

Monitoring Corrosion of Steel Bar in Concrete Using Ultrasonic Wave

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Abstract. The problem of steel corrosion in reinforced concrete structure is very serious. The purpose of this paper is to monitor steel corrosion by ultrasonic guided wave. Ultrasonic guided wave monitoring is a kind of dynamic nondestructive testing technology, which has the advantages of real-time, on-line and continuous. In this paper, an ultrasonic in-situ monitoring technique of steel bar corrosion based on embedded piezoelectric ceramic sensor is introduced. Based on this, ultrasonic guided wave was used to monitor mortar samples with different strengths of uniform corrosion, and scanning electron microscopy was used to observe the interface between reinforcement and concrete at different corrosion stages. The results show that the variation trend of ultrasonic guided wave amplitude can reflect the degree of corrosion. Mortar with different strength will affect the time and trend of corrosion. The scanning electron microscopy (SEM) method shows that the changing process of the interface between reinforcement and concrete is consistent with the trend of ultrasonic guided wave.

Keywords: Ultrasonic guided wave, steel corrosion, non-destructive testing.

1. Introduction

Reinforced concrete is widely used in the world because of its advantages of low cost and high strength. Reinforced concrete is mainly used in modern buildings, Bridges, infrastructure, etc. However, steel corrosion has occurred, which is one of the main problems in the durability of reinforced concrete structures at present[1]. If not found and treated early, steel corrosion damage will have a disastrous impact on the safety and durability of the structure. Therefore, it is necessary to monitor the corrosion process of steel bars. There are various methods for monitoring rust, such as acoustic emission [2] resistance probe [3] and anode-step method [4-6], ultrasonic guided wave[7-12]. Existing methods for evaluating the bond between steel bars and concrete include destructive tests such as pull-out[13-14] or fracture[15], which are not in-situ tests. Compared with traditional detection methods, ultrasonic guided wave has many advantages. First, it can travel a long distance. Second, high sensitivity. Third, the coverage is wide. Therefore, ultrasonic guided wave method has been widely studied in steel rust monitoring. In addition, piezoelectric sheet sensors have the ability to generate and receive lamb waves, which can be used for structural health monitoring. The corrosion of steel bars can be detected by conducting guided waves on them. This paper introduces a method to determine the degree of corrosion of steel bar by using ultrasonic guided wave amplitude curve.

The embedded piezoelectric ceramic sensor is used in this paper. In recent years, the application of piezoelectric intelligent materials in reinforced concrete components and structural damage detection technology is a new development direction in the field of reinforced concrete components and structural condition monitoring (SHM). With the development of electromechanical impedance (EMI) method and inverse electromechanical transmission (EMA) method, the application of piezoelectric ceramics such as lead zirconate titanate (PZT) in SHM has become more effective. PZT has the advantages of small size, light weight, low cost, strong active sensing ability, good long-term stability, convenient application and so on [1-3]. Therefore, PZT ceramics are also used as sensing elements in this study. Two separate piezoelectric lead titanate sheets (PZT1 and PZT2) were used as the transmitting and receiving ends for simultaneous measurement. Therefore, the PZT receives the reflected wave by sending the probe wave.

2. The fabrication of piezoelectric ceramic sensor

The piezoelectric material is a piezoelectric ceramic plate with a diameter of 10 mm and a thickness of 1.0 mm. The coaxial wire is welded to the positive and negative electrodes of the piezoelectric ceramic plate respectively. In order to improve the noise reduction effect of the sensor, it can be obtained by reserving wire. The BNC is welded to the other end of the wire and connected to the signal generator and oscilloscope. The ratio of cement powder, epoxy resin and curing agent with weight ratio of 1:1:0.25 is used as the packaging material of piezoelectric sensor. Glue the sensor on both ends of the steel bar. Piezoceramic parts are shown in Fig 1:

