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THE DEVELOPMENT OF WOODEN BRIDGES THROUGH THE AGES – A REVIEW OF SELECTED EXAMPLES OF HERITAGE OBJECTS. PART 1 – THE MILESTONES

ROZWÓJ MOSTÓW DREWNIANYCH POPRZEZ WIEKI – PRZEGLĄD NA WYBRANYCH PRZYKŁADACH OBIEKTÓW DZIEDZICTWA KULTUROWEGO. CZĘŚĆ 1 – KAMIENIE MILOWE

A b s t r a c t

In this article, selected examples of heritage wooden bridges, which were built over the centuries in various parts of the world, are presented and briefly discussed. The overview allows the observation of not only the continuous progress in the techniques used to construct bridges of this type but also the variety of the design solutions applied.

Keywords: wooden bridge, cultural heritage, historical testimonies, old design solutions

S t r e s z c z e n i e

W artykule zaprezentowano i krótko omówiono wybrane przykłady realizacji mostów drewnianych, stanowiących obiekty dziedzictwa kulturowego i budowanych w różnych rejonach świata na przestrzeni wieków. Zamieszczony przegląd obrazuje nie tylko ciągły postęp w technikach wznoszenia tego typu mostów, ale również różnorodność zastosowanych rozwiązań konstrukcyjnych.

Słowa kluczowe: most drewniany, dziedzictwo kulturowe, świadectwa historyczne, dawne rozwiązania konstrukcyjne

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1. Introduction

Wood, in addition to stone, was probably one of the first building materials intentionally used by man to construct bridges. All around the world, depending on local tradition, accessible wood varieties and carpentry skills, various timber bridge structural systems were developed, these were mostly beam girders and truss bridges. Undoubtedly, before the first masonry bridges known from history were constructed stone and timber seemed to be the only available materials used for bridge building. However, in spite of the fact that at present we have so many examples of very old stone bridges which are preserved intact and often still in use, ancient wooden bridges have not survived to the present day to any degree while historical medieval bridges of this type, preserved in their original conditions, are very rare. It is impressive that the oldest currently known wooden bridges are dated prior to the year 600 BC. The limited information relating to these bridges shows that the builders had to have excellent knowledge with regard to the properties of the various timber varieties which were available and their structural applications. Whilst the stone and masonry bridges may remain standing for many centuries to come, the early timber bridges were destroyed a long time ago, by wars, natural disasters or simply by unexpected fires. Despite such difficulties, a contemporary historian studying the old wooden bridges in general is not without any traces from the past. In fact, every bridge is the engineering object being so intriguing and so remaining in memory that the basic information about it, even it was destroyed a long time ago, lasts over centuries. It is due to the helpfulness of such the bridge experienced both by a casual user and by the rulers when this bridge allows their armies marching across the river. Nowadays, these traces can be read from historical testimonies preserved to the present day. These are mostly to be found in records of ancient and medieval chroniclers, eye witnesses of the past. From these pieces of historical evidence, we can attempt, in this article, to reproduce the fascinating history of the bridges which, in many cases, no longer exist.

2. Basic types of bridges built in ancient Greece

Let the review, prepared by ourselves and presented in this article, begin with the identification and brief description of the basic types of beam bridge structural systems used in ancient Greece from the twelfth century BC to the end of the Hellenistic period, specifically, to the year 30 BC – the time of the Roman conquest of Hellenistic Egypt. At least three main beam bridge construction systems in particular were developed at this time [1]:

- **Bridges with stone piers and decks made of wooden beams**:
  In such bridges, the piers was constructed of locally sourced limestone, with thickness of upto 2 m, perfectly sculpted and structurally joined, while the superstructure was made of wooden beams. This type of bridge is inspired by a particular bridge built much earlier on the Euphrates River (near Babylon) which was constructed either by Queen Semiramis or King Nebuchadnezzar. It is very likely that the Greeks acquired this knowledge from the Assyrians. A representative bridge of this type, which partially exists to this day, is the **Mavrozoumaina Bridge** located between the villages of

Meligala and Neochori, at the southwestern corner of the Peloponnese Peninsula (parts of the ancient bridge, such as the foundations and the lowest part, are still visible today). This bridge was constructed by people from the Mycenaean culture at the junction of two rivers in the fourth century BC (specifically, in the year 369 BC). It is exceptionally interesting from a technical point of view because it is shaped like a letter "Y" in the ground plan, with the arm length equal to almost 20 m and clear spans between the piers equal to 5–7 m. The entire structure, despite the fact that it has been reconstructed many times over the centuries, reveals exceptional skill in the art of the stonemasonry. The present-day superstructure consists of nine semicircular Roman-type arches. They were constructed on the old footings much later, during the Ottoman period; however these seem to be rather clumsy.

