

DETECTION OF SUBTLE CHANGES IN MATERIALS BY CODA WAVE INTERFEROMETRY

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1 Introduction

Ultrasonic velocity measurement is an established non-destructive tool to estimate strength properties and detect damage-induced changes in materials. Difficulties arise, when small changes in velocity have to be detected or the wavelength of the ultrasonic signals is in the same order of magnitude as the internal material heterogeneities. For example, certain deterioration mechanisms in concrete such as alkali silica reaction (ASR) result in small changes in ultrasonic velocities. On the other hand, the heterogeneities within concrete scatter and dissipate the ultrasonic energy. As a result, the velocity changes can not be reliably calculated or go undetected. In this and similar cases, the standard pulse velocity fails to provide a reliable measure of material degradation [1].

An approach called coda wave interferometry (CWI), has been taken here, in which the scattering and dissipation is not regarded as an obstacle but rather as a signature of the micro-structure of concrete. Coda waves constitute the trail of strongly scattered waves in an ultrasonic signal. Coda waves are sensitive to changes in the medium because the scattering that generates these waves causes coda waves to repeatedly sample a limited portion of the material. CWI is a method, which evaluates the changes in the medium by comparing the coda waves before and after an event. This method was developed by seismologists over 20 years ago, mainly to detect slight velocity changes in the earth crust due to seismic effects, mining influence or seasonal variations ([2],[3],[4])[4]. It was not until very recently that CWI was used to detect small changes in concrete microstructure (e.g. [5],[6]).

2 Coda Wave Interferometry

In seismology, the coda is defined as the long lasting diffuse wavetrain tailing a seismic event. The coda waves contain a notable amount of energy, but have lower amplitudes than the event itself (Fig. 1). The waves included in the coda are (at least partially) caused by multiple diffraction [2] and have travelled much longer distances than direct waves. As a result, changes in the material

causing small velocity changes, which may have no effect on the arrival times of the direct waves (first arrivals), result in much longer time shifts in the coda (Fig. 2).

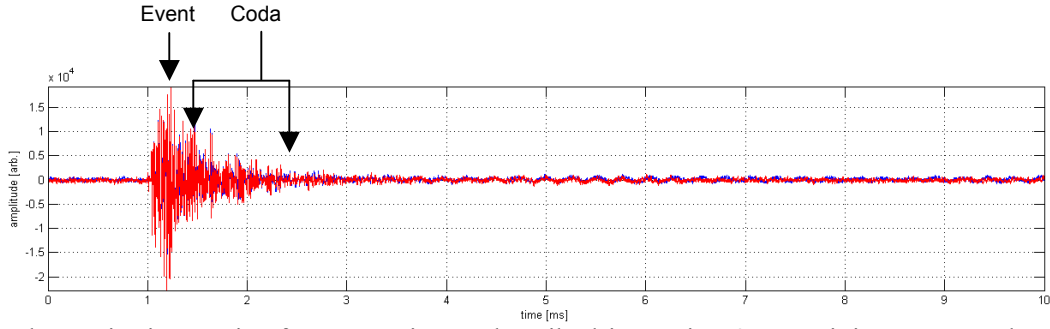


Figure 1. Ultrasonic time series from experiment described in section 3, containing event and coda. (point contact transducers, 32 stacks, 1 ms pre-trigger, 10 ms sampling time, 10 MHz sampling frequency). The blue and red records correspond to the 45 kN- and 48 kN-load steps, respectively.

