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Shaking Table Test on the Seismic Response of the Dual-frame Vibration Control System

TK. Kim[1], KY. Choi[2], HS. Ryu[3], WH. Yi[4], SH. Oh[5]

[1] *MSc Student, Department of Architectural Engineering, Pusan National University, Korea, archistk@gmail.com*
[2] *PhD Student, Department of Architectural Engineering, Pusan National University, Korea, ckysmart@naver.com*
[3] *Senior Researcher, Building Structure and Materials Research Center, POSCO Global R&D Center, Korea, blue887@naver.com*
[4] *Professor, Department of Architectural Engineering, Kwangwoon University, Korea, whyi@kw.ac.kr*
[5] *Associate Professor, Department of Architectural Engineering, Pusan National University, Korea, osh@pusan.ac.kr*

Abstract

Recently, the number of high-rise buildings is increasing due to overcrowding of cities, and the Strength Resistive Core System (SRCS) is becoming one of the most frequently chosen systems for designing high-rise buildings. In case of the SRCS, stress may build on strength resistive cores with a larger lateral stiffness against lateral force more so than the outer moment frames with relatively less lateral stiffness. However, if the strength resistive core and outer moment frame are each regarded as two separate structures and connected with a damper, one can expect that the damper's plastic behavior through relative displacement caused by a difference in the natural period of vibration, will dissipate energy and significantly reduce lateral displacement. This research conducts a shaking table test to verify seismic capacity of a Dual-frame Vibration Control System (DVCS) using a steel hysteretic damper. Also, this study verifies improved seismic capacity of the DVCS by comparing experiment results of the DVCS with the SRCS. This research analyses the characteristics of the dynamic responses of the DVCS by conducting a shaking table test. Specimens are composed of the SRCS and DVCS to conduct a comparison between the existing system and the DVCS recommended by this research. The seismic wave used in this experiment is an El-Centro NS wave, and the Peak Ground Acceleration (PGA) of the seismic wave was divided into 8 steps and processed through a step-by-step process. As a result of the shaking table test, the acceleration of the SRCS and DVCS demonstrated a similar response as far as excitation level 4 during which the structure was experiencing elasticity. However, going over excitation level 6, the response acceleration for the DVCS decreased relatively to the SRCS due to plastification of the damper. During excitation of level 8 in particular, the maximum response acceleration of the DVCS at the top floor was reduced by 55.2% in comparison with the SRCS. Furthermore, the displacement of the SRCS and DVCS demonstrated a similar response during excitation level 2 and 4 during which the structure was experiencing elasticity. However, during excitation level 6 and 8, the damper went through plastification and the DVCS's maximum response displacement was reduced more so than the SRCS. During excitation of level 8, the maximum response displacement of the DVCS at the top floor was reduced by 35.4% in comparison with the SRCS. Moreover, in case of the SRCS, the damage was concentrated on the column in the first floor, while the DVCS showed dispersion of damage throughout all floors. Also, the main structure members such as the beams and the columns sustained almost no damage due to which the damage was mostly concentrated on the damper. At the final excitation level, the damage of the damper was evenly spread out throughout all floors. Although most of the core frame parts went through plastification for the SRCS, the DVCS maintained elasticity although the core frame on first floor sustained some plastification. It has been emphasized that installed dampers in the proposed DVCS reduce the input energy of whole structure by absorbing seismic input energy, leading to a reduction of overall system damage. This demonstrates the improved seismic capacity of the DVCS compared to the SRCS.

Keywords: Strength Resistive Core System, Dual-frame Vibration Control System, Shaking Table Test

1. Introduction

Due to recent overcrowding of cities, the number of high-rise buildings is increasing, and the Strength Resistive Core System (SRCS) is becoming one of the most frequently applied systems for designing high-rise buildings. Although the SRCS allows for effective seismic design due to composition of a strength resistive core that resists lateral force and an outer moment frame that supports gravity loads, stress may concentrated on the strength resistive core rather than the outer moment frame because that lateral stiffness of the former is larger than that of the latter against lateral force. In particular, if the strength resistive core and outer moment frame are made of different material, it is highly probable that this may lead to the concentration of stress on the connecting part, and this may negatively impact workability and economic efficiency depending on complex connection details. However, if the strength resistive core and outer moment frame are not connected but separated, relative displacement will occur due to a difference in the natural period of vibration between the two frames. If a damper is placed in the connecting part to absorb energy by exploiting relative displacement between the two frames, energy is absorbed through plastic deformation of the damper, deterring excessive displacement and to improve the system's seismic capacity.

Previous literature on methods of connecting two different frames with dampers includes those of Park and Kim, who both conducted a numerical analysis on the method of connecting two structural types of a moment frame and shear wall, which have great difference in frequency by a viscous damper and a study which Kim and Ryu conducted on the method of reducing an earthquake response of two buildings by installing a viscous damper in connecting bridge on top of the buildings and connecting part of the two buildings. Also, Zhang and Xu performed research on a method of controlling a response against low-to-moderate seismicity by connecting nearby buildings with a viscoelastic damper. Although previous studies agree on the damping effect of lateral displacement by installing dampers between two different frames, most literature involves analytical studies on the response damping of buildings connected with viscoelastic dampers. This research conducts a shaking table test to verify seismic capacity of a Dual-frame Vibration Control System (DVCS) using a steel hysteretic damper. Also, this study verifies improved seismic capacity of the DVCS by comparing experiment results of the DVCS with those of the SRCS.

