Paper No. 1445. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

BUILDING VIBRATION ISOLATION SYSTEM WITH SPRING AND VISCOELASTIC DAMPER

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ABSTRACT

Vibration isolation system using spring units and viscoelastic dampers can reduce vibration and structure borne noise in a building near subway or other traffic facilities effectively. For applying this system in Japan, it is necessary to confirm the seismic safety. So we have done an experimental and analytical study.
At first we have carried out the static loading tests for spring units and dynamic loading tests for a visco-elastic damper. We have proposed analytical models for spring and viscoelastic damper.
At second we have done shaking table tests for a vibration isolation building model in order to examine the vibration characteristics and behaviors of the structure.
After all we designed a four storied vibration isolated building supported by the system and affirmed the seismic safety of the building from the analysis performed by the proposed model.

KEYWORDS

vibration isolation system, helical steel spring, viscoelastic damper, loading test, shaking table test, response analysis

1. INTRODUCTION

Recently many buildings have been constructed near subways or traffic facilities in the city area of Japan.
And the problem of vibration or noise through building structure makes the surrounding circumstance worse for the inhabitants. To avoid this problem it is useful to adopt vibration isolation system using spring units and viscoelastic dampers. For this purpose an experimental and analytical study has been done. At last a four storied building has been designed with seismic safety.

2. VIBRATION ISOLATION SYSTEM

2.1 Speciality of the system

Helical steel springs are used to support the weight of the building. And the natural frequency of the building

becomes lower and it is easy to reduce the higher frequency parts of the vibration from traffic facilities.
The viscoelastic dampers behave to three dimensions. So it is easy to put those dampers densely at the corner of the building.
Both springs and dampers are used in the state of bundle and the number of units of springs and dampers can be controlled according to the distribution of load from the upper structure.
The system has three characteristics as follows.
1) Helical coil springs support the building and the natural frequency of the building both in vertical and horizontal direction can be set lower. So the vibration or noise from subways or traffic facilities is easily decreased.
2) Viscoelastic dampers can behave three dimensionally and it is needless to prepare dampers for vertical and horizontal direction independently. So it is easy to distribute the devices corners concentratedly.

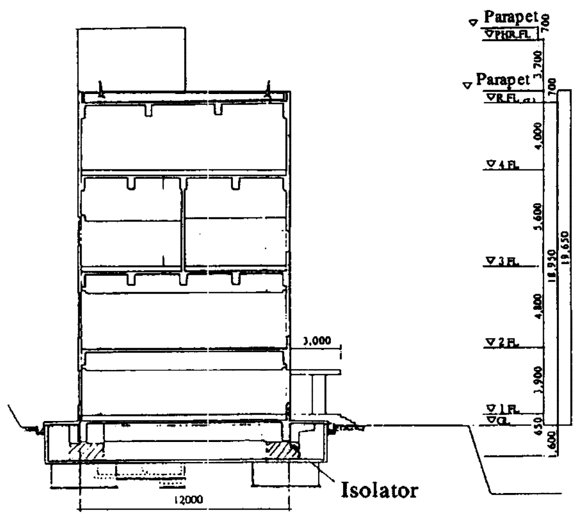


Fig.1 Sectional plan of the building

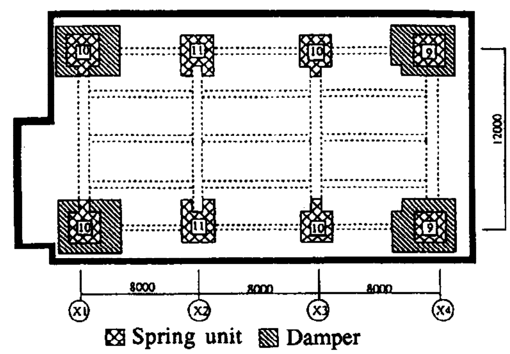


Fig.2 Arrangement of devices in the building

2.2 Composition of the system

2.2.1 Helical steel spring
Several helical steel spring are used as a spring-unit. Generally in a spring unit springs are touched on the top plates and bottom plates and resist only compression forces. But in this system springs can resist compression forces and tension force because both ends of the springs are fixed to the end plates. (See Fig.3)

