Simulation of Nonlinear Behavior of Wall-Frame Structure during Earthquakes

by

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ABSTRACT

The reinforced concrete wall-frame structure is widely used for buildings in Japan because of its high lateral resistance against earthquakes. However, uncertainty exists concerning the evaluation of shear force carried by the wall and column elements. The structural test and the analytical study of a 6-story wall-frame specimen reveal that the rocking movement of the wall during earthquake responses largely affects the damage of the structure as well as the mechanism to carry the lateral loads.

KEYWORDS: Nonlinear Push-over Analysis, Pseudo Dynamic Test, Reinforced Concrete, Wall-Frame Structure

1. INTRODUCTION

The reinforced concrete wall-frame structure is the frame which has continuous structural walls along the height of the structure. During earthquake responses, the structural walls are expected to support most of the lateral loads induced by earthquake ground motions. However, if the basement of the structure is designed to allow the lift up of the bottom of structural walls, the rocking movement of the wall may change the mechanism to carry the lateral loads. Such behavior has not been studied enough since it requires the large scale test of three-dimensional structural frames. This paper presents the results of pseudo dynamic tests and analyses of a 6-story reinforced concrete wall-frame structure, which will be used to develop a rational procedure for seismic design of reinforced concrete wall-frame structures.

2. TEST SPECIMEN

Figures 1 and 2 show the elevation and the plan of the test specimen. The specimen is designed to be 1/3 scale of a real size structure. It has 6 stories, one-bay in the loading direction and two-bays in the perpendicular direction. The basements of X1 and X3 frames are fixed on the floor. The basement of X2 frame is just placed on the rubber sheet as shown in Figure 3, allowing the lift up of the wall by overturning moment. The story weight is 90.5 kN for the Roof floor, 94.0 kN for the 2nd to 6th floors, and 27.5 kN for the base floor, including 61.5 kN supplemental weight on each floor slab. The size and rebar arrangement of each member are presented in Table 1, and material properties are listed in Table 2.

3. PSUEDO DYNAMIC TEST

3.1 Test Setting

Actuators are arranged as shown in Figure 4; one actuator at each floor and two actuators at the top floor to prevent the torsion of the specimen. The displacement of each floor was measured by the magnetic scale from the steel tower built next to the specimen. In total 72 displacement transducers were used to measure the deformation of beams and columns, the relative story displacement, and sway and rocking displacement of the basement. Strain of rebar inside structural elements was measured by using 275 strain gauges. And the axial and shear forces carried by the columns at 1st, 3rd and 5th floor were measured by the load cells embedded in the middle of the columns.

3.2 Unit Loading

Before starting the test, the unit load was applied on each floor to obtain the stiffness matrix of 6-DOF system. Consequently, the natural period

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and the mode shape are obtained as shown in Table 3. From the result of preliminary test, to avoid the divergence of displacement caused by the control error in the pseudo dynamic test, we reduced the freedom of the model to be 2-DOF system and used actuators at 4th floor and top floor only. The effective masses for the 2-DOF system were 350.84 kN for the 4th floor and 148.96 kN for the top floor determined so that the first and second natural periods and the mode shapes match those of 6-DOF system.

3.3 Input Ground Motions

Four different input motions are used for the pseudo dynamic test as listed in Table 4. The time scale was scaled down by according to the scale factor. Also, the amplitude of the record was scaled to be the certain maximum velocity from the original one. The duration of input motion is around 7 seconds determined so that it includes the major portion of the earthquake record.

3.4 Test Results

The relation between top displacement and the base shear in each input motion is presented in Figure 5. The crack distribution of the specimen and the location of rebar yielding after the loading of JMA75 input motion are presented in Figures 6 and 7. The rebar yielding did not happen in the loading of TOH25 and ELC37, however, the natural period of the specimen measured by the free vibration test changed to be T=0.18 second after TOH25 and T=0.23 second after ELC37. The rebar yielding was observed in the loading of JMA50 at the beam ends on the 2nd, 3rd and 4th floors in X1, X3 frames and the basement beams of Y1 frame. The range of rebar yielding was extended to the top floor beams in X1 and X3 frames under the loading of JMA75.

