2014

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Publication details

CORROSION MONITORING IN INFRASTRUCTURES USING ULTRASONIC WAVE PROPAGATION

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ABSTRACT

Building and subsequent maintenance activities of civil infrastructure are responsible for a large quantity of CO$_2$ emissions in the atmosphere. 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 signs of corrosion damage in reinforced concrete bars. Various wave propagation modes have been studied. The emphasis is on discovering hidden degradations such as corrosion of bars inside concrete and submerged plated structures. The mode structures and frequencies that are suitable for discovering the damages of interest are identified through a theoretical model. Reinforcing bars embedded in concrete have been corroded to different extents. The bars have been monitored using the theoretically determined frequencies during the progression of corrosion. Destructive tests are carried out at the end of the exposure to correlate to ultrasonic results. It is observed that specific guided wave modes can be created for identifying different types of corrosion. Thus, along with diagnosis the tests can be effective in prognosis of corroded structures.

KEYWORDS

RC beams, steel plates, corrosion, ultrasonics, guided waves, mode structures

INTRODUCTION

Inspection, diagnosis and prognosis of damage in infrastructural installations are fundamental for their satisfactory operation. Visual inspection, although important, is often ineffective due to elusive deteriorations deep inside the structures. Although many non-destructive evaluation (NDE) techniques are available for investigating the insides of a solid, large size of the Infrastructural installations makes use of these techniques unrealistic. For discovering deep hidden structural degradations in engineering installations, ultrasonic waves offer a potentially effective solution. But the use of ultrasonic bulk waves is limited due to high attenuation and inability to quickly scan large domains. For applications involving large area inspection in a quick way, guided waves have been suggested by various researchers as an effective and viable tool especially in discovering hidden anomalies (Ghosh et al. 1998; Lowe et al. 1998; Chen et al. 2010; Sharma and Mukherjee, 2010, 2011 and 2013; Sharma and
Guided waves have the characteristic ability to propagate over long distances and hence may quickly provide global information. Corrosion has been recognized as the major infrastructural problem affecting the service life of expensive structures. In this work, suitability of ultrasonic guided waves for corrosion monitoring in reinforcing bars embedded in concrete and submerged plates is investigated. Suitable ultrasonic guided wave modes have been identified for picking up delamination and pitting effect of chloride induced corrosion in reinforcing bars in concrete. A similar technique is demonstrated for submerged plated structures. The main contribution of this investigation is identification of specific mode structures for discerning different types of damages.

ULTRASONIC INVESTIGATIONS

Experimental Setup

Two types of samples have been prepared to investigate corrosion. RC beam specimens of dimensions 150 mm x 150mm x 700mm with a centrally place 25mm diameter steel bar were prepared with regular concrete. The bar projected out by 250mm on each side of beam. In natural environments, corrosion process takes many years to occur. The process was accelerated by impressing anodic current. Reinforcing bar was the anode and stainless steel wire mesh wrapped around middle 300mm chosen for corrosion exposure was the cathode and a constant voltage of 30V was applied. A dripping mechanism was fitted on the wire mesh to keep the cotton underneath saturated. For inducing chloride corrosion, 5% NaCl solution was used as drip. (Figure 1). For ultrasonic testing of reinforcing bars, a conventional ultrasonic testing system was used. 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 (DPR 300), the compressional transducers (Contact Type, Karl Deutsch Make) generate an ultrasonic pulse that propagates through the embedded bar in the form of longitudinal waves. The excitation signal consisted of a compressive spike pulse. The pulse transmitted at the other end of the bar was recorded on the receiving transducer.

The second set of specimens was mild steel plates of 4mm thickness in submerged conditions simulating ship and marine structures. To submerge the plates in the laboratory an acrylic tank (1500 mm x 1000mm x 900 mm) filled with water up to 750 mm height is used. Plate specimens (600 mm x 250 mm x 4mm) were placed on wooden blocks in the water tank. A pair of transducers arranged in pitch catch orientation is mounted on holders. The transducers can be moved along any direction by using stepper motors which are controlled individually by a microprocessor unit operated through a user interface. In addition, the probes can be set at a desired angle with respect to the vertical (least count 0.1 degree) (Figure 2). The ultrasonic testing setup was the same in both cases. A pulse of specific duration and amplitude is generated by the PR. The transmitting transducer delivers the pulse to the coupling water. The wave is propagated by the water and it strikes the plate at the desired angle. The transmitted pulse is sensed by the receiving transducer and presented on the display device. The data acquisition system records the signature for further analysis.

