The Moorish Bridges of Andalucia

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INTRODUCTION

The advanced state of Islamic architecture, mathematics, and astronomy during the Umayyad and Abbasid periods of rule in the Middle East is well documented. However, the contributions of Islamic builders to bridge design have rarely been studied. As O'Connor states in the conclusion of his exhaustive study on Roman bridges,

> […] it appears that no accurate review has ever been published of bridge construction in the post-Roman period […] such a review should pay closer regard to regions with civilizations which continued in the Post-Roman period, such as Turkey or Moorish Spain.
>
> (O'Connor 1993, p.188).

Moorish domination on the Iberian Peninsula lasted from their arrival in 711AD until their dispersal at the hands of the Spanish monarchs Ferdinand and Isabel in 1492. Along with mosques and palaces erected during the almost 800 years of Muslim rule in Andalucia - whose name is inherited from the Arabic al-Andalus (Collins 1983, pp.163-224) - the Moors also built or restored a network of roads, which required bridges across the rivers lying in their paths (Maldonado 1990, p.112). In some cases, such as the bridge at Cordoba, this meant repairing existing Roman bridges that had deteriorated since the dissolution of Roman administration on the Iberian Peninsula around 200AD (Richardson 1996, pp.231-235). In other instances, such as the three existing Moorish bridges between Cordoba and Sevilla, the Muslim inhabitants of Spain most likely constructed bridges where there had been none previously (Maldonado, pp.108-118). The attempt to distinguish the Moorish lineage in the bridges of Andalucia is complicated by the fact that in many cases, the bridges have remained in service long after the departure of the Moors (one of the bridges investigated, Pinos Puente Bridge, is still carrying traffic). Their continued utilization means that in addition to the work that might have predated the structure, one must also attempt to distinguish Moorish work from alterations occurring over the thousand-odd years since completion of the structure. The goal of this paper is to begin to identify the traits shared by Moorish bridges for use by subsequent scholars.

OVERVIEW OF BRIDGES

The bridges investigated in the study consist of the following:

Table 1. Bridges Investigated

Name	Location
Nogales Bridge	Cordoba
Cantarranas Bridge	Cordoba
Guadiato Bridge	Cordoba
Quebrado Bridge	Hornachuelos
Guadalbacar River Bridge	Setefilla
Pinos Puente Bridge	Pinos Puente

A treatment of the dimensions and geometry of each bridge is summarized in **Table 2**, which also contains information on five other bridges surveyed but not included in this text. The majority of the bridges in the study share an important defining characteristic known as the horseshoe arch, defined as an arch of a geometry containing more than 180 degrees of a semicircle. The first evidence of an arch in this shape appears in Northern Syria in several structures dating from the fifth century (Creswell 1968, pp.72-73), but its greatest manifestation occurs in Andalucia and Northern Africa during the time of Moorish control in Spain, when it appears in numerous mosques, fortresses, and bridges constructed between the beginning of the 8th to the end of the 15th century.

This field study of six bridges in Andalucia will provide the groundwork for subsequent scholars to begin to appreciate the contribution of Moorish builders to bridge design and construction. A bridge is a technological expression of a culture. The bridges of Andalucia are of particular interest because of their cultural and geographical location, which was for many years the locus of a peaceful and fertile collaboration between Muslim and Christian scholars and a prime interface in the transfer of knowledge between two empires (Collins 1983, pp. 200-207). The question of whether that structural knowledge might have transferred from the Muslim to the Christian inhabitants of Spain, and through them to other parts of Western Europe, remains to be answered.

BRIDGES OF CORDOBA

The bridges investigated in this study fall into two major geographical areas: those in and around Cordoba, and those lying on the Moorish road that at one time connected Cordoba to Sevilla along the valley of the Guadalquivir river. The descriptions below follow the approximate chronology of the center of Muslim political power in Spain, beginning with the bridges in and around Cordoba, the original seat of Muslim power on the Iberian Peninsula followed by the bridges between Cordoba and Sevilla.

Nogales Bridge

The mosque of Cordoba, built on a site occupied previously by a Visigoth church, functioned as the administrative center of Andalucia just after the arrival of the Moors on the Iberian peninsula in 711 until 1031 (Collins 171). Eight kilometers northwest of the city lies Madinat al-Zahra, a palace complex constructed between 936 and 945 by Abd al-Rahman III for use as a summer palace (Collins 171). Nogales bridge **(fig. 1)**, consists of three spans across a stream on the road to Madinat al-Zahra. Although all three spans are intact, the bridge has experienced moderate deterioration during the course of its life.

