On-line monitoring of cracking in concrete structure using embedded piezoelectric transducers

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Abstract.

On-line Damage Detection is of high interest in the field of concrete structures and more generally within the construction industry. The current economic requirements impose the reduction of the operating costs related to such inspection while the security and the reliability of structures must constantly be improved. In this paper, non destructive testing is applied using piezoelectric transducers embedded in concrete structures. These transducers are especially adapted for on-line ultrasonic monitoring, due to their low cost, small size and broad frequency band. These recent transducers are called Smart Aggregates (SMAGs). The technique of health monitoring developed in this study is based on a Ultrasonic Pulse Velocity (UPV) test with embedded ultrasonic emitter-receiver pair (pitch-catch). The damage indicator focuses on the early wave arrival. The Belgian company MS3 takes an interest in evaluating the quality of the concrete around the anchorage system of highway security barriers after important shocks. The failure mechanism can be viewed as a combination of a bending and the failure of the anchorages. Accordingly, the monitoring technique has been applied both on a three-points bending test and several pull-out tests. The results indicate a very high sensitivity of the method which is able to pick-up the crack initiation phase and follow the crack propagation over the whole duration of the test.

Keywords: Non Destructive Testing, Concrete Damage Monitoring, Embedded Piezoelectric Transducers, Smart Aggregates Submitted to: *Smart Mater. Struct.*

1. Introduction

A concrete structure can be subjected to several factors that may damage it and potentially lead it to be turned out of service, or in the most dramatic cases to the complete failure. These factors are either climatic, chemical or accidental. To ensure the safety of a structure, it is important to evaluate regularly its state. Visual inspections and destructive tests were, until recently, the only possibilities to assess the state of the structure. Such inspections require specific equipment and manpower. They are consequently very costly and only a few number of tests can be carried out. Furthermore, visual inspection can only identify macroscopic damage at accessible locations. As an alternative, several non-destructive testing (NDT) techniques have been developed during the last thirty years [1, 2]. The recent developments in the field of NDT have led to the possibility of automation of the tests which greatly improves their repeatability and efficiency [3].

For civil engineering structures, the current trend in research is the development of vibration-based methods relying on ambient low-frequency vibrations caused by the environment (traffic, wind, ...) and measured with accelerometers or, more recently, fiber optic dynamic strain sensors. These methods are more suitable to detect large scale effects than local damage [4]. The detection of local damage requires higher frequencies for which piezoelectric PZT transducers are ideal candidates due to their small size, low cost and large bandwidth. In the field of damage detection using ultrasonic transducers, two major trends coexist. Acoustic emission testing is one of the most widely used techniques. It consists in recording acoustic events generated by the appearance of cracks using a large network of sensors. The technique allows to localize the source of each event by comparing the time of arrival of the acoustic wave on the different sensors [5, 6] or to correlate the acoustic events with the crack mode [7, 8]. The second trend consists in using active ultrasonic systems. In such systems, the acoustic waves are generated by the monitoring system itself. The wavelengths corresponding to the frequency bands used for active sensing are much smaller than the ones used in monitoring systems based on ambient low-frequency vibrations. Consequently, there is a stronger interaction with local defects as cracks which enables their detection [9]. The methods have been first developed and intensively used in aeronautics for metallic and composite materials. During the last twenty years, a few research teams have started to apply these techniques to concrete structures using either surface mounted [10, 11] or embedded transducers. The latter has several advantages which are the added flexibility in the choice of their position, and the better integration in the overall design of the structure. Within this framework, the concept of Smart Aggregates (SMAGs) has been developed by researchers at the University of Houston, Texas [12]. This paper is focused on the development of an active sensing method using embedded piezoelectric transducers.

In the field of active sensing using piezoelectric transducers, several authors have used impedance curves to assess the strength and the damage state of concrete. The impedance curve is measured using a single PZT transducer, which is very attractive from a practical point of view. Experiments show that this technique is sensitive to damage in very local areas around the transducers [13, 14]. Other techniques are based on a pitch-catch configuration and require at least two transducers (one emitter and one receiver). The methods differ mainly in the choice of the signal generated at the emitter side.

Harmonic signals can be used to reveal non linearities due to damage, which generate harmonics of the fundamental frequency [15, 16]. A second type of excitation is the chirp signal which enables to send more energy in the system and therefore enhances the signal-to-noise ratio of the measurements. Such type of excitation signals has been recently used for damage detection in concrete [17, 18]. The main idea of this technique is to measure the evolution of the energy contained in the wave as a function of the evolution of cracking using a wavelet packet decomposition of the signal. This technique has been shown to be sensitive to significant damage.

