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EXPERIMENTAL STUDY ON A NEW FLEXURAL REINFORCED CONCRETE MEMBER WITH DAMAGE CONTROL IN THE YEILD HINGE

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SUMMARY

Taking off the bonding effect between the flexural reinforcing bars and the surrounding concrete in the yielding zone (un-bonded zone) is expected to prevent from cracking and shear strength degrading of reinforced concrete (RC) members, since no tensile stress will be transferred from the flexural reinforcing bars to the surrounding concrete in the un-bonded zone. A series of experiment on RC columns with un-bonded zone is conducted in order to confirm the un-bonding effect mentioned above. The results indicate that the RC member with un-bonded zone could avoid a damage of flexural crack and shear strength degrading.

INTRODUCTION

Reinforced concrete (RC) members are preferred to be designed in many cases in the flexural dominant mode. Flexural reinforced concrete members can dissipate hysteresis energy with the nonlinearity of reinforcing bars, and/or concrete in the yield hinge. Energy dissipation of the reinforcing bars is in stable, while that of the concrete can not be expected as such. Concrete can be expected to sustain compressive stress mainly. Cracking developed in hinge zone of RC members, however, reduces the compressive capacity of the concrete. Therefore, any cracking propagated at hinge zone shall lead up to the loss of strength and the deformation capacity of the RC members.

If the cracking can be controlled at a specific location, stable energy absorption by reinforcing bars would be drastically improved. In order to attain it, the new method: taking off the bonding effect between the flexural reinforcing bars and the surrounding concrete in the yielding zone (un-bonded zone) is considered. Making the un-bonded zone is expected to prevent from cracking and shear strength degrading, since no tensile stress will be transferred from the flexural reinforcing bars to the surrounding concrete in the un-bonded zone. Furthermore, since shear deformation of the concrete in the un-bonded zone is reduced, rigid body rotation produced by elongation of the flexural reinforcing bars constitutes

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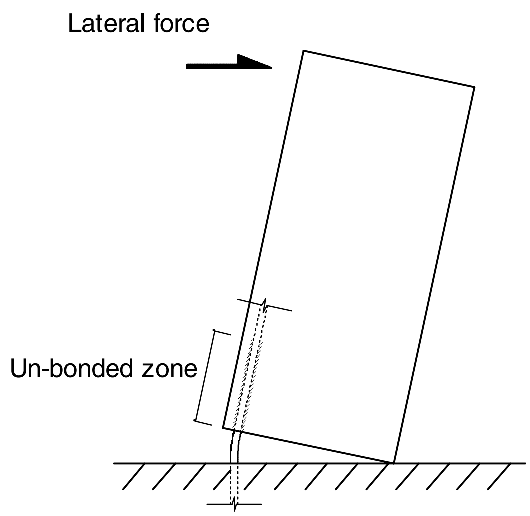

Figure 1 Reinforced concrete member with un-bonded zone

whole deformation. Damage by the cracking is concentrated to the end of the un-bonded zone. Figure 1 schematically shows the relationship between crack width and deformation.

The purpose of this study is to develop a new flexural RC member, which can control damage in the yield hinge keeping cracking of the minimum with concentrated few cracking. RC columns with un-bonded zone were tested under amplitude cyclic lateral loading and verified the fundamental seismic behavior.

Table 1 Specimen description with experimental parameters

	Specimen A	Specimen B	Specimen C	Specimen D
Concrete strength	$F_C = 31.5$ (N/mm^2)			
Shear span ratio	$H/D = 2.0$			
Flexural reinforcing bars	6-D19 ($\sigma_y = 398.4 N/mm^2$), $P_t = 0.96\%$			
Shear reinforcing bars	3-D6@75 ($\sigma_y = 346.5 N/mm^2$), $P_W = 0.43\%$			
Axial stress ratio	0.15 (N = 425 kN)			
Un-bonded length	—	D/2	D/2	D/2
Reinforcement method of the boundary part	—	—	doubly rolled	Spiral + Add'l reinforcement

