

SELECTED ANCIENT STONE BRIDGES WITH CORBELLED FALSE-ARCH STRUCTURE

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Abstract

The oldest man-made false-arch stone bridges are presented and briefly described. It is shown that this construction technique was based on the experiences of the first builders, formed at the junction of ancient Egyptian, Mycenaean as well as Assyrian and Babylonian cultures. Arches in such bridges have not yet been constructed in a classical manner, i.e. one that was later prevalent by the Romans, but these were only the primitive arch-like structures, with a false needle vault, that were shaped mainly by corbelling. This type of the structure, if it was used in bridges, turned out to be much more stable than the well-known at that time and commonly used in gateway passages oval “true-arch” built from sun-dried mud bricks.

Keywords: arch stone bridge, false arch, needle vault, mud brick arch, corbelled arch, culvert, aqueduct.

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1. INTRODUCTION – THE ANCIENT DOMES AND ARCH-VAULTED GALLERIES

It is common knowledge that the oldest man-made building structures, if these were built of stone, were erected in the so-called post and lintel system. In such a system the relatively heavy horizontal beam elements, forming a roof, were held up by the other vertical elements, strong enough and so very thick, giving at that time such a free span between them which could not be very spacious. Increasing the size of this space became possible only after the use for roof construction of the primitive arch-vaulted structure. It is historically confirmed that the roofs of this type were able to build as early as 6000 BC, in circular buildings supporting beehive-shaped and corbelled-vaulted domes made of unfired mud bricks. These can also be seen as undemolished until today, sometimes even in the version made of stone blocks instead of the fine-grained brick structure typically used in an ancient Near East territory. This case occurs for example in relation to the megalithic tomb called Newgrange, located in Ireland near the present-day Dublin, which was built around the year 3200 BC (Fig. 1-left). It is amazing that some ancient dome-like roof structures can be seen today in the background of a bas-relief originating from the famous Assyrian palace in Nimrud (Fig. 1-right).



Fig. 1. Left – A view from the inside on the corbelled-shaped stone vault of the Newgrange tomb [W1]. Right – A drawing that maps a bas-relief excavated from the ancient palace in Nimrud in which the dome-like roofs on the buildings are shown in detail [W2]

Simple brick and stone domes, as we know them from early antiquity, were always geometrically double-curved structures and this fact ensured their self-

stability after erection, without any additional treatments. It was much more difficult, however, to build at that time of the same material the arcaded galleries with arch-vaulted roofs, entering to the tombs or to the other chambers covered with such domes. These were geometrically single-curved structures, and this caused that their stability could not be ensured without any separate bracing system. Relatively early it was noted, however, that the arch-roofed galleries of this type could be easily built as the brick gateways being self-stable during erection if only these galleries had been fixed at their “starting-points” on the non-deformable wall. Structures erected in this way are called today as the pitched-brick vaults because the successive brick layers were leaning (pitched) in them at an angle, each layer leaning against the one next to it (Fig. 2-left). Having thus constructed the preceding layer the next layer was laid above it, with the bricks set at the same angle or, alternatively, laid upright, especially for the front layer. Pebbles and mud mortar were inserted to fill in the gaps between the bricks on the outside of such the vault. This technique of the arch erection allowed the gallery to be completed without the use of centring (which is the name of the temporary and most frequently wood structure upon which the stones of an arch or of a vault are laid during construction). If, as in the cause of an archway, there was no wall at the end of the tunnel, one had to be constructed, which was removed when the arch was completed. Though many brick gateways erected in this way and excavated by archaeologists in the territory of the present-day Egypt are dated to the Old Kingdom period the best known arches of this type are slightly younger. These were discovered in the Ramesseum [1].

