NEUTRON DIFFRACTION STUDIES ON STRAIN EVALUATION OF REBAR IN REINFORCED CONCRETE

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ABSTRACT
The neutron diffraction technique was applied to measure strain distributions in a rebar in a reinforced concrete. At first, absorption coefficients of several kinds of concretes with different compounding ratio of water, cement and aggregate were measured, and it was confirmed that the absorption coefficient of concrete was affected by the amounts of water and aggregate. In addition, it was also clarified by measuring strain change of the rebar under tensile loading that accuracy of the strain measurement in the rebar in the reinforced concrete was not affected by the neutron absorption by the concrete. Secondly, size of anchorage zone was evaluated by measuring strain distributions in the rebar under pull-out loading. The length of anchorage zone measured by neutron diffraction was shorter than that measured by strain gauges. Moreover, detailed strain distributions in the rebar around cracks in the concrete were measured under tensile loading, and it was confirmed that the bond condition between rebar and concrete around cracks could be evaluated using the neutron diffraction technique.

INTRODUCTION
Reinforced concrete is known as the composite material with rebar and concrete, so that the stress balance between rebar and concrete is affected by the bond condition between them [1-3]. Therefore, it is very important to know the strain distribution in the rebar in the reinforced concrete for evaluation of the bond condition. In the structural engineering field, strain gauges are utilized for measuring the strain in the rebar in the reinforced concrete [3]. However, waterproof treatment and wiring of the strain gauges around the rebar probably affect the bond condition. Therefore, the neutron diffraction
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technique, which is nondestructive and noncontact method, might be useful for measuring the strains in the rebar in the reinforced concrete without any effects on the bond condition. However, since concrete is well known as the neutron shielding material the water in hydrated cement and the evaporative water in pore spaces would make the neutron strain measurement difficult. Because of that, there are no reports of the strain measurements of the reinforced concrete structures using the neutron diffraction technique. In this study, we measured the strain distributions in the rebar in the reinforced concrete using the neutron diffraction technique. In particular, this paper shows the results of absorption coefficients of the concretes and verification of accuracy of the neutron strain measurement as well as two examples of the strain measurements in the rebar in the reinforced concrete in order to evaluate the length of anchorage zone and the strain distributions in the rebar around cracks in the concrete.

OPTICAL SYSTEM
The engineering diffractometer for stress analysis, RESA [4], in the Japan Research Reactor No. 3 (JRR-3) at the Japan Atomic Energy Agency (JAEA) was utilized. Figure 1 shows the optical layout of the RESA diffractometer. The large XYZ sample table with the size of 1000 mm x 1000 mm was mounted on the RESA diffractometer. Monochromatic beam of neutrons was obtained by reflection from the (113) planes of an elastically bent perfect crystal of silicon. This monochromatic beam irradiated the sample through the cadmium slit, and the diffracted beam was detected by the position sensitive detector (PSD) after passing through the radial collimator.

ABSORPTION COEFFICIENT
Experimental Procedure
Figure 2 shows the layout of measurement of absorption coefficients of concretes. Neutron with the wavelength of approximately 0.20 nm irradiated the sample, and diffracted neutron profiles were measured by the PSD. Changes in peak intensity were measured as the thickness of concrete increased. Several kinds of samples with different composition were prepared for comparing each of them. Table 1 shows compounding
ratios of each sample. P50 and P30 samples are known as the paste type. The compound ratio of water and cement in the P50 was 5 by 10 and that in the P30 was 3 by 10, but no aggregates were scattered in these samples. C50 sample is known as concrete type, and the compound ratio of water and cement was 5 by 10, which was the same as that in the P50, whereas the C50 included fine and coarse aggregates. In addition, mortar sample was also prepared although the detailed compounding ratio was unknown.

Results and Discussions

Table 1 also shows the result of measured absorption coefficients. Absorption coefficient of type 304 stainless steel is also shown in this table for comparing between concretes and steel. The absorption coefficient of the P30 was lower than that of the P50 because the water content of the P30 was lower than that of the P50, and the absorption coefficient of the C50 was quite lower than those of the P30 and the P50 since the C50 included aggregates with lower absorption. These results indicated that lower water content and higher aggregate content could lead to lower absorption coefficient. Moreover, the absorption coefficient of the C50 was half of that of the steel. Therefore, it would be possible to measure the strain distribution on the rebar in dried concrete with thickness of 50 mm to 100 mm using the neutron diffraction technique.

Table 1 Compounding ratios in mixing and measured absorption coefficients of each sample.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Compounding ratio</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water</td>
<td>Cement</td>
</tr>
<tr>
<td>P50 (Paste)</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>P30 (Paste)</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>C50 (Concrete)</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Mortar</td>
<td>Unknown</td>
<td>-</td>
</tr>
<tr>
<td>304SS</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
ACCURACY OF NEUTRON STRAIN MEASUREMENT

Experimental Procedure

Strain change of the rebar was measured under uniaxial tensile loading in order to verify accuracy of the strain measurement in the rebar in the reinforced concrete. Figure 3 shows the schematic of the sample used in this study. Rebar with diameter of 18 mm passed through the hole with diameter of 20 mm machined in the rectangular concrete cover with the size of \( a \times a \times 150 \) mm. Strains at some positions in the rebar were measured during tensile loading. Two kinds of concrete covers with different size were prepared as \( a=50 \) mm and \( a=70 \) mm. Both concrete covers were absolutely dried, and sample with water curing was also prepared in only \( a=50 \) mm sample. Wavelength of 0.16 nm was selected and the lattice strains of the ferrite 110 reflection, which appeared at \( 2\theta=46 \) deg, were measured. Measurement time of one peak profile was 3 to 5 min for getting 100 counts of the peak intensity.

