On materials science aspects of impact of cannon ball on the stability of the Delhi Iron Pillar

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The Delhi Iron Pillar was struck by a cannon ball with the specific aim of breaking the pillar into two. The history of the cannon ball strike has been traced briefly. The trajectory of the cannon ball has been established from the surface features of cannon ball indentation area as well as from the direction of shock wave propagation. The materials science aspects related to the pillar's response to the cannon ball strike have been explained. The nature and origin of cracks surrounding the cannon ball indentation area have been analysed. Visual evidences have been provided to support the sequence of events that followed the cannon ball impact, in a time period of about a microsecond. These included intense plastic deformation leading to creation and propagation of plastic shock wave, initiation of crack at the rear, spallation of material, horizontal propagation of the main crack, and finally branching of the main crack along lump–lump interfaces. The analysis concludes that fracture of the pillar was avoided by deflection of the propagating horizontal crack that originated from the rear end, diametrically opposite the cannon impact area, along the axial direction of the Pillar through lump–lump interfaces.

Keywords: Cannon ball, Delhi Iron Pillar, plastic deformation, shock wave.

THE Delhi Iron Pillar[1–3] located in the courtyard of the Quwwat-ul-Islam mosque near Qutub Minar, New Delhi is a marvellous engineering construction (Figure 1 *a*), considering that it was forged out of individual iron lumps, almost 1600 years ago during the reign of Chandragupta II Vikramaditya (AD 375–413). Its exceptional atmospheric corrosion resistance (due to the presence of significant amount of phosphorus in solid solution[4]) has further attracted the attention of corrosion technologists and scientists, eager to unravel its mysteries. New insights have been obtained on several aspects of the pillar, including its history[5], manufacturing methodology[6], corrosion resistance[7] and astronomical significance[8].

One of the significant marks on the pillar is the indentation of a cannon ball that struck the pillar for a brief moment ($<10^{-6}$ s) in its history (Figure 1 *a*). The indentation is located at 156 in from the current courtyard ground level (Figure 1 *b*). The diameter of the cannon ball has been estimated to be 5 inches based on plaster of Paris cast of indentation area[9].

The origin of the cannon ball indentation will be first understood, briefly. It is not precisely clear when the cannon ball struck the surface, as there are no historical evidences in the form of inscriptions or documents outlining who fired the cannon ball. While there are literary evidences to prove that cannons were used in the subcontinent in the 15th Century AD, the first large-scale use of cannons was by Babur in the First Battle of Panipat[10] in AD 1526. Therefore, the date of cannon ball strike cannot be more than 500 years, conservatively. Historical traditions maintain that the cannon ball was fired either by Nadir Shah[11,12] in AD 1739 or Ghulam Quadir[13] in AD 1788. Based on historical records, the former is likely to have fired the shot. As the cannon ball was aimed above the central portion of the pillar (Figure 1 *b*), the intention of firing the cannon shot appears to have been to remove the top portion of the pillar, which contains the artistically meritorious decorative bell capital[14]. If the intention was to completely destroy or damage the pillar, there were other efficient methods like mining using gunpowder[15].

Some aspects of the cannon ball strike have been earlier addressed briefly by Prasad and Ray[12]. They concluded that the strike was intentional and that an expert artillerist directed the cannon fire. They proposed that the well-placed cannon did not try a second shot because the deflected cannon ball damaged something else in the vicinity. The possible damage caused to the structures has been analysed in greater detail elsewhere[16]. The location of the cannon that fired the shot can be determined from the trajectory of the cannon ball and location of the indentation. The trajectory has been determined to be 15° based on two approaches as described below. Utilizing the location of the indentation (156 inches from the ground level) and that the cannon must have positioned at a height of 5 ft (or 60 inches) from the mosque courtyard level (i.e. resting on carriage), it is estimated that the cannon was located at a distance of approximately 30 ft (namely 358 inches = 156–60/tan 15) from the pillar when it was fired. This cannon location has been marked in Figure 2 and is well within the courtyard. This discounts the possibility that

