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DESIGN AND ANALYSIS OF A BUILDING WITH THE MIDDLE-STORY ISOLATION STRUCTURAL SYSTEM

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SUMMARY

In this paper, an example of the design of a multifunctional 14-storied building accommodating apartments, office rooms and shops where a seismic isolation system is installed on the middle-story is described. The upper stories constituting apartment area and the lower stories constituting office and shop area are adopted structural systems suited for each function. And a seismic isolation system is installed on the middle-story serving as the connections of each structure. Authors obtain a result that the best building plan can be adopted by connecting different structural systems suited for each function with the middle-story isolation structural system. Furthermore, the dynamic time history analysis verifies that seismic force to the building is reduced by making seismic energy concentrate to the isolation story and that the building can ensure excellent seismic resisting performance.

INTRODUCTION

Generally, in the seismic design of ordinary middle/high-rise buildings, structural characteristics are kept uniform in a building in order to avoid damage concentration to certain stories. However, it is extremely difficult to incorporate a structural design suited for the characteristics of each function adequately in general for the multifunctional building. For a base-isolated structure capable of reducing seismic force to a building, the degree of freedom in the structural design of an upper building gets somewhat high. For the base-isolated structure, however, a seismic isolation system is often installed on the bottom story to prevent seismic input from entering a building directly. This is also because movable parts other than base-isolation materials are minimized by reducing plumbing crossing the seismic isolation story and preventing the elevator shaft from passing across the seismic isolation story deformed largely in the horizontal direction. For an ordinary base-isolated structure, therefore, the clearance required between the building and its peripheral ground constitutes a great restriction on the harmony and continuity between the surroundings and the building on the ground level. This has a major impact on building plans under the present condition. This paper describes an example of the design of a multifunctional 14-storied building including apartments, office rooms, shops and parking lots where a seismic isolation system is installed on the middle-story.

DESIGN OF A BUILDING WITH THE MIDDLE-STORY ISOLATION STRUCTURAL SYSTEM

Outline of the plan for the building

The building located at Koraku 2-Chome, Bunkyo-ku, in Tokyo is given as an example of the design of a building where a seismic isolation system is placed on its middle-story. It is a multifunctional building with 14 stories above ground, two stories below and one-storied penthouse. Fig. 1, Fig. 2, Fig. 3-4 and Fig. 5 show the external view of the building, plan view of the first floor, typical plan views and sectional view of the building respectively. Considering harmony with the surroundings, the formation of a better climate of housing and

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commercial facilities in the urban central area and the coexistence of an office facility, the building is designed to arrange various functions in it as described following.

Fig. 1: External view of the building

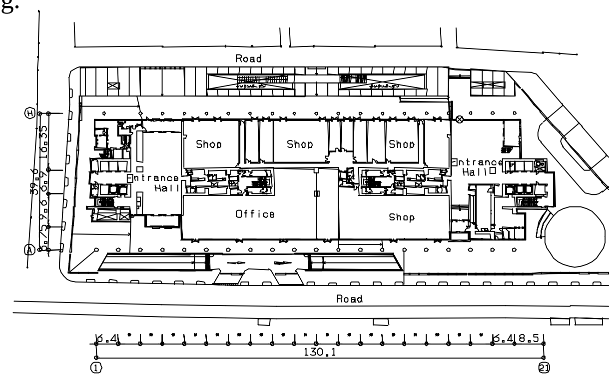


Fig. 2: Plan view of the first floor

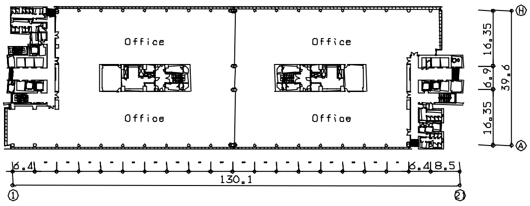


Fig. 3: Lower typical plan view (Office room floor)

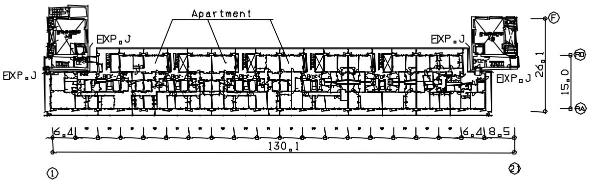


Fig. 4: Upper typical plan view (Apartment floor)

