Earthquake Resistant Performance of High-Rise Reinforced Concrete Buildings under Long-Period Ground Motions

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SUMMARY:
This paper describes the outline of experimental studies on earthquake resistant performance of high-rise RC buildings under long-period ground motions. In order to verify the influences of long-period ground motions, two series of tests were planed. The main one was a shaking table test of a 1/4 scaled 20 story RC specimen, and to support this project, and to verify the performance of some members consisting the shaking table test specimen, the other series of static loading test was carried out. The static loading test specimens were 2 spans and 1 story plane frames consisting of 3 columns and 2 beams. The main parameters were reinforcement ratio of the beams and columns, and the loading program which includes normal cyclic loading path and severe cyclic loading path modelling the hysteresis of high-rise RC buildings under long-period ground motions. Test results indicated that, the capacity and/or ductility of the frames was improved by increasing of the reinforcement ratio, and the skeleton curve of story shear force and story drift relationship was not influenced by the change of the loading program in this test series. The shaking table test specimen had 3 spans in the longitudinal direction and 2 spans in the transverse direction.

Keywords: Static Loading Test, Shaking Table Test, Finite Element Analysis,

1. INTRODUCTION

The long-period ground motion is expected to occur by subduction-zone earthquakes near Japan. Actually the long-period strong ground motions were observed in the off the Pacific coast of Tohoku earthquake (*Okawa(2011)*). In Japan, more than 400 high-rise RC buildings have been constructed since 1970's. It is concerned about that, on such high-rise RC buildings, the height of which is more than 60 meters, the long-period ground motions would have adverse influences. It is expected that the resonance of high-rise building with such a long-period ground motion will occur, and the structural elements in the buildings will be subjected to reversed cyclic loading in many times.

Multiple cyclic loading tests or analytical studies on RC members were carried out by many researchers (*Ishibashi(2009), Sugimoto(2011)*). The results of these researches were summarized that, although the restoring force of the RC beam decreased a little as the times of cyclic loading increased, the skeleton curves of the RC beams subjected to reversed cyclic loads were slightly influenced by the time of cyclic loading. On the other hand, the studies on dynamic behaviour of high-rise RC buildings were conducted analytically. In some analytical studies on high-rise RC buildings, earthquake response analyses were conducted (*Suzuki(2009)*) which focused on the hysteretic restoring force characteristics of the beam model.

In this research, earthquake resistant performance of not only one RC member but also frame substructures containing beams and columns were investigated. And shaking table test was planed. A one fourth scaled 20-story RC frame specimen was designed and constructed for a shaking table test.

2. STATIC LOADING TEST OF PLANE RC FRAMES

2.1. Outline of Loading Test

2.1.1. Objectives

The objectives of this study are followed, (1) to verify the influence of long period ground motions on RC frames, (2) to investigate if the restoring force characteristics of the RC frame could be represented as sum of the characteristics of each beam and/or column, and (3) to investigate the beam axial force generated by column restraint.

2.1.2. Test Specimens

One-fourth scale reinforced concrete specimens were used in this study, which consisted of three columns and 2 span beams. The specimens were designed based on the results of data collections existing high-rise RC buildings (*Katsumata(2011)*).

Table 2.1 lists three specimens and their parameters. ***Figure 2.1*** shows geometry and reinforcement of the specimens. Specimen A had lower reinforcement of beam and column than that of Specimen BN/BL. Specimen BN had the same reinforcement as Specimen BL. The difference between Specimens BN and BL were loading history. ***Figure 2.2*** shows the loading histories of the specimens. The loading history shown in **Fig. 2.2(b)** was decided based on the research by *Koshika(2011)*. ***Table 2.2*** shows the material properties.

2.1.3. Loading Method

Figure 2.3 illustrates loading system setup used in this study. All specimens were subjected to constant axial force and reversed cyclic lateral load applied by displacement control. Three columns were put on pin supports. Therefore, axial forces could be occurred in beams because of the column restraint when the beams were extended longitudinally after flexural yielding of them.