Figure 1. Nogales Bridge.

The bridge consists of a span of 2.9 metres flanked on either side by arches of 2.2 metres, with piers approximately as wide as the two outside spans. The voussoirs of the center span vary between seventy to ninety centimeters in height, making them very large relative to the short distance of the spans. The bridge is 4.5 metres wide and has no visible breakwaters up- or downstream. Stones up to 120 centimetres long by 50 centimetres high of unknown depth (but not likely to be less than 25 centimetres) were observed in the spandrel area between the arches.

Although all three spans of Puente Nogales appear today to be semi-circular, there is ample reason to believe that at least the two flanking arches and perhaps the central span are horseshoe- shaped. A ledge of a depth of approximately 20 centimetres, consistent with the bottom return of the horseshoe shape observed in the other bridges in the study, was visible at the base of the left hand arch. A small amount of excavation at the base of the right-hand span revealed a similar ledge. While the variability of river flows make it difficult to reliably predict a standard rate of soil accumulation (Jimenez-Camino, 2005), it seems reasonable to suggest that soil was deposited about the bridge, covering the bottom portions of the arches. This would account for their semicircular appearance. The bond of the stonework at the bottom of the arches supports this hypothesis. Three courses of stones 25 centimetres wide by 40 centimetres high by 80-100centimetres long, placed on edge, could be surmised to form the bottom of the horseshoe arch. This pattern of stonework is found in the horseshoe arches of the Cantarranas Bridge, the bridges over the Guadiato and Bembezar rivers, and the bridge at Pinos Puente. It is likely that breakwaters original to the bridge have also been buried. A small sign at the bridge indicates that Nogales Bridge, like Cantarranas

Bridge, is administered by archeologists currently excavating Madinat al-Zahra. Further analysis of the bridge would benefit from consulting these sources.

Cantarranas Bridge

Approximately 2 kilometres south of Puente Nogales lies the bridge of Cantarranas **(Fig. 2)**. Much of the underlying stonework is revealed due to a recent archaeological excavation, making Cantarranas especially intriguing. The single span of the bridge is semi-circular and measures 4.97 metres across. The bridge could have been as wide as 8 metres originally, judging from the width of the abutments. The current span measures 4.2 metres wide at the abutments, dwindling to 3.3 metres wide at the center of the arch. A considerable number of voussoirs appear to have fallen from the arch during the life of the bridge. The stones appear to be laid dry, with no visible evidence of mortar anywhere in the bridge. Typical voussoirs measure 100 centimetres high, among the largest of the bridges studied. Stones forming the spandrels above the arches generally measure 120 x 45 x 30 centimetres. These are set in courses with the long axis alternating between perpendicular and parallel to the direction of the traffic, but always resting on the side measuring 30centimetres.This configuration seems inherently less stable than the stones positioned with their widest face down, and the advantage of the more precarious arrangement of stonework is not immediately apparent. The use of stone placed regularly throughout the spandrels of the bridge is unique compared to other bridges in this study. When it was possible to observe the spandrels, they generally seemed to consist of stonewalls at the upstream and downstream faces, with rubble or soil infill between them. This would seem a faster and more economical method of construction, especially when the great weight of the stones forming the spandrels of Cantarranas is taken into account.

The flat, wedge-shaped voussoirs comprising the semi-circular arch of Cantarranas Bridge are set directly on a course of cantilevered stones again placed on edge, defining a small rebate beneath the arch. The voussoirs resting on a single layer of cantilevered stones is related to, but distinct from, the horseshoe arches of other bridges in the investigation. Generally the horseshoe arches are composed of regular voussoirs springing at the imaginary line of a semicircle from three horizontal courses of stones that cantilever into the opening below this line to form the protruding elements of the arch. Here, the stones of the ledge course are followed by the regular voussoirs of the arch **(Fig.3)**. The semi-circular shape of the Cantarranas arch is roughly in keeping with the main spans of the Pinos Puente and Guadiato bridges. However, the single course of cantilevered stones distinguishes Cantarranas from other Moorish bridges at Nogales, Pinos Puente, Guadiato, Quebrado bridge over the Bembezar river and others, in which the voussoirs comprising the main part of the spans lay on top of two additional masonry courses set on edge above the ledge course. This pattern is also followed in many of the exterior arches of the mosque of Cordoba, although not in the arches between the columns on the interior. In the Cantarranas Bridge, the voussoirs are set directly on this first ledge course of stones, although the course of the ledge is supported by two other courses of stones also laid on edge.

Figure 2. Cantarranas Bridge.

