Damage Monitoring in Reinforcing Bars in Concrete using Longitudinal Guided Waves

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ABSTRACT: One of the major causes of catastrophic failures in reinforced concrete structures such as bridges, dams and buildings is the deterioration of reinforcing bars. If the degradation remains unnoticed inside concrete, it further accelerates and causes huge loss of life and property. So there is an urgent need for developing a non-intrusive health monitoring strategy for embedded reinforcements in RC structures which would inspect the bars itself and guided ultrasonic waves offer a potentially attractive solution. In the present work, high frequency longitudinal guided waves have been exploited to develop a damage detection methodology for steel bars embedded in concrete with simulated notch defects. Both pulse transmission and pulse echo techniques have been adopted and the time of flight and signal attenuation have been observed to locate and quantify the damage accurately. The developed methodology is then successfully applied to reinforced concrete beam specimens undergoing accelerated chloride corrosion. It can very effectively relate to the state of reinforcing bar undergoing chloride corrosion.

1. INTRODUCTION

Deterioration of reinforcing bars and tendons embedded in concrete structures such as bridges, dams and buildings is one of the principal causes of their catastrophic failure. The steel degrades due to environmental action and excessive stress and it remains unnoticed inside concrete. The degradation accelerates unless early remedial action is taken. Removal of concrete to visually inspect the reinforcement is detrimental to the structure. Therefore, it is imperative to develop a non-intrusive technique for early detection of degradation in steel embedded in concrete. However, the size and limited accessibility of civil engineering installations prevent adoption of a rigorous technique like C-Scan. There is a necessity of a reliable, non-invasive and real time non-destructive testing methodology that can detect, locate and quantify damage in embedded steel bars. Current methods of nondestructive testing for hidden steel include visual inspection, radiography] and acoustic emission etc. They indicate likelihood of deterioration of the reinforcement but do not quantify it. Fiber optic sensors have also been embedded in concrete to indicate the strain levels or cracking. Ultrasonic wave propagation has started being used in the detection of damages in reinforcing bars. The embedded reinforcements in a concrete can be excited at one end of the reinforcing bar. The bar acts as a wave guide and assists in the propagation of the wave. It is partially reflected back from defects. The defect location can be estimated from the time taken by the wave to travel back to the transmitter. The technique was attempted experimentally by Weight (1994) and then theoretically by Pavlakovic (1998, 1999).This forms the basis of pulse echo method of testing. Also, Pulse transmission simultaneously utilizing two transducers acting as transmitter and receiver on either side of embedded reinforcement can also be used to study the state of reinforcing bar. Alleyne et al. (1997, 1998) observed that for steel bars in air the attenuation is primarily due to material scattering and absorption. When the bars are embedded in concrete, both longitudinal and shear waves leak into the surrounding concrete as identified by Lowe et al.(1994). Thus, the lack of leakage can indicate delamination between concrete and the bars. Towards the development of a damage detection methodology in embedded reinforcing bars, guided waves were chosen Guided waves have the capability of testing over large distances than the conventional non-destructive testing techniques, can be used for multilayered systems as in RC structures and are relatively inexpensive. However, it is important to excite the right mode for detection of particular damage. The waves must traverse the length of the reinforcement with detectably strong signal. Substantial amount of work has been reported in literature on theoretical predictions on cylindrical wave propagation. Pochhammer (1876) and Chree(1889) studied the guided wave propagation in cylindrical free bars. Pao and Mindilin(1960), McNiven and Mindlin(1962) and Meeker and Meitzer(1972) reported further developments in elastic wave propagation in three dimensional solid bars. Dispersion curves for a hollow isotropic cylinder were reported by Gazis (1952), Fitch (1962) compared Gazis predictions for axially symmetric and non-symmetric wave propagation with experiments. Subsequently several authors like Morse(1954), Mirsky(1965), Dayal(1994) and Nagy(1995) reported work on propagation in transversely isotropic cylindrical bars. But extension of these solution methods to embedded systems was difficult due to problems of solving complex Bessel's functions in leaky systems. Developments in the Bessel's functions with complex arguments by Amos (1995) have made it possible to calculate dispersion relations easily. Dispersion curves for systems with an arbitrary number of layers can be generated easily by the software Disperse(2000). The software has been used to identify the modes and frequency range for embedded bars by Pavlokovic(2001). Beard et al. (2002,2003) applied the method to study the use of these waves for inspection of grouted tendons and bolts. Reis et al. (2005, 2008,2009) used the fundamental flexural and longitudinal guided waves for estimation of corrosion damage in steel reinforced mortar.