- **Bridges with stone piers and decks made from stone beams**:
  Bridges of this type were built over narrow to intermediate-width waterways, with small free span between the piers. A representative example of such a bridge is that which was built **in Assus** in Asia Minor, on the northern coast of the Adramyttian Gulf (Fig. 1). This is also dated to the fourth century BC. The deck of this bridge was composed of four to six simply supported stone beams with widths of 0.44–0.46 m, heights of 0.34 m and lengths of 2.70–3.73 m (three of these still exist at the first span and four at the second span). These stone beams were connected to each other using small wooden shear connectors. A span in the center of the bridge was probably bridged with wooden beams, these could be removed more easily as a defensive measure in the event of the hostilities.

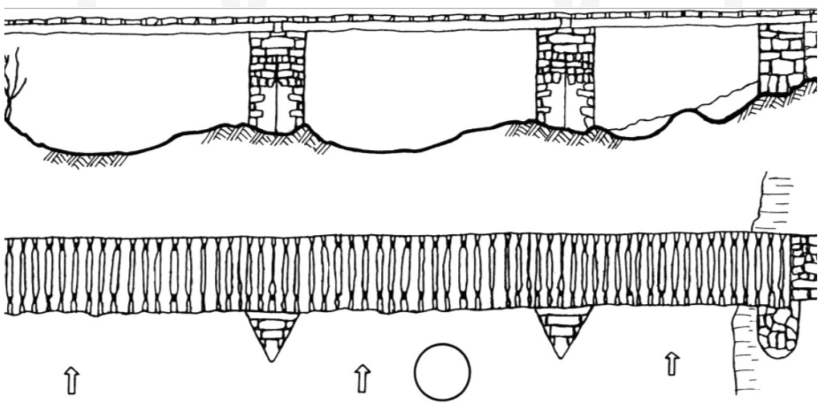


Fig. 1. Views of the ancient bridge built in Assus in Asia Minor. Upper image – a view from the river; lower image – an aerial view (courtesy of G.D. Makris)

- **Bridges constructed entirely from wood, seated on wooden piles**:
  These bridges were constructed over large rivers, where there was a need to reduce the number of piers in order to expand the free span between them. A typical sample of such a bridge is the ancient **Amphipolis Bridge** (Figs. 2–3) which was located in the estuary of the Strimonas River. The total length of this bridge was 275 m. This bridge was reported by Thucydides on the occasion of the battle between the Spartans and the

Athenians that took place in the year 422 BC; however, this report lacks any technical description. The excavations revealed 77 oak piles of circular and square sections which had been vertically driven into the sandy ground on the left bank of the river. The peaks of such piles were sharp and often had iron noses. The deck consisted of wooden beams which could be easily dismantled during wars.

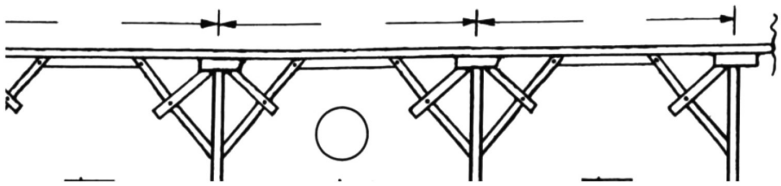


Fig. 2. The scheme of the structural system of an ancient Amphipolis Bridge (courtesy of G.D. Makris)

Fig. 3. Wooden piles of the ancient bridge in Amphipolis as they are today (Courtesy of G.D. Makris)

