SEISMIC RESPONSE CONTROL OF A THREE-STORY CFS STRUCTURE BY MECHANICAL LINKS AND VISCOELASTIC DAMPERS

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Abstract

In this paper, we propose a new seismic response control system. It consists of mechanical links and viscoelastic dampers (MLVED) not only to minimize seismic response as a whole but also for preventing damage concentration to any specific story. We confirmed its availability by conducting a shake table test on a scaled three-story light-gauge cold-formed steel (CFS) structure with/without the MLVEDs. In the test, the MLVEDs are located along the height being jointed to beams on each floor by pin joints, working to prevent the structure from collapsing due to damage concentration even when subject to an extremely severe earthquake ground motion. Viscoelastic dampers are mounted between the two link members to work corresponding to their relative displacement. Thus the MLVED can increase seismic stability of shear type multi-story structures.

The main seismic element of the test frame is a wall consisting of CFS studs and a plywood. In this study, the wall is provided with a friction energy absorbing devise which is developed by the authors. A cross laminated timber (CLT) is used as the floor of the test frame. The primary link member of the MLVED is a channel steel with the dimension of 125×65×6×8 mm, and it is connected to the side of the CLT floor. The 5mm thickness viscoelastic acrylic rubber is used being adhered to steel plates mainly to be subject to shear strain. The input accelerations used are middle-level earthquake provided in the Japanese Building Standard Act, severe ground motions recorded in the 2011 Tohoku earthquake, the 1995 Kobe earthquake and some white noises.

Analysis of white noise test result by subspace identification method indicates that the MLVED really works to increase the higher mode stiffness and the damping ratio. The earthquake shaking test result shows that the MLVED is quite effective to prevent the soft story mechanism and reduce the maximum story drift. All these test results were simulated by the time history seismic response analysis making use of OpenSees. In the analysis, the viscoelastic damper is modeled by the generalized Maxwell model. It is confirmed that the analytical results agree well with the experimental results.

Keywords: Mechanical link; Viscoelastic damper; Damage concentration; Shake table test

1. Introduction

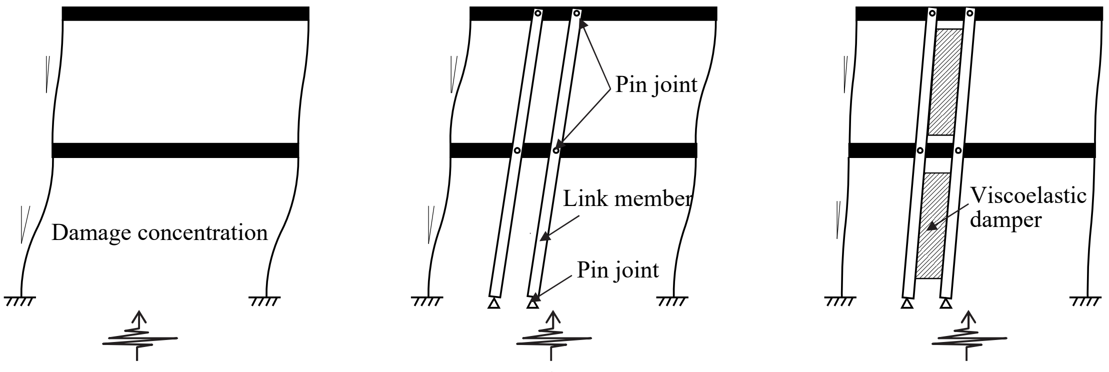
Soft story mechanism of a building is one of the most undesirable collapse mode since it probably causes the loss of human lives. Therefore, the seismic design of a building basically aims to disperse damage over whole part of the building. However, under an extremely severe earthquake ground motion, it is difficult to perfectly control the collapse mode of the building because the seismic response of the building generally shows high nonlinearity during earthquake shaking. In fact, for example in the 1995 Kobe earthquake and the 2016 Kumamoto earthquake, many mid- and low-rise buildings collapsed due to damage concentration to a specific story.

Researches and developments related to seismic structural system that aim to prevent buildings from soft story mechanism have been conducted by some researchers. Alavi and Krawinkler proposed a pin-supported wall system that reduce the deference of story drift of all the stories [1]. Wada et.al showed the effectiveness to install steel dampers into the pin-supported wall system [2]. Soda et.al developed a linked fluid inertia mass damper (LFIMD) that works not only to equalize story drift of all the stories but also to supply negative stiffness and viscous damping [3, 4]. Miyazu et.al proposed a seismic device that utilizes mechanical links and steel dampers, and investigated its basic performance through some experiments and seismic response analyses [5].

In this paper, we propose a seismic device that consists of mechanical links and viscoelastic dampers (MLVED). The purpose of this device is the same as the previously proposed system by the authors, but the specifications of the device such as link members and dampers are different. First, we explain the overview of the MLVED in section 2. Next, we confirm the effectiveness of the MLVED through shake table tests of a scaled three-story light-gauge cold-formed steel (CFS) structure with/without the MLVEDs. Finally, we develop the analysis model of the MLVED and verify its validity through time history seismic response analyses of the shake table test.

