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SUB-STRUCTURE PSEUDO DYNAMIC TESTING ON REINFORCED CONCRETE BUILDINGS WITH SOFT FIRST STORY

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SUMMARY

Sub-structure pseudo dynamic tests for six-story and twelve-story reinforced concrete buildings with soft first story, which consisted of a bare frame in the first story and shear walls in the upper stories, were conducted to investigate the failure mechanism. The behavior of columns in the first story, which were subjected to high varying axial forces and shears, was especially focused in the investigation. The earthquake response analyses of the frames were also executed to confirm the possibility of simulating the test results. This paper shows an outline of the tests and analyses.

INTRODUCTION

Many buildings suffered great damage in the 1995 Hyogoken-Nanbu Earthquake in Japan. Mentioned specially was the damage of reinforced concrete (RC) buildings with soft first story referred to as "*pilotis*-type buildings" in which the strength and stiffness of the first story are extremely lower than those of the upper stories. The damaged buildings were designed by not only the old seismic code before 1981 but also the code used in those days. In view of this kind of damaged buildings, the Ministry of Construction (MOC in those days: At present, the Ministry of Land, Infrastructure and Transport) immediately revised the Notification No.1997 that is related to the provision on the distribution of story stiffness along a building height, and showed some technical points to notice on the seismic design for RC buildings with soft first story [1]. Considering the immense damage of RC buildings with soft first story by the earthquake, the measure by MOC seems to be appropriate. However, since this was an emergency measure just after the earthquake, the technical points showed should be improved on the basis of the future research results. In particular, the causes of collapse in RC buildings with soft first story are not made clear yet including the failure mechanisms, although the concentration of earthquake energy at the first story with large varying axial force and shear in the columns is pointed out as one of the causes in the past researches.

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Sub-structure pseudo dynamic (PsD) tests for six-story and twelve-story RC buildings with soft first story, which consisted of a bare frame in the first story and shear walls in the upper stories, were conducted to investigate the failure mechanism. The behavior of columns in the first story, which were subjected to high varying axial forces and shears, was especially focused in the investigation. The earthquake response analyses of the frame were also executed to confirm the possibility of simulating the test results. This paper shows an outline of the tests and analyses.

SUB-STRUCTURE PSEUDO DYNAMIC TEST

Test Specimens

Two-story plane frame specimens of about two-fifth scale were fabricated, which simulated the lower two stories of the middle frame in six-story and twelve-story RC residential buildings with soft first story shown in Fig. 1. As shown in Fig. 2, the specimens of the six-story and twelve-story frames had the same configuration and are one-span frame of which the length is 4,000mm with a stiff loading beam and a foundation stub in the top and bottom, respectively. Both specimens had columns with a 400mm square section at the first and second stories and a beam with a section of 250mm x 400mm at the second story. Thickness of a shear wall at the second story was 80mm in the six-story frame and 100mm in the twelve-story frame, respectively. At the middle of each column at the first story, load cells shown in Fig. 3 were installed to measure directly the varying axial force and shear in the columns. The details of bar arrangement in the specimens are listed in Table 1. The mechanical properties of the reinforcing bars and concrete used are also listed in Table 2.

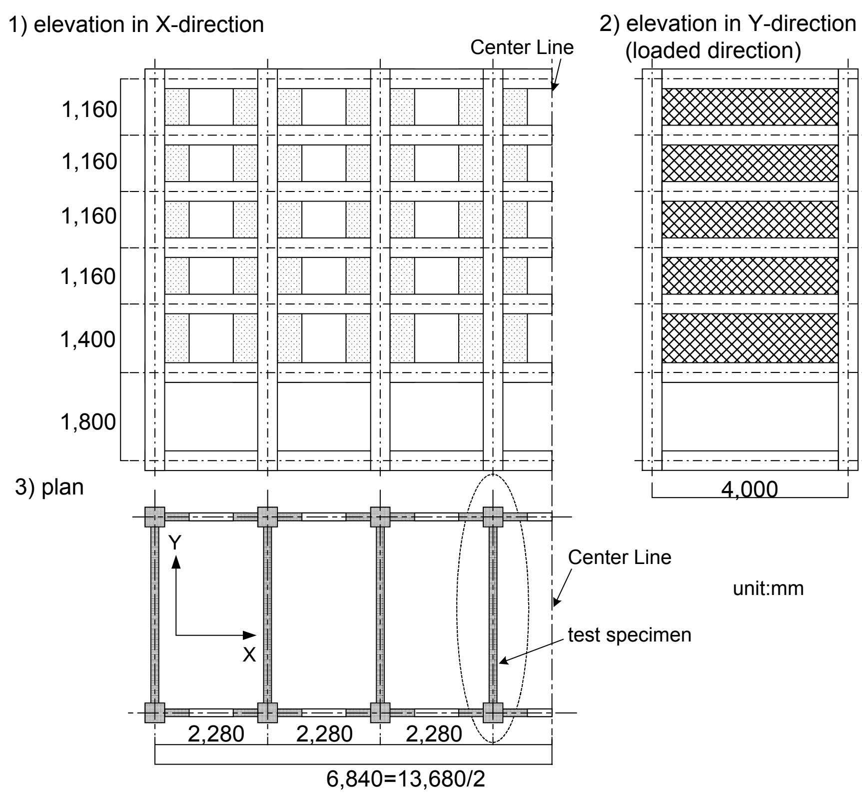


Fig. 1 Outline of Prototype Building (6-Story frame)