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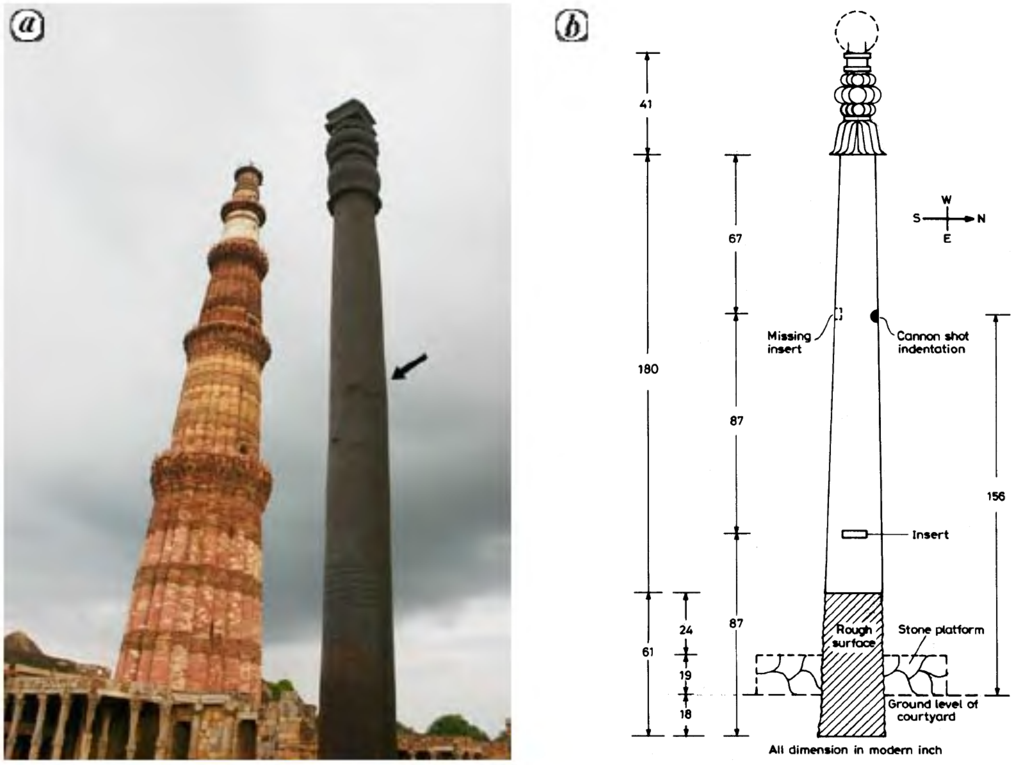

Figure 1. *a*, Delhi Iron Pillar located at the Quwwat-ul-Islam mosque in the Qutub Complex, New Delhi. Arrow shows the cannon ball strike location on the pillar. *b*, Salient dimensions of the pillar showing the relative position of the cannon ball indentation and the inserts. The overall symmetric design of the pillar must be appreciated.

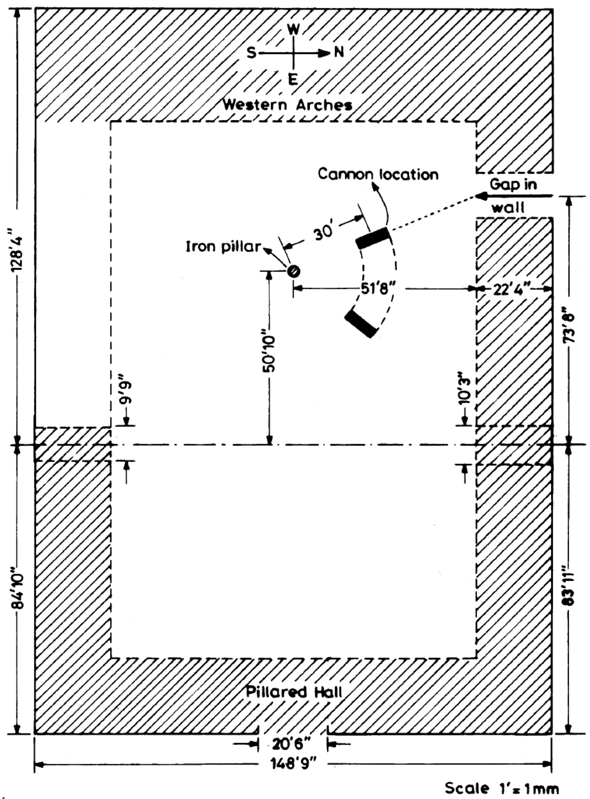

Figure 2. Plan of the Quwwat-ul-Islam mosque showing the salient dimensions of its premises and the possible location of the cannon that fired the shot.

the cannon ball may have reached the pillar's surface after having been lobbed over the mosque boundary.

