HYSTERESIS RESPONSE OF CROSS TYPE SUBASSEMBLAGE RC FRAME WITH SELF-CENTERING STRUCTURE

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ABSTRACT :

The buildings damaged by earthquakes sometimes have to be removed by the reason which the residual deformations are not allowable of the service facilities and residential conveniences, even though the buildings with the residual deformations still have enough earthquake resistant capacities. In order to decrease the residual deformations of RC frames due to severe earthquakes, the authors propose the RC frames with self-centering capacities which are exhibited by the unbonded longitudinal bars inserted through the ducts in the RC columns. The seven cross type subassemblage RC frame specimens are tested under reversed cyclic lateral force and a constant axial load simultaneously. From the test results, it is clarified that the proposed RC frames decrease the residual deformations than those of the conventional RC frames significantly.

KEYWORDS: Residual deformation, Self-centering, Unbond, High strength steel rebar, RC Frame

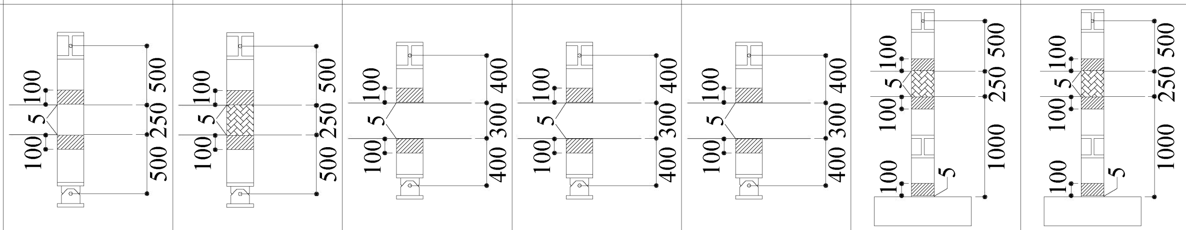
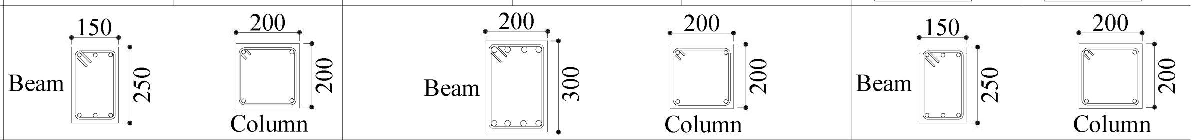
1. INTRODUCTION

Japanese islands are located at circum-Pacific volcanic zone, a lot of RC buildings have been attacked by several earthquakes. The residual deformations owing to not only severe but also moderate earthquakes cause the inconveniencies of the damaged buildings. Therefore, authors try to develop the RC structure which decreases the residual lateral drift of RC columns in which the plastic hinges are formed by earthquakes. Our proposed frame is consisted of the ordinary RC beam and the RC columns with unbonded high strength steel rebars. The rebars are post-tensioned through the ducts embedded in the concrete columns and planned that the additional tensile stresses of them would be introduced according to the increase of lateral drifts of the columns. The introduced tensile stresses would act to restore the lateral drifts as what we call self-centering behaviors.
A total of seven cross type specimens consisted of beams and columns are manufactured and tested under reversed cyclic lateral force and a constant axial load simultaneously. There is one specimen with normal RC column. The other six specimens are proposed frame specimens including the RC columns with the self-centering capacities. The unbonded rebars in the intermediate part of the columns and those in the end part of the columns (i.e., columns at first floor and top floor) are acting in different manners in our proposed frames. Therefore we manufacture two kinds of frame specimens including intermediate cross part and first floor column. In the subassemblage specimens, the only column-parts possess the self-centering effect essentially. In order to estimate the residual deformations of the actual RC frames, it is important to investigate the elastic and plastic behaviors of the beams and the beam-column connections. The test parameters are set as follows: 1) stiffness and strength of the beams; 2) reinforcement at beam-column connections. The other test parameters are shear keys at the connection surface, axial load ratio, compressive strength of concrete, and so on.

