Analytical and Experimental Study on a New Stud-type Hysteretic and Visco-elastic Hybrid Damper System

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Abstract

This paper proposes a new stud-type hybrid damper system for residential houses and building structures. The proposed vibration control system consists of braces, upper and lower rigid frames and a damper unit including hysteretic and viscoelastic dampers (high-hardness rubber). The proposed vibration control system has a high damping capacity and a stable damping performance in a broad response range. A simplified design method for hybrid dampers is then proposed. The proposed design method enables not only to design the hybrid damper system but also to predict its damping capacity in the design stage. Theoretical and analytical studies are carried out using an equivalent linearization method and a time-history response analysis to investigate the damping performance of the proposed vibration control system. Loading tests with full-scale models are conducted to verify the damping capacity of the proposed vibration control system, and to clarify the validity of the proposed simplified design method. The accuracy of the analytical models is evaluated through the comparison of the test results with those of analytical studies. Finally, a nonlinear time-history response analysis is conducted to examine the performance of the proposed vibration control systems in the response reduction of practical residential houses.

Keywords: stud-type hybrid damper system; hysteretic damper; high-hardness rubber damper; simplified design method; free vibration test

1. Introduction

Many passive dampers have been developed and applied to building structures so far to improve the habitability as well as the safety against wind and

earthquake disturbances (e.g. [1-6]). The tuned mass dampers (TMDs) and the story-installation type dampers such as the friction, viscous and viscoelastic dampers are often applied to low-rise building structures due to their effectiveness in dissipating the energy input from wind and earthquake disturbances. Though TMDs are usually used in residential houses for controlling the dynamic responses by small-to-medium earthquake disturbances, they have a difficulty in the tuning and effectiveness of vibration damping during large earthquakes because of the limit in the movable range of added mass. In case of the story-installation type dampers, while they have advantages in cost, manufacturing and installation, it is not so easy for the story-installation type dampers to upgrade their efficiency compared to usual large-scale stud-type or wall-type dampers with steel materials.

In recent years, several studies on hybrid damper systems combining two materials in series have been carried out by many researchers [7-12]. However, existing hybrid damper systems placed in two or more walls of a building structure, or composed in series have some problems such as the balance of energy absorbing capacities of dampers and the damping degradation caused by the stiffness reduction of damper systems. Furthermore the existing vibration control systems developed for large-scale building structures are too expensive to apply to residential houses, and have a difficulty in control.

This paper proposes a new stud-type hybrid damper system for residential houses, which has a high damping capacity and a stable damping performance in a broad response range with low cost and easy installation. Hysteretic and high-hardness rubber dampers are introduced in the proposed vibration control system as energy dissipation devices. The high-hardness rubber [13, 14] produced by the Sumitomo Rubber Industry Corporation, Kobe, Japan has large initial stiffness, small temperature and frequency dependencies compared to general

viscoelastic dampers. The main functions of the stud-type hybrid damper system are as follows; (i) the input energy from large earthquakes is dissipated by the hysteretic dampers to minimize structural damages, (ii) the input energy from small-to-medium earthquakes or strong winds is absorbed by the high-hardness rubber dampers to improve the habitability. Maseki *et al.* [12] have proposed a different type of hybrid damper system adopting buckling restrained braces composed of steel and friction dampers. The main functions of their system are essentially the same as those of the proposed stud-type hybrid damper system.

In addition, this paper proposes a simplified method for designing the hysteretic and high-hardness rubber dampers so that they have the targeted damping capacities at specified responses of building structures. Based on the performance-based design, the proposed design method enables not only to design hybrid dampers but also to predict their damping capacities in design phase. Loading tests with a full-scale model are carried out to investigate the damping capacity and the basic performance of the proposed hybrid damper system, and to clarify the validity of the proposed simplified design method. Moreover, a nonlinear time-history response analysis is conducted to examine the damping performance of the proposed vibration control systems in the response reduction level of practical residential houses.