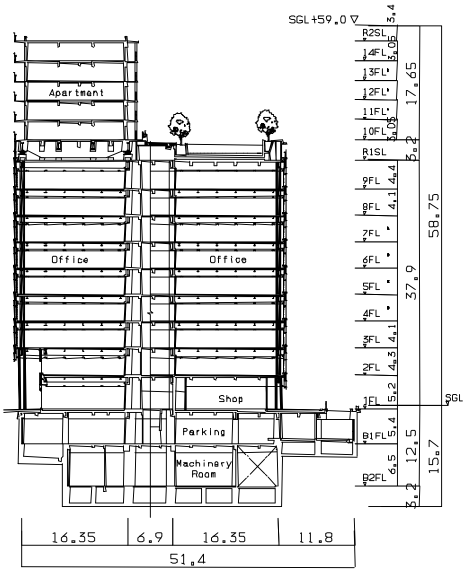


Fig. 5: Sectional view of the building

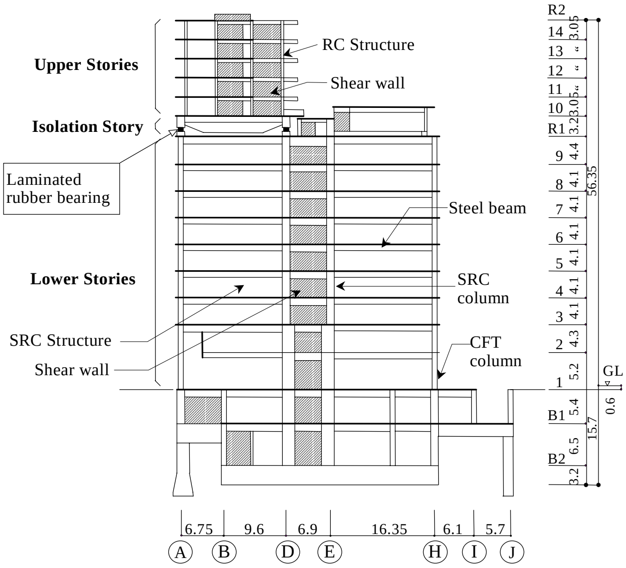


Fig. 6: Framing elevation (Direction of short side)

- Service zones are placed on the basement of the building including parking lots, machine rooms and warehouse. Shops and others are placed on the first floor capable of direct approach from the vicinity to form the area in combination with peripheral commercial facilities.

- A newly installed office facility is placed on the 2nd floor to the 9th floor to form extensive column-free space making large rooms of about 5,000 m^2 maximum available.

- Apartments are placed on the 10th floor to the 14th floor of high-rise area to provide comfortable residential environment. Each apartment unit is designed for ensuring sound insulation, privacy, day lighting and ventilation. A roof garden with an extensive open space is placed on the 10th floor serving as a daily flow line for apartments. The roof garden is designed as a community centre of the residents, and it is also used as the base of temporary evacuation and fire fighting in emergency.

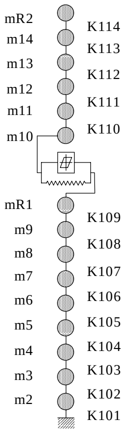
A building plan is made for suiting each of office rooms, apartments and shops and providing environment capable of coexistence by classifying various functions definitely to arrange them. However, providing necessary building performance for each function to the maximum in such formation of spatial uses requires an optimum structural design for each function.