Results and Discussions

Figure 4 shows the result of changes in the diffraction angle with respect to the applied stresses. Average diffraction angles at some positions of the rebar were plotted in this figure. Cross marks in Fig. 4 show the diffraction angles of the rebar without the

Fig.3 Schematic of the sample used in evaluation of accuracy of the strain measurement in the rebar in the concrete.

Fig.4 Changes in diffraction angle with respect to applied stress in each concrete sample and rebar only.

Fig.5 diffraction profiles of the rebar covered by the dried and the wet concretes with the size of \( a=50 \) mm.
concrete cover, and linear response can be observed. Young’s modulus of the rebar is 228 GPa which is close to 221 GPa calculated by Kröner model [5] using single crystal elastic constants of pure iron; $C_{11}=251$ GPa, $C_{44}=112$ GPa and $C_{12}=157$ GPa [6]. Moreover, diffraction angles of each sample condition i.e., a=50 mm dry, a=70 mm dry and a=50 mm wet, were plotted near the same line as that of the rebar only. Figure 5 shows the diffraction profiles of the rebar covered by the dried and the wet concretes with the size of a=50 mm. Difference of the peak shape was not observed between two of them. Therefore, it was confirmed that influences of the concrete conditions i.e., sample size and water content, on accuracy of the strain measurement in the rebar were negligible.

EVALUATION OF SIZE OF ANCHORAGE ZONE

Experimental Procedure

Figure 6 shows the schematic of the specimen used in this study. Rebar with diameter of 10 mm was embedded in the cylindrical concrete with the size of 400 mm length and 50 mm diameter. Pull-out loading was applied to the rebar, and the strain distribution was measured along the rebar by 1 mm pitch. The concrete was absolutely dried after carbonation treatment. Wavelength of 0.20 nm was selected and the lattice strains of the ferrite 110 reflection, which appeared at $2\theta=59$ deg, were measured. Measurement time of one peak profile was 10 min for getting 200 counts of the peak intensity. Strain distribution was measured under the applied stress of 200 MPa.

Results and Discussions

Figure 7 shows the strain distributions in the rebar in the reinforced concrete. Applied stress was gradually decreased from 200 MPa to 150 MPa during strain measurement due to creep of the concrete. The strain distribution under the applied stress of 200 MPa was decreased in the length from X=0 mm to 75 mm. Therefore, it can be said that the length of the anchorage zone measured by neutron diffraction was about 75 mm. Strain distribution measured by strain gauges was also plotted in this figure [7]. Decrease in
the strain was observed in the length from X=0 mm to approximately 200 mm, which means that the length of the anchorage zone measured by strain gauges was about 225 mm. In the strain measurement using strain gauges, the stress balance between rebar and concrete might be affected by the bond condition around strain gauges. Furthermore, difference of measurement region between the neutron diffraction technique and the strain gauge technique would cause the difference of the strain distribution. Average strain in the gauge volume can be measured using the neutron diffraction technique, which means average strain of almost cross section of the rebar was measured in this study. In contrast, the strain gauge technique can measure strains on surface of the rebar. If stress gradient exists in the cross section of the rebar, difference of the strain distribution would be observed between the neutron diffraction technique and the strain gauge technique.

STRAIN DISTRIBUTION AROUND CRACKS

Experimental Procedure

Figure 8 shows the schematic of the specimen used in this study. Rebar with 16 mm diameter was embedded in the rectangular concrete with 800 mm length and 50 mm square cross section. Strain distribution in the rebar was measured around cracks during tensile loading. Wavelength of 0.16 nm was selected and the lattice strains of the ferrite 110 reflection, which appeared at 2θ=46 deg, were measured. Measurement time of one peak profile
was approximately 3 min for getting 100 counts of the peak intensity. Strain distributions were measured under the applied stresses of 150MPa and 300MPa as well as the stress-free condition.

Results and Discussions

Figure 9 shows the strain distributions in the rebar around cracks [8]. Compressive residual stresses can be observed in the stress-free condition due to drying shrinkage. The stresses transferred to the rebar were 60% to 80% of the applied stresses because of stress share with the concrete. Moreover, scattering around cracks were observed probably due to stress relaxation around cracks and also due to stress concentration around ribs. These results indicate that the neutron diffraction technique enables to measure detailed strain distribution and would be helpful to evaluate the damage region around cracks accurately.

CONCLUSIONS

The neutron diffraction technique was applied to measure the strain distributions in the rebar in the reinforced concrete, and we obtained the conclusions as follows. Amounts of water content and aggregate content affect absorption coefficient of the concrete, and the influences of this neutron absorption by concrete on the accuracy of the strain measurement were negligible. In addition, two examples of the strain measurement in the rebar in the reinforced concrete were demonstrated to evaluate the anchorage length and the strain distribution in the rebar around cracks in the concrete. We obtained the results that length of the anchorage zone measured by neutron diffraction was shorter than that measured by strain gauges and that the neutron diffraction method can...
measure detailed strain distribution around cracks.

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REFERENCES