Mechanical Properties of Concrete Beam Made of a Large Amount of Fine Fly Ash

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ABSTRACT :

Purpose of this study is to investigate the ultimate mechanical behavior and deformability of the reinforced concrete beams containing large quantity of fly ash, a kind of coal ashes, while the cement content is kept constant. Eleven test beams of about 1/2.5 scale were fabricated and tested under monotonic bending and shear. The experimental variables among the tests are, 1) the shear span ratio of the beams, 2) the amount of transverse reinforcement, and 3) the amount of fly ash. The test beams were all prismatic with rectangular section of 250x400mm. Test results have indicated that in a range of up to 455 kg/m^3 of fly-ash content per unit volume of concrete, the shear strength and deformability of the beam increase as the mixed quantity of fly ash increases. In cases where large quantities of fly ash were mixed, even a short beam with a shear span ratio of 1.0 can exhibit plenty of deformability.

KEYWORDS: Fly ash concrete, Beam, Ultimate flexural strength, Ultimate shear strength, Deformability

1. INTRODUCTION

The study of the utilization of fly ash which is an industrial by-product dates back to the 1950s. Its effectiveness as a resource has been noted, and research began from the utilization as an admixture for concrete. Since then, owing to the results of many studies, fly ash has become utilized in diverse fields such as cement, concrete, civil engineering, agriculture, forestry, fisheries and construction. The utilization of fly ash in the fields of cement, in particular, accounts for approximately 90% of total use of fly ash in Japan [JSCE, 2003]. However, since the product amount of cement has decreased, caused by the recent stagnancy of construction demands, an increase in the utilization of fly ash in this field cannot be expected. Therefore, new ways of utilizing of fly ash should be developed.

Matsufuji *et al*. [Matsufuji et al., 2001] proposed a method of mixing of fly ash with constant cement content as a new utilization method. It was experimentally revealed that the compressive strength of concrete increases in correlation to the mixing quantity of fly ash up to 300 l /m^3 under water-cement ratio of 65%. Furthermore, Koyama *et al* [Koyama et al., 2006] revealed that the increase in the strength of concrete containing large quantity of coal ash is caused by the segmentation of microstructure of cement hydrates. Ito *et al* [Ito et al., 2007] demonstrated from experimental results of accelerating tests and natural exposure that the rate of the carbonation of the concrete containing large quantity of fly ash with constant cement content is slower than that of the concrete without fly ash but with the same water cement ratio. In other words, it is possible to make concrete superior in strength and durability by mixing large quantity of fly ash with constant cement content even with a high water cent ratio of 65%.

Meanwhile, in order to use concrete containing large quantity of fly ash in actual structures, the clarification of mechanical properties (ultimate mechanical behavior etc.) in structures using such concrete and the establishment of methods for accurate evaluation are desirable.

This study is aimed at the investigation of mechanical behavior in beams of reinforced concrete (hereinafter referred to as RC) containing large quantity of fly ash with constant cement content on an experimental basis. The application of various strength calculation formulas for RC beams using concrete without fly ash, which are recommended by the current design standard [AIJ, 1999], was examined. Expectations for the ultimate strength of RC beams using concrete containing large quantity of fly ash were also examined.

2. OUTLINE OF EXPERIMENT

2.1. Specimens and mixture proportion of concrete

Eleven beams equivalent to 1/2.5 of actual size were prepared, three of them were tested under pure bending, while the other eight beams were subjected to monotonic shear. All of the beams were simply supported during being loaded. The cross section for test specimens was a rectangle of 250mm x 400 mm, and experimental variables were obtained from the following variables: (1) two of fly ash content per unit volume of concrete, (2) three shear-span ratios of the beam, and (3) two ratios of shear-reinforcing bar. Meanwhile, as the tension reinforcements, four deformed bars, D16 (SD345), were arranged for each test specimen with a ratio of tension reinforcement of approximately 0.88%. Figure 1 and Table 1 both show the details for the specimens subjected to monotonic shear. The three beams under pure bending had the same amount of longitudinal rebars as shown in Figure 1 (A-A section), but no transverse reinforcement was provided in order to investigate effect of fly ash content on ductility of concrete.