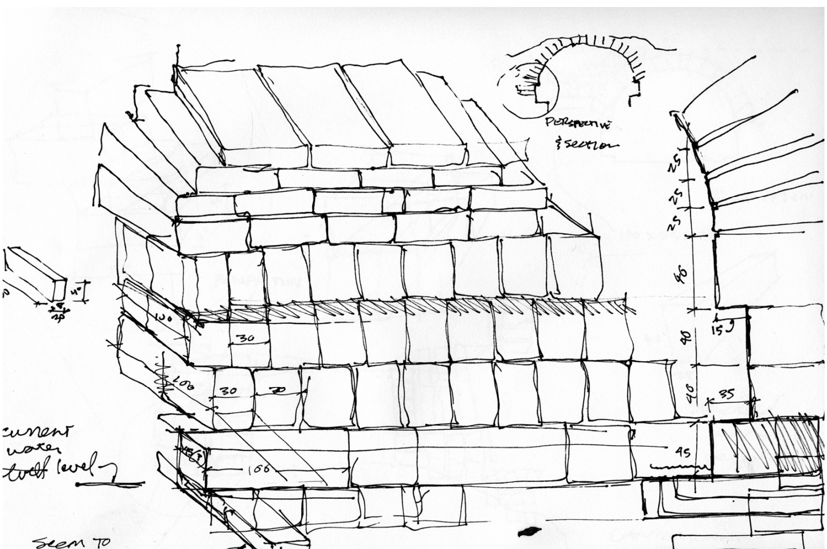

Figure 3. Cantarranas Bridge, masonry.

BRIDGES ON THE ROAD FROM CORDOBA TO SEVILLA

Four bridges that Maldonado dates from the Caliphal Period (corresponding to the caliphate established in Cordoba from 929-1031) can be found between Cordoba and Sevilla. These bridges over various tributaries of the Guadalquivir River were a part of a Moorish road that roughly paralleled the Guadalquivir River to its north side (Maldonado 1990, p.112). This road was distinct from the Roman road established about a millennium earlier, which connected the Roman city of Corduba to Hispalis (modern Sevilla), via a road that paralleled the Guadalquivir River to the south, passing through Ecija and Carmona (O'connor p.19).

Tejera Bridge

In the hills to the northeast of Cordoba lie two bridges within a kilometre of one another, one Caliphal and the other apparently of Roman origin, although Maldonado claims that the latter bridge also dates from the time of Moorish domination (Maldonado 1990, p.106). This assertion is puzzling as the two share very few characteristics, such as the type of stone, shape of arches, or method of construction. The two bridges cross two different streams, the Guadiato and the Guadanuno, close to their confluence. The Caliphal bridge (**Fig 4**) is impressive in size, consisting of nine spans, all but three of which remain intact today. The bridge crosses the Guadiato river on a road that connected Cordoba to Villaviciosa, 20 kilometres to the northwest, before joining a road that led to Badajoz (Maldonado 1990, p.108). The river valley is striking and the bridge a beautiful testament to the knowledge and skill of Moorish builders.

Figure 4. Tejera Bridge.

The majority of the Tejera bridge has voussoirs composed of soft sandstone throughout. The bridge measures 80 metres long and follows a symmetrical layout. The central span measures over 8 metres and is flanked on one side by a slightly ogival arch. Although only this side remains intact, it is likely that the other side would have been the same. The first three spans from either abutment all measure just over 4 metres each. On the left hand side of the bridge, these arches are horseshoe shaped (**Fig. 5**); on the right side two of the three spans have been destroyed, but it seems reasonable to surmise that they would have been horseshoe-shaped as well. The voussoirs of the flanking horseshoe shaped arches measure approximately 65 centimetres high, while those of the three center spans alternate between voussoirs cut from of a single piece of stone 105 centimetres high and those of the same measurement, but comprising two pieces. Maldonado claims that the voussoirs of the spans grow in size from the springing to the keystone (although this trait was not noted in my visit), which suggests to him that the bridge was constructed prior to Abd al Rahmann III. (Maldonado 1990, p.109). The remaining arch on the right side is completely made of brick with several large cracks running through it. The presence of an architvolt of small round stones following the outside periphery of the voussoirs on the central arches suggests an affinity with the bridge over the Guadalbacar, in which the same trait can be found. The piers of the Tejera Bridge over the Guadiato river are built of stones measuring 90 x 45 x 45 centimetres, whose size further suggest to Maldonado that the bridge was constructed sometime during the tenth century (Maldonado 1990, p.109).

