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First application of reinforced concrete in Spain and first European application in bridges: The rehabilitation of the Roman bridge of Alcántara

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ABSTRACT

The Alcántara Bridge is one of the most important Roman bridges in the world and has been a Spanish National Monument since 1924. Since its construction, almost two thousand years ago, it has suffered numerous damages due to the passage of time and human action, which has led to different interventions. The most important was that carried out by Millán (1856–1860), for the reconstruction of the arch demolished in 1810. During a visit to the bridge, areas with reinforced concrete were observed. Given the areas where it appears, the geometry of the reinforcement and its configuration, is possible to think that it is a very old intervention, which could date from the same period as that carried out by Millán. If so, it would be the first application of reinforced concrete in Spain and one of the first in the world. The aim of this study is to date the intervention and validate the initial hypothesis. To this end, based on a 3D survey of the rehabilitated areas using a drone, a comparative analysis has been carried out with the plans of Millán's project, as well as sheets and photographs from different periods to establish the date of the interventions. Research was also carried out in the archives of the Real Academia de Bellas Artes de San Fernando to gather information on the interventions on the bridge throughout the 19th century. Finally, the geometry and layout of the reinforcement is analysed in relation to the knowledge of reinforced concrete from its first patents worldwide to its widespread application in Spain. These analyses allow us to conclude that the date of the reinforced concrete repairs on the bridge is undoubtedly 1857, which would be the first application in Spain and the first in Europe on bridges.

1. Introduction

Reinforced concrete is the most widely used material in the construction of bridges and buildings during the last 150 years. This new material emerged as the result of the combination of concrete and steel bars strategically placed inside the section of the structural element, which allows it to acquire the advantages of both compressive and tensile strength respectively [1].

On the other hand, concrete is the result of combining a binder, fine aggregate and coarse aggregate. The most common binders

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used in the manufacture of concrete have been aerated lime and hydraulic lime, giving rise to common and hydraulic concretes, respectively [2].

The first scientific studies of hydraulic binders were carried out by Smeathon for the construction of Eddystone's Third Lighthouse (1756–1759) in search of a material that would harden under water [3]. But it was Vicat, at the beginning of the 19th century, who deepened his knowledge of the hydraulicity of limes, laying the foundations of hydraulic cement [4], the basis of concrete, and therefore of reinforced concrete.

Throughout the first half of the 19th century, natural cement was developed in Europe, which began to be manufactured in Spain in 1835 [4]. Artificial cement, also known as Portland cement, began to be manufactured in France and Great Britain in the second quarter of the 19th century, but its manufacture in Spain did not begin until 1898, more than half a century late [5].

The first known experience of reinforced concrete or reinforced cement is due to Joseph Lambot, who in 1843 began to manufacture flowerpots and other garden elements with a cement mortar to which he introduced wires [6,7].

The Roman bridge of Alcántara was located in Roman Lusitania, today's province of Cáceres (Spain). It was built by Gaius Julius Lacer between 103 and 106 (AD) to cross the Tajo River. It is one of the largest bridges built by Roman engineering with a height from the river to the road of 47 m and it boasts the largest arch span of the peninsular Roman bridges, with 29 m [8,9], and is still in service, carrying traffic on the EX-207 Cáceres-Portugal inter-regional road. According to [10] the arches are formed by two rings, a lower one of 1.6 m middle thickness and the upper one of 0.5 m, and the stonework was done without mortar. The granite of the stonework is made up of coarse grain granite, often of the porphyritic type that forms part of the Iberian Massif [10]. The roman bridge of Alcántara and its surroundings, the Triumphal Arch and Temple, has been a Spanish National Monument since 13 August 1924, and is in the process of being declared a World Heritage Site by UNESCO.

During a visit to the bridge in April 2017, it was observed that there were interventions with reinforcement in different areas of the bridge, which are not documented, and that due to their typology, a combination of circular, square and flat sections, they are not current. Given the historical and monumental importance of the bridge, over the last few centuries it has been studied by important archaeologists, historians and engineers, who have meticulously documented all the interventions, without mentioning the presence of reinforced concrete in any of them [9–16].

The only references to the existence of reinforced concrete in the bridge are by Durán [17], showing it as an example of a bad intervention on a masonry bridge, without dating it, and Moreno Gallo, who dates it to 1969 [18].

In view of this information on the history of the bridge, this research has been carried out with the aim of dating the date of the reinforced concrete interventions it presents, based on the hypothesis that these interventions could be the first application of reinforced concrete carried out in Spain and the first in bridges at European level, presenting concepts that would be included in later patents. This would represent a fundamental advance in the knowledge of the beginnings of the use of reinforced concrete in Spain and Europe adding heritage value to the Roman bridge. As it is protected, the enhancement of these interventions in reinforced concrete will allow for the approval of exhaustive studies with the taking of samples to investigate the resistance and durability characteristics of the first concretes and steels, exposed to the environment for more than 150 years, fundamental data for the conservation of this material in protected structures.

2. State of art

2.1. Development of concrete in Europe and Spain and initial applications

Based on the research by Smeathon on the construction of the Third Eddystone Lighthouse [3] and Vicat [19], natural cements began to be used as binders for the manufacture of concrete.

The manufacture of the first artificial cement, by calcination at high temperatures of pure limestone and clays, took place in England, with Joseph Aspdin registering his patent in October 1824, which he called Portland cement and which began to be marketed in the 1930 s, with industrial production starting in 1845 [2].

The first natural cement production in Spain dates back to 1835, in Catalonia and the Basque Country, from the calcination of limestone with clay impurities [4]. In 1860 there were eight factories in Spain. Those in Catalonia were self-sufficient in the area, while those in the Basque Country manufactured nationally and internationally, with Guipúzcoa being the province with the highest production, followed by Vizcaya, which was a distant second [20]. The first modern cement production plant dates back to 1852 in Zumaya (Basque Country) [7], while the first artificial cement one dates back to 1898 [21].

In Europe and Spain, concrete was used in construction along two lines: public works and building, with the greatest use during the second third of the 19th century in the former: port works, bridges, tunnels and hydraulic works, despite the efforts to use it in the construction of dwellings [7].

In France, for instance, natural cement concrete had been used in hydraulic works since the 1820 s [7], for example in the water distribution tanks in Rue Racine in 1833 and from the 1840 s onwards in the construction of the Paris sewerage system [22]. Between 1847 and 1850, it was employed in the construction of the piping for the Aillon water supply to the village of Avalon [7]. In Great Britain the most relevant application of Portland cement was in the London sewerage system in 1861 [2].

Among the different concrete solutions, in 1856 Coignet patented the solution of building with concrete under the name "Emploi du betón hydraulique son application aux constructions" [23].

The Revista de Obras Públicas (Public Works Journal), published uninterruptedly in Spain since 1853 by the Colegio de Ingenieros de Caminos, Canales y Puertos, disseminates national and international engineering advances. With regard to concrete, it includes the first application of concrete in 1846 for the protection of the wooden piers of the bridge over the Urumea River in San Sebastián [24].

The wooden piers in the area in the salt water of the sea had deteriorated, and to protect them "it was decided to surround the lower part with concrete". This magazine also reported on the visit to the Coignet factory in Saint Denis [25] or the introduction of the "artificial stone" manufacturing system, the name given to concrete in those years, and in particular the Coignet system [26]. This author indicated that it would have a splendid future due to its economy and ease of construction. He also documents the first use of concrete in the construction of the bridges over the rivers Lavalé and Lumbreras, in Soria, which began in 1862 [27], in addition Bellsolá states that "the idea of hydraulic concrete arches, is nothing new and even less instructive for the readers of the Revista de Obras Públicas.". It took ten years before Pascual Landa used it in the reconstruction and repair of the Luchana bridge, as it was not possible to carry out this repair with traditional materials [7].

However, following the trend in Europe, the major application of concrete in Spain, due to the size of the project and the volume of concrete used, was in the hydraulic works for the water supply to Madrid, known as the Canal de Isabel II, whose project was approved in 1851 [28]. In the reports on the state of the works, which were published each year, the use of concrete is mentioned as a matter of course. Thus, for example, the 1853 report on the works indicates that 8170 m^3 were used for the construction of the canal and 44,554 m^3 the largest volume, in trenches [29].

2.2. The beginnings of reinforced concrete in Europe and Spain

After his first applications, in 1848, Lambot produced a concrete boat with a steel mesh that he called Fer-ciment (iron-cement), which he patented in January 1855, presenting it at the Paris Universal Exhibition of that year, in which interlocking reinforcements were arranged in two directions [30,31].

Also in 1854, the British William Wilkinson patented a system that combined concrete with steel bars, in which the behaviour of reinforced concrete was intuited, by placing the reinforcement in the areas where the concrete was subjected to traction force [32]. Coignet's first patent for reinforced concrete was registered in 1855 [7] and later, in 1861, he set out its principles and proposed various ways of applying it to the construction of floors, vaults, pipes, dams, dykes, etc. [1]. But it was Joseph Monier who developed the technique from his first patent in 1865 with a system of parallel reinforcement in a slab, indicating "a grid-shaped framework made of round, square, flat or any kind of iron., which when finished is bathed in cement on each side", followed by other patents on pipes (1868), panels (1869) or beams (1878) [5,7].