This study is an attempt to explore the effectiveness of high frequency ultrasonic longitudinal guided waves for damage detection in mild steel bars embedded in concrete with a range of simulated notch defects in the form of area reduction. Ultrasonic pulse echo and pulse transmission techniques are used in combination to predict the presence, location and magnitude of notch very efficiently. The methodology is applied in-situ to a bar embedded in concrete undergoing accelerated corrosion. It can successfully relate to the state of reinforcing bar undergoing chloride corrosion.

2 SELECTION OF EXCITATION MODE

In an isotropic cylinder, such as reinforcing bars, waves propagate in longitudinal, flexural and torsional modes due to complex effect of boundaries and they have frequency dependant properties. In such cases specific modes can be excited selectively by choosing a frequency bound. To determine the frequency bound, the eigen values of the characteristic matrix of stresses and displacements in terms of partial wave amplitudes are determined. A standard software [32] is used to determine the dispersion curves. Longitudinal, torsional and flexural waveforms are represented by notation L(m,n), T(m,n) and F(m,n) respectively. The characters 'm' and 'n' represent the circumferential displacement which is a function of $\cos(m\,\theta)$ and the sequential order of the mode respectively. For bars embedded in concrete which is a layered waveguide system, leakage plays an important role. Dispersion curves for a 12mm bar embedded in concrete are plotted **(Figure 1.)** and the properties used for steel and concrete modeling are shown **(Table 1.)**. Only longitudinal modes have been considered in the study. Non-axisymmetric flexural and torsional waves exhibit high attenuation and are neglected. Also, it is easier and practically viable to invoke a strong longitudinal wave. In the past, these waves have been invoked by keeping the transducers at the ends of the bar [40, 41] or by angled transducers on the end of cylindrical bars [42]. In the present work guided longitudinal waves were produced in the embedded bars by keeping compressional transducers parallel to the guiding configuration at the two ends of the bars. The different longitudinal modes were excited by varying the excitation frequencies. The selection of frequencies for testing was done based on the phase velocity dispersion curves **(Figure 1a)**. They were validated by experimentally confirming the signal fidelity. High frequency low loss modes are found to be the best [34]. Phase velocity dispersion curves show the fundamental L (0, 1) mode starting at zero frequency with each higher order mode starting from a higher cut off frequency. Each of the higher mode shows a plateau region around the steel longitudinal bulk velocity line. But L(0,7) mode, shows a different pattern. Instead of each plateau region belonging to a single mode, L(0,7) breaks from this pattern and links the subsequent plateau regions together to form a single mode that propagates close to the longitudinal bulk velocity of steel. The plateau regions correspond to the points of maximum energy velocity **(Figure 1b)** and minimum attenuation **(Figure 1c).** This L(0,7) mode that links all plateau regions together forms a single low leakage mode for this embedded system and is chosen for study. At a frequency of 3.5 MHz, the mode exhibits global attenuation minima of 34.7dB/m and is the fastest propagating mode. High signal output was also observed at this frequency experimentally. The phase velocity as obtained from dispersion curve at this frequency is 6 km/s.

