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Development of Seismic Isolation Device for Improving Structural Performance with Wide Displacement Range of Infinitesimal to Large Amplitude

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Abstract

This paper shows that two types of new seismic isolation (SI) device can address issues of seismically isolated structures by improving SI performance with wide displacement range of amplitude.

Japan anticipates large amplitude earthquakes such as Nankai trough earthquakes and Uemachi fault zone earthquakes that exceed the current design level. There is a risk that tremendous large displacement damage to isolation story would cause the degrading of SI performance if large amplitude earthquakes occurred. Also, there is an issue of habitability to building vibration that seismically isolated buildings in constant use and against small earthquakes and strong wind force are liable to deform compared to seismic resistant structures. Thus, the study must be needed in order to improve the SI performance for each displacement range from infinitesimal to large amplitude.

For issue resolution as above mentioned, first, the SI device of absorbing infinitesimal vibration was developed to countermeasure small vibrations with small displacement range. Then, the device was installed to the real building. This SI device incorporates a damper that is effective in micro-vibration in an elastic sliding bearing and can absorb infinitesimal vibrations of approximately 10μm (micro-meter). The real building with this SI device is a production facility building for using sensitive apparatuses, and the SI device can satisfy with an permissible vibration value by controlling infinitesimal vibrations. By microtremor measurement before and after installing the SI device, it was found that the effect of controlling vibrations of infinitesimal displacement range is approximately 3% of additive damping.

Placing many pieces of SI devices could be the countermeasures for a large amplitude range in order to dampen large displacement in an isolation story. Meanwhile, there are concerns about increasing response accelerations during small and large earthquakes by excessive damping. Consequently, a stop-operation switching device was developed for passively responding to amplitude in an isolation story and its effect and characteristics were analytically verified. This SI device can exhibit effect of reducing large displacement by increasing the amount of damping in a large amplitude range when switch is in operation. In a range other than a large amplitude, it can decrease response accelerations by reducing the amount of damping when switch stops. The values of amplitude at which the SI devices starts to operate, and the quantities of SI device greatly affect the response values of building. Therefore, these optimum values of amplitude and the quantities of SI devices were derived by analytical simulations.

Using the SI device responding to a displacement range between infinitesimal to small amplitude, and the one responding to a large amplitude range can improve the SI performance in a wide range of vibration amplitude.

Keywords: seismic isolation, infinitesimal amplitude range, large amplitude range

1. Introduction

This research is concerned with the improvement of seismic isolation (SI) structure technology through the development of two types of SI devices that improve the issues of SI structures and improve SI performance over a wide range of vibration amplitude. A conceptual diagram of a target amplitude range is shown in Fig.1.

The feature of the SI structure is that it can ensure earthquake-resistant safety against a large earthquake with almost no damage to the building. On the other hand, in the event of a large-amplitude ground motion that exceeds the current design level, such as the Nankai Trough giant earthquake or the Uemachi Fault Zone earthquake, which is expected to occur in the near future, excessive displacement will occur in the SI layer. And, the performance of the SI device may be decremented, causing serious damage [1]. There is an urgent need to develop technology to reduce the response acceleration during small and medium-sized earthquakes and large earthquakes while controlling excessive displacement during an earthquake. Semi-active SI, which variably controls the damping coefficient of an oil damper, is an effective means of simultaneously controlling both acceleration and displacement in a trade-off relationship. In addition to the electromagnetic switching type [2], In recent years, passive type dampers [3, 4] with lower cost and higher operation reliability have been developed.

In addition, there is a problem in habitability that the building is liable to shake as compared with the seismic-resistant structure when the building is used constantly, or when the building is subjected to relatively small earthquake or strong wind. In recent years, the number of production facilities employing SI structures has been increasing remarkably in Japan. When mounting equipment sensitive to vibration in such a facility, there is a concern that the amplitude in the low-frequency region may be amplified and exceed the vibration allowable value. Conventional measures against micro-vibration are mainly to increase initial stiffness by using sliding bearings, or to add damping by adding viscous dampers [5]. There are issues such as an increase in the cost of SI devices and a secure for a damper installation space.

As described above, SI structures with advantages for large earthquakes, However, in the infinitesimal amplitude region and large amplitude region, there are issues specific to SI structures. The research development for new SI devices was conducted to solve these problems and to improve the performance.

