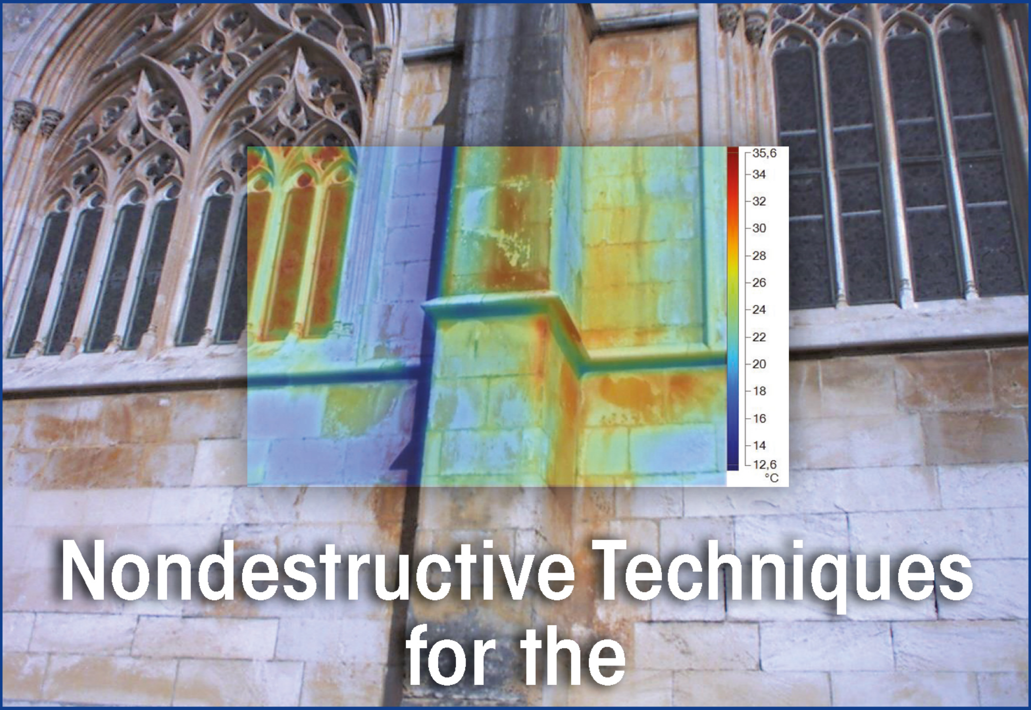
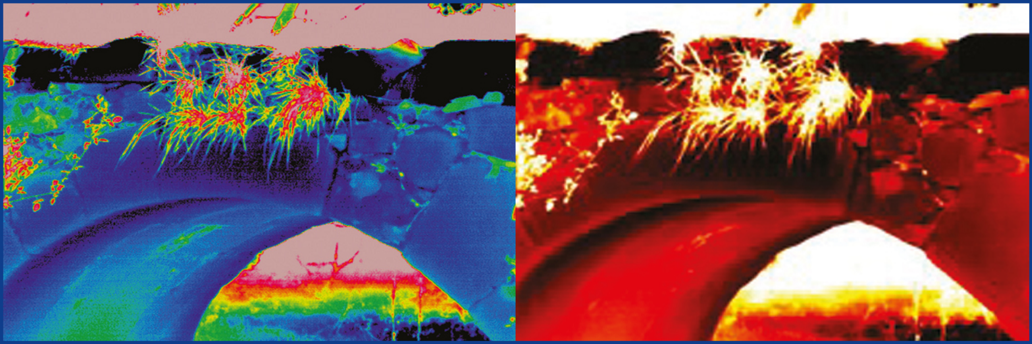


Nondestructive Techniques for the Assessment and Preservation of Historic Structures



Edited by

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Preface

The preservation of the built heritage has long been a public concern, mainly due to fears about the loss of identity, history and heritage of populations. The main concerns are the conservation and restoration of monuments that usually represent important events in the history of a city or a country. More recently, urban residents and policymakers have become aware of the abandonment or degradation of old city cores, leading to mischaracterisation of the buildings and ways of living.

To preserve history and promote building and urban renewal, considering the basic principles of the preservation process, it is important to introduce the least possible disturbance. To start with, the diagnostic process is a key aspect, especially to investigate the construction characteristics and the damage to materials, and to find structural and nonstructural problems.

To start any process, a visual inspection, a study and knowledge of the original construction methods and materials and historical repair techniques can help but may not be sufficient, and the use of conventional techniques to complement the information needed can result in an insufficient understanding or in extensive and unnecessary intrusions in the construction.

In recent years, the rapid growth of science and research, combined with the industry and the need to gather more and accurate information, have led to the fast development of nondestructive testing methodologies that allow the architectural archaeology to be studied, the structural assessment to be supported and information to be given about the material properties. Each technique can be used for a specific purpose, but, in some cases, only a combination of techniques is reliable and gives an accurate interpretation of the data acquired.