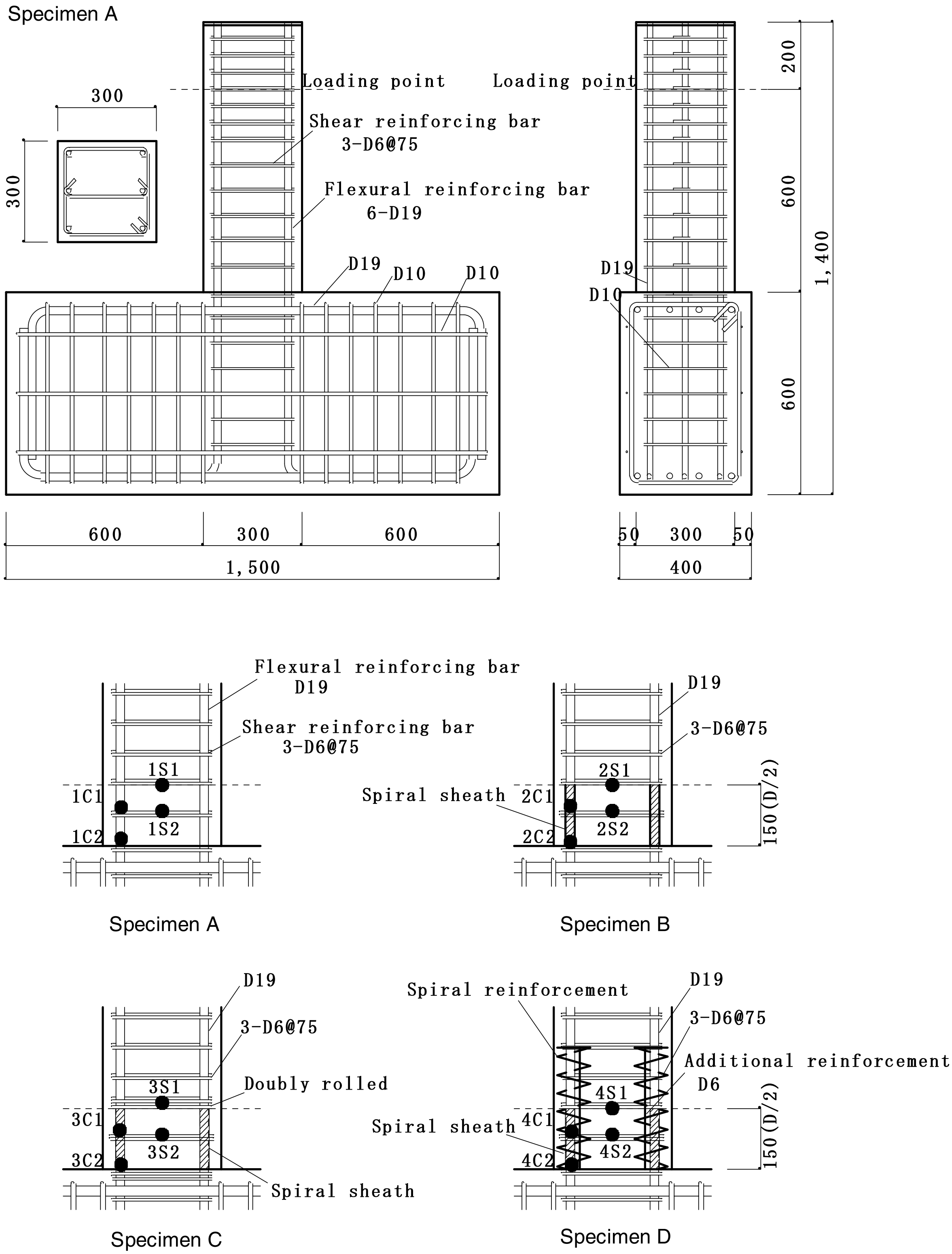

Figure 2 The typical detail of all specimens

EXPERIMENTAL PROGRAM

Specimen Details

Four RC column specimens were manufactured. Main parameters are an existence of un-bonded zone, a hoop ratio and strength in the un-bonded zone. Table 1 shows the description of all specimens. The shear span ratio (H/D) of column is 2.0 and cross section (b × D) is 300 × 300 mm. Compressive strength of concrete is 31.5 N/mm^2. Six bars with diameter of 16 mm were provided as flexural reinforcing bars and the amount was kept constant in all specimens. Shear reinforcing bars with diameter of 6 mm were arranged at the spacing of 50 mm. Tensile strength of flexural reinforcing bars and shear reinforcing bars are 398.4 N/mm^2 and 346.5 N/mm^2 respectively. From the bottom of column to the loading height is 600 mm. The axial stress ratio is 0.15.

Figure 2 shows the typical detail of all specimens. Strain in several location of both flexural reinforcing bars and shear reinforcing bars were measured by using strain gages shown by the mark (●). Specimen A is a conventional RC column provided as shear reinforcing bars ratio of 0.0043. In specimen B-D, taking off the bonding effect between the flexural reinforcing bars and the surrounding concrete, the length was 150 mm from the bottom of column. Flexural reinforcing bars were completely un-bonded by inserting them into spiral sheaths before casting of the specimens.

