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DYNAMIC LOADING TEST OF HYBRID ENERGY DISSIPATION SYSTEM COMBINING A HYSTERETIC DAMPER AND A THIN-LAYERED VE DAMPER WITH A LOAD-REDUCING SYSTEM

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ABSTRACT

Recently, habitability against wind-induced vibration as well as structural safety against earthquakes is required for buildings, especially for high-rise buildings. Motivated by these requirements, the authors have developed a hybrid energy dissipation system named the hybrid brace damper, which is composed of a hysteretic damper and viscoelastic damper in parallel. For this damper, a buckling restrained brace is utilized as a hysteretic damper. To enhance the damping performance against very small amplitudes, a thin-layered (thickness 2mm) viscoelastic damper with a load-reducing system during a great earthquake is utilized. To confirm the performance of this hybrid brace damper, full-scale dampers are tested under dynamic cyclic loading. Test results show that this hybrid brace damper has a wide range of performance of energy absorption. The simple analysis model simulates test results excellently.

Introduction

Hybrid energy dissipation systems have recently been put to practical use to reduce the response to a wide range of amplitudes from daily wind-induced vibration to large deformation during an earthquake (Sano 1996, Watanabe 1999, Soda 2001, Kasai 2002 and Yamamoto 2004). Hybrid energy dissipation systems are provided with stable energy absorbing capacity against small to large amplitudes by connecting a hysteretic damper to a viscoelastic (VE) damper in series or in parallel. The damping force of the VE damper is proportional to the area of attachment of VE material (*S)* and inversely proportional to the thickness of the VE material (*d)*. For the VE damper to act efficiently against very small amplitudes with the hysteretic damper behaving in the elastic range, providing a high damping force by minimizing thickness *d* is desirable. In the case of parallel connection, however, the VE damper suffers the same degree of deformation as the hysteretic damper. Protecting the VE damper from large deformation during a great earthquake therefore requires increasing the thickness of the VE material *d*, and having the VE damper act efficiently against very small amplitudes was difficult. Then, the authors have developed a hybrid brace damper by equipping a thin-layered (thickness 2mm) VE damper with a load-reducing system (sliding system) to control the deformation of the VE damper during a great earthquake and to enhance

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the damping force against very small amplitudes. This paper presents a report on the results of a dynamic loading test using full-scale test specimens.

Configuration of Hybrid Brace Damper

Fig. 1 shows a general view of the hybrid brace damper. Fig. 2 shows a mechanical model of the damper. A VE damper, a sliding system and an elastic spring were connected in series. A hysteretic damper was connected to the series in parallel. A buckling-restrained brace (Narihara 2000) was used as the hysteretic damper. In conventional buckling-restrained braces, the axial member and anti-buckling stiffener could slide mutually. The hybrid brace damper was designed to cause relative displacement between the two components only at the right edge and to apply the relative displacement to the VE damper, by bolting the axis of the brace to the anti-buckling stiffener on the left edge of the buckling-restrained brace. The damping force of the VE damper was proportional to the area of attachment of VE material *S* and inversely proportional to the thickness of the VE material *d*. Thickness *d* was reduced to 2 mm to provide the VE damper with high performance at very small amplitude. Acrylic (ISD111) or dien (SDM1) VE material with low amplitude dependence was adopted for the VE damper. The outer steel flanges of the VE damper were connected to the anti-buckling stiffener, and the center plate in the VE damper was connected to the end joint of the axis of the buckling-restrained brace. Connection by double shear friction using a medium plate with slots and high strength bolts was designed to cause slide under a designated load. The roles of components of the hybrid brace damper are described below.

(a) Buckling-restrained brace

It serves as a hysteretic damper against a large amplitude response affecting the structural safety during a great earthquake to minimize damage to the building.

(b) Viscoelastic (VE) damper

It reduces a relatively frequent small-amplitude response with the buckling-restrained brace staying in the elastic range as in wind-induced vibrations or vibrations during a small to medium earthquake. The objective is to improve occupants' habitability against a small-amplitude response.

(c) Sliding system

It slides at the time of a relatively large amplitude response. Then, the damping force and strain acting on the VE damper connected to the sliding system in series are prevented from increasing extraordinarily. Thus, damage to or fracture of the VE damper or connections is prevented.

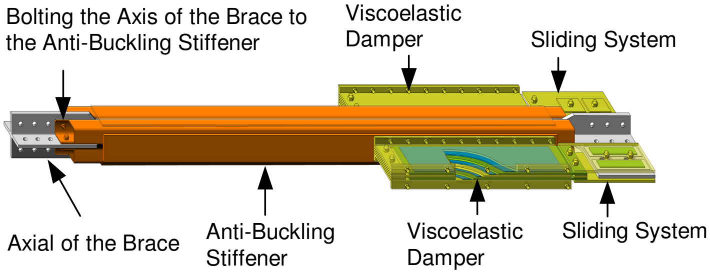


Figure 1. Overview of hybrid brace damper.

