

# Linear and Nonlinear Ultrasonic Techniques for Monitoring Stress-Induced Damages in Concrete

## **Anna Castellano**

Department of Mechanics, Mathematics and Management  
Polytechnic University of Bari, Via Orabona 4, 70125 Bari, Italy  
E-mail: anna.castellano@poliba.it

## **Aguinaldo Fraddosio**

## **Mario Daniele Piccioni**

Department of Civil Engineering Sciences and Architecture  
Polytechnic University of Bari, Via Orabona 4, 70125 Bari, Italy  
E-mail: aguinaldo.fraddosio@poliba.it, mariodaniele.piccioni@poliba.it

## **Tribikram Kundu**

Department of Civil and Architectural Engineering and Mechanics,  
Department of Aerospace and Mechanical Engineering  
Department of Materials Science and Engineering  
University of Arizona, Tucson, AZ 85721, USA  
E-mail: tkundu@email.arizona.edu  
ASME Membership

## **ABSTRACT**

*When stress in concrete exceeds certain threshold value, micro-cracks are nucleated, these microcracks can propagate and coalesce forming macro-cracks, resulting in the gradual decay of the mechanical properties of concrete and eventual failure of the concrete structures. For safety concerns one needs to develop suitable nondestructive testing methods capable of detecting past overloads of concrete structures during its service life.*

*In this work the stress-induced damage in concrete is monitored using ultrasonic techniques, exploiting the coupling between the stress level experienced by concrete and its wave propagation parameters. Cyclic compression tests with increasing maximum load level have been performed on specimens made of concrete with coarse-grained aggregates. Experimental results have been analyzed by two different ultrasonic methods - the linear and the nonlinear ultrasonic techniques.*

*In linear ultrasonic technique, the stress level experienced by the specimens is related to the variations in signal amplitude and velocity of ultrasonic waves. In nonlinear ultrasonic method the Sideband Peak Count (SPC) technique is employed for revealing the stress-induced damage*

*corresponding to each load step. In comparison to linear ultrasonic parameters, the nonlinear ultrasonic parameter SPC-I appears to be more sensitive to the variations of the internal material structures during both loading and unloading phases. Moreover, the SPC technique has shown to be capable of identifying both the initial damage due to the evolution and nucleation of microcracks at the microscopic scale, and the subsequent damages induced by high overload, resulting in an irreversible degradation of the mechanical properties.*

*Keywords: Concrete; Ultrasonic tests; Nonlinear ultrasonics; Microcracks; Stress-induced damage; Sideband Peak Count (SPC) technique.*

## **1. Introduction**

Concrete structures have widespread use because of many advantages of concrete in building processes. Nevertheless, the safety level of these structures is closely linked to the durability of concrete and can be significantly reduced due to various damage inducing conditions. Stress-induced damage is one of the most common and critical damage, that might result in unexpected catastrophic failures.

Indeed, constitutive microcracks are present in natural rocks and some other materials like concrete due to their relatively low tensile strengths. Excessive loads, inducing stresses above certain thresholds, lead to the propagation, growth, and coalescence of pre-existing microcracks and formation of new microdefects. In case of uniaxial compressive loading, the threshold above which a significant evolution of the internal damage is expected can be as low as 30% of the compressive strength, depending on the features of the concrete and on the eventual presence of additives. Indeed, building codes generally require that allowable stresses in concrete should stay below the above threshold. Overloading of concrete structures may occur due to exceeding the design values from variable loads, and also as the consequence of fires and earthquakes, and are potentially very dangerous since the generated damages often remain hidden. As a result, the structure appears or looks to be in good condition, while its load bearing capacity is significantly reduced, especially when maximum past stresses exceed 65% of the concrete strength [1].

For in-situ monitoring of the past maximum stress level in concrete structures and for early detection of the onset of damage, in recent years new Non-Destructive Testing (NDT) techniques have been developed. These techniques are based on nonlinear ultrasonic methods [2, 3], and they can also use purely acoustoelastic theory – the influence of the applied stress on the acoustic

response of materials [4, 5]. In fact, traditional linear ultrasonic methods generally fail to detect initial constitutive microcracks and load induced micro-defects that, on the contrary, can be detected by the nonlinear ultrasonic techniques: the multiple scattering and the interaction between waves of different frequencies that characterize the nonlinear response of concrete can be effectively exploited for determining the evolution of damage. Moreover, unlike traditional linear ultrasonic approach, nonlinear ultrasonic techniques are more sensitive to the concrete material degradation during its early stage of damage [6]. This is a very appealing feature, bringing clear advantages in view of preventing collapses as well as designing prompt and effective strengthening interventions for structural members.

In particular, the use of classical ultrasonic tests based on the observation of the so-called “linear” interactions between ultrasonic waves and propagation solid media is widespread for quality inspection of concrete structures, since these kind of tests are easy to perform and inexpensive. Most popular monitored parameter is the Ultrasonic Pulse Velocity (UPV), very effective for detecting the presence of large cracks or inhomogeneities. However, UPV is not very sensitive to either distributed microcracking [7], or the stress level [8]. Other linear ultrasonic parameters such as the decrease in the pulse amplitude (attenuation) [9] and the shifts in the peak frequency are more sensitive and reliable parameters compared to UPV for characterizing distributed damage and diffuse cracking in concrete. However, both the attenuation and the peak frequency shift are affected by large scatterers in the experiments, and those experiments generally require more complex setups than the current ones [10].

Acoustoelastic approaches are very effective when the nonlinearity is only due to the influence of preexisting strain on the constitutive response to small perturbations like that is induced by the propagation of ultrasonic waves: this is generally the case for metals. Although the latter effect is exhibited, of course, also by concrete, for strongly inhomogeneous media, like concrete, another nonlinear effect is added, due to secondary effects of the load like the opening and the coalescence of microcracks. Thus, often it is difficult to separate the influences of stress and damage on the ultrasonic velocity [11]. Moreover, since the acoustoelastic variations of the wave velocity are very small and an accurate evaluation of the ultrasonic velocity in concrete is very difficult it has been suggested to consider longitudinal and transversal waves polarized along the loading direction. However, this is not practical for in situ measurements [12]. The Coda Wave Interferometry (CWI) technique (or diffuse ultrasound) can be effective in accurately determining wave velocity variations in heterogeneous media like concrete [13]. Also suitable evolutions of diffuse ultrasound have been studied, like the Magnitude-Squared Coherence (MSC) approach, based on a wave similarity parameter evaluated on the entire waveform [14].

Along with acoustoelastic approaches different other nonlinear ultrasonic methods have been studied in the last decades for monitoring concrete structures. Among these methods, Higher Order Harmonics technique; Nonlinear Wave Modulations Spectroscopy (NWMS) and Nonlinear Resonant Ultrasound Spectroscopy (NRUS) have become popular. The increasing interest towards monitoring concrete damage has led to other techniques for this kind of application, e.g., the Scaling Subtraction Method (SSM) and approaches using surface waves.

All the above methods are based on the principle that materials with internal microcracks exhibit nonlinear effects in their acoustic behavior caused by the opening and closing of microscopic cracks when the ultrasonic waves propagate through the material. Thus, these methods are not only capable of detecting stress-induced damage, but also other kinds of pathologic conditions that could lead to the formation of microcracks like alkali-silica reactions, effects of fire and effects of carbonation.

Indeed, some of the first nonlinear ultrasonic investigations on concrete damage in compression make use of the Higher Order Harmonic generation technique that monitors the ratio of the amplitude of the secondary harmonic to that of the fundamental harmonic [15]. This technique has proven to be effective for detecting compressive load induced damage especially when the ultimate strength is approached, but requires the use of a high power tone burst ultrasonic wave drive device and excellent coupling conditions [16]. Issues like the use of transducers with appropriate frequencies for effective detection of damage, the influence of the water/cement ratio and the influence of the voltage of the signals have been also addressed [17].

Another nonlinear ultrasonic technique, the Nonlinear Wave Modulation Spectroscopy (NWMS) technique, has been employed to quantitatively characterize microcrack induced damage, in particular related to alkali-silica reaction [18]. In NWMS, defects are excited by a relatively high amplitude low frequency wave, in presence of a high frequency probing ultrasonic wave sent through the material; a suitable nonlinear ultrasonic parameter describes the degree of nonlinear interaction between these low and high frequency waves [19].

In [20] the Nonlinear Resonant Ultrasonic Method (NRUS), based on a nonlinearity parameter related to the amplitude-dependent frequency shift of ultrasonic pulses, was used for identifying the effects of cyclic loading and of stress-induced damage in concrete, also with reference to thermal loads. The same method was applied in [21] for investigating the effect of a repetitive prestressing force in concrete members, showing that NRUS is much more sensitive than linear ultrasonic methods that monitor the variations of the ultrasonic velocity.

A nonlinear ultrasonic technique that proved to be very sensitive to diffuse damage and stress-induced damage in concrete is the Scaling Subtraction Method (SSM). It extracts the nonlinear features of wave propagation by subtracting the linear reference signal from the acquired signal

[22]. Moreover, in [23] a methodology was developed for separating contributions of damping modulus and the hysteretic nonlinear response (including effects due to the conditioning) through the application of the SSM; to this aim, concrete samples with different grain/aggregates were examined. However, the application of the SSM requires the excitation by a monochromatic ultrasonic signal of a suitable frequency.

More recently, contactless ultrasonic setups based on the propagation of surface waves have been proposed for characterizing microcrack type damage. Suitable experimental setups aim at quantitatively monitoring the damage by measuring the diffuse backscattered energy [24] or by determining a nonlinear ultrasonic parameter related to the principle of Second Harmonic Generation (SHG) [25]. Also in the case of surface wave tests, the obtained results are very interesting, although the use of ultrasonic devices are more complex than the standard ultrasonic apparatus used for concrete inspection.

In this work, the capability of another, very recent nonlinear ultrasonic method, the Sideband Peak Count (SPC) technique [26], hitherto applied to other materials, is exploited to characterize the stress-induced damage in concrete specimens with coarse-grained aggregates subjected to cyclic compression loading.

The effectiveness of the SPC technique in quantitatively assessing the damage induced by stress during both loading and unloading phases is discussed. The SPC results are compared to linear ultrasonic results and to experimental data obtained by mechanical tests; to this aim, a new nonlinear ultrasonic parameter, the SPC index (SPC-I) is introduced. It shows a good correlation between the nonlinearity induced in concrete and the stress-induced micro-damage. From this investigation a promising capability of the SPC technique emerges in evaluating not only the irreversible damage due to large overloads and leading to a marked degradation of the mechanical properties of the material, but also in detecting the initial damage processes related to low loads but yet capable of determining a microstructural irreversible deterioration.

It is worth mentioning here that the SPC technique has shown not only to be very sensitive to stress-induced damage, but also it appears to be very effective for in-situ monitoring of concrete structures. SPC experiments can be performed using the same ordinary ultrasonic equipment normally used for non-destructive evaluations of concrete structural members. The relative ease of the signal processing needed for SPC makes it a very promising and appealing technique.

The paper is organized as follows.

First, the theoretical framework for nonlinear ultrasonic techniques is presented, and the innovative SPC technique is introduced. Then, the experimental program is described - the tested concrete specimens, the main components of the nonlinear ultrasonic experimental setup and the ultrasonic

signal processing and analysis. The results obtained by the conventional linear ultrasonic technique in terms of UPV are compared with the experimentally obtained elastic moduli from mechanical tests. Moreover, the results obtained from the innovative SPC technique are compared with linear ultrasonic results: this comparison brings up the advantages and the capability of the nonlinear approach.

