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Coda Wave Interferometry Method Applied in Structural Monitoring to Assess Damage Evolution in Masonry and Concrete Structures

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Abstract. In this experimental program the main goal is to monitor the damage evolution in masonry and concrete structures by Acoustic Emission (AE) signal analysis applying a well-know seismic method. For this reason the concept of the coda wave interferometry is applied to AE signal recorded during the tests.

Acoustic Emission (AE) are very effective non-destructive techniques applied to identify micro and macro-defects and their temporal evolution in several materials. This technique permits to estimate the velocity of ultrasound waves propagation and the amount of energy released during fracture propagation to obtain information on the criticality of the ongoing process.

By means of AE monitoring, an experimental analysis on a set of reinforced masonry walls under variable amplitude loading and strengthening reinforced concrete (RC) beams under monotonic static load has been carried out. In the reinforced masonry wall, cyclic fatigue stress has been applied to accelerate the static creep and to forecast the corresponding creep behaviour of masonry under static long-time loading. During the tests, the evaluation of fracture growth is monitored by coda wave interferometry which represents a novel approach in structural monitoring based on AE relative change velocity of coda signal. In general, the sensitivity of coda waves has been used to estimate velocity changes in fault zones, in volcanoes, in a mining environment, and in ultrasound experiments.

This method uses multiple scattered waves, which travelled through the material along numerous paths, to infer tiny temporal changes in the wave velocity. The applied method has the potential to be used as a “damage-gauge” for monitoring velocity changes as a sign of damage evolution into masonry and concrete structures.

1. Introduction

In the last decades, the rehabilitation of civil structures has increasingly become an important challenge in the construction market. Among the various methods used to strengthen and repair RC beams and masonry wall, wet lay-up systems of Carbon Fibre Reinforced Polymer (CFRP) sheets represents an effective and convenient method [1]. The advantages of bonding CFRP sheets to the concrete and masonry derive from the light weight due to low density, the high mechanical characteristics in terms of strength and stiffness, the high resistance to corrosion and chemicals and the easiness to adapt to the shape of the structural member. The Acoustic Emission (AE) technique is used to analyse the damage evolution into RC beams and masonry wall during the tests, and to obtain information on the criticality of the ongoing process [2]. In particular, a signal based procedure is proposed to evaluate the damage evolution and the decay of structural mechanical parameters.

The coda of seismic waves consists of that part of the signal after the directly arriving phases. In a finite medium, or in one that is strongly heterogeneous, the coda is dominated by waves which have repeatedly sampled the medium. Small changes in a medium which may have no detectable influence on the first arrivals are amplified by this repeated sampling and may thus be detectable in the coda. We refer to this use of multiple-sampling coda waveforms as coda wave interferometry.

The sensitivity of coda waves has been used to estimate velocity changes in fault zones [3], in volcanoes [4,5], in a mining environment [6] , and in ultrasound experiments [7,8,9]. Temporal changes in the coda waves within a couple of days have been observed in a volcano. In the physics community a related technique called diffusing wave spectroscopy [10] has been used to monitor fluidized suspensions [11].

2. Coda Wave Interferometry Method: nonlinear change velocity in the Acoustic Emission signal

In this experimental program the main goal is to monitor the damage evolution in masonry and concrete structures by AE signal analysis applying a well-know seismic method. For this reason the concept of the coda wave interferometry is applied to AE signal recorded during the tests.

This method uses multiple scattered waves, which travelled through the material along numerous paths, to infer tiny temporal changes in the wave velocity. The applied method has the potential to be used as a "damage-gauge" for monitoring velocity changes as a sign of damage evolution into masonry structures. This one could represent one of the most important parameters to predict crack evolution, in the structural monitoring field. An example of two successive AE signals recorded in the tests are shown in Figure 1. Red signal is recorded at low damage level, whereas blue signal is recorded in the following step when damage increases: the early part of the signal remains largely unchanged while the later arriving waves are altered. In other words, the change in the medium has little effect on the early arriving waves.

