MIDDLE-STORY ISOLATED STRUCTURAL SYSTEM OF HIGH-RISE BUILDING

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ABSTRACT :

For buildings of normal earthquake-resistant construction, it is essential to provide their structural frame with sufficient rigidity and strength horizontally and vertically, ensuring a uniform distribution of rigidity and strength in the plane. To this end, it is typical that those buildings adopt the same type of construction and structural system. On the other hand, in buildings of general base-isolation construction, their upper structure, which is supported by a base isolation layer, undergoes lessened seismic forces and therefore is able to tolerate concentration of rigidity and strength. This makes them available for construction with any types of structural systems, which in turn allows new structural planning realizing a greater freedom in architectural design; the same type of construction and structural system for the upper structure is generally adopted. In contrast, when a high-rise building is provided with an isolation layer in an intermediate level, its upper structure, which is placed above the isolation layer, has high seismic resistance as a seismic isolation structure. And a mass damper effect contributes to decrease in seismic responses in the lower structure, ensuring high seismic resistance of a building. This paper describes the physical properties of a seismic isolation layer system which is built at an middle-story of a building. It also introduce buildings by which potentials for new architectural planning are proposed through the use of this system.

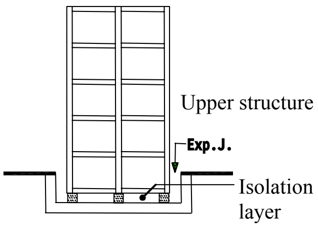
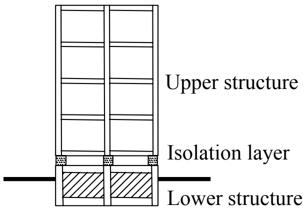
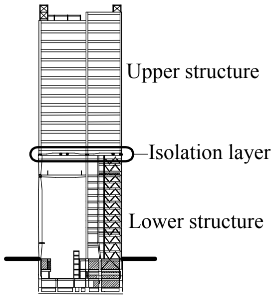
KEYWORDS: High seismic performance , Middle-story isolation , Concentrating seismic energy , Mass damper effect

1. CHARACTERISTICS OF HIGH RISE BUILDINGS WITH MIDDLE-STORY ISOLATED STRUCTURAL SYSTEM

By adopting a middle-story isolated structural system, planning that makes use of the following three characteristics is possible.

The first is that new structural schemes that formerly were not possible become feasible, so it is possible to increase the freedom of architectural planning.
By stacking different structural types (for example S structure or RC structure) or structural forms (for example pure Raman structure and wall structure) with an isolation layer in between to form a single structure, it is possible to provide a three-dimensional architectural layout for a building with the optimum structural type or form for different uses.
If it is possible to ensure relatively large stiffness compared with the laminated rubber bearings and largely elastic behavior in both the lower structure and the upper structure, almost all the seismic energy is absorbed by the isolation layer, so it is possible to design for no damage to the structural framework. As a result it is possible to adopt slender columns which only have to carry vertical loads and do not need energy absorbing capability. Also, it is possible to further reduce the response of the lower structure by adopting a vibration control structure.
The second is that in high rise structures employing a middle-story isolated structural system , the response of the lower structure is reduced by the mass damper effect to a fraction as a result of the isolation effect, although this effect varies depending on the ratio of the mass of the upper structure to the total mass of the superstructure. Also, so it is possible to ensure high seismic performance in which the whole building remains within the elastic range during the major earthquake.