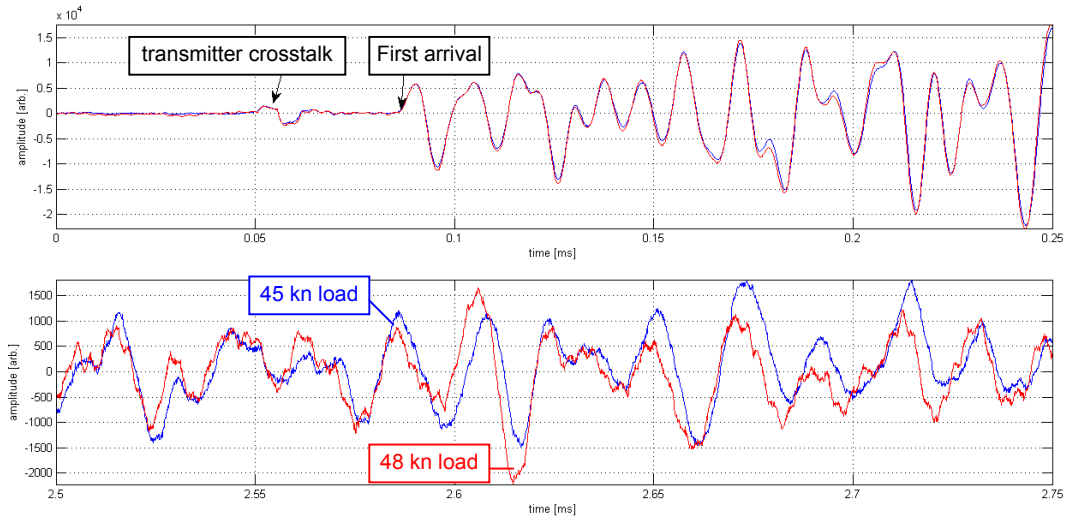


Figure 2. Details of time series of Fig. 1. Top: Around first arrival, only marginal differences. Bottom: Detail of coda wave, significant phase shift.

Two methods to evaluate the phase shift of coda waves or the corresponding relative velocity changes are available. The first one, the “doublet” method, is reported in much detail by Snieder et al. [2]. In this method, the coda is analyzed in a number of non-overlapping windows of equal length. The time shift in each window is calculated by cross-correlation of the respective parts of the time series $h_0(t)$ (reference) and $h_i(t)$ (measured after the i -th perturbation). The final relative time shift (divided by the center time of each window) is obtained by averaging the individual time shifts. The second and more recent one (a.k.a. “stretching” technique) was introduced later [3,5]. In this method, one of the time series is stretched (or compressed) by an assumed small relative velocity change v until an optimum correlation of both time series is reached:

$$CC(v) = \frac{\int_0^T h_i(t \cdot (1 - v)) h_o(t) dt}{\sqrt{\int_0^T h_i^2(t \cdot (1 - v)) dt \int_0^T h_o^2(t) dt}} = \max$$

The stretching algorithm is shown schematically in the flow chart of Fig. 3. The velocity increment and the number of increments have to be determined from experience or trial and error experiments.

