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State-of-the-art non-destructive methods for diagnostic testing of building structures – anticipated development trends

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The paper presents a survey of state-of-the-art non-destructive diagnostic techniques of testing building structures and examples of their applications. Much attention is devoted to acoustic techniques since they have been greatly developed in recent years and there is a clear trend towards acquiring information on a tested element or structure from acoustic signals processed by proper software using complex data analysis algorithms. Another trend in the development of non-destructive techniques is towards assessing characteristics other than strength in elements or structures, particularly the ones made of concrete or reinforced concrete. The paper focuses on techniques suitable for: detecting defects invisible on the surface, estimating the depth of cracks, determining the dimensions of elements accessible from one side only and 2D and 3D imaging of reinforcement distribution in such elements. Finally, directions of further development in this field are indicated.

Keywords: *non-destructive methods, building structures, diagnostic testing*

1. Introduction

The methods used in the diagnostic testing of building structures are divided into destructive, semi-destructive and non-destructive methods. Destructive tests can be applied to samples and natural-scale structural elements. Both are destroyed in the tests. For this reason only a few representative natural-scale elements are subjected to such tests. Semi-destructive tests are also applied to samples and natural-scale elements and structures and they involve a small (usually superficial) intrusion into the structure of the material, resulting in local loss of service properties and requiring repair. There is no such intrusion in the case of non-destructive tests which are applied to mainly natural-scale elements and structures. Moreover, non-destructive tests can be applied to the same elements and structures many times and at different times whereby such methods are suitable for the diagnostic testing of building structures during both their erection and the many years of their service life [3, 9].

Figure 1 shows a classification of non-destructive methods suitable for the diagnostic testing of building structures. The classification is based on [1, 4–5, 8–9].

This paper presents state-of-the-art non-destructive methods for the diagnostic testing of building structures and examples of their application. Much space is devoted to acoustic methods. The latter are being intensively developed and there is a distinct

1.4 UNDERSTANDING THE NDE CHOICES

Once we have decided to employ NDE methods to improve product quality or ensure the integrity of a part, there are several levels to choosing an appropriate NDE method for a specific application. We must have a sense of what NDE methods would maximize the likelihood of detecting the flaw or material property of interest, while also considering economic, regulatory, and other factors.

The basic levels of choosing an NDE method are:

1. Understanding the physical nature of the material property or discontinuity to be inspected
2. Understanding the underlying physical processes that govern NDE methods
3. Understanding the physical nature of the interaction of the probing field (or material) with the test material
4. Understanding the potential and limitations of available technology
5. Considering economic, environmental, regulatory, and other factors

To employ any NDE method, we need to have a reasonable knowledge of what we are looking for—material properties, a discontinuity such as a void or crack, sheet or coating thickness, etc. For material properties, we might be interested in the mechanical properties (elastic constants) or electromagnetic properties (conductivity, permittivity, or magnetic permeability). For discontinuities, we must not only be aware of their character, but also understand its relationship to the parent material, e.g., a crack in a ceramic is very different than a crack in a reinforced polymer composite.

We must also have a basic knowledge of how the various NDE methods work. For example, eddy currents use a magnetic field to create induced currents in the test part as the interrogating field. Thus, eddy-current methods require the test part to be electrically conductive. In addition, we must understand the interaction between the operating principles of the NDE method and those of the property or characteristic of interest in the test part. This is required (a) to determine if a given method will work, (b) to select a method in case of multiple choices, and (c) to determine the compatibility of the method and the part; for example, most ultrasonic methods require a coupling fluid or gel that might contaminate or cause corrosion of sensitive parts.

Non-destructive techniques as a tool for the protection of built cultural heritage

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HIGHLIGHTS

- NDTs are valuable for the protection of built cultural heritage.
- NDTs can assess the preservation state of materials and structures.
- NDTs can evaluate the efficiency of restoration/protection interventions.
- NDTs are integrated into information systems for effective planning of interventions.

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ABSTRACT

Recent technological developments in the field of non-destructive techniques have enhanced their usefulness in the field of built cultural heritage protection, and are indispensable tools for the characterisation of materials, detection of wear and degradation of materials, assessment of interventions' effectiveness and evaluation of compatible materials and processes. State-of-the-art techniques such as digital image processing, infrared thermography, ground penetrating radar, ultrasonic testing and fibre-optic microscopy, and their respective signal and image analyses, validated by in-lab analyses, allow the successful implementation of an integrated approach for the protection of built cultural heritage which encompasses scientific support to decision making.

1. Introduction

The sustainable maintenance, preservation and revitalisation of built cultural heritage, and in particular historic sites and monuments, have been the focus of significant efforts from the scientific and technical community. In the past, decisions regarding conservation interventions and protection of monuments were largely based on prior experience, on inadequate and non-systematic identification of the prevailing problems and on available technological resources. This approach, however, limited the effectiveness of the implemented interventions, whereas, in some cases even caused more decay to the monuments.