2. New stud-type hybrid damper system

A new stud-type hybrid damper system is proposed, which consists of braces, upper and lower frames and a damper unit including hysteretic and high-hardness rubber dampers as shown in Fig.1. This system has following characteristics; (i) high damping efficiency by concentrating the deformations of the upper and lower frames into the incorporated dampers, (ii) easy installation to building structures with different story-height by adjusting the length of braces positioned between the upper and lower frames, (iii) easiness in replacing damaged energy dissipation devices. The proposed stud-type hybrid damper system improves such weaknesses of existing systems through unifying two dampers in a damper unit in parallel. The stiffness of surrounding portions (braces, upper and lower frames) was designed as large as possible to prevent the negative effect of surrounding portions on damping performances of the proposed damper system. Stiffness of stainless steel springs are appropriately designed to be deformed elastically during loading tests. Also, two stainless steel springs, and upper and lower rotation-restrained steel plates of the damper unit make hysteretic and high-hardness rubbers dampers deformed in shear only.

Fig.1 Stud-type hybrid damper system and damper unit.

3. Simplified design method for hybrid damper system

A simplified method for the design of hybrid damper system is proposed. The simplified design method is based on the performance-based design. This method is to design hysteretic and high-hardness rubber dampers so that each damper exhibits proper damping

ratios at different specified responses of the building structure.

3.1 Hysteretic damper for higher damping performance in large response. In the first design phase of the hybrid damper, hysteretic dampers are designed so that they exhibit a targeted performance at

a specified response. The targeted performance of hysteretic dampers in this paper is the equivalent damping ratio $\bar{h}_{eq}$ at a specified response $\bar{\delta}_a$. The key point on designing hysteretic dampers is that hysteretic dampers have a sufficient damping capacity in large response range regardless of the damping capacity of high-hardness rubber dampers incorporated in parallel into the damper unit.

The stiffness ratio κ , i.e. the ratio of the stiffness of a hysteretic damper to that of a bare frame, the ductility factor μ_a and the ratio β of a damper's shear force to maximum resistance are defined as

$$\kappa = k_0^{HD} / k_0^F \quad (1)$$

$$\mu_a = \delta_a / \delta_y^{HD} \quad (2)$$

$$\beta = \frac{Q^{HD}}{Q_a} = \frac{Q^{HD}}{Q^F + Q^{HD}} = \frac{k_0^{HD} \delta_y^{HD}}{k_0^F \delta_a + k_0^{HD} \delta_y^{HD}} = \frac{\kappa}{\mu_a + \kappa} \quad (3)$$

where k_0^{HD} , k_0^F , δ_a , δ_y^{HD} , Q^{HD} , Q^F and Q_a are the stiffness of a hysteretic damper, the stiffness of a bare frame, the elastic deformation of the entire system (hysteretic damper + bare frame), the yield deformation of a hysteretic damper, the shear force in a hysteretic damper, the shear force in a bare frame and the entire system, respectively. It is assumed in this paper that, while hysteretic dampers obey the normal bilinear hysteretic rule, the bare frame keeps its elastic behavior in the specified response range. The stiffness ratio κ can be derived in terms of an equivalent damping ratio h_{eq} and ductility factor μ_a as follows;

$$\kappa = \frac{\pi h_{eq} (\mu_a)^2}{2(\mu_a - 1) - \pi h_{eq} \mu_a} \quad (4)$$

In addition, it is necessary for the design of hysteretic dampers to give their yield deformation to be fully deformed under earthquake ground motions

with the consideration of maximum displacement response of the entire system.

3.2 High-hardness rubber damper for higher damping performance in small response.

In the second design phase of the hybrid damper, visco-elastic dampers are designed. This design phase is to supplement the weak damping effect of hysteretic dampers in small response range. In this paper, high-hardness rubber dampers as visco-elastic materials are used to supplement the weakness. The high-hardness rubber dampers have small temperature and frequency dependency compared to general visco-elastic dampers (see [13, 14]). While the high-hardness rubbers show elliptical hysteretic curves in the small deformation range less than 5% of shear strain, they show bilinear hysteretic curves in the range of more than 5% of shear strain as shown in **Fig.2**. But they have remarkable stain dependency. The mechanical modeling of the high-hardness rubbers has been proposed by Tani *et al.* [13, 14]. The mechanical model of the high-hardness rubber dampers consists of an elastic-plastic element, an elastic element due to dynamic effect and a viscous element. The high hardness rubber possesses the equivalent stiffness k_{eq}^{HRD} [N/mm] and viscous damping coefficient c_{eq}^{HRD} [N·s/mm] as shown below [15](Eqs. (5)-(7)). In Eqs. (5)-(7), S and d are the area [mm²] and thickness [mm] of a high-hardness rubber, $\bar{\gamma}_{max}$ is the maximum shear strain experienced so far and γ_{max} is the maximum shear strain in the current loop. While the equivalent stiffness k_{eq}^{HRD} is obtained from that of the elastic-plastic element and elastic element due to dynamic effect, the equivalent damping coefficient c_{eq}^{HRD} is obtained from that of the elastic-plastic element and viscous element by the geometrical equivalent linearization methods. S/d indicates an aspect ratio here.