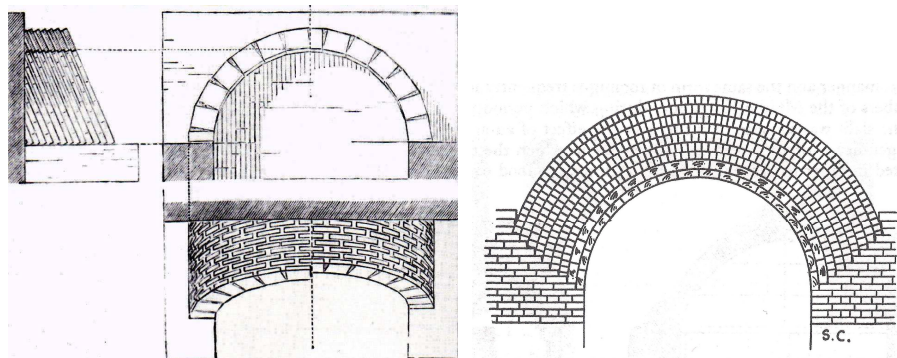


Fig. 2. Left – Technique of the construction of a passage with pitched-brick vault, a front view as well as the top and side views [W3], Right – A typical composite arch-vaulted roof of a gallery passage with inner rings made of specially-shaped bricks and forming a centring for upper rings of ordinary bricks (according to [1])

In the case when the great archways were constructed the inner rings of specially-shaped bricks were used as a centring for a succession of the upper rings of ordinary bricks. These inner rings laid as the stretchers towards the longitudinal axis of the tunnel. Despite the fact that such special rings had been used before for centring the arch, these were not removed when the upper rings were completed (Fig. 2-right). A good example of this type false-arch gallery seem to be the gateways discovered in the necropolis called El-'Asasîf and located near the ancient Thebes. These remnants of arcade passages with a span of 13 feet have six visible rings of bricks [1]. Probably the next four rings still remain inside this structure so none of them can be precisely examined. Consequently, it is not clear how many rings of special arch-shaped bricks were originally constructed.

2. CONCEPTS OF THE STONE FALSE-ARCH STRUCTURE

The specific technique enabling construction of a simple arch-vaulted gallery, described in the chapter introducing to this paper, proved to be ineffective if it was intended to be used in bridge engineering. Every bridge is a relatively narrow structure so it was impossible at that time to brace it efficiently, transversally to its longitudinal axis, by fixing each arch at its end to a non-deformable wall. In addition, the narrow arches in such a bridge should be set in a different order, not one after the other as it took place in the galleries, but one next to the other, creating a free-standing structure. It was also important that ancient engineers sought to construct the bridges which were made of stone, for the proper durability, but it was possible only if this material was available in the nearby area. Let us note that in early antiquity for hundreds years people had been able to built the oval arches, but only of relatively small free-span, that were placed as the gates in the city-walls or even in the ziggurats. These types of the arches, however, were always constructed of small pieces of fired or even of unfired sunny-dried mud brick, never of stone blocks. A good example of a very old arch of this type may be partially reconstructed gate to the ancient Edublalmahr temple in Summerian Ur dating back to 2100 BC (Fig. 3-left) and also a similar arch being a part of the Elamite ziggurat in Chogha Zanbil originating from 1250 BC which was built by the king Untash-Napirsha (Fig. 3-right). Due to the limitations in material strength the structural solution of this type could not be taken into account when the arch-like-bridges were constructed.

Forming the arch in a construction made of stone blocks required in the early antiquity the application of a completely different technique. One of the specific ways to obtain this effect was that invented by ancient Egyptians. The pointed

gable-wise roof was formed in this manner by pairs of large stone slabs leaning against each other. The uppermost relieving of the King's Chamber in the Great Pyramid and also the burial chamber of the Pyramid of Unas were roofed according to this concept. In general, the same form of roofing can be frequently seen in many much younger burial chambers dating back to the times of the Middle Kingdom. Let us note that during this period under surface of such the stone slabs was sometimes cut to give the effect of an arch. In many cases the top of the slabs in roofs of this type was blocked by a hinge-like plug in order to prevent them for slipping (Fig. 4-left).



