Detection of Initiation of Corrosion Induced Damage in Concrete Structures Using Nonlinear Ultrasonic Techniques

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Structural failure due to corrosion of reinforcing steel in concrete structures is quite common. In most cases, corrosion cracks appear on surface at a late stage, thus provide not adequate time for taking any measure. This paper investigates the detection of corrosion damage in reinforced concrete elements by using non-linear ultrasonic techniques. Various linear and nonlinear ultrasonic (LU & NLU) techniques were adopted to identify the most sensitive technique and ultrasonic parameters for corrosion induced damage detection at its early stage. It is observed that the linear techniques are not very effective in detecting corrosion induced damage. Sideband peak count-index (or SPC-I), a relatively new and promising technique, has been found to be an excellent indicator for detection of corrosion induced damage initiation. However, its efficacy for detecting corrosion induced damage has not been reported yet. The present study shows that the SPC-I based NLU technique out-performs (with highest sensitivity) all other NLU techniques for detecting the on-set of corrosion in steel and micro-crack formation in the surrounding material. As the corrosion progresses and crack appears on the surface of the concrete, efficiency of the SPC-I slowly weakens and other technique(s) are found to be quite efficient at that stage.

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I. INTRODUCTION

Corrosion of reinforcement steel is a critical problem which can significantly compromise the performance of reinforced concrete (RC) structural components, especially in the case of bridge, power plant structures and marine structures. When reinforcement steel is corroded due to adverse environment, the corrosion products occupy more volume than that of the un-corroded steel. This expansion results in concrete cover cracking and spalling that further accelerates the rate of corrosion (Angst et al., 2012). If timely corrective measures are not taken then the growth of the corrosion cracks continues (at an accelerated rate) and eventually leads to the structural failure.

Corrosion of steel reinforcement in concrete mainly consists of two stages (Fig. 1): initiation and propagation (Tuutti, 1982). The initiation stage describes the transport of the corrosive agents through the concrete to the steel until conditions are met for corrosion initiation, whereas the propagation stage describes the process of corrosion and accumulation of related damage until a limit state, and thus the end of the service life is reached. Once corrosion initiates, the kinetics may be affected by a number of factors such as pore clogging due to precipitation of corrosion products or other solid phases and self-healing effects in the case of corrosion in cracked zones (Vennesland and Gjorv, 1981), that would both reduce the corrosion rate, or by concrete cracking and spalling that would accelerate the corrosion process. This leads to a non-linear corrosion propagation as schematically shown in Fig. 1. The major problem associated with corrosion induced damage in structure is that it can be observed by visual inspection only at a very advanced stage. At corrosion initiation stage, there is no damage but the volume expansion of the steel takes place, and further corrosion in steel causes the formation of micro-cracks in the surrounding concrete which cannot be detected visually. Presence of visible crack is considered as one of the prime parameters for condition monitoring of lifeline structures like bridges, however the time left from the onset of visual crack to structural failure is very little (Angst, 2018). There are documented cases of
reinforcement corrosion that led to structural collapse (due to loss of steel sectional area) without any outwardly visual signs such as cracks or rust stains (Malumbela et al., 2010, Duffó et al., 2012, Mehta and Monteiro, 2014). It is thus essential to employ the appropriate non-destructive evaluation (NDE) technique to detect the on-set of corrosion process and the stage of corrosion induced internal micro-cracking (inside concrete) which can tremendously help in taking timely measures to ensure structural safety (Robuschi et al., 2021), which the visual maintenance-based techniques are not able to.

![FIG. 1 Structural damage process caused by corrosion (concept taken from Tuutti, 1982)](image)

With this goal, recently various methods have been applied such as electrochemical methods (potential measurement, resistivity measurement, polarization resistance measurement), electromagnetic methods, fiber optical sensing methods, elastic wave methods and infrared thermography methods.

