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THE APPLICATION OF RESPONSE CONTROL DESIGN USING MIDDLE-STORY ISOLATION SYSTEM TO HIGH-RISE BUILDING

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SUMMARY

This report, represent the characteristic of the high-rise building with middle-story isolation interface. The total height of this building is 120 meters (total number of story is 25). The construction of this building has been continued from March 1, 2002. And it will be finished until July 2004.

First, The outline and design concept of the above building is represented. The building comprises office space at the upper floors (number of floor is 14) and a hotel space at lower floors. And especially, the large glass atrium is supplied at the lower floors (the ration of open space area is about 50%). On the principal feature of structural design, the following structural system is represented. At mid building (approximately 50 meters height, between 11-floor and 12-floor), the seismic isolation interface is applied to this building.

Secondly, the effect of the above isolation system and structural design concept are discussed. There are few restrictions involved in planning seismic isolation interface at mid building level. On the other hands, the response of the building to earthquakes is greatly reduced by introducing the seismic isolation interface. Typically without the seismic isolation interface the upper and lower structures would behave in a linear manner during a strong earthquake and be at greater risk for extensive physical building damage. Utilizing this system allowed greater freedom and ease of building design.

At last, with the above isolation system, the feature of the response of building to earthquake is described. The above isolation interface controls seismic vibration by utilizing a concentrated energy absorption mechanism. In this system the vibration energy of the earthquake is changed into plastic hysteretic energy in the damper of the seismic isolation interface. The seismic response of this building based on dynamic numerical analysis is represented. And the influence that the vertical position of isolation interface is applied at middle story is showed. Especially, the deformation mechanism and the energy absorption in the isolation interface are investigated.

INTRODUCTION

One of the characteristics of the seismic isolation structure is that the response shear force of the building during an earthquake is less than that of regular structure without seismic isolation system.

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Because the natural period for vibration of the structure is mainly decided by the natural period of isolation interface, the natural period of building extend. In the case of middle story isolation, it is not an exception, either. With extension of natural period, the seismic response shear force is reduced. This is called the isolation effect.

Another characteristic is that majority of energy acting on the building during an earthquake is absorbed by the damper disposed at the seismic isolation interface. Therefore, it is able to say that the isolated structure is the seismic response control structure with concentration from the damper. This structure is distinguished from ordinary passive seismic control structures by dispersion of damper on any stories.

The structure described in this report, the name of building is “Shiodome Sumitomo Building”, was planned around absorption of energy, the above second feature of isolation structures.

In Japan, the isolation structure is classified into base-isolated structures or middle-story isolation structures according to the level of seismic isolation interface. Generally, there are so many case of the base-isolated structure that has their isolation interface at ground level or under basement.

And in the case of mid story's isolated structure, the majority of examples have the interface at the top or bottom of the 2nd floor's support column. It intends to use under ground space and seismic isolation interface effectively (parking etc.).

For the example of an actual mid story's isolation structure, there is "Koraku 2-Chome building”[1] in Japan. The total height of this building is about 58m. The total height of the described building in this report, “Shiodome Sumitomo Building”, is about 120m. A building 60m or more is called “hi-rise building” or “skyscraper” in Japan. In terms of the volume (area, height) and the height of position of the seismic isolation interface, the building described in this report is the biggest middle story isolation building in the world.

The level of the isolation interface is decided with regards to both architectural planning and structural planning. It is necessary to sufficiently study basic structural and vibration features, because according to the level of the isolation interface, the structure's vibration characteristics (natural period and vibration mode) and response for seismic wave varies.

DESIGN CONCEPT & OUTLINE OF BUILDING

This Building is being constructed at “Shiodome metropolitan development area” in Tokyo, Japan. And this building is a 25story complex building containing both hotel and office space. An outline of the building is available follow, and Photo.1 shows a perspective of this building.

The three most important concepts for the architectural planning of this building were:

1. The upper floor's office space must be open. It should be free of columns, allowing a clear view and increasing the flexibility and comfort of the office.

2. Although the hotel is arranged on the lower floors, this space has superior amenities facing the atrium. And this atrium must be planed close to station (north side in Fig.3) as possible. Because the atrium serves as the main entrance to the building.

3. In order to meet the owner's request of a high seismic grade performance, an isolated structure or response control structure will be adopted.

Floors twelve through twenty-five are office. The office space is designed the large space based on the above concept-1. The office's framing plan is shown in Fig.1. The structure is rahmen frame with non-bracing. The column spacing is 12.8m x 22.5m. For the purpose to maintain the adequate horizontal stiffness, the steel tube column is filled with concrete.

The 11th floor is open to the outside. And the 12th floor is the seismic isolation interface. The isolation interface plan is shown in Fig.2, while Table 2 shows the properties of the isolation device. The isolation interface is composed of 41 natural laminated rubber bearings located under columns, 100 lead dampers and 14 steel dampers.

Photo.1 Perspective

Table.1 Outline of the Building

Building name	: Shiodome Sumitomo Building
Owers name	: Sumitomo
Design	: Nikkenn Sekkei
Location	: Shiodome Tokyo Japan
Number of basement floors	: 3
Number of stories above ground	: 25
Typical floor area	: 4,339 m2 109.6 m x 39.5 m
Standard floor height	:4.2 m
Total height	: 126.1 m
Typical bay size	: 12.8 m × 22.95m
Basement structural type	: Spread foundation (Steel-reinforced concrete)
Structural type above ground	: Steel
Typical column size (office)	: 1100φ × 36
Typical girder size (office)	: H-1150×550×14×32
Typical column size (hotel)	: □ - 900 × 900 × 65 × 65
Typical girder size (hotel)	: H-800×400×14×32