Concrete was prepared using ordinary Portland cement with a fixed ratio of 65% water-cement. The fine powder that can be adapted to class II in JIS(Japanese Industrial Standard) A 6201 was used as fly ash, sea sand as a fine aggregate, and andesite crushed stone (the maximum diameter: 20mm) as a coarse aggregate. Cement content and water content per unit volume concrete were 285 kg/m^3 and 185 kg/m^3, respectively. Table 2 shows

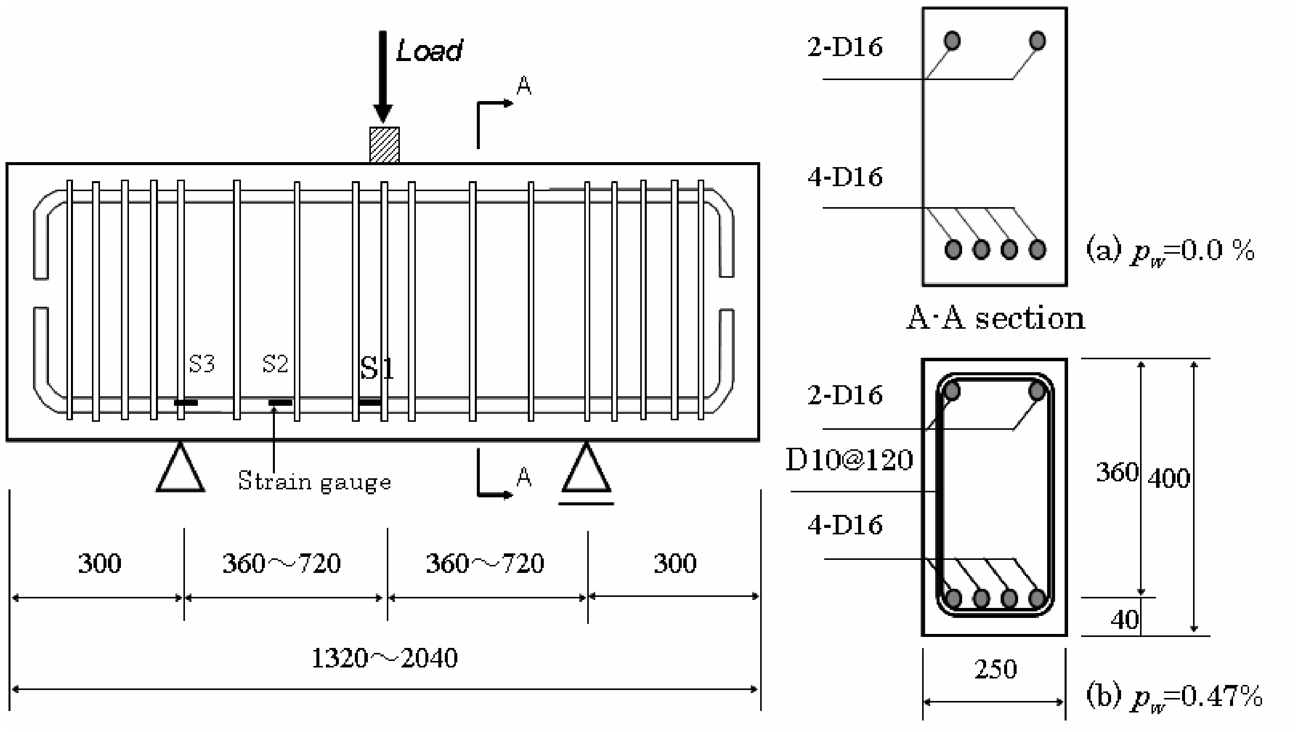


Figure 1 Detail of beam specimens (mm)