In specimen C, in order to anchor the flexural reinforcing bars completely, shear reinforcing bars were doubly rolled in the boundary part of un-bonded zone.

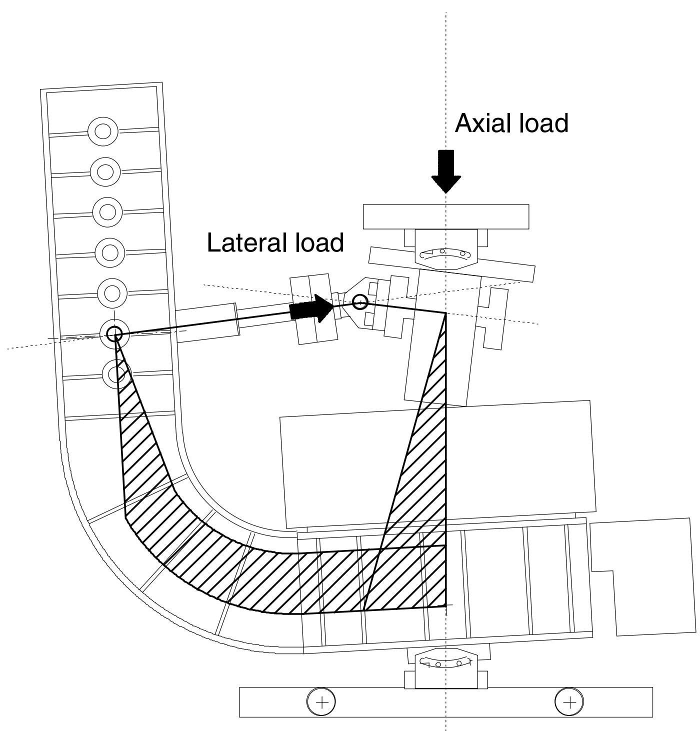

Figure 3 Experimental setup

In specimen D, in order to prevent from crushing concrete and buckling the flexural reinforcing bars, the spiral reinforcement rolled the surrounding of the flexural reinforcing bars. Furthermore, in order to connect un-bonded and bonded zone, additional reinforcement bars were arranged in the boundary part of the un-bonded zone. Additional reinforcement bars with diameter of 6 mm, were set to 300 mm which was twice the length of the un-bonded zone.

The strength of specimen A was calculated according to the design formula of AIJ [1, 2]. Shear strength and flexural strength were 242.3 kN and 238.1 kN respectively. The ratio of shear strength to flexural strength was 1.02.

Experimental Setup and Instrumentation

The specimens were loaded from two directions in cantilever method. Figure 3 shows the loading setup. Moment distribution was shown with slash marks. Although secondary moment affected as deformation angle was propagated, it can be ignored because it had no effect on experimental result. All specimens were tested under constant axial load of 425 kN (axial stress ratio of 0.15). Amplitude cyclic lateral load was applied to at the designed loading point of the column by using an actuator. Lateral load was controlled by deformation angle as shown in Figure 4. The test was continued until the specimens became unable to sustain constant axial load. Horizontal displacements at the loading point of the column, crack width at the column-footing joint and rotation of the column were measured by displacement transducers.

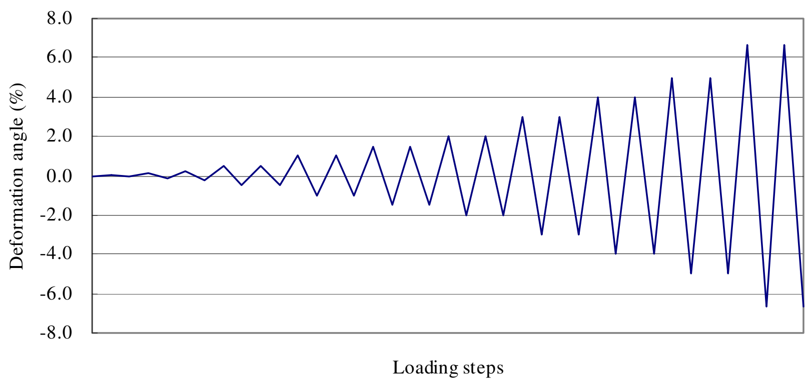

Figure 4 Loading patterns

OBSERVED BEHAVIOR AND FAILURES

Failure Process

Figure 5 shows lateral load and deformation angle curve and Figure 6 shows schematically crack patterns at deformation angle of 0.5 %, 1.0 %, 2.0 % and pictures at deformation angle of 3.0 %.