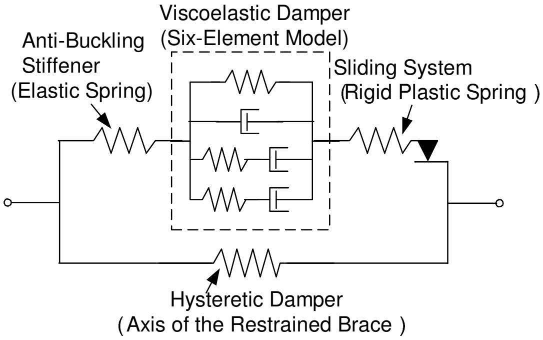


Figure 2. Mechanical model of hybrid brace damper.

Dynamic Load Test for Full-Scale Damper

Test outline

A dynamic load test was conducted to examine very small to large deformation of the hybrid brace damper for verifying the performance of the actual member.

Specimen

Fig. 3 and 4 show the dimensions of the specimen. The axis of the bucking-restrained brace had a cruciform section 80 x 80 x 12 (SN400B). Deformation of the axis at the yield point was 3.7 mm. Axial force at the yield point was 503 kN. Two types of hybrid brace damper specimens were made using acrylic or dien VE material as the VE damper. The VE damper was 140 mm wide, 1000 mm long and 2 mm thick and consisted of four layers. The S/d ratio was 56000 cm per hybrid brace damper. An axial force of 178 kN (89 kN x 2), 50% of normal tensile force of bolt fastening, was applied to high strength bolts (F10T-2 x M20) of the sliding system. The bearing stress and friction coefficient of the friction material were approximately 10 MPa and 0.2, respectively.

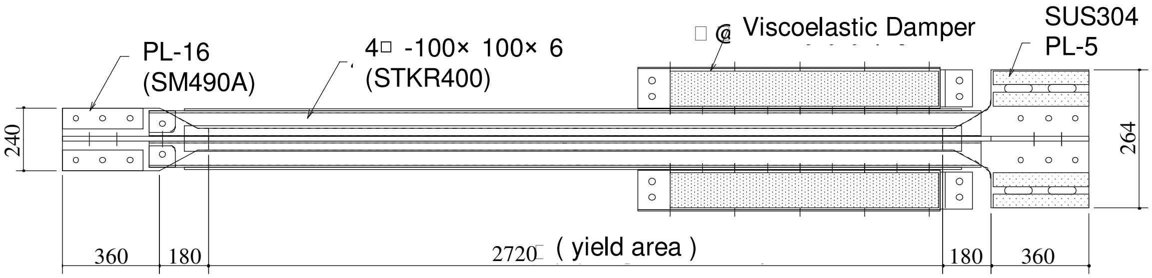
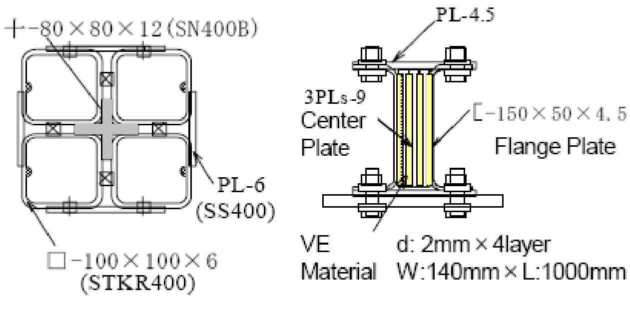


Figure 3. Figure of specimen.



(a) Section of brace (b) Section of VE damper

Figure 4. Figure of specimen.

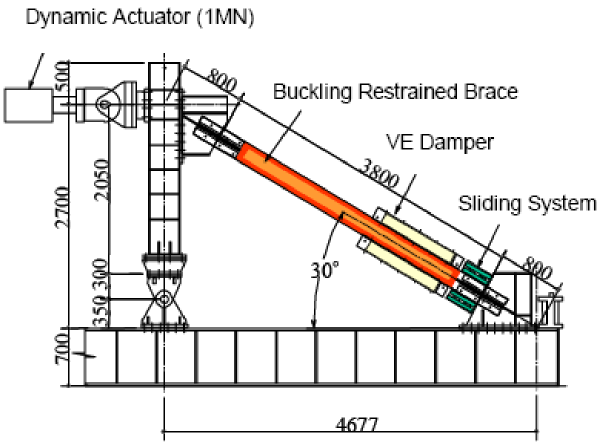


Figure 5. Test setup.