Finally, pulse excitation is traditionally used in commercial systems designed to estimate the quality of the concrete based on the ultrasonic pulse velocity (UPV). The systems consist of external probes which need to be placed on two opposite faces of the concrete specimen, using an adequate coupling agent. In practice, for real structures, this limits the application to through thickness propagation, or repeated wave reflections, which makes the interpretation difficult. It is also often impractical due to limited accessibility when in service. Coupling such systems to embedded piezoelectric transducers can overcome most of these difficulties.

More complex analysis of the wave amplitude generated by pulse excitation can be carried out, such as backscattered waves amplitude analysis. In this method the response signal attenuation form (decreasing exponential) is used as a damage indicator [19]. The backscattered waves are resulting from numerous interactions such as voids, cracks or microcracks in the concrete structure. Each of them contains information over the state of the material. Indeed, in multiple scattering media, the wave path can be compared to the Brownian random behaviour of a particle [20]. Thus, one can describe the average intensity of the wave in time and space by the diffusion equation [21]. Several authors have studied the impact of damage on diffusivity of concrete [22, 23]. Recently some authors have used the so called coda-wave interferometry (CWI) method [9, 24] to study the influence of stress on the wave velocity [25, 26] as well as the evolution of the acoustoelastic parameters of concrete with appearance of damages [27, 28]. This method is based on the principle that the received signal in multiple scattering media is the superposition of the same wave paquets with random amplitudes and delays. The "damaged signal" is therefore a stretched copy of the original signal.

PZT is a piezoceramic material that has the property of generating a certain voltage when a strain is applied on the material, and conversely, in a large frequency range. This kind of material is therefore suitable in order to generate or measure mechanical waves. In the field of design of embedded piezoelectric transducers, one can report two different main approaches. The first are thin PZT patches cast in small mortar pieces with multiple coating layers. The design of these transducers is based on those initially produced at the University of Houston [12]. Most of these transducers have been designed for compression waves (P-Waves) both for damage detection [29,30] and monitoring of early age properties of concrete [12,31]. Such type of embedded transducers has also been developed to measure simultaneously the P-Wave and S-wave velocities [32]. Piezoelectric transducers can also be composed of composite piezoelectric material [33] where the piezoelectric material is embedded in a matrix of cement. The piezoelectric material can be in the form either of particles of piezoelectric material (0-3 composite), multiple PZT plates (2-2 composite) or PZT rods (1-3 composite) [34–36]. Such type of transducers has been used for assessing hydration properties of concrete [37], acoustic emission detection [38] and damage monitoring [39]. They offer a better impedance matching but are more difficult to manufacture.

The transducers used in this study have been developed in the Civil Engineering laboratory at ULB-BATir and belong to the first category. For several reasons such as the mechanical resistance and the electrical shielding, the patch cannot be cast without coating layers (see [31] for more details). Many efforts in the manufacturing process have allowed to reduce drastically the electrical coupling between transducers and electromagnetic interference in comparison to other embedded piezoelectric transducers. Figure 1 shows the different material layers used during the manufacturing of the SMAGs. The process of manufacturing is summarized on Figure 2. The dimensions of the PZT patches are 12x12mm of width, and the thickness is about 0.2mm. Dimensions of mortar pieces are about 2cm of diameter and thickness.

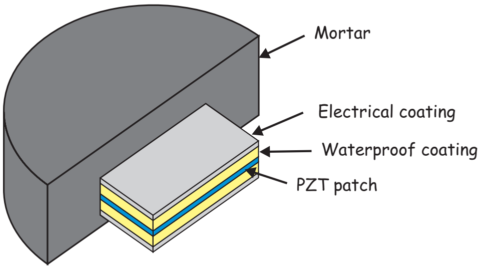


Figure 1. Smart aggregate transducer, detail of different layers.

The technology of embedded piezoelectric transducers has 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

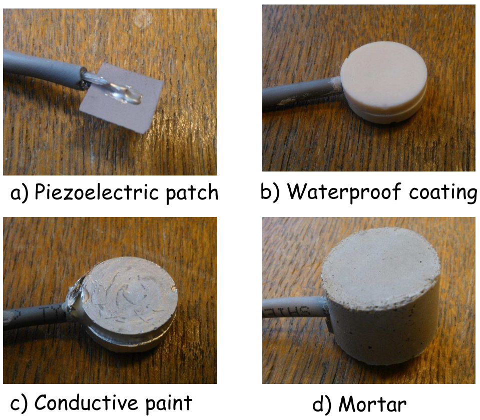

a) Piezoelectric patch b) Waterproof coating
c) Conductive paint d) Mortar

Figure 2. Different steps of the manufacturing of SMAGS.