4. ANALYSIS

4.1 Analytical Model

In the analysis, the structure is modeled as a three-dimensional frame model constituted with line elements with nonlinear springs. Figure 8 shows the nonlinear element models used in the computer program “STERA-3D”, which was developed by one of the authors. The yielding moments of the elements were calculated by the flexural theory using the properties listed in Tables 1 and 2. The full width of slab reinforcement was assumed to contribute the resistance of a beam. The yield rotations of the beam and the column element were evaluated by the following formula proposed by Sugano[1]:

$$\frac{M_y}{\theta_y} = \alpha_y K_0, \quad K_0 = \frac{6EI}{l} \tag{1}$$

$$\alpha_y = \left(0.043 + 1.63 n p_t + 0.043\frac{M}{QD} + 0.33\frac{N}{bDF_c}\right)\left(\frac{d}{D}\right)^2 \tag{2}$$

in which, M_y: yield moment at member ends, θ_y: member end rotation at yielding, *n*: Young’s modulus ratio (= E_s / E_c), p_t : tensile reinforcement ratio, *M/QD*: shear span-to-depth ratio, *N*: axial force, *b*: width of the section, *D*: depth of the section, F_c: compression strength of concrete, and l : total length of member. The yield rotation of the wall element was calculated assuming $\alpha_y = 0.2$ and $K_0 = 2EI/l$ in the above equations. The nonlinear interaction between moment and axial force of the column element is modeled by the Multi-Spring Model proposed by Li and Otani [2], where nonlinear axial springs for concrete and steel are arranged in the sections of member ends. The similar model was developed for the wall element by Saito et.al.[3]. Since the specimen was designed to have flexural yielding at the member ends and have enough shear strength, the shear springs of the member models were assumed to be elastic spring throughout the analysis.

4.2 Nonlinear Push-over Analysis

Nonlinear push-over analyses of the frame model were carried out applying static forces in the loading direction. The distribution of the lateral force along the height of the structure was determined assuming the triangular shape of the seismic coefficient. The force is applied at the center of gravity in each floor, increased until the top displacement reaches 1/80 of the total height of the frame. Figure 9 shows the yielding mechanism and the relation between the top displacement and the base shear force. The frame reached the yielding mechanism with large deformation of perpendicular beams attached to the wall elements including the base beams. The largest base shear force is 450 kN in which the wall shares 40.4 % of the total amount. After the yielding of perpendicular beams to the wall elements, the shear force carried by the wall doesn't change so much. On the contrary, the shear force carried by the columns increases as the external force increases. The results of pseudo dynamic tests and push over analyses are compared in Figure 10. Figure 10-(a) shows the comparison of seismic coefficients, where the seismic coefficient of pseudo dynamic tests was obtained from the actuator's force divided by the weight of the floor at the moment of the maximum base shear in each loading. It is seen that the seismic coefficients at the 4th floor of the pseudo dynamic tests are slightly larger than 0.5 of the triangular shape. Figure 10-(b) shows the comparison of the relation between the top displacement and the base shear. Thin gray line represents the result of pseudo dynamic tests and black line represents the result of push-over analyses. It is seen that the result of push over analyses relatively well envelops the result of pseudo dynamic tests.

4.3 Shear Force Distribution

In the pseudo dynamic test, shear forces of the columns at the 1st, 3rd, and 5th stories are measured by the load cells embedded in the columns. By subtracting them from the actuator's force, the shear force of the wall is obtained. Table 5 shows the ratios of shear forces carried by the columns and the wall at the 1st story at the moment of the maximum base shear in each loading. The ratio of the shear force carried by the wall is changed from 26% (in TOH25) to 42.2% (in JMA75). The distribution of lateral shear force among wall and columns can be evaluated by applying the principle of virtual work to each frame as shown in Figure 11. In the case of X2 frame, the shear force, Qy, of the perpendicular beam can be calculated as $Qy=(My^P+My^N)/l_B$; where My^P: yielding moment of positive bending, My^N: yielding moment of negative bending, and l_B: length of beam. From the principle of virtual work, the shear forces carried by the wall and the columns at the 1st story are obtained as $\sum P_W$ =150.8 kN and $\sum P_C$ =274.7 kN, respectively. Therefore, the maximum base shear is 425.4 kN and the ratio of shear force carried by the wall is 35.5 %, which are almost the same results obtained by push over analyses and pseudo dynamic tests.

5. CONCLUSIONS

This paper presented the results of the pseudo dynamic tests and the push over analyses of a 6-story reinforced concrete wall-frame structure under earthquake loadings in order to evaluate the damage of the structure and the lateral shear force distribution among wall and column elements.