2. DVCS Overview

The strength resistive core of the SRCS works not only as a form of resistance to lateral loads but also as the brace of a frame. If the frame becomes non-swayed, displacement of the frame reduces against the lateral force. However, once the lateral force is applied, and provided that both are placed on the same level of displacement, plastification of the strength resistive core will precede that of the outer moment frame because that stiffness of the former is larger than the latter. This will result the damage caused by an earthquake to concentrate on the core which does not guarantee plastic deformable ability, and therefore, may undermine seismic capacity. Also, if the strength resistive core and outer moment frame are composed of different materials, the probability of failure may increase due to insufficient transfer of stress leading to the concentration of damage on the connection part. However, if the strength resistive core and outer moment frame are each regarded as two separate independent structures and connected with a damper, one can expect that the damper’s plastic behavior through relative displacement caused by difference in the natural period of vibration, will dissipate energy and significantly reduce lateral displacement.

As such, this research recommends the DVCS which connects the strength resistive core and outer moment frame with a damper. The concept of the DVCS is outlined in Fig.1, and restoring force characteristics of each of the components are shown in Fig.2. The strength resistive core has a relatively stronger shear stiffness against a lateral load and a smaller mass since it is designed mainly to resist a lateral load. The outer moment frame is relatively weaker in shear stiffness with a larger mass than the strength resistive core because most of its role involves supporting a gravity loads. During an earthquake, the core frame, with a relatively shorter natural period, vibrates rapidly at a small amplitude, and the outer frame, with a longer natural period, vibrates slowly at a larger amplitude. Accordingly, relative displacement occurs between the core and outer frame, and the vibration control damper connecting the two frames predominantly yields, absorbing the input energy caused by relative displacement to minimize damage by maintaining an elastic state of the whole system.

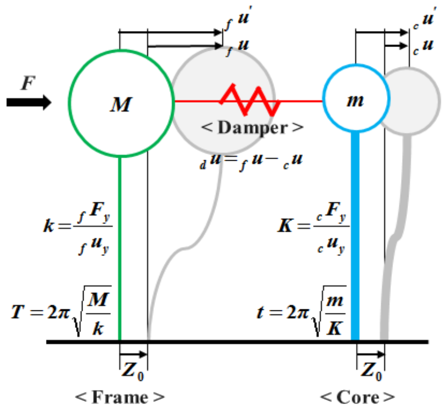


Fig. 1 – Concept of the DVCS

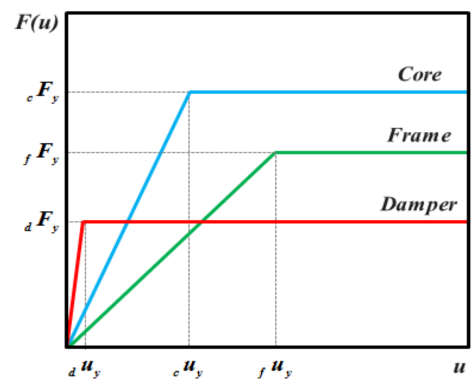
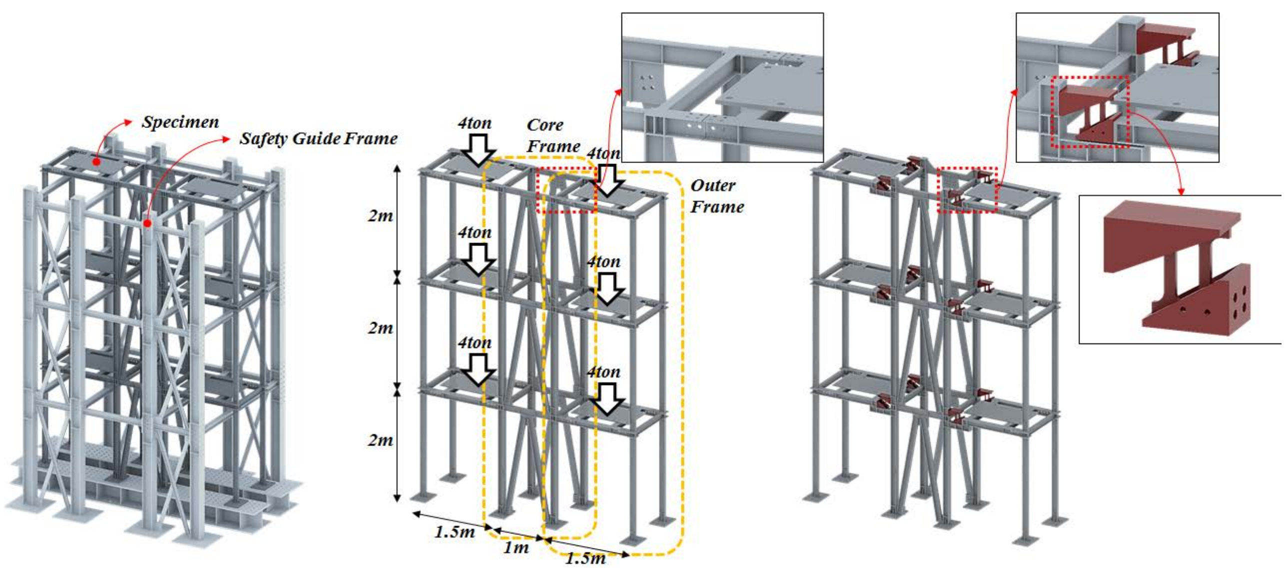