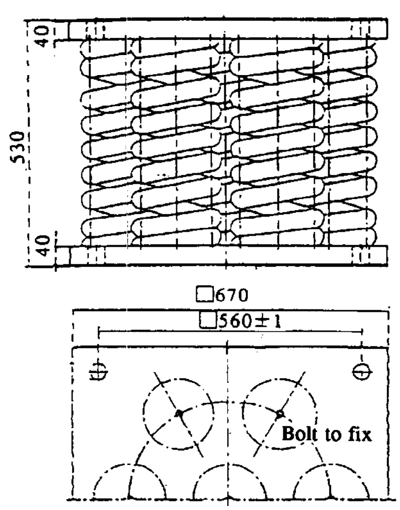


Fig.3 Spring unit

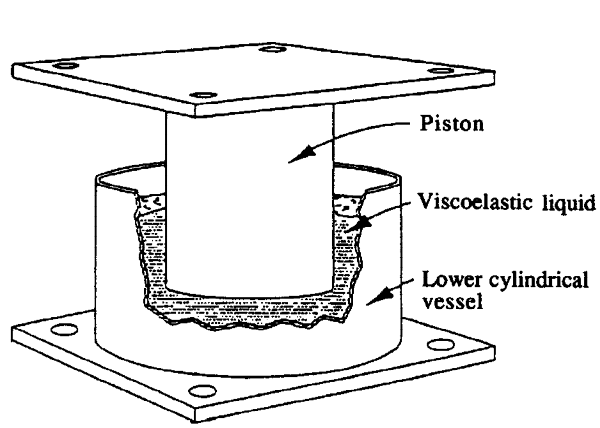


Fig.4 Damper

2.2.2 Viscoelastic damper

Viscoelastic damper is composed of three parts shown in Fig.4.

(1) Lower cylindrical vessel

(2) Viscoelastic liquid filled in the vessel

(3) Cylindrical piston submerged in the viscoelastic liquid

Cylindrical piston moves in the viscoelastic liquid three-dimensionally to the movement of the lower vessel and the vibration energy is decreased.

3. DYNAMICAL TEST OF THE DEVICES

Dynamical tests of the spring unit and the viscoelastic damper were done.

3.1 Dynamical test for the characteristics of the spring unit

3.1.1 Outline of the test

The spring unit is composed of seven helical steel springs fixed to the end plates. The natural frequency of the vertical direction of the spring is 2.5 Hz.

Test pattern is

(1) Horizontal valuable loading test with some displacement to the vertical direction.

(2) Vertical loading test with some displacement to the horizontal direction.

3.1.2 Cyclic horizontal loading test

(1) Loading

At first the spring unit is deformed vertically with the length of -20mm, -10mm, 5mm, 15mm, 40mm. And the unit is pushed to two horizontal directions in a right angle by a cyclic load of a oil pressure jack.

(2) Displacement

The displacement by loading is ±10mm in the first cycle, ±20mm in the second cycle, ±30mm in the third cycle and ±42mm in the forth cycle.

(3) Result

Fig.5 shows the relationship between the horizontal load and the displacement

Fig.6 shows the relationship between the horizontal spring coefficient and the vertical displacement.

From this figure the horizontal spring coefficient increases according to the increase of the the vertical displacement. The results of two horizontal directions loading are same.

