Experimental Application of 3-D Terrestrial Laser Scanner 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)
E-mail: casula@bo.ingv.it

Silvana Fais
Dipartimento di Geoingegneria e Tecnologie Ambientali - University of Cagliari - Cagliari (Italy)
Consorzio Interuniversitario per l'Ingegneria delle Georisorse - University of Roma - Roma (Italy)
E-mail: sfais@unica.it

Paola Ligas
Dipartimento di Geoingegneria e Tecnologie Ambientali - University of Cagliari - Cagliari (Italy)
E-mail: pligas@unica.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 carbonatic stone materials. Our target is to evaluate the state of conservation of stone building materials by correlating ultrasonic longitudinal pulse velocity and frequency spectra of the ultrasonic signals 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; spectral analysis; 3D terrestrial laser scanner; reflectivity; limestones.

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 (LS) techniques help to improve the characterization of the materials for restoration and conservation.

In the last decade new instruments based on laser technology have 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 (Balzani M. et al., 2002; Bornaz L. et al., 2004).

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 (Lee and Choi, 2004; Bornaz et al., 2004).

Sonic or ultrasonic methods are very effective in detecting the elastic characteristics of stone materials and thus their mechanical behaviour (Christaras et al., 1994; Fais et al., 1999; Fais et al., 2002); even though data interpretation is very complex as elastic wave velocity heavily depends on moisture, heterogeneity, porosity and other physical properties (Fais et al., 2004). 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 ancient Church of Santa Chiara in the historical city centre of Cagliari (Italy).

The building materials of the structure are limestones of different chemical-mineralogical composition and with different mechanical properties. These materials were used as building stones on most monumental structures in Cagliari (Italy) because of their good mechanical properties and because they were readily available. As a matter of fact Cagliari rises on hills that are made mainly of carbonate deposits, which can be distinguished stratigraphically in three subunits from bottom to top: namely *Pietra Cantone*, *Tramezzario*, and *Pietra Forte*. The lower member of the carbonate sequence of Cagliari (*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 carbonate content of this rock is 84-90%. The intermediate subunit (*Tramezzario*) consists of more or less marly calcarenites. This rock has more carbonate content (95-98%) and lower porosity than the *Pietra Cantone*. The upper subunit is *Pietra Forte,* a biohermal limestone that is almost exclusively made up of $CaCO_3$ (about 97%). The rock is very compact and characterized by high compressive mechanical strength (Grinzato et al., 2004). The primary porosity is 2-3%. The rock is frequently affected by karst phenomena that generate irregular cavities (of about 2-3 cm). In this case the *Pietra Forte* is characterized by high permeability.

2.1. Petrographical features

In our study a number of representative unaltered samples from the main outcrops and the ancient quarry sites of the study carbonatic sequence were analysed by optical microscopy in order to obtain information on the physical arrangement of their constituent grains that is texture (size, shape, sorting and spatial arrangement). In Figs 2 a, b, c, are shown three representative thin sections of the investigated materials (*Pietra Cantone, Tramezzario, Pietra Forte*).

At microscopic observation *Pietra Cantone* (Figure 2a) shows the typical characteristics of a wackestone (Dunham, 1962) made up of more than 10% calcareous skeletal remains as bivalves and gasteropodae. These grains are supported by a matrix of a mud of microcrystalline calcite (*micrite* Auct.) made up of grains less than 5 µm in diameter. Presence of a silicoclastic terrigenous component made up principally of quartz, feldspar and biotite can also be observed. Furthermore, all samples show variable amounts of iron oxides and hydroxide specks. The rock has a secondary porosity of vug and mouldic types.

Tramezzario can be ascribed to a grainstone (Dunham, 1962). The observations in thin section (Figure 2b) display a grain-supported typical texture with a pore-filling cement of *sparry* (Auct.) calcite that refers to crystals of 5 µm or more in diameter. The rock has a various bioclastic content made up of skeletal grains of bivalves, Lithothamnium algae, gasteropodae, echinidae. *Tramezzario* is generally characterized by mouldic porosity and the internal casts of pores show presence of sparry calcite.

Pietra Forte shows the textures of a typical limestone of reef environment in which the original components were bound together by organisms as abundant Lithothamnium algae and minor mollusks. This texture can be abscribed to a boundstone (Dunham, 1962). The porosity type of this rock is similar to that of *Tramezzario*.

2.2. Ultrasonic laboratory tests

In the present study, in order to contribute to the knowledge of the mechanical characteristics of the above materials, ultrasonic velocity measurements were carried out in the laboratory following NORMAL – 22/86 suggestions on samples of the different carbonate rocks. Several prismatic unaltered specimens (12x12x24 cm) of the three different carbonatic lithologies under study (*Pietra Forte, Tramezzario and Pietra Cantone Auct.)* were prepared for the acoustic measurements. These measurements were performed using a Portable Ultrasonic Non-Destructive Digital Indicating Tester (PUNDIT) and P-wave transducers by C.N.S. Electronics LTD (London, U.K.). A number of experimental sessions were carried out in the ultrasonic range 24-82 kHz, to define quantitatively some dynamic elastic properties of the carbonatic rocks. During this phase different modalities of acquisition techniques were carried out. In particular the indirect transmission (transmitter and receiver on the same face of the sample), the semi-direct transmission (transmitter and receiver on the adjacent faces of the sample) and the direct transmission (transmitter and receiver on the opposite faces of the sample) were carried out. For the experimentation, the silicone snug sheets were chosen as coupling agent because they were evaluated as a better coupling agent compared to vaseline (Concu and Fais, 2003). P-wave mean velocity values resulting from the tests range from 3100 m/s for *Pietra Cantone* to 4750 m/s and 6450 m/s respectively for *Tramezzario* and *Pietra Forte*.