Ultrasonic wave propagation technique is one of the most widely used and popular non-destructive elastic wave-based methods (Yeih and Huang, 1998, Sharma and Mukherjee, 2010, Shafiei et al., 2021). Most of the existing ultrasonic NDE techniques use the linear parameters obtained from ultrasonic measurements (e.g., velocity variation, mode conversion, time of flight (TOF), attenuation coefficients and frequency shift) to detect and monitor the damage progression in concrete structures. However, the technique based on the linear parameters is quite insensitive to
the early stages of damage. The reason being the small damage or micro-crack formation doesn’t enforce significant changes in the linear features extracted from the ultrasonic signal analysis both in time- and frequency-domain (Yang and Chen, 2019). To overcome this, in recent years, various nonlinear ultrasonic techniques have emerged for detection of microscale damage: (1) generation of higher harmonics (Kim et al., 2006; Woodward and Amin, 2008; Korenska et al., 2009; Climent-Llorca et al., 2020), (2) non collinear wave mixing (Ju, 2018), (3) development of intermodulated frequency components (Donskoy et al., 1997; Warnemuende and Wu, 2004; Chen et al., 2008; Liu et al., 2015; Miró et al., 2021), (4) shift of resonance frequencies (Payan et al., 2007; Chen et al., 2010; Eiras et al., 2014; Genovés et al., 2015), (5) scaling subtraction method (Scalerandi et al., 2008; Antonaci et al., 2010; Antonaci et al., 2013), (6) relative velocity variation using coda wave analysis (Payan et al., 2010; Schurr et al., 2011). However, very few studies in concrete corrosion monitoring employing non-linear ultrasonic features are available in the literature (Donskoy et al., 1997; Woodward and Amin, 2008; Korenska et al., 2009; Antonaci et al., 2013; Climent-Llorca et al., 2020; Miró et al., 2021) and extensive research towards identifying the suitable NDE technique is necessary for the timely action based on early warning.

The technique based on the generation of higher order harmonics is difficult to apply without having a proper nonlinear ultrasonic test set-up i.e., a high power ultrasonic wave drive device and appropriate coupling conditions (Shah and Ribakov, 2009). Since this technique depends mainly on the amplitudes of higher harmonics, it is important that the higher harmonic amplitudes must be accurately extracted to get reliable results. Otherwise, it will end up with giving erroneous result if the higher harmonic amplitude is much lower than the fundamental one (Mostavi et al., 2017).

Further, significant attenuation, due to the presence of inherent heterogeneity (individual constituents such as cement paste, aggregates, pores), imposes major challenge in concrete structures in terms of very high exciting power requirement, which is difficult to achieve with the appropriate
spectrum quality (Korenska et al., 2009). As a consequence, it is difficult to detect microstructural
damage from the received signal in which presence of noise hinders the higher harmonic amplitude.
Overcoming the difficulties with the higher harmonic generation, the technique involving
development of intermodulated frequency components does not require high power signal.
Modulation will be developed when two input signals, (i) a low frequency pump signal and (ii) a high
frequency probe signal are used. Although it has advantages over the higher harmonic technique and
has been adopted in detecting corrosion-induced damages, it still experiences difficulties such as,
finding suitable input frequencies, which can satisfy the required binding criteria (Liu et al., 2015) and
using of low frequency excitation that results in reduced accuracy in terms of localisation (Korenska
et al., 2009). To overcome the above mentioned issues with the nonlinear ultrasonic analysis in
frequency domain, scaling subtraction method (SSM) that captures nonlinear parameter from the
temporal signal was successfully applied for corrosion induced micro-cracking and found to be easy
to implement (Antonaci et al., 2013). However, it also requires a high exciting power and the results
are found to be highly dependent on the input-output excitation scenario i.e., the position of
transducers (Porcu et al., 2017).

The presence of inherent heterogeneity (complex internal structure with distinct phases) which
in turn results in significant attenuation, also limits the applicability of widely used, well-developed
nonlinear ultrasonic methods. As briefed above, the most investigated nonlinear ultrasonic
techniques for detecting steel corrosion in RC demands for pure, accurate and high input power. It
is difficult to achieve in bulky, heterogeneous medium like concrete. Therefore, current challenge is
to identify the suitable technique to monitor corrosion-induced damage in RC structures. This is
addressed in the present study by evaluating the nonlinearity from the energy distribution at the
sidebands and the sideband peak count (SPC) (Chen et al., 2008, Eiras et al., 2013; Liu et al., 2014;
Kundu et al., 2019; Kundu 2019; Alnuaimi et al., 2021(a); Alnuaimi et al., 2021(b)). These techniques
have not yet been explored for this purpose. The underlying concept for these techniques is that in a nonlinear medium, propagating elastic waves develop more number of sideband peaks with the energy being re-distributed in the sidebands (Kundu et al., 2019).

With the aim of ascertaining the potential application of SPC and energy distribution technique for early detection of cracks induced by corrosion, ultrasonic parameters are evaluated using these techniques and further compared with those resulting from conventional nonlinear higher harmonic measurement. The primary contributions of the present investigation is, (a) to analyze the effects of damage induced by corrosion on the linear and nonlinear ultrasonic parameters; (b) to identify the suitable measurement protocol for the nonlinear ultrasonic measurements for corrosion-induced concrete damage; (c) to bring out the promising ultrasonic technique for identifying the early stage of corrosion-induced damage in RC structures. In Section 2 experimental procedure followed in the present study is described. Results are presented in section 3 demonstrating the sensitivity of nonlinear ultrasonic parameters. Finally, major conclusions derived from the present work are highlighted in section 4.