## **2. Nonlinear ultrasonic techniques**

The traditional linear ultrasonic experimental approach is based on the analysis of linear interaction between the defects present inside materials and the propagating acoustic waves. The material damage can be correlated to variations of the so-called linear ultrasonic parameters - the Time of Flight (TOF) and the amplitude of the traveling ultrasonic waves. In particular, the assessment of the damage is usually related to the variation of the UPV [27, 28], measured as the ratio of the traveled path length (usually, the thickness of the specimen) and the TOF or, more effectively, to the attenuation of the amplitude during propagation [10].

The linear ultrasonic parameters are effective in assessing the damage only in the presence of defects of dimension comparable with the wavelength of the propagating ultrasonic wave, so this approach tends to fail in detection of microcracks, especially in the initial stage of the damage.

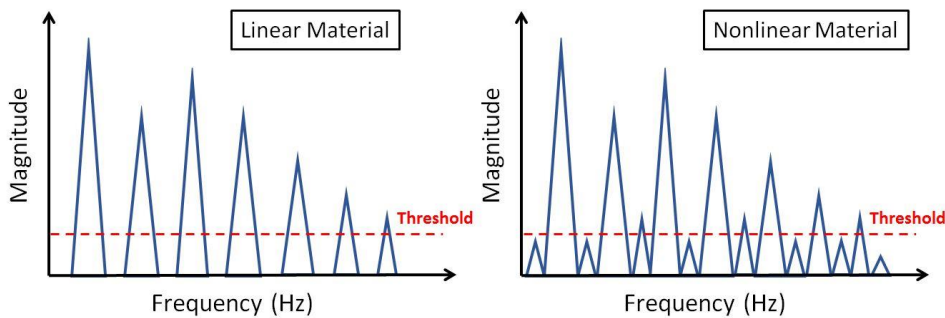
To overcome the above limitation, in recent years some new ultrasonic approaches based on nonlinear parameters have been developed. In general, nonlinear ultrasonic methods are based on the hypothesis of nonlinear elastic behavior of some materials, assuming nonlinear stress–strain relationship. But the nonlinear acoustic response may also be due to the presence of pre-existing micro-cracks and micro-defects and faults in materials like natural rocks, granular materials, and concrete, also called “non-classical” materials [29]. When an ultrasonic wave propagates through a nonlinear “non-classical” material, the internal microcracks continuously opens and closes (known as clapping or breathing phenomena) producing nonlinear response of the material. This nonlinearity can be exploited to detect defects and monitor the evolution of damage. It helps us to prevent macroscopical damage and failures of structural elements.

The most commonly used nonlinear ultrasonic approach is the *Higher Order Harmonic Technique* [15]. It is based on the observation that if an acoustic wave of single frequency is generated in a nonlinear material then multiples of the fundamental frequency of the emitted signal appear in the spectrum of the received signal called higher harmonics. If the frequency of the generated new wave is a fraction (half) of the exciting frequency, then it is called subharmonic wave. No such

higher harmonics or subharmonics are observed for linear materials. An evolution of this phenomenon gave rise to the *Nonlinear Wave Modulations Spectroscopy (NWMS)* method [19]. It requires propagation of two ultrasonic waves with different frequencies in the material. In this case, the nonlinear interactions between the propagating waves in the nonlinear material give rise to secondary waves whose frequencies are linear combinations of the frequencies of the exciting waves.

Higher harmonic, subharmonic, and modulated waves can be effectively used for detecting pre-existing and stress induced damages. In particular, nonlinear ultrasonic methods are very sensitive to small defects like fatigue cracks, fiber debonding and delamination. This is a very interesting feature since the onset of the damage can be assessed in a very early stage.

In particular, a relatively new and promising nonlinear ultrasonic technique is the *Sideband Peak Count (SPC)* technique, proposed first in [30]. SPC is based on the nonlinear interaction between acoustic waves of different frequency in a broad band signal (for example, broad band Lamb wave modes [26]). When the ultrasonic wave is generated by a broadband excitation, then multiple secondary wave modes are produced and, if the material is nonlinear, i.e., damaged for the purposes of the present paper, then the interaction between various wave modes at different frequencies generates multiple sidebands (Fig. 1).



*Fig. 1 Generation of sideband peak due to the wave propagation through a nonlinear (damaged) material*

In particular, the SPC technique is a feature extraction technique aimed at quantifying the degree of nonlinearity in a damaged material from its response to broadband pulse excitations. The level of nonlinearity, related to the damage, is associated with the number of peaks of the sidebands; specifically, the number of peaks above a suitably adjusted threshold value is counted (Fig. 2-a). It is possible to gather information on the degree of damage by comparing the number of peaks of the sidebands as well as major peaks above a threshold value for the initial (undamaged) state and the current (damaged, nonlinear) state, i.e., by studying the SPC difference: the damaged specimen

shows a significantly higher number of frequency-domain peaks especially for low values of the threshold (Fig. 2-b).

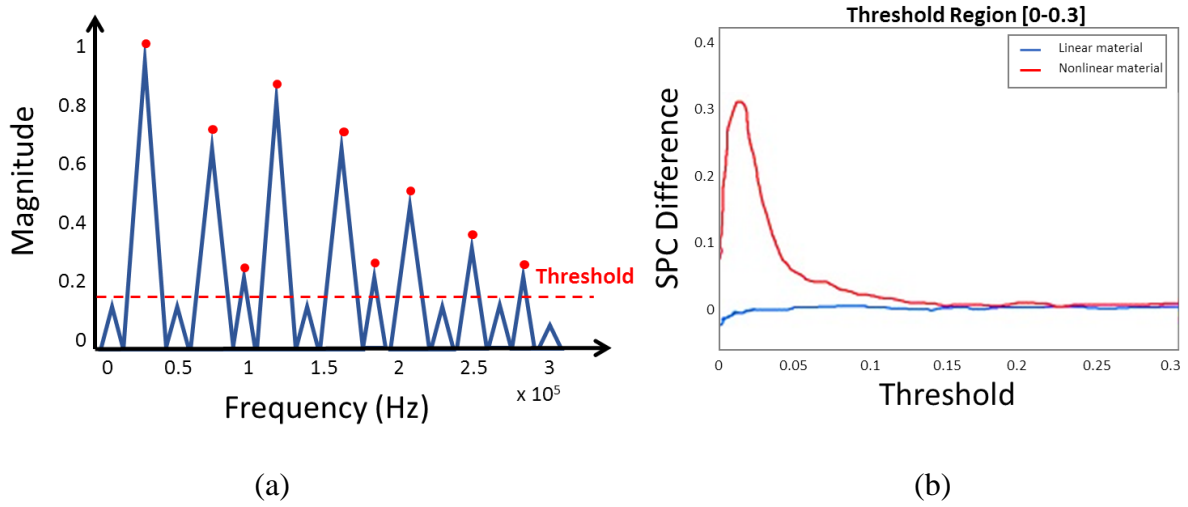


Fig. 2 SPC technique

The SPC results are usually plotted as a variation of the SPC (peak count) with the threshold value (Fig. 3), where the SPC parameter  $SPC(th)$  is defined as the ratio of the number of sideband (modulation) peaks  $N_{peak}(th)$  over a moving threshold (th) to the total peak number  $N_{tot}$  in the considered frequency domain:

$$SPC(th) = \frac{N_{peak}(th)}{N_{tot}} \quad (1)$$

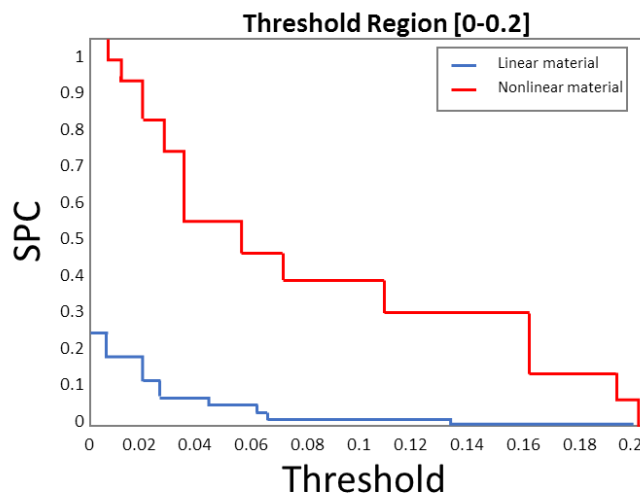


Fig. 3 SPC parameter vs Threshold

SPC technique has been successfully used for monitoring cement composite ageing and concrete curing, as well as for detection of fatigue damage in metals and impact induced damage in composite plates [30–33]. It should be emphasized that, although the data processing needed for SPC is different from that of classical linear ultrasonic methods, the experiments can be performed by standard ultrasonic devices. Thus, SPC appears to be very interesting in view of practical applications, especially in fields where only the use of simple instruments is allowed, such as in the construction industry, for the assessment of existing constructions and for monitoring the effectiveness of strengthening interventions.

### **3. Experimental tests: setup, results and discussion**

The aim of the experimental tests, performed at “*Laboratorio Ufficiale Prove Materiali M. Salvati*” of Polytechnic University of Bari, is to study the capability of the SPC technique in characterizing the stress-induced damage in concrete specimens with coarse-grained aggregates.

To achieve this goal, a nonlinear ultrasonic experiment was carried out on two concrete samples, conducting an ultrasonic through-transmission test in parallel to a cyclic compression load test. The experimental data have been processed for both conventional linear ultrasonic analysis and for obtaining SPC-I (SPC-Index) from nonlinear analysis. Ultrasonic results were also compared with the variations of the elastic moduli, evaluated directly from the mechanical tests, from the strain gauge and loadcell readings, as the compressive load level varied.

#### *3.1 Mechanical properties of concrete specimens*

Cement 32.5 R and coarse-grained aggregates (CG) with maximum size 20 mm were used in the concrete mix design (50% sand, 3% grit, 47% gravel) for fabricating the test specimens. The choice of cement with low compressive strength and of coarse-grained aggregates was aimed at reproducing the features of concretes used in relatively old civil constructions, for which the study of the stress-induced damage has greater relevance.

Three cubic specimens 150 mm x 150 mm x 150 mm were fabricated using mould of this size for determining the cubic compressive strength of the material. Three prismatic specimens of size 150 mm x 150 mm x 450 mm were also fabricated. One of these three prismatic specimens (specimen 1) was subjected to only a compression test until failure to assess the ultimate compressive load for this type of specimens, whereas the other two prismatic specimens were used for the nonlinear ultrasonic tests (indicated in what follows as specimens 2 and 3, respectively).

Cubic and prismatic samples were fabricated and cured in the laboratory according to the standard procedure, ASTM C192. Compression tests were carried out after 28 days of curing, whereas nonlinear ultrasonic tests were carried out after more than 28 days.

The following average values were obtained from the compression tests carried out on the three cubic concrete samples: ultimate load  $F_c=407.85$  kN and the ultimate stress (cubic compression strength)  $f_c =18.15$  MPa. The compression test carried out on the prismatic concrete specimen gave an ultimate load  $F_c=364.73$  kN.

### 3.2 Nonlinear ultrasonic test setup

Uniaxial cyclic compression tests were performed on concrete specimens 2 and 3. The values for the load steps were chosen as a percentage of the ultimate load obtained by the compression test performed on the prismatic specimen (see Section 3.1).

Table 1 shows the number of load steps performed, the corresponding load expressed also in percentage of the ultimate load, and the ID for indicating each load step.