Table 1 Characteristics of each structure

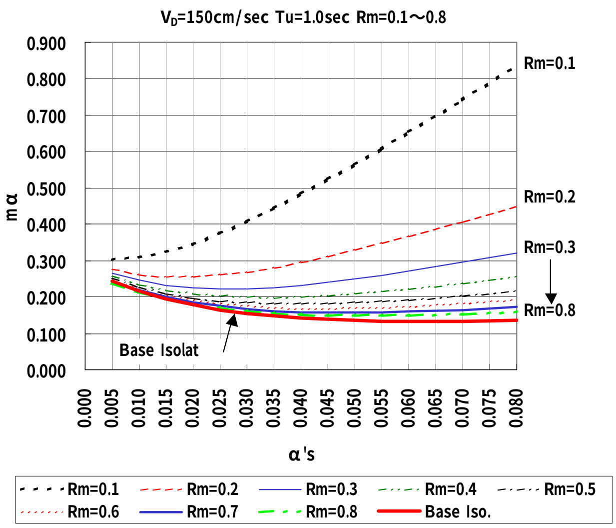
Foundation base isolation structure	Generally adopted middle-story isolated structure	Middle-story isolated structure with untuned mass damper effect
		
• It is possible to reduce the seismic input to the upper structure, so comparatively free structural planning is possible. • An expansion joint is needed around the building, which has a large impact on architectural planning. • It is necessary to make the upper structural form virtually the same, so it is difficult to adjust the structural form to suit the use.	• The seismic forces in the upper structure supported by the isolation layer are small, and the structural form is not chosen, so a high degree of freedom in architectural and structural planning is possible. • The lower structure must provide stiffness and resistance as foundations, so normally an RC structure with sufficient seismic shear walls is used.	• The upper structure has high seismic resistance as a seismically isolated structure, and a high degree of freedom in architectural and structural planning is possible. • As a result of the mass damper effect, the response of the lower structure is also reduced and the seismic performance is increased, so a high degree of freedom in architectural and structural planning is possible. • It is possible to adopt different structural forms for the upper and lower structures, so it is possible to adjust the structural form to suit the use.

The third is by providing an isolation layer at an intermediate level in an existing building with low seismic performance, it is possible to reduce the response in the major earthquake to within the horizontal force resistance of the lower structure, so seismic retrofit is possible with construction to provide the isolation layer at the intermediate level only, while the building is still in use.

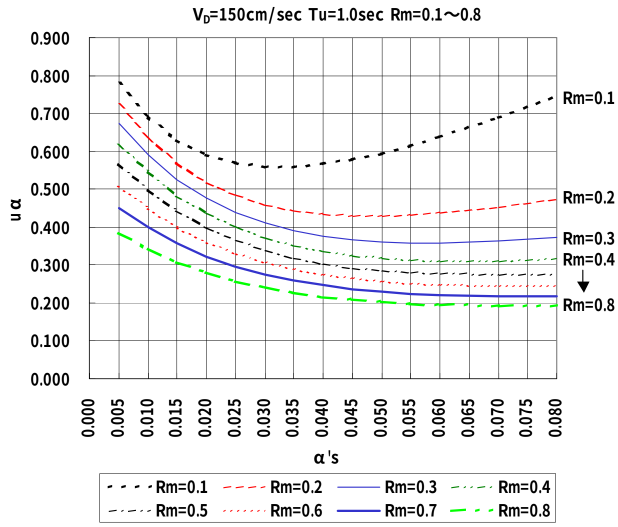
2. RESPONSE PROPERTIES AND DESIGN METHOD FOR HIGH RISE BUILDINGS EMPLOYING A MIDDLE-STORY ISOLATED STRUCTURAL SYSTEM

In a high rise building employing a middle-story isolated structural system, the product of the inertial force considering the upper structure to be a rigid body and the horizontal displacement is governed by the elastic strain energy accumulated in the laminated rubber bearings, so the ratio of the mass of the upper structure (R_m) with respect to the total mass above ground has a big effect on the response reduction effect on the building as a whole. High stiffness and resistance of the lower structure as foundations is not an absolute requirement, and provided the stiffness is large compared with the laminated rubber bearings and the resistance can ensure general elastic behavior, it is possible to concentrate the energy in the isolation layer. Almost all the seismic energy input into the building is absorbed by the dampers, so energy absorption capability similar to that for dampers for base isolation is necessary. Therefore, using the ratio of the mass of the upper structure (R_m) with respect to the total mass above ground as a parameter, response prediction analysis was carried out with an artificial seismic motion in which the input energy equivalent to the major earthquake motion was converted into a velocity value of V_D = 150cm/s. The maximum shear force coefficient in the isolation layer (${}_m\alpha$) and the response shear coefficient at the first story (${}_u\alpha$) plotted against the ratio of the damper yield force (α'_s) with respect to the total weight above ground are shown on the left and right of Fig. 1 respectively. From this figure it can be seen that if the mass ratio of the upper structure (R_m) is about 0.2 or higher, a mass damper effect can be obtained. With the optimum amount of damping similar to the case of base isolation, the optimum amount of damping increases as the mass ratio increases, but for a mass ratio of 0.3 or higher, the amount is in the range 0.03 to 0.05.

