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The Evolution of the Double-horse Chariots From the Bronze Age to the Hellenistic Times

Light chariots with spoked wheels were developed initially in Syria or Northern Mesopotamia at about the beginning of the 2nd millennium B.C. and quickly propagated all over Middle East. The two-wheeled horse-drawn chariot was one of the most important inventions in history. It gave humanity its first concept of personal transport, and for two thousand years it was the key technology of war. Information on chariots of Mesopotamia, Egypt, the Mycenaean and Archaic Greece, China, and Europe, with light and flexible spoked wheels from extant findings of ancient chariots, stone reliefs, and vase paintings is used for a design study of the dual chariot and its evolution in the centuries. Design reconstruction of the dual chariot found in Anyang China is incorporated herewith to prove that its development contains the seeds of a primitive design activity.

Keywords: *Dual-chariots, Axles, Bearings, Spoked wheels, Traction dynamics.*

1. INTRODUCTION

The chariot, an open, two - or four-wheeled vehicle of antiquity, first used in royal funeral processions and later employed in warfare, racing, and hunting, apparently originated in Mesopotamia in about 3000 B.C. The two-wheeled horse-drawn chariot was one of the most important inventions in history. It gave humanity its first concept of personal transport, and for two thousand years it was the key technology of war. It also became the world’s first mass spectators sport event. It was used in warfare during the Bronze and Iron Ages, and continued to be used for travel, processions and in games after it had been superseded as a military machine [1-5].

In western Asia and Europe chariots were preceded by heavy ox-drawn conveyances with one-part or threepan solid disk wheels, attested as early as the fourth millennium B.C. During the excavations of 1927/8 from the British archaeologist, Sir Leonard Woolley to the Royal Cemetery of Ur in modern day Iraq, an artifact known today as the Royal Standard of Ur was discovered. It is dated to the third millennium B.C. Portrayed on one side of this artifact is the Mesopotamian four-wheeled, cart-like structure pulled by four donkeys (Fig.1). The artist depicts it in different states of motion. Initially, the donkeys shown walking, begin to trot, and then gallop. To clarify that this was a war machine a trampled enemy or two are shown under it [5].

Figure 1 shows details of the chariot as used in a royal parade (Top), and in the battlefield (Bottom). The solid wheels consisting of two similar semi-circular parts connected together and with the axles. The wheels rotated on a fixed axle linked by a draft pole to the yoke of two pairs of donkeys or a pair of oxen. Bodywork consisting of a platform with side screens and a high dashboard, framed with wood and covered with skins, forming the superstructure was attached to the wheels’ axle and drawbar. This earliest known depiction of the Mesopotamian chariot was carrying a spearman and a charioteer, and fighting could be also conducted from on-board the vehicle. Shields seem to be applied abreast of the donkeys serving also as the link with the drawbar, which in the left bottom depiction seems to be bent upwards, from the chariot floor towards the donkeys’ necks. A twin circular link is put on top of the drawbar for the harness to pass by, and control the left and right pair of donkeys separately [5].

Figure 1. Standard of Ur, 26th century BC. Bottom panel depicts chariots in action [5].

The wheel was further improved in the Near East, and contributed to the development of the chariot with four spoked wheels. Representations of chariots, can be found on Anatolian seal impressions from the second millennium B.C. Unlike their Mesopotamian prede–cessors, these chariots have spoked wheels. Four small cast copper/bronze wheels (170-177 mm in diameter) found in a context of the first half of the 18th century B.C. in the Burnt Palace at Acemhöyük in Anatolia provide the earliest three-dimensional evidence for spoked wheels so far known. These four-spoked wheels can be compared with extant examples of spoked wheels from Egyptian chariots from later second

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millennium B.C. contexts. Archaeological investigation, however, has suggested that this stage of chariot development occurred at an earlier time in the Eurasian steppes.

The excavation of *kurgans*, graves covered by earth mounds in the Sintasha-Petrovka region in the northern Eurasian steppe on the borders of Eastern Europe and Central Asia, around the Ural and upper Tobol rivers dated to the period 2100–1800 BC, have yielded objects believed to be the earliest known chariots. Sintashta settlements are remarkable for the intensity of copper mining and bronze metallurgy. While the chariots themselves have decayed into dust, the lower part of their wheels left an imprint of their shape and design into slots cut for them in the dirt floor of the burial chamber. Some parts of the chariot structure were also preserved in this way. [5-7].