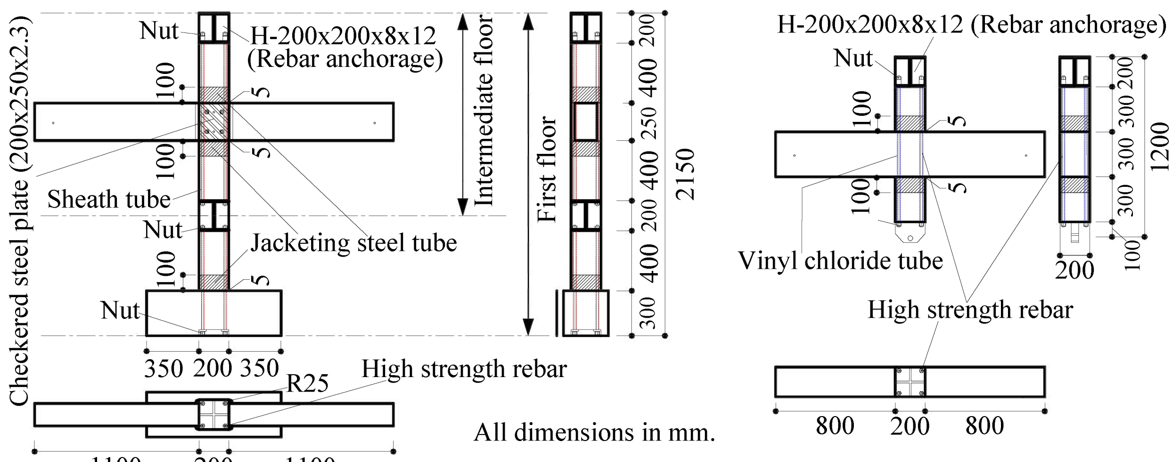
2. TEST SPECIMENS, LOADING PLAN AND MEASURING SYSTEM

The list of cross type subassemblage frame specimens is summarized in Table 1. There are 3 series of test specimens planned in this study. Both specimens in series 1 are intermediate floor cross type frames with weak beams. In order to investigate the effect of stiffness and capacity of the beam on the residual lateral drift, three specimens with strong beams in series 2 are planned to compare with series1. In series 3, either specimen is first floor cross type (foundation type) frame with weak beam. The details of cross type subassemblage frame test specimens are illustrated in Figure 1. The mechanical properties of reinforcement are shown in Table 2. In all specimens, cross section of the column is 200 mm x 200 mm. The columns are also covered by square steel tube (200mm×200mm×2.3mm) whose length is 1/2 of the column depth (the gap between steel tube and joint panel is 5 mm). The steel reinforcement arrangement of the beams of all test specimens is determined according as the flexural failure at top and bottom region precedes other failures.

Table 1 Test specimen of cross type subassemblage frames

Series	Series 1 (cross type & weak beam)		Series 2 (cross type & strong beam)			Series 3 (foundation type & weak beam)	
Specimen	IO-2.5-0.15	IR-2.5-0.15	IBT-2-0.15	IUBT-2-0.15	IUBTS-2-0.15	R-2.5-0.15	R-2.5-0.2
Shape							
Cross section							
Axial force ratio	0.15						0.2
Rebar of column	4-13ϕ (p_g =1.33%)		4-D13(p_g=1.27%)	4-13ϕ (p_g =1.33%)			
Hoop	D6@30(p_w=1.07%)			D6@50(p_w=0.64%)		D6@30(p_w=1.07%)	
Rebar of beam	6-U12.6(p_{gb}=1.11%)		8-D19(p_{gb}=3.83%)			6-U12.6(p_{gb}=1.11%)	
Stirrup	D6@75(p_{wb} =0.57%)		D6@50(p_{wb} =0.64%)			D6@75(p_{wb} =0.57%)	
σ_B	32.2 MPa	27.4 MPa	24.7 MPa			27.4 MPa	
Shear key	Without shear key				With shear key	Without shear key	

▨ : Checkered steel plate, ▨ : Jacketing steel tube (□-200x200x2.3), p_g : Rebar ratio of column, p_w: Reinforcement ratio of hoop, p_{gb} : Rebar ratio of beam, p_{wb}: Reinforcement ratio of stirrup, σ_B : Concrete compressive cylinder strength, All dimensions in mm.



a) Series of beam with small stiffness and capacity

b) Series 2

Figure 1 Details of cross type subassemblage frame test specimens

The high strength longitudinal reinforcement steel bars of series 1 is inserted into the sheath tube embedded in the precast column beforehand and fastened to H-shaped steel placed at both ends of the column by introducing the pretension force utilizing torque wrench through nuts. The specimen of series 3 is composed of series 1 and cantilever column fixed with foundation beam (see Figure 1). In order to clarify the effect of failure mode of joint panel on the residual deformation of the frame, the reinforcement of joint panel is set as one of the test parameters. The beam-column joints of test specimens IR-2.5-0.15, R-2.5-0.15 and R-2.5-0.2 are reinforced utilizing the checkered steel plate (see Figure 2) from both sides by prestressed high strength steel bars that are penetrated across the joints beforehand. The prestressing is also introduced by torque wrench.

The stiffness and capacity of beams of series 2 are larger than those of series 1 by increasing the cross section, rebar and shear reinforcement ratio of the beam, as well as decreasing the length of the beam. IBT-2-0.15 is the conventional RC test specimen in which the column and beam are casting together by arranging the ordinary strength deformed bars for the column. IUBT-2-0.15 and IUBTS-2-0.15 are unbonded RC cross type subassemblage frame test specimens composed of the precast columns and beam shown in Figure 3. In these two specimens, the assembly technique of beam-to-column connection is that the high strength steel rebars are inserted through the vinyl chloride tube embedded in the precast columns and beam, and then the beam and columns are fastened to H-shaped steel placed at both ends of the column by introducing the pretension force into rebars through nuts. The difference between IUBT-2-0.15 and IUBTS-2-0.15 is shear key (the mortar is filled into square steel tube of 40mm×40mm×2.3mm with the length of 20mm) which is set at the concavity molded at cross section central region of the connection of members of IUBTS-2-0.15.

