

Non-destructive analysis in cultural heritage buildings: Evaluating the Mallorca cathedral supporting structures

V. Pérez-Gracia^{a,*}, J.O. Caselles^b, J. Clapés^b, G. Martinez^c, R. Osorio^b

^a Departamento de Resistencia de Materiales y Estructuras en la Ingeniería, Universidad Politécnica de Cataluña, BarcelonaTech, EUETIB/CEIB, C/Urgell 187, 08036 Barcelona, Spain

^b Departamento de Ingeniería del Terreno, Cartográfica y Geofísica, Universidad Politécnica de Cataluña, BarcelonaTech, C/Jordi Girona 1, 08034 Barcelona, Spain

^c Universidad Michoacana de San Nicolás Hidalgo, University City, Avenida Francisco J. Múgica S/N, Morelia, México

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ABSTRACT

Geophysical prospecting surveys are being increasingly used in non-destructive evaluations of structures, and several methods can be applied in the evaluation of cultural heritage buildings. However, accurate studies of cultural heritage structures usually need the application of combined techniques, historic and structural knowledge also being necessary. The present paper describes the application of two non-destructive testing techniques: ground-penetrating radar and seismic tomography, in the analysis of some structural elements' inner geometries and physical properties. This job is part of a more complete project developed to define the Mallorca Cathedral structural behaviour. Both geophysical methods are used in a complementary way. GPR allows the detection of small anomalies (changes of about centimetres), and the results are used to select the most appropriate seismic tomography initial model.

The aim of the study is to define the internal structural configuration as well as the stone quality. Results reveal the internal structure of columns, walls and buttresses, showing different structural elements. Even when the visual inspection points to external damages, the detailed NDT evaluation indicates that the inner structure is in good condition and the ashlar are of good quality.

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1. Introduction

The construction of the Cathedral of Saint Mary, Mallorca (Spain), started in the XIV Century. Actually it is a representative Catalan Gothic Style building (Fig. 1a and b). This style, similar to European Gothic, is characterised by the airy distribution within the building space. The slender columns avoid the visual separation between the three naves of the church. The structure was designed to transmit mainly loads to buttresses. However, this structural solution implies bigger buttresses, reducing natural light. The columns are slim octagonal structural elements, built with limestone ashlar (see Fig. 1b and c). Three pairs of columns, close to the high altar, are older and thinner than the other columns of the church. They are 1.59 m circumscribed diameter, while the last four pairs are 1.80 m [6].

Historical documentation describes structural problems during the Cathedral construction and use, most likely due to a non-appropriate loads distribution design. Nowadays, visual inspections of this building evidence structural problems in most of

the arches [6], and cracks are visible in columns, buttresses and walls [8]. Preservation of this historical building is the objective of several projects, involving exhaustive non-destructive testing (NDT) studies, some of them by means of geophysical surveys. The global objective of these studies is to define accurately the dynamic structural behaviour of the monument. Geophysical prospecting and borehole data point to the changes in the ground quality as a possible cause to the columns bending [18]. Attending this conclusion, the supporting structures conservation state is evaluated with GPR and seismic tomography. This paper describes these surveys and discusses the main results.

2. Methodology

The application of more than one geophysical method has been demonstrated to be a powerful technique to solve or diminish uncertainties associated to all indirect evaluations (e.g. [9,11,18]). In this study, two techniques were selected attending the size of the columns and the known damages. High frequency GPR evaluation provides enough resolution to define discontinuities or changes in materials, as well as the structure shape, but results cannot be easily associated to mechanical material properties. However, high frequency seismic techniques provide less resolution, but results

* Corresponding author. Tel.: +34 93 4137333; fax: +34 93 413 7401.

E-mail addresses: vega.perez@upc.edu (V. Pérez-Gracia), oriol.caselles@upc.edu (J.O. Caselles), gmrui@umich.mx (G. Martinez).