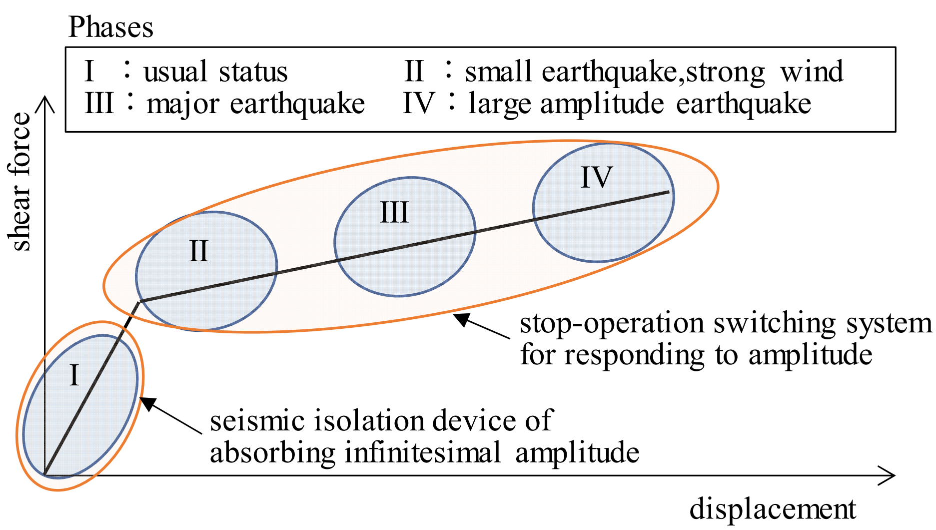


Fig.1 — SI layer displacement-shear force relationship diagram

2. Measures to improve the habitability of infinitesimal amplitude range

2.1 Development of SI device to control infinitesimal vibration

As a measure to reduce the shaking in the minute amplitude range, a method of increasing the initial stiffness of the SI layer and a method of adding damping by a viscous damper are conceivable solutions. We studied the method of adding damping by using a viscous damper that can be installed in a small space while ensuring the response reduction effect during a large earthquake.

As a new SI device, we have developed an elastic sliding bearing with oil damper that combines an elastic sliding bearing as a bearing material with an oil damper as a damping material (Fig.2). An oil damper is installed between the lower of the laminated rubber and upper structure, utilizing the characteristic of the elastic sliding bearing that only the laminated rubber is horizontally deformed until the bearing starts to slide. With this mechanism, this damper operates at the time of small amplitude before the start of sliding, and exhibits a damping effect. After sliding out, it slides together with the elastic sliding bearing, so that it does not affect the characteristics at the time of large amplitude, and the stroke of the damper is small.

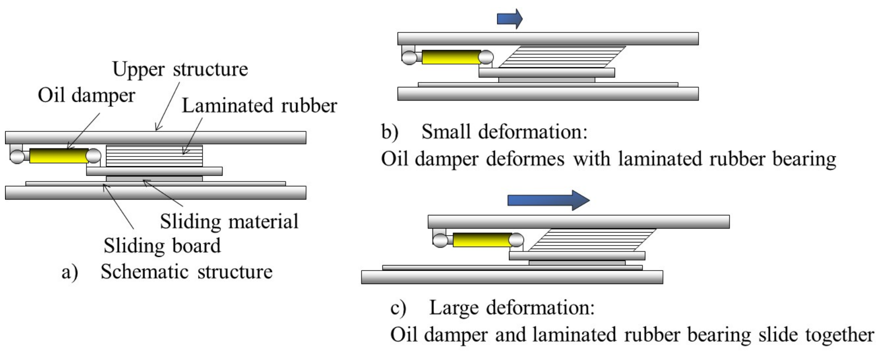


Fig.2 — Mechanism of elastic sliding bearing with oil damper

2.2 Performance test of SI device

The rated characteristics of the oil damper have a velocity-dependent bilinear characteristic (C1=7.8 kN·sec/mm, C2=0.18 kN·sec/mm, relief force=163.8 kN, maximum damping force=250 kN). However, the characteristics in the minute amplitude range have not been clarified because of the difficulty of measuring with a test device. Previous studies have confirmed the effect of attenuation at amplitudes of about 250 μm [6], but few reports have been reported for region of smaller amplitude. When considering micro vibration countermeasures in production facilities such as electronic devices, it is necessary to know the characteristics of oil dampers even in the range of 250 μm or less. Therefore, in order to confirm the damping performance of the micro vibration level, one oil damper was installed in a small SI structure building with a total floor area of about 200 m^2 and a building weight of about 4000 kN, and a vibration test was performed using a vibration exciter [7]. The building's SI device has 8 laminated rubber bearing and 30 steel rod dampers, and the natural frequency of the building obtained from microtremor measurement is 1.0 Hz.

Fig.3 shows the relationship between damping force and displacement at the time of excitation of 1.0Hz and 2.5Hz. As for the excitation force, the results of the maximum excitation force at the frequency and about half the excitation force was shown. Both the 1.0Hz excitation and the 2.5Hz excitation showed stable loops even in the micro vibration region of about 10μm, and the damping performance of the oil damper was recognized.

