moreover, the distance from the bottom of the pillar to ground level is 1 ft. 7 in., and the height from the yard level to the raised platform is 1 ft. 6 in.[5] The stone platform currently surrounding the pillar was erected by Beglar in the 1860s[10] when he investigated the underground regions of the courtyard in great detail. The pillar rises about 17 feet above the platform level and is crowned with the decorative capital.

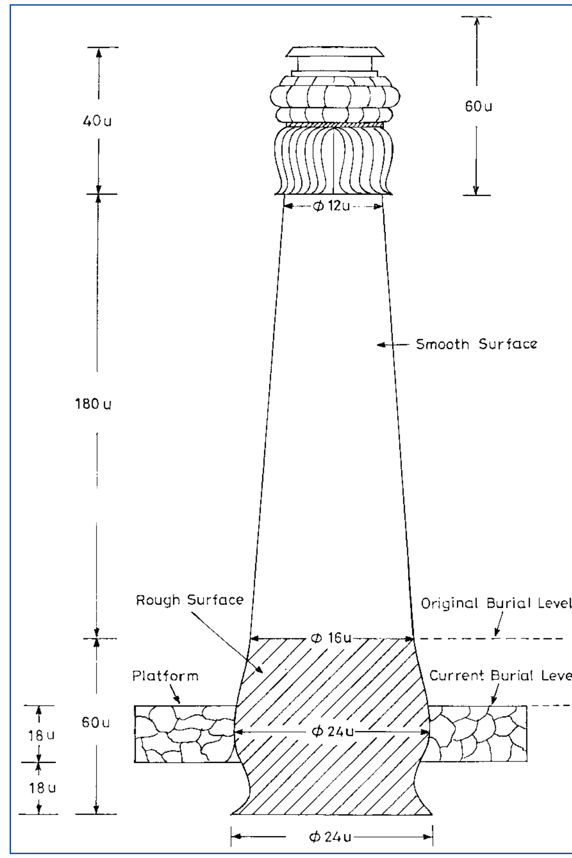


Figure 3. The overall dimensions of the Delhi iron pillar.

The capital was also analyzed in detail for its dimensions (Figure 2). The decorative capital is symmetrical in nature, and its dimensions are relatively uniform. It must be appreciated that the designers of the pillar had originally planned the dimensions very carefully before construction, and the fabricators ensured accurate reproduction of the design.

The overall dimensions of the pillar were also analyzed (Figure 3). The rough portion seen currently at the bottom of the pillar (Figure 4) was originally buried underground in its original location in a Hindu temple; when the pillar was later placed in the mosque, a part of the rough section was exposed.[11] The total length of the pillar, including the top decorative portion adds up to 23 ft. 4 in. The top of the pillar was adorned originally with an idol of garuda (eagle), which was removed when the pillar fell into the hands of the Muslims.[11] The pillar should have measured 25 ft. with the idol on the top of the decorative capital. One fourth (5 ft.) of the main body of the pillar (20 ft.) was placed underground and the rest (15 ft.) appeared above the ground. With the idol atop the pillar, the top decorative portion would have measured one fourth (5 ft.) of the length of the pillar exposed above the ground level, the rest (15 ft.) being the height of the main body above the ground. Therefore, an additional 1 ft. 8 in. of the pillar top is currently missing; this would have been the height of the garuda statue.

General Construction

At the time the Delhi iron pillar was manufactured, the only technique available for manufacturing large iron objects was forge welding, a classic technique that was employed by ancient Indians to manufacture large iron objects.[12] The casting of iron (i.e., the production of liquid iron) was not known in India until later in the 15th century, when furnaces capable of melting iron began operation.[13,14] Moreover, the average composition of the pillar is (in weight percent) Fe-0.15C-0.25P-0.05Si-0.05Ni-0.05Mn-0.03Cu-0.02N-0.005S,[2] from which it is clear that the material is not cast iron (which melts at lower temperatures than mild steel).