2. Overview of MLVEDs

Figure 1 schematically shows the concept of the MLVED. When a building is subjected to an extremely strong earthquake ground motion, as shown in Fig. 1(a), an ordinary building often suffers damage concentration to a specific story. In order to avoid this situation, link members that have enough bending stiffness and strength are mounted along the height of the building and connected to each floor by pin joints as shown in Fig. 1(b). The link member generates resistance proportional to the deference of the story drift of adjacent stories, making the story drift of them uniform. In addition, to further reduce the story drift by enhancing the damping performance of the building, viscoelastic dampers are mounted between the link members as shown in Fig. 1(c).



(a) (b) (c)

Fig. 1 – Concept of seismic response control by MLVEDs

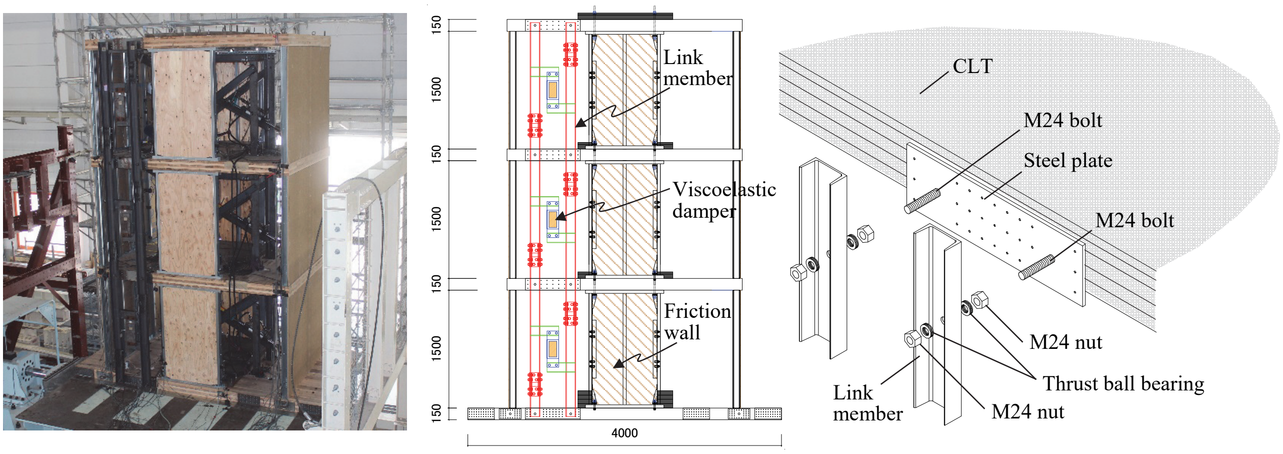
3. Shake table test of three-story CFS structures

3.1 Specification of test frames

Figure 2(a) and 2(b) show the photograph of a test frame mounted on a shake table and the elevation of the test frame, respectively. The main structure of the frame is a three-story CFS structure the height of which is scaled to almost half of real size. The main seismic element of the test frame is a wall that have energy absorbing devices using friction mechanism. The floor member of the test frame is a cross laminated timber (CLT) the thickness of which is 150mm.

The link member of the MLVED is a channel steel (SS400) with the dimension of 125×65×6×8 mm, which is connected to the side of the CLT floor by pin-joints as shown in Fig. 2(c). Viscoelastic dampers are installed between the two link members through channel steels welded to the link members. The detailed specification and the mechanical property of the viscoelastic damper is provided in the next section.

Three types of the test frame, named FR, FR+ML, and FR+MLVED, respectively, are used in this experiment. The FR has neither link members nor dampers. The FR+ML has only link members, and the FR+MLVED has both link members and dampers. Table 1 shows the list of the test frames.



(a) (b) (c)

Fig. 2 – (a) Photograph; (b) elevation; (c) pin-joint between the link member and the CLT.

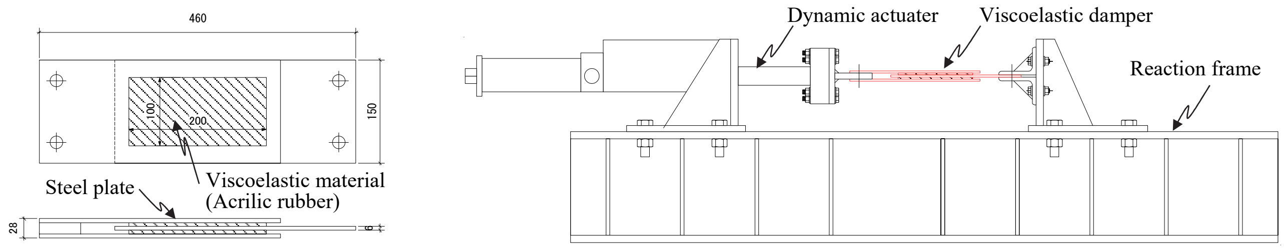
Table 1 – Composition of test frames.

