The 2017 World Congress on
Advances in Structural Engineering and Mechanics (ASEM17)
28 August - 1 September, 2017, Ilsan(Seoul), Korea

Corrosion monitoring of steel bar using guided wave method

*Wensong Zhou[1], Cheng Ma[2] and Hui Li[3]

[1), 2), 3)] Key Lab of Structures Dynamic Behavior and Control of the Ministry of Education, Harbin Institute of Technology, Harbin 150090, China
[1)] zhouwensong@hit.edu.cn

ABSTRACT

This work studies on the corrosion monitoring method for the steel bar without and with concrete cover respectively based on guided ultrasonic wave methods. There are two typical corrosion forms: uniform corrosion and local corrosion for the steel bar without concrete cover. For the former, the time of flight (TOF) of the main packet of the received signal was chosen as the corrosion indicator. For the latter, the amplitude of signal, RMS (Root Mean Square) of first wave packet, and the total energy ratio of first wave packet are chosen corrosion as the indicators. Among of them, the total energy ratio of first wave packet is reference free, thus it is more suitable for the practical applications. For the steel bar embedded in concrete, the amplitude, TOF and frequency spectrum of the guided wave signal were used to distinguish the different corrosion stages. Finite element analyses were carried out to find out the optimal parameters, the characteristic of guided signals, and the quantitative corrosion indicators. A series of electrochemical accelerating corrosion experiments was designed to verify the proposed corrosion indicators. Results obtained from the experiments indicate the validity of the proposed method.

1. INTRODUCTION

Reinforced concrete is the most popular construction material for the infrastructures. The steel bar is used widely as the reinforcing materials to resist tensile stresses in particular regions of the concrete that might cause unacceptable cracking or structural failure. For the steel bars, corrosion is one of the destructive effects, which will lead to the deterioration of the bearing capacity of concrete structures. In normal, the steel bars are embedded within concrete, thus their corrosions are difficult to be detected by the conventional meanings timely.

Among the various structural health monitoring (SHM) or nondestructive testing

[1)] Professor
[2)] Master Student
[3)] Professor

(NDT) methods, guided ultrasonic wave based methods have been proved that they are sensitive to small structural damages or other changes in the structures, such as corrosion (Reis *et al*. 2005, Ervin *et al*. 2009, Sharma *et al*. 2010, Rathod and Mahapatra 2011, Miller *et al*. 2012, Moustafa *et al*. 2014). Moreover, guided wave based methods can conduct a long-range and complete distributed monitoring over the entire structure.

A number of investigations have been undertaken with the aim to detect the corrosions at their early stages. Farhidzadeh *et al*. (2015) proposed a reference-free corrosion damage diagnosis method for prestressing steel strands using guided ultrasonic waves. They focused on the change in the diameter of prestressing steel strands during the corrosion process. Signals with frequency from 300kHz – 700kHz were used to excite L(0,1) mode, whose group velocity changed with the diameter of steel strands. Continuous wavelet transform was employed to identify the frequency of wave packets. This method has low sensitivity for the initial corrosion stage, since the diameter changes a little. Amjad *et al*. (2015) estimated the corrosion level through the differential time-of-flight (TOF) of the propagating wave modes. The differential TOF was obtained from the time-frequency representations and from the high temporal resolution using the cross-correlation technique.

For the steel bar embedded in the concrete, guided waves energy will leak into the concrete materials, which leads to the large attenuation and short propagation distance of guided waves. The wave modes at high frequency have special wave structure, so above problem might be avoided. Pavlakovic *et al*. (2001) studied the specific wave modes at high frequency, which has the minimum attenuation in the concrete. For a steel bar with 12mm diameter, the displacement locates the central region mainly, according to the wave structure of L(0,9) mode at 7.312MHz, the energy leakage reaches the minimum. Experimental demonstrations on a steel bar with 8.1mm diameter indicated also that the attenuation is minimum at frequency about 5MHz. In Ervin and Reis's work (2008), L(0,1) and L(0,9) mode were invoked for low- and high-frequency testing, respectively. The former is sensitive to the combined effects of bond deterioration and mortar stiffness reduction, while the latter is sensitive to the corrosion in the steel cross-sectional area. Sharma and Mukherjee (2011) used pulse transmission and pulse echo to monitor the healthy and corrosion steel bar specimens. Results indicated that pulse transmission could relate to the percentage delamination very efficiently for a steel bar embedded in concrete.