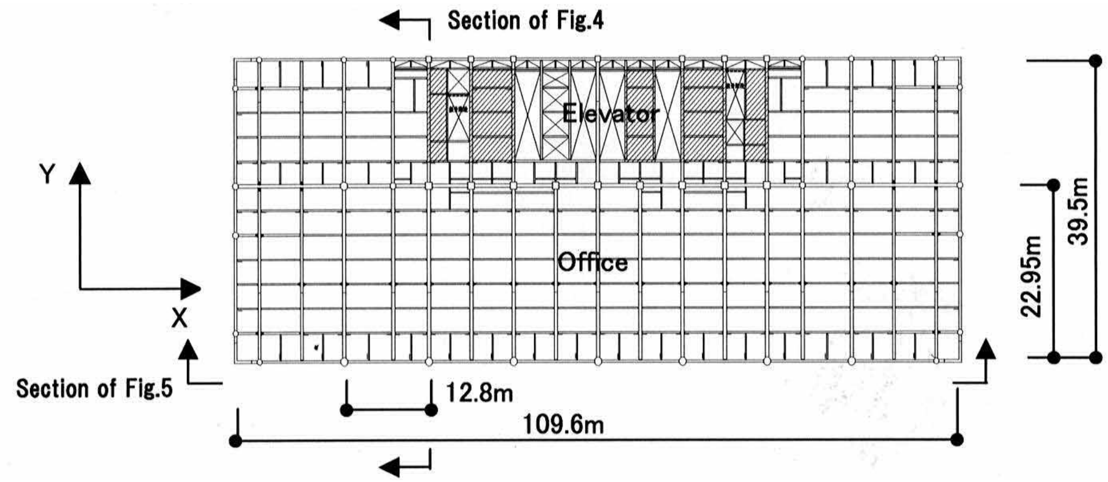


Fig.1 Framing Plan (Office)

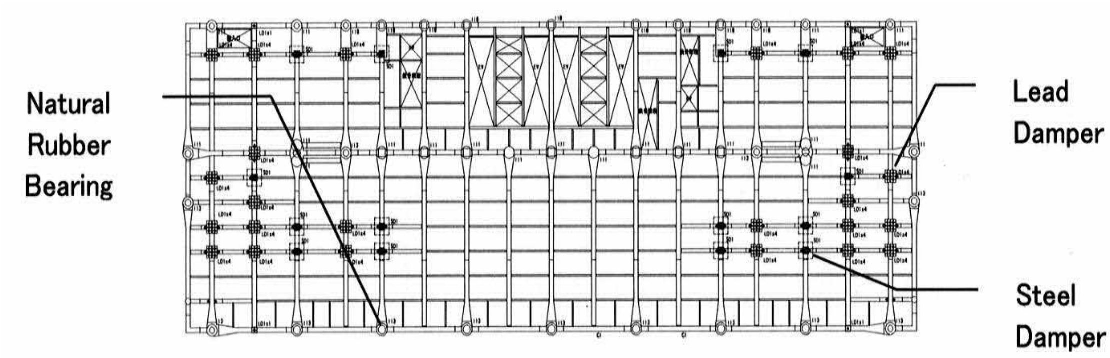


Fig.2 Framing Plan (Seismic Isolation Interface)

Table 2 Property of Isolation Device

Device	Diameter	1 st stiffness	2 nd stiffness	Yield force	Number
Natural Rubber Bearing	1300 mm	1.41kN/mm	-	-	13
	1100 mm	1.98kN/mm	-	-	19
	1000 mm	2.34kN/mm	-	-	9
Lead damper	-	26.50kN/mm	-	220kN	100
Steel damper	-	4.84kN/mm	0.157kN/mm	250kN	14

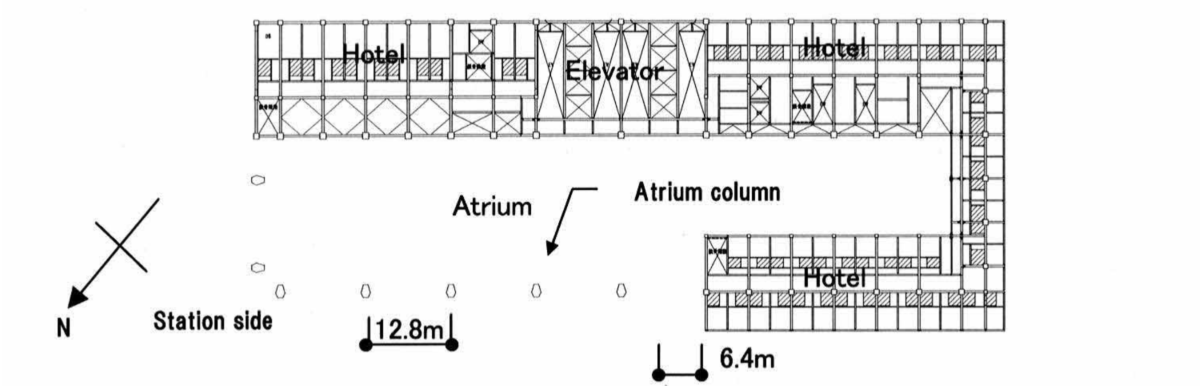
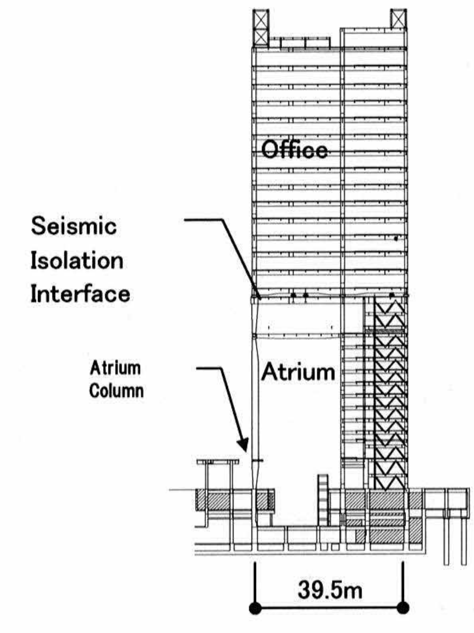
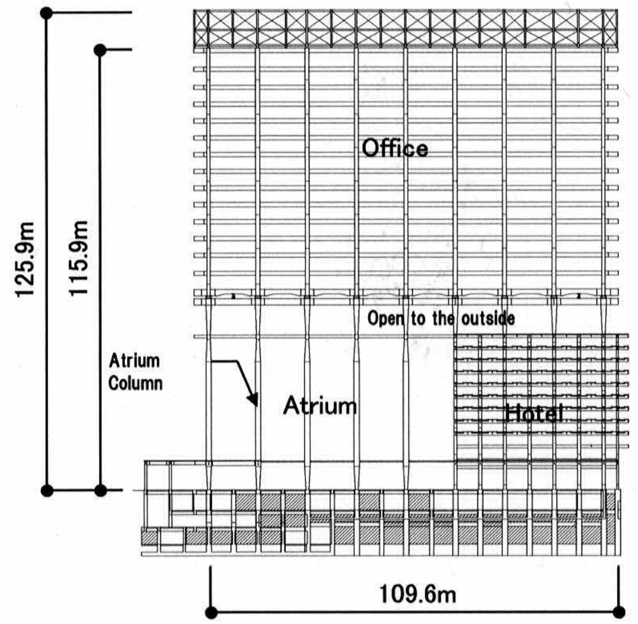


