

# Non-Destructive Techniques for the Assessment and Preservation of Historic Structures

## Table of Contents

### *Chapter 1 - Non-Destructive Techniques for the Assessment and Preservation of Existent Constructions*

**Luisa Gonçalves, Hugo Rodrigues, Florindo Gaspar**

The interventions in historic constructions are one way of preserving the cultural history of people, a region or even a country. Choosing the most appropriate way of intervening in a building should require a careful decision that always takes into account its historical significance, as well as bearing in mind a number of other concerns such as its physical condition, namely the knowledge of the pathologies or the degree of the integrity of the materials.

The present chapter gives an overview of some non-destructive technologies that provide the technical knowledge regarding data acquisition techniques that are used in the characterization and preservation of important monuments and common constructions, such as: multispectral images, geophysical data (GPR), flat-jack tests, infrared thermographic images, laser scanning data and ultrasounds, which are also applied and discussed in detail in each chapter providing a wide range of case studies based on real-world experience using samples gathered from different geographical realities.

### *Chapter 2 - Characterization of building stock and its pathologies: case study of the historical city centre of Leiria, Portugal*

**Tiago Gomes, Hugo Rodrigues, Florindo Gaspar**

The purpose of this chapter is to report on the survey of the different types of buildings present in the historical city centre of Leiria in Portugal. Over 75 buildings were surveyed in detail to determine their material and their current state of deterioration, and more than 200 were surveyed with a simplified approach. The cataloguing process of the building typologies is presented herein as a synthesis of the main construction forms. For the rehabilitation process it is essential to have a complete understanding of the buildings, and the pathologies to support qualified, conscientious and sustainable future interventions.

### *Chapter 3 - The use of Multispectral Images and 3D-GIS analysis for monitoring the state of conservation of buildings: case study of the historical city centre of Leiria, Portugal*

**Luisa Gonçalves, Ana Falcão, Tiago Cerejo, Andreia Almeida**

In order to preserve the historical centres, it is necessary, in a initial stage, to proceed with the assessment of the state of conservation of the buildings' roof materials. The traditional techniques used to obtain the information require an individual and in-situ analysis of each building, making it time-consuming and demanding for large areas under assessment. This chapter presents the application of multispectral aerial images with Very High Spatial Resolution (VHSR), in the monitoring of the state of conservation of roofs where building

degradation usually starts. The test was carried out using multi-spectral aerial images with a spatial resolution of 0.5 m, from different years of the historical city center of Leiria in Portugal. To extract the required information, a hybrid methodology was developed and a change detection of roofing materials and pathologies was carried out, using multispectral images from 2004 and 2010, respectively. For the map of roofing materials, it was found that the global accuracy was 90% and 72%, respectively, while for the roof pathologies, the global accuracy was 90% and 84%, respectively. This paper also presents the results of the 3D-GIS model developed for the historical city centre of Leiria, enriched with the pathologies information identified during the study. The final model allows an interactive system for the management, integration and presentation of historical urban geoinformation.

#### *Chapter 4– Mechanical Characterization of Masonry Walls with Flat-Jack Tests*

**Patrick Pinheiro, Paulo Fernandes, Pedro Santos, Hugo Rodrigues**

Flat-jack tests are presently used widely for assessing the mechanical characteristics of stone masonry all around the world. This technique remains one of the most versatile in situ test procedures for the estimation of the main mechanical properties of masonry walls. This chapter presents and discusses the results of an experimental field campaign of flat-jacks carried out within the scope of the rehabilitation process of the city centre of Leiria. At the end, similar tests performed in laboratory controlled conditions will also be presented to compare with the field results.