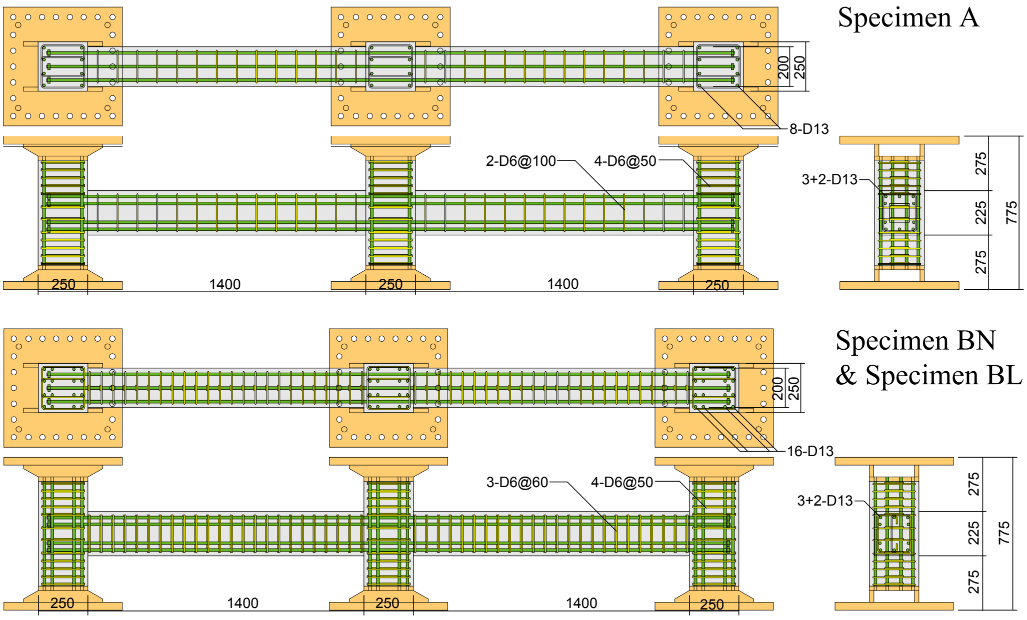
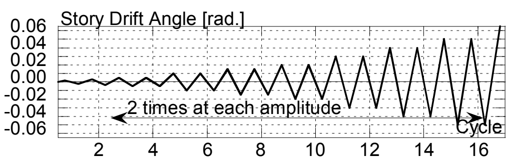
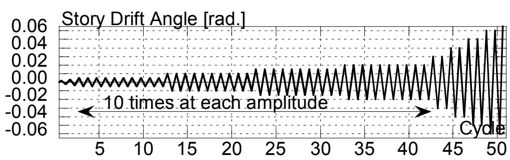


Figure 2.1 Geometry and reinforcement of the test specimen (unit [mm])



(a) Specimen A and BN



(b) Specimen BL

Figure 2.2 Loading histories of story drift angle

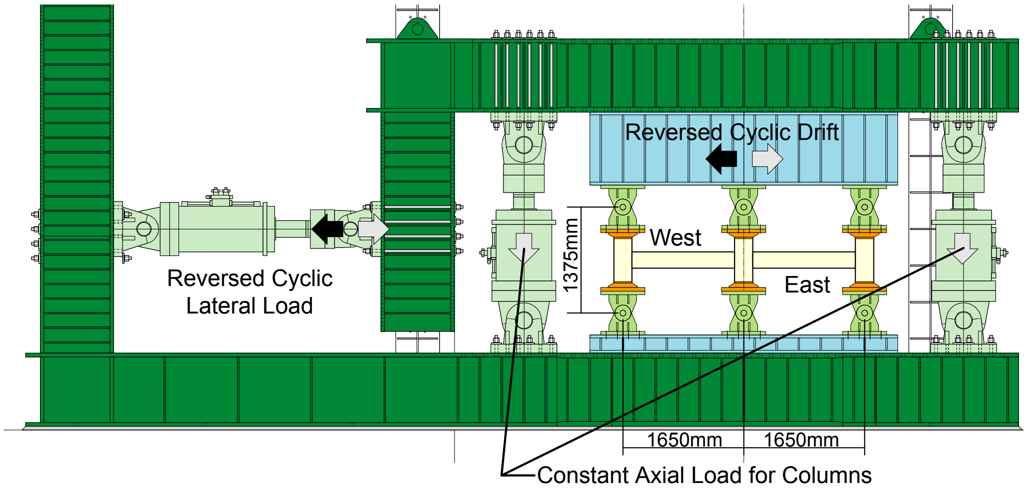


Figure 2.3 Loading system setup

Table 2.1 Test specimens and parameters

	Spec. A	Spec. BN	Spec. BL
Column(Bc x Dc x H) Long. Reinforcement Trans. Reinforcement	250 x 250 8-D13(SD490) 4-D6(SHD685)@50	250 x 250 16-D13(SD490) 4-D6(SHD685)@50	
Beam(Bb x Db x L) Long. Reinforcement Trans. Reinforcement	200 x 225 3+2-D13(SD490) 2-D6(SHD685)@100	200 x 225 3+2-D13(SD490) 3-D6(SHD685)@60	
Loading History	2 times at each rotation	2 times at each rotation	10 times at each rotation

Table 2.2 Material Properties (unit [N/mm^2])

(a) Concrete

	Compressive Strength	Young's Modulus	Tensile Strength
Column	81.8	4.14 x 10^4	4.28
Beam	49.2	3.21 x 10^4	3.51

(b) Reinforcing Bars

	Yield Strength	Young's Modulus	Ultimate Strength
D13	540	1.93 x 10^5	744
D6	697	1.92 x 10^5	927

2.2. Test Results and Discussion

2.2.1. Observed Damage and Restoring Force Characteristic

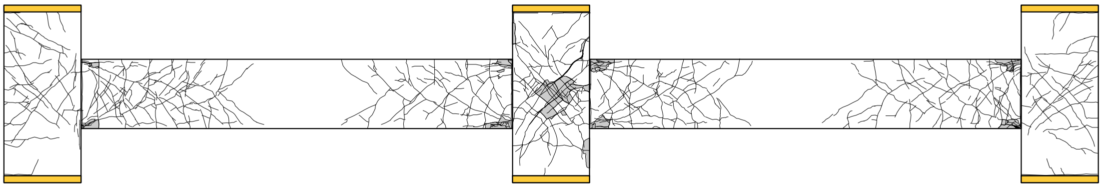
Figure 2.4 illustrates the observed crack pattern. In each specimen, yielding of beam longitudinal reinforcement was observed at the loading cycle of drift angle from 0.01 radian to 0.015 radian. Concrete crushing at the beam end started after the yielding. At the loading cycle of 0.03 radian, longitudinal bars of columns and hoop bars in interior beam-column joint yielded.

