Detection and Evaluation of Autonomous Crack Repair by Acoustic Emission

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Abstract. The service life of concrete is dramatically reduced when cracks are not immediately detected and efficiently treated. In contrast to traditional manual repairing techniques (injection of healing agents into the crack), several innovative approaches aim at autonomous crack treatment during the concrete's service life. Mimicking the mechanisms from nature that enable injured organisms to recover, our research team manufactures concrete that regains its tightness, strength and stiffness after damage by embedding encapsulated healing agents into the material. In more detail, during concrete casting brittle glass capsules filled with two-component healing agent are placed at the areas where damage is expected. Crack formation breaks the capsules and the released agent fills the cracked plane. Local repair is achieved since the adhesion of the healing agent resets the material cracking resistance. The efficiency of such smart recovering technology is evaluated by performing small-scale bending tests on concrete beams and measuring the loading response in case of crack reopening after healing. Regain of mechanical properties is an initial sign of healing but does not provide sufficient information about the crack closure mechanism. A deep understanding of cracking damage and recovery is obtained by applying the Acoustic Emission (i.e. AE) technique. Resonant AE sensors, attached to concrete beams surface, capture the fracture activity and detect the initial crack opening and reopening after healing. It is concluded that AE hits activity correlate well with regain in strength and stiffness when reopening of healed cracks occurs. Finally, AE locates the area where healing successfully repairs damage.

Introduction

Plethora of loading circumstances charge concrete and cause widespread crack openings and various damage patterns. Tackling of cracking degradation derives from inserting an autonomously activated healing mechanism that prevent damage extension and amplify the overall resistance to cracking [1]. Adhesive chemical agents carried by brittle, tubular macro-capsules are introduced into concrete during casting [2]. Following the design requirements, numerous capsules are distributed at the concrete zone where tensile cracks form as loading occurs. Crack widening process forces the capsule rupture and encapsulated healing agent release ensues. Fluid healing agent covers the crack plane, interacts with air, water or accelerator components embedded into capsules and polymerizes forming a durable adhesive zone that restricts forthcoming damage. Mechanical fracture restoration can be traced on the loading response of healed concrete as crack opening mode fracture is imported once again. Anticipated healing recovery leads to retarded crack opening or elimination of local crack reformation [3, 4].

The recent years, the research at Magnel laboratory of Ghent University and at MeMC department of the Free University of Brussels established an autonomous healing system built on the aforementioned innovative approach. Couples of short borosilicate glass, tubular capsules are filled with two-component healing agent: one carries polyurethane-based expansive adhesive and the second one water-based accelerator that expedites the polyurethane polymerization process [3].

The healing efficacy is evaluated by means of resistance to further fracture of previously formed single or multiple cracks [5]. On that direction, two cycles of opening mode testing lead to crack initiation and healing activation (cycle of loading) and crack reopening and healing response to damage (cycle of reloading). The complex damage performance of concrete and the adventitious crack propagation nature due to material multi-scale particles hinders the assessment of healing reset. Therefore, Acoustic Emission (AE) is introduced to clarify the fracture phenomena in concrete. AE appears an essential tool indicating healing activation, by means of capsule rupture and agent release and estimating cracking response [6, 7]. At the following paragraphs, reviewing the recent research, series of concerns elucidated by AE application are presented and briefly discussed.

1. Experimental Details

1.1 Material and testing configuration

Small scale concrete beams with dimensions 800x100x100 mm are tested on an INSTRON loading frame under three- or four-point bending. The plain concrete mix proportions are given in Figure 1. The testing speed is 0.04 mm/min. A notch, 10 mm high, is introduced at the case three-point bending tested specimens at the middle of the beams to insure the singularity of crack formation and the crack widening is measured by applying a crack mouth opening device at the bottom of the beam covering the pre-notched region [8]. Regarding the four point bending beams, the minimum reinforcement is applied and a wide upper span of 250mm aims to multiple crack formation. In both cases, pairs of glass capsules are placed above the bottom of the beam (typically, series of tubes are located 10 and 25 mm from the bottom of the beam). Designing details of capsules are provided in Figure 1. Bending deformation is applied up to 0.30mm of crack opening. Subsequently, the beams are cured for 24 hours and healing polymerization occurs. Afterwards, bending reloading, under the same conditions, permits the evaluation of healing performance by means of crack closure.

