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FROM ENGINEERING TO AESTHETICS: MORPHOLOGY AND CONSTRUCTIVE TECHNIQUES OF THE NEW BRIDGE OF RONDA (SPAIN)

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Abstract. This study analyzes the morphology and construction techniques of the New Bridge of Ronda, focusing on its key engineering elements. Existing publications on the bridge's construction history, along with research on stone bridge technologies, were used to identify elements in the New Bridge. The morphological characteristics and materials used were analyzed to deduce the techniques employed. The research shows that the New Bridge follows construction methods typical of stone bridges from Roman times, despite being built in the 18th century. Its height required large abutments and multi-level vaults, resembling medieval bridge designs, resulting in a unique structure compared to most stone bridges. This paper fills the gap in knowledge about the construction techniques and morphology of the New Bridge, offering a deeper understanding of its design. The value of this study lies in its contribution to the understanding of the New Bridge's construction methods, shedding light on its historical significance and aiding in its preservation. This study enhances the appreciation of the New Bridge, supporting efforts for its preservation for future generations.

Keywords: construction techniques, historic structures, historical engineering, heritage, New Bridge of Ronda, stone bridge construction, 18th-century bridges.

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1. Introduction

Masonry bridges, built with stone, brick, mass concrete, or weakly reinforced concrete, dominated Spanish construction until the late 18th century and persisted into the 20th century (Martín-Caro Álamo, 2001; Fernández, 2017). Today, 15% of Spanish road bridges are masonry structures, celebrated for their exceptional durability and minimal maintenance requirements, which underscore their sustainability (Fernández, 2017).

The origin of bridges is unclear, but early structures likely emerged to facilitate communication between communities, leading to increasingly solid and durable designs. In the Iberian Peninsula, the Romans left a significant legacy of stone bridges, combining structural efficiency with aesthetic mastery through the use of stone ashlar, brick, and mortar (Durán, 2017). Over time, construction methods evolved, with the pointed arch emerging during the Middle Ages (Martín-Caro Álamo, 2001) and the escarzana vault appearing during the Renaissance (Martín-Caro Álamo, 2001). Until the 18th century, Spanish bridges adhered largely to Roman principles, crafted by master builders rather than trained engineers, a contrast to contemporary practices in Italy or France (Durán, 2017).

From the 19th century, the rise of iron, steel, and reinforced concrete marked the decline of masonry bridges, though some continued to be constructed, particularly for roads and railways (Durán, 2017). Among these, the New Bridge of Ronda, built in the 18th century, stands out for its monumental height (90 meters), unique morphology, and strategic location in the Tajo de Ronda gorge. Its construction history and significance have been recently explored in depth by researchers (Torres-Blanco et al., 2025). This article explores its design and construction, highlighting its enduring significance in civil engineering history.

2. Methodology

To conduct this research, an initial review of publications on the New Bridge of Ronda (e.g., Camacho & Miró, 1994; Cadiñanos Bardeci, 2014) was carried out. While some works focus solely on the bridge, particularly its history and visual significance, most include information about it within broader contexts. For instance, we identified studies on its architect, José Martín de Aldehuela (Camacho Martínez, 2014), or urban and historical analyses of Ronda (Miró, 1987).

Additionally, technical literature on masonry bridges (Huerta, 2004; Fernández Troyano, 1999), similar to the New Bridge, provided valuable context. Despite studies on specific bridges, no work directly addresses the technical aspects of the New Bridge's morphology, materials, and construction techniques, which are the core focus of this research.

Using publications on the bridge's construction history and masonry bridge technology, including comprehensive reviews of traditional techniques (Orfeo, 2023), and other specialized studies (Orfeo et al., 2022, 2024; Brencich & Morbiducci, 2007; Méndez-Hernán & Plasencia-Lozano, 2017; León, 2017; Martín-Caro Álamo, 2001; Huerta, 2000), focusing on their characteristic elements (e.g., arch forms, robust abutments, and pier design) and fundamental construction techniques (e.g., masonry bedding and stone jointing), the characteristic elements of masonry bridges in the New Bridge of Ronda were identified, and their morphological and design features described. Further investigation into the materials used facilitated deductions about the construction techniques employed.

2.1. Morphology of the New Bridge of Ronda

The general design of the New Bridge of Ronda can be described as follows: "Made of stonework, inspired by Roman aqueducts, it has a completely classical air" (Miró, 1987). This highlights the prominence of stonework, the superimposition of arches, and the minimalist decoration in the bridge's design (Figure 1).

In the *Treatise of Re Aedificatoria* by the Italian architect Leon Battista Alberti (1404–1472), published in 1485 (Huerta, 2000), bridges are composed of four parts: "the retaining wall on the banks, the piers, the arches, and the roadway" (Urruchi-Rojo et al., 2017). More recent sources further define the key components of stone bridges as the foundation, piers, abutments, and arches, with additional elements like spandrels, the roadway, and the fill between them. Decorative features such as impost blocks, columns, and sculptures may also be included (Huerta, 2000). These elements, characteristic of masonry bridges, are present in the New Bridge of Ronda (Figure 2).