The first reference to the use of reinforced concrete in Spain is in a document of 1867 by the military engineer Rodríguez de Quijano for the execution of defensive constructions [7], but its mass application did not come until 1884 with the introduction of Monier's patent by the engineer Francesc Macià i Llussà in Catalonia [6].

2.3. Interventions carried out on the Roman bridge of Alcántara

The bridge and its ensemble has been a Spanish National Monument since August the 13th 1924, but its heritage value had been recognised for centuries before that, as attested to by the large number of reports issued by the Real Academia de Bellas Artes de San in Madrid, the body responsible for monitoring the work carried out on the Alcántara Bridge due to its heritage value between the 18th and 19th centuries, in response to concerns about its state of conservation [15].

During its almost twenty centuries of history, the bridge has been depicted in models, such as García Galiano's model of 1772 [33], in sheets, such as those of Fernando Rodriguez of 1797, which, although they are planimetric, do not reflect important features of the bridge, such as the ridge-shape slope [34] or the Laborde of 1811, which, without having the delineation of the previous one, does reflect details such as the slope or damage to the parapet [35]. This provides an insight into the evolution of the bridge in the 18th and 19th centuries.

The damages it suffered gave rise to various interventions. The first, contemporary with the development of concrete and reinforced concrete, was that of Alejandro Millán to rebuild the fifth arch destroyed in 1810 during the War of Independence [36,37]. The previous intervention had been carried out by the military engineer Diego Bodick in 1778 [36], and this was the date when the first works on conglomerates appeared, but concrete as such had not yet appeared. The reconstruction of the damage in 1810 had several projects, the first in 1816 using two ashlar arches with the addition of a central pier; the next project was for wooden trusses in 1819; from 1831, an ashlar arch was planned for the building [38], project whose execution was directed by the engineer Alejandro Millán between 1856 and 1860 [39] and of which the original plans are on public display at the Fundación Iberdrola España in the Conventual de San Benito in Alcántara (Cáceres) [40]. The next and last documented intervention was the repair in 1969 of the undercutting of piers 3 and 4 with concrete [41].

In addition to the demolished arch, the bridge showed significant damage to the ashlars due to the deterioration of the granite, causing cracks and cavities [12,42]. In 1857, the Revista de Obras Públicas (Public Works Journal) reports on the progress of the work, indicating that cement from Vizcaya (Basque Country) is being used as a material to fill the holes in the degraded ashlars [42]. Other research locates the origin of the cement used in Zumaya (Basque Country) [43]. Even this review picked up the controversy in the newspapers over the repair of the triumphal arch [44].

In the repairs, according to the inspection report by the architect Peró, Millán took special care in trying to give "the same appearance as the old masonry" [12]. In the works report issued by Millán in 1859, he indicates that the work has two parts: the reconstruction of the arch and the repair of the rest of the damage, stating that "This second part has been as important, or perhaps even more important than the first, due to the delicate, difficult and dangerous work it has required" [12].

3. Research methodology

3.1. Introduction

The research methodology used to date the intervention was organised in five phases. In the first phase, a survey of the repairs and reinforced concrete interventions on the bridge was carried out using a 3D survey. Two technologies have been used for this, drone and laser scanner. In the second phase, the dating of the interventions was carried out using graphic bibliographic documentation extracted from historical archives: engravings, photographs and plates, including the plans of Millán's project [40]. In the state of the art, a temporal analysis has been carried out that includes dates prior to the demolition of the arch in 1810 to the present day, so this bibliographic search goes from 1854 to 1931, the last information on the bridge in the archives of the Royal Academy of Fine Arts of San Fernando. In the third phase, a comparative study is carried out between the information on the interventions documented in the first phase and the graphic information extracted from the second phase. The fourth phase analyses the professional careers of the engineers who may have worked on the bridge and their relationship with reinforced concrete. Finally, the scheme of reinforcements applied to the cornices is extracted, analysing their configuration with the knowledge of the technique at the time.

3.2. Geometry survey of bridge interventions using drone and generation of 3D model

In order to spatially locate the reinforced concrete interventions on the bridge and to be able to relate it to the information collected in historical sheets and photographs, a 3D model has been developed from two surveys. The first one was carried out in 2015 with a laser scanner, which, due to access limitations, showed areas with low definition. To resolve this issue, a drone survey was carried out in April 2017.

In this survey, more than 900 georeferenced photographs were taken, which, due to their resolution, allowed for a detailed observation of all areas of the bridge. The point cloud generated has an accuracy of two centimetres, which is sufficient to detect and delimit the repair areas and define the reinforcement diagrams.

In addition, two months after the drone flight, coinciding with a lower riverbed level, high-resolution photographs were taken of the cornice area.

Orthophotos of the upstream and downstream elevations of the bridge and of the central pier are obtained from both surveys, allowing a precise delimitation of the areas with interventions.

3.3. Dating of interventions through bibliographic analysis

Given the bridge's heritage value for more than three centuries, any intervention had to be validated and supervised by the Real Academia de Bellas Artes de San Fernando [12]. This institution was created in 1752 for, among other issues, the "protection of the arts and cultural heritage, particularly [.] architecture". Proof of its diligence are the numerous visits and reports that were carried out during the works in 1857 [13,14].

For this reason, an analysis has been carried out of the archives of the institution of the minutes, correspondence and reports on the control and monitoring of interventions in heritage works, such as the Alcántara Bridge, between 1854 and 1884.

This analysis is completed with the study of bibliographic and graphic documentary sources from the collections of the Spanish National Library, in particular the photographs taken by Clifford and Jean Laurent, who travelled around Spain photographing monuments between 1850 and 1863 and 1860–1870 respectively. Finally, high-resolution images of the plans drawn up by Millán to define the intervention on the bridge, exhibited in the Conventual de San Benito in Alcántara, provided by the Iberdrola España Foundation, are analysed [40].

3.4. Comparative study between 3D survey information and bibliographic analysis

Information from historical sheets, engravings, photographs and plans provide a valuable insight into the state of the bridge at a particular date. The most valuable information is found in photographs, as they are a faithful image of reality. Somewhat less accurate, but of great value, is the graphic information from project plans that must be validated with the reality of the photographs and current survey.

Therefore, in this phase, a comparative analysis is carried out of the graphic information on the bridge at different dates, with the 3D survey carried out of the reinforced concrete interventions. This analysis allows the dating of the interventions with high temporal and spatial accuracy.

3.5. Designers of the interventions and their relationship with reinforced concrete

The bridge is part of the infrastructure of the Salamanca to Badajoz trunk road [14], which became a transversal road under the 1851 law [45]. Therefore, any action on the bridge, as an element of the transversal road, was the responsibility of the provincial corps of civil engineers [46] In 1857, a Public Works Office was created in each province [47]. Therefore, the analysis focuses on the engineers of the Public Works Department of the province of Cáceres, to which the bridge belonged, and their professional activity until 1884.

3.6. Definition of reinforcement diagrams on the bridge

Based on the 3D survey and detailed photographs, a survey of the reinforcement diagrams that appear on the bridge is carried out. In order to determine their value as a step forward in the development of reinforced concrete, these diagrams are analysed in

