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Design and Validation of Embedded Piezoelectric Transducers for Damage Detection Applications in Concrete Structures

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Abstract. Current maintenance of concrete civil infrastructure such as buildings, bridges, dams and highways, is based on scheduled inspection consisting in visual and/or local inspection techniques (i.e. acoustic/ultrasonic methods, radiography, eddy-current methods). A major trend in the field is the development of automated on-line monitoring systems. The current study is focused on the use of ultrasonic wave propagation techniques based on embedded piezoelectric transducers for the on-line monitoring of the damage state in concrete. The technique is based on the use of an ultrasonic emitter-receiver pair and the construction of a damage indicator focused on the early wave arrival. The proposed simple monitoring system is implemented during several pull-out tests on concrete blocks. The results demonstrate the excellent performance of the system which is able to detect the initiation and follow the evolution of the cracking until complete failure.

Introduction

Concrete is one of the leading materials used in civil infrastructure, such as buildings, bridges, dams and highways. Current manual inspection techniques are costly and time demanding, and their effectiveness is limited due to the lack of accessibility of several locations of the structure.
Many efforts have been made in the last decades in order to develop automated structural health monitoring (SHM) systems for such kinds of infrastructure [1]. The trend is to use very large sensor networks which can be easily integrated in the design of the structures. SHM systems rely on dynamic signatures of structures which are either generated by the ambiance, or by the monitoring system itself. Ambient excitation is generally suitable for the low frequency range, exciting the first few vibration modes of the structure which are not very sensitive to local damages. On the other hand, higher frequency signals carry much more local information. These high frequency signals need to be generated by the monitoring system itself. Ideal candidates for the generation of such signals are piezoelectric PZT transducers, due to their small size, low cost, large bandwidth, simple implementation and possibility to be used as both actuators and sensors.
In the non-destructive testing (NDT) application field, many commercial systems have been developed for the estimation of the quality of concrete using the ultrasonic pulse velocity (UPV) technique. The systems are based on external piezoelectric transducers which need to be placed on two opposite faces of the concrete specimen (Fig. 1). The main limitations of the technique are the need for a coupling agent and flat surfaces and the lack of flexibility in the transducers arrangement. This usually limits the application to through thickness ultrasonic wave propagation, and the technique is not adapted for on-line applications.

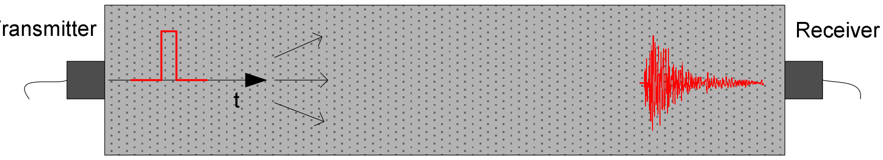

Fig 1: Classical ultrasonic test system based on large external transducers

A possible alternative is to replace the large external probes by low-cost piezoelectric transducers embedded inside the concrete structures, following the 'Smart Aggregates' (SMAG) concept previously developed at the University of Houston [2-4] and recently developed in the Civil Engineering laboratory at ULB-BATir (Fig. 2) [5]. The main advantages are to avoid the use of a coupling agent, to provide a much larger flexibility in the arrangement of the transducers, and to give the possibility of an on-line implementation.
The embedded transducers can be used to generate a compressive wave (*P*-wave) at the emitter side by imposing a short pulse excitation and to measure the wave at the receiver side after it has travelled a certain distance in the concrete (Fig. 2). The measured signal can be post-processed to measure the traveling time and deduce the mechanical properties [4], or to build a damage indicator representative of the evolution of damage between the emitter and receiver [5].

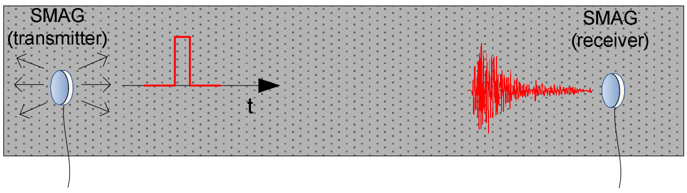

Fig. 2: On-line ultrasonic test system based on embedded "Smart Aggregates"

The recent studies performed in the Civil Engineering laboratory at ULB-BATir have attracted the interest of the Belgian company MS3 (http://www.ms3.be) for monitoring the damage state of concrete slabs to which highway safety rails are attached. Of major interest is the possibility to check the quality of the concrete after the security rail has endured a major shock from a vehicle, and to reach a better understanding of the damage evolution around the anchorage systems. The loading applied on the concrete to which a safety rail can be seen as the combination of bending and pull-out forces. The present study is focused on the application of the previously developed damage monitoring system to pull-out tests.