Table 1 Specimens Subjected to Shear

<table>
<tr><th>specimens</th><th>mix.</th><th>M/(Vd)</th><th>p_w (%)</th><th>F_c (N/mm^2)</th><th>$Q_{u,exp}$ (kN)</th><th>$R_{u,exp}$ (0.01rad)</th><th>Q_{my} (kN)</th><th>Q_{su} (kN)</th></tr>
<tr><td>SSN-0</td><td>A</td><td rowspan="6">1.0</td><td rowspan="3">0.000</td><td>38.6</td><td>688</td><td>0.84</td><td rowspan="6">550</td><td>555</td></tr>
<tr><td>SSN-244</td><td>B</td><td>59.2</td><td>809</td><td>1.51</td><td>759</td></tr>
<tr><td>SSN-455</td><td>C</td><td>73.7</td><td>883</td><td>1.99</td><td>902</td></tr>
<tr><td>SS120-244</td><td>B</td><td rowspan="2">0.477</td><td>59.2</td><td>899</td><td>1.86</td><td>938</td></tr>
<tr><td>SS120-455</td><td rowspan="4">C</td><td rowspan="4">73.7</td><td>875</td><td>2.06</td><td>1081</td></tr>
<tr><td>SS60-455</td><td>0.953</td><td>1019</td><td>3.04</td><td>1155</td></tr>
<tr><td>SMN-455</td><td>1.5</td><td rowspan="2">0.000</td><td>610</td><td>4.72</td><td>367</td><td>624</td></tr>
<tr><td>SLN-455</td><td>2.0</td><td>437</td><td>5.58</td><td>275</td><td>477</td></tr>
</table>

M/(Vd) : shear span ratio
p_w : ratio of shear reinforcing bar
F_c : strength of concrete cylinders at flexural shear loading test of the beam
$Q_{u,exp}$: maximum shear force (by experiment)
$R_{u,exp}$: relative rotation at $Q_{u,exp}$,
Q_{my} : calculated flexural yield strength
Q_{su} : calculated ultimate shear strength

Table 2.2 Mixture proportions of concrete

<table>
<tr><th rowspan="2">No.</th><th rowspan="2">W/C (%)</th><th>W</th><th>C</th><th>F</th><th>S</th><th>G</th><th>ad</th><th rowspan="2">air (%)</th></tr>
<tr><th colspan="6">(kg/m^3)</th></tr>
<tr><td>A</td><td rowspan="3">65</td><td rowspan="3">185</td><td rowspan="3">285</td><td>0</td><td>872</td><td>947</td><td>2.85</td><td rowspan="3">4.5±1.2</td></tr>
<tr><td>B</td><td>244</td><td>583</td><td>884</td><td>4.23</td></tr>
<tr><td>C</td><td>455</td><td>439</td><td>884</td><td>5.92</td></tr>
</table>

W:water, C:cement, F:fly Ash, S: fine aggregate, G:coarse aggregate, ad:chemical admixture

the mixture proportion of concrete. As shown in Table 2, an increase in the quantity of fly ash mixed into concrete is approximately proportionate to a decrease of fine aggregate sand.

Five of eight test specimens were constructed using beams without shear-reinforcing bars, and the remaining three specimens were constructed using deformed bars, D10 (SD345) as shear-reinforcing bars. The stress-strain curves of the steel reinforcements used here are shown in Figure 2.

The numbers affixed to names of the test specimens in Table 1, such as 0, 244, 455 etc. illustrate the fly ash content per unit volume of concrete.

2.2.Loading test and measurement method

As shown in Figure1, the concentrated shear strength was applied at the center of each specimen until it was blown up under the boundary condition of simple support. The vertical direction displacement in the center of the beam was measured with a displacement meter, and the strain of tension reinforcement was measured with three strain gauges placed as shown in Figure. 1.

3. RESULTS AND DISCUSSION

3.1. Outline of results

The compressive strengths of the concrete at the age when the experiment was conducted are shown in Table 1 together with the experimental strengths of the beam and the relative rotations when the shear force was maximum. The relative rotation of a beam was obtained with vertical displacement in the center of the span and divided by the shear span.

As shown in Table 1, as the fly ash content increased, the compressive strength of the concrete also increased to the twice of the concrete without fly ash. Furthermore, as the strength increased, the shear strength of the beam and the relative rotation when the shear force was maximum also tended to increase. Even in cases where the shear span ratio was 1.0, although the increased quantity of fly ash could not prevent shear failure, the relative rotation at the shear failure was as large as 0.02 rad. This demonstrated sufficient deformability. In cases where the shear span ratio was more than 1.5, the specimens of mixture proportion C (F=455 kg/m^3) showed a deformation capacity of more than 0.04 rad even without shear reinforcing bars.