Figure 1. New Bridge and Tajo de Ronda (source: Pexels, 2023)

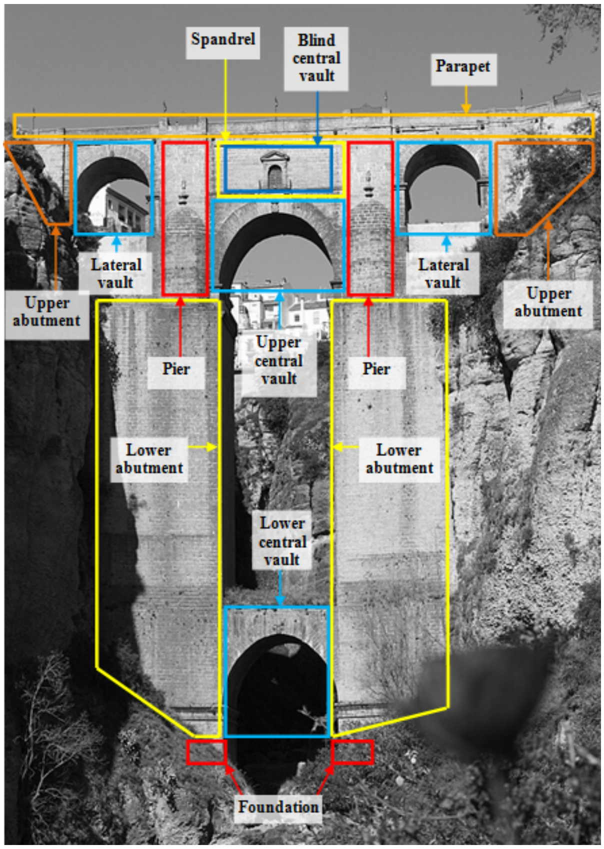

Figure 2. Identification of elements of the New Bridge of Ronda. Edited by authors in 2024 (source: Doctor, 2011)

2.1.1. Piers

The piers in masonry bridges connect the arches and extend from the riverbed or nearby areas. Their number and height depend on the riverbed's characteristics or depression to be crossed, as well as the capacity to withstand flow increases if the bridge spans a river (León, 2017). Additionally, the difficulty of foundation construction influences their design (Gaztelu, 1910; Orfeo, 2023).

In the New Bridge of Ronda, however, the piers do not align with the riverbed but are positioned above it, resting on two large abutments that extend from the foundation and support the bridge platform. This unique feature distinguishes the New Bridge from most masonry bridges. Notably, at the junctions of the upper arches, the piers are wider at the base than at the top, next to the bridge platform. This tapered design is accentuated by decorative caps, resembling torches, at their peak (Figure 3).

The morphology of piers with variable sections has been a typical solution for masonry bridges, with sections usually rectangular and rarely curved (Martín-Caro Álamo, 2001). However, there are examples of masonry bridges with curved piers, such as the Stone Bridge of Logroño (Spain) (Figure 4). For tall piers, their section was increased perpendicular to the wind, as seen in the Alcántara Bridge (Cáceres, Spain) (Figure 5). Additionally, arches could be placed on piers for reinforcement, a solution more common in aqueducts (Martín-Caro Álamo, 2001).

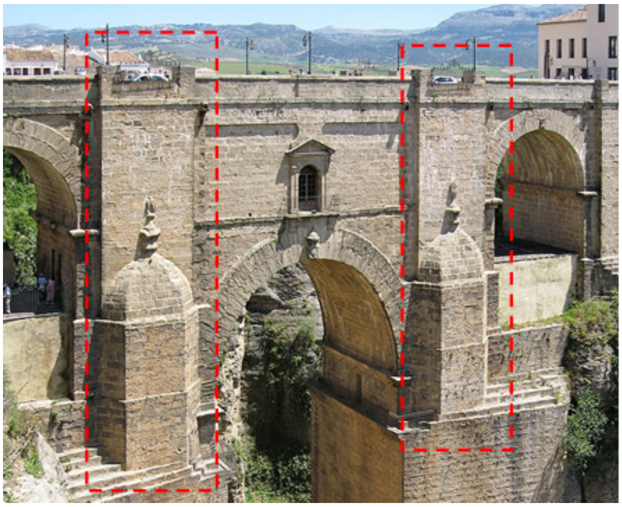

Figure 3. Piers of the New Bridge of Ronda. Edited by authors in 2022 (source: Tausch, 2008)

In the analysis of the piers of the New Bridge of Ronda, above them, at platform level, there are balconies with views of the surrounding area. One of these piers is crossed by a vaulted gallery (Figure 6) made of ashlars, with a stone staircase lined with ceramic tiles that provides access to a room beneath the blind arch.

One of the morphological parameters investigated was the relationship between the dimensions of the piers and the span of the arches. In urban masonry bridges, the spacing between piers is typically 20 to 25 meters, although there are examples with greater spans, such as the 28.80 meters between the central piers of the Alcántara Bridge (León, 2017). The dimensions of the pier sections varied based on parameters such as river flow or platform size.

The choice of pier width in masonry bridges was based on accumulated experience. Alberti's "Treaty of re aedificatoria" states that the width of piers should be one-quarter of their height, while Palladio's "The Four Books of Architecture" compiles relationships between pier widths and arch spans, ranging from 1/2 to 1/6. Simón García proposed that the width of piers should be between 1/3 and 1/6 of the arch span (Huerta, 2000).

