MULTIDISCIPLINAR APROACH TO HISTORICAL ARCH BRIDGES DOCUMENTATION

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ABSTRACT:

This paper describes the project of the Close Range Photogrammetry and Remote Sensing Group, University of Vigo, Spain, involving historic arch bridges in Galicia, Spain. The first aim of this Project consists on building a database of the historic arch bridges in Galicia, documenting location, surroundings, geometry, singular characteristics, structural faults, building material and state of conservation. On the other side, a methodology is being designed to optimize measuring and analysing techniques: Close Range Photogrammetry and Laser Scanning as 3D modelling tools for geometry and cracks documentation (Arias et al, 2005), Ground Penetrating Radar for inner material characterization and zones description, and FEM as structural analysis tool to establish stress distribution compatible with the detected damages, allowing identifying its possible causes. This stage includes the development of a procedure to synergize these techniques to obtain more reliable results.The data and results that have obtained until the date are described in detail. Building styles, singular characteristics of the arch bridges in this region, building materials, and the state of conservation are reported. Further, the methodology for the 3D modelling by digital close range photogrammetry of the bridges, which have varying locations, size, geometry and accessibility is also described, including the requirements which have been considered to grant the utility of the 3D models in further stages of the project: GPR analysis and structural analysis by FEM.

1. INTRODUCTION

In the last decades public institutions have shown increasing interest in heritage conservation and monuments protection. Masonry bridges are civil engineering constructions that usually have a complex geometry. This complexity makes that the appliance of measurement devices traditionally used in heritage documentation is not feasible. Locations, building peculiarities, structural behavior, etc., are factors that make the employment of new image based techniques which allow the documentation of this kind of constructions without direct contact.

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. Historic bridges might be considered the main witness of the Galician infrastructures of past centuries. Due to the irregular relief numerous bridges dating from every historic epoch can be found in varying states of conservation. Nowadays it is assumed that the cultural heritage and landscape are fragile and irreplaceable resources. Unfortunately, Spanish heritage protection policies have revealed to be frequently inefficient in the preservation of historic bridges and in several cases the course of time has evolved into a deterioration of materials and the degradation of the ancient construction; moreover the damages caused by reforms frequently consisting on the addition or substitution of materials end up leading to the destruction and loss of the historical construction in its original appearance.

Any research process aimed at the planning of preservation and/or restoration interventions in architectural heritage monuments might be based firstly on an accurate updated documentation of all what concerns the geometric shape, the peculiarity of its architectural characteristics, the characteristics of materials and the structural analysis (ICOMOS, 2001) in order to locate highly stressed areas were fractures might emerge and/or identify likely causes of current cracks. Also the accurate surveying and monitoring of cracks in the structure, as these are the first apparent signs of structural fails or collapse, is essential for any preservation approach in order to achieve an adequate diagnosis of the state of decay of the monument and to establish priority levels in the restoration interventions.

Several catalogs and studies involving the documentation of Spanish historical bridges have been published (Duran et al. 1991, Arrúe and Moya, 1998) They include varying typologies from roman bridges to modern styles dating from the 20th century and built in concrete, iron or and wooden materials. For this reason the definition of the term “historical bridge” is not a simple task. In this research, the masonry arch bridges built before 1800 are considered.

Several researchers have analyzed architectural heritage surveying and structural analysis separately. Main research advances in surveying techniques lead to the application of terrestrial laser scanning and close range photogrammetry, as they both allows collecting thousands of points per second without any contact device for performing the acquisition; besides they both have shown to be precise and good for creating high-resolution 3D mesh models and realistic models

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of built up structures. But laser scanner technology still lacks in mesh model generation from random scanned data; this is a non-trivial task that usually requires a complex time-consuming reconstruction process and significant amount of computation. Besides, the high density of laser point clouds demands powerful software to handle this kind of data.

On the other hand, either analytical or finite elements methods have been commonly used for the determination of the structural response of masonry structures (Lourenço, 2002, Lourenço, 2006). But whatever the method is applied, the geometry of the structure is usually considered simple. The availability of accurate 3D modelling techniques as Close Range Photogrammetry and 3D laser scanner requires new ways to integer this information in the computation of the structural behavior of the structure in mathematical terms.