Loading setup

Fig. 5 shows the setup for loading. The specimen was placed diagonally between the grade beam and a column for applying loads like a brace. Loads were applied horizontally on the column head using a dynamic actuator with a maximum load ± 1 MN.

Items to be measured

Measurements were taken to evaluate load-deformation relationships in different parts of the hybrid brace damper. Deformations of the specimen as a whole, VE damper and sliding system were measures. The load on the brace was also measured using a strain gauge attached in the section where the axis of the brace behaved in the elastic range. The load on the VE damper was evaluated by subtracting the load on the brace from the total load on the hybrid brace damper calculated based on the reading of the load cell of the actuator. The temperature of the VE material and the tensile force of bolt fastening in the sliding system were also measured.

Test cases

Table 1 lists test conditions. The test was conducted under steady load using sinusoidal waveform with varying amplitude, and under programmed load using waveform for wind and earthquake response analysis.

Table 1. List of loading tests.

	Elastic Loading					Elastoplatic Loading		
disp (strain of VE) frequency	0.1mm (5%)	0.2mm (10%)	0.4mm (20%)	0.6mm (30%)	1mm (50%)	2mm (100%)	10mm (500%)	30mm (1500%)
0.25Hz	○	○	○	○	○	○	-	-
0.33Hz	○	○	○	○	○	○	○	○
0.5Hz	○	○	○	○	○	○	-	-
Wind resp (4s)	-	◎	◎	◎	-	-	-	-
Wind resp (4s)	-	◎	◎	◎	-	-	-	-
Hachinohe eq resp (4s)	-	-	-	-	-	◎	◎	◎
Hachinohe eq resp (4s)	-	-	-	-	-	◎	◎	◎

○ : 10cycle steady load using sinusoidal waveform
◎ : programed load using waveform for wind and earthquake response

Results of loading

Elastic loading

Fig. 6 shows hysteresis loops for the dien specimen that were obtained as a result of loading using sinusoidal waveform with an amplitude of 0.2 mm and a frequency of 0.33 Hz. Fig. 7 shows hysteresis loops for the acrylic specimen that were obtained as a result of loading using wind response waveform (a model of a building with a natural period of four seconds and a maximum deformation of 0.6 mm). Fig. 8 shows time histories of load, deformation and temperature of the VE material when wind response waveform was used for loading. Very-small-amplitude loads were applied on the assumption of daily wind-induced vibration. As a result, the axis of the brace stayed in the elastic range and no sliding yet occurred. The VE damper exhibited ellipsoidal loops, so stable hysteresis loops were confirmed even in the case of very small deformation with an amplitude of 0.2 mm (strain of the VE material: 10%). The time history of deformation indicated that relative deformations at both ends of the specimen were concentrated on the VE material because the anti-buckling stiffener was sufficiently rigid. A change in temperature of the VE material due to loading was sufficiently small to be ignored.

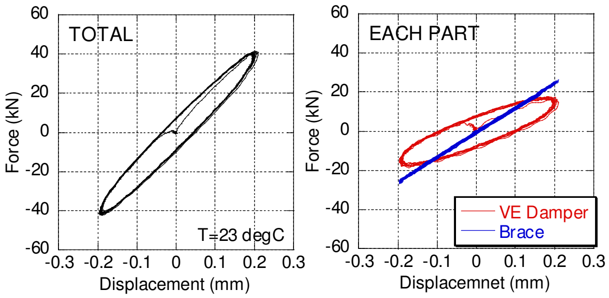


Figure 6. Load – deformation relationships (dien) (sinusoidal loading : 0.2mm,0.33Hz).

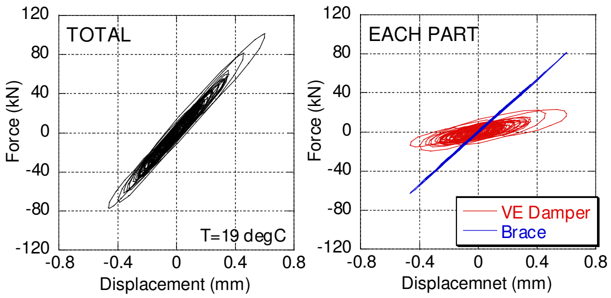


Figure 7. Load – deformation relationships (acrylic)(wind response loading : 0.6mm).

