# Damage Detection and Healing Performance Monitoring using Embedded Piezoelectric Transducers in Large-Scale Concrete Structures

Grigorios KARAISKOS [1], Eleni TSANGOURI [1,3], Dimitrios G. AGGELIS [1], Kim VAN TITTELBOOM [2], Nele DE BELIE [2], Danny VAN HEMELRIJCK [1]
[1]Vrije Universiteit Brussel (VUB), Faculty of Engineering, Department of Mechanics of Materials and Constructions (MeMC), Pleinlaan 2, B-1050, Brussels, Belgium (gkaraisk@vub.ac.be, etsangou@vub.ac.be, daggelis@vub.ac.be, dvhemelr@vub.ac.be)
[2]Ghent University, Faculty of Engineering and Architecture, Department of Structural Engineering, Magnel Laboratory for Concrete Research, Technologiepark 904, B-9052, Zwijnaarde, Belgium (Kim.VanTittelboom@UGent.be, Nele.DeBelie@UGent.be)
[3] SIM vzw, Technologiepark 935, B-9052, Zwijnaarde, Belgium

Contact e-mail: gkaraisk@vub.ac.be

**Abstract.** Concrete keeps being the leading structural material due to its low production cost and its great structural design flexibility. However, concrete is prone to various ambient and operational loads which are responsible for crack initiation and extension, leading to decrease of its anticipated operational service life. The current study is focusing on the use of ultrasonic wave propagation techniques based on low-cost and aggregate-size embedded piezoelectric transducers for the online monitoring of the damage state and the healing performance in concrete structures with an autonomous healing system in the form of encapsulated polyurethane-based healing agent embedded in the matrix of concrete. The crack formation triggers the autonomous healing mechanism which promises material recovery and extension of the operational service life. The proposed technique is applied on large-scale, steel reinforced, concrete beams (150mm × 250 mm × 3000 mm), subjected to four-point bending. After the capsules are broken and the healing agent is released, which results in filling of the crack void, and polymerized, the concrete beams are reloaded. The results demonstrate the ability of the monitoring system to detect the initiation and propagation of the cracking as well as to assess the performance of the self-healing system.

## Introduction

Concrete is the most widely used construction material in the world (e.g. bridges, dams, skyscrapers, nuclear power plants etc). Except its high complexity, brittleness, heterogeneity and anisotropy, it is also characterized by such a high compressive and low tensile strength. Due to a series of operational and ambient factors, cracks are inevitably formed which deteriorate its anticipated mechanical performance and decrease the length of the operational service life [1-3].

After significant tensile stress is induced in the concrete structure, cracking is expected which according to the size and position, could either be detectable by the naked eye at the surface or could be internal in a non-accessible area of the structure. For a long time, the common way to reliably assess the structural integrity of concrete structures has been to perform manual, time-consuming, costly and destructive strength testing on a few small samples drilled from the inspected structure based on a scheduled maintenance strategy. For various reasons (e.g. non-accessible concrete volume of interest) this is not always feasible, let alone in large-scale concrete facilities (e.g. dams, tunnels) where there is a great spatial variability of measurement points and as a result, a reliable condition evaluation is extremely costly and time consuming. Although the classic destructive testing provides direct, accurate and reliable information about the structural integrity and quality of the concrete, these methods are harmful for a new construction, let alone for a degraded one. Conversely, a great potential for increased reliability at an affordable cost could be the implementation of online, automated and harmless non-destructive evaluation (NDE) tests, but they provide indirect information that needs further post-processing [4-7].