Laid these foundations, our work is divided in two phases: the first was focused on creating Singular Historical Bridges Inventory documenting the geometry and the structural damages; the second was focused in applying non destructive geomatic techniques in accurate studies about the structure.

The monoscopic photogrammetry and the terrestrial laser scanner are going to provide accurate metric data, which together with GPR results will give us an important information source to obtain structural analysis. In these sense, the damages will be identified with high accuracy and assessed in extension and size (Arias et al, 2007).

2. THE HISTORICAL BRIDGES INVENTORY.

A previous knowledge about the element which is going to be surveyed is needed to accomplish a detailed documentation study. In that sense, the idea arises to create a catalogue of bridges that gathers reliable and accurate data about the state of the buildings as well as to know the physical limits when field work (photogrammetry, laser scanning and GPR surveys) is carried out. At the same time, the inventory collects the technical data of a representative sample, in constructive typology and state of conservation, of a hundred of Galician historical bridges.

A database of the historical arch bridges in Galicia documenting location, surroundings, historic evolution and structural description, geometry, singular characteristics, structural faults, building material, can be a useful to evaluate the state of conservation of every bridge.

Also, the bridges surveyed by means of photogrammetry, laser scanning and GPR were selected on the base of damages and degradation, constructive typology and bridge surroundings.

The inventory information was very useful to plan the field work before going to the bridges with accurate equipments.

The structural damages and the presence of degrading elements are collected in tables, plans and photographs. Tabs and photographs are linked in order to identify the pathologies as well as possible, in location and shape. (Figure 1; Figure 2.)

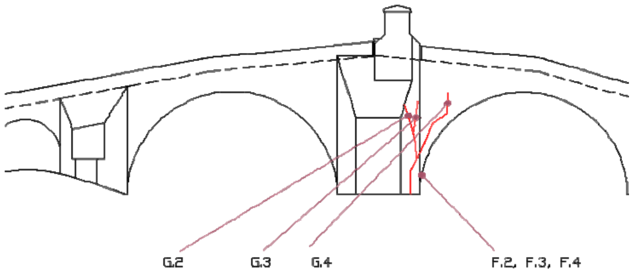

Figure 1. Front view of structural damages mapping in the Carracedo Bridge

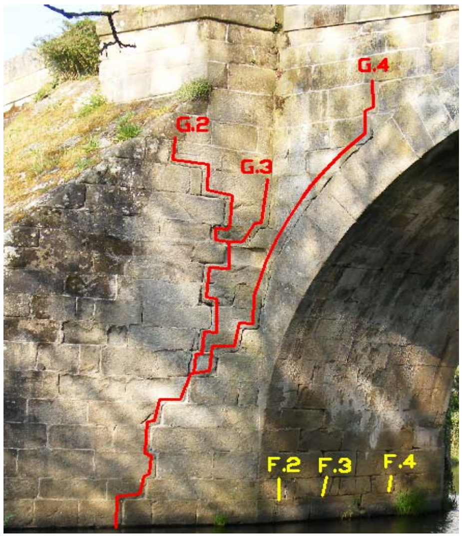

Figure 2. Cracks in the Carracedo Bridge.

The surveying equipment consisted on mesurement tapes, plummets and poles. Digital cameras allowed collecting the location and extension of structural damages. The vertical measuring system was based on the plum lines, that is, a plummet was linked to the measurement tape. The cutwaters and the rest of the projecting elements were measured by mean of poles and plummets.

3. ACCURATE STUDIES

3.1 The photogrammetric survey

In the last years close range photogrammetry has increased its presence in the heritage documentation field. This technique has been frequently used to obtain very accurate measurements of architectonic features (Yilmaz et al., 2007) and archaeological studies. Bridges have been studied as cultural heritage elements by means of photogrammetry in Şeker et al (2006), where photogrammetry is combined with photorealistic texturing techniques to obtain virtual models of the building. Jáuregui et al. (2006) proposes photogrammetric based procedures in routine bridge inspections.