II. EXPERIMENTAL INVESTIGATIONS

Reinforced concrete prism specimens of size 100 × 100 × 500 mm were cast in steel molds, containing a single reinforcement steel bar (diameter 16 mm), located approximately in the centre of the specimen, leaving an exposed steel area of 240 cm² (approximately). Before placing the steel bar into the empty mold, the steel surface was cleaned from the native corrosion products. The concrete specimens were compacted mechanically, finished, and left in the molds over 24 h. After demolding, the specimens were cured in water for 28 days. Concrete mix constituents include Ordinary Portland Cement (OPC) of grade 53, fine aggregate (FA), coarse aggregate (CA) (of 10 mm and 20 mm size) and water; the mix proportions by weight of cement, FA and CA were 1:2.25:2.35, with a water-to-cement ratio of 0.5. Superplasticizer was added (100 ml per 50 kg of cement).
A. Accelerated corrosion test set-up

The accelerated corrosion test was performed by applying an electric field between the reinforcement bar (anode) and an external cathode, consisting of a steel plate. The test, which lasted for 14 days, was run by maintaining a constant voltage of 10 V (volt) using a power supply unit. During the tests, the bottom of the specimen was kept over a steel plate, in contact with water containing 3.5% NaCl solution and the height of the contact between water and specimen was 66 mm, just above the reinforcement bar level, in order to maintain an adequate level of electric conductivity for the material. (see Fig. 2). Every day, damage (appearance of first crack and crack propagation) was visually inspected and continuous current measurements were also performed using the multi-meter to record on the current flow in the corroding system during the entire corrosion test and to further correlate the same with the ultrasonic measurements as damage progresses. Evolution of crack was inspected by measuring the width of crack using Hensoldt Wetzlar made pocket microscope model no. 75234 (40x magnification). Due to the adopted corrosion test set-up and specimen geometry, the cracks due to steel corrosion appeared only at the end, on lateral and bottom surfaces of the specimen, not on the top surface.
B. Ultrasonic measurement set-up

The measurement protocol for the ultrasonic testing is shown in Fig. 3. Measurements were conducted using a Waveform generator (Keysight33500B) with maximum operating voltage range of 10V (peak to peak, denoted as pp), two channel isolated amplifier (Keysight 33502A), two 23 mm diameter ultrasonic transducers (PA956 manufactured by Precision Acoustics Ltd.), a digital oscilloscope (Keysight InfiniiVision DSOX4024A) and personal computer with software installed. 5-cycle Hanning type tone burst signal of 10 V (peak to peak, before amplification) amplitude with varying excitation frequencies of 25, 50 and 75 kHz was first generated and then, it was sent to the amplifier that amplifies the signal amplitude five times and fed into the specimen through the transmitting transducer. The ultrasonic signal received at the receiver location was captured and visualized using the digital oscilloscope. The input signals before and after amplification were also visualized in the oscilloscope. Finally, the oscilloscope was connected to a computer from where waveform generator was controlled and digitized signals were acquired and stored. The NLU measurements were conducted for both direct transmission mode and indirect/surface transmission mode. Fig. 4 shows a layout of the reinforced concrete specimen with the positions of the ultrasonic transducers and also, it provides the information indicating which transducer acts as a transmitter and as a receiver for different transmission modes considered. The transducers were placed on the specimen using grease as a coupling agent. Measurements were taken at an interval of 24 hours (daily at the same time), starting from day 0 (just before the start of the accelerated corrosion test) until the end of the test.
FIG. 3 Measurement protocol used for determining damage sensitive ultrasonic parameters (a)
Schematic diagram of ultrasonic measurement set-up, (b) Ultrasonic measurement set-up

FIG. 4 Positions of the transducers. T: Transmitter. R: receiver. (A1, A2, A3, A4, A5, A6 sensor arrangement represents T1-R1, T2-R2, T3-R3, T3-R4, T4-R5-R4, and T4-R3)

A time window of 2.5 ms was used for acquisition of the waveforms. While performing the frequency analysis, the frequency spectrum of the windowed signal was obtained using the Fast Fourier Transform method. Then, the amplitude of the fundamental frequency was determined for amplitude attenuation calculation.
III. RESULTS AND DISCUSSIONS