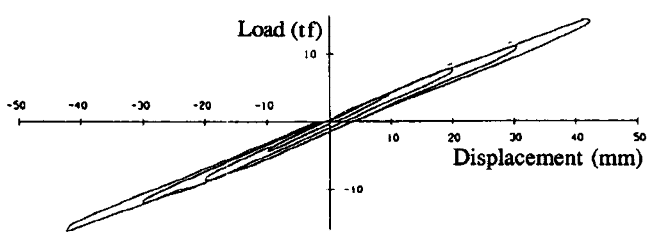


Fig.5 Horizontal load-displacement relationship

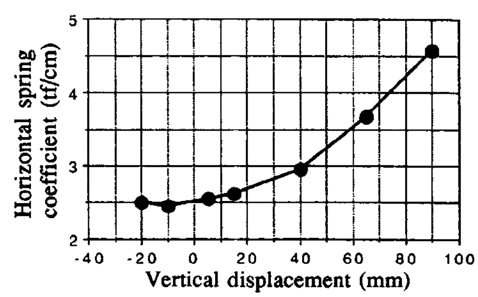


Fig.6 The relationship between horizontal spring coefficient and vertical displacement

3.1.3 Cyclic vertical loading test

(1) Loading

At first the spring unit is deformed horizontally with the length of 0mm, 30mm, 42mm. And the unit is pushed to the vertical direction by a cyclic load of a oil pressure jack.

(2) Displacement
At first the spring unit was pressed by 40mm from the free state. And then the displacement by vertical loading is ±20mm in the first cycle, ±30mm in the second cycle, ±40mm in the third cycle and ±50mm in the forth cycle.
(3) Result
Fig.7 shows the relationship between vertical load and horizontal displacement
Fig.8 shows the relationship between vertical stiffness and horizontal displacement.
From this figure vertical stiffness increases according to the increase of horizontal displacement.

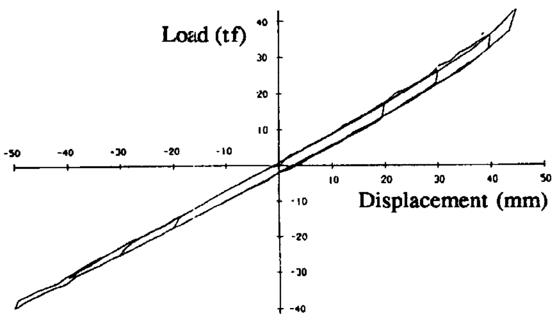


Fig.7 Vertical load-displacement relationship

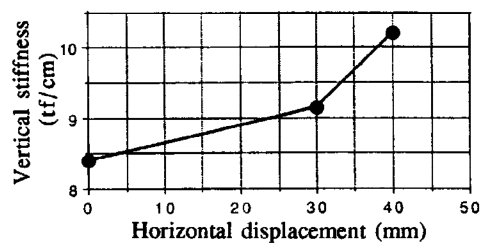


Fig.8 Vertical stiffness-horizontal displacement relationship

3.2 Test for the characteristics of the viscoelastic damper

3.2.1 Outline of the test
The vertical and horizontal characteristics of the viscoelastic damper were found by the random band noise forced vibration test and the sinusoidal forced vibration test of several frequencies.

3.2.2 Vibration test in the vertical and horizontal directions
(1) Vibration
The types of the vibration are the random noise forced vibration and the sinusoidal forced vibration.
The frequency range of the random noise forced vibration was between 0 to 5 Hz and 3 to 50 Hz. And the amplitude range was very small.
The amplitude range of the vertical sinusoidal forced vibration was 5~45mm in 1 Hz, 5~15mm in 2 Hz and 2~12mm in 5 Hz. And the amplitude range of the horizontal sinusoidal forced vibration was 5~30mm in 1 Hz, 5~15mm in 1.5 Hz and 2~15mm in 3 Hz.

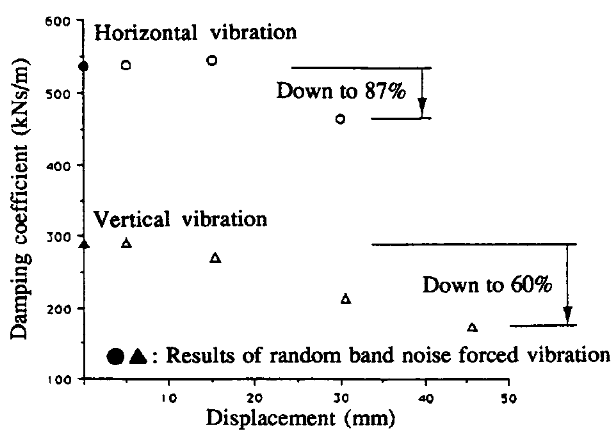


Fig.9 Displacement dependency property of damping resistance

(2) Result

From the test the damping coefficient decreases and the stiffness increases according to the increase of the frequency.

