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DISCOVERING HIDDEN DEGRADATION USING ULTRASONIC WAVE PROPAGATION: THEORY AND EXPERIMENTATION

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Abstract. *Building and maintenance of civil infrastructure is one of the largest contributors in global warming. Extending the life of infrastructure through regular monitoring and retrofitting can reduce environmental damage to a great extent. Inspection, diagnosis and prognosis of damage in installations are imperative for avoiding their catastrophic failures. This paper illustrates the ability ultrasonic guided waves to pick up the signatures of structural damage. Discovering hidden degradations such as corrosion inside reinforced concrete and submerged plated structures has been demonstrated. The theoretical development of propagation of ultrasonic waves is also reported.*

1 INTRODUCTION

Although many non-destructive evaluation (NDE) techniques such as liquid penetrant dye, radiography, holography, eddy current, magnetic flux, thermography are available for investigating the insides of a structure, the large size of the installations makes use of these techniques unrealistic. For discovering deep structural degradations ultrasonic guided waves offer a potentially effective solution since they can travel long distances and pick up signals of early deterioration. It involves introducing a high frequency stress pulse or 'wave packet' into a material and observing the subsequent propagation and reflection of the pulse. The wave characteristics change due to the deterioration in the structure and these are sensitive to the location, extent and character of damage.

In this work, suitable ultrasonic guided waves have been used for damage detection of embedded and submerged structures. For embedded systems, suitable guided wave modes have been identified through modeling which are sensitive to different types of corrosion induced damages encountered in reinforcing bars embedded in concrete. Corrosion of reinforcing steel in concrete is one of the major durability problems faced by civil engineers. Ultrasonic guided waves have been used to develop a non-intrusive corrosion monitoring technique for early detection of corrosion induced damages in steel embedded in concrete. Corrosion manifests itself in debond and pitting steel bars. But it is imperative to excite the right mode for detection of a particular type of corrosion. A guided wave excited in the reinforcing bar in concrete would be reflected from the defects simulating area reduction due to pitting caused as a result of corrosion thus facilitating the detection of these defects accurately. Amplitude and time of arrival of these reflections can be used to identify or locate defects. Ultrasonic pulse transmission utilizing two piezoelectric transducers at the two ends of the reinforcing bars is also used in conjunction with pulse echo testing method to quantify the extent of corrosion induced defects in embedded bars.

On the other hand, many structures like ship hulls, oil storage tanks, off shore oil platforms etc. are assemblies of large plate like components which are prone to deterioration and damages due to environmental degradation, excessive loads, material fatigue, corrosion, etc. Criticality in such cases is further compounded due to economic constraints like high out of service costs associated with frequent health monitoring checkup schedules. The ultrasonic guided wave methodology is applied for damage detection in such plate structures seeded with defects like notches especially in submerged states like ship hulls in water. Submerged nature of the specimens also limits the use of available and conventional NDT techniques. Guided waves are a successful means for detection of deterioration of such structures.

2 GUIDED WAVES FOR CORROSION MONITORING

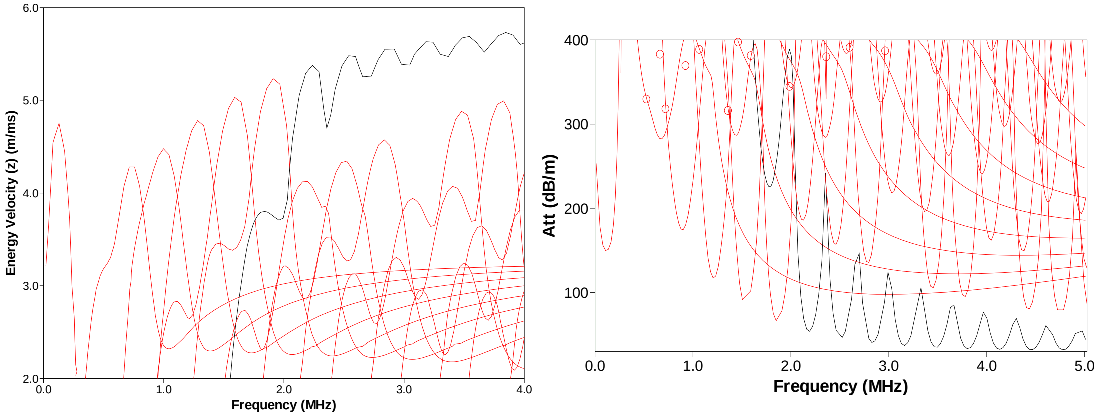
Reinforced concrete (RC) is the most popular, economical and versatile construction material as it can be moulded into any shape. It has proven to be successful in terms of both structural performance and durability. But in humid conditions, atmospheric pollutants percolate through the concrete cover and cause corrosion of steel reinforcements. The formation of the corrosion products on the surface of the reinforcing bar having higher volume than the corresponding volume of steel results in an outward pressure on concrete. Corrosion, in the form of pitting may also reduce the ductility of the steel bar by introducing crevices on the surface. But the size and limited accessibility of civil engineering installations prevent adoption of many currently used nondestructive testing methods such as radiography, acoustic emission etc. Hence, there is a need for non-intrusive, in-situ and real time corrosion monitoring system for RC structures. In this study, guided waves have been used to develop a non-intrusive corrosion monitoring technique for early detection of corrosion induced damages in steel embedded in concrete.