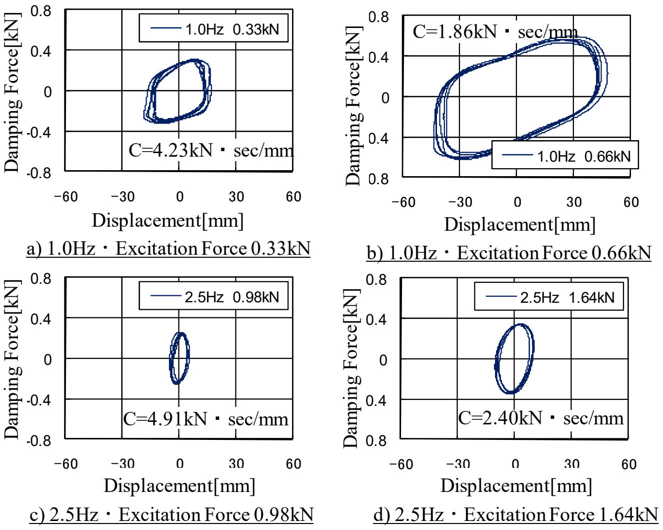


Fig.3 — Displacement-damping force relationship diagram

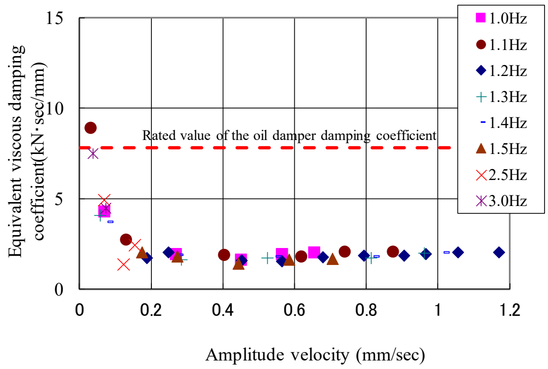


Fig.4 — Equivalent viscous damping coefficient

Fig.4 shows the relationship between the equivalent viscous damping coefficient obtained from the damping force history of the oil damper and the velocity amplitude of the oil damper. At a velocity amplitude of 0.25 mm/sec to 1.2 mm/sec, the equivalent viscous damping coefficient was about 2.0 kN·sec/mm, which was about 1/4 of the rated value of the oil damper damping coefficient.

2.3 Confirmation of effect by time history response analysis

Time history response analysis was performed to confirme the effect of applying an elastic sliding bearing with oil damper to a building. In the analysis model, assuming a steel-frame production facility building, the upper structure was considered as one mass point, and the damping ratio was considered as 1%. Fig. 5 shows the analysis model. The SI device was considered as a laminated rubber bearing, elastic sliding bearing, elastic sliding bearing with oil damper, and oil damper [8].

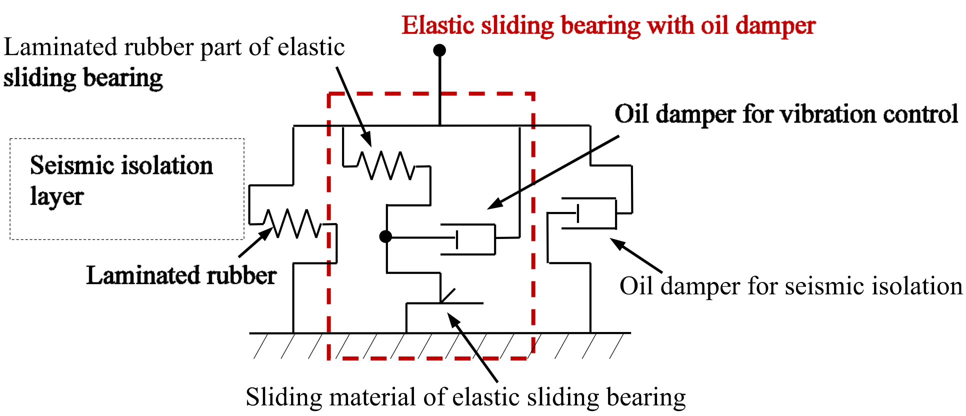


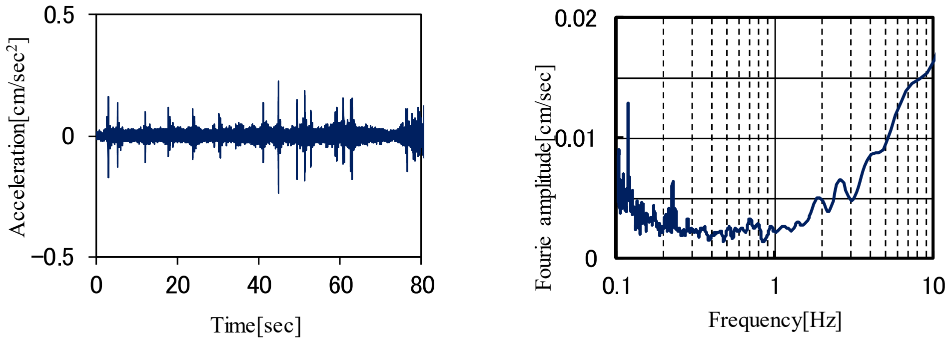
Fig.5 — Analysis model diagram

Table 1 — Analysis model specifications

Upper structure	Weight	497,722kN
Siesmic isolation layer	Elastic sliding bearing with oil damper : 4 units Laminated natural rubber : 38 units Elastic sliding bearing : 3 units Oil damper in each direction : 5 units	
Whole building	Frequency	About 1 Hz

The stiffness of the laminated rubber bearing was adjusted so that the natural period of the building in the micro-vibration region was about 1 second, referring to actual measurements and the like so far (Table 1). Further, the damping coefficient of the oil damper was set to 2.0 kN·sec/mm from the result of the single-unit performance test described in 2.2.

The micro-vibration used for the input was the one observed on the site of the model building. Fig.6 shows the time history of the input acceleration of infinitesimal vibration and the Fourier spectrum after the Parzen Window 0.1Hz smoothing process.



a) Acceleration time history b) Fourier spectrum

Fig.6 — Input micro vibration

Fig.7 shows the transfer function of the response analysis result by the micro vibration input. The elastic sliding bearing with oil damper reduced the response by about 30% in one second of the predominant period compared to the conventional elastic sliding bearing. In the figure, the result of sliding bearing, which have the same initial stiffness as the seismic-resistant structure, are also shown for comparison.

