APPLICATION OF RAYLEIGH WAVE TO DIAGNOSTICS OF DEGRADATION OF HISTORIC CONSTRUCTION MATERIALS

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Summary

Paper presents results of degradation modelling of historical construction materials based on Rayleigh surface wave velocity (CR) measurement for two marbles widely used as the structural and decorative material in historical constructions. Environmental loading is modelled by freezing and thawing cycles performed in laboratory. Rayleigh wave measurement method does not need any coupling medium between the stone and ultrasonic probe and is 100% non-destructive. It is shown that exponential law can be used to model the proces of degradation of elastic properties of the tested materials.

Keywords: degradtion modelling, material integrity, Rayleigh wave, edge probes, historical materials.

ZASTOSOWANIE FALI RAYLEGHA DO DIAGNOSTYKI DEGRADACJI HISTORYCZNYCH MATERIAŁÓW KONSTRUKCYJNYCH

Streszczenie

Praca przedstawia wyniki modelowania degradacji historycznych materiałów konstrukcyjnych na podstawie pomiarów prędkości fali Rayleigha dla dwóch marmurów szeroko stosowanych w zabytkowych budowlach jako materiał konstrukcyjny i dekoracyjny. Obciążenia środowiskowe modelowane są cyklami zamrażania i rozmrażania przeprowadzonymi w laboratorium. Metoda pomiaru fali Rayleigha nie wymaga żadnego ośrodka sprzęgającego pomiędzy materiałem a sondą ultradźwiękową i jest w 100% nieniszcząca. Wykazano, że proces degradacji właściwości sprężystych badanych materiałów dobrze modeluje prawo wykładnicze.

Słowa kluczowe: modelowanie degradacji, integralność materiału, fala Rayleigha, sondy ostrzowe, zabytkowe materiały.

1. INTRODUCTION

Diagnostics of historical construction materials includes, among the others, assessment of their nowadays physical na mechanical properties. This is done mainly in a non-destructive way because of the great cultural value of historical constructions. However evaluation of the degradation processes and their dynamics cannot be done by measuring actual properties only.

It is necessary to compare the actual data with the properties of original non-degraded materials and the same properties at several levels of degradation to descibe a susceptibility of the material to environmental loads like day and night thermal cycles, freezing and thawing in winter times etc.

In the case of stones used as a construction material it is possible to obtain fresh-from-quarry samples of the material to perform laboratory investigation of the degradation evolution. Reference measurements are done for fresh, intact matrial and then the same measurements are done after prescribed number of cycles of experimentally medeled environmental loads.

In the present work two stones - Marble Cervaiole (MC) from Buca quary in Seravezza (Italy) and Marble Gioia (MG) from Gioia quarry near Carrara (Italy) -were tested. Independent variable of an artificial ageing process was the number of freezing and thawing cycles. The number of cycles was correlated with the changes of ultrasonic Rayleigh surface wave [1] velocity.

Degaradation analysis is based on the non-destructive evaluation of the rate of the loss of material integrity under assumption of proportionality between surface wave velocity and dynamic shear modulus of elasticity [2].

Collected data were used to evaluate the degradation process of the marbles using the mathemathical model based on phenomenological description of the loss of meterial integrity [3].

2. DIAGNOSTIC METHOD

Rayleigh wave [1] was primarily used in stone testing for measurement of elastic constants of stones [4]. This comes from the fact that elastic constants can be expressed by means of longitudinal, (compressive) and transversal (shear) wave velocities [2].