Corrosion manifests itself in debond and pitting steel bars. But it is imperative to excite the right mode for detection of a particular type of corrosion. This study investigates the effect of local loss of material and loss of bond on the propagation of ultrasonic waves through the reinforcing bars. Simulated pitting effects were created by notches on the surface of the bar in varying percentages of its crossectional area. Simulated debond was generated by wrapping a double sided tape of varying length on the bar embedded in concrete. Conventional techniques of pulse echo and pulse transmission have been used in combination to predict the presence, location and magnitude of the damages. An experiment is carried out to create accelerated actual corrosion in RC samples. Both the simulated and actual corrosion samples were ultrasonically monitored using guided waves. The results have been compared to estimate the suitability of simulation techniques [1]. The effect of degradation due to corrosion on the ultrasonic signals is reported [2]. Effective combination of suitable guided wave modes could relate to the state of reinforcing bar corrosion.

Description of Experiments

For simulating corrosion in reinforcing bars in concrete , concrete with proportions of cement, sand and stone aggregates as 1:1.5:2.96 was taken (w/c ratio = 0.45). RC beam specimens of dimensions 150 mm x 150mm x 700mm were cast. 12mm diameter plain mild steel bars of 1.1 m length were placed at the centre of crossection of the beams at the time of casting with a projection of 200mm on each side of beam. One set of bars with simulated damages in the form of notches (with symmetrical 0%, 20%, 40% and 60% diameter reduction) were introduced in the middle of the bar before casting them in concrete. Another set of bars were wrapped with a double sided tape in varying percentages of 0, 12.5%, 25%, 50%, 75% and 100% simulating delamination and were then cast in concrete.

The RC beams were ultrasonically monitored using the standard UT set-up consisting of a pulser receiver and transducers. Contact transducers ACCUSCAN "S" series with center frequency of 3.5 MHz is used for the 12mm bars. The transducers were attached at the two ends of the bars by means of a holder and a coupling gel between the bar and the transducer. Driven by the pulser, the compressional transducer generates a compressive spike pulse that propagates through the embedded bar in the form of longitudinal waves. In a reinforcing bar, different modes can be excited selectively by choosing a frequency bound. To determine the frequency band, standard software, Disperse [3] was used. Only longitudinal modes were considered for excitation since they are least attenuative. They were produced by keeping compressional transducers parallel to the guiding configuration at the two ends of the embedded bars by varying the excitation frequencies. The selection of frequencies for testing was done based on the phase velocity dispersion curves and validated by experimentally confirming the signal fidelity. High frequency low loss modes as identified by Pavlakovic [4] were chosen. L(0,7) mode corresponding to maximum energy velocity (Fig. 1a) and minimum attenuation (Fig. 1b) was chosen for study at a frequency of 3.5 MHz. Testing of the embedded bar was done in both pulse echo and transmission modes.