Fig.3 Framing Plan (Hotel)





* the position of section of the above figures, refer to Fig.1

Fig.4 Framing Elevation (Y-frame) Fig.5 Framing Elevation (X-frame)

Photo.2 Construction of Isolation Interface

The maximum diameter of rubber bearing is 1300mm. A picture of the girder and rubber bearing at the isolation interface is showed in Photo.2. The rubber bearing is installed between upper and lower rigid girder. The maximum size (height) of these girders is 1700mm.

Both of these lead and steel dampers are hysteresis type energy absorbers. The lead and steel dampers are connected to rigid beam too, and shear force that occurred at damper is translated through upper and lower slab. The yield shear force of total dampers is about 25500kN.

Photo.3 Construction of Atrium column

When designing the above seismic energy absorber, we must consider the most suitable total yield shear force of dampers for response performance to seismic vibration. Further, the yield shear force of damper and the deformation of the isolation interface under strong wind load must be careful. As a result, we decided the number of dampers that should be elastic at strong wind (500 year return expectation value).

Floors one through ten are hotel's spaces. The hotel's framing plan is shown in Fig.3. The framing elevation is shown in Fig.4 and Fig.5. The hotels span is 6.4m in girder span direction (it is half of office span), and the area of the large atrium is half of the standard floor area (about 4,300m^2). The height of atrium is about 40m. And the building provides the atrium space as partial arrangement on structure (based on concept-2). Then, in order to maintain the lower story's proper stiffness and torsion stiffness, the lower structure is designed as a rahmen structure with a seismic brace considering the position and the axial stiffness of brace.

The Atrium structure is constructed of 7-slender columns. The section of the column is Hexagon, and welded box consisted of steel plates (thickness is 36mm and 70mm). And the top and bottom of column is steel casting, the wide of top section is smaller than center section, the bottom of column is pin detail shown in Photo.3. These columns are about 40m long, to prevent buckling, and support large vertical permanent load (about 20,000 kN).

THE CONCEPT OF INTRODUCTION OF MIDLLE STORY ISOLATION SYSTEM

Decision of Response Control System

For architectural request, the large space for offices on upper floor and for the atrium on the lower floors, we reduced the number of horizontal resisting elements, columns and brace, to obtain. In order to maintain the open space (atrium) and the large elevator duct, the lower structure, especially, has a flexible frame. Thus, in order to build flexible structure, reduction of seismic response shear force is indispensable, and it is common to adopt a certain seismic response control system.

In the case of this building, because there is not structural frame suitable for arranging the response control element on each floor, especially on lower floor, the seismic isolation interface concentrating the hysteresis type energy absorbers is arranged at mid floor.

We call this seismic response control structure a "Concentrated type response control structural system". On the other hand, we call the general passive response control structure a "Dispersion type response control structural system". In the case of this building, we judged the "Concentrated type response control structural system" superior to the dispersion type based on its efficiency for absorbing seismic energy, and the building has increased earthquake safety as a result.

That is to say, it is possible to avoid the following risks.

1. Stress concentrates as result of the shear force fluctuation at each story according to either the damage of the main structural element or the yield of the response control element

2. Deformation under torsion of building occurs as a result of the yielding of the response control element causing the horizontal stiffness of each frame to change

We decided the core of the structural design concept is that the main element (column and girder) at the upper and lower sections (stories) without isolation interface will remain elastic during strong earthquake, and the displacement of each stories is not so large (displacement equivalent to story's angle 1/200). This is especially important for the lower flexible section (stories), and became possible using a "Concentrated type response control structural system".

Terms of Introduction

When we decided level of seismic isolation interface, we considered not only architectural plan but also the following structural restriction.

1. Even if a large horizontal deformation occurs in isolation interface during earthquake, there needs to be no trouble.

2. In-plane stiffness of upper and lower floor of isolation interface is rigid, because the horizontal shear force is translated between upper and lower isolation interface.

According to the restriction-1, the use of the upper floor is different from the lower (office & hotel). Then there is an architectural condition of non-continuity between the upper and lower floors.

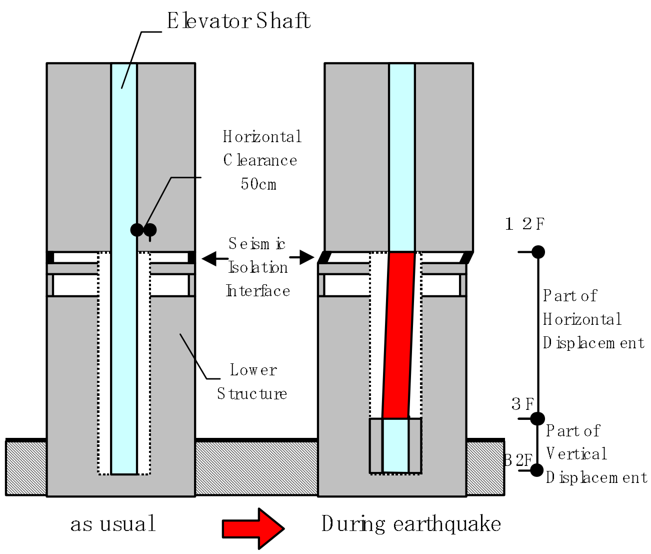


Fig.6 System of Elevator for Large Displacement of Seismic Isolation Interface

This condition is an important factor for adoption of middle story isolation. Concerning elevator shaft of the seismic isolation interface with a large horizontal displacement during earthquake, it is necessary to consider its adaptability to this displacement.