Further, Prasad and Ray[12] noted several smaller diameter indentation marks and concluded that these indicated that sledgehammers were first used to topple the pillar and thereafter the cannon shot was fired. The sledgehammer marks (Figure 3 *a*) belong to a time when the pillar was originally forge-welded from individual lumps (of approximate weight 20–30 kg) by horizontal forge-welding method, with the metal lumps added to the main body in a sideways fashion[6]. Some smaller indentation marks located about waist level (black arrowed location, Figure 3 *b*) are craters due to shots fired from small arms, and not due to cannon fire.

The main aim of the present article is to analyse the impact of the cannon ball on the stability of the pillar, from a materials science perspective, utilizing physical evidences. The sequence of events that took place, from the moment the cannon ball impacted the surface, will be analysed. These events took place in a time period of less than a microsecond.

Plastic deformation on impact

The cannon shot indentation area holds valuable material evidences for understanding the material response to the cannon ball impact. A close-up view of this area is shown in Figure 4 *a*. The following observations can be readily

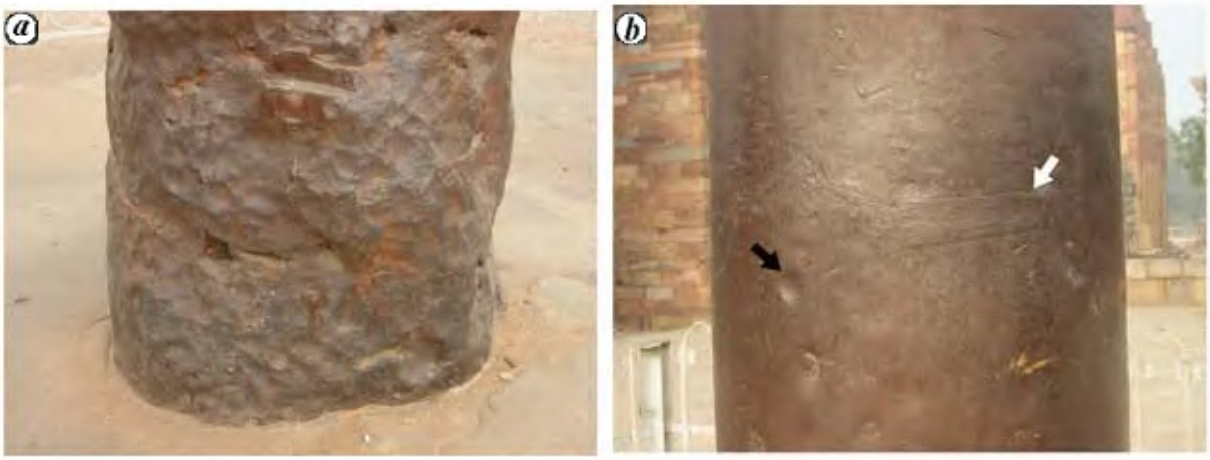

Figure 3. ***a***, Sledgehammer marks on the bottom portion of the pillar due to the original manufacturing technology. ***b***, Indentation mark (black arrow) caused by a shot from the fire arm. The outlines of a rectangular insert can be noted at the location indicated by the white arrow.