A. Corrosion induced cracking-Visual inspection

Amount of current required to maintain the constant potential of 10 V between two electrodes of the corroding system is shown in Fig. 5. Critical points (A to E) are noted by correlating the current flow values with the observed crack evolution during the test. Fig. 6 presents the images corresponding to the evolution of the crack appeared on the side face (longitudinal) of the specimen. The figure also includes the measured values of the crack width. The current versus time plot shows almost a steady low rate of increase in the current with minimal fluctuations till the 6th day, apart from a minor spike observed on day 4 (marked as ‘B’). After that a rapid jump in the current value is noticed that coincides with the first cracking (maximum crack width = 0.14 mm) on the specimen surface noted visually and shown in Fig. 6 (a). The second jump in the current value was observed on the 9th day which may be due to the generation of new cracks or the propagation of pre-existed cracks. This is also visually noticed that the crack propagated more and the maximum width of the crack is found to be about 0.24 mm (Fig. 6 (b)). The test is terminated when the maximum crack width reached 0.3 mm and fully developed longitudinal crack is observed with an abrupt increase in the current flow. It is also noticed from Fig. 6 (b) and (c) that as crack forms and propagates further, corrosion products fill up the open cracks.

FIG. 5 Typical variation of current flow in the specimen (under same voltage) during the corrosion experiment
FIG. 6 (a) Photo taken after the end of corrosion - cracking on one lateral surface; (b) – (d)
Images showing progression of maximum size of crack at zoomed portion in (a)
B. Analysis of spectral sideband for corrosion damage detection

When a wave of single frequency interacts with contact-type cracks/interface, owing to the effects of reflection, scattering from the interface etc., wave distortion takes place. Due to self-modulation of the contact stiffness variation, waveform distorts and it results in the progressive transition of a harmonic wave into saw tooth- or N-type waves (see Fig. 7(a)). As a result, new waves of many other frequencies can be generated in the material. In a heterogeneous material like reinforced concrete, when an ultrasonic wave approaches a crack, it causes the crack surface to open and close alternately, thus allowing the compressive part of the wave to pass through while the tensile part of the wave gets scattered back to concrete or steel medium. This results in “breathing crack,” which is due to the “clapping” behaviour at the interface as given in Fig. 7(b).

During corrosion process, the wave propagation path gets even more complicated due to effects of multiple scattering from newly formed interfaces (rust formation, crack initiation at the steel-concrete interface) which results in additional peaks generation with the distribution of energy to sidebands in the output spectrum, as illustrated in Fig. 7(c). Potential application of sideband energy and number of peak counts for early detection of cracks induced by corrosion is investigated in the present study.
FIG. 7 (a) Single frequency in reinforced concrete medium; (b) wave-interface (inclusion/defect) interactions in concrete; (b) Output spectrum showing additional peaks and sideband generation

C. Nonlinear ultrasonic parameters

As mentioned in Section 2, in order to accelerate the corrosion process, constant potential of 10 V was maintained and the specimen was kept in the electrolytic solution (3.5% sodium chloride (NaCl) by the weight of the water). It is important to note that due to the presence of reinforcement at the centre and the concrete portion below the reinforcement being submerged in electrolytic solution during the corrosion process, cracks didn’t initiate on the top surface. Cracks were observed only on the specimen’s bottom surface, lateral surface and surrounding the rod. Hence, there is no significant change in the measured ultrasonic signature using the sensors arrangements A3, A4, A5 and A6 where the sensors were placed above the reinforcement for direct measurement in transverse direction. This is due to the fact that micro-cracking that initiates (and propagates further) far away from the transmission path (as in the case of sensor arrangements A3, A4, A5 and A6) may go undetected and hinders the sensitivity. That was the phenomena exactly observed visually too, i.e. cracks were initiated not on the mid surface till the end of test. Hence, the ultrasonic signals measured using the sensor arrangements in longitudinal direction, A1 (indirect measurement) and A2 (direct measurement) are analyzed and the results are presented below. It should be noted that signals received for 50 and 75 kHz excitation frequencies are found to contain more noise with high attenuation. Hence, the nonlinear ultrasonic parameters are obtained from the 25 kHz excitation frequency and discussed below.