All specimens achieved the flexural strength at deformation angle of about 1.0 %. The flexural strength was almost the same as the calculated value and stress intensity at the moment capacity was 8.8 % of compressive strength of concrete.

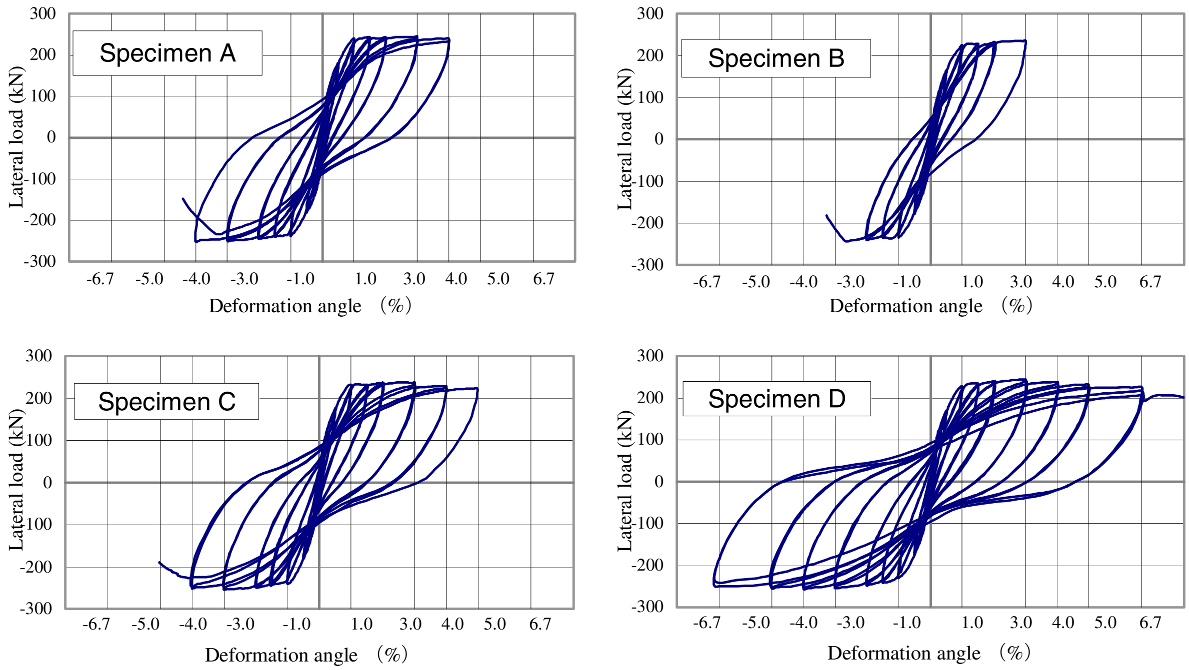

Figure 5 Lateral load vs. Deformation angle curves of all specimens

In specimen A, the flexural crack started at the column-footing joint at deformation angle of 0.25 %. As the lateral load progressed, flexural cracks occurred at the several locations on both sides of the column. Diagonal shear crack occurred at deformation angle of 0.5 %. At deformation angle of 4.0 %, the final failure took place with the wide opening of diagonal shear crack resulted from the yielding of shear reinforcing bars. Lateral load and deformation angle curve clearly showed a typical shear failure.

In specimen B, the flexural crack started at the column-footing joint at angle of 0.125 %. Diagonal shear crack and flexural cracks occurred in height of 250 mm from the bottom of column at deformation angle of 0.5 %. Cover concrete of the column crashed at deformation angle of 1.0 %. At deformation angle of 3.0 %, the final failure took place with the wide opening of diagonal shear crack resulted from the yielding of shear reinforcing bars.

In specimen C, the final failure took place with the wide opening of diagonal shear crack resulted from the yielding of shear reinforcing bars at deformation angle of 5.0 % after showing the similar behavior to specimen B.

In specimen D, the flexural crack started at column-footing joint at deformation angle of 0.125 %. There was almost no damage up to deformation angle of 0.5 % after that. It showed a better behavior as the damage was concentrated only at the column-footing joint. Diagonal shear crack occurred and cover concrete of the column crashed at deformation angle of 1.0 %. Diagonal shear crack and flexural crack did not develop even if deformation angle passed over 5.0 %, and the column did not fail.