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.

In the present study, a three-point bending test is performed on a reinforced concrete (RC) beam (Figure 3a) and several pull-out tests on concrete blocks (Figure 3b). These tests are aimed at studying separately the two effects (bending and pull-out) which are combined in the anchorage system. The goal of the monitoring system is to detect and follow crack growth using embedded piezoelectric transducers. Two pairs of SMAGs are cast in the RC beam, each pair being composed of one emitter and one receiver. Two piezoelectric receivers and one emitter are cast in each concrete block.

The major innovations presented in this paper lie on the combined use of embedded piezoelectric transducers and the UPV method for real-time damage assessment in concrete, and the definition of a robust and fast-to-compute damage indicator. This damage indicator takes into account both the decrease of the amplitude and the increase of the time of reception of the early received wave. The results indicate that the method developed in this study is able to pick-up the crack initiation phase and is therefore highly sensitive to very small damage. The study also shows that the evolution of the damage indicator can be related to the failure process of the concrete specimens. The main advantages of using embedded transducers instead of using external probes is the added flexibility, and a better coupling to the host structure leading to an improved signal-to-noise ratio of the measured signals. The signal processing time and the time of acquisition are very low in comparison to other damage monitoring methods using embedded piezoelectric transducers and particularly those based on chirp signals.

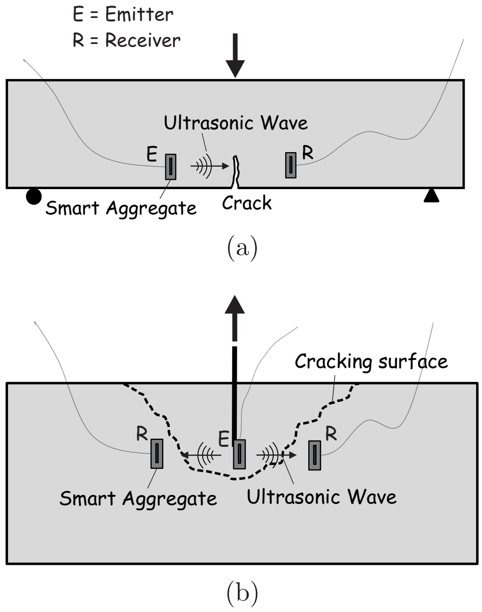


Figure 3. Experimental tests monitored by embedded piezoelectric transducers: (a) Three points bending test, one emitter and one receiver, (b) Pull-out test, two receivers and one emitter

2. Structural health monitoring method

SMAGs are embedded in the RC beam and in the concrete blocks. The system is based on the following principle. An excitation signal is transmitted to a piezoelectric actuator which transforms it to a mechanical wave which propagates through the structure, a piezoelectric sensor measures strains created by this wave and transmits the signal to a DAQ system. Cracks or micro-cracks in the structure appear with the load increasing. This modifies the internal structure of the specimens and the paths of waves and therefore the received signals. The signal at each damage state is compared to the initial state. In the case of the beam, a high-quality picture corresponds to each excitation signal sent; it is then possible to compare modifications in the response signal with a visual assessment of the appearance of cracks.

2.1. Monitoring system

The UPV system is based on the FreshCon system, a commercial system designed by the University of Stuttgart for evaluating fresh parameters of concrete (see Figure 4). The FreshCon System allows to send a high voltage short pulse signal to a specific piezoelectric actuator and measure the time of propagation of the P-wave transmitted by analyzing the sensors signal. In this work, this system is coupled to the SMAGs and is only used to generate the pulse excitation and measure the received signal. Post-processing is implemented in MATLAB. This system is launched during the loading with a frequency of measurements of one pulse every 10 seconds. With such a long delay between two measurements, the probability of catching an acoustic event during the test is very low, as confirmed by the experiment. This period corresponds to the minimum value in the FreshCon settings. The duration of each pulse is 10 μs at a voltage of 800V and the response is measured at a sampling rate of 10MHz. Previous tests have revealed that this pulse width was optimal for our application.

