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Original article

Crack assessment in marble sculptures using ultrasonic measurements: Laboratory tests and application on the statue of David by Michelangelo

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ABSTRACT

The large marble statues can suffer serious fractures, due to the stress states originated by the weight and the shape, often thin and articulated. Fractures are often triggered by surface cracking. For this reason, it is important to assess the severity of the apparent cracks, by performing periodic nondestructive surveys. The ultrasonic method is well suited for this purpose. This paper presents a research activity finalized at improving the application of the ultrasound method to the detection of crack depth in marble elements. Two different techniques are presented. These, after having been validated in the laboratory by operating on marble specimens, have been applied to a diagnostic investigation of the Michelangelo's David, one of the most famous masterpieces of Western art. The results obtained have allowed us to provide useful information about the severity of the damage. The depth was estimated with good reliability for some of the more evident cracks present in the left leg and in "broncone", the false tree trunk on which the left leg rests. The maximum depth is evaluated at approximately 20 mm. In other areas, diffuse cracking or surface deterioration of the marble have been detected.

1. Research aims

The purpose of this research is to evaluate the effectiveness of ultrasonic investigations to assess the depth of surface cracks on marble artworks, and to develop instrumental apparatus and experimental procedures suitable for this particular application.

Ultrasonic tests are commonly used for nondestructive investigations of metal, stone, concrete and many other materials. The application on the marble artworks presents some specific aspects, such as the presence of curved surfaces and the inability to use coupling materials that would cause a permanent alteration of the marble surface. Furthermore, the surface cracks often present an irregular shape and points of contact between the two edges. This makes unreliable the use of the instrumental setup currently used on stone materials.

Our goal is to overcome these difficulties, by developing and testing on site a reliable and noninvasive procedure to assess the depth of surface cracks in marble elements.

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2. Introduction

Many researchers have devoted their efforts to the diagnosis of cracking in stone or marble elements, and in particular in marble artworks. The same problem is also present for concrete structures and in general for all stone materials.

A useful review of the use of ultrasonic testing as a nondestructive tool for the investigation of stone is presented in [1].

The RILEM recommendation [2] represents a reference document for ultrasonic investigation, and presents a very simple method called "time of flight diffraction" (TOFD), with the aim to estimate the depth of a crack. According to this method, the estimate is based on the comparison between two different values of the time of flight (TOF), both measured on the same surface were the crack is visible. One of them is obtained by placing the transducers on opposite sides of the crack, in such a way that the wave path should circumscribe the crack.

In [3] a different technique based on measuring the TOF is presented, where several TOF measures are done, placing the receiving transducer at increasing distance from the emitting one, on both sides of the crack. This method was used for assessing the depth of surface cracks in marble statues in Greece.

An analysis of the methods used for cracking assessment in marble statues is presented in [4]. In [5] the use of methods based on

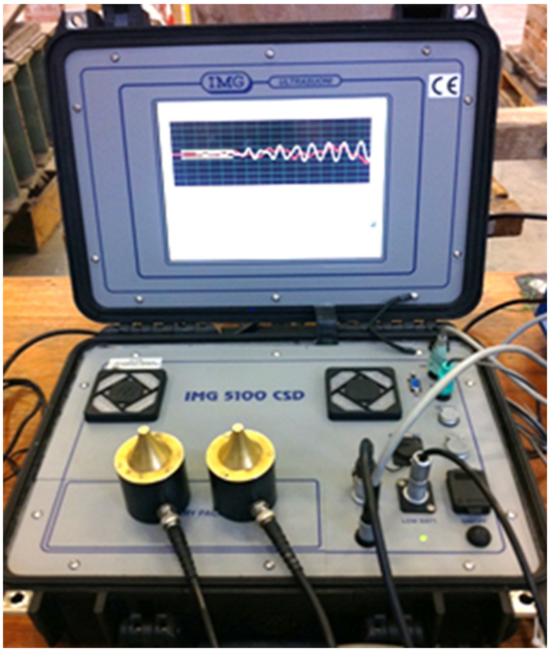

Fig. 1. Ultrasonic equipment and transducers.

TOF is presented for several applications, based both on sonic and ultrasonic tests.

The theoretical, numerical and experimental research presented in [6] and [7] deals with nondestructive evaluation of the depth of surface-breaking cracks in concrete pipes by using the wavelet transform. A newly proposed wavelet transmission coefficient (WTC) is measured using an equal spacing configuration for the crack depth evaluation in concrete pipes and plates.

