PROCEEDINGS of the
23rd International Congress on Acoustics

9 to 13 September 2019 in Aachen, Germany

Use of Higher-Harmonic Generation To Detecting Cracks due To Steel Corrosion In Reinforced Concrete

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ABSTRACT

Reinforced concrete is of vital importance in many civil and industrial structural applications. Corrosion or other interface deboning in steel-concrete is a typical failure mode during the long service period of the structures, which can severely reduce the load-bearing capacity. Higher-Harmonic-Generation (HHG) have been used to detecting the onset of microcracking due to steel corrosion in model reinforced concrete elements. The specimens were of prismatic shape with a single steel rebar. The corrosion was forced by admixing an appropriate amount of sodium chloride at the moment of preparing the concrete mix, and by the application of an electric field, using a constant current density power source. The results indicate that the onset of cracking seems to be accompanied by the appearance of higher-harmonic generation at the output signal, when the system is excited by means of an ultrasound wave.

Keywords: Non-Linear Ultrasonic Test, Cracks, Corrosion

1. INTRODUCTION

A review on non-linear ultrasonic techniques for non-destructive assessment of micro-damage in a material can be found in [1]. Some of these techniques are based on changes in the resonance frequency (spectroscopy) [2] or on the generation of higher order harmonics [3]. In particular, harmonic generation relies on the generation of higher harmonics whose amplitude is directly linked to the damage occurrence. In brief, the degradation of a material is linked to a non-linear mechanical behavior of it so that as the micro-damage grows, non-linearity increases. As a result, when an ultrasonic wave propagates through the material an interaction with these microstructural changes induces the generation of nonlinear terms linked to these higher order waves. Many authors have successfully used this technique to characterize the damage of granite samples subjected to compressive loadings [4], to investigate thermal damage in sandstone [5], or for in situ real time monitoring of load-induced damage in concrete [6]. Accordingly, given the potential of this technique in terms of early damage detection it was found worth investigating its applicability to the study of micro-cracking induced by corrosion processes in concrete.

This work shows some preliminary results on the use of a non-linear ultrasonic technique based on harmonic generation to study the micro-cracks produced in reinforced cement mortar under forced steel corrosion. For this purpose, several prismatic reinforced cement mortar specimens were prepared and subjected to a forced corrosion test that accelerated the damage.

Preliminary results indicate that the use of a non-linear ultrasonic technique can be very useful for the early damage detection and durability assessment of corroded cement-based structures.

This paper is organized as follows: Firstly, the materials used in this work and how they are prepared and damaged (corrosion test) are described. Secondly, the ultrasonic methods (linear and nonlinear) and the experimental setup are explained. Finally, some results are exposed and discussed and at the end a brief conclusion is presented.

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2. MATERIAL

2.1 Sample preparation

The experimental tests were performed over two sets of three prismatic reinforced cement mortar specimens having the same dimensions and composition. The choice of cement mortar instead of concrete as experimental basis was expected to ensure a better adhesion in the steel-mortar interface besides reducing the heterogeneities different that the micro-cracking to be induced by the corrosion phenomena.

First, the cement mortar was prepared mixing a standard siliceous sand aggregate and a sulphate resisting ordinary Portland cement, CEM I 52.5 R-SR 3, in accordance with the UNE-EN 197-1 standard [7]. A kneading process was then performed mixing the cement mortar with sodium chloride dissolved in water, being the Water/Cement (W/C) ratio used 0.5. The chloride sodium let obtain a 2% Cl^- relative to the cement weight in the hardened mortar and thereby accelerate the corrosion process. In a following step, the cement mortar mix was arranged in 100 x 100 x 350 mm3 plastic moulds for 24 hours before being extracted for mechanical compaction and curing during 7 days in a humidity chamber at 20 ºC and 95 % relative humidity. Each of these moulds allowed centre-crossing a steel rebar of 12 mm in diameter along each sample 10 mm beneath its upper surface. The steel rebars were previously weighted and cleaned from native corrosion products following a recommendation procedure [8], covering the ends with vinyl electric tape to avoid the steel-mortar-air interaction. This layout was chosen so as to favour the micro-cracking produced by the corrosion process to emerge on the upper surface of the samples and thus ease the monitoring of the micro-crack width growth over time using a microscope. The preparation data of the cement mortar mix is given in Table 1.