The fundamental contribution and aim of this book is to give a full overview of several case studies where different nondestructive techniques have been applied, in several cases using multidisciplinary approaches, which aim to highlight the importance of the information acquired and encourage the use of these techniques in future studies.

The book brings together 16 chapters focused on nondestructive testing techniques applied at the urban building level and also applied to monumental buildings, archaeology and cultural heritage, bringing together more than 40 international researchers and experts in the field, who are the source of practical case studies supported by a theoretical background.

Luisa M. S. Gonçalves, Hugo Rodrigues and Florindo Gaspar

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Editors

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Hugo Rodrigues is a senior lecturer at the civil engineering department of the School of Technology and Management, Polytechnic Institute of Leiria, Portugal, teaching several topics related to structural analysis, building pathology and rehabilitation. He received his PhD in Civil Engineering from the University of Aveiro in 2012. His experience is in seismic analysis, having participated as a team member in research and development projects, specialized consultancy studies ordered by several public institutions and companies regarding the assessment of seismic risk. His major research interests are building rehabilitation, structural health monitoring and seismic safety, including experimental and numerical activities. He is a research member of the RIsks and Sustainability in COnstruction (RISCO) research centre. He has co-authored more than 150 publications in top-tier peer-reviewed journals and national and international conferences.

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1 Nondestructive Techniques for the Assessment and Preservation of Existent Constructions

Luisa M. S. Gonçalves, Florindo Gaspar and Hugo Rodrigues

CONTENTS

1.1 INTRODUCTION

Interventions in historic constructions are one way of preserving the cultural history of people, a region or even a country. According to Violla (2012), investment policies and scientific research can act as a stimulus to communities, not only to protect physical assets but also to preserve construction methods, which include histories, and environments, thus supporting the sense of continuity and identity, which will lead to the promotion of a physical regeneration of monumental complexes, isolated buildings or city centres. 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. That is, it is necessary to understand the pathologies or the degree of the integrity of the materials. In addition, monitoring the conservation state of historical constructions is extremely important for planning any maintenance interventions, thus allowing the associated costs to be minimised. However, construction health monitoring usually requires a wide variety and combination of procedures, including traditional methods and new technologies, which always require (1) exhaustive on-site visual inspection; (2) sample extraction for laboratory analysis; and (3) detailed and time-consuming analysis of the data (Valença et al. 2013). Due to recent developments in digital equipment, new opportunities are emerging for construction assessment. Thus, research studies have focused on the development of digital technology applications for the analysis of heritage degradation and degradation-monitoring surveys (Zheng 2015).

The present chapter gives an overview of some nondestructive technologies. It provides technical knowledge regarding data acquisition techniques that are used in the characterisation and preservation of important monuments and common constructions, such as multispectral images, geophysics data (ground-penetrating radar [GPR]), flat-jack tests, infrared thermographic images, laser scanning data and ultrasound, which will be applied and discussed in detail in each chapter. Despite the availability of detailed overview information on these nondestructive techniques (e.g. Wehr and Lohr 1999, Lillesand and Kiefer 2000, Li et al. 2008, Moropoulou et al. 2013), there are always new data regarding the rapid development and the new applications used in cultural heritage, on the one hand, and on the other hand, facing the challenge of being capable of shedding new light on these new interesting techniques and application examples. Thus, the various chapters of this book provide a wide range of case studies based on real-world experience using samples gathered from different geographical realities.

1.2 NONDESTRUCTIVE TECHNIQUES FOR DATA ACQUISITION AND PROCESSING

1.2.1 Terrestrial Laser Scanning

1.2.1.1 Short Overview

The development of laser scanning (LS), also referred to as LiDAR systems (light detection and ranging), and its use on different platforms (airborne laser scanning [ALS] or terrestrial laser scanning [TLS]) go back to the 1970s. Laser scanning has revolutionised 3D data acquisition, and in contrast to the 'classical' manual data acquisition techniques, such as terrestrial surveying and analytical photogrammetry, these automatic recording methods allow an automated dense sampling of the object surface within a short time (Pfeifer and Briese 2007). Laser scanning systems constitute active sensing systems, which use a laser beam as a sensing carrier (Wehr and Lohr 1999), and they measure the time lag between the emission of a laser beam and the detection of its backscattered echo. These systems generate geometric results in terms of distance, position, intensity and coordinates (Ackermann 1999). The emitted beam travels through the atmosphere and interacts with objects along its path. The strength of the backscatter may be recorded as well, resulting in what is normally referred to as 'intensity', a value that is given as a digital number. The 'intensity' values recorded by laser scanning measurements are subject to a wide range of influences, such as spreading loss, surface roughness, object reflectivity and atmospheric attenuation. Although these data have been mainly used for visualisation purposes, the expectation is that the normalisation of these measurements will be suitable for classification purposes (Pfeifer and Briese 2007).

