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AN EXPERIMENTAL STUDY OF REINFORCED CONCRETE BEAMCOLUMN JOINT WITH PARTIALLY HIGH STRENGTHENED LONGITUDINAL BAR

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Abstract.

It is necessary to generate the yield position away from the column face to minimize damage to the beam-column joint during a large earthquake in a reinforced concrete building. The same efficacy can be realized using partially high strengthened rebar. The number of longitudinal bars can be calculated for a bending moment smaller than the column face, reducing their number compared to the conventional bar-arrangement method. This paper describes reinforced concrete an interior beam-column subassemblage tests using this rebar as the longitudinal bars of beams and a column. The beam yield hinge was formed at a position apart from the column face, and the damage to the beam-column joint was less than the conventional bar-arrangement method. Additionally, the good performance was obtained if the bending strength of the column was large, even if the shear capacity margin of the beam-column joint was small. The column-beam flexural strength ratio and shear capacity margin at the beam-column joint need to be set with consideration of their relationship.

Keywords: Induction heating, partially high strengthened longitudinal bar, reinforced concrete beam-column joint.

1. Introduction

The seismic design of high-rise buildings prevents their collapse during large earthquakes by creating yield hinges on the first-floor column bases and the column face of the beam. It is necessary to minimize the damage of the beam-column joint ensure the assumed collapse mode. One of the methods for suppressing damage to the beam-column joint and obtaining a hysteresis loop with excellent seismic resistance is to increase the number of longitudinal bars near the beam-column joint and move the hinge position away from the column face in reinforced concrete beams. These are called hinge relocations. However, the method for increasing the number of longitudinal bars has not been widely used because the arrangement of the longitudinal bars is overcrowded and the number of the longitudinal bars is limited. Therefore, partially strengthened rebar was developed as a construction method capable of realizing member performance with excellent seismic resistance while eliminating the overcrowding arrangement. This rebar is arranged on the longitudinal bar of the beam so that the vicinity of the beam-column joint has high-strength (the design yield strength was set to 700 MPa). The hinge relocation is realized by yielding at the strength boundary part. The number of longitudinal bars can be reduced to aămaximum of 56% (= 390/700) compared to using 390 MPa longitudinal bars in the conventional method. This paper describes the experiment of an interior beam-column joint using partial high-strength rebar as the longitudinal bars of the beam and column to confirm the effectiveness of this partial high-strength rebar and obtain design data.

2. Manufacture of rebar

2.1. Heat treatment method

The heat treatment method is shown in Figure 1. The heat treatment of the rebar was performed by induction heating. The partially high strengthened rebar was manufactured by fixing the heating coil and moving the rebar in the heating coil. Energization by high-frequency current for quenching was performed, when the part to be strengthened passed through the coil. It is difficult to partially increase the strength of one rebar using the furnace heating. However, induction heating allows for easy partial heating, and it is possible to manufacture partially high-strength rebar.

2.2. Strength distribution

The schematic diagram of the strength distribution of one rebar is shown in Figure 2. The actual hardness distribution measurements are shown in Figure 3. The raw material was a commercially available rebar with a standard yield strength of 390 MPa, and

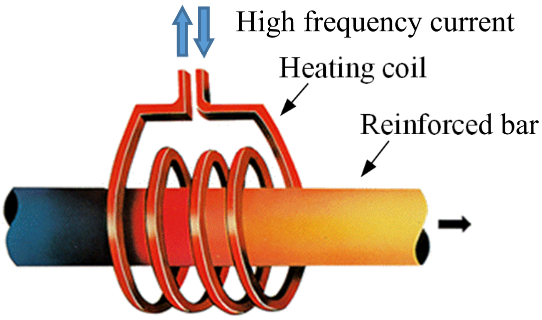

Figure 1. Heat treatment method.

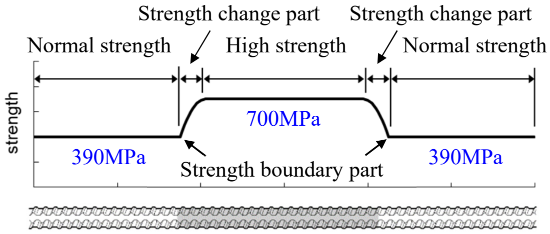

Figure 2. Schematic diagram of the strength distribution.

