4th INTERNATIONAL CONFERENCE ON NDT
Hellenic Society for NDT
11-14 October 2007, Chania, Crete-Greece

EXPERIMENTAL APPLICATION OF 3-D TERRESTRIAL LASER SCANNING AND ACOUSTIC TECHNIQUES IN ASSESSING THE QUALITY OF STONES USED IN MONUMENTAL STRUCTURES

Giuseppe Casula
INGV- Istituto Nazionale di Geofisica e Vulcanologia – Centro Nazionale Terremoti - Bologna (Italy)
casula@bo.ingv.it
Silvana Fais
Dipartimento di Geoingegneria e Tecnologie Ambientali - University of Cagliari – Cagliari (Italy) - sfais@unica.it
Paola Ligas
Dipartimento di Geoingegneria e Tecnologie Ambientali - University of Cagliari – Cagliari (Italy) - pligas@unica.it
Paolo Mora
Dipartimento di Scienze della Terra e Geologico-Ambientali – University of Bologna (Italy)
paolo.mora@unibo.it

Abstract

This paper briefly describes the preliminary results of an experimentation aimed to test a new non-destructive methodology based on the integrated application of 3-D terrestrial laser scanning and acoustic techniques in the ultrasonic range (54 kHz) in evaluating the quality of stone materials. Our target is to evaluate the state of conservation of stone building materials by correlating ultrasonic longitudinal pulse velocity and frequency spectra with the reflectivity or reflectance of the reflected 3-D laser scanner beam pulse transmitted to the target of an investigated surface.

Keywords: Ultrasonic technique, 3D terrestrial laser scanner, reflectivity, spectral analysis.

1. Introduction

Early identification of damage and degradation of monumental structures is essential in assessing and monitoring their status and in planning their restoration. Therefore an effective non-destructive evaluation (NDE) is urgently required. The integrated use of independent methods can assist the diagnostic process on the materials in several engineering applications. This paper presents an example illustrating how integrated application of ultrasonic and 3D laser scanner techniques help to improve the characterization of the materials for restoration and conservation.

In the last decade new instruments based on laser technology has been developed able to acquire parts of lands and building of different shapes and sizes in a very fast and cheap way, these instruments are called 3D Terrestrial Laser Scanners (TLS).

The modern Time Of Flight (TOF) 3D TLS specifically implemented for metric survey application of building can be considered as strongly automated motorised total stations which can acquire millions of points in few minutes [1,3,9].

Using 3D-TLS technology the travelling time of the laser pulse is converted into the distance between the instrument and the investigated object. The distance and direction of the acquired laser pulse are then converted into coordinates of the part of the target surface at which the scanning pulse is reflected. The result of a 3D-TLS survey are a high dense clouds of points, for each point of the cloud are given: the coordinates in an arbitrary reference system, the value of Red Green Blue (RGB) colour scale, and the reflectivity parameter, an indicator of the amount of energy reflected by the point of surface surveyed [3,9].

Sonic or ultrasonic methods are very effective in detecting the elastic characteristics of stone materials and thus their mechanical behaviour [4,5,6]; even though data interpretation is very complex as elastic wave velocity heavily depends on moisture, heterogeneity, porosity and other physical properties. Accurate ultrasonic signal processing procedures based not only on pulse velocity analysis but also on frequency spectra analysis can improve the results of the ultrasonic survey.

2. Materials

The study was carried out on the masonry structure of the choir (Figure 1) of the Santa Chiara ancient Church in the historical downtown of Cagliari (Italy).

The building materials of the investigated structure are limestones of different chemical-mineralogical composition and different mechanical properties. These materials were used as building stones on most monumental structures of Cagliari (Italy) because their good mechanical properties and their availability. In fact Cagliari rises on hills that are made mainly of carbonate deposits, which stratigraphically can be distinguished in three subunits from bottom to top named: "*pietra cantone*", "*tramezzario*", and "*pietra forte*". The lower member of the Cagliari limestones ("*pietra cantone"*) is made up of very soft, dark yellow, fossil-rich marly-arenaceous limestones. The mechanical properties of this rock material strictly depend on its degree of alteration. The great alterability of this rock is due to its relatively high porosity and high hygroscopicity caused by its high clayey mineral content.