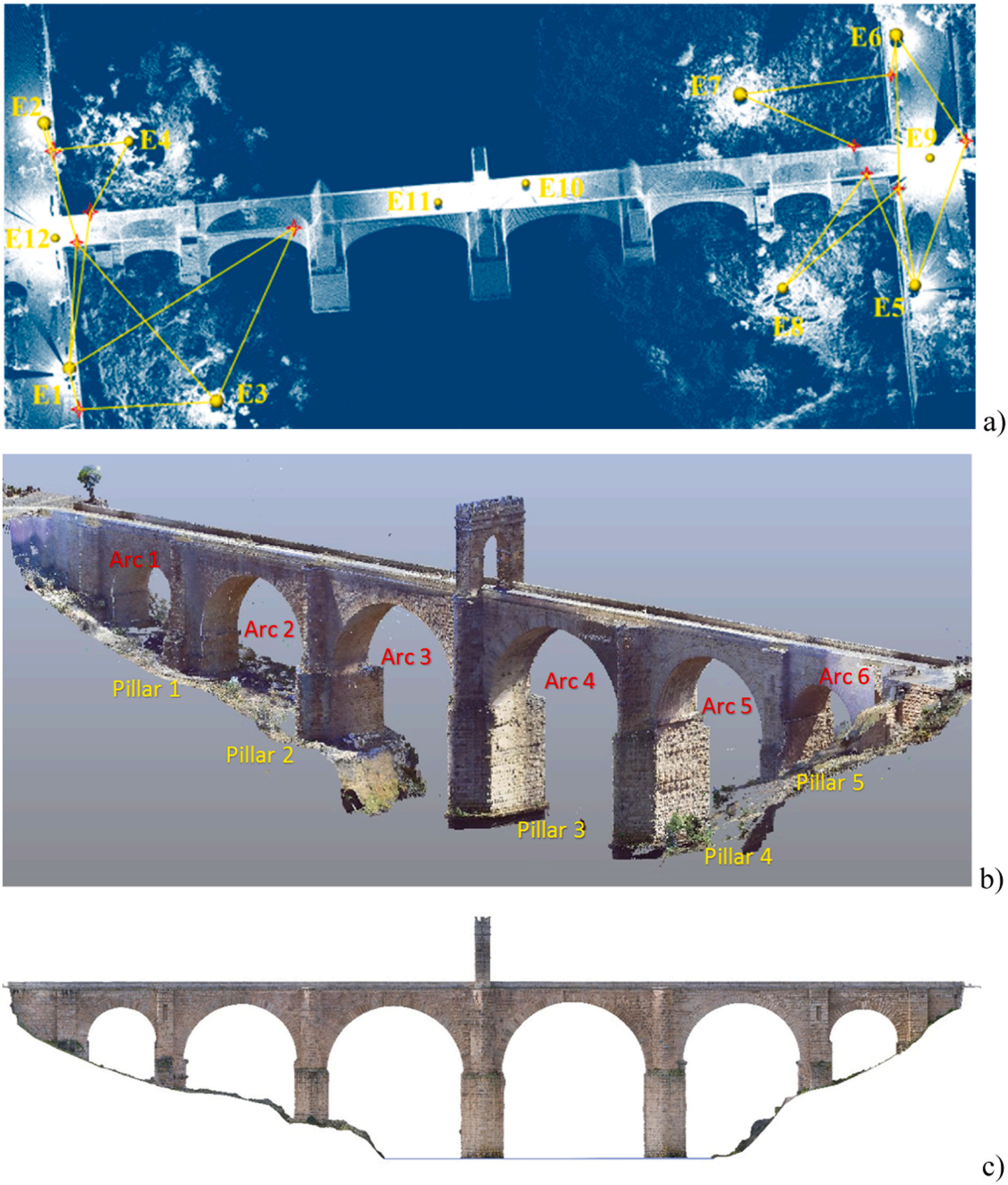


Fig. 1. Images of the surveys carried out a) 3D view of the point cloud made in the survey from the upstream right bank, with nomenclature of arches and piers (2015), b) 3D view of the point cloud and positions of the scanning points and c) orthophotography of the upstream elevation from the drone survey (2017).

comparison with the patents and reinforcement diagrams from the years 1854 [6]1865, first patent for reinforced concrete, and 1865, massive launch of Monier patents [5].

4. Results

4.1. Survey

Fig. 1 shows several images of the upstream elevation of the bridge obtained from the laser scanner survey and different photographs of intervention areas on the bridge. In the Fig. 1.a the positions of the laser scanner can be seen in the 2015 shot, which condition the definition of certain areas. In Fig. 1.b the 3D view of the 2015 survey with the nomenclature of arches and piers is shown. It shows areas with low definition, e.g. the soffit and spandrel of arch 4. In Fig. 1c, is the orthophotography of the upstream elevation of the bridge obtained from the 2017 drone survey, in which the accuracy is much higher than the previous ones.

Fig. 2 and Fig. 3. show the upstream and downstream elevations of the bridge, respectively, indicating the interventions on the orthophotos of the 2017 drone survey. Interventions with concrete and reinforced concrete are marked in red. Some examples of the interventions and reinforcements are shown in the detail photographs referenced in these figures. Although there are other areas of intervention, only those of the elevations and the central pier are shown here, as these are the damage survey plans carried out by Millán [40].

Therefore, in Fig. 2.a, the current damage to the left elevation of the buttress of the spandrel of the third or central pier can be seen, as well as the refilling of the ashlars. The detail image shows the stitched reinforcement on the right side of the third arch (Fig. 2.a.1). In Fig. 2. b and c reinforcement can be seen in the cornice of pier 3. In Fig. 2.d refilling and repairs appear in arch 4. Finally, in Fig. 2.e the reinforcement of the cornice of pier 4 is shown in the cutwater area and the inner face of the side of arch 4.

In Fig. 3. a detail of the refilling and a possible repaired ashlar in the buttress on pier 5 is shown. In the Fig. 3.b a change in the tone of the ashlars of the coping of pier 4 is observed, as well as repairs to the nozzle on the left side of arch 4 and mortar refilling of the interior of the arch and pier. In Fig. 3.c there is a break in the ashlar of the cornice of the shaft of pier 4 and reinforcement visible in the part of the cornice on the face parallel to the downstream elevation. Fig. 3d shows the repairs of the damage in the arch ring of the fourth arch. Fig. 3.e shows the current damage to the cornice of pier 3 in the repaired areas, leaving the reinforcement visible. Fig. 3.f and g present the mortar repairs of the arch ring of the third arch and the interior of the arch, as well as the repairs of the pier's cap of pier 2. Finally, Fig. 3h and i, show the work on the arch ring and the refilling of the spandrels of the second arch.

For the project to rebuild the fifth arch and the general rehabilitation of the bridge, Millán drew up plans with an exhaustive survey of the state of the bridge prior to the intervention [40]. In Fig. 3.a and b the upstream and downstream elevations are shown, respectively, highlighting in dark areas where ashlars are missing or where there are cavities that need to be repaired, as well as vegetation.

The elements with the most significant damage and which required the greatest intervention were the triumphal arch and pier 3 on which it rests. In order to detail them, Millán carried out an exhaustive survey of the central pier (Fig. 4.a and Fig. 5.a). They show the

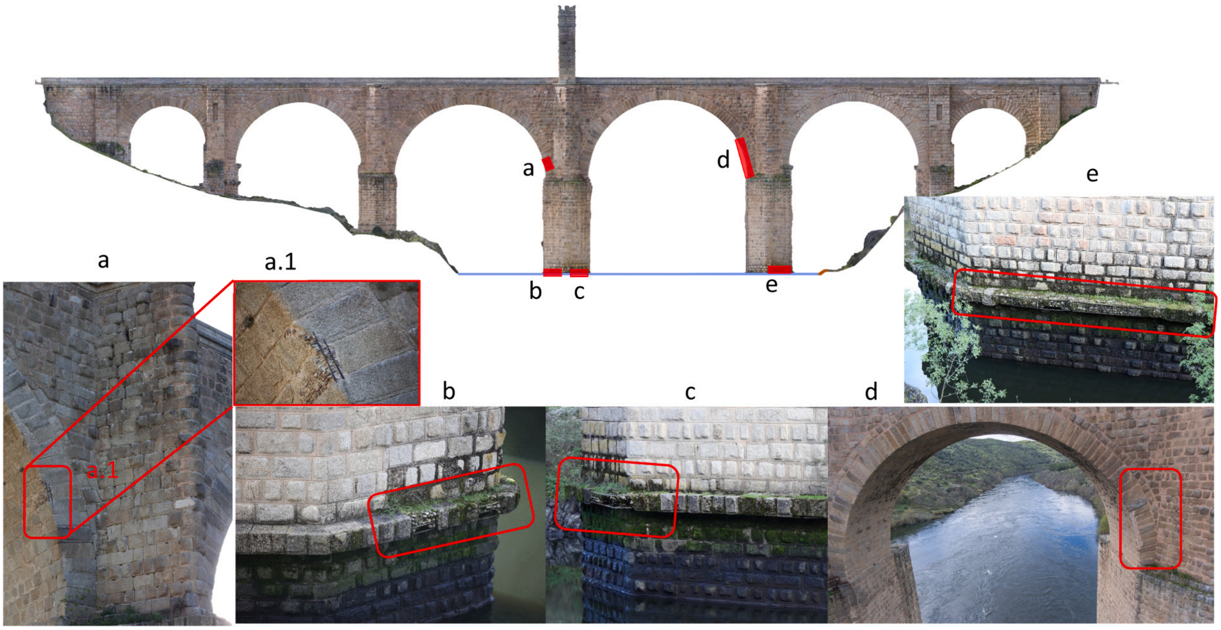


Fig. 2. The central figure shows the orthophoto of the upstream elevation in which some of the areas where concrete and reinforced concrete have been used are highlighted. Figures a) to e) show detailed images of these interventions.