3 EXPERIMENTAL DESCRIPTION

3.1 Simulated Damages

Concrete with mix proportions as 1:1.5:2.96 and w/c ratio of 0.45 is used for casting beams of dimensions 150mm x 150mm x 700mm. 12mm diameter extruded mild steel bar of 1m length is embedded in the beam during casting having projections of 150mm on each side of beam. Extruded bars were used to avoid complexities due to ribs on the reinforcing bars. Bars with simulated damages in the form of notches (with symmetrical 0%, 20%, 40% and 60% diameter reduction) is introduced in the middle of the bar before casting them in concrete. Two samples of each specimen were tested to examine the repeatability and precision of the results. The ultrasonic testing system consisting of a pulser /receiver, transducers, and display devices is used. Driven by the pulser, the compressional transducer generates ultrasonic pulse that propagates through the embedded bar in the form of longitudinal waves. In this study, contact transducers ACCUSCAN "S" series having a longer wave form duration and a relatively narrow frequency bandwidth with center frequency of 3.5 MHz is used for the 12mm bars. The transducers were driven by a DPR 300 Pulser/Receiver system with a gain of 33 dB and input voltage of 400V. A PC and an Acquiris Digitizer card were used to capture the received signal and its further processing. The transducer is mounted in a holder and attached to the specimens using an industrial coupling gel. The excitation signal consisted of a compressive spike pulse with pulse duration ranging from 10-70 ns. The reinforced beams were ultrasonically monitored using the set-up shown in **Figure 2**. When there is an interface such as a crack, void or flaw in the wave path, part of the energy is reflected back from the interface and received by the same transmitting transducer. From the display, the time of flight between the excitation and reflected pulse is measured. Knowing the velocity of the excited longitudinal wave mode in the steel bar called the phase velocity, the location of the defect can be calculated as follows:

$$D = \frac{Vt}{2} \qquad (1)$$

Where D = Distance of defect from transducer end, V = Phase Velocity of excited mode and t = Time of Flight

Table 1. Material Properties of Steel & Concrete

SNo.	Material Property	Steel	Concrete
1.	Modulus, E (GPa)	210	29.6
2.	Density(ρ),(kg/m^3)	7932	2200
3.	Longitudinal Attenuation (np /wl)	0.003	0.2
4.	Shear Attenuation (np/wl)	0.008	0.5
5.	Longitudinal Velocity (m/s)	5960	4100
6.	Shear Velocity (m/s)	3260	2300
7.	Poisson's Ratio	0.2865	0.27

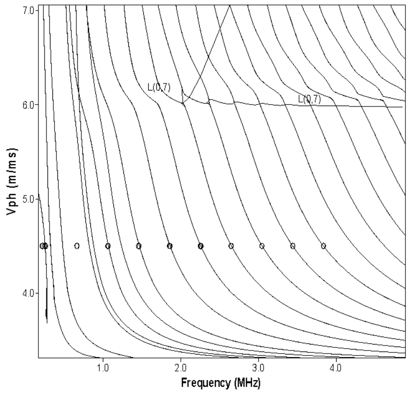


Figure 1a. Phase Velocity Dispersion Curve

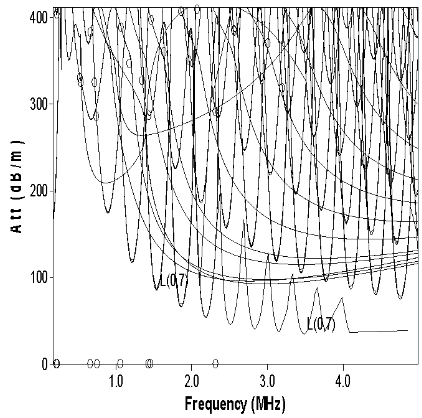


Figure 1b. Attenuation Dispersion Curve

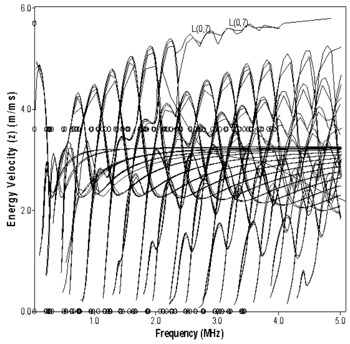


Figure 1c. Energy Velocity Dispersion Curve

This method of testing referred to as the pulse echo technique is explored. Pulse-transmission method of testing is also used in which an ultrasonic transmitter introduced the wave from one end of the bar and a receiver is placed at the opposite end to record the transmitted pulse. By measuring the relative change of the amplitudes of the input and the received signals, the relative severity of the damage is assessed. The results were reported in the form of voltage-time curve (v-t).