Traditionally, the cracked concrete is manually sealed and healed by injecting epoxy- and cement-based agents into the cracks, providing only local material restoration because only visible macroscopic damages, at accessible locations of the damaged structure can be inspected and rehabilitated [8]. Recently, the so-called self-healing materials, a class of smart materials, have the structurally incorporated ability to autonomously repair the generated cracks. Encapsulated healing agent is embedded in the material which is fully aligned to the potential of an autonomous rehabilitation of the formed cracks [9]. Until now and within the Flemish SIM-SECEMIN project, the encapsulated self-healing strategy has been focusing on the performance evaluation of only small-scale, pre-notched, concrete beams under mode-I fracture [10]. Initially, the design of the test led to a unique crack formation (three-point bending), isolating the healing process [11] and in a next step, a series of reinforced, small-scale, concrete beams with embedded, encapsulated, healing systems was subjected to four-point bending, where the healing performance was highly affected by the multiple cracks which were formed [12].

## 1. Materials and Methods

### *1.1 Design of the Concrete Beams*

In the present study and based on the promising results obtained, the embedded, encapsulated, polymer-based, healing agent is implemented in a large-scale lab test, in order to further evaluate the measuring and monitoring performance of the Ultrasonic Pulse Velocity (UPV) based on the low-cost and aggregate-size embedded piezoelectric transducers [11]. Two reinforced concrete beams of 150 mm × 250 mm × 3000 mm were prepared (Figure 1(a)). The reinforcement of the beams consisted of four Φ10 steel bars, equally distributed and placed at 20 mm height in the tensile zone (Figure 1(b)). One of them was used as a reference (REF) beam (i.e. no healing system applied), and in the second beam, the healing system consisted of about 350 glass capsules (50 mm length, 3 mm inner diameter, 3.35 mm outer diameter) filled with a one-component, expansive, polyurethane (PU)-based, healing agent. The agent polymerizes when it comes in contact with air and moisture. The filled capsules were positioned within the wooden mould through a network of very low stiffness plastic wires which were attached to the walls of the mould. The capsules were equally distributed at the same height (10 mm into the tensile zone) (Figure 1(b)).


**Fig. 1.** (a)Wooden moulds before the concrete casting and (b) close-up view of the encapsulated PU-based healing agent, the reinforcement and an embedded piezoelectric transducer used.

In order to keep the healing system intact, a needle vibrator was avoided for compaction of the concrete and finally two slightly different self-compacting concrete (SCC) mixes were used. After the concrete casting in the moulds and until their demoulding (six days later), both beams were subjected to membrane curing in order to prevent moisture loss [13].

*1.2 Experimental Set-Up*

In order to achieve multiple crack formation, four-point bending tests were performed, 28 days after the concrete casting. For extra ease in monitoring the cracks formation, extension, healing and sealing, both beams were loaded through a manual screw jack (Figure 2(b)) in upward direction. The supporting span was L=2800 mm and the loading one was l=1000 mm symmetrically oriented with regard to the middle of the beams (Figure 2(a)). Except the exerted load measured through the load cell (Figure 2(b)), the average crack width was also recorded. Therefore, a linear variable differential transducer (LVDT) was lengthwise and symmetrically positioned with regard to the middle of the beams covering a zone with length of 1400 mm (Figure 2(b)). Initially, the beams were loaded in four-point bending, until the average crack width (i.e. LVDT measurement divided by the amount of cracks formed within the monitoring zone of 1400 mm) was equal to 250 μm and then both beams remained loaded for seven weeks. The healing of the PU beam was normally finished one day after crack formation, but in order to improve the healing agent polymerization and to simulate regular rain showers, both beams were automatically showered with water during the last six weeks.

In the PU beam, as soon as a crack forms and propagates, the activation of the healing process is triggered through the rupture of the fragile glass capsules filled with the healing agent. Previous study has already established a method for detecting the capsules' rupture during crack formation and propagation as well as for identifying the conditions under which healing and sealing activation occurs [14]. The rupture of the capsules led to the release of the healing agent in the gap of the formed cracks, which were anticipated to be sealed and healed. The beams were initially intended to be unloaded, reloaded and finally unloaded after healing until the average crack width was equal to 150 μm, 300 μm and 250 μm, respectively. In practice, after passing the seven-week healing period and the first unloading step, the REF and PU beams obtained average crack widths equal to 180 μm and 210 μm, respectively. Any possible rehabilitation of the mechanical properties due to the released and hardened healing agent was assessed by the reloading test.