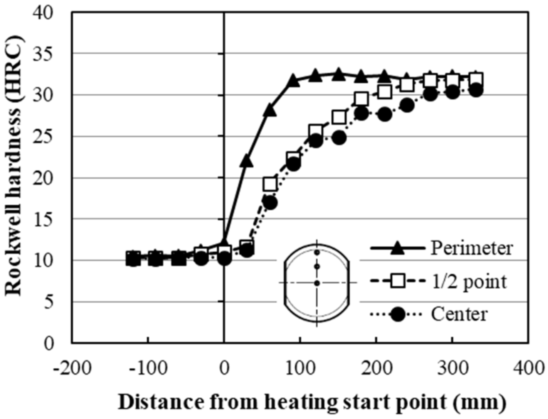

Figure 3. Actual hardness distribution measurements.

the high-strength part was set so that the design yield strength was 700 MPa. The heat treatment was performed on the rebar at a constant speed. As a result, the temperature gradient occurs in the heating coil when the current is turned on and off at the start and end of the high-strength part. The part where the intensity changes at the boundary between the normal-strength part and high-strength part is formed. The hardness at the center, half point, and outer circumference was confirmed by cutting the rebar every 30 mm since the strength of the strength changing part cannot be confirmed by a tensile test. Additionally, iron does not transform until approximately 720 degrees. Therefore, the strength rapidly increases at the strength boundary part. Initially, there was concern that the strength was reduced at the strength boundary part. However, it was confirmed that there was no weakened part as a result of the measurement.

3. Test Program

3.1. Test Parameters

Test results from nine specimens [1–3] are selected and reported here. Table 1 provides characteristics of the specimens. The specimen shape and rebar arrangement are shown in Figure 4. The test specimens are an interior beam-column joint of about 1/2 scale. Each specimen was designed to be a flexural yield type. Seven are specimens using partially high-strength rebar. However, specimen A-1 and B-1 are test specimens of the conventional bar-arrangement method for comparing ordinary rebar for both the longitudinal bars of the column and beam. The experimental factors of the specimen using the partial high-strength rebar were the column-beam flexural strength ratio and the joint shear capacity margin to confirm the effect of each value on the damage properties and hysteresis loops.

The strengthening length of A-3 and B-3 was set to 320 mm, and the flexural strength of the beam was equal to that of A-1 and B-1 for comparison with the conventional method. The purpose of A-4 was to confirm the effect of the high-strength length. The purpose of A-5 and A-6 was to confirm the effect of reducing the longitudinal bars of the column compared to A-3. The difference between A-5 and A-6 was the strength of the longitudinal bars of the column. The column longitudinal bars of A-5 were a normal strength rebar, but A-6 was a partially high-strength rebar, and the purpose is the effect of high-strength rebar. B-1 is the specimen using ordinary rebar like A-1, but the flexural strength of B-1 was greater than A-1. The beam and column longitudinal bars of MA-1 and MA-5 used partially high-strength rebar as in A-6. The strengthening length of the beam longitudinal bars in MA-1 and MA-5 was set to 400ămm, and the stress generated on the column face of the beam was greater than that of the other specimens. The results of the MA-1 experiment showed that the beam-column joint had a relatively severe failure, so MA-5 was used of increase the flexural strength of the column by increasing the total longitudinal bars. The longitudinal bars of A-1, A-3, B-1, and B-3 beams buckled during a large deformation. The distance between the shear rebar of the other specimens was narrowed. Furthermore, the distance of the beam shear rebar in the high strengthened part of A-5 and A-6 was narrowed in order to confirm the confinement effect of the concrete by rebar. The shear rebar of the column and beam in MA-1 and MAŋ5 was normal strength.

3.2. Loading Methods

The specimen was supported by a roller at the beam end and by a pin at the lower column. The specimen was loaded horizontally by a horizontal jack after the introduction of the axial force of the column. The loading was applied once at the story drift angle of

