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Smart passive control of buildings with higher redundancy and robustness using base-isolation and inter-connection

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Abstract. It is known that a base-isolated building exhibits a large response to a long-duration, long-period wave and an inter-connected system without base-isolation shows a large response to a pulse-type wave. To compensate for each deficiency, a new hybrid passive control system is investigated in which a base-isolated building is connected to another building (free wall) with oil dampers. It is demonstrated that the present hybrid passive control system is effective both for pulse-type ground motions and long-duration and long-period ground motions and has high redundancy and robustness for a broad range of disturbances.

Keywords: base-isolation; building connection; hybrid system; passive damper; structural control; robustness; redundancy

1. Introduction

In the seismic resistant design of building structures, it is desired to design building structures safely for a broader class of earthquake ground motions (Kobori 2004, Takewaki 2006, Takewaki *et al.* 2012). This comes from the common understanding that earthquake ground motions are highly uncertain and it appears difficult to predict the forthcoming events precisely in time, space and character (Takewaki 2006, 2011, Takewaki *et al.* 2011, 2012a, b). It is also recognized that the building structural properties (especially the properties of base-isolation systems and passive control system, etc.) are not deterministic (Ben-Haim 2001, 2006) and their variation brings various difficulties in the seismic resistant design of building structures in terms of robustness and redundancy. In fact, it is usual in Japan to take into account the variability of mechanical properties of isolators and dampers in the design of base-isolated building and passively controlled buildings. In this design procedure, the worst combination of mechanical properties of isolators and dampers is investigated (Ben-Haim 2001, 2006, Elishakoff and Ohsaki 2010, Takewaki *et al.* 2012a) and all the design conditions are checked for this worst case.

It is well known that, while base-isolated buildings are effective for pulse-type ground motions whose characteristic period is not resonant with the fundamental natural period of the base-isolated buildings (Jangid and Banerji 1994, Jangid and Datta 1994, Hall *et al.* 1995, Heaton *et al.* 1995, Jangid 1995, Kelly 1999, Naeim and Kelly 1999, Jangid and Kelly 2001, Morales 2003, Takewaki

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2005, Li *et al.* 2006, Takewaki 2008, Hino *et al.* 2008, Takewaki and Fujita 2009), they are not necessarily resisting for long-period ground motions with the characteristic period of 5-8s (Ariga *et al.* 2006, Irikura *et al.* 2004, Kamae *et al.* 2004). This is mainly due to the resonance of the base-isolated buildings with the long-period ground motions. The long-period ground motions with the characteristic period of 5-8 s were of great interest in the structural design of base-isolated buildings and super high-rise buildings since Tokachi-oki earthquake in 2003. It is famous that a large oil tank was resonant with such long-period ground motions. On the other hand, it is also well understood that, while building structures including passive energy dissipating systems are effective for long-duration and long-period ground motions (Takewaki 2007, Patel and Jangid 2011, Takewaki *et al.* 2011, 2012), they are not necessarily resistant for pulse-type ground motions. Smart resolution of these two issues may be one of the most controversial issues in the field of seismic resistant and control design (Koo *et al.* 2009, Petti *et al.* 2010, Karabork 2011).

In this paper, a new hybrid passive control system is investigated in which a base-isolated building is connected to another non-base-isolated building (free wall) with oil dampers. A similar type of buildings without base-isolation is being designed and constructed by Obayashi Corporation in Japan as an apartment house with a car parking tower (Nishimura *et al.* 2008) and the new system with base-isolation investigated in this paper was first proposed by Obayashi Corporation (Nishimura *et al.* 2011). However buildings with the new system have never been constructed so far and it is recognized that more detailed and deeper investigation is required. It is demonstrated that the present hybrid passive control system is effective both for pulse-type ground motions and long-duration, long-period ground motions. It is also made clear from the energy analysis that, although the connecting dampers in the hybrid system are not effective for a pulse-type wave, those are effective for a long-duration, long-period wave from the beginning of the vibration. Finally it is also demonstrated that the present hybrid passive control system has high redundancy and robustness for a broad range of disturbances.

2. Base-isolated building interconnected to outer frame

The new hybrid passive control system consists of a 40-story base-isolated main building (apartment house), another support building of 26 stories (car parking tower; called free wall) and a group of interconnecting oil dampers as shown in Fig. 1. The oil dampers are installed at 4, 8, 12, 16, 18, 20, 22, 24 and 26th floor levels. The floor mass of the main building is 1.7×10^6 (kg) and that of the free wall is 2.2×10^5 (kg). The base-isolation floor mass is 5.1×10^6 (kg). The story height is 3.5 (m) in all the stories.

The super-structure of the main building is designed so as to have the fundamental natural period of 3.0 (s) and a straight fundamental mode for a fixed base model. On the other hand, the free wall is designed so as to have the fundamental natural period of 0.63 (s) and a straight fundamental mode.

The fundamental natural period of the hybrid system is 6.72 (s). The higher-mode natural periods of the hybrid system are 1.72 (s), 0.965 (s), 0.672 (s) and 0.640 (s). The fundamental natural period (0.63 s) of the free wall corresponds to the natural period 0.640 (s) of the 5th mode of the hybrid system. The structural damping ratio of the super-structure (stiffness-proportional damping) is set to 0.03 and the damping ratio of the base-isolation story for a rigid super-structure is 0.15. The interconnection oil dampers are allocated uniformly to the floors mentioned above and the approximate lower-mode damping ratio for a rigid free wall is set to 0.15 under non-modal-coupling approximation.

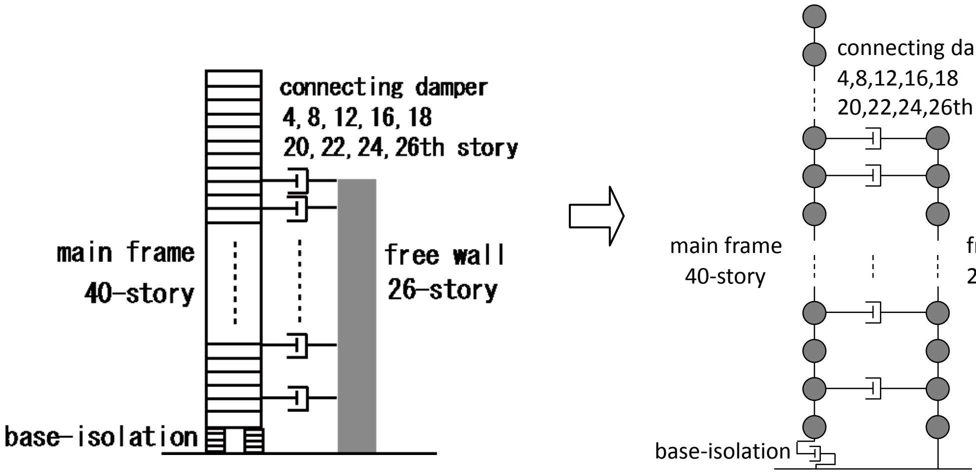


Fig. 1 Hybrid passive control system consisting of a 40-story base-isolated main building, another support building of 26 stories (free wall) and a group of interconnecting oil dampers

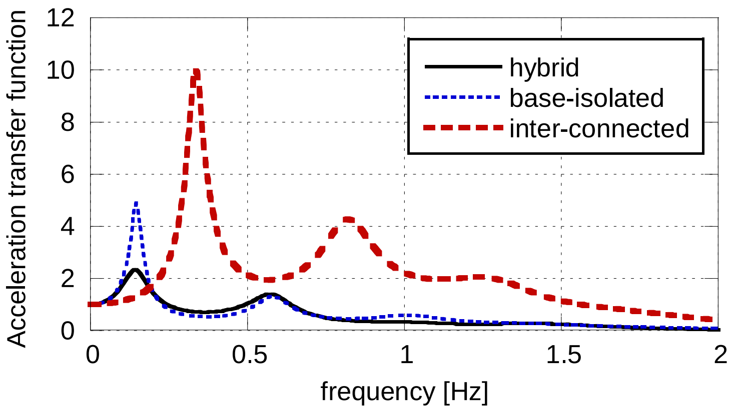


Fig. 2 Acceleration transfer functions at top of main frame for the hybrid model, the base-isolated model without interconnection and the interconnecting model without base-isolation

3. Transfer function characteristics

It may be useful to show the transfer characteristics of the present new hybrid passive control system to the base input. Fig. 2 shows the acceleration transfer functions at the top of the main frame for the hybrid model, the base-isolated model without interconnection and the interconnecting model without base-isolation. On the other hand, Fig. 3 presents the displacement transfer functions (deformation of base-isolation story) for the two models including the base-isolation story among three. It can be seen that the hybrid system is superior to other two models both in the acceleration and displacement transfer properties. Especially the hybrid system possesses an effective control performance at the fundamental natural period of the base-isolated main building.