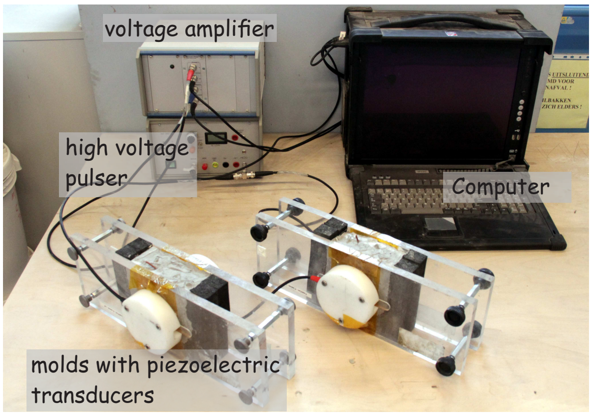


Figure 4. The FreshCon System.

2.2. Damage Index

It has been observed that the damage affects two main parameters which are the time of propagation and the amplitude of the received signal (Figure 5). These observations were also reported in previous studies [40, 41]. Shokouhi *et al* point out that the amplitude of the received signal is a more sensitive parameter in order to assess damage appearance than the evolution of the time of propagation [42]. However, these two parameters are difficult to evaluate correctly, as a decrease of the amplitude causes the signal to reach the noise level, causing potentially a large error in the determination of the time of propagation. The choice of the damage indicator is based on the following reasoning: the first wave received by the sensor corresponds to the shortest wave path, which is affected only by the mechanical properties of the concrete between the transducers. The other waves are diffracted and refracted and arrive later to the sensor, and are therefore not considered.

The first half period of the signal mainly contains the contribution of a direct wave between the SMAGs [30, 43]. As a consequence, we have chosen to define the damage indicator based on the root mean square deviation (RMSD) between the amplitude of the healthy signal and a damaged signal computed in the time window corresponding to the first half-period of the undamaged signal. This indicator is therefore impacted both by the increase of time of propagation and the decrease of amplitude. It is given by Equation 1

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

where $x_j(t)$ corresponds to the amplitude of the damaged signal and $x_0(t)$ is the amplitude of the healthy signal, t_n is the time of arrival of x_0, $t_p - t_n$ corresponds to the duration of the 1st half period (Figure 5).

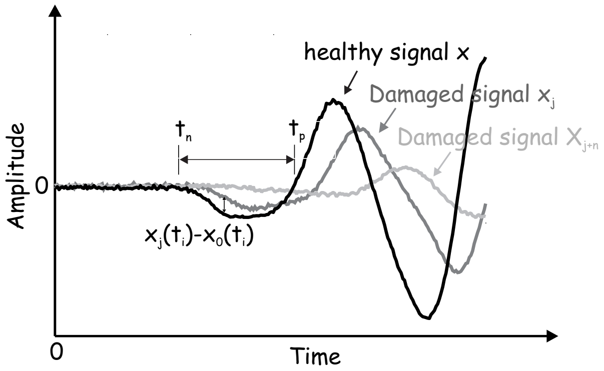


Figure 5. Definition of the time window, t_n is the time of reception of the undamaged signal, $t_p - t_n$ corresponds to the duration of the 1st half period of the undamaged signal.

With such a definition, the indicator has a zero-value when the compared signals are identical in the period of interest $(t_p - t_n)$, which implies that no damage is detected. Conversely, when the amplitude of the damage signal is too weak or the waves arrives latter than the tested period, the damage indicator is close to one. This indicator is therefore impacted both by the increase of the time of propagation and the decrease of amplitude without computing explicitly their values. Once the amplitude of the received signal is equal to zero in the first half period, the damage index saturates. Consequently, the damage index is not designed to monitor high damage.

3. 3-Points bending test

3.1. Specimen

Two couples of transducers are inserted in the beam as shown on Figure 6. One is located near the bottom axis and the second one is located near the neutral axis. They are disposed on each side of the center of the beam at a distance of about 20cm. It has to be noted that both couples of transducers are not interrogated simultaneously. This ensures that the signals emitted by one emitter cannot be intercepted by the receiver of the other couple. Furthermore, the time delay between measurements is sufficiently long so that the acoustic wave of the previous test is totally attenuated. The components of concrete are given in Table 1. The strength properties of the concrete have been characterized by a compression and a brazilian test (splitting test) on specimens poured at the same time as the beam and disposed in similar environmental conditions. The E-modulus has been identified by ultrasonic methods as described by Carette *et al* [44]. The results are given in Table 2. Figure 7 gives information on geometrical characteristics and the computed strength of the beam. Due to the heterogeneity of concrete, cracks are not always exactly initiated at the center of the beam. That is an undesirable effect for this test. A notch permits to reduce locally the strength of the beam. It also creates stresses concentration. This pre-cracking should ensure the crack initiation at the right location.