Based on the state of the art in this topic, in this work, a series of corrosion indicators is proposed to quantify the different type corrosion for both the steel bar without and with concrete cover. In the remaining part of this paper, the guided waves in steel bar will be presented first. Finite element analysis is performed in detail to study the characteristics of guided waves in the presence of the simulated corrosion. Finally, the experimental setup, procedure, and results of the experimental test will be presented and discussed.

2. GUIDED WAVES IN STEEL BAR

Guided waves in steel bar are more complex than those in plate-like structures, in which there exist only symmetric (S) mode, anti-symmetric (A) mode and SH mode waves. The frequency wavenumber relation of guided waves in steel bar is described by the Pochhammer-Chree (PC) frequency equation, whose exact solutions were first studied by Gazis. For the wave propagating along the axial direction of the steel bar, these solutions lead to three different classes of wave propagating modes: the axisymmetric torsional modes T(0,n) and longitudinal modes L(0,n), and the non-axisymmetric flexural modes F(m,n). Here, m stands for the circumferential order and n stands for the wave family number. They are all dispersive except the fundamental torsional mode, T(0,1).

Fig. 1 shows the dispersion curves for a 12 mm steel bar. Torsional modes are not considered in the curves, since they are not easy to generate usually. Through the dispersion curves, the group velocity for different wave mode can be determined at arbitrary frequency. This will be helpful for signal analysis by using wavelet transforms, which can obtain TOF of signals at arbitrary frequency.

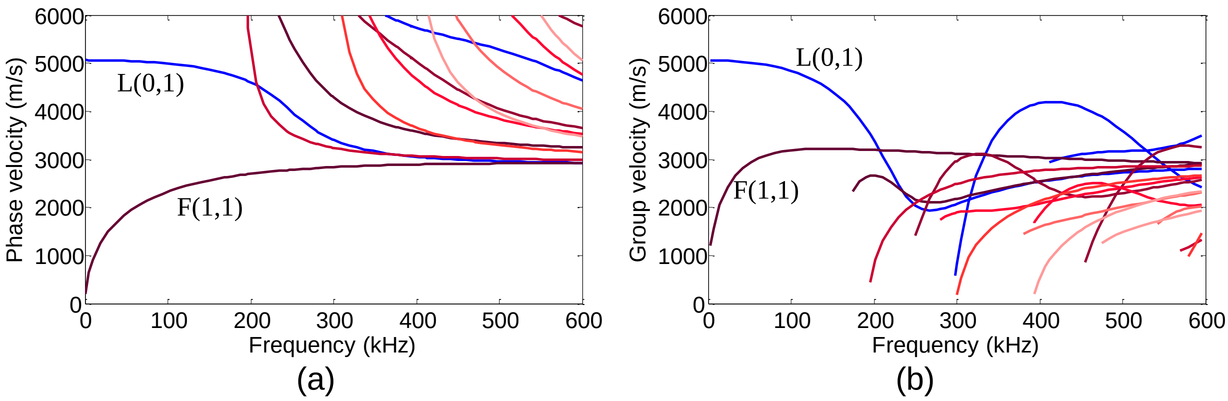


Fig. 1 Dispersion curves for 12 mm steel bar: (a) phase velocity vs frequency, (b) group velocity vs frequency.

For the steel bar embedded in concrete, it can be considered as an isotropic cylinder enveloped in the infinite object. This can be modelled by a two-layered structure, and various methods are used to solve this guided wave propagation problem, such as global matrix technique. Since the acoustic impedance of steel and concrete is similar, the leakage of guided wave energy is considerable, and the signals after long-distance propagation are weak and disordered.