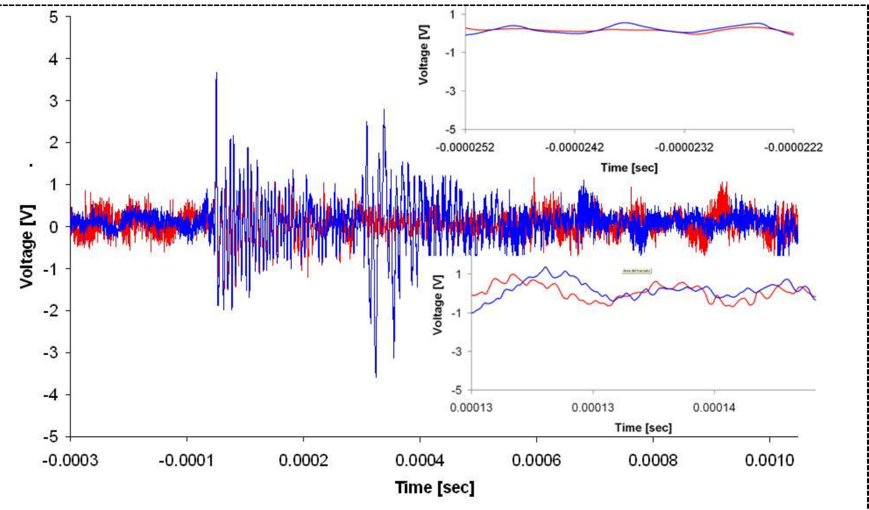

Figure 1. Two successive AE signal recorded in the tests with early part of the signal and the coda signal

Therefore these early arriving waves can not be used to detect this change. However, the coda waves are more sensitive to the change and, therefore, can be used to estimate the change in the medium.

Generally, the impulsive waveform presented a peak of variable amplitude and a subsequent damping due to material attenuation.

The cross-correlation function *R(t,T)* of AE signals at two different instant of the test in a moving time window is computed:

$$R^{(t,T)}(t_s) \equiv \frac{\int_{t-T}^{t+T} u_{unp}(t')\, u_{per}(t'+t_s)dt'}{\sqrt{\int_{t-T}^{t+T} u_{unp}^2(t')dt' \int_{t-T}^{t+T} u_{per}^2(t')dt'}} \qquad (1)$$

Here $u_{unp}(t')$ is the unperturbed velocity wave, $u_{per}(t')$ is the perturbed velocity wave and t is the center time of the moving time window. The cross-correlation *R(t,T)* weakly depends only on t and can be assumed to be constant within the time window of length T. The window length is equal to T = 0,1 ms. t_s is the time shift of the cross-correlation function. In a next step T is fixed and treat *R(t,T)* as a function of shift time t_s to extract the value of its maximum, R_{max}, and the position of its maximum, δt. R_{max}(T) is a measure for the similarity of two AE signal at time t and $\delta t(t)$ is a measure of the phase shift between them.

The phase shift increment observed comparing AE signals at different instant of the test can be explained by the temporal decrease of the mean velocity into the structural elements in advance to their fracture process and consecutive structural collapse. The basic theory of coda wave interferometry [8] assumes that the wave paths of multiple scattered waves remain constant, because source, receiver and scatterer location are identical. If the wave path is the same, is correct to assume an increment or a decrement of the wave velocity, which results for a homogeneous change on the relative velocity [8]: $\delta v/v = -\delta t(T)/T$, where $\delta v/v$ is the relative change of velocity between two test steps. To apply this expression to the experimental data a best linear fitting of the $\delta t(t)$ curve is carried out. The slope of this best fitting gives the temporal velocity change $\delta v/v$.