The plan is designed to install a seismic isolation structural system on the middle-story in order to adopt structural systems suited for each function arranged spatially and continuous connection between the ground surface and the building. A seismic isolation system composed of 800-mm-dia laminated natural rubber bearings and lead dampers is installed on the lower story of the 10th floor as shown in Fig. 6. The upper stories of the 10th floor and higher on which apartments are placed use a shear wall system of reinforced concrete (RC) structure. And the lower stories of the 9th floor and lower on which office rooms and shops are placed use a combined shear wall and moment resisting framing system of steel reinforced concrete (SRC) structure (partially using concrete filled steel tubular (CFT) columns) with steel beams. Thus, this design adopts the structural system differed largely in the upper part and lower one of the building. This structural system realizes office rooms of column-free space with a span of 16 m for the lower stories and implemented a system by which columns and beams don’t protrude through the surface, which is suitable for function as apartments, for the upper stories. The seismic isolation system placed on the lower story of the 10th floor is also used as the part of the trench for the equipment. And emergency elevators for apartment stories linking to the ground level are placed on both ends of the building so that they can be erected directly from the lower stories as elevator towers. Such placement allows the elevator towers to be linked easily to the apartment stories outside the building through an expansion joint.

Vibration characteristics of a building with the middle-story isolation structural system

To grasp the vibration characteristics of a building with the middle-story isolation structural system, earthquake response analyses are performed using a vibration analysis model allowing for a real building. The analysis model used is about 20 percent of the weight of the entire building in upper building weight as shown in Fig. 7. It is an 1-dimentional analysis model with a total of 15 mass points including 9 mass points in lower stories and 6 mass points in upper stories. Main studies included the relation between the yield strength of the damper in the isolation story and the weight of a building, changes in building stiffness, and the sensitivity characteristics of the structure with respect to variations in upper building weight. An artificial seismic wave is used to simulate the level-2 earthquake motion (large earthquake motion). The artificial seismic wave is made setting the velocity response spectra in the long period range at Sv=100 cm/sec (h=0.05).

Figures 8 and 9 show the maximum deformation of the isolation story in changing the volume of the damper and the relation between the maximum shear coefficient of each portion. The transverse axis includes αs (yield strength of the damper/weight of the upper stories) and $\alpha's$ (yield strength of the damper/total weight). This shows that the maximum deformation of the isolation story decreases with increase in the volume of the damper and that it gets steady at about $\alpha's=0.02$ - 0.025 ($\alpha s=0.09$ - 0.12). The maximum shear coefficient of the lowest story (10th floor) of the upper stories indicates a little larger value than for the ordinary base-isolated structure, but it can be concluded that it has an adequate seismic isolation effect. Though the lower stories are made elastic for the model, worthy of special note is that the maximum shear coefficient of the 1st story (of the lower stories) indicates a value as small as $C_B=0.24$ at $\alpha's=0.025$ ($\alpha s=0.12$). The value of C_B of the 1st story indicates a stable value in the range on the order of $\alpha's=0.02$ - 0.03 ($\alpha s=0.09$ - 0.14). This value is small as compared with ordinary earthquake-resistant buildings of the same size taking into account the plasticity of frames. In other words, it indicates that the seismic force of the entire building can be reduced by the middle-story isolation structural system and that the entire building can offer excellent earthquake resisting performance.

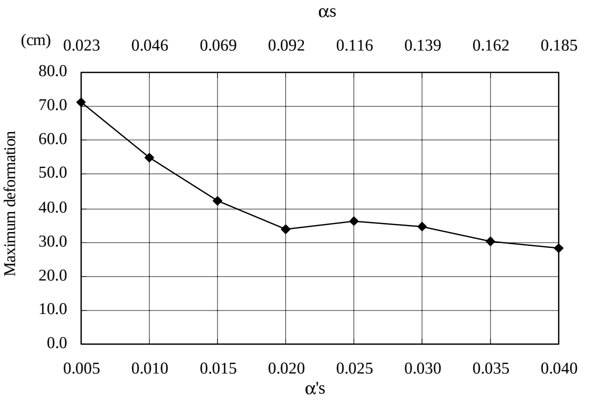


Vibration analysis model

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

Fig. 7: Outline of vibration analysis model



Constants of vibration analysis model

Fig. 8: Relation between the damper volume and the maximum deformation of the isolation story