To have relatively cheap and easy to operate techniques is fundamental when a project with a great scope, as the presented in this work, is tackled. The photogrammetry validity is well contrasted as high precision technique in architectonic documentation.

Using the inventory information, it was possible to do a previous planning of the photogrammetric field works. Also the topographic survey was planed in order to have all the control points.

Due to the bridges dimensions, it was necessary to split the bridge's project in smaller models, in order to obtain a good precision. Also vegetation in banks makes difficult to obtain photographs of the whole bridge from different viewing angle.

Camera calibration

The photographs were made with a Canon EOS 10D, which has a RGB CMOS sensor with a resolution of 6,3 megapixels. A Canon EF 20mm wide-angle lens was used to take the images.

The interior orientation parameters of the camera (focal length, position of principal point, and distortions) are known by means of the Photomodeler Pro camera calibration application. To calibrate the camera, a plane target grid was photographed from at least 6 different positions.

Data acquisition

Field works have consisted in the image acquisition and the measurement of coordinates of the center of the targets with a total station equipped with laser distanciometer. The first task was to define all the models that compose the whole bridge. Then circular artificial targets were located on the walls and vaults. At least six targets were placed in each model, keeping at a minimum of three targets in the overlapping area between adjoining models. A minimum of three photographs of each model were taken, accordingly to the principles of monoscopic photogrammetry (see Luhmann et al., 2006), but commonly four images per model were gathered in order to improve results.

Data processing

The photogrammetric restitution was carried out in Photomodeler Pro. The internal orientation was achieved thanks to the camera calibration file. After that, the relative orientation of the whole models was achieved identifying common targets. Then all the models were joined in order to have a unique model. Finally, the absolute orientation was done thanks to the topographic coordinates of control points.

Results

Great amount of data is obtained after to restitute the bridges. In the follow table are shown some examples, and the precision obtained.

Bridge	Total length	Nº points	Error X (m)	Error Y (m)	Error Z (m)
Cernadela	72 m	25713	0,007	0,009	0,005
Fillaboa	69 m	34991	0,005	0,006	0,004

Table 3. Error obtained in the Cernadela Bridge and Fillaboa Bridge.

Finally wire frame models were built (Figure 4), where also damages were identified (cracks, lack of materials, etc.) (Figure 5) and their dimensions. Solid models were created in order to use them in structural analysis, and to make photorealistic texturing.

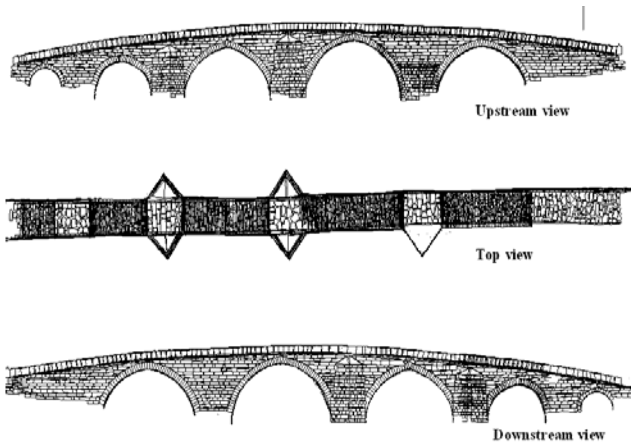

Figure 4. Wire frame of Cernadela Bridge.

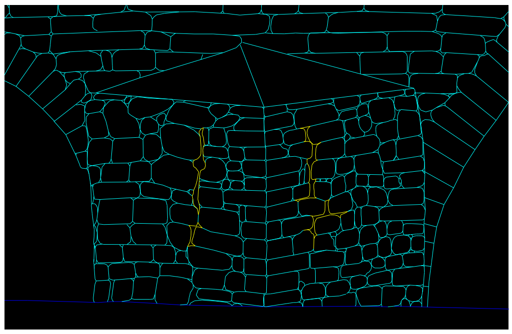

Figure 5. Cracks in Fillaboa Bridge

3.2 The laser scanning survey

The collection of 3D coordinates of millions of point over an object surface in few minutes represents a powerful tool to survey architectonic heritage, where the geometric precision and photorealistic details are essentials (Voltolini et al., 2007). The terrestrial laser scanner allows collecting a great amount of metric data in a short period of time; also the data acquisition is almost automatic. Furthermore, the "time of flight" (TOF) laser scanner range and the possibility of obtaining the radiometric information of the point clouds, make that laser scanners are optimum to survey heritage elements.