$$k_{eq}^{HRD} = \frac{S}{d} \left(\frac{0.32 + 0.11\varepsilon^{0.38}}{1 + \varepsilon} \bar{\gamma}_{max}^{-0.62} + \frac{0.32\varepsilon - 0.11\varepsilon^{0.38}}{1 + \varepsilon} \frac{\bar{\gamma}_{max}^{0.38}}{\gamma_{max}} + 0.10\gamma_{max}^{-0.66} \right) \quad (5)$$

$$c_{eq}^{HRD} = \frac{S}{d} \left(\frac{0.64\varepsilon - 0.22\varepsilon^{0.38}}{\pi\omega} \frac{\bar{\gamma}_{max}^{0.38}}{\gamma_{max}} + \frac{0.306}{2\pi^2} \left(\frac{\omega}{2\pi} \right)^{-0.75} \gamma_{max}^{-0.75} \right) \quad (6)$$

$$\varepsilon = \left(0.94 |\gamma_{max}|^{0.73} \right) / \left(|\gamma_{max}|^{0.73} + 0.01 \right) \quad (7)$$

Fig. 2 Restoring-force loops of high-hardness rubber damper in small and large deformation range

Fig.3 Design example of hybrid damper by simplified design method

The magnification coefficient η is introduced for the design of the high-hardness rubber dampers. The coefficient η is defined as the ratio of the equivalent damping ratio h_{eq}^{HRD} of the high-hardness rubber damper to the maximum equivalent damping ratio h_{max}^{HD} of the hysteretic damper. The equivalent damping ratio h_{eq}^{HRD} at a prescribed response $\bar{\delta}_a$ is described as

$$h_{eq}^{HRD}(\bar{\delta}_a) = \eta \times h_{max}^{HD} = c_{eq}^{HRD} / 2\sqrt{mk_{eq}^{HRD}} \quad (8).$$

In Eq. (8) $h_{eq}^{HRD}(\bar{\delta}_a)$ and m are the equivalent damping ratio of the high-hardness rubber at a prescribed response $\bar{\delta}_a$ and the mass of a bare frame modeled into an SDOF system. Substitution of Eqs. (5) and (6) into Eq. (8) leads Eq. (9) for the cross-sectional area $S[mm^2]$ of the required

high-hardness rubber, where $f_k(\gamma)$ and $f_c(\gamma)$ are the values obtained by dividing the equivalent stiffness k_{eq}^{HRD} and viscous damping coefficient c_{eq}^{HRD} of the high-hardness rubber damper by the aspect ratio S/d , respectively.

For the design of a hybrid damper, the thickness d of the high-hardness rubber damper has to be given additionally. This paper suggests that d be given not to exceed 200% of shear strain at the maximum response of the entire structural system because the high-hardness rubber damper shows the effective damping in the range up to 200% of shear strain. Although the proposed design method is for the design of the hybrid damper system, it is necessary to conduct some successive calculations for assessing the total damping capacity of the designed hybrid damper system at the prescribed response through the equivalent linearization technique. **Fig.3** indicates a design example of a hybrid damper designed by the proposed simplified design method. The design examples present that a hysteretic damper are designed to exhibit a sufficient damping capacity in the response range of $\delta_a = 14mm$ with the given yield deformations ($\delta_y^{HD} = 6mm$), and then a high-hardness rubber damper is designed so as to exhibit the targeted damping capacity ($\eta \times h_{max}^{HD}$) at the specified response ($\bar{\delta}_a = 6mm$) with the given different thicknesses ($d = 6mm$).

$$S = 2 \cdot d \cdot m \cdot \eta \cdot h_{\max}^{HD} \cdot f_c^{-1}(\gamma) \times \left\{ 4 \cdot \eta \cdot h_{\max}^{HD} \cdot f_k(\gamma) \cdot f_c^{-1}(\gamma) + \sqrt{\eta^2 \cdot (h_{\max}^{HD})^2 \cdot f_k^2(\gamma) \cdot f_c^{-2}(\gamma) + \omega \cdot m^{-1}} \right\} \quad (9)$$

4. Equivalent linear model of stud-type hybrid damper system

The mechanical model of the stud-type hybrid damper system is shown in Fig.4. The hysteretic dampers are assumed to obey a normal bilinear hysteretic rule. The stiffness of surrounding portions (braces, upper and lower frames) is regarded to be rigid because they are designed as stiff as possible compared to that of the hybrid damper system. The flexibility of the surrounding portions is neglected in the equivalent linear model of the proposed damper system.