The intermediate subunit ("*tramezzario*") consists of more or less marly calcarenites. This rock has more carbonate content and lower porosity value than the "*pietra cantone"*. The upper subunit is *Pietra Forte*, a biohermal limestones that is rather exclusively composed by $CaCO_3$, about 97%. The rock is very compact and characterized by high compressive mechanical strength [2]. The primary porosity is of 2-3%. The rock is frequently interested by karst phenomena that generate irregular cavities (of about 2-3 cm). In this case the *Pietra Forte* is characterized by high permeability. In the present study, to contribute to the knowledge of the mechanical

Figure 1 - Choir of the Santa Chiara Church

characteristics of the above mentioned materials, ultrasonic velocity measurements by the direct transmission mode (transmitter and receiver on two opposite faces of the investigated object) were carried out on unaltered samples of the different carbonate rocks. Starting from the comparison of these values with the velocity values measured *in situ* on the structural elements made up of the same lithotypes, it is possible to estimate the intensity of the alteration and detect the presence of defects (fissures, fractures, etc.) inside the materials.

3. TLS survey

3.1 Data acquisition

In order to model the shape of some interesting damaged part of the choir of the Santa Chiara Church, we planned and executed a 3D TLS laser scanner survey.

The test survey was done using a Leica HDS2500 TLS, this instrument which is characterised by both horizontal and vertical Field Of View (FOV), is able to acquire 1000 points per second for single scan, has a single point accuracy of 4mm, and a spot size little than 6mm in a 0-50m range of distance (Leica Geosystems HDS2500 products specification, 2003). The survey was executed with the support of the Leica Geosystems Italy.

Three point clouds were acquired in a few minutes using only one station position in front of a restored sectors old damaged choir of the Church of Santa Chiara where ultrasonic non destructive tests were performed in order to be able to combine, after the post-processing phases, the two techniques.

About 99.000 points were briefly acquired, for each of the point acquired, the coordinates X, Y, and Z, the colour scale RGB value, and the reflectance parameter have been computed (Figures 2-3).

3.2 TLS Data Processing and results

The Santa Chiara Church 3D TLS data were processed using Leica Cyclone 5.7 software package, a comprehensive suite of object-oriented graphic tools suitable to process 3D TLS data.

The 3D TLS data processing procedure we operated can be divided in two main steps, at the beginning a pre-processing procedure was applied followed by a 3D modelling of the surveyed objects.

3.3 Data pre-processing, Registration

During the data pre-processing phase the data were filtered in order to eliminate data gross errors and outliers. In a second time, registration processes were applied in order to define an absolute reference frame for all the point clouds and to unify them. In fact, in a LS survey several data-sets are created referred to a local arbitrary reference frame held to the position of the LS. A registration process is then needed by which all the data-sets are referred, by means of a 3D similarity transform, to the same absolute coordinate system [3,9,7,8]. The final result of the pre-processing phase was a complex, noise cleaned, and unified geo-referenced point cloud, this final data set was used as input for the 3D modelling stage of the surveyed objects.

3.4 3D surface object modelling

During the 3D modelling processes a set of complex operation was done starting from the unified and cleaned point cloud in order to produce a surface model of the surveyed objects. This phase has been performed interactively by means of Leica Cyclone 5.7 software package and the results obtained for the Santa Chiara choir are shown in figure 2. In figure 3 is shown the reflectivity analysis of a damaged sector of the above mentioned choir, the damaged zones are evidenced by the higher value of the reflectivity parameter (white colour in the figure). It can be noticed that, owing to the technical characteristics of the scanner, the same reflectance levels are measured in the damaged areas as well as in the easy recognisable pictorial elements of the Church choir (higher part in the Figure 3).

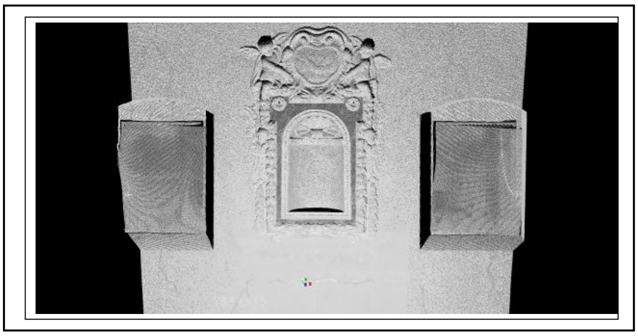

Figure 2 – Example of 3D TLS modelling of a damaged altar of the Santa Chiara church which was subjected to restoration in the past. A test survey was done by means of Leica HDS-2500 TLS. Data were processed with the aid of Leica Cyclone Vs 5.7 software.

