The Remarkable Pu Jin Bridge of Yongji, China

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ABSTRACT

Reported to be the first iron bridge in the world, the Severen River Bridge at Coalbrookdale, United Kingdom, was completed in 1779. However, the ancient Yellow River Floating Pu Jin Bridge of Yongji, China, whose anchorages were recently found, was composed not only of wooden pontoons and a timber roadway, its main structural elements consisted of wrought iron chains and cast iron anchorages. More remarkable still is the fact that the Pu Jin Bridge was constructed in A.D. 724, more than a thousand years before the Coalbrookdale bridge and it contained more than twice as much iron. Equally remarkable was the discovery that a large portion of the anchorage iron was made in the form of huge oxen, extremely realistic animal figures that may have been, at the time of their making, the largest cast iron animal statuary in the world. This paper describes part of the story of the construction of this bridge, the remarkable Pu Jin Bridge of Yongji, China.

INTRODUCTION

Reputed to be the first cast iron bridge in the world, Abraham Darby's open spandrel rib arch span over the Severn River at Coalbrookdale, United Kingdom, was completed in 1779. Was this truly the first cast iron bridge in the world? You be the judge.

A millennium before the construction at Coalbrookdale, more than 700 years before Columbus's voyage of discovery, more than 500 years before the completion of Peter of Coalchurch's Old London bridge, and even more than a century before the beginning of the Viking invasion of Britain, an unusual event took place in a fabled land called Cathay near the end of the known world. Near the west gate of the ancient walled city of Puzhou, a throng of technicians, craftsmen and artisans (in present day vernacular engineers, smelters, founders, blacksmiths, sculptors, artists, masons, carpenters, and boatwrights) were brought together by the emperor of that land, Xuan Zong, to reconstruct a more permanent floating bridge across the main channel of the mighty Huang He (Yellow River.) The Pu Jin Bridge (Figure 1), a bridge that became renowned throughout the Orient, was destined to serve the Chinese Empire's road network intermittently for over 600 years. Its 1000+ foot (300+ meters) spans of pontoons and larger than life-sized portal sculptures (Figure 2) evoked surprise and admiration by those personally experiencing the structure. Their glowing reports reverberated throughout the Orient in their own time and echoed down through the ages in Chinese historical literature and local legends. Remarkably, the main structural elements of this bridge were composed of iron; the pontoon chains of wrought iron, and the huge sculptured chain anchorages of cast iron. Equally remarkable is the fact the Pu Jin Bridge contained more iron than the bridge at Coalbrookdale. More remarkable still is the fact that this structure's appearance received as much care and attention as the composition, characteristics and configuration of its primary structural elements. This paper shares the story of the Pu Jin Bridge.

IRON TECHNOLOGY

> Although iron had been smelted and used since ancient times, the iron bridge [at Coalbrookdale] of 1779 represents the beginning of the use of iron for bridge components, in contrast to its limited use for fasteners such as nuts and bolts.[1]

This statement reflects the common mistake by historians who thought that iron bridges originated in the United Kingdom. They apparently were either unaware of the early accomplishments of Chinese iron founders

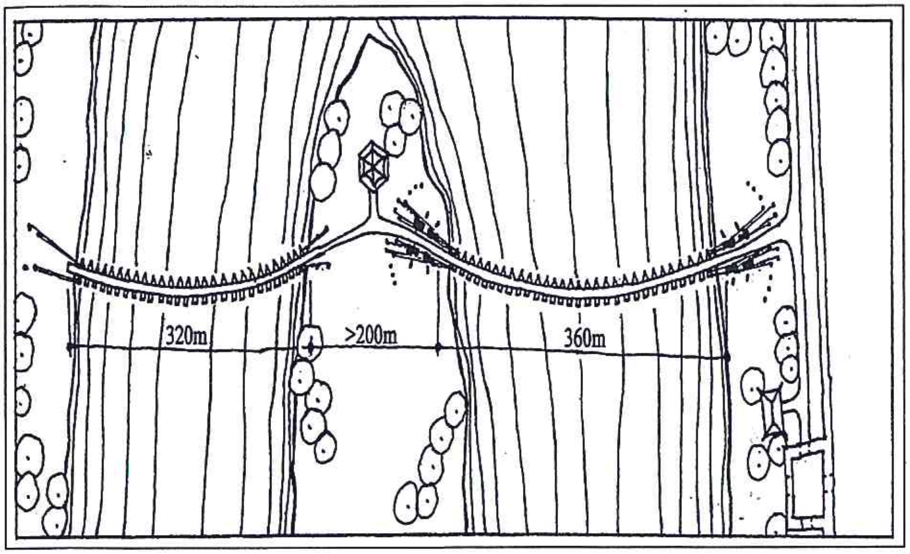


Figure 1: A plan view of the reconstructed two-span Pu Jin Bridge shows the chain-linked eastern span across the main channel of the Yellow River and the bambo-tied western span over the overflow channel.

and bridge engineers, or they discounted the appearance of wrought-iron chain suspension bridges in ancient China as unusual peculiarities. Derrick Beckett, writing in 1969, had a more qualified opinion about the appearance of iron in the Coalbrookdale Bridge, and at least had an awareness of the early use of iron for suspension bridges in China and India.

> The completion in 1779 of the Iron Bridge ... marked the end of the reign of stone and timber as the dominant materials for bridge construction . . . Not until the end of the 18th century was iron employed as a major structural material, particularly to replace timber columns in industrial buildings, *although wrought-iron chains were used for suspension bridges in China and India as early as the first century AD* [italics added] [*].[2]

* Actually, a study of Chinese historical records indicates that the first iron chain suspension bridge in China was the Fan River Bridge of Han Zhong. It was constructed in 206 BC.