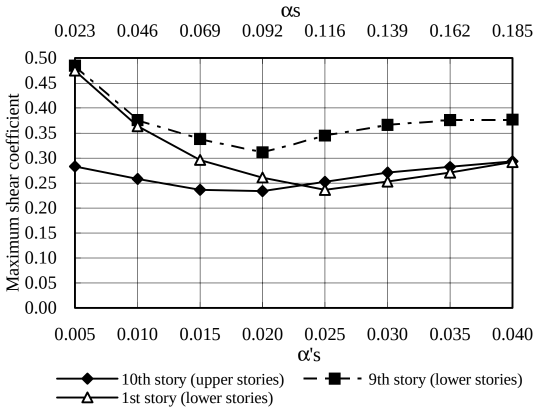


Fig. 9: Relation between the damper volume and the maximum shear coefficient of each portion

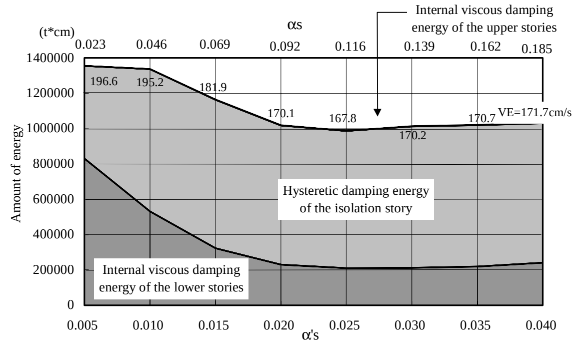


Fig. 10: Relation between the damper volume and the amount of energy of each portion

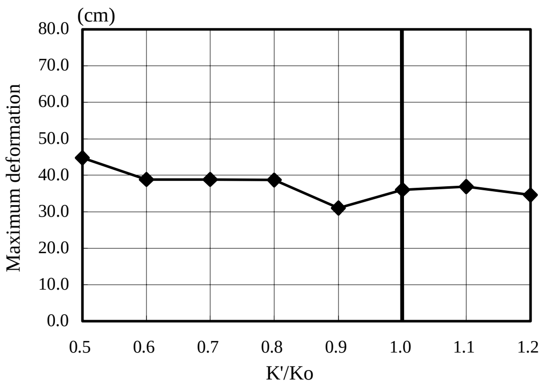


Fig. 11: Relation between the stiffness of the lower stories and the maximum deformation of the isolation story

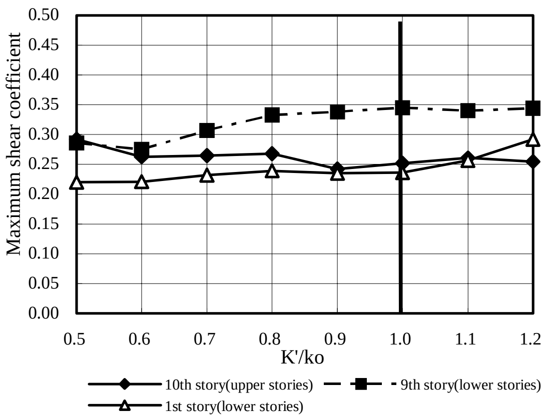


Fig. 12: Relation between the stiffness of the lower stories and the maximum shear coefficient of each portion

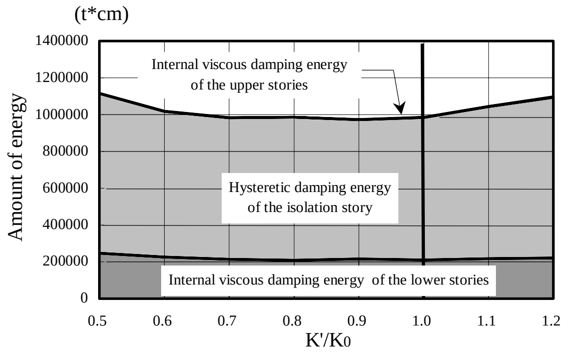


Fig. 13: Relation between the stiffness of the lower stories and the amount of energy of each portion

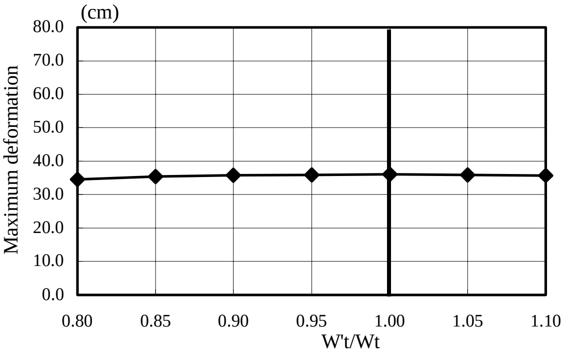


Fig. 14: Relation between the mass of the upper stories and the maximum deformation of the isolation story

