Study on Base Isolation for Torsional Response Reduction in Asymmetric Structures Under Earthquake Motion

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1. INTRODUCTION

Recently, several buildings with base isolation systems have been constructed and effectiveness of those systems to reduce earthquake input are reported by several observation results. However, the system is now adopted only in the regular shape building which is symmetry in stiffness and mass distribution in plan and elevation, where torsional response is negligible.

To apply this system to more general building, it is important to establish the design philosophy how to arrange the system so that the torsional effects can be minimized.

In this paper, torsional response characteristics of asymmetrical building models with base isolation systems and effectiveness of usage of those system in reducing the torsional earthquake response are described by dynamic tests and analyses.

2. EXPERIMENTAL MODELS

2.1 Outline of Experiments

<u>Test Model</u>

The test model consists of two floors as shown in Fig.-1 and Photo.-1. The upper floor supported by four steel columns represents a building and has 1 axis eccentricity in stiffness or mass disribution as follows.

1) An asymmetrical Model in stiffness distribution (Model A series)
   Two pairs of different stiffness steel columns (Column L ,Column S) are utilized. The eccentric rate R_x is 0.430.

2) An asymmetrical Model in mass distribution (Model B series)
   Additional mass is eccentrically attached on the upper floor supported by four same stiffness steel columns (Column M). The eccentric rate R_x is 0.205.

The lower floor has a base isolation system underneath. Two types of isolation systems are employed, one of which is four laminated rubber bearings (Rubbers) usage only, and another is two cantilever type dampers of prestressing steel bar (Dampers) added together.

Regarding the arrangement of Rubbers, same stiffness rubbers are utilized to avoid stiffness eccentricity of base isolation system except Model B-3 and B-4 cases in which two different kinds of Rubbers are installed to coincide the centroid of stiffness of base isolation system with that of gravity of superstructure.

Table-1 summarizes the test models and characteristics of model components such as Weight, Column, Rubber and Damper. In this table, Model A-1 and B-1 are base fixed case for comparison usage.

Measurement systems with regard to response accelerations, displacements, input acceleration and strains of steel columns and Dampers are also shown in Fig.-1.

Testing Program

One directional (X direction) input motions are applied on shaking table, where maximum accelerations are controled so that the steel column and Rubber remains in elastic.

1) Resonance test
Natural frequencies and vibration modes of test models are examined by sine wave input motion.

2) Earthquake response test
Three earthquake waves such as El Centro 1940 NS, Taft 1952 EW and Hachinohe 1968 EW are employed where time scale is reduced to 1/2 to take account of scale effect. In this paper, El Centro 1940 NS tests are mainly explained.

2.2 Results of Dynamic Tests

Resonance Curve and Vibration Mode (Dynamic characteristic)

Eigen values obtained from resonance tests are shown in Table-2.

Earthquake Response

Fig.-2 show time history response displacements of upper floor, where input motion is El Centro 1940 NS 150gal and response direction is the same of that of input. In these figure, N means north and indicates weaker stiffness column side for Model A series and additional mass allocated side for Model B series.

In fixed base cases, the displacements of the weaker stiffness columns side in Model A-1 and the additional mass allocated side in Model B-1 are larger than those of the other side, then torsional deformations occur fairly. On the other hand, in base isolated cases, the response displacements of both sides are nearly equal, and no significant torsional deformations occur. In regard to Model B-3 and B-4, the centers of stiffness of the base isolation systems are set to coincide with those of gravity of superstructure.

Besides, when comparing displacements of base isolation systems between only Rubbers usage Model and Dampers added together Model, the latter displacements are smaller than those of the former as a result of energy absorption effect of Dampers.

From these results, it seems very effective to use the base isolation system for the reduction of torsional deformation of asymmetrical buildings.

3. SIMULATION ANALYSIS

Outline of Analysis

Simulation analysis is conducted using shear-type vibration model as shown in Fig.-3, where two translational and a rotational degrees of freedom are provided at the center of gravity of each floor[1]. Each column stiffness is evaluated by Multiple Shear Spring model (MSS model)[2] as shown in Fig.-3 to take account of the interaction effect between two-dimensional forces beyond elastic region. Viscous damping coefficients are assumed 0.4%, 6.0%, and 0.0% for steel column, laminated rubber bearing and prestressing steel bar, respectively.

Results of Simulation Analysis

Analytical results of eigen values, time history waves of earthquake response displacement are shown in Table-2 and Fig.-3, respectively, together with the test results. From these results, simulation analysis results provide good agreement with the test results in all cases.