Table 1 – Composition of the Cement Mortar

Material	Amount (g)
Cement (CEM I 52,5 R SR(3))	450
Standard siliceous sand	1350
Deionized water	225 (w/c = 0.5)
NaCl	14.8 (2% Cl^- relative to cement weight)

Photographs of the sample preparation process and the final process are shown in Fig. 1 and 2.

Figure 1 – Left: Preparation process. Right: Sample prepared.

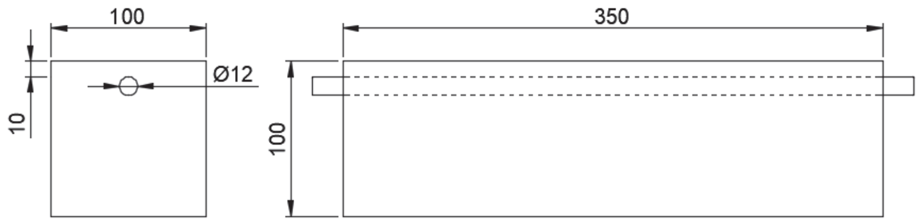


Figure 2 – Dimensions of samples

2.2 Forced Corrosion Test

The forced corrosion test was performed by using an electrophoretic power source that applied of a constant current density of 40 μA/cm2 between the steel rebar (anode) and an external galvanized steel grid (cathode) placed in the bottom of the specimens. Samples were partially submerged (5 mm height) in a recipient filled with tap water so as to keep an appropriate electric conductivity throughout the material, a polypropylene sponge being used between these and the steel grid. The forced corrosion test was then performed over each of the sets above described, the duration of the experiment being of 23 days for each set. Given that the electrophoretic power source provided a constant current density, it was possible to corrode three specimens simultaneously in a single test by connecting these in series. The tests were performed under pseudo-controlled conditions with a relative humidity of 84±4% and a temperature of 23±1ºC to minimize the influence of additional factors on the measurements. Fig. 3 shows an image of the forced corrosion test.

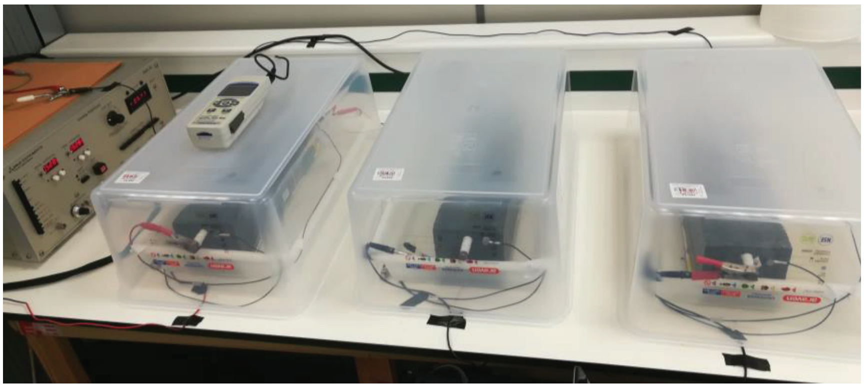


Figure 3 – Experimental setup of the forced corrosion test

3. METHODS

3.1 Ultrasonic Pulse Velocity (UPV) test

Ultrasonic Pulse Velocity (UPV) test is a linear technique that allows determining the ultrasonic wave velocity through a given material from the transit time of a pulse between separate emitting and receiving transducers. This test is normally used to detect the presence of defects or cracks in concrete in a simple manner: the lowering of the velocity of the ultrasonic pulse relative to a reference state (i. e. undamaged conditions) indicates the presence of cracks. Moreover, this method can also provide information regarding the attenuation of concrete and be helpful in the determination of its elastic properties. A detailed description on the application of this measurement procedure to concrete materials can be found in the standard ASTM C597-16 [9].

Despite being considered a very extended technique to assess the quality of concrete, it is less sensitive to micro-cracks and therefore to early damage detection that the non-linear technique to be described next.