One of the most remarkable aspects of the Pu Jin Bridge is the high level of technical expertise in iron technology developed by the eighth century in China. Not only did it predate by six centuries the beginning of the Occident or European cast iron experience of the fourteenth century, by the eighth century in China, cast iron, wrought iron and steel technology had already matured during a thousand years. Recent archeological finds show that China was producing cast-iron farming implements as early as the B.C. fourth century, almost one and one-half millenniums before their European counterparts.[3]

Although the Orient and Occident developed blast furnaces for the reduction of iron ore, the actual processes adopted and developed by these two cultures were radically different. For example, the early blast furnaces of the Occident were typically large fixed structures provided with an intermittent air blast. Since only moderate temperatures could be achieved in such furnaces, they were limited to the production of spongy or plastic clumps of

Figure 2: When discovered in 1989, the eastern anchorage was about 20 feet (6 meters) below the current ground level and nearly two miles (3km) east of the Huang He (Yellow River) channel.

iron and slag, called blooms, that were reheated and hammered to create wrought iron. Such iron was relatively free of impurities, had a very low carbon content and thus was a very ductile and desirable material. However, to produce useable objects with the iron from such blast furnaces, the resulting iron blooms had to be hammered or pressed into desired shapes. This limited wrought iron applications until large rolling mills were built to shape it into structural shapes. The European discovery of or interest in cast iron did not really take place until the fourteenth century, almost a millennium and a half after the Chinese, when the need for cast-iron cannon balls became crucial in battles for supremacy between different city states or other political subdivisions.

The early Chinese, on the other hand, developed small blast furnaces, some meant to be portable, for the reduction of iron ore. These furnaces used double acting piston bellows that provided a continuous air blast (Figure 3). They achieved high temperatures and produced molten iron relatively free of impurities. Although the high carbon content made this molten iron (cast iron) very brittle, it had a wide applicability since it could be cast into almost any shape. Iron production soon became an empire-wide industry primarily for producing farming tools and plow blades. By the beginning of the ninth century, the empire's yearly iron production was an estimated 1325 tons (1200 metric tons).[4]

Chinese iron production was not limited to cast iron. Very early, it was discovered that the brittleness could be made more ductile (decarbonized) by stirring the molten iron in a heated basin or on an open air finning platform (oxidizing the carbon) to produce low carbon, spongy clumps of ductile wrought iron. Some iron founders even specialized in mixing and heating proportions of high carbon cast iron with low carbon wrought iron in closed crucibles for an intermediate carbon content (steel) used in swords and other cutting instruments.

Even the emperor of the eighth-century Tang Dynasty, whose primary concern lay with the strategic importance of the Pu Jin Bridge's unifying of the empire's two major land masses, was aware of cast iron's brittle nature and the improved mechanical characteristics of wrought iron. This is illustrated by a comment made about the periodic failure of the Pu Jin Bridge and the need to replace its bamboo ropes with wrought iron chains. The minister Zhang Yue reported in "Regards to the Pu Jin Bridge", that the emperor Xuan Zang said, "This chain must be stronger but less brittle."[5]

Following the emperor's directions, a staff of the empire's specialists (engineers, artists, sculptors, iron founders, boatwrights) was brought together to plan for a permanent reconstruction of the Pu Jin Bridge. And because of its unusual characteristics, they also had to devise special procedures and precautions to construct it.

PU JIN BRIDGE

Figure 1 shows a plan rendering of the Pu Jin Bridge. Based on a synthesis of historical accounts and examinations at the bridge site, the bridge had two primary spans, an eastern one of 1,180 feet (360 meters) across the main river channel and a secondary one of 1,050 feet (320 meters) across the western overflow channel. They were joined by a short 650-foot (200 meter) roadway across a central island. The stability of this island and the integrity of the bridge anchorage played a central role in a loss and rescue drama during the Pu Jin Bridge's fourth century of service.

The bridge site is near the ancient walled city of Puzhou in modern Yongji County, in the extreme southern end of Shan Xi province. It is located 93 miles (150 km) east of the ancient capitol city, Ch'ang-an (modern Xi An).

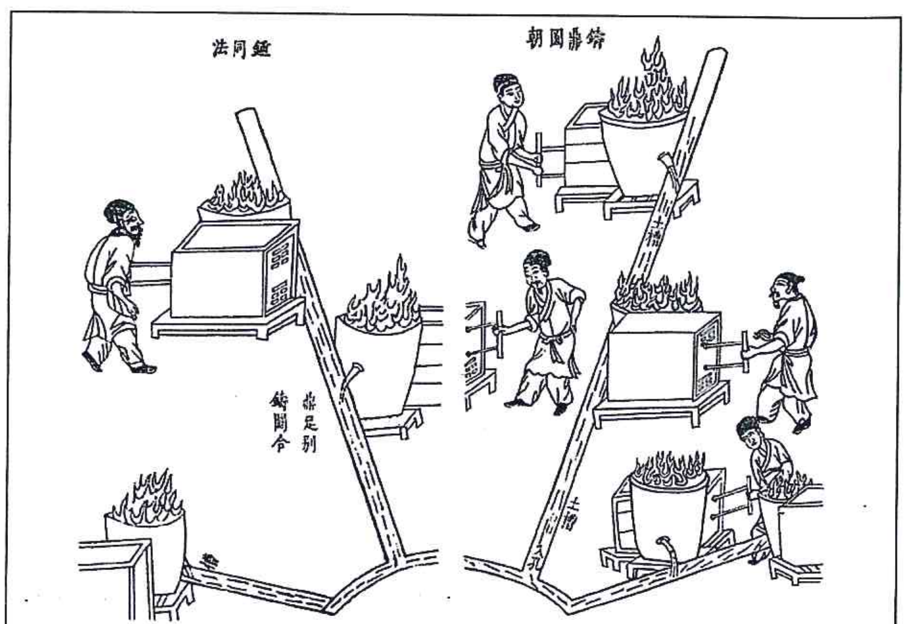


Figure 3: Chinese furnaces were often grouped together to provide sufficient metal for the continuous castings of large bronze objects. In like fashion, larger and even more numerous blast furnaces were used to provide the molten iron for the continuous casting of the cast-iron elements of the Pu Jin Bridge. These images appeared in *Tian Gong Kai Wu* (note 8).

