17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan - September 13th to 18th 2020

STATUS OF PERFORMANCE VERIFICATION OF SEISMIC ISOLATION AND DAMPING DEVICES

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Abstract

In Japan, more than 4500 seismically isolated buildings have been constructed since the first construction of seismically isolated building in 1983. In addition, 1400 vibration-controlled buildings have been constructed by 2017. Many seismic isolation devices and damping devices are used in such seismically isolated buildings and vibration-controlled buildings. In order to secure the safety and functionality of seismically isolated buildings and vibration-controlled buildings, it is important to verify the performance of the seismic isolation devices and damping devices. Therefore, the group organized by Tokyo Institute of Technology conducted a questionnaire on performance verification methods to the members consisted of major Japanese seismic isolation and damping device manufacturers. In Japan, it is necessary to evaluate the performance of seismic isolation devices in accordance with the notification of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), and the questionnaire results indicate that it complies with the notification. With regard to seismic isolation devices, ultimate characteristic tests are conducted with full-scale test specimens, but basic characteristics such as restoring or damping force characteristic tests are often conducted with reduced scale specimens because of the velocity limit of test equipment. In both cases of lead rubber bearing (LRB) and high damping rubber bearing (HDR), the ultimate characteristic test is not carried out until their breaking strain. The restoring force characteristics of LRB and HDR were modeled as bilinear model respectively. From the questionnaire's results, it is confirmed that analytical models have been proposed for both seismic isolation and damping devices based on the characteristics of the materials used for devices. The analytical models have been verified by comparing with experiment results in a range that does not exceed the breaking or buckling. The direction of the verification and validation method of the devices for accuracy improvement of simulation and design considering such as business continuity planning (BCP) was discussed.

Keywords: Seismic Isolation Device; Damping Device; Analytical Model; Verification & Validation; Ultimate Characteristics

1. Introduction

In 2018, the Cabinet office's "Basic Plan for Resilience of the Land" was designed to protect human lives, maintain important functions of the nation and society, and to minimize damage to people's property and public facilities. Goal of the plan is quick recovery and reconstruction after a great disaster [1]. In addition, the Ministry of Land, Infrastructure, Transport and Tourism has provided technical advice (MLIT Housing Bureau Guidance No. 1111) for studies on large-amplitude ground motions such as Nankai Trough earthquake and Sagami Trough earthquake, which greatly exceed conventional seismic ground motions for design specified in the Building Standards Act. It is recommended to clarify the continuity of function by quantitatively evaluating the amount of deformation and damage of the structural, non-structural elements and equipment during a major earthquake [2].

In the case of a building, unlike an automobile or a like, it is difficult to perform a full scale experiment, therefore the degree of dependence on simulation is high. For large scale structures that are considered to have a large impact on urban functions and industries, to prevent damage and collapse due to a large earthquake, it is necessary to clarify the degree of destruction of the structural members and equipment that make up the structure, so it could be provided safety and function recovery. In order to evaluate the availability of the buildings after a large earthquake accurately, it is necessary to confirm the accuracy of the simulation and upgrade it.

For this reason, construction industry will need methodology for verification and validation (V&V) to ensure reliability of simulation. In order to establish V&V, it is necessary to enhance objective information such as seismic response observation data of structures and experimental data of structural elements such as structural members, seismic isolation / damping devices, and collate them with analysis.

From this background, we have investigated status of evaluation of seismic isolation / damping devices. We also looked for what kind of evaluation is needed in the future to ensure the reliability of the seismic response simulation.

2. Histories of seismically-isolated structures and vibration-controlled structures in Japan

The first seismically isolated building in Japan was completed in 1983 [3]. Later, the effectiveness of seismically isolated buildings was widely recognized in the 1995 Hyogo-ken Nanbu Earthquake and the 2011 Tohoku-Pacific Ocean Earthquake, and the spread of seismically isolated buildings was promoted. By 2017, 4557 seismically isolated buildings had been constructed. Especially, 363 seismically isolated buildings were constructed in 2013 after the 2011Tohoku-Pacific Ocean Earthquake.

According to a survey by the Japan Society of Seismic Isolation [4], the market share of each seismic isolation device in 2017 was 37% for natural rubber bearings, 27% for lead rubber bearings (LRB), 29% for high damping rubber bearings (HDR), 13% for elastic sliding bearings, 2% for tin rubber bearings, and 1% for natural rubber bearing with metallic damper [3].

Vibration-controlled buildings are not specified by the Building Standards Act. It is difficult to determine the number of buildings built accurately. However, by 2017, 1430 vibration-controlled buildings had been built. The market share of each type of damping device was 37% for metallic type, 20% for oil damper, 18% for viscous fluid type, 8% for friction type, 5% for viscoelastic type, and 5% for tuned mass damper. Tuned mass damper is a damper using inertial force [4].