Specimens		A-1	A-3	A-4	A-5	A-6	B-1	B-3	MA-1	MA-5
Concrete compressive strength [MPa]		34.7	34.7	42.6	47.4		39.2	40.3	37.8	36.8
Beam	Width × Depth [mm]	250 × 400								
	Longitudinal tensile rebar	-D16 4+2	2-D16 2-D16+4-D13				-D16	4-D13	4-D16	
	Strengthening length [mm]	–	320	200	320	–	320		400	
	Beam stirrups	2-U7.1 @150		2-U7.1 @150	2-U7.1@50		2-U7.1@150		2-D6.1@50	
Column	Width × Depth [mm]	350 × 350								
	Longitudinal total rebar	10-D16			6-D16		16-D19		6-D19	10-D19
	Strengthening length [mm]	–			350		–		350	
	Axial force ratio	0.16		0.13		0.10	0.16		0.10	
	Column hoops	2-U7.1@100							2-D6@50	
Joint	Joint hoops (ratio)	2-U7.1/4set(0.32%)							2-D6/6set (0.35%)	
Yield point strength [MPa] Normal part / high strength part	D13	371	366/1145	379/972	388/997		–	366/1145	–	–
	D16	–	371/1116	396/964	427/850 399(A-		366	371/1116	402/823	409/870
	D19	–					366		411/893	562/920
	U7.1	1309		1434	1393		1309		–	
	D6	–							420	438
Column-Beam flexural strength ratio		1.42	1.42	1.52	1.13	1.42	2.10	2.13	1.58	2.41
Joint shear capacity margina		1.10	1.13	1.38	1.28	1.28	1.19	1.25	1.16	1.12

* The equations adopts AIJ Guidelines for RC Buildings [4].

TABLE 1. Outline of the specimens.

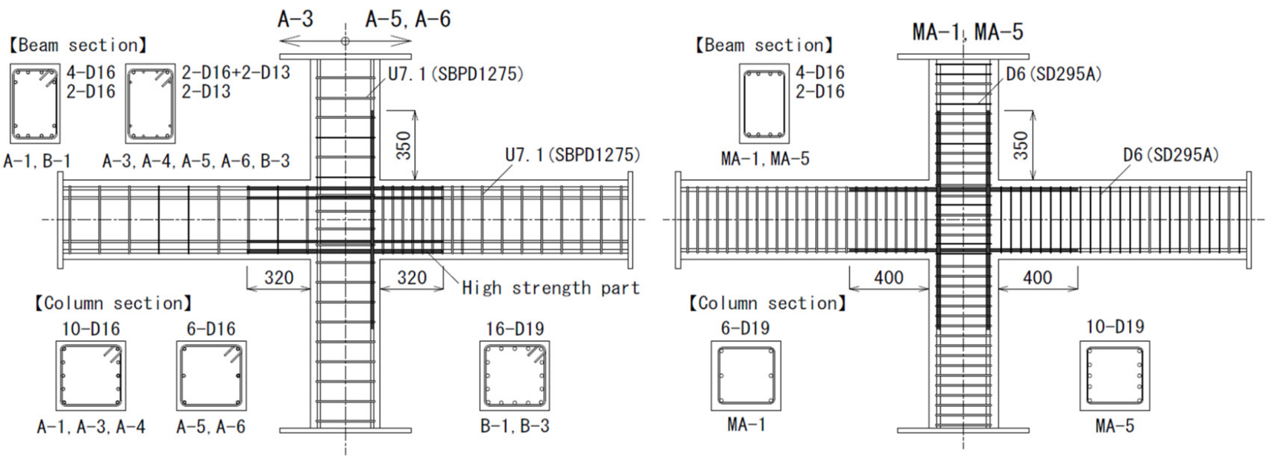

FIGURE 4. Specimen shape and rebar arrangement.

0.25%, twice at story drift angles of 0.5%, 1.0%, 2.0%, 3.0%, and 4.0%, and then to 5.0-6.0%. The loading setup are shown in Figure 5.

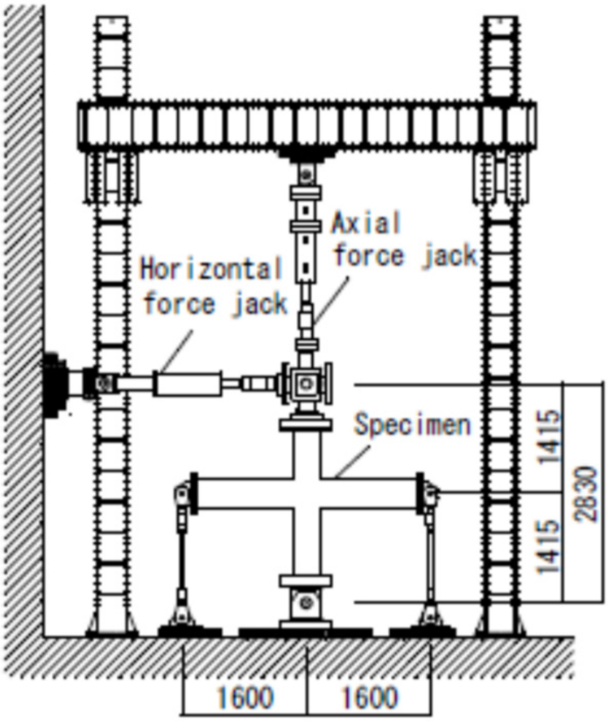

Figure 5. Loading Setup.