3. Materials, specimens and mechanical behaviour during the test

Brickwork walls, measuring 250 x 250 x 120 mm^3, are strengthened by two different reinforcement methods: a double layer of structural mortar, or two CFRP sheets applied (Fig.2) on both the external surfaces of the specimens. The tests are conducted in shear loading condition, by means of a diagonal compressive stress, subjecting the walls to fatigue cycles up to failure. In Figure 3, the shear deformation vs. time is plotted for mortar and CFRP reinforcement specimens. For each specimens typology, three samples are tested. For both sets of tests the three phases of creep phenomenon can be well recognized. For mortar reinforcement specimen, the primary creep phase corresponds to the interval $0 \leq t/t_{max} \leq 0.1$, the secondary creep phase corresponds to the interval $0.1 \leq t/t_{max} \leq 0.9$ and the tertiary creep phase corresponds to the interval $t/t_{max} \geq 0.9$. For CFRP reinforcement, the three phases correspond to the intervals: $0 \leq t/t_{max} \leq 0.05$, $0.05 \leq t/t_{max} \leq 1$, the tertiary creep is absent.

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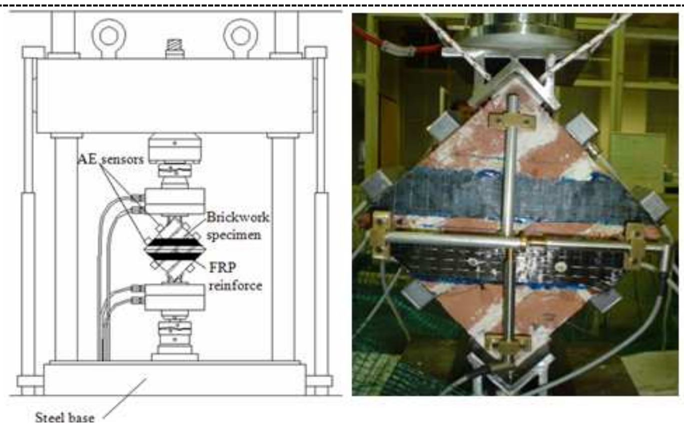

Figure 2. Loading scheme, the masonry specimens are tested in diagonal compressive condition using a servo-controlled machine (MTS) (Nondestructive Testing Laboratory, Director: Prof. Pietro Bocca, Department of Structural and Geothecnical Engineering - Politecnico di Torino).

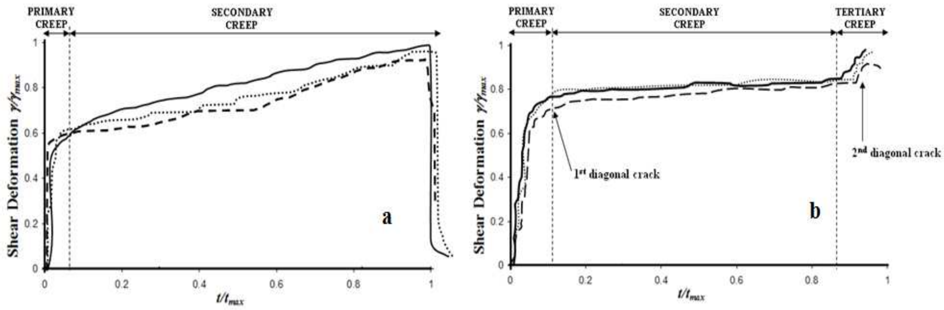

Figure 3. Shear deformation γ vs. time *t* for three CFRP reinforcement specimens (MF01 dashed line, MF02 dotted line, MF03 continuous line) (a) and for three mortar reinforcement specimens (MR01 dashed line, MR02 dotted line, MR03 continuous line) (b).