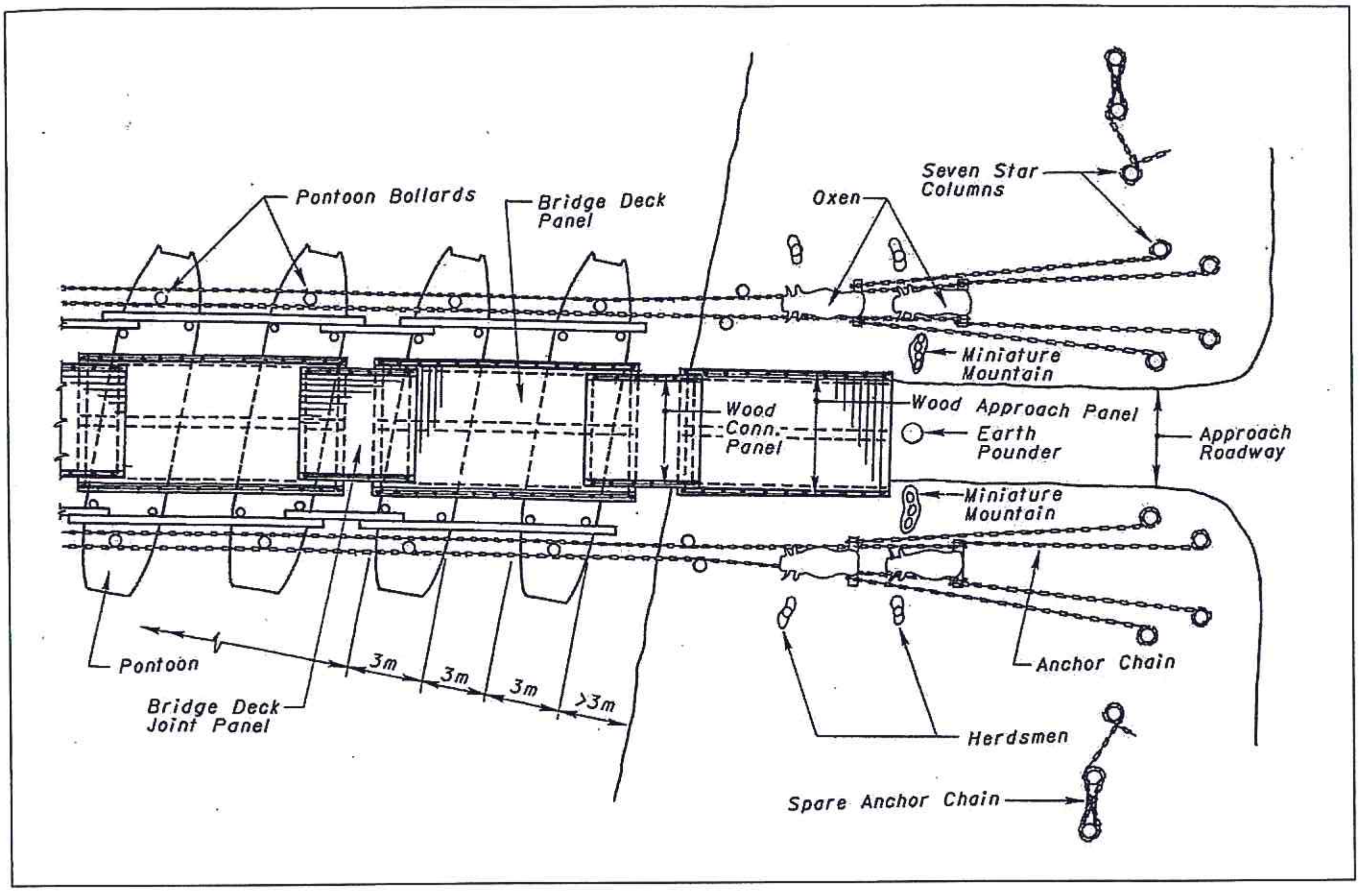


Figure 4: This partial plan view of the floating Pu Jin Bridge, completed in A.D. 724, shows the main channel near the ancient city of Puzhou (modern Yongji County, Shan Xi Province, China) Details are based on historical records and archaeological excavations.

From earliest times, the empire's main roads leading north and northeast to Ch'ang-an and the great central plain of China crossed the Yellow River at Puzhou.

> The first recorded bridge [at Puzhou was] built in 541 BC... In the third century BC . . . Qin troops used a similar bridge to enter the Central Plain during their triumphant conquest of the whole of China, and later the great general Cuo Cao (155-220AD) crossed here in his campaigns against rival warlords to the west.[6]

Ancient Chinese floating bridges consisted of wood pontoons lashed together and anchored to the shore with woven bamboo ropes. Floating timber during floods, winter pack ice, and flow ice during spring thaws occasionally broke the ropes and damaged or carried away these bridges. After each failure, a ferry service was employed until new ropes, pontoons and floor timbers could be assembled to restore the bridge. Eventually, the continued failure of the strategically important bridge at Puzhou motivated Emperor Xuan-Zong to demand a more permanent reconstruction.

> In 723 AD, the Emperor and his staff [went] to Yongji to see what could be done about the problem. After discussing it with his prime ministers, he decided to replace the bamboo ropes with iron chains and to use iron sculptures as anchorage for permanent security.[7]

At the completion of the bridge's reconstruction, the prime minister, Zhang Yue, was honored with a request to write an inscription.