Thank to the inventory information, a previous planning was made before to visit the bridge with the laser scanner equipments. In this sense, using the inventory plans and photographs was possible to estimate the number of scan positions and their respective field of view, in order to obtain an accurate point cloud of the whole bridge and to optimize the field works.

Data acquisition

The point clouds acquisition was made with a RIEGL LMS-Z390i, technical specification are in (RIEGL, 2008). A Nikon D200, with a resolution of 10,2 million of pixels, was mounted on the laser in order to obtain the RGB information. All the data acquisition process was controlled by means of the Riscan Pro software.

The first task was to calibrate the camera mounting, this is to calibrate the camera position regarding to the laser scanner sensor. That was made through the identification of at least tree common reflecting targets between the point clouds and the photographs taken with the camera.

In order to make the registration of the different scan positions, flat reflecting targets with a diameter of 5 cm or 10 cm were located in different planes. A minimum of tree common targets were used between different scans. When the reflecting targets cannot be placed, the registry of scan was made by means of common planes in the Riscan Pro software. The resolution of general scans of the bridge was 3-5 mm, and where cracks were watched the angular precision was 0,002º (equivalent to 0,001 m at a distance of 30 m).

At least, the coordinates of tree targets are necessary to level the global point cloud. For this reason, a topographic survey was executed in order to obtain the coordinates of at a minimum of four targets in the global point cloud. This survey was made with a Leica TRC 1102 total station.

Data process

When field works finished, the first step was to define the project coordinate system (PCS) from the topographic data. Then the rotations and translation matrix in the first scan position was calculated to have the first scan in the project coordinates system. The rest of scans were registered with the registered scans by means of common targets.

After the registry, the point clouds were filtered in order to obtain point clouds with a regular density of points. Also, the 3D points were colored from RGB information of the images taken with the camera (figure 6).

Figure 6. Coloured point cloud of Carracedo Bridge.

Then, the point cloud were triangulated in order to obtain solid 3D models and textured with the images. Finally, longitudinal and transversal sections were obtained from the solid model because they allow studying the shape and dimensions in vaults, cutwaters, walls, etc. Also, orthophotos were created.

Results

In the follow table (table 7) the results of four bridges are presented:

Bridge	Registry	Registration error	Nº of points in global point cloud
Traba	Targets and planes	0,02 m	12 millions
Cernadela	Targets	0,015 m	23 millions
San Antón	Targets	0,008 m	11 millions
Carracedo	targets	0,009 m	13 millions

Table 7. Registry system and global error; and size of point clouds of four bridges.

One of the purposes of this project is to obtain an accurate documentation of damages. In order to carry out multitemporal analyses of structural problems, all the damages observed were scanned accurately. An example is the crack observed between an arch ring and the ashlars of the wall of the Traba Bridge, which was scanned with a precision of 1mm.

Figure 8. Coloured scan of a crack in an arch ring of Traba Bridge.

3.3 The Ground Penetrating Radar Survey

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 antennas over the ground, an image of the shallow subsurface under the displacement line is obtained. These images, called radargrams or B-scans, are XY graphic representations of the reflections detected where the X axis represents the antennas displacement and the Y axis represents the two-way travel time of the emitted pulse.

GPR equipment usually consists of a laptop, a central unit and a pair of antennas. Depending on the depth being investigated and the required resolution, different antennas are selected. Antennas at central frequencies ranging from 200 MHz to 1 GHz are the best suited for the study of historical masonry bridges. 500 MHz antennas 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 antennas work better, but those at central frequencies below 100 MHz have insufficient vertical resolution. 1 GHz antennas are suited for very shallow studies, and are an especially effective tool for structure inspection: detection of cracks in buildings, estimation of wall thickness, detection of humidity inside structures, etc.
GPR surveys were carried out in a total of twenty-five masonry arch bridges by using 250 and 500 MHz shielded antennas in

order to obtain significant information about its internal structure and locate cracks, hollows and faults.

