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A STUDY ON USE OF SEVERED REINFORCING BARS TO IMPROVE FLEXURAL DUCTILITY OF RC COLUMNS

Hisato HOTTA[1] And Kentaro WAKIMOTO[2]

SUMMARY

A new method to improve flexural ductility of RC column subject to relatively high axial load has been developed. It is to add several longitudinal bars once cut at the critical section and weakly rejoined by spot welding. In this paper, the authors discuss the effectiveness of this method to columns with multiple arrangement of longitudinal bars, and several methods to relax strain concentration to the ordinary bars at the cut position, where the section property is discontinuously changed. The absorbed plastic energy until the specimens became unstable against axial compression was compared between the ordinary RC column specimen and the ones to which proposed method was applied. Three relaxing methods of the strain concentration were also investigated. As a result, the proposed method is quite effective to improve the flexural ductility of columns and several effective methods to relax the strain concentration were found**.**

INTRODUCTION

Generally ductility of RC member is ensured by flexural failure at the ends, moreover tensile yielding of longitudinal reinforcement. However, columns, particularly base ones are far less ductile than beams even when they fail due to bending, because there exists relatively high axial compression, and concrete often fails due to compression before tensile rebars yield. In spite of less ductility of columns, bottom ends of base ones to which higher compressive stress is applied are permitted to yield in the present limit state design method, therefore it is important to ensure the columns have sufficient ductility.

A new method to improve the flexural ductility of columns has been developed. This method is to add several longitudinal bars symmetrically to some regions of columns where plastic hinge is planned, as illustrated in Fig.1. The additional bars are cut at the critical section and rejoined weakly by spot welding, and they are expected to work only in compression. By adding those reinforcing bars, column sections become the ones where more compression bars are arranged eccentrically against any direction of **bending. Consequently, their** flexural ductility is greatly improved [Hotta 1996]. Figure 2 shows typical M-ϕ relationships of columns subjected to relatively high axial compression. More reinforcement improves only strength but does not improve

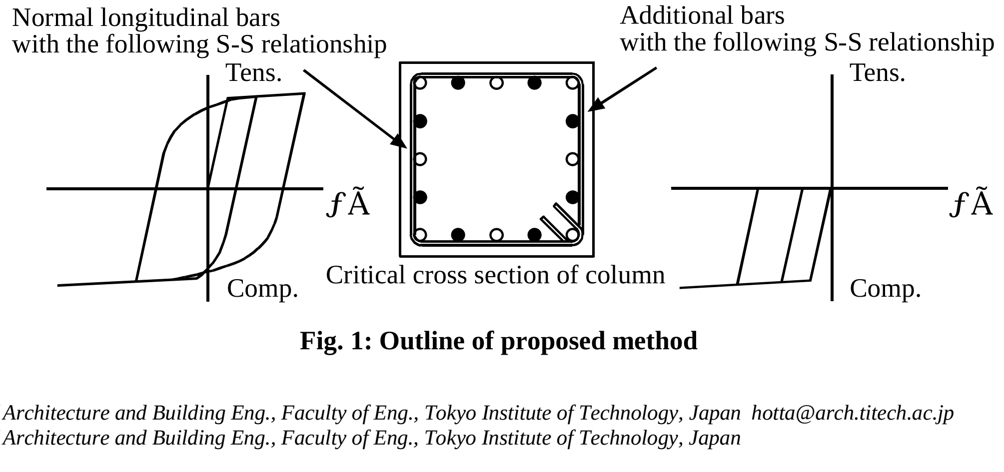

Fig. 1: Outline of proposed method

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[1] *Dept. of Architecture and Building Eng., Faculty of Eng., Tokyo Institute of Technology, Japan hotta@arch.titech.ac.jp*

[2] *Dept. of Architecture and Building Eng., Faculty of Eng., Tokyo Institute of Technology, Japan*

ductility, however, adding rebars only to compression side does it quite well. The effectiveness of this method using severed bars was also briefly confirmed through some empirical examination [Hotta and Takiguchi 1997], [Hotta and Takiguchi 1998]. However, in the test previously carried out, applied compressive stress was very high ($N=0.5bD\sigma_B$) and relatively thick rebars compared with ordinary actual members were used, therefore, some issues such as strain concentration to ordinary rebars at the cutting position due to discontinuous change in section property are still pending in the previous study.