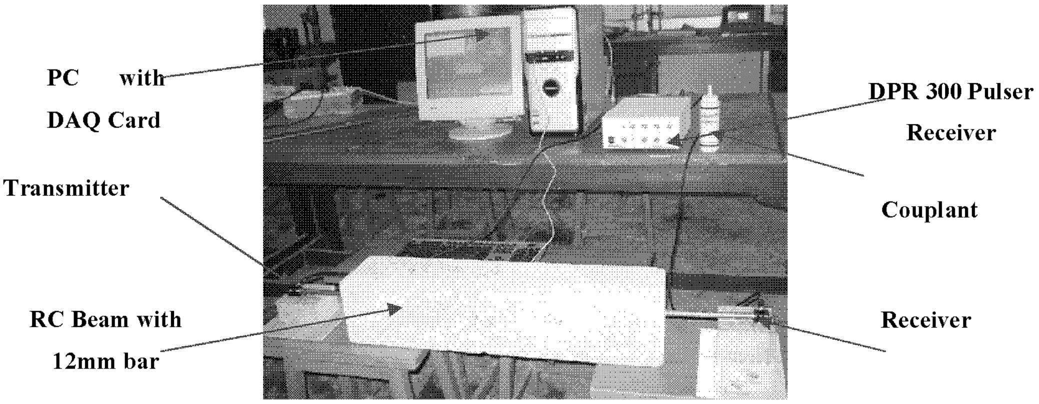


Figure 2. Experimental Set Up for Pulse Transmission monitoring of RC Beams

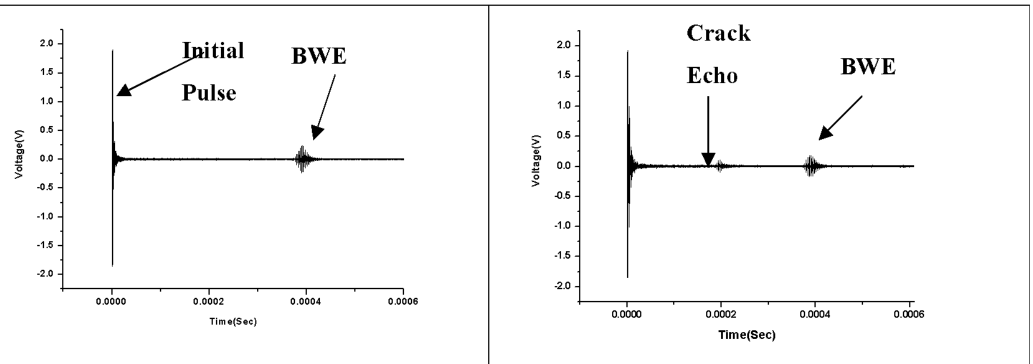
3.2 Accelerated Corrosion Monitoring

Corrosion of reinforced concrete structures is one of the major durability concerns faced by the civil engineers today. Corrosion leads to infrastructural problems associated with repair and maintenance costs, aesthetics and safety. Hence, there is a need to develop a reliable, non-invasive and in-situ corrosion monitoring methodology which would give condition of embedded reinforcement well in advance before the degradation becomes catastrophic. To explore the suitability of guided wave monitoring methodology developed above for RC beam specimens with notched defects, the experiments were extended to beams undergoing accelerated corrosion. Corrosion process takes several years to occur naturally and hence the process was accelerated using impressed current. Positive and negative terminal of the power supply were attached to the projected bar and stainless steel wire mesh of 300mm width wrapped in the middle of the beam to complete the circuit. Constant Voltage of 30V was applied. 5% NaCl solution was pumped onto the top of the wire mesh to induce and chloride corrosion. Beam undergoing accelerated chloride corrosion was ultrasonically monitored both in pulse echo and pulse transmission modes continuously for 8 days till the signatures completely vanished. Then the corroded beam was opened and the extracted bar was tested for mass loss and tensile strength to relate the ultrasonic testing results to the actual state of bar.

