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Effect of Surface Condition and Corrosion-Induced Defect on Guided Wave Propagation in Reinforced Concrete

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ABSTRACT: *Corrosion of reinforcing steel bars is a major concern for ocean engineers when reinforced concrete structures are exposed to marine environments. Evaluating the degree of corrosion and corrosion-induced defects is extremely necessary to pursue a proper retrofit or rehabilitation plan for reinforced concrete structures. A promising inspection should be carried out for the evaluation, otherwise the retrofit or rehabilitation process would be useless. Nowadays, ultrasonic guided wave-based inspection techniques become quite promising for the inspection, mainly because of their long-range propagation capability and their sensitivity to different types of defects or conditions. Evaluating how the guided waves response to the different types of defects or conditions is quite challenging and important. This study shows how surface conditions of reinforcing bars and a corrosion-induced defect, separation, affect guided wave propagation in reinforced concrete. Experiments and associated signal analysis show the sensitivity of guided waves to the surface conditions, as well as the amounts of separation at the interface between concrete and steel bar.*

1. Introduction

The corrosion of reinforcing steel can be initiated either when the hardened cement paste carbonates to the cover depth reducing alkalinity, or when chlorides migrate through the concrete cover and build up in sufficient quantities to break down the passive oxide layer (Batis et al., 2003). Once the reinforcing steel corroded, the rust occupies a volume two to four times greater than the parent steel, resulting in bursting stresses that ultimately crack and spall the concrete cover (Jamil et al., 2004). Those crack and spall accelerate the corrosion more; hence, a proper corrosion control is required to sustain its demanded service life and be able to resist the ravages of time and deleterious effects of harsh environmental conditions.

In marine environments, reinforcing steels embedded in concrete structure have more chance to be corroded mainly due to seawater, chloride ion in air, and deicing materials used in winter season. In addition, current global climate change may be another source of accelerating the corrosion since the change makes the rise of sea level as well as sea temperature although the effect has not been well established yet. This effect can be treated slightly but we should not definitely grant it negligible since there have been discussions about how the change affects on corrosion of steel structures (Mesa et al., 2003; Watanabe et al., 2003; Neville and Hodgkiess, 1996; Kai et al., 1997). Especially, Melchers (1999) showed that the higher temperature leads to greater corrosion of steel structures for short-term exposure and for water temperatures greater than about 10°C. Thus, it seems valuable to investigate the temperature effect on reinforcing bars in marine environments as well. In addition, other environmental factors such as oxygen, salinity, PH effects, microbiological influences, seawater fluid flow, pollution, etc. make the corrosion mechanism more complicated (Al-Malahy et al, 2003; Shifler, 2005). Therefore, the corrosion of reinforcing steel in concrete should be carefully controlled on design, construction, and maintenance stages, otherwise the design life can not be guaranteed and cumbersome inspection and retrofit should be frequently accompanied.

In design stage, the analysis of chloride ion penetration should be performed to estimate how the design life would be and how an efficient and economic protection is designed. In general, the traditional ways of the corrosion protection are: (1) improving the quality of concrete and increasing cover depth (Jamil et al., 2004), (2) protection at the concrete surface, (3) implementing cathodic protection, and (4) protecting the reinforcement at the steel/concrete interface. The last mentioned protection method usually employs coating of the reinforcing steel. Several coating materials are available such as zinc coating, hot-dip galvanizing (Cheng et al., 2005), epoxy coating (Erdoğdu et al., 2001), interpenetrating polymer network system based coating (Asthana et al., 1999), and inhibited cement slurry coating (Vedalakshmi et al., 2000). Coatings applied to reinforcing steel offer an effective and reliable solution for the embedded reinforcing steel at new construction stage while during

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maintenance other protection methods are more practical and effective. In construction stage, the storage and transportation of reinforcing bars should be well operated to prevent any degradation of reinforcing bars due to atmospheric corrosion (Batis and Rakanta, 2005; Castro et al., 1997).