Beam bridges, especially those in which wooden deck beams were used, are not the only bridges typical of ancient Greece. Certainly, much older than these are some purely stone bridges. A small beam stone bridge dating back as far as the Minoan period was discovered in Crete on the southern side **of the palace of Knossos**, on the Elysian river. It was constructed between 2000 BC and 1450 BC. It has three spans with lengths of 3.1 m, 3.25 m and 2.3 m and heights from 5.0 m up to 5.5 m. Additionally, other small entirely stone bridges with a pseudo-arc shape of a triangle, such as the bridge built in **Eleftherna** (total length 9.0m, span 3.85 m, width 5.35 m and height 4.6 m), were constructed in Crete before the end of the fourth century BC. Furthermore, almost 20 small stone culverts were also constructed in the Peloponnese Peninsula, during the Mycenaean period – some of these still exist today in a good condition. An excellent example of such culvert is the **Kazarma Bridge** (length – 12 m, width – 5.0 m, height – 6–7 m) which was erected in approximately 1200 BC. Common characteristic of the Minoan and Mycenaean bridges was corbelling with

coarsely processed bulky stones (which was the first version of the current cantilevering) and the covering of the free span with continuously converging walls (abutments). The gap between the walls, provided that it has not been totally bricked like it was in the **Eleftherna Bridge**, was covered by a horizontal stone beam (as was the case with the **Drakonera Bridge**, located northwest of the citadel of Mycenae) or by a wedge-like stone (as with the **Kazarma Bridge**). Bridges of this type do not appear to have been developed further, in the classic period of the Ancient Greece, and were probably abandoned [1].

3. Selected wooden bridges from the Roman period

Early timber bridges constructed by Romans were simple beam structures frequently made of the felled tree trunks spanning between timber piled piers. One of the best known and earliest recorded timber bridges from Roman times is **Pons Sublicius** (Fig. 4), built 660–616 BC, during the reign of Ancus Marcius who was the fourth king of Rome. This bridge survived with regular repair until the times of Constantine (the first half of the fourth century AD).

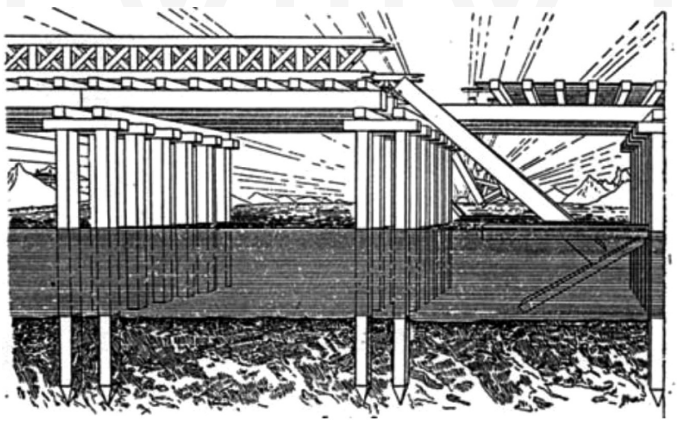


Fig. 4. The structural system of Pons Sublicius (reconstruction according to [2])

The other well-known Roman wooden bridge is that named **Caesar's Bridge** (Fig. 5). It was erected across the River Rhine in the middle of the first century BC. Julius Caesar himself described that it was built in just 10 days (Caesar "Gallic War", IV, 17). A separate description of the construction of such a bridge is given by Plutarch in "The life of Julius Caesar" (part of "The Parallel Lives"). It is believed that this structure was built under the direction of Vitruvius who was a designer of the Emperor's war machines. As is shown in a later drawing sketched by Palladio in the sixteenth century AD, the considered bridge was composed of longitudinal beams resting on crossbeams supported by inclined piles. Joints were used to connect these piles to the crossbeams.

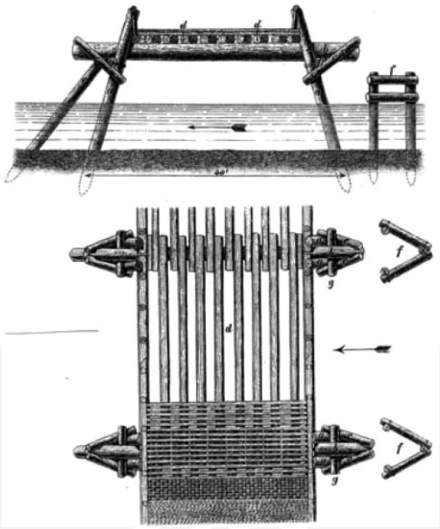


Fig. 5. A cross-section and an aerial view of Caesar's Bridge (reconstruction according to [2])

The third ancient wooden bridge which may be regarded as characteristic of the Roman period is **Trajan's Bridge** (Fig. 6). It was erected in the year 105 AD and consisted of 20 piers up to 45 m high, joined by semicircular timber arches of 52 m in length. It was raised across the Danube River. This bridge was constructed by the Greek architect Apollodorus of Damascus by order of Emperor Trajan for the deployment of Roman troops during the conquest of Dacia.