Table 2 Properties of reinforcement

Reinforcement		a (cm^2)	σ_y(MPa)	σ_u (MPa)	E (GPa)	ε_u (%)
D6	All specimens	0.32	378	535	185	14.1
U12.6	Series 1	1.25	1381	1470	212	7.8
	Series 3		1359	1465	195	6.4
D13	IBT-2-0.15	1.27	353	521	182	26.7
D19	Series 2	2.47	446	690	203	16.2
13ϕ	Series 1 and series 2	1.32	1209	1272	201	8.7
	IUBT-2-0.15 and IUBTS-2-0.15	1.32	1210	1273	176	11.2

Notes:
a = cross section area, σ_y = yield strength of steel, σ_u = tensile strength of steel, E = Young's modulus of elasticity, ε_u = breaking elongation of steel.

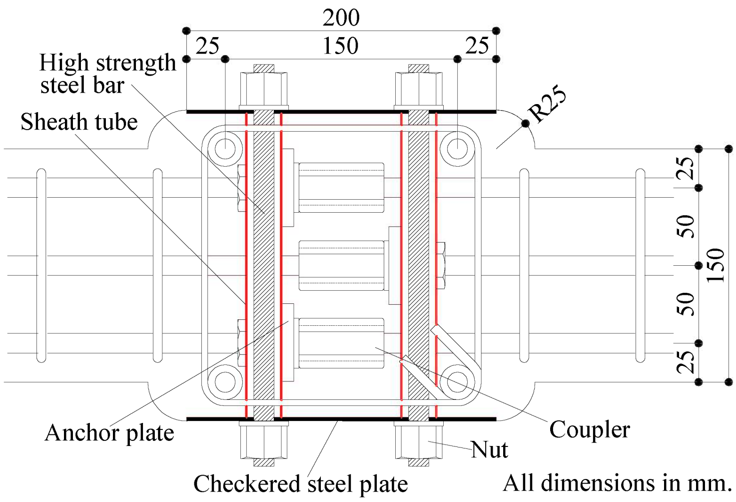


Figure 2 Anchorage method of checkered steel plate (IR-2.5-0.15, R-2.5-0.15 and R-2.5-0.2)

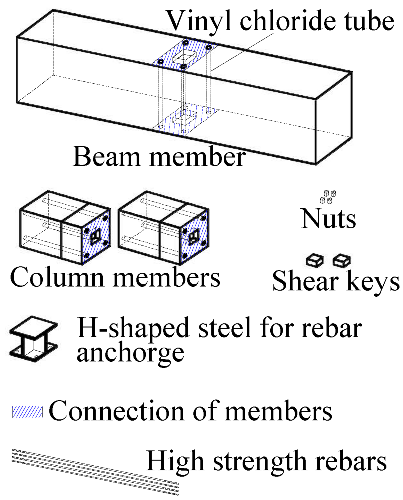


Figure 3 Materials of connection (IUBTS-2-0.15)

The axial force is applied by a combination between vertical jack and pretension force of unbonded high strength rebars, and set the value of 0.15 and 0.2 as the axial force ratio $N/(bD\sigma_B)$, where N is axial force, b and D are width and depth of column respectively, and σ_B is compressive strength of concrete. The axial force of IBT-2-0.15 is only applied by the jack, but the axial forces of the other specimens include the initial reaction forces by the pretension forces of rebars. The value of pretension force is as large as $N/(bD\sigma_B)$ =0.05 except for the specimen R-2.5-0.2 whose pretension force is as large as $N/(bD\sigma_B)$ =0.1. The total value of $N/(bD\sigma_B)$ is controlled as 0.15 or 0.2 considering the pretension forces of rebars.

The cyclic lateral force is applied to the test specimens at the position shown in Figure 4 utilizing the loading apparatus illustrated in Figure 5. The displacement transducers are installed in the measurement frame supported by pin and roller in the screw bolts embedded in both end of the beam (see Figure 5). The lateral drift of the column between the positions of black circle marked in the Figure 4 is measured. The value dividing the lateral drift by the distance between black circles is defined as story drift angle *R*. In the subassmblage specimens, the only column-parts possess the self-centering effect essentially. In order to estimate the residual deformations of the actual RC frames, it is important to investigate the deformations of the beams and the beam-column connections. The lateral displacement between black circles shown in the Figure 6 is also measured, and the value dividing the relative lateral displacement between black circles by the distance between black circles is defined as a rotation angle θ of the joint panel. The pretension force of high strength rebar is measured by strain gauge pasted on doughnut-shape metal washer with thickness of 30mm. The lateral loading cycles include three successive cycles at each story drift angle of *R*=±0.5, ±1.0, ±1.5, ±2.0, ±2.5, ±3.0%.

