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The shallow arch: A step towards bridges styling in the early 19th century

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ABSTRACT

Several formulations for masonry arches were appearing since 18th century, mostly based on the acquired experience in bridge construction. That led to a generalized use of shallow arch. The innovations supposed an evolution in the shape of masonry arch bridges, at the expense of increasing the thickness of voussoirs and vault. The question is: were the mentioned changes related with a clear structural improvement? Or were they mainly aesthetic or fashion-driven changes? This paper tries to give deeper insight and response this query by making a comparison among different formulations, and analyzing the rise to span ratio and backfill influences in both ultimate load capacity and maximum stress. Moreover, a multi-span arch bridge is analyzed, performing a comparison among different typological possibilities, and using examples of real structures in the Carrión river basin (Spain).

1. Introduction

The arch is one of the basic elements in masonry bridge construction. Several authors have analyzed the arch possibilities, such as Alberti and the *Re* Aedificatoria treatise in 1542, and other focused in national cases, like Santiago Huerta [1] as the most outstanding for those built in Spain. Due to its importance, this building technique has been revisited in multiple technical studies analyzing its shape, the barrel thickness, the span, the rise, and the connection among them. These have revealed certain typological predominance during particular historical periods, and even some trend variations.

Knowledge evolution has affected to the shape of some bridge parts: piers, cutwaters, arches… However, this paper is focused only in circular masonry arches, where the link between theoretical mechanical basis and the empirical observation was described by the use of crude design rules published by different bridge builders. These empirical relations have been identified many times, and different examples have been provided [2–4]. In addition, many recent works are focused in the use of novelty non-linear and advanced 3D numerical simulation to be applied in the assessment of load capacity of old bridges for current loads [5–7], or to extend previous studies to skew arches [8–11]. The complexity of interaction among different variables has moreover been included in different cases. For example the importance of infill in the global response was showed by Fanning and Boothby [12] or Milani and Lourenço [11]; Conde et al. [6] remarked this parameter by using a combination of 3D model with non-destructive techniques. In [8] the contact between masonry blocks, the non-linear tensile behavior, and the rigidity of hinges is analyzed as well. The three-dimensional models allow considering the transverse bending in vault, to explain for instance the barrel cracking or a non-linear infill behavior [12]. A novel finite element 2D approach has been recently proposed by Bertolesi et al. [13] to include the effect of composite reinforcements in ancient arches with the validation of an experimental campaign. The effect of irregular geometric or construction defects in masonry structures have also been analyzed using similar computational techniques [8,14].

However, no specific works have been performed to identify the possible relations between the design principles of arch shapes and the evolution of their aesthetics, which have been generally explained as a mere style change based on the repetition of empirical relations, and requires a better understanding. From this point of view, some changes in masonry arch geometry can be observed throughout centuries. In fact, there was a progressive increase of radius of curvature, and hence an evolutionary change of arch shape can be identified. It was a stepped approach towards a segmental arch, searching for more aesthetic types. But, to our knowledge, no additional justifications have been identified.

Main parts of a masonry arch are showed in Fig. 1, including the most important magnitudes involved in their behavior. We will use the rise-to-span ratio (r/s) as a basis of our study, a parameter that can be used to distinguish between different circular arch typologies. Following formula can be derived as mathematical relations:

$$r = \frac{1 + 4 \times (r/s)^2}{8 \times (r/s)} \times s \tag{1}$$

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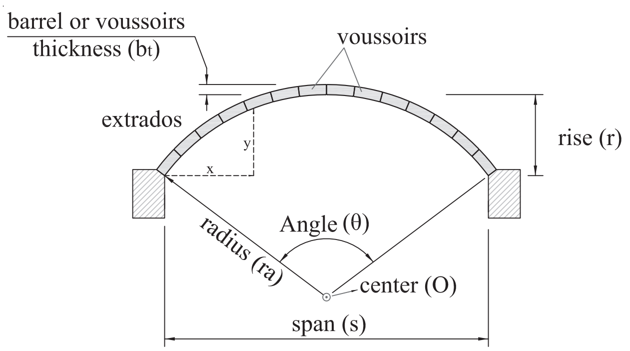

Fig. 1. A sketch of a masonry arch, including most important parts and abbreviations used in this paper.

$$\theta = 4 \times \left(\frac{\pi}{2} - \arctan\left(\frac{0{,}5}{(r/s)}\right)\right) \tag{2}$$

In function of previous expressions, three main circular arch types can be described as shown in Figs. 2, 3, and Table 1: round, semi-shallow, and shallow arches. The last two are subtypes of the generic segmental type.