4. Test results

4.1. Outline of the test results

The story shear-story drift angle relations are shown in Figure 6. Photo 1 shows crack pattern at the end of the second story drift angle of 4.0%.

The beam longitudinal bar yielded and the maximum strength reached a cycle of the story drift angle of 2.0% in the conventional bar-arrangement methods A-1 and B-1 using only normal strength rebar. Thereafter the strength gradually decreased. The damage of the beam-column joints of A-1 and B-1 was greater than that of the other specimens, and the hysteresis loop was slightly a slip type. The beam longitudinal bars of B-1 was 2.3 times greater than A-1. However, the crack pattern and hysteresis loop were nearly the same, and the effect of increasing the amount of the longitudinal bars was not observed.

The specimens using partial high-strength rebar as the beam longitudinal bar had less damage to the beam-column joints than the conventional bar-arrangement methods A-1 and B-1, and the cracks in the beam were concentrated outside the strength boundary. All specimens using partial high-strength rebar as the beam longitudinal bar showed a tendency to increase in strength even after yielding of the beam longitudinal bar. The hysteresis loop was spindle-shaped until the maximum strength, and the crack pattern was different due to the difference in the experimental factors.

The column longitudinal bar of A-3 yielded at the cycle of the story drift angle of 3.0%, and the strength decreased from the second cycle at the story drift angle of 4.0%. This decrease in strength was due to buckling of the longitudinal bar near the strength boundary part.

The column longitudinal bar of A-4 yielded on the way to the 6.0% story drift angle. However the hysteresis loops of A-4 and B-3 were spindle-shaped until the end, and the strength reduction was small.

A-5, which has the lowest column-beam flexural strength ratio, showed relatively large damage at the beam-column joint. The column longitudinal bar also yields after the beam longitudinal bar yields, and the increase in strength was small.

A-6, with longitudinal bars of A-5 with partially high-strength rebar, yielding of the column longitudinal bar did not occur, so the hysteresis loop became more spindle-shaped than A-5. The damage of the beam-column joint of A-6 was less than A-5, but the hysteresis area was smaller than A-3, A-4, and B-3. The effect of densely arranging the shear rebar in the high strengthening length was not particularly recognized.

MA-1 with the high strengthening length of the beam longitudinal bars of 400 mm and normal strength rebars for the shear rebar of columns and beams showed severe damage to the beam-column joint, and the shear crack of the beam-column joint extended to the column side at maximum strength. The strength did not reach the calculated flexural strength on the negative side.

MA-5, in which the longitudinal bar was greater than MA-1, suppressed the failure of the beam-column joint more than MA-1. However, the strength decrease after the maximum strength was greater than that of the A series and B-3.

4.2. Comparison with the calculated maximum strength

The comparison between the maximum strength experimental values and calculated values are shown in Table 2. The flexural strength was calculated by a cross-sectional analysis of the Fiber model assuming that plane sections remain plane. A bilinear model was used for the longitudinal bar, and an e-function model was used for the concrete. The beam-column joint shear strength was calculated by the equations of AIJ Guidelines for RC Buildings [4].

The maximum experimental strength on the positive side was greater than the calculated flexural strength for all the specimens. However, the maximum experimental strength on the negative side of the specimens where the shear failure of the beam-column joint was relatively severe (A-1 and B-1 using only normal-strength rebar as the longitudinal bars,