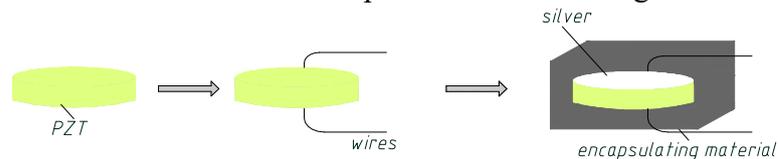


Fig.1 The fabrication of piezoelectric sensor

3. Experimental procedure

Mortar with proportions of cement, sand as 1:2 was taken, and water–cement ratio was kept at 0.45. The dimension of the specimens were 40mm×40mm×140mm. The diameter of the steel reinforcing bar tested was 10 mm and its total length was 140 mm, which was embedded in the center of the specimen at the time of casting. Plain bars were used to avoid such mechanical bonding in the experiment. The sample was immersed in 5% NaCl solution in order to accelerate the corrosion of steel bars. The embedded reinforcement bar in the specimen was connected to the anode of the direct-current power and the cooper rod was connected to the cathode of the direct-current power[16].

The two ends of the steel bar are connected with a signal generator (Tektronix AFG2021-SC) and an oscilloscope (Tektronix TPS2024). Sine waves are generated by signal generators and applied to piezoelectric sensors. The signal voltage amplitude is +5V. The pulse signal of the same parameter is sent out by the signal generator, the signal received from the oscilloscope at different time intervals is measured, and the maximum voltage amplitude of the signal is calculated. The signal is recorded every 3 hours until the cracks appeared. Water on the surface of the specimen must be cleaned to avoid the solution to have damped influence on ultrasonic guided wave. The experiment equipment was showed in Fig 2:

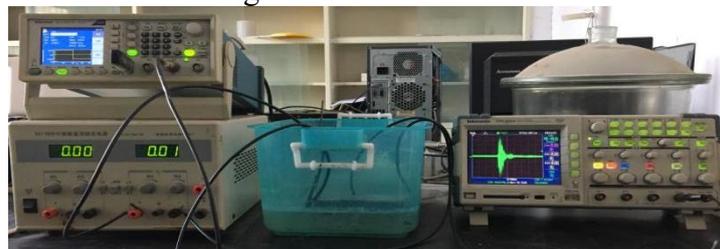


Fig.2 the experimental diagram of ultrasonic guided wave

4. Results and discussion

The time domain signal of ultrasonic guided wave is collected every 3 hours by oscilloscope. The trend of the amplitude can be seen in Fig.3. From the beginning to 50h of corrosion, the amplitude showed a decreasing trend, and the lowest amplitude was 50h of corrosion. The amplitude increases from 50 to 110h. Until 110h to the end, the amplitude maintained a steady trend.

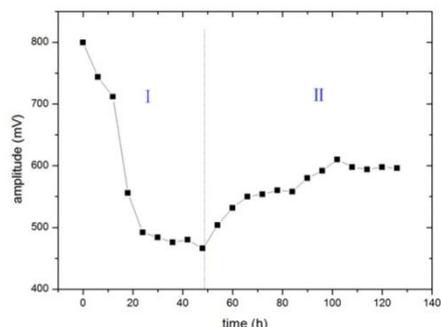


Fig.3 the trend of the amplitude of ultrasonic guided wave

The amplitude variation can reflect the degree of corrosion of the steel bar. The decrease in amplitude corresponds to the corrosion process of the steel bar in the first stage. With the increasing degree of corrosion of steel bars and the increase of corrosion products, the interface bond between steel bars and mortar becomes weaker and weaker. As a result, the ultrasonic guided wave energy leaks into the surrounding mortar, and the signal becomes weaker and weaker. As the degree of rust increases, more and more waves leak into the surrounding mortar. At the same time, the generation of rust produces greater stress on the surrounding mortar.

When the amplitude reaches its lowest point, the mortar begins to crack. The process of amplitude rise corresponds to the second stage of steel bar corrosion. At this time, cracks gradually appear in the mortar. The interface between steel bar and mortar appears disadhesion phenomenon, the coupling between steel bar and mortar and corrosion products decreases, the rust products become loose, and the binding force between steel bar and concrete decreases. With the increasing of energy accumulation caused by corrosion, the concrete microcracks transform into obvious cracks on the specimen surface. The mortar cracks and causes a lot of bond damage, and the amplitude shows an upward trend.