Selection of Excitation Modes for Ultrasonic Testing

The selection of frequencies for testing was done using the software Disperse (Pavlakovic and Cawley, 2000). They were also validated by experimentally confirming the signal fidelity. The modes that are easily distinguishable and have lowest signal attenuation were selected. For bars embedded in concrete, which is a layered waveguide system, leakage plays an important role. Frequency regions with lowest attenuating modes are the ones with displacement profiles centered in the middle of the bar to minimize leakage but at a low enough frequency to avoid substantial absorption. From the dispersion curves for 25mm diameter bar in concrete (Sharma and Mukherjee, 2013) fundamental mode, L (0, 1) mode at 100 kHz starting at zero frequency with low attenuation was selected. Another mode L (0, 7) at 1 MHz forms a low leakage mode corresponding to maximum energy velocity and minimum attenuation was also used for ultrasonic investigations.
The main feature for the selection of modes was its mode shape that determines the radial distribution of displacement and energy density. Chloride induced corrosion leads to delamination of the bar from the surrounding concrete due to formation of rust product and further leads to pitting inside the bar. Thus, a mode that has significant surface component would be sensitive to delamination effect of corrosion and \( L(0, 1) \) is such a mode and is referred to as surface sensitive mode (Figure 3a) (Sharma and Mukherjee 2011). The pitting effect of chloride corrosion, on the other hand, would manifest itself in a mode that progresses mainly through the core of the bar and has negligible surface component. \( L(0, 7) \) is such a mode and is referred to as the core sensitive mode (Figure 3b). Thus, these two modes would be used in combination to investigate chloride corrosion. Pulse transmission was monitored once each day for 28 days. The signals had no significant variation after that time.

Similarly in plates, specific Lamb wave modes of \( S_0 \) at 0.5 MHz and \( S_1 \) at 1 MHz were selected based on the principle of lower material attenuation, scattering and mode conversions at lower frequencies (Sharma and Mukherjee, 2014 a). Studying the mode shape of \( S_1 \) mode at 1 MHz indicates significant displacement or energy distribution near the surface as compared to the core of the plate and is similar to the core sensitive mode as in RC beams. Similarly, the behavior of \( S_0 \) mode at 0.5 MHz shows more energy concentrated at the mid plane of the plate and hence is core sensitive mode. In this work, the efficacy of these modes to detect surface and deep pits due to corrosion in submerged structures will be established.

### RESULTS AND DISCUSSIONS

#### Visual Observations

Beams undergoing accelerated corrosion showed formation of large parallel cracks accompanied by oozing out of liquid corrosion product and extensive rust stains. A longitudinal crack appeared parallel
to the bar within 7 days. The cracks initiated at the surface of the beam and progressed along the direction of the reinforcement. The crack length and width increased with increase in exposure. At 28 days of corrosion, there were two large and wide longitudinal cracks that divided the entire beam into wedges and the beam was in a significantly damaged condition. Similarly, the mild steel plates undergoing accelerated chloride corrosion showed blackish brown corrosion products floating in on water within 6 hours of exposure. After 2 days of subjecting to corrosive environment, corrosion patches in the form of small pits were observed on the plate. The pits deepened and spread on the surface of the plate with increasing exposure. The process continued till 13 days and was stopped when pits gave way to two holes in the plate.

Monitoring with Surface Sensitive Mode

Figure 4a shows ultrasonic voltage trends of the received signal in the RC beam specimens using surface sensitive mode L (0, 1) at 100 kHz. Rise in signal amplitude was observed right from the 2nd day indicating loss of bond between steel and concrete and this continued until 12 days. After 12 days of exposure, the signal amplitude continuously dropped until it became more or less constant after 21 days. The ultrasonic observations matched closely with the chloride corrosion mechanism. Initially, the formation of corrosion products on the surface of the bar caused its delamination from the surrounding concrete. This continued until a considerable amount of delamination took place. Later, presence of chloride ions resulted in deterioration of the bar through local loss of material. It leads to attenuation of the signal and that continued throughout the remaining period of exposure.

Ultrasonic PT signatures in the plate were also recorded periodically at predetermined locations using the surface sensitive S1 mode at 1 MHz. Initially, the signature is characterized by a strong pulse at all locations of the plate. With the onset of corrosion, changes are observed in PT signatures. Figure 4b shows normalized peak to peak voltage ratio amplitudes of the transmitted PT signals (Vn) at various locations on the plate using the surface sensitive mode with increasing days of corrosion. The transmitted signal attenuates with increasing exposure to corrosive environment indicating material loss due to corrosion. Maximum drop in voltage amplitude is observed at locations marked on the plate where formation of holes takes place in 13 days. It suggests significant localized corrosion in these regions. Another observation is that the signal drops significantly only in the first 6 days of corrosion. It drops to 20% of its original value in the first 6 days. As corrosion progresses (7-13 days), no significant attenuation in the signal is observed. This is due to the surface sensitive nature of the mode which picks up early surface modifications but is not responsive to the deep pits with increasing exposure.

