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Original article

Reconstruction of the appearance and structural system of Trajan's Bridge

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ABSTRACT

Trajan's Bridge, built by Romans over the Danube River in the first years of the II century, was the first kilometer-long bridge ever built. It was a marvel of Roman engineering, especially taking into account challenging site conditions, available resources and record time for construction. The bridge's still-standing columns are witnesses to its masterful construction. The bridge was later intentionally destroyed by Romans, and several researchers in the past studied the bridge and attempted to reconstruct its appearance and structural system. However, the dearth of information generally associated with destroyed ancient structures makes their reconstruction extremely challenging. In the case of Trajan's Bridge, the only confirmed representation of the structure is on Trajan's Column, found just north of the Roman Forum. Nevertheless, several studies performed in the past proposed a structure different from the one shown in the Column. Most of these studies are not based on detailed structural analysis, and thus some of them do not seem to be credible from the engineering point of view. The aim of this paper was to reconstruct the structural system and appearance of Trajan's Bridge using structural analysis, and to determine to what extent the representation of the structure on Trajan's Column could be accurate. This is successfully performed by determining the number of degrees of freedom associated with the structure and by analyzing the materials, stresses, and the bridge construction technique.

1. Research aims

The main aim of this paper is to reconstruct the appearance and structural system of Trajan's Bridge, i.e., to determine the number of structural elements (beams and arches), their configuration, and their approximate dimensions. The bridge representation on Trajan's Column shows a multi-span structure. Each span contains three parallel segmented arches, mutually connected by radial beams, with each arch comprising four beams. Several studies performed in the past proposed a structure different from the one shown in the column. Many of these reconstructions either do not seem structurally sound or propose structurally sound reconstructions that were, however, unlikely to be understood and built by Romans. Structural analysis is a branch of civil engineering that evaluates structural stability and safety. It is used in this research to achieve the aforementioned aim. The structural system was identified and its stability examined based on the number of degrees of freedom (*nDOF*) of the ensemble of connected structural members. The safety of the structure was examined by analyzing materials used, Roman construction techniques, and forces generated in the structure due to dead load and live load. Based on the analysis, the reconstruction of the structural system is proposed.

2. Introduction

Trajan's Bridge was the first kilometer-long bridge ever built in the world. It was constructed between 103 and 105 AD by the order of Roman emperor Trajan, over the lower Danube, East of the Iron Gates and near the present-day cities of Kladovo (Serbia) and Drobeta-Turnu-Severin (Romania). The design and construction of the bridge were conferred to the emperor's chief engineer Apollodorus of Damascus [1]. The bridge represented an important milestone in civil engineering: it was indicative of a mastering of the construction techniques, as the structure was built swiftly and efficiently. Furthermore, parts of it, such as the columns, are still standing today, thereby confirming its excellent endurance. The design needed to be efficient, as it needed to be strong enough to support the weight of troops and vehicles and had to be simple enough to be constructed in only two years. The bridge was probably destroyed either immediately by Trajan's successor Emperor Hadrian [2] or 170 years later by Emperor Aurelian [3] (there is a conflict in literature, e.g., Procopius states that: "...the bridge was completely destroyed by the floods of the Ister and by the passage of time [14]").

Since the bridge was destroyed so long ago, all that remains today are two piers on either side of the Danube. The remains of the

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other piers are underwater and were last mapped by archaeologists during a survey in 2003 [4]. The only confirmed representation of the structure of Trajan's Bridge is engraved on Trajan's Column in Rome. The aim of this paper is to identify the structural system of Trajan's Bridge based on structural analysis and to determine the extent to which the representation of the bridge on Trajan's Column could be accurate.

3. Methodology

The previous reconstructions of Trajan's Bridge are first closely examined and main structural members identified. The facts about the bridge are then studied, including the depiction from Trajan's Column, approximate determination of dimensions based on on-site measurements, identification of the type of wood used in the bridge, and Roman construction techniques. Our premise is that for bridge reconstruction to be plausible, it should be structurally sound, i.e., it has to fulfill two basic engineering principles: the structure has to be stable and dimensions of the structural members must guarantee structural safety under the loads. Thus, first the structure's determinacy and stability is determined based on a study of the number of degrees of freedom (*nDOF*), then the dimensions of structural members are verified based on structural analysis, and finally, the possible reconstruction of Trajan's Bridge's structural system is identified.

4. Trajan's Bridge – Contemporary representations and previous reconstructions

The two contemporary images that provide us with an idea of what the bridge's structural system and appearance might have looked like are depicted on Trajan's Column and on a Roman coin issued in 105 AD.

