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Experimental study of a pull-out test of corroded steel and concrete using the acoustic emission monitoring method

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HIGHLIGHTS

- The characteristics of the AE signal for the pull-out specimens were analyzed.
- The AE location was consistent with the actual crack development.
- The AE location can determine the initial location of the damage.
- The AE signal was consistent with the test phenomena and macro mechanical parameters.

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ABSTRACT

Based on an acoustic emission (AE) test system, pull-out tests were conducted to study the bond behavior between corroded steel bars and concrete with different corrosion degrees. The characteristics of the AE signal for the pull-out specimens were analyzed. The results showed that the AE location was consistent with the actual crack development. The characteristics of the AE signal reflected the bond behavior, the failure process and the characteristics of the specimens under different degrees of corrosion. Two critical states of crack development and the process of splitting failure slip were obtained. As a result, the stress distribution tends to be uniform along the steel bar with increasing degree of corrosion, and the peak value gradually shifted toward the free end.

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1. Introduction

Due to the long-term effects of loading and the environment, the corrosion of reinforcing steel bars (rebars) inevitably occurs in reinforced concrete (RC) structures. Corrosion decreases the cross-sectional area of the rebar and thus deteriorates the mechanical performance. In addition, the bonding interface between rebar and concrete changes after rebar corrosion. The formation of corrosion products substantially increases the rebar volume, resulting in expansive stresses in the concrete around corroded rebars. These stresses can cause cracking and spalling of the concrete cover and can also decrease the confining contribution of the concrete to the reinforcement, resulting in a degraded bond between the rebar and concrete. Consequently, the load-bearing capacity and stiffness of the concrete structure decrease, reducing its safety and serviceability [1]. Many studies have investigated the degradation of the bond behavior between corroded deformed rebars and concrete from the perspective of macro mechanics. If combined with the mechanical evolution process and crack propagation, acoustic emission (AE) signal analysis could clearly describe the degradation process of the corroded steel bars and concrete.

Green [2] noted that the AE technique could be used to monitor the entire process of concrete damage. The AE signal produced from concrete is a precursor to concrete damage, and the location of the structural defects could be determined using the AE positioning technology [3]. Using the AE technique to evaluate the stability and safety of concrete structures has been shown to be effective [4,5]. The value of AE was very random and discrete with the parameter changes and the state of the specimens. However, in the entire AE process, the characteristic parameters reflect the difference between a process and another process. The AE was a whole behavior covering both the random and discrete, which fully reflects the material's mechanical process and structure evolution process. The AE was a process of multiple

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parameters coupled with the information process [6–8]. Kuksenko et al. [9] have conducted a pull-out test of specimens using AE monitoring techniques. The test showed that the AE characteristic signal increased suddenly before the macro instability. The theory of AE rate was proposed and the relationship between AE parameters and stress was established by Ohtsu et al. [10,11]. In this work, the pull-out test was carried out for steel bars with different degrees of corrosion using the AE technique. All of the collected characteristics of the AE signal were analyzed. The positioning effect of the AE was compared to the actual failure pattern. The AE signal catastrophe corresponding to the drawing process of two critical states was found. The effects of corrosion degree and bond stress were analyzed and discussed. The bond stress increased along the anchorage length with increasing degrees of corrosion.

2. Test design and parameter setting of AE

2.1. Specimen material

The hot-rolled ribbed rebars (HRB335) were 20 mm in diameter with yield strengths of not less than 335 MPa. The concrete was cast using ordinary Portland cement, river sand with a fineness modulus of 2.5, coarse aggregate with a maximum grain size of 20 mm and tap water. To accelerate the concrete corrosion, a 5% NaCl solution was used instead of water. The mix proportion of the concrete is shown in Table 1.

2.2. Specimen design

Cubic reinforced concrete pull-out specimens were designed with a length of 150 mm. The bond length of the steel bar and concrete was 90 mm. Using a PVC hose covering, the rebar was not bonded to the concrete at the two sides over a length of 30 mm, as shown in Fig. 2. Using the strain gauge method, the position and number of the reinforcements are shown in Fig. 1. The epoxy resin was used to fill the steel groove, and then the two halves of the steel were closely combined. The screw nut was screwed off from the specimens after 24 h, after which the specimens were then weighed and casted.