(a) Energy Velocity (z) Vs Frequency (b) Attenuation Vs Frequency

Fig.1: Dispersion Curves for a 12mm bar in concrete [3]

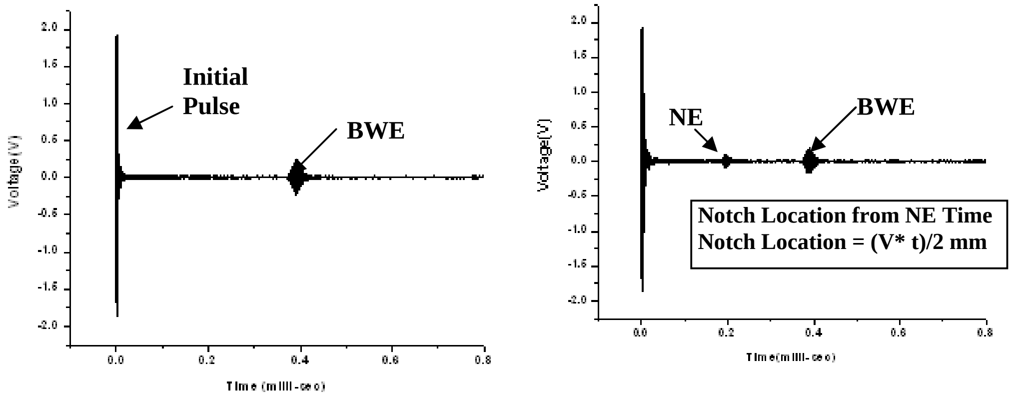
To determine the suitability of the simulated corrosion experiments by ultrasonic guided waves, another set of beam specimens were subbjected to actual accelerated corrosion. The projected bar was made an anode by connecting it to a positive terminal of a DC power supply. The middle 300mm of the beam was selected for exposure to corrosive environment. A thick cotton gauge was placed in this region wrapped with a stainless steel wire mesh around with a dripping mechanism of 5% NaCl fitted on top of it. The negative terminal was connected to the wire mesh and a constant voltage of 30V was applied between the two terminals. Beams undergoing accelerated chloride corrosion were ultrasonically monitored both in pulse echo and pulse transmission modes. The pulse transmission signatures disappeared in 8 days. Then the corroded beams were dug out and the extracted bars were tested for mass loss and tensile strength. The ultrasonic test results were compared to the actual state of the bar.

Results and Discussions

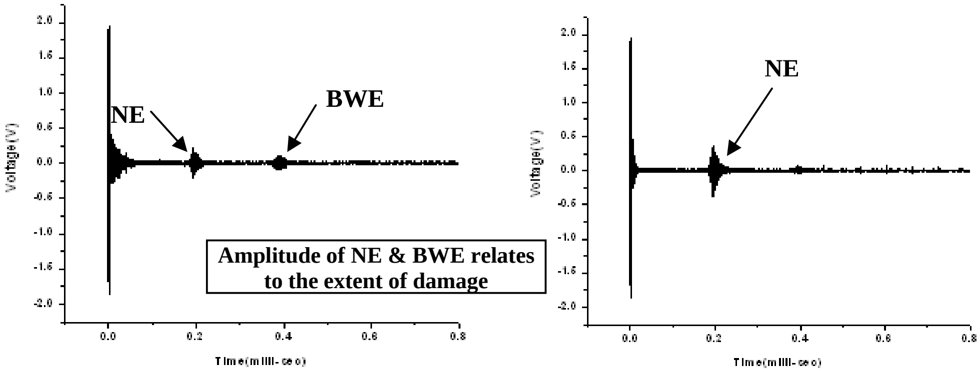
Simulated Notch Damage Study

Pulse echo records for a 12mm bar in concrete show the notch echo (NE) as well as the back wall echo (BWE). In a healthy specimen, the peak is the BWE (Fig. 2a). In a notched specimen, the 1st peak is NE and the 2nd peak is BWE (Fig. 2b). Appearance of NE indicates presence of the defect in the embedded bar. By knowing the time of flight of this echo, the location of the damage can be calculated .The magnitude of damage can be directly related to the magnitude of NE as well as BWE. It is observed that the amplitude of NE increased and that of BWE reduced with the increase in the notch dimensions (Fig. 2). As the magnitude of notch increased, more signal energy is reflected back from the notch and less of it is travels to the back wall.

