TERRESTRIAL LASER SCANNING AND NON PARAMETRIC METHODS IN MASONRY ARCHES INSPECTION

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ABSTRACT:

Historical bridges are not only elements of our cultural heritage but also civil engineering structures. They are usually researched with destructive technologies, but their geometry is being more and more used in order to perform structural analysis, and this way it would be possible to make a diagnosis of their state of conservation. Laser scanners collect a great amount of data that allows building accurate 3D models that can be then used to make dimensional and structural analysis of these civil structures.
This paper presents a geometrical research carried out in the Roman Bridge of Segura (Spain). A 3D model of the bridge was built by means of a terrestrial laser scanner, and then its geometry was analyzed by two different methods. Firstly, by means of a direct way, a graphical analysis in CAD systems was performed and the main geometrical parameters were obtained and evaluated; secondly, using statistical nonparametric methods, developed for this kind of structures, it was possible to identify pathologies on the structure thanks to the measurement of deformations in vaults by means of a symmetrical study. The results of both methods are presented in this work, and then they are compared and discussed.

1. INTRODUCTION

Historical Bridges are consolidated as key elements in order to facilitate the population movements and also the economical and cultural development of countries. This fact is present since the Roman period by means of the construction of Roman pathways where bridges played an important role as join elements. For that reason, they are the artefact designed by the engineering science in order to solve the obstacles existing in the Nature, having an important role as communication and transportation infrastructures. The constructive typology in the beginning of time was the masonry arch bridge. This way it was being consolidated as heritage legacy of the origin of the engineering discipline, with a special value in the ancient world and in particular in Europe and Spain.

Historical bridges normally have some vulnerabilities that require a special attention. The presence of heavy traffic, direct exposure to floods, seismic movements and also the possible defects in the construction of the bridge make that the civil engineering should pay attention in this kind of infrastructures. Thanks to the implication of several world organizations for the preservation and conservation of the cultural and historical heritage (UNESCO or ICOMOS, 2001) non destructive methodologies have been promoted for the documentation of historical monuments and also for the evaluation of their state of conservation.

Masonry bridges are civil engineering constructions that usually have a complex geometry. This complexity makes the application of the measurement devices traditionally used in heritage documentation not feasible. Building peculiarities, location, structural behavior, etc., are factors that make feasible the employment of new image based techniques, which also allow the documentation of this kind of constructions without direct contact.

Unfortunately, many technicians currently involved in heritage conservation still work on the documentation of monuments in a rather traditional way. However, in the last years close range photogrammetry and laser scanning techniques have been applied to bridges inspection works, as well as other architectural and archaeological tasks. Some examples can be found in Arias et al. (2007); Jauregui et al. (2005) and Riveiro et al. (2008).

The collection of 3D coordinates of millions of points over an object surface in few minutes represents a powerful tool to survey civil engineering structures, where the geometric precision and photorealistic details are also essentials. In the last years this technology has been proved in engineering structures, where measurement and monitoring of deformations are usually ejected (Zogg and Ingensand, 2008; Lovas et al., 2008, and Qiu and Wu, 2008). All the results reinforce the validity of the laser scanning technology as a useful tool in civil engineering structures. Furthermore, the "time of flight" (TOF) laser scanner offers the possibility of obtaining the radiometric information of the point clouds, making them to be optimal to survey heritage elements. In addition to this, the integration of 3D models created from laser data with Ground Penetrating Radar offers interesting tools in bridges analysis (Solla et al., 2009).

Definitely, it is a fact that historical bridges should be researched by means of reliable methods; also, taking into account that in arch bridges the structural stability is, in essence, a function of their geometrical shape (Guastavino, 2006). Consequently, changes in the geometry comparing to the

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original design can compromise their stability, so that an excessive deformation inevitably results in collapse.

