Damage Detection and Repair Control of Marble Elements

Détection des défauts et contrôle de la réparation sur des éléments en marbre

Schadenserfassung und Reparaturkontrolle bei Bauelementen aus Marmor

Angelo DI TOMMASO
Professor
Univ. of Bologna
Bologna, Italy

Giovanni PASCALE
Assoc. Professor
Univ. of Bologna
Bologna, Italy

Francesco CIANFRONE
Techn. Dir.
Soc. Ital. Contr. e Collaudi
Padova, Italy

SUMMARY

This paper presents an experimental study carried out using the microseismic method on blocks of marble in which defects such as cracks and cavities were created artificially. The purpose is to evaluate the ability of the method to detect internal defects in stone blocks, and to judge the effectiveness of resin repairs.

RÉSUMÉ

Cet exposé présente une recherche expérimentale par la méthode microséismique effectuée sur des blocs de marbre contenant des vides et des fissures. L'objectif de la recherche était d'évaluer dans quelle mesure cette méthode permet d'identifier les défauts internes et de juger de l'efficacité d'une réparation effectuée avec de la résine.

ZUSAMMENFASSUNG

Der Bericht präsentiert eine experimentelle, nach der mikroseismischen Methode vorgenommene Forschungsarbeit an Marmorblöcken, die künstlich eingebrachte Fehler wie Risse oder Hohlräume aufwiesen. Ziel der Forschung war es festzustellen, inwiefern mit dieser Methode Fehler im Innern von Steinblöcken entdeckt und Reparaturen mit Kunstharz beurteilt werden können.

1. INTRODUCTION

The repair of stone elements in historic structures requires a complete knowledge of the type of damage. This is an essential premise in order to plan the intervention accurately. A simple visual analysis is normally not capable of providing reliable indications. In addition, once the repair has been done by means of resin injections, it is important to check the effectiveness of the repair. In both cases, it is necessary to have a method capable of identifying internal cracks, hollows and discontinuous areas.
Methods based on the propagation of elastic waves are undergoing a considerable evolution, also due to the availability of processing methods based on the use of appropriate software, such as for sonic tomography [1] and the impact echo method [2,3]. The use of radiography techniques requires extremely high power. The application of radar to this sector is still in the experimental stage.
This paper presents an application of microseismic analysis. These are a useful instrument for this type of analysis, but require the use of instrumentation, procedures and interpretation criteria suited to the purpose [4,5,6,7,8,9]. The paper presents some results of an experimental study carried out on marble blocks with the following aims:

- to evaluate the sensitivity of the method in identifying defects, by simulating defects of varying size and repeating the measurements in the same condition each time;
- to estimate the size of the defects based on velocity and attenuation measurements;
- to evaluate the adequacy of the method in checking the effectiveness of a resin injection, by comparing measurements taken on the same trajectories in the following situations: integer block, block with defect, repaired block.
- in the case of cracked stone elements, to use the appropriate experimental methods to evaluate the extension of the area in which the material has undergone damage.

2. EXPERIMENTAL PROGRAM

2.1. Characteristics of the samples

A quasi-homogeneous and not stratified Greek marble was employed, with grain between 2 and 3 mm. A block 34x34x20 cm^3 was utilized for the tests, four 4x4x16 cm^3 prisms were used to determine the mechanical properties of the material.

2.2. Material specifications

The tests run on the prisms provided the following average values:

Uniaxial cubic compressive strength	σ_{rc}	= 179	N/mm^2
Flexural strength	σ_{rf}	= 12.9	N/mm^2
Young's secant modulus (0-50 N/mm^2)	E_c	= 66250	N/mm^2
Volumic mass	m	= 2898	kg/m^3

The pulse velocity of the P waves in the tests was rather variable depending on the anisotropy of the material, and falls between 4000 and 5100 m/s.

2.3. Instrumentation

A microseismic analyzer was employed, the most important details of which are:

Piezoelectric transducers, either emitting or receiving, with a flat active surface (emitting or receiving) with a diameter of 30 mm .

- ***Two on-line commutators***, allowing the operator to activate any emitting or receiving probe, among fixed multiple transducers applied to the stone specimen.

- ***Operator-adjustable pulse repetition rate,*** avoiding reverberation and resonance giving rise to disturbed measurements or to the impossibility of carrying them out.

- ***Pulse frequency***: this was set at 70 KHz, being the resonance frequency of the emitting and receiving probes, tuned and applied to the specimen.

- ***Pulse energy:*** the instrumentation was designed to power the emitting probes at various energy levels from 0.25 μJ to 50 μJ, according to the absorbing characteristics of the specimen and trajectory lengths. The emitting probes were powered respectively with 2.5 μJ for the smaller specimens (prisms) and 250 μJ for the larger ones (blocks).