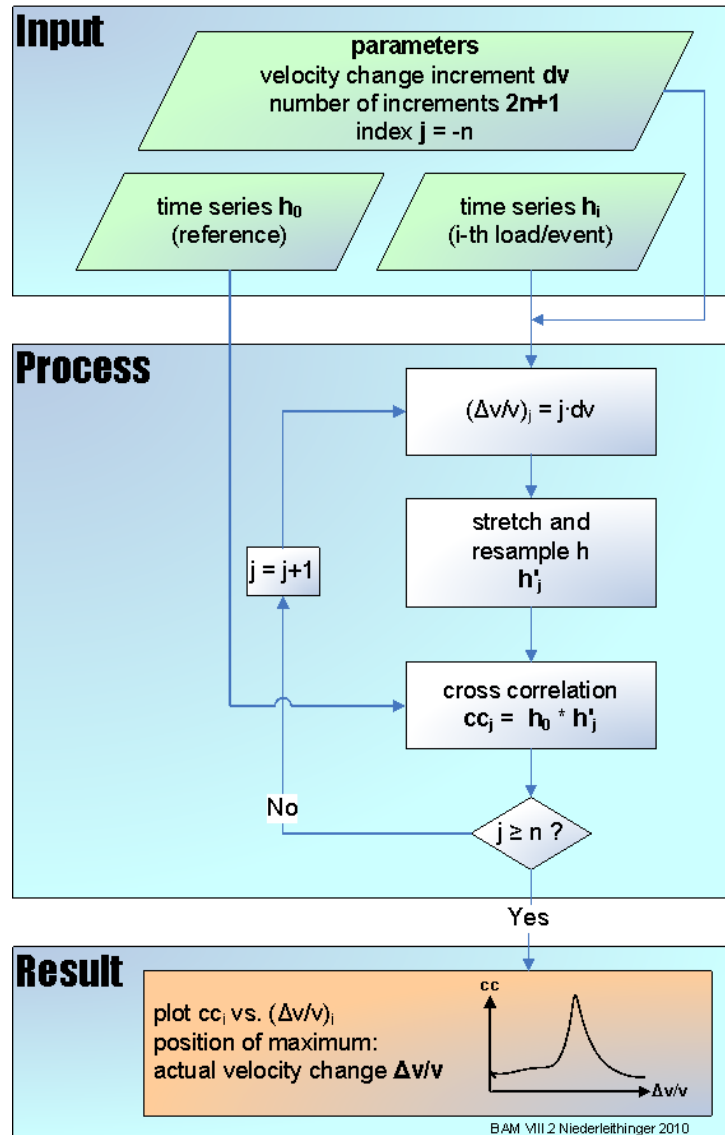


Figure 3. Flow chart for Coda wave interferometry (stretching technique).

3 Preliminary experiment

A preliminary experiment on two concrete cubes ($0.15 \times 0.15 \times 0.15 \text{ m}^3$) was conducted at BAM to evaluate the potential of CWI in concrete assessment and support a field study at the University of Leipzig. Two ultrasonic setups, normally used for time of flight measurements, were used to generate and receive signals in transmission mode (Fig. 4). The details of this experiment can be found in [6].

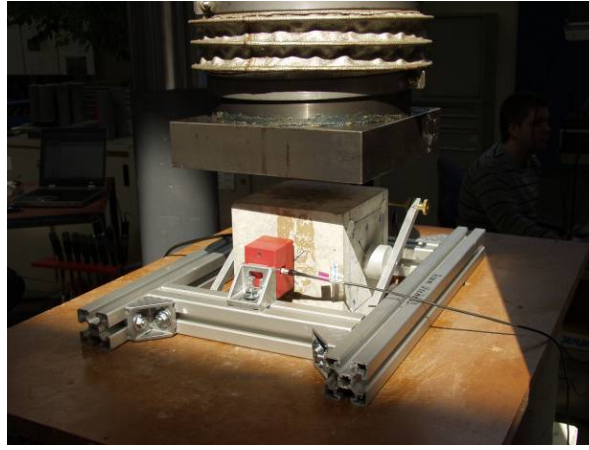


Figure 4. Experimental setup: Concrete cube under 1 MN load frame, equipped with 125 kHz point contact (red, front/back) and 250 kHz conventional piezo transducers (silver, left/right).

As the first step, the ultrasonic pulse velocities (Fig. 2 top) were evaluated by calculating the time of flight (TOF). Due to the high noise level caused by the load frame, 32 measurements had to be stacked before the time-picking algorithm could be applied. The Akaike information criterion (AIC) as proposed by Tronicke [8] was used to pick most of the arrival times.

Compression wave velocities (calculated from TOF) and CWI velocities (calculated according to the flow chart depicted in Fig. 3), plotted vs. load cycles are shown in Fig. 5. The first arrival times remain unchanged during the early load steps. The slight velocity change expected at low to intermediate loads (the acoustoelastic effect) is not visible in TOF velocities, due to the high level of scatter caused possibly by noise and sample interval. The irreversible velocity drop is only measurable at higher loads (caused by microcracking) and reaches about 10%.