3.2. Load-Curvature relationship

Figure 3 shows load versus curvature relationships of the three specimens under pure bending. The curvature shown in Figure 3 was normalized by section depth D (400mm). As obvious from Figure 3, while the maximum load didn't increase as the amount of fly ash, the curvature at the peak load significantly increased with the fly ash content. The reason for little, if any, increment in load capacity of the beam not to be observed is that the compressive region in the beam section was small and the effect of fly ash content on mechanical properties of concrete couldn't be fully developed.

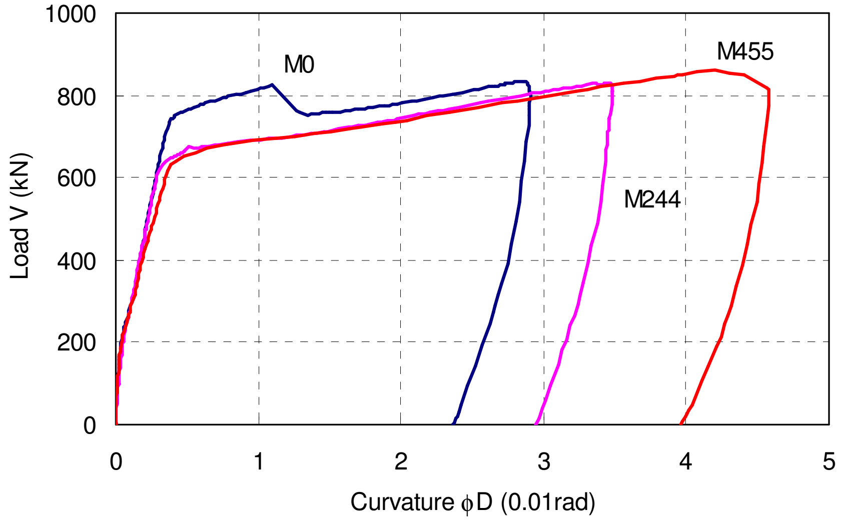


Figure 3 Load – Curvature Relationship

3.3. Shear force – relative rotation relationship

Figure 4 shows the experimental results of the relationship between shear force and relative rotation of each test specimen. The dashed line in each figure shows the calculated value of flexural yield strength of the RC structure beam made of concrete without fly ash, and the solid line shows the calculated value of the ultimate shear strength by an Ono and Arakawa's equation. These values were calculated by Equations (1) and (2) as demonstrated later.

In cases involving the test specimen SSN-0 with a shear span ratio of 1.0, without fly ash, shear cracks began to

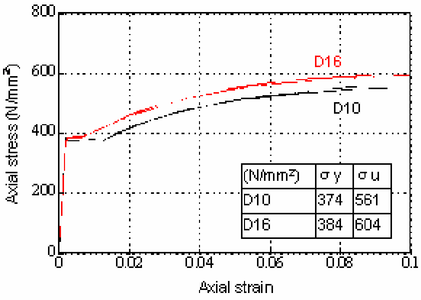
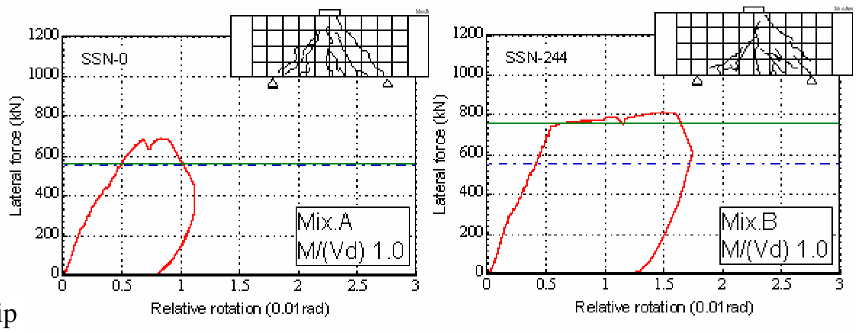