In this paper, the authors discuss the effectiveness of the proposed method in more practical situation. First of all, shear bending tests with more practical moment distribution for base columns under lower axial compression were carried out. Next, applicability of the proposed method to columns with multiple arrangement of longitudinal rebars was examined. Finally several relaxing methods of strain concentration were proposed.

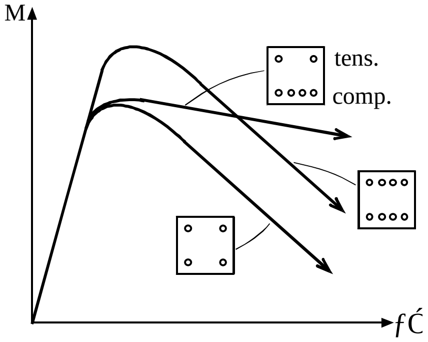


Fig. 2: Comparison of M-ϕ relationships between the ordinary cross sectionsand the one with more compressive rebars

EFFECTIVENESS OF THE PROPOSED METHOD APPLIED TO ONLYPRASTIC HINGE REGION OF COLUMN

Specimens and Testing Procedure

Four specimens modeled after base columns of high-rise building at bottom ends of which plastic hinge was planned to occur were made and tested. They are listed in Table 1 and illustrated in Fig.3. All specimens had a cross section of 160x160mm and clear length of 640mm. Specimen N-4 was a standard RC column with four corner longitudinal bars. Specimen N-8 was strengthened by adding four more reinforcing bars near the bottom end, and specimens BO and NB were the columns applying the proposed method, that is to add four severed reinforcing bars. All longitudinal bars were deformed bars with nominal diameter of 10mm (D10) and yield strength of 4.68t/cm^2. The tensile strength of the severed bars was about 1/3 of the yield strength as listed in Table 2. The difference between specimen BO and NB was the bond property of the severed bars. In order to relax a strain concentration of the normal bars due to discontinuous change of section property at the severed section, the bond of the additional bars was removed by paraffin wax in specimen NB. Hoop ratio was 0.59% for all specimens. The compressive strength of the concrete was about 345kg/cm^2 for specimens N-4 and BO, and 360kg/cm^2 for N-8 and NB as shown in Table 1.

Table 1: List of specimens for bending test with axial compression

Specimen		N-4	BO	N-8	NB
b×D×h (mm)		160×160×640			
Longitudinal Reinforcing Bars	Normal Bars	4-D10 (1.11%)			
	Additional Bars	――――	Severed Bars	Nomal Bars	Severed Bars
			4-D10 (1.11%)		
Hoop Reinforcing Bars		2-6ƒ Ó@60 (0.589%)			
Compressive Strength of Concrete ƒ Ð$_B$ (kgf/cm^2)		340	348	362	365
Axial Force (tf)		26 (0.30bDƒ Ð$_B$)		28 (0.30bDƒ Ð$_B$)	

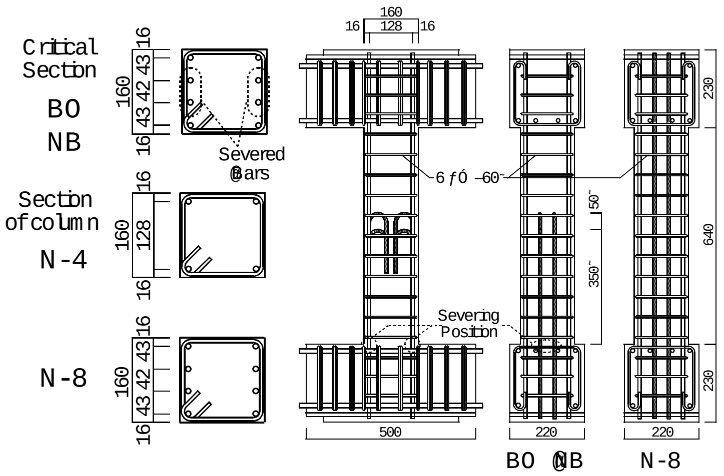


Fig. 3: Dimension and detail of specimens for bending test with axial compression