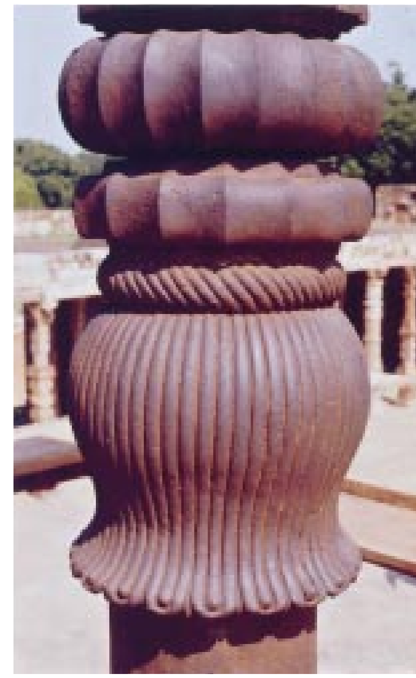
The iron required for forge welding was received in the form of lumps that were obtained by the solid-state reduction of iron ore in the presence of charcoal.[13,14] The iron lumps were later forged together, and the large mass of the pillar was fabricated. The various aspects of the forge-welding (i.e., vertical or horizontal) technology employed to construct the top portion of the Delhi iron pillar have recently been critically analyzed.[12] The analysis reveals that the main body of the pillar must have been manufactured by the vertical-forging technique, while the finishing operations on the pillar (done in order to produce the smooth surface) must have been performed with the pillar in the horizontal position.

Well-preserved Sanskrit inscriptions on the pillar indicate that it was constructed during the reign of Chandragupta Vikramaditya II (375–414), one of the important monarchs of the Gupta dynasty; several significant advances were made in science, arts, and literature during the Gupta rule in ancient India (300–500). The pillar is, therefore, about 1,600 years old. Incidentally, the forging of such large iron objects began in the West in the 19th century.[15,16]

The decorative bell capital has been thought by many authors to be a single mass of metal,[13,17] and moreover, it has been speculated that the decorative top could have been manufactured by casting.[17] However, it can be clearly seen in Figure 5 that the capital is not a single piece, but is composed of several individual parts. Close observation of the surface of the rounded circular discs reveals the remnants of hammer marks. This strongly supports the view that forge welding was used for its construction.

Figure 4. Hammer marks clearly visible where the rough region changes to a smooth region. This rough region was buried underground when the pillar was located originally in a Hindu temple.

The iron lumps obtained from the metal-extraction process had to be shaped into useful objects by the blacksmiths. Forge welding joins pieces of iron by forging the iron lumps in the hot state such that fusion is obtained between the pieces. This process involves the heating of lumps to a relatively high temperature in a bed of charcoal in order to first make them soft and amenable for deformation. Then one lump is placed on top of another and force is applied to weld them into the solid state. As the force is dynamic in nature, it is called forge welding. It can be concluded that casting was not used to manufacture the top portion of the iron pillar.



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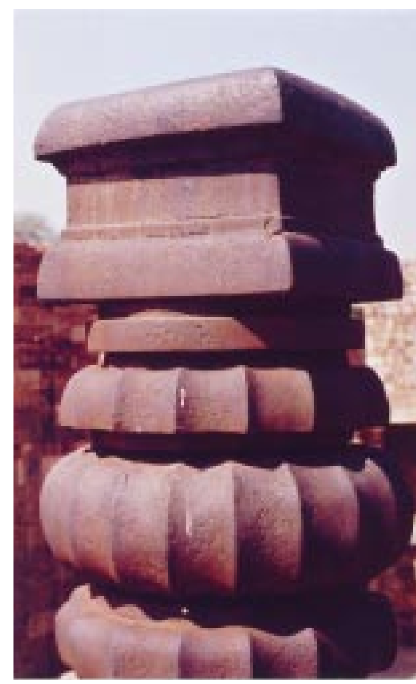

b

Figure 5. The (a) lower section and (b) upper section of the Delhi iron pillar's decorative capital.