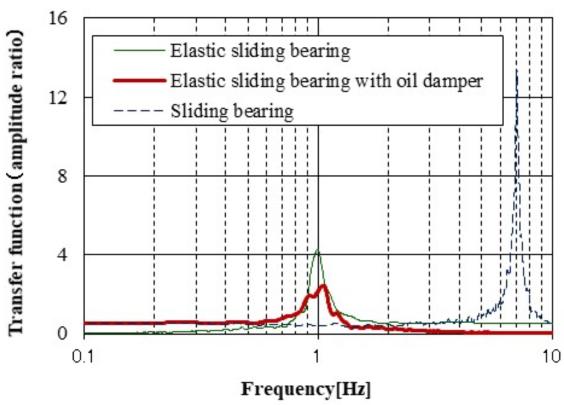


Fig.7 — Transfer function(Micro vibration)

2.4 Installation in buildings and actual measurement results

Since the production facility assumed in 2.3 was designed and equipment sensitive to vibration was installed in the building, an elastic sliding bearing with oil dampers was adopted. The scale of building is 5 stories above the ground and the eave height is 30m. The structural type is a steel framed with base SI structure. The SI device uses laminated rubber bearing, elastic sliding bearings, and oil dampers. Of the seven elastic sliding bearings, four elastic sliding bearings with oil dampers were arranged. Fig.8 shows the shape and installation status of the device.

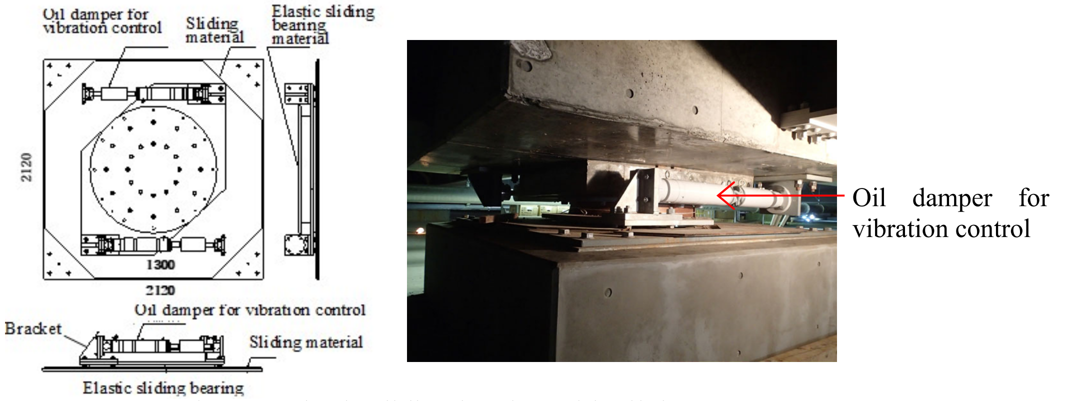
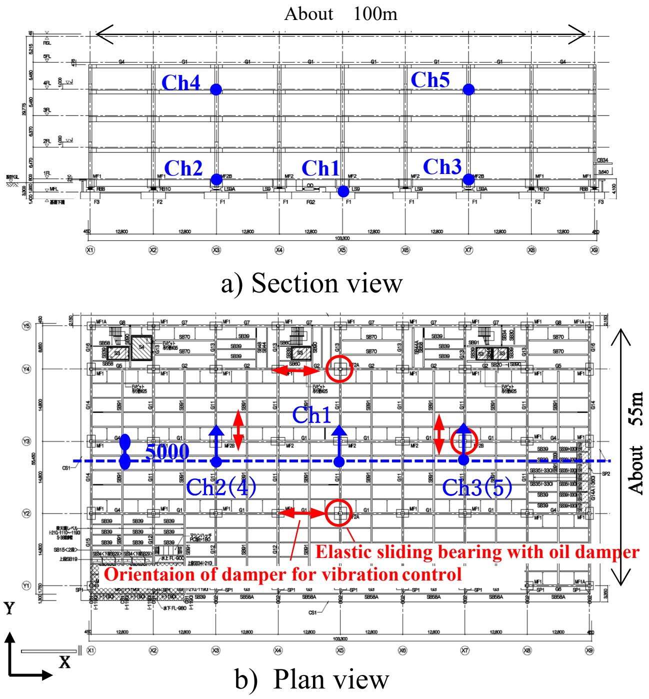


Fig.8 — Elastic sliding bearing with oil damper

In order to confirm the performance of the elastic sliding bearing with oil damper, microtremor measurement was always performed before and after installing the oil damper of the same device. The measurement points are shown in Fig.9. The measurement points were one point on the floor of the SI layer, and two points each on the first and fourth floors directly above the SI layer, for a total of five points [9].



a) Section view

b) Plan view

Fig.9 — Measurment point

Fig.10 shows the transfer function before and after the installation of the oil damper, with the acceleration on the floor of the SI layer (Ch1) as input and the translational acceleration on the fourth floor (Ch4,5 average) as the output. As shown in the figure, the amplification factor after the installation of the oil damper was reduced by about 10% compared to before the installation. Also, the base of the peak is wider than before the oil damper was installed, and a significant difference was confirmed in the damping ratio described later.