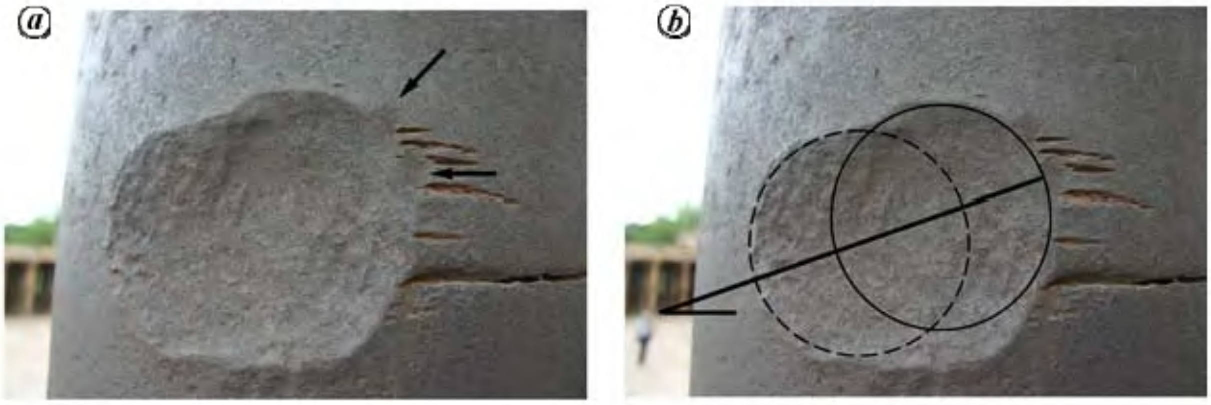

Figure 4. Close-up view of the cannon ball indentation location. ***a***, Two shear lips around the cannon ball crater (arrows). ***b***, Analysis of the indentation area showing the location where the cannon ball first made an impact (dotted circle) and location where the cannon ball came to a halt (full circle). The trajectory of the ball is indicated by the slanted line.

made. First, the complete impression of the cannon shot is not perfectly circular and the depression is skewed. The depth at the right side (Figure 4 *a*) of the indentation is more than that at the left side (Figure 4 *a*). The left side of the indentation, due to its lower depth[9], indicates grazing of the ball on its way to the impact. The exact location of the final impact is on the right side of the indentation.

The direction of the cannon shot is deduced to be from the northern direction (Figure 2). The cannon ball first made contact on the left side of the indentation area (dotted circle, Figure 4 *b*) and then came to rest on the right side (full circle, Figure 4 *b*). The trajectory of the canon ball can also be understood by noting the relative position of the centres of these two circles (slanting line, Figure 4 *b*). The trajectory points from the bottom to the top, thereby confirming that the cannon shot landed on the pillar on its upward motion from the cannon. Another important conclusion is that the angle of the trajectory is 15°, as determined using the slanting and the horizontal lines in Figure 4 *b*.

The plastic strains generated due to the initial grazing motion of the ball and the final impact can also be clearly distinguished on the indentation area (Figure 4 *a*). The surface features on the left of the cannon ball indentation area reveal material removal due to grazing motion of the high-velocity projectile. The features on the right reveal higher degree of deformation caused by the final impact. That the final impact was on the right side of the indentation is further corroborated by a important material evidence, namely the creation of shear lips just at the right of the cannon ball strike location. This is indicated in Figure 4 *a*, where two shear lips are shown (arrows).

The origin of the shear lip is due to material erosion effects at the high velocity projectile impact. When a dense material (like lead cannon ball) impacts the surface with force, it is shattered due to the impact force and the shattered small pieces cause further deformation at the edges of the main impact location[17]. The appearance of these shear lips confirms the fracture of the cannon ball into smaller fragments after striking the surface. It is indeed surprising to still notice such visible evidence even after such a long period after the event. It has been shown elsewhere[9] that the cannon ball that struck the pillar was about 5 inches in diameter and the material of the shot was most likely lead.

The heat generated during the high energy impact has to be dissipated. Generally more than 90% of the energy expended in plastic deformation is converted to heat[18]. The metal flow is not homogeneous and therefore, the deformation is localized and temperature rises within this local region. Because the flow stress of a material generally decreases with rise in temperature, further deformation is concentrated in this localized zone and the process continues till fracture occurs, if the impact is of sufficient energy.

A rapidly applied load is not instantaneously transmitted to all parts of the solid body. After a brief moment when the load has been applied, the remote portions of the body remain undisturbed. Depending on the velocity of impact, two events may take place. The first is local fracture at the impact area, by which the impact energy is dissipated. The second process is the generation of a compressive stress wave that propagates at high velocity into the material. The deformation and stress produced by the load move through the body in the form of a shock wave.

