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Historic bridge modelling using laser scanning, ground penetrating radar and finite element methods in the context of structural dynamics

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ABSTRACT

This paper presents a general methodology to evaluate a masonry structure, considering the fact that the geometry of the structure is complex and that material properties are unknown and cannot be directly assessed. A multidisciplinary approach is presented that integrates laser scanning, ground penetrating radar (GPR) and finite element analysis (FEM) in the documentation of a medieval masonry bridge. The complex geometry of the structure is prepared using the data collected by a laser scanner. Since the bridge internal construction is not well known, GPR techniques are used in the geometric survey to estimate its homogeneity or heterogeneity. The resulting information is used to properly define a finite element-based structural model, which is then used to model the structural behaviour of the bridge. Moreover, the sensitivity analysis of the influence of the variation of Young's modulus as a significant material parameter on the dynamic response of the bridge is performed. The study shows that this methodology has significant importance, particularly in the evaluation of the state of historic structures where, using non-invasive methods such as laser scanning and GPR is more appropriate.

1. Introduction

The topic discussed in this paper forms part of the Research Project entitled "Dimensional and structural analysis of constructions using close range photogrammetry, terrestrial laser and close range radar", Grant No BIA2006-10259, a valuable effort of the Spanish government in the documentation and analysis of medieval and Roman historic bridges in Northwest Spain. In this region, the bridges constitute a patrimonial legacy of singular value. The types of materials and forms of construction are very diverse. The historical bridges are numerous in this region of the country primarily because of the irregular orography of the landscape and population dispersion. They have played an essential role as the infrastructure of transportation and some are still in use. Nevertheless the state of conservation of many of them is deficient. Frequently, the passage of heavy, rolling traffic over these bridges has introduced excessive loads and vibrations. In addition, in many cases abandonment of the rural surroundings has caused historic bridges to be useless and forgotten. Decay, invasion of vegetation in walls, paths and other elements and extraction of pieces to be used as building material in other close constructions, are some of the problems that affect historic bridges.

The primary goal of the mentioned project is to inventory the historical bridges of Galicia, a region in Northwest Spain (see Fig. 1). The inventory includes the documentation and analysis of characteristic styles of the historic bridges dating from the roman to late medieval periods. Currently, the second phase of the project is running. It concentrates on a series of singular bridges in the inventory to perform a detailed characterization of the geometry and internal material and a structural analysis of them. The objective of this phase is to document the present state of certain emblematic bridges of the region and to develop a methodology to analyze historical bridges.

In this paper, we describe the modal analysis of the Cernadela bridge due to its importance in structural damage detection and, what follows, the heritage maintenance. The structure is located in the municipality of Mondariz, in Northwest Spain (see Fig. 1). This bridge belongs to a route that runs between historic bridges (Bridge *Remedios*, Bridge *Partidas* and Bridge *Fillaboa*) along the Tea River, surroundings that have been integrated in the Network Natura 2000 because of their natural and landscaping value.

The Cernadela Bridge has five pointed arches with the longest span of 11.5 m, upstream and downstream cutwaters with triangular section and pyramidal small hats, a double slope stone path, straight cornices and parapets of whole pieces prepared vertically. The whole structure is 74 m long and 3.7 m wide. Dating from the XVth century, it is thought that the Cernadela Bridge in its present form was raised on the remains of a Roman bridge.

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Fig. 1. Location of the Cernadela Bridge: Mondariz, in Northwest Spain. (From: Microsoft Virtual Earth).

In a first study of this bridge (see [1]), two finite element models were prepared based on the geometry taken from photogrammetry data. Next, structural analysis was performed to evaluate both models to emphasize the significance of the use of homogeneity or heterogeneity while modelling the bridge interior. In this paper, we develop the investigation in two advanced directions — preparing geometry and finite element modelling. We apply laser scanning equipment to obtain the structure geometry and then use the GPR data to study the internal structure of the bridge. The laser scanning facilitates to build a 3D model of the bridge as the structure is very massive and hence dimensionally reduced model cannot be applied (e.g., [2]). GPR results allow us to decide about the bridge dynamic model in the context of its heterogeneity. On that base we defined a dynamic model containing two types of building materials described by different Young's modulus. The effect of Young's modulus variation upon the structural dynamics is investigated with the aid of sensitivity analysis. Its range reflects the authors' uncertainties about the exact value.

2. 3D TLS measurement of the bridge geometry

The terrestrial techniques applicable to 3D modelling of infrastructures are basically traditional topography, close range photogrammetry and the terrestrial laser scanner (TLS). The measurement by total station is a commonly used technique, but to a great extent the quality of the resulting digital model depends on the ability of the worker to take a sufficient number of points and a suitable election of them to develop a trustworthy model of the structural elements of the bridge. The use of terrestrial photogrammetry is limited by the difficulty required to digitize points on non-regular surfaces without easily identifiable singular points; in addition, it has restrictions on the geometry of the data acquisition that are difficult to satisfy in wide rivers. Furthermore, it depends on the conditions of illumination and requires topographic support to ensure suitable precision (see e.g., [3]).

Terrestrial laser scanner (TLS) technology is starting to replace traditional geometric techniques. There are two primary types: those based on triangulation, which are short-range devices (order of meters), and those named *time of flight* laser scanners (TOF), which are long-range measuring devices (hundreds of meters up to four kilometers). The TOF scanners are applicable to the modelling and measurement of bridges and infrastructures. The measurement is based on the emission of a laser beam with a wavelength in the optical or near infrared domains that affect the object directly, so that the distance from the point of emission to the surface is obtained from the flight time of the signal. The distance measurement system is combined with a baffle plate for the ray, which aims the ray in the direction of the surface to be measured. The horizontal and vertical angles that correspond to each emitted pulse are determined by coders. Thus, a spherical coordinate system centred on the scanner is defined, from which Cartesian coordinates $(X; Y; Z)$ are obtained for any point measured on the surface of the object.

With respect to other techniques, TLS systems offer a number of advantages: it acquires the 3D geometry of the entire surface area of an object without direct contact with the structure, which avoids alteration of the material and allows access to structural elements that may be otherwise inaccessible (vaults, central piers, etc.); it provides huge density of data (million of points), high accuracy and high rate of data acquisition. Park et al. [3] point out another essential advantage: the measurement does not require specific illumination conditions.

The combination of precision, speed and range in the same instrument has caused TLS systems to be adopted in different fields, ranging from 3D modelling and reconstruction of archaeological sites and heritage monuments [4,5], to forensic anthropologist investigations [6], urban modelling [7], or geomorphological studies [8]. In studies of infrastructure stability, the works of Park et al. [3] are relevant. They propose a procedure based on TLS for the measurement of deflections in bridges and buildings, and Kang et al. in [9] present a system of structural health monitoring.

2.1. Instrumentation

The equipment used in this work was a 3D long-range TLS (TOF) Riegl LMS-Z390i. This equipment measures distances in a range of 1.5–400 m, with a nominal precision of 6 mm, 50 m distance in normal illumination and reflectivity conditions. The vertical field of vision has an amplitude of 80 sexagesimal degrees, and 360 degrees in the horizontal plane. It has a minimum angular resolution of 0.2 degrees and a maximum of 0.002 degrees, and the rate of measurement of points oscillates between 8000 and 11,000 points per second. The software used for the recording and alignment of clouds of points is RiSCAN PRO Software, Riegl©.

This scanner is used in combination with a calibrated Nikon D200 camera. This camera incorporates a CCD sensor (Charged