In the pulse transmission signatures, the peaks observed (Fig. 3) are the transmitted peaks obtained after traveling length ‘L’ of the embedded bar. It may be noted that the arrival time of the pulse is not affected by the presence of the notch. Thus, the notch location is not discernible through pulse transmission. However, studying the relative change in the amplitude of input pulse and the transmitted pulse (P/T-Notch), an assessment of the severity of the damage can be made.

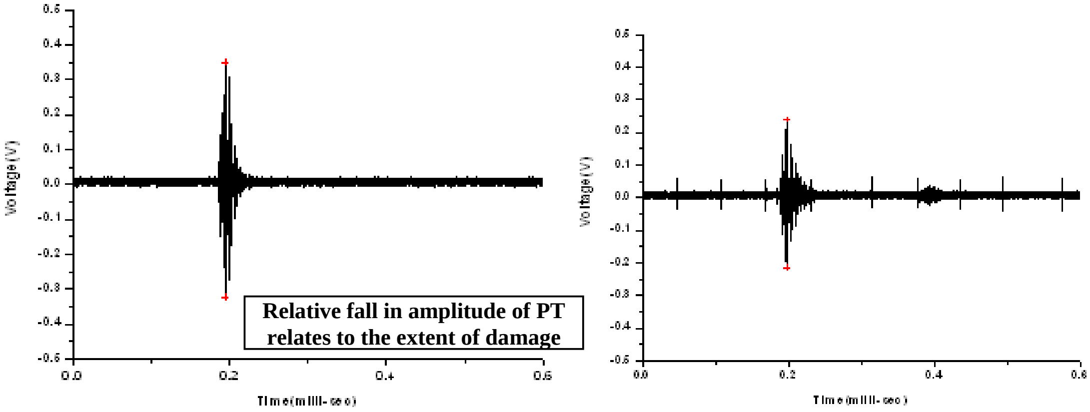


(a) Healthy Specimen (b) 20% notch in embedded bar



(c) 40% notch in embedded bar (d) 60% notch in embedded bar

Fig. 2: Pulse Echo Signatures of a 12mm, 1.1 m bar embedded in 700 mm of concrete [4]

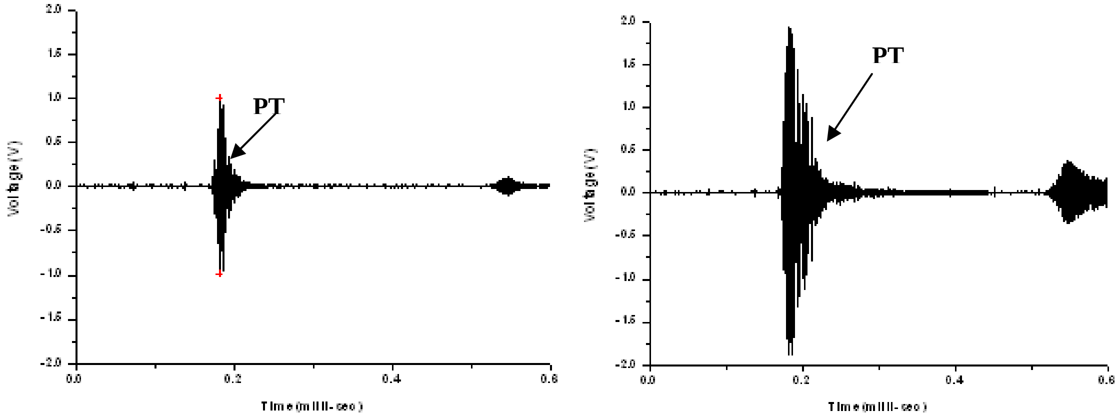


(a) Healthy Specimen (b) 60% notch in embedded bar

Fig. 3: Pulse transmission signatures of a 12mm bar embedded in concrete [4]

Simulated Debond

In simulated debond specimens, as the percentage of delamination increases, the transmitted signal strength (P/T-Debond) keeps on rising (Fig. 4). This is due to decrease in the amount of energy leaking into the surrounding concrete with increase in percentage delamination. Hence, an increase in P/T-Debond can successfully relate to the presence as well as extent of delamination.