Generally, fracture occurs at the location of the impact for projectile velocities above 30 m/s in case of metallic materials[18,19]. The impact of the cannon ball did not fracture the pillar at the location of the impact because the region of impact shows ductile deformation and no fracture in the cannon ball impact area (Figure 4 *a*). This important observation confirms that the velocity of the cannon ball was not greater than 30 m/s.

Generation of plastic shock wave

The impact did not fracture the pillar at the impact area, but resulted in the generation of intense plastic compressive stress shock wave. Due to the high rates of deformation, there is insufficient time for appreciable metal flow, and near adiabatic conditions are maintained. This leads to adiabatic shear deformation, which produces adiabatic shear bands. The adiabatic shear bands will be of microscopic nature and cannot be seen by the naked eye, but can be seen using transmission electron microscopy. Indirect evidence for the presence of shear bands can be obtained by carefully analysing the *in situ* optical micrograph taken from this location of the pillar[20]. An intense band of straight lines can be seen in the *in situ* micrograph taken near the cannon shot indentation location (see figure 3, Ganesan[20]). These bands of deformation lines indicate severe plastic deformation at this location and more importantly, the mechanism of deformation (i.e. adiabatic shear).

From a materials science perspective, the generation of shock waves due to the impact is of great interest, in particular flow and fracture under rapid rates of loading. On viewing the spectrum of strain rates that are available for deformation of materials, for strain rates 10°/s and above, the deformation is essentially adiabatic shear because the internal heat generated during plastic deformation does not have sufficient time to be dissipated away. Under faster rates of loading (10^2–10^4/s), elastic and elastic–plastic wave propagation must be considered in detail, while for still higher strain rates (10^4–10^6/s), plastic shock wave propagation and reflection are important[18,19].

Several material properties come into play when deformation at high strain rates is analysed, like effect of temperature on flow properties and the fundamental mechanical behaviour of the material (i.e. stress–strain curve).

Physical evidences confirm compressive flow of material at the impact location (Figure 4 *a*). The relationship between the velocity of the compressive stress wave and material velocity needs to be understood. The velocity of the material at the point of impact is a function of material property and is given by[18]

$$v_x = \int_0^e \left(\left(\frac{\mathrm{d}s}{\mathrm{d}e} \right) / \rho \right)^{1/2} \mathrm{d}e, \tag{1}$$

where ds/de is the slope of engineering stress (s)–engineering strain (e) relation and ρ the density of the material. Equation (1) leads to the important conclusion that at the tensile strength of the material, when ds/de = 0, the velocity is zero. This condition defines the critical impact velocity. Had the pillar been struck with a velocity greater than the critical velocity, then it would have ruptured at the impacted area at the instant of the impact and only a weak compressive stress wave would have propagated across the pillar. The value of critical impact velocity[18] for most materials is of the order of 30–150 m/s. There is no physical evidence of fracture at the point of impact (Figure 4 *a*). Therefore, it is important to focus on the plastic deformation and the propagation of plastic deformation waves (shock waves or compressive stress waves).

The propagation of the stress wave will depend on material properties[21,22]. The velocity of the stress wave (σ_x) scales linearly with the material velocity according to the following relation

$$\sigma_x = \rho c_0 v_x, \tag{2}$$

where c_0 is defined as $(E/\text{density})^{1/2}$ and known as the elastic wave velocity, E the Young's modulus.

The particle velocity, given by eq. (1) above, is important because it tells what would be the effect of the impact based on material property (i.e. the engineering stress vs engineering strain behaviour). The slope of the engineering stress–engineering strain curve (i.e. $\mathrm{d}s/\mathrm{d}e$) is an important consideration. This changes with degree of plastic strain, and therefore each increment of plastic compressive wave propagates with different velocities. Therefore, the shape of the plastic wave changes as it propagates through the material.