Although a large array of analytical techniques are available, that can be used in the field of built cultural heritage protection, the difficulties associated with the accessibility and irreversible destructive sampling on monuments do not permit extensive use of such available analytical resources. In contrast, the use of Non-Destructive Techniques (NDTs) that can be applied in situ and do not require destructive sampling, is preferred. Recent research and developments on their sensors and associated data analysis software have enhanced their usefulness and are nowadays an indispensable tool in the field of cultural heritage protection for the characterisation of materials, detection of their wear and degradation, assessment of the effectiveness of interventions and evaluation of compatible materials and processes applications.

Decay of the building materials can be defined as the degradation over time of the materials' properties (physical, chemical, mechanical, etc.) and characteristics (mineralogical, texture, etc.), leading to their failure as building components. Decay phenomena develop at the interface of materials with the environment or at the interface of materials with other materials and are a function of intrinsic and extrinsic factors. The analysis of these factors is essential to the study of the decay pathology of the monument, but also in helping to elucidate the information obtained by the NDT. Intrinsic factors include the type of building materials, their properties, their mass distribution, their origin and the processing technology, their "history" (prior conservation interventions) and their compatibility with other materials.

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Application of gamma ray scattering technique for non-destructive evaluation of voids in concrete

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HIGHLIGHTS

- ▶ Improved gamma scattering technique for NDE of voids in concrete.
- ▶ A unique algorithm to calculate the path length in each scattering voxel.
- ▶ A novel attenuation correction and density reconstruction method.
- ▶ Three dimensional images of the concrete samples with voids reconstructed.

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ABSTRACT

This paper describes application of the gamma ray scattering technique for NDE of concrete voids. A novel nonlinear extrapolation method is employed to correct for self-absorption and multiple scattered intensities. The attenuation data obtained from transmission method is employed for reconstruction of scattered images and the results show a good agreement in size and position of the voids with good spatial resolution. Intercomparison of the results of scattering and transmission techniques shows a good agreement in the position of the voids.

1. Introduction

A particular area of interest for Non-Destructive Testing and Evaluation (NDT, NDE) techniques is detection of defects in concrete structures. Moreover, NDE techniques are useful for condition assessment of concrete structures. The most common defects present in concrete are internal cracks, voids, shallow delamination, honeycombing and surface opening cracks. The main NDT techniques used to inspect concrete structures are ultrasonic, ground penetrating radar, impact echo, electromagnetic techniques and radiography. In the case of reinforced concrete structures, these techniques are expected to provide information about thickness variations as well as the inclusions such as the reinforcing bars, cracks, voids and delamination, deteriorated zones and moisture. The durability of concrete is influenced by factors such as cracks, voids and delamination. The development of NDE techniques to meet the following needs would bring high benefit: detection of corrosion in steel liners that are buried (covered by concrete) and detection of voids in concrete. Detection of defects before they propagate to the point of causing failure is very essential and techniques such as ultrasound and radiography generally provide only qualitative information. Hence, they are not practical for measuring the dimensions of structure, mapping density distributions, or for precisely locating, orienting and sizing the defects. In addition, the complex geometry of the concrete structure, restricted accessibility, and presence of reinforcement and prestressing tendons further complicate the problem. The goal of any NDE technique is to detect and locate the anomalies with in an optically opaque concrete medium through appropriate imaging techniques.

Imaging of concrete structures is very important due to the aging and deterioration of infrastructures (Buyukozturk, 1998). NDE of concrete structures through imaging presents many challenges, since concrete is a non-homogeneous composite material having variable grain size distribution and different properties of each constituent materials. Imaging can be achieved using techniques such as radiography, radioactive computerized tomography,

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Influence of carbonation depth on concrete strength evaluation carried out using the SonReb method

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ABSTRACT

The structural evaluation of existing concrete structures is becoming everyday more important for several reasons ranging from their seismic assessment to the presence of increased design loads, from the damage caused by fire to forensic investigations and so on. Whilst it is generally recognized that concrete coring provides the most reliable information on concrete strength, it should also be mentioned that this kind of test is responsible of slight damage to the structure and that it can be carried out only for structural elements with sufficient spacing between the reinforcing bars. Thus, it would be highly desirable to obtain reliable information by means of non-destructive techniques (NDT). One of the major drawbacks of the well-known combined method SonReb is the effect of the carbonation on the rebound number. In this paper two correction formulas for this index based on the thickness of the carbonated concrete cover and, to a smaller extent, on the strength of the concrete itself, are proposed. The formulas have been determined by means of finite elements modeling (FEM) of the impact between the plunger of a Schmidt hammer and the concrete surface. Results from FEM have shown a good agreement with experimental results. The proposed correction formulas can provide a more reliable concrete strength evaluation without significantly increasing the cost and the time for the experimental tests.