Name	Link members	Viscoelastic dampers
FR	Not included	Not included
FR+ML	Included	Not included
FR+MLVED	Included	Included

3.2 Mechanical property of viscoelastic dampers

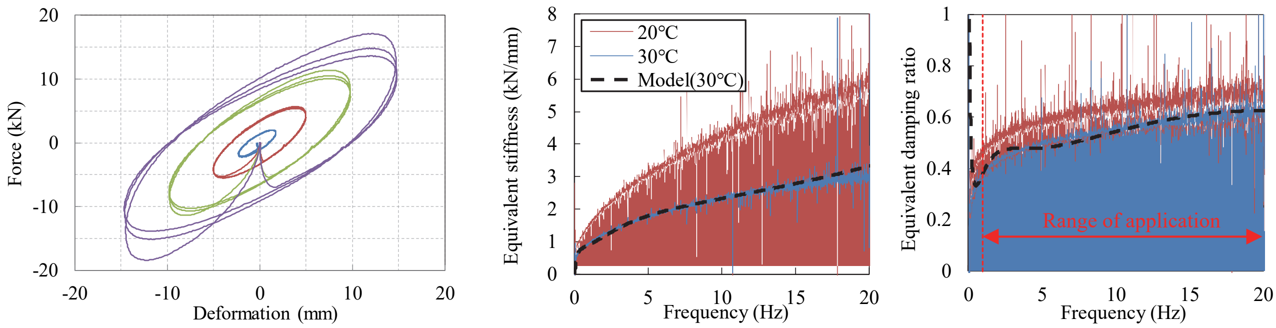
The dimension of the viscoelastic damper used in the shake table test is shown in Fig. 3(a). The viscoelastic material is 5 mm thickness acrylic rubber adhered to the steel plates with the thickness of 6mm. In order to examine the dynamic mechanical property, dynamic loading tests are conducted using a dynamic actuator under displacement control. The setup of the experiment is shown in Fig. 3(b). Input waves are sinusoidal wave and band-limited white noise. The frequency and the amplitude of the sinusoidal waves are from 0.5 to 3.0 Hz and from 2 to 15 mm, respectively. The white noise contains the frequency from 0.1 to 20 Hz, and its maximum amplitude is 2 mm.

Figure 4(a) shows the force-deformation relation obtained by the sinusoidal loading tests for four different amplitudes with the frequency of 0.5 Hz and the temperature of 25°C. It is confirmed that the damper shows the stable loops and linear characteristic. Figure 4(b) and (c) show the frequency dependency of the equivalent stiffness and the equivalent damping ration obtained by the white noise loading under the temperature of 20°C and 30°C. It is found that the equivalent stiffness highly depends on the frequency and the temperature, whereas the equivalent damping ratio is relatively stable. The black dashed lines in the figures indicate the propery of the six-elements generalized Maxwell model used for analytical study in section 4.



(a) (b)

Fig. 3 – (a) Dimension of the viscoelastic damper; (b) setup of the experiment.



(a) (b) (c)

Fig. 4 – (a) Force-deformation relations under sinusoidal loading tests; (b) equivalent stiffness under white noise loading test; (c) equivalent damping ratio under white noise loading test.

3.3 Test procedure

One directional shaking is conducted through all the shake table test. Input ground motions are a simulated ground motion and two recorded earthquake ground motions. The response spectrum of the simulated ground motion corresponds to the spectrum of the medium scale earthquake defined in the Japanese building standard act. The recorded ground motions are the EW component recorded at KiK-net Haga in the 2011 Tohoku earthquake and the NS component recorded at JMA Kobe in the 1995 Kobe earthquake. The KiK-net Haga record is scaled to 30, 60, and 80% of its original data in order to control the damage of the test frames. Table 2 shows the order and the abbreviations of shakings.

3.4 Test results

We first evaluate the natural frequency and the damping ratio of each test frame in their initial state, before the test frames are subjected to earthquake ground motion shakings. The acceleration response data obtained by the shakings of No. 1, 7, and 12 are analyzed by the PI-MOESP method that is one of the system identification method classified in subspace identification methods. The input and the output data used in this analysis are the ground acceleration and response acceleration at the 2nd, 3rd, and the roof floors, respectively. The order of the model and the number of rows of the block Hankel matrix are set to 8 and 60, respectively.

Table 2 –Order of shaking.

