Introduction

Reinforced concrete has been employed as an economical construction material in civil engineering structures, such as buildings, bridges, and dams. However, environmental factors such as acid rain, chloride, loading fatigue, and carbonization have simultaneous harmful effects on concrete. The results lead to steel corrosion. At present, steel corrosion has become a major problem worldwide, especially for structures exposed to aggressive environments. This problem has reached alarming proportions in the past three decades, leading to very high repair costs, sometimes even above the initial construction cost, or to the final collapse of the structures in extreme situations [1].

The current methods of detecting concrete structural damage of steels include electrochemistry detection, ultrasonic wave testing, acoustic emission technique, and Fiber Bragg Grating sensors [2, 3]. However, these methods have shortcomings. Electrochemical methods are sensitive to the surface state of engineering structures and have been widely utilized for corrosion monitoring [4]. As the double layer does not result from pure capacitive conditions and the data cannot be actually analyzed according to partial data of electrochemical impedance spectroscopy, the corrosion monitoring methods based on electrochemical impedance techniques still need to be improved [5]. Ultrasonic waves propagate in short distances and are only sensitive to significant defects [6]. Acoustic emission is not sensitive to slight corrosion damage degree because of the low corrosion energy release. Thus, a more precise and efficient method is urgently needed.

A type of ultrasonic wave propagation involves a wave that is guided between two parallel surfaces of the test object. Ultrasonic guided waves (UGWs), as a developed tool, have many advantages compared with traditional detection methods. It can propagate in long distances because of its slight attenuation in steel [7]. This characteristic is especially suitable to detect long range bridges. Guided waves were chosen because of the possibility of analyzing guided wave behavior in certain frequency ranges to distinguish between the loss of bar cross-sectional area and change of interface conditions [8]. High sensitivity is another merit of this...
method. UGWs have many different modes at a single frequency, and these modes are sensitive to different defects [9].

The progressions of rebar corrosion in concrete in chloride and oxide environments were monitored by UGWs. The effect of corrosion rates, surface and core-seeking guided wave modes, and effective combination of guided wave modes were introduced [9]. Corrosion has been simulated in various ways, such as by introducing debonding between steel and concrete in the form of polyvinyl chloride pipes or by wrapping a tape on the bar [10, 11]. The sweep frequency technique was adopted to optimize the guided wave exciting frequency. The waveform energy attenuation at different frequencies was presented and discussed in terms of corrosion damage. The testing results were verified because the fundamental longitudinal mode of propagation can correctly express steel corrosion damage. Ervin et al. [12] employed high-frequency UGWs monitoring corrosion of rebar embedded in mortar. Through different guided mode comparisons, the \( L(0, 9) \) mode was adopted to monitor uniform and localized corrosion in reinforced mortar undergoing accelerated corrosion. Thus, ample evidence shows that corrosion could be detected by UGW techniques. However, the whole steel corrosion process and damage evolution has not been reported utilizing UGW testing. This study reports that the steel corrosion damage monitoring adopted UGW. The testing results were verified through another corrosion evaluation method.

2. UGW Propagation Theories in Steel Rebar

The geometry profile of a rebar is presented in Figure 1. Three different modes propagate in cylindrical waveguide, longitudinal modes \( L(m, n) \), torsion modes \( F(n, m) \), and flexural modes \( T(n, m) \). In this expression, \( m \) and \( n \) stand for circumferential order and modulus, respectively. The displacement is symmetrical corresponding to \( n = 0 \), where \( n = 1, 2, 3 \ldots \) that refers to asymmetrical displacements. Therefore, \( L(0, m) \), \( T(0, m) \) are symmetrical modes and \( F(n, m) \) are asymmetrical modes.