For this building, the different planning between the upper and lower sections provides the elevator shaft enough space to spread this displacement out over many stories because the elevator services the upper office floors does not stop within the lower floors (hotel area). We adopt the system for absorption of the large displacement of isolation interface at this lower part (height is 40m), as shown in Fig.6.

Furthermore, we made good use of the separation caused by the seismic isolation interface to position the columns on the upper floors differently than those on the lower floors. Those columns are suited to their space, with different cross section as appropriate (circular tube for the upper floors, welded box for the lower floors). The vertical and horizontal force is transferred through the rigid girder at isolation interface.

STRUCTURAL DESIGN CRITERIA

Design of Seismic Isolation Interface

In accordance with the stable deformation of multi-layered rubber bearing and clearance of various devices, we decide that the allowable displacement of the seismic isolation interface is less than 50cm. The permanent stress on laminated rubber bearing is within about 15 N/mm^2. In addition, the natural period concerned determined by the mass above the isolation interface and the liner stiffness of the rubber bearing is about 5sec.

The capacity of the damper is established with consideration for the allowable displacement of the seismic isolation interface (50cm). For practical design, we decide that the desired displacement of seismic isolation interface is less than approximately 35cm during a strong earthquake (refer to Table 6 and Fig.9), considering the safety of building. On the laminated rubber bearing, no “pull-out” occurs during the strong earthquake.

In order to minimize the response shear force of the structure, we analyzed the appropriate capacity of damper. The result of numerical response analysis using of the capacity of damper (as a parameter) was that the ratio of yield shear force of damper to the above ground weight of the building was about 2%.

When we consider that the damper should not yield during strong winds, the capacity of the damper is established as a 3% ratio of the shear yield force to the above ground weight. Because the building is near the sea, the design wind is strong for considering wind force reduction effects according to the density of high-rise buildings. And the passive area of wind is large (long side of building is about 100m). In the case of the described building, the number of required dampers was determined by the above factor of wind.

Design of Upper and Lower structure & Atrium column

The lower and upper structure without isolation interface is as above-mentioned elastic during strong earthquake, and allowable displacement is equivalent to story’s angle 1/200. However, the the allowable displacement of glass curtain wall of atrium is equivalent to story’s angle 1/150.

The structural design concept about this atrium column is that the column bear only vertical force including changing force during earthquake, do not bear horizontal force. Then the end of this column is designed as the lucid pin detail. The columns are elastic at strong earthquake.

INVESTIGATION OF RESPONSE CONTROL SYSTEM

Dynamic property & Analysis Model

The structure of this building was designed based on the investigation of the seismic response for strong earthquake. First, we analyzed using the simple model shown in Fig.7. This analysis model is 1-dimensional (horizontal direction) model. Finally, it has been analyzed using by the 3-dimensional model and the translation of horizontal force at the lower structure is especially investigated. In this report, the result for analysis using the simple model is represented.

The horizontal stiffness of each story is represented by the equivalent shear spring. The restoring force characteristic of this spring is linear (elastic). The gravity of each story is 1-mas with 1-freedom without torsion freedom.

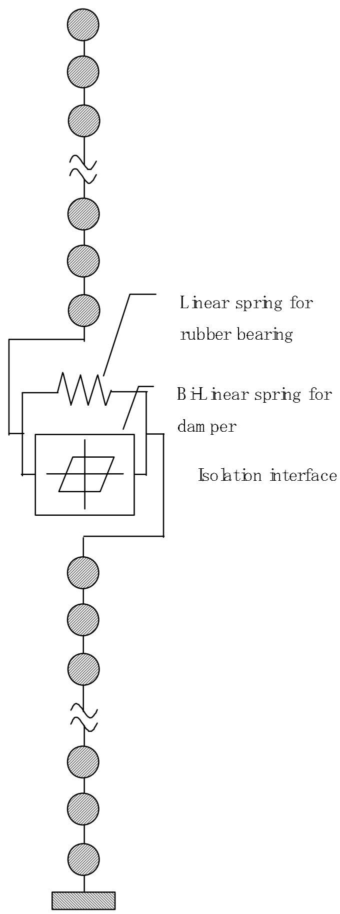


Fig.7 Dynamic analysis model

Table 3 Dynamic analysis model

Story	Gravity (kN)	Stiffness (kN/mm)	
		Direction-X	Direction-Y
R	56580	2131	1511
25	33950	2355	1734
24	33810	2883	2111
23	30170	2959	2168
22	30250	3010	2240
21	30350	3076	2336
20	30570	3271	2486
19	31070	3255	2484
18	31090	3355	2586
17	30650	3334	2589
16	30720	3429	2652
15	30800	3404	2631
14	31250	2987	2321
13	34990	3989	3106
12	39530	*1	*1
Isolation story	30680	1269	1083
11	30670	5601	4452
10	16880	5294	4791
9	16650	5245	4953
8	16850	5286	5204
7	16820	5364	5361
6	16830	5575	5707
5	17000	5707	5923
4	16930	6118	6344
3	25330	2301	2675
2	30210	2720	3178
1			

*1 Refer to Table 4

Table 4 Stability characteristic of isolation interface

Element	1sr-stiffness	2nd-stiffness	Yield shear force
Multi-rubber bearing	807 kN/cm	—	—
Lead Damper	26500 kN/cm	—	22000 kN
Steel Damper	678 kN/cm	22 kN/cm	3500 kN

In Table 3, the gravity and horizontal shear stiffness is described. The direction-X is direction for long neighborhood, and direction-Y is direction for short neighborhood of the building (refer to Fig.1).

Further, the analysis model has 26 masses as each story's gravity and 1 freedom per mass. The 1st floor is the position of input wave and is fixed. The weight of the entire building without substructure is about 716,000 kN, and the weight of upper part on the isolation interface is about 491,000 kN. Therefore, the weight ratio of the upper part to the lower is about 2.