> On both the east and west shore of the main channel, there stand four cast iron oxen, each weighing many tons, with a cast iron statue of a man either leading or driving them. There are cast iron pillars under the oxen buried in the earth. At the front and back of the sculptures there are 18 cast iron columns, and two cast iron supports, all of which form the anchorage of the iron chains of the bridge.[8]

Anchorage Complex

As illustrated in Figure 4, the wooden pontoons of the Pu Jin Bridge were linked together with forged iron chains. Multiple chains were located on both the upstream and downstream ends of the pontoons and were then fastened to a series of cast-iron elements. There were no less than fifty-five cast-iron elements in the eastern anchorage complex. Presumably, the western anchorage had the same number. Although there are duplicate castings, it is clear that many were unique, having been made from different models and molds.

Since archaeological excavation of the western anchorage has been delayed for preservation purposes, it is impossible to know the precise nature of both anchorages.

The forged anchor chains of the bridge have not yet been recovered. The number, composition and weight of these chains can only be assumed from historical records on this and other chain-anchored or supported bridges.

In addition to structural or functional purposes, the bridge elements were obviously chosen, configured and placed to serve other purposes. A reasonably complete description and explanation for these elements can be gained from published sources on the bridge and a thorough knowledge of ancient Chinese culture and beliefs.

Cast Iron Oxen

In ancient China, it was a common custom to set up carved stone models of real animals along waterways to suppress or control water spirits or monsters and prevent damaging floods. Originally the sculptured forms of powerful amphibians, like hippopotami, served this purpose. For greater realism, life-size statues of both men and rhinoceros where made. When hippopotami and rhinoceros became rare, sculptured replicas of domesticated farm animals were adopted for this purpose. By the eighth century, with increased bronze and cast iron production and improved model- and mold-making skills for casting, three materials, stone, bronze, and iron, were in common use. So the adoption of larger-than-life cast-iron replicas of oxen at the Pu Jin Bridge anchorage not only followed historical precedents but also satisfied local customs and beliefs. While providing the weight to resist the pull of the anchor chains, they also fulfilled a mystical suppression of water spirits and floods.

The four oxen, along with their supporting pillars, constituted the primary anchorage elements of the Pu Jin Bridge (Figure 4). There are two teams of two oxen each standing in a line parallel with the upstream and downstream sets of pontoon anchor chains. Each ox is designed to be connected to a separate set of anchor chains. The realism of their modeling is outstanding.

> These enormous figures, cast in solid iron, are master pieces of sculpture and justly renowned as one of the great technical and artistic achievements of their time [Figures 2 and 5]. Seldom, if ever, has the Tang genius for lifelike representation been so skillfully displayed. Larger than life, these massive creatures hold their own among the great animal statuary of the world.[9]

The leading and trailing oxen represent different animals. The leading ox is obviously larger, older and more fully developed, while the rear ox appears to be a younger animal. They both face the river with heads lifted, legs out thrust and shoulder muscles bulging in apparent response to the powerful pull of the anchor chains.

Although it appears that every effort was made by the artist and sculptors of the Pu Jin Bridge to achieve extreme realism, including having each animal accompanied by a different herdsman, there is one aspect of the oxen modeling that appears inconsistent. Instead of facing away from the load being pulled, as is usual with beast of burden, the oxen face the bridge (Figure 2). Also, instead of being fastened to a harness hanging from the neck and bearing upon the oxen's chest and shoulder, the chains were intended to connect to transverse bollards at the oxen's rear that contact their rumps (Figure 5). What could have been the reasons for this peculiar oxen orientation and chain attachment method?

The possible explanations appear, as with the other anchorage elements, to include both mystical and struc-

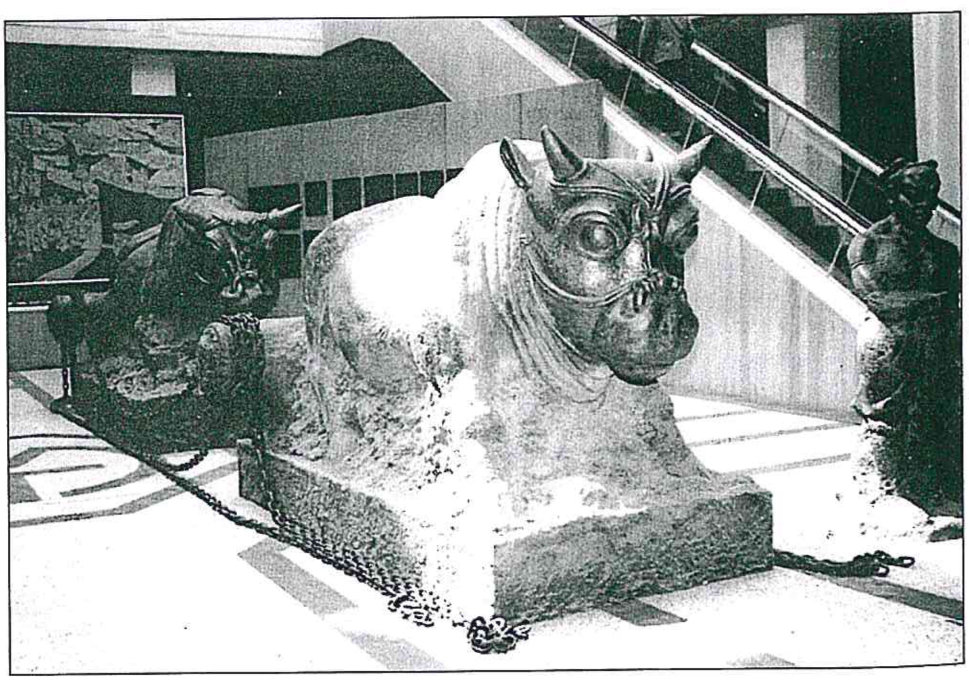


Figure 5: These oxen and herdsmen reproductions in the Yung Ji Museum in China were copied from the original cast-iron castings and demonstrate the realism achieved by the sculptors and founders of the Tang Dynasty.