3.2 Non-linear Ultrasonic Test

The non-linear technique used in the present study is based on the harmonic generation in standing waves [5]. In this test, two transducers are placed opposite each other on both sides of a finite solid material, a purely sinusoidal wave being generated until standing wave conditions are achieved. The non-linear elastic response of the solid medium is responsible for the distortion of this wave and the higher harmonic generation, whose magnitude depends on the elastic properties thereof. While these elastic properties slightly change in the early stage of a damage process, the harmonic generation is sensitive to defects whose sizes are smaller than the wavelength of the emitted signal (e. g. micro-cracks), thus making this method more useful when compared to the UPV test.

Harmonic generation can be determined by examining the amplitudes of the fundamental and harmonic frequencies in the frequency spectrum of the received signal. Assuming that the changes in the wave propagation velocity and the attenuation are small, the parameters of non-linearity can be approximated as $Bn = A_2/A_1^2$, and $Bpn = A_3/A_1^3$ A_1 ,A_3 and A_2being the amplitudes of the fundamental and second harmonic waves, respectively. In practice, the variation of this ratio relative to initial undamaged conditions is used as an indicator of the micro-structural damage [3]. The main advantage of the standing wave method when compared to the propagative one is that it can be used even for specimens whose thickness is smaller than the wavelengths of the fundamental and second harmonic waves. In short, this non-linear technique is expected to be more sensitive to microscale damage than the linear method above described, as it will be shown in section 3 (results).

3.3 Experimental Setup

The experimental setup developed to perform both the linear and non-linear ultrasonic tests over the prepared specimens is described next. A custom-made application was implemented using the system-design development software LabVIEW© (see fig.4).

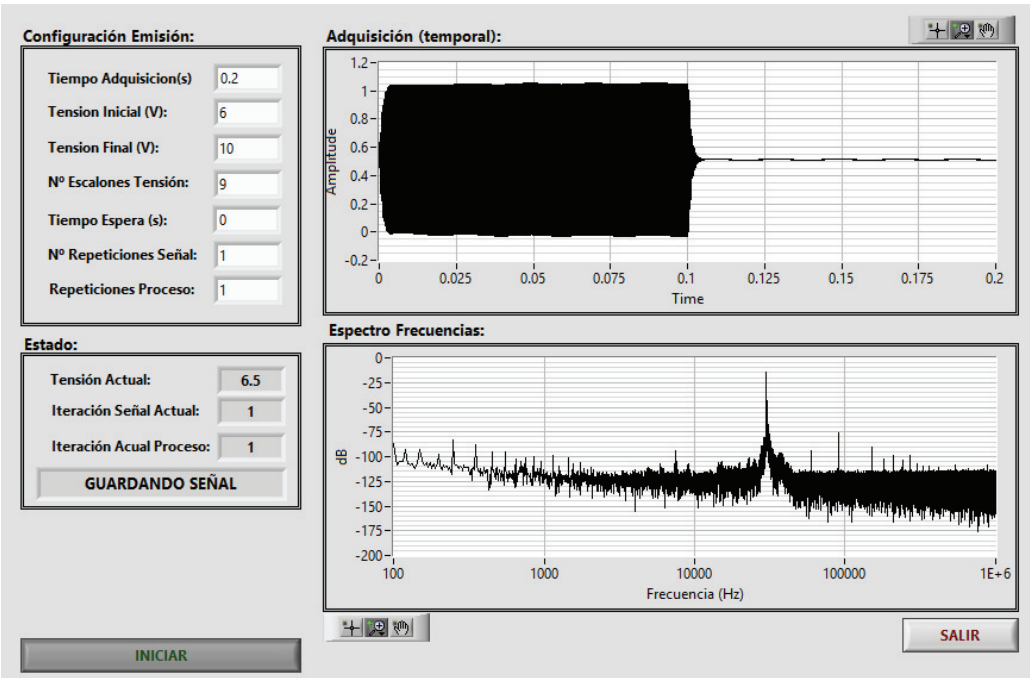


Figure 4 – Custom-made application implemented using software LabVIEW™

The application was run using the acquisition platform NI USB 6361, whose sampling frequency was set to 2 MHz.