(a) 12.5% Delamination (b) 100% Delamination

Fig. 4: Pulse transmission signatures in simulated delamination [4]

Comparison of Notch and Debond

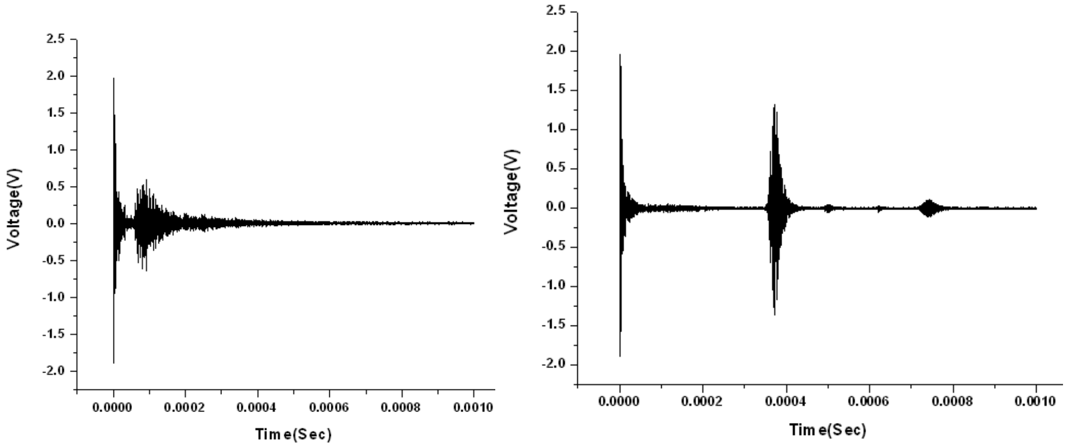
As the percent of damage increased from 0% to 60%, the magnitude of P/T-Notch reduces. This is because as the notch dimensions increased, more energy is reflected back and less of it travels through the bar to reach the other end. The counterbalancing effect of the two manifestations of corrosion –debonding and pitting is clear. Pitting that is similar to a notch reduces the strength of the transmitted pulse (P/T- Notch) while debonding increases the strength of the transmitted pulse (P/T-debond). Thus, it would be interesting to compare the simulated corrosion with the actual corrosion.

Actual Corrosion Study

Beams undergoing accelerated chloride corrosion showed reddish brown patches of corrosion products. A longitudinal crack appeared parallel to the bar within 3 days. With the increase in the volume of corrosion products, another crack parallel to the bar appeared on another face of the beam after 6 days. A reddish brown liquid oozed out of the cracks and the ends of the beam. The crack length and width increased with the increase in exposure. At 8 days of exposure, there were two large and wide longitudinal cracks that divided the entire beam into wedges.

Ultrasonic pulse echo signatures were monitored everyday during the exposure to the corrosive environment. In the healthy bar, the signature is characterized by a strong BWE (Fig. 5a). As the exposure proceeds, BWE attenuates rapidly and disappeared completely on 4th day. This is contrary to the expectation if corrosion is manifested through delamination only. Due to the non-uniform loss of material from the bar caused by chlorides, the waveguide is disturbed, thus resulting in scattering of waves. The scattering reduces the strength of the transmitted pulse further.

Another significant observation was the appearance of a peak between the initial pulse and BWE on the 2nd day (Fig. 5 b). This indicates that pulses are reflecting from a localized neck formed in the bar due to corrosion. From the time of flight of the peak, the location of the neck was estimated at the bar-beam interface. After completion of the corrosion process, concrete was removed and the extracted bar was observed. A large notch was indeed seen at the estimated location. As corrosion increased, amplitude of this peak increased indicating further loss of area from the interface. Figs. 6 and 7 compare the pulse echo results of simulated and actual corrosion. It is observed that corrosion in the presence of chlorides is characterized by localized loss of material similar to notches. In the present sample, one major notch developed due to corrosion resulting in a close match.