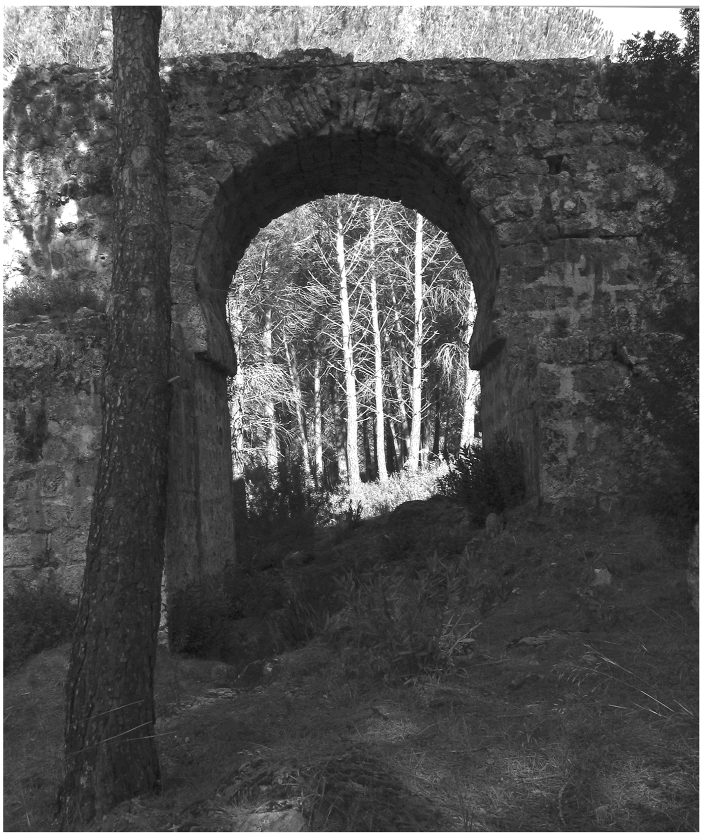

Figure 5. Tejera Bridge, detail.

The bridge is notable in part for the massive size of its foundations, which for the most part rest on the solid rock of the riverbed. The breakwaters are semicircular in plan upriver and rectangular downriver. Both of the fallen spans are likely to have collapsed due to problems with their foundations, although the soil around the failed pier could have accumulated since the bridge was completed over one thousand years earlier. The fact that nearly the entire block of the foundation remained joined together even in failure (**Fig. 5**) speaks to the strength of the mortar used throughout the bridge, which is approximately 1 centimetre thick at most of the joints. The third collapsed span terminated onto a steep sandy bank at the end of the bridge. This arch has apparently failed since the last visit of Maldonado to the site, because he only mentions the collapse of one of the arches. Ruins of what looked to be a failed wing-wall were observed in the brush at the end of the bridge; movement of the soil at the abutment is likely to have played a role in the destruction of the final span.

Quebrado Bridge

Proceeding from Cordoba toward Sevilla, the next Moorish bridge crosses the Bembezar River, a little less than a kilometre south of the town of Hornichuelos. The remains of the Moorish bridge, known as Puente Quebrado, or “Broken bridge” (**Fig. 6**), stands below the dammed section of the river, and are accessible via a footpath from the dam.

Figure 6. Quebrado Bridge

Maldonado speculates that this bridge consisted of two central spans of 7.9 metres each (Maldonado 1990, p.113), which seems reasonable, although there was no visible foundation remaining to support this hypothesis. The sole remaining arch, which would have flanked the two central spans, has a pronounced horseshoe shape, with a breakwater whose plan matches those of Puente de la Tejera: semi-circular upstream and rectangular downstream. The arch measures 4.5 metres across, consisting of voussoirs 95 centimetres high by 60 centimetres thick by 30 centimetres on the underside of the barrel vault. The remaining pier is 3 metres across and stands on solid rock. Maldonado mentions that the piers consist of concrete inside the outer facing of rock (Maldonado, p.114), but we were unable to verify this during our visit. Notably, the breakwater on the downriver-side was pulling away from the pier in a manner that suggested that it was added after the construction of the pier. The stones of the breakwater were not knit together with the stones of the pier and a large crack had developed as a result. The largest stones of the pier measured approximately 50 x 60 x 120 centimetres. The type of stone changes five courses from the bottom of the pier.