In maintenance stage, systematical planning and budgeting of maintenance activities are necessary to avoid unexpected large-scale rehabilitation because of negligence of periodic maintenance (Zen, 2005). Without a promising and reliable inspection, retrofit would be inefficient; hence, there has been a concerted demand for the development of non-destructive technique mainly due to the widespread corrosion problems of reinforcing steel in concrete structures. A number of electrochemical techniques such as half-cell potential mapping have been developed to assess in situ the corrosion equilibrium and corrosion rate of the reinforcing steel (Leelalerkiet et al., 2004). However, while the instantaneous corrosion rate may be used as a guide to estimate the probable loss of steel, concerns remain over the accuracy of these monitoring techniques and the reliability of such estimates. In order to acquire more accuracy, linear polarization resistance (LPR) measurement is employed to measure the loss of steel due to corrosion (Law et al., 2004). AC impedance is also one of methods used to measure corrosion rate but it is generally considered unsuitable for field application.

Secondary defects due to corrosion such as delamination and crack can be also inspected by several methods. Acoustic emission coupled to electrochemical techniques is applied to detect concrete cracking during corrosion (Assouli et al., 2005). X-ray is often the preferred method because it gives the positive identification of an object on a developed X-ray film (Rens et al., 2000). Ground penetrating radar (GPR) method is capable of detecting both voids and delaminations because these discontinuities create interface between concrete and air within the bulk concrete (Scott et al., 2000). Impact echo method could be used for detecting voids in grouted ducts or reinforced concrete structures (Carino and Sansalone, 1992). Ultrasonic methods are applied to inspect voids at the interface between grouts and steel tendons in ducts (Pavlakovic et al., 1998). Ultrasonic guided wave based nondestructive techniques have been applied to detect corrosion-induced defects in concrete (Na and Kundu, 2002; Rizzo and Lanza di Scalea, 2005). The potential of ultrasonic guided waves are well established since guided waves propagate a long distance and they have several wave modes that can be sensitive to different types of defects. However, due to the complexity of ultrasonic guided wave propagation, well-designed devices and techniques for transmitting, propagating, receiving, and analyzing guided waves are required.

With those challenges and demands above, this study mainly concerns about developing a nondestructive testing technique capable of monitoring or detecting the surface condition of reinforcing steels or corrosion-induced defects in concrete. The inspection technique adopted here is the ultrasonic guided waves-based nondestructive technique because of its capability mentioned previously. As mentioned earlier, for the successful application, a well-designed device and technique should be used. Thus, here, a hybrid sensing mechanism i.e. the combined use of PZT (Piezoelectric Zirconate Titanate Transducer) and EMAT (Electromagnetic Acoustic Transducer) is designed. This study is focused on not only detecting the corrosion-induced defect but also estimating how the corrosion condition on the steel surface affects on the guided waves. For the purposes, three different corrosion conditions such as corrosion free, corroded, and zinc coated and corroded are inspected for the inspection and, for each surface condition, three different degrees of separated specimens are fabricated to see the effect of the separations, a kind of corrosion induced defect. As a signal analysis tool, after ultrasonic guided waves testing, time domain signals are transformed to time-frequency signals through a continuous wavelet. Then, the time-frequency domain signals are carefully examined to verify the potential of the ultrasonic guided wave testing employing the hybrid sensing and the continuous wavelet transform (CWT). Finally, the observations have made and concluded.

2. Hybrid Sensing

Figure 1 shows the conceptual layout of how guided wave generated. Refraction and reflection of P or S wave propagating through a specific waveguide causes mode conversions so that a wave packet is finally generated, this wave is called guided wave. For the successful guided wave propagation, a hybrid sensing combined PZT as a transmitter and EMAT as a receiver is designed. This design is based on fact: (1) PZT gives relatively less consistent testing results due to the use of coupling materials such as water, vaseline, etc. (2) EMAT generates relatively low energy strength. Thus, the combined use of PZT and EMAT can overcome those disadvantages mentioned above. Figure 2 shows the schematic layout of the hybrid sensing as well as the experimental setup used. Figure 3 shows the pictures of EMAT and PZT used during experiments.

Three different corrosion conditions of reinforcing steels are investigated: (1) corrosion free (set #1), (2) corroded (set #2), and (3) zinc-coated and corroded (set #3). Figure 4 shows the pictures of three corrosion conditions. The corroded specimens in specimen set two and three had been left outdoors for natural corrosion. Each specimen set consists of three specimens having different separated regions at the reinforcing steel and concrete interface. Those are 0%, 25%, and 50%, respectively as shown in Fig. 4. Thus, total nine specimens are tested by the ultrasonic guided wave technique employing the hybrid sensing mechanism shown in Fig. 2.