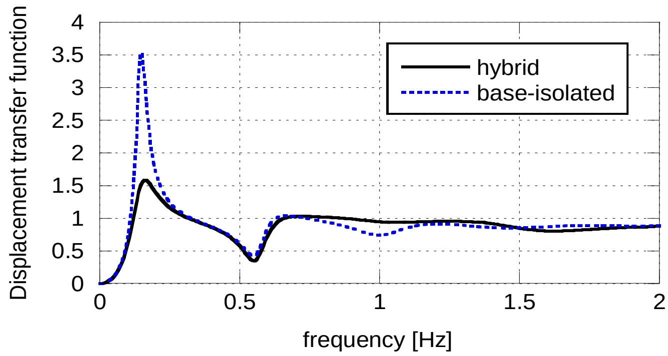
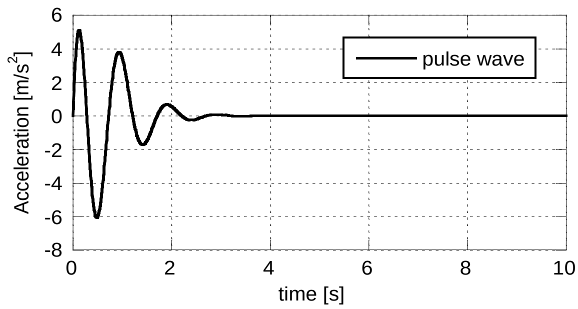
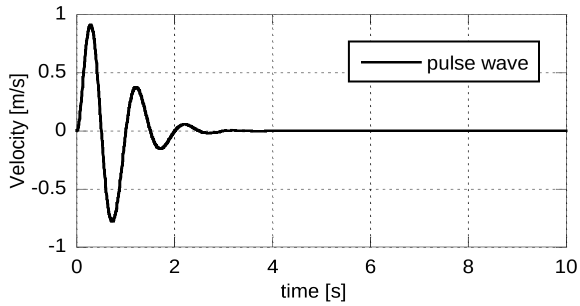


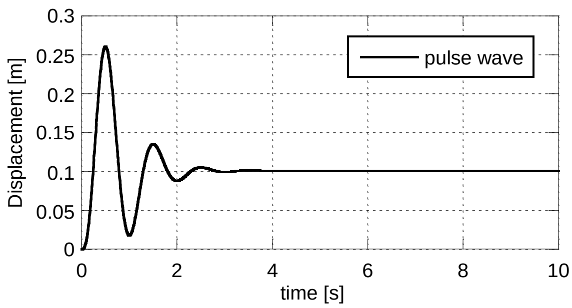
Fig. 3 Displacement transfer functions (deformation of base-isolation story) for the hybrid model and the base-isolated model without interconnection



(a) Ground acceleration



(b) Ground velocity



(c) Ground displacement

Fig. 4 Pulse-type wave

4. Pulse-type ground motion and long-period ground motion

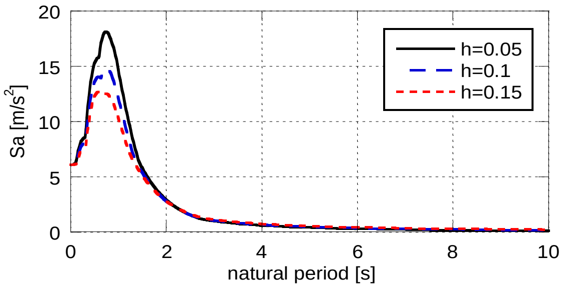
It is a common understanding in the field of earthquake engineering that pulse-type ground motions and long-duration, long-period ground motions are two representative ground motions with extremely different characteristics. The former one has been discussed since 1990s (Northridge 1994, Kobe 1995, Chi-chi 1999, etc.) and the latter one since 2000s (Tokachi-oki 2003, Tohoku 2011, etc.). The former one is usually induced in the near-fault environment and the latter one is in the long-distance environment.

In order to investigate the effectiveness of the hybrid system both to pulse-type and long-duration, long-period ground motions, a typical pulse-type ground motion has been generated first following He (2003), Xu *et al.* (2007), He and Agrawal (2008) and Takewaki and Tsujimoto (2011). Since it may be possible to use only typical recorded ground motions, simulated motions are expected to bring the underlying and fundamental properties of the present hybrid system to the pulse-type ground motions. An investigation using a recorded ground motion will be conducted later in this paper.

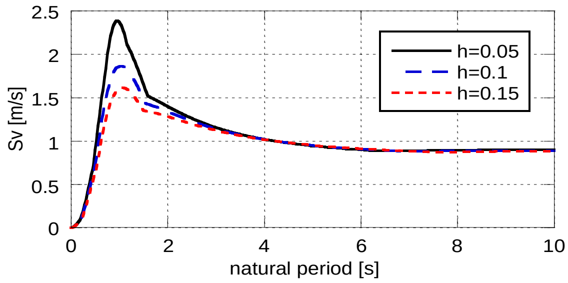
Fig. 4 shows the acceleration, velocity and displacement profiles of a generated typical pulse wave. The velocity pulse wave can be expressed by

$$\dot{u}_p = Ct^n e^{-at} \sin \omega_p t \tag{1}$$

The parameters used are $T_p = 2\pi / \omega_p = 1.0\text{s}$, $n = 1$, a = 2.51 and C = 6.7. The maximum ground acceleration is about 6 (m/s^2) and the maximum velocity is almost 1 (m/s) which are compatible with the recent great earthquake ground motions during Northridge earthquake in 1994 and Kobe earthquake in 1995. It can be observed that about 0. 1 (m) residual displacement exists.

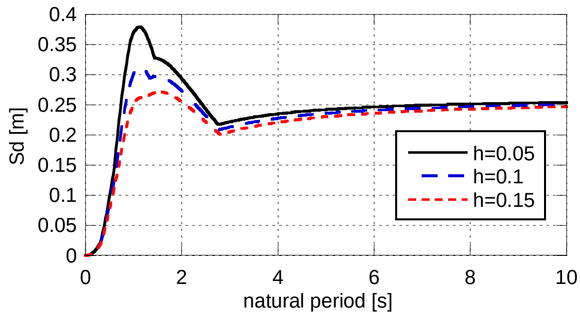


(a) Acceleration response spectra



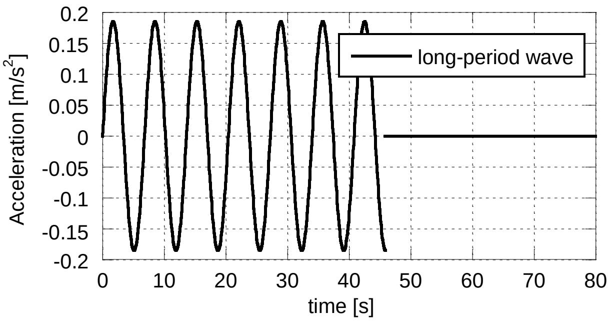
(b) Velocity response spectra

Fig. 5 Acceleration, velocity and displacement response spectra for generated pulse-type wave