It is important to consider material response for the cases when $\mathrm{d}s/\mathrm{d}e$ decreases or increases with strain. In the general case, $\mathrm{d}s/\mathrm{d}e$ decreases with strain and therefore, the wavefront becomes diffuse. However, if the material shows pronounced yield point phenomenon, $\mathrm{d}s/\mathrm{d}e$ increases with strain. In such a case, higher compressive waves travel faster and the wavefront sharpens into a plastic shock wave[23]. Large strains travel faster than small strains and the wavefront sharpens into a plastic shock wave. Since the material of the pillar is BCC iron, the latter case will apply and therefore, it is reasonable to conclude that an intense shock wave propagated through the body of the pillar immediately after impact. This is another major conclusion of the present study based on careful observation and technical analysis of the cannon shot indentation area.

Propagation and reflection of shock wave

The consequences of propagation of plastic shock wave (compressive stress wave) through the pillar will be now explored. It is assumed that the compressive stress wave travels in one direction, in the direction of the shock front. This is strictly true for the case of thin plates. The shock wave propagation will be in all directions in case of the relatively bulky cylindrical shaped body of the pillar. However, even with this simplifying assumption, fairly good insights can be obtained.

In particular, it is important to consider the reflection of shock waves due to the free surface, to understand the nature of cracking seen on the side and rear side of the cannon ball indentation area. Reflection of stress waves generally occurs at the free surface and fixed ends, at changes in the cross-section and at discontinuities within the solid[18]. The effect of shock waves on material fracture can be understood[18] by considering Figure 5. A compressive shock wave propagates through the solid and approaches the surface from left to right (Figure 5 *a*). At the free surface, the wave is reflected back as a tensile wave from right to left (Figure 5 *b*). Therefore, the net stress is obtained at this location by summing up the incident compressive stress and the reflected tensile stress. It is noted that there is rapid build-up of tensile stress as the wave is reflected back from the free surface (Figure 5 *b*). When this tensile stress reaches a high enough value, fracture occurs.

The local fracture adjoining the impact location (to the right of the cannon ball crater) is aligned along a certain direction (Figure 6). Its origin is due to the interaction of the travelling plastic compressive stress shock wave with the free surface. Its arrest resulted due to the velocity of the moving plastic wave being higher than the crack velocity. Shock waves propagate in solids at the rate of 1–6 km/s, while the velocity of crack propagation[18] is of the order of 2 km/s. Therefore, with impulsive loading, it is generally noticed that cracks form but do not have time to propagate before the stress state changes. This explains the cracking seen on the right side of the cannon ball mark on the pillar (Figure 6).

It is also possible to estimate the trajectory of the cannon ball by relating the crack direction to the direction of the travelling shock wave. Since the cracks adjoining the indentation area are related to the direction of propagation of the wave, it is reasonable to conclude that the trajectory is given by the alignment of the cracks with respect to the horizontal. This has been marked by a slanted line in Figure 6. The angle it makes with the horizontal is 15°. The estimated trajectory matches well with that estimated from features of indentation area (Figure 4 *b*).

Spallation

Once the travelling shock wave reached the free surface, it resulted in cracking (Figure 7). In the rear location, one

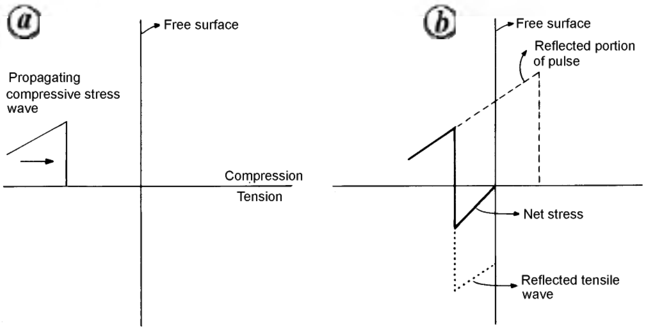

Figure 5. (*a*) Propagation of compressive stress wave and (*b*) reflection as a wave from the free surface resulting in net tensile stress near the free surface.

Figure 6. Cracks on the right side of the cannon shot indentation area are aligned in the direction of propagation of the shock wave generated due to the impact (slanted line).

can see a triangular piece of metal and an almost rectangular lump of metal that fractured and spalled out of the surface (Figure 7). The outline of the missing rectangular material, delineating a missing insert, has been highlighted by dotted lines in Figure 7.