This article presents a geometrical research carried out in the Roman Bridge of Segura (Spain). A 3D model of the bridge was built by means of a terrestrial laser scanning, and then its geometry was analyzed by two methods. Firstly, by means of a direct way, a graphical analysis in CAD systems was perform and the main geometrical parameters were obtained and evaluated; secondly, using statistical nonparametric methods, developed for this kind of structures, it was possible to identify pathologies on the structure thanks to the measurement of deformations in vaults by means of a symmetrical study.

2. THE SEGURA ROMAN BRIDGE.

The survey presented in this paper was performed in the Roman Bridge of Segura, which is located in the frontier between Spain and Portugal, on the West of the Iberian Peninsula.

It crosses the river Eljas, a frontier river which is an affluent of the Tajo River, the longest Spanish watercourse. Over this bridge, a national road communicates the councils Piedras Albas (Province of Cáceres, Spain) and Segura (Province of Castelo Branco, Portugal).

Figure 1. Downstream view of Segura Bridge.

Many authors place the origin of this bridge in the Roman Period. Recent studies (Duran, 1996) reveal that medieval ashlars and several marks typical during this period are present in the building. This fact indicates that Segura Bridge only conserves the original Roman construction in the final arches, abutments, and pillars. The fabric of these structural elements is the typical ashlars with hewn rims.

According to Duran (2005) the central arches of the bridge have been rebuilt in the second middle of the XVI century, after a collapse caused by an important growth of the river flow in 1565. This way, in the bridge reconstruction, the roman fabric and new masonry, imitating the roman hewn stones, were used.

In the reconstruction works the drainage area was increased making central arches higher. Consequently, the original horizontal grad line was converted in a great sloped platform. A posterior reformation in the bridge is documented by Duran (2005), when the spandrel walls were elevated and the grad line was horizontal again.

Segura Bridge is one of the best Roman Bridges conserved in the Iberian Peninsula. It is also considered a replica of the nearby famous Alcántara Bridge, recognized as one of the best Roman Bridges built in the world by the Romans. It is made of five arches and four pillars with triangular cutwater on the upstream side.

3. 3D MODELING OF SEGURA BRIDGE

3.1 Instrumentation

The point clouds acquisition was performed with a long range time of flight TLS Riegl LMS-Z390i. This scanner measures distances in a range of 1,5 to 400 meters. The nominal accuracy is 6mm, 50 m in normal illumination and reflectivity conditions. It offers a great resolution with a minimum angle stepwidth of 0.002º, being 0.2º the maximum. This instrument has a field of view of 360 sexagesimal degrees in the horizontal plane and 80 degrees in the vertical plane and a rate of measurement between 8000 and 1000 points per second. The operations of recording point clouds with this RIEGL scanner are controlled with Riscan PRO Sotware (Riegl©).

A Nikon D200 digital camera, with a CCD sensor (Charged Coupled Device), DX format with a resolution of 10.2 million pixels was mounted on the laser in order to obtain the RGB information. The CCD sensor surpasses CMOS sensors in dynamic range (relation between saturation level and threshold for the signal 7 reception) and in terms of noise. The Nikon D200 camera is equipped with a matrix color measurement system 3D II (AE) with an exhibition sensor/color RGB of 1,005 pixels. The lens used for the measurement was a great angular Nikkor 20 mm f/2.8D high frequency, digital angle with a view of 70 degrees.

A total station Leica TCR 1102 was employed in the topographic survey. This instrument is equipped with a laser distanciometer, with a range measurement of 80 meters in standard illumination conditions.

3.2 Data acquisition

In order to obtain the geometry information of the whole bridge, several scan positions around the building were necessary. In total, seven positions were finally necessary, and the point clouds acquired from each station were then aligned thanks to the location of flat reflecting targets in different planes in the surroundings.