4. RESULTS AND DISCUSSIONS

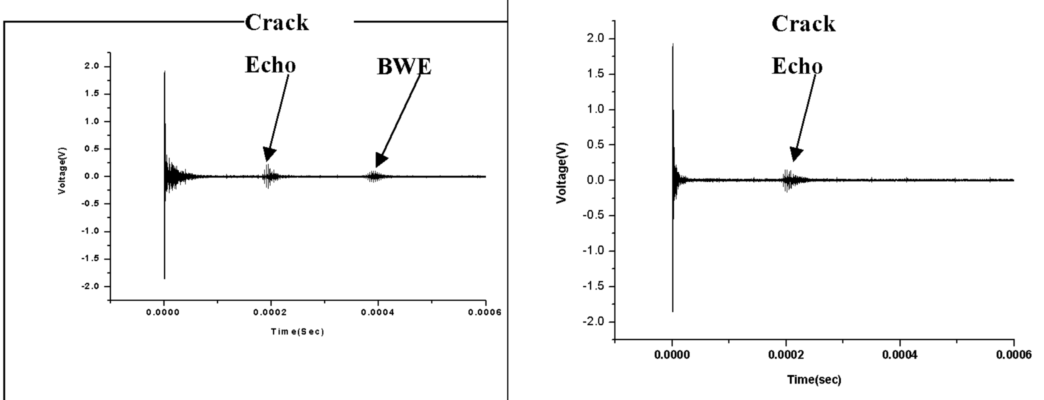
4.1 Simulated Damages

In the pulse echo method, there will be reflections from the damage as well as the back wall (BWE). In a healthy specimen, the peak is the reflection from the back wall (BWE) as shown in **Figure 3a**. In a notched specimen, the 1st peak is the reflection from the notch (Crack Echo) and the 2nd peak is the BWE as shown in **Figure 3b.** Appearance of a crack echo indicates the presence of defect in the embedded bar. By knowing the time of flight of this echo, location can be exactly computed from (1) Comparing the peak-peak voltage amplitudes of crack echoes and BWE's in **Figure 3 (b,c,d)** an idea about the extent of crack also can be made.



(a) Healthy Beam

(b) 20% notch in embedded bar



(c) 40% notch in embedded bar

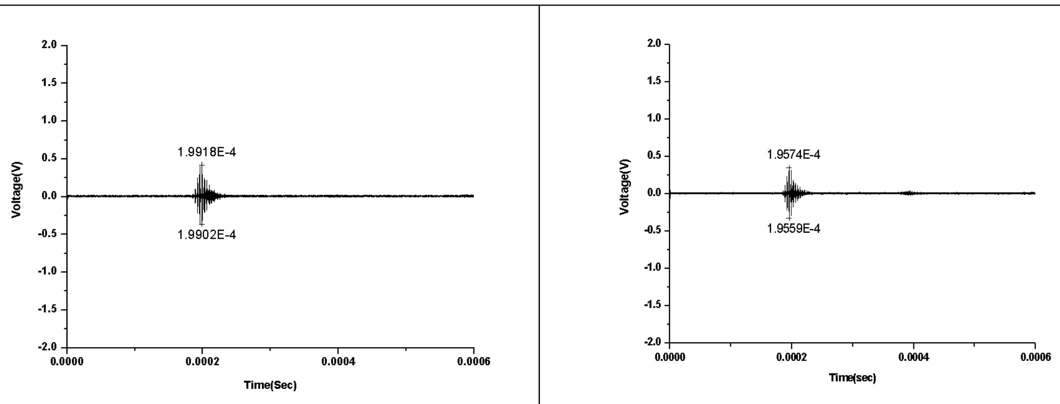
(d) 60% notch in embedded bar

Figure 3. Pulse Echo Signatures of a 12mm bar embedded in concrete

In pulse transmission method, the peaks observed in **Figure 4** are the transmitted peaks obtained after travelling distance 'L' where L is the length of embedded bar **(Figure 4 a,b,c,d).** Studying the relative change in the amplitude of input pulse and the transmitted peak, an idea about the severity of the damage can be made in transmission technique.

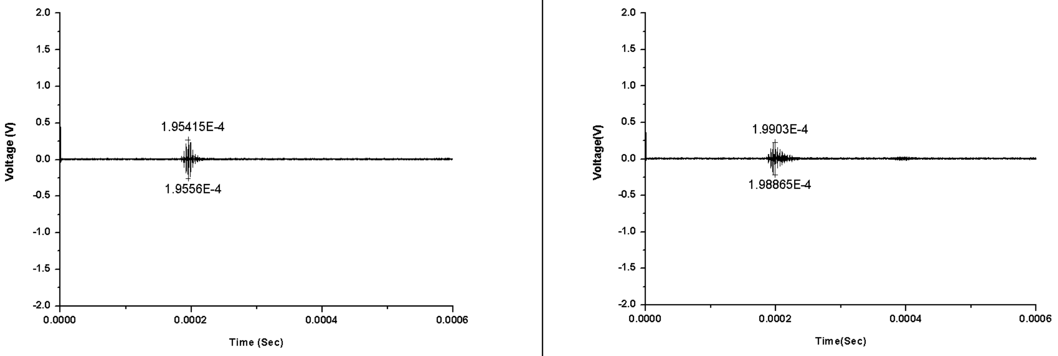
Figure 5(a, b) shows the peak to peak voltage amplitude ratio trends for reflected and transmitted peaks in pulse echo and transmission methods respectively.