3. FINITE ELEMENT ANALYSIS

Finite element analysis using ANSYS is first conducted prior to experimental investigations to understand the effects of local corrosions to the characteristics of guided waves. The steel bar and a pair of piezoelectric wafers are modeled by solid185 and solid5 element, respectively. The piezoelectric wafers are attached on the end of the steel bar to generate and receive the L mode waves. The excitation signal is an *n*-cycle Hanning windowed toneburst signal. Fig. 2 shows the steel bar with simulated local corrosion in ANSYS. For the case of the multiple corrosions, the case 2 has two simulated corrosion, and so on.

The excitation frequency is 200 kHz for all simulation cases. Simulation results are given in Fig. 3. It can be found that for the severe local corrosion, the amplitude of the first wave packet decrease too much. There are three indicators to describe the corrosion degree. The first one is the amplitude of the first wave packet, the second one is the root mean square (RMS) of energy of the first wave packet, expressed as Eq. (1); the third one is the ratio of energy of the first wave packet to all wave signals, expressed as Eq. (2).

$$X_{RMS} = \sqrt{\frac{1}{N}\Sigma_{n=1}^{N} X_n^2} \tag{1}$$

$$R = \frac{\Sigma_{m=0}^{N1} X_{1m}^2}{\Sigma_{n=0}^{N0} X_{0n}^2} \tag{2}$$

Fig. 4 shows above three indicators decrease with the corrosion degree for the single corrosion and the multiple corrosions. All indicators can evaluate the corrosion degree reasonably.

4. EXPERIMENTAL STUDY

Experimental investigations were conducted on the steel bar without and with concrete cover. For the former, the uniform corrosion was test first. A 1 m-long steel bar with diameter of 10 mm was used for the measurements reported here. Two piezoelectric wafers were mounted at the two end of the steel bar by the super glue. The piezoelectric wafer was driven by a function generator (AFG3252C, Tektronix, Inc.), into which was preprogrammed. A wideband (DC-2MHz) power amplifier (TEGAM 2350) was used to amplify excitation voltage. The signal received by the sensor was collected directly with 2 GS/s sampling rate by a digital oscilloscope (DPO 2024, Tektronix, Inc.). To corrode the steel bar specimens, an accelerated corrosion test setup was designed and implemented, shown as Fig. 5.

Fig. 6 shows the photo of uniformly corroded steel bar. Apparent reduction of the diameter can be found. Fig. 7 shows the results of time-frequency analysis for different corrosion time, from which TOF can be extracted. Fig. 8 shows that TOF decreases as the corrosion time. This figure indicates that TOF can be used to measure the corrosion degree for the uniform corrosion.

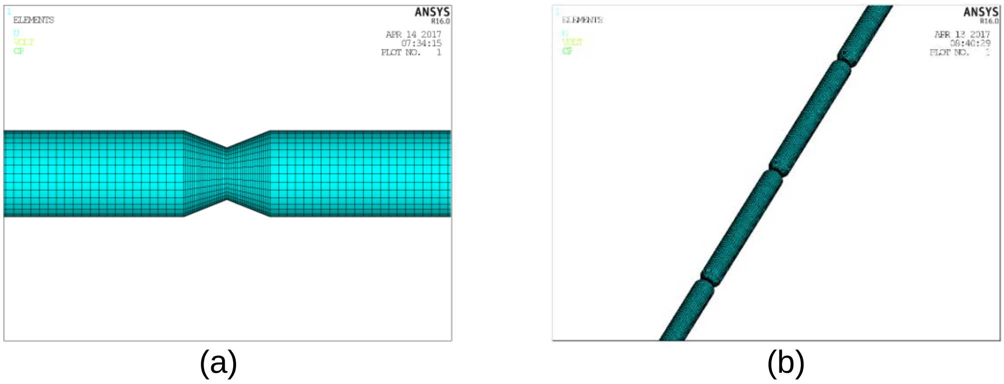


Fig. 2 The simulated local corrosion: (a) single corrosion, (b) multiple corrosions