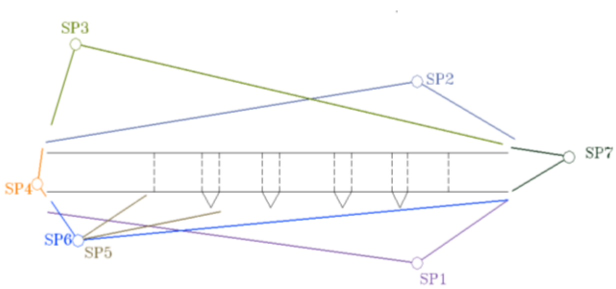

Figure 2. Different scan positions and field of view from each station around the bridge.

Once the scanner was positioned, the first task consisted of calibrating the camera mounting, this is to calibrate the camera sensor position regarding to the laser scanner coordinate system. That was made through the identification of seven common reflecting targets between the point clouds and the photographs taken with the camera, distributed around the whole field of view of both instruments. This way, the transformation matrix was calculated for the camera coordinate system with a residual distance mean less than 1 pixel.

The scanning procedure consisted of measuring two kinds of point clouds in each scan position. Firstly, an overview with low resolution (0.2º) was recorded; this information was used to create a digital terrain model of the bridge surroundings. Then, a detailed scan was captured in order to have an accurate geometry of the bridge. The scanner resolution was fixed in 0.02º (which implies around 1 cm separation between consecutive points on the bridge surface in a distance of 30 meters). The time consumption mean was around 15 minutes per detailed scan.

Having the bridge leveled with high precision is essential in order to analyze the vaults symmetry. For this reason, a topographic survey was performed, and the coordinates of the center of each target were measured with a total station. This task allowed us not only to level the bridge, but also to improve the registration of different scans.

3.3 Point clouds processing

After the field works finished, all the acquired information was processed in Riscan Pro software. The first task was the registration (alignment) of the different point clouds, with a final error of 8 mm. Then all the points that did not belong to the bridge surface were manually deleted.

Finally, the global point cloud of the bridge was composed of 8.296.667 points. In order to obtain a regular density of points defining the surfaces, an octree filter (Wang and Tseng, 2004) was applied to the global point cloud. This process reduced the density of the point cloud to 1259148 points (Figure 3).

Figure 3. Global point cloud of the Segura Bridge.

The point cloud of the second vault was isolated in order to apply the non parametric algorithm to this structural element. A total of 32282 points defined the surface of the second vault.

3.4 3D Polygonal model

Once a regular density of the points of the bridge was obtained, the next step consisted of converting the point cloud to a 3D model based on surfaces. This operation was performed by means of a planar triangulation, based on the Delaunay triangulation. This procedure was executed in Riscan Pro software.

The next task in this modelling process consisted of adding the realistic texture to the model surface. For this task, the photographs acquired with the Nikon D200 camera were used. Then, orthophotos of the main planes of the structure were created to be used as a complement in the metrical analysis.

In order to analyze the 3D model of the bridge by means of CAD systems, it was necessary to create sections of the structure. In this sense, a total of 115 equidistant sections were created from the 3D model and exported to a CAD system.

4. RESULTS

4.1 CAD Analysis

The sections created in Riscan Pro were exported as dxf files to a CAD system. There the maps of the structure were outlined with the help of orthophotos. Figure 4 shows the orthophoto and the plane of the upstream wall of the bridge, where the arches' voussoirs were also drawn.

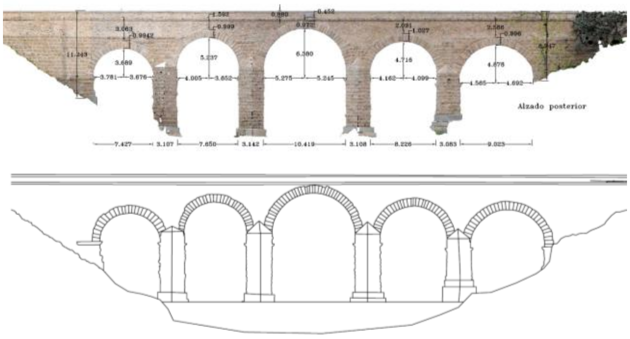

Figure 4. Orthophoto and plane of the upstream wall.