Let us denote the measured velocities of shear and longitudinal waves as V_S and V_l respectively. Then the material constants called “dynamic material constants” can be expressed by the equations:

$$\nu_d = \frac{0.5-(V_s/V_l)^2}{1-(V_s/V_l)^2} \tag{1}$$

$$E_d = \rho V_l^2 \frac{(1+\nu_d)(1-2\nu_d)}{(1-\nu_d)} \tag{2}$$

$$G_d = \rho V_S^2 \ , \tag{3}$$

where ν_d is the Poisson’s ratio, E_d is the Young’s modulus, G_d is the shear modulus and ρ is the material density. Theory [2] confirmed by experiments e.g. [4] shows that surface wave can be used to approximate the value of shear wave velocity, $V_R \approx 0.9V_S$, and hence used to calculate dynamic shear modulus of elasticity as:

$$G_d \approx V_R^2 \tag{4}$$

This formula serves as a basis for evaluation and modeling of the process of marbles degradation.

2.1. Rayleigh surface wave measurements

The measurement procedure does not need any energy transmitting medium between the specimen and ultrasonic probe and is 100% non-destructive [5]. Apparatus consists of a pulse generator, a set of two edge probes, signal processing and sampling unit and a PC. The probes consist of steel edges and piezoelectric transmitting/receiving transducers [6].

The edges are configured to ensure the contact nibs of both probes being parallel to each other and their geometry being suitable to generate and sense the surface Rayleigh wave in a stone outer skin layer.

The idea of the measurement method is sketched in Figure 1and the edge probes are shown in Figure 2. The surface wave velocity is calculated on a basis of the recorded travel time of the ultrasonic pulse over a distance between the edges’ nibs. The distance between both nibs is measured with digital slide caliper or alternatively can be fixed in advance to the measurements to the required value by using the calibrating plate inserted between the nibs.

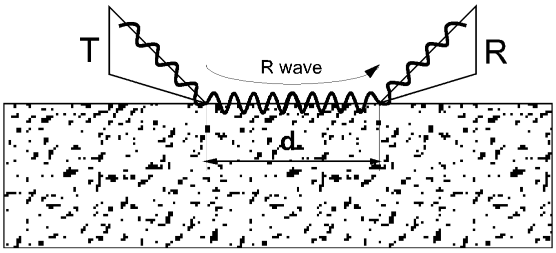


Fig. 1. Surface Wave measurement principle

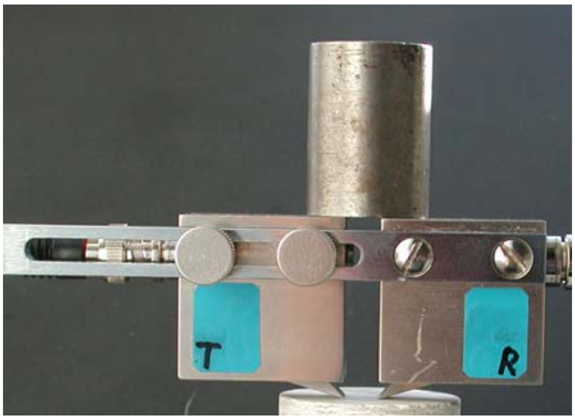


Fig. 2. Edge probe used for the Surface Wave velocity measurements

A computer was used as an oscilloscope screen and for software manipulation which allowed signal recording and pulse travel time measurement. Travel time measurements were corrected for apparatus characteristic delay time of the pulse travelling trough the both probes. Rated frequencies of the probes were 1000-2000kHz, with the lower one used for the MG specimens showing greater attenuation of surface waves [7].

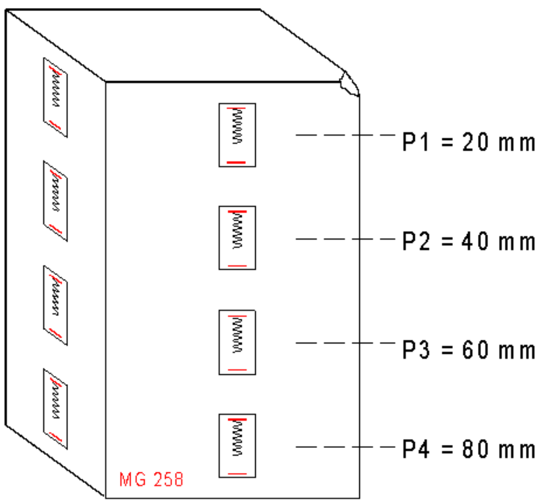


Fig. 3. Locations of Surface Wave velocity measurements

The specimens of 10 cm height were used and four equally spaced locations were chosen on two perpendicular specimens surfaces. This is schematically shown in Figure 3.