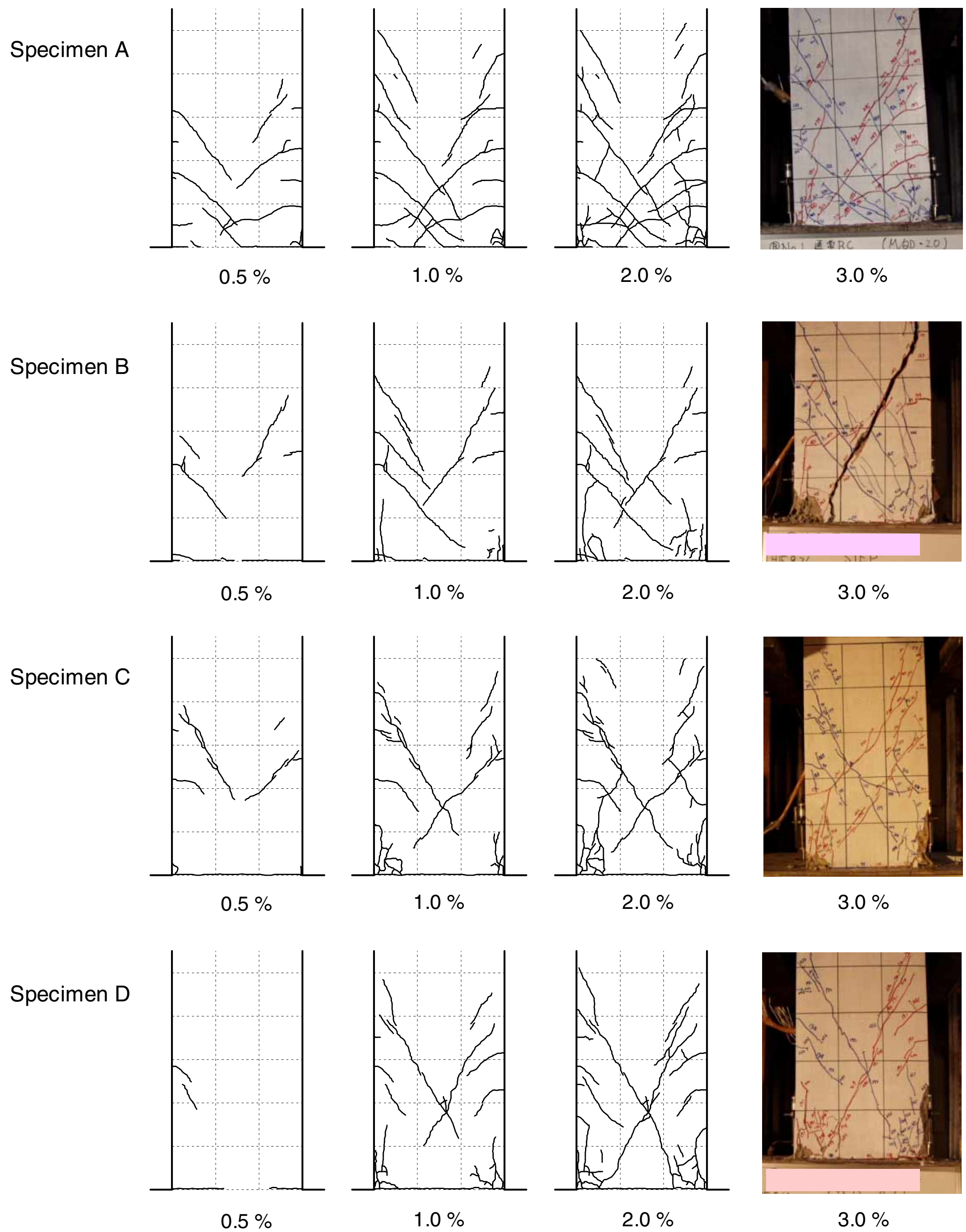

Figure 6 Compared cracks patterns and damages for all specimens

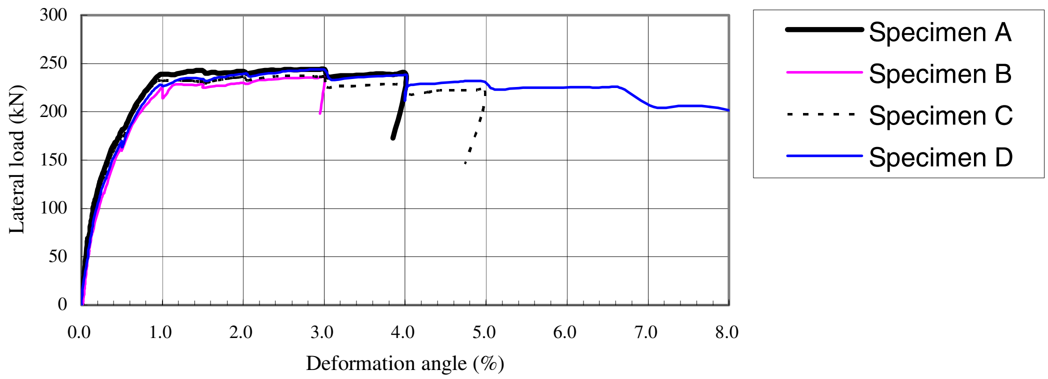

Figure 7 Loateral load vs. Deformation angle envelope curves

Envelope Curves
Figure 7 shows comparison of lateral load and deformation angle envelope curve in all specimens. Specimen A and B were failed in shear at deformation angle of 4.0 % and 3.0 % respectively. The ductility of the specimen B was reduced by making the un-bonded zone. It was clearly observed that the ductility of the specimen C and D were improved. The specimen D showed a typical flexural failure. It was indicated that strengthening the boundary part and/or inside of the un-bonded zone could improve the ductility.

Initial Stiffness
Table 2 shows the stiffness of all specimens at deformation angle of 0.25 % and 1.0 %. The stiffness at deformation angle of 0.25 % which was cracking point of specimen A set to K_C, and the stiffness at deformation angle of 1.0 % which was yielding point of specimen A set to K_Y. The K_C of specimen B, C and D with un-bonded zone reduced it slightly as compared with the K_C of specimen A. On the other hand, K_Y was almost the same in all specimens. The existences of un-bonded zone had almost no effect on the yield stiffness.

Table 2 Initial stiffness of all specimens

	Specimen A	Specimen B	Specimen C	Specimen D
Stiffness at 0.25 % (K_C)	91.2	80.9	84.5	81.4
Ratio to specimen A	—	0.89	0.93	0.89
Stiffness at 1.0 % (K_Y)	39.6	38.0	38.9	38.3
Ratio to specimen A	—	0.96	0.98	0.97

