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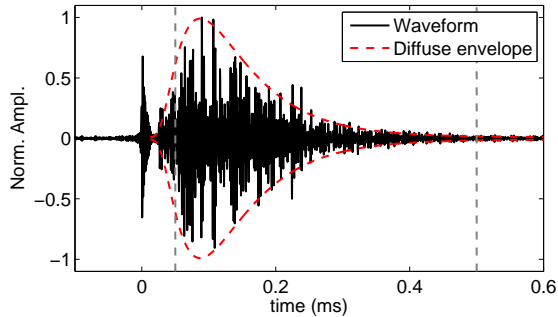


FIG. 2. Typical waveform $h[t]$ collected through the concrete sample. The processed time-window marked by two vertical dashed lines extends from 50 μs to 500 μs .

such as concrete¹⁴, than in homogeneous media, and most results have considered variations under significant applied stress. To our knowledge, the use of diffuse ultrasound to evaluate the effect of stress loading on velocity variations has only been reported by Grêt et al.¹⁵ and Payan¹⁶. In these works the multiple time-window *doublet* technique was used to infer relative velocity variation with a relative resolution of 10^{-3} to 10^{-4} for stress variation of the order of 1 MPa. Here, we propose to monitor weaker relative velocity variations in concrete down to $2 \cdot 10^{-5}$ under weaker load variations (50 kPa). Such precision requires high frequency data (here 500 kHz diffuse ultrasonic data) and a more sensitive data processing technique than the *doublet* technique.

The experimental data presented here were acquired on a concrete sample of 16 cm in diameter, and 28.5 cm in height. The concrete was prepared with 17% (in weight) of cement, 31% of fine sand, 43% of gravel (size ranging from 2 to 10 mm) and 9% of water. Two ultrasonic transducers are used in the experiment, one as a source and one as a receiver (labeled S and R, respectively, in Fig. 1). The lateral size of the active part of the transducers (0.7 mm) is much smaller than the wavelength, which makes them very sensitive to multiply scattered waves. The transducers are glued onto the sample using a hot chemical glue (phenyl-salicylic acid) that solidifies with cooling (below 43°C). The ultrasonic experiment was performed several months after casting the sample.

During the ultrasonic measurements the concrete specimen was subjected to uniaxial loading. A preliminary load was applied (5 MPa) at which point the reference ultrasonic data $r_0(t)$ were acquired. The applied uniaxial load was then increased to 5.5 MPa in ten step of 50 kPa with ultrasonic acquisition at each stress increments, k , to provide $r_k(t)$. Each ultrasonic acquisition involved a source excited with a 10V chirp $s(t)$ of frequencies ranging linearly from 200 kHz to 800 kHz and of duration 10 s. The received signal $r_k(t)$ was amplified by 40 dB and stored in the computer. The recorded waveforms were subsequently cross-correlated with $s(t)$ (time-compression) to provide an estimate of the impulse

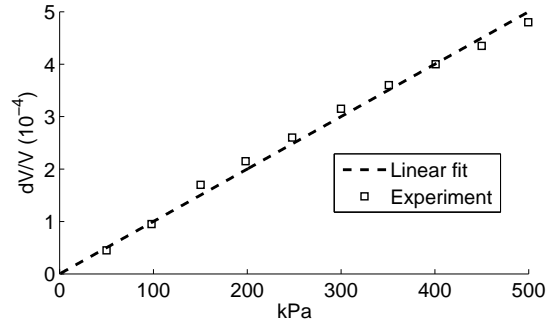


FIG. 3. Relative velocity variations dV/V versus stress variation $\Delta\sigma$.

response of the sample $h_k(t) = r_k(t) \times s(t)$, for each increment k . The effective duration of the time-compressed signal $h_k(t)$ is about 0.6 ms. $h_0(t)$ is the reference waveform corresponding to $r_0(t)$ correlated with $s(t)$. It is noted that the source and receiver positions were kept fixed for all acquisitions and the excitation waveform $s(t)$ was not changed. Note also that the velocity change due to strain is one order of magnitude smaller than the one due to stress change, and is neglected here. The time separating two consecutive measurements is 5 minutes, over which no stress change was recorded and the ultrasonic records were reproducible. Creep was observed over much longer time scales (several hours) and was negligible in the present experiment.