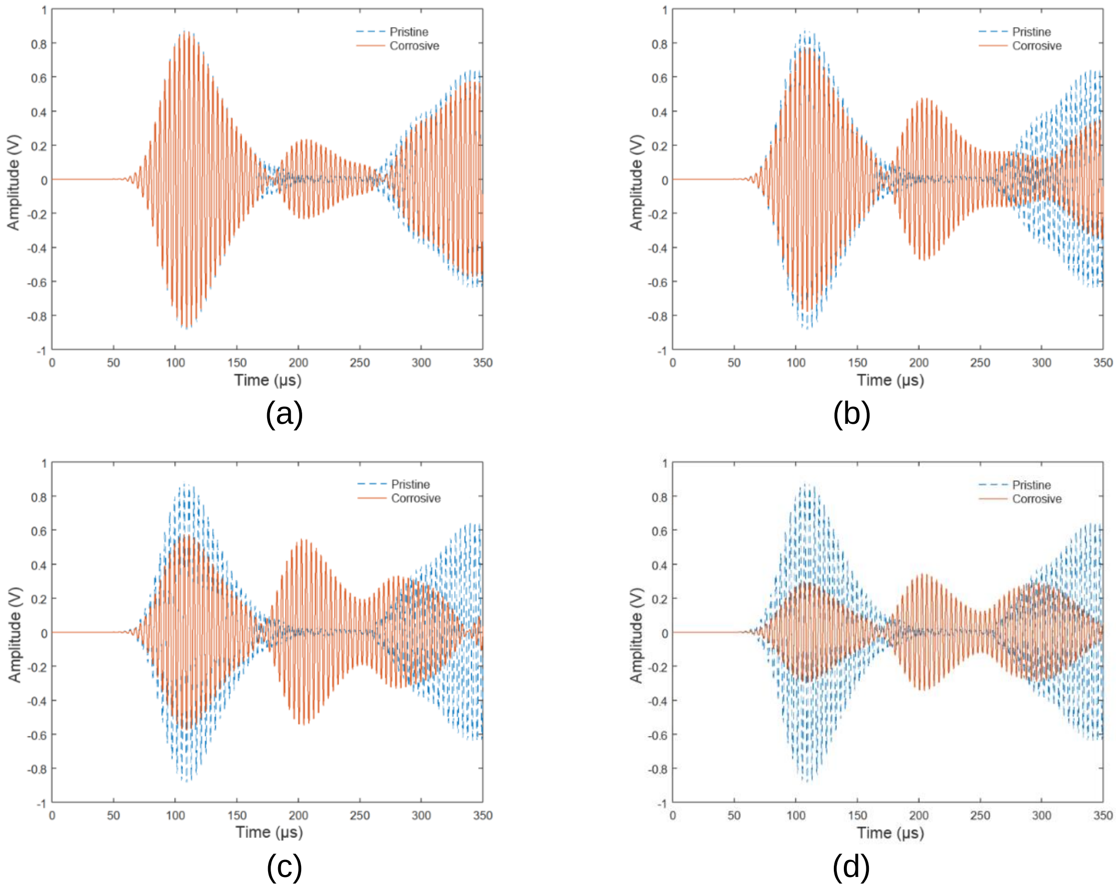
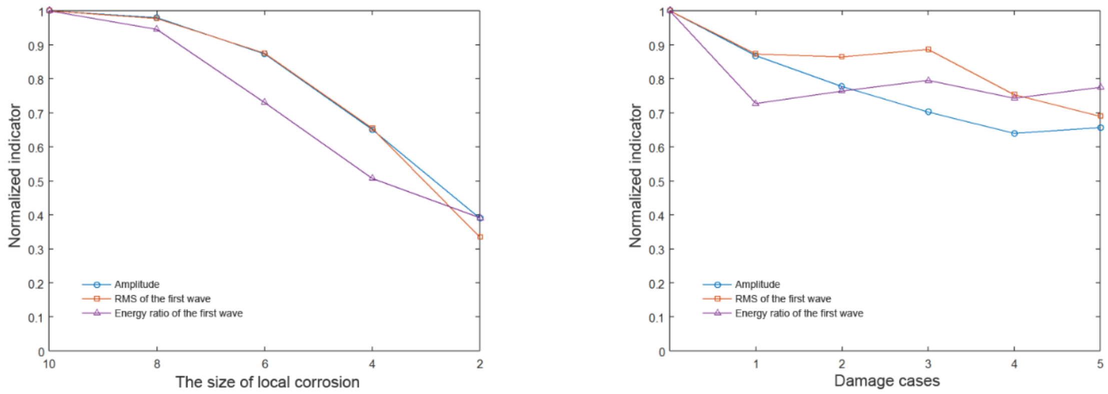


Fig. 3 The guided wave signals received for different corrosion size: (a) 8mm, (b) 6mm, (c) 4mm, (d) 2mm.