Apart from AE technique, other advanced experimental methods are invoked. Characteristically, Digital Image Correlation visualizes the fracture process on concrete surface and measures in detail the crack widening or restriction movements and water permeability tests quantify the crack sealing achieved. Both methods crucially contribute and assist understanding the AE activity [9].

1.2 Acoustic Emission testing configuration

A series of eight resonant and wide band sensors are attached on concrete surface at different locations covering the fractured zone. The acoustic signals received by the different sensors, are pre-amplified by 40 dB, stored and analyzed by AE-win data acquisition program.

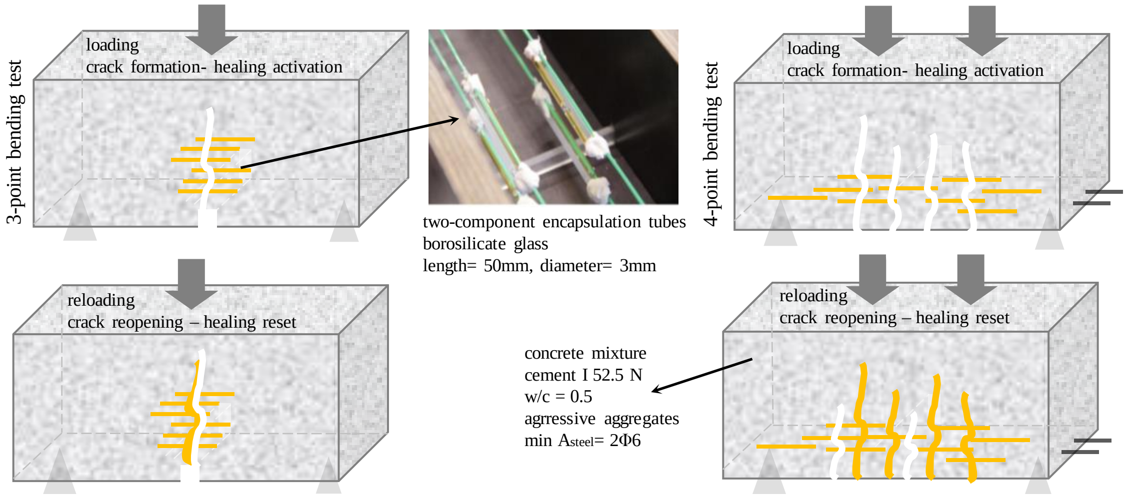

Fig 1. Typical AE signal and its main characteristics.

The wave propagating velocity is measured equal to 4000 m/sec and 3-D location of AE events is obtained based on the arrival time of 4 or more AE sensors hits. Several AE descriptors are considered, including the energy, the duration, the amplitude, the counts and the measured frequency of the hits. Furthermore, other parameters indicating the morphology of hits, such as the rise time, the counts to peak and the signal strength are considered. Finally, the overall AE activity during testing and the location of the fracture events significantly contribute to the analysis of healing performance.

2. Results

2.1 Singular crack formation/healing monitoring by AE

Figure 2 shows the loading graph of specimens tested at two cycles under three-point bending. The bending performance of healed specimens is compared to ones that do not carry any healing agent. Those reference specimens form cracks at the first loading cycle and lack resistance to further damage at the reloading cycle. The second graph of Figure 2 testifies the healing recovery by means of strength and stiffness reset and overall fracture resistance regain. Eventually, no other information can be derived from the bending loading graphs regarding the conditions under which healing occurs and the effect on concrete cracking fracture. Acoustic Emission contributes exceeding those restrictions as presented at the following paragraphs.