Another significant observation from the above graphs is the huge amount of signal attenuation experienced by the input pulse because of the presence of attenuating concrete. Hence, it is signifies the selection of an ideal low leakage mode for damage detection in RC structures.



(a) Healthy Beam

(b) 20% notch in embedded bar



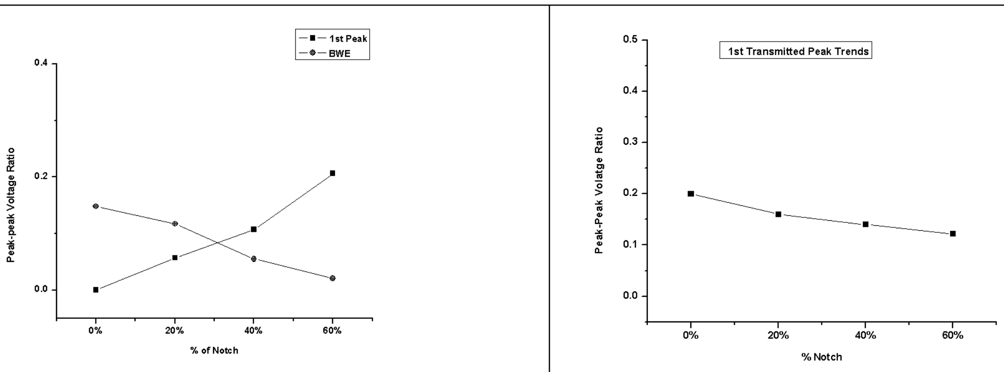
(c)

40% notch in embedded bar

(d)

60% notch in embedded bar

Figure 4. Pulse Transmission Signatures of a 12mm bar embedded in concrete



(a) Pulse Echo

(a) Pulse Transmission

Figure. 5: Peak-Peak Voltage Ratio Trends of Reflected and Transmitted peaks

Hence, from the two techniques the diagnosis of damage in the reinforcing bar can be done in the following way:

(i) Presence of damage: Appearance of a peak between the initial pulse and back wall echo in Pulse Echo mode of testing indicates the presence of damage or defect in the embedded bar specimen under diagnosis as can be seen from **Figures 3 (b-d).**

(ii) Location of damage: The time of flight of the 1st peak i.e crack echo from the v-t signature in Pulse Echo is used to find the exact location of the notch. Knowing the time of flight from the signature and velocity of guided wave mode in embedded steel from Disperse, the exact location of damage can be known.

(iii) Extent of damage: Both pulse echo and transmission methods when effectively used in combination can relate to the extent of damage. In Pulse Echo, magnitude of damage can be directly related to the magnitude of the peak received after reflection from the crack boundary (1st Peak) as well as back wall echo (2nd Peak). It was observed that the amplitude of 1st Peak increased and that of 2nd Peak reduced with the increase in the notch dimensions **(Figure 5a)** As the magnitude of notch increased, more signal energy is reflected back from the crack and less part of it is travels to the back wall. In Pulse Transmission, the extent of damage in bar can be ascertained by observing the peak-peak voltage trends of the transmitted peak. As the % of damage increased from 0% to 60%, the magnitude of the transmitted peak reduces continuously. This is because as the notch dimensions increased, more energy is reflected back and less travels through the bar to reach at the other end. Hence, relative signal attenuation of the transmitted pulse can relate to the extent of the damage in the bar.

4.2 Accelerated Corrosion Monitoring

Beam undergoing accelerated corrosion showed development of reddish brown corrosion products and a longitudinal crack parallel to the bar within two days. Reddish brown liquid product oozed out of the crack along with increase in crack length as corrosion progressed. Ultrasonic pulse echo monitoring of the beam showed that with the increase in age of corrosion, peak to peak voltage amplitude of the BWE kept on falling. It vanished completely on the 3rd day pointing towards severe non-uniform pitting corrosion taking place because of chlorides. Another significant observation was the appearance of a peak between the initial pulse and BWE on the 2nd day **(Figure 6 a,b).** From the time of flight of the peak, it was found to be the reflection from bar-beam interface giving indication of severe pit formation at the interface. As corrosion increased, amplitude of this peak increased indicating increased reflections and hence, increased loss of area from the interface.