(a) 1st day signature

(b) 7th day signature

Fig.5: Pulse echo signatures during accelerated corrosion [4]

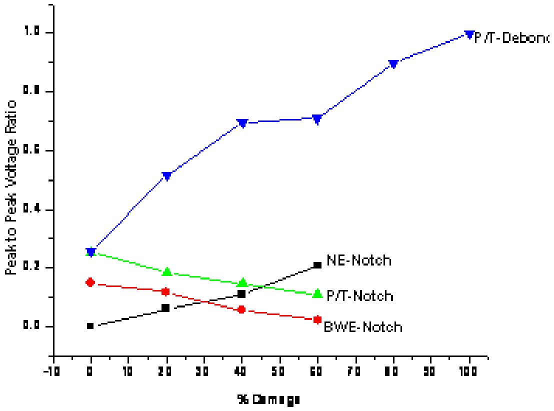


Fig. 6 : Peak-Peak voltage ratio trends of reflected and transmitted peaks [4]

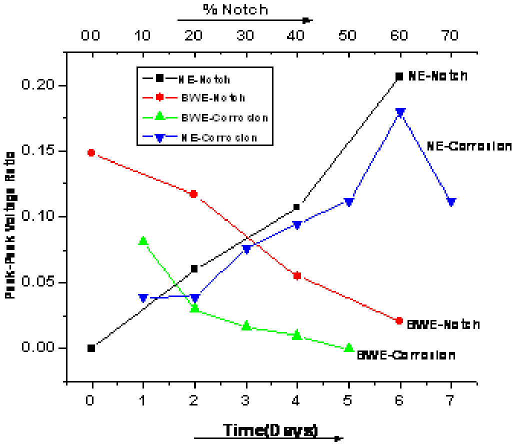


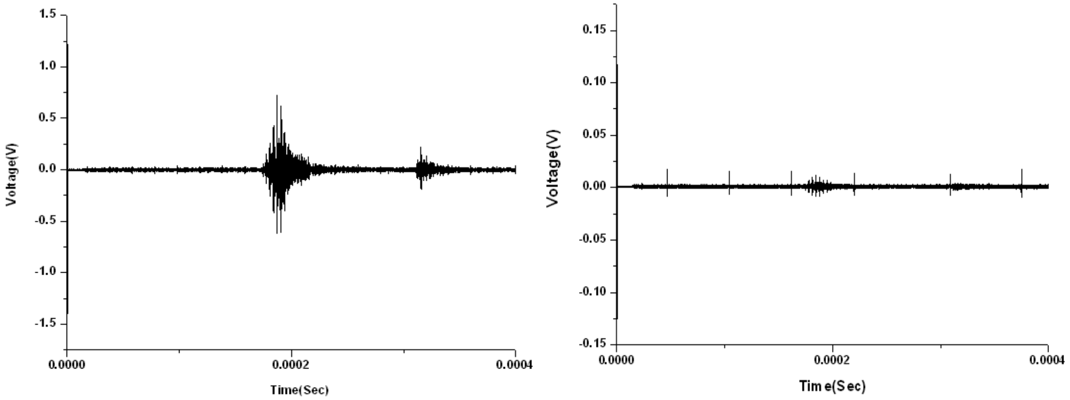
Fig. 7: Peak to Peak voltage ratio in pulse echo[4]

The pulse transmission studies where corrosion has been simulated as the loss of bond indicate that the transmitted signal strength goes up. Contrary to this observation, the transmitted pulse steadily lost strength as the corrosion progressed. It disappeared completely on the

7th day (Fig. 8). As discussed, the most likely cause of this phenomenon is the development of large pitting that further restricts the passage of waves. While notches restrict the passage of the waves, smooth delamination would facilitate the passage. Thus, pitting and delamination counteract each other. Fig. 9 compares the peak-peak voltage ratios of simulated and actually corroded bars. Clearly, the results of notch specimens are in closer agreement with the actual chloride corrosion. Thus, chloride corrosion is simulated better as notches rather than delamination.

The bars were subjected to a series to destructive tests after the period of exposure was completed. After eight days, the bar was removed from concrete and its mass loss and tensile strength were calculated. The bar had lost 18.6% of its mass. In tensile test, the bar failed in the region where a huge area loss was observed. The tensile strength reduced to 20% of that of undamaged bar.

These reductions in mass and ultimate tensile strengths correlate well with the ultrasonic monitoring results wherein the signal experiences huge 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 corrosion.