With high rise buildings having an isolation layer at an intermediate level, it is necessary to carry out a time history response analysis to determine the detailed behavior during an earthquake, but (Murakami et al ,2001) proposes response prediction equations for schematic design for use as a guide. The proposed response prediction equations were obtained from energy balance and a characteristic function obtained from modal analysis of the two-mass model, after checking that a multi-mass intermediate level isolation structure model could be replaced with the equivalent two-mass intermediate level isolation structure model. From this response prediction method, it is possible to numerically evaluate the specific effect of the energy input to the building, the mass ratio of the upper structure, the yield force ratio of the dampers, and the period of the isolated structure on the response shear force and relative deformation of the isolation layer, and the base shear coefficient of the lower structure. By comparing this response prediction method with the vibration response analysis results under the major earthquake for the "Iidabashi First Building, First Hills Iidabashi", it was found that the predicted values virtually enveloped the analysis values, so the method is effective as a response prediction method for schematic design. Also, from the results it was found that the optimum ratio of the damper yield force (α'_s) with respect to the total weight above ground was about 0.025 to 0.03.



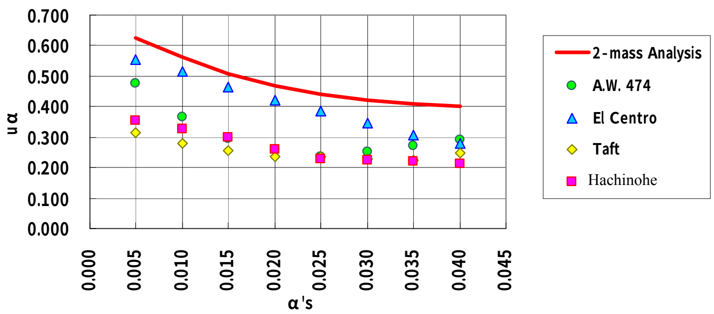
Response maximum shear force coefficient in isolation layer ${}_m\alpha_{max}$



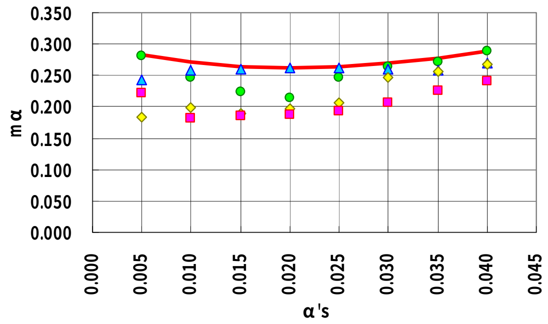
Response maximum base shear coefficient of lower structure ${}_u\alpha_{max}$

Figure 1 Maximum predicted response value in each part when the velocity conversion value of the energy that contributes to damage is V_D=150cm/sec

Comparison of theoretical values and analysis values
(Iidabashi First Building)



Comparison of theoretical values and analysis values
(Iidabashi First Building)



Response maximum shear force coefficient in isolation layer mαmax
Natural period of the isolation layer with isolators only: ${}_mT_f$=3.5sec
Damper elastic natural period of the isolation layer: ${}_mT_s$=0.5sec