The ultimate load capacity of a masonry bridge is known to be seriously influenced by varying the r/s parameter toward a higher curvature. González Parejo [15] studied different geometries changing θ from 180 to 130 degrees. That was equivalent to change r/s from 1/2 to 1/3.14. In our work, we have increased the analysis of ultimate load up to r/s = 1/20 so that we completed previous range. Our structural analysis have included the influence of compacted soil backfill in the ultimate load behavior, which has been shown as a key point by previously published works such as Callaway et al. [16], Bjurström and Lasell [17], Cavichi and Gambarota [18], or González Parejo [15]. Moreover, the authors of current paper can assure the use of these backfills in most of the masonry bridges on whose maintenance have been involved. To achieve this, the geometry of twelve real masonry bridges has been analyzed. In summary, the paper is organized as the following:

- First, authors describe the historical framework of arch shape evolution and aesthetics, focusing immediately in Carrión river basin during the 17th, 18th and 19th centuries.
- The article continues analyzing a single span bridge from a double approach: ultimate load capacity, and maximum stress. Calculations are performed using a software tool and continuing previous studies, by varying two different variables (presence or not of compacted backfill, and mainly a wide range of r/s) to understand their combined effect and the subjacent design decisions.
- A multi-span bridge case is additionally analyzed through four alternatives, to understand design criteria. A real example of a bridge in Carrión river basin is used.
- Finally, conclusions briefly explain the reasons of bridge builders for r/s choice and the evolution of arch shapes during 18th and 19th centuries, and show how relatively low r/s ratios are able to achieve good structural response and behavior. In addition, an explanation to the standard solution for multi-span bridges in Carrión basin is also included.

2. The evolution of the r/s parameter in the Carrión river basin bridges

Roman bridges have been used, in general, as example for further masonry arches by simple imitation, improving defects and making use of their virtues. Regarding to segmental arches there are some remaining examples in Spain such as the Alconetar Bridge (Cáceres), a remarkable model cited by González Parejo [15]. The study of roman circular arches has shown some connections between barrel thickness and span length, but nothing special about the r/s that could help during a classification. Besides, a few medieval examples of segmental arches are available due to the extensive use of round arch during Middle Ages.

Many authors have analyzed the geometric relations between voussoirs or barrel thickness and span length, the historical recommendations about arch type use, or the connections between previous parameters to piers dimensions. In Castilla, a Spanish historic region, Friar Laurence of Saint Nicholas emerged as a conservative theoretician during 17th century due to the large amount of ruined bridges during this period. Regarding to arches, Friar Laurence recommended the round arch type and to add compacted soil to backfill the barrel. In addition, as mentioned by Huerta Fernández [1,19], he recommended to fill up the inner part of piers using a specially compacted fashion, and continue this procedure up to 2/3 of the arch rise at extrados. This way to backfill at spandrels became a custom in the country, as was verified during rehabilitation interventions in Spain. That is the reason why the 2/3 value has been used by researchers during structural analysis of masonry bridges, as in the case of González Parejo [15].

The emergence of analytic calculations provoked an extensive use of formulations during 18th century and later. Different bridge engineers proposed some expressions that were used to design multiple structures. Several of them are summarized in Table 2, including the mentioned by Oliveira et al. [3], Manjón [20] and Martín-Caro [21].

There were no specific differences between round arch and segmental arch until the 18th century, which can be understood as an indicator of the extensive use of the semicircular type as a trend. To check this hypothesis, the geometry of all masonry arches in the Carrión river basin has been analyzed (Fig. 4). This means the study of 12 bridges and up to 101 arches. As shown in Table 3, most of them are included in the round arch typology. However, there was a trend change during 18th century, when segmental arches (including semi-shallow and shallow cases) emerged as a building possibility. In fact, most of arches built from 18th century were segmental arches.

When using expressions from Table 2, only Perronet distinguished segmental arches during 18th century. His proposal reduced voussoirs or barrel thickness when r/s grown, and in any case when s was larger. Nevertheless, Déjardin (19th century) pointed a paradoxical conclusion

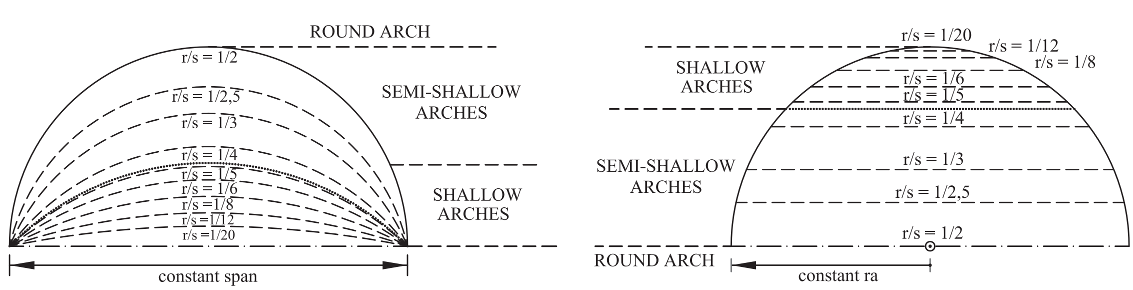

Fig. 2. Circular arch types, in function of r/s parameter, for constant span (left) or constant radius (right).