The two-wheeled version soon proved superior in battle because of its higher maneuverability. Greater speed was attained by the use of teams of two or four onagers and by the evolution of the light, spoked wheel. The introduction of the horse as a draft animal in about 2000 B.C. in Mesopotamia was the final step in the development of the chariot into a military weapon that revolutionized warfare in the ancient world by providing armies with unprecedented mobility. A horse can pull a chariot at a trot at up to 8 miles an hour - and at a gallop twice as fast. Light two-wheeled chariots with spoked wheels were developed initially in Syria or Northern Mesopotamia at about the beginning of the 2nd millennium B.C. and quickly propagated all over the Middle East. Its superstructure is made of a light wood, and its wheels are not solid; their rims are of bent wood, held in place by spokes. The weight of a third-millennium European wagon, the product of stone-tool carpentry, might be 600 or 700 kg. By Tutankhamun's time sophis–ticated joinery, carefully chosen woods, and spoked wheels had achieved vehicles as light as 35 kg [4-5].

Based on archaeological evidences, the anthropo–metrical standards, performance flexibility, aesthetics considerations of the time, safety and construction capabilities of the time, a preliminary design study of various versions of a well preserved in Anyang China dual chariot is attempted here. Transport kinematics is investigated too. The proposed methodology provides enough information about the ancient chariot design and operation, and renders for similar investigations of ancient transport equipment and reconstruction.

2. HITTITE CHARIOTRY

Chariotry contributed to the victories, in the 2nd millennium B.C., of the Hyksos, Semitic-Asiatic tribes, who immigrated into Egypt's delta region and gradually settled there during the 18th century B.C., the Hittites in Anatolia, the Aryans in northern India, and the Mycenaeans in Greece. The chariot became one of the most innovative weaponry in Bronze Age warfare. The critical invention that allowed the construction of light, horse-drawn chariots for use in battle was the spoked wheel. Saddle-pads were placed on the horses' backs and the yoke was attached to them. http://www.reshafim.org.il/ad/egypt/timelines/topics/pics/chariot_carriage.jpg Leather girths around the horses' chests and bellies prevented them from slipping. A single shaft attached to the yoke pulled the chariots (Fig. 2). The two-wheeled war chariot carrying a driver and an archer armed with a short compound bow provided increased military power and changed war tactics after 1700 BCE. This type of chariot spread throughout the Middle East and Egypt into Asia Minor, Greece and in Northern Europe by 1500 B.C. [5-7].

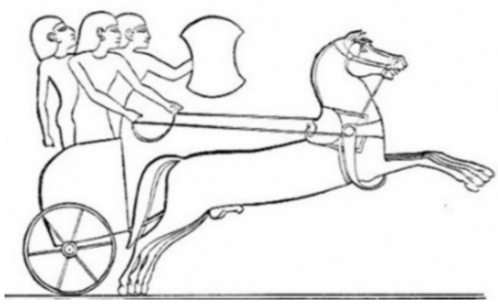

Figure 2. A Hittite chariot with two horses, the archer, the charoteer and a shield bearer [4].

The Hittite (as well as other Mid-Eastern) style chariot was considerably lighter than the Mesopotamian with the solid wheels, with a central axle. It carried a crew of three, consisting of a driver, shield-bearer and an archer. Fig. 3 depicts a relief in basalt from Carchemish, 9th century BC; battle chariot. This type of chariot with six-spoked wheels and forward located box belongs to a late Hittite style with an Assyrian influence [5].

Figure 3. A Hittite chariot with two horses, late Hittite style with an Assyrian influence [5].

3. ACHAEAN CHARIOTRY

The Achaeans adopted the chariot for use in warfare in the late 16th century BC as appearing in Mycenaean tombstones, gravestones, seals and rings. The use of the chariot was diffused in the Greek mainland from the Near East after the Middle Bronze Age (about 1950-1550 BC) as a result of the Central and East Europe migration flows and Achaeans' trade contacts with those regions. Roads for wheeled vehicles were constructed by the end of the Bronze Era, mainly for bridging streams and rivers, remnants of which can still be found in the Mycenae area. It was not until the mid 15th century BC that the chariot appears on the Crete island, as attested by a seal engraving and the Linear B tablets [7-8].

Different variants of the Achaean chariots are traced since the middle of the 15th century BC not only used as mobile fighting platforms but also for battlefield transport. Both these utilizations are also mentioned in the Iliad At this time the horse was mainly used as chariots drawer. No complete Achaeans chariots survived, although some metallic parts and horse-bites have been found in some graves and settlements. Furthermore, chariots bodies, wheels and horses are inventoried in several Linear B tablets [7-8].