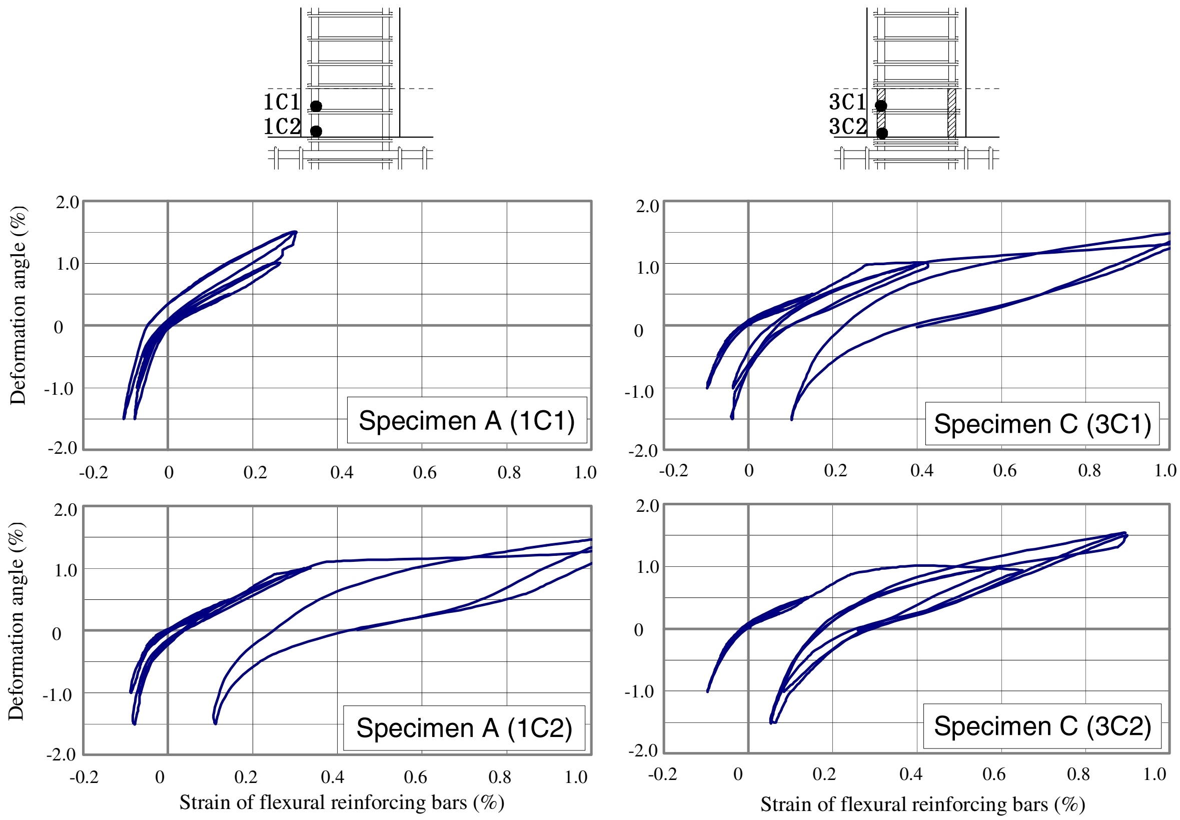

Figure 8 Deformation angle vs. Strain of flexural reinforcing bars

Strain of Flexural Reinforcing Bar

Figure 8 shows the strain of flexural reinforcing bars and the deformation angle curve up to deformation angle of 1.5 % in specimen A and C. As for the specimen A, although 1C2 achieved the yield strain at deformation angle of 1.0 %, 1C1 did not achieve it. The strain was found to be primarily concentrated near the column-footing joint. In specimen C, 3C1 and 3C2 achieved the yield strain at deformation angle of 1.0 %. It did not concentrate on the critical region but the strain was distributed evenly on the whole un-bonded zone.

Rigid Body Rotation

After the flexural reinforcing bars in the un-bonded zone yielded, the expansion of the flexural reinforcing bars caused lifting up column-footing and the column come up rigid body rotation. Figure 9 shows the deformation angle and the body rotation angle curve in specimen A and C. At deformation angle of 3.0 %, the rate of body rotation angle to deformation angle of the specimen A and C were 64.8 % and 81.1 % respectively. The rate of body rotation of the specimen C increased.