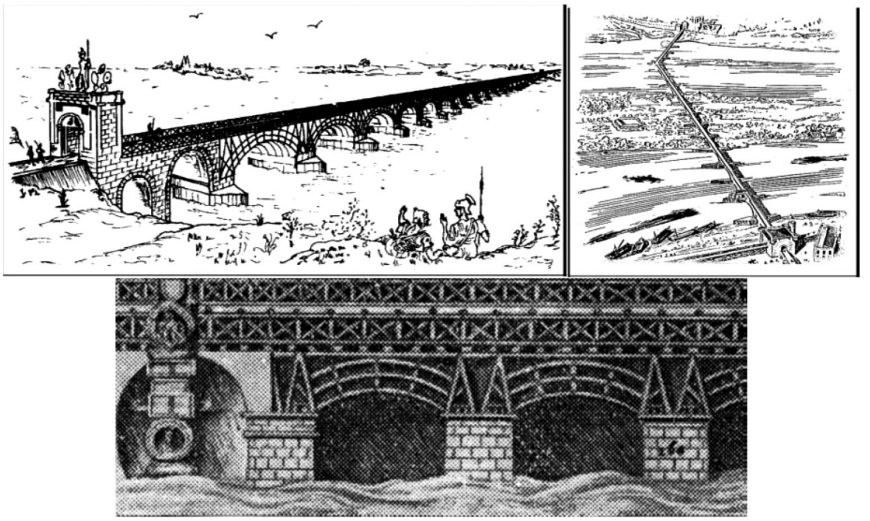


Fig. 6. Reconstruction of Trajan's Bridge (according to [2])

In the days of the Byzantine Empire, the Byzantines continued the erection of bridges based on knowledge gathered in the Roman period. The Byzantine bridges were usually wooden or stone arched. The piers in these bridges were strengthened with noses of triangular or circular sections (starlings), so that they were protected from the pressure of water. Moreover, towers and chapels were often located on these bridges. The medieval bridge built in the year 1440 AD **in Karytaina** in the middle of the Greek Peloponnese is a good example of such a structure. Let us note that the wooden deck could be easily removed from such a bridge. This meant that it could be made unusable when required in the event of an emergency (for example during the military invasion).

Fig. 7. The medieval bridge in Karytaina (courtesy of G.D. Makris)

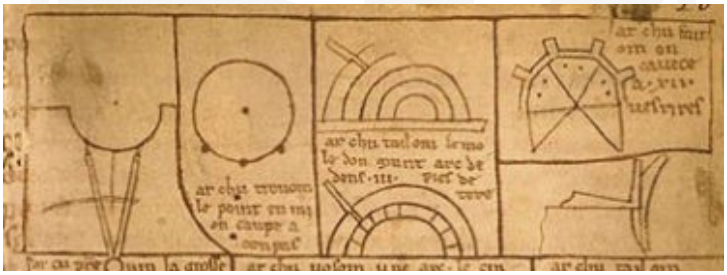


Fig. 8. The scheme of a wooden bridge with classical timber struts – technical drawing taken from the sketchbook belonging to Villard de Honnecourt
(source: http://catreims.free.fr/art021.html, access: April, 2016)

4. The renaissance concepts of wooden truss bridges

A careful analysis of structural schemes relating to some wooden bridges built in the times of the Roman Republic and later, in the days of the Roman Empire, allows to conclude that the builders at that time well understood the role of a bracing system in ensuring the integrity and the global stability of a bridge. Knowledge of this type, however, especially

in the early Middle Ages, underwent gradual oblivion. The oldest known early medieval wooden bridges were simple beam structures with small spans. It seems surprising that the schemes using classical wooden struts were not developed before the first half of the thirteenth century (they are shown in a sketchbook from the year 1230 belonging to Villard de Honnecourt [3] – Fig. 8). The idea to use the pure truss timber girders in place of the main longitudinal wooden beams to achieve a longer-span bridge structure is more recent as it comes from the sixteenth century. In the year 1570, an Italian architect Andrea Palladio published some alternative truss structural systems ("I quattro libri dell'architettura", libro VII), relating to a timber bridge spanning 30m, built over the Cismone River in North – East Italy, which was constructed earlier, in around 1550 (Fig. 9). Let us note that Andrea Palladio was also a designer of a famous timber covered bridge **Ponte degli Alpini**, built in the year 1560 in Italian Bassano del Grappa. This bridge is still in service (Figs. 10–11).