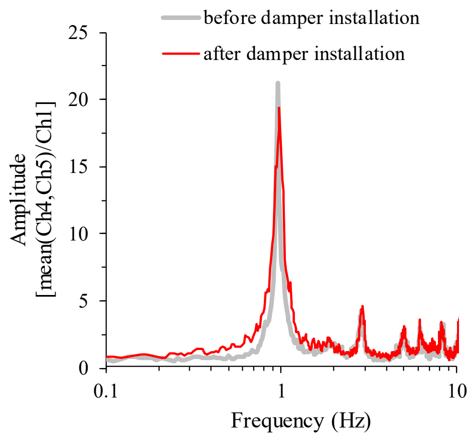


Fig.10 — Transfer function

The damping ratio was identified for the 1st mode for sway motion using the curve fitting method, the autocorrelation function method [10], and the RD method of the transfer function in consideration of the variation due to the difference in the analysis method. Fig.11 shows comparisons of free vibration waveforms before and after the installation of the oil damper using the RD method as an example. A clear difference between the two can be confirmed. Table 2 shows comparisons of the results of identification of the damping ratio calculated by the three methods. From the table, although there is some variation, the average value is about 2.0% before the installation of the oil damper and about 5.3% after the installation of the oil damper, and the oil damper functions effectively even in the infinitesimal vibration region, about 3.3% additional damping was confirmed.

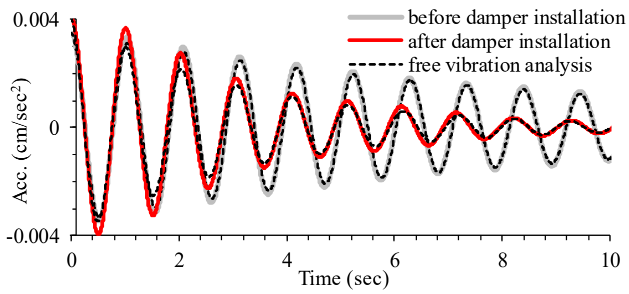


Fig.11 — Comparison of free vibration waveforms obtained from RD method

Table 2 — 1st mode damping ratio identification results

Identification method			Average
Curve fitting method	Autocorrelation function method	RD method	
2.20%	2.10%	1.80%	2.00%
4.40%	6.50%	5.10%	5.30%

3. Measures to improve the habitability of large amplitude range

3.1 Development of SI device for large amplitude earthquake

In the case of large-amplitude region, it is conceivable to use a large number of dampers so that the displacement of the SI layer does not become excessive.However, due to excessive attenuation, there is a concern that the response acceleration will increase during small or large earthquakes. Therefore, we developed a mechanism that switches the "operating-stop" state of the damper according to the amplitude of the SI layer, and its effects and characteristics are analytically verified [11]. This is a SI device that increases the amount of attenuation in the large amplitude region to control excessive deformation, and reduces the amount of attenuation in the lower amplitude region to reduce response acceleration and enhance SI effect. Fig.12 shows the specific shape of a device (dead zone mechanism). This dead zone mechanism is used by connecting to the SI oil damper.

Fig.13 shows the specific behavior of the dead zone mechanism. When this mechanism is in the spread process , Blue circle part of the stepped rod (gray part) pushes the slider (light blue part), and the slider moves in the extension direction while contracting the spring (red part) (①②). When the slider reaches the other side, the connected oil damper operates and generates damping force (③). On one side of the slider, a cushioning rubber is provided to reduce the impact due to the collision between the sliders. The same concept is applied to the case of the compression step. Due to the above behavior, when the relative displacement of the SI layer is smaller than the set amplitude (medium and small earthquake level), the dead zone mechanism only slides and no damping force is generated in the oil damper, and when the amplitude is larger than the set amplitude (medium to small) (Earthquake level or higher) It is possible to generate a damping force on the oil damper and control excessive displacement. The oil damper connected to this mechanism has damping force characteristics as shown in Fig.14.