The triangular piece appears to have been a patchwork used to even out the surface. Careful observation revealed that the smooth surface of the pillar was produced by filling all cavities on the surface with smaller bits of iron and later the entire surface was chiseled, burnished and polished[6]. It is confirmed that the triangular piece was a patchwork by noting that the cracking had not progressed from the edges of the triangle. Rather, cracking is evident below the spalled triangular region (Figure 8).

The material from the rectangular-shaped spalled region is not patchwork material. It is a rectangular insert originally present at this location to aid in the manufacture of the pillar[6]. Briefly, the insert is the remnant of the handling clamp used to manipulate the pillar during its manufacture. Later on, once the pillar was fabricated, it was chiselled away, leaving only the rectangular insert buried on the surface. A similar rectangular insert can still be found in the lower region of the pillar and the two inserts are symmetrical placed with respect to the pillar's dimensions (Figure 1 *b*). The location of this remaining insert is shown in Figure 3 *b* (white arrow).

Figure 7. View of the cracked region on the rear, diametrically opposite to the cannon ball strike location. The outline of a previously present horizontal insert is highlighted with dotted line. Note that the material to the left side of the insert was removed by ductile shearing.

Figure 8. Close-up view of the triangular-shaped spalled region on the rear side.

The rectangular shape of the spalled insert can be confirmed by well-delineated straight lines on top and right of the region (Figure 7). However, the shape at the left bottom region is not perfectly rectangular and additional material appears to have been sheared with the insert. This can be concluded based on fracture features (plastic tearing) observed on the bottom left portion of the area (see Figure 7 and right side of Figure 8 for higher magnification view). Therefore, it is reasonable to conclude that when the remnant of the clamp was dislodged from the surface, it had fractured some of the material of the surface by plastic tearing.

Deflection of crack

The interaction of the fast propagating horizontal crack, which originated from the rear, with the material structure of the pillar will finally be understood. In particular, the interaction of the crack with defects in the structure needs to be considered. While the cracks will travel relatively unhindered in a homogeneous material, the propagating cracks may release energy by forming smaller cracks at locations of material discontinuities and inhomogeneities.

On a microscopic scale, the major imperfections are entrapped slag particles[20,24–27], which are distributed over the microstructure and they are relatively small in size compared to the grain sizes. Therefore, the shock waves will not cause major damage at these locations. On a macroscopic scale, the major defects are the lump–lump interfaces which were created during the process of forge welding the lumps together during the original manufacture of the pillar[6].

Observation of the cracking pattern noted on the side (Figures 6 and 7) and back side of indentation mark area indicates that the propagating horizontal crack from the rear side has opened out some of the lump–lump interfaces (Figure 9). The nature of cracks (i.e. close relationship between the horizontal crack and the deflected cracks delineating lump–lump interfaces) confirms that lump–lump separation is not due to the onward travelling compressive shock wave, but due to the deflection of the horizontal crack propagating from the rear of the pillar surface.

It further appears that the separation of lump–lump interfaces is also realized within the body of the pillar at this location (Figure 9). In non-destructive studies conducted on the pillar[27], evidences for the presence of curved, hollow spaces were obtained near the cannon ball strike location by gamma radiography. The thickness of these hollow spaces is very small. These elongated, curved, hollow spaces are shown schematically in Figure 10. The imaging of the region around the cannon ball mark by gamma radiography provides valuable proof of fabrication of the main body (using iron lumps forge-welded on the horizontal pillar in a sideway manner). It also offers convincing proof of deflection of the propagating horizontal crack along lump–lump interfaces.

Figure 9. Side view of the pillar at the cannon ball strike location showing deflection of the horizontal crack from the rear (right side of the image) to the axial direction of the pillar by cracking of lump–lump interface.