Progressive number of the load step	% of the ultimate load ( $F_c$ )	Load	Load Step ID
1	0%	0 kN	CG_1_0%
2	20%	72.95 kN	CG_2_20%
3	30%	109.42 kN	CG_3_30%
4	20%	72.95 kN	CG_4_20%
5	40%	145.89 kN	CG_5_40%
6	20%	72.95 kN	CG_6_20%
7	50%	182.37 kN	CG_7_50%
8	20%	72.95 kN	CG_8_20%
9	60%	218.84 kN	CG_9_60%
10	20%	72.95 kN	CG_10_20%
11	70%	255.31 kN	CG_11_70%
12	20%	72.95 kN	CG_12_20%
13	80%	291.78 kN	CG_13_80%
14	20%	72.95 kN	CG_14_20%
15	0%	0 kN	CG_15_0%

Table.1 Load steps

In Fig. 4, a schematic representation of the cyclic test conducted on the two concrete specimens in terms of the load levels achieved in the load steps (percentage of the ultimate load  $F_c$ ) is shown. It can be seen that the test strategy consists in reaching 20% of the ultimate load (step 2), and then performing the following cycles: first the load is increased until a maximum value incremented of 10%  $F_c$  with respect to the maximum load reached in the previous cycle, and then the load is decreased to 20%  $F_c$ . The last value has to be considered as a “base” condition, representative of the state of the concrete under normal service load, after each overloading. In real life the overloading

maybe due to wind, earthquake, fire, or can be due to unusually large ocean waves for offshore structures.

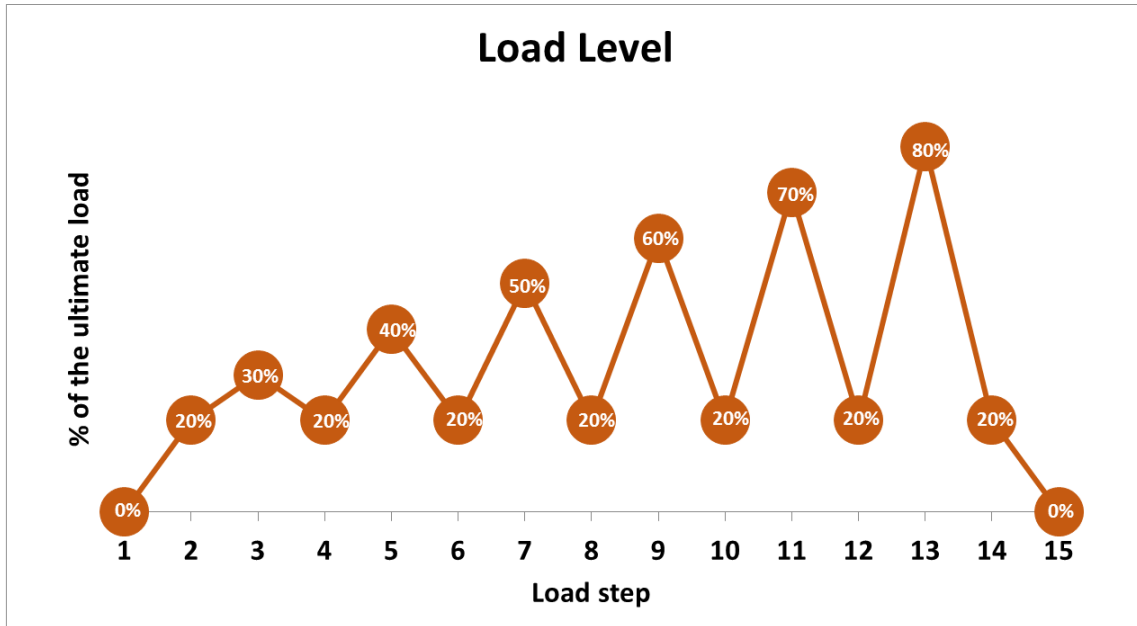


Fig. 4 Load steps applied during acoustoelastic tests

The nonlinear ultrasonic setup is shown in Fig. 5: a concrete specimen was placed between the two bearing plates of a servo hydraulic machine MetroCom (maximum load capacity 5000 kN) applying the cyclic compressive loading.

On two opposite faces of each sample two HBM LY strain gauges were attached by using a two-components methylmetacrylate cold curing glue one parallel and one orthogonal to the axis of the sample, measuring the deformations required for determining the Young’s modulus and the Poisson’s ratio of the concrete for each load step.

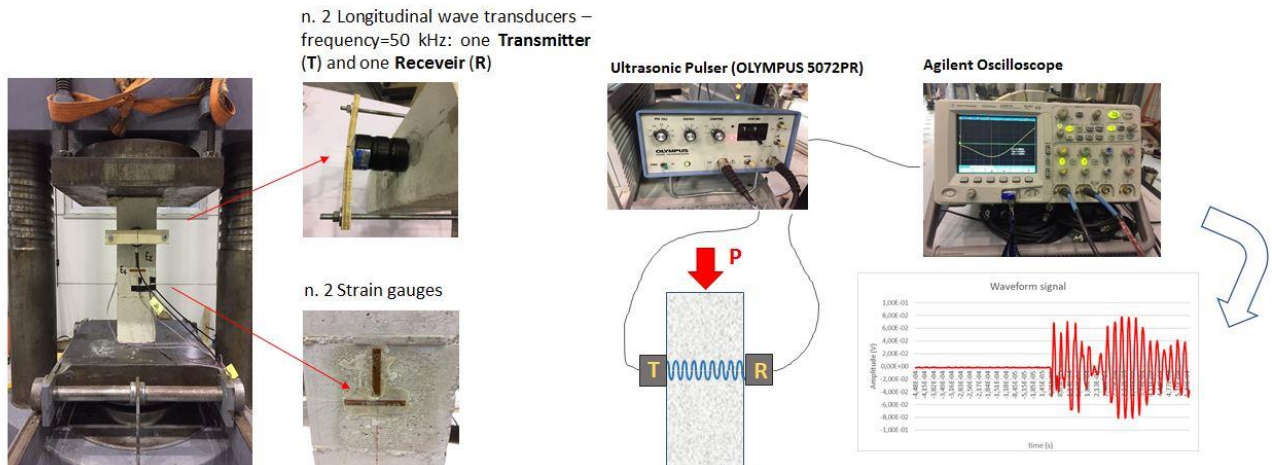


Fig. 5 Acoustoelastic setup

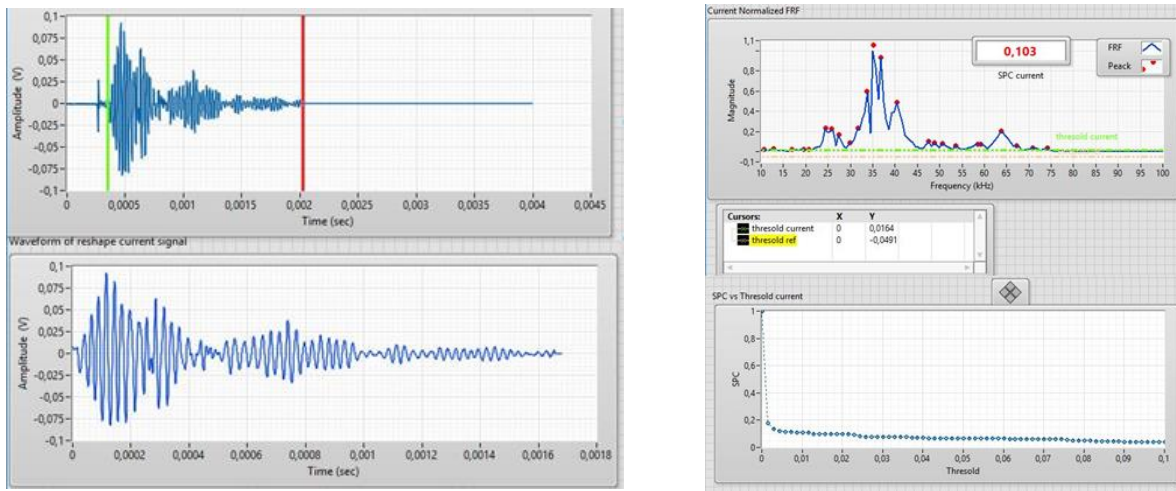
In order to study the dependence of nonlinear acoustic behavior of concrete on the past stress history, ultrasonic contact tests were conducted by the through-transmission method. Two ultrasonic longitudinal Panametrics narrowband piezoelectric transducers with resonance central frequency of 50 kHz were attached to the two opposite faces (the same faces where the strain gauges were attached) of each concrete specimen by a suitable clamp. The petroleum jelly was used as the acoustic couplant. During the entire experiment transducers were permanently fixed to the concrete sample by the clamp; thus, the same pressure on the transducers placed on the specimen surface was guaranteed. Therefore, variations in the signal scattering patterns due to the repositioning of the transducers or due to uneven pressure levels on the transducers are avoided. Thus the observed variations in secondary frequency peaks for SPC evaluations are ascribable only to the load variations.

Ultrasonic signals were generated by an ultrasonic pulse/receiver (OLYMPUS 5072PR). This way, during the execution of cyclic mechanical test, longitudinal ultrasonic waves propagate in the concrete; the ultrasonic signal is acquired during each load step, by a data acquisition unit consisting of a digital oscilloscope (AGILENT DS06014A, 100 MHz, 4 channels). The sampling frequency for recording signals was 1 MHz or  $10^6$  Hz, with a time window of 1 ms: this value, according to Nyquist's theorem is large enough for good accuracy in wave reconstruction.

All acquired signals were subsequently processed to determine the relevant linear acoustic parameter, i.e., the UPV, and the nonlinear acoustic parameter SPC(th) for each load step. The UPV has been evaluated starting from the average of the time of flight (TOF) values, and ignoring the the acoustic path length change because of the compressive loads: indeed, the maximum transverse strain measured by the strain gauges was in the order of  $2.19 \cdot 10^{-4}$ , much smaller than the maximum observed variation of UPV, in the order of about 1%. An ad hoc Labview software was developed in order to determine the nonlinear results: the Fast Fourier Transform (FFT) of the acquired acoustic signal, and the SPC vs threshold graph (Fig. 6).

It should be pointed out that at the end of each load step the testing machine was stopped with the load kept fixed, and both mechanical and ultrasonic measurements were taken after a time suitable for stabilizing the readings.

It should be pointed out that the ultrasonic setup needed for SPC experiments is quite similar to that normally employed for nondestructive inspections of concrete structures: this is an appealing aspect of SPC technique for in-situ monitoring of concrete structures.



**Fig. 6** Graphic interface of the Labview software developed for SPC technique

### 3.3 Linear Ultrasonic results

Figures 7-10 show linear ultrasonic results (UPV) and allow for comparing the variation of UPV with the variation of elastic moduli (Young’s modulus and Poisson’s ratio) for each load step. It is worth mentioning here that the elastic moduli have not been determined from the measured ultrasonic velocity, but derived directly from the measured load and the deformations, as measured by the strain gauges. For example, Fig. 7 shows for specimen 2 the measured values of the UPV of longitudinal waves and of the Young's modulus for each load step, whereas in Fig. 8 the variation of UPV values are compared with the variation of Poisson's ratio. Similar comparisons are presented in Figs. 9 and 10 for specimen 3. Please note that in each figure there are two diagrams. For convenience and easy comparison, the experimental results for increasing load (denoted in one diagram as “Loading” - steps 1, 2, 3, 5, 7, 9, 11 and 13) and decreasing load (denoted in the other diagram as “Unloading” - steps 1, 2, 4, 6, 8, 10, 12, 14 and 15) are presented separately.

For specimen 2 (Figures 7 and 8) it can be seen that UPV undergoes no appreciable variations for low loads (until loading step 10); moreover, no substantial difference appears between the loading steps and the subsequent unloading steps to 20% of the failure load. At loading step 11 however, when the load reaches 70% of the failure load, UPV shows a sudden drop, permanently acquired for further loads and for all subsequent unloading steps, until step 15 (complete unloading). Apart from the first two steps (from step 1, totally unloaded specimen to step 2, loaded to 20% of the failure load), the Young’s modulus remains almost constant until step 10, then at step 11 it shows a sudden drop. Initial variation of Young’s modulus can be justified in this manner - the application of the load stabilizes the material. Then it shows no variation up to 60% of the failure load application. However, at 70% of failure load the material clearly goes through some significant internal change

resulting variations of both UPV and Young's modulus. This change is permanent and hence is not recovered during unloading.