The three concrete beams (B31, B32, B34) were tested up to failure by means of four point bending tests and measuring 200 x 250 mm rectangular section and a length of 3000 mm (Fig. 4). The beams were reinforced with two longitudinal ordinary steel bars ø16 mm, placed at the top and bottom along the whole length, and ø8 mm transversal stirrups, spaced 150 mm apart. The beams were strengthened longitudinally by a wet lay-up system at the intrados and transversally by U-wrapping with 200 mm wide mono-directional CFRP sheets, whose properties are as follows: tensile strength of 4800 N/mm^2, modulus of elasticity of 240 kN/mm^2, maximum deformation between 1.5% and 1.8%, density of $1.78*10^{-3}$ daN/cm^3. The tissue has a weight of 0.32 daN/m^2, a thickness of 0.177 mm and a maximum load at rupture greater than 640 daN/cm. The fibres were glued to the concrete with epoxy adhesive.

Four point bending tests were carried out with loading points located at 450 mm on either side of the midspan. The measuring instrumentation includes three displacement transducers to measure vertical displacements and six potentiometric transducers, located at the intrados and extrados of the beams, with measuring bases of 250 mm, to determine longitudinal mean strains and mean curvatures.

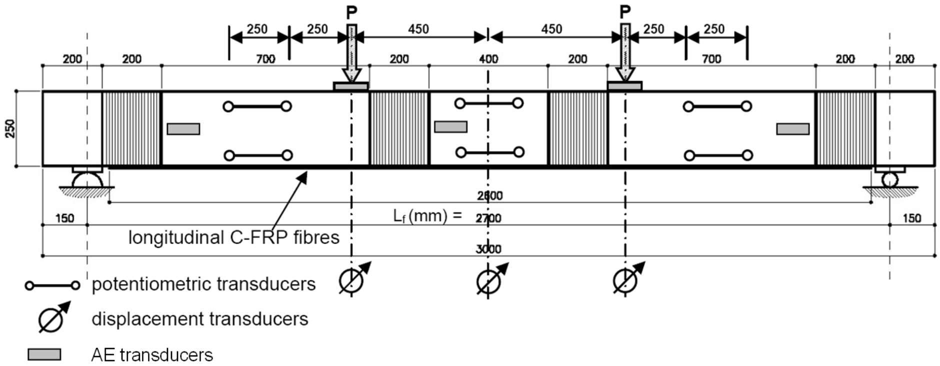

Figure 4. Beam 31, 32, 34: geometrical properties layout of the longitudinal and transversal CFRP sheets and position of the measuring instrumentation.

During the test the following phases are considered:

- loading phase, in load control, where the loads are gradually increased up to a total load of 72kN that corresponds to about 70% of the maximum theoretical load of the beam B00;
- unloading phase, in load control;
- loading phase, in displacement control, where the loads are increased up to a load corresponding to a midspan vertical displacement of 32 mm, which is the double of the vertical displacement measured on B00 for the load of 72 kN;
- unloading phase, in displacement control;
- loading phase, in displacement control, with increasing loads up to collapse of the beam.

In Figure 5, the load vs. midspan displacement is plotted for Beam B31, Beam B32 and Beam B34.

4. Acoustic Emission equipment

The AE signals can be received and recorded by transducers applied to the surface of the structural elements. The leading-edge equipment adopted by authors consists of six memory units USAM®, that can be synchronized for multi-channel data processing. Every reinforced specimen was equipped by six AE sensors to detect the AE signal during the tests and by a couple of displacement transducers for each side in order to measure the horizontal and vertical displacements. The most relevant parameters acquired from the signals (frequencies in a range between 50 and 800 kHz, arrival time, amplitude, duration, number of events and oscillations) are stored in the USAM® memories and then downloaded to a PC for a multi-channel data processing.