#### *Chapter 5 - 3D structural analysis to support the design facade retention system*

**Pedro Cardoso, João Veludo, Vitor Lopes**

The rehabilitation of existing buildings in urban centres, with the demolition and renovation of their interior, often requires the retaining of their facades, especially in constructions of heritage value or in dense urban areas. This can be a complex and expensive process. Nowadays there are several systems using different materials, steel or wood structures, modular or built specifically for each case study. The purpose of this paper is to present the facade retaining system studied for an old three-storey building developed with the aid of a numerical modelling. The building under study has a structure composed of masonry walls, wooden floors, and wooden partition walls called *tabiques*. The aim of this study is to characterize the building under different conservation conditions from the point of view of the mechanical characteristics of the materials and the influence that the arrangement of the structural elements, such as walls, floors, roof and contiguous buildings, has on the structural behaviour. The results of this analysis are compared with the dynamic analysis performed in-situ, using seismographs, thus enabling the calibration of the model.

#### *Chapter 6 – 3D structural analysis to support the rehabilitation of old masonry buildings*

**Nelson Silva, João Veludo, Pedro Santos**

The rehabilitation of the built heritage is fundamental to ensure the preservation of existing cities and to promote their economic development, creating new opportunities for residential housing, commercial and service activities. This activity is critical when the existing constructions were built using mainly materials such as masonry or timber, instead of concrete and steel.

This paper describes a case study involving an existing building, in the old centre of Leiria, where masonry and timber are the main structural materials. The construction is characterized (materials, construction method and techniques) and a 3D model of the building using the latest 3D CAD tools for structural analysis and detailing is presented. Special attention was given to stress distributions and deformations, as well as stress concentrations in critical zones (joints, section variation, etc.). An experimental study was performed to characterize the experimental behaviour of the interior wooden walls of the building, called *tabiques*, when subjected to compression loads, aiming to define the axial and bending stiffness. The main conclusions are presented, highlighting the difficulties linked to this type of analysis due to the lack of information about existing old buildings.

*Chapter 7 - Characterization and rehabilitation of one of the historical buildings of the Polotsk campus of the Polotsk State University*

**Yahor Lazouski, Aliaksandr Paprauka, Dzmitry Lazouski, Alexander Bakatovich**

The architectural ensemble of the Polotsk Jesuit Collegium is an 18<sup>th</sup> century monument of late Baroque architecture. One of its masonry buildings was almost totally damaged over its lifetime. The authors present their practical experience in the field of surveying, characterization and rehabilitation of this building (one of the PSU Polotsk campus houses, which is now situated in the ensemble of buildings of the ancient Jesuit Collegium). The short historical review of the building and Collegium, the non-destructive methods for the determination of the properties of the structural materials, the decisions on how to restore the carrying capacity and strengthening methods, which were applied to this restored building, are presented in this chapter. Special attention is given to the authors' improved method of increasing the rigidity of masonry buildings.

*Chapter 8 - Applications of GPR in the study of cultural heritage: examples of the ability of the method in assessing different features*

**V. Pérez-Gracia, S. Santos-Assunção, O. Caselles**

Cultural heritage buildings are often complex structures, with elements that are modified or added during different epochs. Irregular maintenance and modification of elements facilitate the appearance of pathologies. The visual evaluation of damage is often difficult and limited. Additional studies with non-destructive techniques (NDT) are often necessary to obtain enough information before rehabilitation tasks. Ground penetrating radar is an NDT tool widely used in cultural heritage assessment. However, results depend on the type of structure and on the problem under study. This chapter describes two GPR surveys in cultural heritage, showing its ability to obtain information depending on the case. The first case study is the assessment of masonry columns in an important Art Nouveau style of architecture, analyzing 2D sections and 3D radar images to detected targets embedded in the structure and to determine the arrangement of the bricks inside the column. Cracks observed in the visual inspection compelled an analysis of the damage. This study was supported with seismic tomography and two destructive tests: endoscopy and a load test of one column. The second case study is focused on the assessment of hidden wooden beams, detecting areas that need further analysis or direct actions to maintain the structure, because of possible significant damage.

*Chapter 9 - Survey and characterization of the Founder's Chapel pathologies of the Santa Maria da Vitoria Monastery - Batalha*

**Flávio Vazão, Florindo Gaspar, Hugo Rodrigues**

The Monastery of Santa Maria da Vitória, also known as the Monastery of Batalha, is one of the most beautiful examples of Portuguese and European architecture and has been part of the UNESCO World Heritage List since December 1983.