In original bridge construction documents, simple mathematical rules for sizing elements like piers or arches were commonly outlined. Since the dimensions of these elements were recorded in already constructed bridges, those built in the 18th and 19th centuries were designed based on these references (Huerta, 2000). The width of piers in surviving masonry bridges ranges from 1/3 of the arch span in Roman times to 0.55 times that span in the Middle Ages, due to lack of confidence in foundations (Martín-Caro Álamo, 2001). In the 18th century, pier widths were greatly reduced, ranging from 1/6 to 1/10 of the arch span, following new rules proposed by Perronet (León, 2017) (Table 1).

The morphological analysis, which relates the width of the piers to the span of the arches of the Puente Nuevo in Ronda, was carried out using three images of its west

Figure 4. Stone Bridge of Logroño (Spain) (source: Restivo, 2004)

Figure 5. Roman Bridge of Alcántara (Cáceres, Spain) (source: Santi, 2006)

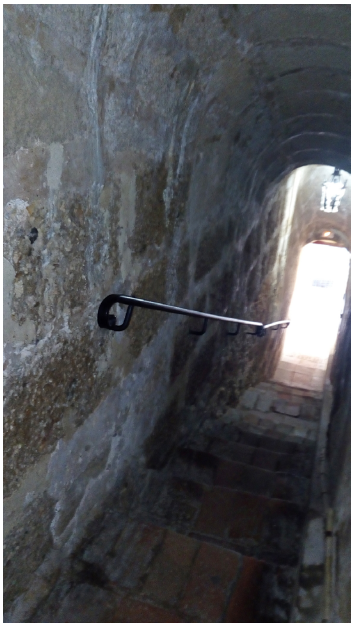

Figure 6. Gallery crossing one of the piers of the New Bridge (source: authors)

Table 1. Proposed sizing dimensions for pier width in masonry bridges (source: compiled by authors)

Period or author	Method for sizing the width of pierds
Roman bridges	1/3 of the span of the vaults
Medieval bridges	0.55 times the span of the vaults
Alberti	1/4 of the height of the piers
Palladio	1/2 to 1/6 of the span of the vaults
Fray Lorenzo de San Nicolás	1/2 of the span of the vaults
Simón García	1/3 to 1/6 of the span of the vaults
18th-century bridges	1/6 to 1/10 of the span of the vaults

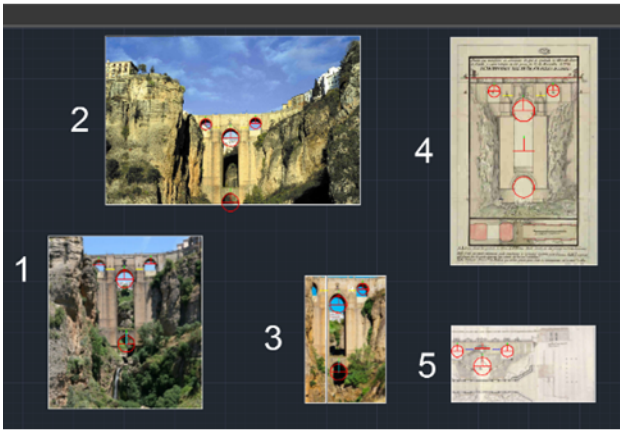

Figure 7. Measurement of elements in images of the New Bridge using AutoCAD (source: authors based on Gumerg (2011), Kostecka (2015), Parpadeo (2010) and historical plans from España, Ministerio de Cultura, Archivo General de Simancas, MPD, 42, 19 (Martín, 1786) and España, Ministerio de Cultura, Archivo General de Simancas, M.P. y D. 34-6 (Martín, n.d.))

face and two historical plans. Measurements of these parameters were performed using AutoCAD 2022 software (Figure 7), and the results of the measurements and their relationships are presented in Table 2.

The digital photographs of the bridge, selected to offer the most frontal view possible of the Puente Nuevo's face, were inserted into the software to minimize potential perspective distortions. However, the objective was not to obtain absolutely exact measurements of each pier and/or arch span, but rather to determine the proportional relationships between the pier width and the arch span, as shown in Table 2. Thus, the bridge images, along with the historical plan images, underwent a geometric correction process. This correction was based on known and real dimensions of bridge elements, such as the height and span of its upper side arches, to ensure the reliability of the results obtained by contrasting the measurements from the three images with those from the two historical plans. This approach allowed for the determination of the key proportions that characterize the morphology of these elements.