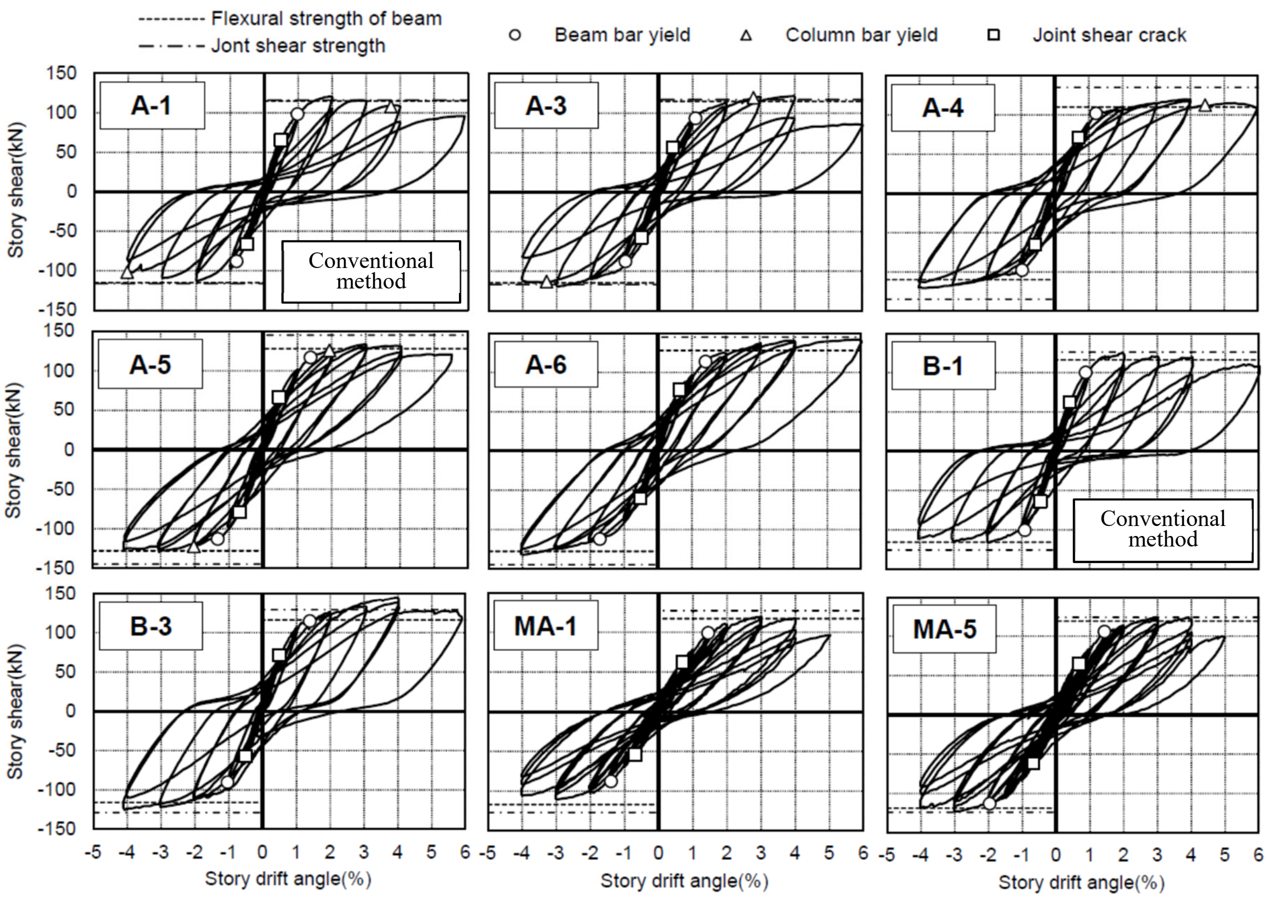

FIGURE 6. Story shear-story drift angle relations.