Furthermore, it is assumed that the steel springs remain linear elastic even in a rather large deformation range. The equivalent stiffness k_{eq} and viscous damping coefficient c_{eq} of the stud-type hybrid damper system may be described as Eqs. (10)-(13). In Eqs. (10)-(13), k_0^P , ω , k_{eq}^{HD} and c_{eq}^{HD} are the stiffness of the two steel springs, the excitation circular frequency, the equivalent stiffness and viscous damping coefficient of the hysteretic damper. δ_a/d indicates the maximum shear strain $\gamma_{\max} (= \bar{\gamma}_{\max})$.

$$(a) \quad \delta_a \leq \delta_y^{HD}$$

$$k_{eq} = \frac{(k_0^P + k_0^{HD}) \times \delta_a}{\delta_a} + k_{eq}^{HRD} \\ = k_0^P + k_0^{HD} + \frac{S}{d} \left\{ \frac{0.32 + 0.11\varepsilon^{0.38}}{1 + \varepsilon} \cdot \left(\frac{\delta_a}{d} \right)^{-0.62} + \frac{0.32\varepsilon - 0.11\varepsilon^{0.38}}{1 + \varepsilon} \cdot \left(\frac{\delta_a}{d} \right)^{-0.62} + 0.10 \cdot \left(\frac{\delta_a}{d} \right)^{-0.66} \right\} \quad (10)$$

$$c_{eq} = c_{eq}^P + c_{eq}^{HD} + c_{eq}^{HRD} \\ = 0 + 0 + \frac{S}{d} \left\{ \frac{0.64\varepsilon - 0.22\varepsilon^{0.38}}{\pi\omega} \cdot \left(\frac{\delta_a}{d} \right)^{-0.62} + \frac{0.306}{2\pi^2} \left(\frac{\omega}{2\pi} \right)^{-0.75} \cdot \left(\frac{\delta_a}{d} \right)^{-0.75} \right\} \quad (11)$$

$$(b) \quad \delta_y^{HD} < \delta_a$$

$$k_{eq} = \frac{k_0^P \times \delta_a + k_0^{HD} \times \delta_y^{HD}}{\delta_a} + k_{eq}^{HRD} \\ = k_0^P + \frac{k_0^{hd}}{\mu_a} + \frac{S}{d} \left\{ \frac{0.32 + 0.11\varepsilon^{0.38}}{1 + \varepsilon} \cdot \left(\frac{\delta_a}{d} \right)^{-0.62} + \frac{0.32\varepsilon - 0.11\varepsilon^{0.38}}{1 + \varepsilon} \cdot \left(\frac{\delta_a}{d} \right)^{-0.62} + 0.10 \cdot \left(\frac{\delta_a}{d} \right)^{-0.66} \right\} \quad (12)$$

$$c_{eq} = c_{eq}^P + c_{eq}^{HD} + c_{eq}^{HRD} \\ = 0 + \frac{4k_0^{HD}}{\pi\omega\mu_a} \left(1 - \frac{1}{\mu_a} \right) + \frac{S}{d} \left\{ \frac{0.64\varepsilon - 0.22\varepsilon^{0.38}}{\pi\omega} \cdot \left(\frac{\delta_a}{d} \right)^{-0.62} + \frac{0.306}{2\pi^2} \left(\frac{\omega}{2\pi} \right)^{-0.75} \cdot \left(\frac{\delta_a}{d} \right)^{-0.75} \right\} \quad (13)$$