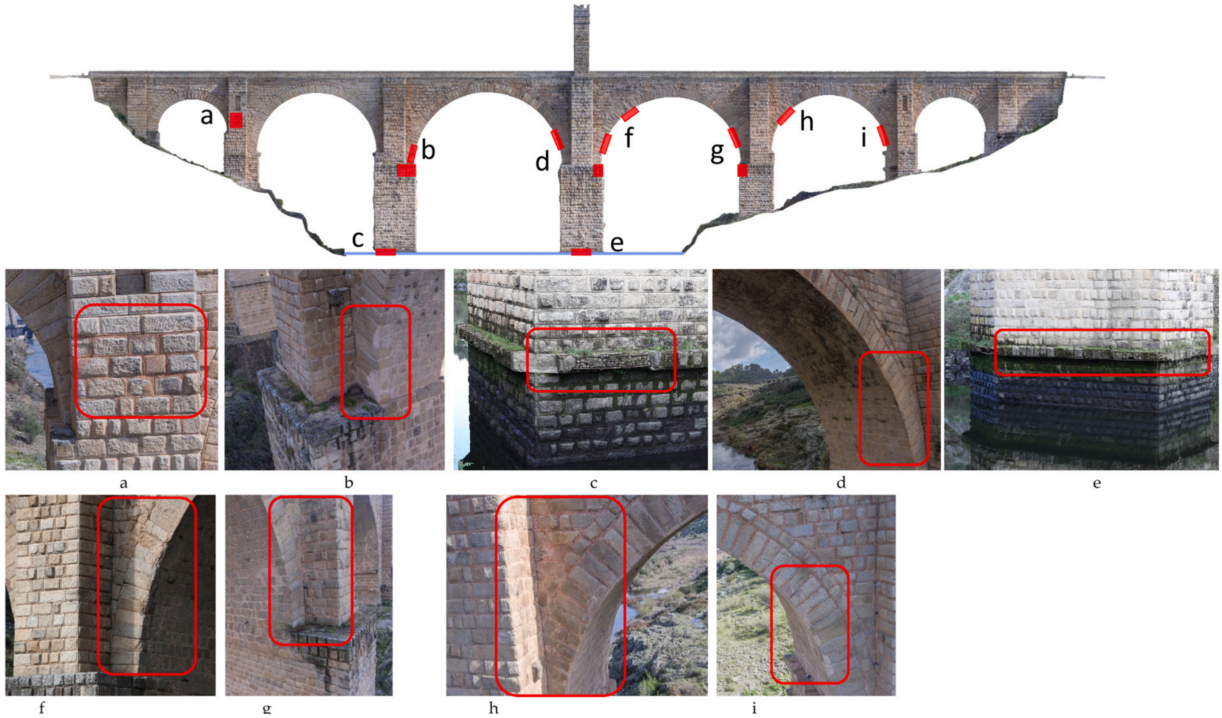
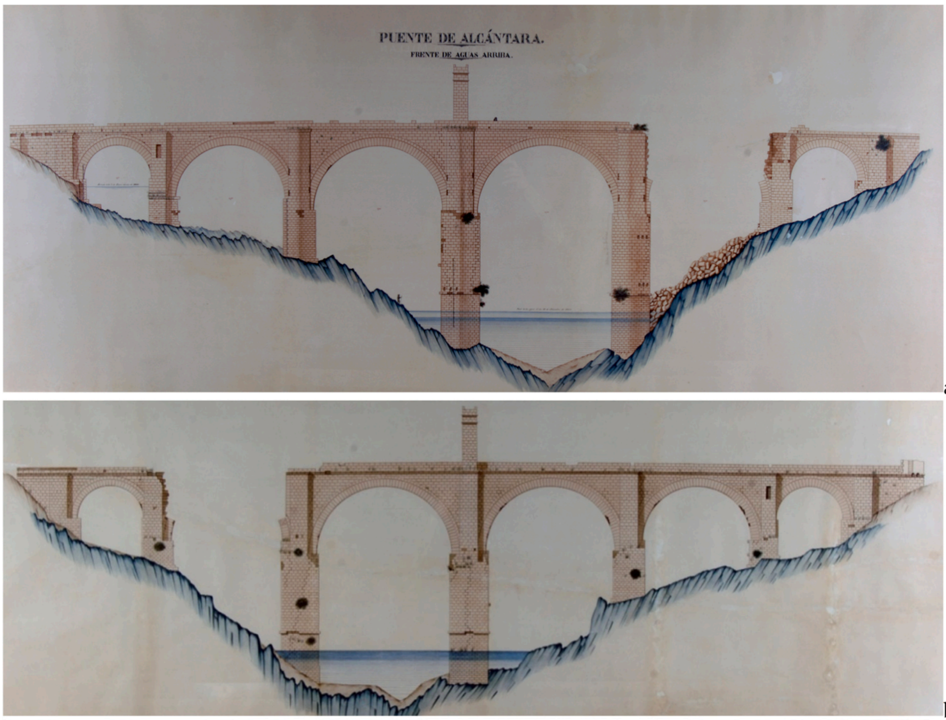


Fig. 3. The upper figure shows the downstream elevation highlighting some of the areas with concrete and reinforced concrete interventions. The lower figures a) to i) show detailed images of these interventions.



a)

b)

Fig. 4. Plans of the upstream elevation, upper, and downstream elevation, lower, with the damage survey by Millán [40].

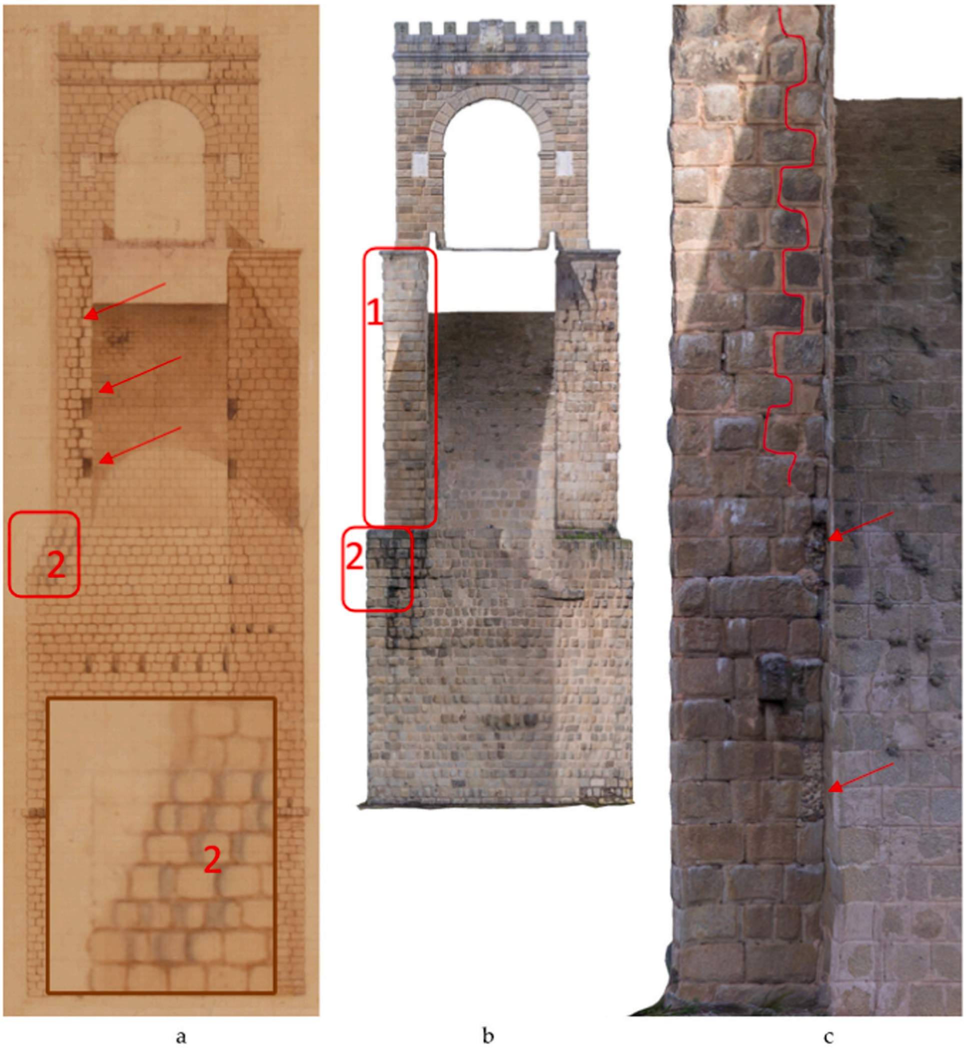


Fig. 5. Elevations of the central pier (3) as seen from arch 3: (a) survey by Millán [40], in zone 2, the pier cap heightening is faintly profiled (b) orthophoto of the drone survey and (c) detail of orthophoto with the repairs that have been carried out in zone 1 marked in (b).

cracks in the buttress in the spandrel area, as well as the symmetrical shaded areas on both sides, possibly points of support for the formwork used by the Romans. In Figs. 4b and 5b, orthophotographs of the 2017 survey are shown from the third and fourth arch respectively.

Regarding Figs. 4c and 5c, it is shown that the shaded areas in Figs. 4a and 5a have been filled with concrete, even identifying the type of aggregate used in the manufacture of the concrete.

Moreover, in zones 2 of both pictures (Figs. 4a and 5a), is observed in a fainter line which what has to be the final geometry of the pier cap, which is materialised in Figs. 4b and 5b.

The restoration work is reflected in a photograph taken in 1858 by Clifford [48], which Millán sent to the academy and which shows the state of the works in 1858, such as the dismantling of the triumphal arch (Fig. 6). It shows that the stepped section of the central pier cap (zone 1) has not yet been reconstructed, while that of pier 4 has been executed, both of which are shown in the plans prior to the work (Fig. 3.a and b). In addition, in Fig. 6 it can be seen that the cornices of piers 3 and 4 (zones 1 and 2) have been reconstructed with respect to what Millán reflected in his survey (Fig. 3.a and b).

