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# Ultrasonic Methods for Damage Evaluation in Limestone Columns

## Méthodes par ultrasons pour l'estimation des dommages dans des colonnes en calcaire

## Ultraschallmethoden für die Schadensermittlung in Kalksteinpfeilern

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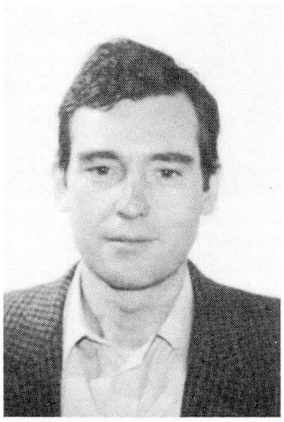

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## SUMMARY

The paper examines the possibility of assessing the damage level evaluation of sandstone and limestone columns from non-destructive testing carried out by means of ultrasonic probes, with a view to finding out relations able to relate material parameters before and after strengthening operations. The discussion of an experimental program regarding the columns of a monastery in Bologna allows for a practical application of the proposed damage indicators.

## RÉSUMÉ

L'article examine la possibilité d'évaluation des dommages de colonnes en calcaire et en molasse à partir d'essais non-destructifs conduits à l'aide de moyens ultrasoniques, afin de déterminer des relations entre les paramètres du matériau avant et après des actions de renforcement. La présentation d'un programme expérimental sur des colonnes dans un couvent à Bologne montre une application pratique d'indicateurs de dommages proposés.

## ZUSAMMENFASSUNG

Der Bericht prüft verschiedene Möglichkeiten zur Ermittlung des Schädigungsgrads von Kalk- und Sandsteinsäulen auf der Basis einer zerstörungsfreien Prüfmethode mittels Ultraschall. Ziel ist die Ermittlung der Beziehungen zwischen Werkstoffparametern vor und nach Verstärkungsmassnahmen. Ein experimentelles Programm für die Säulen eines Klosters in Bologna wird vorgestellt und die praktische Anwendungsmöglichkeit der Schadensermittlungsfaktoren diskutiert.

## 1. INTRODUCTION

Ultrasonic pulse velocity attenuation measurements are non destructive monitoring methods well suited for the evaluation of the damage level or the effect of strengthening in structural materials such as concrete, wrought or cast iron or, hard stones which are homogeneous at the macro level [1,2,3].
As a matter of facts several signal properties and transducer arrangements are available in order to assess the damage or strengthening indicators of structural slender elements such as sandstone or limestone columns [4].
More precisely pulse velocity, amplitude dacay, or spectral content can be measured; following the relative position and the form of transducers, direct or indirect (side) layouts alongwith planar or punctual probes can be used.
Thus, it is important to point out that a careful selection of the testing features is not only necessary in order to obtain useful informations, but is a complicated task too, which must take into account even non mechanical factors such as uman and environmental ones.
In the paper direct and indirect testing methologies are reviewed pointing out some simple analytical treatments which allows for a preliminary evaluation of damage or strengthening indicators as a relative measure to a selected specimen assumed the reference state.
Then, some results of an experimental program carried out on the sandstone columns of the cloister of the Archeological Museum in Bologna are discussed.
Finally, the evaluation of the parameters from the test measurements is worked out in order to show the effectiveness of the proposed relations.

## 2. ULTRASONIC SCANNING FOR DAMAGE EVALUATION

The preservation of isolated uncoated structural elements such columns and vaults is strongly withstood by the combined attack of loading and environmental agencies; in this respect, it is well known that the presence of ambiental vibrations, diffusion of wet air pollutant and a high sustained load can often lead to a premature failure of the structural element.
With relation to the metric of the microstructure, we can have concetrated or geeralised damage; in the first case, which is typical of fine grain materials (marble, granite and brittle metals), it arrives finally at a well defined crack pattern or even to a material spalling [5,6].