Fig. 2 – Restoring force characteristics of the DVCS

3. Shaking Table Test

3.1 Specimen overview

This research analyses the characteristics of the dynamic responses of the DVCS by conducting a shaking table test. Specimens are composed of the SRCS as shown in Fig.3 (b), and the DVCS as mentioned in Fig.3 (c) to conduct a comparison between the existing system and the DVCS recommended by this research.



(a) Set-up (b) SRCS (c) DVCS

Fig. 3 – Global view of specimens

Although specimen should be high-rise structure with dampers on each floor as outlined in Fig.4, considering environment of this experiment they are designed as structure with dampers installed on every three floors. Also, the specimen is composed of both the core and outer frame. The column of the core frame has been designed to be stronger than that of the outer frame as to have a relatively stronger stiffness. Also, using gravity loads calculations used in past studies to induce sufficient amount of damage behavior on the specimen, the load for each floor of the specimen is set as 80kN. As shown on Fig.6, the concrete shear wall possesses strengthdegrading restoring force characteristics against cracks when lateral force applies. In case of braced frames, the brace possesses restoring force characteristics similar to a concrete shear wall due to its buckling when a lateral force applies. As such, the strength resistive core is designed as an inverted V-type steel braced frame for ease of specimen preparation. Each section of the members of the DVCS are identical to those of the SRCS, and a damper is installed between the column of the core frame and the beam edge of the outer frame. Also, since the core and outer frame of the DVCS is connected by a damper, when the damper breaks it may collapse as it fails to resist gravity caused by the weight of the upper part of the outer frame. As such, a short cantilever beam was built within the column of the core frame to resist a gravity loads in case of damper failure, as shown on Fig.5. The final design of the members of the specimen are listed in Table 1.