Response maximum base shear coefficient of lower structure uαmax
Natural period of a 1 mass model formed from the total mass and the equivalent stiffness of the lower structure ${}_uK_{eq}$: T_u=1.0sec

Figure 2 Relationship between quantity of dampers and maximum response values in each part under the major earthquake (V_D=150cm/sec)

3. EXAMPLES OF HIGH RISE BUILDINGS ADOPTING A MIDDLE-STORY ISOLATED STRUCTURAL SYSTEM

3.1. Example 1 – "Iidabashi First Building, First Hills Iidabashi" in which the optimum structure and framing forms for each use were stacked vertically (Murakami et al , 1998)

Example 1 is a 14-story compound building comprising residential, office, and commercial facilities. External and internal views of the building are shown in Photo 1, and the framing elevation is shown in Fig. 3.

Use: Offices, condominiums, retail
Height: Height of highest part: 63.20m, eaves elevation 59.00m
No. stories: 1 basement floor, 14 above ground floor, 1 penthouse floor
Structural form: Steel reinforced concrete structure (in part CFT columns), reinforced concrete structure

• Rm (upper structure mass / total mass above ground) = 0.22
• α's (damper yield force / total mass above ground) = 0.03

Photo 1 External and internal views of Iidabashi First Building, First Hills Iidabashi

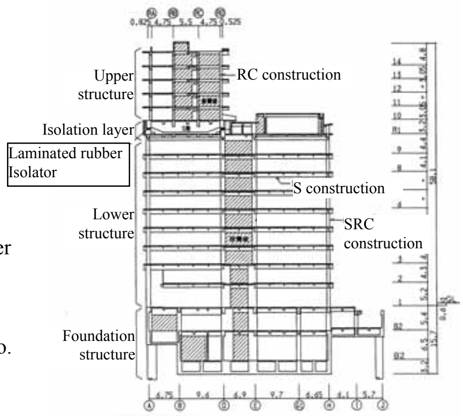


Figure 3 Framing elevation (in short direction)

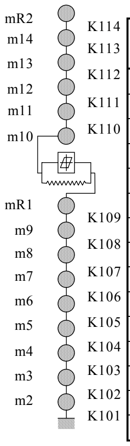
In this building an isolation layer was provided by using the equipment and piping space provided between the residential part and the offices part, to give an intermediate layer isolated structure with an untuned mass damper effect. In the office area, spaces with no columns were formed by using a steel framed structure, and in the upper residential area privacy was maintained with an RC wall type structure to give spaces with a high degree of freedom without beams and columns. Further, an expansion joint was not necessary at the ground level, so it was possible to maintain the necessary continuity with the surroundings as a commercial facility. The isolation layer comprised 800φ natural rubber laminated rubber isolators and lead dampers.

In order to determine the vibration characteristics of Example 1 with a middle-story isolated structure, a vibration response analysis was carried out using a vibration analysis model of the building. As shown in Table. 6, in the vibration analysis model the mass of the upper part of the building was about 22% of the total mass above ground, and the ratio of the damper yield stress to the total weight above ground (α's) was 0.03. The vibration analysis model was a 15 mass shear translation model, with 9 masses in the lower structure and 6 masses in the upper structure. Also, the internal viscous damping in both the lower structure and upper structure was assumed to be h1 = 0.02 in both cases. The seismic motion wave forms used in the analysis were three actually measured wave forms (El Centro NS, Taft EW, Hachinohe NS) and an artificial seismic motion wave form (ARTWAVE474), each with a maximum velocity of 50cm/sec. The artificial seismic motion wave form was produced using the phase characteristics of measured seismic wave motion wave forms, setting the acceleration response spectrum shape in the long period region so that in the velocity response spectrum Sv = 80cm/sec (h = 0.05). The response spectra of these seismic motion wave forms are shown in Fig. 4.

The response analysis results in the major earthquake for the short direction of the building are shown in Fig. 5.

The maximum response story shear force in the building compared with the case where there is no isolation layer is about 1/5 for the upper structure , and about 1/2 in the lower structure, so the response story shear forces are greatly reduced. At all stories the stresses in the structural frame were maintained within the limits for elastic resistance, so a high seismic performance was maintained.