In the latter case, which is proper of large grain or composite materials (metamorphic stones or concrete), the damage involves an overall net of microcracks at microscopic level; these last sometimes can coalesce to a macrocrack but anyhow they change the structural properties of the material [7,8]. As a consequence, a proper testing method must take into account the nature of the investigated phenomena in order to select procedures able to quantify the damage and suggest the repair techniques.
More precisely, in presence of rough localised cracks, ultrasonic scanning can be used in a way similar to tomography, by means of several intersecting travelling paths, which enable to draw information on the geometry of cracks [9] (fig.1).
Alternately, when we are dealing with sandstone or limestone and no macrolevel cracks are present, we can analyse the ultrasonic velocity and amplitude decay data in order to evaluate the site properties of the material [1,3,8].
Moreover, the comparison of these data with those obtained from a reference specimen (which often can be found enclosed in foundations, walls or other undamaged sites of the construction), leads in a nearly straightforward way to an accurate damage definition. In lack of a reference specimen, the material data of an active quarry or even given from Literature can be used, but anyway with fuzzier results.

## 2.1 Damage Indicators

Referring now to the case of generalised damage, we look for a link between the ultrasonic test results and the damage index; as a matter of fact this last can be conveniently defined making use of a mechanical property and a suitable metric scale [5,10]. By example, selecting the ultrasonic velocity itself and a linear scale with respect to a reference velocity $v_o$, we pose:

$$D_E = 1 - \frac{v_{us}}{v_o} \quad . \tag{1}$$

On the other hand, following the direct relationship between the ultrasonic velocity and the dynamic modulus of the material, a very common definition of the damage indicator is:

$$v_{us} = \sqrt{\frac{n\ E_d}{\rho}}\,, \qquad n = \frac{1-\nu}{(1-2\nu)(1+\nu)}\,, \qquad D_E = 1 - \frac{v_{us}^2}{v_o^2} \quad . \tag{2}$$

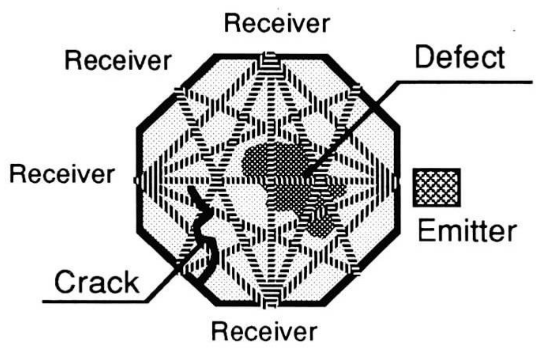


**Fig. 1** : Multi path scanning for defect positioning

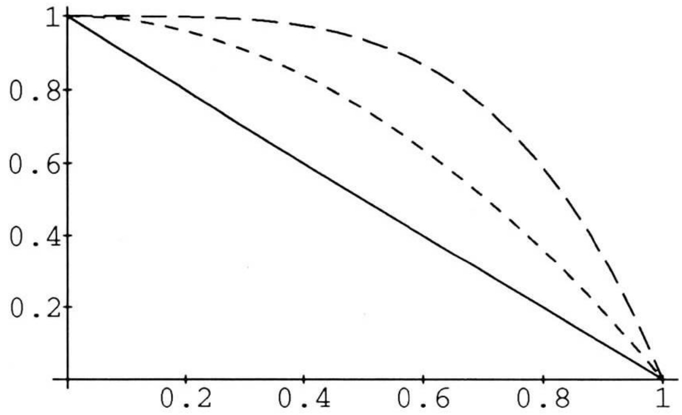


**Fig. 2** : Damage index as a function of the proposed velocity relations

As a further step, we can suppose that the damage may be interpreted as a strength reduction; again, making use of a linear index, and expressing the strength as a function of the dynamic modulus at the origin [11,13], we obtain:

$$D_f = 1 - \frac{f_{kus}}{f_{ko}}, \qquad E = \frac{E_{ref}}{k_d}\sqrt{\left(\frac{w}{w_{ref}}\right)^3 \frac{f}{f_{ref}}}, \tag{3.a}$$

hence:

$$f = \alpha\, v_{us}^4, \qquad D_f = 1 - \frac{v_{us}^4}{v_o^4}. \tag{3.b}$$

As a matter of fact, the relation (3.a) encompasses nearly all formulas proposed in the Literature, once adjusted the reference strength $f_{ref}$, the reference weight density $w_{ref}$, and the static-dynamic ratio $k_d$; in particular, referring us to natural sedimentary stones and including some results for low strength concretes [1] it arrives at:

$$E = 1800\sqrt{f}, \quad (E \text{ and } f \text{ in MPa}). \tag{4}$$

In fig. 2 the results of the presented damage laws are compared; As is clearly apparent, the different order of the exponent gives rise to a divergence of the indices; on the other hand, each definition is tailored on a different parameter and this should be taken into account when a damage measure has to be kept.