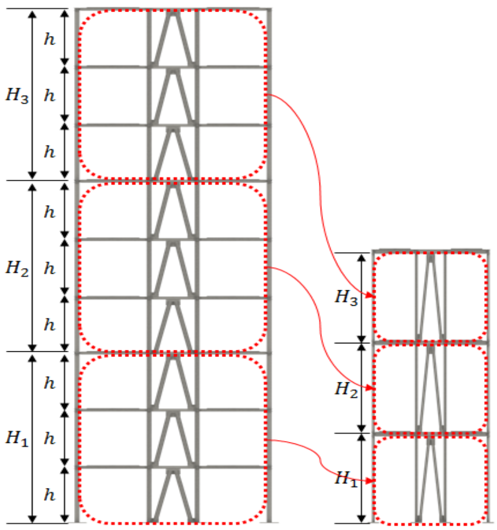


Fig. 4 – Scaling of the specimen

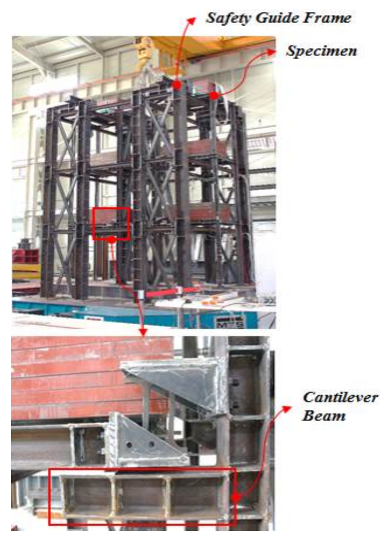


Fig. 5 – Setting up the specimen

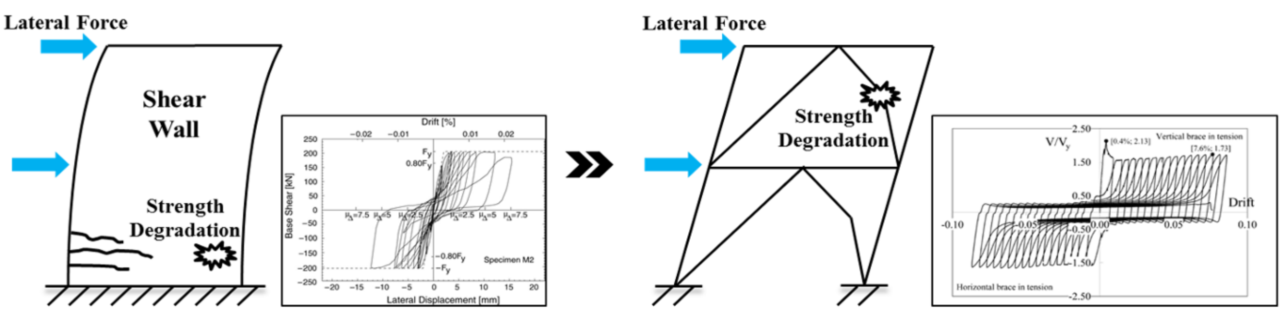


Fig. 6 – Lateral behavior of concrete shear walls and steel braced frames

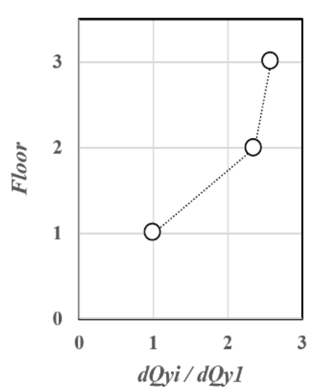
Table 1 – Properties of members

Members		Section(mm)	Length(mm)	Steel Grade
Core Frame	Column	H-100X100X6X8	2000	SS400
	Beam	H-100X50X4X6	1000	
	Out-of-plane beam	H-100X50X4X6	1000	
	Brace	C-100X50X5X7.5	1840	
Outer Frame	Column	H-100X50X4X6	2000	
	Beam	H-100X100X6X8	1500	
	Out-of-plane beam	H-100X50X4X6	1000	

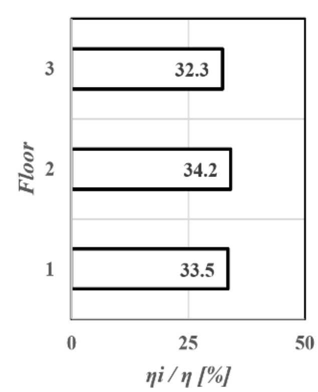
Unlike the SRCS, the strength resistive core and outer moment frame are connected with a damper in the DVCS. In this research, a steel hysteretic damper was used to design the DVCS specimen in consideration of its high energy absorption and construction ability. With a steel hysteretic element, an energy absorbent type is formed by creating a plastic deformation through the yield displacement of the steel member in advance to other ambient members, which is designed comparatively larger lateral stiffness than the main frame with a low yield strength. Among those, the Steel Slit Plate Damper has the advantage of an easy repair characteristic and maintenance being freely enabled in the design.

We initially calculated the strength and stiffness of the outer frame in order to calculate the strength and stiffness of the respective dampers of each floor of the specimen. Based on the result of the previous research regarding energy-absorbing efficiency of the damper according to the strength and stiffness ratio of the damper, the damper of the first floor was designed with (x 0.6) times of strength of the first floor of the outer frame, along with (x 4) times of stiffness, which is sufficiently large. A repeated analysis was conducted to evaluate the strength and stiffness of the upper floor damper using the non-linear dynamic seismic response analysis program called CANNY (Ver. C2012). An El-Centro NS (for use in the experiment) input wave was used and the response analysis was performed with the input wave adjusted by a 200% scale in order to verify the result of sufficient plastification.

Fig.7 (a) shows the strength distribution of a damper designed in each floor. The x-axis is exhibited by normalizing through the division of the strength of each floor damper by the strength of the first floor damper, and the y-axis is shown with in the floors. The strength of the damper is calculated to be weakest on the first floor, and strongest on the third floor; meaning the relative displacement by the difference of natural period between the two fixed structures to the ground shows the largest on the top floor. As such, we have designed the strength of the top floor damper to be the largest in order for the Accumulated Plastic Deformation Ratio to be equal in all floors. Accumulated Plastic Deformation Ratio is a value represented in a dimensionless quantity of the elastic deformation energy against the plastic deformation energy of the structure up to its yield when an earthquake occurs. Definition of Accumulated Plastic Deformation Ratio of each element is expressed as Eq. (1). Strength distribution of each floor for Accumulated Plastic Deformation Ratio distribution in Fig.7 (b) is equal to Fig.7 (a) and damper specifications designed with the strength of Fig.7 (a) is equal to Table 2.



(a) Strength distribution



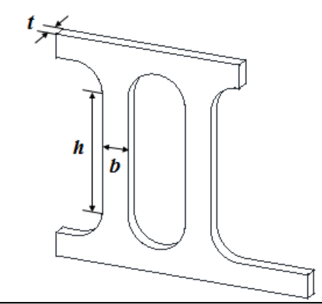
(b) Accumulated plastic deformation ratio

Fig. 7 – Dampers distribution factor

$$\eta = \frac{W_p}{Q_y \delta_y} \tag{1}$$

Where, W_p: Plastic Deformation Energy, Q_y: Yield Shear Strength, δ_y: Yield Displacement

Table 2 – Damper specifications of each floor

	Floor	t (mm)	δ (mm)	h (mm)	Qy (kN)	k (kN/mm)	δy (mm)	ηi	ηi / η (%)
	1	12	14.0	100	5.10	7.37	0.69	363	33.48
	2	12	21.5	100	12.03	24.08	0.50	371	34.17
	3	12	22.5	100	13.18	27.81	0.47	351	32.35