(a) 2nd day Signature (b) 5th day Signature

Fig. 8: Pulse transmission signatures during corrosion [4]

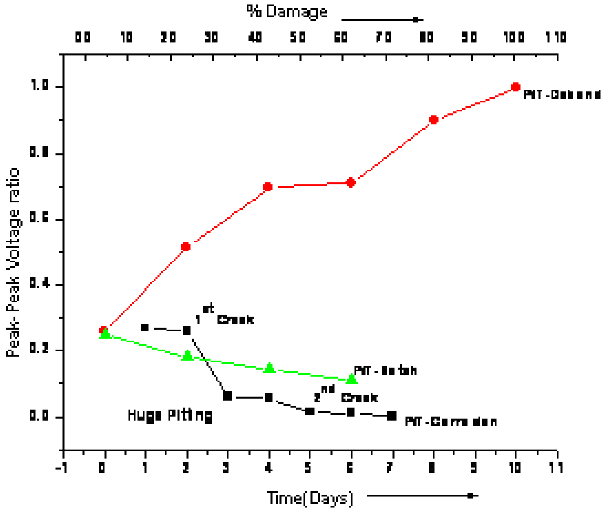


Fig. 9: Peak to Peak voltage ratio in pulse transmission [4]

GUIDED WAVES FOR DAMAGE MONITORING IN SUBMERGED STRUCTURES

Many structures like ship hulls, oil storage tanks, off shore oil platforms etc. are assemblies of large plate like components which are prone to deterioration and damages due to environmental degradation, excessive loads, fatigue loads, corrosion, etc. Criticality in such cases is further compounded due to economic constraints like high out of service costs associated with frequent health monitoring checkup schedules. The ultrasonic guided wave methodology is further applied for damage detection in such plate structures seeded with defects like notches, holes etc. where structure remains in submerged state. Presence of water makes it all the more challenging as water loaded structures exhibit higher attenuative behavior due to comparatively lesser impedance mismatch, but on the other hand it can be used to advantage as a natural couplant. This obviates the subjectivity that may creep-in while using direct contact techniques. Similar UT set-up is used for damage detection in submerged plate specimens with the scanning set up as shown in Fig. 10.

Symmetric Lamb wave modes in plates were preferred because of ease of excitation. Selection of a particular mode is dependent on the type of damage to be monitored. For guided waves in plates, not many studies exist. Basically, two types of Lamb wave modes can exist in isotropic, homogeneous plates-Symmetric and Anti-Symmetric. Fundamental symmetric and Anti symmetric modes describe a longitudinal wave and bending motion of the plate respectively. As compared to the bulk waves used in UT, these modes are dispersive in nature, i.e., propagation velocity depends on the frequency. Guided waves may be produced by varying the excitation frequency or by changing the angle of incidence. Placing a transducer on the specimen, a guided wave can be excited that interrogates the whole structure.

The ultrasonic guided waves have been used for damage detection in plated steel structures using frequencies of the order of 1-3 MHz. Ultrasonic techniques of pulse echo and pulse transmission can be effectively used in combination to detect the presence, exact location and quantification of the damage. Steel plate specimens with simulated defects in the form of localized area reduction were monitored in damaged state and compared with healthy specimens. Guided waves were generated by varying the input frequencies of the transducer. Different modes are excited at different frequencies and the suitable mode was chosen relevant to the defect to be characterized and ones corresponding to highest signal fidelities. Comparison of the wave signatures in healthy and simulated damaged state can easily reveal the existence, location and extent of damage with reasonable accuracy.

Plate geometry results in the generation of multi mode dispersive guided waves which are again obtained using software Disperse [3]. Different modes (symmetric and anti-symmetric) of varying orders can be selectively excited by offering subject structure at various critical angles to the incident energy. Different modes have varying levels of sensitivities to different types of defects like notch, dent, holes etc. Suitable modes are selected by testing the specimen implanted with a particular defect of varying degree in pulse transmission mode and observing the corresponding response of the received signal for various modes. Then specimen is tested in pulse transmission technique to ascertain the presence of the defect and subsequently pulse echo technique is employed to localize the same. The data obtained from these two techniques can be used to obtain the defect terrain of the specimen in the form of nice tomograms as shown in Fig. 11.