The stability characteristic of isolation interface has been replaced to following. The stiffness of isolation interface is evaluated as the above-mentioned parallel spring

1. The rubber bearing is replaced to equivalent elastic spring.
2. The steel damper and the lead damper are elastic-plastic spring that has Bi-linear type restoring force characteristic (Table 4).

The coefficient of internal viscous damping is estimated from the mode damping as the stiffness proportional to damping. The damping constant of the upper and lower structures is 2%, while the damping constant of the seismic isolation interface is 0%.

Establishment of Static Design Force

The change in stiffness of the upper and lower structures changes the response shear force to several seismic waves that have various frequency features. In this design, after deciding level, stiffness and yield shear force of the isolation interface, we established the static design load for earthquakes through numerical analysis.

At the same time, the optimum horizontal stiffness of the upper and lower structures is established. In this analysis, the response story deformation angle is used as a parameter with a range from 1/300 to 1/150 [3].

Basic Effect of Response Control

For buildings with a middle story's seismic isolation interface, the vibration feature is affected by the 2nd or 3rd high number mode. The 2nd mode or the 3rd mode is due to the vibration mode of only the upper structure or lower structure. The above feature is not seen in the case of general base isolation structures.

In Table 2, natural periods are shown. And the vibration modes are described in Fig.8. The stiffness in direction for long neighborhood is as same as short. And the period of the building for its long side (X-direction) to be almost the same as for its short side (Y-direction).

Table 5 Natural Periods for Liner Stiffness of Rubber Bearing

Number of Mode	Direction	Natural period	Modal Participation Factor
1	X	5.95 (3.26)	7.47 (7.97)
	Y	6.04 (3.42)	7.45 (-7.82)
2	X	1.06 (1.06)	3.16 (2.44)
	Y	1.17 (1.15)	-1.56 (2.57)
3	X	0.96 (0.65)	2.60 (-1.76)
	Y	0.96 (0.70)	3.77 (1.87)
4	X	0.52 (0.48)	-0.11 (0.98)
	Y	0.60 (0.53)	-0.17 (-1.31)

The value in ( ) shows the Natural period at the time of initial stiffness.

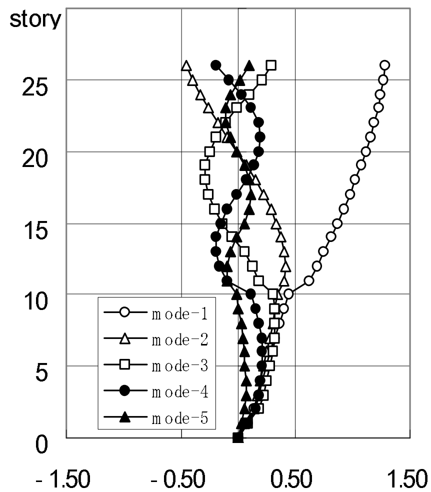


Fig.8.1 Vibration Mode For initial stiffness

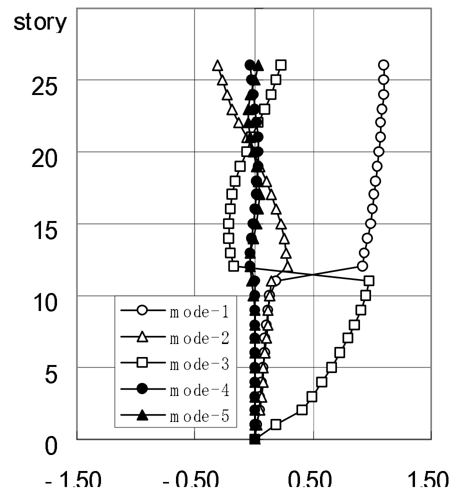


Fig.8.2 Vibration Mode For Liner Stiffness of Multi-Rubber

Table 6 Property of input wave for dynamic analysis

Input wave name for analysis	K1 wave	K2 wave	K3 wave
Max. Acceleration (cm/sec^2)	349	293	381
Max. Velocity (cm/sec)	48.8	52.9	54.6
Max. Displacement (cm)	42.0	51.9	38.4
Step time (Sec)	0.02	0.02	0.02
Analysis Time (Sec)	60.0	60.0	60.0