Fig. 3. Left – Partially reconstructed flat „true-arch” brick gate of a small free-span to the Edublalmahr temple in Summerian Ur dating back to 2100 BC [W4], Right – An opening topped with a flat “true-arch” being a part of the Elamite ziggurat in Chogha Zanbil, originating from 1250 BC, reconstructed partially from original brick (photo taken in 2015 by M. Maślak)

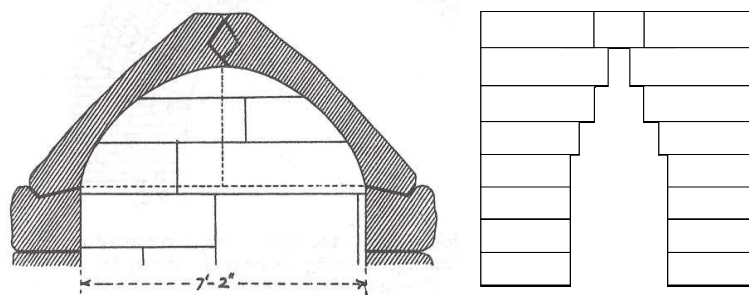


Fig. 4. Left – A false-arch roof made of two large stone slabs pinned at the top with under surface of such slabs cut to obtain the effect of an arch (according to [1]). Right – A false-arch flat stone gate shaped by corbelling [W5]

Undoubtedly, the approach most commonly used by our ancient ancestors to obtain the flat arch-like stone structures was the construction of so-called corbelled false-arch. The arch of this type was erected by offsetting successive courses of the stone blocks (or bricks) lying in each course, after the wall had attained the required height, somewhat further forward than the one below. This was made simultaneously from each supporting side until the courses were close enough to be spanned by a single roof-block (Fig. 4-right).

The earliest corbelled stone roofs, as we know them today from an ancient Egypt, are those from the chamber in the Pyramid of Sneferu at Mejdûm (about 2600 BC) and from the Grand Gallery of the Great Pyramid of Giza (about 2560 BC). In the period of the Middle Kingdom similar corbelling technique was frequently used in the roofing of chambers both in younger pyramids and in mastabas. The best preserved of this type seems to be the structural solution applied in the chamber of one a mastaba located in Dahshûr, which was built in times of reign of the XIIth dynasty (1991-1802 BC) [1]. Let us note, however, that these relatively early-dated examples refer to the arches used to build the three-dimensional roof structures rather than to the flat two-dimensional arches discussed in this chapter and, without a doubt, more difficult to construct.

Ancient Egypt was not the only region where the false-arch structures were built using the corbelling technique. In this chapter we also want to mention the comparably old building tradition which has been developed in the world of the Mycenaean culture. In fact, the Mycenaean were also the builders of many unique objects where corbelling was successfully applied. However, the specificity of their constructions was the fact that, in contrast to the Egyptian structures in which the carefully worked stone blocks were generally used as a basic building material, only the so-called Cyclopean walls were built, of unworked stones. Of course, the typical corbelled false-arches could be easily constructed also from the stones of this type. However, we would like to draw the reader's attention to one construction detail that seems to be specific for this culture. The Mycenaean in the structures which were built by themselves, if they intended to make an entrance hole in Cyclopean walls, could effectively distribute the gravity vertical loads into two supporting reactions arranged on the sides, doing so thanks to the application of a large triangularly-shaped rock block. Such a stone block was acting there as a strain relief disc standing on the massive horizontal beam of the architrave. This allowed for such the opening to obtain a free-span that was significantly larger than that being achievable when using the archaic post a lintel system. The most famous disc of this kind was that applied in the Lion Gate (13th century BC) which was constructed as a main entrance to the citadel of Mycenae (Fig. 5-left).



Fig. 5. Left – A corbelled stone false-arch applied in the Lion Gate structure in the citadel of Mycenae in which the massive triangular disc relief the architrave beam [W6]. Left – An analogous triangularly-shaped corbelled stone false-arch used in the entrance to the tholos called the “Treasury of Atreus”, located also in Mycenae but on the Panagitsa Hill, in which the large stone disc is not inserted into the gate structure [W7]

Such a triangular shape is in general specific to the whole considered region because it was repeated many times, always when the arcade gateways to the numerous tombs or temples were constructed. It is essential, however, that the stone disc itself was no longer inserted into the gate structure. This concept is very well visible in the corbelled triangularly-shaped construction of the entrance to the tomb called the “Treasury of Atreus” (around 1250 BC), also located in the ancient Mycenae but on the Panagitsa Hill (Fig. 5-right).

