BOND RESISTANCE OF REPAIRED CRACKED-CONCRETE EMBEDDED WITH REBAR IN VARYING SIZE UNDER CYCLIC LOAD

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The bond behavior of concrete planted in varying size re-bar D19, D32, D43 and D57 subjected to a cyclic loading pullout test, was investigated through a systematic experiment accompanying with a real-time acoustic emission (AE) monitoring. Another series of tests of concrete including an existing crack repaired by epoxy were also engaged to compare the behavior of repaired concrete under cyclic loading. The ultimate bonding load capacity as well as ultimate bond stress increases with the steel bar size. The repaired bonding load capacity of concrete turns out higher than those un-cracked. In addition, the slip at ultimate peak load is reduced with increasing in rebar diameter. The acoustic signals revealed by AE can be applied to analyze and compare the behavior of concrete with each sized re-bar. The information obtained from the test results provide useful technique to access the safety of NPP RC structure after reparation to resist the cyclic load.

Keywords: Acoustic emission, Pull-out test, Repaired concrete, Epoxy.

1 INTRODUCTION

A plenty of nuclear concrete containments around the Pacific-rim area were built in 1970s which have experienced a number of huge earthquakes. The building code for concrete containments design during the period seemed to pay less attention on the seismic resistance. This may become an important factor to induce cracks on those concrete structures. The seismic load is classified to the low frequency and high stress loading type. The ACI 408 (ACI Committee 408 1999) adopted the pull-out test as the primary method to investigate the bond behavior between rebar and concrete under cyclic loading. The cyclic load rate with high stress and low frequency could be adopted. In a typical earthquake, a reinforced concrete structure can be subjected to seismic load below 100 cycles and approaching to the ultimate stage. Cao and Chung (2001) have investigated the bond between concrete and rebar under loading by using electrical resistance method. The bond loss could not be observed from the surface of concrete. After few cycles of loading, the electrical resistance suddenly grew up and the bond failed. It is felt valid and necessary to investigate the bond behavior of concrete and repaired concrete under dynamical loading in a mechanical manner to provide more practical information for engineers to access the seismic existing concrete structure.

The acoustic emission method has been used for homogeneous materials for many years and is getting more and more applications for concrete materials. However, the relationship between concrete materials and mechanical characteristics needs more research effort to explore. During the material experiment process, the acoustic emission technique can be used to monitor the emitted...
sounds to establish the relationship between acoustic emissions, microscopic mechanisms, and mechanical characteristics to: (1) analyze the relationship between material cracking, deformation, and mechanical behavior; and (2) establish a broad acoustic emission signals database. The mechanics of slip of deformed bars in concrete with the support of experimental data were reported by Lutz and Gergely (1976). Grosse and Finck (2006) reported the results obtained during fracture mechanical experiments at concrete specimens demonstrating the capabilities of quantitative AE techniques. A study by Mindess (1982) found that the number of AE counts passing the threshold increased with the increase of loading during pure concrete compression tests. As the load being increased about 80% to 90% of the ultimate load, the AE signals inside the concrete appeared increasing which indicates the forming of cracks in the concrete.

2 TEST PROGRAM

The bond performance of concrete with varying size re-bar, under cyclic loading were investigated via an experimental program complying with the ASTM A944 (ASTM 2022). And a real-time acoustic emission (AE) monitoring was conducted simultaneously. Another series of tests of concrete including an existing crack repaired by epoxy were also engaged to compare the behavior of repaired concrete under cyclic loading. The experiment focuses on the cyclic pull-out tests to compare the bond performance of the un-cracked and repaired concrete embedded with different re-bars (D19, D32, D43 and D57). The acoustic signals revealed by AE were applied to analyze and compare the behavior of concrete with each sized re-bar.

2.1 Specimen Preparation

The mix design was used in this test as shown in Table 1. The concrete strength designed in this study was 27.4 MPa. The pull-out test cube was fabricated in which varying size of re-bar was embedded. The specimen dimension was 260 mm × 260 mm × 260 mm with a pair of V-notches on two sides of the specimen, as shown in Figure 1, to produce a crack face for reparation by epoxy later. The repairing procedure for cracked concrete used by Kan et al. (2021) were followed in this study. The accompanying cylindrical specimens (100 mm × 200 mm) were also cast for the same batch to fabricate the cubes to determine the compression strength of the concrete. Three concrete specimens for each bar size were cast, and tested after 28 days of curing.

Table 1. Concrete mixture.

<table>
<thead>
<tr>
<th>W/C</th>
<th>Cement*</th>
<th>Water</th>
<th>Aggregate</th>
<th>Sand</th>
<th>SP**</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.62</td>
<td>299</td>
<td>185</td>
<td>1132</td>
<td>751</td>
<td>0.99</td>
</tr>
</tbody>
</table>

*Unit of weight is kg per cubic meter; **superplasticizer

Figure 1. Pullout specimen design.
2.2 Test Method

2.2.1 Pull-out test

In this study, the pull-out test method of ASTM C234 accompanying with real-time AE monitoring is conducted to examine the bond behaviour between concrete and re-bars. A rubber plate was placed between the steel bearing plate and concrete specimen to ensure the stress being uniformly distributed. In addition, an LVDT was mounted for slip measurement between the re-bars and concrete. Four AE sensors were mounted on specific locations of the specimen to monitor the cracking signals under loading. The pull-out tests were engaged on an MTS system and the AE sensors are allocated as shown in Figures 2 and 3, respectively.