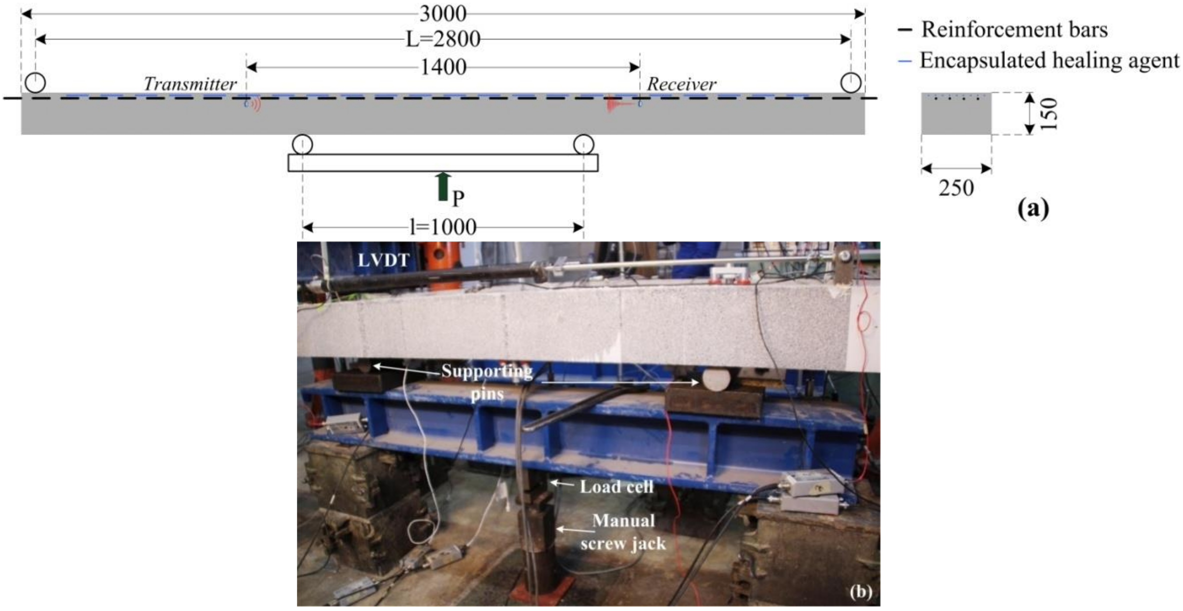

**Fig. 2.** (a) Diagram of the four-point bending test set-up and (b) overall view of the test set-up.

*1.3 Ultrasonic Pulse Velocity*

The UPV is one of the most reliable and cost effective NDE methods which determines material properties, detects defects and assesses structural integrity. The method is based on the measurement of the velocity of the ultrasonic longitudinal stress wave propagation using a pitch-catch (external transmitter-receiver) configuration (Figure 3(a)). Initially, a high-amplitude and spike-shaped pulse excites the transmitter (i.e. piezoelectric transducer) to vibrate at its resonant frequency and this vibration excites the material through contact with a wide range of ultrasonic frequencies and generates stress waves. The generated stress waves propagate through the material and they are finally detected by the receiver (i.e. similar piezoelectric transducer), which is also held in contact with an opposite surface of the tested specimen at a known distance $L$ from the transmitter [15]. The conventional UPV method is based on the use of external and bulky piezoelectric transducers and the quality of the received signal is depended on the coupling of the transducers to the concrete surface. Flat surface and special coupling agent is required in such a way to eliminate the presence of air pockets between the transducers and the material. These limitations put extra labour and cost which don’t make the technique suitable for permanent monitoring of the structures.