3. Signal Analysis

In general, raw signals are time-amplitude representations. These time-domain signals are often needed to be transformed into other domain such as frequency domain, time-frequency domain, etc. for signal analysis. Transformation of signals helps to identify distinct information, which might otherwise be hidden in the initial domain. Depending on application, the transformation techniques should be selected, and each technique has its own advantages or disadvantages (Na et al., 2006).

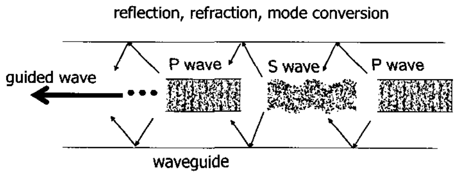


Fig. 1 Conceptual layout of how guided wave generated

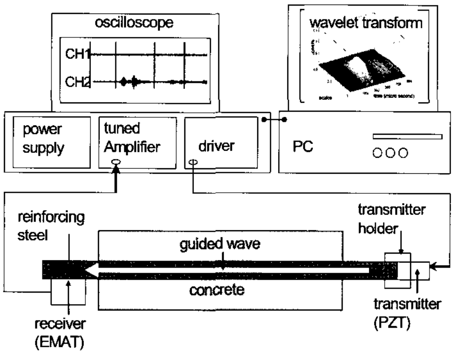


Fig. 2 Schematic layout of the hybrid sensing and experimental setup

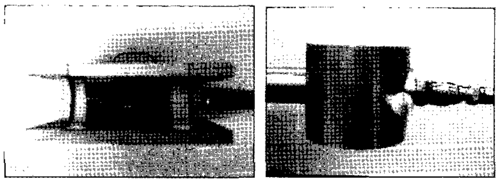


Fig. 3 Pictures of EMAT (left) and PZT (right)

Figure 5 shows one of the original time domain signals obtained from the test. After transforming the time signal using the wavelet called db10 (Daubechies 10), the following figures, Fig. 6, Fig. 7 and Fig. 8 are obtained for each specimen set and specimen. Daubechies 10 is an orthogonal and asymmetrical mother wavelet (Na et al., 2006). In the figures, scale is the inverse of frequency so it is time-scale view of the signal. By comparing those figures, it is observed that the surface conditions affect the coefficients on the CWT in the following ways: (1) corrosion free specimens have higher coefficients than corroded specimens in specimen set #2 and #3. (2) By comparing set #2 and #3, zinc coated specimens (set #3) have less coefficients than set #2. (3) This shows that although zinc is used for corrosion protection, once the steel corroded, it attenuates ultrasonic guided waves significantly. In terms of the degrees of the separated regions, it is shown that the more separated the larger coefficients.

Thus, it is concluded that the ultrasonic guided wave test is effective for distinguishing the states of surface corrosion of the reinforcing steels as well as the amounts of the separated regions at the interface between concrete and steel.

To investigate the effect of zinc coating on guided wave propagation, four different numerical models are constructed