Terrestrial laser scanners mainly use round trip time measurements and phase-based ranging. Round trip time ranging scanners are better suited for outdoor operations where longer ranges are measured. The purpose of using the largest ranges probed with the pulse round trip time measurement principle is to obtain centimetre accuracy. Shorter distances, for example up to 100 m, can be measured faster and more accurately with the phase-based measurement technique. Shorter distances, for example up to 2 m, can be measured with even higher precision, for example, accuracy better than ±1 mm, with triangulation (Pfeifer and Briese 2007).

The difference between pulse round trip time scanners and phase-based difference measurement scanners in TLS, according to Pfeifer and Briese (2007), is that pulse round trip laser scanners have a higher range, while phase-based laser scanners have higher measurement speeds and better precision. In a triangulating laser scanner, the laser energy is widened so as to form a plane rather than a beam. This method of scanning is restricted in depth, because the quality of the intersection of a bundle of rays has a tendency to decrease with range. Therefore, this type of scanner is restricted to ranges of one or even a few metres. The precision is normally better than ±1 mm. Further information about this method can be found in Pfeifer and Briese (2007).

With the rise of low-cost 3D, imaging systems can be seen as an economic and available simple imaging alternative. These systems have the advantage of having much lower investment costs and are usually very user-friendly (Paulus 2014). In addition, they can be used without intensive training. However, common low-cost sensors have the limitation of a trade-off between range and accuracy, which provides either a low resolution of single objects or a limited imaging field.

For most applications, a single sensor is commonly not able to fulfil all the requirements. Thus, the use of multiple sensors is necessary (Dupuis et al. 2014). The advantages and potentials of the combined use of multiple sensors have been presented in Hall and Llinas (1997) and are also used nowadays in cultural heritage (Guidi et al. 2008). Dupuis et al. (2014) have recently developed an automated approach focusing on the fusion of unorganised point clouds that came from a different sensor using a characteristic 3D shape. The approach combines the advantages of using multiple sensors when measuring volume and resolution, and this leads to generating a multi-resolution map.

More information about the TLS technique can also be found in Chapters 12 and 14 of this book.

1.2.1.2 Applications of Terrestrial Laser Scanning Data

The field of applications for TLS and ALS is very diverse. Several studies have demonstrated that TLS can be considered an interesting option for acquiring a digital terrain model, archaeological site model or city model including the roof forms and the geometry of the facades (e.g. Ackermann 1999, Guidi et al. 2008, Lerma et al. 2010). Usually, imagery obtained with a digital camera is also acquired, so that the geometric model can be textured. This combination enables an efficient, flexible and reliable acquisition, with the advantage of a photorealistic representation, and is mostly used in terms of the documentation of cultural heritage (Dupuis et al. 2014). In the documentation of cultural heritage, laser scanning is applied, ranging from small artefacts of a few centimetres in diameter, to statues and monuments with a height of one or a few metres, up to entire buildings and castles (e.g. Guidi et al. 2008). The accuracy with which this can be achieved is dependent on the relationship between the LS point-sampling density and the size of the objects to be classified or modelled (Steel et al. 2003). Since the precision and measurement volume requirements are very diverse, more than one laser scanner is normally used to cover all the applications in cultural heritage. Figure 1.1 shows an example of scans acquired with two different TLS systems to obtain a 3D model of a thumb in the Santa Maria da Vitoria Monastery of Batalha.

Recent applications also show that this technology can be used not only to record the object geometry and play a role in record-keeping aspects, but also to protect against targeted degradation and to provide a more meaningful interpretation function (Zheng 2015). In Chapter 9, TLS was used to verify the verticality of the Founder's Chapel of Batalha's Monastery, and in Chapter 12, examples are presented of TLS application to ancient masonry arch bridges to obtain a quicker measurement of the visible geometry of the bridge, including its superficial pathologies, giving extra information regarding their sizes and depths, which are the latest indicators of their severity.

The integration of TLS with other nondestructive methods has also been used to improve the comprehension of interactions between different phenomena and to allow a better decision and planning process. In Chapter 14, a 3D reconstruction of the Roman site *Aquis Querquennis* (Bande, Spain) was performed using TLS data acquisition combined with 3D GPR data acquisition. The data were then georeferenced, and the hybrid outcomes were merged into a single image, allowing the reconstruction of the visible reality of the archaeological site with the integration of the unexcavated subsurface structures that were detected and their integration into a geographic information system (GIS).

FIGURE 1.1 Two scans performed in the Santa Maria da Vitoria Monastery of Batalha, Portugal, which were acquired with two different TLS systems.