The longitudinal modes that propagate in steel rebar only have two types of displacement: radial and axial displacements. The boundary condition is \( u_\theta = 0 \), and \( u_r, u_\tau \) are independent of \( \theta \). Considering the boundary condition \( u_r = u_\tau = 0 (r = a) \), the Pochhammer frequency equation can be achieved by solving the wave equation [13]:

\[
\frac{2\alpha}{\lambda} \left( \beta^2 + k^2 \right) J_1 (\alpha a) \left( \beta a \right) - \left( \beta^2 - k^2 \right) J_0 (\alpha a) \left( \beta a \right) - 4k^2 \alpha J_0 (\beta a) = 0,
\]

where \( \lambda \) is the length of guided waves, \( \omega \) is the angular velocity, \( k \) is the wave number, \( J \) is the Bessel function, coefficients \( \alpha^2 = \omega^2/c_L^2, \beta^2 = \omega^2/c_T^2 - k^2 \), \( c_L \) is the velocity of longitudinal guided wave, \( c_T \) is the velocity of transverse guided waves, and \( c_p \) is the phase velocity. This expression is a transcendental equation with independent variables \( \omega \) and \( k \); thus, the same frequency \( \omega \) corresponds to multiple wave numbers; namely, more than one solution existing at a single frequency \( \omega \). This phenomenon corresponds well with the fact that many modes exist at a single frequency. This condition is the multiple modes property of UGW.

3. Dispersion Curves of UGW Propagation in Steel Rebar

The curves that depict the relationships between frequency and eigenvalue, as well as phase velocity and group velocity, are called dispersion curves. The parameters utilized to characterize the properties of wave guided propagation are phase velocity and group velocity, which have been described above. All waveguides, both symmetrical and asymmetrical, and other irregular shapes have special dispersion curves. Besides, only with the dispersion curves of UGW in steel rebar could an ideal UGW mode be excited by selecting the appropriate excitation frequency.

Take a 20 mm diameter rebar as an example. HRB335 ribbed bars were employed in this study, whose properties are shown in Table 1.

The effect of ribs on a ribbed bar can be ignored when the ratio of the diameter and the length is less than 0.4 [8]. The ratio between the diameter and the length is 0.029; thus, the steel rebar can be seen as a smooth cylinder. Based on Section 2, the transcendental equation can be solved with guided wave propagation theory. The dispersion curve of guided waves propagating in the steel rebar can be obtained by numerical calculation. The relationship between wave velocity and frequency (wave number and frequency) is represented by dispersion equation (1) and dispersion curve. However, as a transcendental equation, wave velocity and frequency (wave number and frequency) analytic solutions are too complicated to be obtained from dispersion equation (1), which could only be solved by the numerical analysis method. The program is divided into several steps as follows:

(a) The cutoff frequency that corresponds with the corresponding mode is determined. The solution of the dispersion equation is based on the cutoff frequency, and the roots that meet the equation are determined by scanning the frequency range. These roots are cutoff frequencies that correspond with the corresponding mode, and these roots are set as initial points of each modal dispersion curve.

(b) Each modal begins with the initial point. The next point that meets the dispersion equation with a certain step length is searched (e.g., 5 Hz). The initial
Table 1: Properties of HRB335 ribbed bars.

| Diameter | Length | Cross-sectional area | Density | Young's module | Poisson ratio |
|----------|--------|-----------------------|---------|----------------|---------------|
| 20 mm    | 700 mm | 254.5 mm²             | 7858.5 kg/m³ | 206 GPa        | 0.28          |

Table 2: C30 mix proportion of concrete (kg/m³).

| PC32.5R cement | Water | Medium grained sand | Rock fragment |
|----------------|-------|---------------------|---------------|
| 434            | 182.5 | 524.9               | 1226.5        |

Figure 2: Dispersion curves of group velocity.

Figure 3: Reinforced concrete beam.

Figure 4: Reinforced concrete corrosion experimental devices.

The 20 mm diameter rebar dispersion curve is displayed in Figure 2. Only three modes can be produced, namely, \( L(0, 1) \) longitudinal mode, \( T(0, 1) \) torsion mode, and \( F(1, 1) \) flexural mode. These modes could be acquired in the vicinity of the 40 kHz frequency, where the slopes degree of UGW in these three modes is most mild. 40 kHz is selected as the excitation frequency to excite the longitudinal UGW mode. The guided wave of \( L(0, 1) \) mode, which disperses most indistinctly and propagates fastest at this frequency, is chosen to detect the corrosion damage of reinforced concrete.