A reconstruction of an Achaean dual-chariot shows the typical Achaean traction system composed by the lower draft pole, the upper horizontal shaft and the reinforcement vertical pole stay is shown in Fig. 4. The pole stay, which was L-shaped, was connected to the draft pole near the front of the box. Between the pole stay and the draft pole there were either leather thongs or wooden lashed braces that created an arcaded effect reinforcing the structure [7].

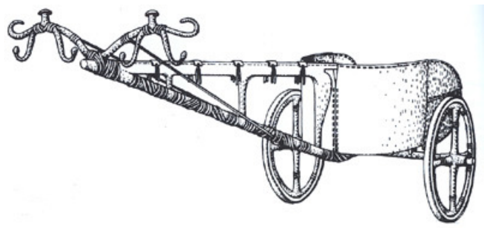

Figure 4. The Achaean chariot with L-shaped pole-stay [7].

A type of military chariot described in the Iliad (1194-1184 B.C.). is shown in Fig. 5 [7-10]. This light Achaean chariot was used in the Trojan War and the names of the various parts are shown in the drawing. This light chariot with two horses is a typical example of the light military vehicle that would be used until the emergency of cavalry at the time of Alexander the Great.

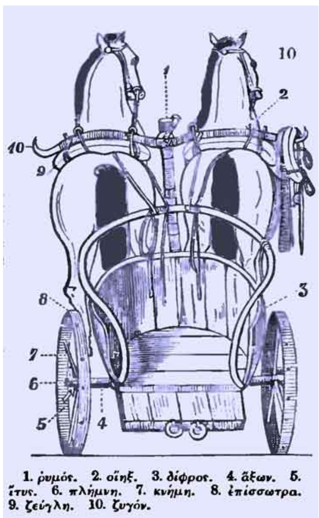

Figure 5. The Homeric Achaean chariot: 1. Draft pole, 2. Reign, 3. Superstructure box, 4. Axle, 5. Spoke, 6. Wheel hub, 7. Rim, 8. Tire, 9. Connecting saddle with horse, 10. Yoke.

In the Iliad, Book 23, Nestor, King of Pylos, appears to instruct Antilochos, his son, how to win the chariot race, organized by Achilles in honor of his dear friend Patroclus, who died in a duel with the Trojan Prince Hector. According to the Homeric account, the race track had an oblong shape. The chariots started from one end towards the other, where they had to execute a quick 180-degree anticlockwise tum about a wooden pole and then return to the starting point. During this inversion of motion the chariot was moving along a semi-circular course with very small radius, this being the most difficult part of the race, by which not only should the horses be very fast, but also the charioteer should exhibit exceptional skill or he would not manage to control the inertial forces successfully. Homer in this book through Nestor's notice that *if Archilochus would achieve this operation first, no other chariot even with very fast horses, would be able to overcome him*, describes in much detail the laws of mechanics for curvilinear motion [9].

4. EGYPTIAN CHARIOTRY

The Egyptians improved the design of the chariot by making it lighter, changing the position of the chariot's axle so that the driver would stand closer to it and covering parts of the axle with metal in order to reduce the friction between it and the wooden wheelhub. A single shaft attached to the yoke pulled the chariots. Various kinds of wood were used, some of which had to be imported: elm, ash for the axles and sycamore for the footboard. Some wooden parts were strengthened by covering them with metal sleeves. These changes reduced the load on the horses and greatly improved their performance. Saddle-pads were placed on the horses' backs and the yoke was attached to them. http://www.reshafim.org.il/ad/egypt/timelines/topics/pics/chariot_carriage.jpgLeather girths around the horses' chests and bellies prevented them from slipping.

Increasing skills of craftsmen in wood processing is particularly evident in wooden chariots that were found in excavations in graves that remained intact, also due to the climate of Egypt providing very useful information. In chariots found in Egypt, the wheels were very light and each such chariot consisted from more than 50 different pieces. Wood used by the ancient empires for carts and wheels had been imported in its majority from West Asia and in different species. Spoke wheels were much lighter and could be made in a much larger diameter, up to 2 meters, so that a chariot could be driven at much higher speeds over rough terrain, that allowed many battles, where those kind of chariots had been used for the first time, to be won[4-5,9].