Smart Aggregates

The SMAGs developed and fabricated at ULB consist of a low cost flat piezoceramic PZT patch (12mm x 12mm x 0.2mm) which is wrapped in a waterproof coating and embedded in a small mortar cylinder (Fig. 3). In order to transmit the electrical signals to and from the transducer, electrical wires are conductively glued on both faces of the PZT patch. For several reasons, the patch cannot be cast without protections. On one hand, concrete contains a certain quantity of water which can be responsible for a capacitive coupling between the transducers. The application of a waterproof coating is necessary to avoid this undesirable effect. Additionally, a thin layer of conductive paint is also applied to provide efficient electromagnetic shielding. As the PZT patch is really thin and brittle, the waterproof layer also provides mechanical protection. An additional protection is provided by a small mortar cylinder.

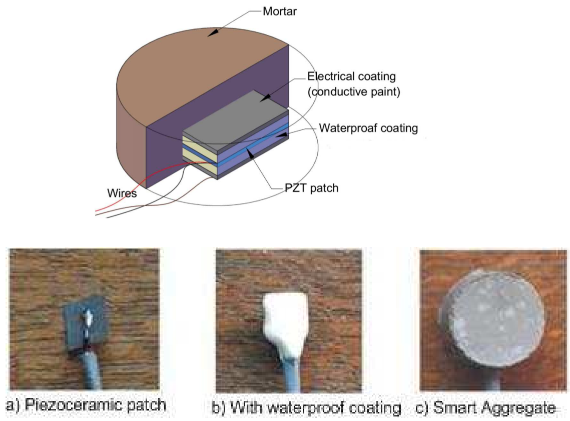

Fig. 3: Principle of a Smart Aggregate (SMAG): a) Piezoceramic patch, b) Patch with waterproof coating, c) Smart Aggregate [4]

Description of the test setup

A series of three pull-out tests has been designed and executed in the laboratories of MS3. The test specimens consist of concrete blocks with an embedded short metallic bar. A vertical force is applied to the metallic bar using an hydraulic hand pump (Fig. 4a,b) until complete failure of the concrete. This failure occurs in the form of a concrete cone which suddenly detaches from the concrete block when the ultimate load has been reached (Fig. 4c).

(a) (b) (c)

Fig. 4: (a) Test setup for the pull-out tests, (b) hydraulic hand pump and (c) concrete block failure

The monitoring system consists in three SMAGs embedded in each concrete block (Fig. 5). The central transducer is used as a high frequency ultrasonic wave emitter and the two others are used as receivers. During the test, after a certain level of loading, microcracks start to appear inside the concrete blocks. These cracks modify the internal structure and the wave paths, and therefore the received signals. In order to capture these changes, the hardware used in the test consists of a high frequency data acquisition system (DAQ), a high voltage pulser and a voltage amplifier (Fig. 6). A short rectangular wave (10µs) excitation signal is generated in the DAQ system and is amplified through a high voltage pulser before passing to the SMAG emitter. The mechanical wave generated by the emitter propagates through the concrete and is measured by the two SMAG receivers at a sampling rate of 10MHz after being filtered and amplified by the voltage amplifier.