4. ANALYTICAL MODEL

Outline of Analytical Models

Analytical model (Model C series) is shown in Fig.-4. The superstructure has 2 axis asymmetry in stiffness, consists of three pairs of different stiffness columns (Model C1, C2 and C3 in Table-3), but each model has the same eccentric rate $R_X = R_Y = 0.420$. The base isolation system under the lower floor consists of nine pairs of Rubber and Damper, and has no stiffness eccentricity. The fundamental lateral period of isolation system is 1.5 sec.
Each member stiffness is evaluated by MSS model and viscous damping coefficients are assumed 2.0%, 2.0%, and 0.0% for column, Rubber and Damper, respectively.
El Centro 1940 earthquake waves are used, as NS-compornent is for X-direction input and EW-compornent is for Y-direction input.

Results of Analysis

Analytical results of eigen values are shown in Table-4. As the superstructure (Model C-1～3 series) becomes more flexible, the 1st mode period of base isolated model (Model C-4 ～6 series) becomes longer by the coupled effects with the lateral isolating period.

Maximum values of earthquake response at the center of gravity of each floor are shown in Table-5, and time history response accelerations and relative story displacement orbits at the diagonal corners of each floor are shown in Fig.-6.

To compare with fixed base models and base isolated models in Table-5 and Fig.-6, relative story displacements, rotational angle and response accelerations of superstructure are drastically reduced in base isolated model. As regards the relative story displacement, columns of fixed based models (Model C-1 ～3 series) show elasto-plastic response, but those of base isolated models (Model C-4～6 series) remain in elastic region.

From these results, base-isolation system is very effective for a building with 2 axis eccentricities to reduce its torsional response

5. CONCLUSION

Folloing are concluded through the present study :

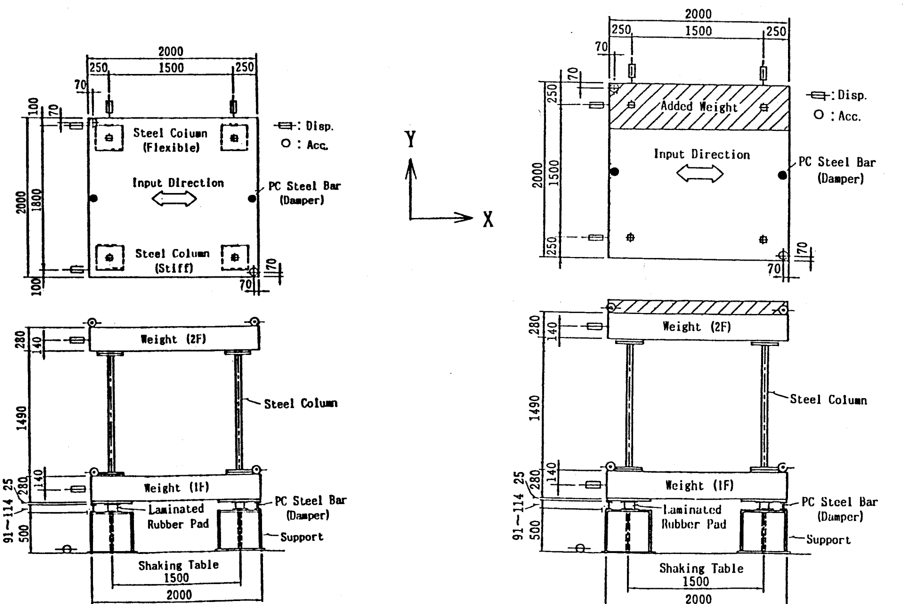
1) Base isolation system provides great promise for the reduction in torsional and lateral forces of buildings. Therefore this system may lead cost effectiveness in the construction of torsionally unbalanced building.

2) Torsional deformation can be minimized when the structural design is carried out so that the center of stiffness and strength of isolation system coincide with that of gravity of superstructure.

3) Dynamic analysis method used in this study is effective to predict the response behavior of isolated system because of a good agreement obtained between simulation analysis and test results.