6. REFERENCES

1. S. Sugano, Experimental Study on Restoring Force Characteristics of Reinforced Concrete Members, Doctor of Engineering Thesis, University of Tokyo, 1970 (in Japanese).
2. K-N.Li and S. Otani, "Multi-Spring Model for 3-Dimensional Analysis of RC Members", Journal of Structural Engineering and Mechanics. Vol. 1, 1993.
3. T. Saito, J. Ogawa, J. Shibuya and J. Fu, "Analysis of Inelastic Behavior of Wall-Frame Structures", Proceedings of the Japan Concrete Institute, Vol.13, No.2, pp.613-618, 1991 (in Japanese).

Table 1 Members and Rebar Arrangement

Beam	B×D (mm)	Main Rebar		Stirrup
		Lateral	Side	
1 Floor (X1, X2)	200 × 450	4-D10	6-D6	2-D6@100
1 Floor (Y1, Y2)	200 × 450	6-D10	6-D6	2-D6@50
2-R Floor	150 × 250	3-D10		2-D6@60
Column	**B×D (mm)**	**Main Rebar**		**Hoop**
1-6 Story	200 × 200	12-D13		2-D6@60
Wall	**t (mm)**	**Rebar (Vertical and Horizontal)**		
1-6 Story	80	D6@100		

Table 2 Material Properties

Rebar	Young's Modulus (GPa)	Yield Strength (MPa)	Break Strength (MPa)
D6	166	349	501
D10	176	353	496
D13	176	345	472
Concrete	**Young's Modulus (GPa)**	**Compression Strength (MPa)**	
(average)	26.647	37.1	
Rubber	**Young's Modulus (GPa) (from the compression test in displacement range [0.2-0.5mm])**		
(average)	0.0586		

Table 3 Vibration Modes from Unit Loading Test

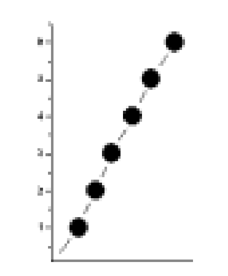
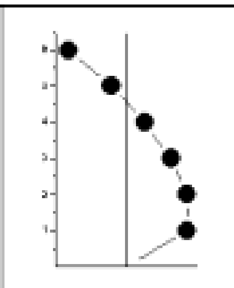
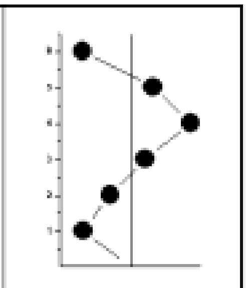
Mode			
T(sec)	0.157	0.050	0.018

Table 4 Input Earthquake Ground Motions

Date of Experiment	Name	The Maximum Velocity Level (cm/s) *	Original Record
2003.9.19	TOH25	25	Tohoku University, 1978 Miyagi-ken-oki earthquake
2003.9.20	ELC37	37	Imperial Valley, 1940 El Centro earthquake
2003.9.22	JMA50	50	JMA Kobe, 1995 Hyogo-ken-Nanbu earthquake
2003.9.23	JMA75	75	ditto

* scaled from the original records

Table 5 Shear Force Distribution in Pseudo Dynamic Test

Input Earthquake	Time (sec)	Base Shear (kN)	Columns (%)	Wall (%)
TOH25	4.42	128.3	74.0	26.0
ELC37	2.52	-288.9	65.7	34.3
JMA50	0.89	-460.5	62.9	37.1
JMA75	1.03	513.0	57.8	42.2

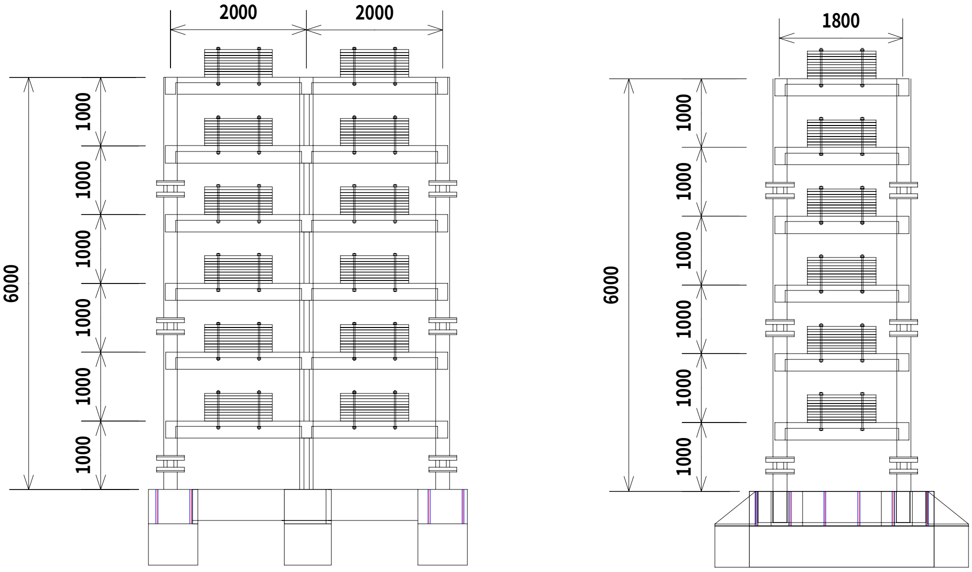


Figure 1 ElevationView (UNIT: mm)