Let us note that an analogous triangular shape of a corbelled stone roof one can observe also for an archway tunnel dating back to 2000-1600 BC and excavated in the ancient Tirins located on the Peloponnese peninsula (Fig. 6-left). This is not a surprise because, according to the historical records, it was a city that developed in the circle of the Mycenaean culture. It is not so easy to decide, however, whether, and if so to what extent, the influence of the Mycenaean determined the construction technique used for the similarly corbelled tunnels that constituted an entrance to the so many Sardinian nuraghes located relatively far from the present-day Greece territory. One of the tunnels typical to this kind, that being a part of the so-called Nuraghe Santu Antine (19th-18th centuries BC)

which is located in Torralba in Italian Sardinia, is presented in Fig. 6-right for comparative purposes.

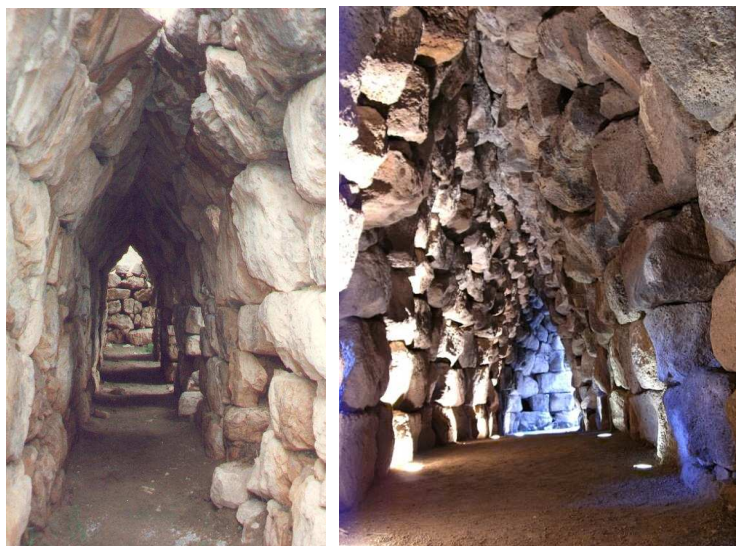


Fig. 6. Left – A corbelled stone tunnel with a triangularly-shaped false-arch roof excavated in the ancient Tirins [W8]. Right – A similar corbelled stone tunnel but in this case typical for the Sardinian nuraghes, being a part of the ancient Nuraghe Santu Antine [W9]



Fig. 7. Left – The needle-vaulted corbelled stone entrance to the ancient Royal Palace in Canaanite Ugarit [W10]. Right – Hellenistic corbelled stone bridge in Eleutherna in the Crete island with a purely triangular shape of a vault [W11]

The corbelled stone false-arches were at that time commonly built in the countries of the ancient Near East territory, also in the arcade gateways both to the tombs and to the temples and palaces. Obviously, that were constructed only in the regions where the stone blocks were easily accessible. Let us note, however, that in those areas the pure triangular shape of such the openings, characteristic for the Mycenaean culture, was in general replaced by the other one being slightly more rounded, and therefore the vaults covered with such molded roofs are called today as the needle vaults. The good example of such the solution can be the entrance to the Royal Palace in Canaanite Ugarit (erected 15th-13th century BC) (Fig. 7-left).

3. THE WORLD'S OLDEST CORBELLED FALSE-ARCH BRIDGES BUILT IN THE REGION OF ARGOLIDA

After the presentation of basic principles how to construct a stone false-arch using a corbelling technique it is time for a brief overview of selected arch stone bridges built in this manner and considered by historians to be the world's oldest bridges of this type. Let us start this overview from a short description of the Eleutherna Bridge with a characteristic triangularly-shaped stone false-arch (Fig. 7-right). This shape of a vault was in fact typical for an ancient Mycenaean culture which had been discovered, however, about one thousand years before the considered bridge structure was constructed. This bridge is located on the Greek island of Crete and is still in use. Its structure made of the unmortared limestone blocks is undoubtedly very primitive because it is not very old. It is dated on the Hellenistic period only. A more precise dating of this bridge is hampered by the lack of proper finds, however, Galliazzo suggests to date it on the end of the 4th or even on the beginning of the 3rd century BC. In modern times the Eleutherna Bridge was firstly described by T.A.B. Spratt after he had visited this site in 1853. At that time another ancient bridge, also with a triangular false-arch, was still standing a few hundred metres away, but, judging from a later report, it was destroyed before the year 1893.