The data obtained, and reflected in Table 2, show that the relationships between the width of the piers and the span of the arches of the Puente Nuevo de Ronda are closer to the proportions of bridges built during the Middle Ages, unlike what happens with bridges in the 18th century, where these relationships were significantly reduced (between 1/6 to 1/10, according to Perronet). In this way, the average relationships between pier widths and

Table 2. Measurement of vault span and pier width of the New Bridge. Calculation of the Relationship between Both Dimensions (source: compiled by authors)

		Image 1	Image 2	Image 3	Average of calculations	Image 4 elevation plan Aldehuela	Image 5 detailed section plan Aldehuela
Top left vault	Span (m)	11.528	11.1715			11.5279	
	Pier width (m)	7.6115	6.8898			10.0266	
	Pier width/span	0.6603	0.6167		0.6368	0.8698	
Top right vault	Span (m)	11.1584	11.1579	11.158		11.4563	
	Pier width (m)	7.2251	7.1947	8.1093		9.8525	
	Pier width/span	0.6475	0.6448	0.7268	0.6730	0.8600	
Central vault	Span (m)	16.797	16.8703	16.5302		21.1634	
	Left pier width (m)	7.6115	6.8898	8.1093		10.0266	
	Right pier width (m)	7.2251	7.1947	6.8712		9.8525	
	Left pier width/span	0.4531	0.4084	0.4906	0.4507	0.4738	
	Right pier width/span	0.4301	0.4265	0.4157	0.4241	0.4655	
Upper central blind vault	Span (m)						15.0263
	Left pier width (m)						7.1592
	Right pier width (m)						7.1592
	Left pier width/span						0.4764
	Right pier width/span						0.4764

the spans of the side arches are around 0.6–0.7, therefore, higher values than those used in the 18th century. In the case of the central vaults, these relationships are 0.42–0.45, lower relationships than those of the side vaults, but still remain higher than the proportions recommended in the 18th century, being in fact closer to the proportions of Roman bridges (1/3 of the span).

This morphological characteristic of the Puente Nuevo, with relatively wide piers in relation to the span of the arches between which they are located, confers great robustness to this construction, reminiscent of designs from periods prior to the construction of this bridge, contrasting with the tendency followed in 18th-century bridges where the reduction of pier sections predominated.

2.1.2. Abutments

The abutments support the bridge at the riverbanks or depression it spans, containing the terrain at its ends and transitioning between the structure and the ground (León, 2017).

In the New Bridge of Ronda, the abutments are located under the bridge deck, adjoining the lateral upper arches, connecting the structure to the access road. Additionally, the bridge features two large "machones", as described in its construction history, which rise from the foundation near the riverbed. These "machones", unlike traditional piers, do not connect arches but function as tall abutments, resting on the lateral terrain of the "Tajo de Ronda".

The left abutment, viewed from the west elevation, contains an internal staircase leading to a balcony beneath the central vault. The right abutment houses an Arab-origin canal, a gallery that channels water from the Guadalevín River to former flour mills at the canyon's base (Figure 8) (Carrasco, 2003).

Figure 8. Access to the gallery located under the right abutment of the New Bridge (source: authors)

2.1.3. Vaults

The New Bridge of Ronda features two central vaults and two upper lateral vaults. The central vaults, spanning 16 meters (Table 2), are positioned at distinct heights: the lower vault is approximately 25 meters above the riverbed, measured from the intrados of the keystone, while the upper vault is about 62 meters above the lower one.

The lateral vaults are located above the lower abutments, which frame the two central vaults. Additionally, an interior blind vault is situated above the upper central vault and between the lateral ones. Beneath this vault is a accessible space housing an interpretation center dedicated to the bridge.

A key parameter analyzed in the morphology of the vaults is the rise, also called sag. This is calculated as the ratio between the rise (*R*) and the clear span (*S*) of the vault's springing points, expressed as *R/S* (Martín-Caro Álamo, 2001) or *S/R* (León, 2017). Urruchi-Rojo et al. (2017) classify arches based on this parameter (Table 3).

Table 3. Classification of arches based on the ratio of rise (*R*) to span (*S*) (source: compiled by authors based on Urruchi-Rojo et al., 2017)

Type of arch	Intrados depth (*R/S*)
Pointed	$R/S > 1/2$
Semicircular	$R/S = 1/2$
Segmental	$1/2 > R/S > 1/4.82$
Elliptical	$R/S \leq 1/4.82$

Another key parameter analyzed in the vaults of the New Bridge is slenderness, calculated as the ratio of the vault's depth at the keystone (*d*) to the clear span (*S*), expressed as *d/S* (Martín-Caro Álamo, 2001) or *S/d* (Ramos, 2015).

Table 4 summarizes slenderness proposals from various authors and construction periods for masonry bridges (Durán, 2004; Huerta, 2000; León, 2017).

To determine the rise and slenderness of the New Bridge of Ronda, clear spans, rises, and thicknesses of the vaults were measured using bridge images in AutoCAD 2022 (Figure 7) following a similar procedure to that explained for the relationship between the piers and arch

Table 4. Proposed sizing dimensions for the slenderness of vaults in masonry bridges (source: compiled by authors based on Durán, 2004; Huerta, 2000; León, 2017)

Period or author	Sizing of vault slenderness
Roman bridges	1/10th of the span of the vaults
Medieval bridges	>1/20th of the span of the vaults
Alberti	1/10th of the span of the vaults
Palladio	1/12th of the span of the vaults
Fray Lorenzo de San Nicolás	1/12th of the span of the vaults
Wiebeking	1/24th of the span of the vaults
Perronet	1/24th of the span of the vaults