REFFERENCES

1. Suzuki, T., Okada, H., etc. (1988). Torsional Response Characteristics of Building with Base Isolation System (Part 1)," Report of the Technical Research Institute OHBAYASHI CORP. , No. 36, pp.67-71.
2. Wada, A., Kinoshita, M. (1985). Elastic Plastic Dynamic 3-Dimensional Response Analysis by using a Multiple Shear Spring Model (Part 1, Parat 2), Summaries of Technical Papears of Annual Meeting, AIJ, B, pp.313-316.



a. Model A series (Stiffness asymmetry model) b. Model B series (Mass asymmetry)

Fig.-1 Asymmetry test Models

Table-1 List of Experiment Models

	Specimen	Column	Rubber	Damper	Refferences	
Stiffness Asymmetry Model (Model A Series)	Model A-1	Column S Column L	— —	—	Fixed-Based Model (Elastic)	Weight · 1st floor weight : W_1=3.12t · 2nd floor weight : W_2=2.89t · Added weight : W_3=1.18t Stiffness of Column · Column S : k_H=0.164t/cm · Column M : k_H=0.289t/cm · Column L : k_H=0.556t/cm Rubber (Laminated Rubber Bearing) Material:Natural Rubber · Rubber 2M : k_H=37.0kg/cm * Diameter:80mm , Height:75.0mm · Rubber 3M : k_H=59.2kg/cm * Diameter:100mm , Height:89.4mm *Stiffness k_H changes slightly under Working Load Level. Damper (Cantilever Type) Material:PC Steel Bar Diameter:11mm , Length:75mm Yielding Disp.:5mm
	Model A-2	Column S Column L	Rubber 2M Rubber 2M	—	Isolated Model	
	Model A-3	Column S Column L	Rubber 2M Rubber 2M	○	Isolated Model (Elasto-Plastic)	
Mass Asymmetry Model (Model B Series)	Model B-1	Column M Column M	— —	-	Fixed-Based Model (Elastic)	
	Model B-2	Column M Column M	Rubber 3M Rubber 3M	-	Isolated Model (Elastic)	
	Model B-3	Column M Column M	Rubber 3M Rubber 2M	-	Isolated Model (Elastic)	
	Model B-4	Column M Column M	Rubber 3M Rubber 2M	○	Isolated Model (Elasto-Plastic)	

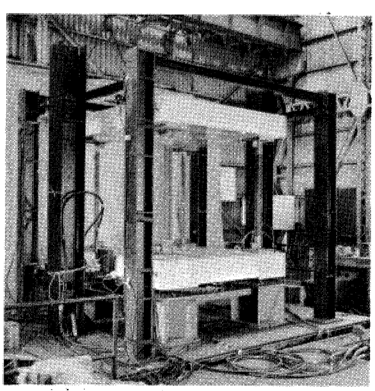
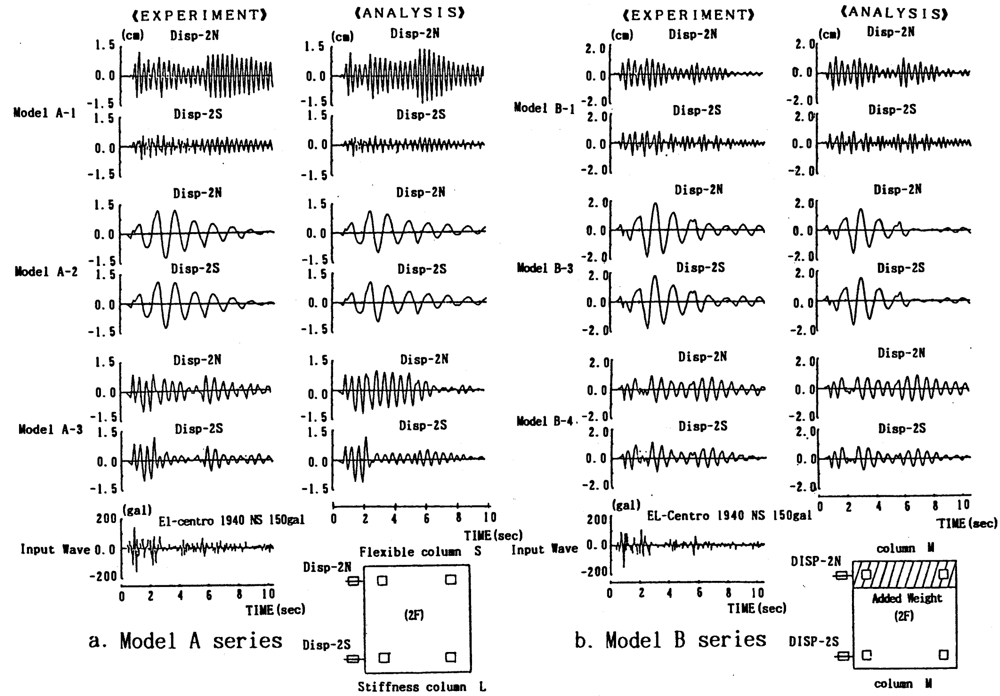


