Documentation and evaluation of historic masonry arch bridges by means of geomatic techniques

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ABSTRACT: This paper shows a multidisciplinary approach to heritage documentation involving Close Range Photogrammetry and Ground Penetrating Radar techniques. The geometric shape, the building material homogeneity and the current damages and its causes are obtained. The usefulness of Close Range Photogrammetry in the accurate 3D modelling and cracks detection and mapping is analyzed. Further, a non destructive test through GPR is employed for the interior material homogeneity analysis and zones description. For both techniques, the methodology followed for data collection and data processing aimed at minimisation of time consuming and optimisation of results is described in detail.

1 INTRODUCTION

The interest of the study of traditional architectonic heritage lays in the fact that it is witnesses of the ways of life and the history of the modern societies, and characterizes the landscape of a region, as it is one of its main elements. Nowadays it is assumed that the architectonic cultural heritage is a fragile and irreplaceable resource. Nevertheless Spanish heritage protection policies have revealed to be frequently inefficient and in some monuments the course of time has developed into a noticeable deterioration of materials and degradation of the whole or parts of the structure. The planning of preservation and restoration interventions in architectural heritage monuments might be based on an accurate updated documentation of all what concerns the geometric shape, the architectural characteristics, the characteristics of materials and the structural analysis in order to locate highly stressed areas were fractures might emerge and identify likely causes of current cracks (Genovese 2005). This all information should be taken as a decision tool to plan strengthening interventions or restoration actions.

Unfortunately, many technicians actually involved in heritage conservation still work on the documentation of monuments in a rather traditional way. However, in the last years some interesting approaches have been developed involving the application of new technologies to heritage documentation. Some examples related to heritage monuments 3D modelling through Digital Photogrammetry can be found in Guidi et al (2004) and Arias et al (2005); it might be pointed out that the application of this technology to bridges modelling have just recently started to be accomplished (Jáuregui et al 2005) probably due to the structural complexity of this kind of constructions. Ground Penetrating Radar (GPR) has been applied to the heritage documentation field by Ranalli et al (2004); specifically in masonry bridges in Colla et al (1997), and Clark and Forde (2003).

These all approaches have focused in specific fields of the monuments documentation: 3D modelling, analysis of building material, structural analysis or others. In the last years several conservationist's and restoration's have asserted the importance of adopting documentation protocols including advanced non contact surveying techniques and rigorous scientific analysis methods to document the cultural heritage properties and current state of decay (Genovese 2005).

In this paper a multidisciplinary approach to heritage documentation is presented. Close Range Digital Photogrammetry and GPR techniques are used in the geometric survey, building material homogeneity analysis; they are also employed in cracks detection and mapping, since cracks are the external appearance of severe structural problems. The resulting information was also used to properly define a finite elements based structural model (FEM), which was used to model the structural behaviour of the bridge in several load hypotheses, but it is not the aim of this paper to include the structural study -which is widely expounded in Arias et al (in press)-, focusing the research in the application of geomatic techniques for study and documentation. The methodology has been tested in the Fillaboa Bridge, a masonry monument which date back from the roman period and is placed over the Tea River, in the Salvaterra de Miño Council, Northwest of Spain.

2 THEORETIC GROUNDS AND STATE OF ART

2.1 Close range digital photogrammetry

Image-based measurement techniques play an increasingly important role in virtually all natural sciences and engineering disciplines since they can provide amount of qualitative and quantitative information and knowledge about observed objects in a global, non-contact way with high spatial resolution. In the last years some interesting approaches have been developed involving the application of Close Range Photogrammetry in the heritage documentation field. Some examples can be found in Alby et al (2003) and Arias et al (2005). But the application of this technology to bridges modelling and documentation have just recently started to be accomplished (Jáuregui et al 2005). This specific application requires a particular methodology in data collection and data processing.

The standard procedure to survey an object trough Digital Photogrammetry is described in Benko et al (2001). The main steps are: data collection; data processing; restitution and 3D modelling. In this study a digital monoscopic system has been employed because it is considered more feasible in heritage documentation applications in terms of cost-efficiency balance than stereoscopic photogrammetry, single image processing procedures, or even laser scanner based surveys.

When the data collection is performed through a convergent multistation system, consisting on taking shots from several positions all around the object, a functional model called multistation bundle adjustment might be applied. This process performs simultaneously the whole photogrammetric data processing: either interior or relative orientation of the network, as well as the network scaling and levelling (for further information see Cooper and Robson (2001)). It is based on collinearity equations, coplanarity condition and least squares adjustment.