Data acquisition

The initial data acquisition in each bridge consisted in the following methodology:

A 500 MHz shielded antenna was used to measure two longitudinal parallel profiles with a separation of 0,18 m between transmitter and receiver, a 2 cm in-line spacing and a time window of about 90 ns (Y axis). Furthermore, two longitudinal parallel profiles were acquired with a 250 MHz shielded antenna and a separation between transmitter and receiver of 0,3 m, a 5 cm in-line spacing, and a time window of about 200 ns.

Data processing

Radargrams were filtered to improve the Signal to Noise ratio and enhance the structural elements detected. Main filters applied were: Dewow (DC-Shift Removal), Geometrical Divergence Compensation, Band Pass, and a Static Correction (topography + antenna tilt correction). The photogrammetric measurements were used to obtain the topography of the bridge.

The following software packages were used for data processing and interpretation: Ground Vision (Malå Geoscience), ReflexW (K.J. Sandmeier) and GPR Slice (D. Goodman).

Results

Figure (8) shows an example of the radargrams obtained with a 200 MHz unshielded antenna in an ancient medieval bridge in Cerdedo (Galicia).

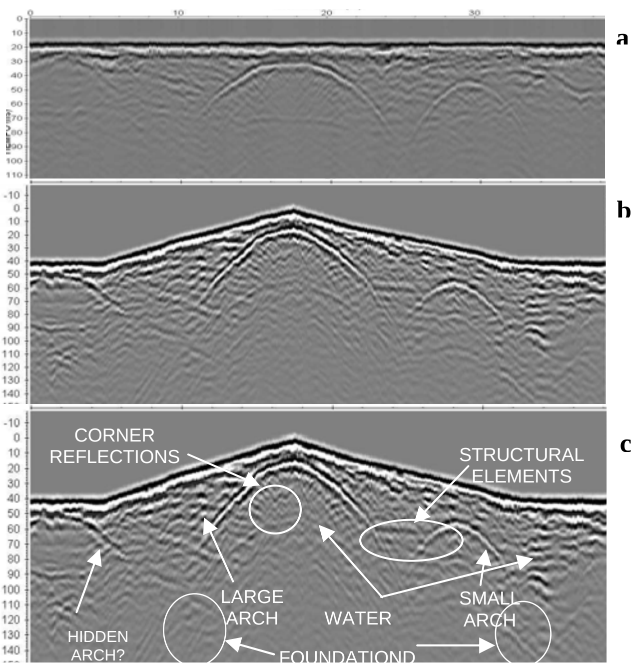

Figure 8. Data obtained with a GPR 200 MHz unshielded antenna: a) Raw data, b) After a basic processing sequence. c) Interpretation. Horizontal axis: Distance (m), vertical axis: Time (ns).

The figure clearly shows the arches and foundations of the bridge, as well as other structural elements and significant characteristics of the filling material.

GPR interpretation is aided with FDTD simulations using the software GPRmax (A.Giannopoulos). Models used by this program are obtained from precise external geometric information extracted from the photogrammetric data.

4. CONCLUSIONS

A great variety of historical arch bridges were documented and included in the Historical Bridges Inventory of Galicia: Roman bridges, medieval bridges with gothic arches, roman and medieval bridges with modern reconstructions.

Geometry, structural damages and the presence of degrading elements allowed us estimating a preliminary state of conservation.

The creation of the Historical Bridges Inventory is a great progress in the Spanish heritage policies, because it involves the first extensive accurate database in architectonic heritage. In the future, many researches could use this technical information in order to keep on researching about historical bridges.

The photogrammetric and laser scanning results reinforce the validity of these techniques to carry out heritage surveys. This way, the results show that photogrammetry and laser scanning allow obtaining accurate metric data and identifying structural pathologies, in shape and dimensions. Also, GPR can provide information about bridge’s internal structure: filling material homogeneity, foundations, possible cracks or voids, etc. All this information can be used for a more accurate structural analysis simulation

By means of this multidisciplinary approach will be possible to monitor the damages along the time and also, to adopt restoration decisions.

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