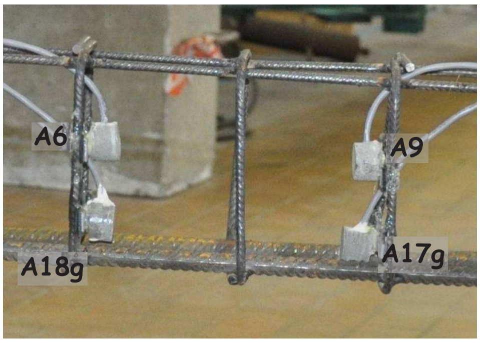


Figure 6. Reinforcement bars in the RC beam, location of the SMAGs

Table 1. Composition of concrete

Water	190	kg/m^3
Cement (CEM I 52.5 R HES)	350	kg/m^3
Sand (0/4)	665	kg/m^3
Aggregates Limestone (4/20)	1172	kg/m^3
Adjuvant (Viscocrete 4)	1.25	kg/m^3
Total (wet density)	2378.25	kg/m^3

Table 2. Concrete properties

Density	2340	kg/m^3
Compressive Strength (f_c)	57.1	MPa
Tensile Strength(f_t)	2.86	MPa
Young modulus (E)	33	GPa

3.2. Loading procedure

The loading machine used for the experiment is a 200kN hydraulic jack bending testing machine (Figure 8). The test was performed in two different phases. In the first phase, the beam is totally unloaded slightly after appearance of the first cracks. Figure 9a

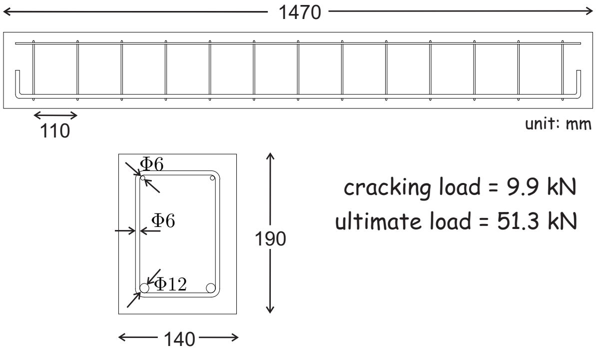


Figure 7. RC beam properties

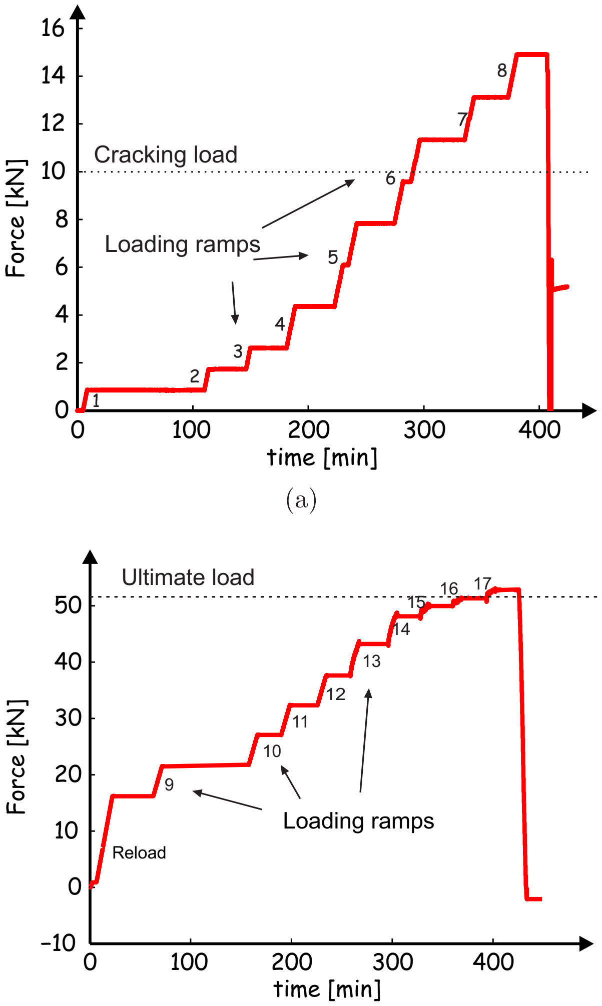
summarizes the loading procedure of the first phase. The loading procedure for the second phase is shown on Figure 9b; the beam is loaded close to the maximum acceptable load. During the second phase, in addition to the force and displacement sensors of the testing machine, a LVDT extensometer (Linear Variable Differential Transformer) is used to measure the deflection at center of the beam and six other LVDT extensometers (3 on each side) are used to measure cracks width. Cracks width has therefore only been measured on the second day. Extensometers are then correctly placed to measure the main cracks width which appeared after the first phase.