For performing the frequency analysis, the frequency spectrum of the received signal is obtained using the Fast Fourier Transform method. Figs. 7 and 8 show the time domain responses and their frequency spectra corresponding to the start of the test and on the critical days during the corrosion testing. It should be noted from Figs. 8 and 9 that that signals received for 50 and 75 kHz
excitation frequencies are found to contain several frequency peaks even in Stage A (before start of test) that may be due to the noise in the signal and interactions. It is also noticed that for A2 sensor arrangement with the transmitting and receiving transducers separated by significantly larger distances, higher (50 and 75 kHz) excitation frequencies are significantly more attenuated than the lower (25 kHz) excitation frequency. Hence, the nonlinear ultrasonic parameters are obtained from the 25 kHz excitation frequency and discussed below.
FIG. 7 8 Ultrasonic signals received on critical days for A1 sensor arrangement (a) Time-domain signal and (b) frequency spectrum (A and E are two limit stages of corrosion as depicted in Fig. 6 5) for different excitation frequencies: (i) 25 kHz; (ii) 50 kHz; (iii) 75 kHz.
Nonlinear parameters based on the energy distribution at the sidebands and SPC, are evaluated from the frequency spectra to monitor corrosion-induced damage progression. The sensitivity of the applied techniques for crack detection is then shown through a comparison with results from a
conventional higher harmonics generation method and linear time of flight, attenuation measurements.

1. Sideband energy distribution

As nonlinearity increases, sideband energy grows in the frequency spectrum. Nonlinearity parameter, D based on the energies contained in all of the spectral bands generated by the interaction ($W_{NL}$), at the low ($W_{f1}$) and high ($W_{f2}$) input frequencies proposed by Chen et al., (2008) is as follows:

$$D = \frac{W_{NL}}{W_{f1} \times W_{f2}}$$

Nonlinearity parameter obtained from the above expression has been reported to provide satisfactory results in nonlinear wave modulation technique in which the medium is excited with low frequency ($f_1$) vibration in addition to the high frequency ($f_2$) probing ultrasonic wave to induce their nonlinear motion (Van Den Abeele et al., 2000; Payan et al., 2010).

For single excitation frequency, similar approach is adopted in the present work and the nonlinear parameter is defined as follows:

$$\alpha = \frac{W_{NL}}{W_f}$$

where $W_{NL}$, $W_f$ represent the energy contained in the sidebands and at excitation frequency respectively. Frequency band that contain more than 80% (90% considered in the present study) of the total energy of the entire spectra is the spectral band of concern (including side and main band). If the peak amplitude is denoted by ‘A’ then it is assumed that the main band starts at a frequency for which the amplitude value is reduced to 0.2 times and the centre of main band is at the excitation frequency. Thus, side band length is defined from starting point of the considered spectral band to the starting point of the main band.
Frequency band between 0-50 kHz is found to contain more than 90% of the total energy of the entire spectra and this is the main spectral band of concern. Redistribution of energy among sidebands (0-20 kHz and 30-50 kHz) is computed from frequency ranges on either side of the fundamental frequency (20-30 kHz). Fig. 9 10 shows the measured nonlinearity of specimen in terms of measured change in $\alpha$ (i.e. normalization by the $\alpha$ value on day 0) as corrosion induced damage progresses. From Fig. 9 10, it can be seen that, no clear trend exists with change in $\alpha$ at the initial period. However, for A2 sensor arrangement the change in nonlinear parameter $\alpha$ starts to have a sudden increase from day 5 and it reaches its peak value on day 7, when cracks on the lateral surface appear. Similarly, for A1 sensor arrangement $\alpha$ reaches its peak value on day 6, one day before the visible crack’s appearance. This can be interpreted as increase in nonlinearity due to cracking resulting in distribution of energy to the sidebands in frequency spectra; thereby contributing more to the sidebands. However, here the significant change in nonlinearity is observed at a later stage of micro-cracking induced due to corrosion. It is observed just before the occurrence of the clearly visible surface crack. It is also important to note here that there is a decrease in change in nonlinearity parameter after day 7 (day 6 for A1), discussion of which is provided later in this paper.

FIG. 9 10 Change in nonlinear parameter ($\alpha$) in sideband energy
(A1 and A2 are measurement protocol described in FIG. 4)
2. Sideband peak count

SPC technique calculates the number of peaks that are generated in addition to the excitation frequency peaks (Kundu et al., 2019). In undamaged stage, peaks appear nearer to the input excitation frequency in the frequency spectra, whereas, in damaged stage, more weak peaks start to appear in the neighborhood of the input frequency. The ultrasonic wave interacts with the material nonlinearity, cracks or any other anomalies and gets scattered and modulated which results in these additional sideband peaks. In the present work, the SPC technique is adopted to monitor corrosion-induced cracking—from crack nucleation to macro-crack formation and propagation. SPC technique has been successfully implemented for monitoring aging of glass fiber–reinforced cement, detecting fatigue cracks in metal plates and impact-induced damage in composite plates (Eiras et al., 2013; Liu et al., 2014; Alnuaimi et al., 2021(a)). In this work, the SPC technique is applied for the first time to monitor corrosion-induced damage in RC structures.