After the modelling process, the metrical exploitation consisted of the following sections:

- Arches analysis
  - Typology
  - Symmetry
  - Arch ring thickness/span quotient
- Pillars
  - Inclinations
  - Skew
  - Slenderness
- Walls
  - Inclinations

A summary of the main geometric parameters of bridge's elements is shown in Table 1. It is important to mention that in the nomenclature for bridges, arches are consecutively numbered from left to right from the upstream side.

Arch	Span	Rise	Arch ring thickness	Pillar	Wide
1	7,492	3,667	0,994	1	3,107
2	7,657	5,237	0,999	2	3,142
3	10,520	6,381	0,972	3	3,108
4	8,261	4,716	1,027	4	3,083
5	9,257	4,878	1,104		

Table 1. Main geometric parameters of arches and pillars.

The Segura Bridge is supporting a road, so it is complicated to know exactly where the beginning and the end of the bridge are, and consequently its total length. But, if we consider that the total length of the bridge is defined by the parapet length, the bridge has a measurement length of 87.5 meters.

4.1.1 Arches analysis

Typologies

Knowing the typology of an arch we can identify when the bridge was constructed, or restored (Duran, 2003). In this sense, semi-circular arches are typical from the Roman period, the gothic arches were the predominant arch typology during the medieval period, and elliptic or segmental arches date from later times. Based on these approaches, the arches of Segura Bridge should be round arches and consequently the quotient between the arch rise (R) and the theoretical radius of the circumference (Rc) should be 1. In Table 2 the quotient of each arch in the upstream wall is shown.

Arch	Rc (meters)	Rise (meters)	R/Rc	Typology
1	3,793	3,690	1,028	Round
2	3,925	5,237	0,749	Segmental
3	5,194	6,381	0,814	Segmental
4	4,178	4,716	0,886	Segmental
5	4,643	4,878	0,952	Round

Table 2. Typology of arches depending on the Rise quotient.

Results confirm that the restoration was executed in the XVI century (Duran, 2005). The first and the fifth arches conserve the Roman metrics, the three central arches were elevated but the rise of the arches was reduced regarding to the semi-span.

Symmetries

In order to analyze the symmetry of each arch, and consequently the possible geometric (structural) changes in relation to the original construction, a simple mathematical equation was set out: in a symmetric arch, the quotient between the left semi-span and the right semi-span is 1. If this proportion does not come true, the asymmetry percentage is calculated according to equation 1.

$$\%_{asymmetry} = \frac{|SL - SR|}{S/2} \times 100 \quad (1)$$

where SL = left semi-span
SR = right semi-span
S = span

According to this expression, asymmetries were calculated for each arch in table 3. In order to define the axis of symmetry, a vertical straight line was drawn from the highest point of the intrados.

Arch	Span (m)	SL (m)	SR (m)	SL/SR	$\%_{asymmetry}$
1	7,457	3,781	3,676	1,029	2,816
2	7,657	4,005	3,652	1,097	9,220
3	10,520	5,275	5,245	1,006	0,570
4	8,261	4,162	4,099	1,015	1,525
5	9,257	4,565	4,692	0,973	2,744

Table 3. Asymmetry percentage in the arches.

Results show that four arches are more or less symmetric, but the second arch has an evidence for an asymmetry, almost a 10%.

Arch ring/spam quotient

Another dimensional parameter in masonry bridges is the arch ring thickness regarding to the span. Table 4 presents the results obtained in the arches of Segura Bridge.

Arch	Arch Ring Thickness	Span	S/ART
1	0,994	7,492	1 / 7,537
2	0,999	7,657	1 / 7,665
3	0,972	10,520	1 / 10,823
4	1,027	8,261	1 / 8,044
5	0,996	9,257	1 / 9,294

Table 4. Relation between arch ring thickness and span.