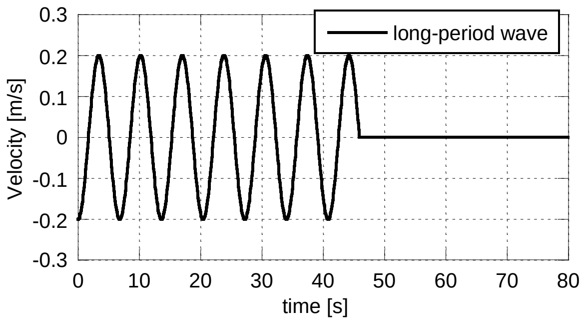


(c) Displacement response spectra

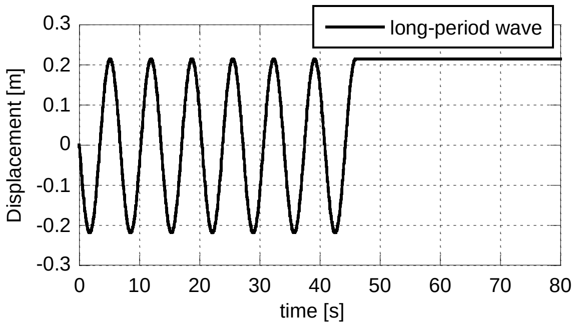
Fig. 5 Continued



(a) Ground acceleration

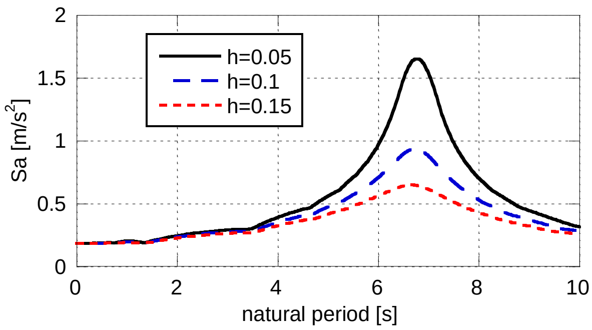


(b) Ground velocity

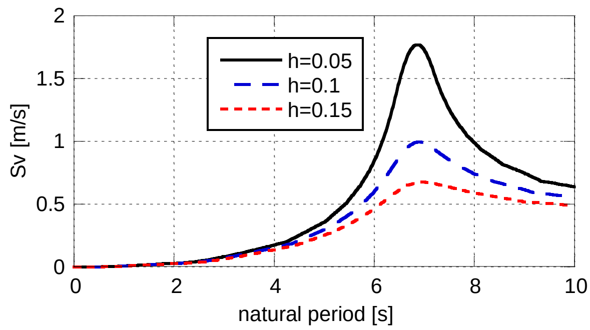


(c) Ground displacement

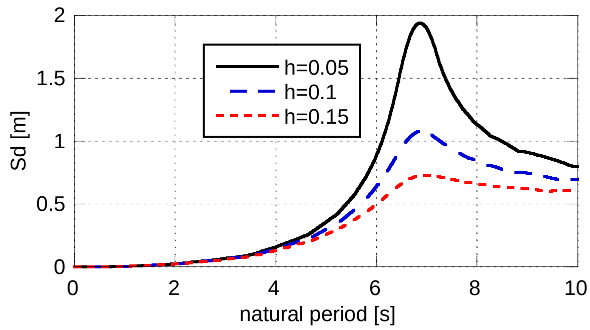
Fig. 6 Long-duration, long-period wave



(a) Acceleration response spectra



(b) Velocity response spectra



(c) Displacement response spectra

Fig. 7 Acceleration, velocity and displacement response spectra for generated long-duration, long-period wave

Fig. 5 presents the acceleration, velocity and displacement response spectra with respect to three damping ratios h = (0.05, 0.1, 0.15) for the generated pulse wave. It can be observed that, while the acceleration response spectrum has its peak at the period slightly shorter than 1.0s, the displacement response spectrum has that at the period slightly longer than 1.0s.

On the other hand, Fig. 6 shows the acceleration, velocity and displacement profiles of a generated long-duration, long-period wave. The period of the wave is 6.8s and the duration is 47.6 s. This period has been chosen so that the fundamental natural period 6.72 (s) of the hybrid system is resonant with this input motion period. The maximum ground acceleration is about 0.2 (m/s^2) and the maximum velocity is 0.2 (m/s). About 0.2 (m) residual displacement exists. Fig. 7 presents

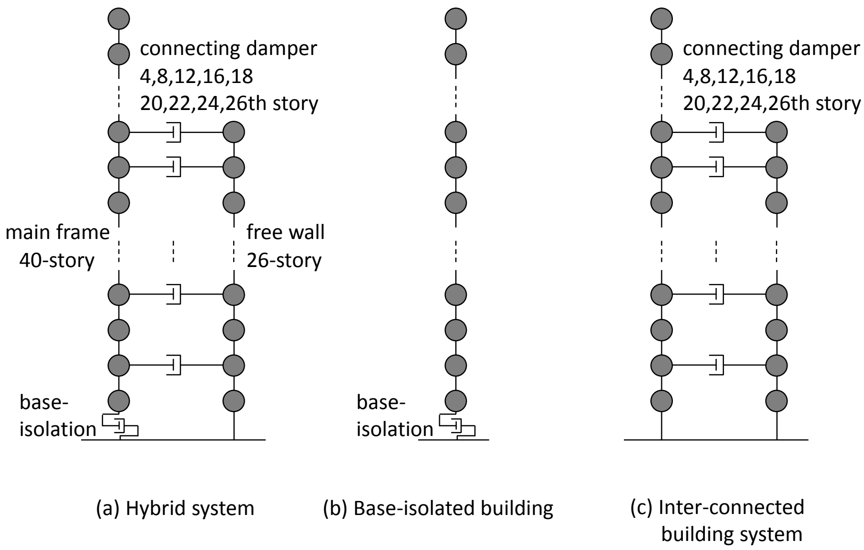


Fig. 8 Hybrid system, base-isolated building and interconnected building system

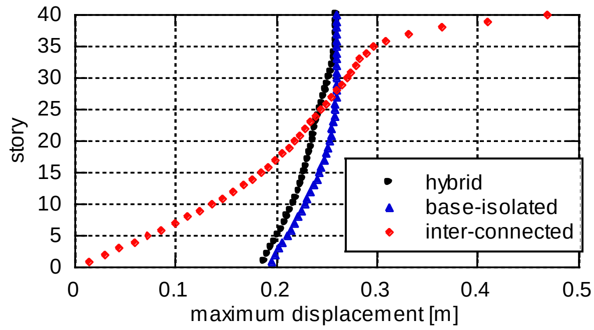
the acceleration, velocity and displacement response spectra with respect to three damping ratios h = (0.05, 0.1, 0.15) for the generated long-duration, long-period wave. It can be observed that the peaks in the acceleration, velocity and displacement response spectra exist around 6.8s.

5. Response characteristics of smart passive control building system

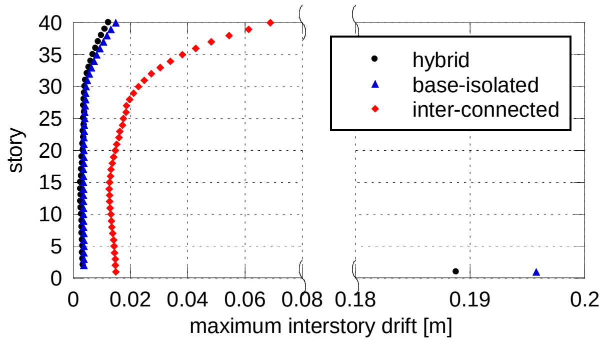
5.1 Response to simulated pulse-type ground motion and long-duration, long-period ground motion

The smart hybrid passive control building system with a base-isolation system and interconnection dampers is subjected to the pulse-type ground motion and the long-duration, long-period ground motion mentioned above. For comparison, the corresponding base-isolated building without interconnection and the corresponding interconnected building system without base-isolation are also subjected to the same inputs (see Fig. 8).