Fig.9 shows the displacement dependency property of the damping coefficient of the damper. Horizontal damping coefficient decreased to 87% of the value gained by the random noise forced vibration when the amplitude was 30mm. Vertical damping coefficient decreased to 60% of the value gained by the random noise forced vibration when the amplitude was 45mm.

4.SEISMIC RESPONSE ANALYSIS OF THE VIBRATION ISOLATED BUILDING

4.1 Analysis model

Analysis model was shown in Fig.10.
(1)Upper parts of the building were assumed as concentrated masses connected by springs.
(2)The ground floor was assumed as a solid floor.
(3)Spring elements and viscoelastic elements were put under the columns of the ground floor.
(4)The analysis model was assumed as the three dimensional model.
The datum for the analysis were shown in Table 1.

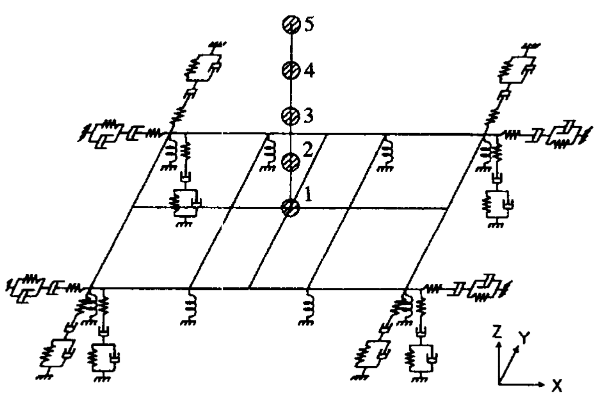


Fig.10 Analysis model of the building

Table 1 Input data of the building

Mass	Weight (tf)	Spring coefficient (tf/cm)		
		Kx	Ky	Kz
5	444.2	4897	2037	86120
4	508.5	5032	3528	90970
3	629.2	4143	3640	63300
2	462.4	4143	3640	63300
1	541.2	3007	4704	40250

4.1.1 Modeling of spring

The spring coefficient of the spring is valuable according to the deformation of the spring. So The model of the spring(shown in Fig.11) was composed of the vertical spring element and the multi spring element for the horizontal shear direction The values of both elements were given restoration characteristics from the experiments. The response calculation was done step by step with the tangential stiffness of each step.

4.1.2 Modeling of damper

The damper had the displacement dependency property of the damping coefficient from the experiments.
The dynamic characteristics of the damper was shown as the four elements model shown in Fig.12.

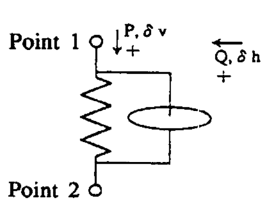


Fig.11 Isolation spring element

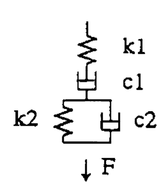


Fig.12 4 elements model

Table 2 Constants of 4 elements model

	Horizontal	Vertical
c1 (tf · s/cm)	0.5259	0.2132
c2 (tf · s/cm)	0.8251	0.2146
k1 (tf/cm)	33.38	11.15
k2 (tf/cm)	17.86	63.42

And the damping coefficients and the stiffnesses for every frequency were fitted according to the experiments. From Fig.9 the damping coefficients of the damper were decreased to 87% in the horizontal direction and 60% in the vertical direction at every frequency. The constants of 4 element model were shown in Table 2.