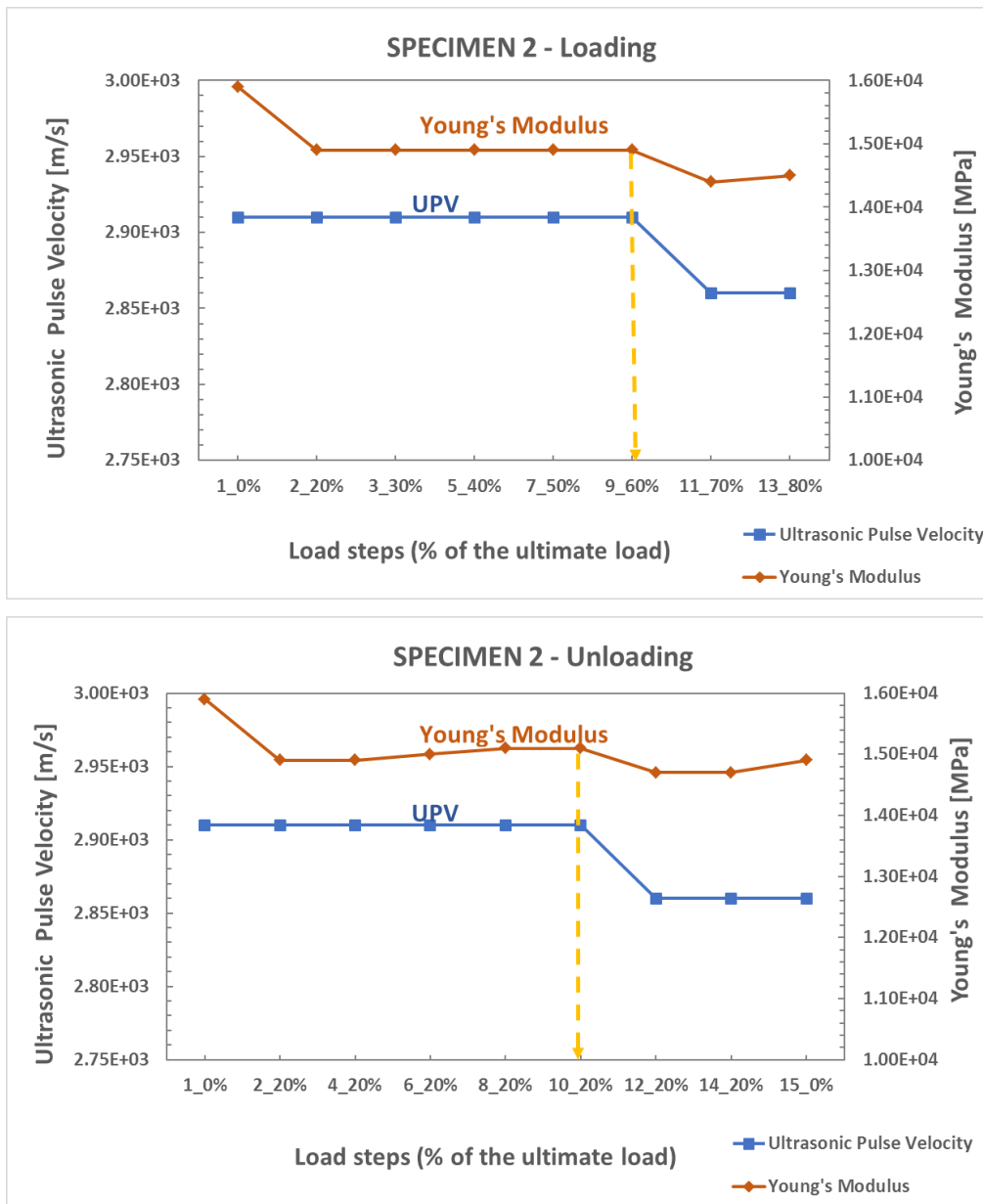


Fig. 7 UPV and Young's Modulus vs load steps (specimen 2)

In Figure 8 the evolution of the Poisson's ratio with load steps is more complicated. For Poisson's ratio also the first application of load appears to induce a stabilizing effect; then with increasing load up to 80% of the failure load, Poisson's ratio remains almost constant. However, during unloading a gradual decrease can be noticed starting from step 10, i.e., after the application of 60% of the failure load (step 9).

The response determined for specimen 3 (Figures 9 and 10) is less clear. Although these curves have some similarities with those curves for specimen 2, they have some significant differences

also. For example, UPV shows an initial adjustment for low loads (until 20%) of the failure load, and then is practically constant until step 10, both for loading and unloading. At step 11 (70% of the failure load) UPV suddenly drops, and in this case at the complete unloading (step 15) the velocity drops further. Here, the Young's modulus shows a slightly increasing trend until step 11. Then a drop occurs; for specimen 3, the decrease of the Young modulus beyond 70% of the failure load is more pronounced than that for specimen 2. Finally, for specimen 3 the Poisson's ratio shows initially a slight decreasing trend and then a slight increasing trend.

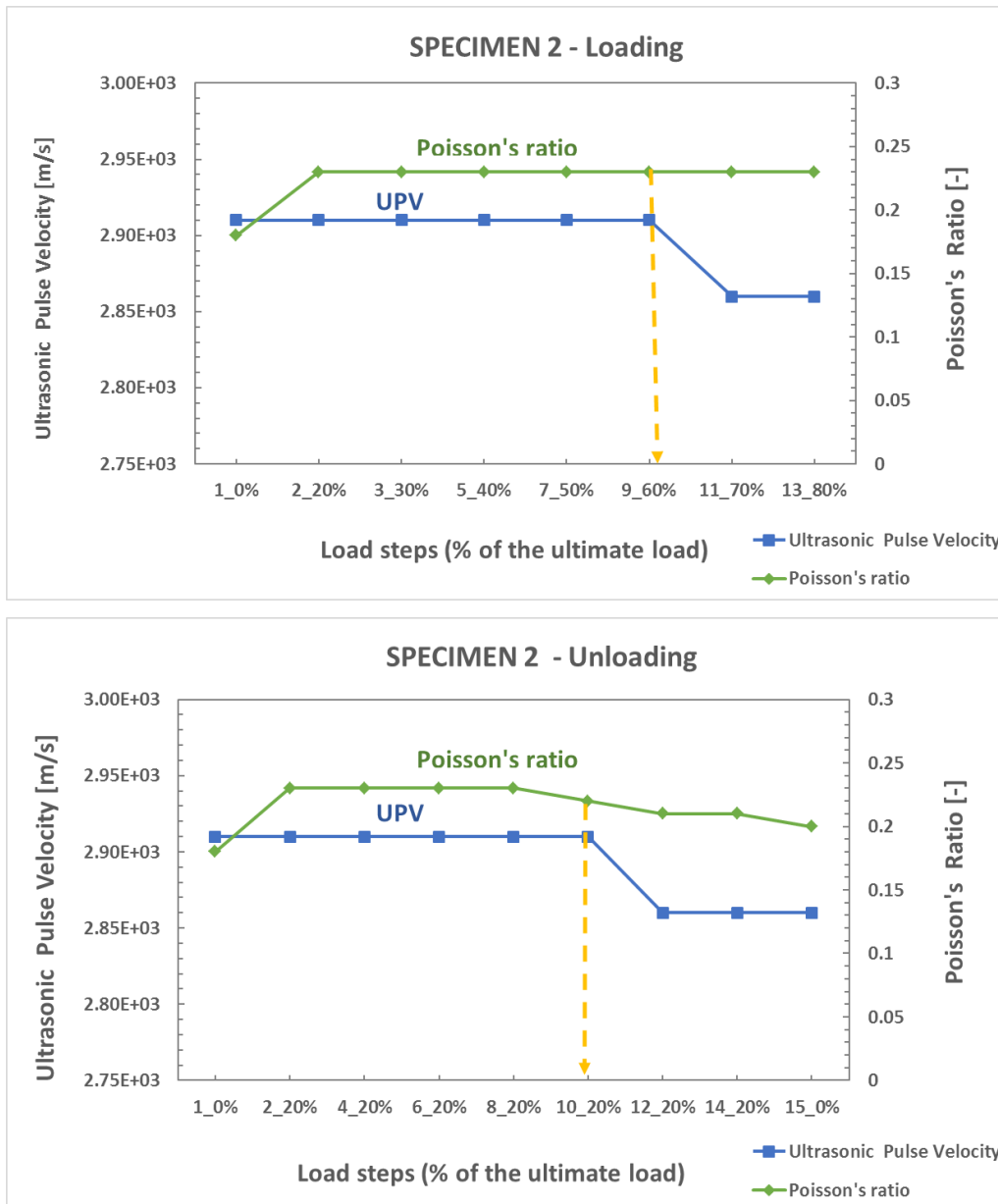


Fig. 8 UPV and Poisson's ratio vs load step (specimen 2)

Although the observed behavior has some differences between the two specimens it shows some similarities as well. For example, the variation of the linear ultrasonic parameter UPV is consistent

with the findings reported in [8]. Popovics et al. [8] also observed a slight increase in velocity at small loads up to about 20% of the ultimate load, followed first by a practically horizontal region at medium range loads up to approximately 70% of failure stress level, and then by a marked decrease in pulse velocity. This was explained as, since small loads do not produce large amount of microcracks but they close under small compressive load resulting in a velocity increase; further increase of the load gives rise to increase in microcrack density but still many of those cracks remain closed under compressive load, and only when microcracking becomes extensive, a velocity drop is observed.