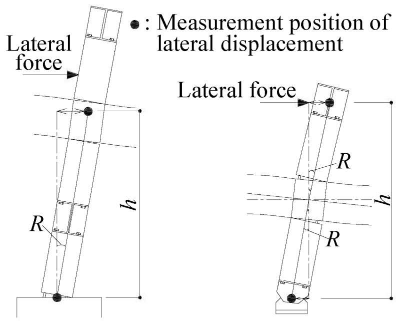
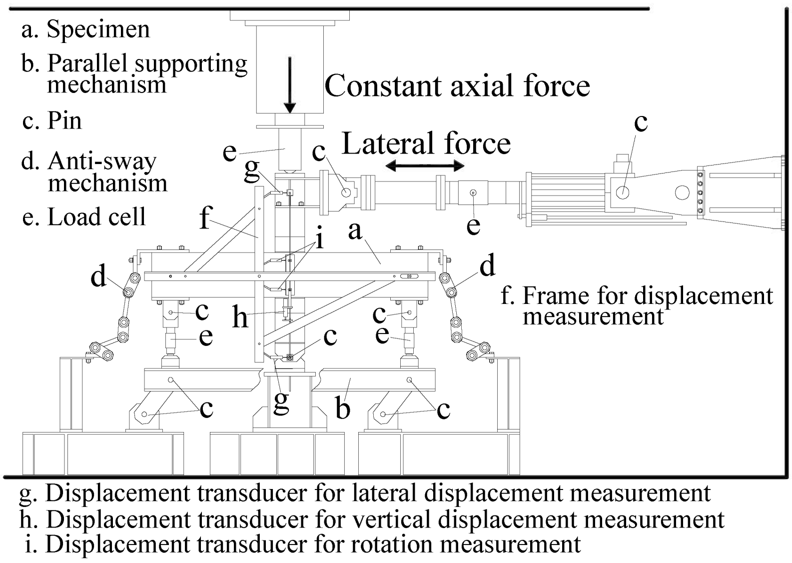


Figure 4 Loading position and deformation graph of test specimens



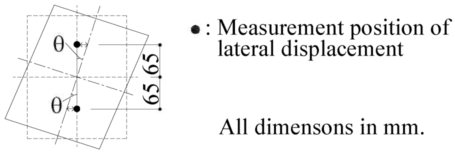


Figure 6 Deformation graph of joint panel

Figure 5 Details of test setup and measurement apparatus of test specimen

3. EXPERIMENTAL AND ANALYTICAL INVESTIGATIONS

The relationship between the experimental lateral shear force *Q* and the story drift angle *R* is presented in Figure 7. The solid lines show the experimental *Q-R* curves and the dotted lines show the calculated flexural strength based on Figure 13. Only the maximum lateral load of conventional RC specimen IBT-2-0.15 attains the calculated capacity. The other experimental lateral capacities do not reach the calculated flexural strengths. It is the reason why the high strength rebar does not yield. All specimens except for IBT-2-0.15 exhibit the hysteresis curves which are similar to the origin oriented one, but the residual deformations of them are also left to a certain extent. The differences of the results are discussed hereafter.

The Crack patterns of the specimens in the side parallel to the cyclic loading direction after test are illustrated in Figure 8. In both specimens of series 1, whose stiffness of the beams is smaller than that of the specimens of series 2, at about story drift angle *R*=0.5%, the initial flexural crack occurs in the beam adjacent to joint panel. Small flexural cracks are observed in the beam of the both specimens (see Figure 8) when *R* reaches 1.0%. Flexural crack of the column adjacent to joint panel expands gradually when *R* exceeds 1.5%. In IO-2.5-0.15 whose joint panel is not reinforced, the diagonal crack is observed in the joint panel when *R* exceeds 2%. On the other hand, the phenomenon that the flexural crack in the beam and column adjacent to joint panel widens is observed in IR-2.5-0.15 whose joint panel is reinforced by checkered steel plate.

In conventional RC frame IBT-2-0.15 with stiff beam, only flexural crack happens in the column adjacent to joint panel when *R* reaches 0.5%. The shear crack is generated in column-to-beam connection when *R* exceeds 1%. However, in both test specimens IUBT-2-0.15 and IUBTS-2-0.15 utilizing unbonded high strength rebar, only the crack formed at column adjacent to joint panel expands by degrees when *R* is larger than 1.5%. The residual deformations of these two specimens are smaller than those of IBT-2-0.15, IO-2.5-0.15 and

IR-2.5-0.15. In series 2, small flexural cracks are generated at the beam of any test specimen, but they are fewer than those formed in the test specimens of series 1.