During experiments the probes were placed on a specimen surface to span the desired location symmetrically with the both contact nibs. The distance of the nibs was varying from 8 mm to 16 mm depending on the wave attenuation within a specimen.

2.2. Modeling of environmental loading

The artificial aging events were Freeze and Thaw (F-T) cycles. Each cycle consisted of 4 hours freezing to -10°C and then 4 hours thawing at 21°C [7]. The cycles were carried out in series of 20 F-T events which made one weathering cycle step. The specimens were dried in an oven after each cycle step in 40°C to the constant mass and ultrasonic pulse travel time was measured as described above.

Thermal effect of the drying process was evaluated before the beginning of systematic artificial ageing in order to establish the proper drying temperature at the end of the prescribed number of F-T cycles. It was shown that applied drying temperature of 40°C does not introduce the change in measured surface wave velocities. During freezing phase of the cycle and during drying of the specimens temperature measurements inside a reference specimens were performed. The reference specimens were drilled to a depth of 5 cm parallel to their longer axis and a thermocouple was used to measure the temperature inside the specimen. Three specimens of Cervaiole Marble (MC) and Gioia Marble (MG) were used for measurements in each cycle step except the step zero were reference values of surface wave velocities were measured for fresh, from quarry stones. In this case five specimens of each marble were used. The recorded data were used in further marble degradation analysis based on the observed mean values of surface wave velocity.

3. EXPERIMENTAL RESULTS

Measurements of ultrasonic surface waves were performed according to the above described procedure [7].Five specimens of MC and MG marbles were tested before weathering and three others each time new specimens after 20-100 F-T cycles. The specimens tested after 100 F-T cycles were additionally weathered and tested in step after 120 cycles.

Values of surface wave velocities which has been used to analyse RC and MG stones decay are collected in Table 1. There are presented mean values for each cycle step calculated for X and Y planes of Cervaiole and Gioia Marbles specimens. Mean data are accompanied by standard deviations based on 36 the measurements for each data in general, except of two cases for Gioia Marble where only 30 measurements were successful due to greater wave attenuation.

Table 1. V_R [m/s] measurements with edge probes

marble & side	MC X		MC Y	
No. of F-T cycles	Velocity	St.dev.	Velocity	St.dev.
0	2740	24	2720	43
20	*2580*	*84*	2590	23
40	*2880*	*138*	2850	92
60	2580	29	2620	106
80	2670	67	2630	71
100	2560	98	2500	37
120	2580	61	2530	42
marble & side	MG X		MG Y	
No. of F-T cycles	Velocity	St.dev.	Velocity	St.dev.
0	1900	187	1900	142
20	1500	173	1450	201
40	1600	235	1700	290
60	1500	134	1500	186
80	1450	85	1500	94
100	1300	172	1300	110
120	1500	164	1400	107

Scattering of the results is usually greater for MG marble which is of granoblastic (homoblastic) microstructure and is less homogeneous than the xenoblastic RC marble. It is also seen that MG marble has lower average surface wave velocity and more distinct weathering trend then RC marble. Both weathering trends seem to be non-monotonic while looking at average values.

To describe the real weathering tendency the measured velocity values were compared with phenomenological mathematical model of weathering decay of stones which has been done in the next section.

4. ANALYSIS

Dynamic elastic properties of the marble were assessed on a basis of measured surface Rayleigh wave propagation velocity. It can be seen from the formulae (2 - 4) that the square of the elastic wave velocity is proportional to elastic moduli of the tested material. Thus one can introduce Material Elasticity Index (MEI) as a square measure of a ratio of actual and reference wave velocity according to equation:

$$MEI_{VR} = \left(\frac{V_R}{V_{R0}} \right)^2 \quad (5)$$

where actual V_R velocity was measured after F-T artificial weathering and reference V_{R0} velocity is that measured for intact marble (fresh, from quarry). Freezing and thawing increases stone surface deterioration which decreases dynamic elastic properties of the stone thus lowering the surface wave velocity. Hence observed elasticity index $MEIv_R$ is a decreasing function of stone degradation with value of 1 for the intact marble.

