Concrete cracking behavior monitored by acoustic emission

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ABSTRACT: In this research, an acoustic emission monitoring system was employed to record and analyze the signals correlated with the fracture behavior during the load test. The test results showed that the AE signals turn out a distinction between splitting fracture and debonding behaviors. Most AE signals take place near the peak load, in particular, for those repaired concrete. The signal in splitting fracture also turns out a brittle failure type. It also showed that there exist two peaks in AE signal for those pull-out loading test, which reflect different bonding condition between concrete and rebar.

1. INTRODUCTION

1.1 Fracture of concrete

Cracks always occur before a concrete structure deteriorates or fails. The study of cracks in concrete is referred to as concrete fracture mechanics, which was begun by Kaplan1. A number of testing methods have recently been suggested to RILEM, such as Jenq and Shah’s (1985) two-parameter model2 and Hillerborg’s (1985) fictitious model3, both of which provide methods for determining the fracture properties of concrete. Rare research evaluated the fracture behavior by other useful physical property, such as acoustic. This work attempts to examine fracture behavior and acoustic emission of the concrete specimens during loading process. Concrete cracks in splitting and de-bonding with steel rebar are focused in this research.

1.2 Acoustic emission applying to concrete

Acoustic emission monitoring was first formulated by Obert4 (1941), who applied the technique in predicting the rock bursts in mines, generating during the excavation process. Recently, the AE technique has been used extremely as a monitoring tool for metallic structures in nuclear, chemical and aerospace industries.

The earliest application of AE in concrete was performed by Robinson (1965) who studied AE in the range of 13-14 kHz in mortar and concrete cubes with various amounts and sizes of aggregates. His results revealed that AE technique can provide an earlier detection than other conventional methods before structural failure. Wells (1970) conducted a similar experiment and observed that noise emission starts somewhere over 50 percent ultimate strength and increases as the failure load is approached. Rossi (1994) applied the acoustic emission in fracture mechanics of concrete and creep of concrete to detect the propagating of micro-cracks. Kan and Pei et al. (2007) monitored the acoustic emission signals of a reinforced concrete slab under a load test and revealed a crack incubation phenomenon which can be referred to as the Kaiser effect. It has also found that an increasing amount of research and practice dealing with the AE technique being conducted on concrete structures.

2. EXPERIMENTAL PROGRAM

2.1 Specimen preparation

In this study, two water-cement ratios (w/c) were 0.39 and 0.64 for concrete mixtures as shown in Table 1. Quartzite was used as aggregates with the maximum grain size of 19 mm and a fineness modulus of 6.73. Its specific gravity was 2.56 measured from the test. Regular sand with a maximum particle size of 4.75 mm was used to fabricate all the concrete specimens. The mechanical properties of concrete at 28 days were shown in Table 2. The specimen dimension for both splitting test and pullout test is 150 mm x 150 mm x 150 mm with two notches in opposite sides of each specimen. The test setups for both above complying to ASTM C900 and ASTM C 496, respectively, were designed. Companions of φ 100 mm x 200 mm cylinders were made to determine their mechanical properties. All specimens were then de-molded and cured in a 100% relative humidity environment for 28 days. The fundamental property of epoxy is also shown in Table 2.

Table 1 Mixture of Concrete

<table>
<thead>
<tr>
<th>Mixture</th>
<th>I</th>
<th>II</th>
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<tbody>
<tr>
<td>Water</td>
<td>kN/m²</td>
<td>1.73</td>
</tr>
<tr>
<td>Cement</td>
<td>kN/m²</td>
<td>3.10</td>
</tr>
<tr>
<td>Slag</td>
<td>kN/m²</td>
<td>1.33</td>
</tr>
<tr>
<td>Aggregate</td>
<td>kN/m²</td>
<td>10.1</td>
</tr>
<tr>
<td>Sand</td>
<td>kN/m²</td>
<td>7.33</td>
</tr>
</tbody>
</table>

Table 2 Strengths of concrete

<table>
<thead>
<tr>
<th>Concrete</th>
<th>f'c', MPa</th>
<th>f', MPa</th>
<th>E, GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix I</td>
<td>35.7</td>
<td>3.74</td>
<td>27.8</td>
</tr>
<tr>
<td>Mix II</td>
<td>49.9</td>
<td>4.42</td>
<td>38.7</td>
</tr>
</tbody>
</table>

2.2 Test methods for concrete cracks

All tests were conducted using a closed-loop servo-hydraulic loading system (MTS), as shown in Figure 1. Two types of cracking mechanism – splitting crack and pull-out crack were investigated herein. The former specimen tested to obtain a splitting crack was loaded in a manner to generate a splitting crack. The test configuration was thus designed for loading with rollers on two notches on opposite sides of a specimen as shown in Fig. 2(a) to develop a crack through the concrete.

Figure 1 Closed-loop servo-hydraulic loading system (MTS)
The specimen was loaded in a closed-loop servo-hydraulic testing system with a displacement control for both types of tests. A loading rate of 0.008 mm/sec was used until concrete failure. During the loading process, four AE sensors on four faces were mounted to monitor the signal from the specimen. All the signals were recorded and analyzed later.