As it was mentioned above, the opening in the considered bridge was cut in the shape of an isosceles triangle, the height of which is 1,84 m. The overall length of the whole bridge measures 9.35 m whereas its width varies from 5.10 to 5.20 m, with the structure slightly converging towards its center point located directly above the vertical axis of the false-arch (in this place the width of the bridge is the smallest and equal to 5.05 m only). The total height of such the bridge is between 4.00 and 4.20 m.

It is important to emphasize that the structure of the Eleutherna Bridge is definitely outdated and it does not fit into its time. One has to be born in mind that at the same time (i.e. in the 4th century BC) on the Greek island of Rhodes a

more modern bridge has already been built in which the true voussoir stone arch was successfully constructed. This bridge is also still in service but in modern times it is used as the famous Rhodes Footbridge.

It is widely acknowledged by historians that the oldest stone arch bridges in the world, being still used by local villagers, are the corbelled culverts that can be found even today wandering the so-called Mycenaean route which traverses the Argolida region in the northern part of the Peloponnese peninsula. This path leads today from the present-day Tiryns to the current Epidauros. On this route one can find at least three well-preserved corbelled arch bridges, especially near the village of Arkadiko. Such the ancient Mycenaean bridge structures consist of numerous courses of the large limestone blocks that form in general a corbelled false-arch, shaped typically as an inverted triangle, through which the river flow was once allowed. When necessary, the retaining walls were used to the sides of these bridges to protect both the bank and the bridges from erosion. The most famous and the best known of them is the Kazarma Bridge, called also as the Arkadiko Bridge (Fig. 8-left). This structure is dating back to the Greek Bronze Age, i.e. to the period 1300–1190 BC which corresponds to the times of the Trojan War. The considered bridge is 22 m long and 4 m high. Furthermore, it is 5.60 m wide if measured at the foundations level and only about 2.50 m wide in relation to the roadway at the bridge top. It is built of limestone boulders without binding mortar, in the characteristic Mycenaean masonry called "Cyclopean". The other famous corbelled false-arch stone bridge, made of the same material and located on the same aforementioned Mycenaean route, is the Petrogephyri Bridge (Fig. 8-right) sometimes named as the Western Arkadiko Bridge, which crosses the same stream but 1 km to the west of the Arkadiko Bridge. These both bridges are similar both in size and in appearance, however, the Petrogephyri Bridge has a larger free-span and a little higher vault. The third ancient corbelled false-arch stone bridge, the one located nearest to the present-day Epidauros at the eastern part of the Mycenaean route, is not used today because at this site only the ruins of the previous bridge have been discovered.

A fourth, well preserved and well known Mycenaean bridge is that located in the region of Lykotroupi, so it is called as the Lykotroupi Bridge. This structure, however, is a part of the other historical Mycenaean road. In spite of this fact, its measurements are close to that characterising the Arkadiko Bridge. In particular, it is 5.20 m wide at the bottom and 2.40 m wide at the top. Furthermore, this bridge is 15 m long and its total height is equal to 2 m. It has a corbelled stone arch with a free-span of a little more than 1.00 m.



Fig. 8. Left – The Kazarma Bridge also called as the Arkadiko Bridge, the current state [W12]. Right – The Petrogephyri Bridge also known as the Western Arkadiko Bridge, the current state [W13].

According to [2], one more bridge should be added to the group containing the previously described antique false-arch stone bridges which were built by the Mycenaeans using the corbelling technique. This is the ancient Dragonera Bridge with the structure which is about 15 m long, 4 m wide and 1.5 m tall. It is worth emphasizing that the construction principles relating to the ancient Mycenaean pseudo-arch stone bridges, based on the use of a corbelling technique which seems to be typical for people who lived at that time in this region, especially with respect to the cases when they erected the structures made of the huge Cyclopean blocks, has not yet been sufficiently well understood from the engineering point of view. An unquestionable gap in this field seems to be partly filled by an interesting work [3] in which the static behaviour of two best known Arkadiko Bridges is analysed in detail for the case when these structures are subject to external gravitational loads.