The construction took over 150 years, in several phases, and consisting of several styles namely: Gothic, Manuelino and some renaissance details. A number of changes were made to the initial project, resulting in a vast monastic complex that today includes a church, two cloisters with annexed dependencies and two royal pantheons, the Founder's Chapel and the Unfinished Chapels.

The built heritage, under the ambient conditions, even with a proper maintenance can have pathologies and defects due to the deterioration of materials, repeated loading and exceptional events. Within this process, inspection and diagnosis techniques play a major role, providing information and allowing the definition of adequate remedial measures. To start this procedure in the Monastery of Santa Maria da Vitória, the Founder's Chapel was selected for a detailed survey and to be subjected to non-destructive tests, using thermography and ultrasonic testing, a preliminary diagnosis with pathology mapping and laser scanning.

*Chapter 10 - Dynamic measurements as support to the assessment of the Monastery of Santa Maria da Vitoria - Batalha*

**Micael Pedroso, Hugo Rodrigues, Humberto Varum, António Arêde**

The present chapter presents the analysis of the ambient vibrations at the Monastery of Batalha. This monument is in the city centre of Batalha and close to busy roads. The vibrations caused by moving vehicles have led to more frequent structural and non-structural damage, especially in historical buildings. In this paper, traffic-induced ground vibration is measured, its characteristics in terms of distance to the road are discussed and limits are discussed and analysed. The results are compared with international standards of permitted vibration levels. Finally, the effects of the traffic-induced vibrations on the safety of the building structures adjacent to busy roadways are discussed.

*Chapter 11 - Rehabilitation of historical masonry buildings in Belarus: Case studies of Peter the Great's House in Polotsk and Liubcha Castle*

**Aliaksandr Bakatovich, Nadezda Davydenko, Aliaksandr Ivanenko, Anton Finogenov, Yahor Lazouski**

In this chapter, the results of the technical inspection of the monuments of the 16<sup>th</sup> – 17<sup>th</sup> centuries are presented. The main goal is to view the experience in the field of Belarusian rehabilitation of historical masonry buildings with two significant case studies: the house of Peter the Great, one of the attractions of the city of Polotsk, and Liubcha Castle with the use of Ground Penetrating Radar (GPR) for soil scanning and a Ferroskan device for the detection of metal elements in masonry. The non-destructive methods for monitoring the properties of the structural materials and the decisions on how to rehabilitate the historical view are also presented. With the help of a developed 3D architectural model of the castle complex, the authors designed the rehabilitation and restoration project.

*Chapter 12 - Optical and electromagnetic sensing for the inspection and characterization of ancient masonry arch bridges*

## **Mercedes Solla, Belén Riveiro, Susana Lagüela, Iván Puente**

This chapter presents the use of terrestrial laser scanning, infrared thermography and ground penetrating radar as suitable technologies for the inspection and characterization of historical masonry arch bridges. A brief introduction to the fundamentals of the technology is included. Methodologies for data acquisition are also included, discussing the most relevant limitations to take into account and some solutions to optimize the surveys. The different results that could be obtained with each technique for the evaluation of bridges are summarized, including some examples of application. Finally, a discussion is presented trying to define the possible complementarities and synergies between the techniques, which will be presented according to the challenges presented in each case study.

### *Chapter 13 - Ground Penetrating Radar for archaeology and cultural-heritage diagnostics*

#### **Lara Pajewski , Mercedes Solla, Melda Küçükdemirci**

This chapter offers a short overview on the activities carried out by Members of COST (European COoperation in Science and Technology) Action TU1208 “Civil engineering applications of Ground Penetrating Radar,” concerning the use of Ground-Penetrating Radar (GPR) and complementary non-destructive testing (NDT) techniques in archaeology and cultural-heritage diagnostics.