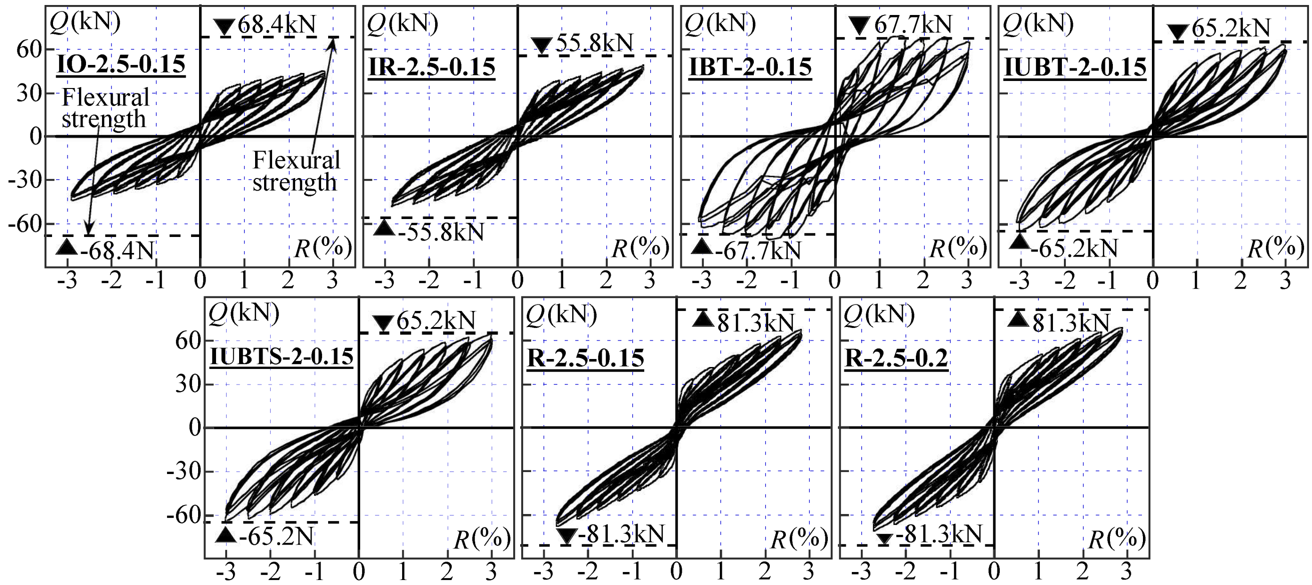


Figure 7 Measured Q-R relationship

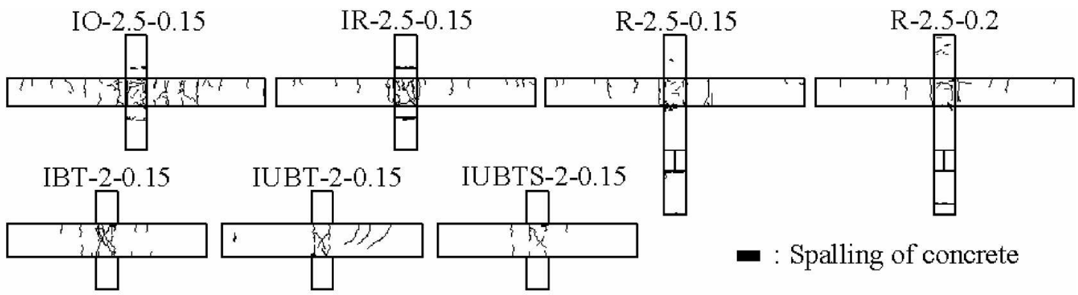


Figure 8 Observed cracking patterns after the end of test

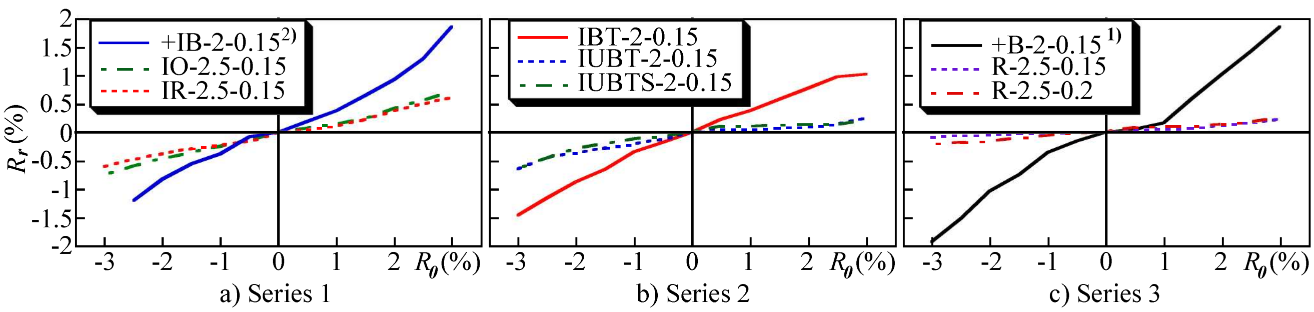


Figure 9 Relationship between experienced story drift angle R_0 and residual story drift angle R_r

In both test specimens of series 3, small flexural cracks are generated at the beam region when R exceeds 1.0%. The cracks formed at end of the two columns adjacent to joint panel widen gradually when R exceeds 1.5%. The phenomenon that the flexural cracks in the beam and column adjacent to joint panel expand is observed when R exceeds 2.0%.