Reeded Sections

The bottom of the Delhi iron pillar's capital possesses a reeded bell-shaped design (Figure 5a) reminiscent of the fluted bell capitals that are commonly observed on stone pillars erected in ancient India, notably by Ashoka (272–232 B.C.). Philosophically, this part signified the purna kalasa or "bowl of plenty." The allegory of the "vase with petal and flower" motif is water nourishing the plant trailing from its brim; this is one of the most graceful forms in the whole range of Indian architecture.[18] The bell-shaped design (or kalasa design) is one of the characteristic features of pillar designs that have remained from ancient to modern times. It must be emphasized that the pillar is the main pillar placed in front of the sanctum sanctorum in the main temple courtyard of a Hindu temple.

Figure 6a is a picture of an Ashokan stone pillar capital currently lying upside down at Sanchi, Madhya Pradesh, in which the reeded bell design can be seen. This basic bell design was also adapted by the Guptas, who refined this concept and added further embellishments on top of the design in the construction of their pillars (e.g., at Kahaom and Bittari[18]). The characteristic bell design of the Delhi iron pillar can also be seen in the only standing garuda stone pillar (garudstambh literally meaning "pillar topped with garuda") from the ruined Vishnu temple at Eran (earlier called Erakina), Madhya Pradesh (Figure 6b), constructed around 480 during Gupta rule.[19]

The design of the Delhi iron pillar's decorative capital firmly establishes the date of the pillar's construction during the time of the Guptas. The visible Sanskrit inscriptions on the iron pillar prove that it was constructed during the reign of Chandragupta Vikramaditya II.

Although the Delhi iron pillar is sometimes referred to as the Ashokan pillar, this is certainly incorrect. The similarities in the design of the capital's bell design is the obvious reason for the mistaken identification. However, iron produced during the time of Ashoka did not contain phosphorus, unlike iron produced during the Gupta times, which usually contained a high amount of phosphorus (0.10–0.25%).[20] The history of the pillar has been elucidated recently by Anantharaman.[21]

The decorative reeded bell design of the Delhi pillar's capital was constructed by welding individual iron bars to an iron base. This is seen in Figure 7, which shows the bottom view of the joint between the pillar main body and the reeded bell section. A long iron rod has been forge welded on to the base (possessing the basic bell shape) and after it has reached the bottom, it has again been curved up and taken to the top (Figure 5a). Between the space formed by this bent rod, a straight rod extending from the top to the bottom has been welded. Notice that the long rod that has been bent in the lower portion of the bell capital has also been slightly flattened at the bent region (see also Figure 5a). The central straight rod comes to an end at this bent portion. The straight rod is bulbous at the point where it comes to an end. There are 20 such three-rod assemblies in the fluted design (i.e., 20 straight bars and 20 long rods that have been bent at the bottom), providing a total of 60 rods that meet at the top of the reeded design. This construction results in the reeded design as seen from the bottom of the pillar.

Gaps are created at the bottom of the base between the three-rod asemblies because the bottom of the base has a larger diameter than the top and the rods are of uniform diameter. Small straight rods, extending for a fourth of the distance into the reeded section, are provided between each three-rod assembly to fill the space and aid the visual perspective when viewed from the bottom. These rods can also be seen in Figure 7. There are a total of 20 such rods provided between the three-rod assemblies, providing the visual effect of petals emanating from a bowl, the basis of the purna kalasa design.[18]

The construction method employed for this portion of the pillar attests to the high degree of skill and planning of the ancient Indian blacksmiths. The bell-shaped structure is also symmetric. The total length of the bell section is 17 in., and the diameter is 13.8 in. at the top and 13.4 in. at the concave region. Moreover, the concave section occurs approximately one third from the bottom. The diameter at the bulbous section and at the bottom is 16 in. The bulbous section occurs at one-fourth the total distance from the top of the reeded bell structure (Figure 2). It should be further noted that the diameter of the rods comprising the three-member assemblies are of uniform

a

b

Figure 6. Reeded bell designs of stone pillars on (a) an Ashokan pillar at Sanchi and (b) a Garuda pillar at Eran.

