FLEXURAL FAILURE BEHAVIOR OF RC BEAMS WITH REBAR CORROSION AND DAMAGE EVALUATION BY ACOUSTIC EMISSION

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Abstract

It is important to interpret and evaluate the fracture mechanism of deteriorated concrete structures with rebar corrosion. Monitoring by means of acoustic emission (AE) technique based on the clarified fracture process of the deteriorated concrete is also useful for maintenance scheme. This paper presents an experimental investigation on the flexural failure behavior of RC beams having different weight loss of 0, 5, 10 and 30% due to corrosion. AE was also monitored during the loading tests of the deteriorated concrete beams. As corrosion levels represented by weight loss increased, load carrying capacity of the beams decreased dramatically. In the case of the severest damage having weight loss of 30%, the rebar was eventually broken at the final stage. The mechanical behavior was attributed to the decrease of cross section of rebar and deterioration of bond properties (debonding) between concrete and rebar with corrosion. The deterioration of bond properties also provided the decrease of number of cracks within the beams. Regarding observation of AE activity, the number of AE events in the beams increased with increasing the corrosion levels, especially as it became more intense at the initial loading level before yielding of rebar. The bond deterioration in the beams with corrosion might occur around the rebar at an early loading stage. The AE sensors attached directly onto the rebar detected more AE signals with lower frequency than that of concrete. It was concluded that such detected AE signals with lower frequency appear to be generated by debonding behavior due to corrosion.

Keywords: Reinforced concrete (RC), Corrosion, Bond deterioration

Introduction

Corrosion of rebar is one of the serious deterioration phenomena in concrete structures, affecting their safety. Past research works and specifications classify the deterioration processes due to corrosion as dormant stage, initiation stage, accelerated stage and deterioration stage. For maintenance scheme, it is important to identify the deterioration process more specifically. Previous research on AE applications to corrosion of reinforced concrete aimed at evaluating the corrosion process of rebar, including cracking of concrete and corrosion of rebar itself [1-3]. However, there was few investigation on AE activity of corroded RC members subjected to external loading.

In this study, loading tests were conducted to clarify two main objectives: One is to interpret fracture processes of RC beams with a rebar corrosion; the other is to characterize a detected AE signal in RC beams with a rebar corrosion during loading tests, and also to identify the bond characteristics of the RC beams through AE technique.
Specimens

Table 1 gives the specified mix proportions of concrete used in the tests. The cement, fine aggregate, and coarse aggregate were ordinary Portland cement with a density of 3.15 g/cm³, river sand with a density of 2.55 g/cm³, and river gravel (maximum size: 15 mm) with a density of 2.57 g/cm³, respectively. The chemical admixture was an air entraining and water reducing agent. The slump and air content of the mixed concrete were 7.5 cm and 2.2%, respectively.

Table 1. Mix proportions of concrete.

<table>
<thead>
<tr>
<th>W/C</th>
<th>s/a</th>
<th>Unit content (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>56.5</td>
<td>49.6</td>
<td>W</td>
</tr>
<tr>
<td></td>
<td></td>
<td>176</td>
</tr>
</tbody>
</table>

* Air entraining water-reducing agent

Beam specimens measuring 140 x 80 x 1460 mm were used for bending tests, as shown in Fig. 1. A deformed rebar with a nominal diameter of 13 mm and nominal yielding strength of 345 MPa was placed in the specimen. All stirrups were wrapped with polyvinyl tape to prevent corrosion of stirrups themselves. One specimen was fabricated for each series. After being de-molded at the age of 1 day, specimens were covered with wetting-cloth, and cured in a thermostatic room at 20°C for 28 days. Compressive strength of the concrete at the age of 28 days was 22.7 MPa.

Fig. 1. Specimen configuration.

Fig. 2. Setup of accelerated corrosion tests.
Table 2. Weight loss of rebar after corrosion tests.