The seismically isolated building was officially recognized in 1998 as a building structure under the Building Standards Act. Along with this, the Ministry of Construction (currently the Ministry of Land, Infrastructure, Transport and Tourism) promulgated the notifications of seismically isolated buildings (MLIT notification No. 2009) and seismic isolation materials (MLIT notification No.1446) in 2000. The notification (MLIT notification No. 2009) stipulated a method for evaluating seismic isolation devices (restoring devices, energy-absorbing devices) used in seismically isolated buildings. Therefore seismic isolation devices have been evaluated according to this notification. After the evaluation results were examined by peer reviewers to comply with the Building Standards Act or not. Seismic isolation devices approved of complying the Building Standard Act, can obtain a certification from MLIT. Currently, all seismic isolation devices, which used for seismically isolated buildings in Japan, should be required this certification.

At this time, the Building Standards Act does not clearly define the structure of a vibration-controlled building as a building structure. However, in 1999 Waseda University published a draft of guideline on seismic reinforcement design using viscoelastic dampers [5]. In 2000, Design Method for Response Control Structural was published by Japan Structural Consultants Association [6]. In 2004, the Japan Society of Seismic Isolation (JSSI) published JSSI Manual for Design and Construction of Passive Vibration Controlled Structure [7], [8]. As described above, private guidelines on vibration-controlled structures and damping devices are also being actively published. The development of methods for designing vibration-controlled structures and damping devices and of methods for evaluating damping devices are in progress.

3. Survey overview

There are various types and sizes of seismic isolation / damping devices. For this reason, seismic isolation devices were surveyed for LRB, HDR, high friction slide bearing, U-shaped steel damper, and spherical surface slide bearing. The damping device's survey carried out for viscous wall damper, friction damper, viscoelastic damper, wall type friction damper (WFD), Hybrid damper (combining viscoelastic and friction elements), unbonded brace damper (BRB, buckling restrained brace) and high damping oil damper. The following surveys were conducted for manufacturers of these seismic isolation devices and damping devices. The first survey's questions were:

- Type of device, material, shape, dimension
- Maximum load of devices designing at earthquake level 2
- Device's performance verification by experiment (if verified by experiment using reduced scale specimen)
- Model used in device's design
- Analytical model used for response simulation
- Validation by experiment
- Examples of advanced initiatives

The additional survey's questions were:

- Type and size of the building implemented devices
- Type and quantity of implemented devices
- Analytical model for seismic response simulation
- Largest size of seismic isolation / damping devices of the same type and future outlook

4. Status of seismic isolation devices

Fig.1 shows classification of seismic isolation devices. Table 1 shows the first survey results of seismic isolation devices. Table 2 shows the results of the additional survey. Fig. 2 shows the appearance of the seismic isolation device surveyed.

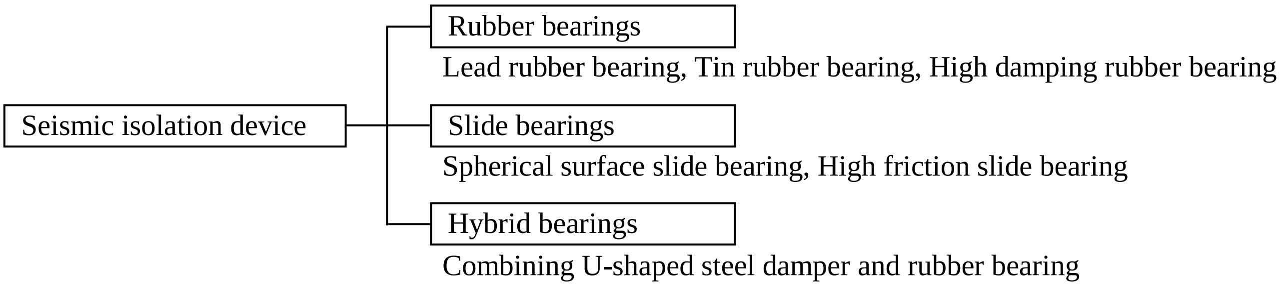

Fig.1 – Classification of seismic isolation devices

Table 1 – First survey's results of seismic isolation devices

	Lead rubber bearing(LRB)	High damping rubber bearing(HDR)	U-shaped steel damper	Spherical surface slide bearing	High friction slide bearing
Material	Natural rubber Lead plug	High damping rubber	SN490B special spec.	SUS304 SM490A PTFE	Natural rubber PTFE with special filler
Shape,Dimension	□600～□1600 ϕ 600~ ϕ 1500	ϕ 600~ ϕ 1800	5 series	Slider diameter：ϕ 150~ ϕ 600	Slider diameter：ϕ 300~ ϕ 1500
Maximum load at designing earthquake level 2	Supported load：15~30MPa Tensile load：1MPa Horizontal displacement：250~300% Maximum horizontal velocity：100~200cm/s	Designed to be within ultimate strength	Maximum response displacement designed to be within ultimate displacement Confirmation of cumulative fatigue damage	Compressive surface pressure≦411MPa	Maximum supported load：35000kN
Performance verification by experiment	By full scale specimen	By full scale specimen	By full scale specimen	By full scale specimen	By full scale specimen
Model used in device's design	Modified bi-linear model	Modified bi-linear model	Bi-linear model	Bi-linear model	Bi-linear model
Analytical model used for response simulation	Modified bi-linear model	Modified bi-linear model	Bi-linear model	Bi-linear model	Bi-linear model
Validation by experiment	Carried out	Carried out	Carried out	Carried out	Carried out
Examples of advanced initiatives	Arbitrary assessment of long-period ground motions	Advanced analysis model Verification of scale effect	Development of locking member for bolts to fix damper	Performing two-directional dynamic loading test	Estimated large-size performance by mechanical thermal analysis