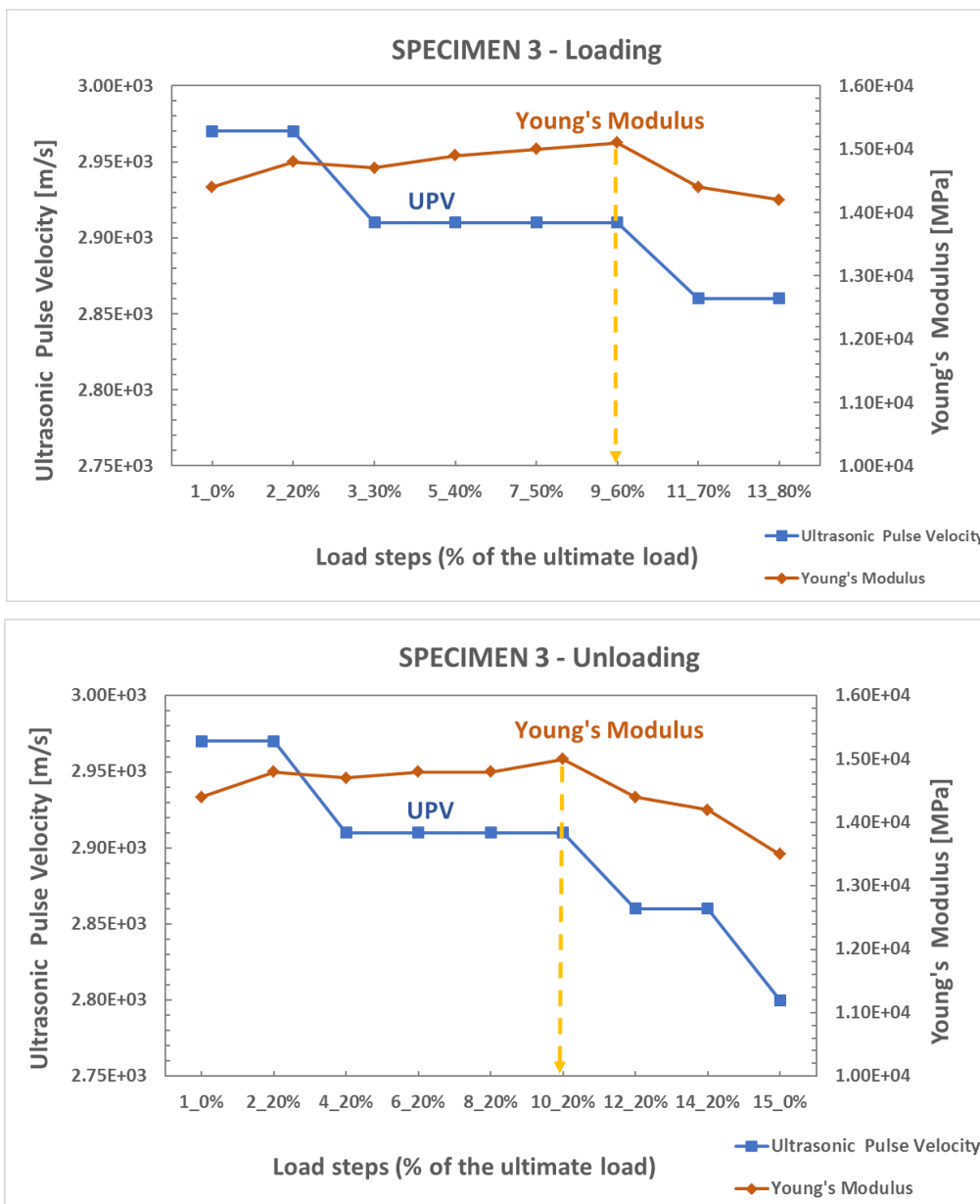


Fig. 9 UPV and Young's Modulus vs load step (specimen 3)

Thus, linear ultrasonic parameter (UPV) and linear elastic modulus (Young’s modulus) are sensitive only to a marked or noticeable damage, like the one taking place in concrete when the threshold of 70% of the failure load is achieved. This load level can be acknowledged as critical for a substantial development and diffusion of microcracks affecting UPV and Young’s modulus. However, these parameters are not very sensitive to the initial development of damage, that certainly occur, especially for old concretes lacking special additives in the manufacturing stage. In the loading range 20-70% of the failure load no indication of damage accumulation in concrete from the linear ultrasonic tests prohibits engineers to take necessary precautionary measure, as reported in [20].

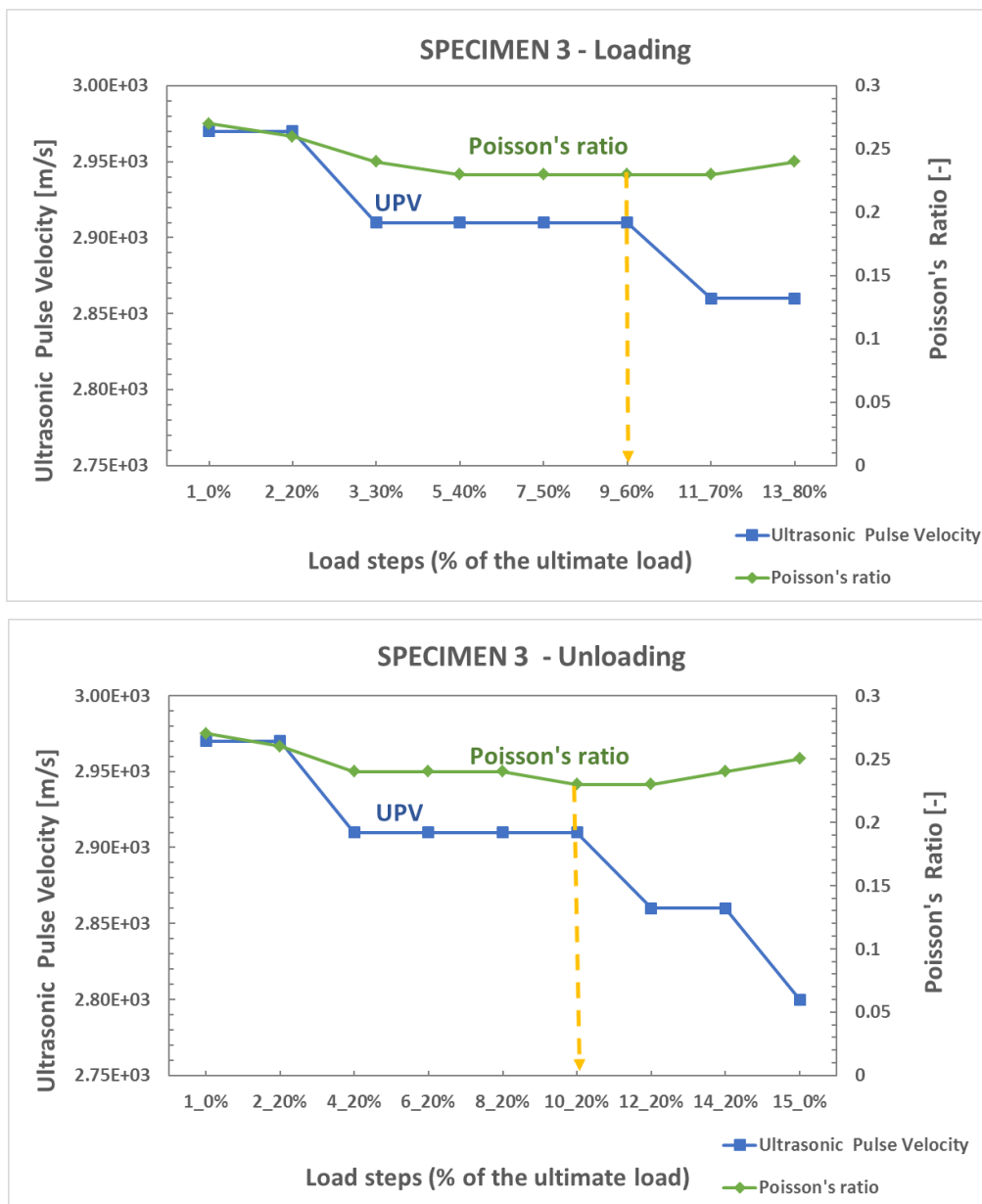


Fig. 10 UPV and Poisson’s ratio vs load step (specimen 3)

It is worth noting that for both specimens the variations of UPV, Young's modulus and Poisson's ratio as the loading steps progress is limited, around only a few percentage points: this confirms the well-known fact that linear ultrasonic and linear elastic parameters are not suitable for in-situ assessment of the past maximum stress level that concrete experienced, since the actual variations can be easily hidden in experimental errors.

### 3.4 Nonlinear Ultrasonic results

Nonlinear ultrasonic results obtained from the acoustoelastic tests are reported here. For the sake of brevity, only the results obtained from specimen 2 are shown. The results obtained from specimen 3 are quite similar, with no appreciable difference.

A first evidence in the nonlinear ultrasonic behavior induced by the performed load steps emerges from the analysis of the FFT of the acquired signals, compared to that of the reference undamaged state (step 1). In particular, Figures 11-14 show the differences between unloaded and loaded specimens due to the stress induced damage for some load steps: step 2 (20% of  $F_c$ ), step 5 (40% of  $F_c$ ), step 11 (70% of  $F_c$ ) and the last step (step 15, corresponding to the complete unloading).

From Fig. 11, one can see that when the FFT of loading state 20%  $F_c$  is compared with that of the reference undamaged state, an increase of the strength of the secondary peaks around the primary peaks occurs. These differences become more pronounced for loading steps 5 (Fig. 12) and 11 (Fig. 13), whereas for loading step 15 (Fig. 14) a marked reduction of the fundamental frequency was also observed. All plots in Figures 11 to 14 are normalized with respect to their peak values.

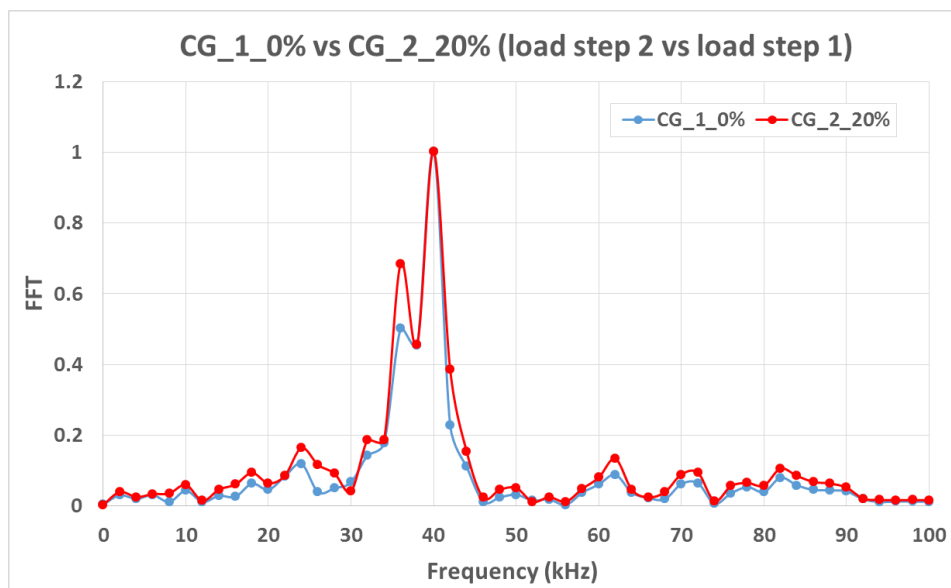
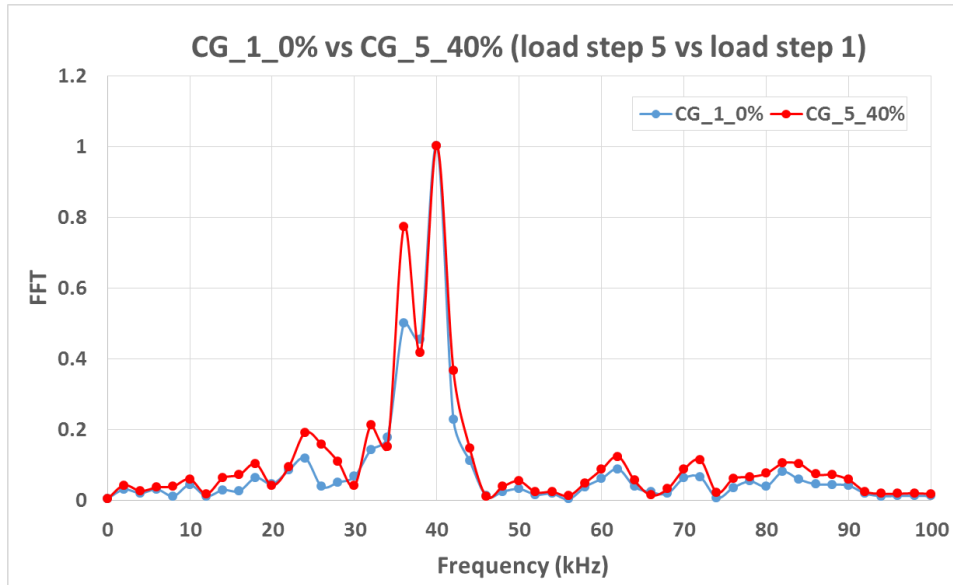
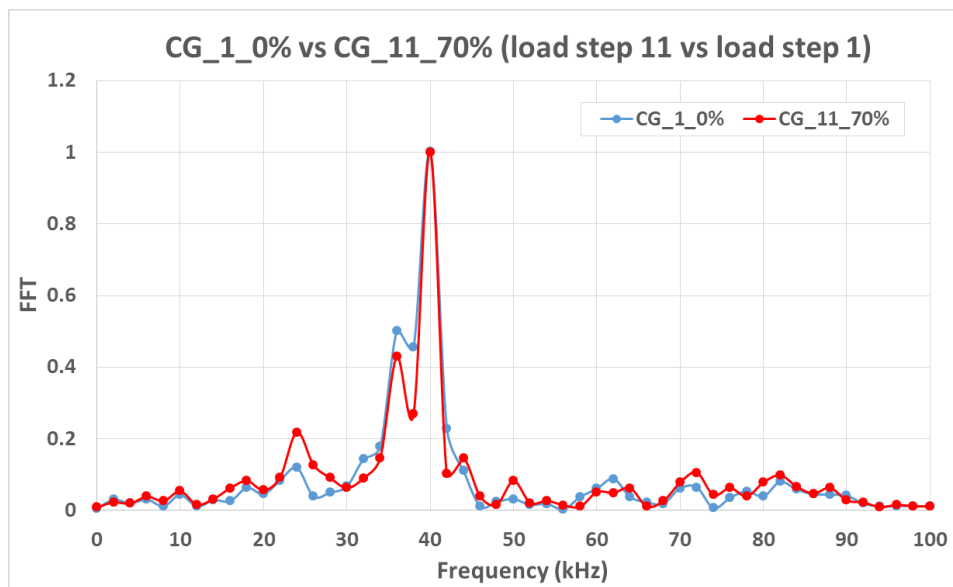