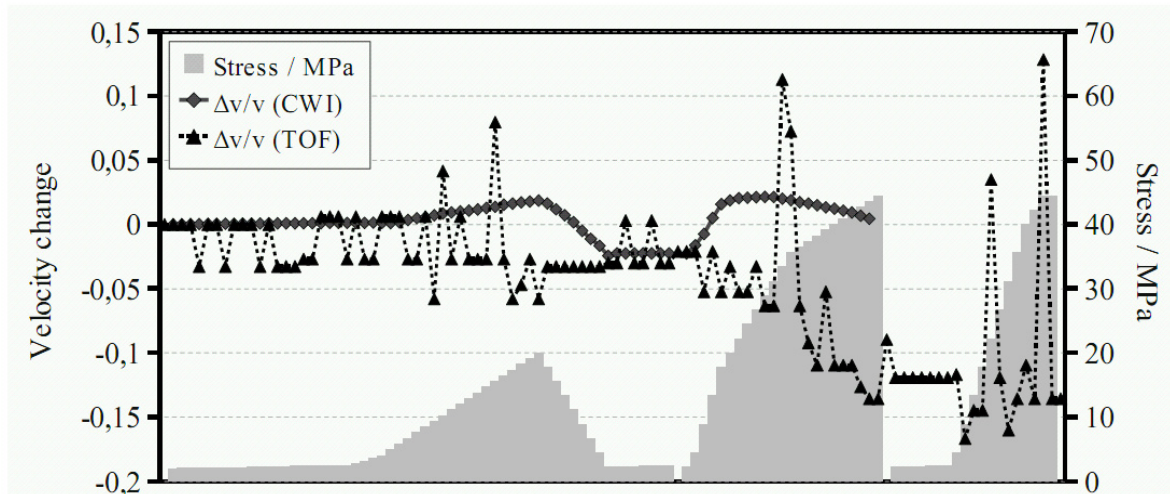


Figure 5. Comparison of stress-induced wave velocity change estimations from TOF and CWI. CWI is suitable for detecting small velocity changes but problematic for larger ones. For TOF the velocity drop after high load is visible, velocity increase at small loads is not.

Contrary to TOF velocities, the coda waves show significant phase shifts even for small load changes. As depicted in Figure 6, an expected linear relationship between stress and the velocity

change (due to acoustoelastic effect and lateral expansion) was recorded, even at very small stress levels.

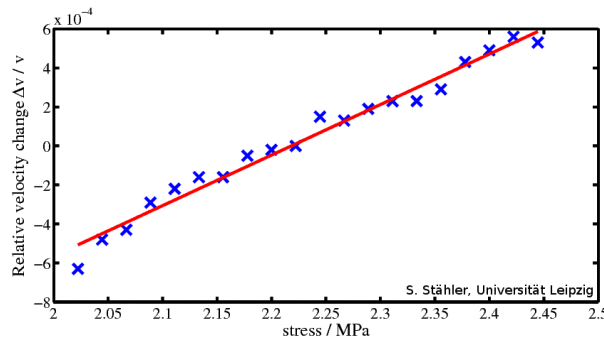


Figure 6. Velocity changes at small stress levels evaluated by CWI (corresponds to load step 1 to 21 of Fig. 5.)

4 Detailed experiment

In the second experiment, a prismatic $0.2 \times 0.2 \times 0.6 \text{ m}^3$ of typical concrete (water/cement ratio $w/c=0.55$, maximum aggregate size 16 mm) was subjected to one cycle of uniaxial compression, applied in load steps of approximately 50 kN (1.25 MPa) until the specimen broke. The schematic and actual test setup are shown in Fig. 7. At every load step, through-transmission ultrasonic measurements were taken in two directions: parallel and perpendicular to the loading. Pairs of identical 100-KHz longitudinal (dry-point contact transducers) were used for the measurements in both directions. The same data acquisition setup as used in the previous experiment was employed here. The test parameters were also identical to those in the previous experiment (sampling frequency = 10 MHz, record length = 10 ms, pre-trigger = 1 ms). The measurements were repeated ten times at every load step.