In a static load test, the control mode of displacement control was used with a loading rate of 0.01 mm/s, and the acoustic emission monitoring system was used to record sound signals inside the concrete simultaneously. The data acquisition controller was used to record the load added from MTS and the slip from LVDT. In a cyclic load test, the load control was applied with the load range around 10% to 90% of the load capacity in the static pull-out test with a loading rate of 0.1 Hz for every 50 cycles during a loading period. If no AE signal appears in that period, both the upper and the lower load are increased 20% in the next loading period. The signals recorded during the test were used in later analyses.

3 RESULTS AND DISCUSSIONS

3.1 Bonding Properties of Concrete

Table 2 shows bond properties of un-cracked and repaired concrete obtained from the pull-out tests for concrete with varying size rebar. The pullout specimen embedded in D57 re-bar had the greatest ultimate loading capacity $P_m$ followed by the specimens with re-bar of D43, D32, and D19. Also, the ultimate bond stress $U$ turns out the similar trend. It is determined from $P_m / \pi d_b h$ in which $d_b$ and $h$ are the re-bar diameter and the embedded length in concrete. Besides, the pullout specimen embedded in D19 re-bar was observed to have the largest slip $\Delta_m$ at ultimate peak load, followed by the specimens embedded in D43, D32, and D19 re-bar.

In addition, the ultimate bond stress of cracked concrete after reparation $U_r$ has the same trend as $U$, and perform higher values than those un-cracked. The ratios of $U_r / U$ are 1.02, 1.43, 1.71 and 1.28 for re-bar of D19, D32, D43 and D57, respectively; while, the ratios of bond slip at the
peak load for those repaired concrete in terms of $\Delta_m$ to $\Delta_m$ are 1.55, 2.38, 1.18 and 2.50 for concrete embedded in re-bar of D19, D32, D43 and D57, respectively. It implies that the bond stress after reparation conducts higher strength and ductility than that of un-cracked for a given size of re-bar. A comparison of ultimate bond stress for un-cracked and repaired concrete can be shown in Figure 4.

<table>
<thead>
<tr>
<th>Rebar</th>
<th>$P_m$ kN</th>
<th>$P_{mr}$ kN</th>
<th>$\Delta_m$ mm</th>
<th>$\Delta_{mr}$ mm</th>
<th>$\Delta_{mr} / \Delta_m$</th>
<th>$U_m$ MPa</th>
<th>$U_r$ MPa</th>
<th>$U_r / U_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D19</td>
<td>118</td>
<td>121</td>
<td>0.75</td>
<td>1.16</td>
<td>1.55</td>
<td>7.78</td>
<td>7.91</td>
<td>1.02</td>
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<tr>
<td>D32</td>
<td>129</td>
<td>184</td>
<td>0.24</td>
<td>0.57</td>
<td>2.38</td>
<td>5.04</td>
<td>7.19</td>
<td>1.43</td>
</tr>
<tr>
<td>D43</td>
<td>136</td>
<td>234</td>
<td>0.11</td>
<td>0.13</td>
<td>1.18</td>
<td>3.78</td>
<td>6.48</td>
<td>1.71</td>
</tr>
<tr>
<td>D57</td>
<td>149</td>
<td>190</td>
<td>0.06</td>
<td>0.15</td>
<td>2.50</td>
<td>3.26</td>
<td>4.17</td>
<td>1.28</td>
</tr>
</tbody>
</table>

Note: $U = P_m / \pi d b_h$; $U_r = P_{mr} / \pi d b_h$

Figure 4. Ultimate bond stress for un-cracked and repaired concrete.

### 3.2 Cyclic Pull-Out Test

The cyclic pull-out test for the un-cracked concrete specimen embedded in various size rebar were shown in Figure 5. The number of cycles to failure for all sizes of rebar are less than 50 under load range between 10% and 90% of $P_m$. While, the cyclic pull-out test for those repaired were shown in Figures 6 to 9, respectively.

### 3.3 AE Signals for Repaired Specimens

Acoustic emission technique was used to detect the cracking events inside concrete as being loaded. A typical AE signals recorded in the history of a cyclic pull-out test for repaired concrete specimen embedded in D19 rebar is demonstrated as an example in Figure 6. Under a cyclic load ranging from 10% to 90% of the load capacity and a loading rate of 0.1 Hz, no AE signal appears until exceeding the 800th second of loading. After, the AE signal increases apparently and achieving the peak at 863 seconds. Similar patterns are demonstrated in Figures 7 to 9 for those embedded in rebar of D32, D43 and D57, respectively.
Figure 5. Cyclic loading test for un-cracked concrete embedded with various rebar.

Figure 6. AE signal variation during the load test for D19.

Figure 7. AE signal variation during the load test for D32.

Figure 8. AE signal variation during the load test for D43.

Figure 9. AE signal variation during the load test for D57.

4 CONCLUSIONS

In this study, the analysis and results can be summarized into the following conclusions. The ultimate bonding load capacity as well as ultimate bond stress increases with the steel bar size. The repaired bonding load capacity of concrete turns out higher than those un-cracked. In addition, the slip at ultimate peak load is reduced with increasing in rebar diameter. The bond between concrete and rebar may perform well under a designated cyclic loading range. However, once the first peak in AE signal monitoring occurs, only limited loading cycles are needed to achieve peak at the bond failure.

Acknowledgments

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