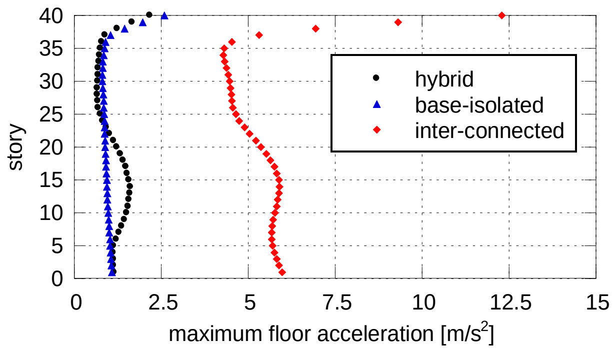
Fig. 9 shows the maximum distributions of story displacement, interstory drift and acceleration to the pulse-type wave. It can be seen that the hybrid system and the base-isolated system exhibit an almost similar maximum response and are superior to the interconnected system all in the story displacement, interstory drift and acceleration. The large interstory drifts in the first story in the hybrid model and the base-isolated system indicate the displacement of the base-isolation story. The large response amplification in the stories higher than the 26th story in the interconnected building may result from the connection of the main frame and the free wall by the connecting dampers in the stories lower than the 26th. This large response amplification is a special characteristic in the response to the pulse-type wave. However it is interesting to note that, while the hybrid system has the same connecting system, it does not exhibit such large response amplification in the higher stories. A small amplification of acceleration in the 5-20 stories in the



(a) Maximum story displacement



(b) Maximum interstory drift

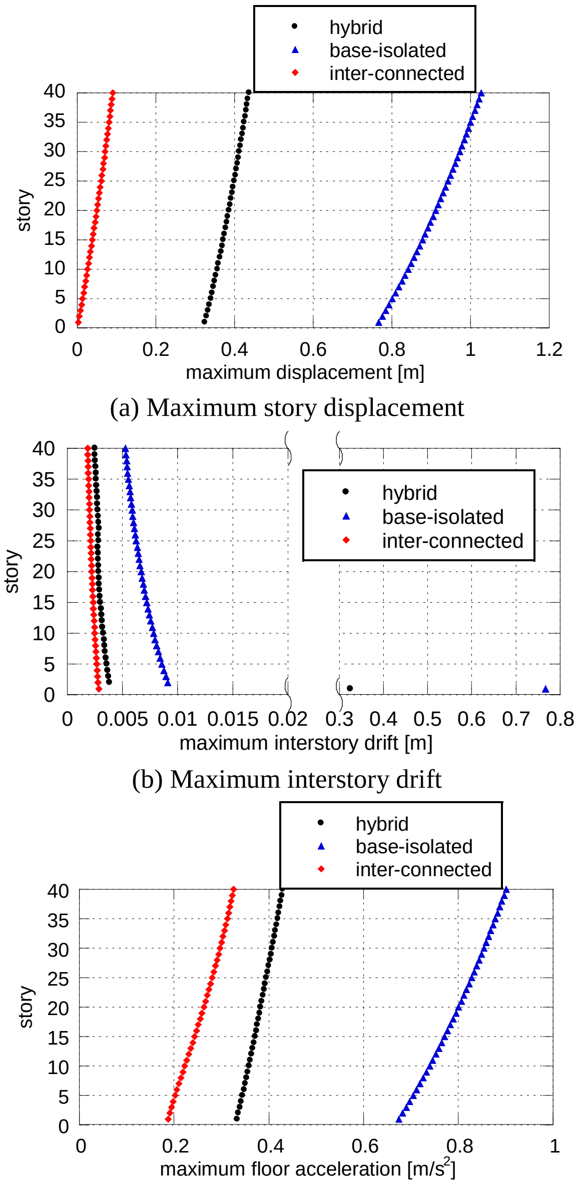


(c) Maximum floor acceleration

Fig. 9 Maximum distributions of story displacement, interstory drift and acceleration to pulse-type wave

hybrid model seems to result from the effect of connection to the free wall. It should also be remarked that only the hybrid system and the base-isolated building satisfy the usual acceleration limit condition of 2.5 (m/s^2) which guarantees the protection of slippage or overturning of furniture etc.

Fig. 10 shows the maximum distributions of story displacement, interstory drift and acceleration to the long-duration, long-period wave. It can be seen that, since the fundamental natural period of the interconnecting system is far from the period of the input, the response of the interconnecting system is small. In the comparison between the hybrid system and base-isolation system, the hybrid system is superior to the base-isolation system all in the story displacement,



(a) Maximum story displacement

(b) Maximum interstory drift

(c) Maximum floor acceleration

Fig. 10 Maximum distributions of story displacement, interstory drift and acceleration to long-duration, long-period wave

interstory drift and acceleration. In particular, the large displacement of the base-isolation story in the base-isolated system seems to be fatal for the safe design of the base-isolation story. Even in this point, the hybrid system exhibits a promising performance. Furthermore, while it is well known that the excessive installation damping in the base-isolation story in the base-isolated building often amplifies the acceleration at the top story, the hybrid system can decrease both the deformation in the base-isolation story and the acceleration at the top story.

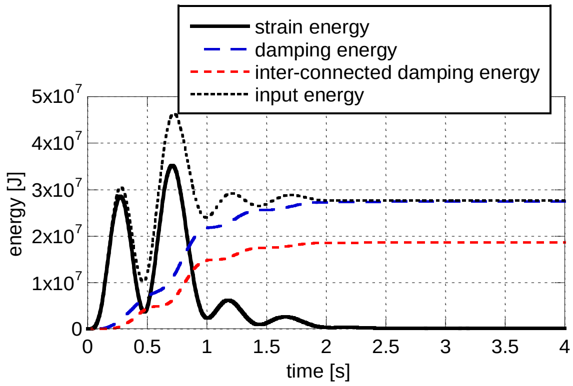


Fig. 11 Energy time history of hybrid system to pulse-type wave

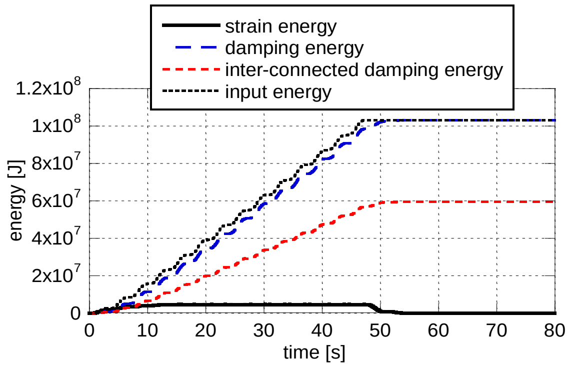


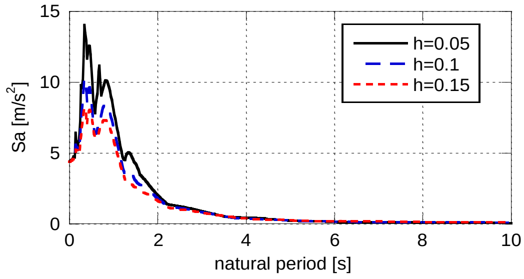
Fig. 12 Energy time history of hybrid system to long-duration, long-period wave

5.2 Energy response to simulated pulse-type ground motion and long-duration, long-period ground motion

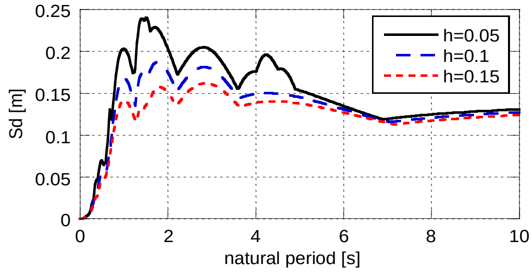
Fig. 11 shows the energy time history of the hybrid system to the pulse-type wave and Fig. 12 presents that to the long-duration, long-period wave. It can be seen from Fig. 11 that the hybrid system exhibits a usual energy response to the pulse-type wave, i.e., a large amplitude vibrating phenomenon in a short duration. On the other hand, it can be understood from Fig. 12 that the energy is absorbed in a long duration both in the base-isolation story and in the connecting dampers appropriately to the long-duration, long-period wave. The step-wise increase of the total input energy is a remarkable phenomenon to the long-duration, long-period wave.

