1. Introduction

Rehabilitation and preservation of historic monuments and ancient structures is attracting more and more interest in Portugal. However, the conservation of architectural heritage is a difficult task due to the complex geometry of buildings and large variability of construction materials. Such task requires substantial research work as well as construction techniques and materials different from those used in new construction. The tasks of inspection and diagnosis of ancient buildings require obtaining a certain number of parameters, which provide information about geometry and construction methodology, material properties, structural behaviour and possible defects. It is a multidisciplinary work that requires the contribution of different scientists and professionals in order to collect all the data necessary for the intervention. From a structural point of view, relevant issues are: geometry; wall section morphology; presence of voids, discontinuity and inclusions in the walls and piers; characterisation of mechanical behaviour and its parameters (state of stress, compressive strength, elastic modulus, Poisson ratio, etc.).

In the last decades, the strategic importance of historic buildings due to cultural and economical reasons caused a large increase in studies dealing with historic structures and materials. In the case of ancient clay brick masonry, studies have been focusing on the main mechanical properties (compressive strength and elastic modulus) and behaviour of the composite material (Binda *et al.*, 2000), retrofitting techniques (Binda *et al.*, 1999), seismic vulnerability, physical and chemical deterioration, pollution (Wijffels and Nijland, 2004; Cultrone *et al.*, 2000), among others.

Studies related to historic clay bricks deal mainly with physical, chemical and mineralogical composition (López-Arce *et al.*, 2003; Cardiano *et al.*, 2004; Pauri *et al.*, 1994), durability, deterioration agents (Wijffels and Nijland, 2004) and deterioration modelling (Cultrone *et al.*, 2000; Binda *et al.*, 1997; Binda *et al.*, 1996), neglecting mechanical properties. However, the mechanical properties of clay brick are very relevant as the strength and durability of masonry depend greatly on the mechanical characteristics of the brick.

Generally, the most important parameters to gather during the inspection of a masonry structure are related with the characterization of materials, geometry and construction techniques. Although the complete characterization of old materials can be a time consuming and expensive task, it is necessary to avoid erroneous assumptions and to provide the most efficient cost/benefit approach for conservation works.

Physical characterization is fundamental to estimate the resistance and durability of materials subjected to moisture actions such as saturation, freezing/thawing and salt crystallisation. The porosity and suction rates are particularly relevant as, generally, no precaution was taken to prevent water from penetrating into the materials.

The study on chemical composition of materials allows to identify the presence of compounds that can affect the durability of materials, together with contamination and resistance to environmental pollution.

Mechanical characterization is a fundamental task for structural purposes and safety assessment, being the compression strength a key parameter in the case of masonry structures. In fact, compressive strength of masonry in the direction normal to the bed joints has been traditionally regarded as the most relevant structural material property, at least until the recent introduction of advanced numerical methods for masonry structures.

Finally, the survey of geometrical data and structural integrity of historical buildings are needed for safety assessment. In fact, historic buildings are characterized by complex structural elements, constituted by irregular and several material layers, most of the time exhibiting damages that need to be detected and mapped. To reliably and non-destructively obtain this information, few methods exist. Boroscopy (Binda *et al.*, 2004; Binda and Saisi, 2002) is well known and widely used to obtain data about element thickness. It makes use of existing cracks and voids or, alternatively, of small holes drilled in the surface but only retrieves local information. Sonic and ultrasonic pulses produce elastic stress waves that propagate through the material. However, air prevents the propagation, and no information is generally obtained about layer constitution or thickness. Ground Penetrating Radar (GPR) is a technique based on electromagnetic waves and is able to map large areas continuously in order to detect any discontinuity.

Ground Penetrating Radar is a non-destructive technique that has been used in the last decade for the diagnosis of historic masonry structures (Binda *et al.*, 2004; 2003; 2000; Colla and Maierhofer, 2000; Colla *et al.*, 1997). It has reached a state of mature technique (Annan, 2002) although constant technological advancements in hardware and software contribute to an increase of its use and to an expansion of its broad range of applications (Reynolds, 2002).