Fig.4 Mechanical model for stud-type hybrid damper system

5. Loading test with full-scale experimental test model

5.1 Full-scale model and measurement system. A full-scale experimental test model was prepared for loading tests. The loading frame consists of two steel columns, a floor beam and three sheets of steel lump as shown in **Fig.5**. The loading frame's natural period T is about 0.33s which is the same as that of a practical lightweight steel residential house. The loading frame was designed to remain elastic during tests. The stiffness k_0^F of the loading frame is $477N/mm$, and the mass m of the loading frame modeled into an SDOF system is about $1630kg$. The loading frame is set up for easy control during the loading tests. The proposed damper system is incorporated between the loading frames. **Table 1** presents the steel sections of the loading frame and

damper system. The point $d4$ in **Fig.5** is for measuring the actual deformation of the damper unit to that of the loading frame ($d2-d3$). The absolute acceleration of the floor beam is measured at the point $a1$ (or $a2$) and the shear force in the loading frame is evaluated by multiplying the absolute acceleration by the mass ($m=1630kg$). The story drift is measured by $d1$. Introducing a concept called an Effective Deformation Ratio, $EDR, d4/d1$ (δ_d / δ_a), the basic performance of the damper system is assessed with the evaluation of the real stiffness of the surrounding portions. The loading frame is first loaded with quasi-static speeds using an oil-jacket up to about 6mm. After the quasi-static loading, the loading frame is led to be under free vibration by taking out the oil-jacket. The sampling frequency for data acquisition is 100Hz.

Table 1 Steel sections of loading frame and damper system

Portion	Steel type	Steel sections
Reaction column frames	SS400	$H - 400 \times 400 \times 13 \times 21, L = 3300mm$
Reaction beam frames	SS400	$H - 400 \times 400 \times 13 \times 21, L = 4000mm$
Ceiling beam	SS400	$H - 200 \times 200 \times 8 \times 12, L = 1400mm$
Floor beam	SS400	$H - 300 \times 300 \times 10 \times 15, L = 2400mm$
Steel lumps	SS400	$PL - 600 \times 100, L = 798mm$ (3sheets)
Loading frames	SS400	$H - 200 \times 100 \times 5.5 \times 8, L = 2600mm$
Upper frame	SS400	$C - 150 \times 75 \times 6$
Lower frame	SS400	$C - 150 \times 75 \times 6$
Brace members	SS400	$PL - 32 \times 6, L = 671.3mm \times 2$

Fig.5 Full-scale model and measurement system

Fig.6 Hybrid damper

Table 2 Properties of hysteretic and high-hardness rubber dampers

Hysteretic damper					High-hardness rubber damper			
Notation	κ	δ_y^{HD} (mm)	$h_{eq}(\mu_a = 3)$	h_{max}	Size	η	S [mm^2]	d [mm]
HD	0.312	1	0.04	0.043	HRD 1	0.25	64	3.2
					HRD 2	0.50	144	
					HRD 3	1.00	289	

5.2 Hybrid damper. Fig.6 shows the designed hybrid damper composed of two hysteretic dampers, a high-hardness rubber damper, two steel springs and rotation-restrained steel frames. The hysteretic dampers are designed so as to exhibit 4% of equivalent damping ratio when their ductility factor μ_a is 3. From preliminary tests for the loading frame only, it was confirmed that the dynamic stiffnesses of the loading frame and two steel springs are $k_0^F = 363N/mm$ and $k_0^P = 33N/mm$, respectively. With the given conditions of $h_{eq} = 0.04$ and $\mu_a = 3$, the stiffness ratio κ could be obtained as 0.312 using Eq.(5). The yield deformation δ_y^{HD} of the

hysteretic dampers is given as 1mm upon consideration of the limited equipment capacity. In the second design phase, the magnification coefficients η at the specified response $\bar{\delta}_a = 1mm$ are set-up as 0.25, 0.5 and 1.0. Finally the thickness d of high-hardness rubber dampers is given as 3.2mm not to exceed 200% of shear strain at the maximum response $\bar{\delta}_a = 6mm$. Table 2 presents the properties of the designed hysteretic and high-hardness rubber dampers for each magnification coefficient η .

6. Test results and discussion

6.1 Stiffness of surrounding portions. To confirm the damping performance of the proposed damper system, it is necessary to examine whether the surrounding portions (braces, upper and lower frames) are sufficiently stiffer than that of the incorporated hybrid dampers. In this paper, the efficiency of the proposed damper system is estimated by the Effective Deformation Ratio, $EDR = \delta_D / \delta_a$. **Fig.7** (a) shows the displacements ($d4$) of the damper unit with respect to story drifts ($d1$) during free vibration. The average slope of the curve here means EDR . This test result shows that the average EDR is about 0.985. **Fig.7** (b) indicates the shear force in the damper unit (HD + two steel springs) versus story drifts ($d1$) and its approximated curve (least-square method). In common with EDR , the slope of the approximate curve presents the stiffness of the damper unit. The obtained damper unit's stiffness ($k_0^D + k_0^P$) is about $149.3N/mm$. From the test values of EDR and $k_0^D + k_0^P$, the stiffness k_0^B of the surrounding

portions can be obtained approximately from the following linear relations.