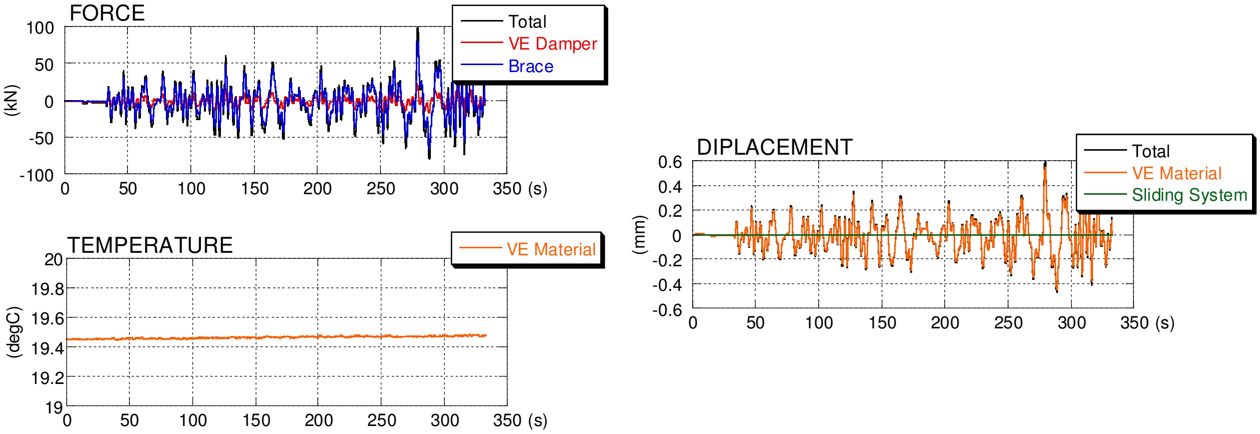


Figure 8. Time history waveform (acrylic) (wind response loading : 0.6mm).

Elastoplastic loading

Fig. 9 shows the results of loading of the dien specimen using sinusoidal waveform with an amplitude of 30 mm and a frequency of 0.33 Hz. Fig. 10 and 11 show the results of loading of the acrylic specimen using the Hachinohe earthquake response waveform (a model of a building with natural period of four seconds and a maximum deformation of 30 mm). Large-deformation-inducing loads were applied on the assumption of an earthquake. The brace exhibited stable spindle hysteresis loops as a steel hysteretic damper. The VE damper exhibited elastoplastic hysteresis loops because of sliding. The load on the VE damper was controlled by the sliding load, so the maximum strain of the VE material was reduced to 250% (deformation of 5 mm), sufficiently below a marginal strain of 500% (deformation of 10 mm). The temperature of the VE material increased 0.5 deg C due to loading. There were, however, no changes in bolt axial force.

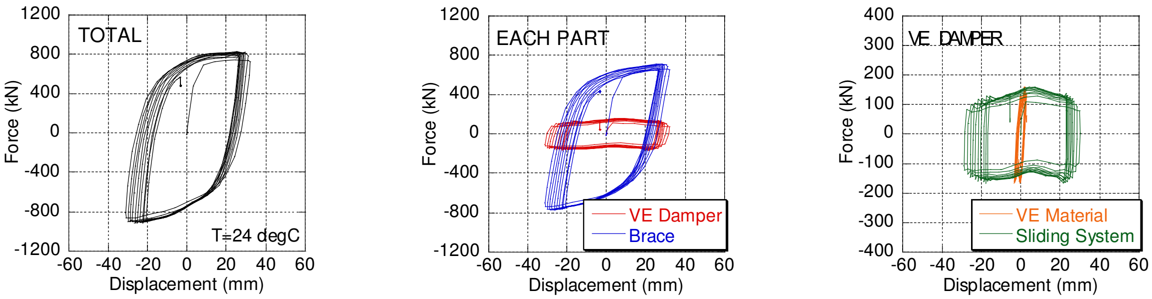


Figure 9. Load – deformation relationships (dien) (sinusoidal loading : 30mm,0.33Hz).

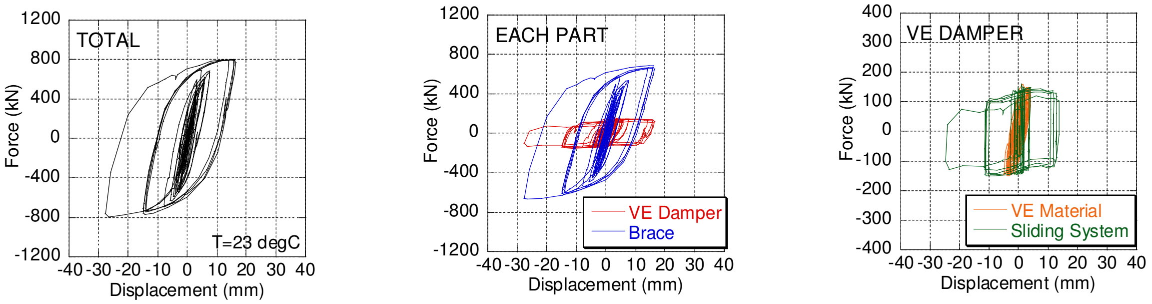


Figure 10. Load – deformation relationships (acrylic) (Hachinohe earthquake response loading : 30mm).