Table 2: Mechanical properties of longitudinal reinforcing bars

Deformed Bar		Normal Bar	Severed Bar				
			1	2	3	4	5
D10	Yield Strength (tonf/cm^2)	4.72	——				
(SD390)	Tensile Strength (tonf/cm^2)	6.22	1.53	1.23	1.70	1.43	1.68

The moment distribution applied to the specimens and the outline of a loading setup are illustrated in Fig.4. Controlling member angle R to obey the loading schedule as illustrated in Fig.5, the moment at the bottom end M was measured. The axial force was constant and equivalent to $0.3bD\sigma_B$.

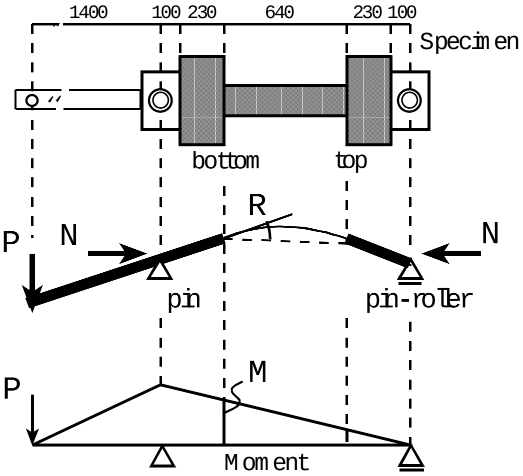


Fig. 4: Bending moment distribution

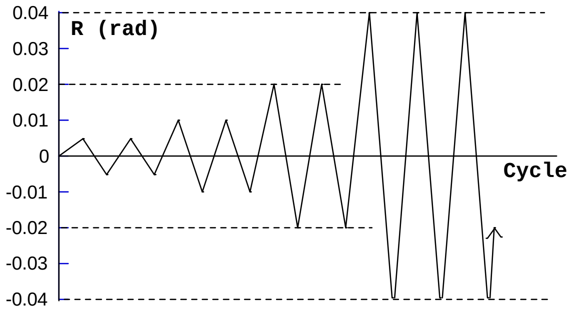


Fig. 5: Loading schedule

Test Results

The test results are shown in Figs.6 and 7. Figure 6 stands for the end moment M versus the member angle R hysteretic curves, and Figure 7 the changes in axial displacement for all specimens. Solid circles in the figures stand for the point at which the specimens began to be unstable against the axial compression, defined as “the point of stable limit” in this paper. The accumulative plastic energy absorbed by the specimens until they reached to the point at which the end moment was degraded to 85% of the maximum strength and the point of stable limit is described in Table 3. Specimen N-8 with the most longitudinal reinforcement showed the highest strength but the ductility was not improved, however, the specimens applying the proposed methods (BO and NB) showed more ductile property than the ordinary RC column specimen. As the rebars used in the test were relatively thick compared with the actual RC column, that means stricter condition of bond, bad influence of the discontinuous change in section property due to cutting rebars was not observed at all. However the issue of the strain concentration is still pending as mentioned in the introduction, because the condition of the bond becomes well when thinner reinforcing bars are used.