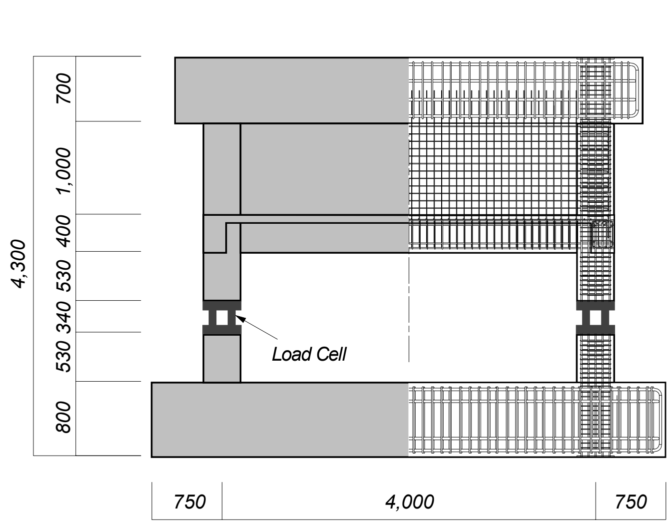


Fig. 2 Test Specimens

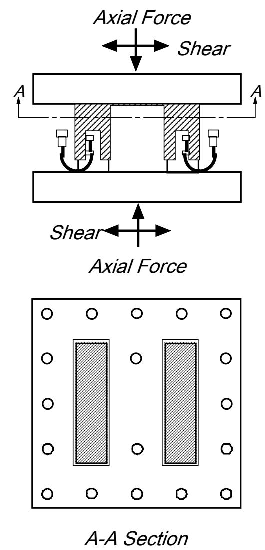


Fig. 3 Load Cell to Measure Stresses in Columns

Table 1 Detail of Bar Arrangement

	Member	Story	b x D (mm)	Long. Reinf.	Trans. Reinf.
6 story	Column	1 and 2	400 x 400	16-D13	D6@50
	Beam	2	250 x 400	12-D13	D6@80
	Shear Wall	2	Thickness (mm)	Arrangement	
			80	D6@80	
12 story	Member	Story	b x D (mm)	Long. Reinf.	Trans. Reinf.
	Column	1 and 2	400 x 400	20-D13	D6@40
	Beam	2	250 x 400	16-D13	D6@80
	Shear Wall	2	Thickness (mm)	Arrangement	
			100	D10@80	

Table 2 Mechanical Properties of Materials Used (Unit: N/mm^2)

6 story

Concrete			
σ_B	ε_c	E_c	
29.8	0.213	2.64 x 10^4	
Reinforcing Bar			
Diameter	σ_y	ε_y	σ_u
D6	376.9	0.221	515.8
D13	396.4	0.236	542

12 story

Concrete			
σ_B	ε_c	E_c	
29.8	0.198	2.50x 10^4	
Reinforcing Bar			
Diameter	σ_y	ε_y	σ_u
D6	277.4	0.191	409.7
D10	343.7	0.201	368.1
D13	373.0	0.222	460.3

Loading Method and Loading Apparatus

The sub-structure PsD testing method was applied to six-story and twelve-story RC frames with soft first story in which the lower two stories were each experimental portion (i.e. specimens) and the upper four stories in the six-story frame and the upper ten stories in the twelve-story frame were corresponding to each analytical portion.

For conventional PsD tests, explicit integration schemes such as the central difference method are normally used to avoid iterative computations and the corresponding load reversal. However, when the explicit integration scheme is used for sub-structure PsD tests, the time interval applied has to be very small to meet the constraint of stability and this could make the experiment impracticable. About ten years ago, several unconditionally stable implicit and mixed implicit-explicit integration schemes have been successfully implemented for sub-structure PsD tests in the Building Research Institute (BRI) [4]. Among them, it is found that the mixed implicit-explicit operator splitting (OS) method, originally proposed by Hughes et al. [3] and successfully implemented for sub-structure PsD tests, is very convenient for incorporation into many existing dynamic response analysis codes using implicit integration procedures. The method of sub-structure PsD tests used in this study had been developed in BRI based on the above research. The algorism is as follows:

(a) Input external forces in the next loading (i+1) step, F_{i+1}

(b) Predict the displacement and velocity at the i+1 step in both experimental and analytical portions, $\bar{d}_{i+1}$ and $\bar{v}_{i+1}$:

$$\bar{d}_{i+1} = d_i + \Delta t \cdot v_i + \left(\Delta t^2/4\right)\cdot a_i$$

$$\bar{v}_{i+1} = v_i + \left(\Delta t/2\right)\cdot a_i$$

where, d_i, v_i and a_i express the displacement, velocity and acceleration at the i step and Δt is an interval from i to i+1 steps.

(c) Calculate restoring forces in the analytical portion, R^{ana}_{i+1}:

$$R^{ana}_{i+1} = K^{ana} \cdot \bar{d}_{i+1}$$

where, K^{ana} is the stiffness of a member in the analytical portion.