- ***Amplification of received signal:*** amplification varying between -16 and +80 dB, in 1-dB steps, was used for the electric signal of the receiving probes. The amplification value was both digitally displayed to the operator and available as electric output for recording equipment during measurements.

- ***Transit time and intensity variations:*** the CRT (Cathode Ray Tube) of an oscilloscope was used for continual display of time function vibrations, as received by the probe and suitably amplified.

2.4. Experimental procedures.

The program of the experiment proceeded according to the following stages:

Initially the probes (three emitting and three receiving) were glued to a block in the positions indicated in figure 1.

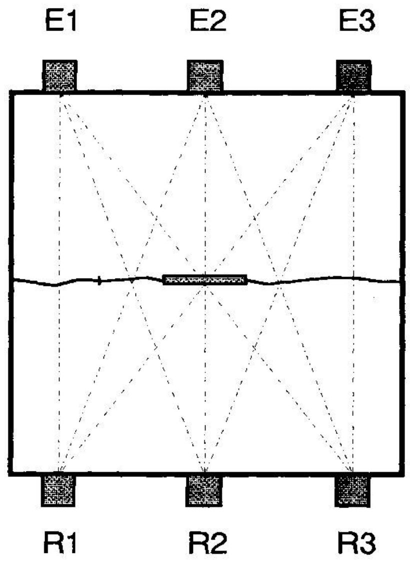

Fig. 1 Marble block and paths

The probes were glued on the block surface during the experiment in order not to introduce disturbing parameters due to repeated removal and repositioning of probes and thus to avoid variations in coupling points, acoustic coupling between probes and material, electric connections, etc. Using two specially-built commutators, each of the emitting probes was then connected to each of the receivers, and the microseismic parameters were determined (P-wave propagation velocity and attenuation) along the paths indicated in figure 1. An average tension of 12 N/mm^2 was applied to the sample.

The block was cracked horizontally, rotating it at 90°, and a splitting test was performed; the sample was then replaced in its initial position (see fig. 2). The same pressure was then applied once again, and the measurements taken along the same trajectories.

Without moving the lower part of the block, a circular cavity 20 cm in diameter was then created in the upper part by milling (see fig. 3). After replacing the block in its initial position, the pressure of 12 N/mm^2 was applied again, taking into account the reduction of the compressed area, and the measurements were repeated.

This operation was repeated several times, progressively increasing the diameter of the cavity, and always taking the microseismic measurements with a constant average pressure.

Finally, the crack and the cavity were sealed by applying a technique used for repairing damaged stone elements, consisting of the injection of epoxy resin after spackling the edges (see figs. 4 and 5). Once this procedure was completed, the measurements were repeated in the same conditions.