No.	Test frame	Input wave	Normalization	Abbreviation
1	FR+MLVED	White noise	-	WN
2	↑	Simulated ground motion	-	Kokuji
3	↑	2011 Tohoku earthquake_KiK-net Haga_EW	30 %	Haga30
4	↑	↑	60 %	Haga60
5	↑	↑	100 %	Haga100
6	↑	1995 Kobe earthquake_JMA Kobe_NS	100 %	Kobe100
7	FR+ML	White noise	-	WN
8	↑	Simulated ground motion	-	Kokuji
9	↑	2011 Tohoku earthquake_KiK-net Haga_EW	30 %	Haga30
10	↑	↑	60 %	Haga60
11	↑	↑	100 %	Haga100
12	FR	White noise	-	WN
13	↑	Simulated ground motion	-	Kokuji
14	↑	2011 Tohoku earthquake_KiK-net Haga_EW	30 %	Haga30
15	↑	↑	60 %	Haga60
16	↑	↑	80 %	Haga80

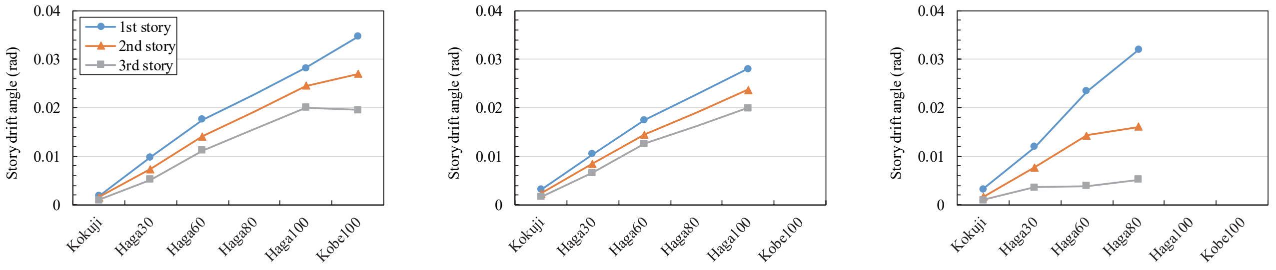
Table 3 shows the natural frequency and the damping ratio from 1st to 3rd mode of each test frame. It is found that the natural frequency of the higher modes increases when the test frame has the link members. It is also seen that the damping ratio of the FR+MLVED is larger than that of the FR+ML.

Table 3 –Natural frequency and damping ratio of the test frames.

Test frame	1st mode		2nd mode		3rd mode	
	f_1(Hz)	h_1 (%)	f_2(Hz)	h_2 (%)	f_3(Hz)	h_3 (%)
FR+MLVED	3.16	4.34	11.0	7.26	20.5	3.44
FR+ML	2.91	4.05	10.7	4.38	20.5	2.38
FR	2.97	4.20	10.0	4.53	16.3	4.34

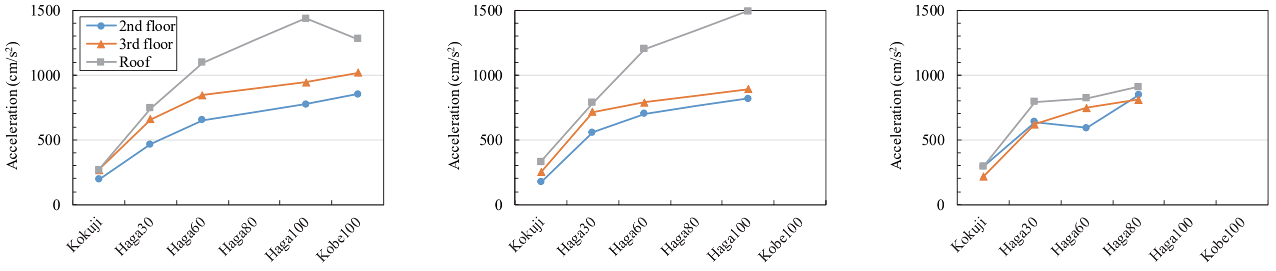
Figure 5 shows the maximum story drift angle of each story under earthquake ground motion shakings. It is found that the damage concentration to the lower story is clearly seen in the FR especially when the input ground motion is intense, whereas the story drift angle of all the stories becomes uniform and its maximum value decreases in the FR+MLVED and the FR+ML. This result indicates that the link members really work to disperse damage to all the stories. When we compare the results of the FR+MLVED and the FR+ML, it is seen that the influence of the viscoelastic dampers is not conspicuous than we expected. One of the reasons is that the temperature of the viscoelastic material was around 31°C, which was approximately 10°C higher than the temperature expected in the planning stage of the experiment. As mentioned in section 3.2, the temperature highly affects the mechanical properties of the viscoelastic damper. The maximum acceleration response of each floor are shown in Fig. 6. It is seen that the acceleration of the roof tends to become larger when the link members are installed.