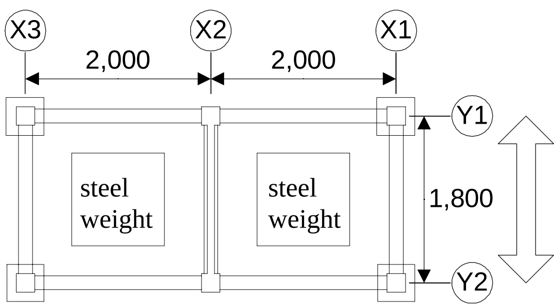


Figure 2 Plan View (UNIT: mm)

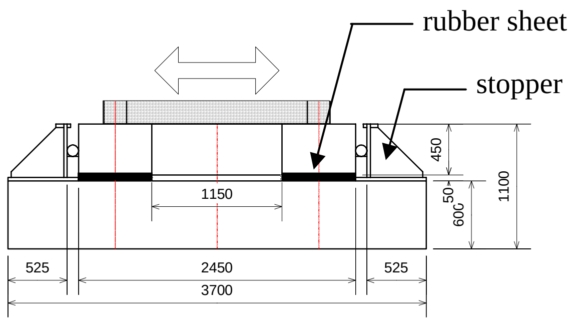
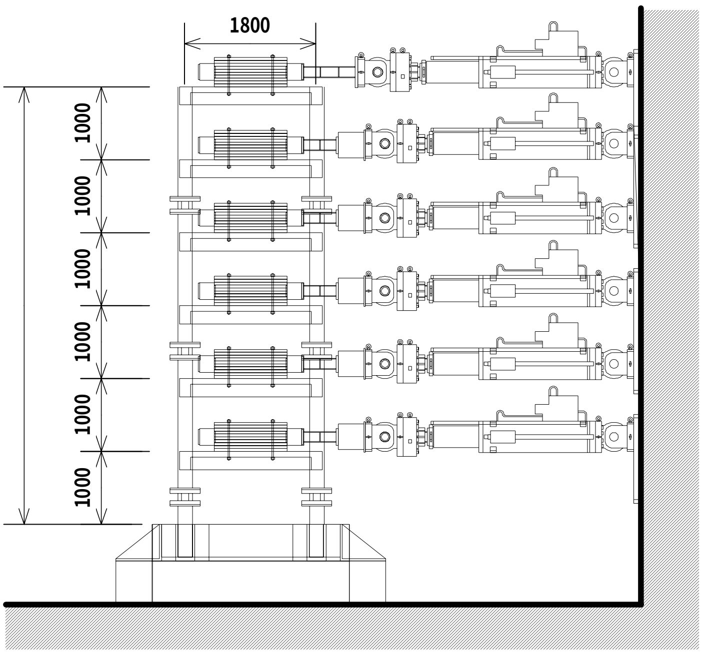
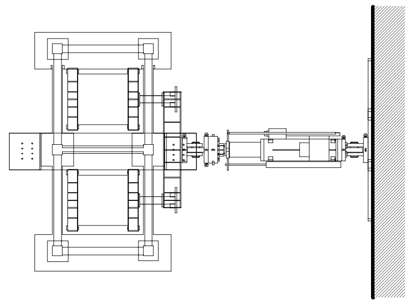


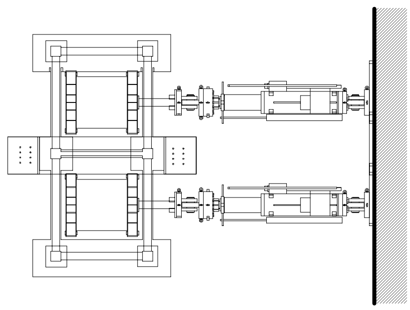
Figure 3 Basement of X2 Frame



(a) Elevation



(b) Plan (2F-6F)



(c) Plan (RF)