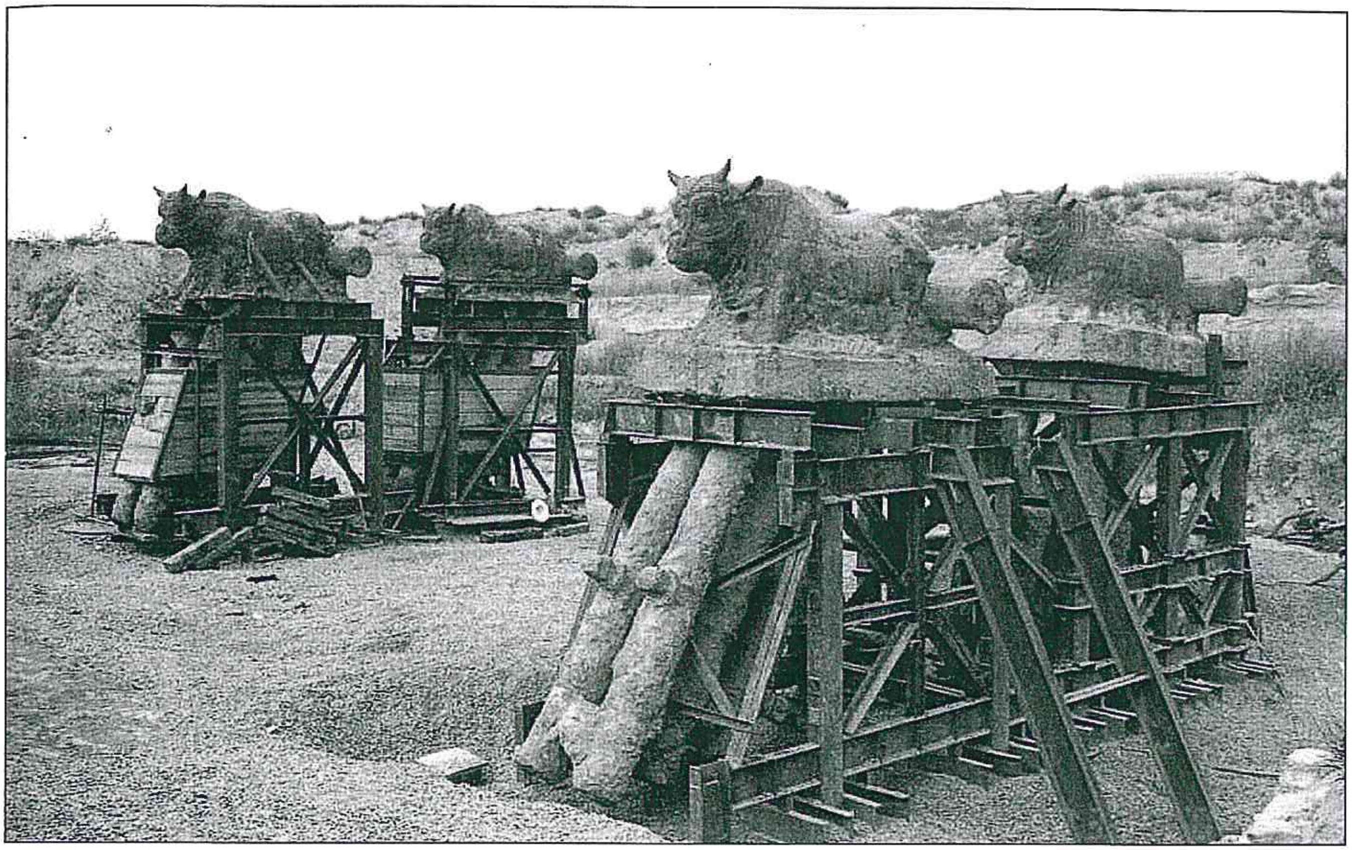


Figure 6: These four cast-iron oxen of the eastern anchorage, with their six raked support pillars, were recently excavated.

tural purposes. Although mystical purposes may have had priority, the resulting figures also fulfill important functional requirements.

Since animal figures were made and placed on the waterway banks to suppress water spirits, no purpose would be served if the oxen were not courageous enough to face their adversaries. In accordance with the mysticism of the time, no other choice existed for the bridge designers.

With the oxen facing the river and the load being resisted, the designers had to fabricate a connection with the anchor chains. The oxen could have been realistically modeled with harnesses, but this would have required a mechanical device. Such a device would be difficult to connect and disconnect while the chains were under tension by the force of the river flow on the pontoons. Additionally, such a configuration would inappropriately put tension on the cast iron, which is notoriously weak in tension. By the eighth century, Chinese engineers had almost a thousand years of experience with cast iron, and they were thoroughly familiar with its primary mechanical characteristics.

Bollards had historically been used for belaying bamboo ropes of other floating bridges and large diameter ship hawsers. A single individual can make a connection merely with one or two turns of a hawser around a bollard. Additionally, by attaching chains to bollards on both sides of the oxen, the pull on the anchorage would be symmetrical, the oxen would be subjected to only compression and shear, and the bollards themselves would be subject to torsion, shear and some tension.

To minimize the stresses on the bollards, a second ox and supplementary vertical poles were employed. The suitability of the anchor chain attachments is attested to by the structure's resistance to river currents and roadway traffic for over 600 years.