Ground Penetrating Radar uses electromagnetic waves, which are sensible to the dielectric properties of materials and to their moisture content. These radiowaves are characterised by a specific frequency, which corresponds to the central frequency of the broad spectrum of frequencies emitted by the transmitter antenna. When a large contrast between dielectric

properties between adjacent materials or objects occurs, these electromagnetic waves are reflected towards the receiver antenna.

Masonry, and in particular ancient masonry, is considered a low-loss medium and, therefore, allows a good propagation of electromagnetic waves. Old masonry structures frequently exhibit cracks, voids and detachments adding to the presence of high amounts of moisture that results frequently in high contrast reflections in radar outputs. However, the complexity of geometry and the high level of material and structural heterogeneity that characterizes such old structures make results from GPR often difficult to analyse and interpret. Additionally, the large dimensions that characterise such structures are generally resolved by using medium to high frequencies, which can have an impact on the final resolution of the results. Nevertheless, the vast output possibilities and acquisition schemes allow GPR to be versatile enough to solve most problems.

1.1. Scope and objectives of the research

This research is two fold, aiming at the characterization of handmade clay bricks and the assessment of the Ground Penetrating Radar (GPR) non-destructive technique. The link between ancient clay brick and GPR is provided by the masonry wall, in which brick is often a basic constituent material and in which GPR measurements will be carried out. The knowledge of the materials that exist in a historic building is essential to assure a correct intervention, the use of correct replacing materials and to allow a minimal impact on the structure. Thus, the objectives related to clay bricks are the following:

- Characterization of the more relevant physical, chemical and mechanical parameters of Portuguese old bricks. For this purpose, samples from the 12 to 19^{th} centuries, belonging to six different monuments, have been considered.
- Characterization of new bricks traditionally manufactured, used as replacing material.
- Study of an innovative methodology based in the microdrilling technique to assess mechanical information of clay bricks from correlation curves.

The GPR investigation focussed on the following objectives:

- Assessment of the technique for the detection of the constitution of three-leaf stone masonry walls.
- Assessment of the technique for locating embedded elements inside masonry (wood, polystyrene and steel).

- Assessment of the technique for locating cracks and damaged areas.
- Application of novel non-standard post-processing techniques (3D volumes and tomography) and new high-frequency antennas (1.6 GHz)

1.2. Outline of the thesis

This work is divided in two main parts. The first one is dedicated to the characterization of old and new handmade clay bricks and the assessment of the microdrilling technique. The second part deals with the efficiency of Ground Penetrating Radar in assessing geometry and dimensional characteristics of ancient structures and locating deficiencies.

The first part is composed by three chapters. Chapter 2 presents a short state of the art about historic clay brick and a brief description of the most typical properties available in the literature. Chapter 3 reports the results from the characterization of old clay bricks and new handmade bricks. The main physical properties of old and new clay bricks related to the durability were assessed (porosity, water absorption by immersion, by capillarity and suction) as well as the compressive strength and the most important chemical constituents. Chapter 4 describes an innovative minor-destructive test (MDT) based in microdrilling in order to determine the drilling resistance of old and new bricks. The results are then analyzed in an attempt to establish satisfactory correlations between non-destructive tests and mechanical characteristics. Additionally, the chemical composition of old clay bricks was compared with a database of chemical compositions from archaeological remains using a multivariate statistical analysis with the purpose of determining the source of the raw clay. Finally, Chapter 5 is reserved for concluding remarks and recommendations for future work.

The second part is constituted by three chapters. Chapter 6 presents the Ground Penetrating Radar (GPR), with a short but concise description of the operative mode, main characteristics, limitations and main applications. Chapter 7 shows the results from GPR laboratory and field acquisitions in specially designed specimens and historic monuments from several European countries. The original objective of this investigation was to complement the research carried out previously (characterization of clay bricks) with radar experiments carried out in structural elements built with clay bricks, namely, three-leaf walls and arches. However, time and technical issues prevented the preparation of these specimens. Instead, alternative specimens were constructed with available material (three-leaf granite masonry walls). Finally, the conclusions of this second part of the work are presented in Chapter 8, with recommendations for future developments.