The relationship between experienced story drift angle R_0 and residual story drift angle R_r is shown in Figure 9. The experimental result of conventional RC frame specimen +IB-2-0.15 (deformed rebar was arranged in the

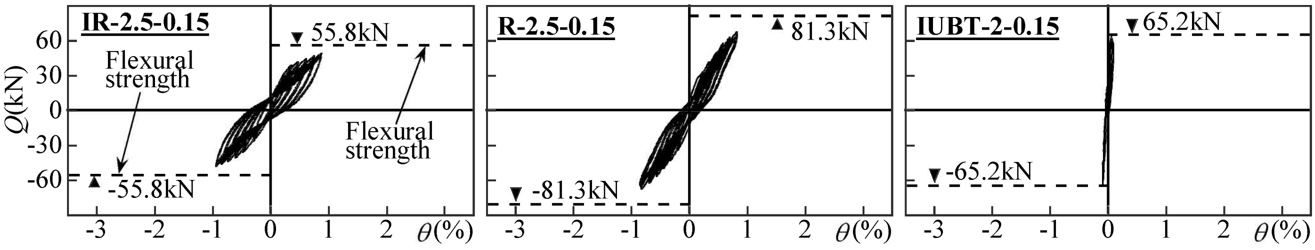
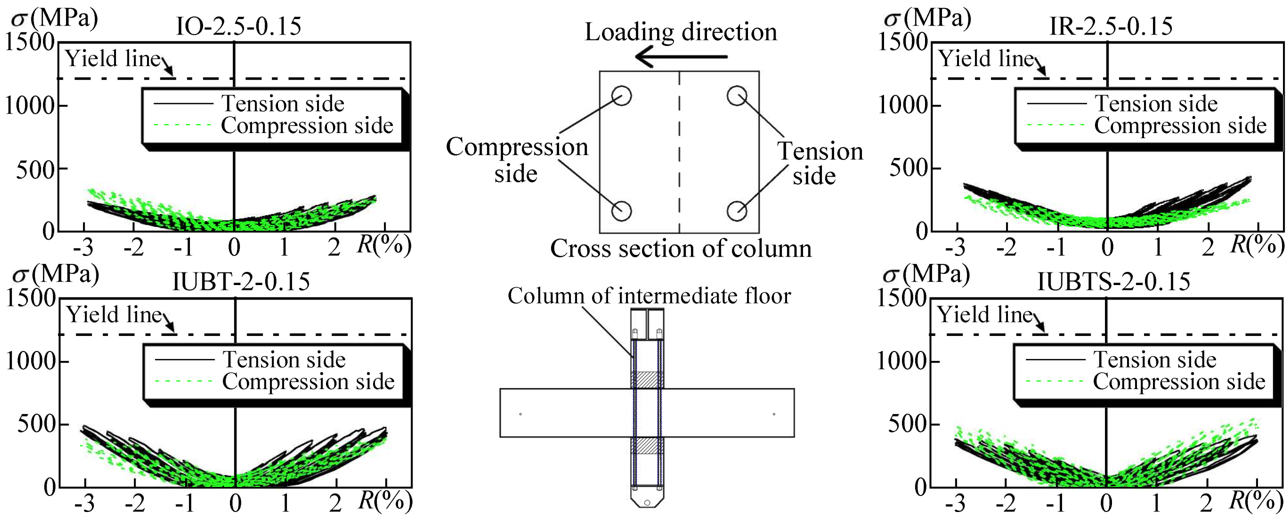
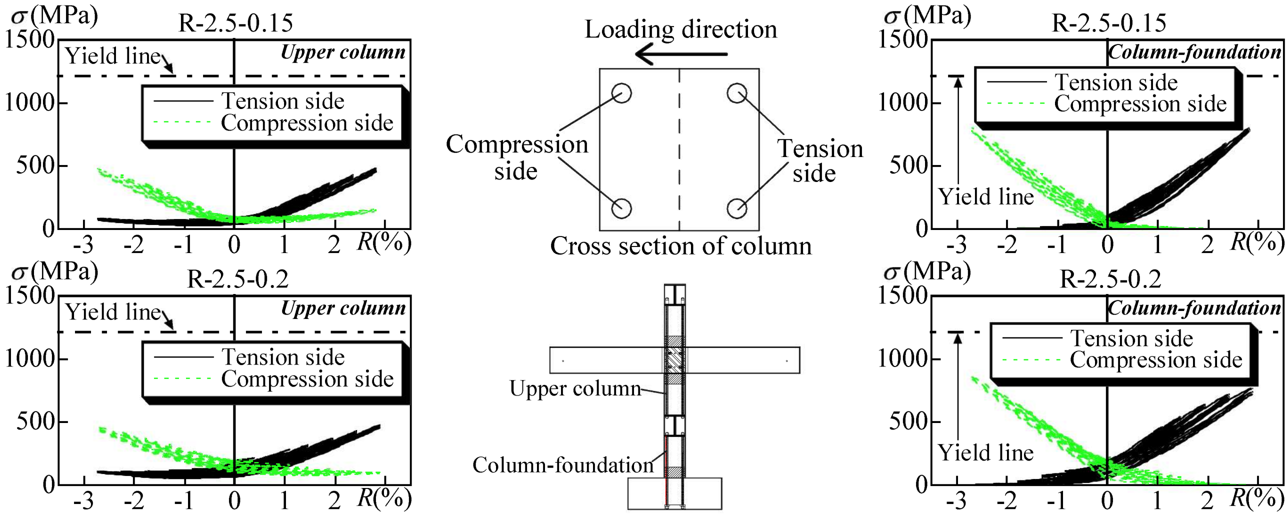