4. Steel Rebar Corrosion UGW Detection Experiment and Results Analysis

4.1. Reinforced Concrete Corrosion Specimen Preparation. In this experiment, the size of the specimen was 500 mm × 120 mm × 150 mm, in which the thickness of steel rebar’s protective layer was 20 mm and the concrete grade was C30. The hot rolled ribbed steel rebar had a diameter of 20 mm. The steel rebar was outstretched by 100 mm outside the concrete to satisfy the need of UGW detection when the specimen was corroded. The weight of the steel rebar was weighed before the concrete specimen was casted. Ordinary Portland cement 32.5R from the China Dalian Jinzhou third cement factory was utilized to prepare concrete. Medium grained sand was selected for the experiment. The rock fragment particle size was 5 mm to 15 mm. The water cement ratio was 0.42, whose detailed mix proportion is shown in Table 2. The laboratory temperature was 25°C, and the relative humidity was 80% when the specimen was casted. The test was conducted after a 28 d of storage in a standard curing room. The detailed size is presented in Figure 3.

The corrosion of reinforced concrete in the natural environment is so slow that the method of electrochemistry is employed to accelerate corrosion to obtain a higher amount of corrosion within a short time. The device utilized in the experiments was a stable DC power supply (Figure 4), which could ensure the stability of the current. The device model was PS-603D with exporting current of 0 A to 3 A (precision of 10 mA) and exporting voltage of 0 V to 60 V (precision of 0.1 V). In the electrochemistry experiment, the steel rebar was selected as the anode, whereas stainless steel was the cathode.
4.2. Design of Reinforced Concrete Corrosion. The amount of electrochemical corrosion of the steel reinforcement was calculated in accordance with Faraday’s law:

\[ m = kI t, \]  

(2)

where \( m \) is the loss of corroded metal (g), \( k \) is the coefficient of different metals with different properties, \( I \) is the current size (A), and \( t \) is the conduction time (s).

Based on Faraday’s law, the amount of electrochemical corrosion of steel reinforcement could also be calculated with

\[ m = \frac{t \times I \times 55.487}{2 \times 96487}. \]  

(3)

The amount of electrochemical corrosion of the steel reinforcement is in proportion to the conduction time and current size. In this equation, 55.487 is the molar mass of iron atoms, 2 is the number of electrons lost when an iron atom turns into a ferrous ion, and 96487 is the charge needed as electrolysis consumes one mole of substance.

The corrosion current should be neither too large nor too small. If the current was too large, the reinforcement would corrode faster and the damage of the steel rebar would be concentrated at both ends of the steel rebar; thus, the steel rebar does not corrode uniformly. If the current was too small, the reinforcement would corrode slower and the time of corrosion would last much longer, resulting in the loss of human and financial resources. Approximately 1 mA/mm\(^2\) is the standard value, wherein the corrosion current equal to the parcel area of the steel rebar in reinforced concrete is multiplied by 1 mA/mm\(^2\) and calculated as follows:

\[ I = 1 \times 3.14 \times 20 \times 500 = 314 \text{ mA} = 0.314 \text{ A}. \]  

(4)

Thus, 0.3A is selected as the corrosion current of electrochemical corrosion of steel rebar. Five specimens were corroded for 0, 5, 10, 15, and 20 d. During the corrosion, a UGW device was employed to detect the specimens every day to record the voltage and current sizes.

4.3. Experimental Results and Analysis. A UGW device was utilized to detect guided waves of the steel rebar in reinforced concrete. The specified detection principle is shown in Figure 5.

Two piezoelectric ceramics were arranged at both sides, one of which was the exciting sensor while the other was the receiving sensor. The sensor placement is shown in Figure 6. Five-cycle sinusoidal waves with central frequency of 40 kHz are modulated utilizing the Hanning window employed as UGW excitation signals (Figure 7).