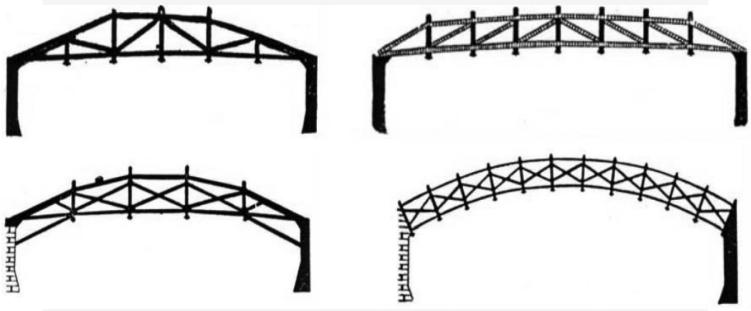


Fig. 9. The wooden longitudinal truss girders proposed by Andrea Palladio as an alternative structural system for the timber bridge built over the Cismone River in North East Italy (published in "I quattro libri dell'architettura", libro VII, in the year 1570) – selected drawings, according to [4]

Fig. 10. The current state of a wooden covered bridge Ponte degli Alpini in Bassano del Grappa (source: https://anotherheader.wordpress.com/2010/12/23/italy-bassano-del-grappa, access: April, 2016)

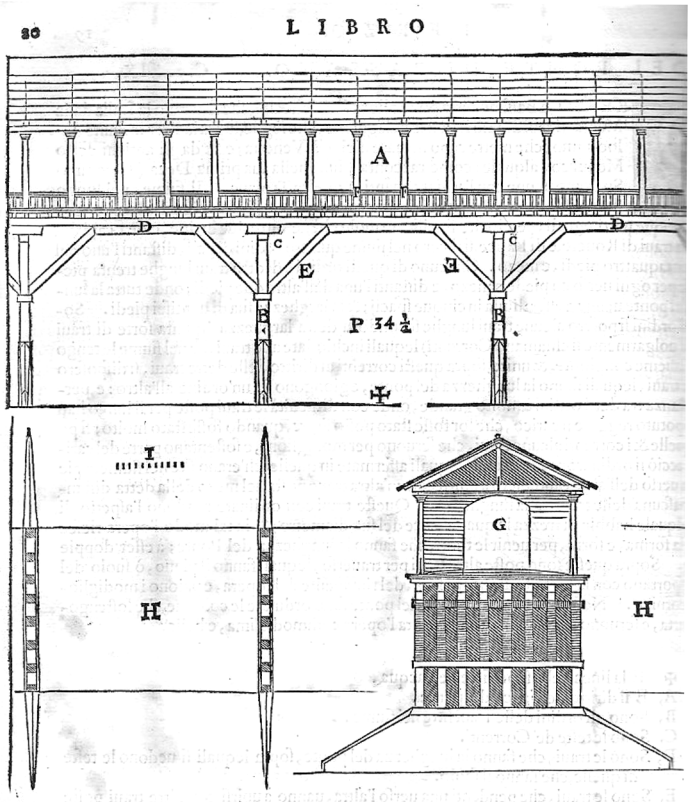


Fig. 11. The scheme of the wooden bridge Ponte degli Alpini, technical drawing by Andrea Palladio (published in "I quattro libri dell'architettura", libro III, in the year 1570) (source: commons.wikimedia.org, access: April, 2016)

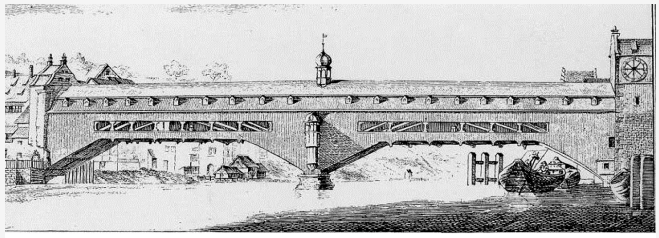
5. The iconic heritage timber bridges of Switzerland