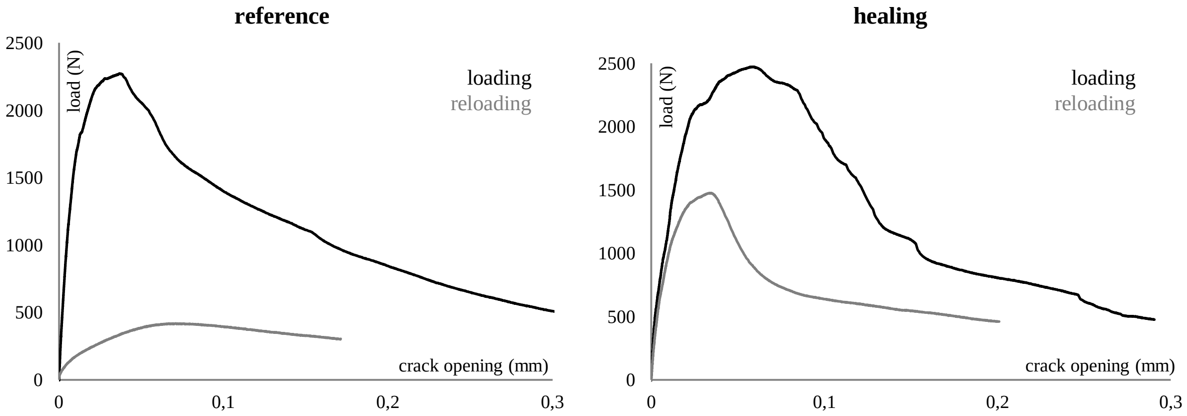

Fig 2. Loading graphs for reference and healed specimens tested under 3-point bending respectively.

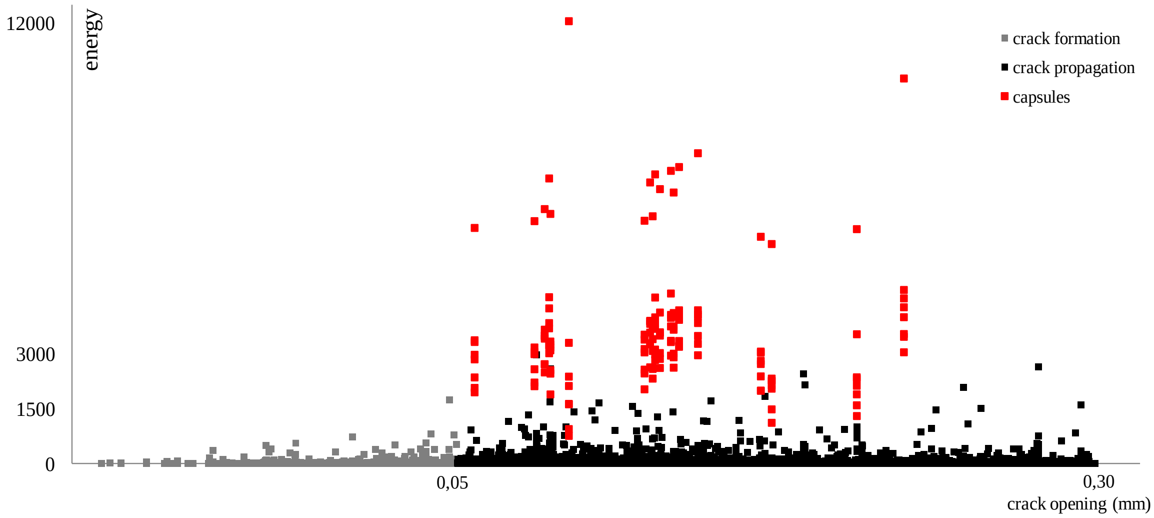

Fig 3. The capsule breakage is captured by AE as instant significant energy release.

AE continuous monitoring provides the testing stage and the regions at which healing process is activated. The release of adhesive material, initiated as the tubular capsules break, is detected at the AE hits activity as peaks of energy values. Apparently, stress concentrates at the tubular capsules faces located at concrete regions that deform due to cracking. Brittle nature of glass leads to instant capsule rupture and fracture energy release [10]. The moments of capsule breakages are colored at the load-crack opening graphs of Figure 3.

The crucial information derived from the graphs above is that capsules rupture as soon as crack forms and break at several moments during crack propagation. In other words, the mechanism that triggers healing is the cracking of concrete. This observation confirms the proper functioning of designed healing carriers.

Filtering the capsule breakage derived AE data, the remaining AE hits corresponds to the fracture activity of concrete. At the graphs of Figure 4 the standardized (to relevant maximum values) hits activity is plotted for reference-damaged and healed concrete beams. At the first loading cycle of the reference beam, the two tendencies noted correspond to crack formation and crack propagation stages of loading (before and after reaching the loading capacity of the beam respectively). The two hits activity modes are not recurred during reloading, where an almost linear hits increase indicates absence of crack resistance to further fracture.