1.2.2 REMOTE SENSING

1.2.2.1 Short Overview

Remote sensing is the science of obtaining information about an object, area or phenomenon through the analysis of data acquired by a sensor that is not in contact with the object, area or phenomenon (Lillesand and Kiefer 2000). However, remotely collected data can be in many forms, and in this section, only a short overview is presented of the electromagnetic energy data recorded by sensors that operate from drones, airborne or space-borne platforms, or even a terrestrial camera and their application for the evaluation and documentation of heritage structures. These sensors can be active (generating their own source of illumination) or passive (measuring reflected sunlight), and they record variations in the way the surface features of an object reflect and emit electromagnetic energy. Electromagnetic energy has many forms. In applications to assist in inventorying, mapping and monitoring heritage constructions, visible light, near-red, thermal and microwave energy are usually used.

To automatically extract information from the multispectral images provided by passive sensors, there are several classification methods, which use different approaches and methodologies. Classification methods are based on the fact that different objects have different spectral characteristics, and the wavelength is dependent on their reflective characteristics. However, many materials have similar spectral characteristics in one wavelength range and quite different ones in others (Lerma 2005). This allows the selection of a wavelength range that will enhance the characteristics of a surface to detect damage.

The most commonly used classifiers are supervised ones, which perform the classification in two phases: 1) training areas, which are descriptors of the spectral characteristics of the classes, are identified for each class in the image; 2) the results obtained in the first phase are used, so that one or several classes (if soft classifiers are used) are associated with each spatial unit of the image. Another important stage in the production process is the validation of the results, which is usually done when comparing the classification results with the reference data that are obtained from a sample of points, and using field observations or other sources of higher accuracy, which are supposed to represent the ground truth.

In the described classification process, there are many sources of uncertainty that influence the final results of the classification. Therefore, the obtained results depend on the choices made and the approaches used, such as the training sample chosen and the applied classification method (Doan and Foody 2007).

1.2.2.2 Applications of Remote Sensing

Since the launch of the IKONOS satellite, which was the first to provide very high-spatial resolution data, the increasing availability of new active and passive satellite sensors that provide very high spatial resolution data has opened up new application opportunities to document and evaluate heritage constructions (Agapiou 2017).

Remote sensing archaeological research, for example, has been increasingly motivated during the last decades, and especially after the launch of the IKONOS satellite sensor in 1999 (Agapiou 2017). Recently, Nebbia et al. (2016) used remote sensing and GIS to create a risk map of Libyan archaeological sites.

Some methods were also developed to obtain accurate information on construction materials and the pathology of building facades and roofs. This was carried out through an automatic classification of visible and near-infrared photographs (Lerma 2005, Valença et al. 2013) and the gathering of information on roofing materials and pathologies, which was achieved through an automatic classification of visible and near-infrared aerial images (Gonçalves et al. 2009). There are also algorithms capable of detecting discontinuities in multispectral images, such as cracks that were analysed through a series of variations of the intensity of the pixels (Gonzalez and Woods 2002, Dare et al. 2012). Since cracks can be regarded as discontinuities in an image texture, their characterisation can be automatically found (Dare et al. 2012, Valença et al. 2013).

Multi-scale and multi-temporal approaches have also been developed based on the use of interferometric synthetic aperture radar (InSAR), particularly persistent scatterer interferometry (PSI), to detect and map the effects visible at the surface of both vertical and horizontal urban dynamics, including the susceptibility of heritage assets to structural damage (Tapete and Cigna 2012, Pratesi et al. 2016). These kinds of images, obtained by active sensors, and approaches have been shown to be particularly useful in historic urban centres, where these dynamics typically add onto existing issues related to structural and/or geological instability, the maintenance of the built heritage and the management of infrastructures.

In Chapter 3, an application of multispectral images of very large resolution, taken at different dates, was made for the automatic detection of changes over time of buildings' roofing materials and nonstructural anomalies.

1.2.3 GROUND-PENETRATING RADAR

GPR is an electromagnetic pulse reflection method based on physical principles similar to those of seismic reflection. It is a geophysical technique for shallow investigations with high resolution, with several developments and new applications in the last decades. These geophysical methods are based on the emission of a very short electromagnetic pulse in a specific frequency band.

Frequencies between 10 and 1000 MHz are used for geological and engineering investigations, and frequencies higher than 1000 MHz are usually advantageous for material testing.

Usually, for monuments, the centre frequency of the antennae used is between 200 MHz and 1 GHz. The high-frequency antenna (1 GHz) is suited for very detailed and surface studies, and can be a useful tool for structure detail characterisation; it is used in the detection of cracks, estimation of wall thickness, and detection of humidity inside structures, different elements, reinforcing steel bars, and so on. For subsoil investigation, depending on the objective of the use, in the first 2–3 m, a 500 MHz antenna can produce a very high-resolution map. However, for higher depths, lower-frequency antennae are more useful (Arias et al. 2007).

The antenna is moved over the area under study, and an image of the shallow subsurface under the alignment used is obtained. The results are images representing the reflections detected, which are representative of the two-way travel time of the pulse emitted.