4.2 The procedure of the response analysis

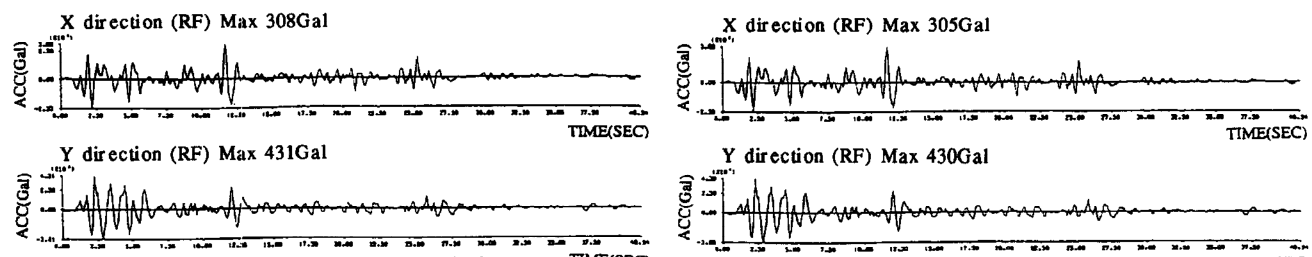
With the help of the three dimensional frequency response analysis program and the three dimensional time historical response analysis program the response analysis was done as follows.
(1) The spring elements of the spring unit were assumed as linear. And the three dimensional frequency response analysis program was run. Next the three dimensional time historical response analysis program was run. Then the similarity of the two wave forms of the two analyses was confirmed.
(2) The spring was modeled as the combination of the vertical spring element and the multi spring element for the horizontal shear direction The damper was modeled as the four elements model shown in Fig.12. Then the three dimensional frequency response analysis program was run.

4.3 Earthquake records used

Used earthquake records were modified from those of El Centro,Taft and Hachinohe Earthquakes. The strength levels of the earthquake records were 50 kine for the horizontal NS and EW direction vectors in the maximum speed.

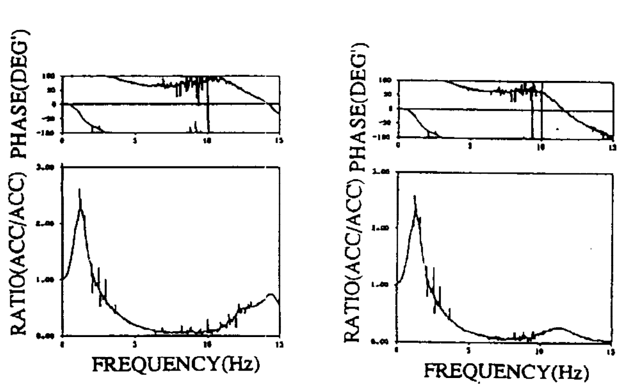
4.4 Result

The acceleration waves of X and Y directions of the roof floor got from the three dimensional frequency response analysis and the three dimensional time historical response analysis in the case of EW wave of El Centro to the X direction were shown in Fig.13. Both waves were very similar in the wave form and the maximum value.



(a) Frequency response analysis (b) Time historical response analysis

Fig.13 Acceleration response (RF X,Y-direction)



(a) Frequency response analysis (b) Time historical response analysis

Fig.14 Transfer function (RF X-direction)