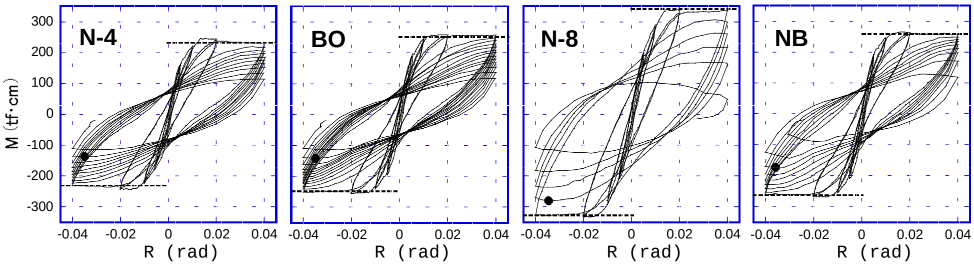


Fig. 6: End moment – end rotation relationships

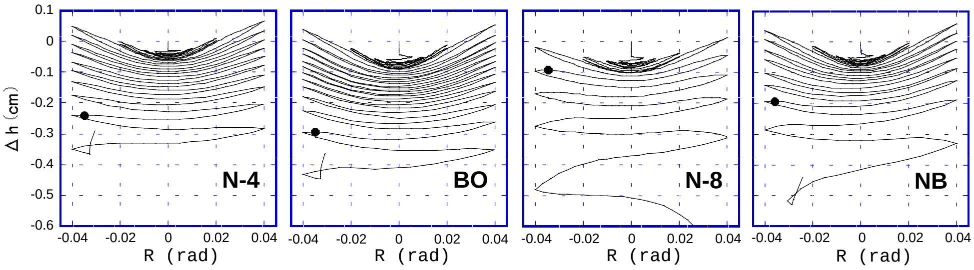


Fig. 7: Axial displacement – end rotation relationships

Table 3: Accumulated energy absorbed due to bending

Specimen		N-4	BO	N-8	NB
85% of the Max Strength	Loop *	8-	11+	8+	10-
	Energy(tf¥cm)	38.9	72.7	53.0	68.5
Stable Limit against Axial Load	Loop*	15+	18+	8+	13+
	Energy(tf¥cm)	118.6	149.6	53.0	100.6

¯ { Positive Loading, | Negative Loading

EFFECTIVENESS OF THE PROPOSED METHOD IN COLUMNS WITH MULTIPLE ARRANGEMENT OF REBARS

Specimens and Testing Procedure

Five specimens listed in Table 4 and detailed in Fig. 8 were made and tested. They were supposed to be base columns of high-rise building at bottom ends of which the plastic hinge was planned. All specimens had a cross section of 160x160mm and a length of 640mm. Specimen NN meant the ordinary RC column in which sixteen D6 rebars were arranged as longitudinal reinforcement (pg=2%). The others were the columns to which the proposed method was applied i.e., the half number of rebars were replaced with the ones severed at the critical section. D6 bars were used in specimens SBO6 and SNB6, and D10 bars SBO10 and SNB10 as severed bars. The severed bars were processed as follows in this experiment. They were once cut perpendicular to their axis, the cut surface of which were smoothed, and divided two surfaces of which were rejoined by spot welding at their ribs. Tensile strength of the severed bars and the normal bars used in the experiment are shown in Table 5. The tensile strength of the severed bars is about 1/6 of the yield strength for D6 bars and 1/3 for D10 (see Table 2). The difference between SBO and SNB specimens is presence or absence of bond of the replaced rebars. In SNB specimen, the bond of the additional bars was removed in the region of 120mm from the end by paraffin wax in order to relax the strain concentration to the ordinary rebars. The severed bars were arranged only at the bottom part of the columns as shown in Fig.1 where the plastic hinge was planned. Hoop ratio was 0.35% for all specimens. The compressive strength of the concrete ranged about from 360 to 400kg/cm^2. The planned moment distribution and the outline of the loading setup are similar to the test mentioned in the previous chapter (Fig.4). Controlled member angle was also the same as the tests in the previous chapter (Fig.5). The moment at the bottom end M was examined. Applied axial compression was constant and equivalent to 0.3bD□$_B$.