Table 5. Measurement of span, rise, and depth of vaults of the New Bridge. Calculation of camber (*S*/*R*) and slenderness (*S*/*d*) (source: compiled by authors)

		Image 1	Image 2	Image 3	Average of calculations	Image 4 elevation plan Aldehuela	Image 5 detailed section plan Aldehuela
Top left vault	Span (m)	11.528	11.1715			11.5279	11.5280
	Rise (m)	6.0772	5.6254			5.7606	6.1663
	Depth (m)	1.9737	2.0584			2.1305	1.9377
	S/*R*	1.8969	1.9859		1.9346	2.0012	1.8695
	S/*d*	5.8408	5.4273		5.8400	5.4109	5.9493
Top right vault	Span (m)	11.1584	11.1579	11.158		11.4563	11.6864
	Rise (m)	5.8534	5.8331	6.7742		5.7282	6.1792
	Depth (m)	1.3774	1.8999	2.2097		1.5954	1.6713
	S/*R*	1.9063	1.9129	1.6471	1.8264	2.0000	1.8912
	S/*d*	8.1011	5.8729	5.0496	6.8061	7.1808	6.9924
Central vault	Span (m)	16.797	16.8703	16.5302		21.1634	17.3109
	Rise (m)	10.5156	9.9793	11.3878		12.9268	10.3771
	Depth (m)	2.5606	2.9737	3.1741		2.0173	1.6718
	S/*R*	1.5973	1.6905	1.4516	1.5877	1.6372	1.6682
	S/*d*	6.5598	5.6732	5.2078	6.3645	10.4910	10.3546
Upper central blind vault	Span (m)						15.0263
	Rise (m)						4.6171
	S/*R*						3.2545
Lower central vault	Span (m)	16.2351	17.2462	16.3097		20.5529	
	Rise (m)	9.9715	10.6368	10.7834		12.6267	
	Depth (m)	2.5606	3.4636	2.8597		2.2324	
	S/*R*	1.6282	1.6214	1.5125	1.5873	1.6277	
	S/*d*	6.3403	4.9793	5.7033	5.6743	5.6561	

spans in Section 2.1.1. The camber (rise-to-span ratio) and slenderness (span-to-thickness ratio) were calculated, and an average of these values was used to classify the vaults.

The same method was applied to two original plans by architect José Martín de Aldehuela, enabling a comparison between the built vaults and the designs outlined during construction (Table 5).

The data in Table 5, in the first place, indicate a great correspondence between the design of the bridge's arches as depicted in the plans and what was executed. For the central vaults, the (*S*/*R*) and (*S*/*d*) ratios obtained from Aldehuela's plans are very close to those of the built vaults. These proportions show a robust and relatively low arch section, such that, in comparison with Table 3 (Arch Classification according to *S*/*R* value) and Table 4 (Slenderness *S*/*d* values), it implies that the design of the arches of the Puente Nuevo of Ronda is rather conservative, aiming to achieve a structural stability characteristic of bridges of great span and height.

In the case of the upper side vaults, they show greater lightness than the central ones, and the built vaults maintain a close correspondence with what was projected. These values fit the proportions of semicircular arches, although with a still considerable slenderness that contributes to the overall solidity of the structure. This correspondence between design and construction highlights the meticulousness in the planning of this monumental bridge, achieving a great balance between aesthetics and the objective of supporting large loads and the bridge's height. It is worth noting that, although this is an 18th-century bridge, the proportions of its arch elements imply an influence or a conscious choice of a design that prioritizes robustness, being more typical, as indicated in the relationship between pier width and vault spans, of medieval or even Roman bridge typologies, in contrast to the design trends contemporary to this bridge, which reduce these proportions.

2.1.4. Spandrels

The spandrel is the vertical element above the vaults that extends to the bridge platform (Martín-Caro Álamo, 2001). It serves to support the parapet, connect vaults, and contain either earth fill or enclosed vaults beneath the deck (León, 2017).

Spandrels typically have a vertical profile and a straight or curved plan, depending on the bridge layout. Their thickness, generally not less than 0.50 meters, often increases near the vaults, creating stepped or sloped inner faces (Martín-Caro Álamo, 2001).

Figure 9. Balcony on central spandrel (source: Konstantin~commonswiki, 2025)

In the New Bridge of Ronda, central spandrels are located between the two upper lateral vaults, while others sit above these lateral vaults. The central spandrels, on both the east and west sides, enclose the upper central vault to form a chamber, connect piers, and support the platform's parapet. These elements rise from the extrados of the central vault to the intrados of the blind vault above it, ending at the parapet base. Central spandrels also feature openings with triangular pediments and wooden doors leading to small balconies (Figure 9) (López, 2008).

The spandrels above the upper lateral vaults are minimal in size, as the extrados of these vaults align with the parapet base.

2.1.5. Deck

The deck of masonry bridges allows the passage of people and vehicles. It may be horizontal or slightly inclined. Its width varies, ranging from 20 to 40 meters in urban bridges, and around 3 meters for bridges on communication routes (León, 2017). Roman bridges had wider decks than those of the Middle Ages, as they were designed for vehicles and livestock, while medieval bridges typically had 2-meter-wide decks for carriages (Durán, 2004).