Through the time domain analysis of the received signal, the amplitude of the ultrasonic guided wave signal is related to the corrosion time. The amplitude parameter is sensitive to the process of steel corrosion, and the variation trend of amplitude can reflect the difference of steel corrosion stage.

5. Different strength of the mortar influence on rebar corrosion

M30,M40,M50 were used by the experiment, and the proportions were showed in table1:

Table1.Basic parameter of the specimen

The strength	The proportion	The type of rebar	The diameter of rebar	The dimension of the specimen
M30	1:2.6:0.5	HRB335	8mm	40 × 40 × 140mm
M40	1:2.2:0.45	HRB335	8mm	40 × 40 × 140mm
M50	1:1.6:0.4	HRB335	8mm	40 × 40 × 140mm

The sample is made of ordinary Portland cement, crushed sand and coarse aggregate according to the above proportion and placed in the mold. The sample was cured for 24 hours at a temperature of about 20°C and relative humidity of more than 80%. The specimens were wet cured for 28 days, and the hulled specimens were cured in 20 water tanks for 28 days. Electrolytic rust test was carried out after curing. The sample was immersed in an aqueous solution of 5% sodium chloride solution, and the charging current was controlled at 0.02A. The signal is recorded every six hours until the crack appears.

The result:

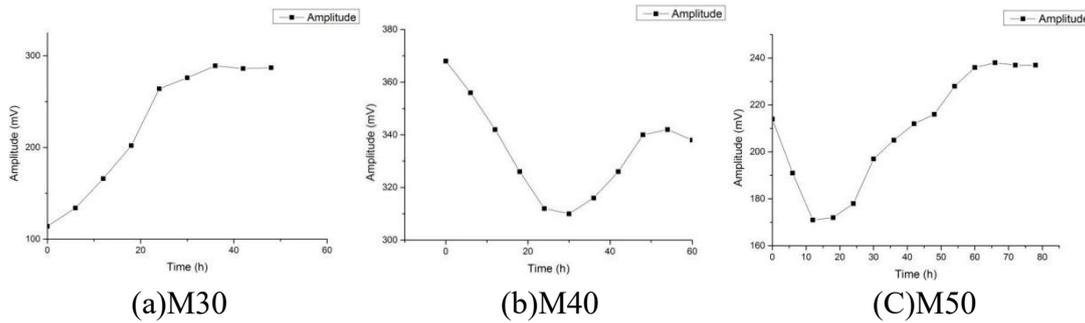


Fig.4 The trend of the time and amplitude using ultrasonic guided wave

As shown as Fig4, we can know that the more the strength of the mortar is, the longer the time of rebar corrosion is. The strength of the mortar can be changed by changing the water–cement ratio according to Table1. When the water–cement ratio is lower, the pores of the mortar get thinner, and the mortar is more dense. This dense mortar can increase the obstruction that Cl^- enter into the interior mortar. In conclusion, the mortar’s strength is stronger, so the speed of the corrosion is slower, the time of corrosion is longer. As shown as Fig4(a), the amplitude of M30 is rise as time increases, because mortar’s internal porosity is too large, the diffusion velocity of the oxygen and water entering into internal mortar increases. Hence, the corrosion speed can be accelerated so that the early corrosion production can fill into the internal mortar. However, as shown as Fig4(b)(c), the trend of M40 and M50 are decline at the initial stage. Because the brittleness of M50 is stronger, so the cracks get more and more. Thus, the peak of M50 exceed the initial point, and the rise stage is more longer than the decline stage. Finally, three strengths get steady, because corrosion production passed into the cracks.