Table 4: List of specimens for bending test with axial compression

Specimen		NN	SBO6	SNB6	SBO10	SNB10
b×D×h (mm)		160×160×640				
Longitudinal Reinforcing Bars	Normal Bars	16-D6 (2.0%)	8-D6 (1.0%)			
	Additional Bars	————	Severed Bars			
			Bond	No Bond	Bond	No Bond
			8-D6 (1.0%)		8-D10 (2.2%)	
Hoop Reinforcing Bars		2-3ƒ Ó@25 (0.35%)				
Compressive Strength of Concrete ƒ Ð$_B$ (kgf/cm^2)		359			393	
Axial Force (tf)		28 (0.30bDƒ Ð$_B$)			30 (0.30bDƒ Ð$_B$)	

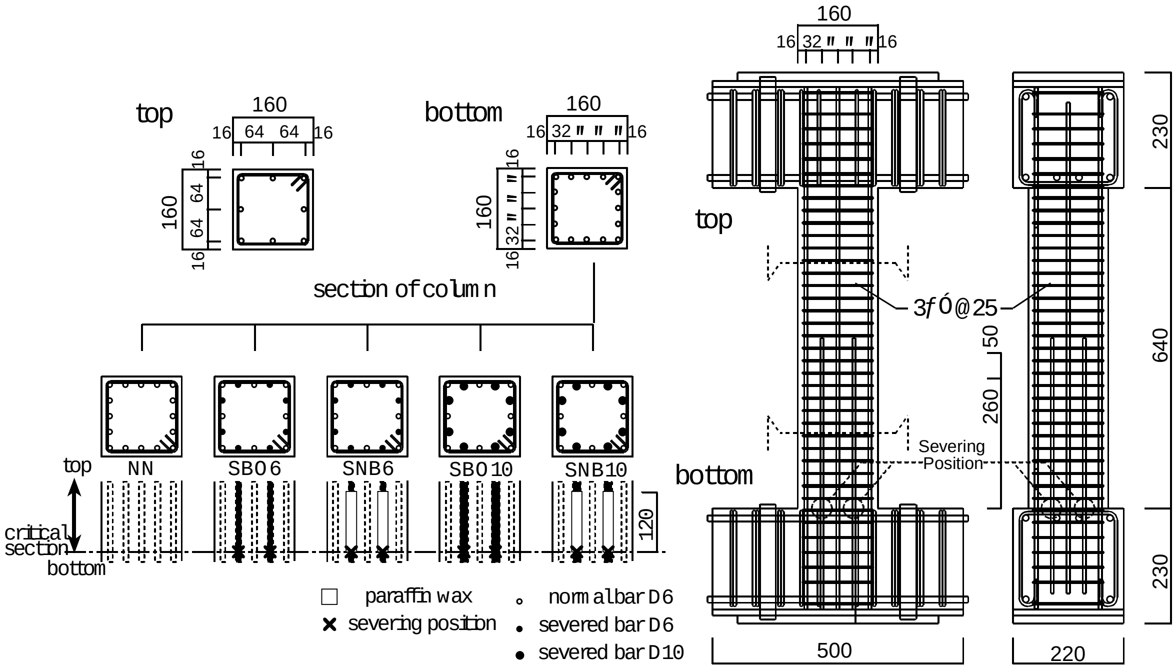


Fig. 8: Dimension and detail of specimens for bending test with axial compression

Table 5: Mechanical properties of longitudinal reinforcing bars

Deformed Bar		Normal Bar	Severed Bar				
			1	2	3	4	5
D6	Yield Strength (tonf/cm^2)	3.87	——				
(SD345)	Tensile Strength (tonf/cm^2)	4.57	0.61	0.51	0.78	0.48	0.47

Test Results

The relationships between the end moment and the member angle for all specimens are shown in Fig. 9, and the change of the axial displacement is shown in Fig. 10. The dashed lines in Fig. 9 stand for the theoretical bending moment calculated based on additional theorem. Both the maximum end moment actually measured and the theoretical ones are not so different from each other between the specimens. That means that to apply the proposed method to columns almost has no disadvantages in strength of members. The solid triangles stand for the point on which the specimens began to be unstable against the axial compression, defined as "the point of stable limit" in this paper. The specimens to which the proposed method is applied are far more ductile than the ordinary RC specimen (NN). The plastic energy absorbed by the specimens until they reached to the point of stable limit is listed in Table 6. The table also remarkably shows the effectiveness of the proposed method.