Table 2 – Additional survey's results of seismic isolation devices

	Lead rubber bearing(LRB)	High damping rubber bearing(HDR)	U-shaped steel damper	Spherical surface slide bearing	High friction slide bearing
Type and size of the building implemented devices	Story：39 Height：200m Structure：Middle floor seismic isolation structure	Story：6 Height：32.8m Structure：Middle floor seismic isolation structure	Height：36m Width：144m Depth：64m Structure：Base seismic isolation	Height：33.5m Width：160m Depth：98m Structure：Base seismic isolation	Story：11 Height：43m Structure：Base seismic isolation
Type and quantity of implemented devices	Isolation device：LRB 66 sets Oil damper 24 sets	HDR 44 sets	UD55	Maximum diameter of sliderφ500 Ultimate Disp.550mm	LRB 58 sets NRB 18 sets
Analytical model for seismic response simulation	Upper：Mass spring model Seismic isolation device：Modified bi-linear model	Upper：7 mass spring model Seismic isolation device：Modified bi-linear model	Upper：Mass spring model Seismic isolation device：Bi-linear model	Upper：Mass spring model Seismic isolation device：Modified bi-linear model	Upper：16 mass spring model Seismic isolation device： Seismic isolation device： LRB Modified bi-linear model NRB Linear model
Largest size of device of same type	ϕ 1500, □1600	ϕ 1800	UD60	Slider diameter：ϕ 600	N/A
Future outlook	Verification of simulation accuracy is important	Verification of simulation accuracy is important	Open source model will be required	Open source model will be required	Countermeasures for long-period and long-term earthquake

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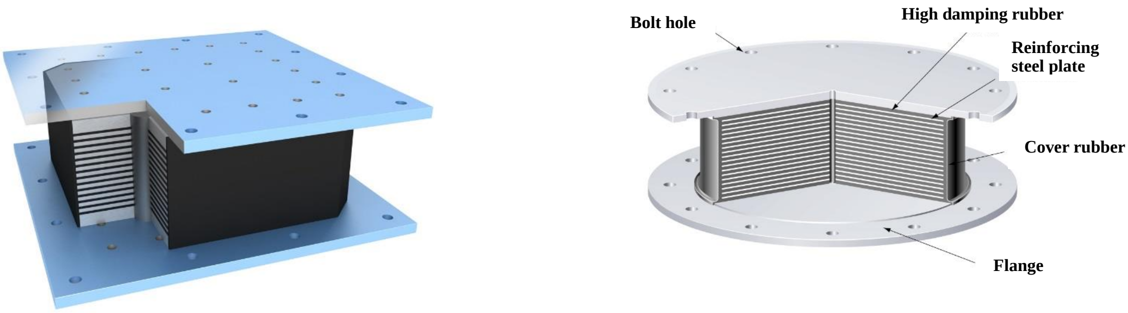
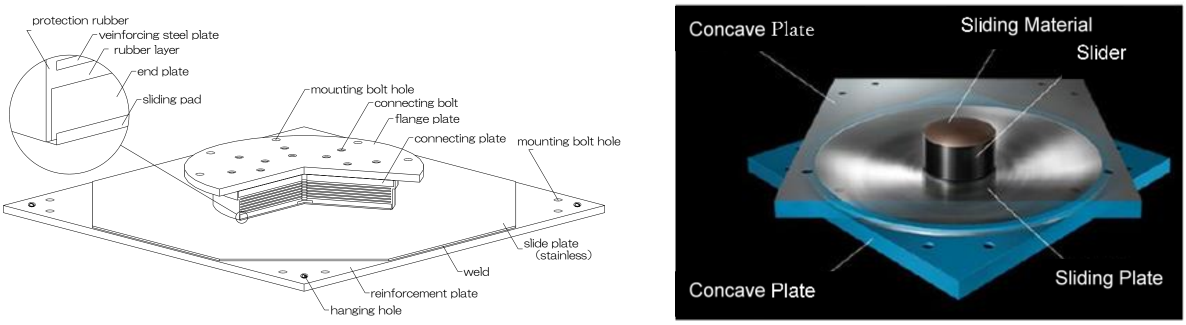
As examples of the ultimate characteristic test, Fig. 3 shows the test results of a lead rubber bearing and a high damping rubber bearing. In each case, the test was conducted on a full scale specimen. However, the measurement was not performed up to the breaking shear strain, due to load limit of testing machines. In the case of high damping rubber bearings, the product with maximum diameter of 1800 mm and maximum supporting load of 38000 kN has been developed.