In this research, a self-developed AE system using data acquisition (DAQ) components of National Instruments Co. and real-time program (LabView7-) was assembled for inspection. The system can continually record (4 digital channel/800kHz/16bit) emissions over the entire load test (up to 4 hours). The obtained binary data can be displayed and counted for later analysis. In this research, the sensor with 40dB Integral Preamp function and 500kHz spectral response range (150kHz Max.) was used. Emissions with frequency in 10k~140kHz were mainly concerned. The sensor locations are shown in Figure 2(a) and 2(b) for splitting test and pull-out test, respectively.

3. FINITE ELEMENT ANALYSIS

Numerical analysis was also conducted through the ANSYS, a finite element code, to simulate both splitting and pull-out tests adopted in this study. The stress analysis and the possible mechanism to trigger the crack propagation for each type of test were figured out before the test. A two-dimensional four-node element was used to simulate each specimen in the analysis. The analysis assumed plane stress type with a constant thickness of 150 mm. The modulus of elasticity of 28.5 GPa and Poisson ratio of 0.2 were assumed as material properties in the analysis. For the splitting test, a quarter region of the specimen was constructed and analyzed due to symmetry in geometry and loading setup. A distributed load applied on each side of the angled notch is simulated to that the load transmitted from the roller to the bearing plate attached to the notch side of the specimen, as shown in Figure 3(a). Similarly, a quarter region of the pull-out specimen was analyzed due to symmetry in geometry and loading setup. A radial distributed load applied along the corner edge on which the rebar is located is simulated as the bond force coming from the rebar to the concrete, as shown in Figure 3(b).

2.3 Testing procedure

The pull-out test specimen was also cast a pair of notches on opposite sides as shown in Fig. 2(b) in order to create a crack between two notches. Acoustic emission (AE) sensors were placed on appropriate positions as shown in the figures above to receive the signals while each specimen was being loaded.

The crack was repaired later by epoxy to examine the strength after restoration of cracked concrete. Each beam was completely broken into two pieces and then reassembled with a 1 mm wide crack apart. The resin was then injected using a syringe from the bottom port and output from the outlet port to ensure that the crack region could be fully filled with the resin. The sealing of each beam took approximately 2 days. After the surface sealer had set, the epoxy resin was injected into the fractured region and air-cured for 7 days. The surface sealer had to be removed using a grinder or a chisel and hammer to clean up the beam surface around the sealing area before the test to eliminate the effect of the surface sealer.
4. RESULTS AND DISCUSSIONS

4.1 FE analysis

Finite element analysis was conducted before the test via ANSYS to analyse the stress and potential crack propagation for splitting test and pullout tests to ascertain that a crack through two notches can be obtained in each case.

From the result of simulation, it can be seen from Figure 4(a) that higher stresses concentrate along the line through two notch tips and the highest stresses are located at two tips of the notches. Namely, the cracks will take place from the tips and propagates from the tip. Figure 4(b) shows that higher stresses also concentrate along the line through two notch tips but the highest stresses are located at two vertexes at the top and bottom of the rebar. Namely, the cracks will take place and propagates from the vertex to the tip of notch.

4.2 Splitting fracture of concrete

Figure 5 and Figure 6 show the AE signals recorded during the loading process for normal strength and high strength concretes in splitting test, irrespectively. The signals are displayed in terms of accumulative counts of events per second and are correlated with the load. It is noted that small noises occur in the beginning and the first peak of the signal taking place around 1.5 kN which can be referred to the friction between the bearing plates and concrete. After then, no apparent peak except numerous tiny noises still continue to occur during the loading test. Finally, the extreme peak takes place as the load reaches the peak. This implies a brittle fracture in the test.

Figure 5 AE analysis for normal strength concrete loaded in splitting test

Figure 6 AE analysis for high strength concrete loaded in splitting test

4.3 Pullout behaviour of concrete

From the AE signal analysis in the pullout test, it is found that little noise takes place in the beginning stage and apparent signals to about start to increase till the load reaches to 90% of the peak load for normal strength concrete and high strength concrete, as shown in
Figure 7 and Figure 8. It is interesting that a minor peak occurs after the extreme peak load for both normal strength concrete and high strength concrete. The first peak in the AE plot is due to the creation of splitting crack of concrete, and the minor peak can be attributed to the friction between the ribs of rebar and concrete.

1. The fracture behaviour for splitting test and pullout test can be successfully predicted by finite element analysis. This is useful for specimen design for the fracture test.
2. Splitting test turns out a brittle type of fracture which can be observed from the results of loading test and AE monitoring and analysis.
3. From the pullout test, it is observed that the acoustic signals become apparent after 90% of extreme peak load is reached. The extreme peak in AE signal occurs concisely with the peak load.
4. Two peaks occur in both AE signal and loading curves in the pullout test. The former peak refers to the occurrence of splitting crack of concrete and the latter one can be attributed to friction between the ribs of rebar and concrete.

6. REFERENCES


ACKNOWLEDGEMENT

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5. CONCLUSIONS

Based on the test results and analysis, several conclusions can be drawn from this study.