6. Micro-mechanism analysis basis on scanning electron microscope

6.1 Cutting of the specimen

The specimen monitored by ultrasonic guided wave was cut along the cross-section, and it should preserve the original form of the interface of rebar and concrete. Sand the surface with (180,120,0, 4/0) sandpaper. Disparate stage of corrosion was observed by SEM, mainly watching corrosion morphology of the interface to analyze corrosion of rebar corrosion. According to the trend of amplitude monitored using ultrasonic guided wave, The specimen that was cut was shown in Fig5, obtaining three specimens : S1、S2、S3, respectively..

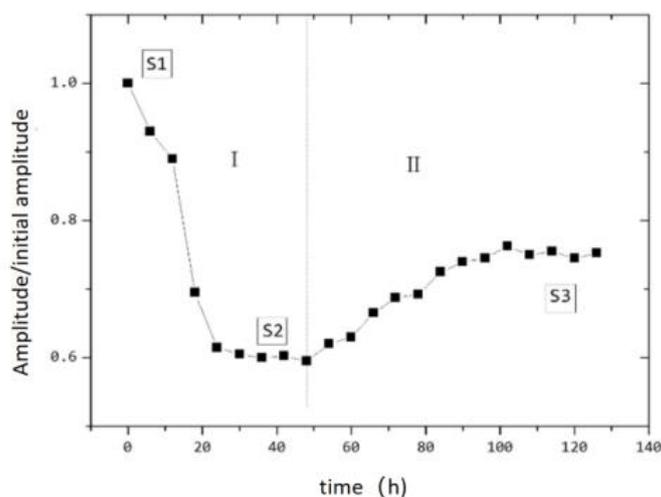


Fig.5 the select specimens to microscopic observation

In order to avoid destroying in the process of cutting, the specimen was steeped in the epoxy resin before cutting. The sectional dimension of the specimen was 40mm×40mm and the thickness was 20mm. After polishing the sample surface, and then metal was sprayed. The specimen was shown as Fig6.

Table2. the specimen S1、S2、S3

Numble	failure form
S1	Uncorroded
S2	Corroded
S3	Corroded and crack appeared

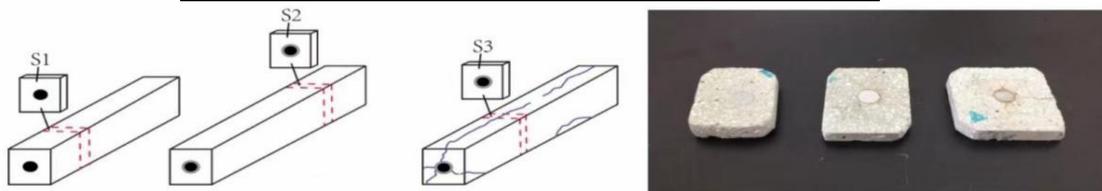
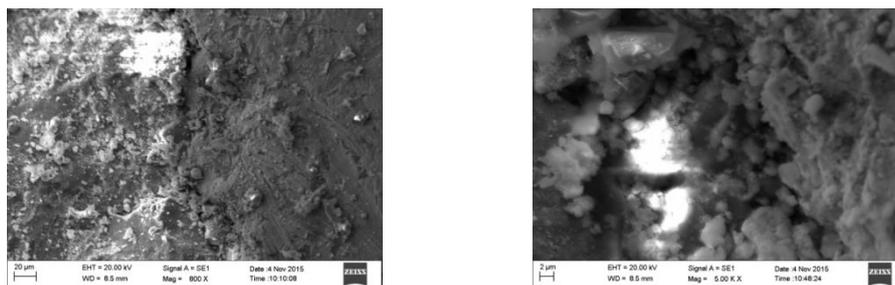