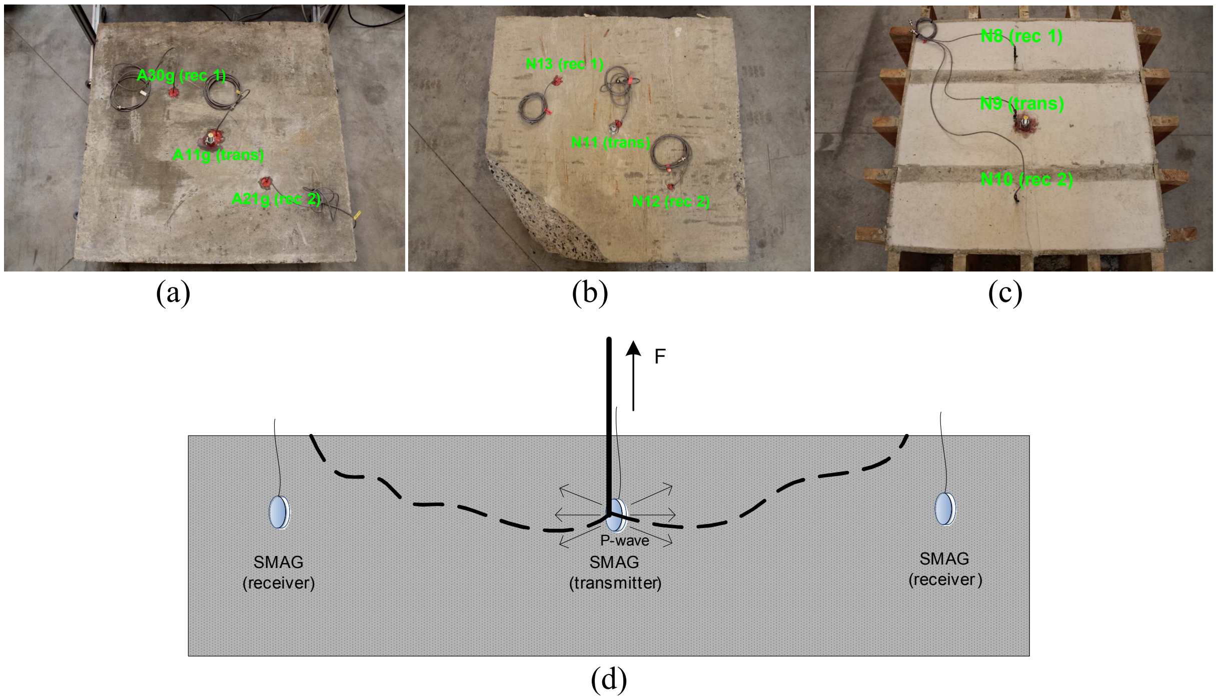

Fig. 5: (a,b,c) Blocks 1,2 and 3 instrumented with three SMAGs. The metallic bar is embedded in the middle of the block. (d) Schematics of the principle of the pull-out test instrumented with three SMAGs to monitor the evolution of damage in the concrete block until failure

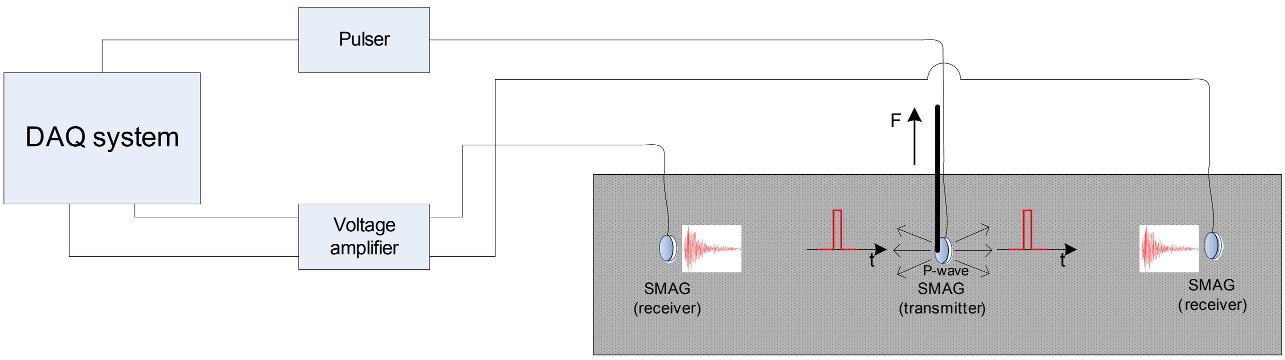

Fig. 6: Details of the hardware used for the monitoring of damage during the pull-out tests

Results

The transmitted wave is subject to a high level of scattering due to the multiple obstacles (aggregates) in the wave path. By the time the mechanical wave reaches the SMAG receivers, it is transformed into a complex waveform. The early part of that waveform mainly contains the contribution of a direct wave between the SMAG transmitter and SMAG receiver and therefore carries information about the state of the microstructure in the direct path between the emitter and the receiver. The damage indicator is therefore based on the early part of the measured waves, as in [6]:

$$I_j = \sqrt{\frac{\int_{t_n}^{t_p} (x_j(t) - x_0(t))^2 dt}{\int_{t_n}^{t_p} x_0^2(t) dt}} \quad (1)$$

Where $x_j(t)$ corresponds to the amplitude of the damaged signal and $x_0(t)$ is the amplitude of the healthy one, t_n is the arrival time of $x_0(t)$, and t_p-t_n corresponds to the duration of the first half-period of the healthy signal (Fig. 7). The measurement is performed every 10 seconds during the progressive application of pull-out loading. Based on the experimental signals recorded by the receivers, the values of I_j for the 1st, 2nd and 3rd concrete blocks and for each emitter-receiver pair are calculated as a function of the load.