Spoked wheels, appear at the beginning of the era of brass. Their development could not have become reality without the metal saw. The invention of the lathe although not definitely known, from the artifacts found it appears to be in use by 1500 B.C. in the area of eastern Mediterranean. It is used frequently after 900 B.C. and Plato refers to lathes by 400 B.C. The use of the lathe has also greatly enhanced the development of light chariots. Fig. 6 depicts a light chariot found in Thebes, Egypt in 1828-29 by I. Rossellini, manufactured around 1500 B.C. (it has been dated to the 18th Dynasty (1550-1292 B.C.) The chariot with 4-spokes wheels provides the first evidence of lubricated wheel bearings with animal fat, a technique that was still in use up to 100 years ago. The Egyptian horse drawn chariot consisted of a light wooden semicircular frame with an open back surmounting an axle with two wheels of four or six spokes [4-8,11].

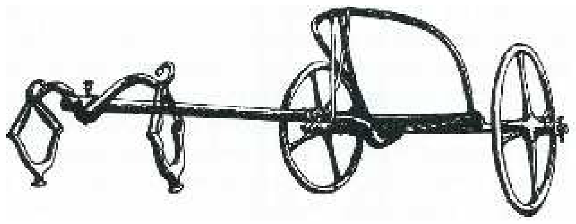

Figure 6. A two-horses drawn chariot with 4-spokes wheels and lubricated wheel bearings Thebes, Egypt, manufac– tured around 1500 B.C. [9].

By 1435 B.C. Egyptians were making chariots, and by the end of the century chariots with four-spoked wheels and light design had been introduced to Minoan Crete and the southern European mainland. Six chariots preserved in the fourteenth-century tomb of Turankhamun, intended for one or two standing passengers with railings reaching to hip height, had floor dimensions averaging 1030 mm wide and 470 mm front to back; wheel averaged 930 mm in diameter, and wheel track averaged 1700 mm.

A carpenters' shop manufacturing spoked wheels for carriages is shown in Fig. 7 [4]. On top the picture shows clearly consecutive phases of wheel production by different workers. Another important information yielding from Fig. 7 is the availability of the various parts required for the final carriage assembly [4-11]. In Fig. 7 (Bottom) in the left, two wheelwrights are forming rims, bending two lengths of wood inserted between two upright poles stuck in the ground. Working in such a way, the strain on the uprights is minimal. At the centre a seated worker is shaping a piece of wood with an adze. On his right two hoops, probably part of the framework, and what looks like the chassis with the axle. At the far right one of two wheelwrights putting together a wheel.

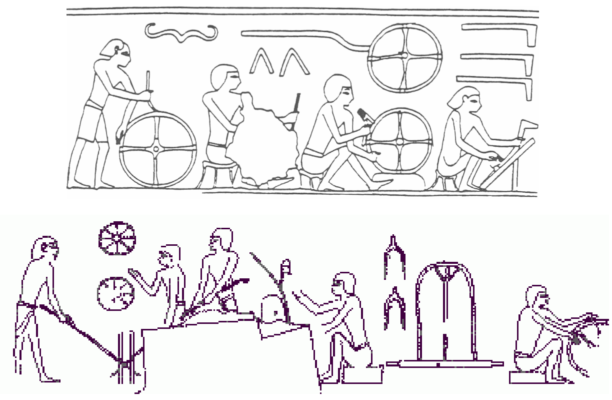

Figure 7. A carpenters' shop manufacturing spoked wheels for carriages [4].

The Egyptians knew two types of chariots, the war-chariot which had six-spoked wheels while the carriage chariots had only four spokes. The six spoked wheels could be made lighter and were better supported than the heavier four spoked wheels, making the whole chariot more reliable. The lack of springs made the chariots unsuited for use in rocky terrain, where they could easily overturn or break. Egyptian war chariots were manned by a driver holding a whip and the reigns and a fighter, generally wielding a bow or, after spending all his arrows, a short spear of which he had a few [12-14].

Pharaohs, used chariots in warfare, the most famous perhaps being Ramesses II at the Battle of Kadesh (Fig. 8), where both the Egyptians and their enemies, the Hittites, had chariots in their armies. The chariots of the Egyptians, unlike the Hittite chariots, were lighter and faster. The Egyptian chariot was also perfectly suited to chasing down fleeing enemies [15].

Figure 8. Ramses II at the Battle of Qadesh rides a chariot (relief at Abu Simbel) [15].

The spokes of the wheels were made by bending six pieces of wood into a V-shape. These were glued together in such a way that every spoke was composed of two halves of two V-shaped pieces, forming a hexagonal star. The tips of the V's were fastened to the hub by wet cattle intestines, which hardened when dried. The tires were made of sections of wood, tied to the wheel with leather or raw-hide lashings which passed through slots in the tire sections. The thongs did not come into contact with the ground, making the chariot more reliable by reducing the wear and tear. [12-14].