Figure 8. Bending testing machine

3.3. Visual inspection

A high quality photo camera takes pictures of the notch every 10 seconds, which corresponds to the FreshCon measurement frequency. The main idea is to join the pictures to signals and later detect and follow the initiation and the propagation of cracks by analyzing these pictures.

It is difficult to visually detect very small cracks with the basic pictures as shown on Figure 10a. Image processing tool as Photoshop allows the application of various numerical filters which improve the visual detection of cracks (see Figure 10b).



(a)

(b)

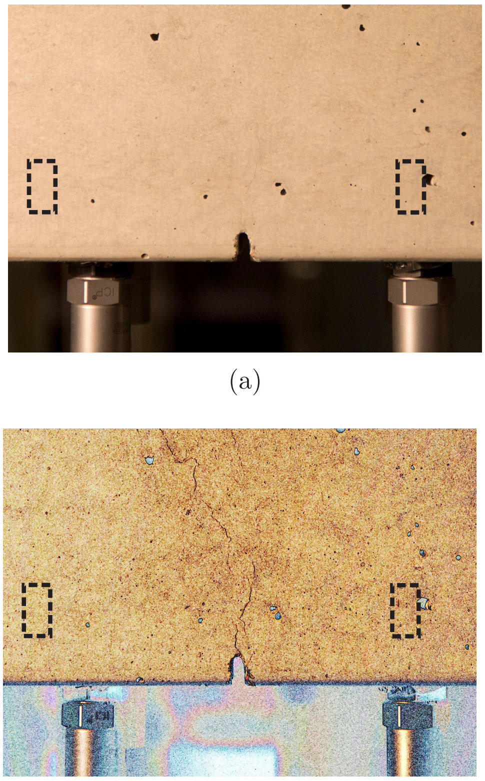
Figure 9. Loading procedure for the RC beam. a) Phase 1. b) Phase 2

It is important to point out that processed pictures cannot be used for evaluating cracks width. Indeed, the processing tools tend to increase the width. Digital Image Correlation (DIC) is certainly a better tool to follow the crack initiation and could be used in this study, but was not available at the time of the test.

It was observed that in the area between the SMAGs, some micro cracks seem to appear around the notch corresponding approximatively to a load of 10kN. The crack at the center of the beam is totally formed under a force of 14 kN. The width of the cracks is around 0.07 mm, which is very small. It is important to note that other cracks were observed under smaller loads but these were outside of the region monitored with the SMAGs.

3.4. Results

Figure 11 shows the evolution of the damage index for the pair of SMAGs that are located near the bottom of the beam (A18g-A17g on Figure 6). Unfortunately, the



(a)

(b)

Figure 10. Image processing for visual detection of cracks. The crack width is approximately 0.1mm. The corresponding load is 14 kN. a) Before numerical processing. b) After numerical processing.

other pair of SMAGs was defective and the results can not be presented.

The evolution of the damage index shows a good correlation with the observations during the experiment. This damage indicator increases between 5 and 15kN which are the values of the initiation of the observed cracks. This index saturates after the appearance of cracks and therefore, does not evolve anymore when crack is growing. It saturates largely before the service limit. This index is an excellent indicator for detecting crack appearance but does not give any information about the the evolution or the size of the damage.

4. Pull-out tests

A series of three pull-out tests has been designed and executed in the laboratories of MS3. A vertical force is applied to the metallic bar using an hydraulic hand pump 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 is reached (see Figure 12). The monitoring system consists in three SMAGs embedded in each non-reinforced concrete block as exposed on Figure 3b.