5.3 Response to JMA Kobe NS 1995 (typical near-field ground motion) and Tomakomai EW 2003 (typical long-period ground motion)

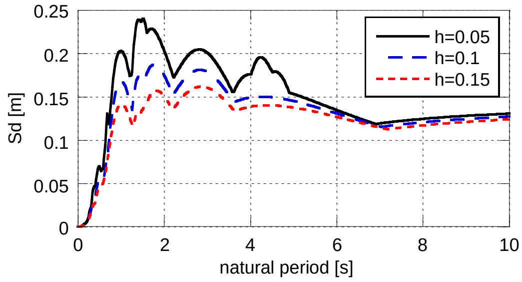
Since it seems useful to investigate the response characteristics of the present hybrid system to recorded ground motions, two representative ground motions have been chosen. One is JMA Kobe NS (typical near-field ground motion) during 1995 Hyogo-ken Nanbu earthquake (maximum ground velocity is 0.5 m/s) and the other is Tomakomai EW (typical long-period ground motion)



(a)Acceleration response spectra



(b)Velocity response spectra



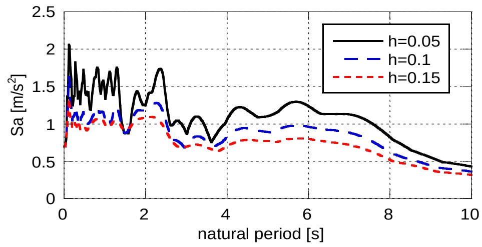
(c)Displacement response spectra

Fig. 13 Acceleration, velocity and displacement response spectra for JMA Kobe NS 1995 during 1995 Hyogo-ken Nanbu earthquake (maximum ground velocity is 0.5m/s)

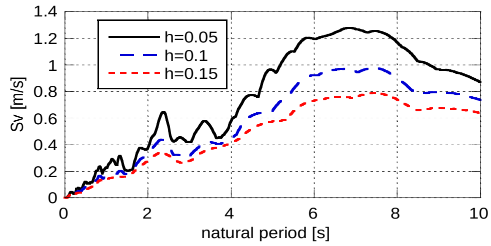
during 2003 Tokachi-oki earthquake. Fig. 13 shows the acceleration, velocity and displacement response spectra for JMA Kobe NS (maximum ground velocity is 0.5 m/s) and Fig. 14 presents those for Tomakomai EW.

Fig. 15 shows the maximum distributions of story displacement, interstory drift and acceleration to JMA Kobe NS (maximum ground velocity is 0.5 m/s). It can be seen that the response characteristics are similar to those to the pulse-type wave. The displacement of the base-isolation story in the base-isolated system and that in the hybrid system are almost half of those to the pulse-type wave. The same tendency can be found in the maximum interstory drifts.

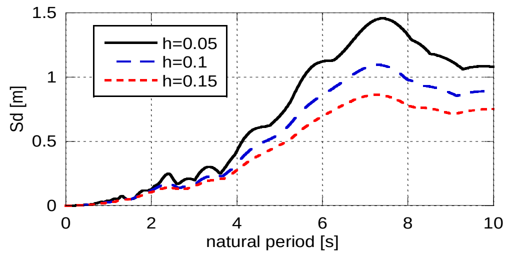
Fig. 16 shows the maximum distributions of story displacement, interstory drift and acceleration to Tomakomai EW. It can be understood that the response characteristics are similar to those to the long-duration, long-period wave. As in the case of the response to the long-duration, long-period wave, the large displacement of the base-isolation story in the base-isolated system seems to be fatal for the safe design of the base-isolation story. Even in this case, the hybrid system exhibits a promising performance.



(a)Acceleration response spectra

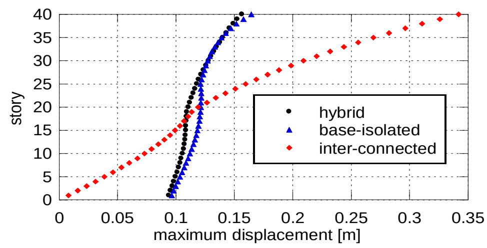


(b)Velocity response spectra

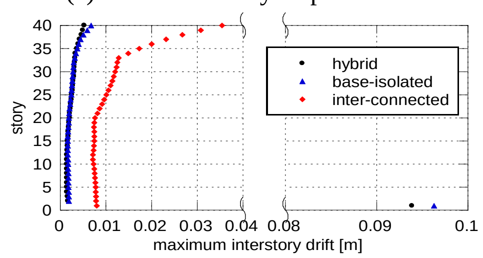


(c)Displacement response spectra

Fig. 14 Acceleration, velocity and displacement response spectra for Tomakomai EW during 2003 Tokachi-oki earthquake

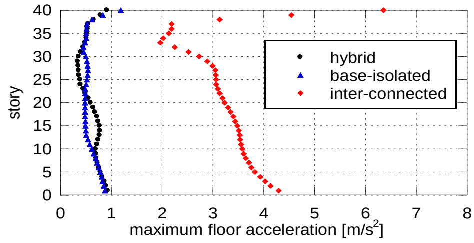


(a) Maximum story displacement



(b)Maximum interstory drift

Fig. 15 Maximum distributions of story displacement, interstory drift and acceleration to JMA Kobe NS



(c)Maximum floor acceleration

Fig. 15 Continued

Table 1 Comparison of response properties among base-isolated, interconnected and hybrid models to pulse-type wave and long-duration, long-period wave

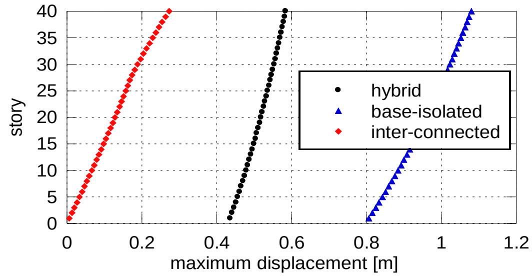
	pulse-type wave			long-duration, long-period wave		
	Deformation of base-isolation story	Maximum interstory drift	Maximum top-floor acceleration	Deformation of base-isolation story	Maximum interstory drift	Maximum top-floor acceleration
base-isolated	○	○	○	×	×	×
interconnected	／	×	×	／	◎	◎
hybrid	○	◎	◎	○	○	○

(◎: high performance, ○: moderate performance, ×: low performance)

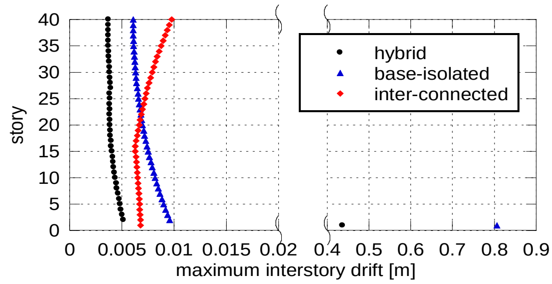
Table 2 Comparison of response properties among base-isolated, interconnected and hybrid models to three standard recorded waves and JMA Kobe NS of Level 2