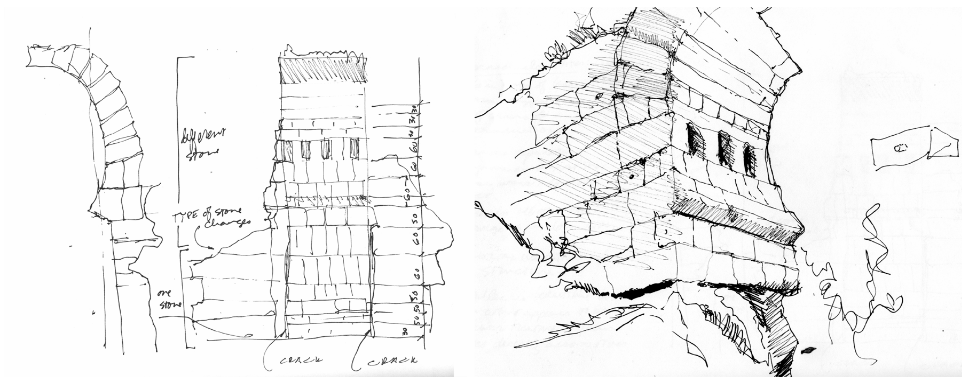

Figure 7. Quebrado Bridge, masonry

The bond at the springing of the horseshoe arch of the bridge over the Bembezar river is similar to that of the Pinos Puente, Tejera, and Guadalbacar bridges: three courses of stones laid on edge form the bottom of the horseshoe above the ledge, upon which the voussoirs of the main body of the arch are placed (**Fig. 7**). The presence of numerous holes of a diameter of approximately 8 cm in a significant number of the voussoirs and stones comprising the piers and spandrels of the bridge (**Fig. 8**) distinguish Puente Quebrado from other caliphal bridges. Most of the holes occur at what appears to be the approximate centroid of the stones, which lends credence to Maldonado's theory that the holes might have been used to provide a purchase for lewis pins used to lift them in place with some sort of machinery. If we assume sandstone to have a unit weight of 20 kN/m3 (Heyman 1995, p.12), a single stone measuring 50 x 50 x 100 centimetres would weigh 5kN, or over 1,100 lbs. Stones of this weight suggest that the builders of the Guadiato, Cantarranas, and Bembezar bridges would have benefited from the use of machinery in the erection of the bridges.

Nevertheless, the Bembezar river bridge is the only Moorish bridge in this investigation to contain evidence of holes that might have been used for lifting. Notably, the remains of the, apparently Roman, bridge approximately 8 kilometres down river in the town of Estacion Hornachuelos has ample amounts of holes of similar dimensions in the voussoirs and the stones comprising the piers and spandrels.

Figure 8. Quebrado Bridge, voussoirs

Bridge over Guadalbacar River

The next bridge encountered on the Moorish road from Cordoba to Sevilla is located approximately 2 kilometres north east of Setefilla, a small village. Only the two peripheral spans, measuring approximately 2.8 and 3.8 metres, remain intact of what Maldonado hypothesizes was a bridge consisting of three spans over the Guadalbacar river (Maldonado 1990, p.117). This theory seems plausible given the angle of the springing of what might have been the central arch that remains intact on the right side (**Fig. 9**). If this theory were true, the road over the bridge would have had a pronounced ridge in the center, as the fallen middle arch would have had to rise considerably in order to span the distance required, even if the arch were flattened from semicircular to slightly segmental, as Maldonado has drawn it (Maldanado 1990, p.117). A central arch so much wider than the two flanking arches would distinguish the bridge from the other bridges in the investigation so far; although many of the bridges encountered have slightly larger spans in the center, the central arch of the Setefilla bridge would be almost three times as large as the flanking spans. This ratio contrasts with the other bridges in the study such as the bridge over the Guadiato River, whose larger central spans are less than double those of the periphery. The width of the bridge, 4.4 metres, is in keeping with the other bridges studied in this investigation.