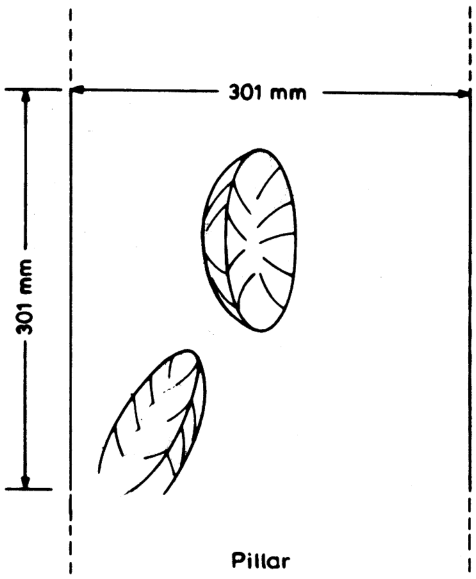

Figure 10. Schematic of elongated, curved, hollow spaces in the main body of the pillar near the location of the cannon ball strike. This has been recreated using the gamma radiographs presented in figure 3 of Raj *et al.*[27].

It is important to appreciate the fact that lump–lump interfaces were not aligned across the cross-section in a horizontal manner. The manufacturing methodology of the pillar resulted in vertical lump–lump interfaces. A full discussion of the positioning of the lumps during fabrication of the pillar is available elsewhere[6]. The vertical alignment of lump–lump interfaces is also confirmed from the cannon ball strike area (Figure 9), thus discounting the vertical forge-welding methodology of manufacture of the pillar[28,29].

Recreation of the sequence of events

The sequence of events after the cannon ball strike can be recreated as follows. The cannon ball was directed from the north direction, based on the position of the cannon shot indentation on the northern side of the pillar. The cannon was located quite close to the pillar, when it fired the shot. The cannon ball impacted the surface of the pillar on its upward trajectory. It first grazed the surface before coming to rest. The cannon ball shattered on impact. The impact did not lead to fracture at the impact location, but resulted in the creation of an intense compressive plastic shock wave, indirectly confirming that the velocity of the cannon ball was less than 30 m/s. The intensity of the shock wave increased with distance of propagation, due to the material of the pillar (i.e. BCC iron) exhibiting yield point phenomenon. The result was a highly concentrated stress wave. This compressive stress wave was reflected by the free surface at the end diametrically opposite the cannon impact area. The reflected wave was tensile in nature and resulted in the generation of a tensile stress in the rear. This led to horizontal cracking of the main body of the pillar. A triangular-shaped patchwork material and rectangular-shaped insert on the surface were removed due to the fast-propagating horizontal crack. This horizontally travelling crack did not lead to fracture of the pillar into two, because it was deflected in the axial direction of the pillar due to the presence of lump–lump interfaces aligned along the axial direction of the pillar. In this manner, the horizontal crack did not traverse the cross-section of the pillar and broke it into two.

The processes by which the impact energy of the cannon ball was dissipated were heat and sound generation, creation of the crater (i.e. plastic deformation) at the point of impact, cracking on the side and the rear, horizontal cracking and spallation of lumps from the rear and deflection of fast-propagating horizontal crack by separation of lump–lump interfaces. It is important to note that the ductility and strength of the pillar (or toughness, which considers both strength and ductility) were not important because the critical fact that determined the pillar's stability was the presence of lump–lump interfaces.

In fact, the design of advanced composite materials with improved toughness relies on dissipation of crack energy by deflecting the fast-propagating crack in the matrix phase through weaker matrix-reinforcement interfaces in the material[30].

The structural mechanics aspects of the problem of stability of the pillar, on account of the impact of high-velocity projectile, may be further analysed rigorously through computational tools. The metallurgical response of the pillar can be substantiated with a more objective methodology, such as 'a simplified shell theory-based mathematical model of a cylinder being impacted by a spherical ball, or a numerical simulation employing a commercial explicit contact-impact finite element analysis code'.

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ACKNOWLEDGEMENTS. I thank the Archaeological Survey of India (ASI), New Delhi for the co-operation extended during studies on the Delhi Iron Pillar. I also thank Dr B. Venkataraman, Defense Metallurgical Research Laboratory, Hyderabad, and Dr G. Sundararajan, International Advanced Research Centre for Powder Metallurgy & New Materials, Hyderabad for fruitful discussions on the subject of high-velocity projectile impact on properties of engineering materials. I wish to acknowledge the reviewers for their critical comments and Mr V. N. Prabhakar, ASI for assistance.

Received 19 May 2008; revised accepted 5 July 2008