The restitution process is aimed at the representation of the object geometry as a cloud of points and/or edges. In close range monoscopic photogrammetry it can be performed with manual or automatic procedures. Automated methods generally provide very dense point clouds, but mismatches, irrelevant points and missing parts could be present in the results, requiring a post-processing check of the data (Remondino 2003). In these automated procedures is often quite difficult to turn randomly generated point clouds into polygonal structures of high quality and without losing important information. If the data processing is done in manual mode, there is a higher reliability of the results, although a smaller number of points describe the object (Remondino 2003). The manual data processing in monoscopic digital systems is performed identifying all those points which represent the object geometry, and marking them in at least two photographs.

Finally, the goal of the 3D modelling step is to obtain a digital model of an object to accurately present an object surface description as reliable as the project requirements demand. Approaches to transform a point cloud to a CAD representation can be classified into two categories: triangular polyhedral mesh based method and segment-and-fit based method. The second approach might be applied when a surface might be fitted to a hugely dense unestructured data as terrestrial laser point clouds. For the former method many algorithms have been developed, which convert a set of points into a consistent polygonal model, being the Delaunay algorithm the most common and frequently available in commercial software; then, given the polygonal surface, various techniques can be used for a curvature-continuous surface generation (smoothing, texturing) and for the visualization of the 3D model.

2.2 Ground Penetrating Radar

Ground penetrating radar is a remote sensing and geophysical method based on the emission of a very short electromagnetic pulse (1-20 ns) in the frequency band of 10 MHz - 2.5 GHz. By moving the antennae over the ground, an image of the shallow subsurface under the displacement line is obtained. These images, called radargrams, are XZ graphic representations of the reflections detected where X axis represents antenae displaceament and Z axis represents the two-way travel time of the pulse emitted. GPR equipment usually consists of a laptop, a central unit and a pair of antennae. Depending on the depth being investigated and the required resolution, different antennae are selected. Antennae with a 200 MHz - 1 GHz centre frequency are best suited for the study of historical masonry bridges. 500 MHz antennae have limited ground penetration, but they give a very high resolution map of the subsoil in the first 2-3 meters. Below this depth, lower frequency antennae work better, but those with a centre frequency below 100 MHz have insufficient vertical resolution. 1 GHz antennae are suited for very shallow studies, and are a specially affective tool for structure inspection: detection of cracks in buildings, estimation of wall thickness, detection of humidity inside structures, etc. Details about the fundamentals and methods of GPR technique can be found in Annan (2003) or specially thought in archaeologists in Conyers (2004).

Regarding the employment of GPR techniques for the evaluation of masonry structures, it is possible to find some studies in the bibliography, as Binda et al (1998), who used it to study stone and brick masonries, detecting inclusions, voids and other defects, Flint et al (1999), who combines acoustic, electrical and radar methods to evaluate changes in the condition of masonry, Maierhofer and Leipold (2001), who constructed different physical models containing various brick materials to investigate the influence of structural features in masonry on the propagation of impulses emitted by GPR antennae, and Ranalli et al (2004), who uses GPR to evaluate the state of conservation of the facade of the Collemaggio Basilica in L'Aquila (central Italy), identifying the thickness of its walls, the forms and deterioration of its masonry. There are also some contributions regarding the application of GPR to investigate stone masonry arc bridges, as in this study, as Colla et al (1997), Colombo et al (2002), and Clark and Forde (2003). It has not been possible to find any contribution with the joint use of close-range photogrammetry, finite elements analysis and ground-penetrating radar applied together to the study of stone masonry arch bridges, but Lorenzo and Arias (2005) use photogrammetry and GPR together in archaeological site investigations, and Gianinetto et al (2005) make a proposal of joint use of multi-source close-range data to evaluate ancient structures which includes both methods together with laser scanner and thermal cameras.

3 INSTRUMENTATION

- Digital calibrated non-metric camera, Canon EOS 10D, 6,291,456 pixels CCD resolution. The calibration process was performed without zoom lens for the minimum diaphragm (maximum field of view). Calibration parameters are shown in Table 1.

Table 1: Calibration parameters of the Canon EOS 10D camera.