When a chariot was not in use the constant pressure of its own weight tended to deform the wheels. When the vehicle was stationary for any extended period of time, they were therefore removed -as was done in the tomb of Tutankhamen-or the chariot could be turned over. German carpenters who reconstructed such a chariot needed about six hundred man-hours to complete it [14].

5. CHINESE CHARIOTRY

Horses were not native to China but probably existed in Mongolia. Although domestication of the horse goes back at least to the fourth millennium B.C. in the steppes of western Asia, horses were not used there as draft animals until after long experience with oxen, donkeys, and other equids. In China no wheels of any kind earlier than the spoked wheel of Anyang chariots have been found (1200 B.C.). From the oracle inscriptions and bronze inscriptions found at the Anyang or Yinxu site, in the angle of the Huan River north-east of todays Xiaotun city and across the river at

Sanjiazhuang, identified as the last capital of the Shang dynasty, it is estimated that the reign of the first of the nine kings of the dynasty Wu Ding was around 1200 B.C. Among the well preserved findings of the excavations in Anyang there are a 10,000 m^2 bronze foundry, more than 1200 scrificial pits, and cemeteries with large tombs excavated since 1935, 1950, 1976 and in continuation up today. Textual records of China were not as durable and cheap as the clay tablets of the Near East of the same period. The earliest samples of cryptic royal texts on bones oracle inscriptions were apparently copied from writings on perishable materials. [16].

An impressive finding of a well preserved chariot burial, at Guojiazhuang M52, Anyang, Yinxu is shown in Fig. 9. The square pit dimensions are 3,500 mm and 1800 mm deep. Two men twenty-five to thirty years old and two horses were killed and laid in the pit before the chariot was lowered into place. The wheels, axle, and draft pole were fitted into trenchcs allowing the chariot box to rest on the bottom of the pit, thus preventing deformation of the wheels. Similar chariots found in tombs provide information that the lightly constructed chariots with multispoked wheels up to 1460 mm dia. proved effective for command, observation and archery and were supported by the infantry of the Shang army. Dimensioning of the chariot on the picture provides additional information for the reconstruction of this chariot [16].

The M52 chariot was unusually large but standard in construction, with two spoked wheels rotating on a fixed axle. The axle is located halfway between the front and back edges of the chariot box. The dratft pole length is 2680 mm made of a square cross-section. rested on top of the axle, it was curved upward from the under side of the box to the height of the yoke. The yoke, 2350 mm long. carried inverted-V-shapcd yoke saddles which rested on the horses' necks forward of the withers. The wheels had eighteen spokes and were about 1600 mm dia. The construction of the wheel rims implied by other Anyang chariots reveals they were made from two pieces of bent wood into which the spokes were fastened. Bronze axle caps with wood linchpins kept the wheels in place on the axle, but the wheels themselves had no metal parts (the rims and hubs of Zhou Chariots were sometimes reinforced with metal fittings).

The axle had an overall length of 3080 mm and the distance between the wheels was 2300 mm. The chariot superstructure box sat on top of the draft pole and axle. It measured 1500 mm from side to side and nearly 1000 mm from front to back, large enough for three kneeling passengers. The sides of the box were formed by a lattice of wooden bars about 500 mm high; the entrance, 400 mm wide at the back. Traces of red and black lacquer were found on the floor and sides, and it may be that all the wooden parts of the chariot were lacquered, for protective as well as decorative reasons. Yoke saddles, axle caps, a mechanism for joining the draft pole to the box, and a few small ornaments were made of bronze. The horses wore bronze frontlets, headstalls ornamented with cowry shells, and perhaps red cloth, and one had a bronze bell of the type *ling* at its neck. No bits or cheek pieces were found, but both are known from other Anyang chariot burials. Skilled carpenters were needed not only to build chariots, but also to keep them in running order. Harness making was another essential specialty. Available measurements for six Anyang chariots provide the following averages: floor dimension 1340 by 850 mm, wheel diameter 1370 mm, wheel track 2270 mm [14-16].