In most cases, archaeology exploits the great potential offered by the GPR techniques in limited areas and without complementing it with other NDT approaches, whereas the combined application of high-resolution prospection methods at the scale of landscapes and their integrated interpretation are still uncommon. Hence, this chapter starts with a rapid review of large-scale inspections carried out in Carnuntum (Austria) and Stonehenge (United Kingdom), where extraordinary results were obtained, leading to a new way of carrying out archaeological studies.

The chapter continues with a brief review of significant case studies where Members of the Action investigated structures of high historical value from different time periods, ranging from the 13th century BC to the modernist period and including tombs, monuments, cathedrals, buildings, bridges and statues.

A rich bibliography is provided, where the interested reader can find more information on the presented activities.

### *Chapter 14 - 3D reconstruction of the Roman site "Aquis Querquennis" by means of TLS and GPR methods*

#### **Iván Puente, Javier Sanjurjo-Pinto, Mercedes Solla, Rafael Asorey-Cacheda**

A 3D-GPR and LiDAR data acquisition were carried out on the Roman site of “AquisQuerquennis” (Bande, Spain), providing high resolution images and three-dimensional visualization. All the 3D images were georeferenced, which can be integrated in a Geographic Information System (GIS) environment. The purpose was to reconstruct the original design of the archaeological site through the integration of both a 3D model of the visible constructions and the 3D images of the underground space. The 3D-GPR data revealed the existence of some buried structures. A recent excavation conducted in the campaign of 2016 has confirmed such an interpretation.

### *Chapter 15 - Earthquakes, tsunamis and harbours. A geoarchaeological GPR-based approach for mapping the extent and magnitude of natural hazards and human structures in Ancient Falasarnaharbour*

#### **Michael Styllas, Klisthenis Dimitriadis**

Ancient coastal structures such as harbours and jetties, provide significant archeological and geological information about the interaction of humans with the natural environment. When such structures have been displaced by natural disasters such as earthquakes or even when they have been covered by tsunami deposits, triggered by major seismic events, a wealth of geophysical and archaeological information is to be revealed once excavated. However, excavations are costly and, if certain measures are not taken, can damage ancient and historical constructions, so non-destructive methods are employed instead, to reveal the complex information stored underground. In this chapter we demonstrate the multi-faceted usefulness of Ground Penetrating Radar (GPR) for revealing both geophysical and archaeological information at the archaeological site of Ancient Falasarna. The GPR profiles presented here revealed the extension of the harbour jetty and other smaller structures. Detailed mapping of the subsurface findings can direct future archaeological excavations. Furthermore, by utilizing the existing geological information from an excavated trench, we were able to groundtruth GPR profiles, to correlate them with tsunami deposits from historical (AD 66 and AD 365) earthquakes and also to map their lateral and vertical extents in the vicinity of the harbour. In the absence of detailed chronological information on earthquakes in the eastern Mediterranean region, deciphering the spatial extents of tsunami deposits with non-destructive methods, provides invaluable information about the tsunami characteristics (e.g. significant wave height, period, etc.) by means of inverse modelling and can greatly help to assess future risks of natural hazards.

#### *Chapter 16 - Ground Penetrating Radar for non - destructive structural imaging of ancient sculptures*

**K. Dimitriadis, I. Konstantakis, S. Avlonitou, I. Panagakos, G. Moraitou**

An innovative tool adapted to objects, using the Ground Penetrating Radar (GPR) method of geophysics, was developed by GEOSERVICE Ltd in collaboration with the Conservation Department of the National Archaeological museum of Athens and applied to ancient sculptures in order to locate with the maximum accuracy the metal dowels used in the past for joining the statues. The tool has been applied to the important marble sculptures from the Antikythera Shipwreck collection at the National Archaeological Museum of Athens and specifically to the statues: Wrestler, Hermes, Ulysses and Achilles. The main purpose was to evaluate their structural capacity prior to the transfer of the above statutes to the Antikenmuseum Basel und Ludwig Museum in Switzerland for a temporary exhibition. The success of the method was unexpected and reached the percentage of 90 % regarding the selected targets.