Figure 7. A bottom view of the joint between the pillar main body and the reeded bell section's base. Notice the nature of the rods that have been welded to the base.

diameter (about 0.75 in.).

The next section located on top of the reeded bell structure is a reeded slanted section, consisting of an assembly of rods placed at an angle of 45 degrees in order to produce the fluted design (Figure 8). This appears just above the bell-shaped part. These two parts thus reproduce the design of the capital on the stone pillars (Figure 6). The iron support base for the slanted iron bars is also evident in Figure 8. There are 52 rods (of approximately 0.75 in. diameter) placed in the slanted position in order to create this structure. It is further clear on close inspection that the slanted rods must have been forge-welded onto a base. In the forge-welding operation, a heavy force has to be applied for fusing the rods on to the base; it is very likely that the rods would have lost their rounded shape due to hammering. The hammering down of the round rods can be noted in Figure 8, in which close observation of the rods' surface shows that the rods have been flattened, attesting to the forge-welding technique used to place the rods on the base. Remnants of faint hammer marks are also visible on the surface of other rods. Finally, as the diameter of the rods in this region and in the bell section below are similar, periodic "dislocations" have been created at the interface where the slanted and straight rods meet (Figure 8) in order to facilitate optimum matching of the iron bars. Therefore, it is tempting to state that herein lies the first description of dislocations.

Traces of lead can be discerned in the gaps between the rods, where it appears as a black filling (Figure 8). The presence of lead is also indicated in the joints between the slanted reeded section and the sections above and below it. Lead solder is evident in the joint between the capital and the main body. A detailed analysis of the presence of lead in the iron pillar has revealed that lead was used as a solder material in the fabrication (of iron rods to the base) and joining of the individual sections of the capital.[22] However, in the case of the capital, traces of lead can be discerned only in the gaps between the rods, where it appears as a black filling (Figure 8) and not over the rods. The presence of lead is also indicated in the joint between the slanted reeded structure and the iron disc above it (Figure 8). Therefore, it appears that lead could have also been used as a solder or filling material in the fabrication (of iron rods on the base) and joining of the individual sections of the capital.

Circular Sections

On top of these two reeded rod structures, a 16 flat-sided circular decorative iron disc of 15.6 in. diameter is placed. The outer surface of this part shows hammer markings (Figure 5a) that are indicative of the forge welding technology employed to construct the part. It is important to also note the projections at the top (Figure 9) and bottom regions (Figure 8) of this disc. This flat portion of the disc is clearly visible in Figure 9, which is a close-up view of the joint between the circular disc and the one above it. The flat portions are each approximately one inch in thickness and 12 in. in diameter. Close examination of Figure 9 reveals another projection (similarly flat, 16 sided, and 10 in. diameter) that projects into the section above it. The height of this section is 0.5 in.

A larger 20 sided circular disc with a 17 in. diameter, similar to that of the lower 16 sided disc, appears next. This piece is thicker than the one below it. From Figures 9 and 10 it can be concluded that this piece contains a hollow slot in the central axis and does not have a flat region in its upper and lower regions like the discs below and above it.

Figure 8. Details of the reeded slanted rod section of the Delhi iron pillar.

Figure 9. A close-up view of the joint between the 16 sided circular disc and the one above it.

Figure 10. A close-up view of the joint between the 20 sided circular disc and the one above it.

Figure 11. A close-up view of the circular part just below the topmost square pedestal.

On top of the 20 sided disc is fitted another 16 sided circular disc (Figure 5b), whose diameter (14.4 in.) is slightly smaller than that of the two discs that come below it. This section is not completely curved like the lower two parts; it is only half-curved, with flat bottom (Figure 10) and top (Figure 11) projections. These flat portions are also 16 sided and 0.5 in. thick. In the bottom of the flat region, there is another projection (visible in Figure 10) 10 in. in diameter and 0.5 in. tall that protrudes into the 20 sided section below it. Notice that the gaps between the individual parts are well maintained, indicating the careful engineering design and accurate reproduction of design.