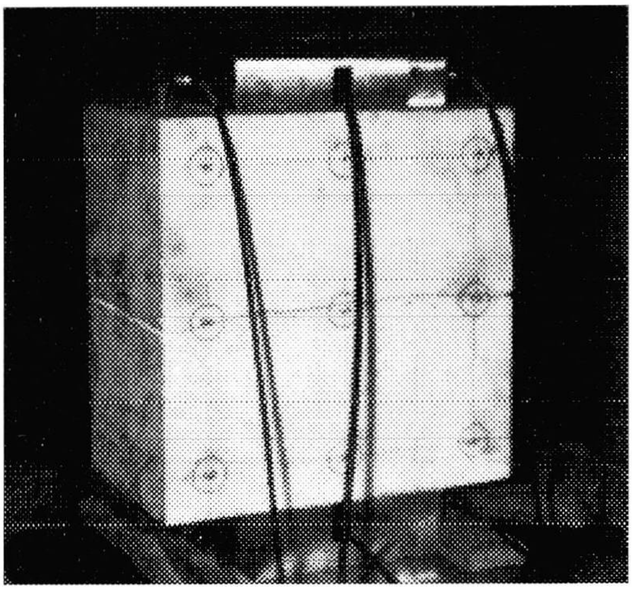

Fig. 2 Marble block with glued probes

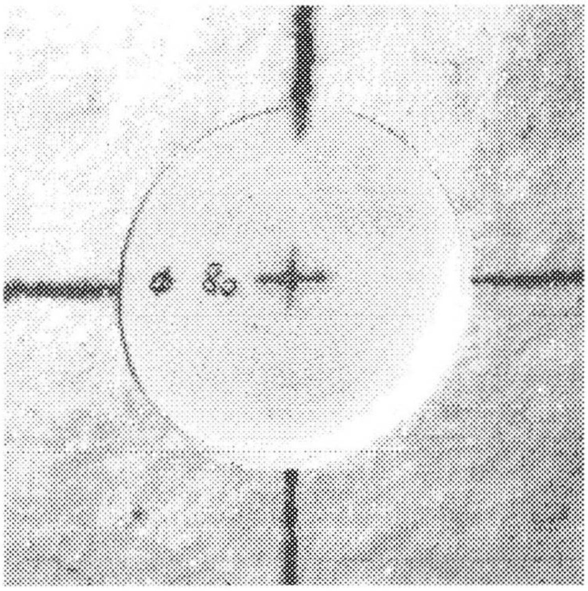

Fig. 3 Milling a circular cavity

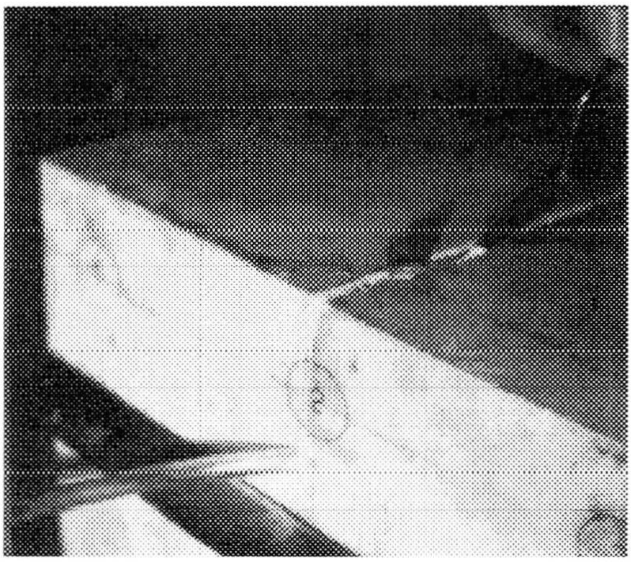

Fig. 4 Preparing the block for repair

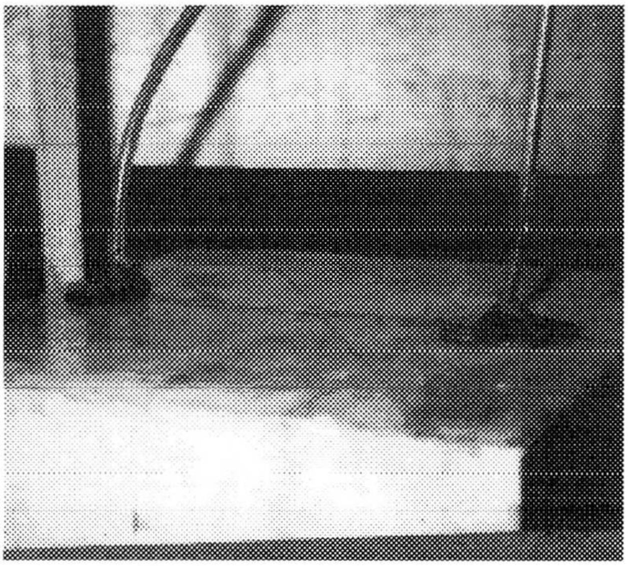

Fig. 5 Epoxy resin injection

2.5. Presentation of the results

The results obtained are shown in tables 1 and 2, and in graphic form in figures 6 and 7. In the latter, the data regarding the measurements taken along equivalent paths have been grouped together and averaged.

A: vertical path E2-R2, which intersects the cavity;

B: diagonal paths crossing the cavity (E1-R3, E3-R1);

C: diagonal paths that do not cross the cavity directly (E1-R2, E2-R1, E2-R3, E3-R2).

Cavity	Path								
Diam.(mm)	E1-R1	E1-R2	E1-R3	E2-R1	E2-R2	E2-R3	E3-R1	E3-R2	E3-R3
Integer	4625	4619	4516	4847	4802	4661	4822	4841	4695
0	4593	4578	4478	4835	4768	4613	4800	4777	4631
20	4600	4584	4478	4841	4768	4613	4795	4777	4631
40	4593	4584	4474	4836	4748	4619	4779	4777	4637
60	4600	4584	4450	4835	4715	4631	4758	4790	4637
80	4606	4590	4409	4828	4631	4625	4716	4803	4619
100	4587	4561	4386	4796	4569	4625	4649	4809	4631
120	4575	4538	4337	4758	4508	4596	4589	4777	4581
140	4508	4505	4268	4746	4397	4527	4564	4727	4544
155	4508	4477	4238	4715	4307	4466	4521	4691	4550
Repaired	4566	4523	4393	4709	4679	4523	4763	4764	4659