Figure 2.5 shows story shear force and story drift relationship of each specimen. ***Table 2.3*** lists observed and calculated shear forces. The maximum strength of specimen A was lower than those of the other specimens for about 7 to 8%. The ultimate displacement, which was determined as the displacement when the story shear force declined 80% of the maximum strength, of specimen A was smaller than those of the other specimens too. On the other hands, slight difference between specimen BN and BL was observed in their load-displacement relationship. Observed maximum and flexural yielding strengths were higher than calculations about 30%.

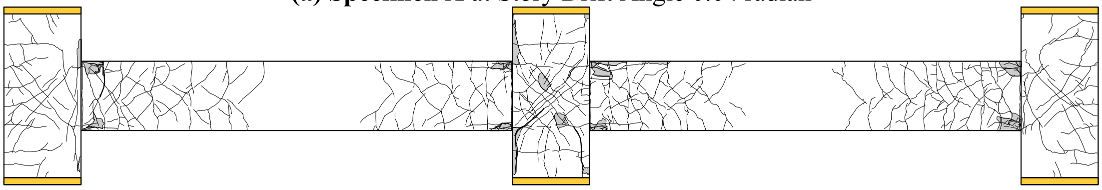
For specimen BL which was subjected to many cyclic loads at each amplitude, the damage at interior beam-column joint was slighter than specimen BN. At exterior beam-column joint of specimen BL, wide vertical crack originated from the anchor of beam longitudinal bar was observed as shown in ***Figure 2.6***. The bond stress along the longitudinal bars of the beam might be deteriorated because of the many cyclic loads.

Table 2.3 Test Results (unit [kN])

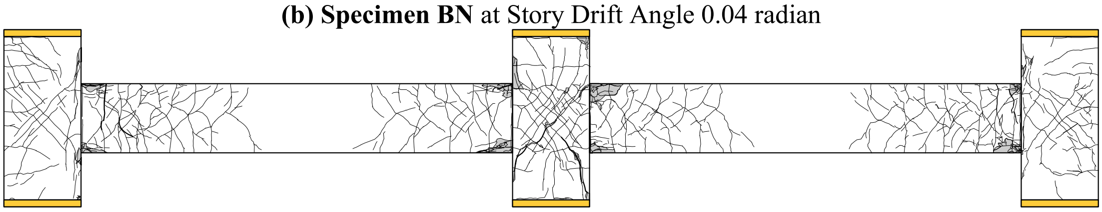
		Spec. A	Spec. BN	Spec. BL
Yield strength (1st reinforcement)	Test Result	185	191	202
	Calculation	171		
Yield strength (2nd reinforcement)	Test Result	246	254	255
	Calculation	189		
Maximum strength	Test Result	249	269	274
	Calculation	198		



(a) Specimen A at Story Drift Angle 0.04 radian

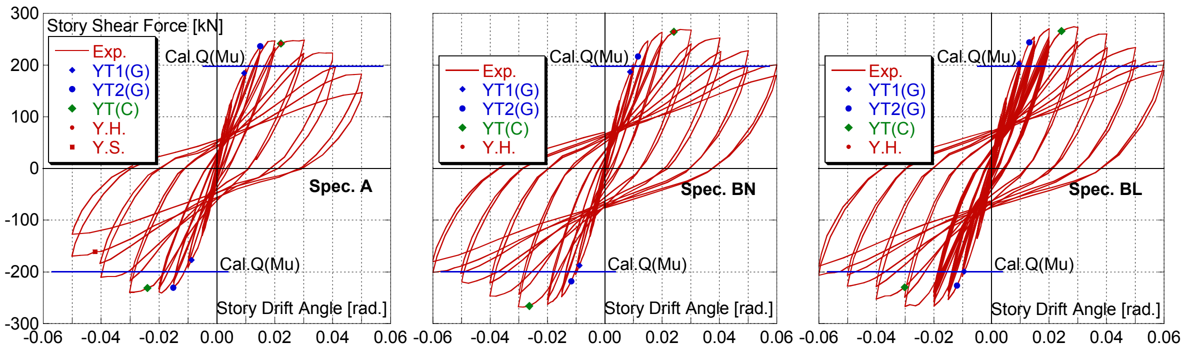


(b) Specimen BN at Story Drift Angle 0.04 radian



(c) Specimen BL at Story Drift Angle 0.04 radian

Figure 2.4 Crack patterns



Cal.Q(Mu): Calculated ultimate flexural strength, YT1(G),YT2(G):Yielding of 1st or 2nd reinforcement in beam, YT(C):Yielding of reinforcement in column, Y.H: Yielding of hoop bar, Y.S: Yielding of stirrup