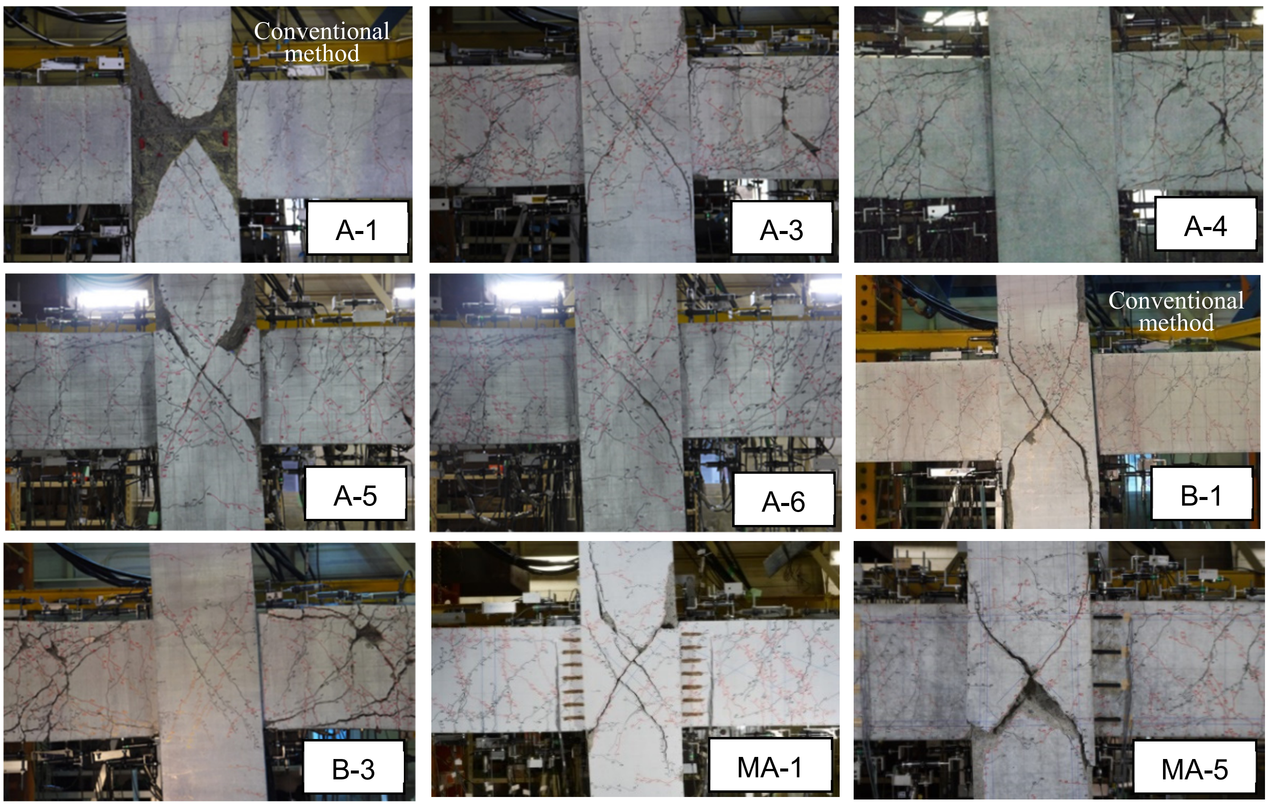

FIGURE 7. Crack pattern.

Specimens		A-1	A-3	A-4	A-5	A-6	B-1	B-3	MA-1	MA-5
Attained maximum story shear Q_{exp} [kN]	+	120.5	121.4	119.9	133.6	141.8	125.0	145.2	119.3	124.0
	−	112.8	119.8	120.9	129.6	132.4	116.7	125.5	110.9	123.6
Beam flexural strength Q_{mb} [kN]		115	115	110	128	128	116	116	117	119
Column flexural strength Q_{mc} [kN]		163	163	167	144	182	244	247	185	287
Q_{exp}/Q_{mb}	+	1.05	1.06	1.09	1.04	1.11	1.08	1.25	1.02	1.04
	−	0.98	1.04	1.10	1.01	1.03	1.01	1.08	0.95	1.04
Column-Beam flexural strength ratio		1.42	1.42	1.52	1.13	1.42	2.10	2.13	1.58	2.41
Joint shear capacity V_{ju} [kN]		855	855	987	1064	1064	931	948	908	891
Joint shear strength V_j [kN]		780	756	717	833	833	780	756	781	794
V_{ju}/V_j		1.10	1.13	1.38	1.28	1.28	1.19	1.25	1.16	1.12

Note: $+$: Positive loading, $-$: Negative loading.

Table 2. Maximum strength experimental and calculated values.

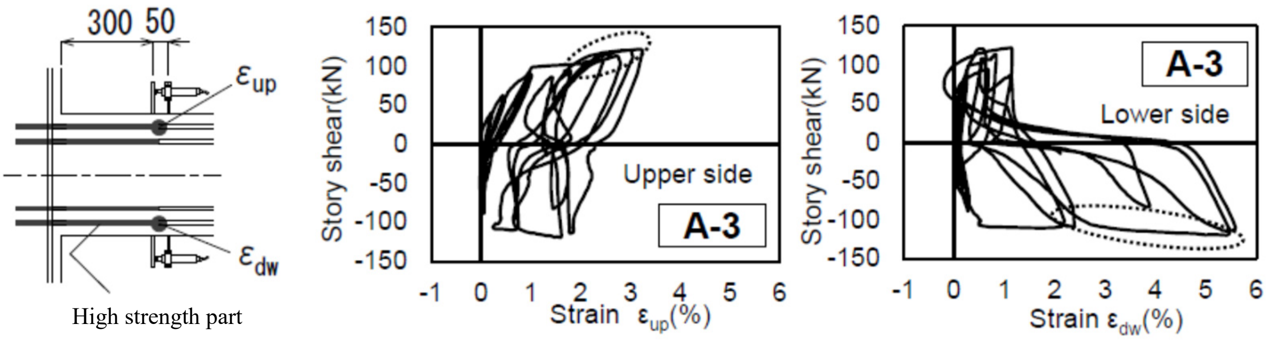

Figure 8. Strain at outer longitudinal bar position calculated from the displacement sensor.