Figure 4 Test Setting

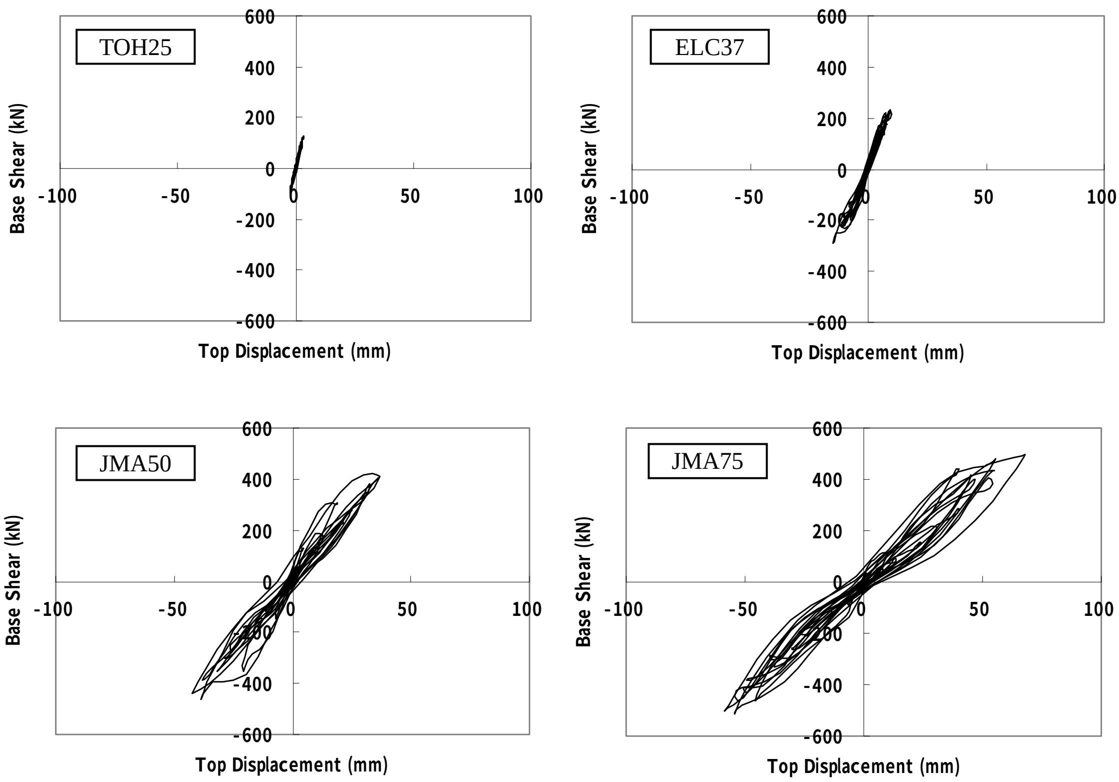


Figure 5 Top Displacement and Base Shear Relationship

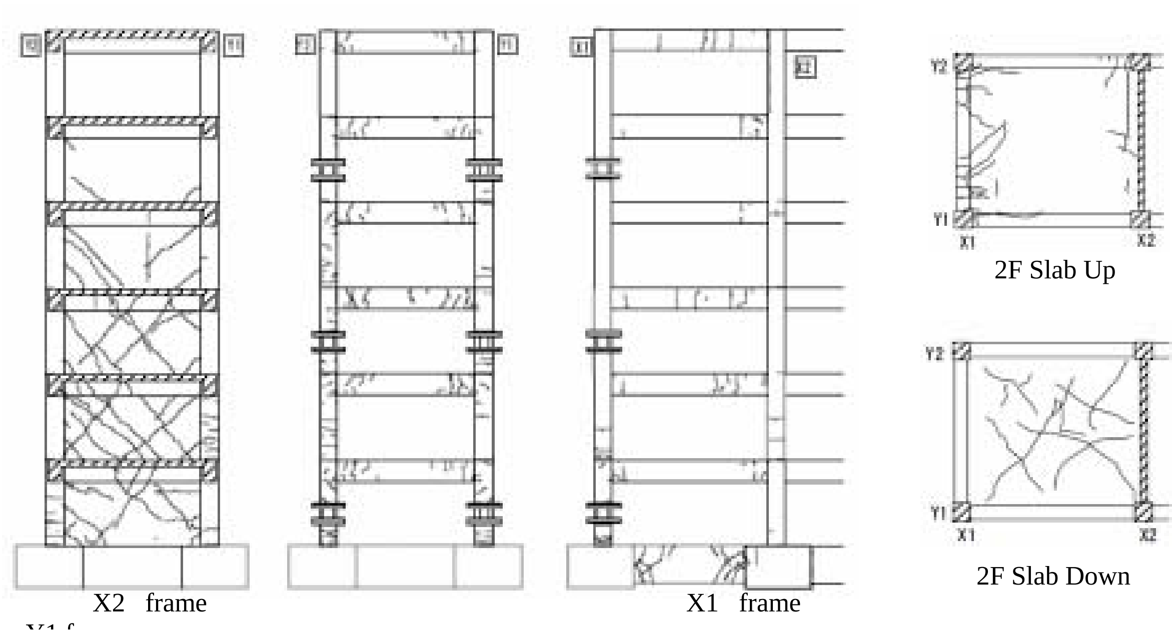


Figure 6 Crack Distribution (After JMA75)