Figure 2.5 Experimental results of story shear force and story drift relationship

2.2.2. Moment Distribution of Each Member

Each column top and bottom was connected by steel web plates to the pin support. As shown in ***Figure 2.7***, strain was measured at the steel web plate surface. Flexural moments at the column top and bottom were calculated by using the measured strain. ***Figure 2.8*** illustrates the moment distributions estimated from the moment at the end of the columns. From this figure, some features are derived as follows; the shear force of upper and lower column is almost the same at the interior column, and at the exterior column, lower or upper column shear force is smaller than the upper or lower column shear force. The difference between upper and lower column shear force equals to the beam axial force. A main reason that the observed maximum strength was higher than the calculation is considered the axial force of beams originated by the column restraint.

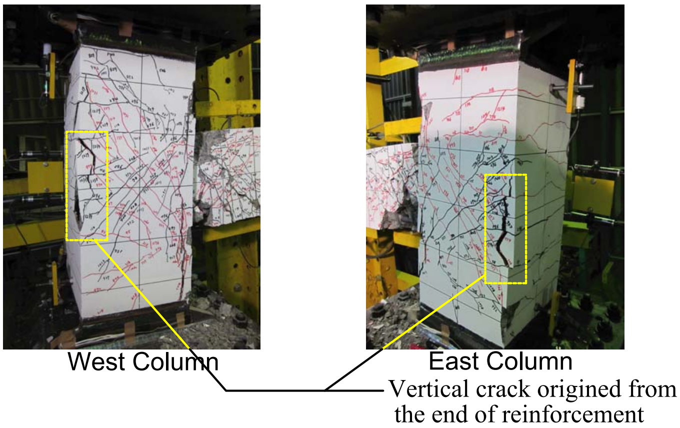


Figure 2.6 Damage situation of specimen BL

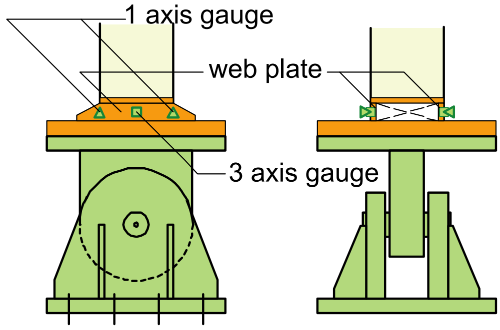
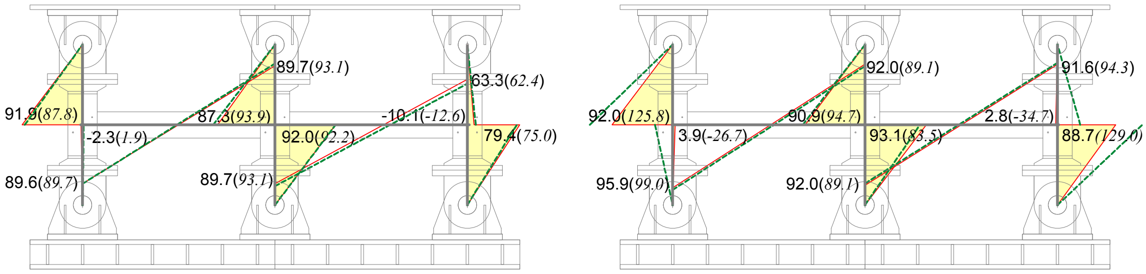


Figure 2.7 Detail of the joint between pin support and column

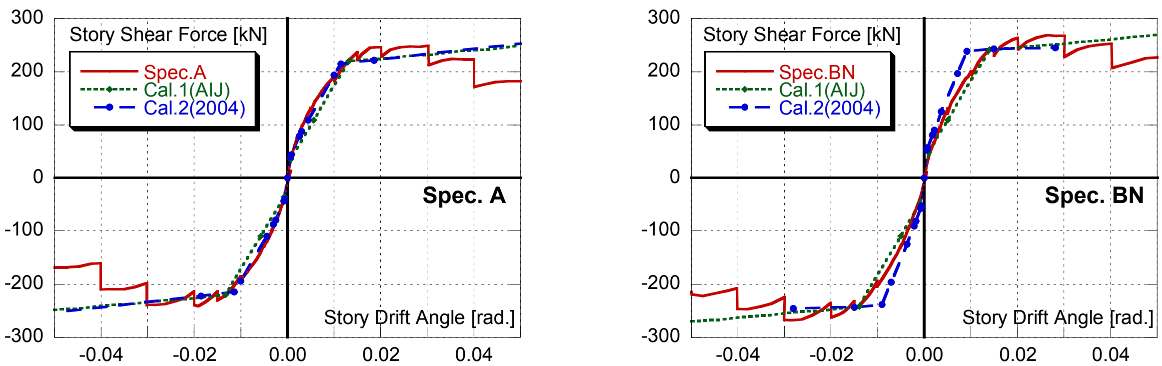


(a) Specimen A **(b) Specimen BL**

Value written in bold type and solid lines: calculated from 3 axis strain gauge

Value written in italic type and broken lines: calculated from 1 axis strain gauge