(d) Calculate axial forces applied to the top of the experimental portion, P^{exp}_{i+1}, using R^{ana}_{i+1}.

(e) Apply lateral story forces with keeping the axial forces of P^{exp}_{i+1} for the experimental portion, until the corresponding displacement reaches $\bar{d}_{i+1}$.

(f) Measure restoring forces in the experimental portion, R^{exp}_{i+1}

(g) Modify the external forces assumed in the i+1 step, F^*_{i+1}

$$F^*_{i+1} = F_{i+1} - C \cdot \bar{v}_{i+1} - R^{ana}_{i+1} - R^{exp}_{i+1}$$

$$a_{i+1} = \left[M + \left(\Delta t/2\right)\cdot C + \left(\Delta t^2/4\right)\cdot K^{ana}\right]^{-1} \cdot F^*_{i+1}$$

$$v_{i+1} = v_i + \left(\Delta t/2\right)\cdot\left(a_i + a_{i+1}\right)$$

$$d_{i+1} = d_i + \Delta t \cdot v_i + \left(\Delta t^2/4\right)\cdot\left(a_i + a_{i+1}\right)$$

(h) To next loading step.

In the developed method, the analytical portions are calculated using equivalent elastic frame models. In order to obtain the equivalent stiffness of members including shear walls of the upper four stories in the six-story frame and the upper ten stories in the twelve-story frame, which are corresponding to the analytical portions, the inelastic push-over analyses for the whole frames using the Multi-Spring (MS) Model [4] were executed before the tests. The results indicated that the behavior of the upper stories in both the frames were almost elastic without occurring shear cracking in shear walls. Then, the upper stories in both the frames were analyzed as bare frames with equivalent elastic columns considering the structural properties of shear walls during the tests. In the analyses during the tests, the viscous damping was assumed to be 3% for the natural period of the first mode and be proportional to the initial stiffness.

Table 3 Input Time of Earthquake Waves

Input No.	Wave	6-story	12-story
1	Elc-10	7.00sec	6.28sec
2	Elc-25	7.00sec	6.56sec
3	Elc-50	7.00sec	6.72sec
4	JMA	4.50sec	6.04sec

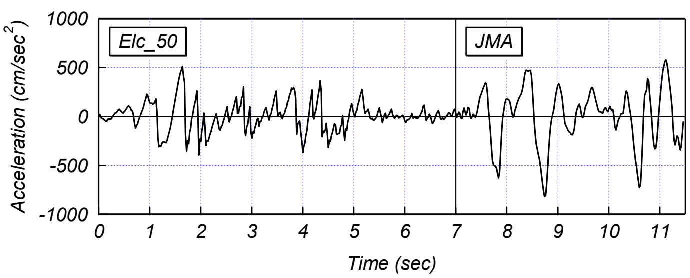


Fig. 4 Earthquake Ground Motions Inputted

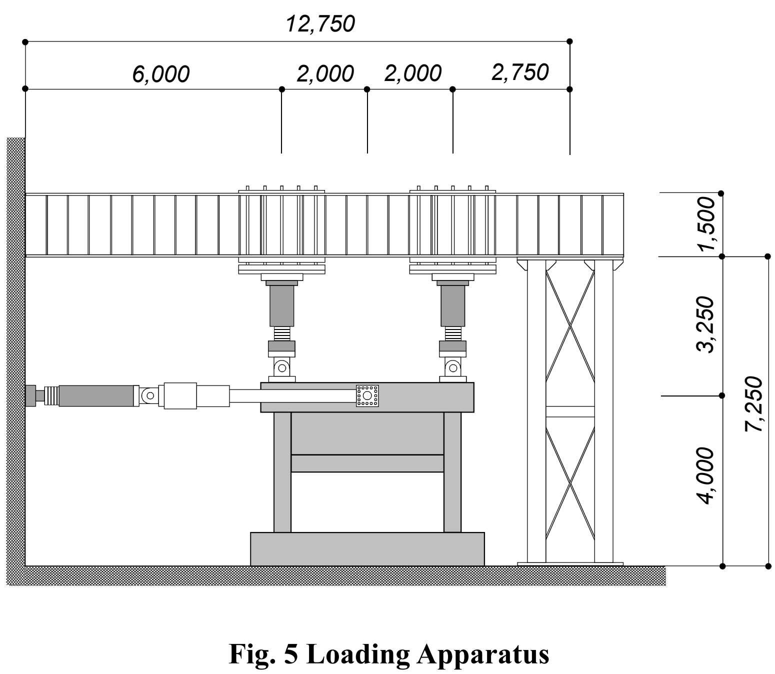


Fig. 5 Loading Apparatus

Four earthquake ground motion records were used in the tests. One was NS component of the 1995 Kobe Marine Observatory record of Japan Meteorological Agency (JMA). Other three were NS component of the 1940 El Centro records for which the level of the maximum velocity was normalized to 10cm/sec, 25cm/sec and 50cm/sec (ElC-10, ElC-25 and ElC-50), respectively. The input time used for the experiments are shown in Table 3. The earthquake waves used for ElC-50 and JMA motions are drawn in Fig. 4.