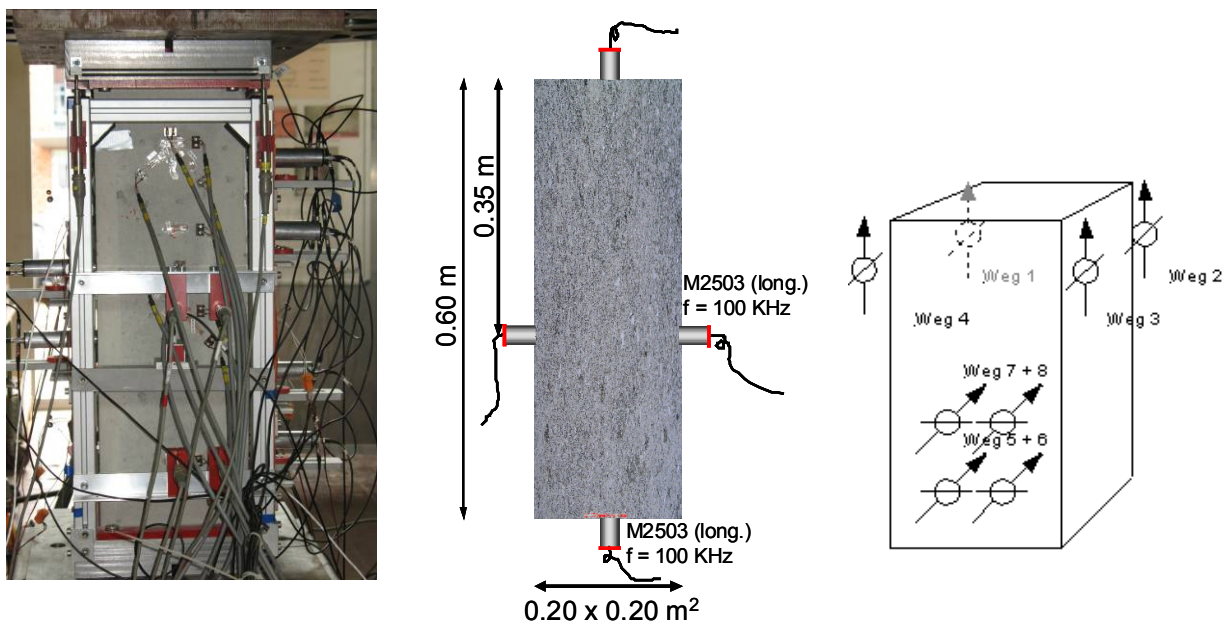


Figure 7. Test setup for the second experiment including the schematics of both ultrasonic and deformation measurements.

Besides the ultrasonic measurements, the deformation of the specimen in both longitudinal and lateral directions was measured by LVDTs and strain gauges to allow corrections for the longitudinal contraction and lateral expansion of the specimen at every load step.

The early parts (just after the first arrivals) of the ultrasonic records are shown in Fig. 8. The examination of the records reveals that as the load increase, the arrival times of both set of records slightly change. The first maxima have been marked to make the changes more visible. As the noise level was considerably lower than in the preliminary experiment, a simple time-picking algorithm was employed here to calculate TOF velocities. The relative changes of velocities vs. stress (normalized to the strength) calculated using both the TOF and CWI are illustrated in Fig. 9.