Figure 3 – Example of 3D reflectivity map of a sector of Santa Chiara choir obtained by 3D TLS data, the damaged parts are evidenced by the reflectance map analysis. Data are obtained by means of Leica HDS2500 TLS instrument and processed with the aid of Leica Cyclone Vs 5.7 software package.

4. Ultrasonic investigation

In view of the nature of the building materials, the *in situ* ultrasonic investigation was carried out with the aim of detecting any mechanical discontinuities or damaged zones through the study of velocity anomalies (low velocity) in the propagation of the acoustic signal. In fact, as it is known, acoustic methods are based on the principle that the characteristics of the acoustic signal are strictly related to the elastic status of a material. Alterations in the material are known to cause velocity variations (decrease of velocity) and may provide valuable information on the elastic characteristics of the materials and therefore on their integrity.

The ultrasonic investigations on the choir (Fig. 1) of the surveyed Church were planned taking into account the aims of the work, the general conservation state of the materials and on the basis of the 3D TLS results.

Longitudinal ultrasonic velocities were measured *in situ* using a portable ultrasonic non-destructive (ND) digital indicating tester (PUNDIT) with 54 kHz transducers manufactured by C.N.S. Electronics Ltd (London, U.K). The ultrasonic output signals were recorded by a digital oscilloscope interfaced with a PC computer to allow further signal analysis. Ultrasonic measurements by indirect or surface transmission (transmitter and receiver on the same surface of the investigated structure) were carried out using the "step by step" modality [6,10]. The measurements were carried out along six parallel profiles in a horizontal direction. During the data acquisition phase, several tests were carried out to select the proper acquisition geometry, such as transmitter-receiver distance. In fact, the "step by step" acquisition technique was applied using different offset (transmitter-receiver distance), in order to check the elastic conditions of the different materials (mortar and building materials) within the superficial part of the investigated masonry structure and detect the presence of mechanical discontinuities, such as fissures or fractures under the mortar. The ultrasonic velocity maps obtained by interpolating velocity values measured along the profiles were effective in detecting the presence of inhomogeneities such as fissures and cracks in the masonry. Their analysis was integrated by the results obtained with the spectral analysis of the digitized wave forms. Time window size was selected sufficiently large (in time) that the results are stable. The spectral analysis was performed by means of the fast Fourier transform (FFT) method estimating the spectral power density. Figure 4 show as an example the spectral composition of the ultrasonic signals acquired respectively in damaged (Fig. 4 a) and intact (Fig. 4 b) sectors of the masonry. As can be easily observed the two spectra are different from one another, particularly for the higher frequencies. The spectral changes can be caused by the scattering of the ultrasonic energy off irregular surfaces like fissures and microcracks, as results from our experimentation on a great number of different situations.

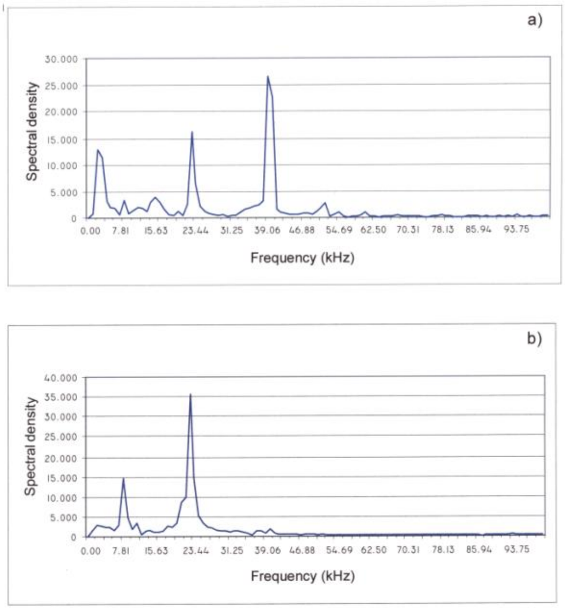

Fig.4 - FFT spectra of the ultrasonic waveforms acquired in an unaltered (a) and altered (b) sectors of the investigated masonry.