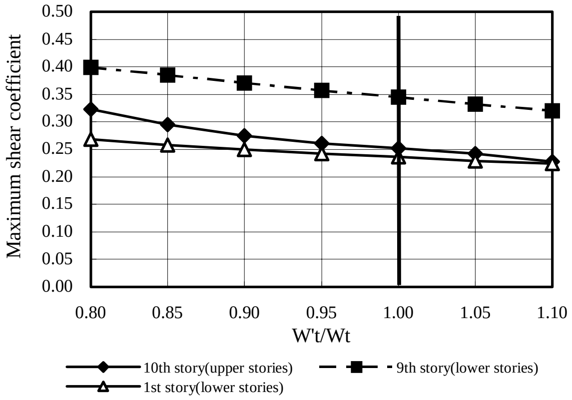


Fig. 15: Relation between the mass of the upper stories and the maximum shear coefficient of each portion

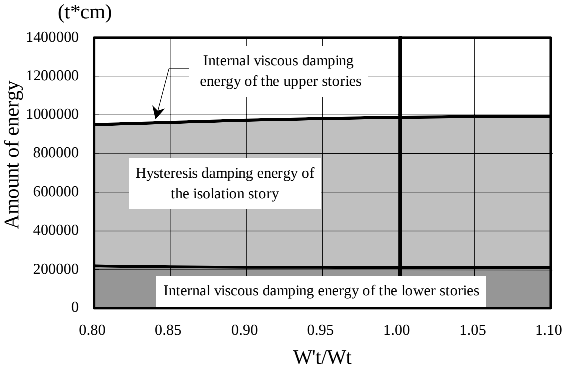


Fig. 16: Relation between the mass of the upper stories and the amount of energy of each portion

A probable reason for it is that seismic input energy can be intensively absorbed in the isolation story. The tendency is given in Fig. 10 as the relation between the amount of seismic input energy and the amount of energy absorption in each structural portion. There is slight variability in the amount of seismic input energy, but the amount of energy is equivalent to the level-2 earthquake motion (large earthquake motion) suggested by Akiyama. With an increase in the damper volume, about 70 to 80 percent of seismic input energy is absorbed by hysteretic damping of the isolation story (damper). The amount of energy absorbed by internal viscous damping of the upper stories is as small as 0.1 to 0.3 percent with respect to the amount of seismic input energy in the same case of ordinary base-isolated buildings. With an increase in the volume of the damper, the amount of energy absorbed by internal viscous damping of the lower stories is as small as 20 to 30 percent of seismic input energy and stable.

Figures 11 to 12 show the relation between the stiffness of the lower stories and the maximum deformation of the isolation story, that between the maximum shear coefficient of each portion when the damper volume is set at $\alpha's=0.025$. Figure 13 shows the relation between the changes in the stiffness of the lower stories and the amount of energy absorption of each portion when the damper volume is set at $\alpha's=0.025$. It is seen from these figures that the reduction in the stiffness of the lower stories causes a slight increase in the maximum deformation in the isolation story and variation in the maximum shear coefficient in each portion, but its effect is small. As shown in Fig. 13, it is because a small amount of energy is absorbed by internal viscous damping of the upper and lower stories due to the absorption of most seismic input energy by hysteretic damping of the isolation story.

Figures 14 to 15 show the relation between the mass of the upper stories and the maximum deformation of the isolation story, that between the maximum shear coefficient of each portion when the damper volume is set at α's=0.025 with respect to the weight of the entire building used as a criterion. Figure 16 shows the relation between the mass of the upper stories and the amount of energy absorption of each portion when the damper volume is set at α's=0.025. Even in this case, there is a slight variation in the maximum deformation of the isolation story and the maximum shear coefficient of each portion with respect to the changes in the mass of the upper stories. However, its effect is small because of stable proportion of the energy absorption in each portion. These studies reveal that the middle-story isolation structural system provided insensitive vibration response with respect to variations in material properties, weight ratio and others to consider in design.