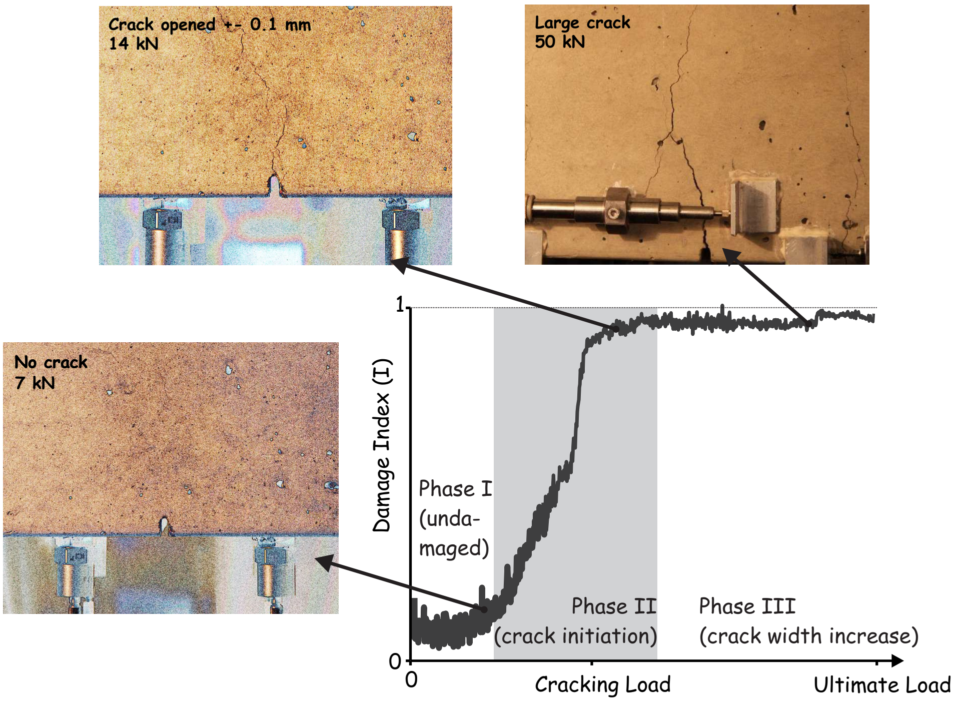


Figure 11. Damage index for the RC beam, comparison with the visual observations

Figure 12. Pull-Out test: concrete cone at ultimate load

4.1. Specimen

The test specimens consist of concrete blocks with an embedded short metallic bar as shown on Figure 13. Three different specimens have been cast by MS3. The concrete used in the different tests differs in terms of age and the ultimate load varies from test to test.

4.2. Loading procedure

A vertical force is applied to the metallic bar using an hydraulic hand pump until complete failure of the concrete. The force has been applied as slowly as possible in order to follow the evolution of the damage and has been recorded by a force sensor.

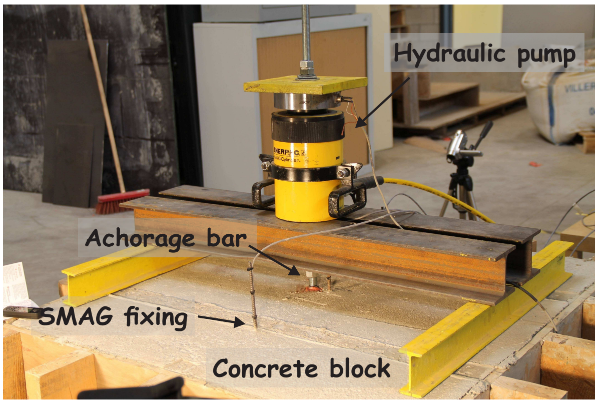


Figure 13. Pull-out test

4.3. Results

Figure 14 shows the evolution of the damage index for the test performed on block 1. The figure shows that 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.

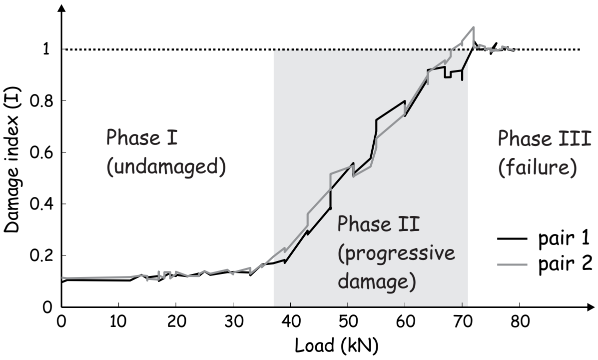


Figure 14. Damage index block 1 as a function of load

The evolution of the damage index for blocks 2 and 3 is represented on Figures 15 and 16. 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 SMAGs pairs mainly in phase II. For block 3, the damage phase shows two major jumps representative of two sudden cracking events.