Photo.-1 Test Model A

Table-2 Results of Eigen Value

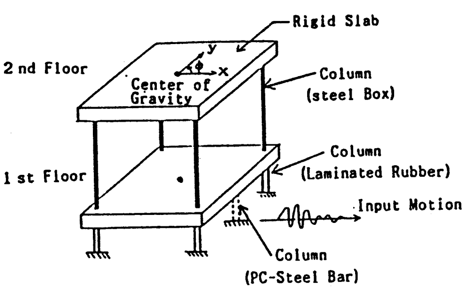
Specimen	Vibration Mode (Hz)	1st.	2nd.	3rd.	4th.	5th.	6th.
Stiffness Asymmetry Model (Model A series)	Model A-1	3.07	-	4.92			
		3.02	3.52	4.91			
	Model A-2	0.77	-	-	4.30	-	6.88
		0.771	0.773	1.00	4.27	4.94	6.88
Mass Asymmetry Model (Model B series)	Model B-1	2.55	-	3.64			
		2.55	2.67	3.56			
	Model B-2	0.88	-	-	4.14	-	5.67
		0.881	0.915	1.21	4.02	4.20	5.63
	Model B-3	0.83	-	-	4.15	-	5.62
		0.830	0.831	1.06	4.01	4.17	5.57

Upper row values ; experiment ,Lower row values ; analysis.- ; not measured

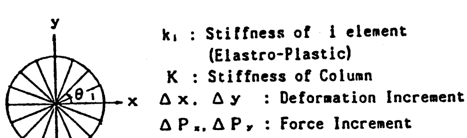


a. Model A series　　b. Model B series

Fig-2 Test and Analysis results of eathquake response



a. Stiffness Vibration Model



$$\begin{Bmatrix} \Delta P_x \\ \Delta P_y \end{Bmatrix} = [K] \begin{Bmatrix} \Delta x \\ \Delta y \end{Bmatrix}$$

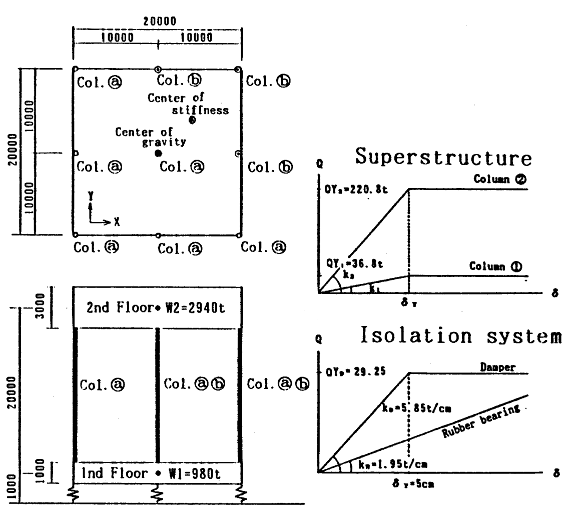
$$[K] = \begin{bmatrix} \Sigma k_i \cos^2\theta_i & \Sigma k_i \cos\theta_i \sin\theta_i \\ \Sigma k_i \cos\theta_i \sin\theta_i & \Sigma k_i \sin^2\theta_i \end{bmatrix}$$

b. Evaluation of column

Fig.-3 Analytical Model

Table-3 List of Superstructer Columns

Superstructer Model		Model C1	Model C2	Model C3
Column ⓐ	k_1	80.0 t/cm	20.0 t/cm	5.0 t/cm
Column ⓑ	k_2	480.0 t/cm	120.0 t/cm	30.0 t/cm
ΣK= 3Columnⓐ+6Columnⓑ		1920.0 t/cm	480.0 t/cm	120.0 t/cm
Yielding displacement δ_Y		0.46 cm	1.84 cm	7.36 cm



Isolation system

Fig.-4 2 axis Eccentricity Model

Table-4 Results of Eigen Value (2 axis asymmetry model in stiffness)

Analytical model / Base condition	Model C Series	Superstructer model	1st.	2nd.	3rd.	4th.	5th.	6th.
		Vibration Mode (Hz)						
Fixed base Model	Model C-1	Model C1	3.18	4.03	6.21			
	Model C-2	Model C2	1.59	2.01	3.10			
	Model C-3	Model C3	0.794	1.01	1.55			
Base Isolted Model	Model C-4	Model C1	0.658	0.660	0.930	6.48	8.14	12.5
	Model C-5	Model C2	0.630	0.640	0.895	3.43	4.19	6.42
	Model C-6	Model C3	0.537	0.572	0.792	2.08	2.35	3.50