4.1.2 Pillars

Inclinations

By means of the sections exported to CAD from the 3D model, a study of inclinations was performed. After studying all the pillars through these sections, we concluded that inclinations or deformations in their faces are not present.

Skew

One of the main problems detected thanks to the sections was a skew in the first pillar. A rotation of 2º was measured in the CAD software (figure 5). It is probable that this anomaly shows a seat at the support, taking also into account the fact that the second arch has an important asymmetry.

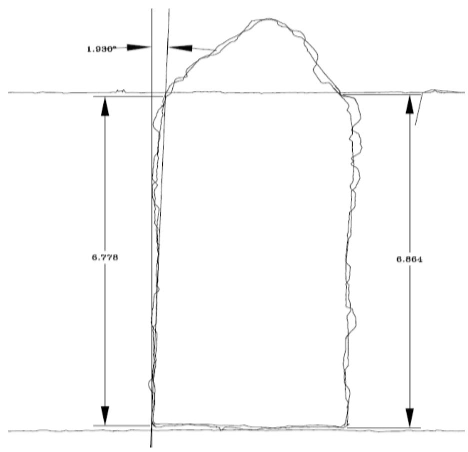

Figure 5. Plant view of the skew in the first pillar.

Slenderness

Slenderness in bridges is normally quantified by means of the span / pillar width quotient. These proportions are presented in table 5.

Pillar	Width	Arch	Span	Quotient	
		1	7,423	2,389	S1/P1
1	3,107			2,464	S2/P1
		2	7,656	2,437	S2/P2
2	3,142			3,316	S3/P2
		3	10,419	3,352	S3/P3
3	3,108			2,647	S4/P3
		4	8,227	2,669	S4/P4
4	3,083			2,927	S5/P4
		5	9,023		

Table 5. Slenderness in Segura bridge.

4.1.3 Walls

Internal irregularities in structures can cause an alteration in the drives equilibrium. Deformations on the wall surface normally appear associated to this fact. This way, after researching all the transversal sections along the 3D model of the bridge, a deformation in the downstream right abutment was detected. This bend was quantified in the CAD software regarding to the vertical line of the wall in that section. Figure 6 illustrates the deformation measurement, which has an inclination of almost one degree.

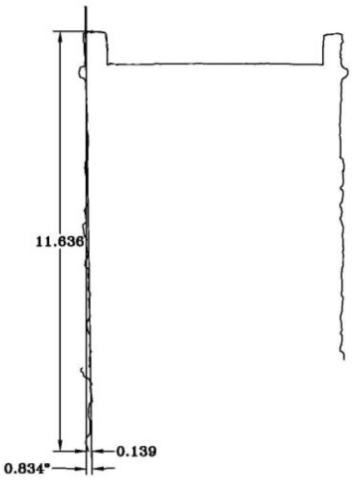

Figure 6. Deformation in the right downstream wall in a transversal section of the bridge.

4.2 Analysis with nonparametric algorithm

The geometry of the second vault, where the percentage of asymmetry is close to 10%, is analyzed in detail by obtaining cross sections of the vault through a non parametric estimation based on local bivariate kernel smoothers. An important advantage of this approach is that it allows the estimation of the cross sections without preestablishing any parametric shape.

Binning is used as computational acceleration technique. Equidistant grid points in the 3D space are defined along the X, Y, Z axes. The simple binning consists in assigning a weight to each grid point equal to the number of observations in its bin. In the so-called linear binning this weight is the sum of inverse relative distances between the observations and the eight closest grid points. In this way we transform the original cloud of points sample in a binning cloud where the number of points is significantly lower.

Once the binning sample is built, local constant kernel estimators are used to obtain cross sections along the vault. The estimator assumes that the real surface is continuous and smooth enough so that it can be approximated locally by a constant. The non parametric estimator contains a smoothing parameter that determines the adjustment to the real shape. The mathematics of the estimator, as well as the methodology for the choice of the most appropriate smoothing bandwidth is described in Roca et al (2008) and Wand (1994).