	El Centro Level 2			Taft Level 2		
	Deformation of base-isolation story	Maximum interstory drift	Maximum top-floor acceleration	Deformation of base-isolation story	Maximum interstory drift	Maximum top-floor acceleration
base-isolated	○	○	○	×	○	○
interconnected	／	×	×	／	×	×
hybrid	○	○	○	○	◎	○
	Hachinohe Level 2			**JMA Kobe Level 2**		
	Deformation of base-isolation story	Maximum interstory drift	Maximum top-floor acceleration	Deformation of base-isolation story	Maximum interstory drift	Maximum top-floor acceleration
base-isolated	○	○	○	○	○	○
interconnected	／	×	×	／	×	×
hybrid	○	○	○	○	○	○
	Tomakomai					
	Deformation of base-isolation story	Maximum interstory drift	Maximum top-floor acceleration			
base-isolated	×	○	○			
interconnected	／	○	○			
hybrid	○	◎	◎			

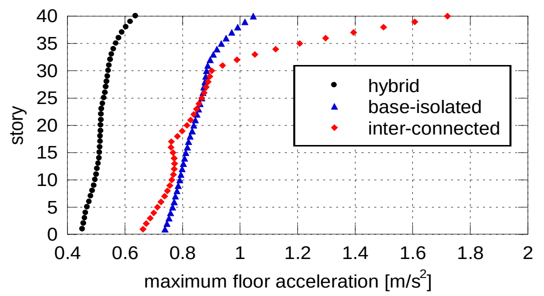
(◎: high performance, ○: moderate performance, ×: low performance)



(a) Maximum story displacement



(b) Maximum interstory drift



(c) Maximum floor acceleration

Fig. 16 Maximum distributions of story displacement, interstory drift and acceleration to Tomakomai EW

5.4 Summaries of response properties of smart passive control system (hybrid system)

The results in Sections 5.1 and 5.3 are summarized in Tables 1 and 2. Table 1 shows the comparison of response properties to the pulse-type wave and long-duration, long-period wave. It can be understood that the hybrid system possesses a superior property to the base-isolated building and the interconnected building system both for pulse-type and long-duration, long-period waves. In addition, Table 2 presents the comparison of response properties to three standard recorded waves (Level 2: maximum velocity = 0.5 m/s), JMA Kobe NS of Level 2 and Tomakomai EW. It may be concluded that the hybrid system is superior or equivalent to other two systems (the corresponding base-isolated building without interconnection and the corresponding interconnected building system without base-isolation) in all the deformation of base-isolation story, the maximum interstory drift and the maximum top-floor acceleration also for representative recorded ground motions. It should be remarked that the hybrid system does not have an evaluation of × in all the response parameters.

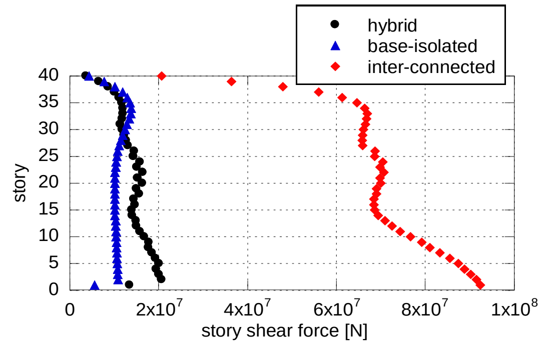


Fig. 17 Comparison of story shear forces in main frame under pulse-type wave

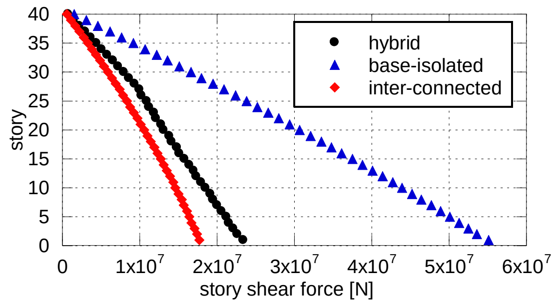


Fig. 18 Comparison of story shear forces in main frame under long-duration, long-period wave

Fig. 17 shows the comparison of story shear forces in the main frame under the pulse-type wave. It can be understood that the base-isolated system and the hybrid system are superior to the inter-connected system without base-isolation. It seems that this result from the fact that the fundamental natural periods of the base-isolated system and the hybrid system are greatly different from that of the inter-connected system without base-isolation. On the other hand, Fig. 18 presents the comparison of story shear forces in the main frame under a long-duration, long-period wave. It should be remarked that, while the base-isolated system exhibits large story shear forces to a long-duration, long-period wave due to the resonance, the hybrid system shows a much lower response almost equivalent to that of the inter-connected system without base-isolation. This demonstrates clearly the superiority of the hybrid system.

5.5 Effect on free wall

Fig. 19 shows the comparison of story shear forces in the free wall under the pulse-type wave. The unsmooth distributions in the combined systems certainly result from the discrete allocation of connecting dampers. It can be understood that the hybrid system is superior to the inter-connected system without base-isolation (combined with earthquake resistant building) and the independent free wall structure in terms of the shear force in the free wall. On the other hand, Fig. 20 presents the comparison of story shear forces in the free wall under a long-duration, long-period wave. It should be remarked that, while the hybrid system exhibits larger story shear forces compared to the independent free wall structure and the inter-connected system without base-isolation

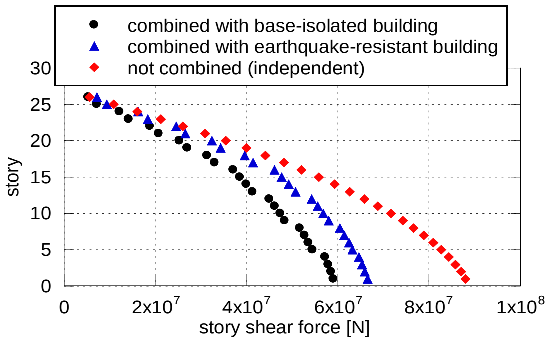


Fig. 19 Comparison of story shear forces in free wall under pulse-type wave

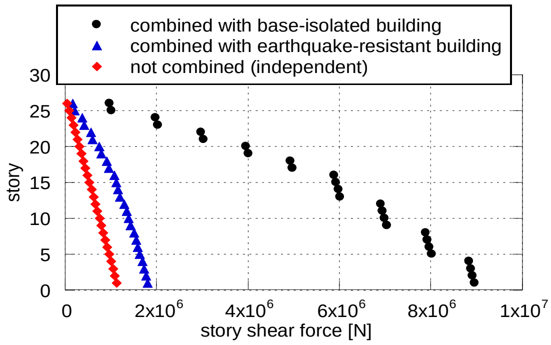
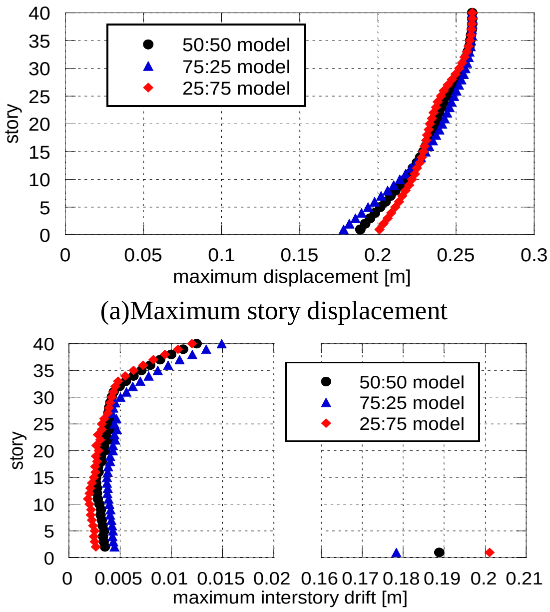


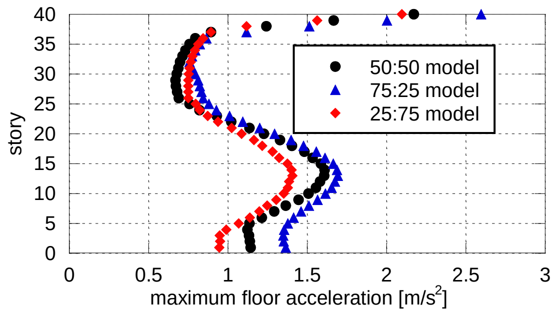
Fig. 20 Comparison of story shear forces in main frame under long-duration, long-period wave



(a)Maximum story displacement

(b)Maximum interstory drift

Fig. 21 Maximum distributions of story displacement, interstory drift and acceleration to pulse-type wave for three damper distributions



(c)Maximum floor acceleration

Fig. 21 Continued

(combined with earthquake resistant building) to a long-duration, long-period wave, the response level is much lower than that under the pulse-type wave. This demonstrates clearly the validity of the hybrid system.