Table 2 Dynamic analysis model



Name of mass point	Mass ($t*s^2/cm$)	Name of Spring	Spring Constant (t/cm)
mR2	1.69	K114	9614
m14	2.35	K113	16908
m13	2.35	K112	20502
m12	2.36	K111	23320
m11	2.36	K110	35093
m10	4.10	KH	See below
mR1	12.95	K109	7306
m9	5.01	K108	7604
m8	5.01	K107	8115
m7	5.19	K106	8714
m6	5.28	K105	9301
m5	5.29	K104	10011
m4	5.31	K103	11173
m3	5.64	K102	13062
m2	5.54	K101	12541

KH=IK+F(x)
IK=54.0t/cm
F(x):Bi-Linear type
Initial stiffness=82.83t/cm per α's=0.001
Yeild strength=69.03t per α's=0.001

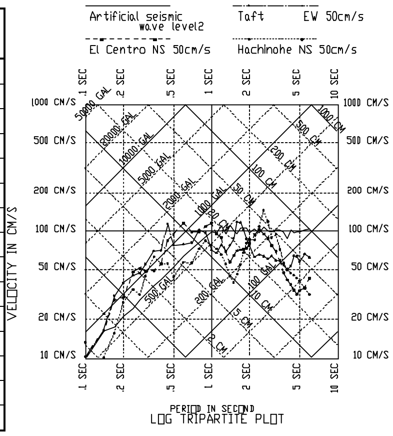


Figure 4 Earthquake response spectrum of each seismic wave (h=0.05)

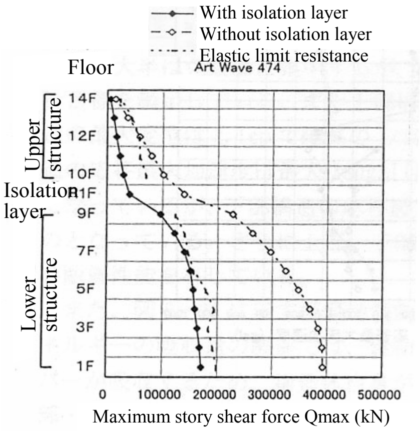


Figure 5 Comparison of response story shear force with/without isolation layer

3.2. Example 2 Application to “Shiodoı building having a large atrium in the lower levels (Sueoka et al.2004)

Example 2 is a 120m high multiple-use building with 3 basement levels and 25 stories above ground. The top part of the building is a 14-story office area, and the lower part is an 11-story hotel. In the upper office floors, where the emphasis was on maintaining the view, a high rise Raman structure was adopted with column spans of 23m in the maximum span direction × 12.8m in the length direction of the building. In the lower levels, a large transparent atrium (B×D×H = 68m×23m×41m) was provided on one side of the building in relation to the main flow lines. The whole area was a redevelopment area, and around the lower levels of the building there is a complex underground connection with transport modes and connections to adjacent buildings. In addition, one of the given design conditions was a high level of seismic resistance. Photos 2 and 3 show external and internal views of the building, and Figs. 6 to 8 show the framing plans and framing elevation.

In this building , middle-story isolated structural system having a untuned mass damper effect was adopted by providing the isolation layer in the lower part of the 12th floor, which was between the hotel and offices. Almost all the seismic energy is absorbed by the isolation layer, so it is possible to reduce the response during an earthquake not only in the upper structure, but also in the lower structure. This permitted architectural planning satisfying the required conditions, which is impossible with normal structural shapes, to be achieved. In other words, the large span structure in the upper levels as well as the irregular plan shape of the main structural steel framing in the lower levels remain in the elastic state even under postulated very rare earthquakes, and in contrast to the complexity of the building shape, a safe structural form was achieved in which the overall flow of forces is clear. Also, the atrium did not include a megatruss or similar, but was designed based on a clear stress state with pin-ended slender columns that only take axial forces, having lightness and a high factor of safety with respect to axial forces.