In loading tests, as shown in Fig. 5, two horizontal actuators applied lateral story forces at the floor level of the third story which is 3,200mm in height from the column base, and two vertical actuators applied varying axial forces at the top of each column in the second story with initial loads of 441kN in the six-story frame and 892kN in the twelve-story frame. As mentioned the above, the loadings were conducted to be met the values of varying axial forces for each column and lateral displacement at the floor level of the third story calculated from the earthquake response analysis at each loading step.

TEST RESULTS

Failure Process

The final failure situations of the specimens after JMA input are sketched in Fig. 6 for the six-story frame and showed in Photo 1 for the twelve-story frame. In the loading of ElC-10 input, no crack occurred in both the specimens.

6-Story Frame

In the ElC-25 input of the six-story frame, slightly flexural cracks of columns at the first story were observed in the bottom of the east side at the story drift angle of the first story, R_1, of 1/517 (1.8 sec), in the top of the west side at R_1 of 1/388 (2.2 sec), in the bottom of the west side at R_1 of -1/609 (3.8 sec), and in the top of the east side at R_1 of -1/413 (4.2 sec), respectively. The occurrence and propagation of cracks were significant in the ElC-50 input of the six-story frame. Flexural cracks in a beam and slabs and shear cracks in a shear wall at the second story were observed at R_1 of 1/366 to 1/179 (1.2 to 1.3 sec). The similar cracks in the beam, slabs and shear wall also occurred at R_1 of about -1/140 (about 1.6 sec) in the loading of the opposite direction. In the loading of JMA input, spalling of cover concrete in the top and bottom of the west side column at the first story was observed at R_1 of about -1/60 (0.9 sec). Although the occurrence of new cracks was not so many, the propagation of cracks occurring in ElC-50 input was significant in this loading. Finally, the story collapse mechanism at the first story was formed with flexural yielding of columns.

12-Story Frame

In the ElC-25 input, compression cracks in the bottom of the east column and flexural cracks in the top and bottom of the west column at the first story were observed at R_1 of 1/470 (1.2 sec). After that, flexural cracks in a beam and shear cracks in a shear wall at the second story were observed at R_1 of 1/387 to 1/183 (1.4 to 1.5 sec). Flexural cracks in the shear wall at the second story and shear cracks in the east column at the first story were observed at R_1 of 1/248 to 1/118 (1.7 to 1.8 sec). In the ElC-50 input, spalling of cover concrete in the top of the west column at the first story was observed at R_1 of 1/75 (1.5 sec). Spalling of cover concrete in the top and bottom of both columns at the first story and shear cracks in the shear wall at the second story were observed at R_1 of 1/113 to 1/74 (1.8 to 1.9 sec). In the JMA input, the occurrence and propagation of cracks were observed at R_1 of about 1/40 (1.1 to 2.1 sec). Finally, as well as in the six-story frame, the story collapse mechanism at the first story was formed with flexural yielding of columns.

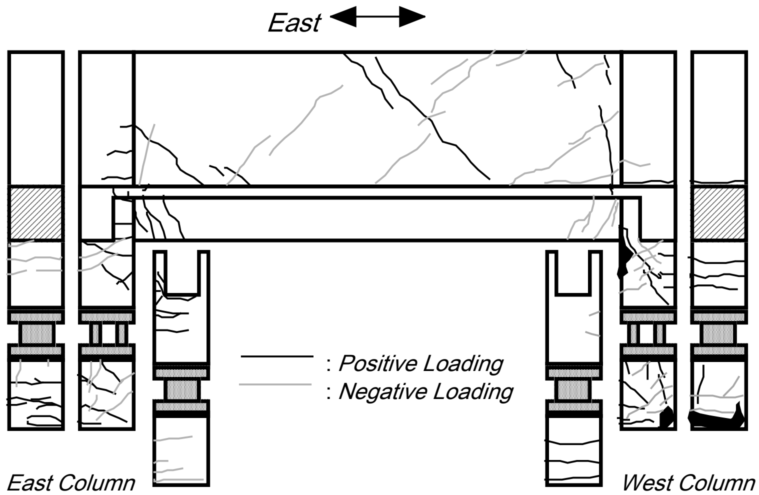
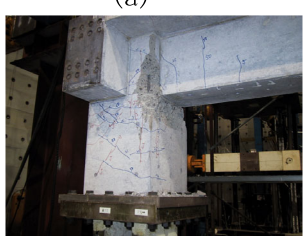


Fig. 6 Failure Situation after Testing(6-Story)

(a)

(b)



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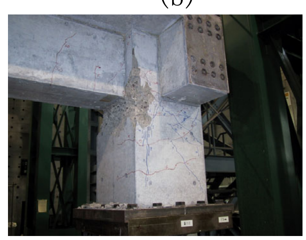

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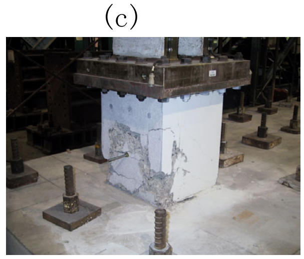

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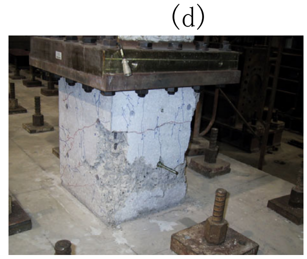


(f)

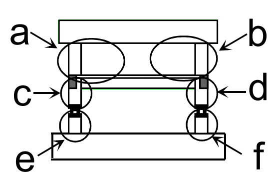


Photo 1 Failure Situation after Testing(12-Story)

Load versus Displacement Relations

Figure 7 shows the story shear versus lateral displacement relations for each earthquake motion inputted. In this figure, the vertical axis expresses shear applied at the floor level of the third story, and the horizontal axis shows story drift at the first story, respectively.