Mathematical model assuming a loss of stone integrity Ψ proportional to the integrity at the beginning of each cycle [3] was used to evaluate the material degradation.

This assumption can be expressed in a form fo differential equation as follows:

$$-\frac{d\Psi}{dN} = \lambda\Psi \qquad (6)$$

where dΨ/dN is the disintegration rate, minus sign indicates that the integrity is decreasing, λ is the decay constant, and N is the number of cycles.

The solution of (6) is the exponential material degradation law of the form:

$$\Psi = e^{-\lambda N} \qquad (7)$$

The $MEIv_R$ indexes were calculated separately for Cervaiole and Gioia Marbles for X and Y specimen wall on a basis of V_R velocities of 36 measurements recorded for each specimen wall after each artificial ageing cycle. These 36 indexes were averaged and standard deviation errors were calculated. The results were analysed individually for each wall of MC and MG marble categories.

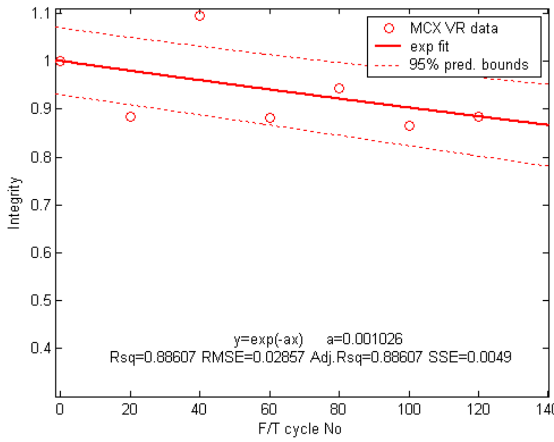
Primary analysis, with all the results included into analysis, showed poor correlations with physically sound fit functions. The correlation R^2 parameter was as low as 0.235 in one case and prediction bounds of 95% probability were very broad. This showed that some of calculated $MEIv_R$ were influenced by other experimental factors then material degradation only. Further analysis showed that discarding the indexes calculated for the cycle No 20 for both marbles improves the fit to the great extend. Three other index values were also removed from the analysis giving all together 7 out of 28 calculated indexes which were unacceptable. After this modification the exponential curves, based on the mathematical model assuming a loss of stone integrity proportionally to the integrity at the beginning of each cycle, were fitted to the calculated indexes. The actual R^2 correlation factor increased to 0.8368 in the worth case and 95% prediction bounds were substantially tightened.

Summarized $MEIv_R$ indexes are given in Table 2. The index values which were excluded from the further analysis are shadowed.

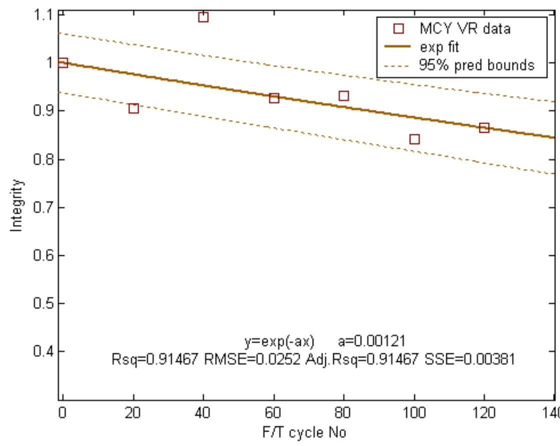
Graphical illustration of the calculated MEI and fit functions are drawn in Figures 4 and 5 for MC and MG marbles respectively. There are also shown prediction bounds and statistical information about the given exponential fit. It is also seen that discarded index values fall apart from prediction bounds of the well-correlated, physically sound fits justifying that some unpredicted experimental errors were introduced during the cycle No 20 of F-T weathering of both marbles and in three other cases as well.