On completion of the works in 1859 Clifford [49] also took photographs (Fig. 7). They show the reconstruction of the pier caps 3 and 4 and their cornices (Fig. 7.a and b). Another photographer, who travelled around Spain and took photographs of different monuments, among them the Alcántara bridge (Fig. 8), was Jean Laurent [50]. This photograph shows the same situation of the bridge as the one shown by Clifford in 1859, with the cornices repaired (1 and 2 in Fig. 8), the pier caps heightening (3 and 4 in Fig. 8) and repairs to the arch rings of arches 3 and 4 (5, 6, 7 and 8 in Fig. 8). The following documented photographs of the bridge date from 1925 [51] to 1929 [52], which do not show any additional interventions or damage to cornices or arches. The following photograph is from 1969 and was taken during the repair work on the foundations of piers 3 and 4, when the bed of the Tajo river dried up during the

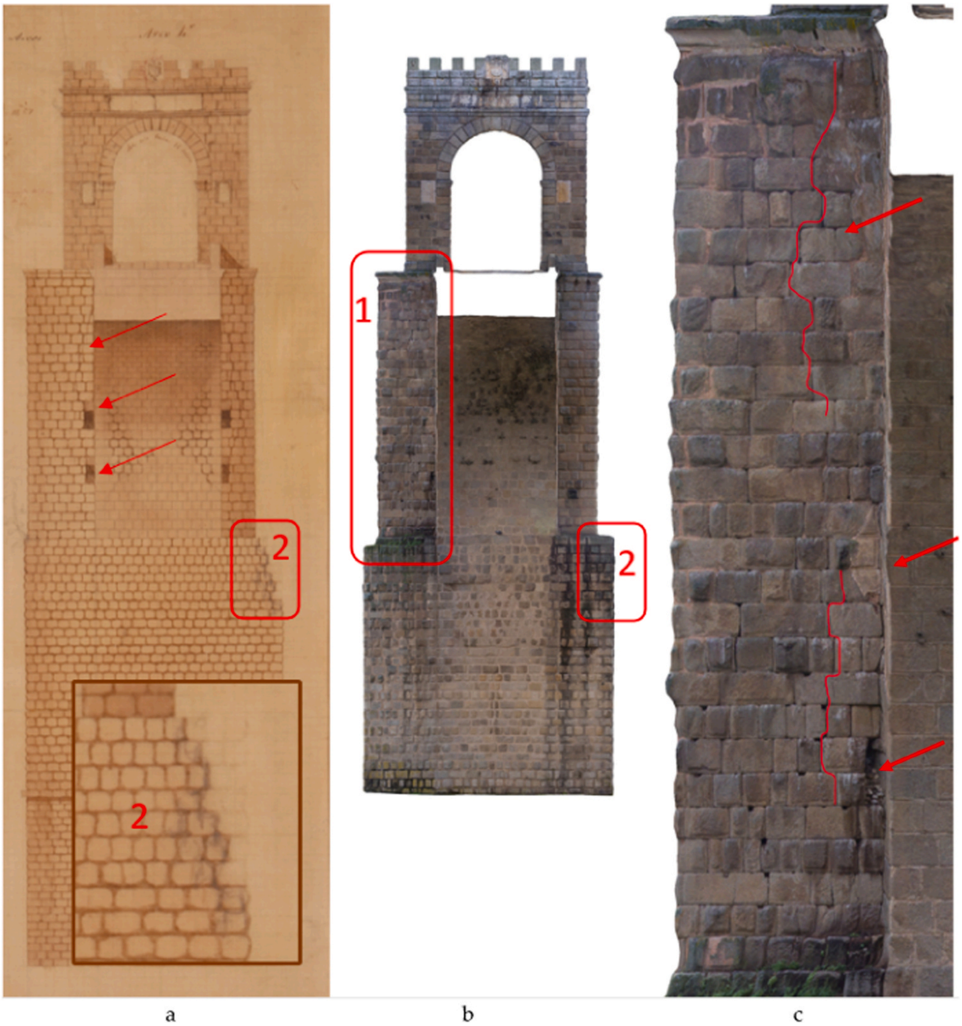


Fig. 6. Elevations of the central pier (3) as seen from arch 4: (a) survey by Millán [40], b) orthophotography of the drone survey and c) detail of orthophotography with the repairs that have been carried out in zone 1 of b).

filling of the Alcántara reservoir, whose dam is 600 m upstream from the bridge (Fig. 9, on the top). This figure shows the erosion of the ashlars in the lower part of pier 3, as well as the presence of reinforcement visible in the cornice of the pier, which, given the level of loss of concrete covering, denotes a significant age. Furthermore, comparing this photograph with current photographs (Fig. 9, on the bottom), the areas with reinforcement can be perfectly traced back to those currently observed and to the damage shown by Millán in his plans (Fig. 3.a and b).

4.2. Interventions in the archives of the Real Academia de Bellas Artes de San Fernando

A search of the digitised archives of the Real Academia de Bellas Artes de San Fernando with the terms "Bridge" and "Alcántara" yields 19 entries, grouped into two blocks of years. In the first one, which goes from previous dates to the construction of the bridge until 1868, reference is made to the reports prior to construction, being the last date in this block the one that refers to the economic reports of the settlements of the work [53].

The other block of dates in which these terms appear is between 1896 and 1931. Although outside the scope of this research, their content has been analysed, being documents which refer to the communications for the declaration of the bridge as a national monument.

4.3. Relationship between the engineer and reinforced concrete

Millán finished his studies in civil engineering in 1846, and began working on the works of Canal de Isabel II until 1856, when he was assigned to the Public Works Office in the province of Cáceres [54]. In the works on Canal de Isabel II he was under the direction of

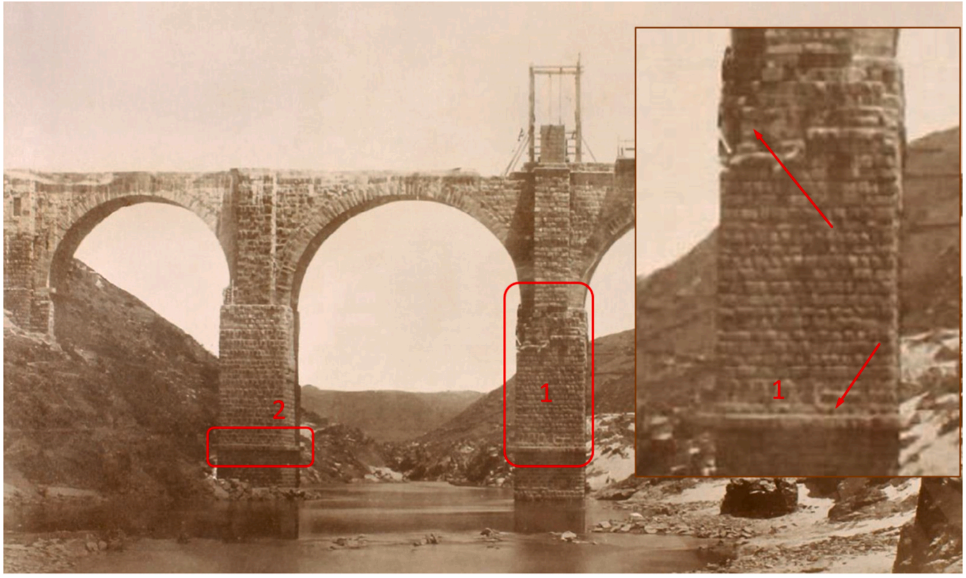


Fig. 7. Photograph of arches 4 and 5 as viewed from downstream by Clifford [48] and sent in 1858 by Millán to the Real Academia de Bellas Artes de San Fernando. In zones 1 and 2, the cornices have been repaired. However, the pier cap 3 in zone 1 is still unrepaired.

Lucio del Valle, who hired Charles Clifford to take photograph of the works of the Canal de Isabel II [46].

As soon as Millán joined the Cáceres headquarters, he took charge of the project to restore the Alcántara bridge, which had been in the timeline since 1831. In March 1858 he became Chief Engineer of the province until 1879, when he was promoted to second class Inspector General and moved to Madrid. As chief engineer in Cáceres he executed the General Road Plans of 1860, 1864 and 1877 [54].

4.4. Description of the reinforcement appearing on the bridge

The elements with the greatest presence of reinforcement and with a reinforced concrete configuration are the cornices of piers 3 and 4 (Figs. 2b, c and e and 3c and e). The other reinforcements have the function of stitching the ashlars together (Fig. 2.a.1).

In Fig. 10 the nomenclature of the types of reinforcement that appear is shown. The general scheme corresponds to the reinforcement of a binding reinforcement, with longitudinal and transverse reinforcement. Therefore, the reinforcement is made up of four longitudinal bars, the upper outer and lower inner ones (called type 1) and the lower outer one (type 2), with circular and square cross-section, respectively (Fig. 10.1 and 2).

The transverse reinforcement consists of horizontal bars of circular cross-section (type 3), which are considerably equispaced, joining the longitudinal bars and continuing up to the pier ashlars, both at the top and at the bottom (Fig. 10.3). These bars are continuous from the outermost longitudinal bar to the masonry. They are connected to the longitudinal bars by means of eyelets in the cross bars. In addition to these horizontal cross bars, there are flat inclined bars (type 4) (Fig. 10.4), which start from the upper outermost longitudinal reinforcement (type 1), to which they are joined by bending their end, and which, with an inclination of approximately 45º, are directed towards the pier masonry, passing over the lower, innermost longitudinal reinforcement (type 1). The number of bars of this type 4 reinforcement is approximately two for each type 3 cross bar. The last type of transverse bars is vertical (type 5). Only one is observed in this area, and it joins the upper and lower longitudinal reinforcement. Its section is flat and the connection with the longitudinal reinforcement is made by bending the end, the upper part inwards and the lower part outwards.

