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Development of technique capable of identifying different corrosion stages in reinforced concrete

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ABSTRACT

In order to develop an in-situ technique capable of identifying the transitions between different stages of corrosion in reinforced concrete, a new type of sensor was developed. The sensor uses piezoelectric elements to generate and receive ultrasonic waves, with a steel bar acting as a wave guide. In a corrosion acceleration test, the onset of corrosion was associated with a steady increase in the wave amplitude resulting from the accumulation of corrosion products at the concrete-steel interface. AE monitoring verified that cracks in the bonding layer act as obstacles to wave propagation, and their development stops the increase in the sensor signal. Bending tests showed that different type of cracks have different effects on signal propagation.

1. Introduction

Reinforced concrete structures should be capable of providing excellent service under a range of environmental conditions for many years. However, when exposed to a corrosive environment, durability can be a severe problem; the major concern in such situations is corrosion of the reinforcing steel bars. Many structural disasters are due to steel bar corrosion, which has contributed to the loss of thousands of billions of dollars [1–5]. Corrosion products tend to cause expansion, which then applies pressure to the surrounding concrete. This expansion pressure induces tensile stresses in the concrete around the reinforced bar, and the continuous increase of this pressure eventually causes cracking through the concrete cover [6]. The corrosion process can be divided into three stages: the dormant stage, the initiation stage and the acceleration stage. The different stages are delineated by the onset of corrosion and nucleation of cracking.

Corrosion monitoring is important for the maintenance of reinforced concrete structures. The identification of the different stages of corrosion and the transitions between them would be useful in practice. However, despite the many techniques available for monitoring corrosion in the laboratory or in the field, few are capable of providing such information [7–14]. The acoustic emission (AE) technique is an exception. It has been reported that the AE technique can give an earlier warning than electro-chemical techniques and can identify the transition from the initiation stage to the acceleration stage [15–18]. AE is based on the phenomenon of transient elastic waves that are generated by the rapid release of energy from a localized source within a material. AE examination is a nondestructive method with demonstrated capabilities for monitoring structural integrity and incipient failure. However, AE monitoring relies on the continuous recording of crack activity to infer the progress of corrosion. The corrosion process occurs over a long period of time, and there is a high chance that environmental noise might be introduced during the monitoring, resulting in 'false positive' signals of fault occurrence. This technique is thus more suited for use in the controlled conditions of a laboratory, and is difficult to implement for in-situ corrosion monitoring applications.

In order to develop an in-situ corrosion monitoring technique that is capable of identifying the different stages and transition periods of corrosion, guided wave technique was used. Guided waves are ultrasonic waves enforced to follow a path dictated by the geometric boundaries of the structure. Guided waves are very sensitive to the discontinues of structures [19,20]. Sensor using piezoelectric elements to generate and receive ultrasonic waves, which are guided by a steel bar, had been fabricated. Piezoelectric materials are the most widely used class of smart material in modern health monitoring. They can exhibit both direct and converse piezoelectric effects [21–23], and both of these are employed in the new corrosion sensor. In contrast with traditional

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ultrasonic methods, this new technique does not use concrete as the wave guide. The interface between the concrete and the steel bar can be examined. Moreover, high frequency waves can be used, and the major shortcomings of previous ultrasonic techniques can be overcome. Enough sensitivity can be ensured to detect even minor damage caused by corrosion.

In this study, the properties of the new corrosion sensor were tested. A corrosion acceleration experiment was carried out to test the validity of the new method. AE monitoring was also employed to interpret the phenomena detected during the corrosion monitoring. Bending tests were also carried out to examine the influence of different types of cracks on corrosion monitoring.

2. Corrosion sensor fabrication and its performance

2.1. Sensor structure and fabrication

The structure of the corrosion sensor is shown in Fig. 1. The corrosion sensor includes two piezoelectric elements for generating and receiving ultrasonic waves, and one steel bar that acts as a wave guide. A piezoelectric ceramic rod with dimensions 5.0 × 5.0 × 12.0 mm was used. First, a coaxial cable was connected to the opposite electrodes of the piezoelectric rod. Then the piezoelectric rod was coated with epoxy for insulation. Finally, the transducer was bonded to the opposite surfaces of the 10 mm diameter round steel bar using epoxy. One end of the corrosion sensor could be stimulated by an electric pulse and the piezoelectric element would emit ultrasonic waves. The waves would propagate through the steel bar and be detected by the piezoelectric element in the other end.