(a) (b)

Fig. 4 The corrosion indicators for: (a) single corrosion, (b) multiple corrosions.

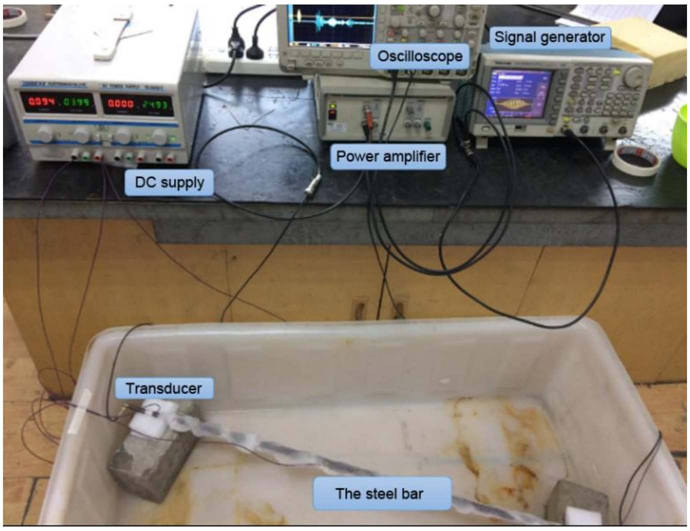
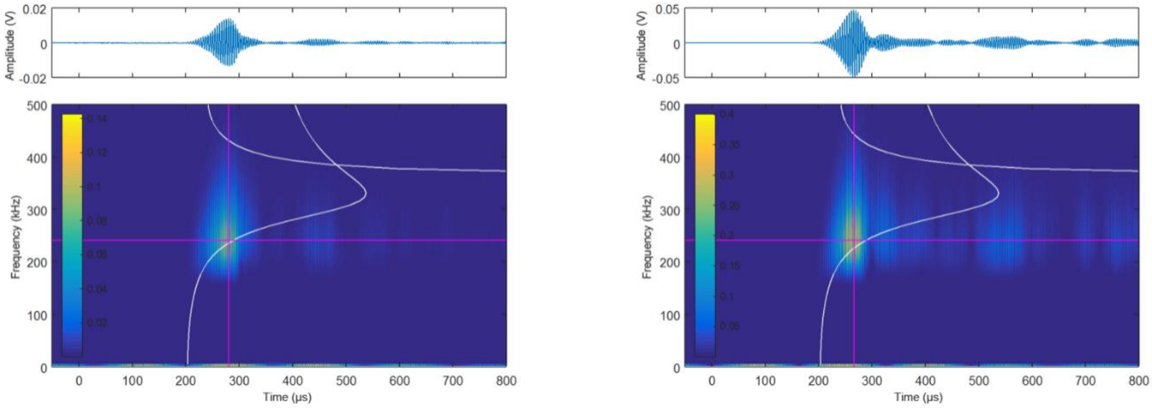


Fig. 5 Experimental setup.

Fig. 6 Uniformly corroded steel bar.



(a) (b)

Fig. 7 The time-frequency analysis for different corrosion time: (a) 1 hour, (b) 76 hours.

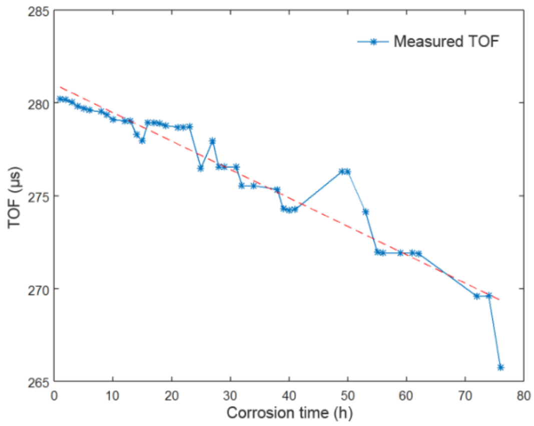


Fig. 8 TOF for different corrosion time.