<table>
<thead>
<tr>
<th>Weight loss of rebar (%)</th>
<th>3%</th>
<th>10%</th>
<th>30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total applied current (A·hr)</td>
<td>69.6</td>
<td>240</td>
<td>602.4</td>
</tr>
</tbody>
</table>

**Accelerated Corrosion Tests and Results**

In order to induce rebar corrosion, an accelerated corrosion test was carried out for the beam specimens, as shown in Fig. 2. The specimens were placed on a copper plate in a chamber filled with NaCl solution (concentration: 3%), and current of 0.6 A (0.907 mA/cm$^2$) was applied to rebar in each specimen. Table 2 tabulates the investigated corrosion levels represented by different weight loss of rebar. The weight loss was controlled by total applied current. Here, we used the relationship between expected weight loss and total applied current proposed by Tamori et al. [4]. Good correlation between weight loss and total applied current was observed in this test, as shown in Fig. 3.

![Amount of rust after corrosion tests](image)

**Fig. 3. Amount of rust after corrosion tests.**

![Crack width](image)

**Fig. 4. Crack width.**
Figure 4 shows the longitudinal crack width measured at bottom surface that is close to a rebar. Basically, crack width became wider with increasing of corrosion levels that represented by weight loss. In severe corrosion case (10 % and 30 % cases), crack width along a specimen axis was not so constant that it indicates that corrosion was occurred locally. Figure 5 indicates the diameter of rebar measured in longitudinal direction at an interval of 50 mm. Nominal diameter of the rebar used in this test was 13 mm. Significant decrease of rebar diameter was observed locally, especially in the case of severe corrosion (30%).

![Figure 5. Diameter rebar measured in longitudinal direction.](image)

### Loading Tests

**Test Setup**

Four-point bending tests were conducted with a constant moment length of 280 mm and total span length of 1260 mm, as shown in Fig. 1. In this test, load and displacement at loading points were measured by a load cell with a capacity of 100 kN (sensitivity: 33 N) and LVDT with a capacity of 50 mm (sensitivity: 0.01 mm), respectively.

**Test Results**

Figure 6(a) shows the measured load-displacement curves in all series. There was no significant difference in 0% and 3% cases. In other cases, however, the yielding and maximum loads became lower with increasing corrosion levels (weight loss). Especially in the case of 30%, rebar was finally broken. Figure 6(b) indicates the load-displacement curves up to displacement of 5 mm. First cracking load of each case was similar to each other, but the tension stiffening zone, which was equal to debonding region of rebar and concrete, was slightly different. As shown in 30% case, the corrosion of rebar gave significantly lower bond properties.

Figure 7 represents the crack patterns after the loading tests. In the case of no corrosion, more than five cracks were observed. Decrease in the number of cracks, which normally represents lower bond property, was observed in only 30% case. In addition, the location of broken rebar agreed quite well with the wider crack width that was also similar to the minimum part of rebar in diameter, as shown in Figs. 4 and 5.
AE Measurement

Test Setup

AE signals were detected by 150-kHz resonant sensors, and amplified 34 dB with integrated pre-amplifiers. The signals exceeding the threshold level of 54 dB were recorded by 16-channel AE monitoring system (AMSY-5, Vallen Systeme). The detected AE signals were characterized by several parametric features and by recorded waveforms. Four sensors were positioned on the concrete surface of the specimen, as shown in Fig. 8. Although ten sensors were attached to the specimen basically, it seems that several sensors frequently detected ambient noise. So only the data of four sensors, that included less noise, was used in this study. In addition, two AE sensors were attached to the rebar, as shown in Fig. 8.
Fig. 8. Location of AE sensors.

Fig. 9. AE hits detected by sensors on concrete surface.

Fig. 10. AE hits detected by sensors on rebar.