All analytical models used for earthquake response simulation was based on bilinear model within the scope of this survey. The hysteresis characteristics of the high damping rubber bearing and the slide bearing have velocity dependency. However, change of their characteristics is small in the velocity range of practical use. Therefore, the velocity dependency is not explicitly incorporated into the analytical model. The analytical model is verified for all products in this survey, but most of the verifications are performed on scaled specimens due to the limit of testing machine capacity. As examples of the verification, Fig. 4 shows the actual measurement and hysteresis characteristics of a lead rubber bearing and a high damping rubber bearing, spherical surface slide bearing and U-shaped steel damper. As shown in Fig.4, each calculated results by analytical model has good agreement with the experimental results, however the modeling range is up to 270% rubber shear strain for both a lead rubber bearing and a high damping rubber bearing. This is because that maximum allowable use range is defined until 2/3 of the breaking strain as the safety likelihood. Even if maximum breaking strain would exceed 400%, the upper limit is set to 400%.



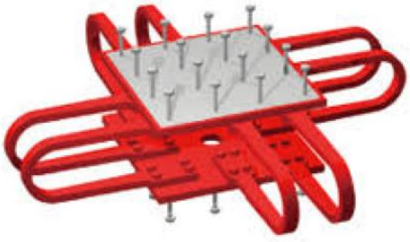
LRB (square type)