Use: Offices, hotel   Height: Height to highest part: 125.90m, eaves height: 115.90m   No. stories: 3 below ground, 25 above ground, 2 penthouse stories
Structural form: Structural steel, reinforced concrete

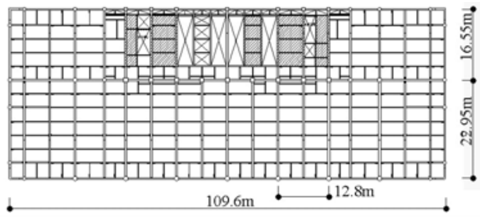
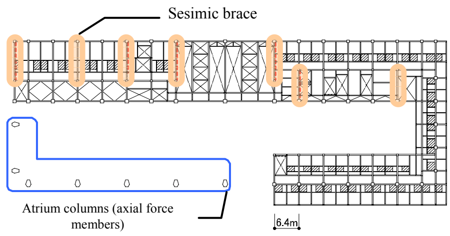


Figure 6 Framing plan of high rise office floors



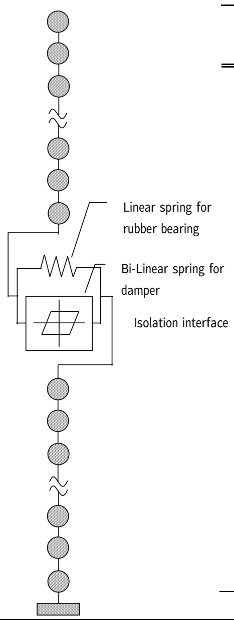
- Natural rubber laminated rubber isolators 1000 - 1300φ: 41 No.
- Lead dampers: 100 No., steel rod dampers: 14 No.
- Rm (mass of upper structure / total mass above ground) = 0.68
- α's (damper yield force / total weight above ground) = 0.033

Photo 2 Building external view   Photo 3 Atrium internal view   Figure 7 Framing plan of lower level hotel

The isolation layer comprises 1000 to 1300φ natural rubber laminated rubber isolators, 100 lead dampers, and 14 steel rod dampers.

In order to determine the vibration characteristics of Example 2, vibration response analysis was carried out using a vibration analysis model of the actual building. As shown in Table. 3 , the in the vibration analysis model the mass of the upper part of the building was about 68% of the total mass above ground, and the ratio of the damper yield stress to the total weight above ground (α's) was 0.033. The vibration analysis model was a 26 mass shear translation model, with 11 masses in the lower structure and 15 masses in the upper structure.

Table 3 Dynamic analysis model



Story	Gravity (kN)	Stiffness (kN/mm)
R	56580	1511
25	33950	1734
24	33810	2111
23	30170	2168
22	30250	2240
21	30350	2336
20	30570	2486
19	31070	2484
18	31090	2586
17	30650	2589
16	30720	2652
15	30800	2631
14	31250	2321
13	34990	3106
12	39530	bellow
Isolation story	30680	1083
11	30670	4452
10	16880	4791
9	16650	4953
8	16850	5204
7	16820	5361
6	16830	5707
5	17000	5923
4	16930	6344
3	25330	2675
2	30210	3178
1		

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

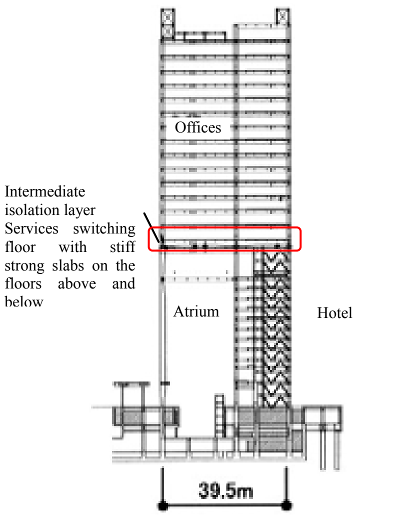


Figure 8 Framing elevation in short direction

Also, the internal viscous damping in both the lower structure and upper structure was assumed to be h1= 0.02 in both cases. The seismic motion wave forms used in the analysis were a rarely occurring seismic motion defined in the Notification. The notification seismic motion wave form was produced using the phase characteristics of measured seismic wave motion wave forms, setting the acceleration response spectrum shape in the long period region so that in the velocity response spectrum Sv=81.5cm/sec (h=0.05). The response spectra of these seismic motion wave forms are shown in Fig. 9.