Figure 7 shows the force-deformation relations of each story under Haga60 shakings that are conducted to all the test frames. The time history of dissipated energy in each story is also shown at the rightmost column in Fig. 7. The red dashed lines in the force-deformation relation indicate the maximum story drift angle of the FR, and the percentage in the time history of dissipated energy indicates the ratio of the total dissipated energy of each story to that of all the stories. It is found that the 3rd story of the FR is almost in the elastic region and the dissipated energy in the 3rd story is quite little, whereas the 3rd stories of the FR+MLVED and the FR+ML show inelastic behavior and dissipate over 10% of the total input energy.



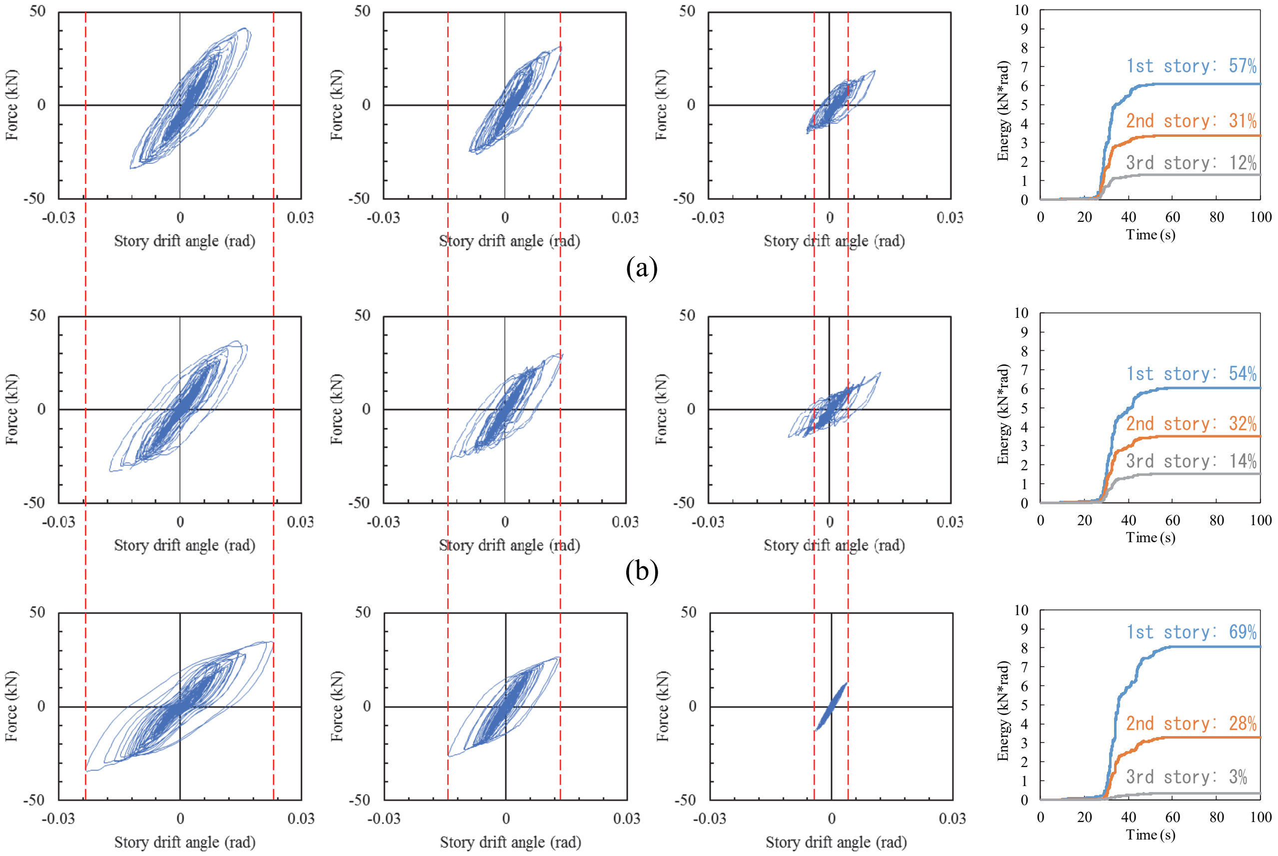
(a) (b) (c)

Fig. 5 – Maximum story drift ratio of each story: (a) the FR+MLVED; (b) the FR+ML; (c) the FR.



(a) (b) (c)

Fig. 6 – Maximum acceleration of each floor: (a) the FR+MLVED; (b) the FR+ML; (c) the FR.