HDR



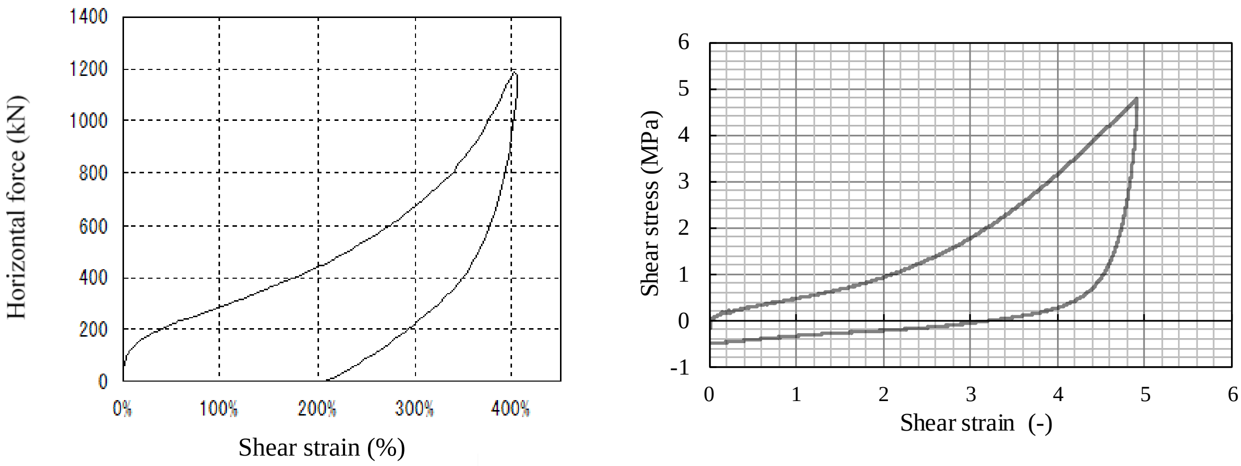
High friction slide bearing

Spherical surface slide bearing



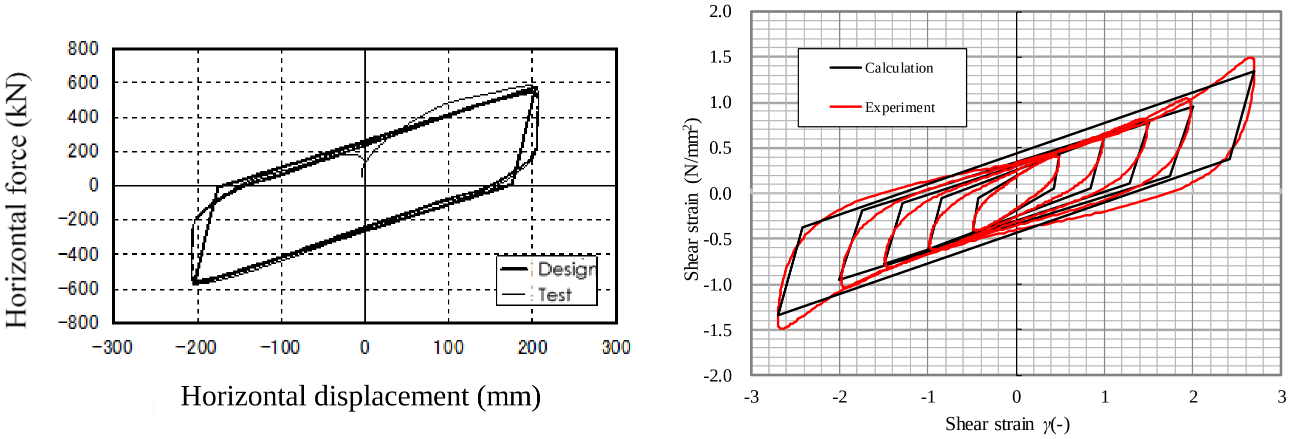
U-shaped steel damper

Fig.2 – Appearance of the seismic isolation devices

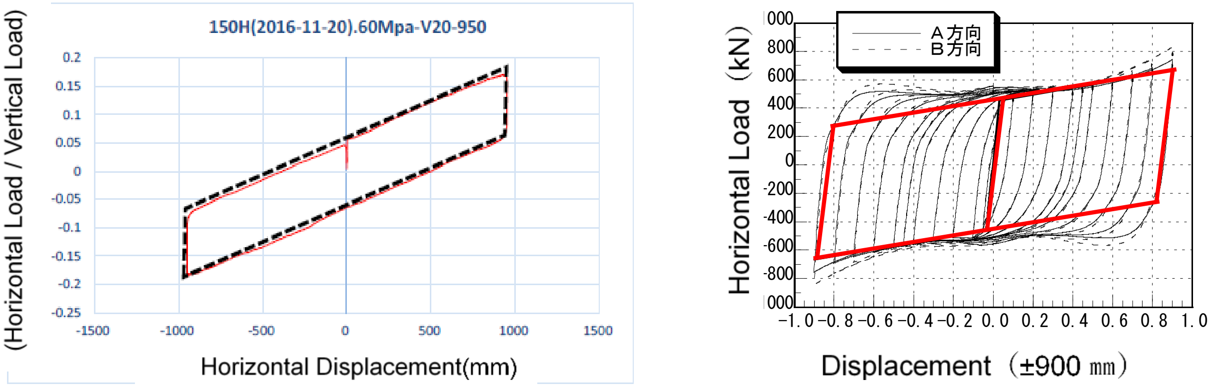


LRB HDR

Fig.3 – Examples of ultimate characteristics of seismic isolation devices



LRB HDR



Spherical surface slide bearing U-shaped steel damper

Fig.4 – Examples of verification for analytical models

In Japan, seismic isolation devices are required to undergo delivery inspections, therefore manufacturers have equipped large scale testing machines. However, the velocity of the testing machines is lower than that of the actual uses. Therefore, the tests by the manufacturers are quasi-static. For this reason, manufacturers use foreign testing machines to verify dynamic characteristics of the seismic isolation devices in full scale.

6. Status of damping devices

Fig.5 shows classification of damping devices by material used in the devices. Table 3 shows the results of the survey on the damping devices. Table 4 shows the results of the additional survey. Fig. 6 shows the appearance of the damping devices investigated.

Damping devices absorb vibration energy in buildings. Unlike seismic isolation devices, damping devices need not to support vertical load of buildings. Therefore, various types of materials, which can absorb vibration energy, are used for the damping device as shown in Fig.5. Typical damping devices include a hysteresis type, a viscous type, a viscoelastic type, a friction type, and an oil damper. As shown in Table 3 and Table 4, the maximum damping force is 1500 kN for the wall type friction damper, 6000 kN for the high damping oil damper, and 8900 kN for the unbonded brace damper.

Damping force of devices, such as wall type viscous damper, viscoelastic damper and oil damper, depends on deformation velocity. On the other hand, damping force of unbonded brace damper depends on deformation of material. The damping force characteristics of velocity dependency type are modelled based on Newtonian viscosity law or a four-elements model (a combination of Kelvin-Voight model and Maxwell model). The damping force characteristics of deformation dependency type are modelled as a bilinear model. Examples of verification by experiment of damping force model of the damping device are shown in Fig.7. Unlike seismic isolation device, ultimate characteristic tests of the damping devices have not been performed much. However, since large velocity does not act in damping devices as in the case of the seismic isolation device. Therefore, damping force of the damping devices has been evaluated at actual velocity and full scale.