The SPC technique counts the number of peaks in the frequency spectra for the given threshold values in the entire frequency range (0-200 kHz). Varying the threshold from 1 to 100 % of the maximum peak amplitude. The SPC is plotted in Fig. 10 as a function of the threshold value. It can be seen from Fig. 10 that sudden jump in SPC value is visible near threshold of 1-10% of peak amplitude which implies that the newly generated sideband peaks have amplitude mostly below 10% of the highest peak value. The further modified indicator SPC-I is defined as the average of the number of peaks counted for different threshold values (Alnuaimi et al., 2021(a)).
FIG. 10 SPC variation with the moving threshold (A to E are various stages of corrosion as depicted in FIG. 5)

The quantitative criterion adopted in this work based on SPC is the change of the SPC-I, relative to the initial value. SPC-I is calculated as the average of the number of peaks counted for threshold values ranging from 1% to 90% of the maximum peak amplitude. Fig. 11 shows the measured nonlinearity of specimen in terms of measured change in SPC-I as corrosion induced damage progresses. It is evident from Fig. 9-12 that change in the parameter (SPC-I) relative to the initial values increases sharply, approximately, 4 days after the beginning of the accelerated corrosion test for the direct measurement (A2) and 5 days for the indirect measurement (A1). In this case, the first microscopic observation of crack on the side surface of the specimen near rod was made on the 5th day from the start of the test. Also, first microscopic observation of crack on the lateral surface of the specimen was made on the 7th day.

FIG. 11
From the flow of current in the corroded system as depicted in Fig. 5, it is observed that a slight change in current is exhibited on day 4 (stage B), before the appearance of visible cracks in the concrete cover region over the protruded steel rebar end on day 5. Such a minute change in current flow caused due to the initiation of micro-crack can also be corroborated from the SPC-I measurement. It is reasonable to interpret that on day 4, before the observation of the first visible surface crack, the micro-cracks would have actively formed at the concrete cover-rebar interface region owing to the corrosion initiation. As corrosion progresses, micro-cracks coalesce, appears on the end surface on day 5 (lateral surface on day 7) and then gradually widen or propagate longitudinally with time. These events are very consistent with the change in SPC-I value (Fig. 11). These correlation between observed microstructural changes and measured SPC-I values will be discussed in detail in Section 3C.

3. **Sideband peak count Higher harmonic generation**

Higher harmonic generation technique is generally used to measure nonlinearity (Woodward and Amin, 2008; Climent-Llorca et al., 2020) and based on which the nonlinear parameters can be calculated from the amplitudes of the fundamental and higher harmonic frequencies. From the frequency spectrum shown in Figs. 8 and 9, a single peak corresponding to the excitation frequency at 25 kHz is present in the signal acquired at the start of the test (denoted as stage ‘A’). With the initiation of the crack, no significant peaks are noticed for indirect (A1) measurement except on day 9 measurement, zoomed view of which is shown in Fig. 12. However, under direct (A2) measurement, the generation of higher harmonics (second and third harmonics) can be clearly observed after the formation of the major crack on day 11 (see Fig. 13). Unfortunately, at the
initial stages of the micro-cracking, no higher harmonics are observed. Thus, harmonic generation technique is not found to be effective since it does not show anything until the visible damage appears. This observation is in line with the previously reported works (Korenska et al., 2009; Shah and Ribakov, 2009; Basu et al., 2021). Though this observation is in line with the previously reported works (Korenska et al., 2009; Shah and Ribakov, 2009; Basu et al., 2021), there are few other works that demonstrates the effectiveness of harmonic generation technique for corrosion-induced damage detection (Woodward and Amin 2008; Climent-Llorca et al., 2020). Hence, in-depth comprehensive studies are further needed to arrive at the firm decision regarding effectiveness of harmonic generation technique for corrosion-induced crack detection at early stages.

Another ultrasonic parameter, peak amplitude at specific frequency, (which is linked to the attenuation) can be also obtained from the frequency spectra. Peaks in the frequency range of 25-28 kHz in the frequency spectra are obtained and the change in magnitude of the peaks i.e. normalized with respect to the peak value obtained before the start of the corrosion test (t=0) is plotted. The normalized peak values at various critical stages of corrosion are shown in Fig. 13.
FIG. 13 14 Normalized peak values are shown at 5 critical stages A to E of corrosion progression (in terms of sudden increase in current flow, see Fig. 5)

In Fig. 13 14, it can be seen that the peak amplitude goes down from stages A to C, then it increase from C to D. No consistent trend is observed beyond D. Increase in peak amplitude from C to D may be due to the filling of the space created by the earlier formed crack with steel corrosion products (Climent-Llorca et al., 2020). However, change in peak amplitude could not give any meaningful clue till the development of visible surface crack, which makes linear parameter (change in peak amplitude, i.e., attenuation) inapplicable to monitor corrosion-induced micro-cracking in the considered RC specimen.