The New Bridge of Ronda features a rectangular deck of 5×29 meters (Figure 10). At its entrances, both from Plaza de España and Calle Armiñán, the deck widens, including sidewalks of 125 cm. The deck has two levels: a lower roadway for vehicular traffic and an upper level, 8 cm higher, for sidewalks. Over the piers, there are balconies with stone benches and wrought iron details. Rainwater is collected via drainage points and channeled through protruding stone pieces.

2.1.6. Parapets

Parapets are safety elements in masonry bridges, preventing falls from the platform into the ravine. Supported by the spandrels, they are located along the bridge's edges (Mateo, 2017). Their designs vary in height, presence of balconies, and decoration.

For the New Bridge of Ronda, the parapets are 125–130 cm high, as specified in the 1777 and 1780 construction plans, designed to protect against falls into the Tajo de Ronda. These parapets also feature a raised section resembling a bench, discouraging proximity to the edge and offering seating. Below, a conduit was planned for water transport to the La Ciudad neighborhood, as per Manuel Godoy's 1780 project (Camacho & Miró, 1994). José Martín de Aldehuela oversaw the parapet construction. Images show the architect's initial design (Figure 11) and the final implemented version (Figure 12).

From the comparison of the two images, it is clear that a simpler construction was chosen, omitting decorative elements such as the ovals on the pilasters and the central commemorative feature seen in Martín de Aldehuela's plan. However, the wrought ironwork on the parapet balconies was retained.

The parapets are 40 cm thick, with a constant section from the base of the seats. In some areas, the thickness increases, forming taller pilasters near the access to the four balconies. At the top of the parapets, wrought iron lampposts are placed, likely dating from the late 19th or early 20th century when petroleum lighting was replaced by electricity in 1897 (Miró, 1987).

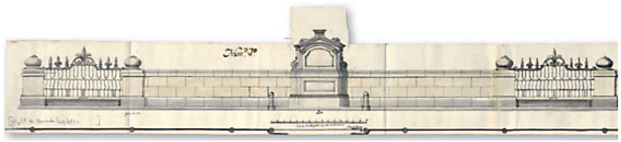

Figure 11. Design of parapets of the New Bridge by architect Martín de Aldehuela. Ministerio de Cultura, Archivo General de Simancas, M.P. y D. 42-20 (source: Martín, n.d.-a)

Figure 10. Platform of the New Bridge (source: Pacheco, 2014)

Figure 12. Parapets of the New Bridge (source: authors)

2.2. Construction techniques and materials of the New Bridge of Ronda

The earliest known document detailing the layout, techniques, materials, or machinery used in bridge construction is from the "Puente de Piedras" (Stone Bridge) in Zaragoza, begun in 1401. Alberti's architectural treatise compiles the knowledge of his time on stone bridges, reflecting bridge designs up to the mid-18th century. Specifically, it addresses bridge construction in Chapter 6 of Book IV, "On wooden and stone bridges, and their pillars, arches..." and in Chapter 6 of Book VIII, "On the main streets of cities, and how they are adorned, gates, ports, bridges..." (Huerta, 2000).

2.2.1. Foundation

In masonry bridges, foundations were either shallow or deep. Shallow foundations were used on rocky terrain with high bearing capacity, sometimes requiring minimal preparation, as seen in Roman bridges where piers started directly from the ground with leveling foundations. These typically matched the piers' footprint, with slabs added if ground settlements occurred. Materials included masonry and occasionally wooden reinforcements, with concrete extensions for protection. During the Middle Ages, shallow foundations were common due to simpler execution, often ignoring soil resistance. Deep foundations, involving wooden piles to transfer loads to more stable soil, were used for low-capacity ground or riverbeds (Martín-Caro Álamo, 2001).

The New Bridge of Ronda's lower abutments start on rocky banks outside the riverbed, providing high load-bearing capacity. On its west face (Figure 2), the right abutment features a footing made partly of ashlar stones and partly of rubble masonry, with a slightly larger footprint than the abutment above it. This footing includes a walkway for accessing facilities at the gorge's base. The left abutment foundation consists of a rubble masonry elevation supporting ashlar stones (Figure 13). Both footings are rigid and similar in ground dimensions to the abutments they support.

Constructing these footings required precise terrain preparation, including potential earthworks, reinforcements, or excavations. Rubble masonry walls reinforce the bases of both abutments (Figure 13). These walls likely used wooden piles and boards to stabilize materials until the structure hardened. A 1756 report by builders Alonso Gil and Pedro Reguera mentions timber sourced from the river "for greater stability" after the collapse of the initial bridge (Cadiñanos Bardeci, 2014).

Figure 13. Foundation under the left abutment of the New Bridge (source: Lin, 2017)

2.2.2. Piers and abutments

Piers and abutments of stone bridges were often built entirely with ashlar stones, typically sandstone, limestone, granite, or marble, especially for piers (Martín-Caro Álamo, 2001). Alternatively, dressed stone or rubble masonry was used for the outer faces, while interiors were filled with lime and rubble mortar, later replaced by mass concrete in the 19th century (León, 2017). Ashlar blocks were sometimes joined with metal clamps or dovetail carvings to prevent displacement due to water erosion of mortar joints (Durán, 2017).