(a)

(b)

(c)

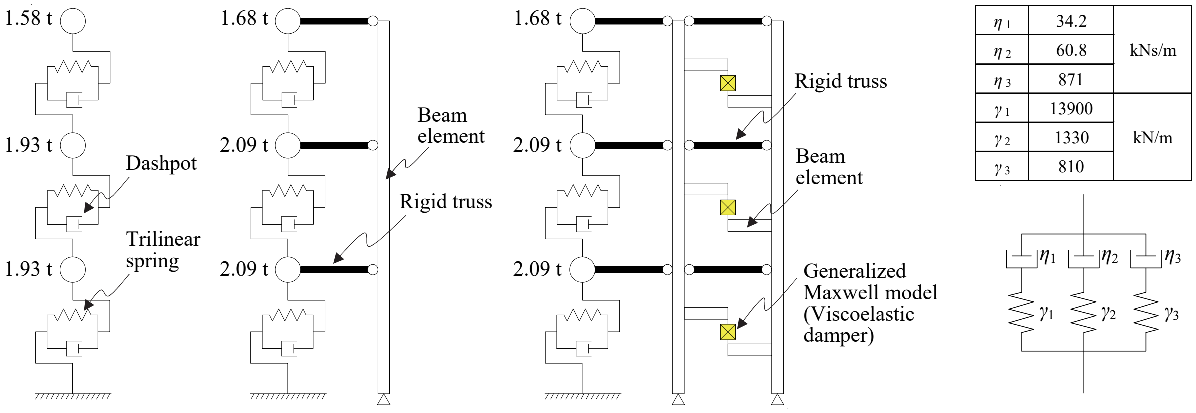
Fig. 7 – Force-deformation relations and time histories of dissipated energy of each story under Haga60: (a) the FR+MLVED; (b) the FR+ML; (c) the FR.

4. Time history seismic response analysis of test frames

4.1 Analysis models

In this section, we conduct time history response analyses to simulate the results of the shake table test conducted in the previous section. Figure 8(a), (b), and (c) illustrate the analysis models used for the FR, the FR+ML, and the FR+MLVED, respectively. The main structure of the test frames is modeled by a multi-mass shear system. The friction wall is modeled by a trilinear springs whose parameters are adjusted to agree with the test results of the FR. The link member is modeled by a beam element supported by a pin joint at the ground. The mass of the main structure and the link member are connected by a rigid truss element since we've confirmed through a prior experiment that the stiffness and the strength of the connection is large enough. The viscoelastic damper is modeled by a generalized Maxwell model that contains three Maxwell models in parallel as shown in fig. 8(d). The parameters of the generalized Maxwell model, listed in Fig. 8(d), are adjusted to approximate the mechanical properties obtained by the random loading test under 30°C shown in section 3.2. The equivalent stiffness and the equivalent damping ratio of the model are shown by black dashed lines in Fig. 4.

Input ground accelerations are the acceleration data measured at the first floor in the shake table test. Damping ratio of 4.2%, which is the evaluated value in section 3.4, is assigned to the first mode of the main structure, and the damping coefficient of each dashpot is proportional to the tangent stiffness of the main structure. Newmark β method with β=0.25 is used to solve the equation of motion. The software used here is OpenSees [6].



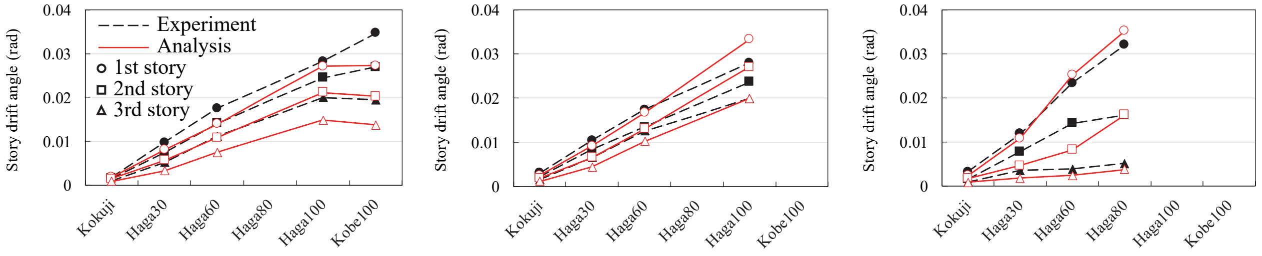
η_1	34.2	kNs/m
η_2	60.8	
η_3	871	
γ_1	13900	kN/m
γ_2	1330	
γ_3	810	

(a) (b) (c) (d)

Fig. 8 – Analysis models: (a) the FR; (b) the FR+ML; (c) the FR+MLVED; (d) the viscoelastic damper.