Figure 2.8 Flexural moment distributions at the story drift angle of 0.02 radian (unit:[kN-m])



(a) Specimen A **(b) Specimen BL**

Figure 2.9 Comparison of skeleton curve

2.2.3. Skeleton Curve of Restoring Force Characteristic

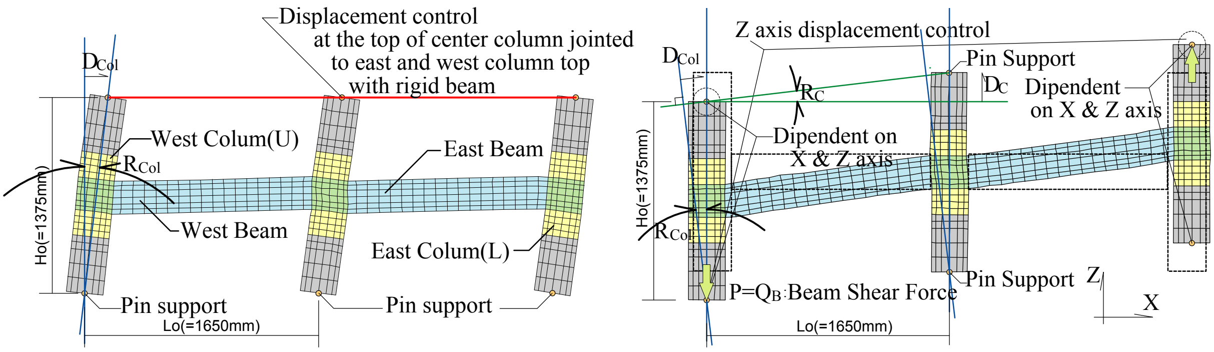
Skeleton curves of beam and column were calculated using two methods. The first one was proposed by authors (*Sugimoto(2004)*), the other one was recommended by *AIJ(2010)*. Skeleton curves of frame specimens were derived from the summation of the characteristics of 2 beams and 2 columns. The axial forces in the beam were assumed to be 100kN and 200kN for specimen A and BN/BL respectively. The calculated results are shown in ***Figure 2.9***. The figure shows that calculations corresponded well to the test results.

2.3. Analytical Studies and Discussion

The analyses were conducted using FINAL, a finite element program for concrete structures (*Naganuma(2004)*). ***Figure 2.10*** illustrates FE meshes and boundary conditions. Concrete is modelled using six-node hexahedral elements, the main bars were modelled using truss elements. Four-node joint type elements were inserted between hexahedral elements and truss elements for the purpose of incorporating bond slip behavior. To verify the effect of column restraint, two cases of boundary conditions were analyzed. The case 1 was the same as the static loading test described in the previous sections. The second one was called as Z-axis loading. As shown in **Fig. 2.10(b)**, for the Z-axis loading case, longitudinal deformation of the beams wouldn't be restrained by the columns. The analytical cases conducted in this study are listed in ***Table 2.4***.

Figure 2.11 shows the analytical results compared with the experimental ones. Analytical results of case AN and BN corresponded well to the experimental ones. On the other hands, analytical results of case DA and DB underestimated the maximum strength.

Figure 2.12 shows the beam axial force derived from the analytical results compared with the experimentally observed ones. The behavior of axial force and story drift relations of the specimen A and the case AN were almost the same, and so were the specimen BN and the case BN. It is assumed that the difference between case AN and BN, or the specimen A and BN, was caused by the difference of longitudinal bars of columns.