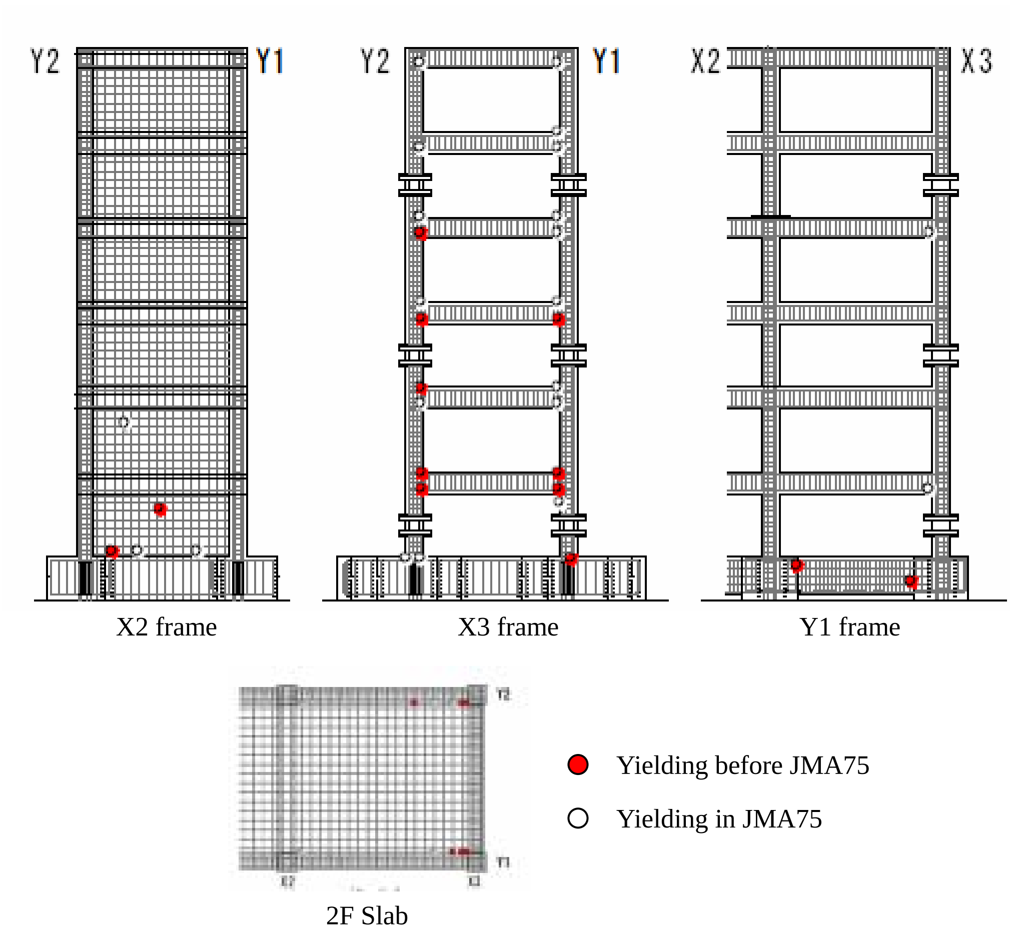


Figure 7 Location of Rebar Yielding