5. Concluding remarks

An experimental integrated use of nondestructive methods based on ultrasonic and TLS measurements has been used for detecting the presence of inhomogeneities such as fissures and cracks in the investigated masonry. In order to derive an appropriate and effective methodology and testing procedure experiments have been performed both in laboratory and *in situ*.

The presence of fissures or microcracks in the investigated materials appears to be relevant in affecting high frequency content of the ultrasonic signals. The spectral changes in correspondence of defects inside the materials indicates that spectral composition of the ultrasonic wave forms can provide a significant contribution in detecting the variations of mechanical status of the carbonatic rocks that made up the investigated monumental structure. From the results of the *in situ* ultrasonic and TLS surveys it can be deduced a good correlation between ultrasonic velocity values, frequency content of the ultrasonic signals and TLS reflectivity. They result well correlated to the mechanical conditions of the superficial part of the investigated materials. Further tests on different lithotypes are at the moment scheduled.

The integration of data from multiple methods is very useful due to peculiarities of each method. In fact, the high productivity of the TLS method is limited by its low penetration depth. This problem can be overcame coupling ultrasonic measurements on critical sector selected by TLS. Integrated application of the two methods appears able to optimise the knowledge of the investigated structure and to objectively evaluate the effectiveness of the restoration.

Acknowledgements

This work was financially supported by the Italian Ministry for University and Research (MUR – 60%, Cagliari University, Responsible scientist S. Fais). We thank Prof. Federico Uccelli director of the Leica Geosystems Italy – Laser Scanner Division for the support given and helpful suggestions in LS data acquisition and processing. The authors would like also to thank the Associazione Culturale Santa Chiara and Ing. G. Bechere for their kind permission to access to and work on Santa Chiara Church.

References

[1] Balzani M., Santuopoli N., Uccelli F., *La luce del laser scanner 3D Cyrax System*. Paesaggio Urbano, XXX-XXXII, luglio-agosto 2002.
[2] Barrocu G., Crespellani T., Loi A.; *Caratteristiche geologico-tecniche del sottosuolo dell'area urbana di Cagliari*; Rivista Italiana di Geotecnica, XV, 2, 98-144, 1981.
[3] Bornaz L., and Rinaudo F.. Terrestrial Laser Scanner data processing. Proceedings of the Geo-Imagery Bridging Continents XXth ISPRS Congress, 12-23 July 2004 Istanbul, Turkey, Commission 5. Vol. XXXV, part B5. pag. 514-519.
[4] Christaras B., Auger F., Mosse E., *Determination of the moduli of elasticity of rocks. Comparison of the ultrasonic velocity and mechanical resonance frequency methods with direct static methods.* Materials and Structures, 27, 222-228, 1994.
[5] Fais S., Tocco R., Casula G., *ND acoustic techniques to assess the preservation of a church colonnade – a case history*. 61° EAGE conference & technical exhibition. Extended abstracts, Helsinki, giugno, 1999.
[6] Fais S., Ligas P., Palomba M., Tocco R., *Evaluation of preservation state of monumental buildings by ND acoustic techniques and mineralogical studies.* Proceed. of the 5th Int. Symp. “Protection and Conservation of the Cultural Heritage of the Mediterranean Cities”, Galan and Zezza eds., Swets & Zeitlinger, Lisse, 307-314, 2002.
[7] Geoff J., *Uses in Building and Architectural Surveys. High-Definition Surveyng: 3D Laser Scanning*, Professional Surveyor Magazine, June 2005a.
[8] Geoff J., *Registration and Geo-Referencing. High-Definition Surveyng: 3D Laser Scanning*, Professional Surveyor Magazine, July 2005b.
[9] Lee I., and Choi Y., *Fusion of Terrestrial Laser Scanner data and images for building reconstruction.* Proceedings of the Geo-Imagery Bridging Continents XXth ISPRS Congress, 12-23 July 2004 Istanbul, Turkey, Commission 5. Vol. XXXV, part B5.
[10] Zezza, F., *Evaluation criteria of the effectiveness of treatments by non destructive analysis.* Proceedings of the 2nd Course of CUN University School of Monument Conservation, 198-207, 1993.