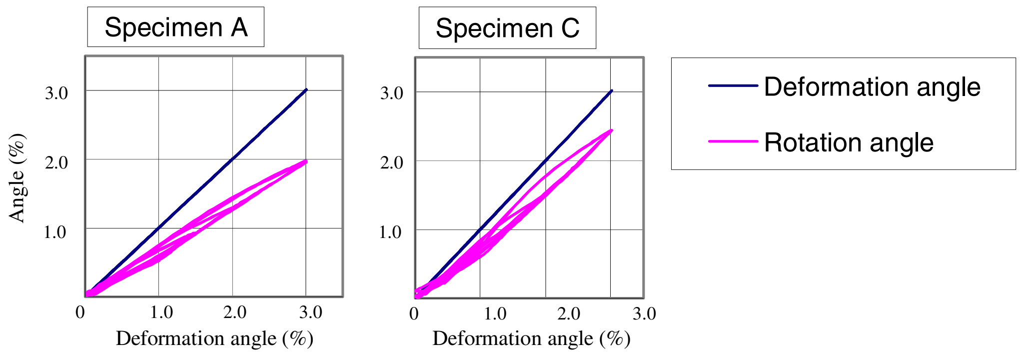

Figure 9 Deformaiton angle vs. Rotation angle

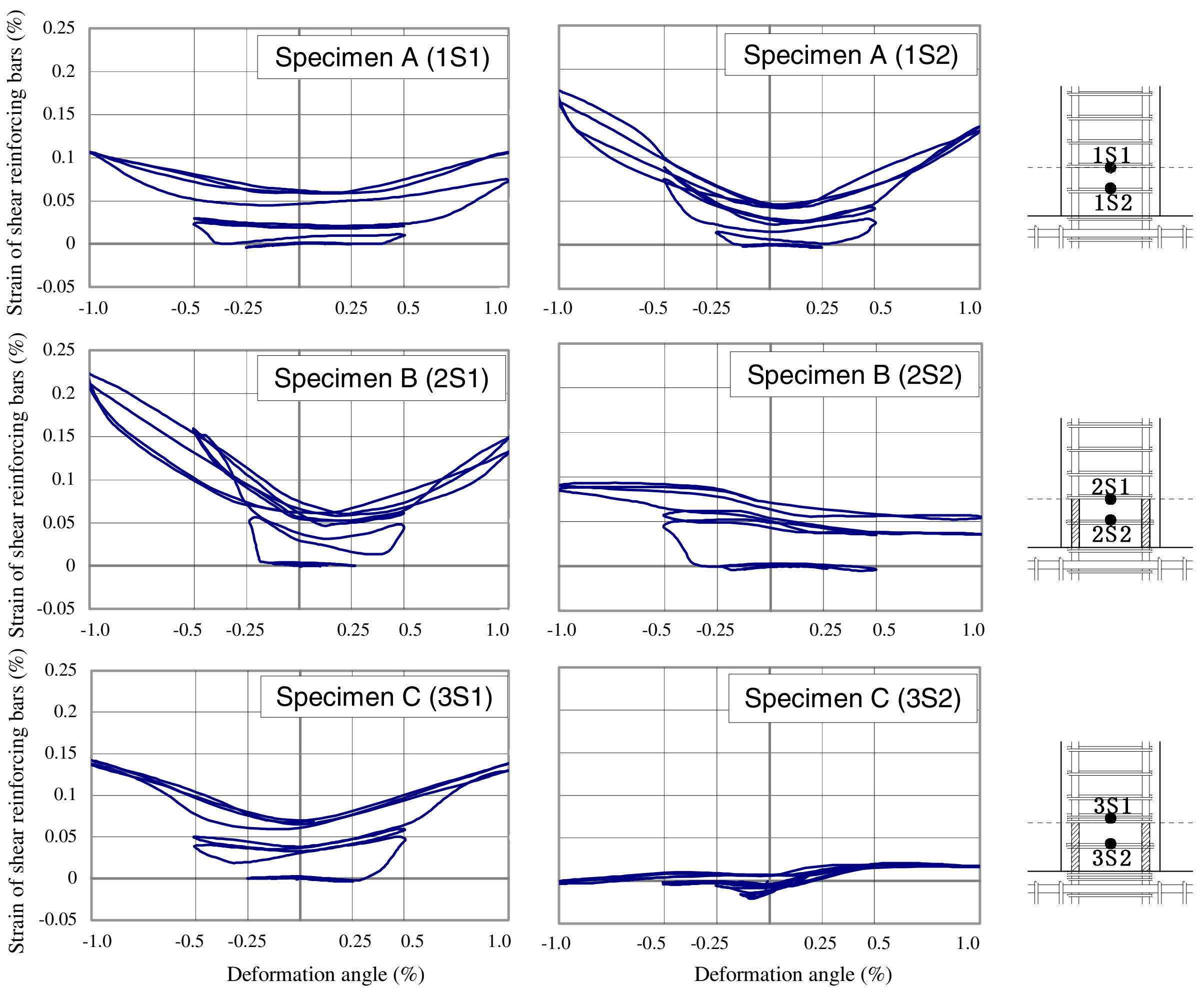

Figure 10 Strain of shear reinforcing bars vs. Deformation angle

Strain of Shear Reinforcing Bar

Figure 10 shows the strain of shear reinforcing bars and the deformation angle curve up to the deformation angle of 1.0 % in specimen A, B and C.

In specimen A, 1S1 and 1S2 increased as the deformation angle progressed. It was apparent that truss mechanism is formed by the shear reinforcing bars. Since the shear reinforcing bars were important to make a flexural mechanism, 1S1 and 1S2 reached nearly the yield strain.

In specimen C, although 3S1 at boundary part of the un-bonded zone increased as the deformation angle progressed, 3S2 which was located in the central point of un-bonded zone kept a low value. It is considered that the concrete body mainly transfers under a diagonal compression although truss mechanism was not formed in the un-bonded zone. Since the shear reinforcing bar at boundary part of the un-bonded zone was important role for specimen C, 3S1 reached nearly the yield strain.

In specimen B, after exceeding the deformation angle of 1.0 %, 2S2 began to increase. It is considered that the compression stress intensity of concrete increased as the deformation angle progressed and concrete began to produce a swelling. Concurrently as 2S1 achieved the yield strain at deformation angle of 3.0 %, diagonal compression with straight thrust line failed. Therefore, compared with the specimen A and the specimen B, the specimen B was failed by smaller deformation angle.

The behavior of specimen D was further improved, because the concrete in un-bonded zone was confined with spiral reinforcement and the ultimate strain of concrete turned up. Therefore, diagonal compression with straight thrust line in un-bonded zone could be sustained to the end.

CONCLUSION

Amplitude cyclic lateral loading test was carried out on four reinforced concrete (RC) columns which were taking off the bonding effect between the flexural reinforcing bars and the surrounding concrete in the yielding zone (un-bonded zone). Based on this study, following conclusions can be drawn.

1) Flexural cracking could be reduced by making the un-bonded zone.
2) As for yield stiffness the RC member with un-bonded zone had the same as the conventional ones.
3) Deformation by lateral load of the RC member with un-bonded zone was close to a rigid body with damage being concentrated at column-footing joint.
4) The ductility of the RC member with un-bonded zone was improved by strengthening in the boundary part of the un-bonded zone.
5) The ductility of the RC member with un-bonded zone was also improvable by confining the concrete in the un-bonded zone.

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