Study of the real building by earthquake response analysis

The above study revealed that the advantage of installing the middle-story isolation structural system on the middle-story lay not only in permitting ease of stacking different frames in structural system but also in stabilizing the excellent earthquake resisting performance of the entire building. Thus, design of the building was made to provide α's=0.02 - 0.03 setting the design target of the isolation story at 40 cm or below in the maximum deformation in the level-2 earthquake. More detailed studies also were made by earthquake response analysis using a 3-dimensional analysis model of a total of 15 stories including nine stories of lower stories, one story of isolation story and five stories of upper stories. Figure 17 and Table 1 give the shape of the analysis model and the natural period of the 3-D analysis model respectively. The seismic waves studied include three ground motion records (EL CENTRO NS, TAFT EW and HACHINOHE NS) of observation seismic waves setting the maximum velocity at 50 cm/sec and the prescribed artificial seismic wave. Figure 18 shows the earthquake response spectrum (h=0.05) of these seismic waves.

Table 1: Natural period of the analysis space model (Sec)

	T1	T2	T3
3-D model of the entire building taking into account the laminated natural rubber bearing and the lead damper	1.35	1.35	1.21
3-D model of the entire building taking into account the laminated natural rubber bearing only	3.47	3.45	3.20
3-D model of the upper stories only	0.29	0.24	0.21

Figures 19 and 20 show the results of response analysis in the level-2 earthquake in the direction of the short side of the building. Most of the deformation of the building concentrates in the isolation story. However, the maximum deformation of the isolation story is 32.6 cm in the extreme periphery, which meets the target. The maximum story drift of the upper stories is 0.20cm which is equivalent to about 1/1530 of the story height, and that of the lower stories is 2.1cm which is equivalent to about 1/195 of the story height. Both are remarkably small as compared with ordinary earthquake-resistant buildings. The maximum response acceleration of the upper stories is 380 gal (14th floor) and that of the lower stories is 557 gal (9th floor). The former is a little more than ordinary base-isolated buildings, but the latter is less than ordinary earthquake-resistant buildings. The maximum shear forces of the upper and lower stories are below the elastic limit strength and have excellent earthquake resisting performance. Figure 21 shows the relation between the amount of seismic energy absorption on each story in the artificial seismic wave. This indicates that about 80 percent of the seismic energy inputted in the building is absorbed by the lead damper in the isolation story. Therefore, it indicates that there is no need for the plastic deformation capacity in frames to absorb seismic energy and that both the upper stories and the lower ones won't suffer damage by earthquakes.

The weight of the upper stories of the building is about 22 percent of the total weight of the entire building. Though the final yield strength of the damper is as high as αs=0.14 compared with the weight of the upper stories, α's=0.03 is given as compared with the weight of the entire building. It is probable that this has almost the same volume of a damper as an ordinary base-isolated building with the natural period of 3.5 seconds when only the laminated rubber bearing is installed.