Table 1 Pulse Velocity (m/s)

Cavity	Path								
Diam. (mm)	E1-R1	E1-R2	E1-R3	E2-R1	E2-R2	E2-R3	E3-R1	E3-R2	E3-R3
Integer	32.5	37.5	45.0	40.5	32.0	40.0	47.5	36.0	33.5
0	35.5	38.0	46.0	42.0	33.5	41.0	49.0	36.5	37.5
20	35.5	38.0	46.0	42.0	34.0	41.5	49.0	37.0	38.0
40	35.5	38.0	46.0	42.0	34.0	41.5	49.5	37.0	38.0
60	36.0	39.0	46.0	42.0	35.0	42.0	49.0	38.0	38.0
80	36.0	40.0	46.0	42.5	36.0	44.0	49.5	41.0	38.5
100	36.0	42.0	47.0	43.5	37.0	44.5	49.5	41.5	38.0
120	36.0	43.0	48.0	44.0	40.0	44.0	61.0	42.0	38.0
140	35.5	46.5	67.0	46.0	41.5	48.0	66.5	43.5	38.0
155	35.5	48.5	70.9	47.0	42.5	52.0	70.9	45.0	38.5
Repaired	32.0	42.5	65.5	37.5	43.0	54.0	64.0	41.5	34.0

Table 2 Attenuation (dB)

Along the path A, the velocity in the cracked block is slightly lower than that in the integer block, and the attenuation slightly greater. This is due to the applied pressure, which creates good contact between the edges of the crack. In the presence of the cavity, the velocity decreases as the diameter increases, more so for diameters greater than 60 mm. The total increase is approximately 10%. The attenuation increases progressively, with a total increase of approximately 10 dB. After repair, the velocity returns to a value quite similar to that of the integer block, while this is not the case for attenuation, which remains very near to that found with the largest cavity surface area.

The paths B show a similar velocity pattern to that of the path A. For attenuation, the pattern shows a certain anomaly, due to the formation of a vertical crack.

The paths C do not intersect the cavity until the diameter exceeds 100 mm. Beyond this value, the velocity graph shows a limited decrease. Attenuation instead shows the defect from the very beginning, increasing progressively.