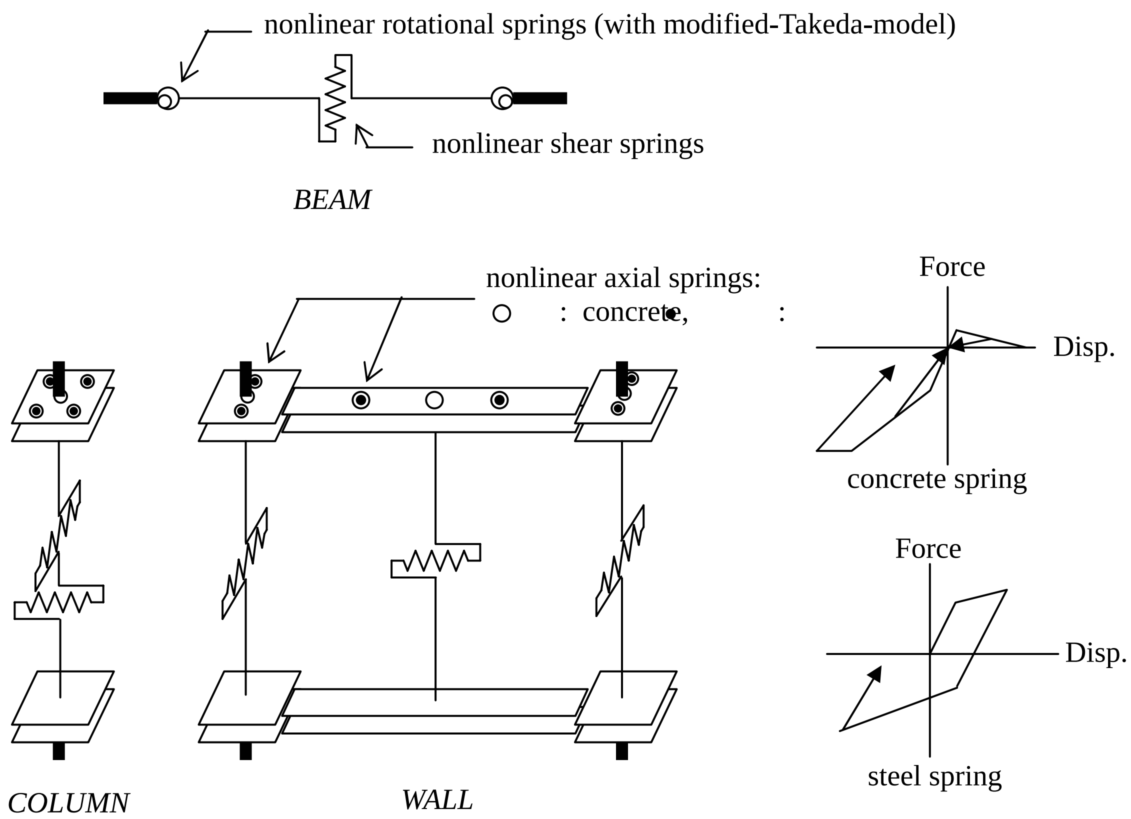
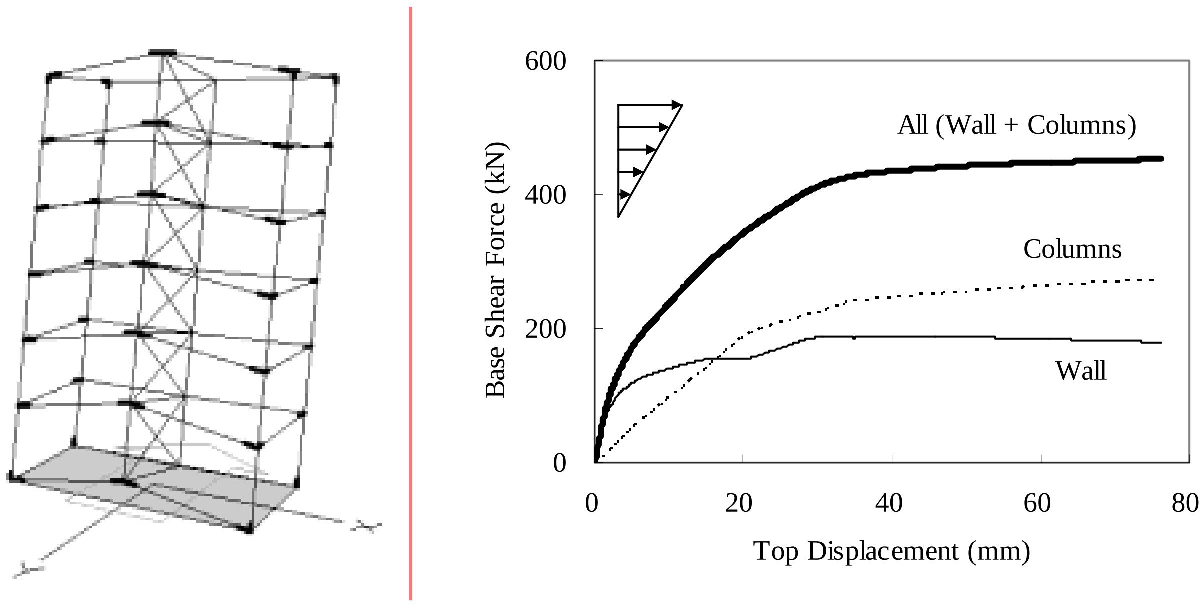