In the loading of ElC-10 input, the behavior of both specimens of the six-story and twelve-story frame was elastic without the reduction of stiffness in the story shear versus lateral displacement relation, and the cracks were not observed.

In the loading of ElC-25 input, the stiffness of the first story in the specimen of the six-story frame was slightly reduced due to the occurrence of flexural cracks in the top and bottom of columns at the first story. In the specimen of the twelve-story frame, the flexural yield in the east column at the first story in the west-direction loading was observed.

In the loading of ElC-50 input, the yield mechanism at the first story in the six-story was almost formed. In the specimen of twelve-story, the yield mechanism at the first story was formed due to the occurrence of flexural yielding in the bottom of east column at the first story in the east-direction loading.

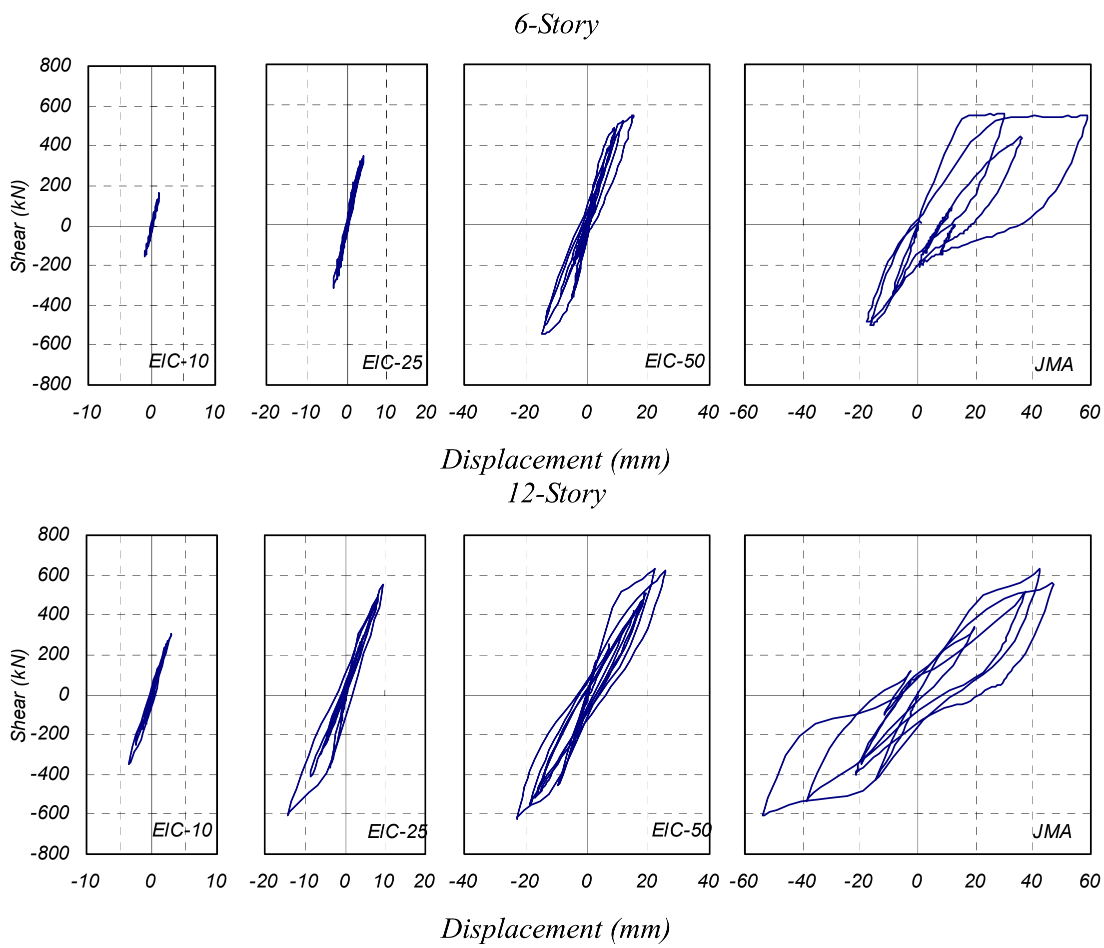


Fig. 7 Story Shear versus Lateral Displacement Relations

The loading of JMA input, significant deterioration in load carrying capacity was not observed even after forming the yield mechanism in both the specimens.

Rotation angle versus Displacement Relations

Figure 8 shows the rotation angle versus lateral displacement relations in the top of the first and second stories for the JMA input. In this figure, the vertical axis expresses rotation angle at the floor level of the second story and the third story, and the horizontal axis shows the lateral displacement. Gray and black lines are for the six-story frame and the twelve- story frame, respectively.