The method presented in [8] determines the crack depth using the energy of the Rayleigh wave propagating over the crack and needs a reliable technique to evaluate the wave energy with measured surface waveforms. A self-compensating frequency response function is proposed to improve isolating the Rayleigh wave components from the accompanying noise. A rigorous procedure using the spectral estimator for noisy measurement is derived for self-compensating. The proposed technique was verified by an experimental application to structural cracks as well as artificial notches in concrete.

The methods based on the TOF are attractive because they are fast, easy and cost effective. They are subject to errors due to several factors, such as the presence of contact areas between the opposite sides of the crack and the irregularity of the crack tip line.

In this research, an effort was made to improve the TOFD method in order to reduce the errors, by increasing the number of experimental measures and improving the instrumental apparatus and procedures.

After having identified the most suitable instrumental setup, laboratory tests were carried out on marble specimens with both natural cracks and artificial notches, to define the most effective experimental procedures.

Subsequently, these procedures have been applied on a case study of great interest, the Michelangelo's David in Florence, which presents a worrying cracking status in the lower part of the legs.

3. Experimental program

3.1. Experimental apparatus and methods

The ultrasonic instrument IMG 5100 CSD was used, shown on Fig. 1. This equipment utilizes low frequency transducers, generally between 25 and 500 kHz. Transducers with frequency of 55 kHz were choosen for this application, in order to have a good compromise between resolution and penetration. The transducers were provided with exponential concentrators (Fig. 1), to reduce the contact area between the transducer and the marble, thus allowing a good contact with the curved and irregular surfaces of the statue. The contact area is 38 mm^2. Coupling material must be used in ultrasonic tests to avoid air between the trasducer and the surface of the tested element. In this application plastiline was used, with the interposition of an adhesive paper tape, useful both to avoid direct contact between plastiline and marble and to mark the test positions.

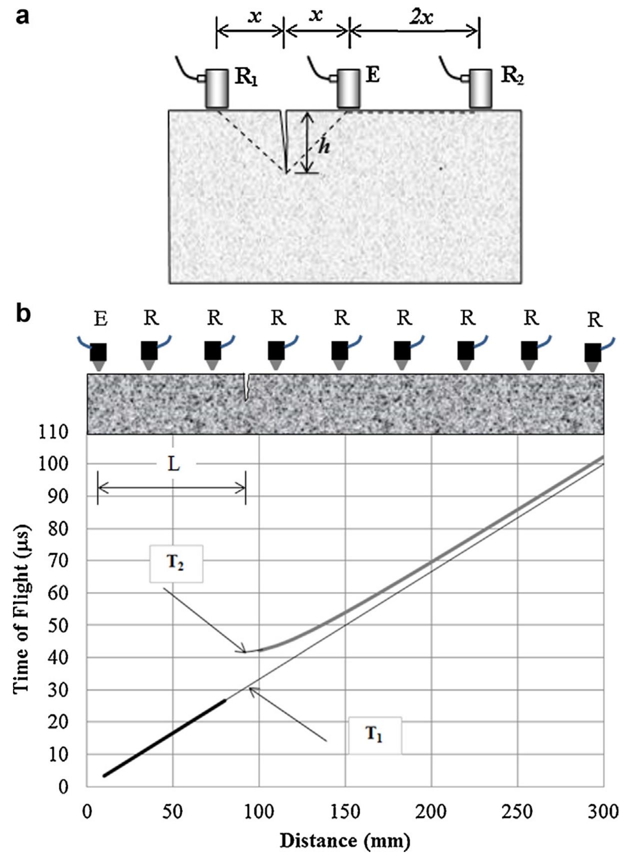

Fig. 2. Methods for estimating the depth of surface cracks by ultrasonic tests based on time of flight diffraction (TOFD) (E: emitter; R1 and R2: receiver positioning): a: two measures of TOF, T_2 on the plain homogeneous material and T_1 across the crack; b: several measures of TOF, with transmitter fixed and receiver moved on different positions.

The time of flight (TOF) and the attenuation (A) of the waves are usually measured in ultrasonic tests, but only the TOF is used when the aim is to estimate crack depth. Two methods can be used to this aim, as shown on Fig. 2. In any case, the emitter (E) and the receiver (R) are placed on the same surface of the tested element.

In the first method (Fig. 2a), two different TOF values are measured respectively across the crack (T_1) and in an uncracked zone (T_2), without varying the distance between the transducers. When the first measure is done (time T_1), the emitter and the receiver are placed at the same distance from the crack. The depth h is estimated using the following equation, in which x is the half path length:

$$h = \frac{x}{T_2}\sqrt{T_1^2 - T_2^2} \tag{1}$$

In the second method (Fig. 2b), the trasmitter is kept fixed and the receiver is moved in different points on both sides of the crack. A diagram similar to the one presented on Fig. 2b is generally