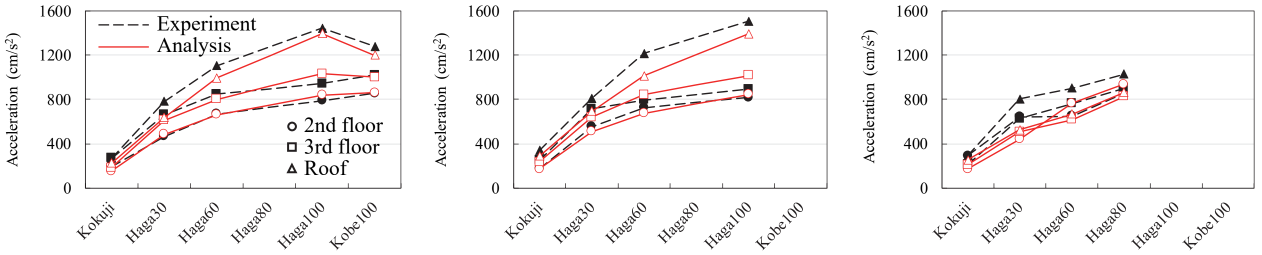
4.2 Results

Figure 9 shows the comparison of maximum story drift angle obtained by the experiment and that obtained by the analysis. Figure 10 shows the comparison of acceleration response in the same manner as Fig. 9. It can be seen that both story drift and acceleration response of the analysis are in good agreement with those of the experiment. Figure 11 shows the comparison of the force-deformation relation obtained by the last shaking of each test frames, namely Kobe100 for the FR+MLVED, Haga100 for the FR+ML, and Haga80 for the FR. The figures in black and red shown at the lower right in each figure are the amount of total dissipated energy evaluated from the experiment and the analysis, respectively. It is confirmed that the whole shape, the maximum force, and the dissipated energy obtained by the analysis and the experiment agree well with each other. Figure 12 shows the force-deformation relations of viscoelastic damper in each story. Although the deformation of the analysis is less than that of the experiment, they are in good agreement on the whole.



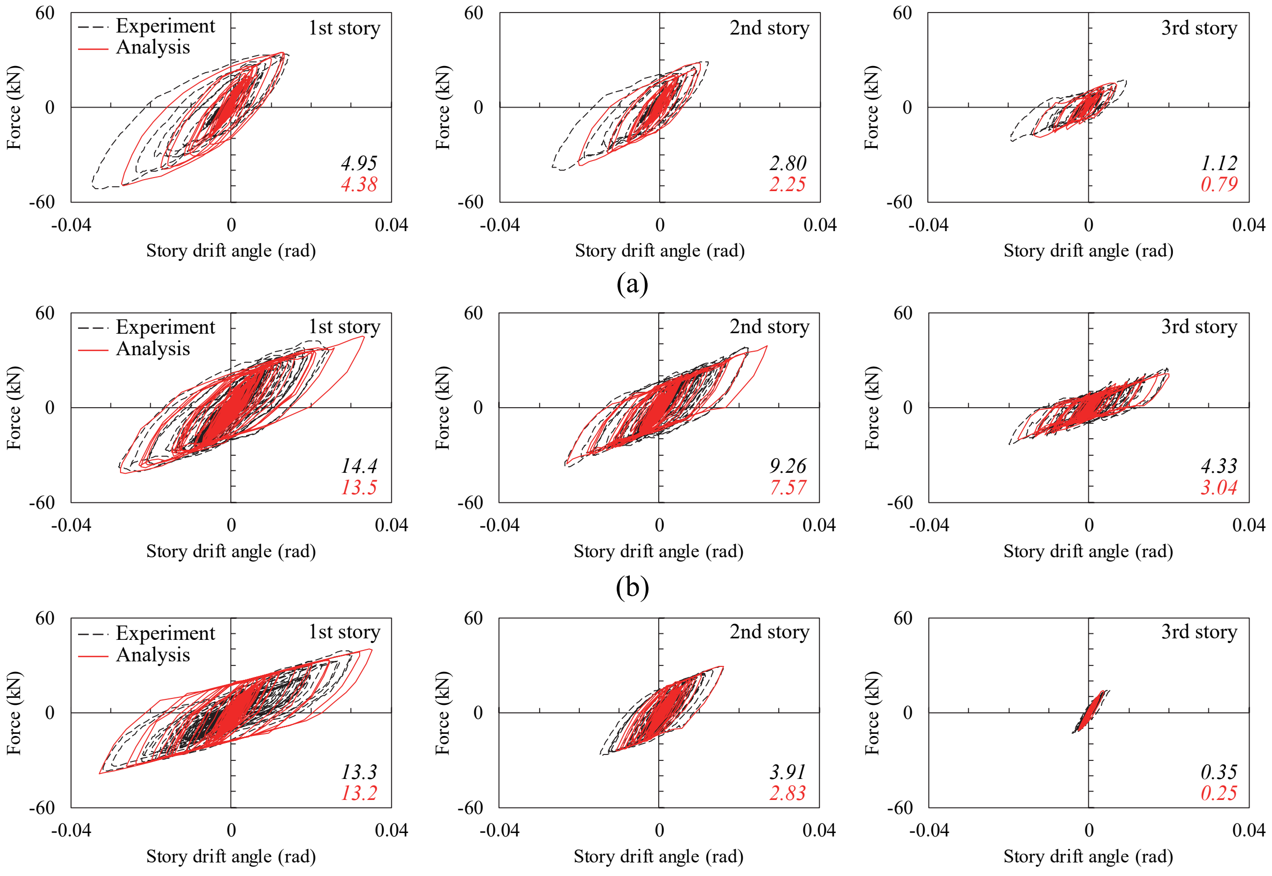
(a) (b) (c)

Fig. 9 – Comparison of maximum story drift angle obtained by the experiment and that obtained by the analysis: (a) the FR+MLVED; (b) the FR+ML; (c) the FR.