Since the local corrosion is not easy to produce. In the experiments, the local corrosion was simulated by cutting notch on the steel bar, shown as Fig. 9. Fig. 10 gives the signals received by the piezoelectric sensor at another end of the steel bar for different depth of the notches. Fig. 11 indicates that in the experiments, the corrosion degree can be also quantified by the proposed indicators for the local corrosion.

(a) (b)

Fig. 9 The simulated local corrosion: (a) single corrosion, (b) multiple corrosions.

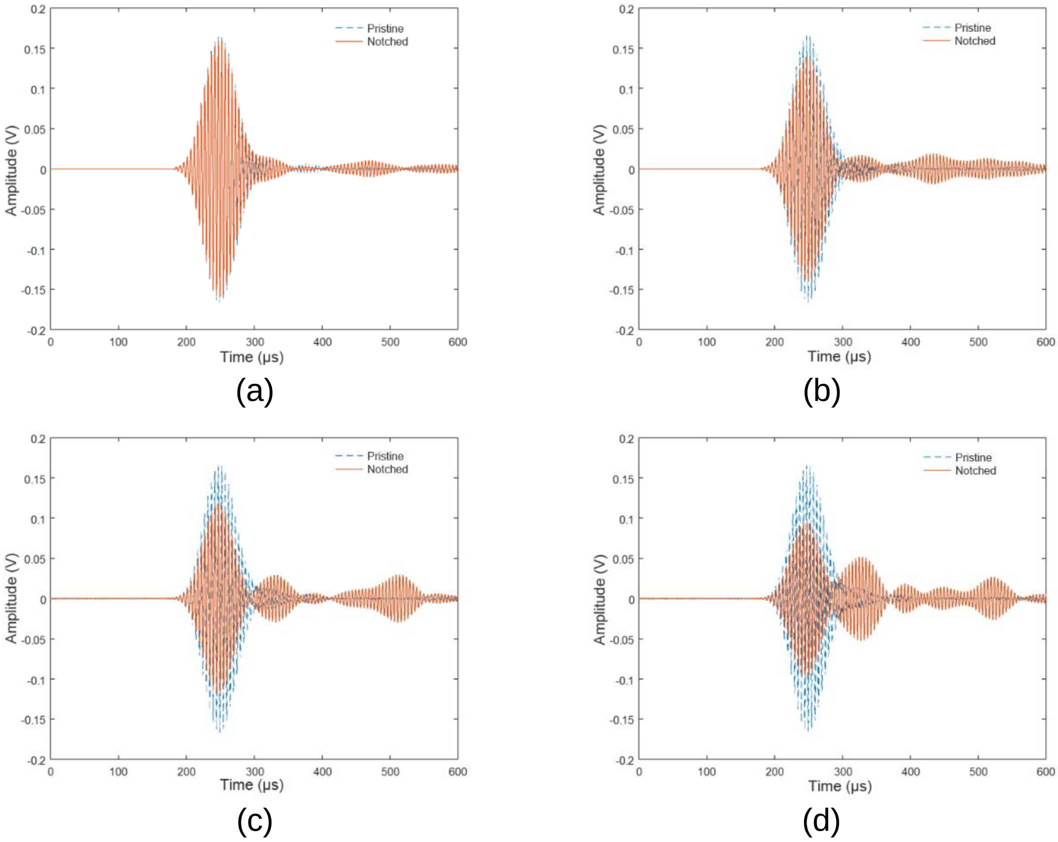


Fig. 10 The guided wave signals received for different corrosion size.

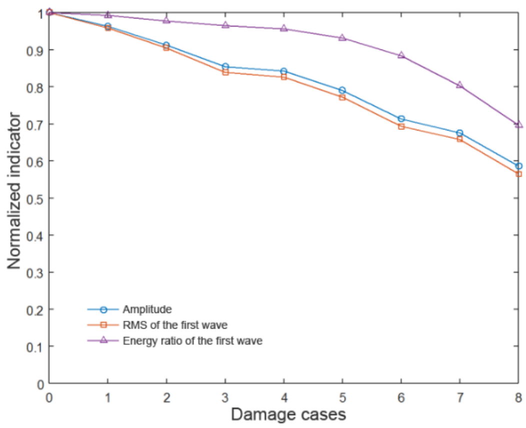


Fig. 11 The corrosion indicator for the local corrosion.