The Kapellbrücke (Chapel Bridge), located in the Swiss town of Lucerne, is one of the oldest timber covered bridges in the world which is still in use. It was built in 1333, but over the centuries, most of its structure has been rebuilt. Furthermore, a large part of the bridge was destroyed by fire in August 1933. The reconstruction was carried out on the basis of the original design drawings, and the renovated structure was reopened for pedestrian use in April 1994 (Fig. 12). The supporting structure consits mainly of oak piles driven into the bed of the Reuss River. Cross-girders, again made of oak timber, connect the pile caps and support the twenty six spans of the main bridge structure. The average span length is 7.65 m, whereas the total length of the entire bridge is now only 204 m. This means that it has been shortened in relation to the original (1333) bridge length which was 285 m, and in relation to the nineteenth-century length when it was reduced to 222 m.

Fig. 12. The current state of the wooden covered Kapellbrücke (Chapel Bridge) in Lucerne (source: http://miriadna.com/preview/chapel-bridge-(lucerne,-switzerland, access: April, 2016)

The other world-famous wooden covered heritage bridge built in Switzerland was the well-known **Rhinebridge** constructed over the Rhine River in Schaffhausen from 1755 to 1758 by the master carpenter Hans Ulrich Grubenmann (Fig. 13). He originally designed the bridge with a single span and a length of 119 m, but shortly after the completion of such a bridge design he was forced by the town authorities to change the concept by introducing

a)



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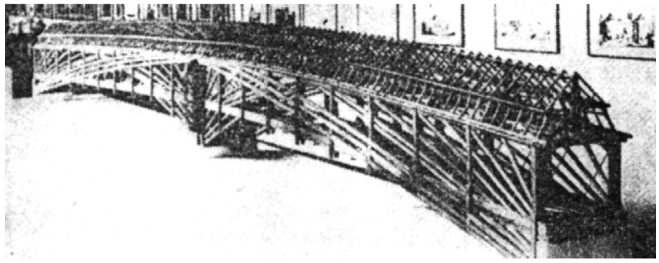

Fig. 13. A wooden Rhinebridge in Schaffhaussen, designed by Hans Ulrich Grubenmann, constructed 1755–1758 and destroyed in 1799: a) the eighteenth-century engraving, at present stored in the Museum Allerheiligen in Schaffhausen (its author is unknown), b) model of the bridge structure, presented in the same museum (source: commons.wikimedia.org, access: April, 2016)

the piers in the middle of the bridge span. As a result of this change, the completed bridge had two spans with lengths of 52 m and 59 m. Hans Urlich with his brother Johannes constructed later the wooden **Wettingen Bridge** over the Limmat River in the town of Wettingen near Zürich which had a span with a length of 60 m. It is believed that this bridge was the first timber bridge in which a true arch was designed as its load-bearing structure. This bridge had an arch-truss combination with an arch of heavy oak beams joined by iron straps rising 7.5 m (Fig. 14). Although both of these bridges were later destroyed, the fame of the Grubenmann brothers influenced designers throughout Europe.

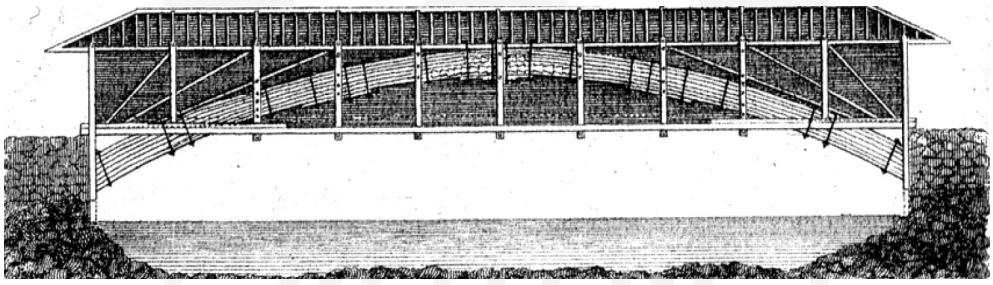

Fig. 14. A wooden covered Wettingen Bridge (also known as the Limmatbrücke), completed by the brothers Hans Ulrich and Jonathan Grubenmann in 1766 and later destroyed (source: www.payer.de, access: April, 2016)