$$\delta_B = \delta_a \cdot (1 - EDR) = \delta_U \cdot (1 - EDR) / EDR \quad (14)$$

$$(k_0^D + k_0^P) \cdot \delta_U = Q_B \quad (15)$$

$$k_0^B = Q_B / \delta_B = (k_0^D + k_0^P) \cdot EDR / (1 - EDR) \quad (16)$$

where δ_U , δ_B , δ_a and Q_B are the displacement of the damper unit, the surrounding portions and the loading frame, and the shear force in the surrounding portions, respectively. **Fig.7** (c) shows the shear force Q_B in the surrounding portions with respect to displacement δ_B . This figure indicates that the surrounding portions' stiffness k_0^B is about $6628N/mm$. It has been confirmed that the surrounding portions are sufficiently stiff compared to both the designed damper elements and the loading frame. However the efficiency of the proposed damper system should be examined in more detail whether it exhibits sufficient damping performance even in practical building structures by simulations.

Fig.7 Stiffness of surrounding portions (braces, upper and lower frames)

Fig.8 Free vibration waves of loading frame with hysteretic, high-hardness rubber and hybrid dampers. (to be continued)

(c) Frame with HRD 2 ($S = 144\text{mm}^2$, $d = 3.2\text{mm}$)

(d) Frame with HYB (HD + HRD 2)

Fig.8 Free vibration waves of loading frame with hysteretic, high-hardness rubber and hybrid dampers.

(a) Frame with HYB 1 (HD + HRD 1)

(b) Frame with HRB 2 (HD + HRD 2)

(c) Frame with HRB 3 (HD + HRD 3)

Fig.9 Equivalent damping ratio with respect to amplitude for designed hybrid dampers

6.2 Free vibration waves and damping characteristics of hybrid damper. Fig.8 shows the free vibration waves of the loading frame incorporating the stud-type damper system with hysteretic (HD), high-hardness rubber (HRD 2) and hybrid dampers (HD + HRD 2), respectively. These results show that, although hysteretic dampers can respond to large response compared to high-hardness

rubber dampers, they are not suitable for small response (Fig.8 (a)). Overall damping of the loading frame with hysteretic dampers in a small response range depends on structural damping only. On the other hand, hybrid dampers exhibit a high damping capacity even in a small response range while maintaining damping performances similar to those of hysteretic dampers in a large response range (Fig.8

(c)). It has been confirmed that these damping aspects can also be observed in the other tests.

The equivalent damping ratios h_{eq} are evaluated from the same free vibration waves. h_{eq} is calculated by the logarithmic decrement method. In the preliminary test for the loading frame only, it was found that the structural damping h_0 is about 0.5%. **Fig.9** presents the comparison of the equivalent damping ratios with respect to amplitudes obtained from the tests, simulations and the equivalent linearization in Section 4 for each of hybrid damper. A

key parameter in the tests is the cross-sectional area of the high-hardness rubber dampers. This figure also shows that the hybrid dampers have high-damping capacities in the prescribed response range (up to $\delta_a = 6mm$). There are differences between test results and analytical results. Those may be caused by the assumption that the hysteretic dampers are elastic-perfectly plastic materials, and the geometrically nonlinear behavior of the hysteretic dampers affects the damping performance of the hybrid damper system in the large response range.

Table 3 Floor mass and story stiffness

Story	First floor	Second floor	Third floor
Mass m_i ($\times 10^3 kg$)	15.5	15.2	9.67
Story stiffness k_i^F ($\times 10^4 N/mm$)	2.66	2.11	1.03

Table 4 Properties of designed hysteretic and high-hardness rubber dampers

Hysteretic damper					High-hardness rubber damper			
Story	κ	k_i^{HD} [$\times 10^3 N/mm$]	δ_y^{HD} (mm)	h_{max}^{HD}	Size	η	S [$\times 10^4 mm^2$]	d [mm]
1	0.312	8.21	6	0.043	HRD 1	0.25	1.88	6
2		6.59			HRD 2	0.50	1.51	
3		3.22			HRD 3	1.00	0.760	