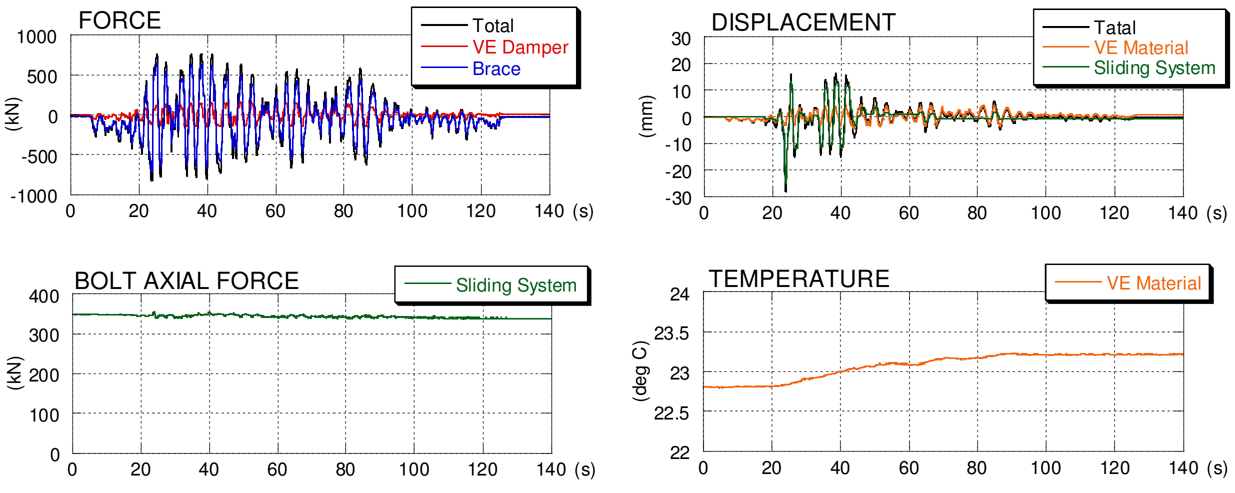
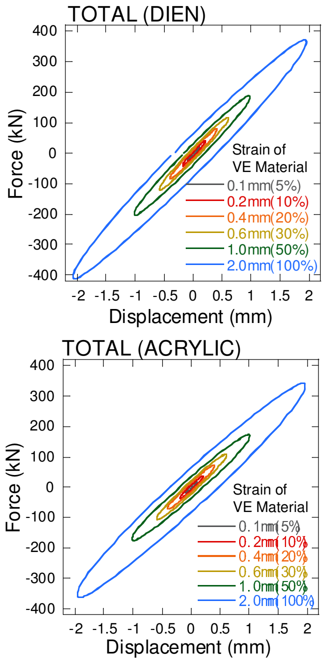


Figure11. Time history waveform (acrylic) (Hachinohe earthquake response loading : 30mm).

Mechanical properties of damper identified based on the loading results

Mechanical properties at very small amplitude

Fig. 12 shows very small amplitude hysteresis loops for the entire specimen obtained as a result of loading using sinusoidal waveform with a frequency of 0.33 Hz (in the third cycle). Fig. 13 shows shear storage modulus *G'* and damping ratio *h (=G"/G'/2)* at different parts of the specimen. Damping ratio *h* was more or less the same either for the dien or acrylic specimen. It is therefore evident that both specimens absorbed the same energy. Both specimens had low amplitude dependence and apparently had stable stiffness and energy absorbing capacity in the case of very small deformation with amplitude of 0.1 mm (strain of the VE material: 5%).



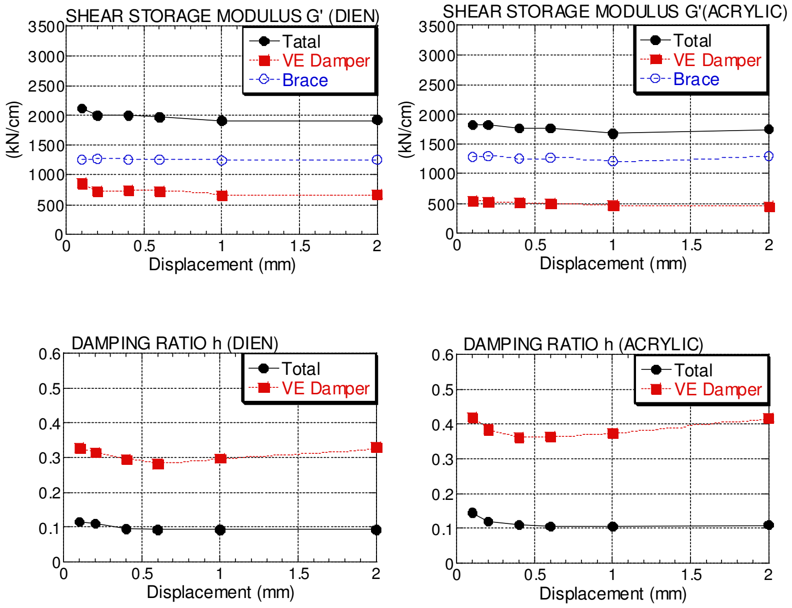


Figure 12. Load – deformation relationships (sinusoidal loading : 0.33Hz).