* Qy: Yield Shear Strength, k: Initial Stiffness, δy: Yield Displacement, η: Accumulated Plastic Deformation Ratio

3.2 Experiment method

In this experiment, we have installed an accelerometer, Linear Voltage Displacement Transducers (LVDT), and strain gauges at each floor in order to measure the deformation of the element, the absolute acceleration, and the relative displacement of each of the floors. The seismic wave used in this experiment is an El-Centro NS wave (PGA 341cm/s², Year 1940), and the Peak Ground Acceleration (PGA) of seismic wave was adjusted by scale into 8 steps and phased. Table 3 shows the excitation protocol of this experiment per step.

Table 3 – Excitation protocol

Step	Scale (%)	PGA (cm/s²)	SRCS Output (cm/s²)	DVCS Output (cm/s²)
1	10	34.1	48.6	48.2
2	30	102.3	140.2	135.0
3	50	170.5	260.3	265.4
4	70	238.7	317.1	357.5
5	100	341.0	517.1	565.4
6	130	443.3	670.7	654.4
7	160	545.6	815.8	807.4
8	190	647.9	902.7	955.2

3.3 Test result and analysis

3.3.1 Material test

In order to understand the mechanical properties of steel members, we have collected tensile test pieces from each member of the structure to conduct a material tensile test. The plate-shaped test pieces were made in accordance with KS B0801 Standard Metallic Material Tensile Test Pieces for the test, and the results of the test are shown in Table 4.

Table 4 – Material test results

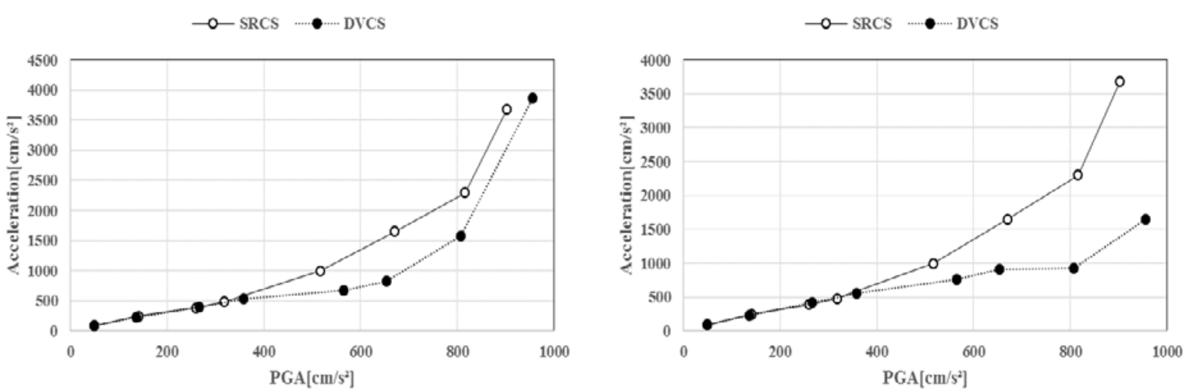
No.	t (mm)	σ_y (MPa)	σ_t (MPa)	E (MPa)	Elongation (%)	Yield Ratio
1	4	294.19	375.98	180771	25.5	0.78
2	6	277.89	418.45	201472	27	0.66
3	12	276.09	424.45	199222	30.83	0.65

* t: Thickness, σ_y: Yield Stress, σ_t: Tensile Stress, E: Young's Modulus

3.3.2 Acceleration response

Fig. 8 shows the maximum response acceleration at the top floor according to output wave PGA. Overall, there was a trend in which acceleration response increased along with the increase in the PGA. In case of acceleration response, the result was somewhat amplified due to various interfering factors such as bolt connection slips and a crash in the connecting part. However, it was deemed that they did not impact on understanding the overall trend, so we have shown the maximum response acceleration of the each floor in accordance with the results from excitation level 2, 4, 6 and 8 in Fig.9.