Starting from the comparison of the P-wave velocity values measured in the laboratory with those 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. Terrestrial Laser Scanner 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 size of the spot 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 HDS inc. 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 measured point, the coordinates X, Y, and Z, the colour scale RGB value, and the reflectance parameter have been computed (Figures 2-3).

3.2. Terrestrial Laser Scanner Data Processing and results

We used Leica Geosystems HDS inc. Cyclone software version 5.7 to process The Santa Chiara Church 3D TLS data. This software is a comprehensive suite of object-oriented graphic tools useful to process 3D TLS data, it provides a large set of work processing options for all users of 3D LS in different disciplines like: engineering, surveying, construction and related applications. Moreover, Cyclone software enables users taking advantage of all resection capabilities of different Leica HDS laser scanners in order to realise relieves that are cost-effective and make the operators able to easily create plant styled building models.

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 (Bornaz et al., 2004; Lee et al., 2004; Geoff J., 2005a,b). 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 Three dimensional 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 Geosystems HDS 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 map 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), i.e. the largest amount of energy reflected back by the part of the target surface at which the scanning pulse is directed. 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).

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 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 in velocity) and may provide valuable information on the elastic characteristics of the materials and thus on their integrity.

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

Longitudinal ultrasonic velocities were measured *in situ* using the above mentioned PUNDIT with 54 kHz transducers. 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. The indirect ultrasonic technique is commonly used as a non -destructive powerful tool to detect the shallow altered zones of the wall masonry faces, as described by Zezza, 1993 and Fais et al., 2005 among others. 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 a 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 map (Figure 5) 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 large enough (in time) for the results to be stable. The spectral analysis was performed by means of the Fast Fourier Transform (FFT) method estimating the spectral power density. As an example Figure 6 shows the spectral composition of the ultrasonic signals acquired respectively in damaged (Figure 6 a) and intact (Figure 6 b) sectors of the masonry. As can easily be observed the two spectra are different from each another, particularly in the higher frequencies. Spectral changes can be caused by scattering of ultrasonic energy off irregular surfaces like fissures and microcracks, changes in the elastic conditions of the materials, intrinsic attenuation of high frequency content and degradation of the ultrasonic longitudinal velocities. However in the case under study differences between spectra resulted primarily caused by intrinsic attenuation of high frequencies, typical of the altered materials.

5. Concluding remarks

An experimental integrated use of non-destructive methods based on ultrasonic and TLS measurements has been used to detect the presence of inhomogeneities such as fissures and cracks in the investigated masonry. In order to achieve an appropriate and effective diagnostic non-destructive methodology and testing procedure, experimental tests have been performed both in laboratory and *in situ*.

The presence of fissures or microcracks and alteration zones in the investigated materials appears to affect the ultrasonic longitudinal pulse velocity and high frequency content of the ultrasonic signals. In the building materials under study scattering of ultrasonic energy off irregular surfaces like fissures and microcracks, changes in the elastic conditions of the materials, intrinsic attenuation of high frequency content and degradation of the ultrasonic longitudinal velocities can all contribute to the observed spectral changes. Considering that the large number of variables makes it relatively difficult to interpret the spectrum, most mechanisms could be forward modelled so as to seek a quantitative meaning of the changes in the spectral composition. However, though the relantionship between ultrasonic signal frequency content and the above mentioned mechanisms is not completely clarified, an analysis of the spectral composition of the ultrasonic waveforms can provide a significant contribution to detect the variations in elasto-mechanic behaviour of the carbonatic rocks that made up the investigated monumental structure also enhancing the diagnostic power of the ultrasonic measurements.

From the results of the *in situ* ultrasonic and TLS surveys a good correlation can be deduced between ultrasonic longitudinal velocity values, frequency content of the ultrasonic signals, and TLS reflectivity. Thus the results of this analysis indicate a relationship between a decrease in longitudinal ultrasonic pulse velocity, an attenuation of higher frequencies, and an increase in TLS reflectivity. They prove to be well correlated with the presence of inhomogeneities and with the degradation of the mechanical conditions of the superficial part of the investigated masonry structure. In this analysis the study of the petrographical features of the materials carried out mainly by optical petrographic microscopy provided an experimental control of the integrated interpretation of the ultrasonic and TLS results. The spatial arrangement of grains such as their orientation, distribution and manner of packing is very important because it controls the porosity and permeability and thus the capability of the rocks to retain and/or be passed through by meteoric waters. The mineralogical composition, texture, presence of moisture and characteristics of the voids, appear to be the main factors that control the chemical and mechanical damages of the investigated carbonatic materials. It is clear therefore that the integration of petrographical information with ultrasonic data is of particular importance, especially as regards the longitudinal velocity and signal frequency content as well as the TLS results above all with reference to the reflectivity parameter.

The integration of data from multiple methods is very useful thanks to the peculiarities of each method, and the fact that two techniques, so different in their formulation, yield results that fit each other is very gratifying indeed. The high productivity of the TLS method is limited by its low penetration depth, a problem that can be overcome by coupling ultrasonic measurements on critical sectors selected by TLS. The combined application of the two methods appears capable of optimising our knowledge on the quality and conservation state of the investigated rock building materials and to provide an objective evaluation of the effectiveness of the restoration.

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