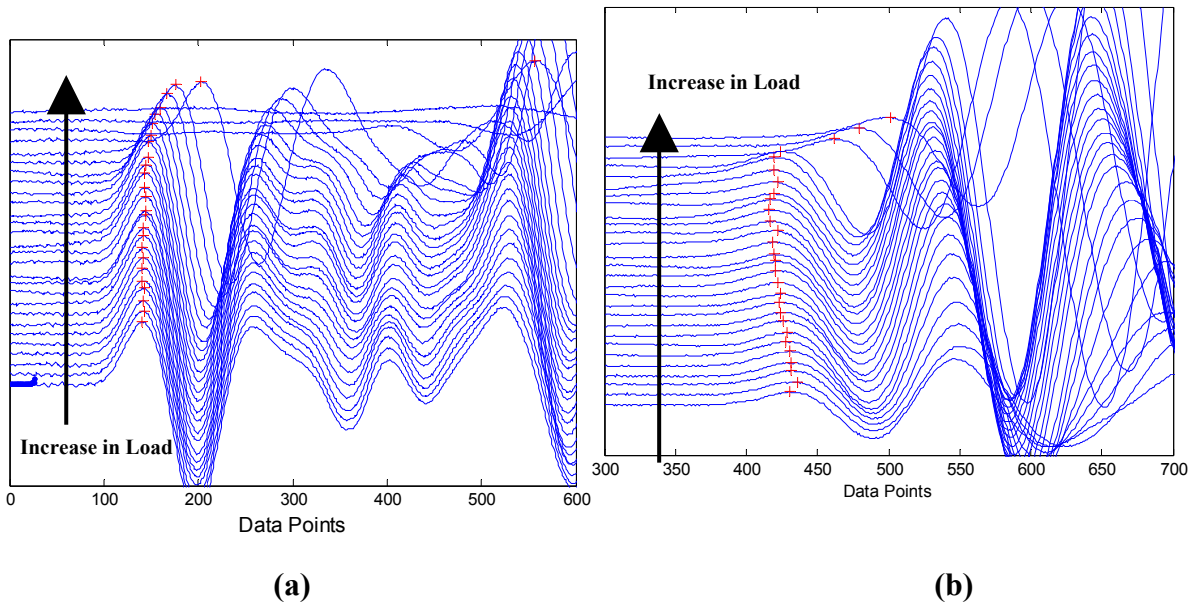


Figure 8. The early part of the ultrasonic signals recorded (a) parallel and (b) perpendicular to the loading. The first maxima are marked with red + signs.

The TOF velocities shown in Fig. 9(b) agree very well with those found in literature [9]. The very same algorithm was used to calculate the TOF velocities in Fig. 9(a). TOF velocities are corrected for the specimen longitudinal and lateral deformations.

A slightly different approach has been taken in calculating the CWI velocities as well. Since the load step size (1.25 MPa) was considerably large in this experiment, the correlation coefficient $CC(v)$ calculated between h_0 (record at the stress-free state) and the records obtained at later load steps, deviated soon from the ideal unity. After a few load steps, it was even hardly possible to detect a reliable peak in the CC vs. $\Delta V/V$ curve (please see Fig. 1) and deduce the actual velocity change. Therefore, an alternative approach was used here. Instead of using the first record as the reference signal h_0 for all the subsequent load steps, the correlation coefficient $CC(v)$ was calculated incrementally between the pair of signals recorded at two subsequent load steps (e.g. $(h_0, h_1), (h_1, h_2), (h_2, h_3), \dots$). The accumulated errors were calculated and proved to be insignificant, as

reflected in the very small size (hardly seen) of the error bars depicted in Figure 7.

The TOF velocities do not show sensitivity to the level of stress and the corresponding damage in the concrete specimen, until the stress reaches critical levels. Apart from showing large variations (as reflected in the large size of error bars), the changes in both directions remain very small until reaching the critical stages of loading, where the specimen is close to failure.