Oxen Support Pillars

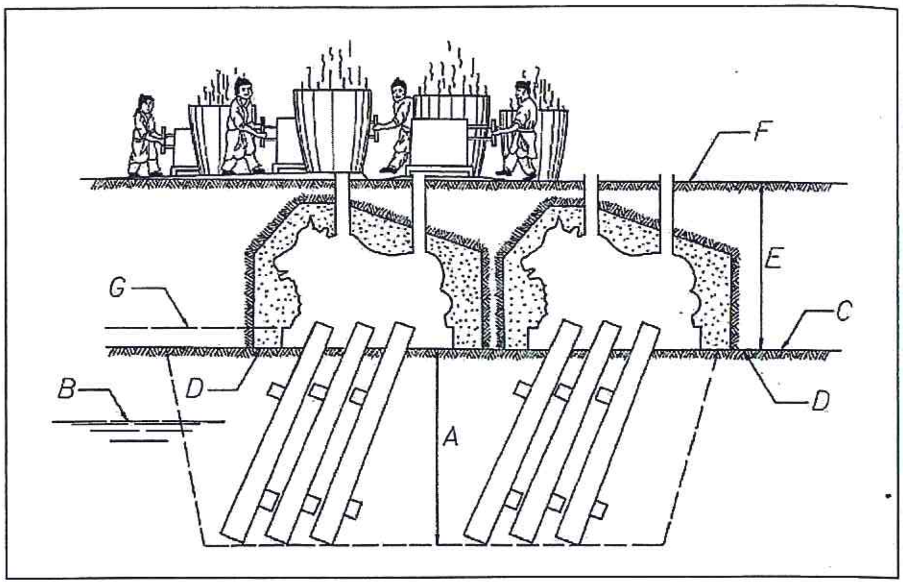
Beneath each ox casting and integrally connected to its base is a raked cluster of six cast-iron pillars (Figure 6). Each pillar is about 16 inches (0.4 meter) in diameter and about 17 feet (5 meters) long. They are spaced on about 2 foot (0.6 meter) centers. Their 30 degree or more batter increased their resistance to the pull of the anchor chains and, along with weight of the oxen above, constituted the primary resistance of the anchorage.

Figure 6 shows the oxen and their pillar supports after their recent excavation. The gates on the pillars (the knobs formed by the holes in the pillar molds through which the molten iron was poured), indicate they were cast individually and then set in position in deep excavations. They were locked in place by hand-tamped earthen backfill. A short length of the pillars was left exposed for joining to the oxen during casting (Figure 7). Since there is approximately 22 cubic feet (0.63 cubic meters) of iron in each pillar, each pillar cluster weighs at least 29 tons (26 tons).

Figure 6 shows that the north and south pair of oxen have different pillar connections, with the south or nearest pair having considerably thicker bases and greater

Figure 7: The molds of the oxen pairs were probably buried together to simplify buttressing with pounded earth and to support the many blast furnaces necessary for the continuous casting of oxen, herdsman, and mountain.

A Excavation required for placing oxen support pillars
B Approximate water level
C Temporary casting bed
D Ox mold
E Pounded earth mold support
F Field foundry surface
G Proposed final paved surface



pillar batter. This was presumably intended to improve the connection between the oxen castings and their support pillars and to increase the pillar's resistance to horizontal forces after the north pair of oxen was cast. The different bases of the two pairs of oxen indicate use of four different molds. All evidence suggests that these animal figures are solid iron castings weighing as much as 83 tons (76 tons).

Herdsmen

Each of the four larger than life cast-iron herdsmen leading the oxen (Figure 2) was modeled after different individuals. Consequently, each has different dress and physical characteristics. Since they are structurally unnecessary to the anchorage, their symbolism appears to have been the primary justification for their presence. In addition, it has been suggested that political considerations also motivated the creation of these figures. A close examination of their physical features and dress suggests that they were sculptured to represent four different nationalities of the Tang Empire. Bringing these sculptured representations together at the Pu Jin Bridge, made a subliminal visual statement that different nationalities could accomplish together what neither could alone.

Seven Star Poles

Located about 33 feet (10 meters) behind each pair of oxen, are seven cast-iron poles one foot (0.3 meter) in diameter and from three to six feet (1 to 2 meters) in height. They are "embedded 10 to 13 feet (3-4 m) deep in the ground."[10] As suggested in Figure 4, four of these poles provide extra anchorage for the chains, and, as is typical for the other anchorage elements, all seven have symbolic purposes as well, being in the shape of the celestial seven stars of the Big Dipper.

> In Chinese astronomy, based on the celestial poles, the Big Dipper played a central role. Its seven stars, always visible, made a complete revolution in the heavens once a year and provided a fixed reference point in the sky. For [Taoist], it was the greatest of all sources of celestial power . . . Its dominant position led to a natural analogy between the dipper and emperor.
>
> These stars poles complete the cosmic symbolism of the bridge. The entire arrangement proclaims that this was an imperial venture involving all parts of the empire. While the powers of the oxen would subdue the water spirits, the dipper would anchor not only the bridge and its supports, but also the great Yellow River, keeping them firmly in their correct place in the cosmos.[11]

Miniature Mountains

There are two miniature cast-iron mountains (with their integral support pillars) placed transversely between the chained oxen and the approach roadway. They are about 3 feet (1 meter) high and 6 feet (2 meters) long and had different models and molds. The north mountain has four peaks while the south has only three.

As with the other elements of the anchorage complex, these mountains appear to have both functional and mystical purposes. According to contemporary beliefs, mountains were sacred places associated with the perfect spirit world above that contrasts with the imperfect human world below. As part of the bridge approaches, they were apparently placed on the roadway shoulders merely to serve as traffic barriers and help funnel traffic onto the narrow bridge.

Earth Pounder

Finally, a giant cast-iron earth pounder is located in the center of the bridge approach roadway between the two miniature mountains. In Figure 2, it is the truncated tapered cylindrical shaft with a hole through its top. The pounder stands about 3 feet (1 meter) above the ground and is a large replica of the actual tools used to construct the anchorage.

