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MONITORING OF CRACK PROPAGATION IN REINFORCED CONCRETE BEAMS USING EMBEDDED PIEZOELECTRIC TRANSDUCERS

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Abstract. The field of structural health monitoring and damage detection has been studied intensively for the last thirty years. The main goal is to reduce inspection costs and risks of unexpected failure using real-time on-line monitoring systems. In this paper, Non Destructive Testing is applied using piezoelectric transducers embedded in the structure. Embedded piezoelectric transducers (Smart Aggregates) have been recently developed. These transducers are ideal candidates for active sensing methods of local damages, due to their low cost, small size and large frequency bandwidth. In this study, these transducers are used to detect and follow the crack propagation in a reinforced concrete beam subjected to a three-point bending test. The beam is equipped with two pairs of embedded transducers, each pair consisting in a sender and a receiver. Two different types of excitation signals are used (pulse and chirp) and the resulting waves are recorded on the receivers. Based on these signals, different damage indicators are investigated and compared. 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.

1 INTRODUCTION

A concrete structure can be subjected to several factors that may damage it during its service life. These factors are either climatic, chemical or accidental. The security requirements are more and more specific and severe. To ensure the safety of a structure, it is important to know its state. For this purpose, different destructive or non-destructive techniques are used. The use of destructive methods in order to determine properties of a material from a structure in service should be avoided as often as possible. Visual inspections are costly and can only identify macroscopic damages at accessible locations.

As an alternative, the field of structural health monitoring has developed during the last thirty years. 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 [1]. The methods are more suitable for large scale effects than for detecting local damages. An alternative, extensively studied in aeronautics for metallic and composite materials, is the use of active systems in which high-frequency waves are generated and measured by means of piezoelectric transducers. The frequency bands used for active sensing can be much higher which enables the detection of local defects as cracks. During the last ten years, a few research teams have started to apply these techniques to concrete structures using either surface mounted or embedded transducers. The latter has two obvious 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 [2].

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 [3, 4]. Other techniques are based on the use of 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 [5, 6]. A second type of excitation is the chirp signal which has a much broader frequency content [7]. 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 make 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 generated by pulse excitation can be carried out, such as backscattered waves analysis. In this method the response signal attenuation form (exponential decreasing) is used as a damage indicator [8]. 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.

In the present study, a three-point bending test is performed on a reinforced concrete (RC) beam. The aim of this work is to detect and follow crack growth using embedded piezoelectric transducers (see Figure 1), recently developed at the Civil Engineering Laboratory of ULB [9] based on the concept of SMAGs [10]. Two pairs of SMAGs are cast in the beam. These pairs consist of one receiver and one emitter. They are located on each side of the center of the beam where the first crack is supposed to appear. In a first step, the beam is progressively loaded with very small loading steps up to the appearance of the first cracks. Secondly, the beam is subjected to larger loads reaching the maximum acceptable load. Cracks or microcracks in the structure appear with the load increasing. This modifies the internal structure of the beam and the paths of waves and therefore the received signals. Two different types of excitation signals are used in this study. The first excitation signal is a high voltage pulse as used in classical UPV and the second excitation signal is a sweep sine from 0.1 to 100 kHz. For each of these excitation signals a specific damage indicator is defined. These damage indicators are both built by comparing the response signal at each damage level with a reference signal recorded before any damage. 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.

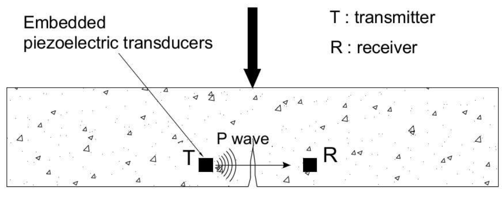


Figure 1: Test principle.

2 SMART AGGREGATES

SMAGs are thin PZT patches cast in small mortar pieces. 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. Such types of transducers have been recently developed in the Civil Engineering laboratory at ULB BATir. Figure 2 shows the different material layers used during the manufacturing of the SMAGs.