The change in TOF is also investigated as it is one of the most commonly used techniques adopted by field engineers for integrity assessment. From the received time-domain signal, TOF, t is calculated using the auto-picking algorithm based on the Akaike information criteria (AIC) (Zhang et al., 2003) and plotted in Fig. 14 15. The plots show inconsistent and small variations of TOF as the corrosion progresses. Initially there is a drop in TOF from Stage A to B for A2 arrangement, beyond that TOF increases with the time of exposure. Whereas for A1 arrangement, change in TOF shows a decreasing trend but is insignificant. Clearly TOF does not show any significant consistent trend for indicating the corrosion-induced damage initiation and progression in the specimen. Therefore, change in TOF may not be a reliable (sometimes can be misleading) parameter for monitoring progression of corrosion-induced damage in RC specimens.
FIG. 14 Variation of TOF at various stages of corrosion A to E (with reference to Fig. 5)

D. Sensitivity analysis

Sensitivity of different ultrasonic parameters towards corrosion-induced damage detection is examined for the purpose of selecting suitable NDE method which can indicate the on-set of corrosion. For most of the derived ultrasonic (linear and nonlinear) parameters, it is observed that A2 (direct transmission) is highly sensitive for monitoring the evolution of corrosion-induced micro-cracking when compared to A1 (indirect/surface transmission). It may be due to the fact that the signal received in surface mode of transmission may contain contribution from both surface wave and waves reflected from the steel bar. This would hinder the sensitivity if micro-cracking initiates far away from the surface and that was the phenomena observed through visual observations as well, i.e. cracks were not initiated on the top surface till the end of test. Also, cracks appeared below the reinforcement rod level and along the length and width of the specimens. This resulted in less sensitivity in the calculated ultrasonic parameters from A1 sensor arrangement. Hence for the sensitivity analysis, values obtained from the A2 sensor arrangement are considered.

Fig. 15 shows the change in ultrasonic parameters. It can be observed that the linear parameters do not show any significant variation due to corrosion-induced damage. Therefore, it can be concluded that no significant change in linear parameters could be achieved. On the other hand, nonlinear parameters show a significant change as corrosion-damage progresses and they provide
significant information on the initiation of crack, well before the appearance of visible surface cracks.

The first crack on the specimen end surface is observed visually on day 5, before which micro-cracking phenomena must have initiated in the specimen near the reinforcement concrete interface. The change in the nonlinear parameter SPC-I clearly shows a detectable change owing to the sensitivity of the SPC-I to the micro-cracking phenomena (see Fig. 15 16). Although energy distribution technique also presents significant change with increasing damage level, the trend of the rate of change of SPC-I and $\alpha$ are different. For the SPC-I technique the rate of change is high in the beginning, reaches its peak on day 4 and then it decreases while for the energy distribution technique the drastic change of $\alpha$ is noticed on day 7. After day 4, micro-cracks coalesce to form macro-crack and reaches the specimen end surface on day 5. This demonstrates that SPC-I is a good measure of nonlinearity caused by micro-crack formation while the nonlinear parameter calculated from the energy distribution method is influenced more by the macro-crack formation. Hence from the present study, it is concluded that the nonlinear parameter SPC-I is most suitable among various linear and nonlinear ultrasonic parameters considered here for detecting the early stage of micro-cracking induced by corrosion in RC structures.

![Sensitivity analysis of different ultrasonic parameters during the progression of corrosion induced damage](image)