Figure 2 Stress – strain relationship of reinforcements



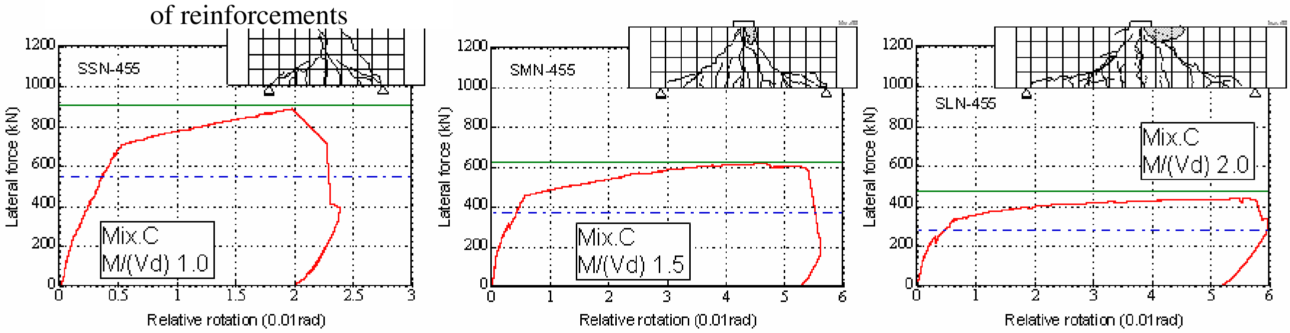


Figure 4 Shear force – relative rotation relationship

appear around at 400 kN of shear strength. A shear crack appeared along the line connecting the load point and the support point when the relative rotation reached 0.0084 rad, and a drastic decrease of strength was observed, which was typical shear failure. Meanwhile, in the case of test specimen SSN-244, prepared by mixture proportion B (F=224 kg/m^3, F is fly ash content per unit volume of concrete), shear cracks began to appear from the support point on the right side of beam at around 650 kN of load. After that, the strength gradually increased and reached a maximum at approximately 0.015 rad of the relative rotation. In the case of test specimen SSN-455, prepared by mixture proportion C (F=455 kg/m^3), shear cracks began to appear before or after 650 kN of the load from the support point of right side of beam like the test specimen prepared by B. However, after that, strength did not decrease and reached a maximum strength (883 kN) at the neighborhood of 0.02 rad of the relative rotation. Subsequently, a shear crack appeared between the support point of right side of beam and the load point, which caused shear failure. From the fact that relative rotation reached up to 0.02 rad when the shear force was maximum, it has been suggested that although concrete containing large quantity of fly ash cannot protect a short RC structural beam from shear failure without a shear reinforcing bar, the deformation capacity can be largely increased because the safety margin of shear strength becomes high resulting from the increase of the ultimate shear strength.