The ductility of the specimens with additional bars in which bond was removed (SNB6 and SNB10) was poorer than the non-treated specimens (SBO6 and SBO10). The reason to become so might be that the paraffin wax made the bars easy to move laterally and deteriorated their compressive property at the severed position. However, one corner rebar of the specimen SBO10 was actually ruptured, therefore some methods to relax the strain concentration of rebars are still necessary and important in the case the rupture of the rebars may occur with high probability. They are investigated in the following chapter.

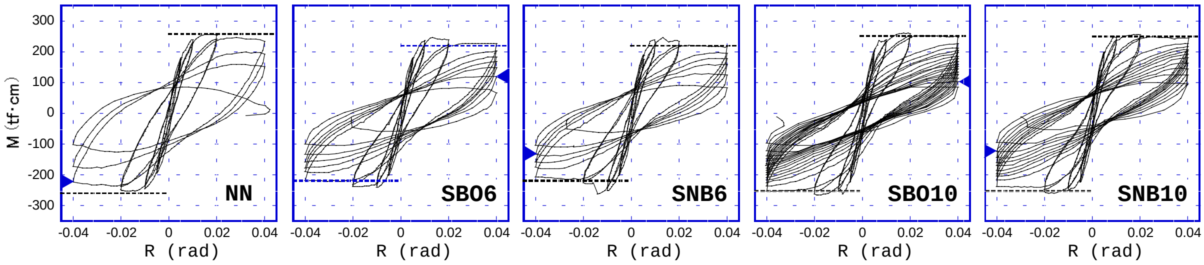


Fig. 9: End moment – end rotation relationships

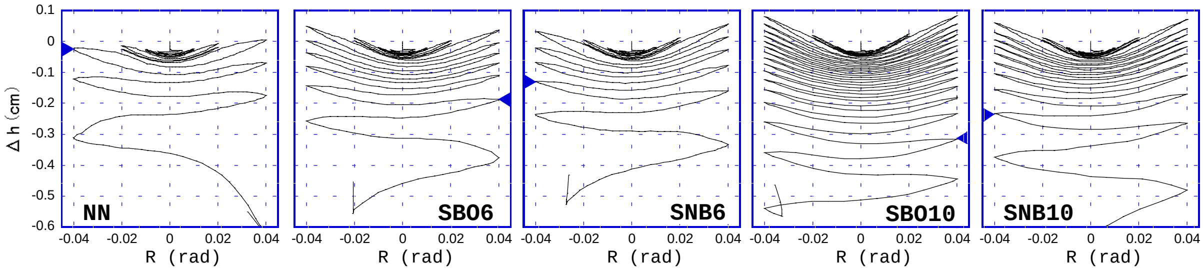


Fig. 10: Axial displacement – end rotation relationships

Table 6: Accumulated energy absorbed due to bending

Specimen		NN	SBO6	SNB6	SBO10	SNB10
Stable Limit against Axial Load	Loop	0.04-1(-)	0.04-6(+)	0.04-4(-)	0.04-15(+)	0.04-9(-)
	Energy(tf¥cm)	28.8	65.9	52.5	123.9	91.6
R (rad) - cycle (times) - (*) @ {Positive Loading, |Negative Loading						