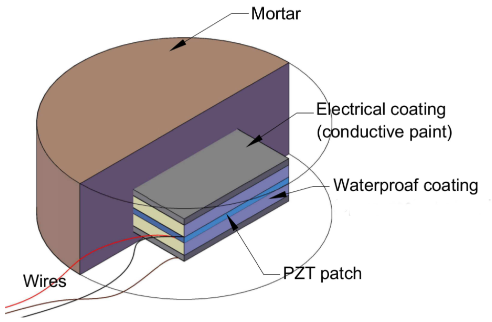


Figure 2: Smart Aggregate transducer; details of different layers.

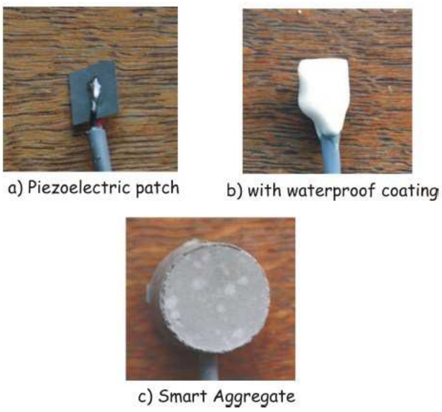


Figure 3: Smart Aggregate transducer manufactured at ULB-BATir.

To transmit the electrical signal, wires are attached to both faces of the PZT patch. For several reasons the patch cannot be cast without protections. At early age, concrete presents a certain quantity of water that is relatively conductive. To avoid an electrical coupling between SMAGs, the introduction of waterproof coating is needed. First SMAGs produced presented important interferences. Therefore, a thin layer of conductive paint was placed as shielding, surrounding the waterproof layer and grounded. The PZT patch is really thin and brittle. The waterproof layer is a first mechanical protection but not sufficient. Then, the sheltered PZT patch is cast in a small mortar cylinder. The process is summarized on Figure 3.

3 EXPERIMENTAL PROGRAM

The test consists of loading a reinforced concrete beam and following the induced cracks growth. The test is a three points bending test (see Figure 4).

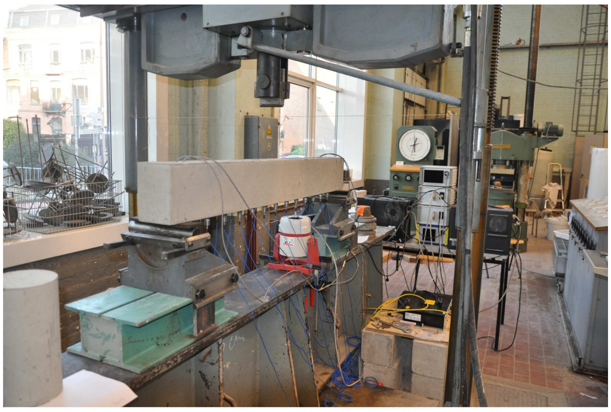


Figure 4: Experimental setup.

SMAGs are embedded in the concrete beam. Excitation signals are sent to the piezoelectric transducers, which create compression waves that are picked up by sensors. Cracks or microcracks in the structure appear with the load increasing. This modifies the internal structure of the beam and the paths of waves and therefore the received signals. The signal at each damage state is compared to the initial state. 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.

3.1 Specimen

Two couples of transducers are disposed in the beam as exposed on Figure 5. 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.

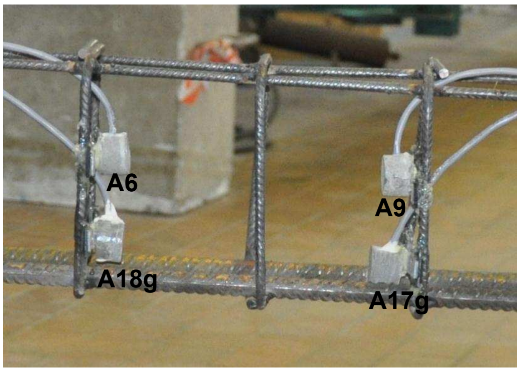


Figure 5: Location of the SMAGs.

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 place.

The constituents of concrete are given in Table 1 and the mechanical properties of the concrete are given on the Table 2. Table 3 gives informations on geometrical characteristics and the computed strength of the beam.