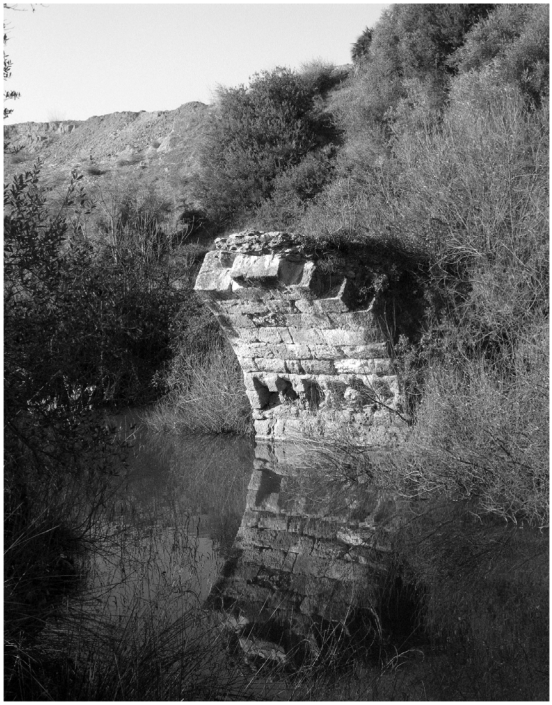

Figure 9. Guadalbacar Bridge

A decorative aspect of the stonework of the bridge over the Guadalbacar differentiates it from many of the other bridges in the investigation, but suggests an affinity with the Tejera Bridge. Alternating voussoirs are typically broken into two segments, which when taken together typically measure 105centimetres tall, a characteristic also found in the Tejera bridge over the Guadiato river. The remaining voussoirs of the central arch over the Guadalbacar river are distinguished by a recess at their outermost edge, into which round stones measuring approximately 7 centimetres across have been set in mortar. This treatment of the voussoirs in an apparently decorative manner is similar to decorative treatment of the voussoirs of the bridge over the Guadiato. There, the voussoirs of the three larger central spans are shaped with what appears to be a decorative reduction in size at approximately 30cm from the extrados. The two side spans have voussoirs measuring 50 centimetres in height, corresponding to their shorter spans and have no distinguishing decorative stonework.

Figure 10. Repairs to Guadalbacar Bridge at the springing of the arch.

The left-hand pier of the bridge over the Gaudalbacar river is 410 centimres wide, angled in plan upstream and semicircular in plan downstream, and it seems reasonable that the other side would be comparable. Maldonado claims that the pier of right hand side of the bridge are angled both up- and downstream; this portion of the bridge was so overgrown that his assertion was impossible to verify. He surmises that the unlikely shape probably indicates a later repair. Evidence of repairs to both the pier and the springing utilizing brick are in the left hand pier and springing of the arch **(Fig. 10)**. The bricks used in the foundation of the right hand piers have the same dimensions of bricks found in twelfth century structures in Sevilla: 30 x 15 x 4 centimetres (Maldonado 1990, p.117). The bricks of the left hand span looked similar to what he describes and seemed more to indicate repair work than original construction, which would suggest that the bridge was repaired in the twelfth century and constructed sometime before that. Maldonado claims that the coursing of the masonry of the vaults is similar to that found in the sections of the Puente Romano most likely to have been constructed by Almohads during the twelfth century; this combined with angled putlog holes leads him to postulate that the Guadalbacar Bridge was constructed sometime during the twelfth century.

Pinos Puente Bridge

The town of Pinos Puente, approximately 12 kilometres northwest of Cordoba on the old road to Granada, has an impressive stone bridge in which two horseshoe spans flank a longer, semicircular center span. The bridge at Pinos Puente has large mounds of garbage collecting at both ends despite remaining in active service, carrying pedestrian as well as vehicular traffic. The right and center spans measure 6.5 metres and 10 metres respectively, with the left hand span visually in the vicinity of the right hand span. The bridge is massive, with the road two full meters above the extrados of the arches. The piers are close to 5 metres wide, projecting close to 3 metres from the up- and downstream faces of the bridge. The breakwaters are semicircular above and rectangular below, in accordance with many of the Moorish bridges so far investigated. The size of the stones match the scale of the bridge: the faces of the stones of the piers measure 90 x 55 centimetres, with the perimeters of the faces dressed in a way that was not observed in any of the other bridges of the investigation. Maldonado claims that the stonework of the bridge at Pinos Puente is similar in appearance to that of the addition to the Mosque of Cordoba performed by Abd ar Rahman II, and he further notes that the notched voussoirs are similar to the Puerta de la Ciudad, in Tarifa (Maldonado 1990, p.120). The same configuration is visible in the Puerta de Sevilla in Carmona.

The horseshoe arch on the right side of the bridge begins with a horizontal course of stones carved in the shape of a cove; above this are three more horizontal courses of stones 50 centimetres high laid on edge, upon which rest the regular voussoirs of the arch, which measure 25 x 42 centimetres at the intrado, of a height of approximately 85 centimetres, although lack of clear access made precise measurement difficult.