Monitoring with Core Sensitive Mode

Figure 5a shows the peak to peak ultrasonic voltage ratios of the received and input signals for the core sensitive mode L (0, 7) at 1 MHz in RC beam. The beam showed no significant change in voltage amplitude of the transmitted pulse until 6 days. After 6 days, there was a continuous drop in the amplitude until it disappeared completely on the 25th day. This pointed towards drastic non-uniform
area loss in the form of pits on the whole length of the bar. The widespread loss of area was confirmed visually by opening the beam. As corrosion progressed, there was increase in loss of energy due to scattering, multiple reflections and mode conversions. Hence, there was a drastic fall in signal amplitude.

From the ultrasonic plots, the mechanism of corrosion of reinforcing bar in presence of chlorides can be understood. Corrosion in the presence of chlorides (CC) begins with the delamination of bar from the surrounding concrete marked by increased signal amplitudes using the surface sensitive mode. As corrosion progresses, it is marked by local loss of area in the form of pitting and crevices along with debonding of bar which is discerned by the core sensitive mode. As exposure increases, there was a drastic fall in signal amplitude in both L(0, 1) and L(0, 7) modes due to increase in loss of energy caused by scattering, multiple reflections and mode conversions.

Figure 5 shows the normalized values of the received signals in steel plates using core sensitive $S_0$ mode at 0.5 MHz with progressive corrosion. PT scanning of the plate using this mode exhibits relatively less changes during the initial 6 days as compared to the surface sensitive $S_1$ mode. Drop in signal is only 30% using core sensitive mode as against 80% drop observed using surface sensitive mode during the initial 6 days. This mode does not sense surface deteriorations as effectively as the $S_1$ mode. As corrosion further progresses, consistent drop in voltage amplitude is observed with this mode throughout the corrosion period. This is due to the core sensitive nature of the mode. This mode picks and points towards massive non-uniform material loss in the form of pits. The widespread loss of material due to corrosion is also confirmed visually. Hence, it can be concluded that the surface sensitive mode picks up the initial surface changes due to corrosion; while the core sensitive mode is effective in picking up the progression of corrosion leading to pitting. Thus, surface corrosion and pitting corrosion can be easily discerned through the proposed method both in case of reinforcing bars in concrete and submerged steel plates.

**Destructive Testing and Results**

A test matrix corresponding to 6, 12, 18 and 28 days of exposure to corrosive environment in RC beams was established. The bars were subjected to a series to destructive tests of pull out, tensile strength and mass loss was also measured. From the destructive test results for different days of exposure for RC specimens, loss in residual mass, pullout strength and tensile strength was observed with the increase in the days of exposure. The 28 day bar had lost 5.15% of its mass, 32.8% of its tensile strength and 28% of pullout strength to that of healthy bar. The higher percentage loss of tensile and pullout strengths in comparison to the mass indicates that the loss of mass is not uniform and is rather local. The visual inspection also confirmed that the bar had experienced severe and widespread pitting. Similarly in case of plates also, consistent loss in mass and tensile strength was observed with increasing corrosion. After 13 days of corrosion, the plate had lost about 3% mass and a maximum of 90% thickness in comparison to the healthy plate. The loss in tensile strength is 94.7%. High percentage loss in thickness and tensile strength is due to localized corrosion resulting in pitting.
The visual inspection also confirmed that the plate had experienced severe and widespread pitting in the exposed area.

CONCLUSIONS

Ultrasonic guided wave monitoring utilizing specific core and surface sensitive modes successfully identifies mechanism of corrosion in submerged and embedded systems as represented by submerged plates and reinforcing bars in concrete. In bars in concrete, huge pitting and non-uniform area loss highlighted by severe signal attenuation marks chloride corrosion is well picked up by core sensitive mode. It begins with delamination shown by signal rise with surface sensitive mode. Thus, through a judicious selection of ultrasonic modes chloride corrosion phenomenon in RC structures can be successfully identified. Similarly, different Lamb wave modes in submerged plates can pick up degradation due to marine corrosion very effectively simulating ship hulls in water. Guided waves utilizing specific core and surface sensitive modes can be successfully used for non-contact scanning of the plates undergoing accelerated progressive corrosion. Uniform and pitting corrosion could be discerned by the selected modes.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support provided by Department of Science and Technology (DST) Govt. of India (Project No: SR/S3/MERC-0035/2012 ) and the Naval Research Board (NRB, DRDO) Govt. of India (Project No. NRB/MAT/289/2013) for carrying out the research.

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