The reinforcement of the cornice of pier 4 (Fig. 11) does not appear as complete as in pier 3, but it can be seen that it follows the same scheme as that one with some differences that are indicated below. The number of type 5 bars is higher and therefore the spacing between them is smaller; type 4 bars are less numerous and therefore more widely spaced and the outermost lower longitudinal reinforcement is circular in section, unlike the previous one, which was square in section. Regarding type 3 and 4 reinforcement of the cornice of pier 4, they have been deduced from the information observed in the cornice of pier 3. To this end, it has been considered that in pier 3 the type 3 reinforcement has an eyelet at the end to join with the longitudinal reinforcement and that the upper and lower ones coincide on the same vertical. Based on this, in pier 4, the upper reinforcement type 3, which is not visible, has been marked on the basis of the lower ones, which are visible, and the type of connection with the type 1 reinforcement. On the other hand, given that in the cornice of pier 3 it has been verified that the connection of the type 4 reinforcement to the longitudinal reinforcement is by bending the end, the type 4 reinforcement in pile 4 has been marked on the basis of this fact, as its inclination was not observed.

It has not been observed in any of the visible areas of the cornice rebars whether the transverse rebars (type 3, 4 and 5) are connected to the ashlar or not, but it has been noticed that they continue from the innermost longitudinal rebar (Figs. 10 and 11b). Otherwise, the only mechanism for resisting the tension generated by the weight of the cantilever would be the tensile strength of the concrete in contact with the ashlar, which would not have supported it during the more than 150 years that have passed. In addition,

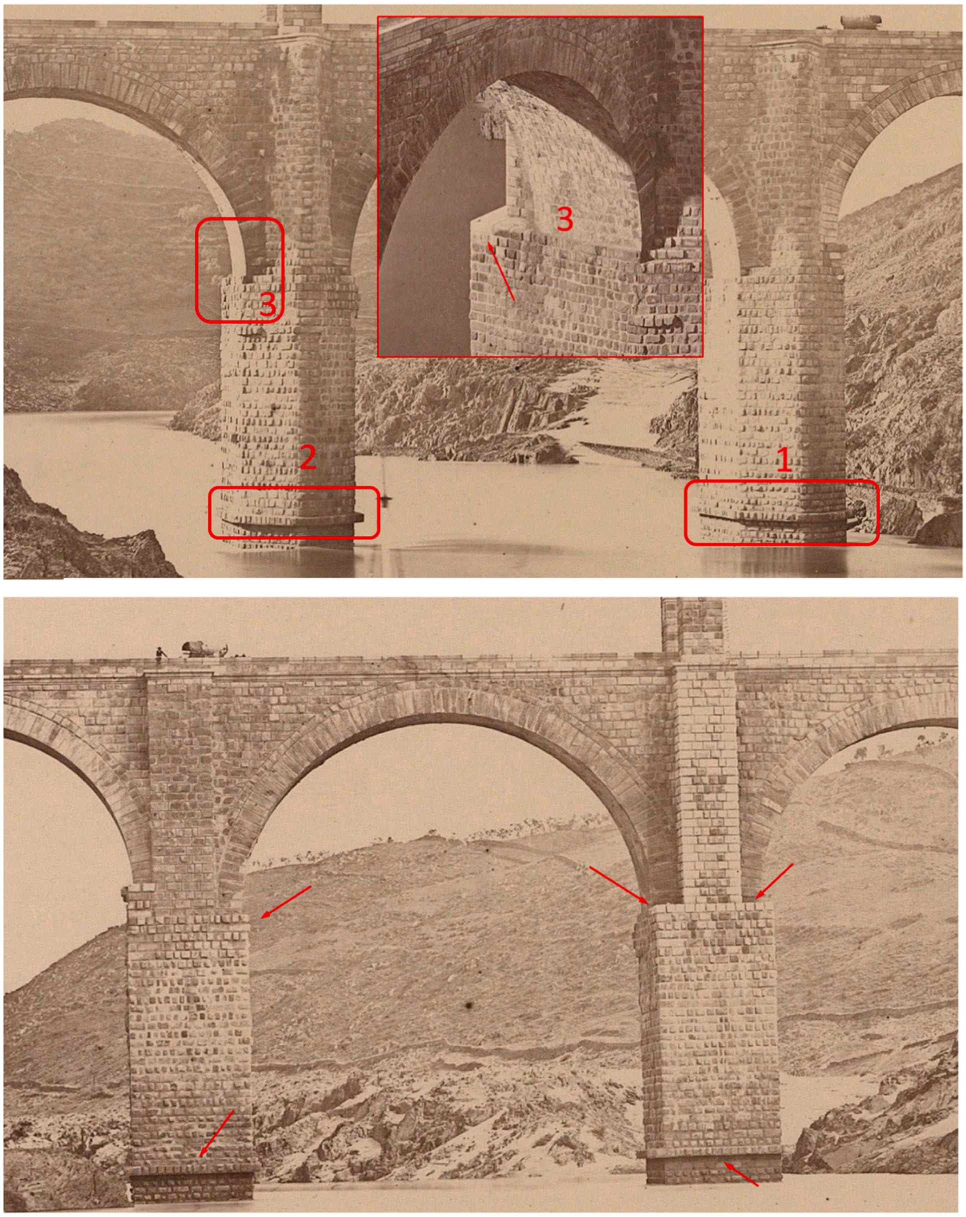


Fig. 8. Photographs taken by Clifford in 1859 of the finished works [49]: (a) upstream elevation and (b) downstream elevation, where all the areas marked on Millán's 1856 plans are repaired.

there are different areas of the bridge where the longitudinal reinforcement is anchored in the ashlar, for example in the Fig. 2a.1.

5. Discussion

In the comparative analysis between the orthophotos of the survey of the interventions carried out and the survey conducted by Millan [40], it can be identified that the areas where concrete interventions are observed as well as those with reinforced concrete (Figs. 2 and 3), are the same areas that Millán reflected in his plans (Fig. 3), and even the reconstructions of ashlars can be seen. For example, downstream in the arch rings of arches 2, 3 and 4 and also in the areas of the cornices of piers 3 and 4, where there are visible reinforcements.

The precision of Millán's survey plans is such that it reflects the exact number of ashlars. Thus, for example, of the two areas to be filled in that are shown in both buttresses of pier 3 (Figs. 4 and 5), the lower filling is on both sides six ashlars above the pile head. This precision can also be seen in the layout of the fissure and the grouting of the ashlars (Fig. 4), where there is currently some displacement between the ashlars of the fissures with respect to what Millán reflected.

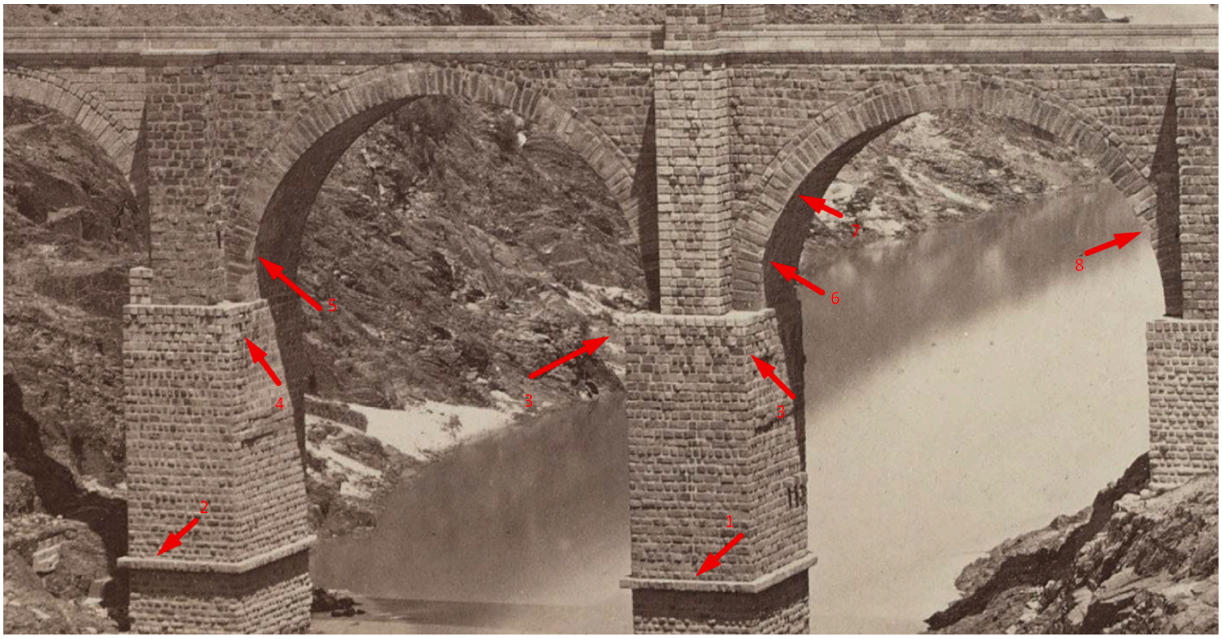


Fig. 9. Photograph taken by Laurent [50] of piers 3 and 4 and arches 3, 4 and partly 5, from downstream.