Scaffolding was essential for their construction, supported by dowels left in the masonry. Wooden beams formed the scaffold framework, a technique dating back to Roman times (León, 2017). Cranes were also used to transport materials and workers.

In the New Bridge of Ronda, sandstone ashlar blocks measuring 90×45 cm were used on the exterior surfaces of piers and lower abutments, while the interiors were filled with lime and rubble. This is evident in the left abutment stairs and the gallery at the base of the right abutment (Figure 8). A 1763 construction report by master builder Pedro Fernández specified that piers would consist of lime and rubble with ashlar cladding (Camacho & Miró, 1994).

The upper abutments at platform level are fully masonry and currently coated with cement mortar and yellow-ocher paint. This cladding, applied during a 1990s restoration by architect Ciro de la Torre Fragoso, prevents material detachment.

Under the upper arches, between piers and abutments, masonry fillings replace ashlar blocks, likely due to the challenging terrain of the Tajo de Ronda gorge, particularly on the east side. These fillings facilitate construction and terrain integration. During the restoration, they were also coated with cement mortar and painted, matching the upper abutments.

2.2.3. Arches

The vaults of masonry bridges are critical structural elements. Semi-circular vaults, with uniform voussoirs, simplify construction and provide strength, also applicable to flattened arches (Urruchi-Rojo et al., 2017; Durán, 2004). Voussoirs in masonry bridges can follow stretcher or mixed bonds, with the latter providing greater strength. Arches may feature single or multiple courses of voussoirs (Martín-Caro Álamo, 2001).

Alberti and Turriano emphasized large, uniform voussoirs, with a keystone placed last by hammering to ensure pressure distribution (Huerta, 2000; Zanetti, 2019). The "kidneys" near the springing of vaults were filled with compacted rigid material to two-thirds of the vault height

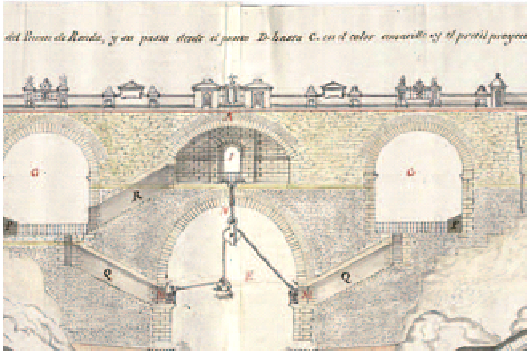

Figure 14. System of pulleys in central vault. Ministerio de Cultura, Archivo General de Simancas, M.P. y D. 34-6 (source: Martín, n.d.-b)

for road bridges, or four-fifths for railway bridges, as seen in Roman structures (León, 2017; Durán, 2017). Granular fillings behind vaults further distributed platform loads (León, 2017).

Vault construction required formwork supported by imposts or recesses in the masonry. The Romans embedded wooden beams for this purpose (León, 2017).

The vaults of the New Bridge are built with sandstone blocks in a header bond, forming a double thread. Above the upper vaults, a bedding of lime and pebbles replaces granular fillings, observed through an opening in the central vault, now part of an interpretation center.

Dovetail slots beneath the vault over the Guadalevín River suggest wooden stringers for formwork. For other vaults, sealed slots or imposts may have supported the formwork. The central vault opening housed a pulley mechanism, designed by José Díaz Machuca, to lift materials during construction. This system, depicted in a plan by the bridge's final architect, José Martín de Aldehuela (Figure 14), reduced the force needed by workers (Moreti, 1867).

2.2.4. Spandrels

Ashlar stone was commonly used for spandrels. When backfilling was present, it was stiffer near the vaults' connections to piers or abutments, forming part of the structural system and enhancing rigidity. The rest of the fill consisted of lighter, granular soils to distribute deck loads to the piers or abutments (León, 2017). Voids were often included in the fill, particularly in long bridges, to prevent overloading the vaults and facilitate rainwater drainage (Martín-Caro Álamo, 2001).

The masonry at the "nozzle" where spandrels meet vaults was typically better crafted and larger than the vault masonry. Different masonry patterns were used at these junctions, and stonemasons often refined the spandrel surfaces for a smoother finish, particularly near vaults (León, 2017).

The New Bridge of Ronda's spandrels are built with sandstone ashlar blocks measuring 70×35×35 cm, smaller than those used for the abutments. The central spandrel walls closing off the upper central vault are 95 cm thick, increasing to 135 cm around the openings to balconies. These features can be observed from the interpretation center inside the bridge.

One spandrel's outer face contains a cavity similar to dovetails found in the lower vault and upper abutments, suggesting the use of scaffolds or platforms during construction. Given the height above the central vault, scaffolding would have been challenging to arrange. Likely, wooden platforms were placed or suspended from the parapet above, with additional anchoring to the spandrels for stability and safety.

2.2.5. Parapets

Parapets in masonry bridges were often made of stone or brick. Skilled stonemasons refined their surfaces, especially for bridges in urban areas (León, 2017). Using scaffolds secured with dovetails or anchored to parapet tops, they meticulously finished joints, moldings, and decorative elements. For parapets near riverbeds, barges were commonly used to support scaffolds.