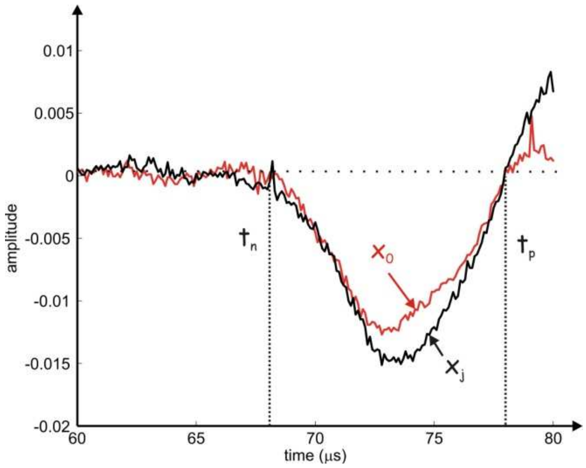

Fig. 7: Definition of the damage index: arrival time of the healthy signal and first half-period

Fig. 8 shows how the early part of the recorded signals is modified with increasing load for one of the two emitter-receiver pairs for block 1. The change of the signals is well captured by the damage index, as shown in Fig. 9 where its evolution is plotted as a function of the applied load for both SMAG pairs. The damage index evolves in the same manner for the two pairs which is representative of the symmetric failure of the concrete in the form of a cone. The graph clearly shows three phases: in the first phase, the damage indicator is very low but non-zero due to a certain level of noise in the signals. The second phase corresponds to the initiation and evolution of damage in the concrete until complete failure (phase III) where the damage indicator is unitary due to the fact that the wave cannot reach the receivers anymore as the concrete cone is fully detached from the block.

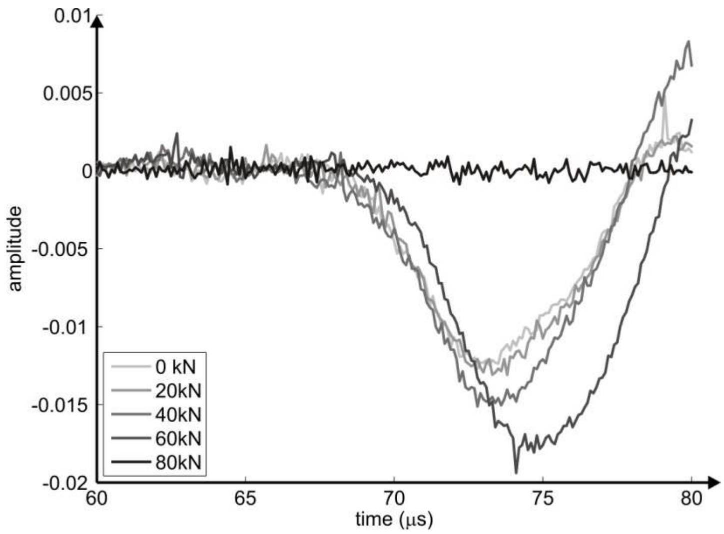

Fig. 8: Evolution of the early part of the measured signals for one emitter-receiver pair for the1st concrete block

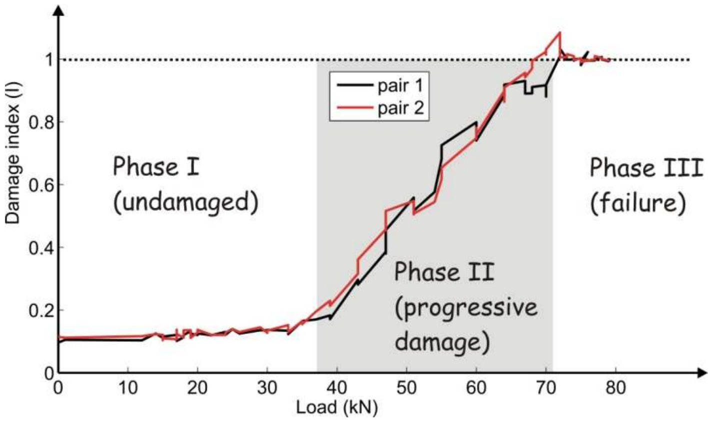

Fig. 9: Evolution of the damage index as a function of the load for both SMAG pairs in the 1st concrete block

The evolution of the damage index for blocks 2 and 3 is represented on Fig. 10 and 11. For block 2, the damage starts earlier, and the failure is less symmetric than for block 1 as evidenced by the difference between the damage indicator for the two SMAG pairs mainly in phase 2. For block 3, the damage phase shows two major jumps representative of two sudden cracking events.