Focal length (mm)	20.21
Principal point (mm)	(11.16; 7.52)
Radial distortion (mm)	A1: 0.000226
	A2: -0.0000004906

- Circular paper targets with cross points.
- Monoscopic digital photogrammetric station. This system is based on the software package Photomodeler Pro 5.0. It is used for the orientation and restitution processes. The results are

obtained in a graphic format (DXF; 3D Studio, RAW, VRML 1.0 and 2.0, Direct 3D, Wavefront and Iges formats are also available).
- Total station: Leica TPS 1100.
- Ground penetrating radar GPR-RAMAC with 250, 500, 800 MHz biestatic antennae.
- Rambshell software for FEM analysis.

4 BRIDGE DOCUMENTATION

The documentation of the Fillaboa Bridge (see Fig. 1) has been sequenced in three steps, which are explained in detail in this section. The photogrammetric process is aimed at the geometric survey through the obtaining of the corresponding 3D accurate wire-frame model of the bridge and at the crack detection and mapping. The second step consisted on a non destructive test through GPR aimed at the analysis of the homogeneity of the interior material in the bridge and the detection of internal holes or cracks. Finally, a finite element model is constructed on the basis of the photogrametric 3D model and the information derived form the material homogeneity analysis, considering different load hypothesis. The crack mapping derived from the first step is taken as reference for the hypothesis confirmation or rejection.

Figure 1: The roman masonry bridge (Fillaboa Bridge) in *Salvaterra de Miño*, NW Spain.

4.1 The Photogrammetric process

Close Range digital Photogrammetry is a non-contact digitizing technique to measure size and shape of an object obtained from some photographs instead by direct measure. The last goal of the photogrammetric process is obtaining a 3D wire-frame model accurately representing the bridge geometry and a 3D photorealistic model properly containing the textures of the bridge. The standard procedure to survey an object trough Digital Photogrammetry is described in Benko et al (2001). The main steps are: data collection; data processing; restitution and 3D modelling. In this study a digital monoscopic system has been employed because it is considered more feasible in heritage documentation applications in terms of cost-efficiency balance than stereoscopic photogrammetry, single image processing procedures, or even laser scanner based surveys. This technique relies on the digital reconstruction of the object from several images taken from different and convergent perspectives to ensure a suitable geometry of intersecting rays.

A digital calibrated non-metric camera, Canon EOS 10D, 6291456 pixels CCD resolution, was used. Prior to the data collection performance, circular paper-targets were placed all along the longitudinal axis in both North and South bridge tympanums and also around arch's basis. Shots were taken from the upper path of the bridge and from both sides of the river, either upstream, downstream or below the arches, trying to satisfy overlapping and convergence conditions (Cooper and Robson 2001). The ground coordinates of the cross points within the paper-targets were precisely measured through the topographic total station Leica TPS 1100.

The data processing was performed through a monoscopic photogrammetric station. Six common points were identified in each pair of convergent photograms for the relative orientation of them. The photogrammetric network levelling and scaling was performed identifying the circular targets in the photographs and assigning the measured coordinates to its middle cross point. Finally a convergent bundle adjustment was performed.

A manual mode for the restitution process was followed in order to achieve the maximum accuracy in the resulting 3D models. Boundary points in the exterior face of the bridge stones were restituted. Then the corresponding boundary line of each stone in the bridge is defined. As a result a 3D wire-frame model is obtained for the whole bridge. Then a Delaunay triangulation is performed to obtain a non continuous model where sets of triangles have been fitted to the stones surface; photo-realistic textures are applied to each surface in order to obtain a 3D photo-realistic model.

4.2 The GPR test

Ground penetrating radar is a remote sensing and geophysical method based on the emission of a very short electromagnetic pulse (1-20 ns) in the frequency band of 10 MHz - 2.5 GHz. By moving the antennae over the ground, an image of the shallow subsurface under the displacement line is obtained. These images, called radargrams, are XZ graphic representations of the reflections detected where X axis represents antennae displacement and Z axis represents the two-way travel time of the pulse emitted.