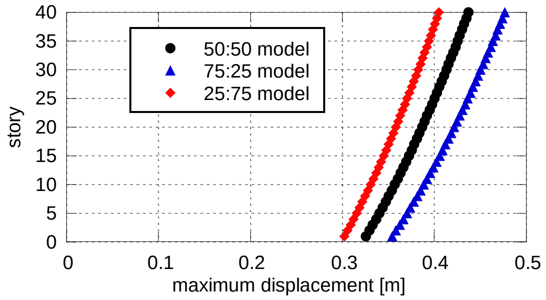
5.6 Superiority of hybrid system in terms of redundancy and robustness

It is well known that the concentration of damping at the base-isolation story induces response amplification or performance deterioration in base-isolated buildings. The present hybrid system distributes the damping to several locations. This distribution of damping leads to high redundancy of the system and realization of a fail-safe mechanism (AIJ 2011, Committee on National Earthquake Resilience Research, Implementation, and Outreach 2011). Furthermore the installation of dampers between the main building and the free wall can reduce effectively the response of the main structure.

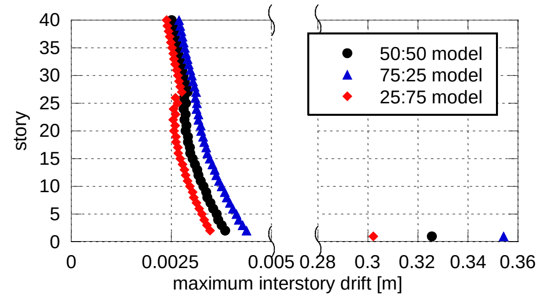
Fig. 21 shows the maximum distributions of story displacement, interstory drift and acceleration to the pulse-type wave for three damper distributions. The 50:50 model indicates the model in which the same quantity of dampers is allocated to the base-isolation story and the connection between the main structure and the free wall. On the other hand, the 75:25 model means the model in which 75% of dampers is allocated to the base-isolation story and 25% to the connection between the main structure and the free wall. Furthermore the 25:75 model is the model in which 25% of dampers is allocated to the base-isolation story and 75% to the connection between the main structure and the free wall. It can be seen that the present hybrid system is robust to the variation of damper distributions between the base-isolation story and the building connections under the pulse-type wave.

Fig. 22 illustrates the maximum distributions of story displacement, interstory drift and acceleration to the long-period, long-duration wave for the above-mentioned three damper distributions. The 50:50 model, 75:25 model and 25:75 model indicate the models as explained above. It can be seen that the present hybrid system is robust to the variation of damper distributions between the base-isolation story and the building connections also under the long-period, long-duration wave.

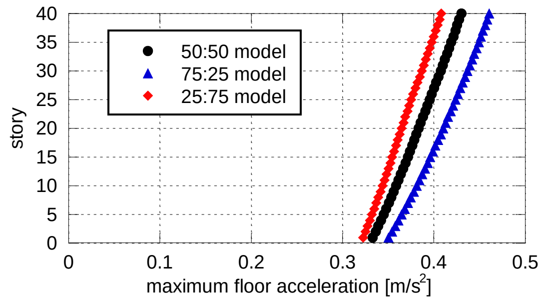
Table 3 shows the comparison of overturning moments in the hybrid system (Fig. 8(a)) and the base-isolated building (Fig. 8(b)) subjected to pulse-type wave and long-period, long-duration wave. It can be observed that, while the hybrid system and the base-isolated building exhibit a



(a)Maximum story displacement

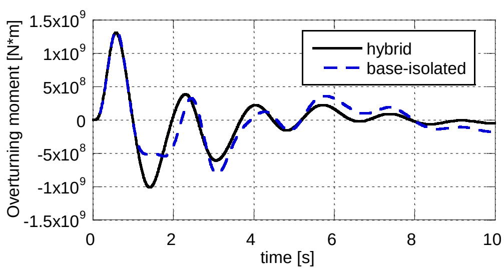


(b)Maximum interstory drift

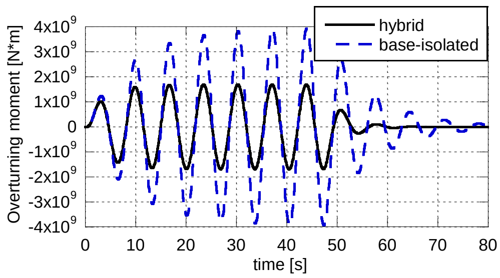


(c)Maximum floor acceleration

Fig. 22 Maximum distributions of story displacement, interstory drift and acceleration to long-duration, long-period wave for three damper distributions



(a)



(b)

Fig. 23 Time-history of overturning moments in hybrid system and base-isolated building; (a) pulse-type wave, (b) long-period, long-duration wave

Table 3 Comparison of maximum overturning moments in hybrid system and base-isolated building subjected to pulse-type wave and long-duration, long-period wave (Nm)

pulse-type wave		long-duration, long-period wave	
Hybrid	Base-isolated	Hybrid	Base-isolated
1.31×10^9	1.34×10^9	1.69×10^9	3.91×10^9

Table 4 Comparison of maximum overturning moments in free wall connected to base-isolated building and that connected to non-base-isolated building subjected to pulse-type wave and long-duration, long-period wave (Nm)

pulse-type wave		long-duration, long-period wave	
Free wall connected to base-isolated building (hybrid system)	Free wall connected to non-base-isolated building	Free wall connected to base-isolated building (hybrid system)	Free wall connected to non-base-isolated building
2.33×10^9	2.99×10^9	5.22×10^8	1.02×10^8

similar maximum overturning moment to pulse-type wave, the hybrid system has an extremely prominent performance to long-period, long-duration wave. Fig. 23 presents the time-histories of overturning moments in the hybrid system and the base-isolated building under pulse-type wave and long-period, long-duration wave. Since the overturning moment is closely related to the axial stress in isolators, it can be concluded that the hybrid system has high redundancy to long-period, long-duration wave from this viewpoint.

Table 4 shows the comparison of the maximum overturning moments in the free wall connected to base-isolated building (Fig. 8(a)) and that connected to non-base-isolated (earthquake-resistant) building (Fig. 8(c)) subjected to pulse-type wave and long-duration, long-period wave. It can be seen that the maximum overturning moment in the free wall connected to base-isolated building (hybrid system) under pulse-type wave is smaller than that in the free wall connected to non-base-isolated building as can be seen in Fig. 19 for base shears. Although the maximum overturning moment in the free wall connected to base-isolated building (hybrid system) under long-duration, long-period wave is larger than that in the free wall connected to non-base-isolated building, that response value is much smaller than that under pulse-type wave as can be seen in Fig. 20 for base shears. This means that the connection of the free wall to base-isolated building does not cause a problem in the response of free wall.

6. Conclusions

The following conclusions have been derived.

(1) A new hybrid passive control system has been investigated in which a base-isolated building is connected to another non-base-isolated building (free wall) with oil dampers.