Figure 5 shows the positions of the transducers transmitters and receivers used. Table 2 completes the information indicating which transducer acts as an emitter and as a receiver.

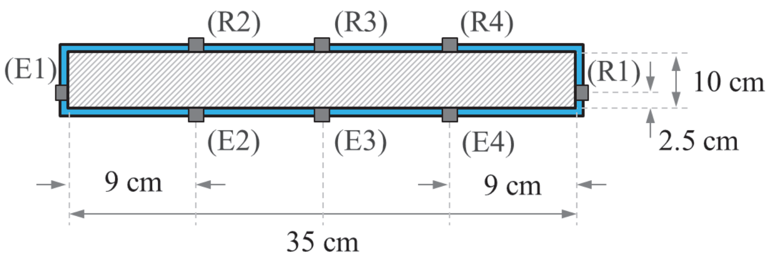


Figure 5 – Position of the transducers in each of the configurations studied

Table 2 – Configurations studied

Configuration	Transducer E/R
C1	E1/R1
C1I	E1/R1
C2	E2/R2
C3	E3/R3
C4	E4/R4

For each configuration a 30 kHz sinusoidal signal was sent to a FS WMA-100 amplifier and then to the emitter transducer, using different peak input voltages from 120 to 200 V in 10 V steps to fed the transducer. Both the emitter and the receiver transducers (Dakel IDK-09) [10] were glued to each end of the reinforced cement mortar specimens, the received signal being amplified using the signal conditioner B&K 2693-A-0F4 and sent to the acquisition platform.

For the CiI configuration, the emitter transducer was supplied with two tones at the same time (f1 = 30kHZ, f2 = 2kHz). A scheme of the experimental setup used for the ultrasonic measurements is shown in Fig. 6.

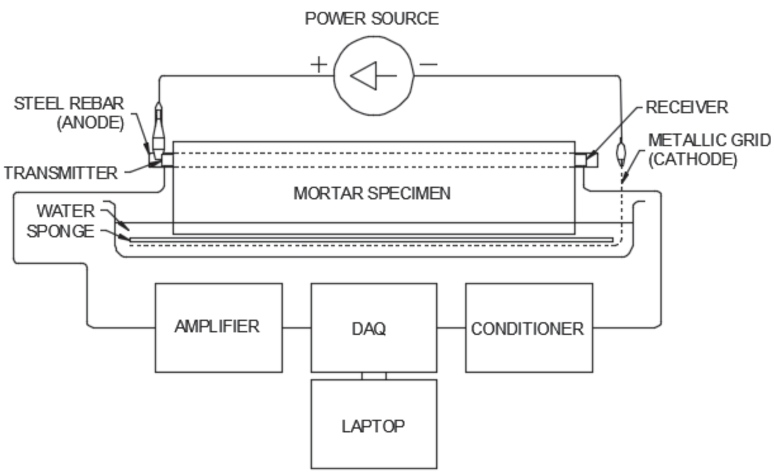


Figure 6 – Experimental setup used for the ultrasonic measurements

A Hanning/Hann/rectangular window was applied to the steady state interval of the received signal, the Fourier transform being used to obtain the frequency spectrum of the windowed signal. It is then straightforward to obtain the amplitudes of the fundamental (30 kHz) and second harmonic (60 kHz) from this spectrum

Both the linear and non-linear ultrasonic measurements were performed at intervals of 12 hours over the 23 days that the forced corrosion test lasted (except weekends).

4. RESULTS

4.1 Microscopic Data

In addition to the ultrasonic tests, microscopic photographs on the upper surface of the samples were taken throughout the whole experiment so as to assess the crack width growth as a function of the corrosion rate. Evolution of the size of the crack is shown in Fig. 7.