For the particular case of building rehabilitation, the investigation of the characteristics of building materials, changes to the original construction, the foundation, and the pathologies and characteristics of the sub-soil are usually required. For this, it is necessary to use nondestructive techniques, among which GPR can be significant as a result of its ease of implementation and reliability of results.

More information about GPR techniques can be found in the literature (Blindow et al. 2007, Conyers 2013, Annan 2009) and also in Chapters 12 and 15 of this book.

1.2.3.1 Applications of Ground-Penetrating Radar

Regarding the employment of GPR techniques for the evaluation of monuments and existent buildings, several cases can be found in the literature. In the key points observed in the majority of the works, a multidisciplinary approach has been used, combining LS, GPR, acoustic, electrical and radar methods supporting the finite element analysis in a final stage.

In monuments, GPR techniques are used in the geometric survey to estimate homogeneity or heterogeneity (Arias et al. 2007, Leckebusch 2000). Ranalli et al. (2004) used the GPR surveys in a medieval church located in L'Aquia with a view to planning the restoration, aiming at the collection of data on wall thickness, internal masonry structure and the location of detachments or cracks. The campaign allows the more degraded zones to be detected and reveals variations in wall thickness, enabling these data to be taken into account in the structural assessment of the monument. Costa et al. (2016) performed the calibration of a numerical model of a stone masonry arch railway bridge using dynamic modal parameters estimated from an ambient vibration test. To define the bridge geometry, GPR tests were performed to obtain the profiles of outer facings of the bridge located in abutments, piers and spandrel walls.

Barraca et al. (2016) used GPR techniques in a masonry house to investigate information for the rehabilitation process (namely, the local geological conditions), map infrastructure networks, locate removed or altered elements, understand modifications and changes in the construction materials, and characterise pathologies and fracturing. The main issues found were related to the choice of antenna, detecting the signatures of different materials, among other things, due to the lack of past experiments with controlled walls.

The use of GPR for the assessment of existent constructions can be a powerful technique. However, it requires a strong background of experience to help in the correct interpretation of the results obtained (Binda et al. 1998). The application of the GPR technique in monuments as well as regular constructions for the detection of pathologies and defects, voids, internal structural elements and a connection between elements, among other things, can encourage the regular use of these techniques not only for research purposes but also for practical architectural and engineering applications. Thus, several application examples are presented in this book, including applications for the inspection and characterisation of ancient masonry arch bridges (Chapters 12 and 13), archaeological prospecting (Chapters 13 through 15), and the assessment of monuments and historical buildings (Chapters 11 and 12), specifically the assessment of masonry columns and wooden beams (Chapter 8).

1.2.4 INFRARED THERMOGRAPHY

Thermography consists of the colour mapping of a particular body or object referencing the different temperatures. Infrared radiation is emitted by the body's surface, and an infrared camera receives the information and converts it into a colour scale. The fundamentals of this technique are given in Chapter 12.

Passive thermography corresponds to the use of natural heat sources, such as solar radiation or the slowly varying temperature of a microclimate, whereas active thermography uses a noncontact thermal input onto a surface of the inspected body by means of lamps, hot or cold air guns, or devices making the surface vibrate. The temperature of the surface around the excited area is measured by infrared thermography, either during or after the application of a thermal input at a suitable frequency (Grinzato 2012). The thermal input can be applied using pulse thermography, performed by stimulating the object with a heating pulse and monitoring its surface temperature evolution during the transient heating or cooling phase, or with a lock-in thermography technique using thermal waves and resulting in sinusoidal temperature modulation (Carlomagno et al. 2005). Sfarra et al. (2016) proposed an innovative hybrid approach combining both the time component and the solar source to obtain quantitative information, such as the depth of the defect. This approach could be useful for the estimation of the depth of small defects that appear inside vertical known structures.

Thermography is used not only for construction surveys but also in other fields, such as mechanics, electronics, and the chemical, aeronautical, medical and military areas (Balaras and Argiriou 2002). In civil engineering, it is useful to distinguish different types of materials as well as heterogeneity, cavity detection, moisture and the degradation state.

Several works have used thermography for heritage inspection and conservation. Passive thermography was used by Grinzato et al. (2002b) to monitor the Scrovegni Chapel (Padova, Italy), to easily detect hidden structures made of different materials buried in the walls and to identify thermal bridges. Pantoja (2016) analysed the architectural complex of Mercedários (Belém do Pará, Brazil). The thermograms generated by the infrared camera allowed the traces of the transformations to which the building had been subjected, such as alterations of forms and closures of openings, in addition to hidden structures in the edifice, to be verified. Freitas (2016) used this technique to identify areas that had lower temperatures due to the presence of water evaporation on the surface at the Diocesan Museum of Mantua (Italy). Avdelidis and Moropoulou (2004) concluded that the recording of thermal images of the surfaces under investigation provided significant information for the assessment of the materials and techniques used in protecting cultural heritage. In particular, it can be used efficiently for the assessment of conservation materials and techniques on the subject of surface cleaning, stone consolidation and the restoration of masonry with repair mortars. Passive thermography was used in the survey and characterisation of the Founder's Chapel pathologies at the Monastery of Batalha, as described in Chapter 9.