4.3.1. Appearance of the Specimen. The appearance of the reinforced concrete structures corrosion.

The appearance of the reinforced concrete beam after corrosion is shown in Figure 8. No. 5 specimen was kept from corrosion, which greatly contrasted with the other specimens. By comparing Figures 8 and 5, the steel rebar would expand during the corrosion of the reinforcing steel, and then longitudinal through-going cracks would appear along the length of the surface direction of the concrete protective layer that caused damage. As the corrosion time increased, cracks on each specimen’s appearance became wider and even the protective layer would
4.3.2. UGW Monitoring for Steel Rebar Corrosion. During the corrosion, a UGW device was utilized to detect the specimens’ corrosion every day. The UGW testing signals of the reinforced concrete before and after corrosion were only listed to save space.

Figures 9, 10, 11, and 12 show that, although the signals of the UGW propagation in reinforced concrete were very complex, the signals of the first wave were very significant and had the typical characteristics of a first-order longitudinal guided wave. With the arrangement of the sensor in this test, only the longitudinal wave guide mode was excited in terms of theory. According to the waveform observed in this test, a series of waveforms after the first wave had other forms of modals apart from the longitudinal modal. This scenario was mainly caused by the manufacturing errors at the end of the steel rebar induced bending mode. The reflection and refraction of the guided wave at the end of the steel rebar and in the contact interface of the steel rebar and concrete make the modes convert. Both reflection and refraction could occur again when the guided wave arrives at the receiving end, and the superposition of the incident wave makes the guided wave more complex. The steel rebar in the reinforced concrete also defected after corrosion because the defects disorganizing the reflection, refraction, and the mode conversion of the guided wave could occur repeatedly. The modes of the testing signal are much richer after the corrosion test. Thus, the amplitude of the first wave was only needed in this study. As seen in Figures 9–12, the amplitude of the head wave of UGW decreased gradually as time progressed after corrosion, except for the No. 1 specimen. The UGW device was employed to detect the specimens every day to record the amplitude of the first wave. The relationship of this set of specimens from Nos. 1 to 4 between the amplitude of the first wave and the time of corrosion is presented as in Figure 13.

Figure 13 shows that the UGW first wave peak value first increased and then decreased slowly. The peak value of the first wave of reinforced concrete specimens with the same degree of corrosion also decreased over time. This condition is because the corrosion products increased during the steel rebar corrosion process, resulting in an increase in the delamination degree between the steel rebar and concrete. The decrease in the UGW energy in the steel rebar leaked into the concrete; thus, the peak value of the first wave of UGW increases. However, as the reinforced concrete corrosion level increases, the pit on the steel becomes larger. This condition would lead to great reflection in the first wave energy, and the direct transmission wave energy would become low. The first wave peak value then decreased slowly.

A steel rebar was removed from reinforced concrete after the test to examine the accuracy of the UGW test. The steel rebar with different degrees of corrosion is shown in Figure 14. The weight was measured after washing the corrosion on the steel rebar with pure water and hydrochloric acid. By evaluating the degree of corrosion with the mass loss rate method, the calculation formula is presented as in formula (5). The degrees of corrosion of reinforced concrete specimens are shown in Table 4:

$$\text{c} = \frac{m_b - m_a}{m_b} \times 100\%,$$

where $c$ is the mass loss rate, $m_b$ is the mass of the steel rebar before corrosion, and $m_a$ is the mass of steel rebar after corrosion.

We made a graph shown in Figure 15 to quantitatively describe the changing rule of the UGW signal of reinforced concrete. The x-coordinate is the mass loss rate of reinforced concrete and the y-coordinate is the change in the peak value (first wave peak value before corrosion subtracted from the first wave peak value after corrosion) of the UGW first wave. No. 1 specimen is not considered in this figure as its peak value increased. From Figure 15, the relative variation peak value of the UGW first wave increased along with the increase in the degree of corrosion, which shows that utilizing the peak value change of the UGW first wave could roughly judge the damage degree of reinforced concrete.
Figure 9: UGW waveform for No. 1 corrosion specimen.

Figure 10: UGW waveform for No. 2 corrosion specimen.

Figure 11: UGW waveform for No. 3 corrosion specimen.
Figure 12: UGW waveform for No. 4 corrosion specimen.