Any symbolism of the earth pounder is unknown, but its practical significance is clear. Based on its position, it, like the miniature mountains, was probably used to control traffic. In conjunction with the miniature mountains, it limited the width of vehicles and helped direct two-way traffic. Further, a timber could be threaded through the transverse hole to bar all bridge traffic at night or as needed. Similar devices — metal poles centered on pedestrian bridge approaches — are used today for the same purpose.

Although much symbolism determined the configuration of the bridge anchorage elements, the designers of the Pu Jin Bridge were also conscious of the most practical aspects of function, durability and aesthetics. The Imperial government spared no expense to make this bridge a permanent river crossing and a showcase of Tang technology, design, and construction.

Anchor Chains

No anchor chains have yet been recovered. Most of what is known comes from documents about this bridge and other historic bridges that were supported or secured by iron chains.

As has been mentioned, most early pontoon bridges in China used tightly woven bamboo ropes. Exposure to chafing wear and constant stress required that they periodically to be replaced.

> [the] recurrent demand for bamboo for new ropes dominated the local economy. Peasants in the area were forced to plant bamboo and those crossing [the bridge] paid a special bamboo tax.[12]

> From the + 8th century we have much information about the upkeep of these important bridges, notably in the MS fragment of the Tang Government Ordinances of the Department of Water-Ways... Here we learn of the bridge keepers... watermen... and maintenance artisans... kept permanently on duty and exempt from military or other services, active in the defense against dangerous floating [timber] in flood time and watchful to undo all fastenings when the ice set hard... [P]rovisions were made for the manufacture, storage and periodic testing of the necessary bamboo hawsers.[13]

> In the 12th year of the Tang Dynasty... the Emperor heard about [the continual failure of the bamboo ropes of the Pu Jin Bridge] and said, I never stop thinking about the Pu Jin Bridge... We have to change the bridge to relieve the people's burden. The new bridge has to be economical so that people can afford it. The usual rope of bamboo must be replaced with iron chain. This chain must be strong but less brittle. The bridge must be stronger and more durable to solve this problem [of continual bridge failures] for a long time. Then, all of our lands can be taken care of.[14]

It is assumed that the links for this bridge chain were made of one-inch (25 mm) diameter bars and were at least six inches (150 mm) long. Each chain is estimated to be about 1770 feet (540 meters) long. Based on these measurements, the chains for this bridge would each weigh about 8 tons (7¼ tons).

Pontoons

Remains of pontoons from the Pu Jin Bridge have not been recovered. Nor have sketches of them been found in historical records. Consequently, specific details of their construction, as illustrated in Figure 4, are based on knowledge of other floating bridges and on an imaginative reconstruction based on known dimensions. The probable lengths are based primarily on the lateral position of the anchor chains (oxen bollards). Reportedly the pontoons were more widely spaced than typical to improve flow ice passage. The pontoon width was calculated from that needed to support the weight of bridge traffic.

About A.D. 724 Prime Minister Zhang Yue wrote about images of birds painted on the bows of the pontoons. Imperial Librarian Chang Yueh made a similar statement.

> The chain secured the lashed boats, and the oxen made fast the [chains] so that the bridge was safe against injury from objects floating downstream. Thus the boats with the pretty birds painted on their bows, all fixed firmly together (supported the road deck above).[15]

These pontoons were built in a special shipyard near the bridge site. Up to half the total number were kept available. Pontoons were continually replaced as they decayed or were damaged during floods.

CONSTRUCTION

Based on a number of observations and considerations, it appears that the cast-iron elements of the east anchorage of the Pu Jin Bridge were constructed in two primary placements, with the northern cluster of elements (oxen, herdsmen, and mountain) placed first and the southern cluster of elements placed second. As suggested by the sketch of Figure 7, casting molds for the northern cluster were buried in thoroughly pounded earth so that the molds would be rigidly supported on the outside against the lateral pressure of molten iron on the inside. Presumably, the huge oxen molds also contained interior iron braces to support the sides of the molds against the outside pressure of pounded earth. After burial, numerous small blast furnaces were then placed on the ground surface surrounding the buried molds somewhat as indicated in the sketch of Figure 3. Although Figure 3 documents the use of numerous small blast furnaces for casting large bronze tripods, similar but larger blast furnaces were used and positioned for casting iron elements. Numerous furnaces of this type were needed to provide enough molten iron to completely fill the mold for each ox in one continuous pouring since the largest ox with the thickest base would require about 83 tons (76 tons) of iron to completely fill it.

It is fortunate that there appears to have been an eyewitness or second-hand account of the casting and forging of the iron elements of the Pu Jin Bridge. In an essay written by the Imperial Librarian at the time, Chang Yueh, construction events are described as follows:

> There were thus collected together the most famous artisans, all eager to demonstrate their art ....[They] followed the classical metallurgical procedures ... of the Chow Empire. The fans of the bellows flew back and forth, and the furnaces furiously blazed. Some smelted and others refined; some were filing while others were forging and beating with hammers. Thus, they connected links together to form a great chain, and they cast iron into the shape of recumbent oxen, images which stood on both banks of the river connecting east and west amidst sandy beaches. The chain secured the lashed boats, and the oxen made fast the [chains] so that the bridge was safe against injury from objects floating down stream.[16]

The construction processes described by Chang Yueh probably frightened local inhabitants with what must have seemed like apparitions from the nether world. The fires of the numerous blast furnaces would have illuminated the night sky by light reflected from the cloud cover overhead. From a distance, the anchorage area itself would also have been illuminated by these same fires but partially obscured by a shimmering ground haze darkened by furnace smoke and soot and the elongated and distorted ground shadows of moving figures. The air would have been permeated with the smell of burning charcoal and molten iron, the constant hish-swish of bellows-driven air, the chant and chatter of distant mingled voices, and the reverberating clang of forging hammers. Following several nights and days of such activities, a quiet would have descended on the anchorage while the multitude of artisans rested from their ordeal and waited while the castings cooled enough so the buttressing earth and confining molds could be removed to discover if their efforts were successful. If so, they would then repeat the same scene three more times to complete the casting and forging all of the major anchorage elements of this unusual and remarkable bridge.