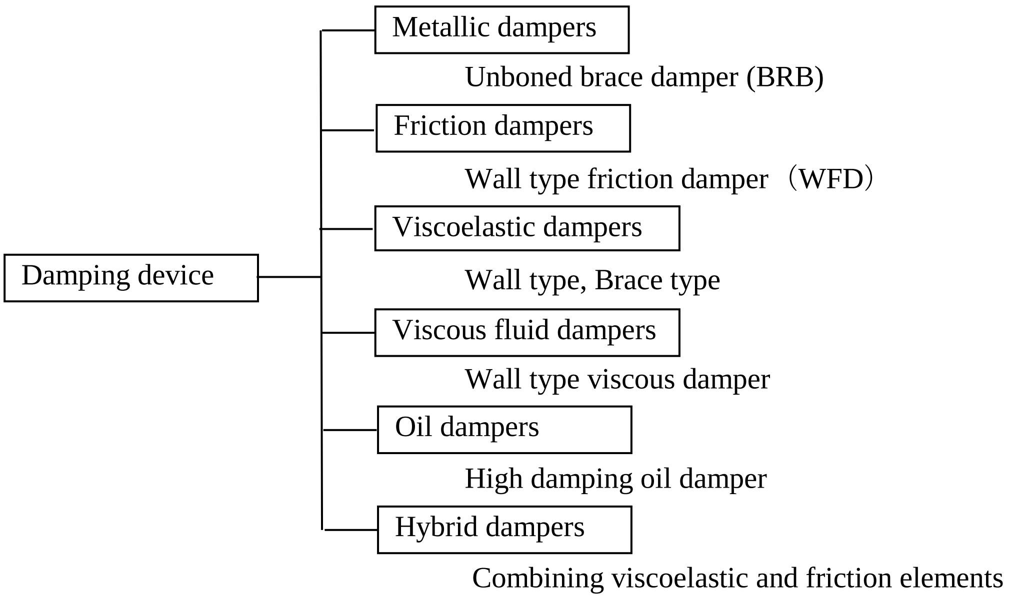


Fig.5 – Classification of damping device by material

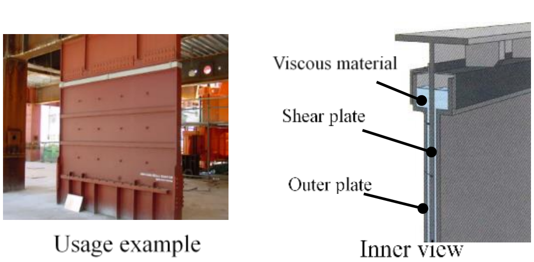
Table 3 – First survey's results of damping device

	Wall type viscous damper	Friction damper	Wall type friction damper (WFD)	Viscoelastic damper	Hybrid damper (combining viscoelastic and friction elements)
Material	Steel: SM490A Viscous fluid	Polymer friction material	Polymer friction material	Viscoelastic material	Polymer friction material
Shape, Dimension of products	Width : 1000~4000mm Height : 1000~3000mm Weight : 10~50kN	N/A	Width : 1500~2000mm Height : 1000mm Weight : 5~10kN	Width : 600~1800mm Height : 675~2075mm Thickness : 47~101mm	Width : 300mm Height : 900~1000mm
Maximum load at designing earthquake level 2	Depends on product size	Maximum load : 500~1000kN Allowable disp. ±60mm	Maximum load : 750~2000kN	Shear strain : ≦300% Ultimate shear strain : ≧450%	Sliding load : 500~1000kN
Performance verification by experiment	By full scale specimen	By full scale specimen	By full scale specimen	By full scale specimen	By full scale specimen
Model used in device's design	Non-Newtonian fluid	Bi-linear model	Bi-linear model	Non-linear 4 elements model	Detailed model: Fractional derivative model Simple model: Kelvin model
Analytical model used for response simulation	Non-Newtonian fluid	Bi-linear model	Bi-linear model	Non-linear 4 elements model	Detailed model: Fractional derivative model Simple model: Kelvin model
Validation by experiment	Carried out	Carried out	Carried out	Carried out	Carried out
Examples of advanced initiatives	N/A	Repeated loading test Thermal analysis	N/A	Experiment data was published	Confirmed the effect of heat generation by finite element analysis

	Unboned brace damper(BRB)	High damping oil damper
Material	Core steel : SN400B,SN490B,LY225 Case steel : STK400 etc.	Steel Mineral oil
Shape, Dimension of products	Core steel : Thickness 9~40mm Width 50~450mm	N/A
Maximum load at designing earthquake level 2	Calculate maximum strain and cumulative damage and confirm that there is no problem with fatigue performance	Maximum 250~2000kN Maximum velocity : 30cm/s
Performance verification by experiment	By full scale specimen and reduced scale model	By full scale specimen
Model used in device's design	Bi-linear model	Maxwell model
Analytical model used for response simulation	Bi-linear model	Maxwell model
Validation by experiment	Carried out	Carried out
Examples of advanced initiatives	Investigation of buckling stability of out-of-plane braces including joints and published in academic conferences	N/A

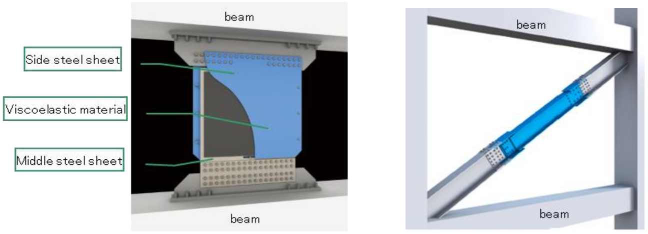
Table 4 – Additional survey’s results of damping device

	Wall type viscous damper	Unboned brace damper (BRB)	High damping oil damper
Type and size of the building implemented devices	Story：43 Height：159m	Office、Steel frame structure Height：195.7m Width：94m Depth：39m	Office and Hall complex Story：50 height：250m Floor area：150000m^2
Type and quantity of implemented devices	Maximum damping force：1509kN	Maximum damping force: 4×8900kN	Maximum damping force 6000kN
Analytical model for seismic response simulation	The accuracy can be improved by testing the damping device alone with the actual response wave.	Earthquake level 2 Maximum interlayer displacement: 1/111 Response simulation using a three-dimensional analysis model	Seismic response simulation not carried out by the manufacture
Maximum size of device of same type	N/A	Maximum compressive load：4×8900kN	Maximum damping 6000kN
Future outlook	N/A	Verification of safety margin by full-scale dynamic three-direction loading test	Try in establishing large-capacity test methods