3.2 Loading Procedure

The test occurred during two different phases. In the first phase, the beam is totally unloaded slightly after appearance of the first cracks. Figure 6a summarizes the loading procedure of the first phase. The loading procedure for the second phase is shown on Figure 6b; the beam is loaded close to the maximum acceptable load. During the second phase, in addition to the force and displacement sensors of the bending 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 different cracks width.

Table 1: Concrete constituents of the RC beam

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

Table 2: Mechanical properties of the concrete

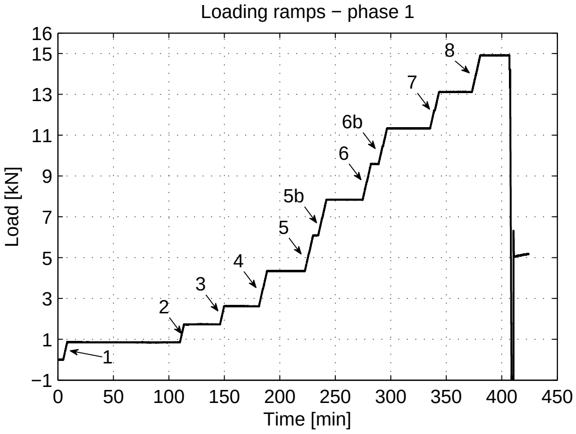
Density	2338.6	kg/m^3
Compressive strength f_c	57.1	MPa
Tensile strength f_t	2.86	Mpa
Young's modulus (4/20)	33000	Gpa

Table 3: RC beam properties

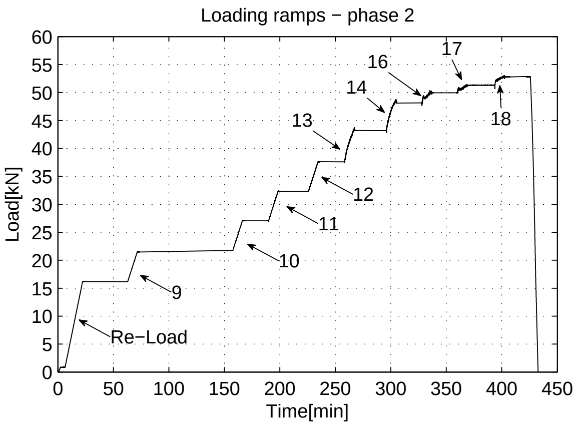
L x l x h	1470x140x190	mm
Bottom reinforcement bars	2x ϕ12	mm
Top reinforcements bars	2x ϕ6	mm
Distance between stirrup	11	cm
Cracking load	9.9	kN
Maximum load	51.3	kN

4 STRUCTURAL HEALTH MONITORING METHODS

As already indicated, two monitoring systems are used in the current study. The UPV system is based on the FreshCon system, a commercial system designed by the University of Stuttgart for evaluating fresh parameters of concrete.



(a) Phase 1: The beam is loaded up to the crack initiation (15kN).



(b) Phase 2: The beam is loaded up to the failure(50kN).

Figure 6: Loading procedure in two phases.

In this work, this system is coupled to the SMAGs. The chirp method system is developed from a Labview environment with a National Instrument (NI) data acquisition system (DAQ). Both systems are based on the same principles. An excitation signal is transmitted to a piezoelectric actuator that transforms it in a mechanical wave that propagates through the structure, a piezoelectric sensor measures strains created by this wave and transmits the signal to a DAQ system. The two systems differ in the excitation signal and the DAQ system. But each of these monitoring systems are based on the same principle. On each step of load, a new measurement of these signals is recorded. A damage index is defined by comparing each damaged signal with the initial undamaged signal.

4.1 FreshCon System

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. This system is launched during the loading ramps of the beam with a frequency of measurements of one pulse every 10 seconds. 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 length of pulse gave better results than other pulse time.

From the measured waves, it was found that the signal did not change significantly for loads below 5 kN. For higher loads, the damage has been found to affect two main parameters which are the time of propagation and the amplitude of the received signal (Figure 7). 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 period of the signal mainly contains the contribution of a direct wave between the SMAGs and the first half-period corresponds to the compression part of this wave. As a consequence, we have chosen to define the damage indicator based on the root main square deviation (RMSD) between the healthy signal and a damaged signal computed in the time window corresponding to the first half-period of the undamaged signal. It is given by :

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

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 reception of x_0, $t_p - t_n$ corresponds to the duration of the 1st half period (Figure 7).