The designers of the pillar had perspective in mind while designing the various components of the decorative capital. The 16 sided circular piece is not fully curved so that when the pillar is viewed from the bottom, as it would normally be, this piece would appear fully rounded. The thickness of this section (2.5 in.) is, therefore, not in strict relative proportion like the other members of the capital. If the disc was fully curved, the visual effect would not be attained. Note also that the bottom flat projection of this piece is thicker, further aiding this section to appear rounded from the bottom.

On the top portion of the 16 sided disc, a flat projection is present similar to the one seen on the bottom. A fully rounded disc 12.8 in. in diameter is placed on top of the 16 sided half-curved disc (Figure 11). The section seen is part of this disc, and its height and diameter are 1 in. and 12 in., respectively.

Box Pedestal

At the top of these decorative circular discs, a square box-like structure was fitted into the pillar, with projecting top and bottom faces. On careful observation of the bottom portion of this structure, an apparent gap is seen between its bottom and lower circular discs. The box-like design represents a pedestal (abacus) on which an idol or emblem was normally placed.[18] The pedestal (which can be either circular or square) is another characteristic of pillar (stambh) designs of North India from the Mauryan times (600 B.C.). The plan of the structure indicates that its top and bottom faces are exactly one foot in length on the sides and 2 in. thick. The total height is 8 in.

The bottom face of the structure has four 0.5 in. diameter holes that are located symmetrically at the four corners of the base. Only one of them is completely open, and the other three contain fractured iron rods protruding from them. The open hole is very clearly visible (Figures 10 and 12) and shows no sign of rusting or distortion at this region. On corresponding locations in the bottom of the top face, fractured rods can be seen at three corners.

Each rod, welded to the top and bottom faces, probably contained a figurine of a lion situated at the corner of the pedestal. This is the standard design that appears at the corners of the decorative pedestals of Gupta garudstambhs (Figure 6b). These figurines and the garuda statue at the top would have been removed from the pillar during the destruction of the temple by the invading Muslims, because the depiction of human and animal figures are forbidden in Muslim architecture. It is likely that the figurines would also have been constructed out of iron, since the entire pillar was manufactured out of iron and there are no visible galvanic corrosion effects noticed at the locations of these holes.

One of the four corners of the top protrusion of this structure is partially fractured, and the rod here is missing. A detailed investigation of this region indicates that the assembly is a single piece of metal (Figure 13) and not constructed out of plates. The box-like pedestal possesses a square section at the top. On the top surface, the presence of a circular 8 in. diameter cylinder intersecting the surface is evident (Figure 14).

A circular slab covers the hollow cylinder. This slab contains a rectangular 6 in. × 2 in. slot at the center to hold a statute of garuda, as discussed earlier. The garuda figure is now missing, and the horizontal slot seen on the top of the pillar indicates the place where the garuda statute was anchored originally. It appears that the garuda idol, con-

Figure 12. Holes in the lower base of the box pedestal.

Figure 13. A fractured section of the top pedestal, indicating that it is a single piece of wrought iron.

Figure 14. The top surface of the Delhi iron pillar's capital.

structed on a circular base, was welded on to the top of the cylindrical pipe, and this is the circular welded region seen in the top plan (Figure 14). It is also reasonable to assume that the garuda statue would have been constructed of metal, although the exact material used for its construction is speculative.

FITTING METHODOLOGY

The possible fitting methodology employed to construct the decorative capital can be deduced by considering several options and is based on present and earlier[5] observations.