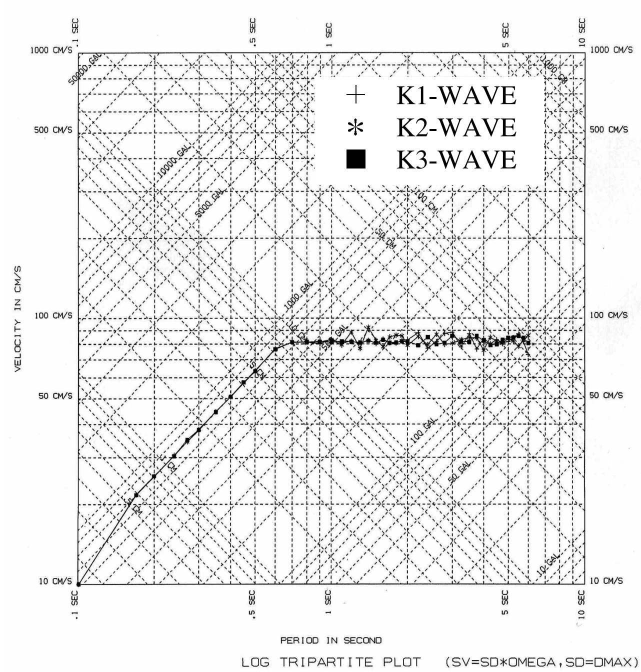


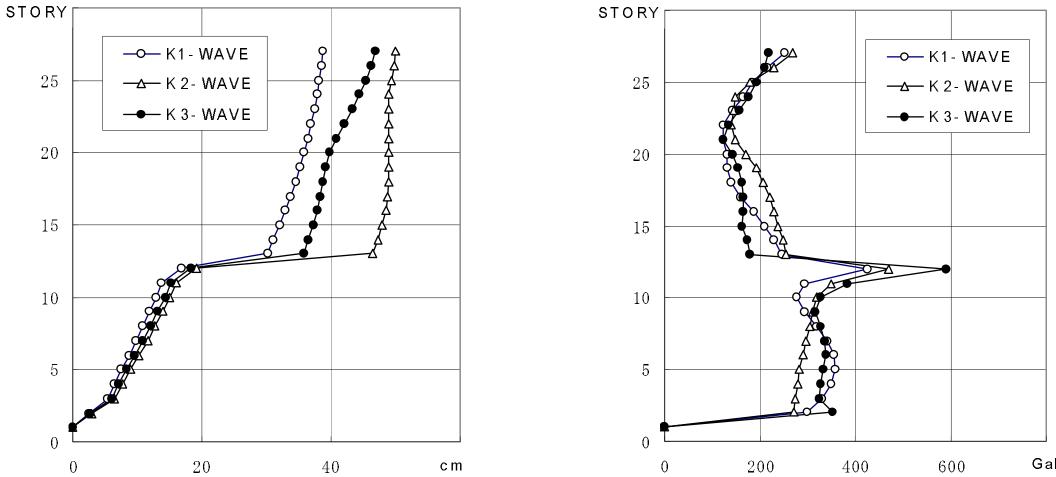
Fig.9 Pseudo-Velocity Response spectrum

Dynamic Response Analysis

Input wave for dynamic analysis

The seismic waves used for the response analysis are three simulated seismic wave. The pseudo-velocity response spectra of each wave are shown in Fig.9. These earthquakes are equal to 500 years return expectation value. These simulated seismic waves have a common target spectrum.

On the other hand, each wave has the phase characteristic of different observational waves. In Table 6, K1-wave has same phase characteristic as “HACHINOHE EW”, and K2-wave has same one as “TOHOKU U. NS.” K3-wave has same one as “JMA KOBE NS”.



Maximum Absolute Displacement Maximum Absolute Acceleration

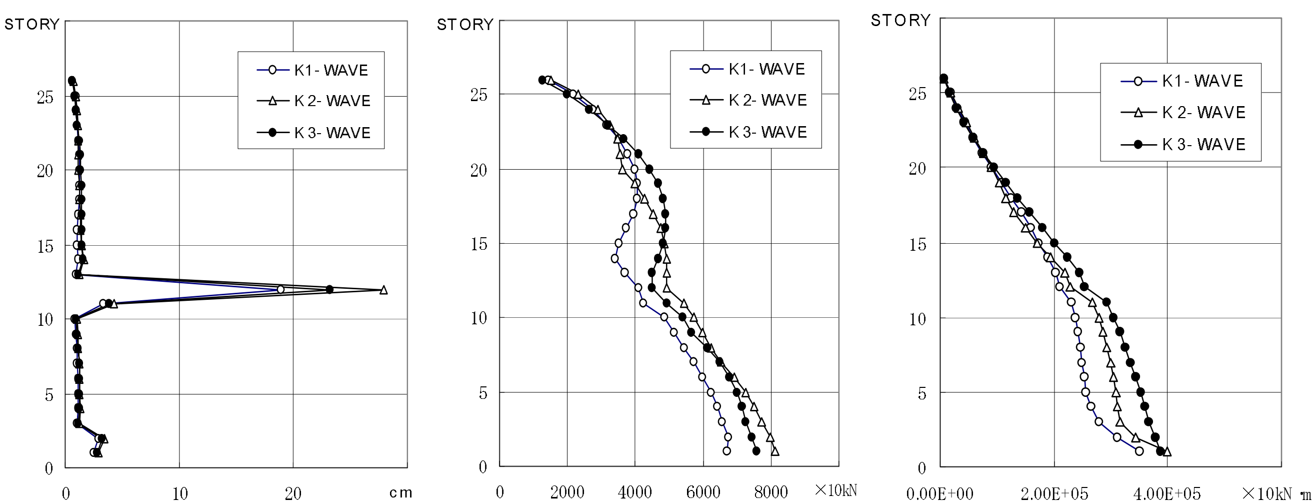
Fig.10 Result of Dynamic Response Analysis

K1-wave is low cycle wave, and K3-wave is high cycle wave. K2-wave is middle cycle wave (The time history of acceleration is shown inFig.12~Fig.14).

Result of response analysis

The result of dynamic response analysis is shown in Fig.10~Fig.12. At right side of Fig.10, Absolute Displacement is shown. The distribution of maximum displacement is as same as shape of vibration mode-1 (refer to considering only stiffness of rubber bearing in Fig.8.2). The several story displacements are presented at left side of Fig.11. The maximum displacement of isolation interface is about 30cm. And the displacements of other story without outside floor (11th floor) are about 1cm ~ 3cm, it is equivalent to the displacement below 1/200 of story deformation angle.

At left side of Fig.10, Absolute Acceleration is presented. The maximum acceleration is produced not on the highest story of a building but on the directly lower floor of isolation interface. This phenomenon can be understood to be the influence of the 3rd vibration mode shown in Fig.8.2.



Several Story Displacement Maximum Shear Force Maximum Overturn moment

Fig.11 Result of Dynamic Response Analysis

The maximum acceleration of lower floor at isolation interface is large, but the acceleration of other floor is not so large. Therefore, it can be said that the isolation effect is large as like the base isolation structure. The maximum response shear force and maximum response overturn moment is represented in center and right side of Fig.11. The above response is under the influence high cycle mode. On the other hand, reducing effect of isolation is shown. Especially, the response shear force and overturn moment at lower structure (lower story) is smaller than the same scale building.

In Fig.12, The time history of acceleration of input "K-1 earthquake wave" (a), the time history of displacement of upper and lower floor at isolation interface (b) the diagram of deformation of the building (c) and the time history of absorption energy so on (d) are represented. The displacement of lower structure increases at the same time with isolation interface, afterward, the only displacement of isolation increases so that Fig. 12 b) and Fig.12 c) may be shown. Therefore, the building shows not a motion that the vibration mode-1 and the vibration mode-3 (refer to Fig.8.2) have been independent mutually but the motion that interlocked.