GENERAL CHARACTERISTICS OF MOORISH BRIDGES

The existence of horseshoe arches in the peripheral spans of multiple-span bridges is the most obvious characteristic identifying a bridge as Moorish in origin. However, it should *not* be assumed that all bridges of Moorish construction have at least one horseshoe arch, particularly in the case of single-span bridges. Bridges such as the Cantarranas, which has a single semicircular arch, is located on a Moorish road and contains enough other characteristics, such as the structural configuration and material of the voussoirs, to allow us to say with reasonable confidence that it was constructed by Moorish builders. Single-span bridges, which generally exhibit semi-circular arches, can be often be distinguished from their Roman counterparts by the smaller voussoirs composed of a more delicate stone, and the unique configuration of masonry around the springing as detailed below. The horseshoe arch is nearly almost always reserved for the peripheral spans of a multispan bridge. Multiple span bridges often have a large semi-circular or segmental arch in the center, flanked by horseshoe arches on the sides. In only one instance, the Arco del Darro, was a single-span bridge, observed to have been constructed with a horseshoe arch. This bridge, of which only a small part remains, is located at the base of the Alhambra in Granada, and likely served ceremonial as well as strategic functions.

The repeated appearance of the horseshoe arch in religious and governmental buildings of indisputably Moorish origin, including the mosque in Cordoba, and the Corral del Carbon, , in addition to the Alhambra in Cordoba, and the Alcazar in Sevilla and various city entrances dating from the Moorish period should be sufficient evidence that the shape was employed by Moorish builders. On the basis of this information it seems reasonable to surmise that bridges with some spans built in this shape can also safely be attributed to Moorish builders. The origin of the shape, and the routes by which it may have traveled to Andalucia, or from Andalucia to Northern Africa and other parts of the Muslim empire, would comprise worthwhile topics for future research, but are beyond the scope of this paper.

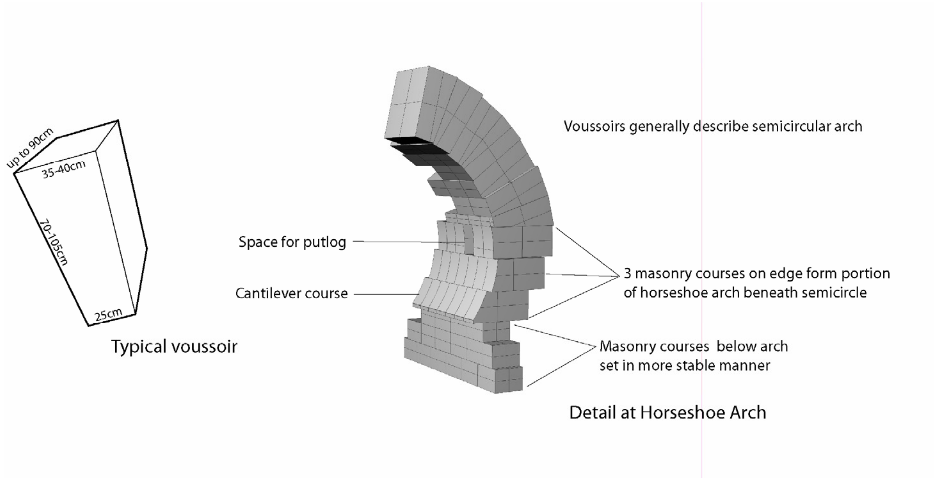

Figure 11. Typical voussoir, and detail at horshoe arch.

Similarities among the masonry configurations used to construct the horseshoe arch can be derived from the bridges in the study **(Fig. 11)**. The geometrical characteristics of the horseshoe arch in Moorish bridges are generally as follows: a horizontal course placed on edge cantilevers to form the bottom course. This is generally followed by two more horizontal courses on edge, followed by voussoirs generally of a softer stone, 65-100 centimetres high. Putlog holes generally occur in the third course of horizontal stone set on edge, suggesting that the first three courses of horizontal stones were placed before any centering was built. The flat voussoirs of a softer stone would then be placed over the temporary centering in a radial pattern roughly perpendicular to the compressive forces acting within the arch. The line of intrados was never observed to go outside the vertical line of support of the columns, which would result in structural problems. Rather, part of the horseshoe arch below the centre of the circle protrudes into the opening. In this way, the roughly triangular protruding aspects of the horseshoe arch are carried by the cantilevered stone in as dead weight, in a manner that resists the sliding that might occur if the radial configuration of the voussoirs were continued past the hypothetical line of the semi-circle. The configuration of the coursing and geometry used to create the horseshoe arch seems to indicate that the builders had a basic understanding of behavior of forces within it. The shape does not reflect the flow of forces in an arch, but the manner in which it was constructed suggest that the Moorish builders used their understanding to create a shape of some symbolic importance. It is only owing to this comprehension that many such shapes are still carrying loads to this day.