4. SENNACHERIB'S AQUEDUCT AT JERWAN AS AN ANCIENT CORBELLED STRUCTURE ICONIC FOR ASSYRIAN BRIDGE ENGINEERING

In the previous part of this article it was pointed out that in the countries of an ancient Near East territory the corbelled stone false-arches were in general formed to be slightly more rounded than those being typical for the Mycenaean culture. For this reason, the vaults shaped in this manner are usually called as the needle vaults. A detailed overview of the stone bridges with such the arches, both ancient and early medieval, is given in [4]. In this chapter we want to briefly describe the only one particular bridge of this type, that which is considered to be the oldest of them all. The remnants of such the structure have been discovered in the present-day Jerwan which is located in the Nineveh Province of Iraq. These are the very extensive ruins of an ancient aqueduct-like

structure being only a part of the artificial Atrush Canal that was built by the Assyrian king Sennacherib between 703 and 690 BC to water the Ninevah's extensive gardens, with water diverted from the Khenis Gorge, 50 km to the north. The route of this new canal required crossing by its water over the Khenis River, perpendicularly to its current. To do this the Assyrian engineers had to built an arch bridge at the site of this atypical intersection (Fig. 9-top). The aqueduct under consideration was constructed of worked stone blocks bonded one to the other using the waterproof cement-like material to prevent the leakage of water. It measures about 300 m in length and 12 m in width (Fig. 9-bottom).

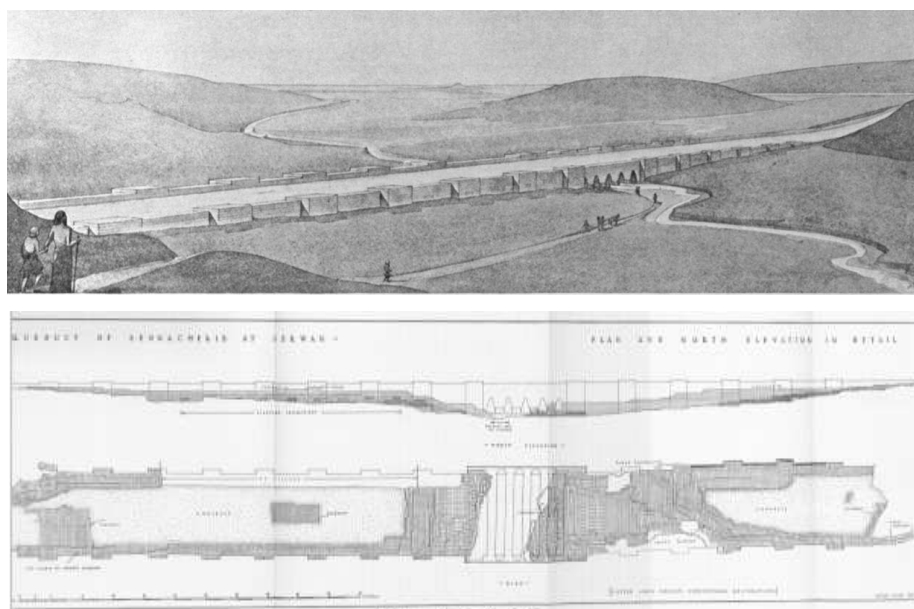


Fig. 9. Top – A general view of an ancient Sennacherib's aqueduct with a bridge at the place of the intersection between the new artificial canal and the current of the Khenis River, as we imagine it today (according to [5]) – [W14]. Above - An inventory of the state preserved to the present day, depicted on the side view as well as on the horizontal projection of the original structure (according to [5]) – [W15]



Fig. 10. Left – The cuneiform inscriptions on the stone blocks used for construction of the Jerwan Bridge structure, preserved to this day [W16]. Right – A current view of one of the corbelled false-arches used in the bridge under consideration [W17]