In the study case the data were collected using 250, 500 and 800 MHz bistatic antennas. Three parallel profiles were recorded with each antenna, moving the system along the bridge, obtaining nine 85 m long radargrams Radargrams were acquired with a trace interval of 2 cm and time window of 250 ns, 125 ns and 70 ns respectively, taking into account their different depth penetration and vertical resolution. The profiles were filtered to enhance the internal reflections from the bridge and from the interface between ashlars arches and air; main filter applied were: Dewow (DC removal), Max Phase correction, Geometrical Divergence Compensation (gain), and Band Pass (butterworth: 50/450). The photogrametric measurements were used to obtain variations on the elevation of the profiles along the bridge, what allows applying the Static Correction and eliminate this effect on the radargrams

5 RESULTS AND DISCUSSION

5.1 Photogrammetric results

In the data collection step several difficulties for keeping theoretical overlapping and convergence conditions arose from the narrowness of the bridge on one side and the impossibility of taking shots from mid river bed on the other side. The accessible locations were just the upper path and the river sides. The upper path was used for photographing the handrails, the own path and the cutwaters up and downstream; but given the small width of the path 114 were needed for recording it ensuring adequate overlapping between consecutive photographs; 12 shots were taken for the cutwaters. From the river sides, the bridge tympanums and the bottom of arches were photographed: 34 were taken upstream, 34 downstream, 12 below the arches. The convergence angles varied from 50º to 100º (for the middle arch). The whole of 130 control points were measured.

The precise restitution of points in a masonry structure has revealed to be a hard slow process due to the advanced erosion state of the stones edges and the absence of vertexes or references that could be easily recognised in two different photographs. The paper-targets and mainly the rock crystals in the bridge stones were used for this end. But given its small size and different aiming view in each photograph, highly detailed views of the stones were needed for its restitution, involving time consume, as well as several reviewing steps for relocating those points whose high error values revealed a wrong position. A cloud of 41.393 points was finally obtained. In spite of these difficulties a wire-frame model accurately representing the bridge geometry was obtained (see Fig. 2): high accuracy values corresponding to the photogrammetric model points have been achieved (see Table 2).

The 3D and 2D models allowed detecting longitudinal cracks in the bottom of the middle arch and in the next arch on its right; cracks in the cutwater between both arches were also detected (see Fig. 3, left). On the basis of the 3D wire-frame model, the photo-realistic textured model was obtained (see Fig. 3, right).

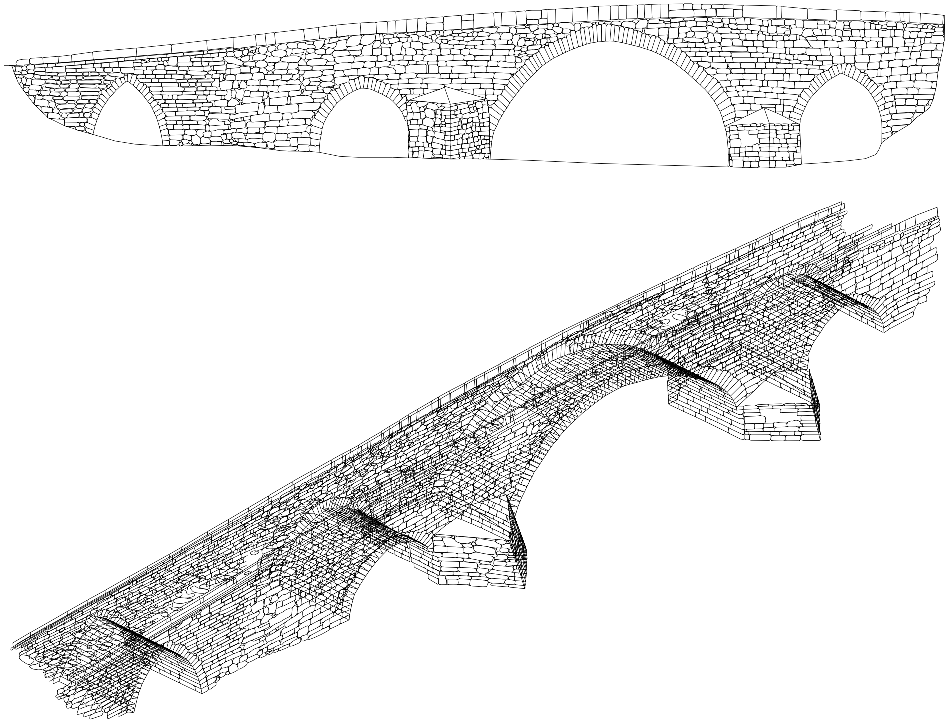

Figure 2: Fillaboa Bridge: 2D (above) and 3D (below) wire frame model

Table 2: Points position error (95% confidence), RMS and Maximum Residual.