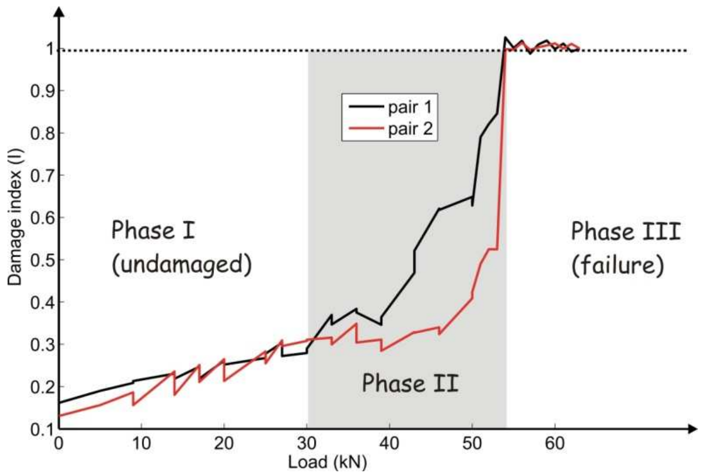

Fig. 10: Evolution of the damage index as a function of the load for both SMAG pairs in the 2nd concrete block

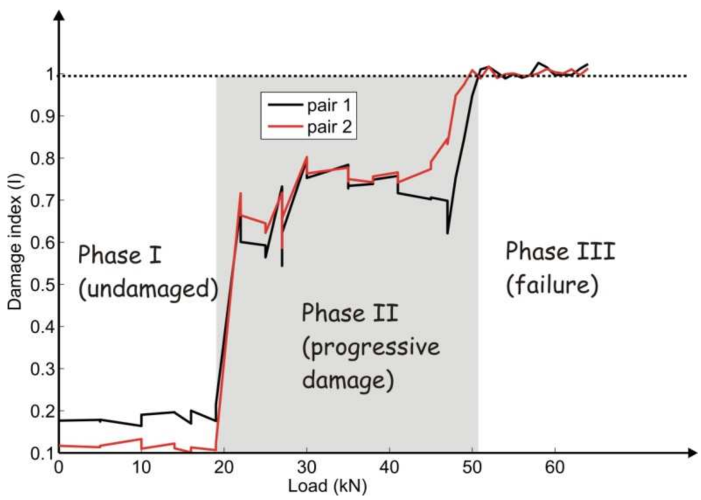

Fig. 11: Evolution of the damage index as a function of the load for both SMAG pairs in the 3rd concrete block

The comparison of the results for the three blocks shows that there is a large test-to-test variability in the pull-out test which is well captured with the monitoring system. In all three cases, the system is able to catch the initiation of damage as well as progressive and sudden damage events until complete failure.

Conclusions and Perspectives

The main goal of this study was to develop an on-line monitoring system to detect and follow the evolution of cracking in concrete structures using embedded low-cost piezoceramic transducers. Three different single-point pull-out tests have been carried out on short metallic bars embedded in concrete blocks. The monitoring system consists in three PZT transducers (one central emitter and two peripheral receivers) and the construction of a damage indicator based on the first half-period of the received signals. This damage indicator is very simple which makes it suitable for on-line monitoring applications. The indicator is efficient to detect the appearance of damage and follow its evolution, but does not give a quantitative evaluation of the damage. It can therefore be used as an efficient tool to trigger alarms, after which other methods can be used to assess the severity of damage. The proposed method seems to be very promising for *in situ* concrete structure damage/crack detection applications. Further studies will be focused on the exploitation of the measured signals to give a quantitative evaluation of damage which can be used for the calibration of finite element models currently developed by MS3 for pull-out tests. One possibility is to estimate an average Young's modulus based on the velocity of the measured signals whose decrease gives a quantitative estimation of the average damage between the two transducers. Another more complex approach consists in extracting multiple features from the measured signals and training a classifier (such as a neural network) to predict the size and width of the crack.

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