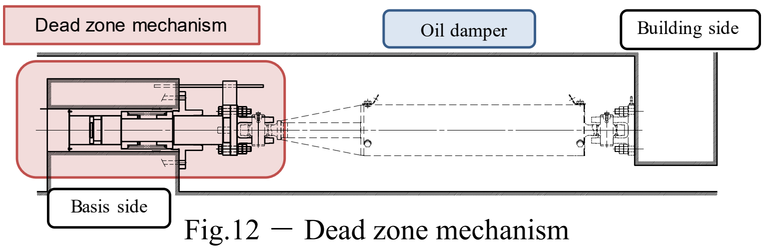


Fig.12 — Dead zone mechanism

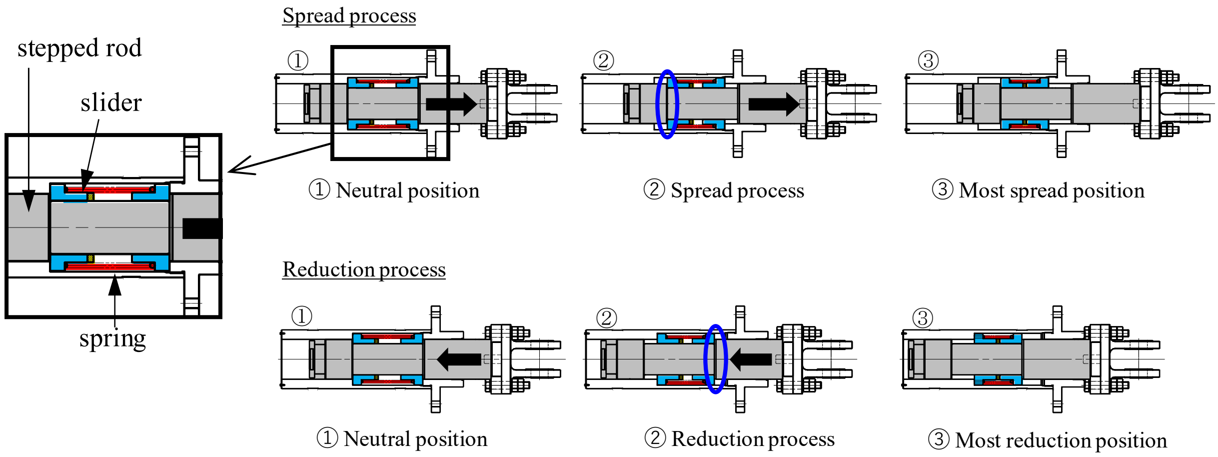


Fig.13 — Dead zone mechanism behavior

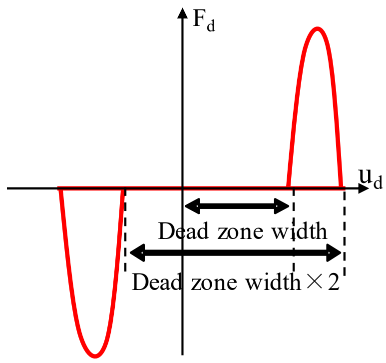


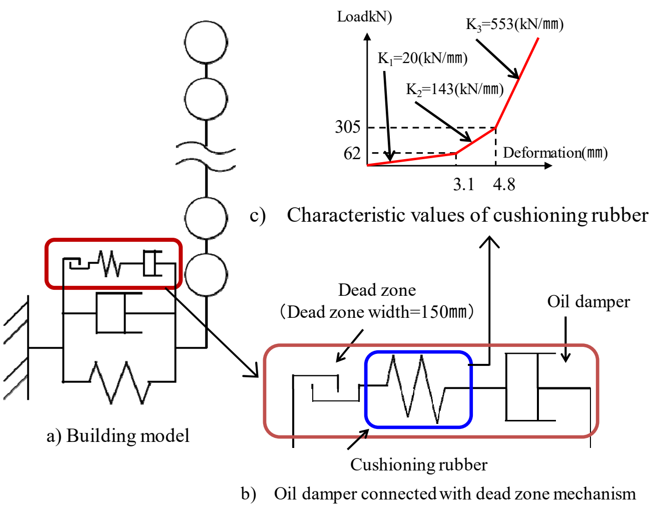
Fig.14 — Damping force characteristics of oil damper connected with dead zone mechanism

3.2 Confirmation of effect by time history response analysis

In order to verify the performance of this mechanism, a comparison was made between the model that applied this mechanism to a building (hereafter, GAP model) and the model that applied a normal oil damper (hereafter, OD model) by time history response analysis. As input earthquakes, a total of 13 L1 to L3 earthquakes shown in Table 3 were used. The bulletin in the table indicates a simulated earthquake that conforms to the design seismic response spectrum specified by the Building Standards Act. For the L3 earthquake here, we used the L2 earthquake whose amplitude was doubled in time history and Nagoya Sannomaru wave of Nankai Trough 4 linked earthquake [12]. The analysis model was assumed to be a reinforced concrete base-isolated building with 25 stories above the ground (with penthouse), and was modeled as a 27-mass system equivalent bending-shear spring (Fig.15). The damping of the upper structure was set at 2% and the damping of the base-isolated layer was set at 0%. The SI layer was composed of 16 laminated rubber bearing, 4 elastic sliding bearings, and an oil damper. The laminated rubber bearing had hysteresis characteristics taking into account hardening (Fig. 16). The number of dampers in the OD model to be compared was determined as the design criterion that the maximum displacement of the SI layer was within 600 mm for the above-mentioned L3 earthquake, and 14 dampers were used to satisfy the conditions. The number of dampers in the GAP model was 14, including 8 oil dampers with this mechanism and 6 normal oil dampers. The dead zone width was 150 mm.