Figure 10 Measured Q-θ relationship of test specimens IR-2.5-0.15 and R-2.5-0.15 and IUBT-2-0.15



a) Series 1 and series 2



b) Series 3

Figure 11 Measured σ-R relationship of high strength rebars

column) carried out in reference 2) is also shown in a) of Figure 8. In the series 1, R_r of IR-2.5-0.15 whose joint is reinforced is a little smaller than that of IO-2.5-0.15 whose joint panel is not reinforced. On the other hand, in the series 2, R_r of IUBT-2-0.15 and IUBTS-2-0.15 which utilize high strength unbonded rebars, are considerably smaller than the case of conventional RC frame test specimen IBT-2-0.15. Since R_r of IUBT-2-0.15 and IUBTS-2-0.15 are not different significantly, the effect of the shear key on the residual deformation is not much observed during test. In the series 3, the experimental result of conventional RC frame specimen +B-2-0.15 (deformed rebar was arranged in the column) carried out in reference 1) is shown in c) of Figure 9. It is proven that the residual deformation occurs rarely even if R is increased. The residual story drift angle of the cross type subassemblage frame utilizing unbonded high strength rebars in this study is less than 0.5 time of the case using conventional deformed rebars. It is proven that it is possible to make residual deformation small by the construction method adopted in this research.

The relationships between the experimental lateral shear force Q and the rotation angle θ of the joint panel of the representative specimens IR-2.5-0.15, R-2.5-0.15 and IUBT-2-0.15, are shown in Figure 10. It is obvious that the residual deformation due to rotation deformation of joint panel occurs in the series 1 and series 2. It seems that the behavior of self-centering becomes weaker due to the flexural deformation of the beam. However, in the series 2, the residual deformation occurs scarcely by enhancing stiffness and capacity of the beam.

The relationships between stress σ of the high strength rebar and story drift angle R are shown in Figure 11. In series 1 and series 2, the column elongates with the increase of R. As a result, since the tensile forces of all rebars are also increased, the reaction forces of the rebars introduce the axial compressive force to the concrete of column. It is recognized that the tensile force of rebar may decrease gradually due to the damage of the concrete in the end of column, when the number of successive lateral loading cycles increases with the increase of R.

In the specimen of series 3, the tensile force became larger with the increase of R in the tension side of column-foundation. On the other hand, the tensile force approaches zero with the increase of R in the compression side. From these results, the resistance mechanism in which the rebars shares part of bending moment is shown in the column base. In the upper column, the tensile force of the rebar in tension side is bigger than the case of compression side with the increase of R. It is different from the resistance mechanism of intermediate floor cross type subassemblage frame. It is proven that the resistance mechanism in which the rebars share part of bending moment. Therefore, it seems that the recovery of the deformation is improved.