As a first comment, we recall that for cementitious materials there is a treshold under which the material behaves as elastic linear neglecting initial defects; moreover, despite damage starts at relatively low stress level [11-13], it begins to be significant near the collapse [3,6,8].

On the other hand, describing the uniaxial constitutive relation with by example the Sargin or the Hognestad formula [13], the derivative of the stress is continuosly varying from the zero strain up; so, neglecting a treshold parameter will result in a damage function null only for virgin materials.

But, as is well understood, the evolution of the volumetric strain is a clear map of the damage rise; in fact, the void increase caused by microcracking turns into materials dilatancy, which appears in a change of sign of the volumetric strain derivative.

In this respect, Cervenka [12] has shown that a suitable interpolation of the stress - volumetric strain relation can accurately reproduce the damage evolution; more precisely, introducing a polynomial interpolation we have:

$$\frac{\varepsilon_c - \varepsilon_{vc}}{\varepsilon_{vc}} = D_{vc} = \begin{cases} 0 \ , & \sigma < \sigma_{vc} \\ \alpha \left(\dfrac{\sigma - \sigma_{vc}}{f_k - \sigma_{vc}}\right)^m \ , & \sigma > \sigma_{vc} \end{cases} \quad . \tag{5}$$

Obviously, assuming $\sigma_{vc}$ null will lead to a continuous damage index; in this case, in order to fit rel. (5) the exponent m must be doubled or so.

If we mean to link the measured ultrasonic velocities with the dilatancy based damage index, it is necessary to select a suitable constitutive relation and set up the relation between the stress and its derivative; in this preliminary study we assume the Hognestad formula:

$$\sigma = f_k \frac{k\,\eta - \eta^2}{1 + (k-2)\eta} \ , \qquad k = \frac{E\,\varepsilon_u}{f_k} \ , \qquad \eta = \frac{\varepsilon}{\varepsilon_u} \ , \tag{6.a}$$

$$E = \frac{1}{\varepsilon_u}\frac{d\sigma}{d\eta} \tag{6.b}$$

where we signed with $(\varepsilon_u, f_k)$ the limit point of the stress strain relation.

Once obtained an ultrasonic velocity measure and upon assuming a reference strength, we can invert rel. (2) and use the computed mean dynamic tangent modulus to determine a mean stress level; finally this allows for the evaluation of the damage index.

Alternately, assuming known the stress level in the column (peraphs, from a numeric analysis), we can solve the nonlinear system 6.a-6.b looking for the actual strain $\varepsilon$ and the strength $\sigma_u$.

A drawback of rel. (5) is the need of the value of $\sigma_{vc}$ which is of difficult definition indeed. However, contrary to the linear damage law, this type of representation involves a filtering (due to the exponent m), which runs finally to a step damage function; in fig.3 the results for m=2 and m=4 (solid lines) are compared with the case $\sigma_{vc}$=0, showing a relative insensitivity to the choice of the various constants.