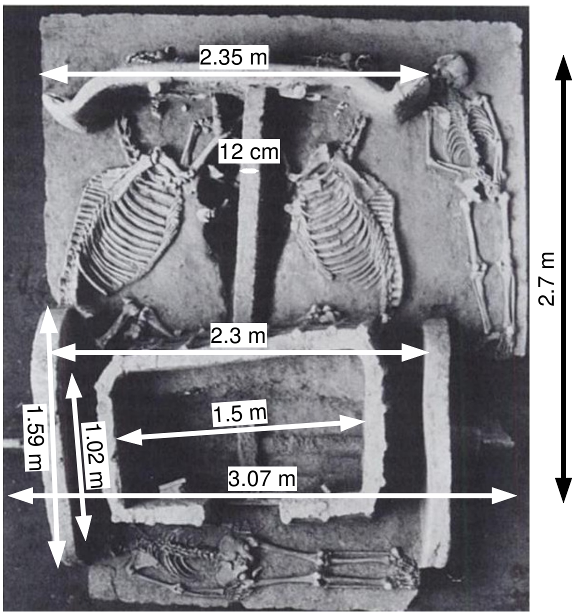

Figure 9. A well preserved chariot burial, at Guojiazhuang M52, Anyang, Yinxu [16].

This horse-drawn chariot is ·a technically sophisticated. artifact requiring special skills and resources for its construction, use, and maintenance. Two specific features of Anyang chariots are the large number of wheel spokes (from eighteen to twenty-six. as compared with four, six, or eight in the Near East) and the mounting of the axle not at the rear edge of the box, but midway between front and back. In western Asia both features are known only from mid second-millennium chariots buried at Lchashen in the Caucasus, and for the moment these are the closest relatives of Anyang chariots, indicating a strong influence from those areas.

6. ASSYRIAN CHARIOTRY AND WHEELED SIEGE TOWERS

During the ninth century BC chariots were being used as shock troops by the Assyrians. By the following centuries, however, the chariot's role on the battlefield was superseded by more efficient cavalry units. Fig. 10 depicts an Assyrian relief from Nineveh, alabaster relief, ca. 650 B.C. with a scene from Ashurbanipal's (668-627 BC) campaign against the Elamite city Hamaru. Fig. 10 shows an 8-spoked large wheel Assyrian chariot with charioteer and archer protected from enemy attack by shield bearers. Another relief from the palace shows that chariots were also used by the Assyrians for lion hunts (Fig. 11) [13-14].

Fig. 12 shows a relief decorating a room in the palace of Ashurbanipal at Nineveh, the king in his ceremonial chariot (topped with a parasol) presiding over the deportation of the conquered Elamites [14].

Figure 10. An 8-spoked large wheel Assyrian chariot with charioteer and archer protected from enemy attack by shield bearers [13-14].

Figure 11. A 6-spoked large wheel Assyrian chariot for lion hunts [14].

Figure 12. Ashurbanipal on his ceremonial chariot (topped with a parasol) presiding over the deportation of the conquered Elamites [14].

7. EUROPEAN CHARIOTRY

The Scythians by the 5th century B.C. had perfected the art of riding and carts making with multi spokes wheels up to 1800 mm. in diameter. The chariots had several handles for 2 or 4 or 8 horses. Generally, carts of war were lighter, faster and more agile [4].

In Europe the chariot was transmitted, perhaps by the Etruscans, to the Celts, who were using it in the British Isles about the 5th century B.C. The bodywork of Celtic chariots was somewhat heavier than that of the Greek, and metal, sometimes inlaid with fine enamels, was used for axle and draft pole, and occasionally for solid wheels. In the Celtic world, where the chariot remained in use until the 4th century A.D., small ponies, yoked four abreast, were used for draft [13-14, 17].

By the time of Alexander the Great (3rd century B.C.), the war chariot had been superseded by cavalry, but chariot racing had become popular in Greece and was a main feature of the Olympic Games and of the Pythian Games at Delphi. In the Roman circus games, chariot racing took foremost place, and chariotry became socially important. Racing vehicles were drawn by two, three, or four horses, although as many as 10 horses were harnessed on spectacular occasions; chariots drawn by dogs and even ostriches are mentioned [13-14].

7.1 TRACTION REQUIREMENTS

Speed, the chariot's advantage over other ground transportation means, depended on horse traction and on light construction, above all on spoked wheels. Domestication of the horse goes back at least to the fourth millennium B.C. in the steppes of western Asia, horses were not used there as draft animals until after long experience with oxen, donkeys, and other equids. Animal traction, whether with vehicles or for plowing, were of an empirical nature for centuries. Watt determined the number of horses his steam engine could replace by using horses to pull a rope passed over a pulley attached to a weight at the bottom of a deep well. Watt established 33,000 ft lb (4562.4 kg m) per min or 550 ft lb (76 kg m) per s as the unit of power, or 1 horsepower (hp).