Active thermography was used by Więcek and Poksińska (2006) to show the invisible structure under the gothic plaster work at the Castle in Malbork (Poland). In the study by Cennamo (2013), defects of mechanical relevance were detected, such as cracks and crevices at the bell tower of Sagittarius and the grange of Ventrile, located in the province of Potenza (Italy). Merla et al. (2009) applied this technique to the historical cultural heritage damaged in the L'Aquila earthquake for crack detection in buildings after the earthquake and moisture detection in frescoes. This technique has proved itself capable of helping to find detached tiles in mosaics at the Archaeological Museum of Naples and the degradation of plaster and frescoes at the archaeological site of Pompeii (Meola 2013). At the historical Arsenal of Venice, active thermography has been applied successfully to enable the understanding of wall bonding, moisture mapping, and the measurement of the thermal diffusivity of bricks and plaster to take place (Grinzato et al. 2002a).

Thermography has also been used in combination with other techniques. Different techniques, such as infrared thermography, ultrasonics and electric-type geophysical methods, were analysed to acquire information on the synergic use of the different methods, which may be useful for the estimation of the sources of the buildings' degradation (Meola et al. 2005, Carlomagno et al. 2005).

1.2.5 FLAT-JACK TESTS

1.2.5.1 Short Overview

One of the main aims of the nondestructive tests is to study the mechanical characteristics of the materials, and this acquires significant importance when the objective is to characterise the mechanics of old construction materials, and in particular masonry structural elements, due to the variability of the materials and their heterogeneity, combining materials with different properties (Binda and Tiraboschi 1999). There are several ways to characterise the material properties, but in many cases, samples cannot be removed for laboratory testing due to the dimensions of the elements and the historical value of the construction under study. The development of nondestructive mechanical testing techniques can play an important role in characterising the properties of materials, and the flat-jack testing technique has been used to accomplish this objective. With this test method, it is possible to determine in situ the properties of undisturbed masonry specimens of large dimensions with minor, controlled and reparable damage. The basis of the flat-jack testing was primarily applied in the field of rock mechanics (Rocha et al. 1966) and later adapted by Rossi (Rossi 1982) for use with masonry. Two tests can be performed with the same technique: the single flat-jack test and the double flat-jack test (Gregorczyk and Lourenço 2000).

The single flat-jack test is used for the assessment of the in situ compressive stress in existing structures (Figure 1.2a). After the cut is done, the installed compressive stress causes the masonry above and below the cut to get closer. The flat-jack will introduce pressure until the original distance between points above and below the cut is re-established. The existent compressive stress in the masonry is estimated from the flat-jack pressure multiplied by factors that account for the ratio of the bearing area of the jack in contact with the masonry to the bearing area of the cut, and the physical characteristics of the jack.

Another possibility is to perform a double flat-jack (Figure 1.2b) after the single flat-jack tests, which allows the stress-strain behaviour under compressions of the masonry wall to be assessed. The test is carried out by inserting two flat jacks into parallel cuts, and the flat-jack pressure is gradually increased, with a monotonic or cyclic load introducing a compressive stress on the masonry between the cuts.

1.2.5.2 Applications of Flat-Jack Tests

The flat-jack test provides a relatively nondestructive way of determining the in situ mechanical properties of masonry. This testing technique has been successfully used in regular brick and stone masonry structures, but its practice on rubble stone masonry structures is not so common. In these cases, the experimental procedures have to be adapted and calibrated (Binda and Tiraboschi 1999).

These testing methods are described by the American Society for Testing and Materials (ASTM 1991) and the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (Reunion Internationale des Laboratoires et Experts des Materiaux, Systemes de Construction et Ouvrages) (RILEM 2004).

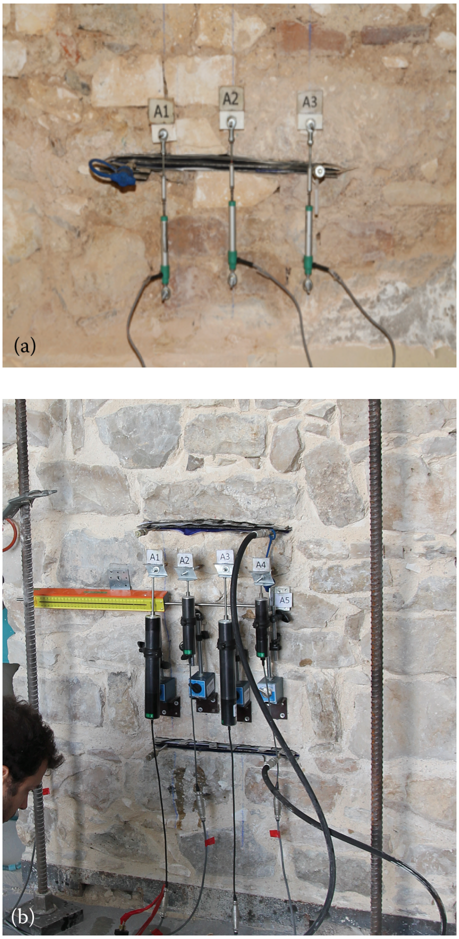

FIGURE 1.2 (a) Single flat-jack test; (b) double flat-jack test.