Shrink Fitting over the Pillar Main Body

The first method by which the individual pieces may be arranged in the form of the capital is by simple shrink fitting of the individual pieces on to the main body of the pillar. This fitting methodology is schematically represented in Figure 15. Although this method seems simple at first glance, the detailed study of the joints between the individual pieces do not support this idea. The diameter of the joint regions has been carefully measured and determined to be nearly constant. The main body of the pillar shows a strong taper: the diameter of the main pillar body at the region just below the fluted design is 12 in., while the diameter at the start of the smooth section at the bottom is 18 in. It is anticipated that the pillar's diameter in the top region would also exhibit this taper, in which case the joint regions in the upper portions should be of smaller diameter than the bottom portions in order to shrink fit the individual pieces. However, this is not so, and it is concluded that the shrink fitting method illustrated in Figure 15 is not the likely method of fitting the pieces. Moreover, the handling of the pillar, with the individual pieces shrunk fit over it, would have proved difficult from a practical point of view.

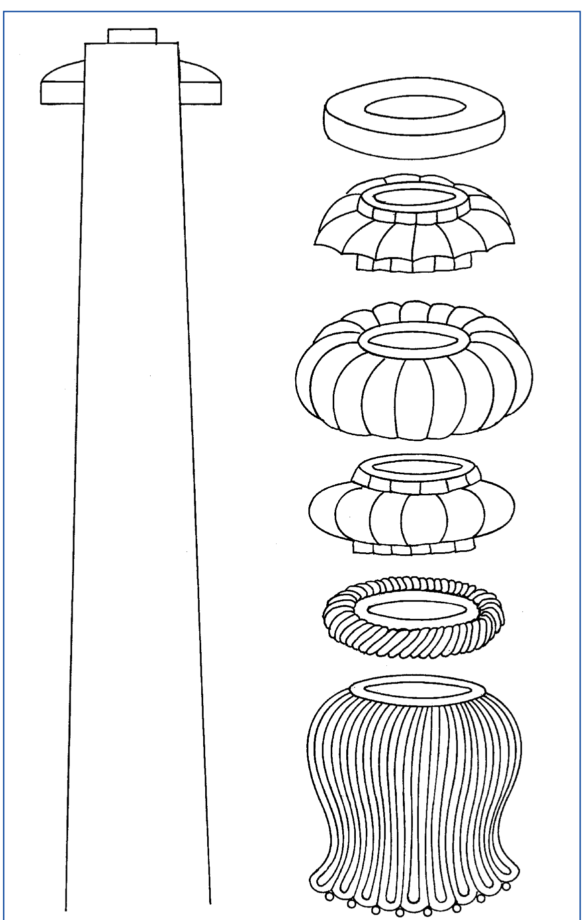

Figure 15. A possible method of shrink fitting the individual sections that constitute the decorative top capital around the main body of the pillar.

Shrink Fitting over the Cylindrical Shaft

Important information regarding the fitting methodology is gleaned from the observations of Ghosh,[5] who studied the top portion of the Delhi iron pillar in 1959. He mentions that the depth of the top slot is 1 ft. 3 in. from the top surface. In the present investigation, it was not possible to measure this as the hole is currently filled with wax. This indicates that a hollow cylinder (whose section intersects the top face of the pedestal) extends to at least 1 ft. 3 in. below the top surface. Measurements of the pillar capital indicate that the distance extends to the bottom portion of the half-curved 16 sided circular disc. Therefore, the pedes-

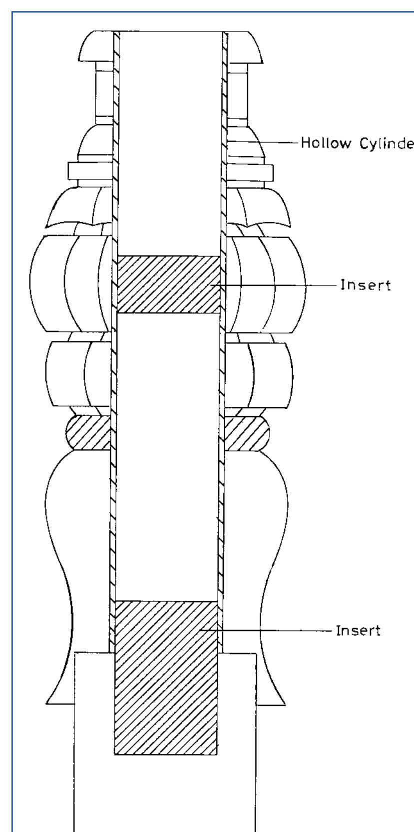

Figure 16. Shrink fitting the individual sections of the capital around a hollow cylindrical iron pipe. The pipe was later connected to the top of the main body of the pillar with the aid of inserts.