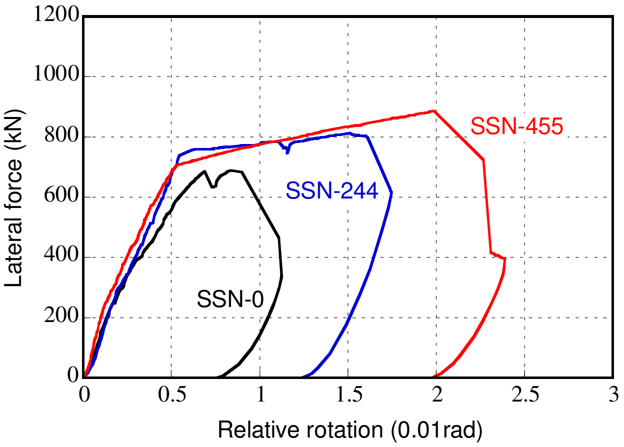


Figure 5 Effect of the fly ash content

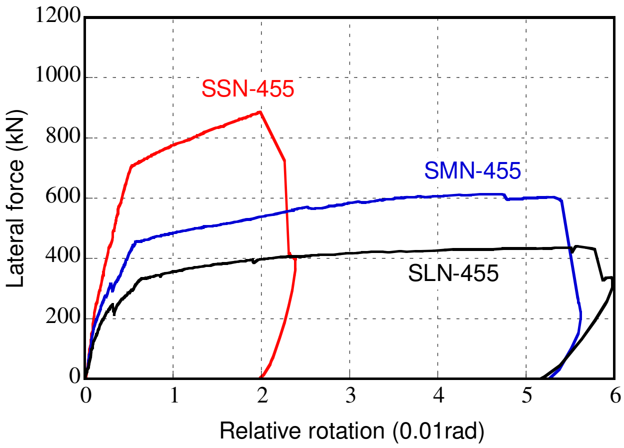


Figure 6 Effect of the shear span ratio

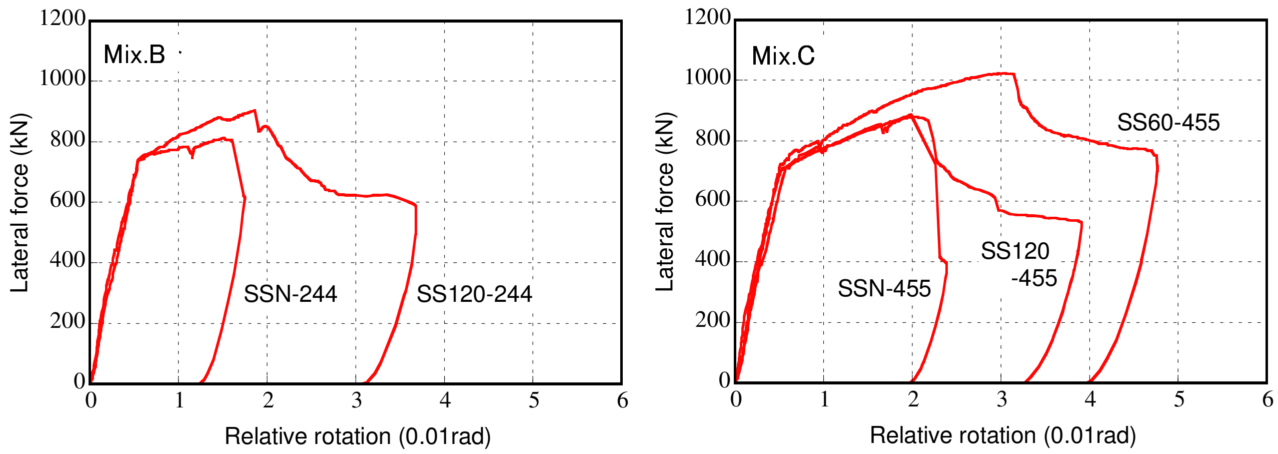


Figure 7 Effect of the ratio of shear reinforcing bar

Meanwhile, concerning cases where specimens prepared by mixture proportion C had a shear-span ratio of 1.5 or more, flexural yield was caused in the relative rotation in the neighborhood of 0.0075 rad. Afterwards, the strength gradually increased which was caused by a strain hardening of tension reinforcement, and the test specimens showed extremely deformable behaviors. The relative rotation of the test specimens of SMN-455 and SLN-455 reached 0.047 rat and 0.056 rad, respectively. Both test specimens reached an end state caused by the crush of concrete near the load points.

Figure. 5 shows how the effects of quantities of fly ash mixed into concrete extended to the mechanical behavior of short beams. As clearly shown in this figure, as increased amounts of fly ash were added, the ultimate shear strength of the beam also increased, and the distortion angle at the peak load was more than twice improved. The enhancement of the strength of the concrete due to mixed quantities of fly ash is considered to be a main cause of the increases in the shear strength and deformation capacity of the beams.

Figure 6 shows comparisons between the mechanical behaviors of the test specimens with different shear spans. The specimens subjected to comparison were of concrete prepared by C, and some were not provided with shear reinforcing bars.

As clearly shown in Figure 6, when compared to beams with a shear span ratio of 1.0, specimens with a shear span ratio of 1.5 or more, even those without shear reinforcing bars, did not exhibit shear failure after flexural yield, but instead held the destructive properties of failing in flexure with extremely high ductility.