1. Introduction

The acronym NDT generally indicates the family of non-destructive testing methods that can be used to evaluate some properties of a specific material without causing damage or producing a limited and superficial damage to the tested material. Most of these methods do not measure the property of interest directly but rather they measure some other property that can be correlated to this at a later stage. In the case of structural concrete, NDT methods can be used for different purposes such as:

1. Checking the homogeneity of concrete.
2. Checking the curing conditions.
3. Checking and evaluating the presence of cracks.
4. Evaluating the concrete compressive strength of new and existing structures.
5. Evaluating the residual strength of concrete after a fire.

NDT techniques become particularly important when it is necessary to assess the load bearing capacity of existing structures given the impossibility of performing tests on molded specimens made with the same concrete used in the construction. Other methods, such as coring, can be used in these cases but the damage they infer to the structure is far above those caused by NDT methods. The importance of NDT techniques is further emphasized considering that a vast part of the built patrimony in many countries is made of concrete structures for which the mechanical properties of the materials are actually unknown, mostly because the original characterization, made during the construction, is no longer available.

It is thus highly desirable to apply a NDT method able to reliably predict the compressive strength of the concrete without damaging the structural elements. The combined method SonReb, that uses at the same time the rebound number and ultrasonic pulse velocity data, seems to be one of the more accurate NDT method for the prediction of concrete compressive strength. However, it has some shortcomings that affect the results of its evaluations.

In this paper the attention is focused on the determination of a correction formula to objectively take into account the errors on the rebound index produced by the carbonated concrete, thereby eliminating one of the major drawbacks of the rebound hammer test. Consequently, the SonReb method could be used with higher reliability in the assessment of existing concrete structures.

Differently from other researches developed for this purpose in last decades, the proposed method defines a correction formula of the rebound index that depends on the thickness of the carbonated layer rather than on the age of concrete itself. This

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Non-destructive testing for the assessment of granite decay in heritage structures compared to quarry stone

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ABSTRACT

Several types of granite found in two architectural heritage monuments were assessed with two non-destructive, portable techniques: Schmidt hammer rebound and ultrasound velocity (V_p). Similar assessments were conducted on the rock from which the granite was originally quarried for comparison. The results obtained, which revealed the existence of a direct correlation, constitute a useful indication of decay, particularly if the approximate dates of construction are known. And conversely, if they are not, such stone assessments may provide a rough estimate of when the structure was built. Both of these convenient, portable and non-destructive techniques may be used as reliable indicators of the degree of stone decay.

1. Introduction

Building stone weathering, and especially the degree of damage and the rate at which it occurs, have long been a matter of research and discussion. The three main approaches adopted in such research are: experimental, man-made structures and geological materials [1]. The durability of rock used for engineering purposes is determined by: geology (*in situ*), production (quarrying and stockpiling), construction (workmanship) and use (type of structure). Physical, mechanical and simulation tests, along with petrographic evaluation, are commonly used to assess rock durability. When the architectural heritage is involved, however, sampling must be reduced to a minimum. In such cases, the use of non-destructive, portable techniques is essential, for in addition to assessing the surface strength of the stone, they provide substantial information about the monuments themselves.

According to RILEM's (International Union of Laboratories and Experts in Construction Materials, Systems and Structures, www.rilem.net/tcDetails.php?tc=SAM), Technical Committee on Strategies for the Assessment of Historic Masonry Structures with NDT (SAM) created in 2005, recent years have brought the development and improvement of a number of methods for on-site monitoring and diagnosis based on non-destructive (NDT) and minimally destructive (MDT) techniques. Two of the most frequently used NDTs were chosen for this study: ultrasound velocity and surface hardness determined with a Schmidt hammer rebound tester. Ultrasound propagation velocity has been widely used to determine the quality and degree of decay in rock and stone materials forming part of the built heritage [2–15]. As early as 1965, De Puy [16] reported that Schmidt hammer rebound testing was suitable for detecting weathered and altered rock, based on the reduction in strength caused by the presence of weak or soft secondary minerals, microcracks, flaws and increases in water absorption capacity. This technique is subject to certain limitations, however, respecting the interpretation of results [17].

Viles et al. [18] reviewed the use of the Schmidt hammer and the Proceq Equotip® hardness tester for assessing rock hardness in geomorphology and heritage science.

Some authors have attempted to establish the relationship between Schmidt hammer surface hardness and compressive strength [19–26], as well as between P-wave velocity and uniaxial compressive strength [22,27]. Of the scant references found on the correlation between ultrasound velocity and surface hardness (Schmidt hammer rebound number R_n) in building materials more dealt with concrete than with rock [28–31]. Nonetheless, a few relevant papers such as [32] have been published on the use of ultrasound pulse velocity and Schmidt hammer tests to predict granite elasticity and strength.

Moreover, weathering generally lowers rock strength, as reflected in the *R*-values indicative of surface hardness [18,32,33].

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