5. Experimental results: nonlinear change velocity in the Acoustic Emission signals

In Figure 6 it is possible to observe the relative change velocity (dv/v) vs. time (t) of the tests for masonry wall reinforced by CFRP and mortar layers. A constant velocity change in the first phases of the tests is remarkable, whereas in the last phase of these ones a further increase in the AE velocity change is shown. As a result a nonlinear velocity change trend is observed. This fact is related to the change in the elastic properties in the materials and for a progressive fracture process which leads to the structural failure. For each specimen typology the tests were replicated under constant conditions in order to check the AE

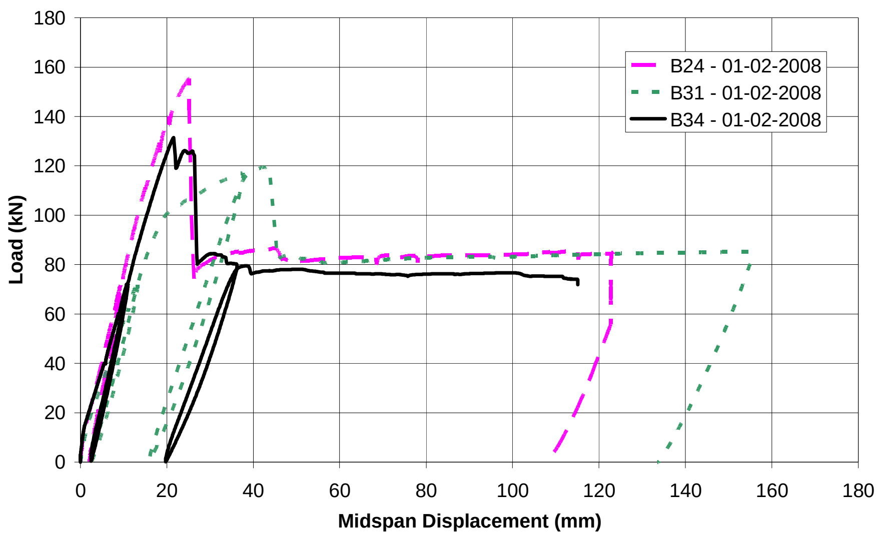

Figure 5. Load-Midspan Displacement curve for Beam B31, Beam B32 and Beam B34.

repeatability. As a result, a good repeatability of the AE change velocities were obtained. In the first phases of the test, for three walls reinforced by CFRP sheets a slightly increasing velocity of $\delta v/v$ = 0,05% ÷ 0.15% was observed; before the collapse, a strongly increase of change velocity is observed ($\delta v/v$ = 0,35% ÷ 0.42%). In the first phases of the test, for three walls reinforced by mortar layer a slightly increasing velocity of $\delta v/v$ = 0,06% ÷ 0.10% was observed; before the collapse, a strongly increase of change velocity is observed ($\delta v/v$ = 0,41% ÷ 0.50%). By these data, in according to our interpretation, the damage inside the specimens increased with the test time: it is clear that during the first phase of the test the decreasing velocity is constant as a sign of progressive and slowly fracture process. Additionally, when the main crack occurs in the six specimens, a sudden increase of internal microseismic activity (i.e. acoustic emission) is observed with a jump in the AE velocity change. Between two AE change velocity branch curves it is possible to detect a critical point where the AE change velocity became nonlinear. This point represents the transition in the materials state from a first phase with evolutive behaviour of internal microcracks (i.e. in accordance with the earthquake science this phase is characterized by signals known as foreshock) up to a new phase characterized by the coalescence of this one (i.e. in accordance with earthquake science this phase is characterized by signals known as aftershock). At the critical point, the coexistence of broken links (voids, microcracks) and entire links (ligament), shown an unstable behaviour materials (brittle fracture). In the AE velocity change curve in relation to the shear deformation vs. time curves the position of the critical point gives an important result in term of AE monitoring because this one can represent an important role of precursor in structural monitoring.