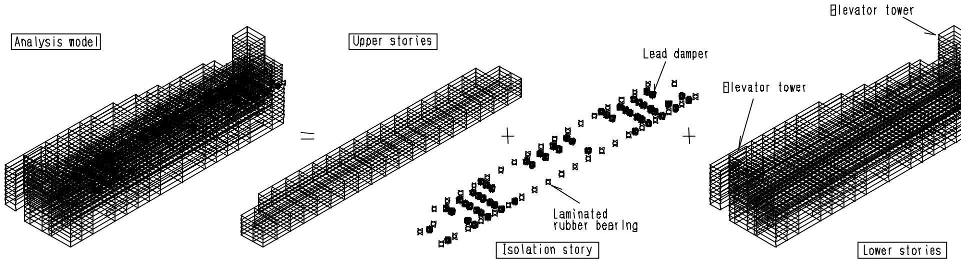


Fig. 17: Shape of the 3-dimentional analysis model

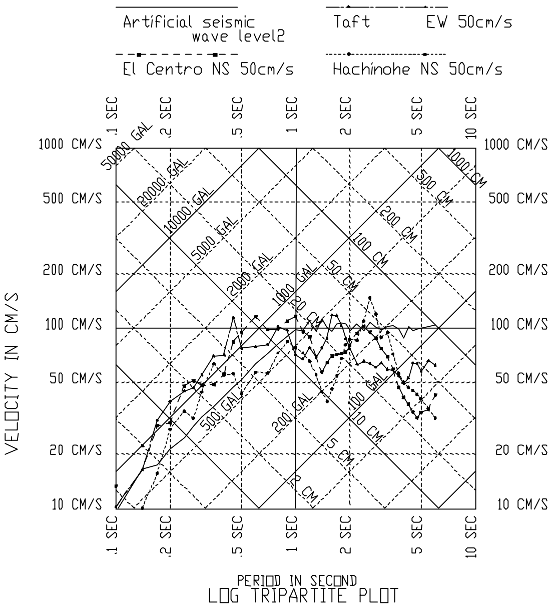


Fig. 18: Earthquake response spectrum of each seismic wave (h=0.05)

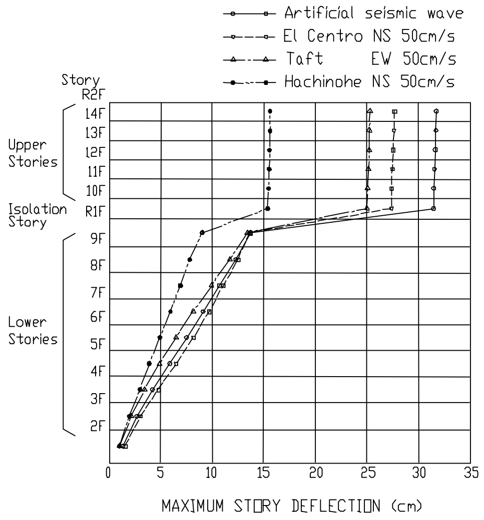


Fig. 19: Maximum story drift (In the level-2 earthquake, direction of the short side)

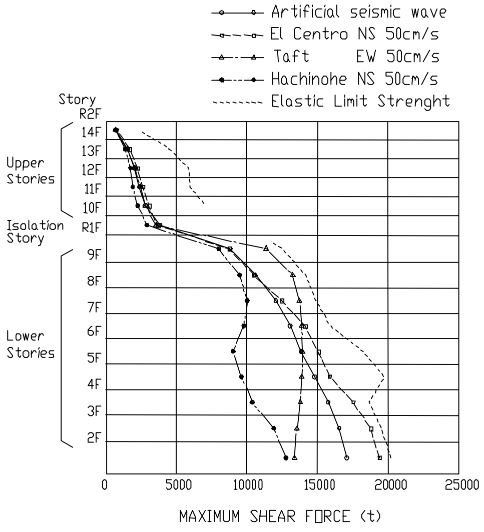


Fig. 20: Maximum shear force (In the level-2 earthquake, direction of the short side)

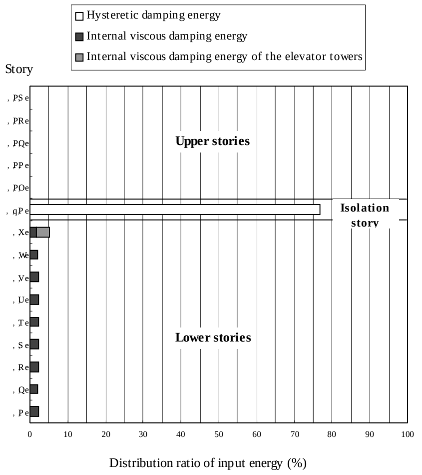


Fig. 21: Input distribution of seismic energy to each story of the building (Artificial seismic wave, in the level-2 earthquake, direction of the short side)

CONCLUSION

It was found that a building with the middle-story isolation structural system had no restriction on the connection between the ground surface and the building, which permitted the vertical combination of different structural systems depending on each function, and that the degree of freedom increased in a building plan.

It was also found that the earthquake response of the entire building including the lower stories as well as the structure of the upper part of the isolation story could be reduced as the characteristic of a building with the middle-story isolation structural system.

It was explained that this effect improved the seismic performance of the entire building remarkably in addition to maintaining performance equivalent to a base-isolated building for the upper stories.

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