The flat jacks have been used in two main applications in terms of monuments: aiming to use the results for either a particular study of a building or an element of a monument (Binda et al. 2003, Carpinteri et al. 2005). In these cases, the flat jacks have also been combined with other nondestructive techniques, in particular with acoustic emission. Although it is difficult to obtain an easy direct relationship with other nondestructive techniques, the combined use increases the accuracy of the obtained results (Carpinteri and Lacidogna 2005, Binda et al. 2003).

Another case of a flat-jack application is its use to characterise the main properties of masonry walls in urban city centres, as in the case studies of Coimbra (Vicente et al. 2015a), Lisbon (Simões et al. 2015) and L'Aquila (da Porto et al. 2013, D'Ayala and Paganoni 2011). In the case presented in Chapter 4, single and double flat-jack tests were applied in four sites located in the city centre of Leiria, giving average results about the mechanical properties of the masonry infill, but also showing the heterogeneities found in the different buildings. In these cases, it is recognised that a large number of flat-jack tests are required to obtain reliable results regarding mechanical properties such as the maximum compressive strength, elastic modulus, which can be linked with the morphological and constitutional features of masonry walls and the state of conservation, so as to coherently establish the correlations among all of them (Vicente et al. 2015b).

1.2.6 ULTRASOUND

The purpose of this technique is to relate the properties of a material with the velocity of propagation of the ultrasound. Through the emission of ultrasonic pulses in the material and its reception at a certain distance, the speed of the waves crossing between these two points (emission/reception) is obtained by the following equation:

$$V = \frac{L}{T} \tag{1.1}$$

where:

V (m/s)	is the ultrasound propagation velocity
L (m)	is the distance between the transducers
T (s)	is the transfer time of the ultrasound between the transducers indicated by the equipment

Three basic types of stress waves are created: longitudinal, shear and surface waves. Generally, the propagation is the fastest for longitudinal waves and the slowest for surface waves (Meola et al. 2005).

The use of ultrasound allows an efficient nondestructive evaluation of various materials, and it can be very useful in determining their characteristics and state of conservation.

The velocity variation is due to the density change. The more the density increases, the higher the ultrasound velocity will be.

Usually, ultrasound measuring devices consist of two transducers: one of them will have the function of transmitting and the other of receiving. There are three methods of performing the test: direct, semi-direct and indirect (Coelho 2010).

In the case of stone characterisation, it is possible, through the variation of the ultrasound velocity, to detect different values due to cracks, porosities, grain reorganisation or degradation due to weathering damage (Moreira 2013) or to make a quality classification (Kahraman et al. 2007).

Several works have used ultrasound for heritage inspection and conservation. Moreira (2013) performed ultrasonic tests on granite stone for the determination of some mechanical properties at the church of Nossa Senhora da Conceição (Porto, Portugal). Bromblet et al. (2012) performed long-term monitoring of the degradation of stone columns in the Church of Saint-Trophime of Arles in France. The first investigation took place in 1993 and the second in 2009. The velocity propagation results of the two campaigns, separated by a 16 year period, were compared, and the columns were separated into five classes of damage. Köhler et al. (1996) used ultrasound to analyse the stone material of the west portal of St Stephen's Cathedral in Vienna. By combining visual inspection with ultrasonic transmission measurements, all the stone elements could be clearly defined in terms of their lithotype. Binda and Saisi (2001) used ultrasonic tests and flat-jack tests together with other minor tests for the study of three similarly damaged cases of Italian church pillars: the Cathedral and the SS. Crocifisso Church in Noto, and the S. Nicolò l'Arena Church in Catania. Grossi and Lama (2015) used ultrasound velocity measurements to assess the state of the stone conservation of the Monument to Ramos de Azevedo (São Paulo, Brazil). Tavukçuoğlu et al. (2010) aimed to discover the thermal behaviour and ultrasonic characteristics of cracks in relation to the depth and the moisture content of the Cenabi Ahmet Paşa Camii, a sixteenth-century Ottoman mosque in Ankara. In Chapter 9 of this book, ultrasound was used in the survey and characterisation of the Founder's Chapel stone at the Monastery of Batalha. Ultrasound has also been widely applied in the nondestructive evaluation of wood (Bucur 2006) to evaluate decay, helping to map the damaged areas (Carrasco and Teixeira 2012), density and mechanical properties (Liñán and Hita 1995).