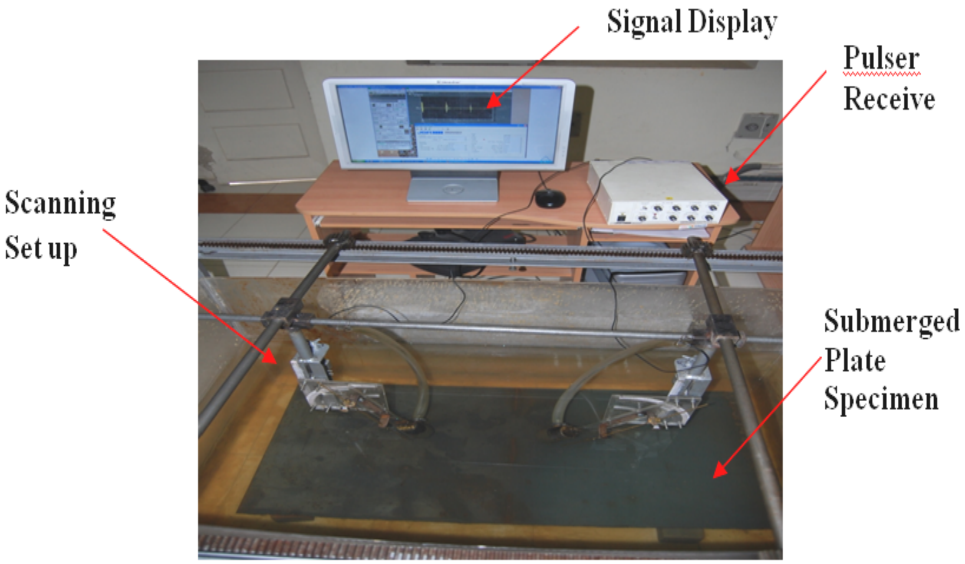


Fig. 10 : Experimental setup for submerged specimen

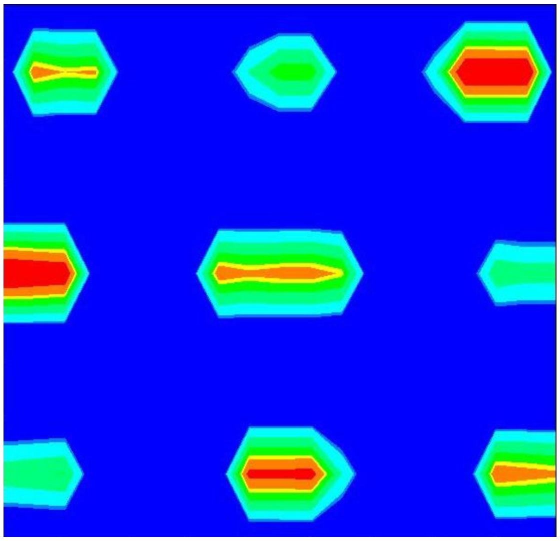


Fig. 11: Defect Terrain on a 4 mm thick submerged steel plate

CONCLUSIONS

Ultrasonic guided waves can be effectively used for monitoring corrosion damages in reinforcing bars embedded in concrete as well as in submerged steel plates by utilizing its wave guide effects. Corrosion in reinforcing bars has been simulated as loss of bond and loss of area. The results have been compared with that of a bar undergoing accelerated chloride corrosion. The notch specimens had a closer agreement with the corroded bars than the debonded specimens. Chloride corrosion roughens up the surface of the bar and creates large pittings. While it is desirable to perform ultrasonic monitoring when actual corrosion is taking place it is extremely time consuming. This paper highlights that a judicious contribution of delamination and notch would be essential to closely simulate the corroded bar. It has also been successfully applied to steel plates submerged in water simulating ship hulls and other hidden plate geometries. Guided waves offer a potentially attractive and a practically viable solution to discovering hidden structural degradations in civil and mechanical infrastructural systems.

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REFERENCES

[1] S. Sharma, S. and A. Mukherjee, Longitudinal guided waves for monitoring corrosion in reinforcing bars in concrete, *Structural Health Monitoring*, **13**, 555-567, 2010.
[2] S. Sharma and A. Mukherjee, Monitoring corrosion in oxide and chloride environments using ultrasonic guided waves, *ASCE J. of Material in Civil Engineering*, 23(2), 207-211, 2011.
[3] B.N. Pavlakovic, and P. Cawley, *DISPERSE User's Manual Version 2.0.1.1, Imperial College, University of London*, *London*, 2000.
[4] S., Sharma, S. and A. Mukherjee, Propagating ultrasonic guided waves through concrete reinforcements with simulated and actual corrosion, *CINDE Journal*, 31(2) 6-12.