Fig. 11 FFT: comparison of second (20% of  $F_c$ ) and first (undamaged material) loading steps

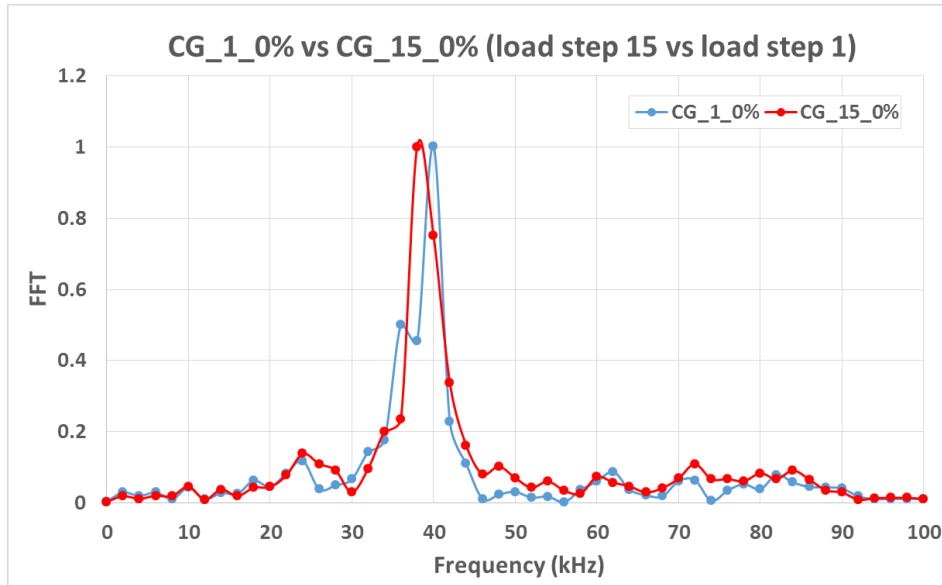


*Fig. 12 FFT: comparison of fifth (40% of  $F_c$ ) and first (undamaged material) loading steps*

Although FFT plots reveal change in nonlinearities in the acoustic response, the change in the damage level are not clearly quantifiable in these plots. A suitable feature extraction technique called SPC technique, for the acquired ultrasonic signals, is needed to quantify the degree of nonlinearity and hence the damage level in the specimen.



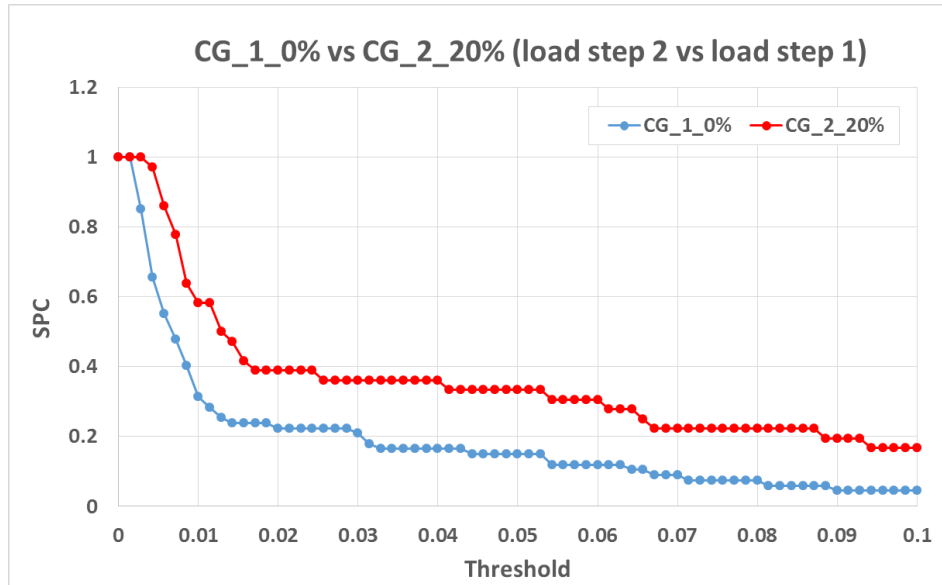
*Fig. 13 FFT: comparison of eleventh (70% of  $F_c$ ) and first (undamaged material) loading steps*



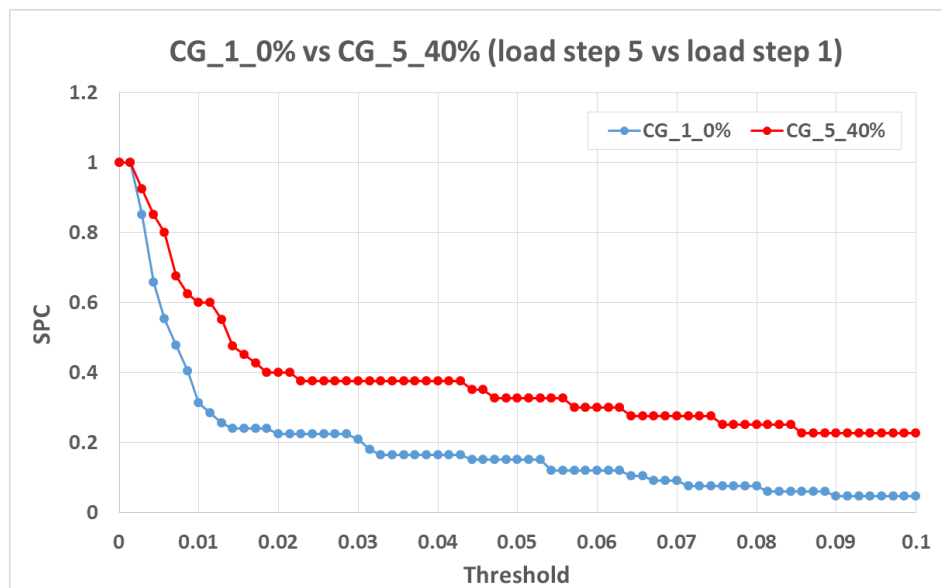
**Fig. 14 FFT: comparison last (0% of  $F_c$ ) and first (undamaged material) loading steps**

In the following it is shown how SPC technique and SPC-Index (SPC-I) can highlight both qualitatively and quantitatively the variations in the nonlinear acoustic behavior of concrete due to the stress induced damage. In particular, as representative examples Figures 15 to 18 show the plots of SPC values (defined in Eq. 1) as a function of the threshold variation. The SPC plots of Figures 15 to 18 correspond to the FFT plots of Figures 11 to 14, respectively. In Figures 15 to 18 SPC curves of four loading steps (2 – 20% of  $F_c$ , 5 – 40% of  $F_c$ , 11 – 70% of  $F_c$  and 15 - after complete unloading) are compared with the SPC curve for the reference undamaged state (step 1).

Although UPV measurement did not show noticeable change for specimen 2 before loading step 11 the SPC curves obtained for loading steps 2 (Fig. 15) and 5 (Fig. 16) show significant change in the SPC plot when compared with the undamaged specimen. It indicates that the degree of material nonlinearity changes in concrete even for low level of loading - 20% of  $F_c$  (loading step 2) and 40% of  $F_c$  (loading step 5). Therefore, even for small loads the evolution of the internal micro-damage in concrete yields to noticeable acoustic nonlinearity. For step 11 (70% of  $F_c$ , see Fig. 16) the SPC curve comes a little closer to the reference SPC curve for the undamaged specimen, while for step 15 (specimen completely unloaded after reaching the maximum load) the SPC curve comes even closer to the SPC curve of the undamaged material.



*Fig. 15 SPC: comparison of second (20% of  $F_c$ ) and first (undamaged material) loading steps*



*Fig. 16 SPC: comparison of fifth (40% of  $F_c$ ) and first step (undamaged material) loading steps*

To investigate if unloading changes the SPC variation, the SPC curve is plotted in Figure 19 at loading step 6, after unloading the specimen from step 5 (40%  $F_c$ ) to 20%  $F_c$ . The SPC variation shows almost no change between Figures 16 and 19. Clearly, the differences between the SPC curves of a loaded specimen and the reference undamaged unloaded specimen indicates irreversible change in the material due to micro-crack generation, since they remain substantially unchanged after unloading. This is very interesting, since it gives the opportunity of detecting past overloading of the structure even after the structure has returned to regular service load condition after being subjected to overloads in the past.

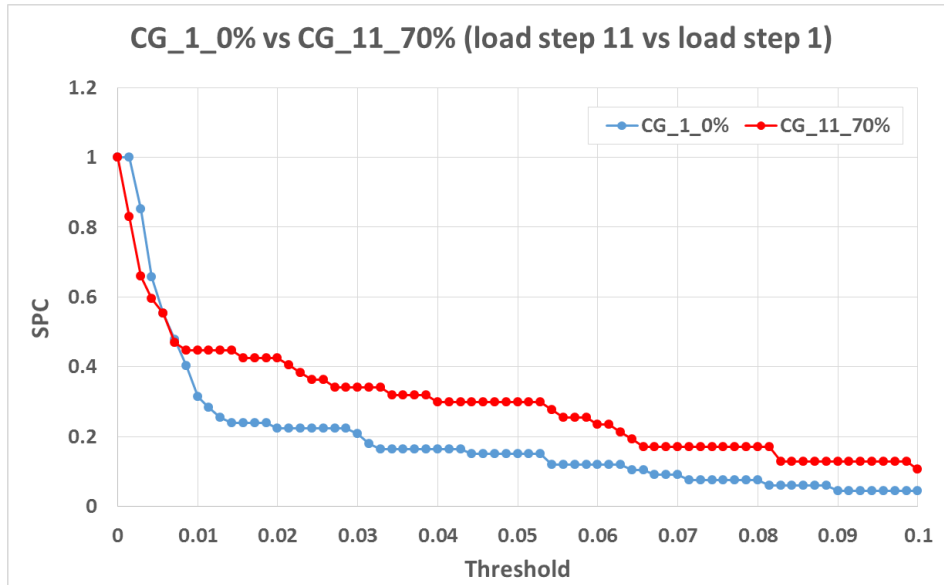


Fig. 17 SPC: comparison of eleventh (70% of  $F_c$ ) and first (undamaged material) loading steps