Test Results

AE hits corresponding to the number of the detected AE signals were used first for the evaluation. Figure 9 shows the AE hits at interval of 1 mm in displacement, which were detected by the sensors attached to the concrete surface. In all cases, the number of AE hits during displacement of 1 to 4 mm was most active among loading steps. As described in the load-displacement curves in Fig. 6, yielding of rebar occur at displacement of 4 to 5 mm. Regarding the no corrosion case, the number of AE hits during displacement of 1 to 3 mm was most active among loading steps. As described in the load-displacement curves, first crack occurred at displacement of about 0.5 mm, and the number of cracks increased gradually. Each crack propagated to the direction of specimen depth. This fracture mechanism agrees well with the trend of
AE hits. By comparison among corrosion cases, the number of AE hits increased with increasing corrosion levels as well, except for 30% case. It seems that corroded rebar induced many AE signals due to debonding behavior of rebar, in addition to the cracking behavior. In the 30% case, the number of cracks in concrete decreased and it caused less AE activity to the specimen.

Figure 10 shows the AE hits detected by AE sensors attached to rebar directly. This figure shows clearly that the number of AE hits increased with increasing corrosion levels. Regarding the number of AE hits up to displacement of 3 mm, a remarkable increase of AE hits was observed in 30% case, because debonding of corroded rebar appears to have started at an early loading stage. Correspondingly, the number of AE hits has a strong correlation with corrosion levels. It was also evident that the technique of using the AE sensors attached to a rebar was useful to recognize fracture mechanism of RC beams with corrosion as well as to evaluate corrosion level.

![Graph 1](image1.png)  
Fig. 11. Frequency of AE signals detected by sensors on concrete surface.

![Graph 2](image2.png)  
Fig. 12. Frequency of AE signals detected by sensors on rebar.

Figure 11 shows the peak frequency obtained from averaging all of derived peak frequencies though fast Fourier transform (FFT) of detected AE waveforms by sensor attached to the concrete surface. The AE signals from concrete surface showed no significant difference in the peak frequency at each step in this experiment. The peak frequency appears to be constant around 150 kHz that corresponds to the resonant frequency of AE sensors used. Figure 12 shows the peak frequency in the case of rebar-mounted sensor, obtained in the same manner as Fig. 11. This figure shows clearly that the peak frequency decreased with increasing corrosion levels. Different crack patterns and difference of restraining condition of rebar by surrounding concrete corresponding to the corrosion level appeared to result in this behavior. It seems that AE signals with lower frequency characterized fracture at interface between concrete and corroded rebar. It was found that AE signals detected by AE sensors on rebar provided sensitive results to detect failure behavior with different corrosion levels.
Fig. 13. Raw data of peak frequency through FFT (white dots: concrete attached AE sensor and black dot: rebar attached AE sensor). (a) No corrosion, (b) 30% corrosion.

Raw data of peak frequency through FFT are shown in Fig. 13. Two extreme cases of no corrosion and 30% corrosion level are demonstrated as in Fig. 13(a) and (b), respectively. No definite trends of peak frequencies of AE hits correlating to corrosion levels could be found for the concrete-surface AE sensor (see white dots); however, a decrease of the peak frequency from more than 150 kHz to about 100 kHz was obtained from rebar-mounted AE sensor (see black
dots). It seems that the ratio of AE events of low frequency to those of high frequency quantitatively evaluate the rebar corrosion level.

Conclusions

In this paper, the experimental investigation on the flexural failure behavior of RC beams having the different weight loss of 0%, 5%, 10% and 30% due to corrosion was conducted, and acoustic emission (AE) was monitored during the loading tests. Following conclusions were obtained;
1) With an increase of corrosion levels represented by weight loss, the load carrying capacity of RC beams was decreased. In the 30% case, the rebar was broken at the final stage. The mechanical behavior significantly depends on the deterioration of bond properties between concrete and rebar with corrosion, especially in 10% and 30% cases. The deterioration of bond properties also decreased the number of cracks within the beams.
2) Based on the AE activity, the number of AE events in the beams increased with increasing the corrosion levels, especially at the initial loading level before the yielding of rebar. The AE sensor directly attached on a rebar detected more AE signals with lower frequency than that of the sensors on concrete surface. It was concluded that the detected AE signals with lower frequency might be generated due to debonding process of corrosion. It seems that the ratio of AE events of low frequency to those of high frequency quantitatively evaluates the rebar corrosion level.

Acknowledgement

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References