Figure. 7 shows the effects of shear reinforcing bars extended to the mechanical behavior of short beams with a shear span ratio of 1.0 using the described preparations of concrete.

As clearly shown in Figure. 7, concerning test specimens of B preparation, both the shear strength and drift ratio at the peak load of beams were increased using shear reinforcing bars. Regarding test specimens of C preparation, the effects of a rise in strength and distortion angle at the peak loads were hardly observed at a shear reinforcing bar ratio of 0.47%. Presumably, this is because the concrete of C preparation has the highest compressive strength and the increase of load capacity by a small amount of shear reinforcing bars cannot compensate for the decrease of concrete at the time when its own shear resistance capacity was lost. .Meanwhile, concerning test specimens where a large volume of shear reinforcing bars were arranged at a ratio of 0.95%, both the shear strength and distortion angle at the peak load of the beam exhibited a remarkable increase.

3.4 Strain of Reinforcement

Figure 8 shows the measuring results of tension reinforcement strain. A broken line in the figure shows strain at the yield point, and a chain line shows strain at the start of strain hardening. Measure points S1, S2 and S3 show the measure points at the center section of the span, the center section between shear spans and the section of supporting point (refer to Figure 1).

As shown in Figure 8, in the case of the beams without fly ash, the tension reinforcement at the center section of span did not yield until the ultimate state. This suggests that these test specimens had been damaged by shear failure and coincides with the results shown in Figure 4. Conversely, in the case of test specimens mixed with a large quantity of fly ash, the tensile reinforcement at the center section of span yielded near the relative rotation of 0.005 rad, and then entered a strain-hardening range as the relative rotation increased. This backs up the phenomenon of increased strength after flexural yield that was observed in the relationship between the shear strength and relative rotations of these test specimens.

From the above discussion, it is possible to change the failure mode of a short RC structure with shear span ratio of 10 to a failing in flexure, which is very deformable, by mixing a large quantity of fly ash with constant cement content.