The increasing rate of top rotation angle for the twelve-story frame with increasing the lateral displacement was larger than that for the six-story frame. The values of rotation angle for the twelve-story frame were about 3 times in the first story and 2 times in the second story of the six-story frame at the same displacement, respectively. Therefore, the concentration of lateral displacement in the first story of the twelve-story frame was less than that of the six-story frame.

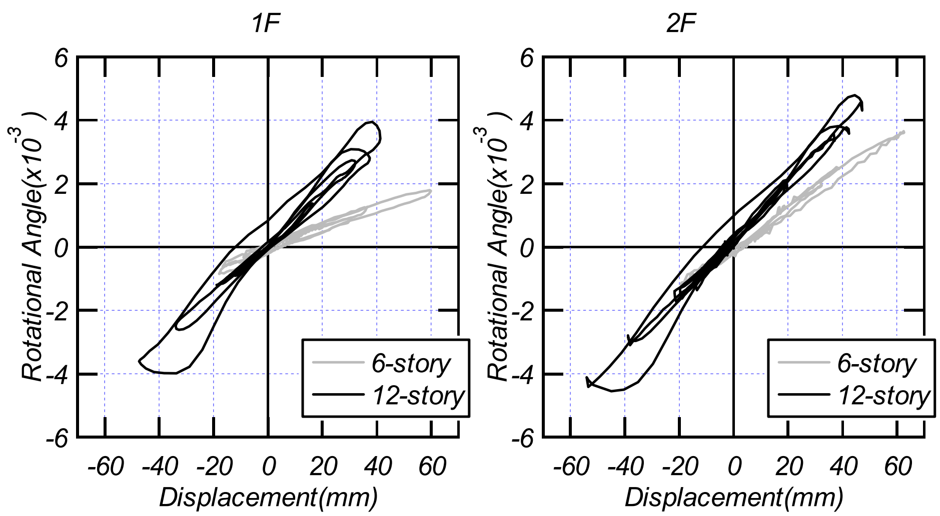


Fig. 8 Rotation angle versus Displacement Relations

Axial Force versus Story Shear Relations

Figure 9 shows the axial force versus story shear relations of the column for earthquake motions of ElC-25 and JMA inputs. In this figure, the vertical axis shows the axial force and the horizontal axis expresses story shear. The axial force and story shear were measured from load cells installed in the middle of the columns at the first story. Dotted line in the figure shows the calculated axial force-shear force interaction curves.

In the loading of ElC-25 input, the axial force of columns at the first story for the six-story frame varied from 72.5kN to 808.2kN with the initial axial force of 441kN. The columns at both compression and tension sides did not yield. For the twelve-story, on the other hand, the variation of the axial force of columns was ranging from -196.1kN to 2257.5kN with the initial axial force of 892kN, and the flexural yielding of the column in tension side was observed.