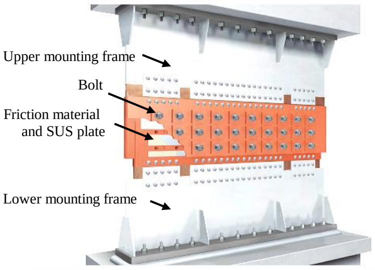
Usage example Inner view

Wall type viscous damper



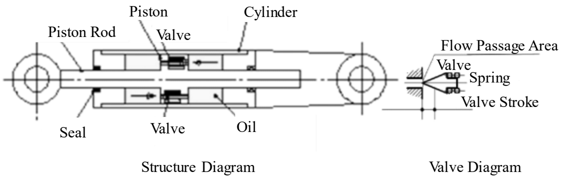
Basic shape (Wall type：left Brace type：right)

Viscoelastic dampers



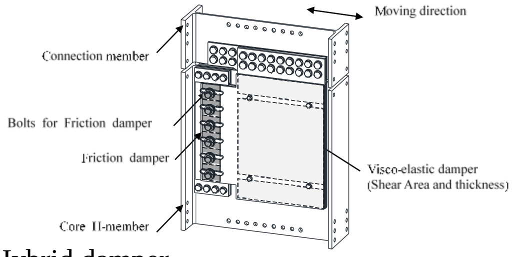
Wall type friction damper

Unbonded brace damper (BRB)



Structure Diagram Valve Diagram

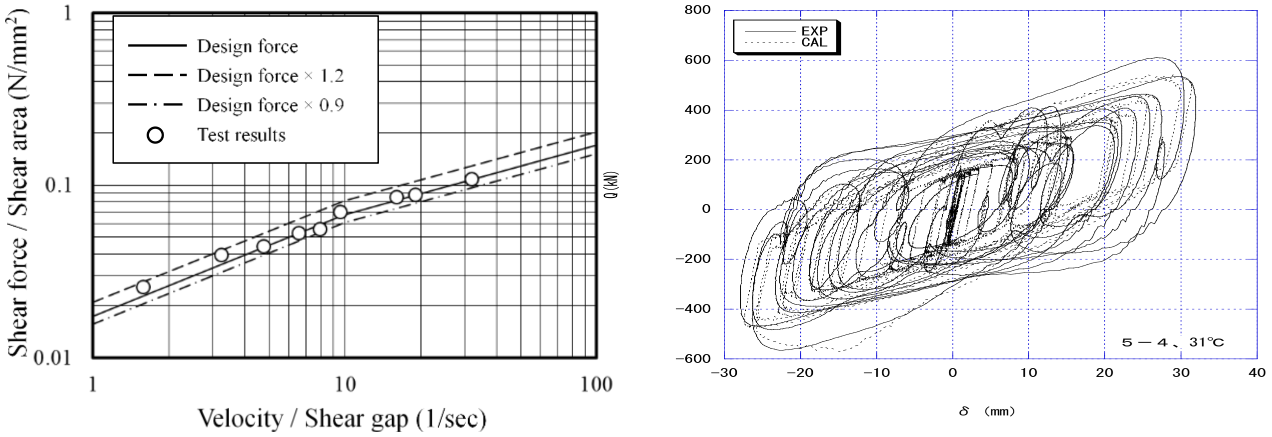
High damping oil damper



Hybrid damper

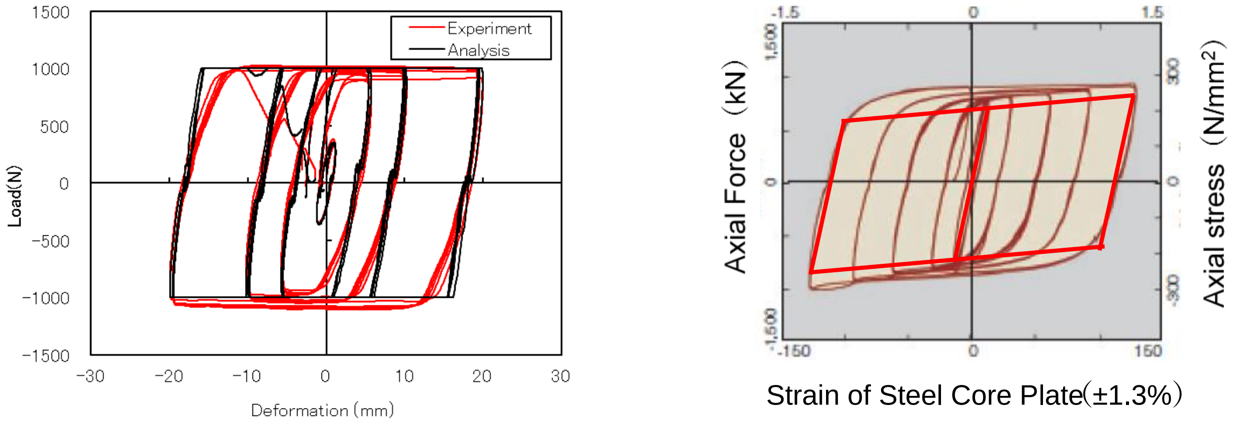
(Combining viscoelastic and friction elements)