(a) BN and AN model (b) DA and DB moderl

Figure 2.10 Boundary conditions

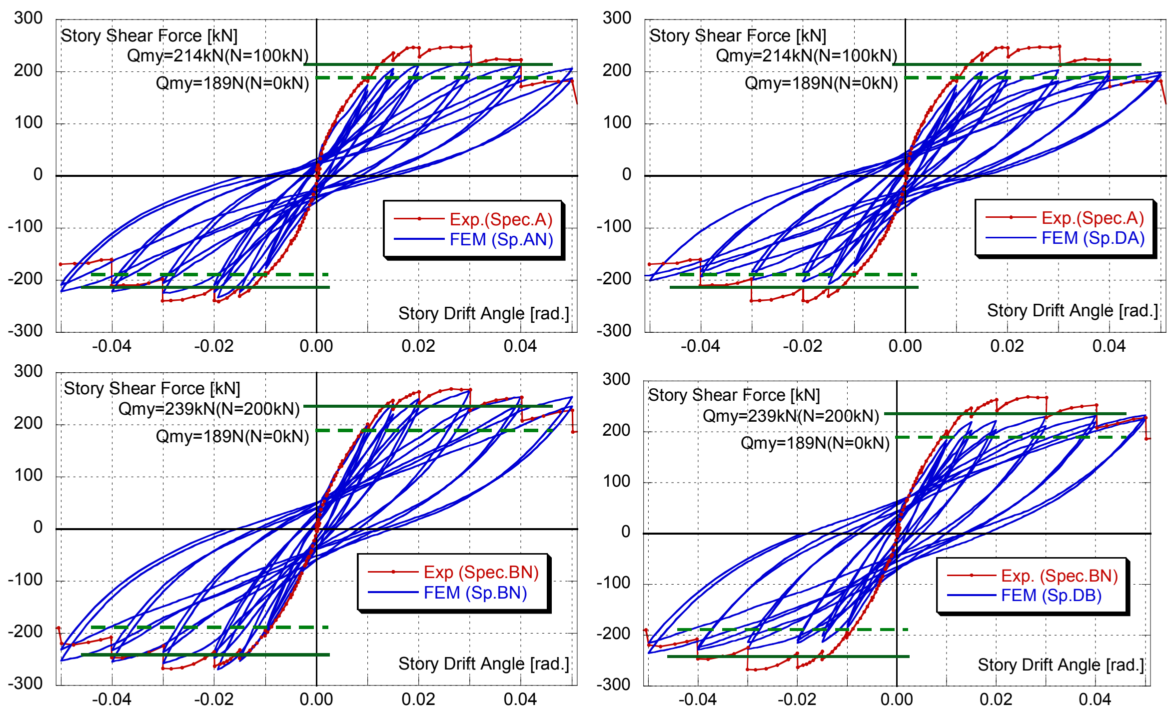


Figure 2.11 Analytical results of story shear force and story drift relationship

Table 2.4 Analytical Cases

Case Name	Specimen	Loading Conditions
Case AN	A	Same as the static loading test
Case DA	A	Z-Axis Loading
Case BN	BN	Same as the static loading test
Case DB	BN	Z-Axis Loading

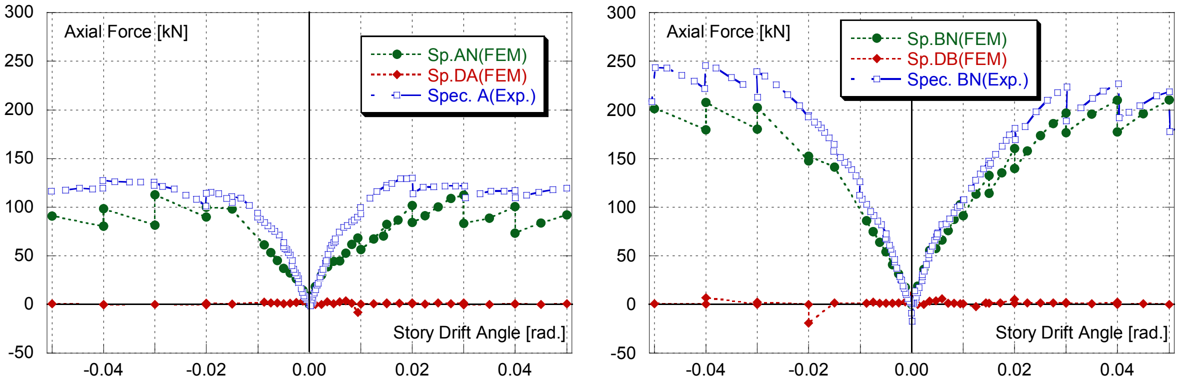


Figure 2.12 Axial force of the beam

3. FULL-MODEL TEST SPECIMEN FOR SHAKING TABLE TEST

3.1. Structural Design of the Test Specimen

The main objective of the shaking table test is to verify the dynamic response characteristics of high-rise RC building under long-period ground motions. The shaking table test will be carried out at E-Defense, Hyogo Earthquake Engineering Research Center, National Research Institute for Earth Science and Disaster Prevent, Hyogo, Japan. The test specimen was constructed at E-Defense.

Figure 3.1 illustrates the plan and elevations of the test specimen. ***Table 3.1*** lists beam and column sections of the specimen. The test specimen was planed based on a 20-story RC prototype building designed in 1990's, which is a moment frame structure as shown in **Fig. 3.1(c)**. The test specimen had 3 spans in the longitudinal direction and 2 spans in the transverse direction. ***Figure 3.2*** shows the reinforcement ratio of the test specimen compared with the result of a survey (*Katsumata(2011)*).

Figure 3.3 shows the distribution of member strength. The ratio of the column to the beam strength is over 1.5 for almost all members. Some columns which subjected to the tension axial force have the value under 1.5. The ratios of the shear to the flexural strength of the beams are over 1.2 for all members.