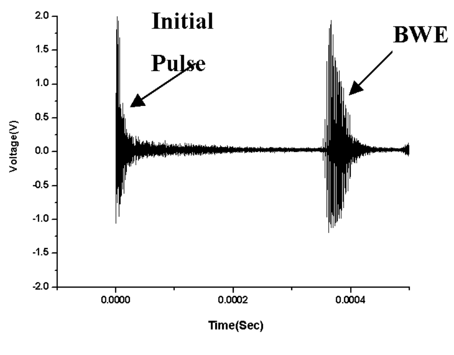


Figure 6 a. 1st day Pulse Echo Signature

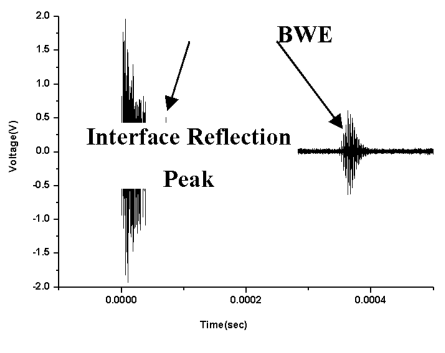


Figure 6 b. 2nd day Pulse Echo Signature

Drastic non-uniform area loss due to severe chloride corrosion was also confirmed by pulse transmission testing of this beam. The peak-to peak voltage amplitudes of the first transmitted peak relative to the input pulse kept to falling drastically until it vanished completely on the 6th day **(Figure 7 a,b)** After eight days, the bar was removed from concrete and its mass loss and tensile strength were calculated. Bar had lost 18.6% mass because of chloride corrosion. While undergoing tensile test, bar failed in the middle rather than at interface where there was huge non- uniformly spread corrosion. Tensile strength reduced to 20% of its original tensile strength. These reductions in mass and ultimate tensile strengths correlate well with the ultrasonic monitoring results wherein the signal experiences huge signal attenuation both in pulse echo and pulse transmission techniques. So the methodology established in the study using ultrasonic pulse echo and pulse transmission can be applied for in-situ monitoring of embedded reinforcements undergoing damages both in the form of cracks or notches or corrosion.

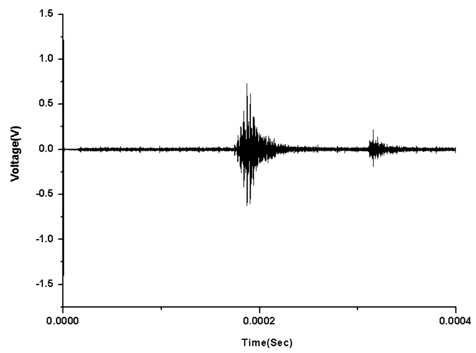


Figure 7a. 2ndt day Pulse Transmission Signature

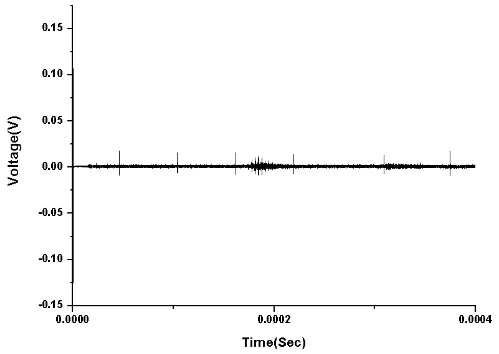


Figure 7b. 5th day Pulse Transmission Signature

5 CONCLUSIONS

Ultrasonic guided waves at high frequencies can be effectively used for damage detection in the form of cracks, notches and corrosion defects in reinforcing bars embedded in concrete by utilizing its wave guide effects. It opens a new regime of non-destructive testing of reinforcing bars in concrete structures which undergo huge deterioration with time as it goes unnoticed due to the embedded state. The methodology established by the study utilizing the Pulse Echo and Pulse Transmission techniques not only indicates the presence of damage but also gives the exact location and magnitude of damage by efficient combination of the two techniques. Different guided wave modes can be generated by varying the input frequencies of the transducers which are sensitive to different types of damages.

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