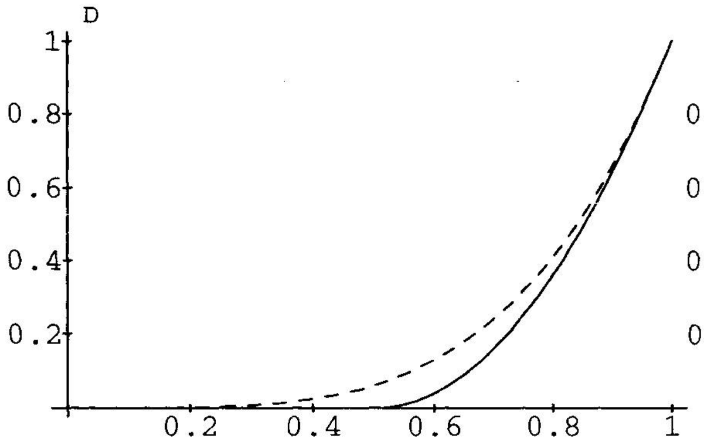


**Fig. 3.a** : Damage evolution as a function of stress level $\sigma/f_k$, as predicted by dilatancy

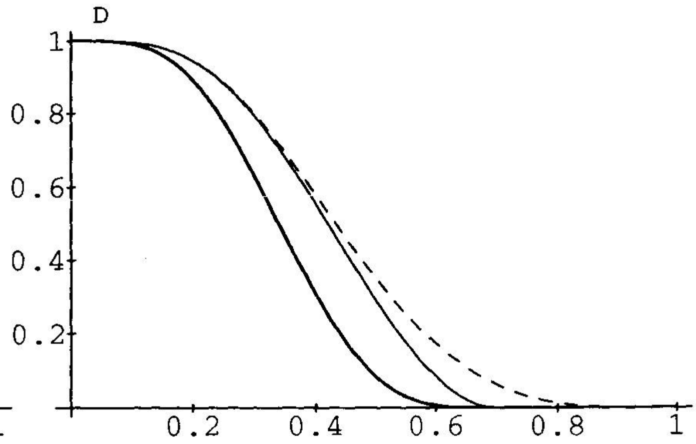


**Fig. 3.b** : Damage evolution as a function of the ultrasonic velocity ratio $v_{us}/v_o$

| Section | Path | Initial | Repaired |
|---|---|---|---|
| 1 | a | - | 2767 |
| | b | - | 3131 |
| | c | 1758 | 2344 |
| | d | - | 2103 |
| 2 | a | - | 1994 |
| | b | 1875 | 1857 |
| | c | 1825 | 1867 |
| | d | - | 1923 |
| 3 | a | 1740 | 2255 |
| | b | 1955 | 2056 |
| | c | 2157 | 1891 |
| | d | 1864 | 2062 |
| 4 | a | 1907 | 2272 |
| | b | 2161 | 1975 |
| | c | 2262 | 1852 |
| | d | 2036 | 2076 |
| 5 | a | 2037 | 2850 |
| | b | 2211 | 2461 |
| | c | 2408 | 2222 |
| | d | 2183 | 2091 |
| | | m/s | m/s |

**Table I**

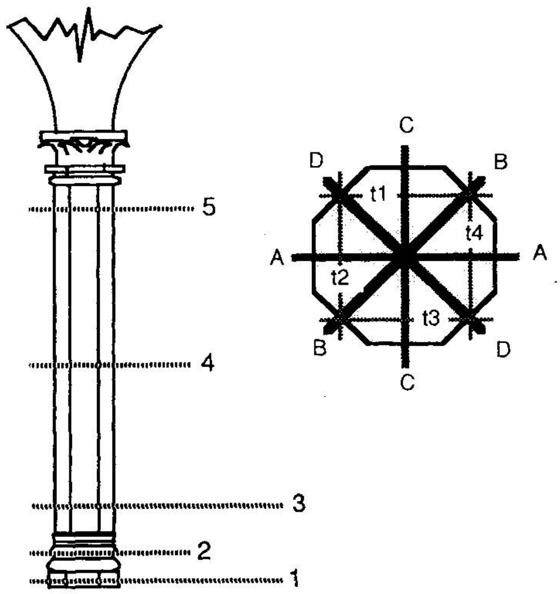


**Fig. 4** : Representation of the measure paths

## 3. THE CLOISTER OF ARCHAEOLOGICAL MUSEUM IN BOLOGNA

The internal cloister of the Archaeological Museum in Bologna contain 16 limestone column of octagonal shape whose material cames from a local quarry which today is thoroghly exhausted. The yellow limestone appears sufficiently uniform but, due to the low strength and the environmental attack several microcracks are present resulting in the ultrasonic velocities reported in fig.4.

In order to achieve a target load increase necessary for architectural purposes, a restoration test was carried out on the selected column; more precisely it was grouted at low pressure with a low viscosity epoxy resin. Following compatibility consideration we selected a resin with an elastic modulus of nearly the value of the virgin limestone.

In the table of fig. 4 the values of the ultrasonic velocities measured after the filling operation are shown; as is apparent, the major change involves the sections what initially were not transparent.

In fig.s 5 and 6 the computed damage indices are compared for both conditions, before and after repair. As we said before, the various statements differ dramatically and is difficult to extract the correct one.