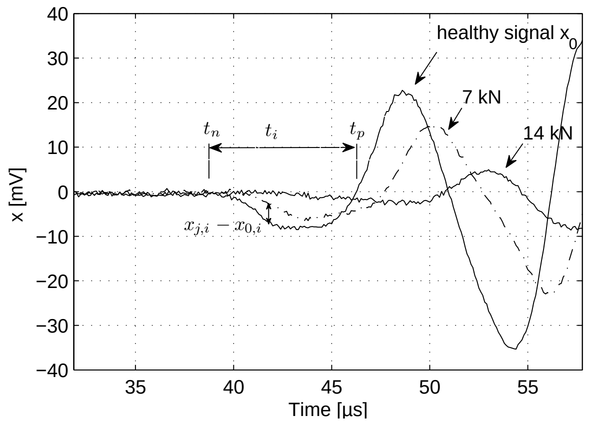


Figure 7: Definition of the time window, t_n is the time of reception of the undamaged signal, $t_p - t_n$ corresponds to the duration of the 1st half period of the undamaged signal.

This definition of the damage index takes into account both the shift of the time propagation and the decrease of the amplitude without computing explicitly their values. The saturation of the damage index means that it is constant and equal to one and therefore, that the damaged signal is equal to zero in the first half period.

4.2 Chirp system

The aim of this system is to observe the effect of damage in the frequency domain. It is a high frequency vibration test. Using a sweep sine excitation has the advantage that each frequency is separately excited. As all the frequencies (in the defined bandwidth) are swept, the spectral energy is constant. This signal is therefore particularly suitable for a frequency analysis. The frequency bandwidth is from 100 [Hz] to 100 [kHz] and is swept in 5 seconds. The response signal is measured at a sampling rate of 204.8 kHz. In comparison with the previous test, the length of the signal is important. Considering the velocity of the sweep sine, from 5kHz the signal can assumed to be in the steady state. Below 5kHz, the energy of the signal is very low compared to the higher frequencies and this part can be ignored (see Figure 8). The chirp is generated by the NI system and amplified by a QuickPack QPA200 voltage amplifier. All the sensors are plugged on the NI DAQ. This DAQ is controlled by a Labview environment on a laptop. The signals are measured at the end of each loading ramp only, as it was not possible to measure simultaneously with the Freshcon system on the same transducers. As for the FreshCon system, the RMSD value is computed to define the damage index. In this case, this value is obtained from the Amplitude of the FRF between the actuator and the sensor computed for the damaged signal and the healthy signal. The FRF is obtained by dividing the Discrete Fourier Transform (DFT) of the output signal by the DFT of the excitation signal. The RMSD value is given by:

$$I_j = \sqrt{\frac{\int_{\omega_n}^{\omega_p} (X_j(\omega) - X_0(\omega))^2 d\omega}{\int_{\omega_n}^{\omega_p} X_0^2(\omega) d\omega}} \qquad (2)$$

Where ω_n is equal to 5kHz and ω_p is equal to 100kHz.

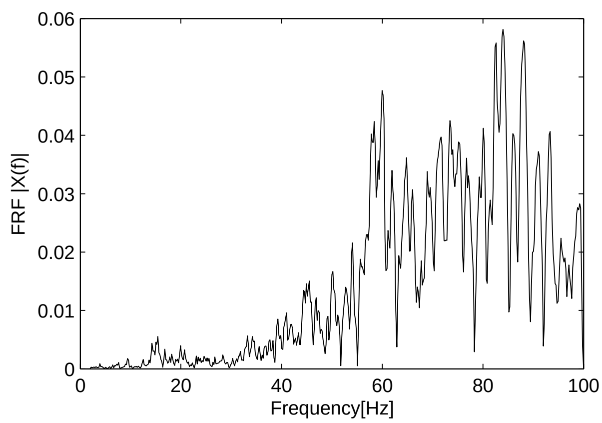


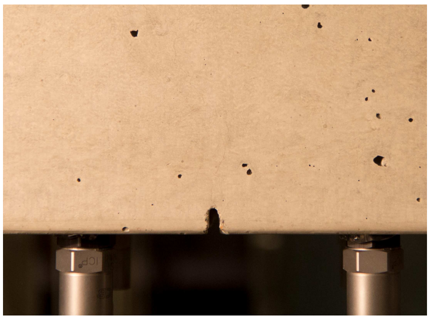
Figure 8: FRF of a signal, the energy at the lower frequencies is very low.