Table 3 — Input earthquake

Earthquke		name	Maximum acceleration (m/sec^2)	Maximum velocity (m/sec)
L1 (Level 1)	Elcentro NS（bulletin）	CODE-EL L1	0.742	0.123
	Hachinohe NS（bulletin）	CODE-HA L1	0.918	0.142
	JMA Kobe NS（bulletin）	CODE-JMA L1	0.950	0.155
	BCJ	BCJ L1	0.719	0.139
L2 (Level 2)	Elcentro NS（bulletin）	CODE-EL L2	2.513	0.586
	Hachinohe NS（bulletin）	CODE-HA L2	3.680	0.612
	JMA Kobe NS（bulletin）	CODE-JMA L2	3.353	0.689
	BCJ	BCJ L2	2.871	0.664
L3 (Level 3)	Elcentro NS（bulletin）	CODE-EL L3	5.026	1.172
	Hachinohe NS（bulletin）	CODE-HA L3	7.360	1.223
	JMA Kobe NS（bulletin）	CODE-JMA L3	6.706	1.377
	BCJ	BCJ L3	5.742	1.328
	Sannomaru EW	SAN	6.277	1.423



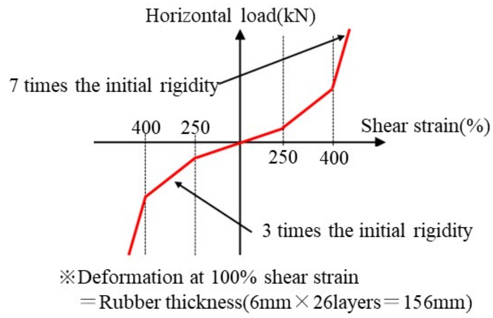


Fig.15 ― Analysis model

Fig.16 ― Modeling laminated rubber bearing

As an example of the analysis result, Fig.17 shows the maximum values of the relative displacement and the absolute acceleration in CODE-JMA. Fig.18 plots the SI layer displacement on the horizontal axis and the maximum value of the top floor absolute acceleration on the vertical axis for each earthquake. In the figure, indicates the average value and maximum value of response acceleration for each earthquake level. For the L1 and L2 earthquakes, the GAP model has a higher acceleration reduction rate than the OD model, and the average value for each earthquake level in Fig.18 shows a reduction of about 10% for the L1 earthquake and shows a reduction of about 15% for the L2 earthquake. Even in the L3 earthquake, the GAP model satisfied the design criteria for all earthquakes, and the maximum acceleration and the maximum displacement were almost the same performance as the OD model. Fig.19 shows a hysteresis loop for each level of the oil damper with a dead zone mechanism. From the figure, it was found that the damper exerted the damping force at the amplitude equal to or larger than the set amplitude, and it was confirmed that the present mechanism exhibited the predetermined performance.

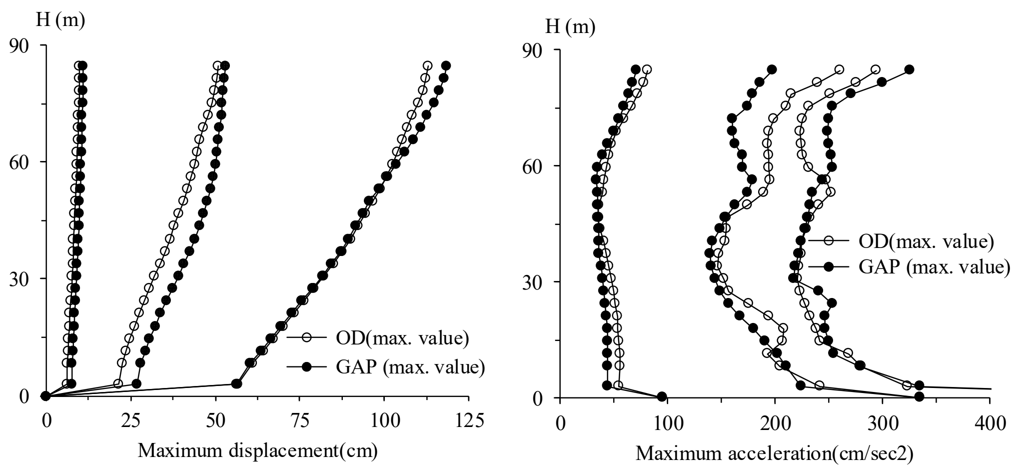


Fig.17 ― Maximum response value

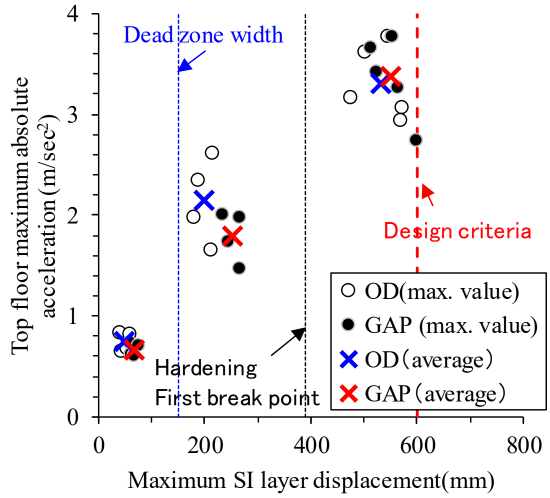
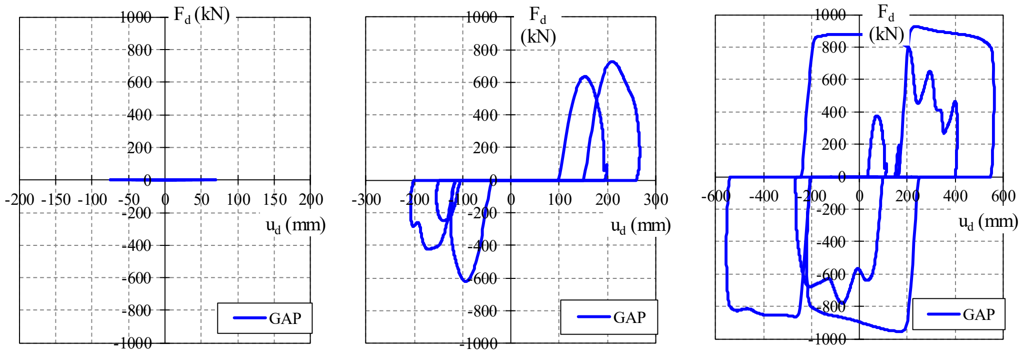