Table 2. Material Elasticity Index based on Surface Wave Velocity measurements

marble & side	MC X		MC Y	
No. of F-T cycles	$(v_R/v_{R0})^2$	St.dev	$(v_R/v_{R0})^2$	St.dev
0	1	0.02	1	0.03
20	0.88	0.06	0.91	0.02
40	1.10	0.10	1.10	0.07
60	0.88	0.02	0.93	0.08
80	0.94	0.05	0.93	0.05
100	0.87	0.07	0.84	0.02
120	0.88	0.04	0.86	0.03
marble & side	MG X		MG Y	
No. of F-T cycles	$(v_R/v_{R0})^2$	St.dev	$(v_R/v_{R0})^2$	St.dev
0	1	0.20	1	0.16
20	0.59	0.14	0.61	0.19
40	0.75	0.22	0.84	0.29
60	0.60	0.11	0.68	0.18
80	0.58	0.07	0.66	0.08
100	0.50	0.14	0.46	0.08
120	0.66	0.14	0.59	0.09

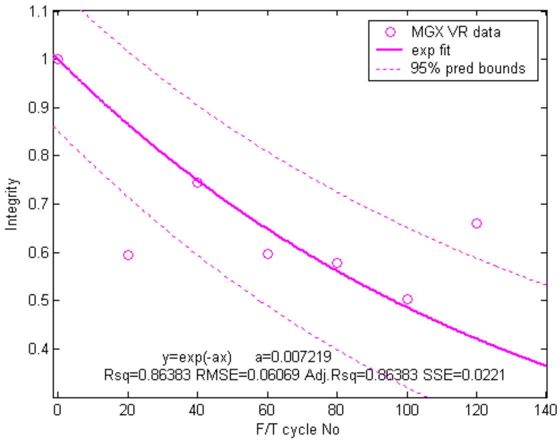


a)



b)

Fig 4. Integrity of Cervaiole Marble after F-T ageing treatment:
a) X-plane, b) Y-plane



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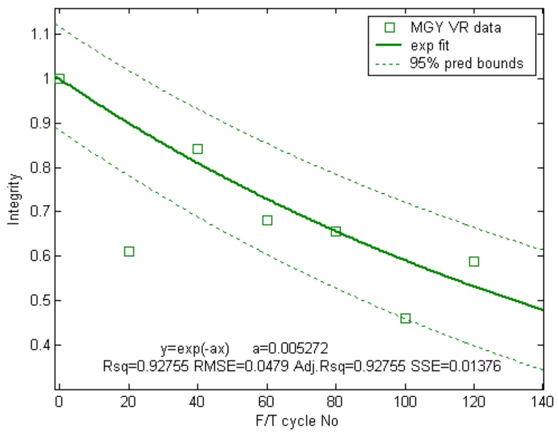

b)

Fig. 5. Integrity of Gioia Marble after F-T ageing treatment:
a) X-plane, b) Y-plane

5. CONCLUSIONS

Research confirmed that Rayleigh surface waves can be efficiently used for diagnostic of surface degradation of historical construction materials. Application of edge probes to the measuremetns of surface wave velocity is especially suitable for testing of monuments because it does not need any coupling medium which may degrade surface of the heritage object. The apparatus is portable and can be used in laboratory and for on-site testings as well.

By virtue of the method only thin surface layer is analysed and many local measurements allow statistical analysis.

Assumed exponential degradation model fits well to the experimental data. Resulting exponential curves were fitted to the calculated experimental indexes with R^2 correlation factor equal to 0.8368 in the worth case.

Data collected for Gioia and Cervaiole Marbles shows that Gioia Marble is much less resistant to Freezing and Thawing ageing factors than Cervaiole Marble.

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