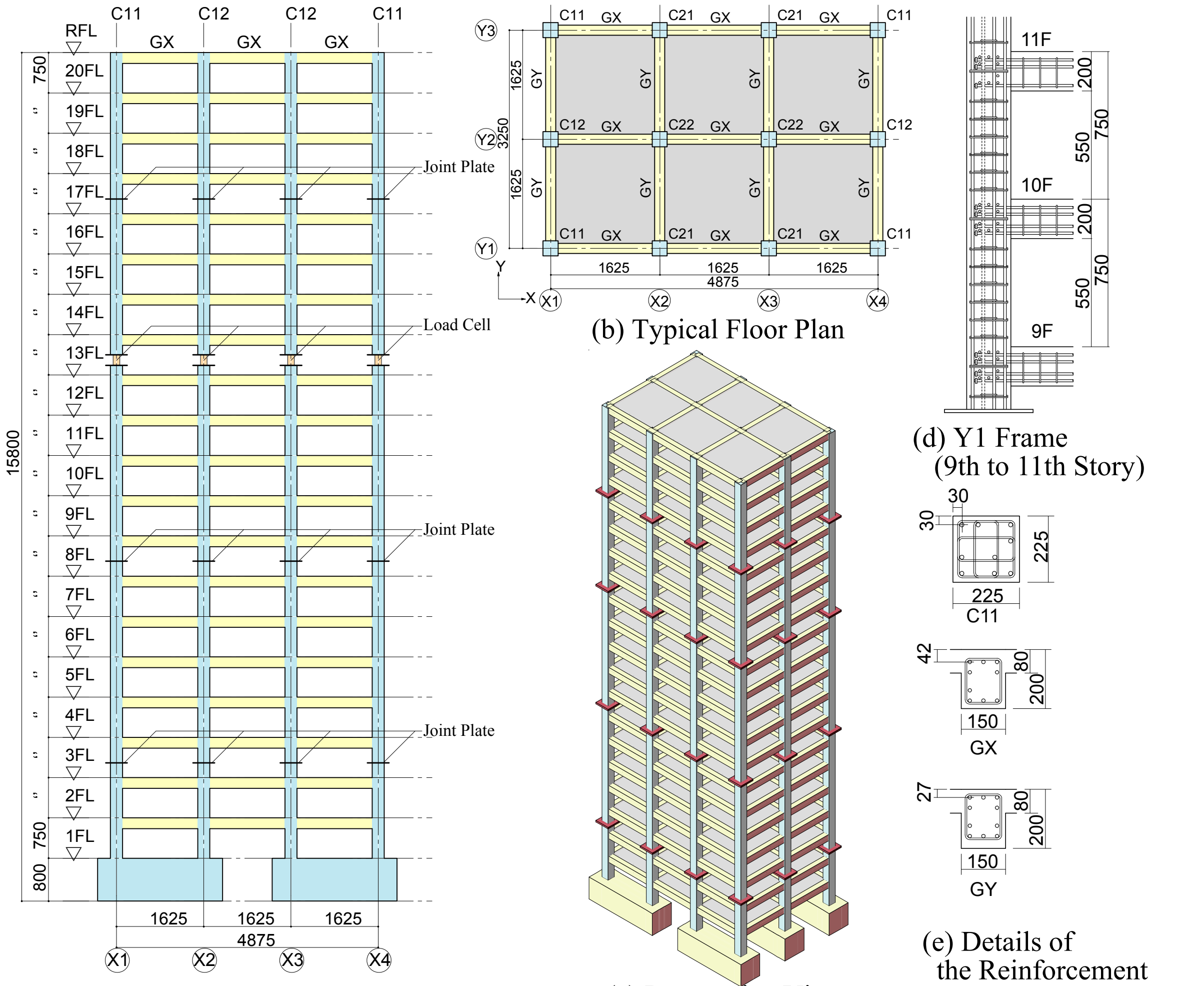
3.2. Construction of the Test Specimen

For shortening the construction period, the test specimen was constructed as separated to five blocks. Each block will be joined by high tension bolts after cast all floors. ***Photo 3.1*** shows the construction procedure. Column reinforcements were assembled prior to the site constructing process. The longitudinal reinforcements of columns were weld to steel plates at the top and bottom of the columns. ***Table 3.2*** lists the material properties. Main bars of columns were tested including the anchorage detail shown as ***Photo 3.2***. ***Photo 3.3*** shows the anchorage of beam reinforcing bars, which have the same detail of the static loading test specimen described previous section. It took 2 month to assemble the column reinforcement, and 4 month to build 5 blocks of the specimen at the construction site in E-Defense.

Table 3.1 Member lists

Floor	COLUMN (225 x 225)				Floor	BEAM (150 x 200)	
	C22	C12	C11	C21		GX	GY
20C-17C	8-D10 SD390 4-D6@90				RG,20G	3/3-D10 SD390 2-D6@100	3/3-D10 SD390 2-D6@100
17C-13C	8-D10 SD390 4-D6@90			12-D10 SD390 4-D6@90	19G,18G	3+1/3-D10 SD390 2-D6@100	3+1/3-D10 SD390 2-D6@100
13C-8C	8-D10 SD390 4-D6@90	12-D10 SD390 4-D6@90	9-D10 SD390 4-D6@90	12-D10 SD390 4-D6@90	17G,16G	3+1/3-D10 SD390 2-D6@85	3+2/3+1-D10 SD390 2-D6@85
8C-3C	12-D10 SD390 4-D6@90	12-D13 SD490 4-D6@90	14-D13 SD490 4-D6@90	12-D13 SD490 4-D6@90	15G-13G	3+2/3+1-D10 SD390 2-D6@85	3+2/3+2-D10 SD390 2-D6@85
3C-2C	12-D10 SD390 4-D6@90	12-D13 SD490 4-D6@90	14-D13 SD490 4-D6@90	12-D13 SD490 4-D6@90	12-9G	3+2/3+1-D10 SD490 2-D6@60	3+2/3+2-D10 SD490 2-D6@60
1C	12-D10 SD390 4-D6@50	12-D13 S490 4-D6@50	14-D13 SD490 4-D6@50	12-D13 SD490 4-D6@50	8-2G	3+3/3+2-D10 SD490 2-D6@60	3+3/3+3-D10 SD490 2-D6@60