7. Response reduction effect by hybrid damper system

To examine the effect of the proposed hybrid dampers system on the response reduction, a nonlinear time-history response analysis is carried out for a practical three-story building structure (residential house). The building structure is modeled into a three-story shear model (hereafter, structural model). The undamped natural frequency is given as 3Hz ($\omega_0 = 19.04 rad/s$). The mass of each story is also given based on a practical building structure. In addition its fundamental eigenmode is assumed as an inverted triangle and the structural damping ratio is 2%. Based on the given conditions such as the natural circular frequency $\omega^{(1)}$, the fundamental eigenmode $u_i^{(1)}$ and the mass m_i of the structural model, the story stiffnesses k_i^F of the structural model are obtained from Eq.(17).

$$k_i^F = \omega^{(1)2} \sum_{j=i}^3 m_j u_j^{(1)} / (u_i^{(1)} - u_{i-1}^{(1)}) \quad (17)$$

Table 3 shows the floor mass and story stiffness of the structural model and **Table 4** presents the properties of hysteretic and high-hardness rubber dampers incorporated into the structural model. The stiffness ratio κ and magnification coefficients η are given as the same values as those of the full-scale experimental test model. In the simulation, the yield deformation δ_y^{HD} of hysteretic dampers and the thickness d of high-hardness rubber dampers are given as 6mm, respectively (see **Table 4**). The stiffness of the surrounding portions used in the simulations is the same as that of the full-scale experimental test model to examine the validity of the stud-type hybrid damper system in practical building structures. A spectrum-compatible ground motion is input to the three-story shear model, which was generated so that it is compatible with the Newmark-Hall design spectrum (damping ratio

$h_0 = 2\%$) [16]. **Figs .10** and **11** illustrate the mean response spectrum and the spectrum-compatible ground motion.

Fig.12 presents the response in the structural model with the designed hybrid damper systems for two different input levels of the sample ground motion. The responses in the first floor are only presented here for the time range from 0 second to 20 second. The input levels 0.2 and 2 of ground motions are the ones multiplying the coefficient 0.2 and 2, respectively, on the original ground motion (**Fig.11**). The maximum story drifts in the structural model for input level 2 are reduced from 14.4mm to 7.8mm, and those for input level 0.2 are reduced from 1.44mm to 0.4mm, respectively, by the hybrid damper system. Most of

the responses in the structural model for input levels 2 and 0.2 are reduced by the hysteretic damper and the high-hardness rubber damper in the hybrid damper, respectively. From the simulation results, it can be observed that the hybrid damper systems behave like a viscoelastic damper system under small vibrations, and like a hysteretic damper system under large vibrations, respectively. Furthermore the simulation results demonstrated that the stud-type hybrid damper system has a sufficient performance in the response reduction of practical building structures against various levels of ground motions, even though the surrounding portions of the proposed damper system are applied to practical building structures as it is.

Fig.10 Displacement response spectrum ($h=2\%$)

Fig.11 Spectrum-compatible ground motion (input level 1)

(a) Response in structure for input level 2

(b) Response in structure for input level 0.2

Fig.12 Response in structures with hybrid damper for two different input levels of sample ground motion

8. Conclusions

A new stud-type hybrid damper system composed of hysteretic and visco-elastic dampers (high-hardness rubber dampers) has been proposed in this paper. The damping performance of the proposed damper system has been examined by full-scale experimental loading tests and simulations. A simplified design method has then been proposed to design the hybrid dampers based on the concept of taking full advantages of both dampers and supplementing each other the weakness of the other one. The quantity of the hysteretic dampers is determined first by specifying the ratio of the initial stiffness of the hysteretic dampers to the bare frame's stiffness. Then the quantity of the high-hardness rubber dampers is obtained by giving the ratio of the equivalent damping ratio at a specific

deformation level (yield deformation of hysteretic dampers) to the maximum damping ratio of the hysteretic dampers.

Through the evaluation on the stiffness of surrounding portions by the concept of 'effective deformation ratio', it has been confirmed that the proposed hybrid damper system can efficiently operate as an energy dissipating device against wind and earthquake disturbances, even if the proposed system is applied to practical residential houses. Experimental tests and simulation results have showed that the proposed stud-type hybrid damper system has a sufficient damping performance in both small and large response ranges. Although the proposed stud-type hybrid damper system has large initial stiffness compared to single damper systems, the

damper system has a high damping capacity in a broad response range in contrast to single hysteretic or high-hardness rubber damper systems.

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