The draft necessary to pull wheeled implements, e.g., wagons, carts, cultivators, is influenced by axle friction, grade, and rolling resistance. Axle friction varies with the load on the wheels, spindle radius, efficiency of lubrication, and materials used in the wearing surfaces, i.e., plain or ball bearings, bronze bushings. The tractive pull required to overcome axle friction varies directly with the radius of the spindle and inversely with the radius of the wheel. For the double horse light chariot, it is assumed; 45 kg gross weight of the chariot structure, 65 kg mass per person for the charoteers and warrior, and 15 kg ammunition.Then, total weight for three persons onboard becomes 255 kg. Assuming 1:7 draft to weight ratio, and 50 % horsepower of the horses of the 2nd millenium B.C. as compared to Watts measurements, 0.6 horses are required to pull the structure at a speed of 3.2 km/h (0.89 m/s) on a level ground.Then, the 2 horses used provide a speed of roughly 10 km/h, which for a limited time galloping can reach 25 km/h [18-20].

8. DRAFT BEAM AND AXLE DESIGN

A spreadsheet was used for a preliminary stress analysis of the draft beam and the axle for the Anyang chariot [1]. It will be assumed that the draft bar is simply supported on the wheels axle and the yoke on the horses necks, and a uniformly distributed load from crew and supplies, totaling 2550 N is applied along the length of the box-structure. At the support stations arbitrary reactionas are assumed initially. Then, the EXCEL Tools Solver was applied to solve for the unknown reaction by making zero the shear and bending moments at a dummy station on the right end of the draft beam. Since the problem is linear Solver returns with aunique solution. For the chariot draft beam reactions at front edge and the back edge are calculated; 290 N acting on the horses necks and 2220 N supported by the wheels' axle. Maximum bending moment 650 Nm occurs at 2300 mm from front end. Figure 13 shows the shear forces and bending moment diagram for the draft pole.

Fir wood properties comprise strength in tension and compression, shear strength, static bending strength, impact strength. Fir is repeatedly mentioned in Homer, praising its good properties [1]. Fir wood is orthotropic, with unique and independent mechanical properties in the directions of three mutually perpendicular axes: longitudinal, radial, and tangential. Modulus of elasticity along the longitudinal axis parallel to the fiber (grain) is E = 1.01E10Pa, and material density 520 Kg/m^3. Tension perpendicular to grain is 1.86MPa. Static bending stress for dry cypress-tree wood is 76MPa and allowable stress for wood in construction 25MPa [32].

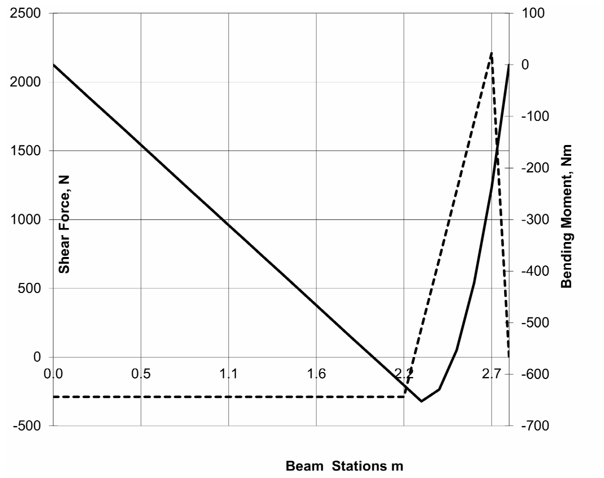

Figure 13. The Anyang chariot shear forces - bending moment diagrams along the draft pole (continuous line: internal moment Nm, dashed line: shear force, N).

Section modulus in bending for the draft beam of rectangular cross-section bxh=110x110 mm^2, is calculated as [1]:

$$W_x \cong bh^2 / 6 \tag{1}$$

or W_x= 0.000288 m^3. Then, maximum stress in pure bending $\sigma_{\max} = M_b / W_x$ yields $\sigma_{\max} = 7.68$ Mpa. From the basic design equation for bending of beams [1] yields

$$\sigma_{\max} \le \frac{S_L}{N} \tag{2}$$

where S_L = 25 MPa, the limiting stress for fir wood, yields safety factor N = 3.25, a quite safe value for dynamic loading.

Assuming 2.80 m active axle length, 120 mm axle diameter, and 2250 N loading uniformly distributed along the 1500 mm box width, the same spreadsheet used for solving the draft pole stresses is used again for the wheels axle internal loading [1]. Spreadsheet-drawn internal loading diagrams are depicted in Fig. 14.