Figure 13: UGW peak variation during the whole corrosion process.
Table 4: Degree of corrosion.

| Specimen number | Corrosion time (d) | Mass before corrosion (g) | Mass after corrosion (g) | Mass loss (g) | Mass loss rate (%) |
|-----------------|--------------------|---------------------------|--------------------------|---------------|--------------------|
| 1               | 5 d                | 1853                      | 1543                     | 40            | 2.59               |
| 2               | 10 d               | 1575                      | 1506                     | 69            | 4.38               |
| 3               | 15 d               | 1590                      | 1474                     | 116           | 7.29               |
| 4               | 20 d               | 1584                      | 1426                     | 158           | 9.97               |
| 5               | 0 d                | 1581                      |                          |               |                    |

(3) The steel rebar corrosion level could be estimated roughly with the relationship of the ultrasonic guided first wave changes in amplitude and the corrosion damage level of the steel rebar. As the corrosion damage level increases, the relative variation for UGW first wave peak value increases first and then decreases.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References

[1] X. F. Zhao, P. Gong, G. F. Qiao, J. Lu, X. Lv, and J. Ou, “Brillouin corrosion expansion sensors for steel reinforced concrete structures using a fiber optic coil winding method,” Sensors, vol. 11, no. 11, pp. 10798–10819, 2011.
[2] Y. Moslehy, H. Gu, A. Belbari, Y. L. Mo, and G. Song, “Smart aggregate based damage detection of circular RC columns under cyclic combined loading,” Smart Materials and Structures, vol. 19, no. 6, Article ID 065021, 2010.
[3] G. Song, H. Gu, Y. L. Mo, T. T. C. Hsu, and H. Dhonde, “Concrete structural health monitoring using embedded piezoceramic transducers,” Smart Materials and Structures, vol. 16, no. 4, article 003, pp. 959–968, 2007.
[4] H. J. de Bruyn, “Current corrosion monitoring trends in the petrochemical industry,” International Journal of Pressure Vessels and Piping, vol. 66, no. 1–3, pp. 293–303, 1996.
[5] F. Kuang, J. N. Zhang, C. J. Zou et al., “Electrochemical methods for corrosion monitoring: a survey of recent patents,” Recent Patents on Corrosion Science, vol. 2, pp. 34–39, 2010.
[6] D. S. Li, T. Ruan, and J. H. Yuan, “Inspection of reinforced concrete interface delamination using ultrasonic guided wave non-destructive test technique,” Science China Technological Sciences, vol. 55, pp. 2893–2901, 2012.
[7] B. Kolesnikov, L. Herbeck, and A. Fink, “CFRP/titanium hybrid material for improving composite bolted joints,” Composite Structures, vol. 83, no. 4, pp. 368–380, 2008.
[8] B. L. Ervin, J. T. Bernhard, D. A. Kuchma et al., “Estimation of corrosion damage to steel reinforced mortar using frequency sweeps of guided mechanical waves,” in *Smart Materials and Structures*, vol. 6174 of *Proceedings of SPIE*, p. 12, 2006.

[9] S. Sharma and A. Mukherjee, “Monitoring corrosion in oxide and chloride environments using ultrasonic guided waves,” *Journal of Materials in Civil Engineering*, vol. 23, no. 2, pp. 207–211, 2011.

[10] F. Wu and F.-K. Chang, “Debond detection using embedded piezoelectric elements in reinforced concrete structures—part I: experiment,” *Structural Health Monitoring*, vol. 5, no. 1, pp. 5–15, 2006.

[11] H. Reis, B. L. Ervin, D. A. Kuchma, and J. T. Bernhard, “Estimation of corrosion damage in steel reinforced mortar using guided waves,” *Journal of Pressure Vessel Technology, Transactions of the ASME*, vol. 127, no. 3, pp. 255–261, 2005.

[12] B. L. Ervin, D. A. Kuchma, J. T. Bernhard, and H. Reis, “Monitoring corrosion of rebar embedded in mortar using high-frequency guided ultrasonic waves,” *Journal of Engineering Mechanics*, vol. 135, no. 1, pp. 9–19, 2009.

[13] J. L. Rose, *Ultrasonic Waves in Solid Media*, Cambridge University Press, London, UK, 2004.