There is also a general similarity in the size and material of the voussoirs employed in nearly all the bridges of the investigation (**Fig.11**). With few exceptions the voussoirs were shaped from a soft brown stone that appeared to be sandstone, perhaps chosen for the ease of working it into the long flat shapes favored by Moorish builders. Voussoirs utilized by Moorish builders are considerably narrower than those of their Roman counterparts. The most common sizes are 25 centimetre at the bottom, widening to 35 or 40 centimetres at the top, 70-105 centimetres tall, and up to 90 centimetres long. The maximum height of a voussoir observed was 110 centimetres. This height was never exceeded, even when the voussoir was split into two pieces. Some of the bridges utilize a distinct type of stone for fabricating voussoirs and another in the rest of the bridge. Every vault observed made use of stretcher bond.

The ratio of span to voussoir height generally falls between 1:3.5 and 1:12.5. This represents considerable variation that might be narrowed with data from additional bridges. Nevertheless, the ratio exhibited here is typically lower than the range between 1:10 and 1:20, which O'Connor observes in Roman bridges. An extreme case of possibly Moorish construction is Arab Bridge in Ronda, where the ratio exceeds 16, but this is an isolated case whose geometry is unlike other bridges visited in the study. The span to pier ratio is generally greater than 1:1.5 and less than 1:2.2. This is a reasonably modest number compared to the range of 1:2 to 1:5 given by O'Connor for Roman bridge construction (O'Connor p.192).

Lastly, it seems likely that the Moorish builders made use of machinery for lifting the stones in order to erecting at least some of the bridges in this investigation. Although the voussoirs are often smaller than their Roman counterparts, various bridges were built of stones exceeding 1000 pounds. The ungainly weight of these stones makes the use of such machinery likely. This hypothesis is strengthened by the presence of holes in many of the stones of the bridge over the Guadalbacar River.

CONCLUSION

The bridges documented in this study show that the Muslim builders in Andalucia were capable of erecting ambitious structures serving functional purposes. The continued existence of these bridges more than a millennium after their completion attests to the knowledge and skill of their builders. Their accomplishment is not diminished by the presence of Roman bridges, of which they were doubtlessly aware. Unlike the design and material with which a bridge is constructed, which persist long after the builder has left the site, the process is lost when the culture of the builder disappears. At the time of the Muslim arrival on the Iberian Peninsula, nearly 500 years had passed since the last of the Roman builders had raised a stone there. The Moorish builders used their structural knowledge to create a unique geometry, the horseshoe arch, which was theirs alone. Hopefully this field research offers a foundation to begin to appreciate the advanced knowledge and method of the Muslims in Andalucia in bridge design and construction. The question of how their bridges might have influenced builders contributing to the great advance of structural understanding elsewhere in Europe beginning in the twelfth century remains to be answered.

Table 2. Bridge Information

Name	River/ Stream	Town	Number of Spans	Longest Span	Height	Voussoir Height
Aljibillo Bridge	Darro	Granada	1	7.32m	3.1m	
Arco del Darro	Darro	Granada	1	8m		
Genil River Bridge	Genil	Granada	5	7.02m		80cm
Pinos Puente Bridge	Cubillas	Pinos Puente	3	10.58m	5.05m	
Roman Bridge	Guadalquivir	Cordoba	15	12.82m		
Nogales Bridge		Cordoba	3	2.9m	1.2m	80cm
Cantarranas Bridge	Cantarranas	Cordoba	1	4.79m	2.63m	100cm
Tejera Bridge	Guadiato	Cordoba	9	8.30m	2.8m1	65cm
Broken Bridge	Bembezar	Hornachuelos	4	7.9m1		95cm
Guadalbacar Bridge	Guadalbacar	Setefilla	3	8.3m1	3.9m1	105cm
Arab Bridge	Guadalevin	Ronda	1	8.2m	3.4m	50cm

Table 3. Comparison of characteristics of the bridges.

Bridge	longest span (cm)	pier width (cm)	Voussoir height (cm)	Span /pier	Span/voussoir
Aljibillo Bridge	732		65		11.3
Genil River Bridge	715	482	80	1.5	8.9
Arco Del Darro					
Pinos Puente Bridge	1058	478	86	2.2	12.3
Roman Bridge*	1040	700	90	1.5	11.6
Nogales Bridge	291	220	80	1.3	3.6
Tejera Bridge	830	375	105	2.2	7.9
Cantarranas Bridge	479		100		4.8
Broken Bridge (Hornachuelos)	790	300	110	2.6	7.2

Bridge	longest span (cm)	pier width (cm)	Voussoir height (cm)	Span /pier	Span/voussoir
Guadalbacar Bridge	830	410	105	2.0	7.9
Arab Bridge	820		50		16.4

*Roman Bridge span and voussoir taken from section most likely to be of Moorish origin

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