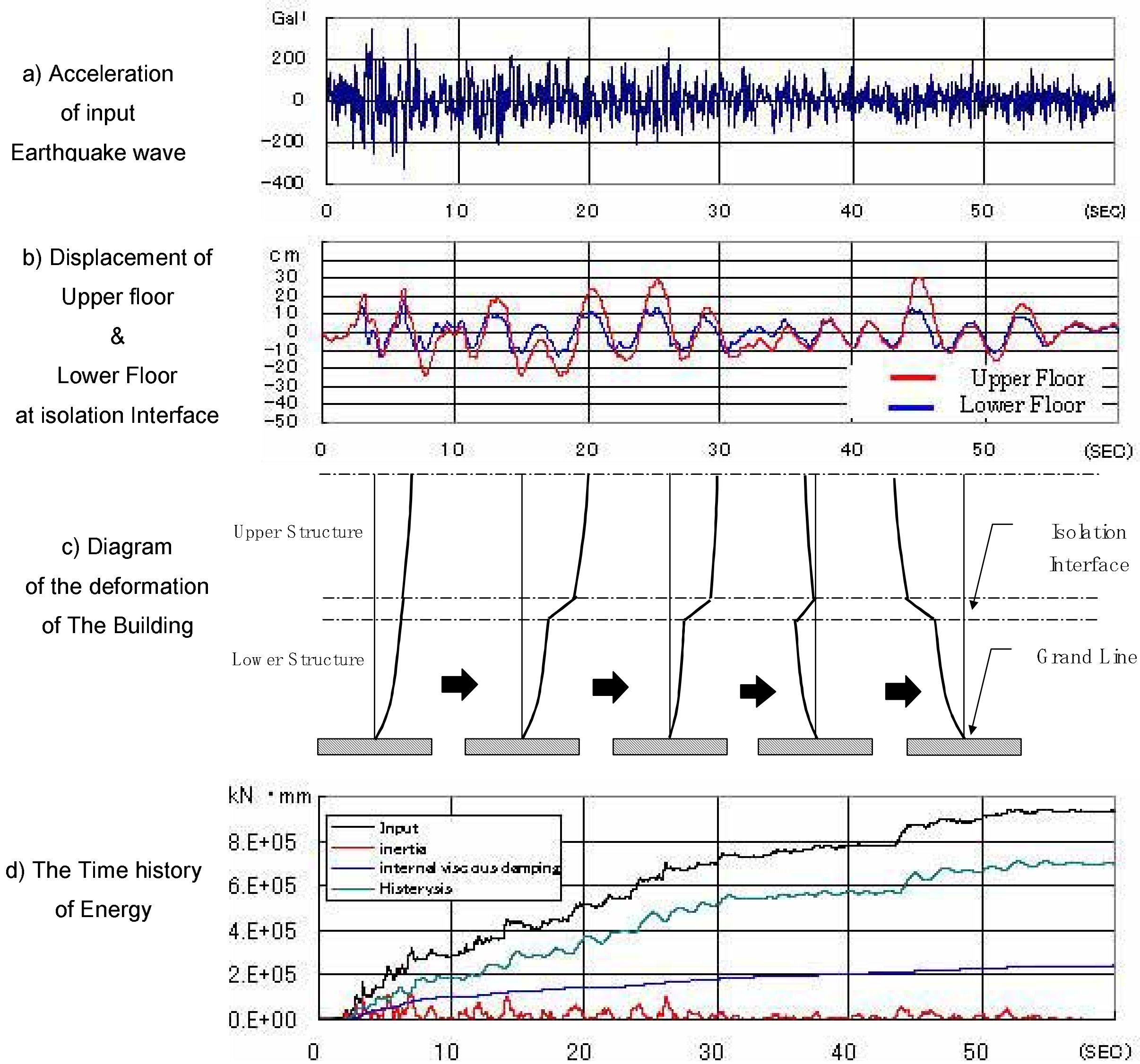


Fig.12 Result of time history of dynamic analysis for K1-wave

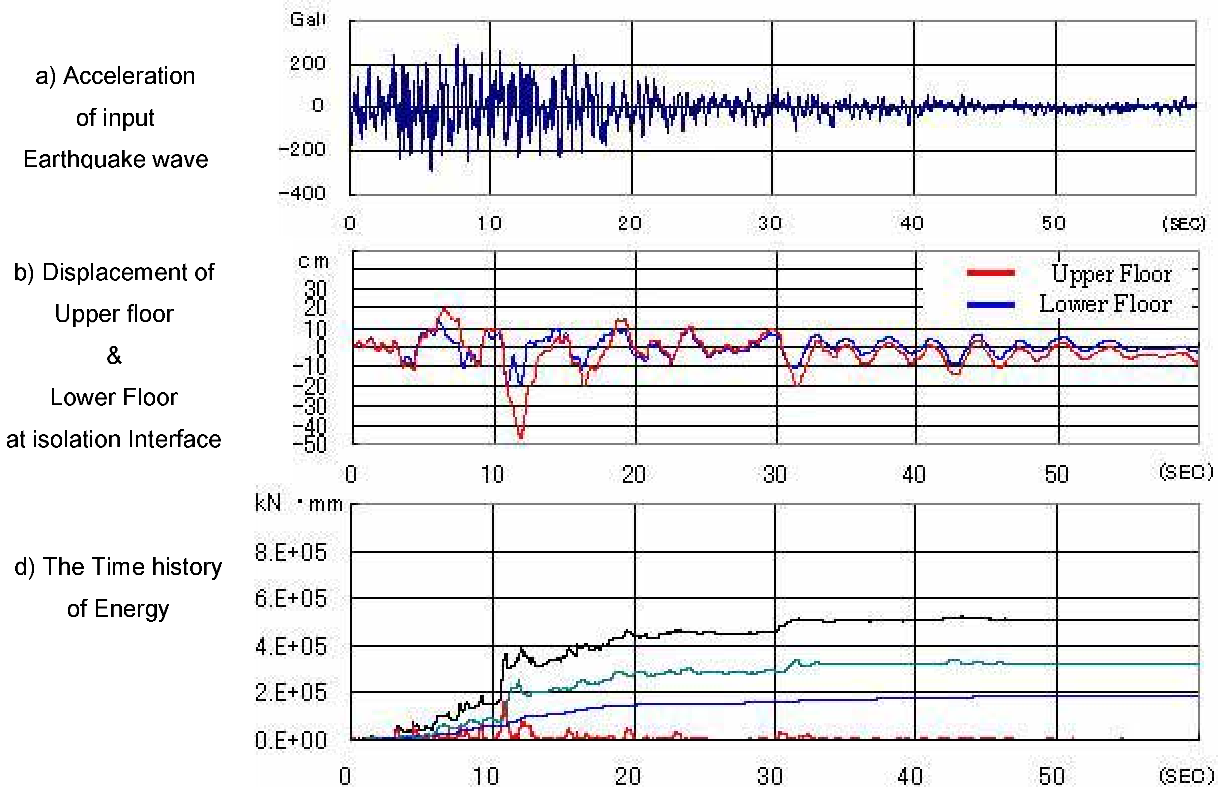


Fig.13 dynamic analysis K2-wave

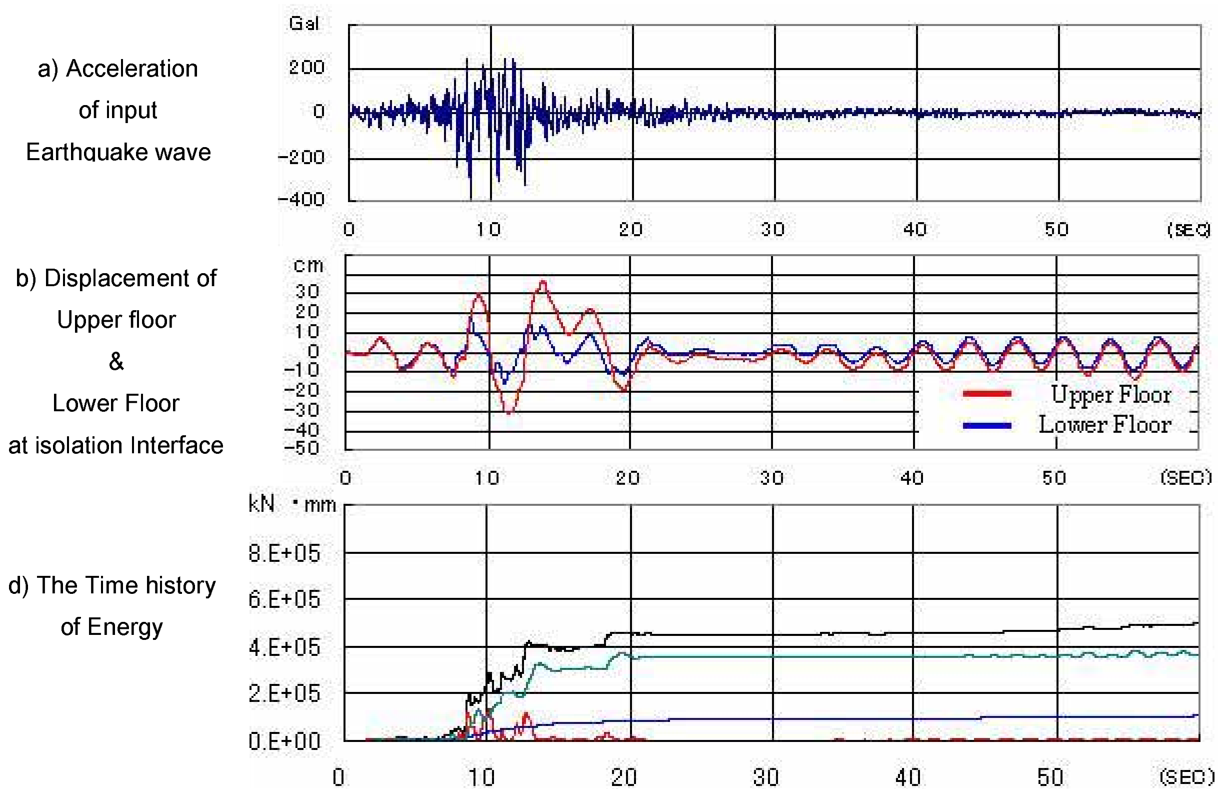


Fig.14 dynamic analysis K3-wave

In the process of turn of deformation, the deformation of lower structure goes ahead of isolation interface. In Fig.12 c), the transitive deformation of the building is described. In Fig.13 b) and Fig.14 b), the response displacement of isolation for other earthquake wave is shown. In the case of high cycle wave, the above behavior is remarkable.

The time history of energy is shown in Fig.11 d), Fig.12 d) and Fig.13 d). The black line is input energy due to earthquake. The red line is inertia energy and decreases with time. On the other hand, the blue line is radiation energy due to internal viscous damper, increases with time. And the green line is the strain energy of all story, the stiffness of the other story without isolation interface is elastic, then this energy is estimated as the absorption energy of histerysis damper at isolation interface. The absorption energy of isolation interface changes according to input wave, but the percentage is 70□`80% of the total input energy, the almost energy is absorbed.

CONCLUSIONS

In this report, we described the structural design outline of a high-rise building with the "Concentrated Type" response control system in the form of a middle story isolation interface. And the both advantage and attention of the structural design using the above response control system and how to solve it are shown.

Generally, in design of base isolated structures, the planning of an isolation interface is the bulk of the design. On the other hand, in the design of middle story isolation structure, the response of the structure is affected by the characteristic high frequency mode according to the vibration features of the upper and lower structures. Because the factors that determine the vibration mode of the building are not only the properties of the isolation interface (stiffness and capacity of damper), but also the stiffness of the upper and lower structures and the weight ratio between them, it appears that there are indefinite factors (parameters) for design and a complex investigation (analytical simulation) is required.

However, as shown in this report, not according to earthquake wave's vibration property, the damper of isolation interface absorb the almost vibration energy. This seismic system is stability seismic response control system for earthquake.

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