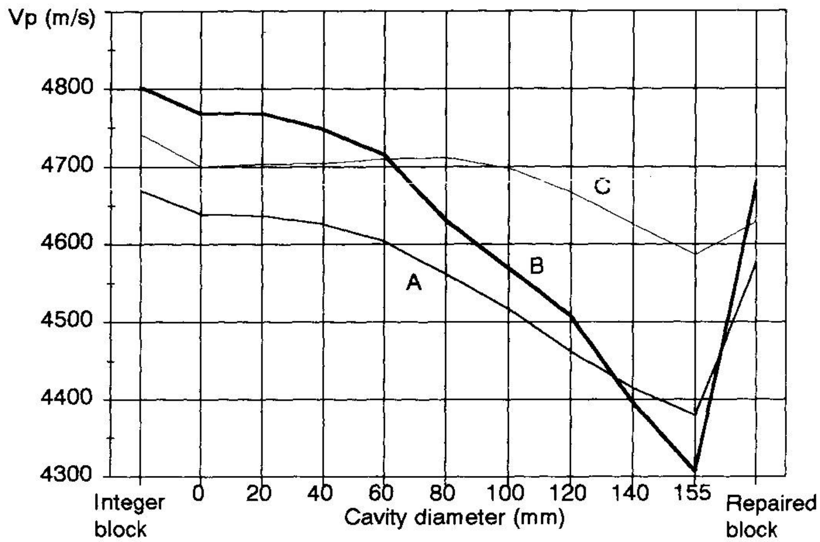

Fig. 6 Pulse velocity along different paths

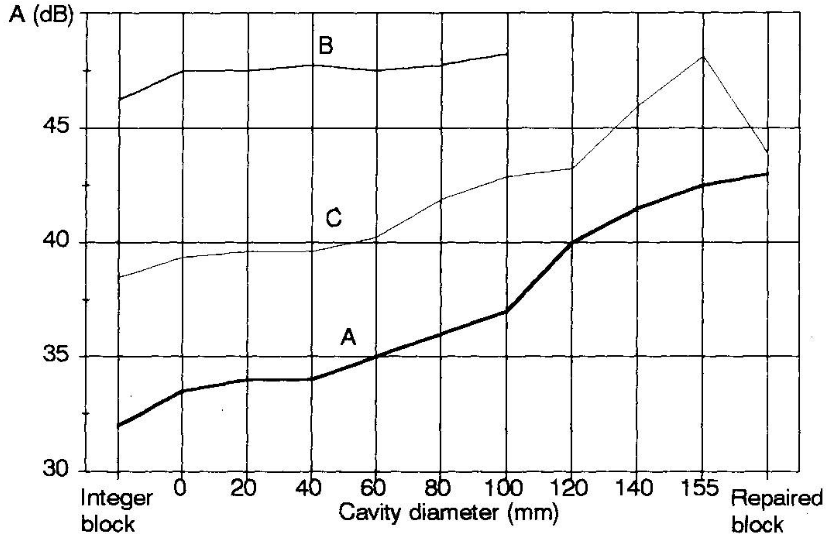

Fig. 7 Attenuation along different paths

3. INTERPRETATION OF THE RESULTS

The graphs in figures 6 and 7 show a different response by the two parameters *velocity* and *attenuation* according to the presence and size of the internal cavity. The cavity reflects a part of the energy, and thus causes an increase in attenuation even if the defect is not directly on the line joining the two probes. The transit time, and thus the apparent velocity, show instead a change only if the joining path crosses the defect. Variations in attenuation may therefore indicate the presence of defects, while in order to determine the position and dimensions it is more appropriate to perform a series of velocity tests.
The following formula is often used to evaluate the size of a defect:

$$d = L \cdot \sqrt{\left(\frac{\Delta t_1}{\Delta t_2}\right)^2 - 1}$$ where:

d = diameter of the defect;
Δt_1 = transit time along the trajectory containing the defect;
Δt_2 = transit time along a trajectory of the same length, in the integer material;
L = distance between the probes.

Based on changes in the transit time along the trajectory E2-R2, the known diameters are compared to the calculated diameters using the above formula. The graph in figure 8 indicates that the estimate becomes reliable beyond 80 mm in diameter.

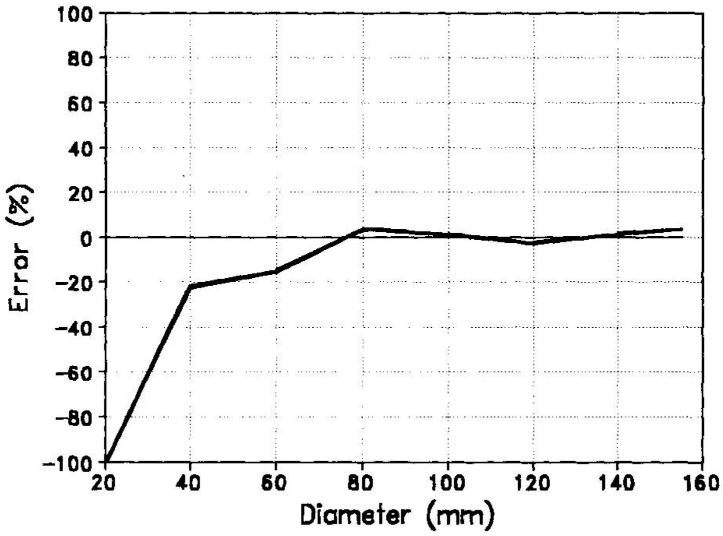

Fig. 8 Error in the evaluation of the diameter

Another purpose of the study was to examine the ability of the method to determine whether a resin filling has been successful. When this technique is used to repair internal cracks or cavities in blocks of stone or marble, it may occur that the filling is incomplete and air bubbles remain, or that the resin separates from the edges of the hole while hardening. In the case in question, the filling was performed correctly, as was subsequently verified by dividing the two parts of the block along the adhesive surface. By examining the graphs in figure 6, we note that in the repaired block the velocity returns very close to the values of the integer block. This would not have been the case if internal cavities were still present, due to a faulty filling . The *pulse velocity* parameter is therefore capable of indicating that the material is once again continuous. The graphs in Figure 7 indicate instead that the filling, even when performed correctly, does not return the attenuation to the value found in the integer block, probably because the resin, which has a different acoustic impedance from that of marble, still causes a considerable part of the energy emitted to be reflected. The *attenuation* parameter therefore is not useful to this purpose.

4. CONCLUSIONS

The study carried out leads to the following conclusions:

- the presence of internal defects is revealed by variations in velocity and, especially, in attenuation;
- both types of measurements are useful in determining the dimensions and position of the defects;
- for evaluating the success of a resin filling, velocity measurements seem more effective.

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The study presented in this paper was carried out thanks to the financial contribution of M.U.R.S.T., Ministero dell'Università e della Ricerca Scientifica e Tecnologica (Italian Ministry of Higher Education and Scientific and Technological Research).