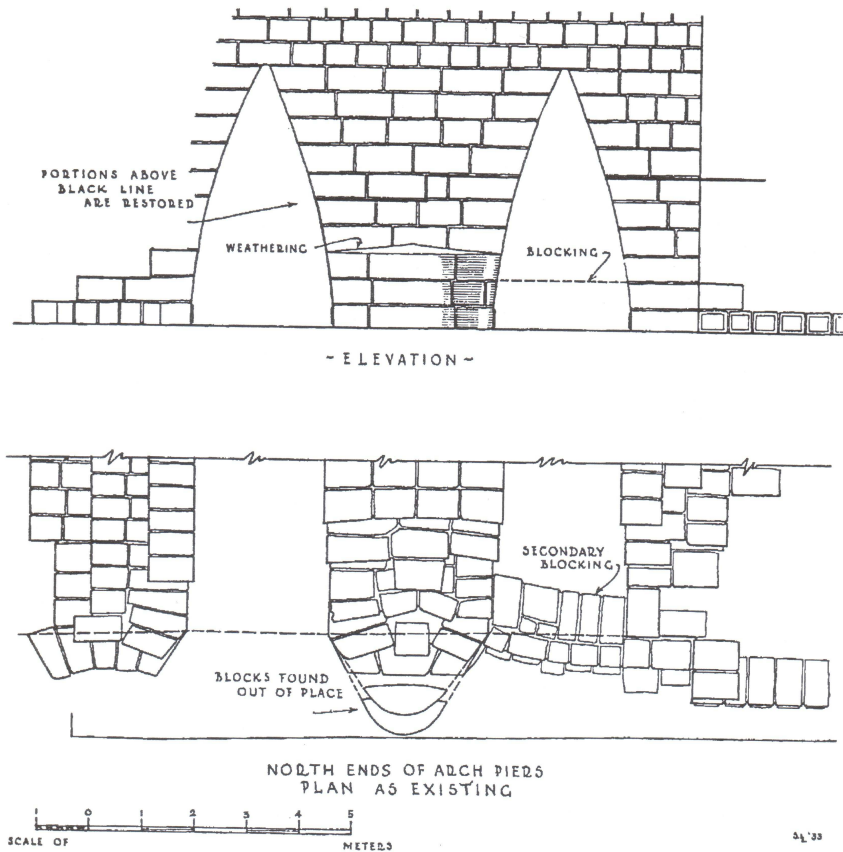


Fig. 11. A reconstruction of the Jerwan Bridge proposed in [5]. At the top – a side view, at the bottom – a horizontal projection

On some of the stones used for the construction the cuneiform inscriptions have been preserved to this day, glorifying the aqueduct founder (Fig. 10-left). In Fig. 10-right one can see a current state of the remnants of a one stone false-arch being a part of the bridge structure. The whole aqueduct, as we see it today, is inventoried in detail in [5]. In the same report a reconstructed view of the structure of considered bridge is proposed (Fig. 11). There are also discussed all the inscriptions deciphered by historians. As one can see in Fig. 11, the structure of a bridge under consideration was supported by the typical corbelled false-arches with needle vaults.

It is very likely that this Assyrian stone bridge itself was reported by ancient chroniclers as the famous Hanging Gardens of Babylon, which are known as one of the Seven Wonders of the Ancient World. In fact, it was only a part of the irrigation works carried out on a much broader scale. Such a hypothesis [6] seems to be confirmed by an ancient bas-relief excavated in the ruins of the North Palace of Ashurbanipal at Nineveh which is currently exhibited in the British Museum of London (Figs. 12 - left and 12 - right). It is easy to see that the considered bridge is depicted in such a relief in its upper right corner. Let us note that king Ashurbanipal (669-631 BC) was a grandson of the king Sennacherib (705-681 BC) so it is not a surprise that he wanted to keep his deeds for posterity.