6. Trestle as a structure typical of wooden bridges built in the USA in the nineteenth century

Trestle bridges made of wood proved to be of ideal structural designs when railways were built across the whole USA territory in the nineteenth century. In general, they were considered temporary until more permanent structures could be built. Many trestles were covered with earth fill, forming an embankment that would remain long after the timber had rotted away. Theodore Judah took advantage of timber to build trestles as quickly as possible when he constructed the Central Pacific Railroad which was designed as a transcontinental route. Squire Whipple and Herman Haupt, two American railroad bridge engineers, are considered to be the first to have developed the computational approach to estimate the stress level in particular truss members in such bridges through which it become possible to determine appropriate dimensions. These methods are equally applicable to both timber and metal trusses. The **Secret Town Trestle Bridge**, built in the Sierra Nevada Mountains in California in 1865 is shown in detail in Fig. 15 as a classic example of a bridge of this type. It was the largest structure of its kind located on the Central Pacific Railroad. Twelve years after erecting this bridge, it was completely buried by earth fill to eliminate the risk of fire and to avoid the necessity of replacing the ageing timbers.

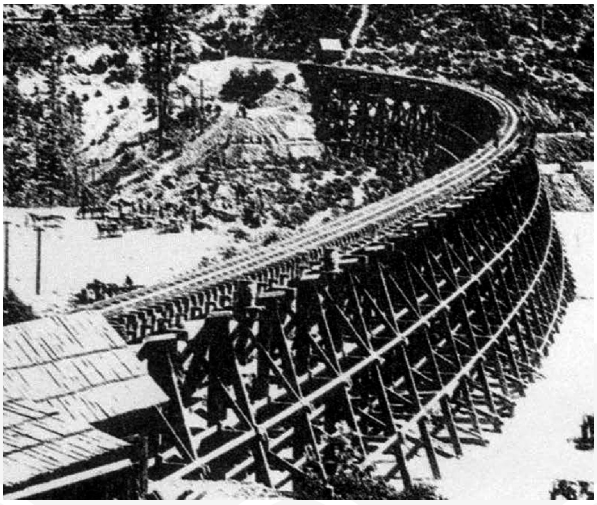

Fig. 15. The structure of the wooden Secret Town Bridge – source: The New York Public Library Digital Collection (source: http://digitalcollections.nypl.org/items/510d47e0-b62c-a3d9-e040-e00a18064a99, access: April, 2016)

7. A brief summary of the part 1

In writing this paper, it was the authors' intention for it to be an expanded version of the introduction to articles [5] and [6] which have been presented in the framework of the VSU scientific conference held in Sofia in June 2015. This paper is divided into two parts. In the first part, the milestones relating to the historical development of the wooden bridge engineering are first identified and then presented with short descriptions. Firstly, the oldest ancient bridges with wooden decks supported on stone piers are discussed in detail. Some of these were already completed in ancient Greece, while others much later – in Hellenistic period. Subsequently, the structural solutions invented by the ancient Romans are briefly presented, especially those associated with timber bridge construction. Particular attention is paid to understanding the stabilizing role of diagonal struts at that time. In the early Middle Ages, the art of building rationally designed wooden bridges, especially those with relatively long spans, was gradually forgotten. The role of the bracing system in bridge structural design was not recognized until the middle of the thirteenth century. Furthermore, in the sixteenth century, the wooden truss bridges are recommended for use by Palladio, due to these being much better than the bridges constructed over the same rivers in a conventional manner. Irrespective of this newly discovered concept, the covered timber bridges were traditionally erected during the Renaissance and the Baroque periods of European history, especially over Alpine rivers located in present-day Italy and Switzerland. The fully-arched timber bridge seems to have been the next milestone in the field of the forming of the wooden bridges. The most famous timber bridges of this type are undoubtedly those designed in the eighteenth century by the Grubenmann brothers. Finally, the timber trestle bridges were

briefly described in this paper, these were commonly built in the USA in the nineteenth century, because they were undoubtedly unique and iconic bridge structures, made entirely of wood and preceding the contemporary modern railway bridges made of structural steel.

In the second part of this article, the authors intend to present other iconic heritage timber bridges preserved until today or only reported in historical sources, especially those associated with the region inhabited by Western Slavs.

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