Figure 13. Shear storage modulus and damping ratio of Hybrid Brace Damper (at very small amplitude).

Relationship between input level to behavior at each part

Fig. 14 shows the relationships of amplitude of loading using sinusoidal waveform with a frequency of 0.33 Hz at a temperature of approximately 20 deg C to the maximum load, maximum deformation and energy absorbed in a cycle at different parts of the dien and acrylic specimens. In both specimens, the brace behaved in the elastic range and the VE damper absorbed energy during very small amplitude loading with amplitude of less than 2 mm. The maximum deformations at different parts of the VE damper show that the sliding system did not work and that only the VE material deformed and absorbed energy. Under large amplitude loading with amplitude of 10 mm or 30 mm, the brace served as a steel hysteretic damper, so it absorbed a large quantity of energy. The load on the VE damper was limited to a certain value by the sliding system. In the VE damper, the deformation of the sliding system became predominant with the increase of amplitude and the deformation of the VE material was held to a certain level.

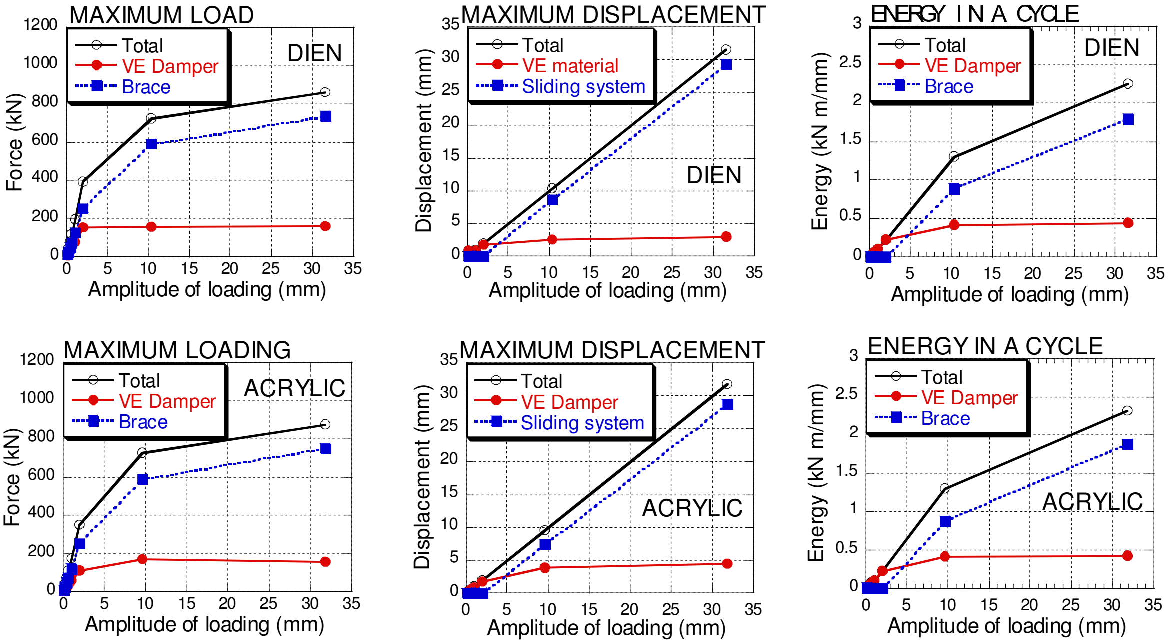


Figure 14. Relationship between amplitude of loading to the maximum load, maximum deformation and energy absorbed in a cycle at different parts.

Simulation Analysis

Analysis model

Fig. 15 shows an analytical model of hybrid brace damper. A bilinear model of the brace was made. The primary stiffness and yield axial force were set based on the results of steel tensile tests. The secondary stiffness was assumed to be one-twentieth of the primary stiffness. A six-element model combining Maxwell and Voigt models was made to represent the VE damper to take the material dependence on the frequency into consideration. Maxwell and Voigt models were combined because a Maxwell model alone could neither represent the characteristics of the VE damper at low velocities (static stiffness) nor reproduce the behavior of the damper in the case of sliding. The coefficients of the six-element model were determined by nonlinear least square method based on the shear storage modulus *G'* and shear loss modulus *G"* (at 20 deg C) obtained from the white noise (0.1 Hz through 10 Hz) displacement excitation with a strain of 100% using a specimen composed only of a VE damper. The sliding system was represented by a bilinear model with rigid plastic hysteretic characteristics. The sliding load was set to be 142 kN based on a friction coefficient of 0.2 of the friction material (mean bearing stress: 10 MPa) and the product of multiplication of a bolt axial force of 89 kN by four.