Figure 17. The presence of a central hole on the top surface of the Ashokan stone pillar at Sanchi indicating that cylindrical inserts were utilized for joining pillar bodies to their capitals.

tal, the round disc below it, and the half-curved 16 sided circular disc have been shrunk fit around a cylindrical hollow shaft.

This fitting methodology is shown schematically in Figure 16, where the cylindrical shaft is shown extending all the way from the top to the bottom of the capital. In this figure, the individual pieces are sectioned in the middle to expose the cylindrical hollow shaft. As the depth of the slot does not extent beyond 1 ft. 3 in., the presence of an obstruction is indicated in the cylindrical shaft in the region of the larger 20 sided circular disc. As the cylindrical shaft should extend all the way to the bottom of the bell-shaped section, the obstruction noted by Ghosh[5] midway to the large piece could be due to the presence of an insert.

It can be assumed, based on this discussion, that the other sections have been similarly shrunk fit around the cylindrical shaft. In view of this, the shaft should extend to the base of the reeded bell-shaped structure. This is also shown in Figure 16; the relative dimensions of the shaft and inserts have also been hypothetically provided. The cylindrical hollow shaft would have aided easy handling of the pillar capital during its fabrication. The capital could have been easily manipulated by placing holding supports at both ends of the hollow shaft that would have been removed when the entire fabrication operation was completed. Moreover, it would have been possible to fabricate the capital independent of the pillar main body's construction.

Once the fabrication of the pillar capital was complete, it must have been fit to the top portion of the main body of the pillar. Later, the top surface of the capital was topped with the idol of garuda, the base of which is still visible on the top surface of the pillar.

Capital to the Main Body

The fitting of the decorative bell capital to the main body of the pillar must have been done in the traditional Indian way, in which the capitals of stone pillars were fit on the main body of the pillars with the aid of inserts. The cylinder around which the various constituents of the decorative capital have been shrunk fit must have been fixed to the top of the main body of the pillar by means of an insert (Figure 16). In order to accomplish this, the main body of the pillar should extend a small distance into the bottom region of the bell-shaped structure. A circular hole must have been provided on the top surface of the main body of the pillar for clamping the insert. The bottom of the hollow cylindrical shaft on which the individual pieces were shrunk fit would grip this insert (Figure 16). This methodology was regularly employed in the fitting of decorative capitals to the main bodies of stone pillars; an example of this is provided in Figure 17, which shows the top section of the (broken) main body of the Ashokan pillar currently lying face down at Sanchi. Its matching decorative capital (similar to that shown in Figure 6a) shows a hole of similar diameter in the center, proving that inserts were used in joining the main body of stone pillars to their decorative tops. Therefore, it can also be reasonably assumed that a similar method must have been used by the ironsmiths in joining the decorative bell capital of the Delhi iron pillar to the main body of the pillar.

CONCLUSION

It is important to perform careful ultrasound measurements on all the various sections of the decorative capital in order to obtain further insights into the shrink-fitting methodology. Nevertheless, based on the amount of information available and with the aid of critical analysis, it is believed that the capital was fabricated from individual pieces (produced by forge welding and not casting). Secondly, the individual pieces that constitute the capital have been shrunk fit on a hollow cylinder in an artistic and aesthetic manner keeping sound engineering principles in mind.

ACKNOWLEDGEMENTS

The author thanks the Archaeological Survey of India for their permission to study the Delhi iron pillar and R.K. Bhatnagar of the Department of Humanities and Social Sciences, Indian Institute of Technology, Kanpur, for his keen interest.

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