2.2. The performance of the sensor

Before the corrosion sensor was embedded in concrete, the properties of the sensor were examined. One piezoelectric element was stimulated by an electric pulse from a signal generator (Tektronix AFG3022B) and the other piezoelectric element was used to receive the ultrasonic wave, which was recorded by an oscilloscope (Tektronix TPS2024). The electric pulse and the received wave are shown in Fig. 2. The input electric pulse was a step function of ±10 V and the peak-to-peak amplitude of the received wave was about 270 mV. The peak-to-peak amplitude is the largest distance between the neighbor positive and negative peaks. The sensor was then cast into a concrete beam with a cover thickness of 10 mm. The ratio of water:cement:sand:aggregate was 1:1.8:4.5:5.5. After the specimen was cured for one week, the above test was repeated; the received wave for this cast sensor is also shown in Fig. 2. The peak-to-peak amplitude of the received wave was about 95 mV.

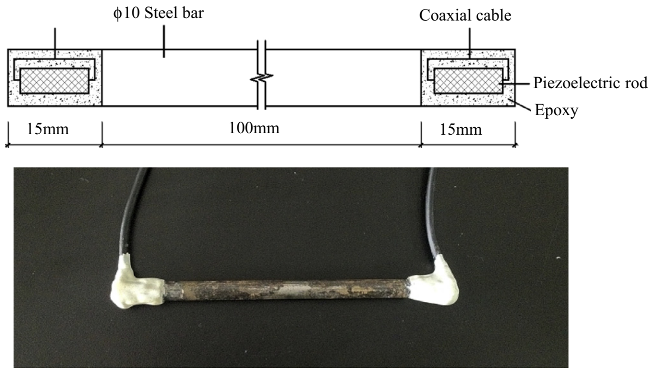

Fig. 1. The structure and picture of corrosion sensor.

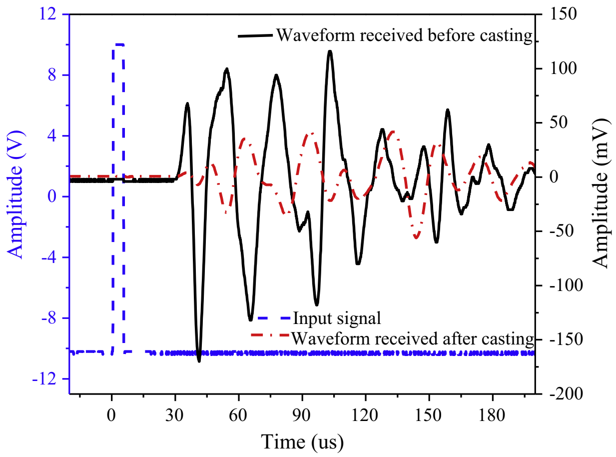

Fig. 2. The input electric pulse and the received waves.

After the corrosion sensor was embedded in concrete, the wave amplitude decreased significantly. Before the sensor was embedded into concrete, the ultrasonic wave was guided purely by the steel bar. In contrast, after casting in concrete a portion of the wave energy was radiated into concrete through the concrete-steel interface, and the wave amplitude decreased.

3. Corrosion monitoring in acceleration experiment

In order to accelerate the corrosion process, after one week curing the concrete beam with embedded corrosion sensor was place in a plastic box with 5% NaCl solution. The testing apparatus is illustrated in Fig. 3. Direct current was also applied to further accelerate the corrosion process. A signal generator was used to generate electric pulses to stimulate the piezoelectric element and an oscilloscope was used for receiving the wave signal. The embedded steel bar was connected to the anode of a DC power source and a copper rod with one end emerged in the solution was connect to the cathode of the power source.

DC power was connected to the mid-point of the steel bar via a cable pre-attached to the steel bar. The current applied in the acceleration test was 0.02 A, and was applied to the system continuously over the duration of the test. When an obvious crack was observed at the surface of the specimen, the experiment was terminated. The development of the normalized wave amplitude from the sensor is shown in Fig. 4. After the onset of corrosion, the wave amplitude began to increase. The increase of the amplitude shows that the sensor is very sensitive to corrosion. After

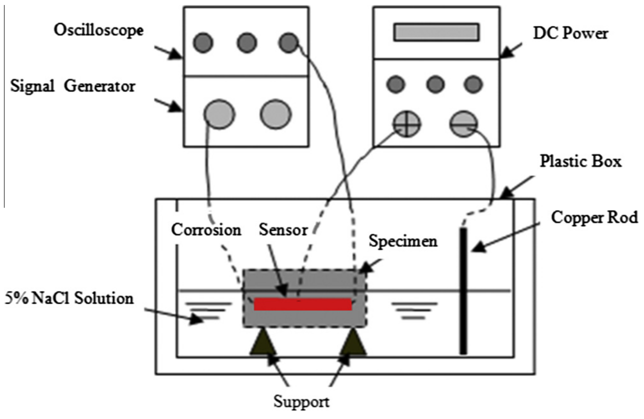

Fig. 3. Instruments for corrosion monitoring in acceleration experiment.