From Fig. 14 maximum internal moment 1,151 Nm and 1,172 N shear force yield for the wheels axle. Section modulus in bending for the circular cross-section with D = 120mm is calculated as [1]:

$$W_x \cong 0.1D^3 \tag{3}$$

or W_x= 0.00017 m^3. Then, maximum stress in pure bending $\sigma_{\max} = M_b / W_x$ yields $\sigma_{\max}$ = 6.61 Mpa. From the basic design equation for bending of beams, Eq. (2) [1] yields N = 3.75 safety factor in bending, a rational number for this design.

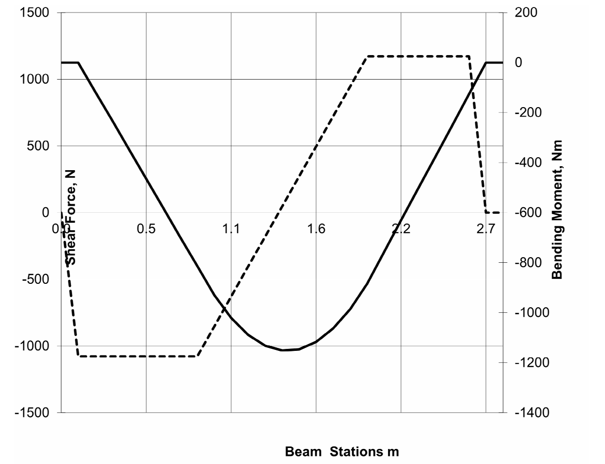

Figure 14. The Anyang chariot, spreadsheet-drawn internal loading diagrams for the wheels axle (continuous line: internal moment Nm, dashed line: shear force, N).

There are two sections of the shaft subjected to shear in each side adjacent to each wheel. Failure criterion for pure shear, considering the influence of normal stress yields the design equation [1],

$$\tau = \frac{4V}{3A} = \frac{4V}{3\pi D^2 / 4} = \frac{S_{sy}}{N} \tag{4}$$

where d=60 mm the axis diameter at wheel bearing, V = 2250 N, shear force at wheel bearings considering the case that all chariot weight is loading one wheel at turns, S_{sy} = 4.79MPa yield strength of wood in shear (perpendicular to grain), and N safety factor. Then the solution of Eq. 12 yields τ = 0.26 MPa, and safety factor in shear, N = 18.05. Considering the high level of stresses due to the diameter reduction at this area of the shaft a reduction of this safety factor by 4 times is a rational choice. Then, the safety factor in shear becomes, N = 4.05, similar to the safety factor in bending, again providing a very good margin of safety for the design. Eqs (2) and (4) yield that the wheels shaft is sufficient for the combined shear and bending loading conditions.

9. CONCLUSION

The two-wheeled horse-drawn chariot was one of the most important inventions in history. It gave humanity its first concept of personal transport, and for two thousand years it was the key technology of war. It also became the world's first mass spectator sport attraction. Based on the archaeological evidences, a design study on the evolution of the dual horse chariot is presented here, along with a design study of the main structural components and loading of the Anyang chariot, based on archaeological evidences.

The two-wheeled horse-drawn chariot was one of the most important inventions in history. Its development is of great engineering significance incorporating the seeds of a primitive design activity. This study lends itself for further development of a detailed reconstruction of two-wheeled chariots accompanied with static, kinematic and dynamic analysis.

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РАЗВОЈ ДВОПРЕГА ОД БРОНЗАНОГ ДОБА ДО ХЕЛЕНИСТИЧКОГ ПЕРИОДА

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Лаке кочије са точковима са паоцима настале су у Сирији или северној Месопотамији почетком 2. миленијума пре нове ере и брзо су ушле у употребу широм Блиског истока. Кочије које вуку два коња биле су један од најзначајнијих изума у историји. Човечанство је тако стекло први појам сопственог превозног средства и две хиљаде година кочије су представљале кључну технологију у вођењу ратова. Подаци о кочијама, које су се користиле у Месопотамији, Египту, Микени и Античкој Грчкој, Кини и Европи, са лаким и флексибилним точковима са паоцима из постојећих открића античких кочија, камених рељефа и сликама на вазнама се користе за проучавање конструисања двопрега и како се оно развијало током векова. Реконструкција нацрта двопрега нађеног у Анјангу у Кини је приказана у овом раду као доказ да се у њему налазе зачеци првобитног дизајна.