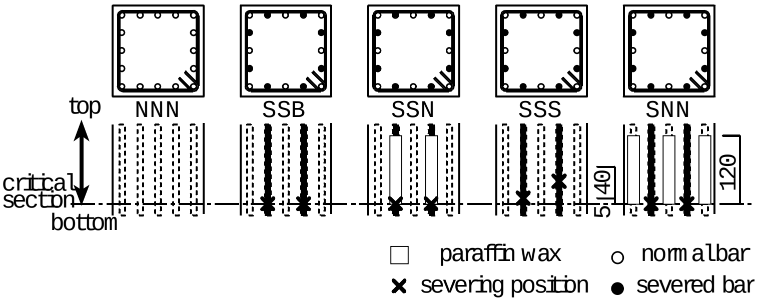
EFFECTIVENESS OF SEVERAL RELAXING METHODS OF STRAIN CONCENTRATION

Specimens and Testing Procedure

Five specimens with the same dimensions as the ones discussed in the previous chapter were made and tested. They are listed in Table 7 and their cross sections and the details around the bottom part are illustrated in Fig. 11. Specimens NNN, SSB and SSN had the same properties as the ones NN, SBO6 and SNB6 in the previous chapter, respectively. Specimens SSS and SNN were the ones to which other methods to relax the strain concentration was treated. In the specimen SSS, the additional bars were cut at two positions that were 5mm and 40mm far from the critical section in order to disperse the cracks to wide region. In the specimen SNN, the bond of the ordinary reinforcing bars instead of the severed bars is removed by paraffin wax. The compressive strength of the placed concrete was 333kgf/cm^2 for the specimens NNN, SSB and SSN, and was 309kgf/cm^2 for SSS and SNN. Cyclic shear bending tests under constant axial load ($N=0.3bD\square_B$) were carried out. The planned moment distribution was the same as the experiment in the previous chapter. The controlled member angle was planned to increase only in positive direction as shown in Fig. 12 so that the rupture of the longitudinal bars would occur with higher probability.

Table 7: List of specimens for bending test with axial compression

Specimen		NNN	SSB	SSN	SSS	SNN
b×D×h (mm)		160×160×640				
Longitudinal Reinforcing Bars	Normal Bars	16-D6 (2.0%)	8-D6 (1.0%)			
	Additional Bars	————	Severed Bars			
			Bond	No Bond	Bond Cut at 2 positions	Bond Normal Bars - No bond
			8-D6 (1.0%)			
Hoop Reinforcing Bars		2-3ƒ Ó@25 (0.35%)				
Compressive Strength of Concrete ƒ Þ$_B$ (kgf/cm^2)		333			309	
Axial Force (tf)		26 (0.30bDƒ Þ$_B$)			24 (0.30bDƒ Þ$_B$)	



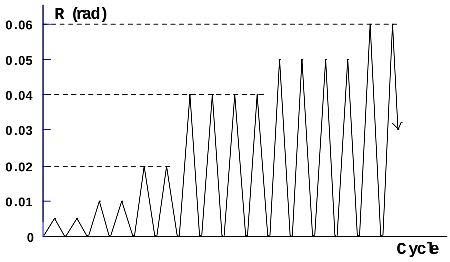


Fig. 11: Details around the bottom part

Fig. 12: Loading schedule

Test Results

The relationships between the end moment and the member angle were described in Fig. 13. The dashed lines in the figure represent the theoretical bending moment calculated based on the additional theorem similar to Fig. 9. The change of the axial displacement is shown in Fig. 14. The solid triangles in Figs. 13 and 14 show the point of the stable limit. The rupture of the rebars was not observed in all specimens. The reason is considered that the compressive strength of the concrete was low compared with the previous experiment, i.e., it was 393kgf/cm^2 for the specimen SBO10 in which a rebar was ruptured. The plastic energy absorbed until the point of stable limit of all specimens is compared in Table 8. As a result, the specimen SSB without any relaxing method of the strain concentration showed the most effective performance to improve the flexural ductility. As for the specimens to which several kinds of relaxing method of the strain concentration were applied, some effect to improve the flexural ductility could be recognized, however, it was less than the specimen SSB showed. Individually discussing, the specimen SSN showed the least efficiency in improving the ductility, because the paraffin wax smeared on the surface of severed bars might deteriorate their own compressive property. As for the specimen SNN in which contrary the bond of the normal bars was removed, although the slip behavior was more conspicuous than the other specimens, the effect in improving the ductility was highest in three specimens to which some kinds of relaxing method were applied. At last, the specimen SSS in which the rebars were severed at several positions from the critical section showed almost the same performance as the specimen SSN showed. The reason is considered that the severed position was too few and was arranged eccentrically in the section, so the cracks could not be dispersed according to the author's expectation. Therefore, it is considered that this method can be more effective in actual scale members, because in the actual scale members more severing positions can be provided to the rebars symmetrically.