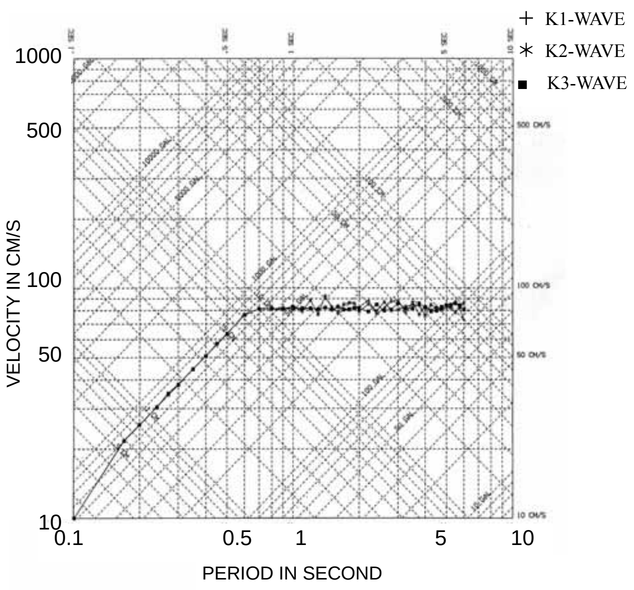


Fig.9 Pseudo-Velocity Response spectrum

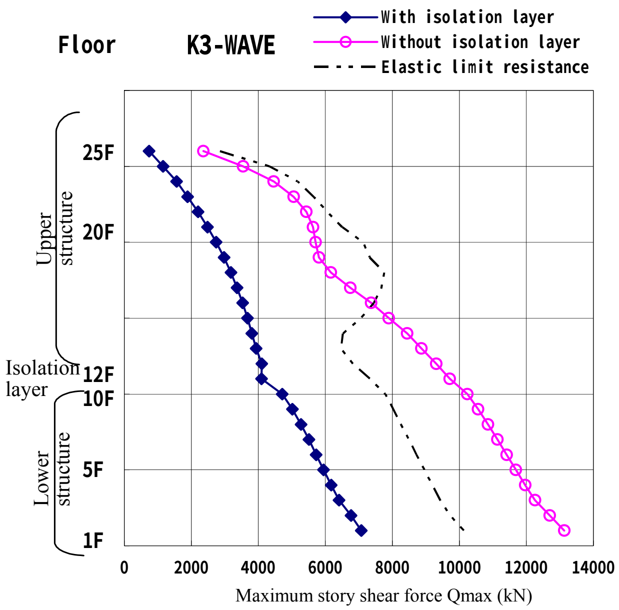


Fig.10 Result of Dynamic Response Analysis

The response analysis results for the major earthquake for the short direction of the building are shown in Fig. 10.

The maximum response story shear force in the building compared with the case where there is no isolation layer is about 1/3 – 1/2 for the upper structure and about 1/2 in the lower structure, so the response story shear forces are greatly reduced. At all stories the stresses in the structural frame were maintained within the limits for elastic resistance, so a high seismic performance was maintained.

3.3. Example 3 – application to the expansion of the upper part of an existing building to form a high seismic performance disaster prevention center "Musashino City Disaster Prevention and Safety Center"

Example 3 is an example of the expansion of a comparatively low seismic performance existing 2-story SRC building to form a 5-story disaster prevention center. An external view is shown in Photo 4, and an outline structural diagram and framing plan are shown in Fig. 11.