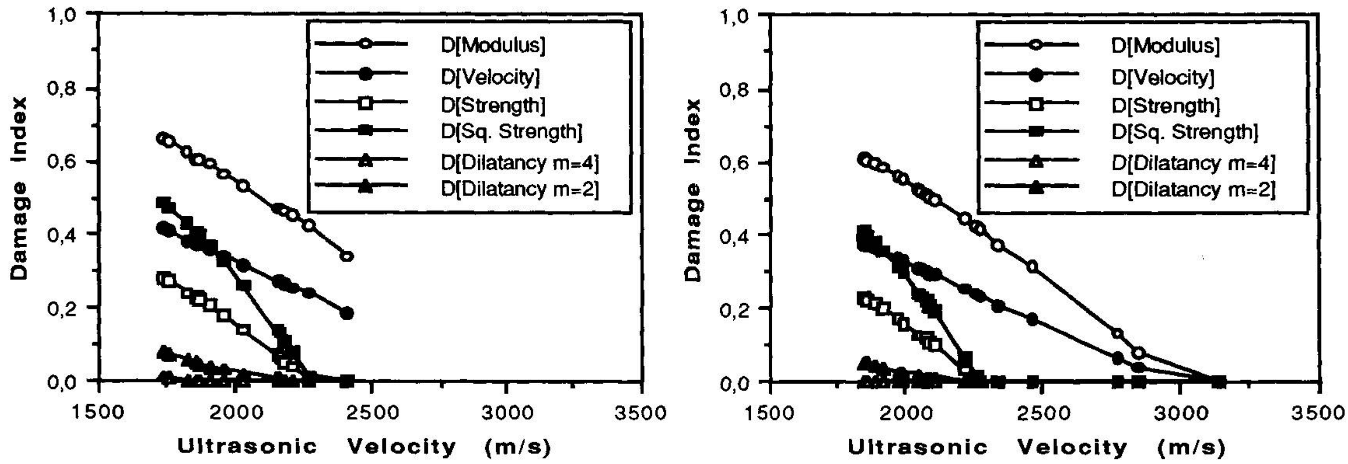


**Fig. 5 & 6** : Damage indices resulting from the various formulations for the damaged and restored column

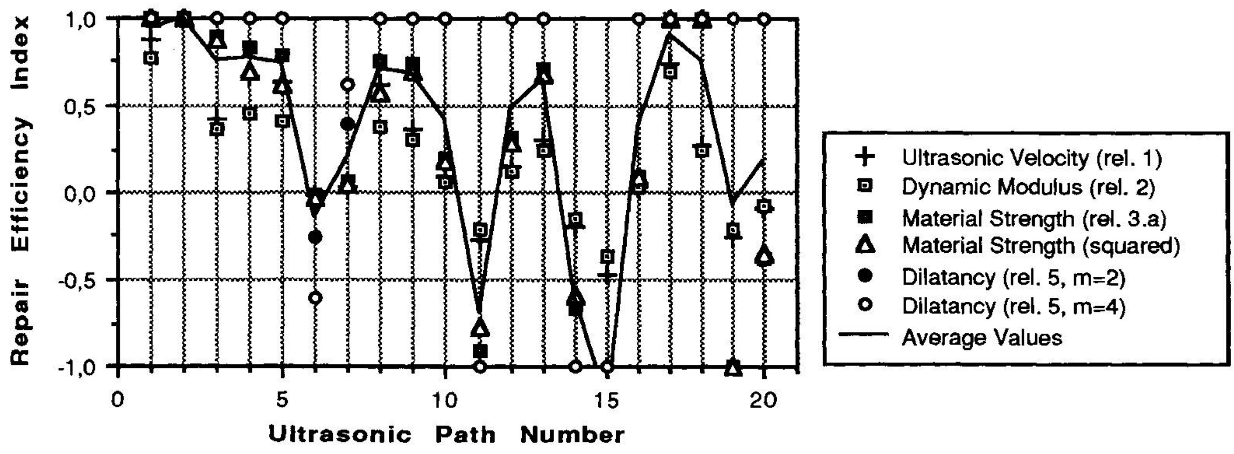


**Fig. 7** : Repair Efficiency as computed from the ratio of damage indices, before and after the strengthening

On the contrary, expressing the efficiency of the strengthening by means of the ratio of the relevant damage indices we can observe a significant agreement of the introduced indices. In fig. 7 the efficiency ratios for the various measurement paths are compared.

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