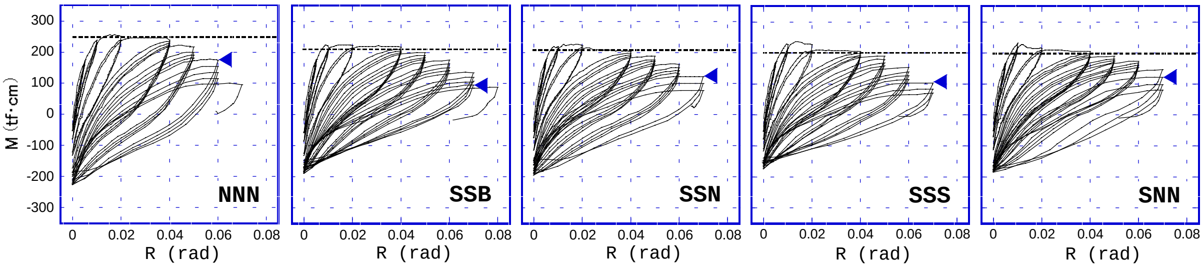


Fig. 13: End moment – end rotation relationships

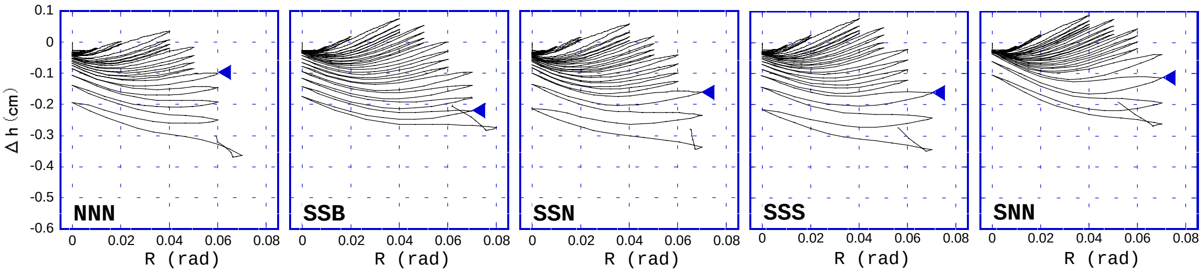


Fig. 14: Axial displacement – end rotation relationships

Table 8: Accumulated energy absorbed due to bending

Specimen		NNN	SSB	SSN	SSS	SNN
Stable Limit against Axial Load	Loop	0.06-1	0.07-4	0.07-1	0.07-1	0.07-2
	Energy(tf¥cm)	53.9	85.9	66.5	66.7	69.2
@R(rad)-cycle(times)						

CONCLUSIONS

(1) To add severed reinforcing bars only in the plastic hinge region of columns is effective in improving flexural ductility.

(2) The proposed method using severed reinforcing bars is effective in improving flexural ductility of columns with multiple arrangement of longitudinal reinforcing bars.

(3) To add severed bars with thicker diameter and with higher strength than normal bars is more effective in improving flexural ductility of members.

(4) There is some probability of rupture of normal reinforcing bars in members to which the proposed method using severed bars is applied under some condition that there is enough bond capacity between the reinforcing bars and the concrete. As the method to avoid the rupture of the normal reinforcing bars, it is effective to remove the bond of the normal bars in some region near the critical section.

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