FIG. 15 16. Sensitivity analysis of different ultrasonic parameters during the progression of corrosion induced damage
The evaluated nonlinear ultrasonic parameter, SPC-I is found to increase with increase in corrosion-induced damage. But, as depicted in Fig. 15, the change in SPC-I does not monotonically increase with increase in corrosion-induced damage. Thus, it is crucial to correlate the change in SPC-I with the damage process occurring in the specimen during progressive corrosion. The change in SPC-I reaches its peak value on the 4th day of exposure and then decreases gradually. Similarly, the initial increase and eventual decrease of a different nonlinearity parameter (relative amplitude) for reinforced cement mortar specimen was reported in a previous research by the current authors (Alnuaimi et al., 2021b), when using a different nonlinear technique based upon harmonic distortion and wave modulation (Climent-Llorca et al., 2020). Similarly, the initial increase and eventual decrease of a different nonlinearity parameter (relative amplitude) for reinforced cement mortar specimen was also reported in previous studies (Climent-Llorca et al., 2020; Alnuaimi et al., 2021b). It has been well demonstrated that the nonlinearity is closely related to the phenomenon of the closing/opening of micro-cracks and it is highest when the faces of micro-cracks are almost closed, corresponding to the micro-crack initiation (Kim and Lee, 2007). With the corrosion initiation, new micro-cracks are formed, then they coalesce to form macro-cracks, come to the surface, widen and propagate further. Thus, the formation of micro-cracks inside the specimen at concrete-rebar interface during corrosion contribute to the increase of the nonlinearity parameter. However, beyond day 4 there is a decrease in change in SPC-I. This could be explained by two ways. One is that, regarding crack growth, previous research has found that the material nonlinearity becomes smaller when micro-cracks are open or not tightly closed (Kim and Lee, 2007; Hafezi et al., 2017; Alnuaimi et al., 2021b). Here, if the pressure exerted by the lack of space to accommodate the rust formation is enough to crack the concrete, micro-cracks are formed, then they widen and coalesce to form larger cracks. Another reason is that the filling of void space created by cracking with corrosion products of steel can slow down the rate of corrosion process; this decline in reaction
rate could affect the measured nonlinearity parameter as well. Perhaps filling of void space created by cracking with corrosion products of steel rate shall affect the measured nonlinearity parameter as well (Climent-Llorca et al., 2020). Thus, from the previous discussions, it is clear that the increase in the nonlinearity is strongly dependent on the initial formation of micro-cracks. With the progress of corrosion, the initially formed cracks widen, and the filling of crack created space resulting in a lesser influence (or sometimes reversal effect) on the nonlinearity parameter. This would result in a decrease of the nonlinearity parameter once the rate of corrosion slows down, as noticed in Fig. 16. In such situations the nonlinearity parameter (both SPC-I and $\alpha$) that is measured at each testing instance might correspond to the newly formed micro-cracks. It is to mention here that the sensitivity analysis has been carried out in the present study using the linear (TOF and attenuation) and nonlinear (sideband energy distribution and sideband peak count) ultrasonic features using the single frequency excitation. The other methods involving probing and pumping frequencies (nonlinear wave modulation spectroscopy) may also be potential for detection of corrosion in embedded steel bar.

The variation of the cumulative nonlinearity parameter with increasing exposure time is plotted in Fig. 16.

![Graph showing variation of cumulative nonlinear parameter with exposure time]

**FIG. 16** Variation of cumulative nonlinear parameter with exposure time
A cumulative value (i.e., area under the nonlinearity parameter versus exposure time plot) might approximately depict the total micro-crack formation or corrosion damage state in a much broader sense (Chen et al., 2010). The cumulative nonlinearity parameters again confirm the above-mentioned inferences that SPC-I is a measure of nonlinearity due to micro-crack formation (defined by the sudden jump in cumulative parameter during days 2 to 4) and the nonlinear parameter based on energy distribution method is influenced by the macro-crack formation (defined by sudden jump in the cumulative parameter during days 6 to 9). Importantly, this cumulative nonlinearity parameter demonstrates that a combination of SPC-I and sideband energy distribution should be used to monitor the full spectrum of damage progression from its initiation stage (micro-crack formation) to the final failure (macro-crack propagation).

IV. CONCLUSIONS

The results presented here confirm that it is feasible to detect micro-cracking at the initial stage of cracking due to the corrosion of reinforcements in RC structures. The appearance of visible surface cracks accompanies with the occurrence of strong nonlinearity in the received signal: drastic change in nonlinear parameter obtained from sideband peak count index (SPC-I) (in frequency domain) is clearly noticed. Nonlinear parameter based on energy distribution is also found to give significant change as damage progresses. However, the change is observed almost on the day of occurrence of visible surface crack. The results also suggest that the linear parameters (TOF and attenuation) are not as efficient as the nonlinearity parameters (α and SPC-I), for detecting the nonlinear characteristics linked with the micro-cracking events induced by corrosion in concrete. The nonlinear ultrasonic parameter SPC-I is found to be performing the best, in terms of efficacy and sensitivity, to indicate the initiation of corrosion inside concrete, when the micro-cracks start to form but is not visible from outside, which is not possible by other techniques.
Another important observation made in the present study is that after the significant events of the micro-cracking phenomena, nonlinear parameter returned to values typical to the previous situation. This may be due to the filling of the void space created by the crack with liquid containing steel corrosion products or the opening of micro-cracks further that reduces the overall nonlinearity. The results and significant observations made from this study are further extended and comprehensive experimental works are being carried to develop a unified model which will enable to detect corrosion induced damage progression from its initiation to final failure of reinforced concrete structures.

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REFERENCES