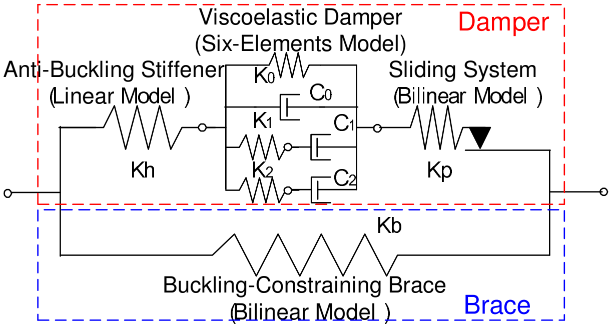


Figure 15. Analysis model.

Analysis results

The effectiveness of the analytical model was verified by comparing test results with analysis results. Fig. 16 shows hysteresis loops for different parts of the dien hybrid brace damper that were obtained as a result of loading using sinusoidal waveform with a maximum amplitude of 0.2 or 30 mm and a frequency of 0.33 Hz. Fig. 17 shows hysteresis loops for the acrylic hybrid brace damper that were obtained as a result of loading using wind response waveform (a model of a building with natural period of four seconds and a maximum deformation of 0.6 mm) (strain of the VE material: 30%), and using the Hachinohe earthquake response waveform (a model of a building with natural period of four seconds and a maximum deformation of 30 mm). Analysis results were in good agreement with the test results. Thus, the validity of the proposed analytical model was verified.

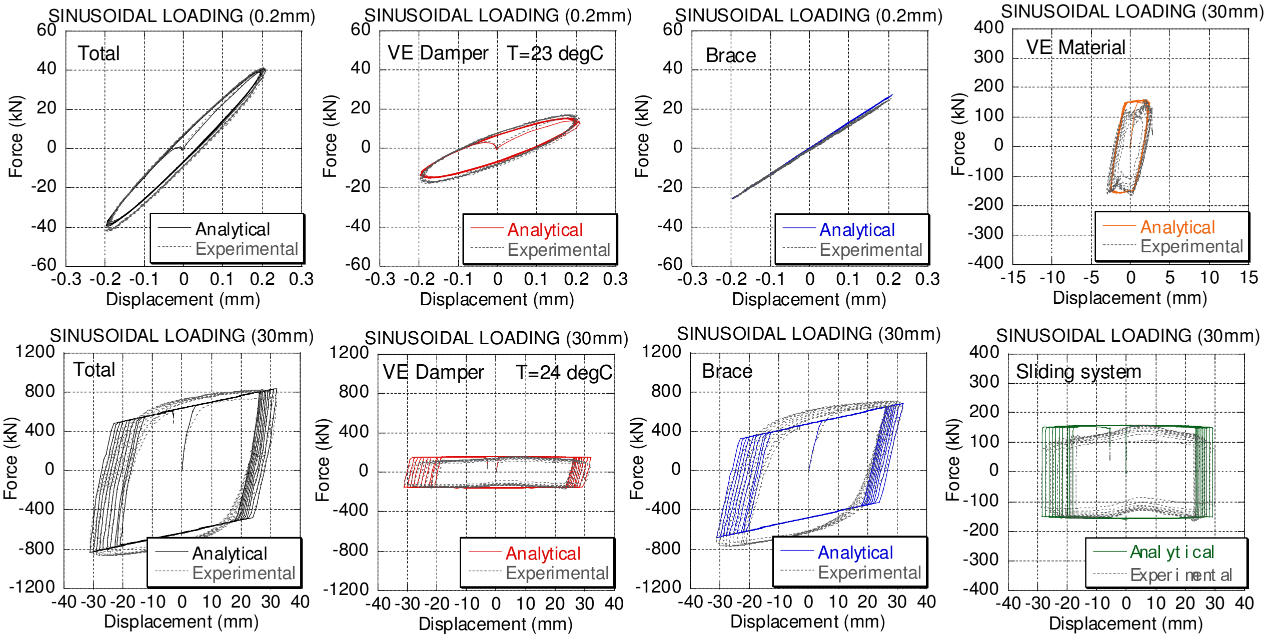


Figure16. Comparison of experimental and analytical results for hybrid brace damper (dien)