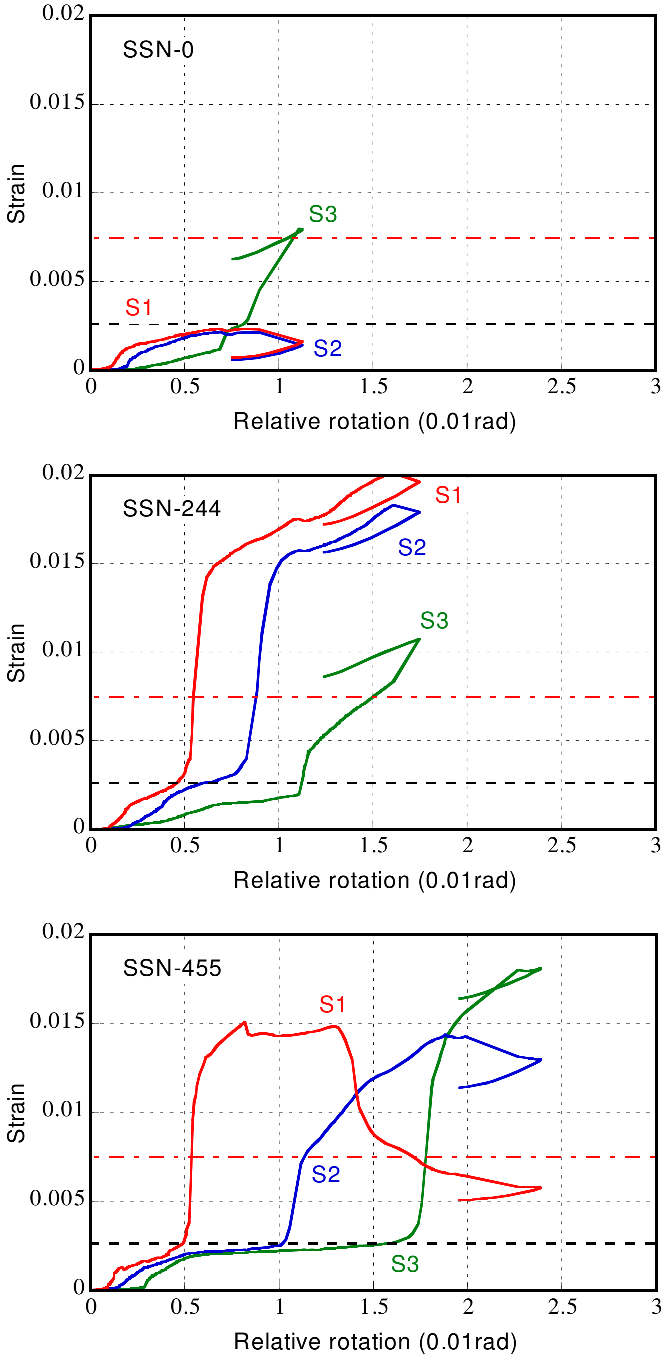


Figure 8 Strain of reinforcements

4. Evaluation of beam strength

The calculation equations from flexural yield strength and the ultimate sear strength of RC structures not containing fly ash were applied to the evaluation of beams containing large quantity of fly-ash and the validity was examined. In this paper, a simplified formula recommended by the AIJ (Architectural Institute of Japan) Standard for Structural Calculation of Reinforced Concrete Structure, and an equation by Ono and Arakawa were used for flexural yield strength Q_{my} and the ultimate shear strength Q_{su}, respectively. Those equations are shown below:

$$Q_{my} = \frac{0.9 \times a_t \times f_{ys} \times d}{a} \tag{4.1}$$

$$Q_{su} = \left\{ k_u k_p \frac{0.115(F_c + 17.6)}{a/d + 0.12} + 0.85\sqrt{p_w f_{yw}} \right\} bj \tag{4.2}$$

a_t : cross-sectional area of tension reinforcement
f_{ys} : yield stress of the longitudinal rebar
d : effective depth (360 mm)
a : shear span of beam
F_c : compressive strength of concrete
p_w : ratio of shear reinforcing bars
f_{yw} : the yield stress of shear reinforcing bars
b : section are of the beam
j : distance between centers of tension and compression (=7/8d)

Calculated values of test specimen strength obtained by equations 4.1 and 4.2 are shown in Table 1.

Regarding specimens not mixed with fly ash damaged by shear failure, the calculated values of Q_{my} and Q_{su} are approximate. It is possible that these test specimens reached shear strength before flexural strength, so that the calculated results did not contradict the experimental results. Meanwhile, all the experimental results of the shear strength of the test specimens containing large quantity of fly ash exceeded the flexural yield strength. This is because, as is clear from equations 4.1 and 4.2, that although the increase in strength in concrete mixed with large quantity of fly ash contributes remarkably to the increase of the shear strength of beam, the flexural strength is scarcely affected. Except for the test specimen SSN-0, which exhibited slightly higher experimental strength, all the experimental strengths of the test specimens which showed shear failure or flexural compressive failure after flexural yield are positively evaluated by shear strength calculated by equation 4.2. From the statements above, the ultimate shear strength of RC beams which contain large quantity of fly ash can be reasonably estimated by the equations of Ono and Arakawa.

5. CONCLUSIONS

As the results of experimental investigations concerning the mechanical behaviors of RC structures containing large quantity of fly ash with constant cement content, the following became clear:

1) When fly ash content per unit of volume of concrete is in a range of up to 455 kg/m^3, shear strength and distortion angle at the peak load of the beam tend to increase with an increase in fly-ash quantity.
2) All the experimental strengths of RC beams containing a large quantity of fly ash exceed the calculated values of yield flexural strength by current standard. It is possible to change the failure mode of beams from a shear type to flexure type, by mixing in large quantity of fly-ash.
3) With 455 kg/m^3 per unit volume of fly ash mixed into the concrete, an elevated ultimate deformation capacity, up to a relative rotation of 0.02 rad, can be applied to a short beam with a shear span ratio of 1.0 as an increase in the safety margin of shear strength, even if the beam is not supported by a shear reinforcing bar.
4) The ultimate shear strength of an RC beam containing a large quantity of fly ash can be reasonably estimated by using an Ono and Arakawa's equation targeting an RC beam which does not include fly ash.

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