Trajan's Column, which is shown in Fig. 1a, contains a bas-relief of the wooden bridge, with Trajan, Apollodorus and Roman soldiers presenting an offering [1]. The image of the bridge depicts the gateways, deck with railing, and five wooden triple-arch spans. This depiction of the bridge shows that each triple-arch was composed of (i) three parallel segmented arches; (ii) each arch consisted of four beams; (iii) radial members connected the three arches, (iv) triangular supports were placed at either end of the arch, (v) and wooden basis ensured connection between the supports and the concrete-masonry column. All these structural elements are highlighted in Fig. 1b with black arrows. However, this depiction of the bridge is not entirely accurate: the height of the deck railing and width of the bridge are disproportionate when compared to the length of the bridge or span of the arches [1] and only five spans are presented. All these inaccuracies are attributed to the shortage of space on the column.

The coin, which is shown in Fig. 1c, has an image of Emperor Trajan on one side and an idealized single span arch bridge on the other. The bridge depicted on the coin is not confirmed to be the Trajan's Bridge; nevertheless, the image on the coin is still a valuable source of information as it shows that the triple-arch system was used by Romans, which adds to the overall credibility of the Trajan's Column representation of the bridge.

Our comment (or critique) for the depiction on Trajan's Column from a structural perspective is that the triple-arch is supported at the pillar by a long radial beam (except at the first pillar), and this beam is then subjected to very high bending moments which is inefficient and may imperil structural safety. However, the three beams that support the long radial beam at the first pillar make the allusion that such elements could actually have been present at every pillar on the bridge, but omitted on Trajan's column due to shortage of space and/or work needed to carve these additional details.

Multiple engineers and historians proposed different reconstructions of the bridge and they are briefly presented and analyzed as follows.

Ludovici Marsigli's (or Marsili) [9] reconstruction (Fig. 2a) in 1726, was fairly similar in form to the representation on Trajan's Column, with each arch having a clear span of roughly 34.1 m. This reproduction was based on his studies and measurements of the ruins of Trajan's Bridge and the forts on either bank of the Danube between 1689 and 1691 [1]. Our comment (or critique) for this solution is similar to the comment for the depiction on Trajan's Column, i.e., the triple-arch could not be supported at the pillars by a long radial beam only.

August Choisy's reconstruction in 1873 [10] was the first to propose a structure for the bridge that was different from that on Trajan's Column. Based on his own intuition, it comprised arches made up of eight segments as opposed to the four segments shown on Trajan's Column. He also proposed the use of curved arch segments built of two members connected in the middle, "broken-shape" radials, and extended the triple-arches to the pillar (Fig. 2b). Our comment is that while extending the triple-arches to the pillar definitely improves structural efficiency, most of the other modifications from Trajan's Column's representation are actually structurally less efficient – curved arches would be more difficult to manufacture and they are more prone to buckling, while creating them from two segments may imperil structural safety. However the main issue with this reconstruction is that the

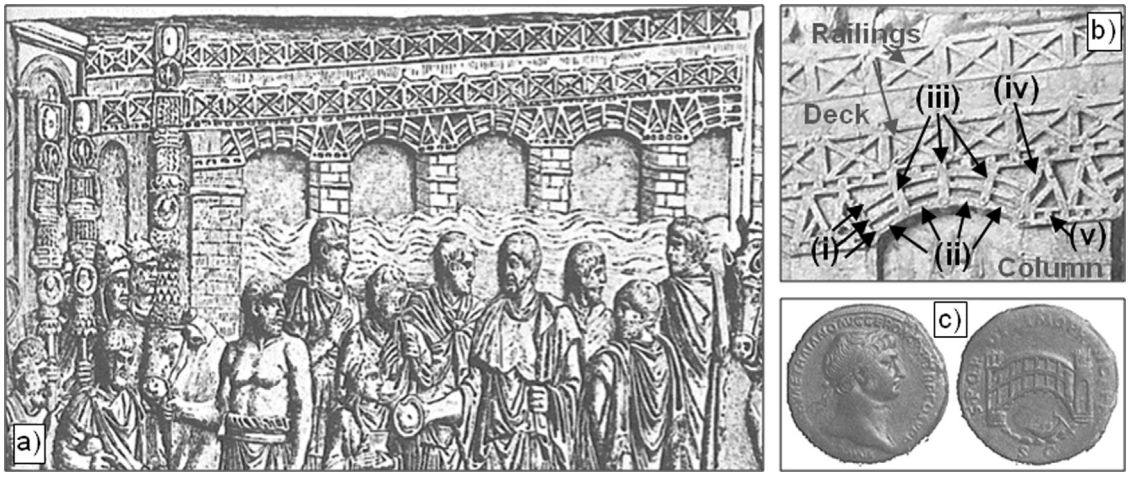

Fig. 1. a: representation of the Trajan's Bridge on Trajan's column [1]; b: detail with one span showing triple-arch system; c: Roman coin from Trajan's epoch with representation of a bridge [1].