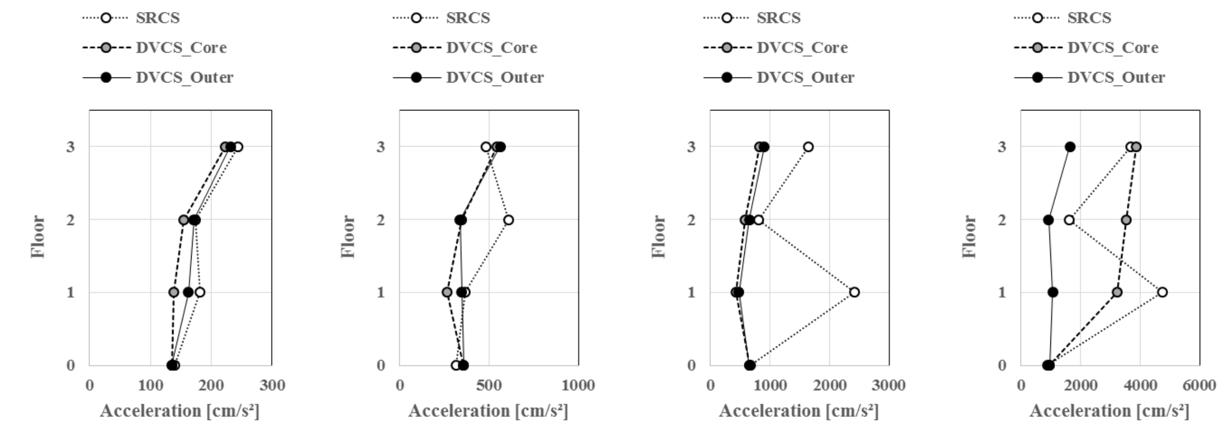
The SRCS and DVCS demonstrated a similar response up to excitation level 4 during which the structure was experiencing elasticity. However, comparing with the SRCS, response acceleration of the DVCS over excitation level 6 decreased due to plastification of the damper. During excitation level 8 in particular, the maximum response acceleration of the DVCS at the top floor was reduced to 55.2% when comparing with SRCS. We assess that the damper installed in the DVCS absorbed input energy from seismic activity and reduced the acceleration being input into the structure, thereby reducing the overall system's acceleration response.



(a) Core Frame

(b) Outer Frame

Fig. 8 – Maximum response acceleration of both systems



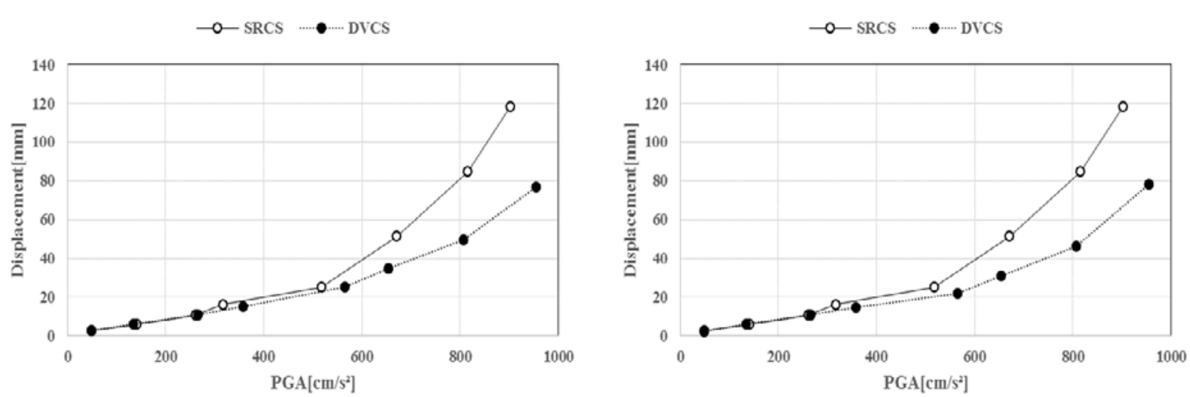
(a) Step 2 (b) Step 4 (c) Step 6 (d) Step 8

Fig. 9 – Maximum response acceleration of each floor

3.3.3 Displacement response

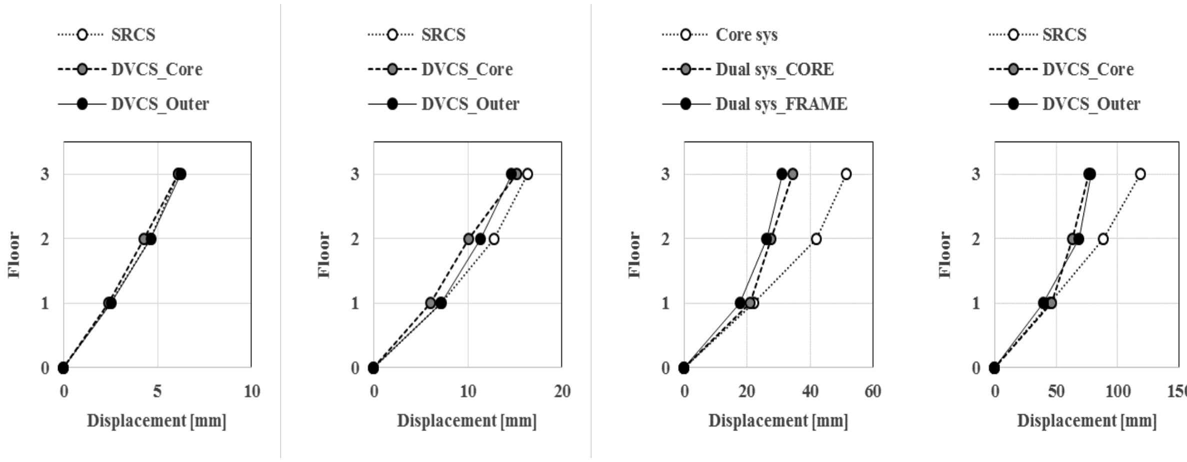
In Fig.10, we have shown the maximum response displacement at the top floor for the SRCS and DVCS's core and outer frame in response to the output wave PGA. Both the SRCS and DVCS showed increasing trends in their maximum response displacement in response to the PGA. However, the DVCS demonstrated larger reduction effects for response displacement as PGA increased. Fig.11 shows maximum response displacement for each floor during excitation 2, 4, 6 and 8.