5 EXPERIMENTAL RESULTS

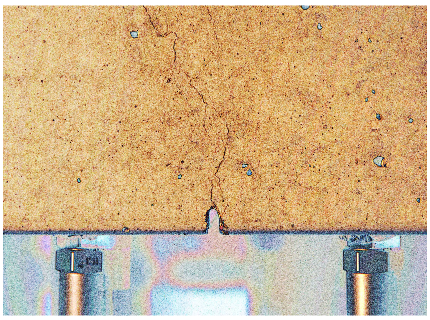
5.1 Visual detection of cracks and cracks width measurement

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 9a. Image processing tool as Photoshop allows the application of various numerical filters that improve the visual detection of cracks (see Figure 9b). 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.



(a) Before numerical processing.



(b) After numerical processing.

Figure 9: Image processing for visual detection of cracks. The crack width is approximately 0.1mm.

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 that mentioned above. Nevertheless they were located outside of zone of interest, which is the area between the SMAGs.

5.2 Damages index

Figure 10 shows the the evolution of the damage indexes for the SMAGs that are located on the bottom of the beam (A18g-A17g). Unfortunately, the other pair of SMAG was defective and the results can not be exposed.

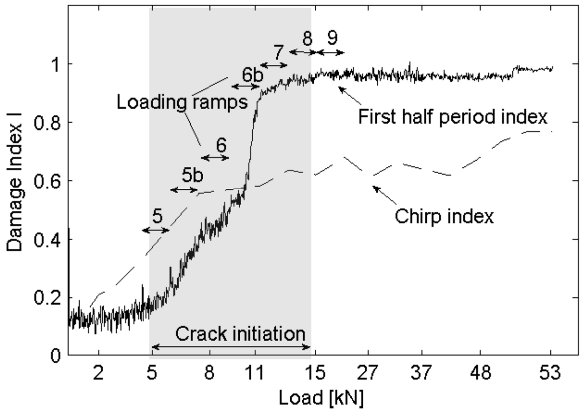


Figure 10: First 1/2 period (UPV) index and chirp index for the couple of SMAGs on the bottom of the beam.

The evolution of the UPV 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 a good indicator for detecting crack appearance but does no give any information about the the evolution or the size of this damage.

The second damage index (chirp) has the advantage of evolving after the appearance of cracks. It can therefore give a qualitative idea about the evolution of the crack width but depends on many parameters that are not well understood. The evolution of this damage indicator is difficult to correlate with the observations. It increases in the first loading steps, where no cracking has been observed. Furthermore, this index does not saturate even close to the strength limit of the beam. The impossibility of distinguishing the local phenomena from the global phenomena is one of the parameters that probably make this index difficult to interpret.

6 CONCLUSIONS

The goal of this research was to develop a method to monitor the damage of a concrete structure using embedded piezoelectric transducers. Two methods have been developed for comparison. One method is based on pulse excitation and post-processing of the measured signals in the time domain, while the other is based on chirp excitation and post-processing of the measured signals in the frequency domain.

The damage index based on pulse excitation has demonstrated a great agreement with the visual observations of crack initiation. It can detect the appearance of cracks but does not evolve anymore when crack is growing and saturates largely before the service limit. The damage index based on the chirp excitation is less sensitive and more difficult to interpret. It does not saturate even close to the failure and should be used with a lot of caution.

An issue concerning the influence of the smart aggregates on the strength of the structure can be raised. Their size are of the same order of magnitude as the largest aggregates used in the concrete. Although they are made of mortar, they are responsible for a certain mechanical heterogeneity in the structure that can cause a local weakness which, in turn, could inflict additional damage.

The damage indices proposed in this study are very simple and based on empirical observations. Further studies will focus on the development of more complex signal processing strategies, for which a deeper understanding of the wave propagation will be developed through analytical and numerical models.

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