Concerning the areas of the pier caps 2, 3 and 4, Millán's sheets show the original staggering of the ashlars, marking their reconstruction with a faint line, an area which appears as reconstructed in the survey carried out (zone 2 of Figs. 5 and 6). This staggering had already been reflected in previous sheets, such as those of Laborde or in the model made by José García Galiano in 1772 [33].

From the analysis of the historical archives of the Real Academia de Bellas Artes de San Fernando of Madrid, the body responsible for monitoring heritage interventions [15], no intervention is documented after Millán's (1856–1860), the last document of this work being from 1868, relating to the final reports of the work [53]. This proves that Millán's was the only intervention until 1969 [41]. If repairs had been carried out in later years on the cornices, areas where the reinforced concrete has appeared, it would have required considerable auxiliary means of access, due to the fact that these piers are surrounded by water as they are in the natural course of the Tajo river. This would have required a project to be carried out, and its execution would have entailed the installation of cranes on the pavement of the bridge, precisely what Millán shows in his plans [40] and that shows the photograph taken by Clifford during construction in 1858 [48]. Furthermore, given Millán's responsibilities as Chief Engineer of the province until 1879, he would have been involved in this possible project. But even more, as vice-president of the Provincial Commission of Monuments of Cáceres belonging to the Real Academia de Bellas Artes de San Fernando [54], if any intervention had been executed on the bridge, Millán would have been aware of it as Chief Engineer, and through him the Commission, a matter that is not documented in the Real Academia.

And yet, in his 1859 report, Millán does refer to "the delicate, difficult and dangerous work" required for the repairs, given the height of the bridge piers, which is more than 40 m high [12].

In different repairs of the bridge, it can be seen how Millán tries to simulate the padding of the ashlars, for example Fig. 3.a and b or in zone 1 of the repair of one of the cavities in the cutwater of pier 3 (Fig. 5). This fact was already pointed out by Peró in his report of the 1858 visit [12]. Precisely because of this simulation, the distance at which the bridge has to be observed in some areas and the moss caused by the passage of time, the repaired areas have gone unnoticed. Even when the passage of time has caused corrosion problems in the reinforcements and these have appeared, they have not been observed, as in the case of the photographs taken by Calleja and the Sociedad Hidroeléctrica Española [55] of the repair of pier foundations 3 and 4 of 1969 [41]. Durán does observe the reinforcement [17], but he qualifies them as bad repair practice without going into their dating. Reinforcements also appear in the cornice of the images of the bridge pier investigated by Pizzo, but they are not mentioned [39]. On the other hand, Moreno Gallo does detect them, but dates them to the same date as the intervention carried out on the foundations in 1969 [18]. As it is shown in Fig. 9.a at that time the reinforcement was already in place, and with practically the same distribution as today (Fig. 9.b and c), therefore, in order to suffer this loss of covering many years must have passed, which is incompatible with the hypothesis that they were executed in 1969.

Therefore, in view of the above results, it is not wrong to think that the reinforced concrete was made by Millán during the reconstruction of arch 5, between 1856 and 1859. Specifically, the most probable date for the execution of the reinforced concrete is 1857, since according to the sheet drawn up by Millán with the breakdown of the execution of the budget and analysed by Rodríguez Pulgar [37], the largest cement budget was executed in that year, there is also a measurement of iron, but the tool iron is not differentiated from the iron that could have been used in the reinforcement. Furthermore, the photograph taken by Clifford in 1858 already shows the finish of the cornices [48].

Millán gained his knowledge and experience of concrete during his work on the Canal de Isabel II project, where this material was

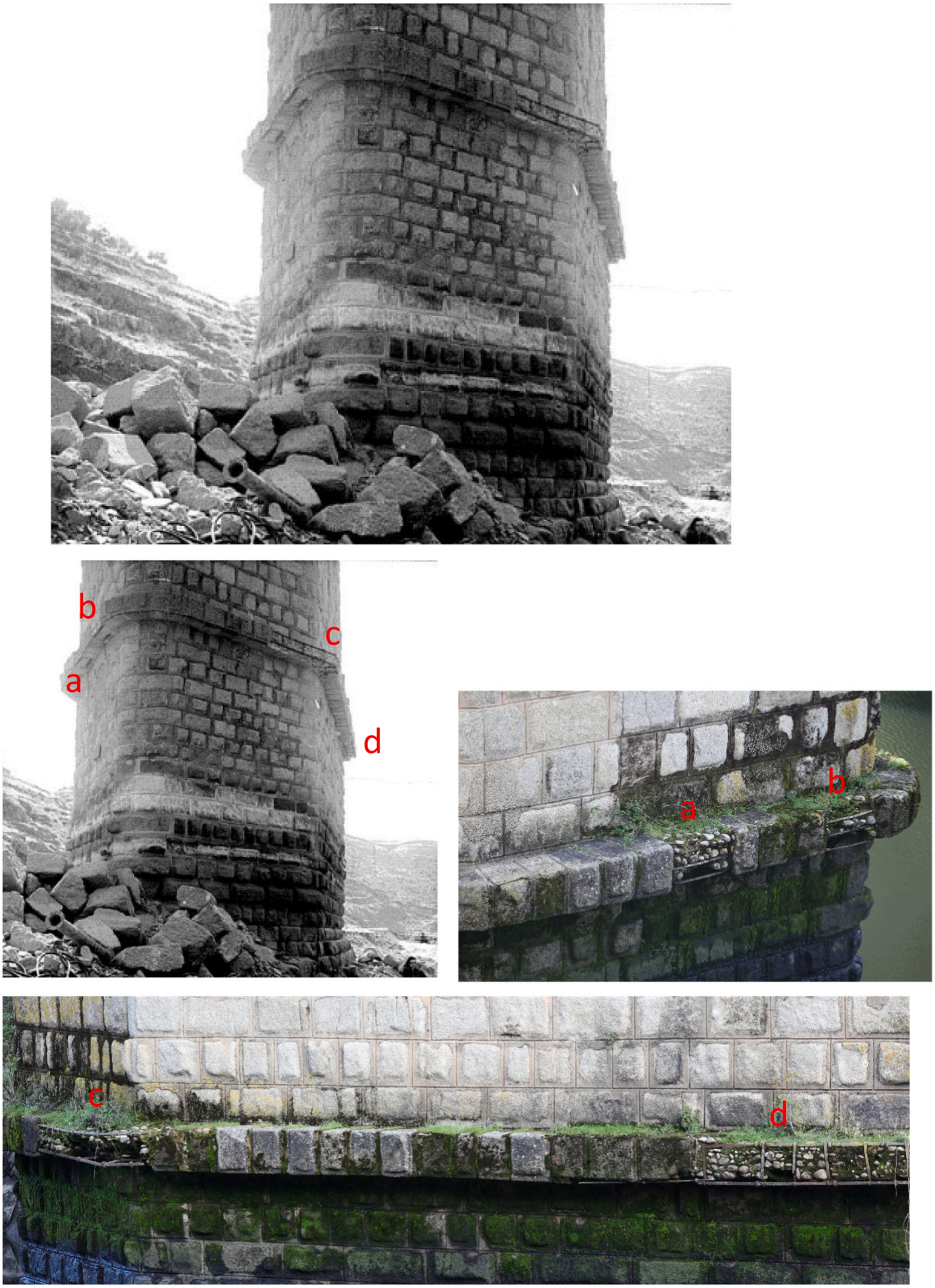


Fig. 10. The top left image is Calleja's photograph of pier 3 [55] in 1969 marking the areas where reinforcement was already present at that time. The top right is a current photograph of the left elevation of the shaft of the pier. The lower image is a 2017 photograph of the right elevation of the shaft of the pier.

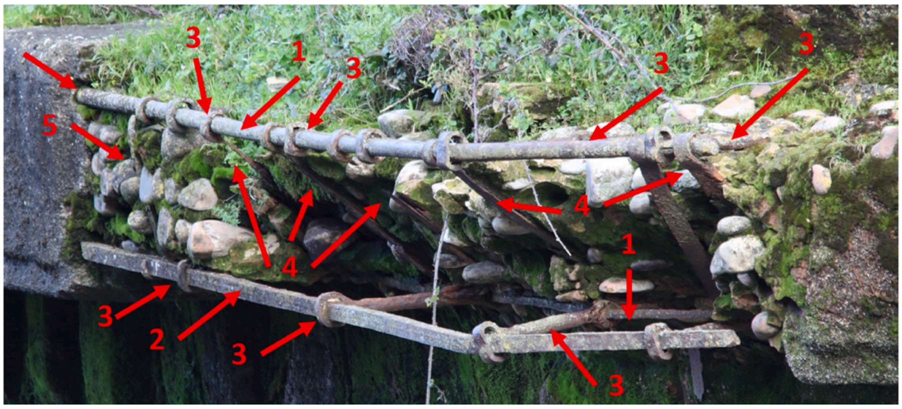


Fig. 11. Description of the reinforcement of the cornices of pier 3 with the designation of each type of reinforcement.

widely used [29]. Millán's knowledge of Clifford also dates from this period [46], fact that led him to be recruited to photograph the bridge during the works and once the work was completed. On the other hand, Millán, as a civil engineer, kept up to date with all the advances in engineering technology through the Public Works Journal. This would have enabled him to learn about their use in the repair of the piles of the bridge over the Urumea river [24], the visits to the Coignet factory [25] o the "artificial stone" manufacturing system, and in particular the moulding qualities of the Coignet system as indicated by Saez and Montoya [26]. This ease of moulding was used by Millán to simulate the padding of the ashlars and, chiefly, to be able to build the cornices, which are cantilevered elements.