Several drawbacks of the conventional UPV method can be overcome by replacing the external bulky transducers with low-cost and aggregate-size piezoelectric transducers which can be embedded in the concrete (Figure 3(b)). Following the concept of ‘smart aggregate’ (i.e. SMAG) [16], low-cost and aggregate-size piezoelectric PZT (lead-zirconate-titanate) ceramic transducers were designed and produced at the Department of Mechanics of Materials and Constructions (MeMC) at the Vrije Universiteit Brussel (VUB) [11]. The monitoring system used in the present study consists of two piezoceramic transducers symmetrically embedded with regard to the centre of the tested beams, with a distance between the transducers of 1400 mm, in order to monitor the widest possible area of the cracked beams. In both beams, the transducers were placed at 90 mm height in the tensile zone of the beams (Figures 1(b) and 2(a)).

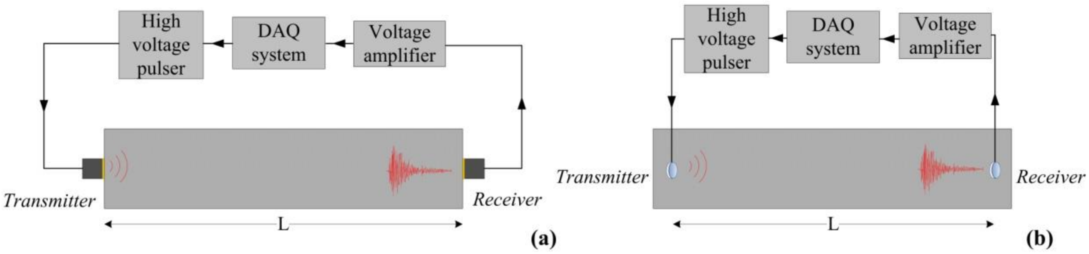


**Fig. 3.** (a) Ordinary UPV test system based on external, bulky transducers and (b) UPV test system based on embedded, low-cost and aggregate-size transducers.

Initially and before placing the transducers in the moulds, calibration tests were performed. Except checking the quality of the received signals, the transit time through the housing of the transducers is calculated. By applying a high-voltage, short-duration, pike-shaped pulse (100 V / 2.5 μs) to the transmitter which is excited to vibrate at its resonant frequency, the receiver is also excited since it is held in contact with the transmitter. Through the Akaike information criterion (AIC), the transit time values for all the calibration tests are calculated. A series of three tests took place in each of the available pair of transducers and the mean values of transit time of the transmitted wave taken from the transmitter to the receiver are 4.63 μs (with standard deviation 0.047 μs) and 4.55 μs (with standard deviation 0.050 μs) for the pair of transducers used in the REF beam and the PU beam, respectively. In Figure 4, the recorded time signals of the calibration tests for both pairs of transducers are shown and they are both characterized by a high signal to noise ratio as well as a high level of repeatability

During the tests and after a certain level of loading, micro cracks start to appear in concrete. These cracks modify the internal structure, the wave paths and therefore the received signals. In order to capture these changes, the hardware used in the tests consists of a high frequency data acquisition (DAQ) system, a high voltage pulser and a voltage amplifier (Figure 3(b)). A short rectangular wave (2.5 μs) excitation signal is generated in the DAQ system and is amplified through a high voltage pulser (800 V) before passing to the transmitter. The mechanical wave generated by the transmitter propagates through the concrete and is received by the receiver at a sampling rate of 10 MHz after being filtered and amplified by the voltage amplifier.

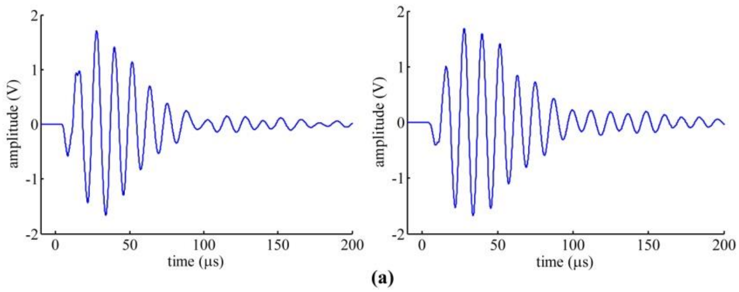


**Fig. 4.** Recorded time signals during the calibration test for the transducers fixed in (a) the REF and (b) the PU beam.