Fig.18 — Relationship between SI displacement and top floor absolute acceleration



a) L1 earthquake b) L2 earthquake c) L3 earthquake

Fig.19 — Load-displacement relationship diagram of oil damper with dead zone mechanism

4. Conclusions

Although the SI structure with advantages for large earthquakes, there are issues specific to the SI structure in infinitesimal amplitude region and the large amplitude region. We researched and developed new SI devices to solve these problems, and improved the performance.

In the range of infinitesimal amplitude, elastic sliding bearing with oil damper was developed, and the effect of controlling vibration was confirmed by excitation test, and the effect of controlling vibration when installed in an actual building was also confirmed by actual measurement.

For the large amplitude region, a mechanism that exerts the effect at a certain amplitude or more was developed, and the response reduction effect in the case of a small earthquake or a large earthquake was confirmed.

With developing two types of SI devices, it is possible to exhibit the vibration control effect over a wide range of amplitudes, and it is expected that the SI structure will be increasingly spread, contributing to the development of a safe, secure and affluent social environment.

5. References

[1] H.Kawabe, Y.Miyamoto, S.Tanaka: Long period ground motion prediction in the Osaka basin for future Nankai Trough Earthquake, 16th World Conference of Earthquake Engineering, Santiago, Chile, Paper No.1555.

[2] T.Suzuki, M.Watakabe, K.Yachiune, S.Inai, Y.Nitta, A.Nishitani: Development of variable damping semi-active seismic isolation structure, Summaries of technical papers of annual meeting Architectural Institute of Japan, pp.395-396, 2013.8(in Japanese)

[3] R.Maseki, I.Nagashima, A.Nii,Y.Kimura, A.Nishitani: Response control of seismic isolated buildings using developed passive-switching oil damper with bi-flow mechanism, Journal of structural and construction engineering (Transaction of AIJ), No.713, pp.1023-1032, 2015.7(in Japanese)

[4] D.Fukumoto, K.Taga: Study on evaluation of earthquake performance and seismic reinforcement in an existing isolated building for pulse-wave ground motions, Summaries of technical papers of annual meeting Architectural Institute of Japan, pp.265-266, 2012.9(in Japanese)

[5] K.Yasui, S.Yamagami, N.Kawai, M.Miyazaki, T.Sawada, K.Nagashima: Development and practical application of multilayer shear viscous damper Part 4 Measures for micro vibration, Summaries of technical papers of annual meeting Architectural Institute of Japan, pp.373-374, 2010.7(in Japanese)

[6] Y.Ishida, Y.Tsuyuki, K.Ishizuka, T.Tsuchihashi, T.Ichikawa, Y.Kondou, N.Izumi: Design of super high-rise CFT building using oil damper Part 2 unit test of oil damper, Summaries of technical papers of annual meeting Architectural Institute of Japan, pp.927-928, 2000.7(in Japanese)

[7] S.Jon, S.Takai, M.Misu, K.Takatsu, K.Matsumoto, T.Tateno: Development of a seismic isolation device incorporating an oil damper for vibration control in an elastic sliding bearing Part 4 Oil damper single unit performance test, Summaries of technical papers of annual meeting Architectural Institute of Japan, pp.383-384, 2010.7(in Japanese)

[8] T.Yamamoto,S.Inai,M.Kanagawa,M.Misu,Y.Yamamoto,M.Miyoshi: Development of a seismic isolation device incorporating an oil damper for vibration control in an elastic sliding bearing Part 6 Analytical study of building response using developed equipment, Summaries of technical papers of annual meeting Architectural Institute of Japan, pp.387-388, 2010.7(in Japanese)

[9] S.Inai, K.Yachiune, T.Ishida, Y.Morita, N.Narita, T.Yamamoto: Performance verification of seismic isolation device incorporating vibration damping oil damper in elastic sliding bearing by micro vibration measurement, Summaries of technical papers of annual meeting Architectural Institute of Japan, pp.581-582, 2016.8(in Japanese)

[10] K.Morita, J.Kanda: Estimation methods of damping ration by microtremor measurement,Journal of structural engineering, Vol.42B, pp.553-560, 1996.3

[11] M.Tokuno ,Y.Ohta, S.Inai, Y.Tsuyuki, T.Ando, M.Misu, N.Kato, H.Shirai: Development of dead zone mechanism connected to seismic isolation oil damper Part 1 Outline of dead zone mechanism and seismic response analysis, Summaries of technical papers of annual meeting Architectural Institute of Japan, pp.403-404, 2016.8(in Japanese)

[12] Aichi prefectural design earthquake ground motion creation business interim report 2014.6, Aichi prefectural design earthquake ground motion research council.