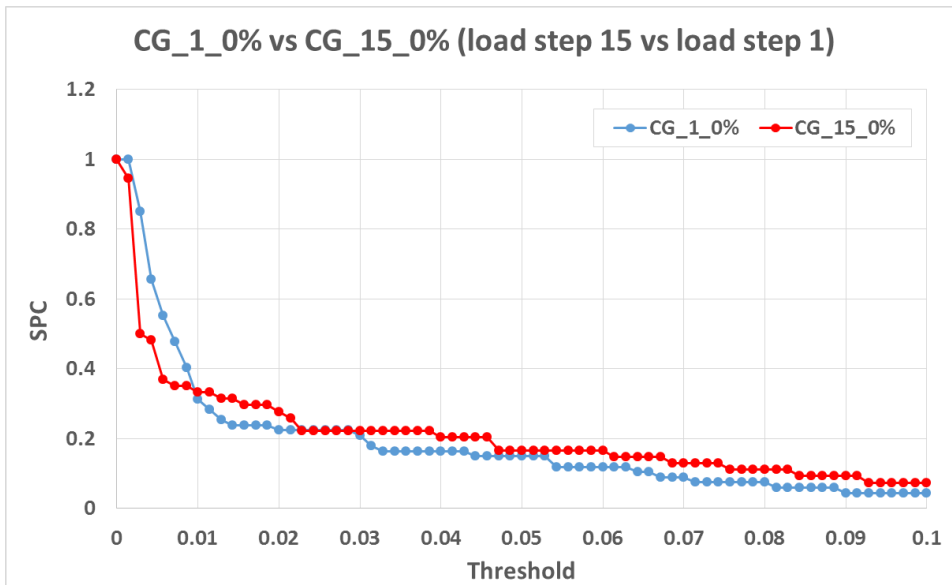
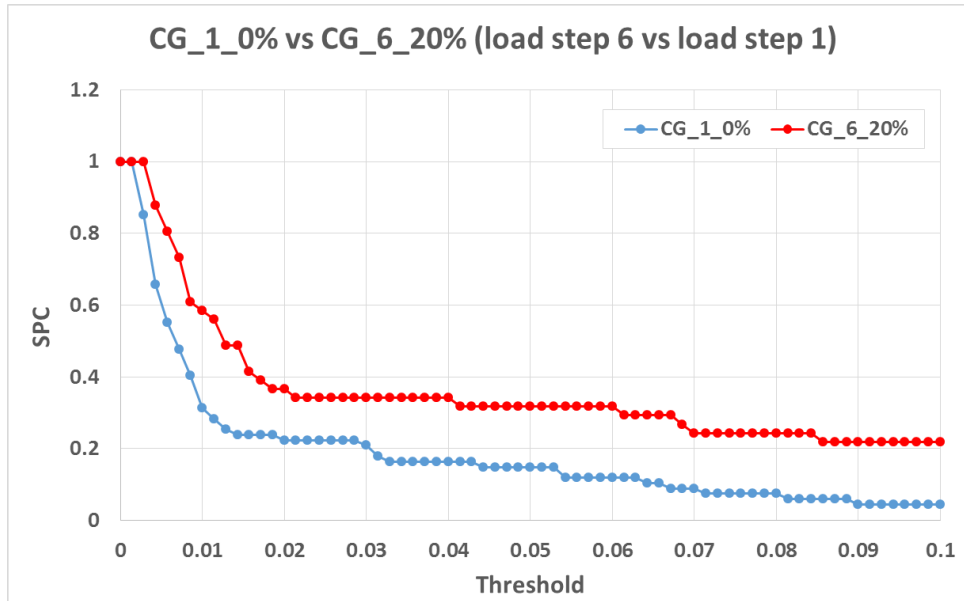


Fig. 18 SPC: comparison of last (0% of  $F_c$ ) and first (undamaged material) loading steps

The above nonlinear ultrasonic evaluations compare the SPC curves obtained for certain load steps (steps 2 to 15) to that of the reference undamaged state (step 1). To render the proposed nonlinear ultrasonic technique even more suitable for applications the SPC index or (SPC-I) introduced by Alnuaimi et al. [32] is used. SPC-I helps us to denote the degree of nonlinearity of a material by a single number instead of a curve. SPC-I is given by the ratio of the sum of the SPC values calculated for all considered threshold values and the total number of threshold values considered:

$$SPC-I = \frac{\sum SPC_i}{N(th)_{tot}} \quad (2)$$



**Fig. 19 SPC: comparison between sixth (unloading from 40% to 20% of  $F_c$ ) and first (undamaged material) loading steps**

In Fig. 20, the SPC index and the UPV are compared as the load varies for specimen 2. The load variation is shown by the dotted line while the two ultrasonic parameter variations are shown by continuous lines. It is clear that the values of the nonlinear parameter SPC-I change noticeably with load variation. Note that the oscillatory nature of loading is not observed in the SPC-I plot. It indicates, as mentioned before, SPC-I measures the damaged state of the material and not the state of stress.

SPC-I shows an increase initially reaching a peak at loading step 5, that can be interpreted as the effect of increasing microcrack density making the material more nonlinear. SPC-I then continuously reduces as the load steps proceed. It may be due to the fact that with further increase of load the micro-cracks coalesce to form macro-cracks. Formation of macro-cracks reduces the micro-crack density and material nonlinearity although the material becomes weaker.

Figure 21 shows the percentage variation of the SPC-I value in addition to its total variation with the loading steps. Notice that the observed variations of the SPC-I are substantial, with an increase of up to 96% (step 5, 40%  $F_c$ ), followed by a remarkable decrease, until reaching only about 11% above the initial value for the completely unloaded specimen (step 15). On the other hand, the linear ultrasonic parameter UPV shows only a drop of about 1.2% at 70% of the compressive failure load (eleventh loading step) in Figure 20.

Therefore, unlike the linear ultrasonic parameter UPV, the nonlinear ultrasonic parameter SPC-I is sensitive to variations of the concrete properties and its micro-structure since the initial applications

of the load. It allows us to detect the irreversible damage process since the beginning of loading, and thus one can closely monitor the stress induced damage in concrete at various stages of loading.

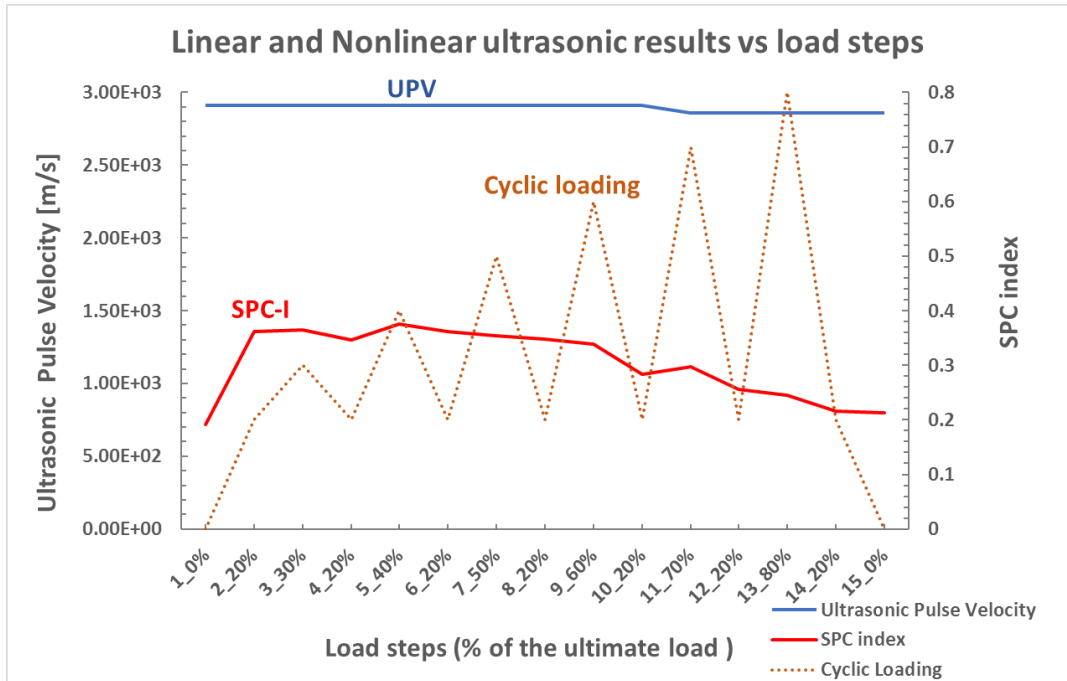


Fig. 20 Linear (UPV) and nonlinear (SPC-I) ultrasonic parameter variations with load steps. Note UPV varies by only 1.2% from load steps 10 to 11 and hardly shows any change for other load steps

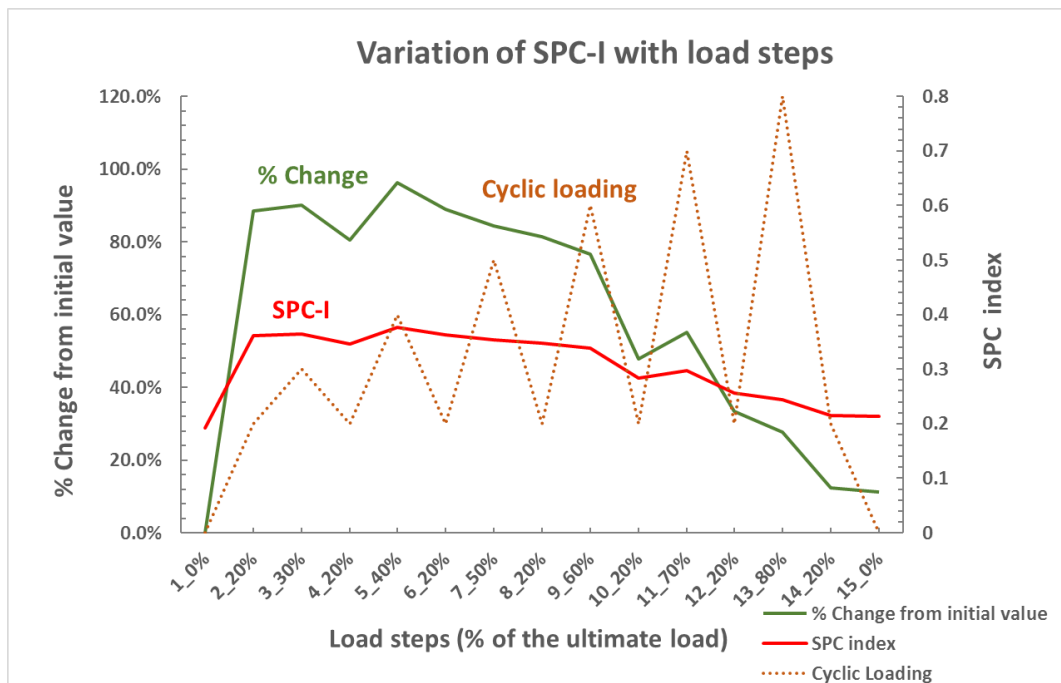


Fig. 21 : Variation of SPC-I with load steps

#### 4. Conclusions

A new experimental technique for the characterization of the stress-induced damage in concrete is proposed, based on the nonlinear ultrasonic Sideband Peak Count (SPC) technique.

The results of nonlinear ultrasonic tests performed on concrete specimens with coarse-grained aggregates under cyclic compression loads indicate that unlike the traditional linear ultrasonic technique that is capable of detecting only the major damage induced by very high overloading, the SPC technique is capable of monitoring the early stage of damage even when the load exceeds the normal service loads by a small amount. In particular, the SPC index or SPC-I, reveals to be very useful for assessing damage in the entire range of the explored loads, whereas linear ultrasonic approaches might detect only very severe stress-induced damage, that is generated as the load approaches its ultimate value.