## 2. Results

### *2.1 The UPV Signals as an Indicator of the Progress of Damage*

When cracking occurs in the monitored area between the transmitter and the receiver, two main parameters of the recorded signals are affected; the amplitude and the onset time (Figure 5). Even for low load, the early part of the UPV signals is greatly modified (the amplitude of the received signals has been progressively decreased for almost five times and the transit time values have been increased for almost 100 μs) compared to the respective ones before loading (0 kN), due to the gradual crack formation and propagation. That early part of the signals mainly contains the contribution of a direct wave between the transducers and therefore carries information about the state of the microstructure in the direct path between the transducers. Additionally, there is a great similarity between the recorded signals in both beams and for both unloaded and loaded states.

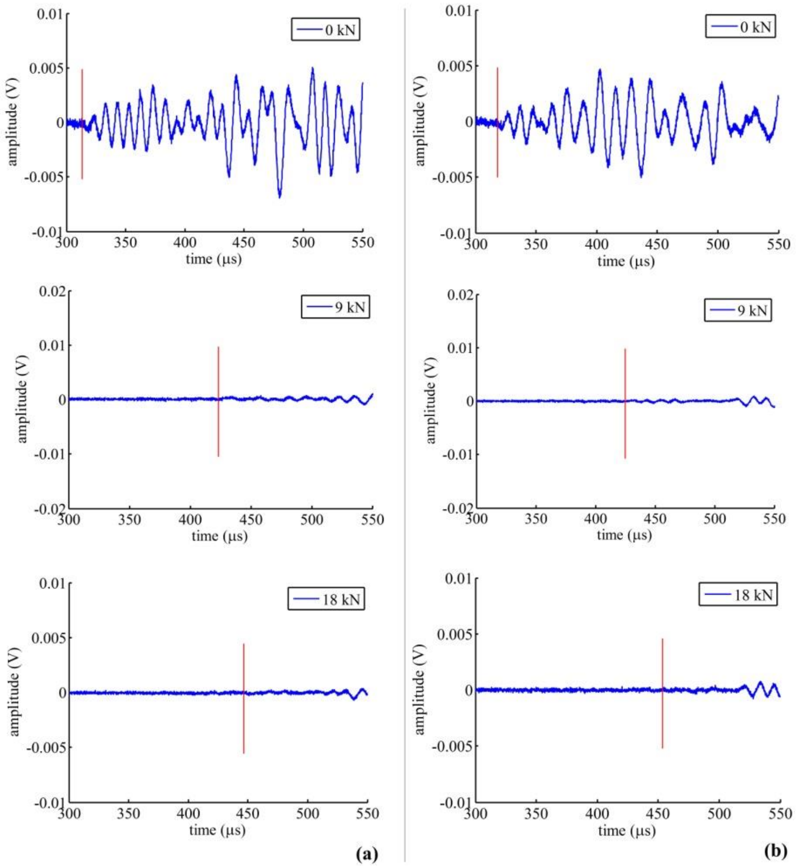


**Fig. 5.** Early part of the UPV signals with mentioned the onset time (red vertical line) for (a) the REF and (b) the PU beam during loading.

### *2.2 Evaluation of the Mechanical Repair after Healing*

Seven weeks after the cracks formation, both beams were reloaded in order to assess any possible mechanical rehabilitation. Except the low load of the PU beam, the received signals of both beams are characterized by low signal to noise ratio and further post-processing is impossible. Thus, the damage is so dominant resulting in wave distortion.

The damage index (DI) used in the present study considers the early part of the wave arrival and is based on the root mean square deviation (RMSD) between two signals, with the first one captured at the healthy stage (unloaded state) $x_o(t)$ and the other one over testing (loading-reloading states) $x_j(t)$, corresponding to the time frame of the first half-period $t_p$ - $t_n$ (i.e. $t_n$ is the arrival time of $x_0(t)$ and $t_p$ is the departure time of $x_0(t)$ in the time frame) of the healthy signal (Equation 1).