(a) (b) (c)

Fig. 10 – Comparison of maximum acceleration obtained by the experiment and that obtained by the analysis: (a) the FR+MLVED; (b) the FR+ML; (c) the FR.



(a)

(b)

(c)

Fig. 11 – Comparison of force-deformation relations obtained by the experiment and that obtained by the analysis: (a) the FR+MLVED under Kobe100; (b) the FR+ML under Haga100; (c) the FR under Haga80.

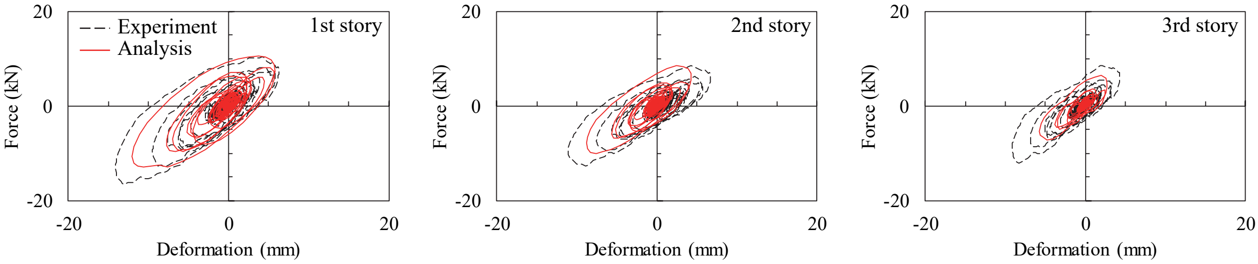
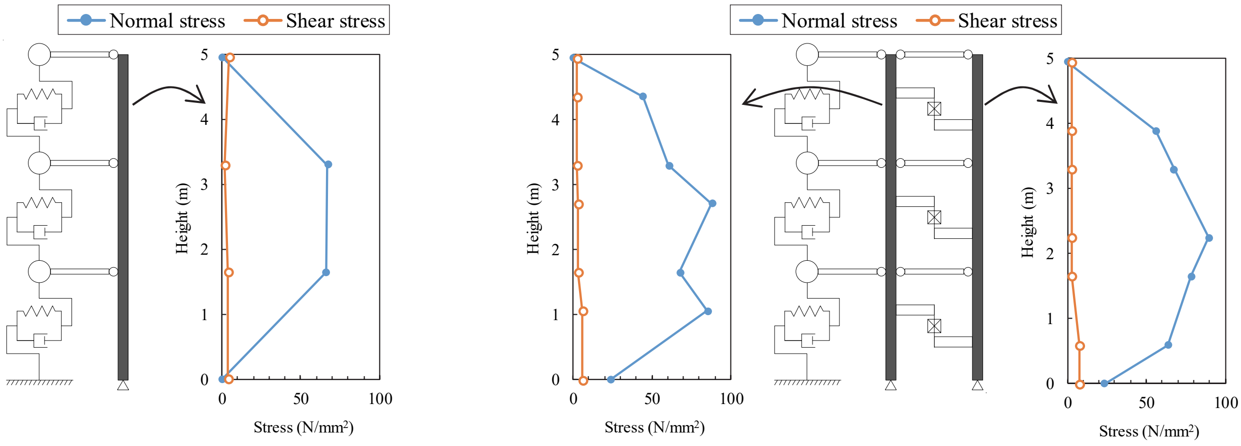


Fig. 12 – Comparison of force-deformation relations of the viscoelastic dampers in the FR+MLVED under Kobe100 shaking obtained by the experiment and those obtained by the analysis.

Figure 13 shows the maximum normal stress and shear stress at each node of the link member evaluated from the analysis results. When the viscoelastic dampers are installed between the link members, the normal stress increases to a certain extent; however, the value is less than allowable stress of the steel material.



(a) (b)

Fig. 13 – Maximum normal stress and shear stress at each node of the link members: (a) the FR+ML; (b) the FR+MLVED.

5. Conclusions

In this paper, we've proposed the new seismic device named MLVED that consists of link members and viscoelastic dampers. Through experimental and analytical studies, it is confirmed that the MLVED really works to prevent damage concentration and enhance energy dissipation performance.

6. Acknowledgements

The authors would like to thank the students of Miyazu laboratory in Tokyo University of Science for their help during the shake table test. This work was supported by JSPS KAKENHI Grant Numbers JP17K06644 and JP17H03346.

7. References

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