(2) It has been demonstrated that, while the base-isolated building exhibits larger responses to a long-duration, long-period wave and the inter-connected system without base-isolation shows larger response to a pulse-type wave, the present hybrid passive control system is effective both for pulse-type ground motions and long-duration, long-period ground motions.

(3) It has been made clear from the energy analysis that, although the connecting dampers in the hybrid system are not effective for a pulse-type wave, those are effective for a long-duration, long-period wave from the beginning of the vibration.

(4) The story shear force and overturning moment in the free wall in the hybrid system does not exhibit an excessive response both for pulse-type ground motions and long-duration, long-period ground motions.

(5) It has been confirmed that the present hybrid system has high redundancy and robustness for a broader range of ground motions and damping variability.

The proposed hybrid system may require the increase of the construction cost. However, the remarkable enhancement of the safety with high redundancy and robustness will compensate for such cost increase.

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References

Architectural Institute of Japan (AIJ) (2011), "Structural design with higher robustness and redundancy", *J. Architect. Build. Sci.*, **126**(1624), 73-79. (in Japanese)

Ariga, T., Kanno, Y. and Takewaki, I. (2006), "Resonant behavior of base-isolated high-rise buildings under long-period ground motions", *Struct. Des. Tall Spec. Build.*, **15**(3), 325-338.

Ben-Haim, Y. (2001, 2006), *Infomation-gap decision theory: Decisions under severe uncertainty*, Adacemic Press, London.

Committee on National Earthquake Resilience Research, Implementation, and Outreach (2011), *Committee on Seismology and Geodynamics, National Research Council*, National Earthquake Resilience: Research, Implementation, and Outreach, The National Academy's Press.

Elishakoff, I. and Ohsaki, M. (2010), *Optimization and anti-optimization of structures under uncertainty*, Imperial College Press.

Hall, J.H., Heaton, T.H., Halling, M.W. and Wald, D.J. (1995), "Near-source ground motion and its effect on flexible buildings", *Earthq. Spectra*, **11**, 569-605.

He, W.L. (2003), "Smart energy dissipation systems for protection of civil infrastructures from near-field earthquakes". Ph.D. Dissertation, The City Univ. of New York, New York.

He, W.L. and Agrawal, A.K. (2008), "Analytical model of ground motion pulses for the design and assessment of seismic protective systems", *J. Struct. Eng., ASCE*, **134**(7), 1177-1188.

Heaton, T.H., Hall, J.H., Wald, D.J. and Halling, M.W. (1995), "Response of high-rise and base-isolated buildings in a hypothetical MW 7・0 blind thrust earthquake", *Sci.*, ***2*67**, 206-211.

Hino, J., Yoshitomi, S., Tsuji, M. and Takewaki, I. (2008), "Bound of aspect ratio of base-isolated buildings considering nonlinear tensile behavior of rubber bearing", *Struct. Eng. Mech.*, **30**(3), 351-368.

Irikura, K., Kamae, K. and Kawabe, H. (2004), "Importance of prediction of long-period ground motion during large earthquakes", *In Annual Conference of the Seismological Society of Japan*, Poster Session. (in Japanese)

Jangid, R.S. (1995), "Optimum isolator damping for minimum acceleration response of base-isolated structures", *Australian Civil Eng. Transact.*, **37**, 325-331.

Jangid, R.S. and Banerji, P. (1998), "Effects of isolation damping on stochastic response of structures with nonlinear base isolators", *Earthq. Spectra.*, **14**, 95-114.

Jangid, R.S. and Datta, T.K. (1994), "Non-linear response of torsionally coupled base isolated structure", *J. Struct. Eng., ASCE*, **120**, 1-22.

Jangid, R.S. and Kelly, J.M. (2001), "Base isolation for near-fault motions", *Earthq. Eng. Struct. Dyn.*, **30**, 691-707.
Kamae, K., Kawabe, H. and Irikura, K. (2004), "Strong ground motion prediction for huge subduction earthquakes using a characterized source model and several simulation techniques", *In Proceedings of the13th WCEE*, Vancouver.
Karabork, T. (2011), "Performance of multi-storey structures with high damping rubber bearing base isolation systems", *Struct. Eng. Mech.*, **39**(3), 399-410.
Kelly, J.M. (1999), "The role of damping in seismic isolation", *Earthq. Eng. Struct. D.*, **28**, 3-20.
Kobori, T. (2004), *Seismic-Response-Controlled Structure* (New edition), Kajima Publisher, Tokyo. (in Japanese)
Koo, J.H., Jang, D.D., Usman, M. and Jung, H.J. (2009), "A feasibility study on smart base isolation systems using magneto-rheological elastomers", *Struct. Eng. Mech.*, **32**(6), 755-770.
Li, H.N. and Wu, X.X. (2006), "Limitations of height-to-width ratio for base-isolated buildings under earthquake", *Struct. Des. Tall Spec. Buildings*, **15**, 277-287.
Morales, C.A. (2003), "Transmissibility concept to control base motion in isolated structures", *Eng. Struct.*, **25**(10), 1325-1331.
Naeim, F. and Kelly, J.M. (1999), *Design of Seismic Isolated Structures*, Wiley, New York.
Nishimura, K, Fukumoto, Y and Wada, Y. (2008), "Response control effect of hi-rised reinforced concrete building using couplaed vibration control structure", *J. Technol. Des.*, AIJ, **14**(28), 417-422. (in Japanese)
Nishimura, K., Fukumoto, Y., Sasamoto, K. and Tanaka, Y. (2011), "Base-isolated building with higher robustness and redundancy enhanced by inter-connecting dampers", *J. Architec Build. Sci.*, **126**(1624), 79. (in Japanese)
Patel, C.C. and Jangid, R.S. (2011), "Dynamic response of adjacent structures connected by friction dampers", *Earthq. Struct.*, **2**(2), 149-169.
Petti, L., De Iuliis, G.G.M. and Palazzo, B. (2010), "Small scale experimental testing to verify the effectiveness of the base isolation and tuned mass dampers combined control strategy", *Smart Struct. Sys.*, **6**(1), 57-72.
Takewaki, I. (2005), "Uncertain-parameter sensitivity of earthquake input energy to base-isolated structure", *Struct. Eng. Mech.*, **20**(3), 347-362.
Takewaki, I. (2006), "Critical excitation methods in earthquake engineering", *Elsevier Sci.*, Amsterdam.
Takewaki, I. (2007), "Earthquake input energy to two buildings connected by viscous dampers", *J. Struct. Eng., ASCE*, **133**(5), 620-628.
Takewaki, I. (2008), "Robustness of base-isolated high-rise buildings under code-specified ground motions", *Struct. Des. Tall Spec. Build.*, **17**(2), 257-271.
Takewaki, I. and Fujita, K. (2009), "Earthquake input energy to tall and base-isolated buildings in time and frequency dual domains", *Struct. Des. Tall Spec. Build.*, **18**(6), 589-606.
Takewaki, I. and Tsujimoto, H. (2011), "Scaling of design earthquake ground motions for tall buildings based on drift and input energy demands", *Earthq. Struct.*, **2**(2), 171-187.
Takewaki, I., Murakami, S., Fujita, K., Yoshitomi, S. and Tsuji, M. (2011), "The 2011 off the Pacific coast of Tohoku earthquake and response of high-rise buildings under long-period ground motions", *Soil Dyn. Earthq. Eng.*, **31**(11), 1511-1528.
Takewaki, I., Moustafa, A. and Fujita, K. (2012a), *Improving the earthquake resilience of buildings: The worst case approach*, Springer, London.
Takewaki, I., Fujita, K. and Yoshitomi, S. (2012b), "Uncertainties in long-period ground motion and its impact on building structural design: Case study of the 2011 Tohoku (Japan) earthquake", *Eng. Struct.* (accepted for publication)
Xu, Z., Agrawal, A.K., He, W.L. and Tan, P. (2007), "Performance of passive energy dissipation systems during near-field ground motion type pulses", *Eng. Struct.*, **29**, 224-236.

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