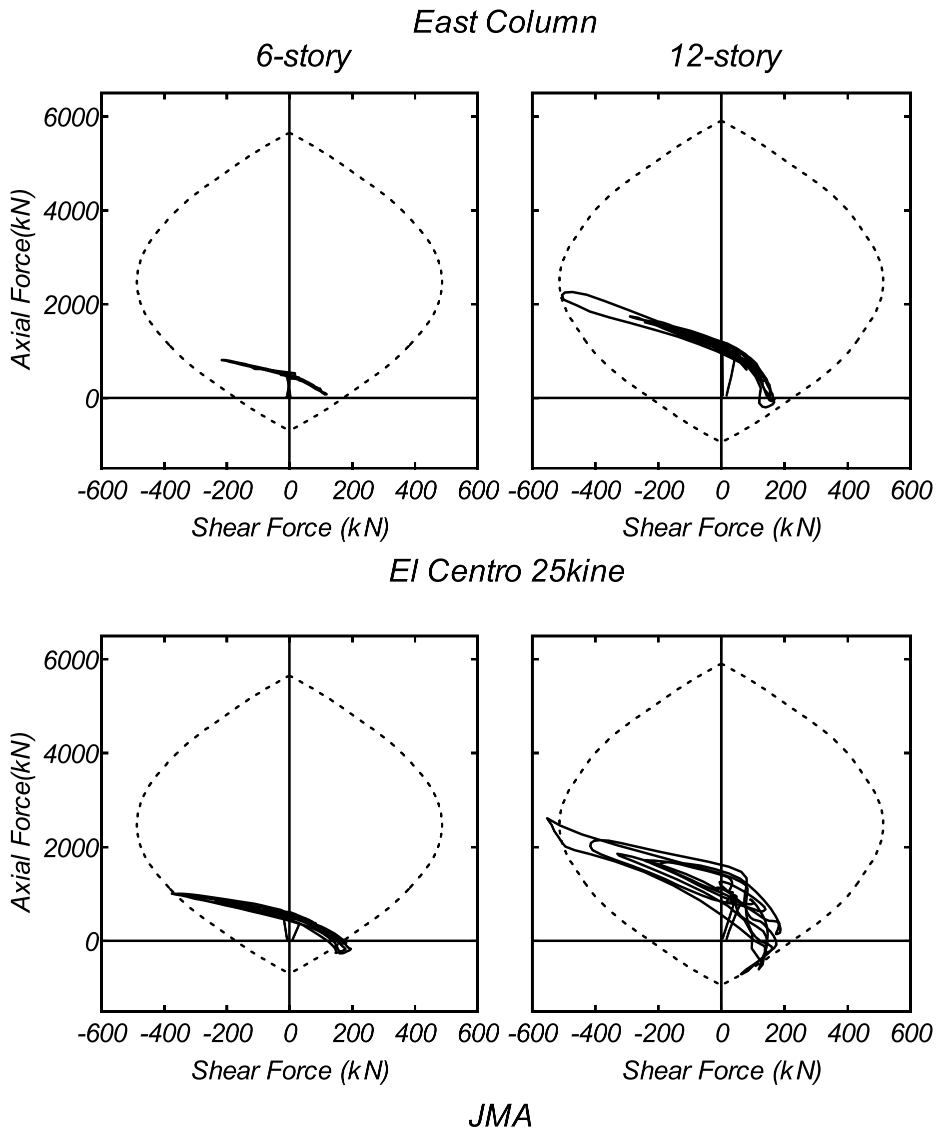


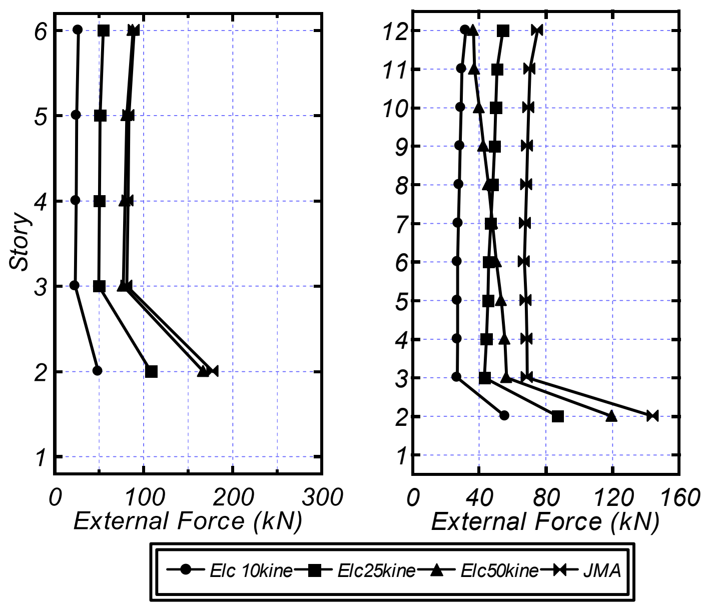
Fig. 9 Axial Force versus Story Shear Relations

In the loading of JMA input, the flexural yieldings of the columns in both compression and tension sides were observed for both frames. The inelastic level of the columns for the twelve-story frame was quite larger than that for the six-story frame.

External Force in Each Story

Figure 10 shows the external force distribution at the maximum response for each earthquake motion inputted. As shown in Fig. 5, the loading system in this test was designed to make the external forces at the first and second stories concentrated at the second story, in order to avoid that the failure situation at the first story is affected by the existence of a loading stub which is to be installed at the floor level of the second story to apply the external force of the first story. In this reason, analyses in the sub-structure PsD tests were executed as a five-story building model for the six-story frame and a eleven-story building model for the twelve-story frame in which the mass of the first story was twice that of the other stories.

Therefore, the external force applied at the second story is about twice that at the third story, while that at the first story is zero, as shown in Fig. 10. It is also indicated that the external forces at the third to sixth stories for the six-story frame and the third to twelfth stories for the twelve-story frame are almost the same value regardless of the level of earthquake motion inputted. These results imply that the external force distributions of the both frames were almost uniform at the maximum response.



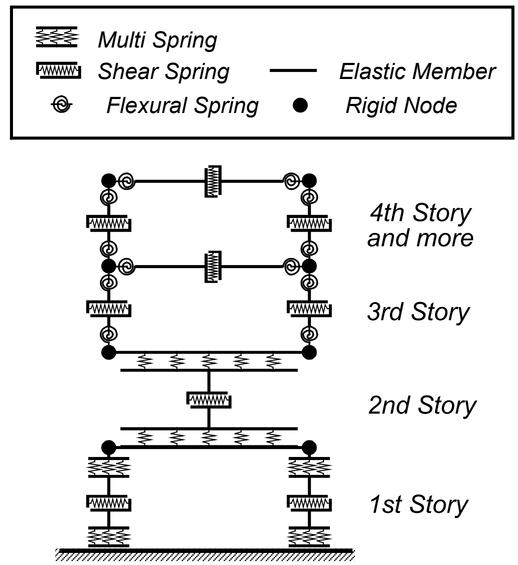


Fig. 10 External Force Distribution

Fig. 11 Analytical Model

COMPARISON BETWEEN PRELIMINARY ANALYSIS AND TEST RESULTS

In the sub-structure PsD test, as mentioned before, lateral shear forces were applied for the specimens to be attained to the objective story displacement and axial forces of columns at the floor level of the third story obtained from the earthquake response analysis for the upper four stories of the six-story frame and the upper ten stories of the six-story frame in each loading step. Therefore, the accuracy of the analysis during tests may seriously affect the test results. In order to confirm the accuracy of both the testing method and analytical tools used, a preliminary analysis was executed before the tests, where modeling for the upper four or ten stories was the same as that used in the sub-structure PsD test and the MS modeling was applied for the lower two stories, the experimental portion, as shown in Fig.11.