A typical ultrasonic record is plotted in Fig. 2. This record is composed of: (1) the impulse response of the concrete sample; (2) a peak at $t=0$ marking the initial excitation and due to the electronic cross-talk between S and R; (3) background electronic noise (about 1% relative amplitude). The impulse response consists of a direct wave arriving at 0.023 ms, which is barely visible, and a following coda due to strong multiply scattered waves. The average intensity of the coda, $I(r, t)$, can be described by a diffusion envelope:

$$I(r, t) = \frac{I_0}{8(\pi Dt)^{3/2}} e^{-\frac{r^2}{4Dt} - \gamma t}, \quad (3)$$

where I_0 is the energy released by the source, D is the diffusion constant, r is the source-receiver distance and γ is the dissipation rate. In this experiment around 500 kHz, we find that \sqrt{I} best fits the data for $D = 5 \text{ mm}^2/\mu\text{s}$ and $\gamma = 25 \text{ ms}^{-1}$. This will represent a slight underestimate for D because Eq. 3 only holds for unbounded media. Nevertheless, D and σ values are in agreement with the literature^{7,8}, and our rough estimation of D confirms that we are in the strong multiple scattering regime.

For each load k , the record $h_k(t)$ is compared to the reference waveform $h_0(t)$ to evaluate the relative velocity change in the concrete sample. Because of strong multiple scattering, the P- and S-wave arrivals mix together and rapidly attain the equipartition regime¹⁷. Let a_{ij} be the relative fraction of time that the wave spends in the state ij (polarization in the direction i while prop-

agating in the direction j), then the velocity variation is $dV = \left\langle a_{ij} \frac{\partial v_{ij}}{\partial \sigma} \right\rangle \Delta \sigma$. Note that we have $\sum a_{ij} = 1$ and that $\langle \cdot \rangle$ denotes ensemble averaging. If the waves are statistically equipartitioned in all directions, we have $\sum a_{i=j} = 9\%$ and $\sum a_{i \neq j} = 91\%$ ¹⁷. In general, a_{ij} has a more complex distribution, but in this work we focus on the average quantity $\langle a_{ij} \beta_{ij} \rangle$. For simplicity, we also assume that the waveforms are just stretched in time. This is again a first order approximation that applies to experimental data in the considered time-window. Nevertheless, velocity variations will progressively decorrelate the waveform¹⁸. This weak decorrelation, also called distortion, is not studied here although it contains precious information on the medium and its evolution. In particular, we stress that strong distortion and weak stretching might indicate a change of structure rather than a global velocity change. However here we do not see significant distortion. To summarize, the velocity change dV for load k results in:

$$h_k[t] = h_0 [t(1 + \nu_k)] + n(t) \quad (4)$$

with $\nu_k = dV/V$ and $n(t)$ accounting for additional fluctuations, including electronic noise and the small distortion mentioned earlier. Two processing techniques have been proposed in the literature to estimate dV/V . The first one, called the seismic *doublet* technique, was developed for geophysical purposes about twenty years ago⁹. The idea is to measure a time-shift between two different records in a limited time-window centered at time t . By measuring such time-shifts (or delay) δt at different times t in the coda, it is possible to evaluate the velocity variation, which is simply the average slope of $\delta t(t)$: $dV/V = -\delta t/t$. Such an approach implicitly assumes that the time-shift is constant within the considered time-window, which is generally not the case. Another idea^{18,19} is to interpolate h_k at times $t(1 - \nu)$ with various relative velocity changes ν ²⁰. Therefore ν_k is the ν that maximizes the cross-correlation coefficient:

$$CC_k(\nu) = \frac{\int_0^T h_k [t(1 - \nu)] h_0[t] dt}{\sqrt{\int_0^T h_k^2 [t(1 - \nu)] dt \int_0^T h_0^2[t] dt}}. \quad (5)$$