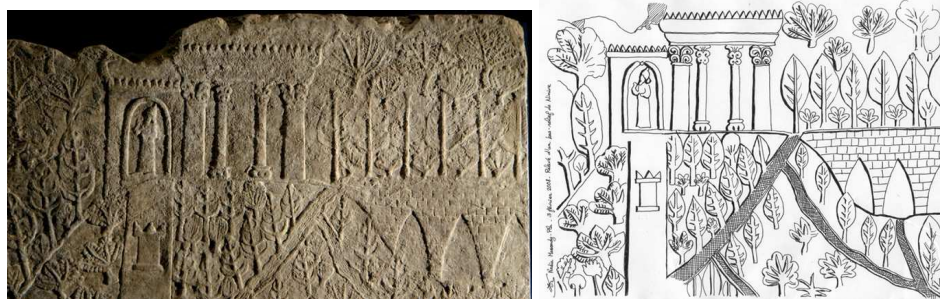


Fig. 12. Left – An ancient bas-relief excavated from the Ashurbanipal’s North Palace in Nineveh in which the Sennacherib’s bridge is depicted [W18],
Right – A drawing that maps such a bas-relief [W19]

5. CONCLUSIONS

In this article, by describing the oldest stone arch bridges which have been identified by historians, we tried to show that at the dawn of time their development was conditioned by the limited skills of the ancient builders. At that time, the principles how the external and internal loads subject to the structure could be transferred into its foundations were understood only intuitive,

and therefore those builders were unable to construct the true voussoir arches, especially when such arches should be made of the huge stone blocks. For this reason, a technique commonly used in ancient times in bridge engineering was the construction of the primitive false-arches that were built using the corbelling. However, it has to be admitted that at the same time also the alternative techniques of the arch construction were known to the ancients, but these concerned mainly the objects erected from sun-dried mud bricks of a relatively small size. Due to the difficulty in ensuring the stability of the constructions built in this way, these alternative techniques were rather used only in three-dimensional objects such as domes, vaults and arcade galleries. Construction of such the primitive false-arches had been developed in different ways in various regions of the ancient world, but, certainly, all of these techniques, described by us in this paper, have common roots being significantly much older. These take their origins as early as in the times when the megalithic structures had been built which was in general thousands of years before the bridges discussed in our paper were constructed.

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- W2 - Fig. 1. Right
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- W5 - Fig. 4. Right
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OPARTEJ NA ŁĘKU POZORNYM

Streszczenie

W artykule krótko opisano najstarsze zidentyfikowane przez historyków starożytne łukowe mosty kamienne. W mostach tego typu, z uwagi na ograniczone umiejętności ówczesnych budowniczych, do konstrukcji stosunkowo prymitywnych łuków nośnych stosowano na ogół tak zwane fałszywe sklepienia oparte na zasadzie łuku pozornego. Zaprezentowane techniki wznoszenia takich łuków wynikały z doświadczeń rozmaitych ludów zamieszkujących różne regiony świata antycznego. Rozwijały się one w zasadzie niezależnie, na styku oddziaływania wielkich kultur, w tym w szczególności kultury starożytnego Egiptu, kultury mykeńskiej a także kultur babilońskiej i wczesnoasyryjskiej. Pomimo pewnych różnic specyficznych dla poszczególnych rozwiązań konstrukcyjnych spotykanych w różnych lokalizacjach dość łatwo da się rozpoznać wspólne korzenie wywodzone właśnie ze stosowania tej samej dla wszystkich podstawowej zasady łuku pozornego. Zanim efektywnie wykorzystano ją w konstrukcjach mostów została ona wielokrotnie zweryfikowana przy wznoszeniu obiektów trójwymiarowych, w tym w kopułach megalitycznych tolosów oraz w prowadzących do tych grobowców arkadowych galeriach wejściowych. Łuki tego typu, ustawione arkadowo, jeden za drugim, stanowiły również elementy nośne bram wprowadzających do starożytnych miast i świątyń. Technika konstruowania łuku pozornego była w zasadzie jedyną dostępną jeśli budowano z lepiej lub gorzej obrobionych wielkich głazów kamiennych. Tam gdzie podstawowym budulcem w miejsce trudnodostępnego kamienia była suszona na słońcu drobnowymiarowa cegła mułowa w analogicznych galeriach skutecznie kształtowano również łuki sklepienie owalnie, były to jednak także łuki pozorne, nie zawierały bowiem w sobie klasycznego zwornika.

Słowa kluczowe: kamienny most łukowy, łuk fałszywy, sklepienie igłowe, łuk z cegły mułowej, łęk pozorny, przepust, akwedukt

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