Once the surface was obtained (using the optimal bandwidth), XZ cross-sections of the vault were obtained along the Y axis. The proposed algorithm allows the extraction of cross-sections for as many points from the reconstructed 3D model of the vault as are needed to precisely define the shape. Figure 5 shows four cross-sections obtained at y=1, 2.5, 4, 4.6 m, showing the two halves overlapped in order to compare them. Each section also includes the asymmetry curve obtained by the differences between the two semi-cross-sections, together with their 95% confidence intervals. Bootstrap methods were used to obtain these confidence intervals.

Figure 7 reveals significant differences between semi-cross-sections along the vault. The asymmetry is of about a few cm close to the keystone, but at the outbursts of the vault the differences reach levels close to one meter. The magnitude of asymmetry seems to indicate that the reconstruction of that arch should be performed on just one half of the vault instead of being a total reconstruction.

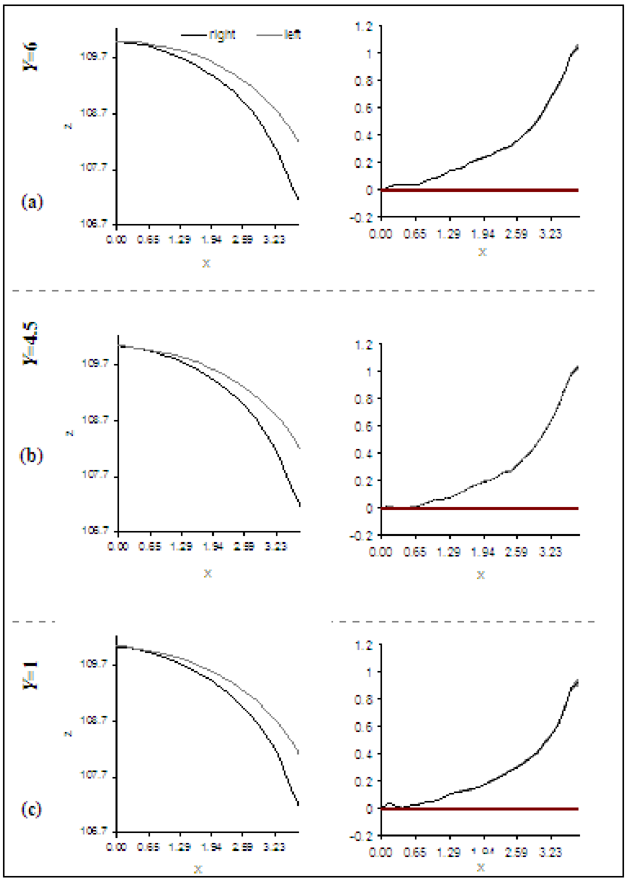

Figure 7. Cross-sections. For each case, a XZ graph with both halves overlapping each other is shown (left column), together with the asymmetry graph plotted with 95% confidence intervals (right column).

The analysis of symmetry curves shown in Figure 5 reveals the presence of peaks that could correspond to displaced ashlars, in the curves for Y = 1 m and Y = 6 m. In general, it is useful to include the confidence intervals together with the difference graphs because they allow the easy detection of statistically significant asymmetries.

5. CONCLUSIONS

Based on the results showed in the present work, terrestrial laser scanning represents a great potential tool in bridges inspection based on geometric analysis. High accuracy combined with fast data acquisition involves the main advantages of this technology.

Thanks to the 3D model of the bridge and the dimensional analysis carried out in CAD systems, an accurate detection of pathologies was performed. In this sense, the asymmetry in arch 2 (almost 10%), combined with the skew of the first pillar indicates a possible seat of the support in pillar 1.

The algorithm used for the geometric analysis in vaults, together with the graphical representation of overlapping semi-cross-sections allows visual inspection and quantification of asymmetries and distortions, facilitating diagnosis based on the arch geometry. Furthermore, by working with (X,Y,Z) coordinates, the damage is always located and measured in the structure.

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