Table 3 Maximum response value

	Part	Seismic wave								
		El-Cengro			TAFT			HACHINOHE		
		X	Y	Z	X	Y	Z	X	Y	Z
Displacement (cm)	R F	6.1	8.3	–	5.7	10.2	–	6.3	16.8	–
	4 F	5.1	7.0	–	4.9	8.5	–	5.4	14.0	–
	3 F	3.8	5.2	–	3.8	6.1	–	4.3	10.3	–
	2 F	2.7	3.7	–	2.9	4.1	–	3.4	7.2	–
	1 F	1.7	1.7	0.6	1.7	1.8	1.5	2.1	3.0	0.8
	①X1-Y1	1.7	1.8	3.1	1.7	1.8	3.9	2.1	3.1	5.5
	②X1-Y2	1.7	1.8	3.4	1.7	1.8	3.2	2.2	3.1	3.3
	③X4-Y1	1.7	1.6	3.5	1.7	1.7	3.0	2.1	2.8	3.1
	④X4-Y2	1.7	1.6	3.2	1.7	1.7	4.9	2.2	2.8	5.2
Acceleration (Gal)	R F	531.3	317.6	–	428.2	522.4	–	408.6	707.4	–
	4 F	399.6	273.8	–	354.2	377.2	–	355.3	572.9	–
	3 F	317.5	227.4	–	283.3	249.3	–	332.4	439.8	–
	2 F	283.8	192.5	–	254.0	270.9	–	342.8	373.1	–
	1 F	270.7	198.4	167.4	288.4	343.5	462.0	359.6	287.9	233.2
	①X1-Y1	270.1	196.9	274.5	285.1	342.0	459.1	359.4	292.9	310.0
	②X1-Y2	271.2	196.9	434.1	291.7	342.0	369.9	359.7	292.9	332.8
	③X4-Y1	270.1	200.0	480.6	285.1	347.5	768.6	359.4	282.2	414.6
	④X4-Y2	271.2	200.0	316.4	291.7	347.5	727.8	359.7	282.2	353.9

The transform functions of the two response analyses were shown in Fig14. Both were very similar under 10 Hz but over 10 Hz the value of the time historical analysis were smaller than that of the frequency response analysis.
The analysis results were shown in Table 3. In the analysis three dimensional earthquake force was used as NS wave to X direction and the vector in the maximum speed of 50 kine.

5.SHAKING TABLE TEST OF THE ISOLATED BUILDING MODEL

Here the results of the three dimensional shaking table test and the simulation of the isolated building model are written.

5.1 Shaking table test

5.1.1 Specimen

The specimen was designed to have the same natural frequency and the same damping ratio as the real building. The isolation system was composed of six springs and four dampers. The accelerations of the top and bottom of the flame and the relative displacement between the bottom of the flame and the top of the shaking table were measured. Fig.15 shows the model and measurement points.

5.1.2 Loading

(1) Sinusoidal sweep vibration
The specimen was shaked with the sinusoidal sweep wave in the direction of the longer side(X), the shorter side(Y) and the vertical direction(Z). The acceleration was 20 gal and the range of the vibration frequency was between 0.3 Hz and 10.0 Hz.
(2) Seismic vibration
Taft wave , El Centro wave and Hachinohe wave were used for the input vibration of the shaking table. For each seismic wave the specimen was shaked in the Y direction only, Y and Z directions and three direction.

5.2 Analytical method

The analytical method of the shaking table test was same as the one written in the former paragraph. Analysis model was shown in Fig.16. The upper structure was assumed as a shear beam element and the weight of the specimen was concentrated in two masses separated in the top and the bottom.
The material properties of the analysis model was decided from the results of the random band noise vibration test without the devices of isolation.