In the present building, a 5-story disaster prevention center was built on an existing 2-story building of comparatively low seismic performance, with an isolation layer in between. The building as a whole has high seismic performance, and the function of the disaster prevention center can be maintained even in the major earthquake. By adopting an intermediate level isolation structure, a minimal amount of seismic retrofit was carried out on the existing part while it continued to be used, and not only is the expanded portion not damaged in the major earthquake, but also it is possible for the computer provided on the 6th floor to continue to function (for floor accelerations of 250cm^2/sec or less). The isolation layer comprises 8 pieces of 700φ natural rubber laminated rubber isolators, 12 pieces of elastic sliding bearings, and 8 pieces of steel rod dampers.

In order to determine the vibration characteristics of Example 3, vibration response analysis was carried out using a vibration analysis model of the actual building. As shown in Fig. 12, the in the vibration analysis model the mass of the upper part of the building was about 63% of the total mass above ground, and the ratio of the damper yield stress to the total weight above ground (α's) was 0.04. The vibration analysis

Photo 4 Building external view

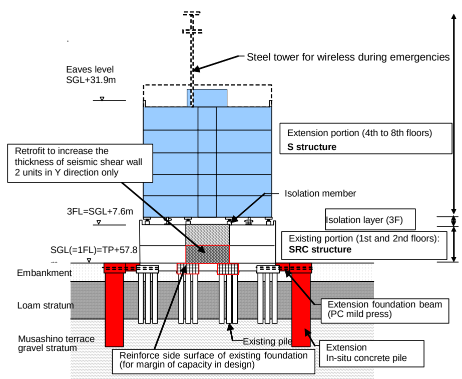
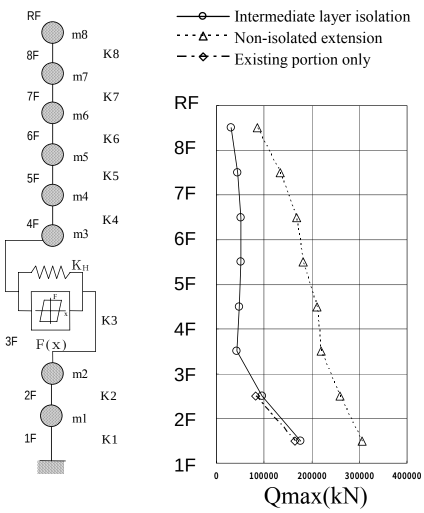


Fig. 11 Outline of the structure

model was an 8 mass shear translation model, with 2 masses in the lower structure and 6 masses in the upper structure. Also, the internal viscous damping in both the lower structure and upper structure was assumed to be directly proportional to the stiffness, and was h1 = 0.02 in the upper structure and h1=0.03 in the lower structure. The seismic motion wave form used in the analysis was the very rarely occurring seismic motion as defined in the Notification, as adopted in Example 2.

The response analysis results in the major earthquake for the building are shown in Figs. 11. The maximum response story shear force in the building compared with the case where there is no isolation layer is about 1/4 – 1/2, so the response story shear forces are reduced. At all stories the stresses in the structural frame were maintained within the limits for elastic resistance, so a high seismic performance was maintained.



(response story shear force for Notification K3－wave, Y direction)

Fig. 12 Vibration analysis results

4. CONCLUSION

In a middle-story isolated structure, the building as a whole is affected by higher mode vibrations, so the vibration characteristics of the building are governed not only by the stiffness of the isolation layer and the number of dampers, but also by the stiffness of the upper structure and the lower structure, and the weight ratio of the upper and lower structures. Therefore, complex consideration of several indefinite elements as parameters is necessary.

This paper describes the characteristics and response properties of high rise buildings with an energy and damage concentration type of vibration control system using a middle-story isolated structure, and points out its effectiveness. Also, three application examples that utilize the merits of middle-story isolated structures were introduced, and it was shown that the degree of freedom of architectural planning can be expanded and the seismic performance increased by the adoption of a middle-story isolated structure.

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