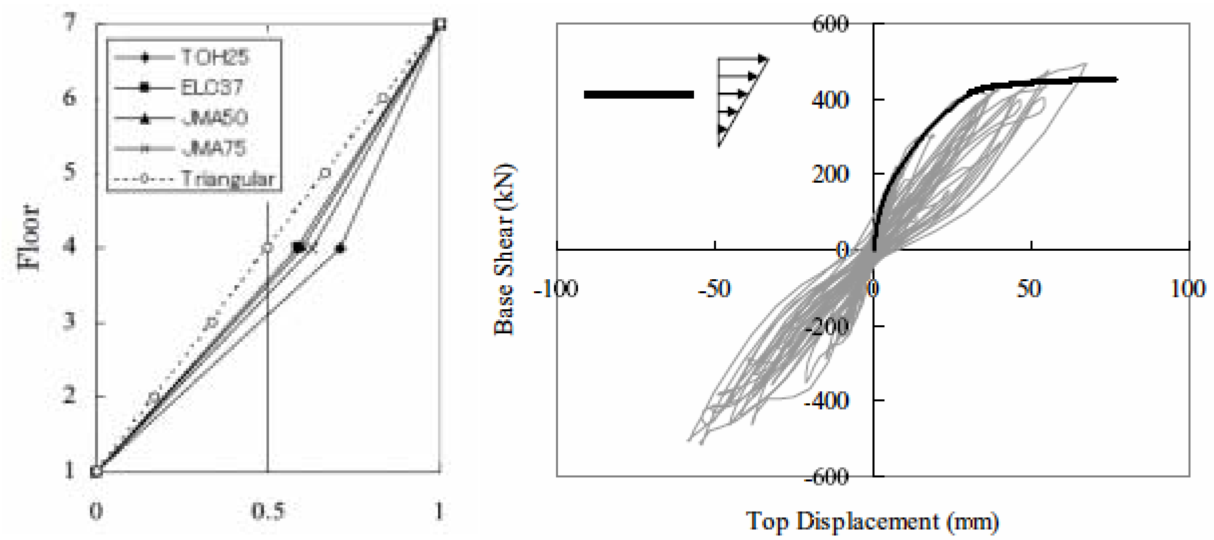
Figure 8 Nonlinear Element Models



(a) Yielding Mechanism

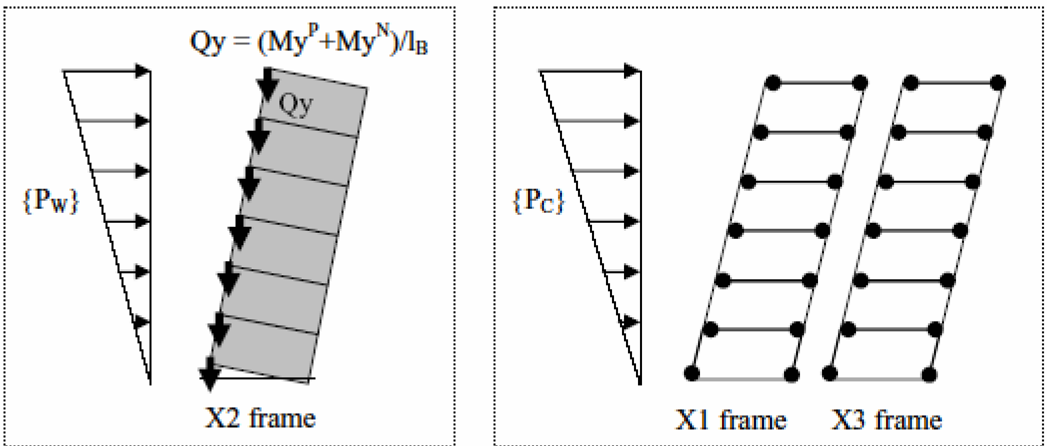
(b) Top Displacement and Base Shear Relationship

Figure 9 Nonlinear Push-Over Analysis



(a) Seismic Coefficient Distribution (b) Top Displacement and Base Shear Relationship

Figure 10 Comparison between Pseudo Dynamic Test and Analysis



(a) Wall (b) Columns

Figure 11 Principle of Virtual Work