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

By definition, the DI is a scalar parameter and considers both the shift of the transit time and the amplitude variations of the received signals. Thus any increase of the DI value towards one indicates crack formation and propagation. Because the DI focuses on the early part of the recorded wave signal, it is very sensitive to a change of the microstructure in the direct path between the transmitter and the receiver and it can be used to early detect the appearance of cracks by following its evolution in real time [17].

In previous studies, the distance between the piezoceramic transducers was up to 200 mm and only a couple of cracks were formed and propagated in that small monitoring area [11, 17-19]. In the present study, the great shift of the transit time of the propagating waves as well as the low signal to noise ratio of the received signals could be attributed to the great distance (i.e. 1400 mm) between the transducers as well as to the multiple crack formation and propagation even at low loads. Thus, the present DI calculation corresponds to the time frame formed by the onset time values of the stress waves when the beam is unloaded and when it is under the maximum load.

In the loading tests, except the acceptable repeatability of the patterns of the DI vs load graphs (Figure 6), the DI evolution consists of two phases, where in the first one (phase I), the DI starts to increase noticeably as cracks form and propagate (at around 2 kN) until the severe failure of the beams (at around 10 kN). From there onwards, the DI is close to one and remains stable (phase II) till the end of the loading test, due to the fact that the stress wave cannot reach the receiver anymore. Concerning the reloading tests, due to the multiple open crack interfaces the stress wave propagation was hindered in the REF beam resulting in signals with low signal to noise ratio which are not suitable for reliable conclusion extraction. In the PU beam, the change of the recorded signals was well captured until the early load of 7 kN. From 7 kN onwards, the received signals are very noisy. According to Figure 6(b), the DI is immediately saturated to one as soon as reloading takes place. Due to the open crack interfaces and the possibly deficient quality and inadequate quantity of the healing agent, there is not any significant recovery of the mechanical properties of the PU beam.

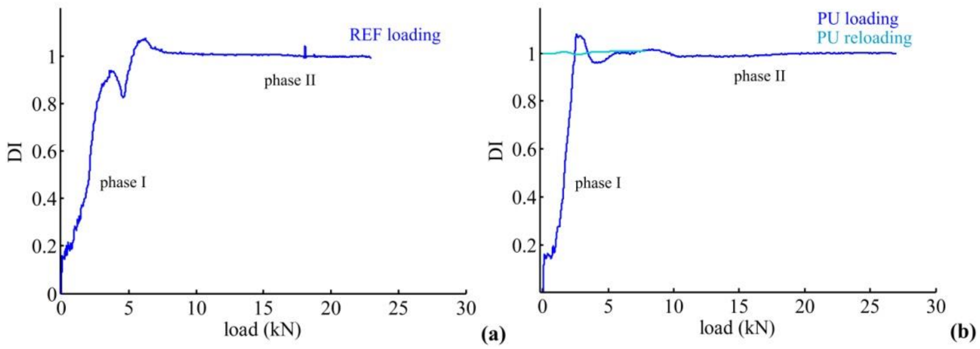


**Fig. 6.** DI versus load for (a) the REF beam during loading test and for (b) the PU beam during loading and reloading tests.

## 3. Conclusions and Perspectives

Low-cost and aggregate-size embedded piezoelectric transducers have been used for the *P*-wave velocity monitoring of a couple of large-scale, steel reinforced, concrete beams, subjected to four-point bending. One of the beams was used as a reference (REF) beam and the second one contained an embedded autonomous healing system based on encapsulated, polyurethane (PU)-based, healing agent. Even though the resulted performance of the self-healing technique used in the present study was not the desired one, the UPV method based on low-cost and aggregate-size embedded piezoelectric transducers was able to detect the multiple crack formation and propagation until severe failure. Next steps on the topic should be the quantitative assessment of damage using the recorded signals, the quality improvement of the healing agent as well as the optimal quantity and placement of the capsules, filled with the healing agent, in the concrete structure.

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