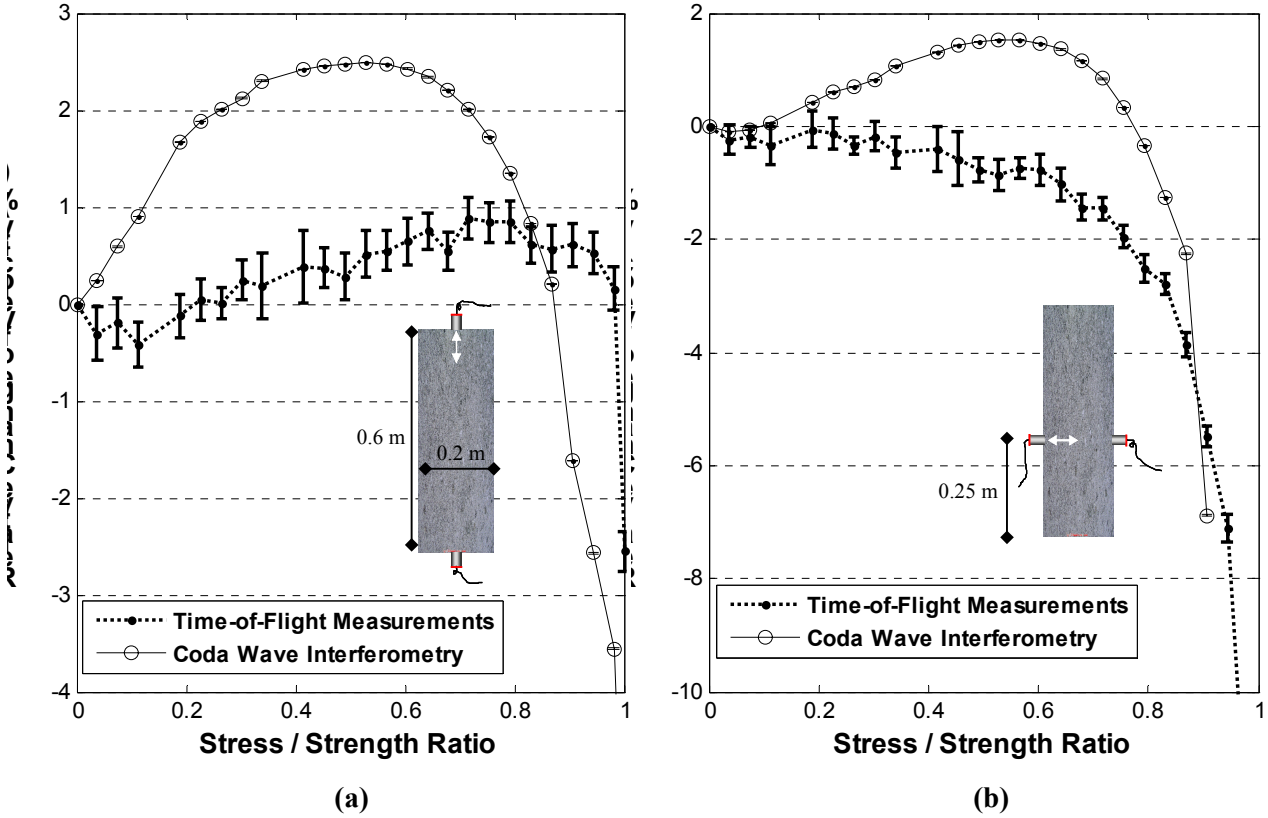


Figure 9. Relative stress-induced velocity changes obtained using TOF and CWI in two directions: (a) parallel and (b) perpendicular to the loading. The error bars correspond to one standard deviation in the calculated velocities from ten repeated measurements at every load step.

The CWI velocities show a greater sensitivity to the level of stress and damage in the specimen. Not only are the velocity changes greater, but they also show particular characteristics, which are useful in monitoring applications. The CWI velocity-stress characteristics match very well those reported for sonic surface wave velocities [7,10]. The velocity changes are direction dependent; the changes in velocities measured parallel to the loading are greater than those measured perpendicular. The CWI velocities measured in both directions attain maxima at a stress-strength ratio of about 55%, well before the specimen reaches the critical levels of stress. Afterwards, the velocities start to gradually decrease. The velocities drop significantly after the stress/strength ratio goes beyond 80%. Therefore, such measurements can be used for monitoring in the warning mode.

It should be noted that the CWI and TOF velocities are not immediately comparable. The TOF velocities shown in Fig, 9 are the longitudinal ultrasonic velocities measured along two perpendicular directions. A diffuse field in a homogeneous solid medium partitions its energy

between transverse and longitudinal waves in a ratio $R = 2(V_P/V_S)^3$, where V_P and V_S denote the compression and shear wave velocities of the medium [11]. Assuming a Poisson's ratio of 0.2, this ratio amounts to about 8.7 for concrete. Although the heterogeneity of concrete makes the diffusive energy partitioning even more complicated. Surface wave traveling around the specimen are involved additionally. Therefore, the CWI velocity is a weighted average of different wavetype velocities, even though vertical component transducers were used. Nevertheless, the CWI velocities show much greater sensitivities to the subtle stress-induced changes in the microstructure of concrete.

5 Conclusions and Outlook

The velocity of coda waves, the diffuse tail of ultrasonic signals, was shown to be very sensitive to the minor changes in the microstructure of concrete. The results of two independent experiments revealed that the coda wave velocity (obtained using CWI) provides a far more consistent measure of subtle stress-induced changes in concrete than the conventional pulse velocity (obtained using TOF). In addition, it is less sensible to measurement noise. This method may be used to monitor small changes in material properties (e.g. due to various deterioration mechanisms), which will go undetected if conventional approaches are taken.

6 References

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