The parapets of the New Bridge of Ronda are constructed with sandstone ashlar blocks measuring 90×45 cm. In 1867, the original stone balcony seats were replaced with stone from the Capitán de Almadén quarries (Ciudad Real). Metal clamps, visible at various points (Figure 15), provide additional security, preventing ashlar block displacement or detachment (Miró, 1987).

Figure 15. Clamp joining ashlar blocks in the parapet of the New Bridge (source: authors)

2.2.6. Deck

The deck of stone bridges often includes a wearing course for pavement, with sidewalks made of various materials and textures. Some bridges use materials like ballast, aligning with the surrounding road for durability, functionality, and minimal maintenance (León, 2017).

On the New Bridge of Ronda, the roadway is paved with granite pavers arranged in two longitudinal rows at the center, with additional transverse pavers. These were laid during the 1990s restoration, replacing an earlier asphalt pavement, as noted by architect Ciro de la Torre Fragoso. The sidewalks are made of sandstone slabs, raised approximately 8 cm above the roadway.

2.2.7. Materials

The primary materials used in masonry bridges are ashlar stone, brick, and mass concrete. Ashlar blocks, typically 3 to 4 times longer than their height, were made from sandstone, limestone, granite, and occasionally marble (García, 2017; Martín-Caro Álamo, 2001). In earlier bridges, ashlar blocks were often arranged dry, requiring precise carving for friction, with joints secured by dovetailing or metal staples (copper, iron, lead, or wood). Wood staples expanded when moistened, enhancing joint strength (Manjón & Martínez, 2007). Mortars were used for leveling and joining blocks, with lime and sand being the standard mixture, as described by Vitruvius in *The Ten Books on Architecture* (Rowland & Howe, 2001). During the Middle Ages, cement mortar, made by adding clay to lime mortar, became common, and in the 19th century, this evolved with the addition of pozzolans and other elements (Manjón & Martínez, 2007).

The materials in the New Bridge of Ronda consist of natural sandstone ashlar with a lime and rubble fill. According to Ciro de la Torre Fragoso, the restoration architect, these stones were sourced from the Tajo de Ronda gorge (De la Torre Fragoso, 2023). However, Eduardo Molina Piernas from the University of Cadiz asserts they came from a quarry near Ronda. Molina's analysis, carried out between 2010 and 2014 at the Faculty of Sciences of the University of Granada, and detailed in his doctoral dissertation (Molina, 2015), revealed that the stone from the Tajo is a low-consistency conglomerate, unlike the limestone used in the New Bridge's construction. Further studies of samples from the "Arroyo del Toro" quarry near Ronda showed that the stones used in the bridge and local monuments have similar lithological properties, including medium-small, spherical or elliptical grains (1–2 mm) of quartz, phyllosilicates, organic material, and metallic ores. The stone has a pink hue and a matte texture (Gómez-Vargas & Moreno-Vargas, 2008, a congress paper).

3. Conclusions

From the conducted research, it is concluded, regarding morphological aspects, that the New Bridge of Ronda has a relationship between the span of the arches and the width of the piers similar to bridges built in the Middle Ages.

Furthermore, the New Bridge of Ronda features two large abutments that extend from the banks of the Guadalevín River to the height where the upper arches rest. Adjacent to these are other lateral abutments, constituting a morphological peculiarity compared to the vast majority of constructed masonry bridges.

Regarding the upper arches of this bridge, the lateral ones are semicircular vaults. The central blind vault, on the other hand, is a lowered vault. Finally, the two central non-blind vaults are confirmed to be cambered vaults.

Concerning the slenderness of the vaults of the New Bridge, with this parameter ranging between 5–6, it represents a moderately high vault slenderness, considering that the lowest slenderness known in stone bridges is found in Roman bridges, which is around. However, the depth of these vaults is of significant dimensions in relation to the span, thus promoting the stability of these vaults.

It is also noteworthy that, through careful measurements performed on digital images of the New Bridge's historical plans, it has been possible to compare the executed construction with what was projected. Specifically for the vaults, a high degree of correspondence has been verified between the plans and the built structure. This finding is particularly significant given the inherent limitations in the precision of graphic representation at the time of the New Bridge's construction.

It is important to acknowledge certain limitations of this study. Our analysis, based on measurements performed on digital images of historical plans and current photographs, inherently carries a degree of precision limited by the original quality of the historical documents and the nature of image-based measurements. While we employed careful methods to maximize accuracy within these constraints, advanced techniques such as drone-based scanning or high-precision topographic surveys of the existing structure were beyond the scope and available resources. Future research could overcome these limitations by incorporating such cutting-edge methodologies to achieve even greater measurement accuracy.

In terms of the construction techniques used in the New Bridge of Ronda, these generally correspond to those applied in masonry bridges built in the Iberian Peninsula until the 18th century.

As for the materials used in the construction of the New Bridge, it is possible that many of them, such as the interior filling materials of the walls, came from the same gorge of the Tajo de Ronda, as this was the nearest and easiest place to obtain them. However, it does not seem so clear that the stonework came from this place, since there are no signs of extraction of large stone blocks in the same, nor do the characteristics of this stone match those of the walls of the Tajo de Ronda gorge.

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