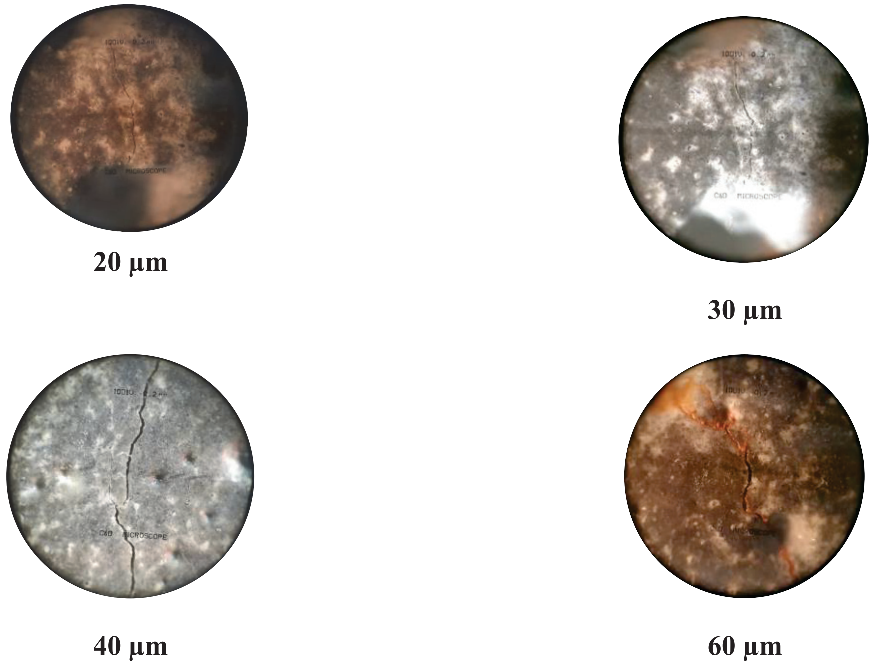


Figure 7 – Evolution of the size of the crack

4.2 Ultrasonic Test

Some significant results are shown. Figure 8 -Left shows the frequency response of the records made with the configuration C1 in measures 1, 10 and 11, when the transducer is excited whit 120 V. It can be seen that the fundamental amplitude (A1) decreases at the same time as the amplitude of the second and third harmonics (A2 and A3) decreases. In the 7-Right figure, the variation of the parameters Bn and Bpn with the measurements is shown. An increase of these parameters in the M9 is noticed. Since the fissure becomes visible one or two days after this growth, it can be assumed that it has been caused by the damage of the material related to the corrosion process. In figures 9 the same representations are made for a voltage of 190 V.

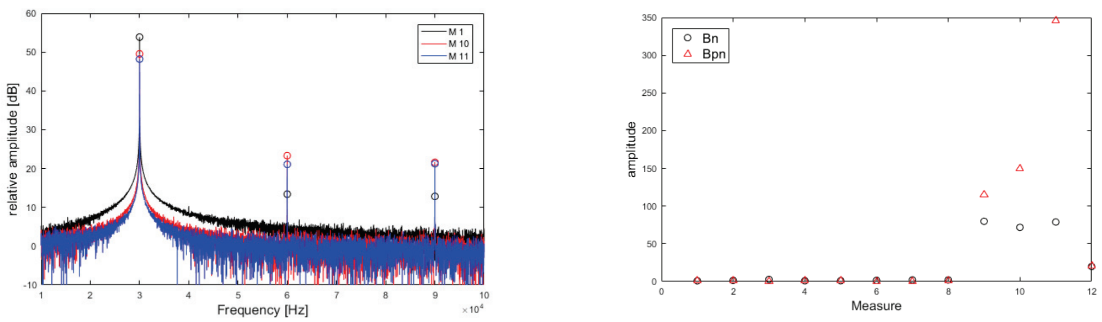
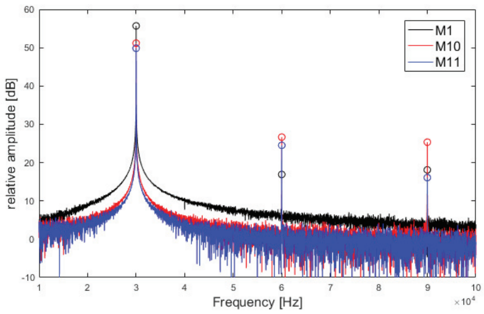