Fig.6 the specimen S1、S2、S3

6.2 The distribution of corrosion production and analysis of morphology

6.2.1 Transition area of the interface of uncorroded rebar and concrete



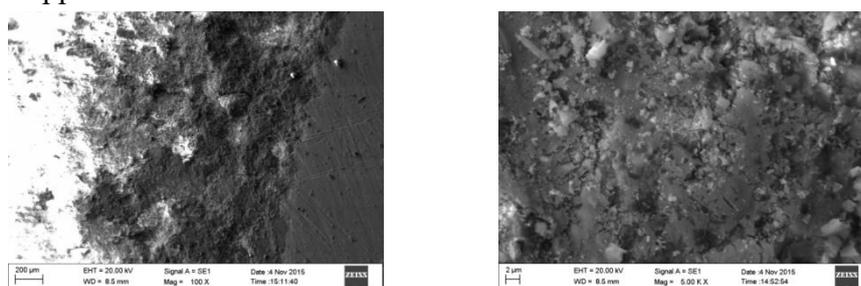
(a) no corroded interface

(b) vulnerable point of interface

Fig.7 The transition area of the interface of the uncorroded steel and concrete

The interface of uncorroded rebar and concrete was very weak, and the features was loose、higher porosity, shown Fig7. From the standpoint of materials, cement-based materials was heterogeneous material, which led to incomplete tightness after molding. Thus, there were numerous voids among the rebar and concrete. In addition, water film was formed by the surface of the rebar, when the concrete was poured. Water was volatilized in the process of concrete hardening, which led the porosity to get larger in the interface of the rebar and concrete. At the same time, the concrete was vibrated poorly in the process of casting. Above reasons formed weak areas in the interface of rebar and concrete.

6.2.2 Crack did not appear in the concrete when rebar was corroded



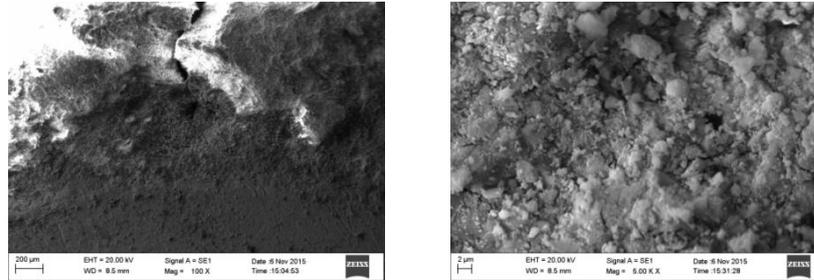
(a)corroded layer at the interface

(b) the morphology of the corroded layer

Fig.8 Transition area between steel and concrete interface when no cracks appear.

As shown as Fig8, corrosion layer transformed close-grained from loose in the interface of the rebar and concrete in the decline stage of amplitude. With rebar was corroded, corrosion production filled the voids in the interface, which formed corrosion layer. Corrosion layer got more and more thicker, and became close-grained and stratified structure. But beyond that, there was the mixture layer including the rust and concrete between the corrosion layer and concrete.

6.2.3 Crack appeared in the concrete when rebar was corroded



(a) Rusted layers and cracks at the interface (b) the morphology of the corroded layer
Fig.9 Transition area between steel and concrete interface when cracks appear.

Crack appeared in the rise stage of amplitude. The volume of corrosion production got larger with the degree of rebar corrosion, which generated corrosion-induced expansion force to surrounding concrete. Thus, crack appeared. The corrosion production of the specimen S3 was looser than the specimen S2, which was shown as Fig9. The reason was that the crack formed inside the concrete, and the corrosion production of the specimen S3 filled to the crack.

7. Conclusions

The paper monitored different degree of steel corrosion by ultrasonic guided wave. And then, the interface of reinforcement and concrete were observed by scanning electron microscope. Details are as follows:

(1) The degree of steel corrosion was monitored by the trend of ultrasonic guided wave. The trend was divided two sections including decline and rise. The decline stage of amplitude meant that corrosion production filled the interface of the concrete and steel. When the amplitude variation curve got minimum point, the fissure of concrete started to occur. The rise stage of amplitude corresponded to the process that crack developed into the concrete. When the surface of the specimen appeared the crack, the amplitude got steady progressively.

(2) The interface of reinforcement and concrete were observed by scanning electron microscope. The interface of uncorroded steel bar and concrete was the weak area where the ratio of void was large. The void was filled by corrosion production in the interface of reinforcement and concrete at the stage which rebar started to be corroded. The morphology of the corrosion production got loose, and the corrosion production spread to the fissure.

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