A-5 with low column-beam flexural strength ratio, A-3 with small shear capacity margin, MA-1 and MA-5 with small shear capacity margin), was less than, or slightly greater than the calculated value.

4.3. Increase in the strength after beam yielding

The relation between strain at the outer longitudinal bar position calculated from the displacement sensor and story shear in A-3 showing the spindle-shaped hysteresis loop is shown in Figure 8.

It is assumed that the calculated strain is different from the value of the strain gage attached to the longitudinal bar. However, the longitudinal bar had been deformed in the region of strain hardening at the strength boundary position. Therefore, the increase in strength after yielding of the beam longitudinal bar is caused by the strain hardening of the beam longitudinal bar. The inside of the strength boundary part is elastic especially in this method, and the outside expands plasticization. The increase in strength due to strain hardening is greater than that of the conventional bar-arrangement method.

4.4. Longitudinal bar strain of beam and column

The relationship between the strain of the beam longitudinal bar and the column longitudinal bar according to the experimental results and analysis results are shown Figure 9. The strains of the beam and column by the analysis were calculated by separate cross-sectional analysis, and values at the same story shear were plotted. The cross-sectional analysis was performed using a Fiber model assuming that plane sections remain plane.

The analysis results well reproduced the experimental results. In addition, the strain of the column longitudinal bar was at most 2000 μas a result, and it is assumed that the design may not always be appropriate even if the flexural strength is sufficient due to the high-strength rebar.

4.5. Beam-column joint shear deformation

The relationships between the shear deformation of the beam-column joint and the story shear are shown in Figure 10. The column-beam flexural strength ratio and beam-column joint shear capacity margin are shown in the figure.

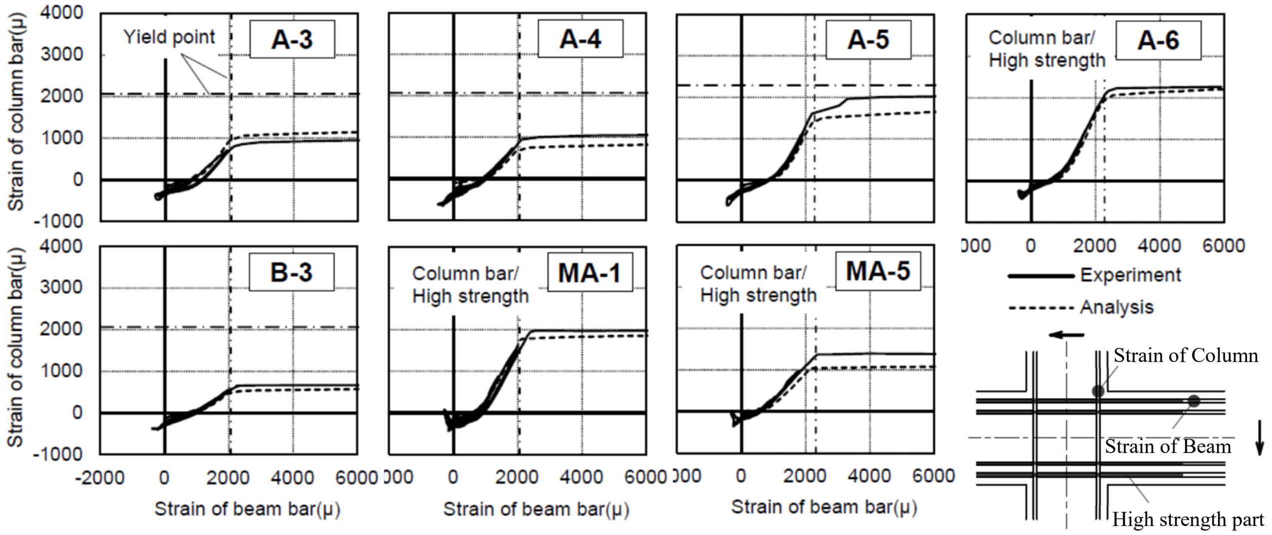

Figure 9. Relationship of the strain of beam longitudinal bar and column longitudinal bar.