In Figure 7 it is possible to observe the relative change velocity (dv/v) vs. time (t) of the tests RC beams reinforced by CFRP sheets. As a result, a good repeatability of the AE change velocities were obtained. In the first phases of the test, for three beams a slightly increasing velocity of $\delta v/v$ = 0,06% ÷ 0.17% was observed; before the collapse, a strongly increase of change velocity is observed ($\delta v/v$ = 0,32% ÷ 0.49%). Also in this case the damage inside the beams increased with the test time: it is clear that during the first phase of the test the decreasing velocity is constant as a sign of progressive and slowly fracture process. When the main crack occurs in the three beams, a jump in the AE velocity change is observed: a sudden increase of internal microseismic activity (i.e. acoustic emission) is detected. Also in this case it is possible to observe the presence of the critical points, which represents the transition between the microcrack and macrocrack phases.

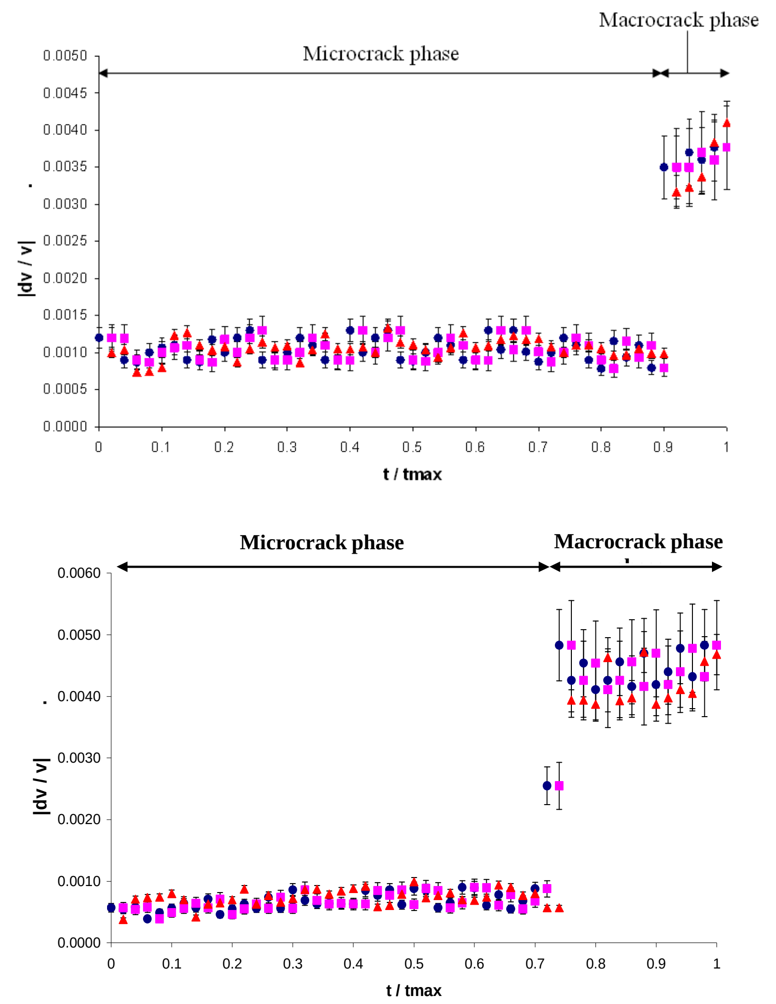

Figure 6. Relative change velocity (dv/v) vs. time (t) of the tests for masonry wall reinforced by CFRP sheets (MF01 square points, MF02 circle points, MF03 triangular points) (top graph) and for masonry wall reinforced by mortar layers (MR01 square points, MR02 circle points, MR03 triangular points) (bottom graph)