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. The high variability in the results is inherent to pull-out tests. It is mainly

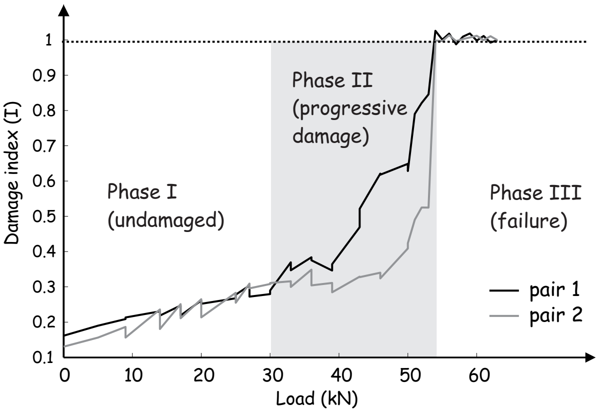


Figure 15. Damage index block 2 as a function of load

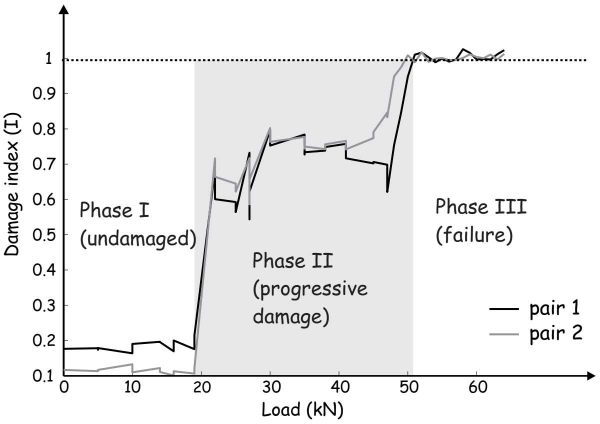


Figure 16. Damage index block 3 as a function of load

due to geometric factors such as the aggregates or the alignment of the metallic bar. Furthermore, the concrete is subjected to a very complex nonuniform triaxial stress field, which makes the failure mechanism difficult to predict, especially when no bearing ring is used to transmit the reaction of the vertical load to the concrete [2]. 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. This method is therefore suitable to follow the evolution of the damage.

5. Conclusions and outlook

In this research an efficient method was developed in order to detect the appearance of cracks in concrete structures using embedded piezoelectric transducers. It has been used successfully in two different applications: a three-points bending test and pull-out tests. The method is based on the ”pitch and catch” principle where the excitation is a short pulse. The definition of the early wave damage index used in this study takes into account the decrease of both the velocity and the amplitude of the transmitted wave. This makes the index very sensitive to small changes in the part of the structure located between to two transducers. In the applications presented, it allows to detect the onset of cracking before the cracks are visible.

In order to develop a long-term SHM method for concrete using embedded piezoelectric transducers it is necessary to differentiate between modifications in the transmitted waves due to environmental effects such as temperature or load variation from those due to modifications in the concrete structure. The damage index proposed in this study is a scalar value which does not allow to filter out environmental variations using statistical correlations [45, 46]. Further studies will therefore focus on the development of more complex signal processing strategies based on multiple wave scattering theory such as coda wave interferometry or diffuse ultrasound, and the extraction of a multivariate feature vector.

An issue concerning the influence of the smart aggregates on the strength of the structure can also be raised and must be studied. Their size are of the same order of magnitude as the largest aggregates used in the concrete which brings a certain mechanical heterogeneity in the structure that can cause a local weakness which, in turn, could inflict additional damage. Nevertheless in this study, no impact of the smart aggregates has been observed on the mechanical behavior of the structure.

The current monitoring system uses a high voltage pulser (800V) which limits the measurement rate due to the important rising time needed by the pulser. As damage progression in concrete can be a fast process, it is necessary to develop an alternative system based on a very fast ultrasonic measurement rate. Early results on this topic have shown that it is possible to simultaneously evaluate the damage using an indicator based on ultrasonic measurement as developed in the current study and detect acoustic events [47]. This requires to filter out the acoustic events from ultrasonic waves generated by the monitoring system using adequate signal processing techniques. It is also possible to couple an independent acoustic emission system with the ultrasonic system, which also requires to filter out events generated by the active system from spontaneous acoustic events [48]. Fast data acquisition necessitates low-voltage pulsing since the rising time of high voltage pulser is too high to adapt to the high sampling rate. This in turn, requires to improve the efficiency of the transducers through better impedance matching. This is the subject of current developments.

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