Several examples can be found of the use of ultrasound for heritage inspection and the conservation of wooden elements. Gatto et al. (2012) aimed to detect the external degree of decay of the wood *Araucaria angustifolia* (Bert.) O. Kuntze species, used in flooring in the historic building of Pelotas (Brazil). Conde et al. (2014) assessed the conservation status of the wooden frame of a building of great historic value known as 'El Corral del Conde' located in Seville (Spain), evaluating the compression strength and density loss due to deterioration of the elements. Estimation of density loss and strength was also done at the Ntra. Sra. de la Granada church (Spain) (Conde et al. 2013). Liñán et al. (2004) obtained the state of damage and the bending strength capacity of the timber roof of the Monastery of Santa Clara in Carmona (Seville). Kandemir-Yucel et al. (2007) applied this technique to timber samples on a thirteenth-century monument, Aslanhane Mosque in Ankara (Turkey), to find changes in moisture content due to microclimatic conditions. Liñán et al. (2015) used ultrasound and thermography techniques for the on-site inspection of wooden structures and the evaluation of their condition in a twentieth-century church in the town of Isla Cristina (Spain). Thermography identifies different materials and moisture content, while ultrasound detects the various degrees of deterioration and loss in density in areas of the wood with high moisture content.

1.2.5 BUILDING SURVEYING AND APPRAISAL

1.2.5.1 Short Overview

Building surveying and appraisal is an essential tool for monitoring the behaviour of a construction, allowing preventative maintenance, repair and rehabilitation.

It is fundamental that a specialist assesses in detail the conservation state of a construction, looking for problems or requirements of the structural and nonstructural elements that describe the actual condition of a construction in relation to its use, using the past, the actual use and future demands as a decision-making tool for future interventions and use of the construction.

Whatever the reason for evaluating or assessing the construction, these actions represent cost and time, and the results should be important in the decision-making process.

There are several ways of characterising and classifying the surveys and appraisals. One important aspect is the nature of the survey, whether it is used for continuous assessment, assessing the construction conditions along with the construction life cycle, or monitoring the changes with time to support maintenance and conservation work. The survey can also be related to a specific moment of the construction, capturing the image and state of conservation and showing the state at a specific moment in time of the construction.

Another use of surveying and appraisals can be applied to a large number of constructions. These surveys are used to assess the state of conservation of building stock, for example, in an old city centre, to support urban planning and to define rehabilitation policies. These surveys are usually performed using generic inspection sheets with checklists for the different construction parts. A significant volume of information is gathered, which is usually difficult to work with. The design of the database to work with this information needs to be carefully prepared to enable significant information, useful for the assessment and decision process, to be extracted.

1.2.5.2 Applications

Building surveying and appraisals have been widely used for research and in practical cases, for rehabilitation, conservation and/or strengthening a building, as well as characterising the state of existent constructions. In fact, the application of any nondestructive test should only be performed after a careful visual survey of the building or site conditions (Kordatos et al. 2013, Moropoulou et al. 2013).

Two different examples can be given for different types of structures. For the assessment of historical buildings, a preliminary on-site visual survey is performed to observe and record the prominent features of the building and of its immediate surroundings, converted into a detailed map locating areas of potential risk (Tavukçuoğlu et al. 2005). Similar procedures can be found for recent structures, where the results of the nondestructive test methods were used, for example, to reinforce a concrete bridge, so as to verify the preliminary conclusions of the visual survey (Choi et al. 2016), among many other examples in literature.

Visual surveys can also be applied after catastrophic events, such as earthquakes, for a construction or on a large scale. In these cases, visual damage interpretation allows the interpretation of the different behaviours of different types of structures and assists in defining guidelines for future construction practices for the country and surrounding regions (Gautam et al. 2016, Romão et al. 2013, Dolce et al. 2006).

Finally, and due to the urban regeneration of several historical city centres, the use of building surveys to characterise the global building stock has a strategic role in supporting the decision and implementation of the construction process. Several examples can be found in the literature, and in Chapter 2, the results of a survey of the historical city centre of Leiria are presented, with two levels of inspection, a preliminary inspection and a detailed inspection, which enable a clear picture to be formed of the main architectural characteristics of the city centre, the types of buildings, their uses, the state of conservation and the main pathologies. Similar studies have been promoted not only in other cities in Portugal (Santos et al. 2013, Vicente et al. 2015a, Lourenço et al. 2006, Furtado et al. 2016) but also in other cities around the word (da Porto et al. 2013, Theodoridou et al. 2011), which highlight the differences in the construction technologies and the main pathologies observed for the same countries and for other regions. Also, the surveys and characterisation of the building stock can be used to define and study other issues, such as energy efficiency, on an urban scale.

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