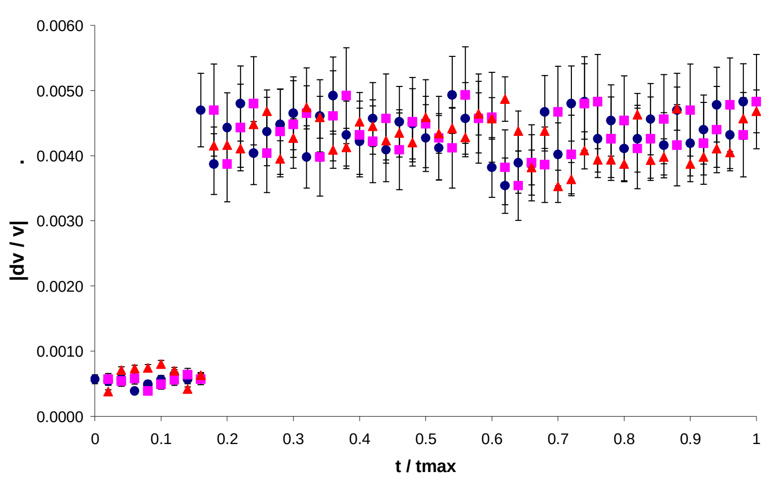

Figure 7. Relative change velocity (dv/v) vs. time (t) of the tests for RC beams reinforced by CFRP sheets (B24 square points, B31 circle points, B34 triangular points).

6. Conclusions

The experimental research presented in this paper confirmed the suitability of apply a seismic method, such as coda wave interferometry, to the AE signal analysis in order to monitor concrete and masonry structures in Civil Engineering. In particular, we have proposed an innovative application, based on the changing of AE signal velocity, for the determination of the damage level into concrete and masonry structures, and hence their stability or the risks arising from micro and macro crack propagation. An important goal of this research is represented by the possibility to predict the structural collapse with extremely simplicity when the AE change velocity became nonlinear. Moreover, the application of coda wave interferometry to the AE signal, represents an innovative point of view to study the AE phenomenon in term of signal analysis respect to the AE classical methods analysis such as ring-down counting and event counting.

References

[1] Teng JG, Chen JF, Smith ST and Lam L 2002 FRP Strengthened RC Structures John Wiley & Sons Ltd., Chichester, UK.

[2] Carpinteri A and Lacidogna G 1996 Damage monitoring of an historical masonry building by the acoustic emission technique *Materials and Structures* **39** 161-167.

[3] Poupinet G, Ellsworth WL and Frechet J 1984 Monitoring velocity variations in the crust using earthquake doublets: an application to the Calaveras Fault, California *Journal of Geophysics Research* **89** 5719-5731.

[4] Ratdomopurbo A and Poupinet G Monitoring a temporal change of seismic velocity in a volcano: Application to the 1992 eruption of Mt. Merapi (Indonesia) 1995 *Geophysics Research Letters* **22** 775-778.

[5] Matsumoto S, Obra K, Yoshimoto K, Saito T, Ito A and Hasegawa A 2001 Temporal changes in P-wave scatterer distribution associated with the M6.1 earthquake near Iwate volcano, northeastern Japan *Geophysics Journal International* **145** 48-58.

[6] Gret R, Snieder A and Ozbay U. 2004 Monitoring stress change in an underground mining environment with Coda wave interferometry *Journal of Mining Applications*.

[7] Roberts PM, Scott Phillips W and Fehler MC 1992 Development of the active doublet method for measuring small velocity and attenuation changes in solids *Journal of Acoustics American Society* **91** 3291-3302.
[8] Snieder R, Gret A, Douma H and Scales J 2002 Coda wave interferometry for estimating nonlinear behavior in seismic velocity *Science* **295** 2253-2255.
[9] Gret A Snieder R and Scales J 2005 Time-lapse monitoring of rock properties with coda wave interferometry *Journal of Geophysics Research*.
[10] Weitz D and Pine DJ 1993 Diffusing wave spectroscopy *Dynamic light scattering, The method* and some applications, 652-720. Clarendon Press, Oxford, W. Brown editor.
[11] Cowan ML, Page JH and Weitz DA 2000 Velocity fluctuations in fluidized suspensions probed by ultrasonic correlation spectroscopy Physics. Review Lettetters 85 453-456.

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