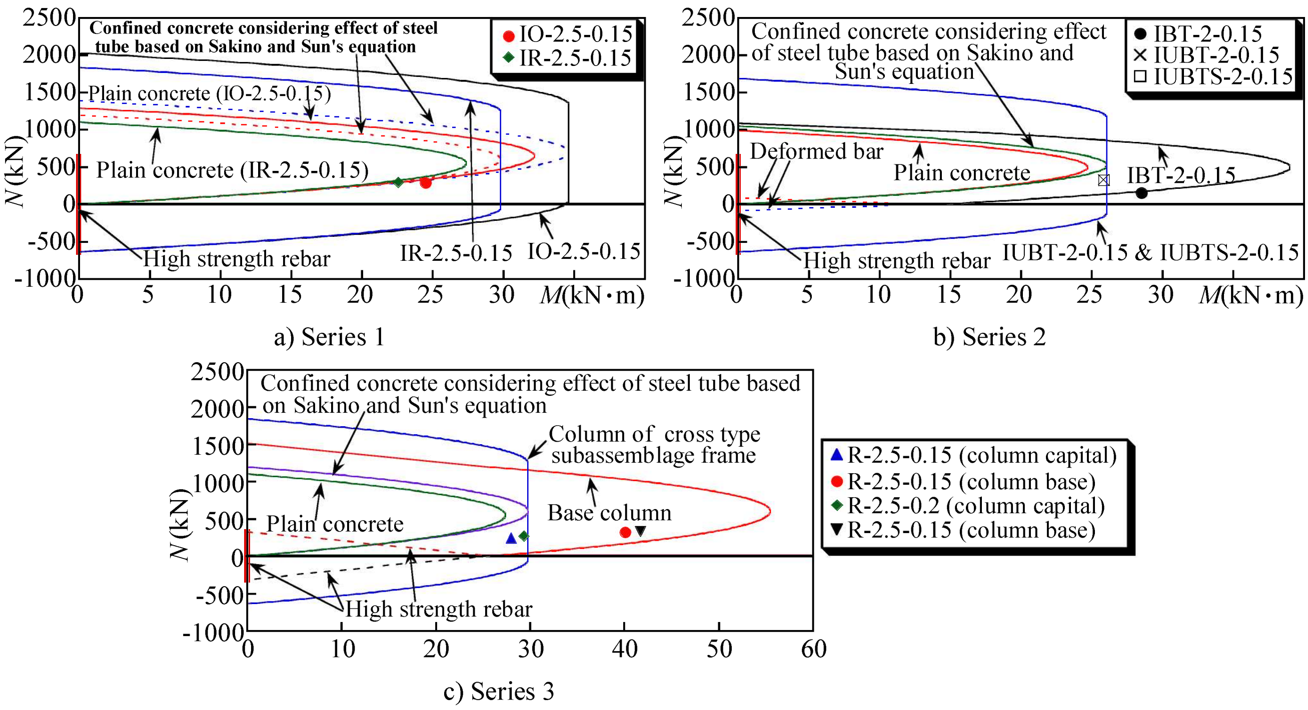
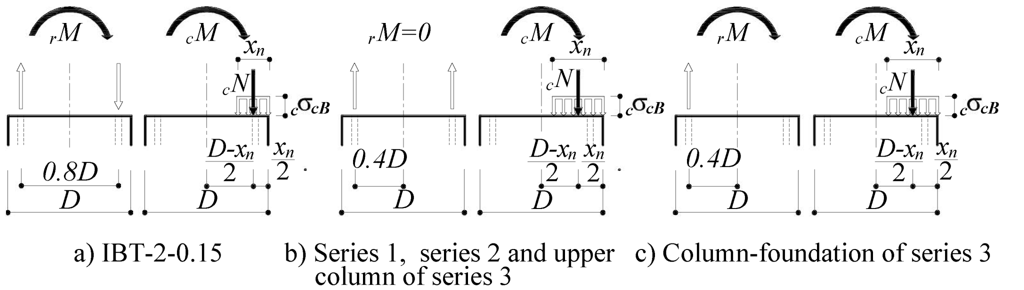


Figure 12 Calculated N-M interaction diagrams by simple addition method and experimental results

A comparison of the experimental results and the calculated N-M interaction curves is shown in Fig. 12, where N is the axial force of column, M is the bending moment. The N-M interaction curves are calculated based on

Figure 13. The ultimate flexural strength is calculated as a combination of ${}_cM$ and ${}_rM$ while the rebar is assumed to be yielded. The lateral confinement effects of steel tube and hoop are considered on the base of Sakino and Sun's equation [3]. According to these results, the experimental strengths of all test specimens except for IBT-2-0.15 are smaller than the flexural strengths calculated by the simple addition method. It indicates that all the unbonded high strength rebars do not yield.



Where, ${}_rM$ = bending moment of rebar, ${}_cM$ = bending moment of concrete, ${}_cN$ = combined compression force of concrete, ${}_c\sigma_{cB}$ = confined concrete strength.

Figure 13 Analytical model for flexural strength of column

4. CONCLUSIONS

In order to investigate the RC fame with self-centering capacities, a total of seven cross type subassemblage RC frames were tested under the reversed cyclic lateral force and a constant axial force simultaneously. The following conclusions were reached.

1) It was possible to make residual deformation small by the construction method proposed in this study.
2) The residual deformation of the cross type subassemblage frame utilizing unbonded high strength rebars in this study was less than 0.5 time of the case utilizing conventional deformed rebars.
3) The residual deformation of test specimen whose joint panel was reinforced was a little smaller than that of test specimen whose joint panel was not reinforced.
4) The experimental lateral capacity of the specimen utilizing unbonded high strength rebar, did not reach the calculated flexural strength. The reason was that the high strength rebar did not yield.
5) The effect of self-centering decreased due to the flexural deformation of the beam.
6) The residual deformation of the cross type subassemblage frame became small, if the stiffness and capacity of the beam was increased.
7) The effect of the shear key at the column ends on the residual deformation was scarce.

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