The SRCS and DVCS demonstrated a similar response to excitation level 2 and 4 during which the structure was experiencing elasticity. However, during excitation level 6 and 8, the damper went through plastification and the DVCS's maximum response displacement was reduced more than the SRCS. During excitation of level 8, the maximum response displacement of the DVCS at the top floor was reduced to 35.4% in comparison with the SRCS. Also, we were able to confirm that there was a difference in the displacement between the core and outer frame of the DVCS, during which we assessed that the damper's plastic behavior was exerted as much as the difference in displacement, dissipating most of the input energy and reducing the overall response displacement of the entire system.



(a) Core Frame (b) Outer Frame

Fig. 10 – Maximum response displacement of both systems



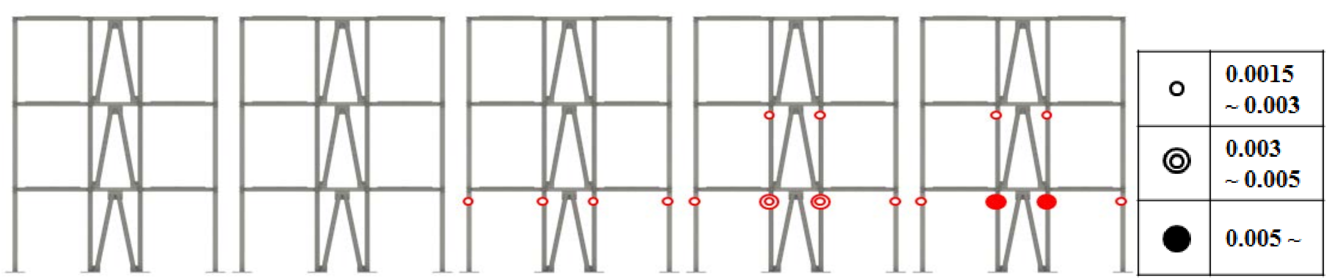
(a) Step 2 (b) Step 4 (c) Step 6 (d) Step 8

Fig. 11 – Maximum response displacement of each floor

3.3.4 Strain of the members

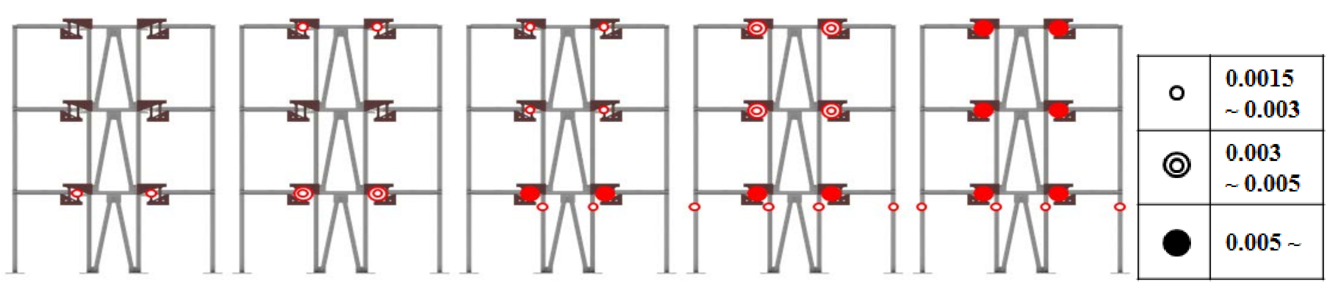
In order to compare the distribution of the yield points after excitation level 4 during which the members begin to yield, Fig.12 shows the SRCS and Fig.13 shows the DVCS. For the installed location of the strain gauge according to the measurement plan, it was determined whether or not the yield occurred based on 0.0015 yield strains as the standard point in accordance with the material test results, and categorized damage distribution into different circular marks by the degree of plastification.

In case of the SRCS, the damage was concentrated on the column in the first floor, while the DVCS showed dispersion of damage throughout all floors. Also, the main structure members such as the beams and the columns sustained almost no damage due to which the damage was mostly concentrated on the damper. At the final excitation level, the damage of the damper was evenly spread out throughout all floors.