On the other side, crack closure at the reloading stage of the healed concrete material is certified, as shown at the second graph of Figure 4. Both activity trends of crack formation and crack propagation are observed corresponding to resistance to re-opening of the healed crack and crack release after reaching the loading capacity of the healed interfaces.

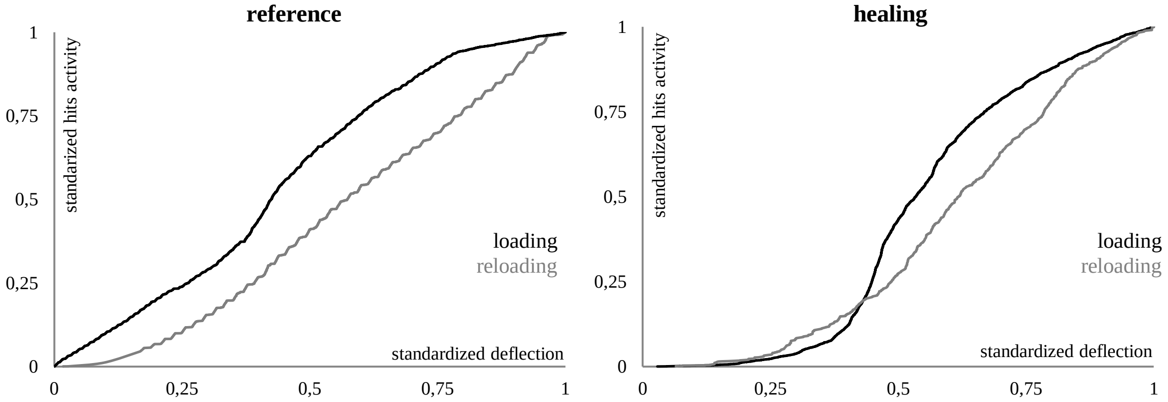

Fig 4. Hits activity at loading and reloading cycles of beams tested under 3-point bending testing.

Commenting on the loading stage of the healed series, the limited hits activity at the crack formation stage intimates local reinforcing and resistance to damage introduced by the tubular capsules standing above the crack tip.

2.2 Multiple crack formation/healing monitoring by AE

Having the experimental evidence of healing reset on single cracks, the testing set-up is modified and multiple cracks are formulated under four point bending, aiming to evaluate the healing restoration on more realistic loading cases.

Comparing the loading response of healed and reference concrete beams shown at the graphs of Figure 5, no evidence of mechanical restoration is observed. In contrast, a reduction of initial stiffness during reloading, indicating concrete damage is presented in both testing series. The loading drops occurring during the crack formation cycle of testing define the capsule breakage events and prove the activation of the healing mechanism at the damaged region of concrete. Respectively, a graph similar to the one presented in Figure 3 could be derived from the AE data. Any conclusion regarding the loading capacity of the beams appears precarious considering the presence of steel bar reinforcement into concrete elements.

Acoustic emission hits activity sheds light on the healing evaluation study as presented in Figure 6. Respectively to the three-point bending case, the standardized hits activity is accumulatively plotted to show the crack evolution during testing. The AE activity of loading cycle shows similar for both reference and healed specimens. Initial limited amount of AE hits corresponding to concrete resistance to damage initiation, is followed by significant and steep increase of hits as the first cracks form and culminates when several cracks propagate covering the tensile zone of concrete. At the reloading stage of the reference case, the progressive hits activity augmentation is not repeated, as premature increase of hits activity is observed. On the contrary, the healing crack reset leads to similar to loading stage AE hits evolution at the reloading stage, as shown at the second graph of Figure 6.