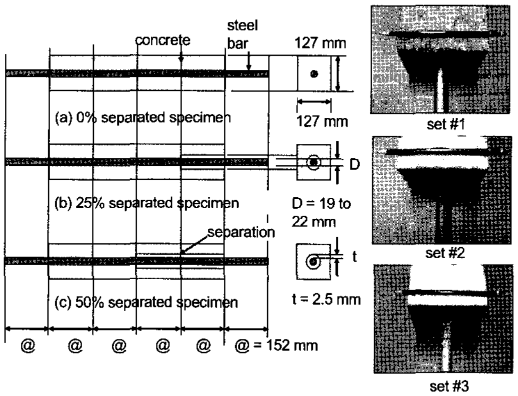


Fig. 4 Layout of specimen

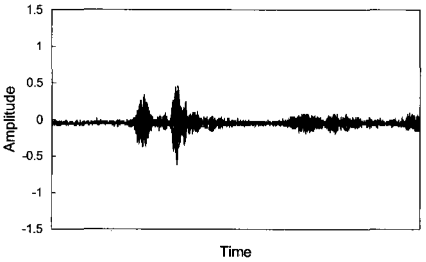
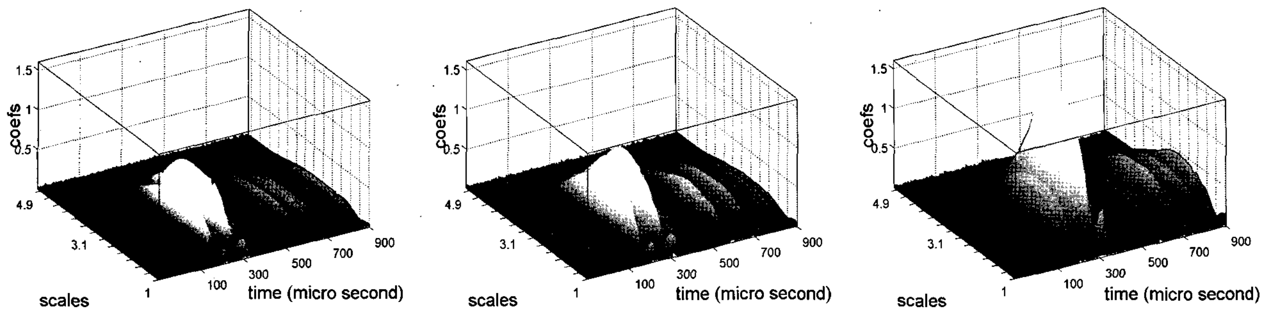
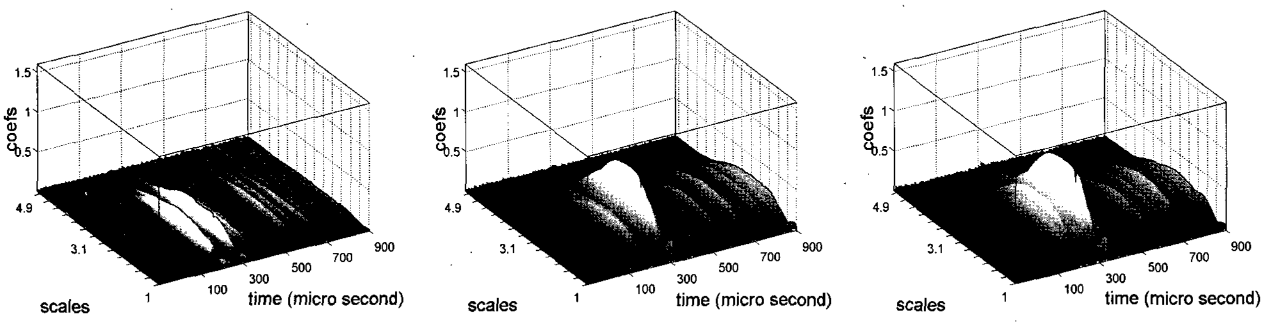


Fig. 5 Time domain signal obtained from the test. The target specimen is 0 % separated without corrosion on the surface of the reinforcing steel (specimen set #1)



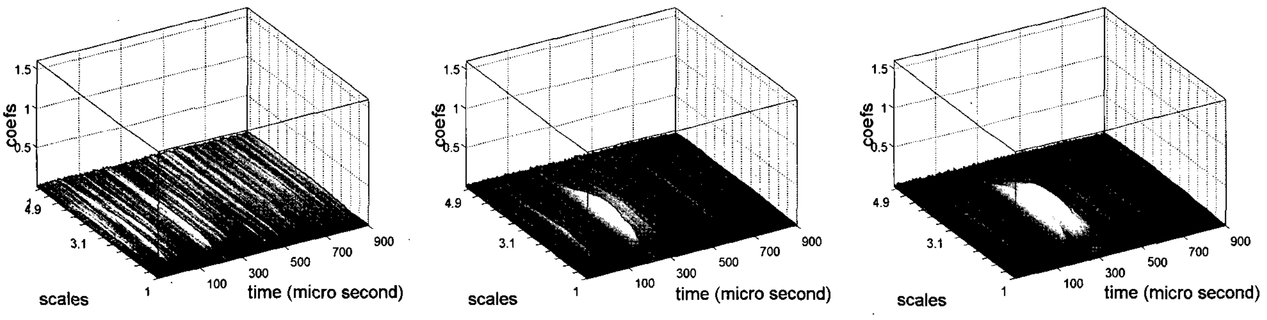
(a) (b) (c)

Fig. 6 Continuous wavelet transform (db 10) for (a) 0 %, (b) 25 %, and (c) 50 % separated specimens. The reinforcements are not corroded (specimen set #1)



(a) (b) (c)

Fig. 7 Continuous wavelet transform (db 10) for (a) 0 %, (b) 25 %, and (c) 50 % separated specimens. The reinforcements are corroded (specimen set #2)



(a) (b) (c)