(a) Step 4 (b) Step 5 (c) Step 6 (d) Step 7 (e) Step 8

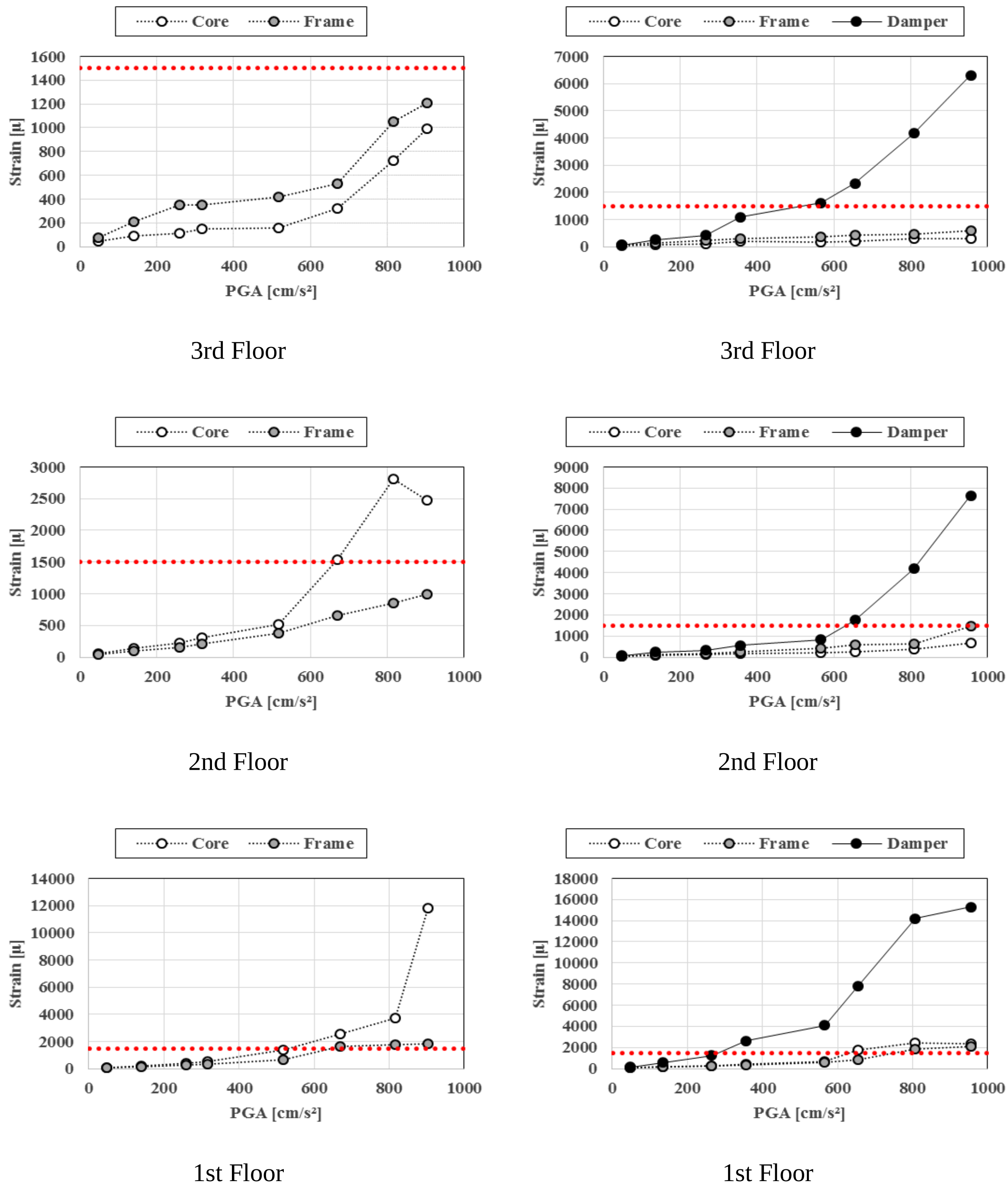
Fig. 12 – Damage distribution of the SRCS



(a) Step 4 (b) Step 5 (c) Step 6 (d) Step 7 (e) Step 8

Fig. 13 – Damage distribution of the DVCS

Fig.14 shows the strain of the SRCS and DVCS in response to output wave PGA. Although most of the core frame goes through plastification for the SRCS, the DVCS maintained elasticity although the core frame on the first floor endured some plastification. This demonstrates the improved seismic capacity of the DVCS compared to the SRCS.



(a) SRCS (b) DVCS

Fig. 14 – Strain of the both systems

4. Conclusion

This study verified the lateral displacement reduction effect of the system with a steel hysteretic damper connecting the strength resistive core and outer moment frame through a shaking table test. The results of this research are as follows.

1) As for maximum response acceleration, the SRCS and DVCS showed a similar response as far as the excitation level during which the elasticity of the structure can be maintained. However, at excitation level 8, maximum response acceleration of the DVCS at the top floor was reduced to 55.2% beyond the SRCS.

2) As plastification of the damper develops, maximum response displacement of the DVCS was reduced more so than the SRCS. At excitation level 8, maximum response displacement of the DVCS at the top floor was reduced to 35.4% beyond the SRCS.

3) While the SRCS showed concentration of damage on the column in the first floor, the DVCS's major structure members sustained almost no damage. The damage was concentrated on the dampers, and at the final excitation level, damage on the dampers spread evenly throughout all floors.

This study verified the seismic capacity of the DVCS through the shaking table test. As a result, it was able to minimize damage on major structure members by deliberately concentrating input energy caused by earthquake to the dampers, and effectively reduced lateral displacement of the whole system. For future studies, it is deemed necessary to establish a design process by conducting a multi-parameter dynamic seismic response analysis and apply such research into actual construction design.

5. Acknowledgements

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