This investigation is appealing not only in view of applications to the Structural Health Monitoring (SHM) of concrete structures, especially after exceptional events like earthquakes, hurricanes or fires, but also for assessing the working conditions of prestressed concrete structural members, where it is crucial for the sake of structural safety to determine the residual prestress and remaining life after a period of use. Moreover, the sensitivity of the SPC technique to the opening and closing of even small microcracks could be fruitfully studied for experimentally assessing the effectiveness of Autogenous Healing or Self-Healing processes in concrete [34] or for characterizing different types of damage like, e.g., chemical damage, fatigue damage, fire damage, etc..

A remarkable advantage of the proposed technique is that the experiments can be performed using standard ultrasonic equipment routinely used for nondestructive inspections of concrete structures. Signal processing needed for SPC-I calculation does not require complex operations. The above speaks in favor of practical applications of SPC technique for monitoring of real concrete structures. However, to reach this goal, some issues deserves to be further investigated. Indeed, even in the undamaged state secondary peaks are expected in the frequency spectrum due to scattering effects, and it should be assessed if and how SPC values are affected by the repositioning of transducers for different measurements, as it would be in real life. Our laboratory experiments were made with permanently fixed transducers to avoid the effect of this variable. On this matter, the marked variation of the SPC-I due to the application of even low compressive loads suggests that moving the transducer might lower the precision of the test, but cannot cause qualitative changes in the results. Anyway, the influence of repositioning of transducers to the SPC values should be studied if the monitoring system cannot be permanently attached to the structure. However, for new

constructions of critical structures such as nuclear power plants and bridges, sensors can be permanently attached to the structures to achieve maximum sensitivity of the SPC-I technique. The investigated samples had water/cement ratio and aggregate size similar to the concrete used some decades ago, since the focus of this study was monitoring the old structures made of that type of concrete. More experimental investigations should be carried out for studying the effect of different aggregate size, water/cement ratio and curing conditions. The effects of the interaction between macrocracks, often present in real structures, and microcracks due to stress-induced damage on SPC measurements should be also studied.

**Acknowledgments.** The last author was an invited professor in the Department of Civil Engineering Sciences and Architecture of Polytechnic University of Bari. Financial support from the Polytechnic university of Bari towards his visit is gratefully acknowledged.

## REFERENCES

1. Malhotra, V.M., Carino, N.J.: Handbook on nondestructive testing of concrete, second edition. CRC Press (2003)
2. Broda, D., Staszewski, W.J., Martowicz, A., Uhl, T., Silberschmidt, V. V.: Modelling of nonlinear crack-wave interactions for damage detection based on ultrasound - A review, (2014)
3. Payan, C., Garnier, V., Moysan, J.: Potential of nonlinear ultrasonic indicators for nondestructive testing of concrete. *Adv. Civ. Eng.* (2010). <https://doi.org/10.1155/2010/238472>
4. Bompan, K.F., Haach, V.G.: Ultrasonic tests in the evaluation of the stress level in concrete prisms based on the acoustoelasticity. *Constr. Build. Mater.* 162, 740–750 (2018). <https://doi.org/10.1016/j.conbuildmat.2017.11.153>
5. Lillamand, I., Chaix, J.F., Ploix, M.A., Garnier, V.: Acoustoelastic effect in concrete material under uni-axial compressive loading. *NDT E Int.* 43, 655–660 (2010). <https://doi.org/10.1016/j.ndteint.2010.07.001>
6. Antonaci, P., Bruno, C.L.E., Gliozzi, A.S., Scalerandi, M.: Monitoring evolution of compressive damage in concrete with linear and nonlinear ultrasonic methods. *Cem. Concr. Res.* 40, 1106–1113 (2010). <https://doi.org/10.1016/j.cemconres.2010.02.017>
7. Selleck, S.F., Landis, E.N., Peterson, M.L., Shah, S.P., Achenbach, J.D.: Ultrasonic investigation of concrete with distributed damage. *ACI Mater. J.* 95, 27–36 (1998). <https://doi.org/10.14359/349>
8. Popovics, S., Rose, J.L., Popovics, J.S.: The behaviour of ultrasonic pulses in concrete. *Cem. Concr. Res.* 20, 259–270 (1990). [https://doi.org/10.1016/0008-8846\(90\)90079-D](https://doi.org/10.1016/0008-8846(90)90079-D)

9. Shah, A.A., Hirose, S.: Nonlinear Ultrasonic Investigation of Concrete Damaged under Uniaxial Compression Step Loading. *J. Mater. Civ. Eng.* 22, 476–484 (2010). [https://doi.org/10.1061/\(asce\)mt.1943-5533.0000050](https://doi.org/10.1061/(asce)mt.1943-5533.0000050)
10. Yim, H.J., Kwak, H.G., Kim, J.H.: Wave attenuation measurement technique for nondestructive evaluation of concrete. *Nondestruct. Test. Eval.* 27, 81–94 (2012). <https://doi.org/10.1080/10589759.2011.606319>
11. Shokouhi, P., Zoëga, A., Wiggenhauser, H.: Nondestructive investigation of stress-induced damage in concrete. *Adv. Civ. Eng.* 2010, (2010). <https://doi.org/10.1155/2010/740189>
12. Chaix, J.F., Lillamand, I., Ploix, M.A., Garnier, V., Corneloup, G.: Study of acoustoelasticity behavior of concrete material under uniaxial compression. In: *Proceedings - European Conference on Noise Control* (2008)
13. Schurr, D.P., Kim, J.Y., Sabra, K.G., Jacobs, L.J.: Damage detection in concrete using coda wave interferometry. *NDT E Int.* 44, 728–735 (2011). <https://doi.org/10.1016/j.ndteint.2011.07.009>
14. Hafiz, A., Schumacher, T.: Monitoring of Stresses in Concrete Using Ultrasonic Coda Wave Comparison Technique. *J. Nondestruct. Eval.* 37, (2018). <https://doi.org/10.1007/s10921-018-0527-8>
15. Kim, J.-Y., Jacobs, L.J., Qu, J., Littles, J.W.: Experimental characterization of fatigue damage in a nickel-base superalloy using nonlinear ultrasonic waves. *J. Acoust. Soc. Am.* 120, 1266–1273 (2006). <https://doi.org/10.1121/1.2221557>
16. Shah, A.A., Ribakov, Y.: Non-linear ultrasonic evaluation of damaged concrete based on higher order harmonic generation. *Mater. Des.* 30, 4095–4102 (2009). <https://doi.org/10.1016/j.matdes.2009.05.009>
17. Shah, A.A., Ribakov, Y., Zhang, C.: Efficiency and sensitivity of linear and non-linear ultrasonics to identifying micro and macro-scale defects in concrete. *Mater. Des.* 50, 905–916 (2013). <https://doi.org/10.1016/j.matdes.2013.03.079>
18. Chen, X.J., Kim, J.Y., Kurtis, K.E., Qu, J., Shen, C.W., Jacobs, L.J.: Characterization of progressive microcracking in Portland cement mortar using nonlinear ultrasonics. *NDT E Int.* 41, 112–118 (2008). <https://doi.org/10.1016/j.ndteint.2007.08.009>
19. Den Abeele, K.E.A.V., Johnson, P.A., Sutin, A.: Nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage, Part I: Nonlinear wave modulation spectroscopy (NWMS). *Res. Nondestruct. Eval.* 12, 17–30 (2000). <https://doi.org/10.1080/09349840009409646>
20. Park, S.J., Kim, G.J., Kwak, H.G.: Characterization of stress-dependent ultrasonic nonlinearity variation in concrete under cyclic loading using nonlinear resonant ultrasonic method. *Constr. Build. Mater.* 145, 272–282 (2017). <https://doi.org/10.1016/j.conbuildmat.2017.03.201>
21. Kim, G.J., Park, S.J., Kwak, H.G.: Experimental characterization of ultrasonic nonlinearity in concrete under cyclic change of prestressing force using Nonlinear Resonant Ultrasonic Spectroscopy. *Constr. Build. Mater.* 157, 700–707 (2017). <https://doi.org/10.1016/j.conbuildmat.2017.09.050>

22. Antonaci, P., Bruno, C.L.E., Bocca, P.G., Scalerandi, M., Gliozzi, A.S.: Nonlinear ultrasonic evaluation of load effects on discontinuities in concrete. *Cem. Concr. Res.* 40, 340–346 (2010). <https://doi.org/10.1016/j.cemconres.2009.09.014>
23. Scalerandi, M., Bentahar, M., Mechri, C.: Conditioning and elastic nonlinearity in concrete: Separation of damping and phase contributions. *Constr. Build. Mater.* 161, 208–220 (2018). <https://doi.org/10.1016/j.conbuildmat.2017.11.035>
24. Ham, S., Song, H., Oelze, M.L., Popovics, J.S.: A contactless ultrasonic surface wave approach to characterize distributed cracking damage in concrete. *Ultrasonics*. 75, 46–57 (2017). <https://doi.org/10.1016/j.ultras.2016.11.003>
25. Kim, G., Loreto, G., Kim, J.Y., Kurtis, K.E., Wall, J.J., Jacobs, L.J.: In situ nonlinear ultrasonic technique for monitoring microcracking in concrete subjected to creep and cyclic loading. *Ultrasonics*. 88, 64–71 (2018). <https://doi.org/10.1016/j.ultras.2018.03.006>
26. Kundu, T., Eiras, J.N., Li, W., Liu, P., Sohn, H., Payá, J.: Fundamentals of nonlinear acoustical techniques and sideband peak count. In: *Nonlinear Ultrasonic and Vibro-Acoustical Techniques for Nondestructive Evaluation*. pp. 1–88. Springer, Cham (2018)
27. Castellano, A., Foti, P., Fraddosio, A., Galietti, U., Marzano, S., Piccioni, M.D.: Characterization of Material Damage by Ultrasonic Immersion Test. In: *Procedia Engineering* (2015)
28. Castellano, A., Fraddosio, A., Marzano, S., Daniele Piccioni, M.: Some advancements in the ultrasonic evaluation of initial stress states by the analysis of the acoustoelastic effect. In: *Procedia Engineering*. pp. 1519–1526 (2017)
29. Johnson, P.A., Jia, X.: Nonlinear dynamics, granular media and dynamic earthquake triggering. *Nature*. 437, 871–874 (2005). <https://doi.org/10.1038/nature04015>
30. Eiras, J.N., Kundu, T., Bonilla, M., Payá, J.: Nondestructive monitoring of ageing of alkali resistant glass fiber reinforced cement (GRC). *J. Nondestruct. Eval.* 32, 300–314 (2013). <https://doi.org/10.1007/s10921-013-0183-y>
31. Liu, P., Sohn, H., Kundu, T., Yang, S.: Noncontact detection of fatigue cracks by laser nonlinear wave modulation spectroscopy (LNWMS). *NDT E Int.* 66, 106–116 (2014). <https://doi.org/10.1016/j.ndteint.2014.06.002>
32. Alnuaimi, H., Amjad, U., Russo, P., Lopresto, V., Kundu, T.: Monitoring damage in composite plates from crack initiation to macro-crack propagation combining linear and nonlinear ultrasonic techniques. *Struct. Heal. Monit.* 20 (1), 139–150 (2020). <https://doi.org/10.1177/1475921720922922>
33. Alnuaimi, H., Sasmal, S., Amjad, U., Hassani, A., Zhang, L., Kundu, T.: Monitoring concrete curing by linear and nonlinear ultrasonic methods. *ACI Struct. Mater. J.* in press, (2021)
34. Ouarabi, M.A., Antonaci, P., Boubenider, F., Gliozzi, A.S., Scalerandi, M.: Ultrasonic monitoring of the interaction between cement matrix and alkaline silicate solution in self-healing systems. *Materials (Basel)*. 10, (2017). <https://doi.org/10.3390/ma10010046>