Table-5 Maximum value of earthquake response at center of grvty

		Fixed based model						Base isolated model						Comment
		Relative story displacement				Accelation		Relative story displacement				Accelation		
Superstructer model	δ_Y cm Yielding displacement	Analytical model	X cm lastic ratio	Y cm Plastic ratio	θ rad $\times 10^{-2}$	X gal Response ration	Y gal Response ration	Analitical model	X cm Plastic ratio	Y cm Plastic ratio	θ rad $\times 10^{-2}$	X gal Response ration	Y gal Response ration	Input earthquake
Model C1	2 F δ_Y = 0.46cm	Model C-1	2.19 (4.77)	1.18 (2.57)	0.132	369.0 [1.08]	295.9 [1.41]	Model C-4	0.236 (0.513)	0.225 (0.489)	0.012	125.1 [0.366]	115.5 [0.550]	wave: El-centro X= 341.7 gal Y= 210.1 gal
	1 F δ_Y = 5.0 cm		–	–	–	–	–		10.18 (2.036)	9.05 (1.81)	0.049	122.7 [0.359]	113.3 [0.539]	
Model C2	2 F δ_Y = 1.48cm	Model C-2	5.04 (2.74)	3.20 (1.74)	0.490	304.3 [0.890]	312.9 [1.49]	Model C-5	0.989 (0.668)	0.989 (0.668)	0.053	130.3 [0.381]	122.7 [0.584]	
	1 F δ_Y = 5.0 cm		–	–	–	–	–		10.73 (2.15)	9.26 (1.85)	0.124	122.9 [0.360]	129.4 [0.616]	
Model C3	2 F δ_Y = 7.36cm	Model C-3	6.82 (0.926)	9.56 (1.30)	0.787	238.7 [0.699]	237.9 [1.13]	Model C-6	4.64 (0.630)	4.55 (0.618)	0.295	136.2 [0.399]	148.3 [0.704]	
	1 F δ_Y = 5.0 cm		–	–	–	–	–		12.28 (2.46)	13.21 (2.64)	0.295	238.3 [0.697]	185.0 [0.881]	

[ ] : Acceleration response ratio ( ) : Ductility factor

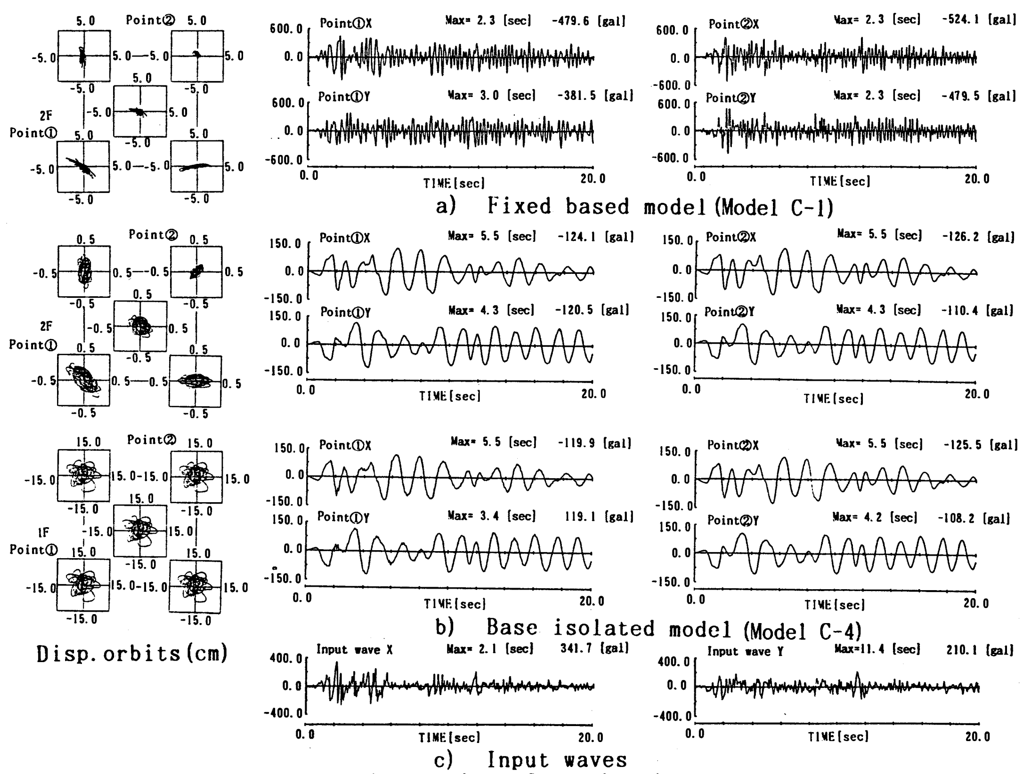


Fig.-6 Analysis vesults of earthquake response