Given the evolution of cement in Spain [4], the concrete used would have natural cement as a binder, since artificial cement was not used industrially until the end of the 19th century [5,21], contrary to Rodriguez Pulgar's statement, which reflects that it would be Portland [13]. Specifically, the origin of the cement would be Vizcaya or Zumaya, both in the only province of the two producing

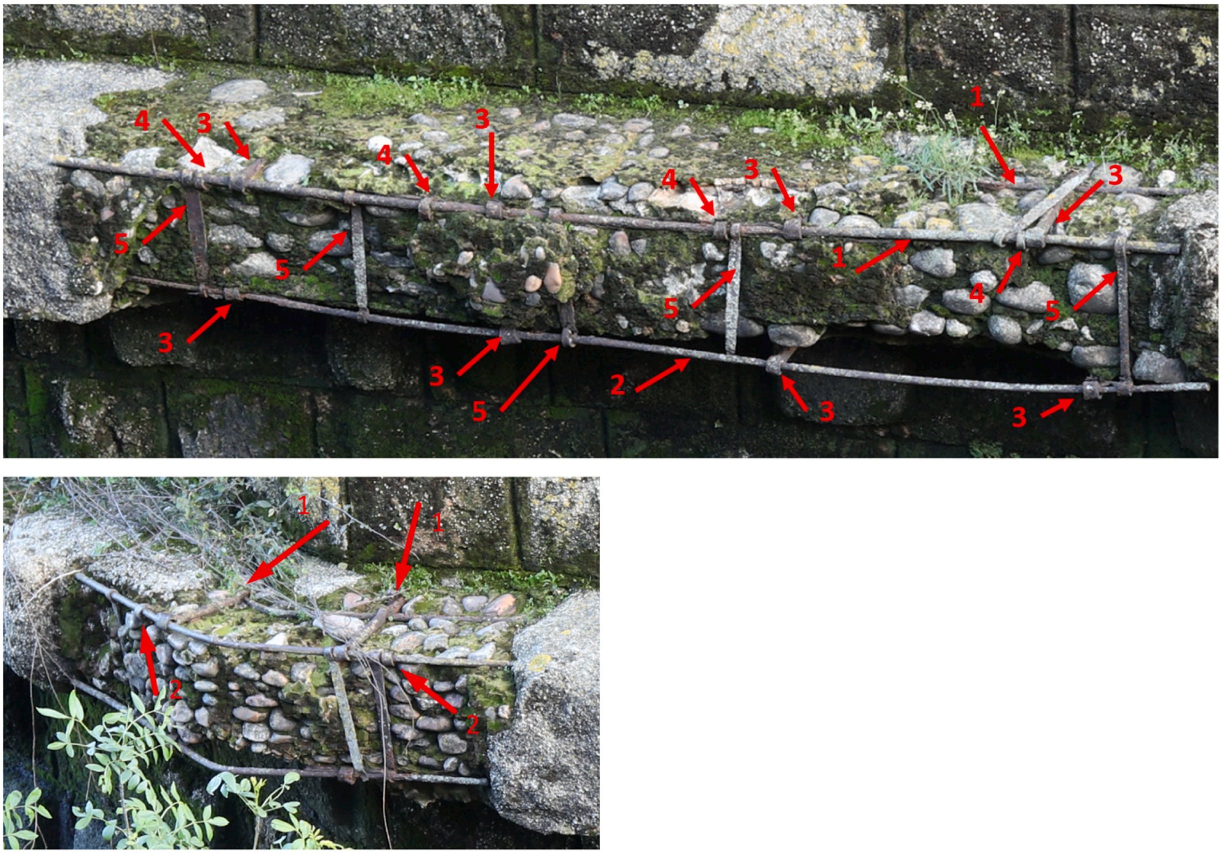


Fig. 12. Description of the reinforcement of the cornices of pier 4 with the designation of each type of reinforcement in the straight work a) and in the break zone b).

provinces in Spain which exported nationally and internationally [20], being the Zumaya factory of 1852 [7], a few years before the start of the repair work on the bridge. This is corroborated by information in the Public Works Journal, which indicates that cement from Vizcaya is being used to repair ashlars [42], without mentioning the use of reinforcement in these repairs.

The work on the bridge was completed in 1859, three years before the Bellsolá bridges in Soria were built in concrete [27]. Bellsolá points out how common knowledge of concrete was at that time, but not so much its use, as it was not implemented again until ten years later in the repair of the Luchana bridge, due to the lack of validity of the traditional materials [7], the same reason that led Millán to use it twenty years earlier.

As far as reinforced concrete is concerned, the only reference to its first application in Spain is in a text by the military engineer Rodríguez de Quijano in 1868 without indicating when and where it was applied [7], nine years after Millán's application in Alcántara.

The reinforced concrete solution used by Millán shows a understanding of the new material ahead of its time. Thus, for example, Lambot's patent of 1855 includes a layer of criss-crossing bars [31] for buildings, but does not define the connection between different levels, as Millán does when he proposes a system of longitudinal and transverse bars on two levels, joined by vertical bars, which configures a reinforcement very similar to the current ones of a binding reinforcement or a beam (Figs. 10 and 11). Millán's concepts are closer to Wilkinson's patent of 1854, in which the bars are arranged in the areas where tension is present [32] but in buildings. In order to connect the cornice with the pier, Millán arranges type 3 upper cross bars that fix the cantilever and reach the outermost longitudinal reinforcement from which the type 4 inclined bars come out (Figs. 10 and 11) designed as struts to take up the compression of the connecting rod generated by the cantilever momentum.

Regarding the section of the reinforcement, it combines, without any apparent criterion, bars of circular section with others of square and flat section, with the circular ones predominating for the horizontal ones and the flat for the vertical and inclined ones. It was this type of section that Monier, six years later, included in his patents [7]. In these patents for beams, the idea of a beam with longitudinal and transverse reinforcement does appear, but it was seven years after Millán applied it, and more than twenty years before reinforced concrete was used on a massive scale in Spain with the arrival of Monier's patent by Maciá i Llussá [6].

Millán's application of reinforced concrete is an absolutely important advance on the birth of reinforced concrete in Spain and internationally, besides on the compression of this new material. In the case of Spain, it is the first example of the application of this new material, moreover in a rehabilitation project, ten years ahead of the first writings on the application of reinforced concrete in Spain [7]. Furthermore, the context in which it has been used is in a rehabilitation project, making it the first documented, as it is twenty years before the first documented application in bridge rehabilitation to date, which was the intervention on the Luchana bridge, where concrete, not reinforced concrete, was used [7] (Fig. 12).

With regard to the effect of the repair on the structural behaviour, it should be pointed out that as it was located on the cornices, it did not affect the overall safety of the structural bridge [9], the only local effects being due to the connection of the reinforcement to the ashlars (Fig. 10).

The reinforced concrete detected shows significant damage, and it is not possible to determine the damage due to the durability of the concrete and the damage caused by the action of water erosion during the floods [9].

Given the heritage value of the bridge, the limitation of this study is the access and the taking of samples to analyse the state of the reinforced concrete and the evolution of its strength and durability characteristics over time. This research will give the reinforced concrete intervention heritage value, facilitating future research on the materials and their durability, not only in the areas where it is visible, but also in those areas where, due to the mimetisation of the concrete with the ashlars made by Millán [12], it is not easy to detect with the naked eye.

6. Conclusions

The Alcántara Bridge is one of the most important Roman bridges in the world due to its size and state of conservation. Since its construction almost two thousand years ago, it has suffered damage because of the passage of time and human action, and therefore, it has required restoration work. During an inspection of the bridge, areas with reinforced concrete were observed, which, due of its typology, suggested that it was a very old intervention. In order to date this intervention, a comparative analysis was carried out between the current situation, the survey plans that Millán made for the repair of the collapsed arch, the sheets from different periods and photographs from different dates. In addition, research has been carried out in the archives of the Real Academia de Bellas Artes de San Fernando on other possible restoration works on the bridge in the 19th century.

Following this research, it can be concluded that the areas of the bridge with reinforced concrete were built during the restoration work carried out by the engineer Millán (1856–1860). Specifically, the application of reinforced concrete was carried out during the year 1857.

Millán's application of reinforced concrete represents a very important advance in the knowledge of the birth of reinforced concrete in Spain and internationally. In the case of Spain, it is the first example of the application of this new material, also in a rehabilitation project, ten years ahead of the first writings on its application in Spain. In addition, it has the particularity of being used in the rehabilitation of a bridge, twenty years before of what would be carried out on the Luchana bridge, the first documented application to date, in which, moreover, only concrete was used.

On an international level, it is a fundamental discovery of how the new material was conceived, because, although there were patents since 1854 applying resistant concepts of the new material, the conception proposed by Millán is ten years ahead of that of Monier for beams, which was the most developed in Europe and the first to be used in Spain, but already in the 1880 s

This shows Millán as the precursor of reinforced concrete in Spain and a pioneer worldwide in the use of the new material.

Declaration of Competing Interest

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Data availability

No data was used for the research described in the article.

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