Figure 8 –Left: Frequency response of the records made with the configuration C1 in measures 1,10 and 11, when the transducer is excited whit 120 V. Right : Evolution of the parameters Bn and Bpn



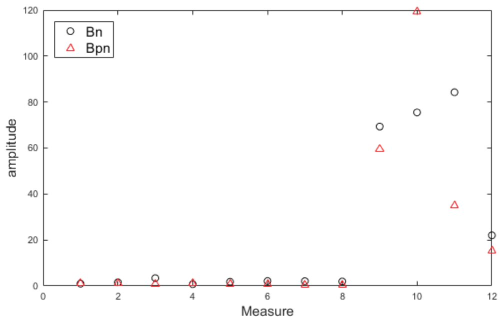


Figure 9 –Left: Frequency response of the records made with the configuration C1 in measures 1,10 and 11, when the transducer is excited whit 180 V. Right : Evolution of the parameters Bn and Bpn

Figure 10 presents the frequency response for the CiI configuration when the emitter transducer was supplied with two tones at the same time (f1 = 30kHZ, f2 = 2kHz) being excited with 180 volts. It can be seen that the amplitude of the products of intermodulation distortion (frequencies 32, 28, 34 and 26 KHz) increases from measure M1 to M12

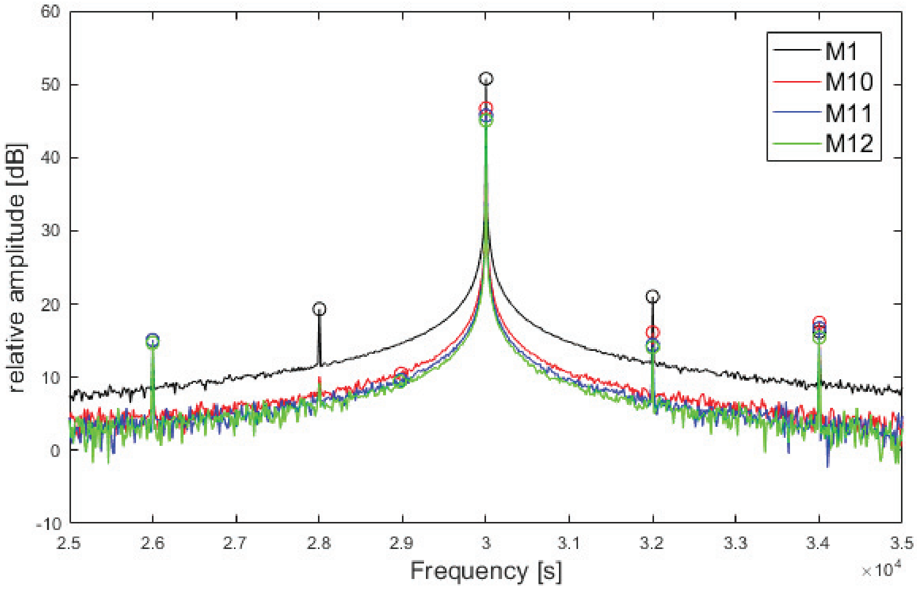


Figure 10 – Frequency response for the CII configuration: The emitter transducer was supplied with two tones at the same time (f_1 = 30kHZ, f_2 = 2kHz) being excited with 180 volts

5. CONCLUSIONS

The preliminary results that are obtained in this work indicate that it is possible to detect micro-cracking of reinforced mortar specimens due to corrosion using higher-harmonic generation. The non-linear ultrasonic measurements yield similar values of times for cracking, as compared to the microscopic observations of the mortar surface. However, these are preliminary results and it is necessary further research.

ACKNOWLEDGEMENTS

This research was funded by the Spanish Agencia Estatal de Investigación (grant code BIA2016-80982-R) and by the European Regional Development Fund (grant code BIA2016-80982-R). M. M. acknowledges a pre-doctoral fellowship from the Spanish Ministerio de Educación, Cultura y Deporte (FPU16/04078).

We would like to thank Carmen Andrade for advice on the details of the corrosion testing. We thank also Lafarge-Holcim Spain for providing the cement samples for preparing the reinforced mortar specimens.

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