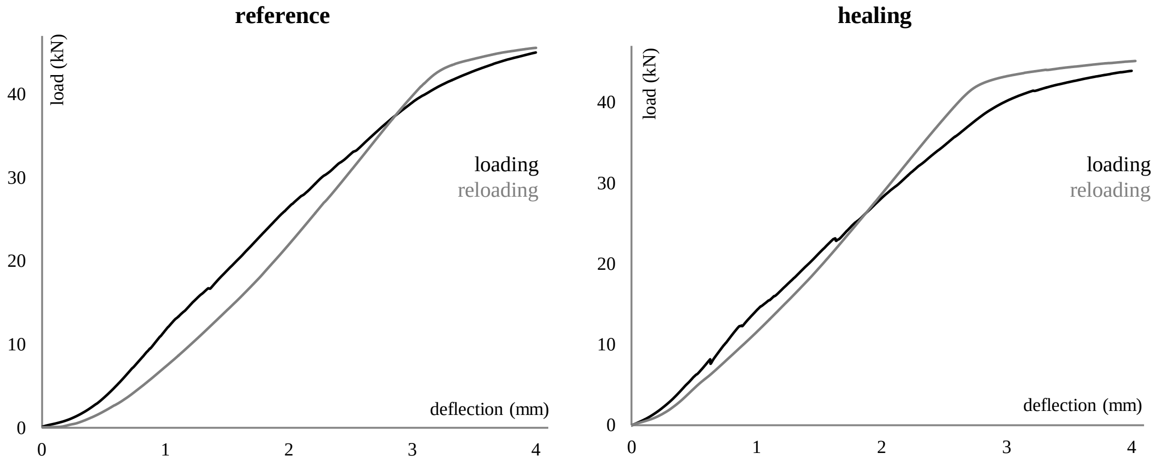

Fig 5. Loading graphs for reference and healed specimens tested under 4-point bending respectively.

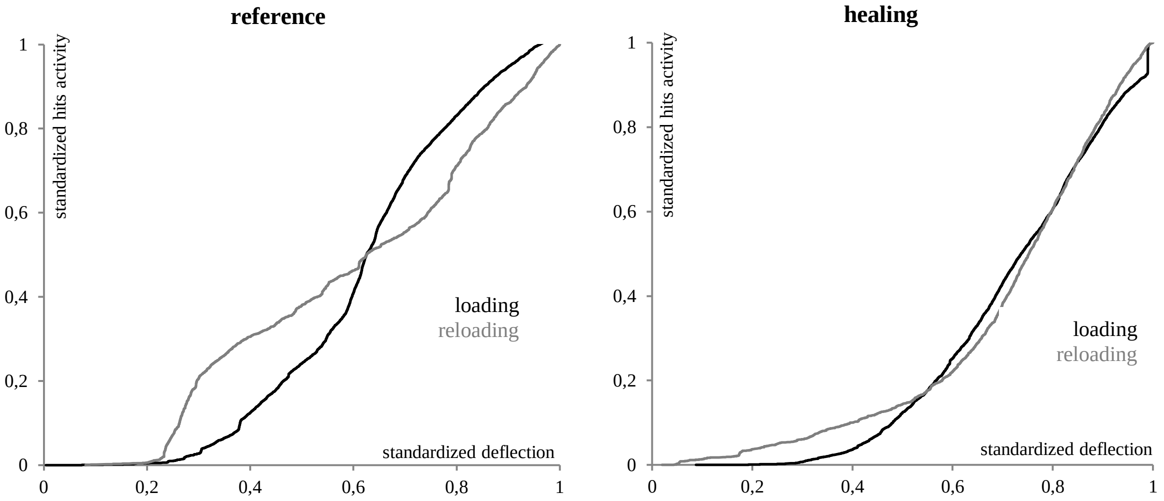

Fig 6. Hits activity at loading and reloading cycles of beams tested under 4-point bending testing.

3. Discussion- Conclusions

The little known on the fracture process of autonomously healed concrete demands an in-situ technique that clarifies the conditions under which crack reset is achieved. In parallel, the service loads of concrete structures, leading to multiple cracking that forms, propagates and automatically closes at different loading stages, asks for a continuous monitoring of damage evolution. Acoustic Emission fulfills those requirements. In our research, AE is applied on small-scale experimental settings simulating realistic crack damage in concrete and indicates different cracking modes and mainly the resistance to fracture of the healed regions into concrete.

The author believes that the study of singular crack recovery by means of AE provides the knowledge and the confidence to investigate and review the healing occurred under complex cracking cases, as the four-point bending tests.

Due to page limitations, only the general overview of normalized AE hits activity is chosen to present the significant AE findings on autonomous healing process. However, several other AE features, such as the signal energy, duration, amplitude, rise time and the number of counts appear promising indicators of fracture modes. Further information regarding the research on that direction can be found at [3, 5, 9, 10].

4. Acknowledgements

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