Note: *-D13: number of longitudinal bars, *+*/*+*: Top bars / Btm. bars
SD390, SD490: Standard of reinforcing bars *-D6@**: Hoop or stirrup and pitch
For all hoops and stirrups, SHD685 was used.



(a) Typical Elevation
(b) Typical Floor Plan
(c) Perspective View
(d) Y1 Frame (9th to 11th Story)
(e) Details of the Reinforcement and the Cross Section

Figure 3.1 Plan and elevation of shaking table test specimen

Table 3.2 Material properties

(a) Concrete

	Compressive Strength [N/mm^2]
17 - 20F(Column), Slab and Beam	47.6
13 - 17F(Column)	50.3
8 - 13F(Column)	60.9
1 - 8F(Column)	80.3
Base	98.0

(b) Reinforcing Bars

	Cross Sectional Area [mm^2]	Yield Strength [N/mm^2]	Young's Modulus [N/mm^2]	Ultimate Strength [N/mm^2]
D6	32	417	2.02×10^5	565
D6	32	649	1.97×10^5	931
D10	71	453 (*450*)	1.98×10^5	653 (*637*)
D10	71	529	1.94×10^5	721
D13	127	534 (*536*)	2.00×10^5	719 (*713*)

(*Italic type*): Test specimen of anchorage detail

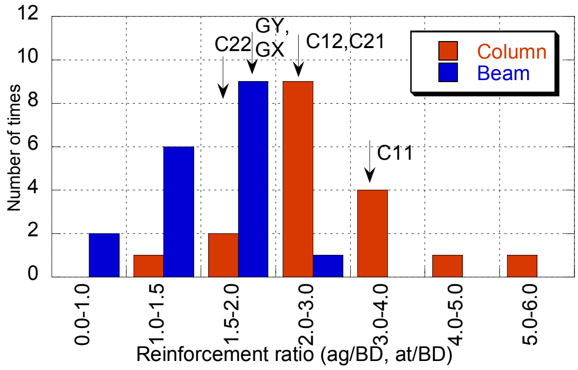
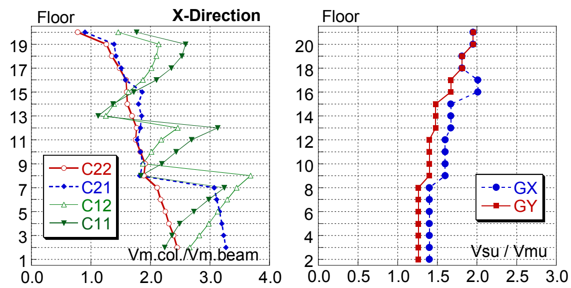


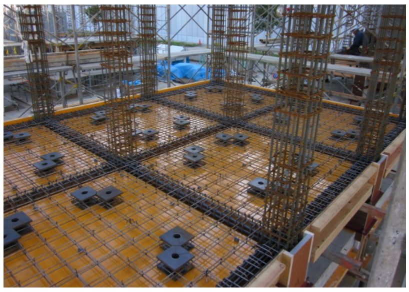
Figure 3.2 Reinforcement ratio of cross sections



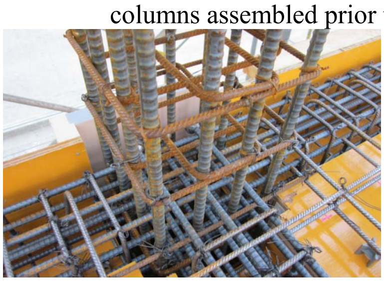
Vm.col., Vm.beam: Flexural strength of columns and beams respectively, Vsu, Vmu : Shear and flexural strength of beams respectively

Figure 3.3 Member strength

columns assembled prior to the site construction



slab and beam reinforcement



beam-column joint

close up of the specimen

2nd and 3rd block

Photo 3.1 Construction process

Photo 3.2 Anchorage of the column reinforcing bar

Photo 3.3 Anchorage of the beam reinforcing bar

4. CONCLUSION

The static loading test of RC frame specimens were carried out and three-dimensional FE analyses were conducted. Conclusions are summarized as follows:

1. The influences of many cyclic loads on RC frame structures were slightly observed, except the damage situations of the exterior beam-column joint.

2. The skeleton curves of restoring force characteristics of frame structure were represented as summation of the beams and columns skeleton curves.

3. The column restraint on the beams caused the axial force on the beams. By the three-dimensional FE analyses, these phenomena were expressed very well.

In addition, the shaking table test was planed and 5 blocks of one-fourth scaled 20 story RC specimen was constructed in about six month.

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