The steel bars embedded in concrete were corroded by the same method as above. Fig. 12 (a) and (b) are the photos of the steel bar embedded in concrete at the severe corrosion stage. The steel bars have been debonded from the concrete totally. They were taken from the concrete and it's found that the uniform corrosion leads to the considerable loss in the diameter, shown as Fig. 12 (c) and (d). The corrosion procedure of the steel bar embedded in concrete can be divided into three stages. In the first stage, the corrosion starts, and the corrosion products result in the pressure between the steel bar and the concrete increases. In the second stage, the continuous expansion of the steel bar lead to concrete damage and cracks. In the third stage, the concrete cracks stop expand, while the steel bar was corroded continuously.

The guided wave signals were collected through the whole accelerated corrosion procedure. Fig. 13 (a) shows the amplitude and attenuation ratio for each day. It can be found that before the fifth day, the signal amplitudes decrease, which indicates the increasing pressure between the steel bar and the concrete leads to more energy leakage from the steel bar to the concrete. Then, the signal amplitude increase rapidly due to the debonding between the steel bar and the concrete. Finally, the severe corrosion results in the amplitude becomes smaller. Fig. 13 (b) shows the FFT amplitudes have the similar change, which can be the corrosion indicator too.

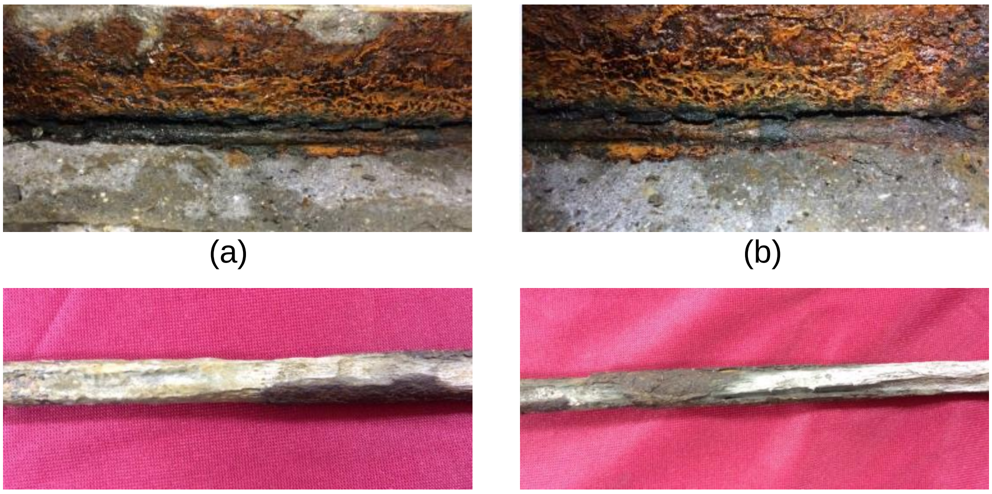
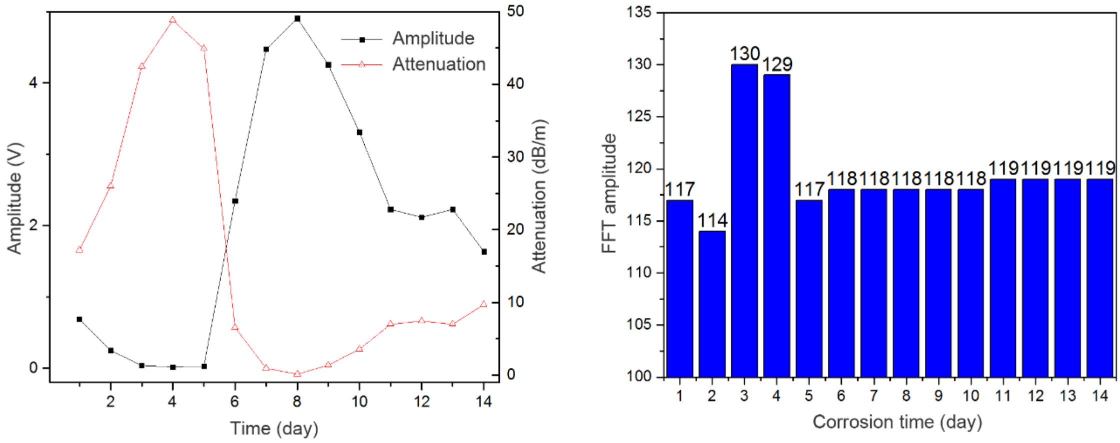