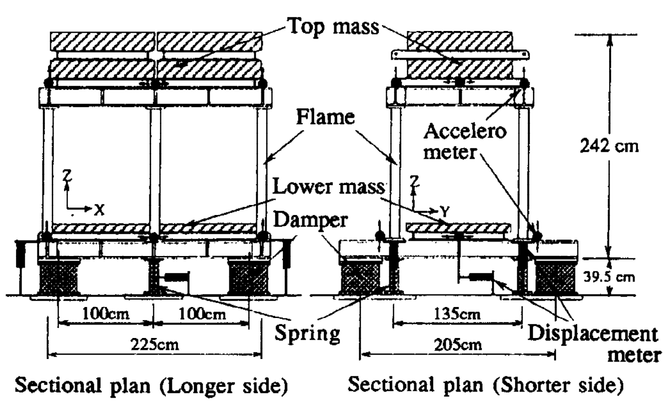


Fig.15 Specimen

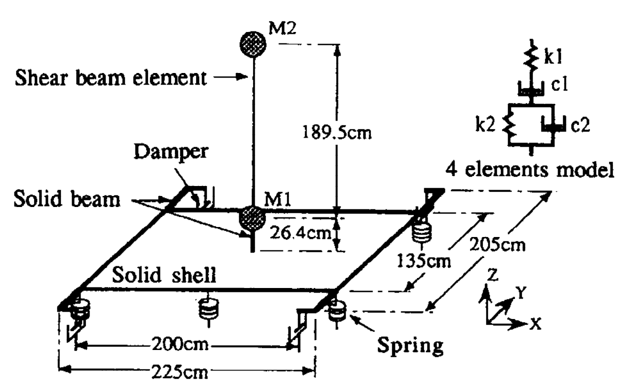


Fig.16 Analysis model

5.3 Comparison of the shaking table test and the simulation

5.3.1 Property of vibration

The natural frequencies in both cases were very similar. The amplitude of the simulation was a little smaller than that of the shaking table test.

5.3.2 Seismic vibration

Y direction time history by the three dimensional vibration of Taft wave were shown in Fig.17. The amplitudes of the simulation were smaller than those of the table test. But the values of acceleration and displacement were very similar. the similarity told that the modeling was proper.

The maximum response acceleration ratio of the model for the maximum acceleration of the shaking table were shown in Table 4. In the cases of El Centro wave and Hachinohe wave the results were with one dimensional vibration. In the case of Taft wave those were with one ,two and three dimensional vibration.

The response acceleration ratio increased little horizontally. But it increased bigger vertically in the three dimensional vibration than in the two dimensional vibration.

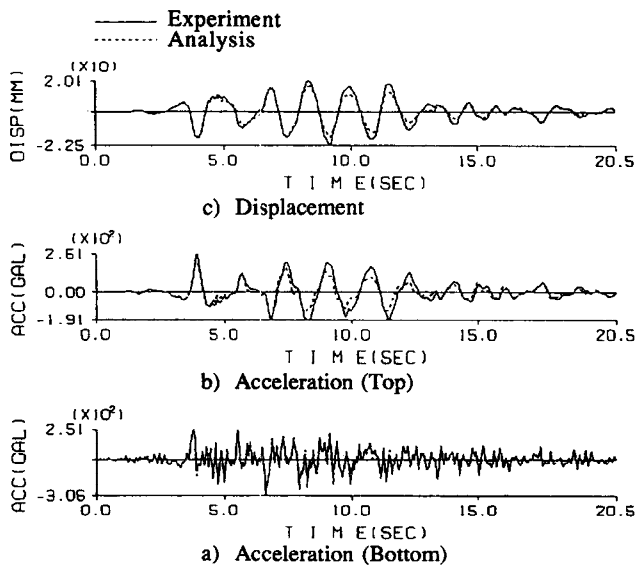


Fig.17 Y-direction time historical wave (on TAFT 3-D)

Table 4 Mzximum acceleration response amplitude

	Experiment			Analysis		
	Y		Z	Y		Z
	Top	Bottom		Top	Bottom	
EL CENTRO One dimension	0.61	0.77	—	0.55	0.81	—
Hachinohe One dimension	0.67	0.73	—	0.66	0.83	—
TAFT One dimension	0.71	0.89	—	0.66	0.93	—
TAFT 2 dimension	0.69	0.91	1.65	0.64	0.92	1.59
TAFT 3. dimension	0.75	0.91	2.69	0.68	0.92	2.45

6. CONCLUSION

A four storied building was designed and the maximum response were certified under the permitted one. From our investigations the followings are concluded.

1) The vibration isolated building supported by spring and viscoelastic damper contributes effectively for reducing vibration and structure borne noise caused by traffics.

2) The characteristics of the devices can be modeled by 4 elements model and multi-direction shear spring.

3) The 3 dimensional analysis of the models shows a good coincidence with the shaking table tests and it is useful for analyzing a real building with the vibration isolation system.

4) The design of a four storied building with the vibration isolated system has been done for construction.