	Average	Maximum
X (mm)	5.5	
Y (mm)	5.9	
Z (mm)	4.3	
RMS residual (pixel)	0.97	
Maximum Residual (pixel)		3.94

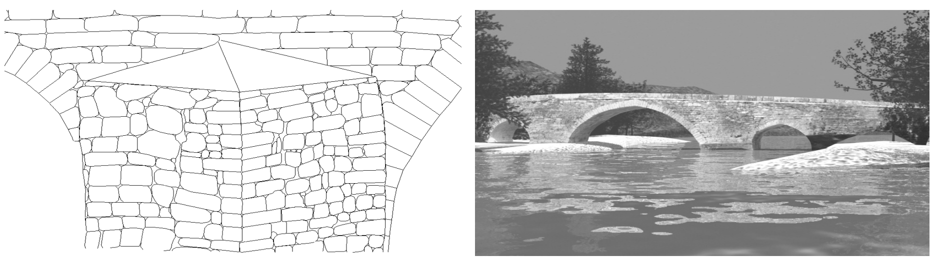

Figure 3: Cracks detection and mapping (left). Photo-realistic textured model (right).

The digital photogrammetric recording provides qualitative information about the bridges stones arrangement. The whole bridge is made of granite ashlars with varying sizes and narrow mortar joints. They are arranged longitudinally in the tympanums, cutwaters and bottom of arches, vertically in the handrails and in a radial direction in the arches boundaries. Stones in the tympanums are quite smaller and more heterogeneous than the rest.

5.2 The GPR test results

The signal of the higher frequency antennas (800 MHz) showed to be very attenuated in the two-way travel, and some of the arches are not recognizable in the radargrams obtained with such antennas, especially those which are deeper in relation to the bridge surface. On the contrary, the pulse of the 250 MHz antenna crossed the whole bridge. Resulting profiles showed relevant information about its internal structure, being possible to point out the reflections related to the foundations of the bridge (Fig. 4). In the radargrams there are no evidences of very big internal cracks, neither reflections related to cavities, holes or similar. The resulting profiles showed that the backing (filling material) is quite homogeneous.

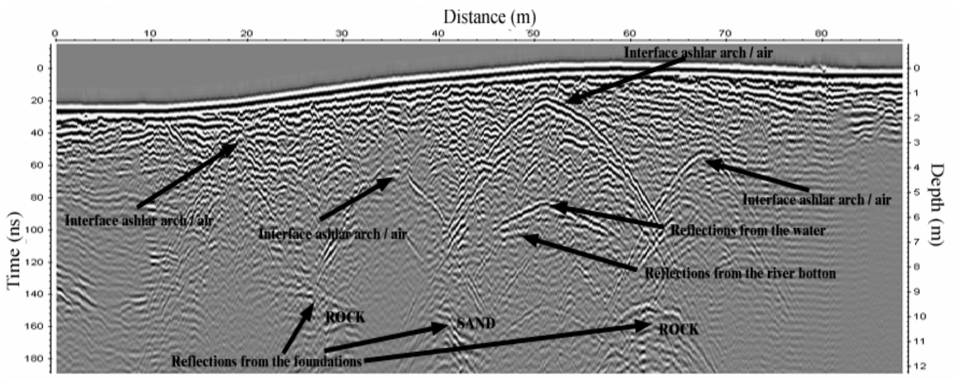

Figure 5: GPR test: 85 m long radargram obtained with the 250 MHz antenna (up) together with the interpretation of some reflections and diffractions detected in it.

The averaged velocity of the radar pulse was estimated on 13 cm/ns for the backing and 16.5 cm/ns for the masonry, which fit with the expected values for these materials (Binda et al 1998), Clarck and Forde 2003). These values for the velocities were calculated using the metric information given by the photogrametric survey, which allows an accurate known of the geometry of the arches and the distances between the surface of the bridge and the arches or the foundations.

6 CONCLUSIONS

In this paper a multidisciplinary approach to heritage documentation is presented involving Digital Photogrammetry, GPR and finite elements analysis. The surveying techniques have been proven to provide accurate information related to geometry, internal and external cracks, and current state of decay. It might be pointed out that since they are non contact demanding these fields can be analyzed avoiding decay aggravation. Information resulting from the photogrammetric process and the GPR test could also be used to define a structural model which allows inferring the causes of the state of decay and further a prediction of the decay evolution can be derived too (see Arias et al (in press) for details). It can be concluded that the described methodology can serve as a decision tool for the kind of reinforcing or restoration actions that might be accomplished to ensure the preservation of heritage masonry bridges.

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