After casting, the specimens were cured in a natural indoor environment at a temperature of 20 ± 3 °C and 95% relative humidity for 28 d. The specimens were then partially immersed in a solution of 5% sodium chloride with the rebars slightly above the solution. Rebar corrosion was accelerated by impressing an anodic current of 200 μA/cm^2 on the specimens. The theoretical corrosion degree was 0% for 1-1, 1-2, and 1-3; 0.5% for 2-1, 2-2, and 2-3; 2% for 3-1, 3-2, and 3-3; 4% for 4-1, 4-2, and 4-3; and 6% for 5-1, 5-2, and 5-3. After the pull-out tests, the specimens were broken and the corroded rebars from the bonded part were obtained. The rebars were cleaned with Clark's solution and then kept in a dryer for 4 h, according to ASTM G1-03 (ASTM, 2003). The masses of the corroded rebars (m_c) were determined using an electronic balance with an accuracy within 0.1 g, and their lengths were measured using a steel ruler. The degree of corrosion (η_s) of the rebars was quantified based on the gravimetric mass loss (the average loss of cross-sectional area of the corroded rebars) and was calculated from the ratios of differences in the mass before and after corrosion to the original mass of the rebars.

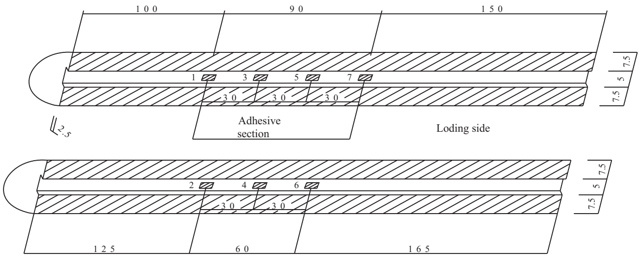

Fig. 1. The location and number of strain gauges.

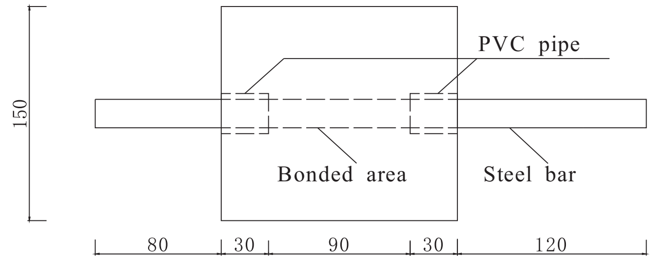

Fig. 2. The specimen dimensions (size: mm).

Table 2
Parameter settings of the AE.

Amplifiers	40 dB	The sample length	1 k
The threshold value	40 dB	The time of peak	80 μ_s
Filter range	1–400 kHz	The time of impact	160 μ_s
Sampling rate	3 M	The lock time of impact	250 μ_s
Touch time	50 μ_s	Rate of location	3150 m/s

2.3. AE parameter setting and sensor arrangement

The monitoring instrument was the SAMOS-48 type AE instrument from the PAC Company. Before the pull-out test, the AE parameters were set up. The sensor was placed in the center position of the two sides of the test block. The threshold value was 40 dB from ten times the lead test, and the concrete velocity was 3150 m/s, which was determined using the time difference method [12]. Refer to relating materials and the parameter settings of the AE are shown in Table 2 [13,14]. The whole process of the pull-out test was monitored by two-dimensional plane positioning, and the square layout of the sensor is shown in Fig. 3.

3. Test results and discussion

3.1. Test specimen failure phenomenon and location analysis

The failure mode of all of the specimens was concrete cover splitting. The specimen was broken and observed from the splitting surface. Obvious traces of steel rib deformation were observed. The front of the concrete rib was crushed, and the root between the transverse ribs of the steel bar was embedded with broken powder concrete and rebar corrosion products. Splitting failure mainly occurred in the reinforced concrete protective layer, and the concrete had little effect on the steel bars. In the pull-out test,

Table 1
Concrete mix proportion.

Concrete grade	Coarse aggregate (kg/m^3)	Sand (kg/m^3)	Cement (kg/m^3)	Fineness modulus (%)	5% NaCl solution (kg/m^3)	The ratio of water to cement
C30	1108	623	404	36	210	0.52

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