Figure 12 shows the time histories of story drift, story shear and axial force of the east column at the first story for ElC-50 and JMA inputs. Solid and dotted lines in the figure express experimental and analytical results, respectively. Good agreements between experimental and analytical results were obtained for responses of not only the story shear and drift but also the axial force of the column. These results give high reliability for the accuracy of the testing method and the validity of modeling in the analytical tools used.

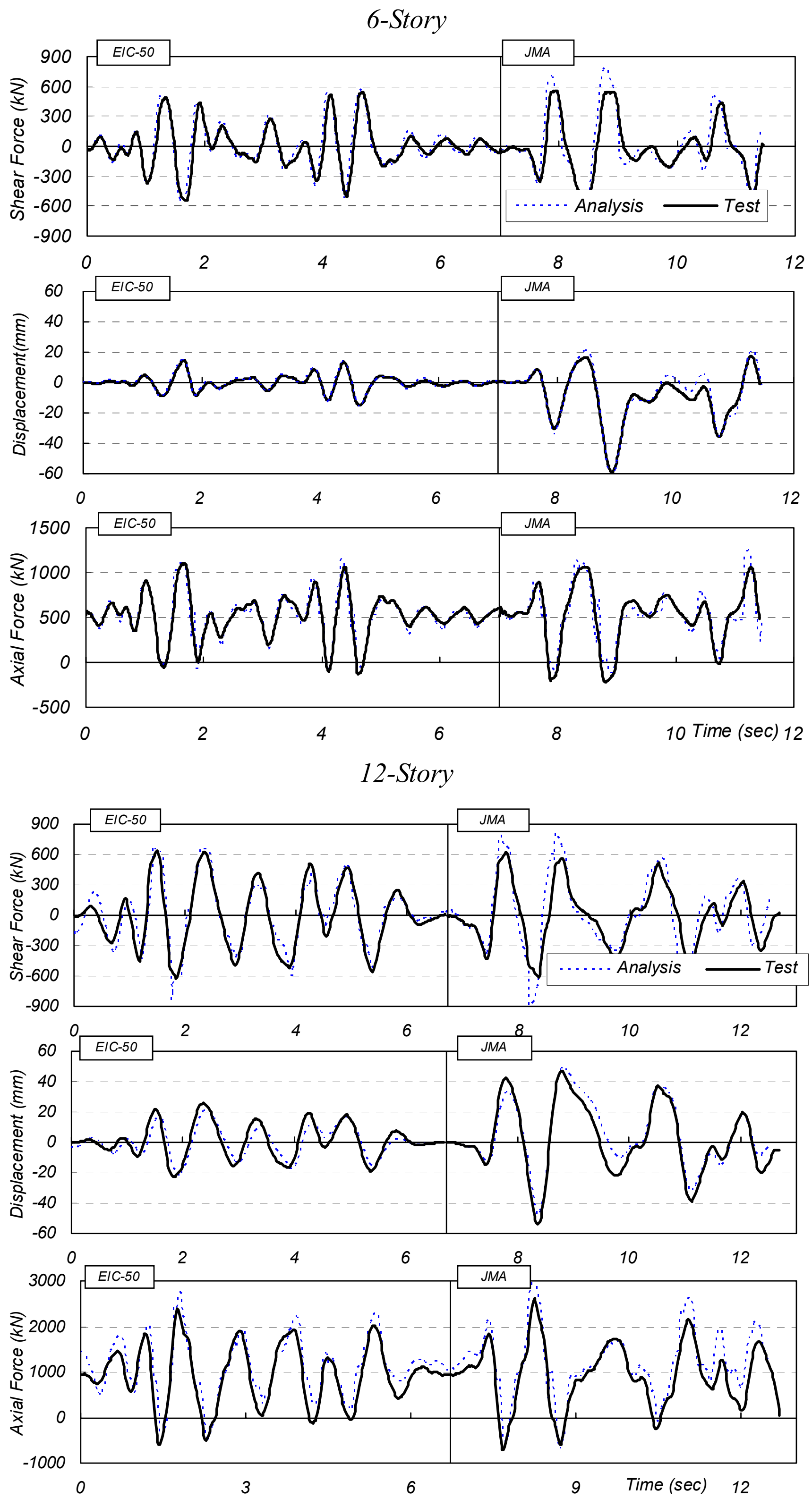


Fig. 12 Comparison between Experimental and Analytical Results

CONCLUSIONS

Sub-structure pseudo dynamic (PsD) tests and analysis for six-story and twelve-story RC buildings with soft first story were outlined. Main conclusions obtained in this study are;

1) The lateral resisting force distributions at the maximum displacement response were almost rectangular shape regardless of the building height.

2) The concentration of story drift in the first story of the twelve-story frame was less than that of the six-story frame because of larger horizontal displacements in the upper stories due to larger rotation of the top of the first story.

3) The preliminary earthquake response analysis executed in advance of the sub-structure pseudo dynamic test gave good predictions for experimental results on the story shear, story drift and axial force of columns at the first story. This implies high reliability for the accuracy of the testing method and the validity of modeling in the analytical tools used.

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