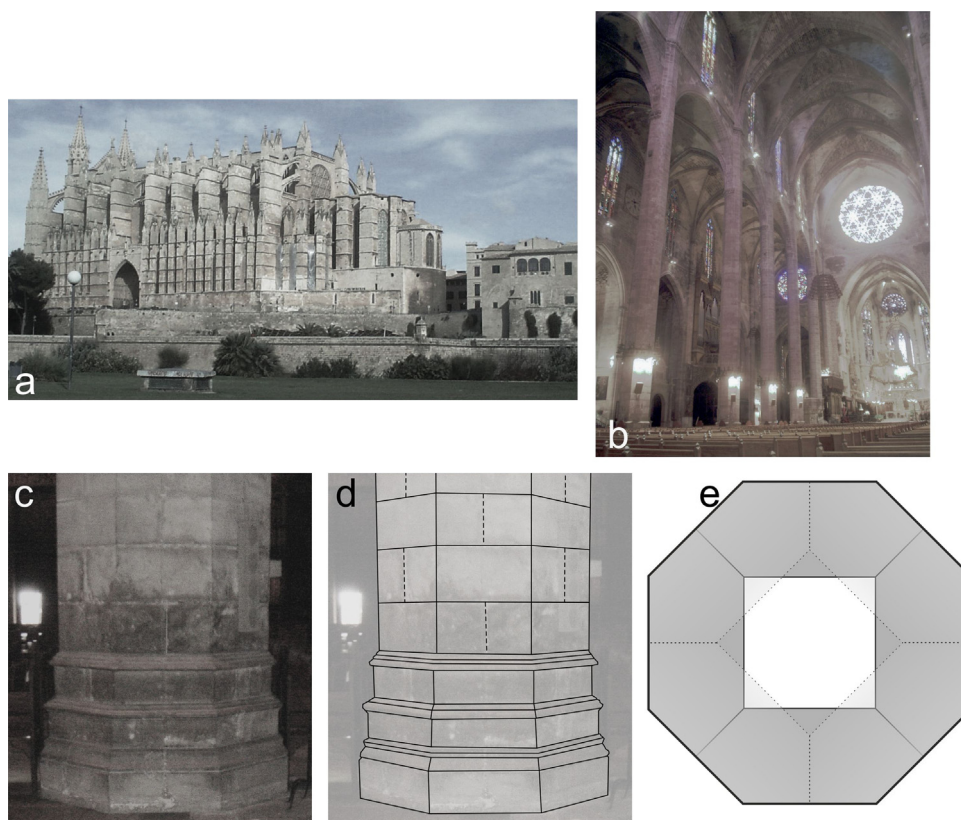


Fig. 1. (a) Mallorca Cathedral. (b) Lateral nave. (c) Detail of one octagonal column. (d) Ashlars distribution in the column (dashed lines indicate ashlars junctions). (e) Octagonal plant and inferred ashlars distribution in plant after NDT evaluation: dashed lines indicate the second ashlar row; the inner white square space was unknown material.

can reveal materials information related with mechanical properties. Moreover, seismic tomography needs an initial model. In many cases, uniform initial models are used. Notwithstanding, convergence of the problem is not always possible by applying those simplified models and, sometimes unreal solutions are achieved. In this way, GPR data could provide enough and valuable information of the inner medium, allowing to define a more accurate first model. As a result, seismic tomography iterations could converge to a more realistic final model.

2.1. Ground penetrating radar (GPR)

GPR is a well-known survey, widely applied to archaeology and cultural heritage [2,7,15,16,19,21]. GPR antennas emit electromagnetic short pulses (1–60 ns) near the VHF/UHF band (30–3000 MHz). The pulses are transmitted towards the studied medium. Reflection of these pulses is produced in interfaces between zones with different electromagnetic properties. There, part of the energy is returned to the surface, arriving to a receiver antenna, and part is propagated through the discontinuity. Receiver antenna incorporates an electronic circuit, “demodulator”, connected to the amplifier and receiver circuit; then, electromagnetic arrivals cause the generation of an audio frequency band pulse that is sent through a highly screened cable to the central unit, where the signal is reconstructed, processed and stored. Each received pulse is shown up as a track. So, moving the antenna on the medium surface, an image record is obtained revealing the existence of anomalies due to inner electromagnetic changes. The horizontal axis represents the antenna position, while the vertical axis corresponds to the two-way travel time (TWT). The conversion TWT into depths depends on the wave velocity knowledge. In the study of the cathedral columns, an average wave velocity could be properly estimated since dimensions

can be measured [15]. Notwithstanding, this value could be vary due to changes in the materials. Variations are expected in fracture or damaged zones because of the contrast between the air dielectric constant and the healthy limestone. Air in cracks produces most likely the wave average velocity increment. The average velocity of the wave in the medium depends on its different phases (solid or mineral components, liquid – usually water – and gaseous or air). The combination of phases determines the electromagnetic behaviour of the soil, including the wave velocity. Because the velocity in air is higher than in minerals, it could be expected that the presence of high number of cracks increases the velocity. In this way, damaged zones could be defined by evident changes on the wave velocity and appreciable reflections in discontinuities.

Resolution depends mainly on the material characteristics and on the wave frequency band. Higher the frequency, greater the resolution, and even the penetration depth diminishes [1,17]. Dimensions of constructive elements analysed in this work allow the application of 900 MHz and 1.5 GHz centre frequency antennas obtaining centimetric resolution.

Attending those previous considerations, the main objectives of the GPR study are the following:

- 1) To define the inner structure of columns, buttresses and walls.
- 2) To detect damaged zones, if existing, in columns due to internal cracks.
- 3) To define a proper first medium model using all this information. This model will be used in the seismic evaluation.

Walls inspection was carried out in three selected zones of the main nave wall (P1–P3 profiles in Fig. 2), in the other three zones in the north nave (P4–P6 profiles in Fig. 2), and another in the north front (P10 in Fig. 2). In each one of these zones GPR data was

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