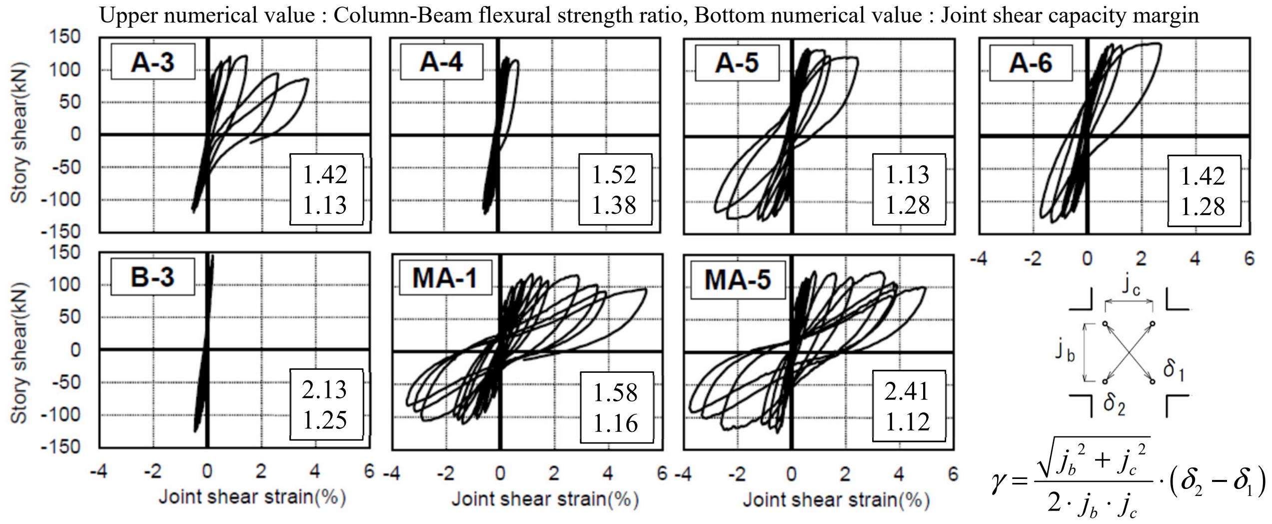

Figure 10. Relationship of the shear deformation of the beam-column joint and story shear.

Even if the shear capacity margin of the beam-column joint exceeds 1.1, the shear deformation of the beam-column joint isn't necessarily suppressed. Furthermore, if the column-beam flexural strength ratio is large as in the case of A-3 to some extent, the shear deformation can be suppressed to a relatively small value. Therefore, it is necessary to set the column-beam flexural strength ratio and the shear capacity margin at the beam-column joint with consideration of their relationship.

5. Conclusions

1. A yield hinge was formed at a position away from the column face using a partially strengthened rebar for the beam longitudinal bars.
2. The damage to the beam-column joint can be mitigated as with other hinge relocation methods.
3. Excellent member performance was obtained with fewer longitudinal bars than the conventional bar-arrangement method, which reduces construction work.
4. The increase in the strength after tensile yielding of the beam longitudinal bar was considered to be due to strain hardening of the beam longitudinal bar.
5. The relation between the strains of the column and beam longitudinal bars was reproduced by cross-sectional analysis assuming that plane sections remain plane.
6. The column longitudinal bars may not require high strength at the time of yielding of the beam longitudinal bar, even if a high-strength rebar is used as the column longitudinal bar. It is necessary to set the column-beam flexural strength ratio by appropriately evaluating the strain condition of the column longitudinal bar in order to obtain a good hysteresis loop.
7. The good performance was obtained if the bend-

ing strength of the column was large, even if the shear capacity margin of the beam-column joint was small. The column-beam flexural strength ratio and shear capacity margin at the beam-column joint need to be set with consideration of their relationship.

8. The good performance was obtained at least if the shear capacity margin of the beam-column joint was 1.2 or more and the column-beam flexural strength ratio was 1.4 or more when a normal-strength rebar was used as the column longitudinal bar. The design data on the relationship between the column-beam flexural strength ratio and shear capacity margin of the beam-column joint was obtained.

Acknowledgements

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