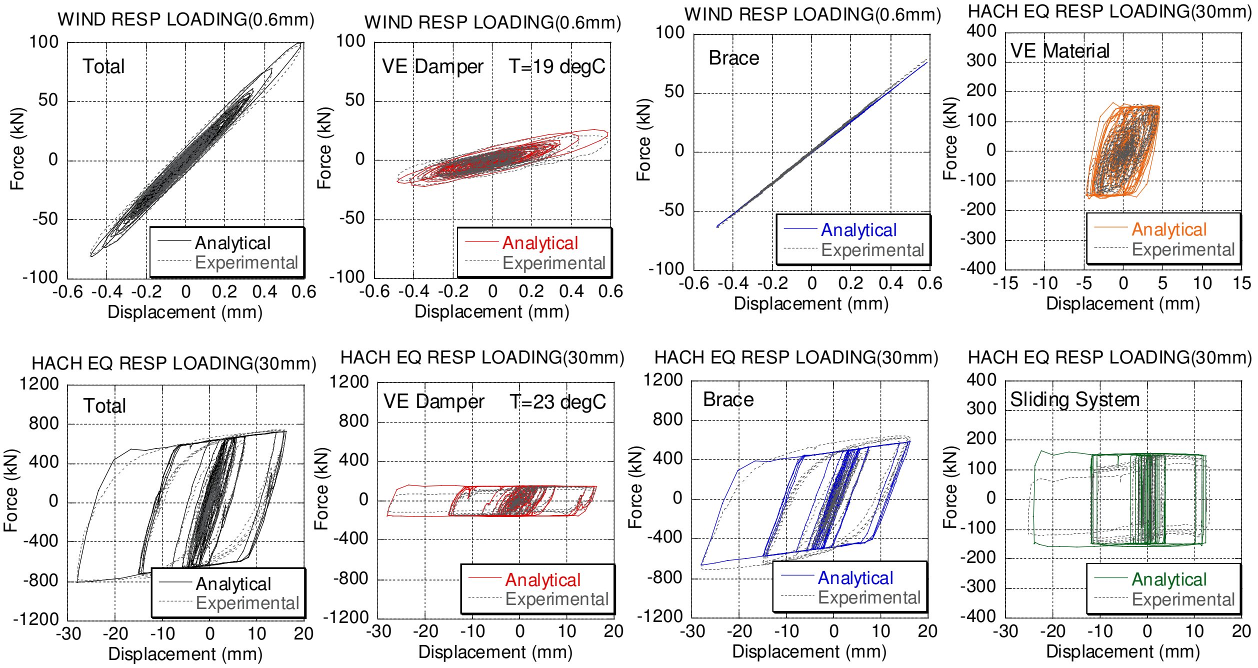


Figure 17. Comparison of experimental and analytical results for hybrid brace damper (acrylic).

Conclusions

In this study, the authors have developed a hybrid brace damper by equipping a thin-layered (thickness 2mm) VE damper with a load-reducing system (sliding system) to control the deformation of the VE damper during a great earthquake and to enhance the damping force against very small amplitudes. To confirm the performance, a dynamic loading test using full-scale test specimens and simulation analysis of test results were conducted. Conclusions are as follows:

(1) At small deformation loading (0.1-2.0mm) with the buckling-restrained brace staying in the elastic range: No sliding yet occurred in sliding system. Relative deformations at both ends of the hybrid brace damper were concentrated on the VE material because the anti-buckling stiffener was sufficiently rigid. The VE damper exhibited ellipsoidal loops, so stable hysteresis loops of the hybrid brace damper were confirmed even in the case of very small deformation with an amplitude of 0.1 mm. The VE damper had low amplitude dependence with an amplitude of 0.1mm-2mm (strain of the VE material: 5%-100%) and apparently had stable stiffness and energy absorbing capacity in the case of very small deformation with an amplitude of 0.1 mm.

(2) At large deformation loading (30mm): The brace exhibited stable spindle hysteresis loops as a steel hysteretic damper. The VE damper exhibited elastoplastic hysteresis loops because sliding occurred in the sliding system. The load on the VE damper was controlled by the sliding load, so the maximum deformation of the VE material was reduced to 5mm (strain of the VE material: 250%), sufficiently below a marginal deformation of 10mm (strain of the VE material: 500%).

(3) The brace was represented by a bilinear model. The VE damper was represented by a six-element model combining Maxwell and Voigt models. And the sliding system was represented by a bilinear model with rigid plastic hysteretic characteristics. The analysis results using this simple analysis model were in good agreement with the test results.

Hybrid brace dampers enable the user to ensure structural safety during a great earthquake using the hysteretic damper, and to enhance occupants' habitability by reducing wind response vibration with the VE damper. Hybrid brace dampers, unlike conventional dampers including tuned mass dampers, require neither additional space nor maintenance cost. They are expected to be applied to high-rise buildings and other types of structures.

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