RIVER RESCUE

With the exception of a short period at the beginning of the 11th century, the Pu Jin Bridge remained in almost continuous service for more than 600 years. At the beginning of the 11th century, a particularly severe flood scoured the west bank of the main channel to such an extent that the four oxen were swept into the river by the force of the flood flow. As another example of the engineering expertise that existed in ancient China, these oxen were located on the river bottom, recovered and restored to their original position in order to place the bridge back into service. A document describing part of this river rescue is given in Needham's "Science and Civilization in China."

> Another monk, Huai-Ping, was responsible for a method of raising heavy objects from the bottom of a river by the use of buoyancy, analogous to the pontoons filled alternately with water and air used in modern salvage operations. The Liang Chhi Man Chih + 1192 [related the following river rescue]:
>
> Another instance of remarkable ingenuity was the following. In Ho-chung Fu there was a floating bridge, fastened to the bank by means of eight iron oxen ...In the Chih-Phing reign period (+1064 to + 1067) the bridge was broken during a sudden flood, and the iron oxen were swept away and buried under the water. Public proclamation was made to find someone capable of recovering them. It was then that the monk Huai-Ping from Chen-ting Fu suggested a method. He used two huge boats filled with earth, cables from them being made fast to the oxen in the riverbed (by divers). Hooks and a huge counterweighted lever were also used. Then the earth in the boats was gradually taken away so that the boats floated much higher and the oxen were lifted off the river bottom (and dragged up the riverbank in shallower water).
>
> Huai-Ping's success was reported to the emperor, who bestowed on him a purple robe of honour as recompense.

Needham concludes, "Presumably the role of the counterweighted lever was to help the divers fix the cables."[17]

Presuming that each ox and its six-raked pillar supports remained intact, this recovery was more spectacular than even this brief account suggests. Considering that an ox and the six pillar support cluster weigh about 112 tons (102 tons), the engineer monk, Huai-Ping, had to literally manhandle four huge, heavy, irregular-shaped objects from the river bottom, move them to their proper position on the bank of the river, and restore the river banks in de-watered excavations to make them rigid enough to resist the pull of the anchor chains.

Needham's suggestion that the lever helped the divers secure the cables around the oxen may be true. But the real purpose of the counter-weighted lever may have been lifting and rotating the 112-ton (102-ton) ox-pillar clusters back into position.

No known records mention recovering the herdsmen, mountains, seven star pillars and earth pounder of the west anchorage. So reconstruction of this anchorage will have to wait for future excavation.

HARD TIMES

The strategically located and durable Pu Jin Bridge continued intermittently to serve roadway traffic for many centuries. The Jurchen armies of the Jin Dynasty burned the bridge in 1222. General Xu Da of the Ming Dynasty restored the bridge for his crossing with ten thousand troops in 1369. Although many of the bridge elements were burnt, swept away and otherwise damaged many times, a document written in 1519 mentions the existence of the iron oxen. A great flood fifty years later changed the river's course, burying the oxen of the west bank in sediment. The oxen of the east bank, now useless, stood forlornly beside the old city wall until they too were finally buried by flood-deposited sediment at the beginning of the twentieth century. Local youngsters no longer knew of the iron oxen in their city and even old residents had only vague impressions about that "ancient bridge."

Finally, in 1989, Fan Wan Lin of the Yongji Museum found the oxen after consulting more than 170 local residents. The oxen and other elements of the eastern anchorage have now been uncovered and raised to near present ground level, but due to channel changes, the river is now located over two miles (3 km) away from the bridge site. Apparently, the Pu Jin Bridge cast iron oxen were unable to permanently quell the water spirits. But their structural strength and commanding presence were sufficient in their prime to have ruled over the mighty Yellow River for over six centuries.

SUMMARY

Based on the size and number of cast-iron elements used in its construction, on the quality and realism of its animal and human reproductions, and on its long and eventful service history, the Pu Jin Bridge is a multiple record holder in the annals of bridge engineering.

The sizes of its various cast-iron elements are an almost unbelievable accomplishment for their time. The largest cast-iron figures, the oxen with thick rectangular bases, weigh about 83 tons (76 tons) each. The longest elements (1772 feet, 540 meters) requiring handling were the wrought-iron anchor chains each weighing 8 tons (7¼ tons). For each anchorage complex, there were more than fifty individual iron castings. In all, there were more than 900 tons (820 tons) of iron used in this structure. For comparison purposes, it has been estimated[18] that the Coalbrookdale Bridge contains just 424 tons (385 tons) of iron.

When considering the huge size of the cast-iron oxen (Figures 2 and 5), one is led to presume that they were the largest or nearly the largest solid cast iron figures ever made prior to the eighth century. If there were earlier larger figures, they have not yet been found. But since it was a custom in ancient China to place life-like reproductions of large animals adjacent to waterways, and since the successful molding and casting techniques used for the Pu Jin Bridge probably evolved over centuries, it is certainly possible that larger cast-iron figures existed earlier. When considering all eight of the oxen reproductions, it is probably safe to say that the number and size of the cast-iron elements in the anchorages of the Pu Jin Bridge have not been surpassed by any other structure. And when considering its 600+ year life, the performance of this remarkable bridge has not been surpassed by any other metal bridge.

The Pu Jin Bridge and its builders lived long in the memories of those generations who had the opportunity to experience the structure during their crossing of the mighty Yellow River. Now, with the discovery of the bridge's anchorage complexes, other generations will be able to marvel at the accomplishments of these early engineers, artists, founders and technicians. The Pu Jin Bridge will thus join other famous ancient structures as examples of what outstanding organizational skills and exceptional abilities can accomplish under extraordinary circumstances.

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