Fig. 8 Continuous wavelet transform (db 10) for (a) 0 %, (b) 25 %, and (c) 50 % separated specimens. The reinforcements are zinc coated and corroded (specimen set #3)

as shown in Fig. 9. The first model (model 1) is constructed to consider extremely small zinc thickness, 1×10^{-7} mm, and the outside concrete is assumed infinite for numerical stability. The second model (model 2) excludes the zinc coating and the outside concrete is infinite. The third model (model 3) shows the ultimate case, in which the zinc is the infinite medium. Finally, the fourth model is constructed to consider 1mm thick zinc coating, in this case also, the outside concrete is infinite. For all models, the diameter of steel bar is 19 mm. Table 1 shows the acoustic properties of steel, zinc, and concrete used for the calculations.

With the constructed numerical models, attenuation dispersion curves, as shown in Fig. 10, are obtained after cumbersome numerical calculations (Na et al., 2005). This curves show how the $L(0,1)$, the first longitudinal guided wave mode, attenuates with respect to frequency. As expected, the zinc thickness 1×10^{-7}mm does not affect the attenuations so that the dispersion curve is exactly match with that of model 2. However, in the case of model 3, the attenuation is much larger than the cases of model 1 and model 2. This fact shows that zinc increases attenuation. In the case of model 4, the attenuation is in the middle between model 3 and model 1 (or 2) although it is slightly less than model 1 (or 2) over very low frequency.

Based on the observation from the numerical calculations, as shown in Fig. 10, it is concluded that the zinc coating increases the attenuation of L(0,1) mode. This observation supplements the observations in Figs. 6, 7 and 8 although the corrosion is not considered in our numerical model.

Table 1 Acoustic properties of steel, zinc and concrete

	Density [kg/m^3]	P wave speed [m/sec]	S wave speed [m/sec]
steel	7932	5960	3260
zinc	7100	4170	2410
concrete	2200	4100	2300

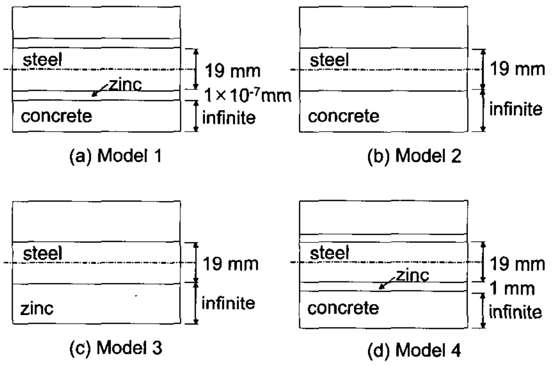


Fig. 9 Four different numerical models to investigate the effect of zinc-coating

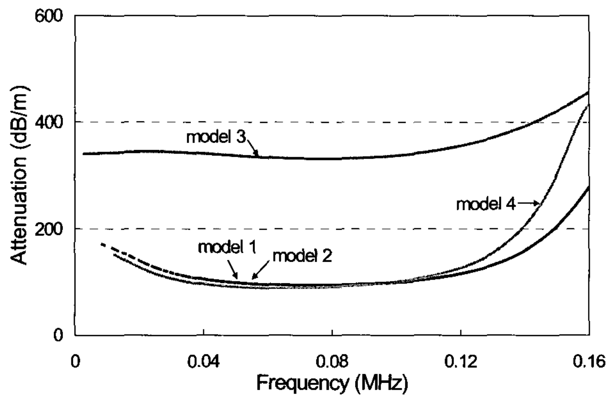


Fig. 10 Attenuation dispersion curves of each model

4. Summary and Conclusion

Guided-waves-based technique is used here for estimating the surface condition of steel reinforcing bars and for distinguishing the degrees of delaminations at the interface between concrete and steel bars. A hybrid sensing using EMAT and PZT is applied for the experiments. From the experiment, time domain signals are experimentally obtained and then these signals are transformed to the time-frequency signals by the Continuous Wavelet Transform. By examining the time-frequency signals, it is shown that ultrasonic guided waves are very sensitive to the surface conditions i.e. corrosion free, corroded, zinc-coated and corroded. It is also shown that the used technique is quite sensitive to the amounts of delaminations (actually they are separations), thus the potential of ultrasonic guided waves are shown here. This study shows that the guided waves techniques employing the hybrid sensing and CWT are quite effective for the selected applications.

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