Fig.6 – Appearance of the damping devices



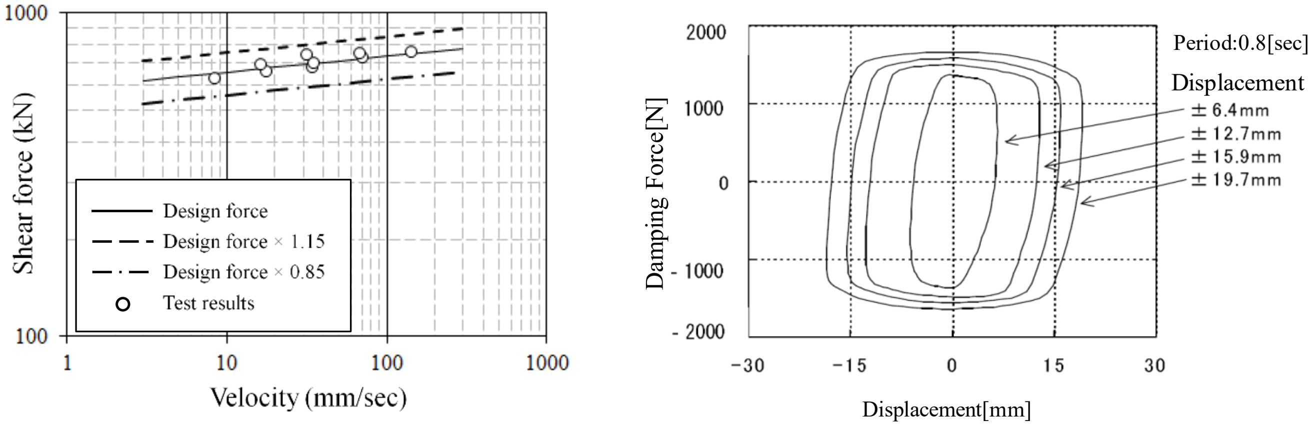
Wall type viscous damper

Viscoelastic damper



Hybrid damper

Unbonded brace damper (BRB)



Wall type fiction damper

High damping oil damper

Fig.7 – Examples of verification for analytical model

7. Issues for advanced simulation

In the case of rubber bearings, the performance of products has been verified in full scale up to 400% shear strain except for some experiments have been performed up to the point of breakage [9],[10]. In Japan, there is no testing machine, which can evaluate dynamic characteristics of seismic isolation devices at the actual horizontal deformation velocity and load. Therefore, dynamic characteristics of seismic isolation device of full scale have been estimated from quasi-static test's results by a correction using dynamic test results of the reduced scale specimen. The analytical model of seismic isolation device is also set appropriately based on the material properties used for each seismic isolation device. The analytical model can reproduce restoring force and hysteretic characteristics of the actual devices. However, the analytical model does not support up to the ultimate state except for some cases [11]. For a 3D response simulation, an analytical model of seismic isolation devices should be corresponded to two directions in horizontal, but at the time of this survey, there is a few model can support to two directional calculation in horizontal except for some analytical models [12].

As for the damping device, the performance of product is verified by using full scale specimen. The analytical model is appropriately set based on the characteristics of the materials used in the damper. The experimental results can be reproduced accurately by using the analytical model. However, there are few experiment and simulation until the ultimate state for most products.

8. Conclusions

From the answers of questionnaires to the manufactures, performance verification of both the seismic isolation devices and the damping devices has been sufficiently conducted with full scale specimen in the range of the designing seismic ground motion level 2 except for some dynamic characteristics of seismic isolation devices. The survey also revealed that the analytical models for earthquake response simulation have been verified their accuracy. However, in order to build a resilient society and achieve BCP, it is essential to advance simulation technology, which enables the prediction of the ultimate state of large buildings and the quick search for damaged parts by simulation. For that purpose, it is necessary to enhance the verification and validation of seismic isolation devices and damping devices. In order to realize these, it is necessary to evaluate both ultimate characteristics and basic characteristics of the seismic isolation and damping device of full scale specimen at the actual deformation and velocity. The analytical model for response simulation should extend to the ultimate state or close to the ultimate state. It is also necessary to verify the analytical model objectively and fairly such as a peer review.

9. Acknowledgments

This survey was conducted by working group 2 established under the project of the theme of "Next Generation Evaluation Method for Large Structures" (leader: Tokyo Institute of Technology, sub-leader: Nippon Steel) promoted by Council on Competiveness-Nippon [13]. Companies of participating working group 2 are OILES Corporation, KYB Corporation, 3M Japan Limited, SWCC Showa Cable Systems Co., LTD., Sumitomo Riko Company Limited, Nippon Steel Engneering Co., Ltd. and Bridgestone Corporation. The authors would like to express sincerely thanks to the cooperation of these companies participating working group 2.

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