Fig. 12 The corrosion steel bar embedded in concrete.



(a) (b)

Fig. 13 The signal amplitude and FFT amplitude during the corrosion procedure.

5. CONCLUSIONS

Guided ultrasonic waves were used to monitor the corrosion of steel bars. For the local corrosion, finite element analysis and experiments were conducted. Results indicate that the signal amplitude, RMS of the first wave and energy ratio of the first wave can be the corrosion indicators. For the uniform corrosion, TOF is an effective indicator, which decreases with the corrosion develops. The steel bar embedded in concrete has been also corroded using accelerated corrosion methods. Guided wave signals were collected during the whole corrosion procedure. Their amplitudes and the corresponding FFT amplitudes can quantify the corrosion. The three corrosion stages can be also distinguished.

ACKNOWLEDGES

The financial support from the National Key Research & Development Program of China under Grant No. 2016YFC0802406 and the National Science Foundation of China under Grant No. 51578191 are gratefully appreciated.

REFERENCES

Amjad, U., Yadav, S.K. and Kundu, T. (2015), “Detection and quantification of diameter reduction due to corrosion in reinforcing steel bars,” *Struct. Health Monit.*, **14**(5), 532-543.

Ervin, B.L., Kuchma, D.A., Bernhard, J.T. and Reis, H. (2009), “Monitoring corrosion of rebar embedded in mortar using high-frequency guided ultrasonic waves,” *J. Eng. Mech*., **135**(1), 9-19.

Ervin, B.L. and Reis, H. (2008), “Longitudinal guided waves for monitoring corrosion in reinforced mortar,” *Meas. Sci. Technol.*, **19**(19), 055702.

Farhidzadeh, A. and Salamone, S. (2015), “Reference-free corrosion damage diagnosis in steel strands using guided ultrasonic waves,” *Ultrasonics*, **57**, 198-208.

Moustafa, A., Niri, E.D., Farhidzadeh, A. and Salamone, S. (2014), “Corrosion monitoring of post-tensioned concrete structures using fractal analysis of guided ultrasonic waves,” *Struct. Control Hlth.*, **21**, 438-448.

Miller, T.H., Kundu, T., Huang, J. and Grill, J.Y. (2012), “A new guided wave-based technique for corrosion monitoring in reinforced concrete,” *Struct. Health Monit.*, **12**(1), 35-47.

Pavlakovic, B.N., Lowe, M.J.S. and Cawley, P. (2001), “High-frequency low-loss ultrasonic modes in imbedded bars,” *J. Appl. Mech.*, **68**(1), 67-75.

Rathod, V.T. and Mahapatra, D.R. (2011), “Ultrasonic Lamb wave based monitoring of corrosion type of damage in plate using a circular array of piezoelectric transducers,” *NDT&E Int.*, **44**, 628-636.

Reis, H., Ervin, B.L., Kuchma, D.A. and Bernhard, J.T. (2005), “Estimation of corrosion damage in steel reinforced mortar using guided waves,” *J. Press Vess.-T. ASME*, **127**, 255-261.

Sharma, S. and Mukherjee, A. (2010), “Longitudinal guided waves for monitoring chloride corrosion in reinforcing bars in concrete,” *Struct. Health Monit.*, **9**(6), 555-567.

Sharma, S. and Mukherjee, A. (2011), “Monitoring corrosion in oxide and chloride environments using ultrasonic guided waves,” *J. Mater. Civ. Eng*., **23**(2), 207-211.