Contrary to the *doublet* technique, we do not assume a constant time-shift in the considered time window $[0, T]$. The comparison between the two waveforms can therefore be performed over the entire record at once, which results in a more stable, and thus more precise, estimation of dV/V . The comparison between the *doublet* and the *stretching* technique will be subject to further investigation²¹. Assuming that h_0 and h_i are stationary waveforms and are well described by Eq. 4, we have a theoretical estimation of CC :

$$CC_k(\nu) = A \frac{\int_{\Delta f} \rho(f) \text{sinc}(2\pi f (\nu - \nu_k) T) df}{\int_{\Delta f} \rho(f) df} + B(\nu) \quad (6)$$

with f the frequency, Δf the bandwidth, $\rho(f)$ the spectral density. The constant A depends on the variance of

h , noted $\langle h^2 \rangle$ and the variance of the additional fluctuations, noted $\langle n^2 \rangle$,

$$A = \frac{\langle h^2 \rangle}{\langle h^2 \rangle + \langle n^2 \rangle}. \quad (7)$$

$B(\nu)$ is a random process of zero mean and standard deviation:

$$\sqrt{\langle B^2 \rangle} = \frac{1}{\sqrt{T \Delta f}} \frac{\langle n^2 \rangle + 2\sqrt{\langle n^2 \rangle \langle h^2 \rangle}}{\langle h^2 \rangle + \langle n^2 \rangle}. \quad (8)$$

If the amplitude of the signal A is much greater than the fluctuations $\sqrt{\langle B^2 \rangle}$ of the cross-correlation coefficient CC_k , the maximum of CC_k is obtained for the stretching $\nu = \nu_k$. It is interesting to note that the peak of the *sinc* function is visible even if the fluctuations (or noise) $n(t)$ are strong. In such a case, increasing the integration time T or the frequency bandwidth Δf can compensate for this strong noise. This is a crucial advantage of the present technique compared to the *doublet* technique. The dV/V resulting from our measurements are plotted in Fig. 3 versus $\Delta \sigma$. A linear regression of the data yields $\left\langle \frac{1}{V} \frac{\partial V}{\partial \sigma} \right\rangle = 10^{-6} \text{ kPa}^{-1}$, which gives an estimate of the non-linear parameter of our sample: $\beta = \langle a_{ij} \beta_{ij} \rangle \approx -40$. The standard deviation from the linear regression for the relative velocity change dV/V is 2.10^{-5} , which indicates that the precision on the evaluation of β is 5%. Note that during the whole experiment, the surrounding air temperature fluctuated within less than 0.8°C . Temperature variations are too weak and thermal diffusion too slow in the sample (compared to the duration of the experiment) to induce noticeable dV ^{10,18,22,23}. This assertion is confirmed by the fact that the velocity variations dV are totally decorrelated from the air temperature variations. We therefore propose that the variations are due primarily to stress effects.

A potential application of this technique is on-site assessment of the non-linear constant β of a concrete structure. Our technique is sensitive enough to provide reliable measurements with additional stress $\Delta \sigma$ of the order of 100 kPa. As the non-linear parameter strongly depends on the micro-damage of the concrete, our technique would form an efficient and non-destructive way to probe the integrity of civil engineering structures. Another application is to evaluate the state of stress of a given structure with a predetermined β parameter, and can be extended to geophysical media^{24,25,26}.

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- ²⁰ The interpolation of the data at times $t(1 - \nu)$ uses a spline interpolation algorithm. It should be noted that this procedure performs well even with our 4 MHz sampling rate. In fact, through numerical tests, we have found that the numerical precision of our processing procedure depends mainly on the signal-to-noise of the data and only feebly on the sampling rate. However even the effect of signal-to-noise is small; in the case of 1% of electronic noise the error of the estimated relative velocity change ν_k is found to be much smaller than 10^{-6} .
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