Experimental Validation on Dynamic Response of RC Shear Wall Systems Coupled with Hybrid Energy Dissipative Devices

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SUMMARY:
Coupling beams in a RC shear wall system must be designed strong enough to maintain structural integrity and to provide frame actions which induce strong resistance to lateral forces, such as wind and earthquake loads. This study proposes hybrid energy dissipative devices applicable to coupling beams in a RC shear wall system. The hybrid energy dissipative device consists of U-shaped steel plates and high damping rubbers. The proposed hybrid energy dissipating system has been developed to provide relatively high initial stiffness, stable hysteresis with the limited but controlled yield strength, and excellent energy dissipation capabilities. In this study, shake table tests are carried out to investigate the dynamic response of RC shear walls coupled with the proposed hybrid energy dissipative devices. This paper presents the advantages of the cyclic response of RC shear walls coupled with the hybrid energy dissipating devices over those with conventional RC coupling beams.

Keywords: shear wall system, coupling beam, hybrid energy dissipative device, energy equivalent velocity

1. INTRODUCTION

Currently, one of the most lateral-force-resisting structural systems is a shear wall system because its significantly larger lateral stiffness compared to other lateral-force-resisting systems. The higher stiffness makes to easily control lateral deflections of a building. This is more prominent for high-rise buildings of which the structural design is mainly governed from the response to dynamic lateral loads. Unlike structural engineer's desire that the large stiffness of a RC shear wall is maintained, openings are usually required to accommodate architectural elements and facilities such as corridors and elevators. Such openings may degrade the lateral stiffness of a building by the loss of cross-section areas of shear walls, which results in problems in controlling structural vibrations.
To address and minimize such problems, it has been suggested that the beams connecting RC shear walls be stiffened compared to conventional RC beams. Steel reinforced concreter (SRC) beams could be a candidate used for coupling beams. However, structural damages may locally occur on shear walls with lower lateral force levels because of relatively high stiffness of SRC beams. Considering the nature of earthquakes that resultant force is transmitted from the bottom to the top and damages are initially concentrated on a certain structural member in a specific floor, shear walls with relatively less yield strengths start to lose their stiffness and strength, which results in decrease of the building's ductility capacity. The damages on shear walls and consequently, the reduction of ductility capacity may cause the loss of structural integrity.
From these observations, it is important that coupling beams develop the controlled yield strength to precede the yielding of shear walls and sustain up to prescribed displacement demands without abrupt strength degradation. In addition, they need to provide robust mechanism for dissipating structural vibration effectively. In this study, a hybrid energy dissipative device consisting of high damping rubber and U-shaped steel plates is proposed to figure out problems that may be observed at conventional coupling beams connecting two shear walls. The proposed device is placed at the mid-span of a coupling beam and is activated by shear deformations. With the configuration and energy

dissipating mechanism, the proposed device develops the controlled yield strength, excellent deformation capacity and increased energy dissipation with relatively larger elastic stiffness. These advantages of the proposed device are usually required for structural elements in seismic-force-resisting systems which expect to develop intended plastic behavior. This study carried out shake-table tests for experimental validation on seismic response of the proposed system and discusses on cyclic behavior of shear walls coupled with a hybrid energy-dissipating device compared to using convention a RC coupling beam.

2. HYBRID ENERGY DISSIPATIVE DEVICE

In a high-rise structure system where shear walls are used as structural elements to resist against lateral loads, the ductility of RC core walls is one of important criteria to be considered in the structural design phase. This is true for the design of RC shear wall systems subjected to seismic excitation. In order to improve the ductility of a shear wall system, ductile behavior of coupling beams without any damages on RC core walls are recommended. The plastic hinges at coupling beams increase energy dissipating capacities of an overall structural system so that its seismic performance would expect to be improved. Therefore, this study proposes a coupling beam-type energy-dissipating device that can improve the plastic deformation capacity. The coupling beam proposed in this study consists of connecting beams (SRC or steel beams) and energy dissipative devices which are placed on the mid-span of a coupling beam, as shown in Figure 1.

The hybrid energy dissipative device proposed by this study comprises two components; high damping rubber dampers and U-shaped steel damper that are welded on the top and the bottom of high damping rubber damper as shown on Figure 2. When a lateral load is applied, the same deformation will occur on each component. The proposed hybrid energy dissipative device presents different hysteresis depending on the states of U-shaped steel dampers. Before the U-shaped steel dampers yield, both the stiffness developed by two components contributes the stiffness of the hybrid energy dissipative device and seismic input energy is mainly dissipated by the high damping rubber damper because the U-shaped steel dampers are in elastic. After the U-shaped steel dampers yield, the stiffness of the hybrid energy dissipative device is determined by that of high damping rubber dampers while an advantage is found in the energy dissipation. Additional energy dissipation mechanism is activated by plastic behavior of the U-shaped steel dampers due to steel's unique outstanding plasticity and ductility behaviors.

From the ideal behavior of the hybrid energy dissipative device, more efficient vibration control against wind inducing structural vibration with small amplitude to design earthquake causing relatively large structural vibration can be achieved if the two components of a hybrid damper is properly designed according to displacement and/or strength demands from vibration sources.

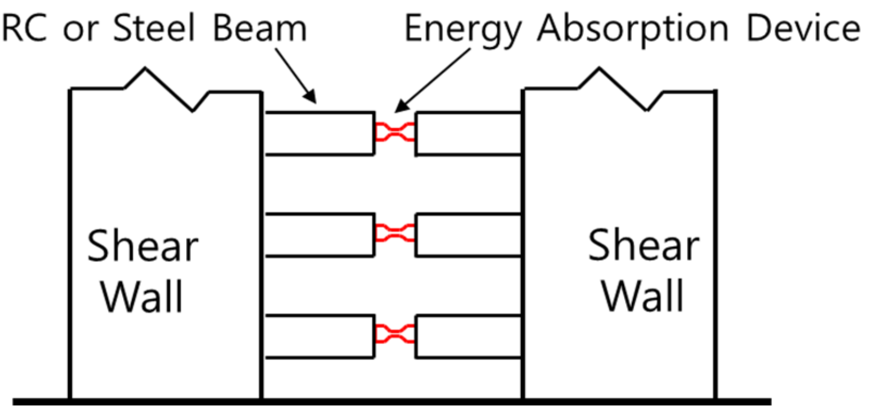


Figure 1. Location of Coupling Beam Proposed in this Study

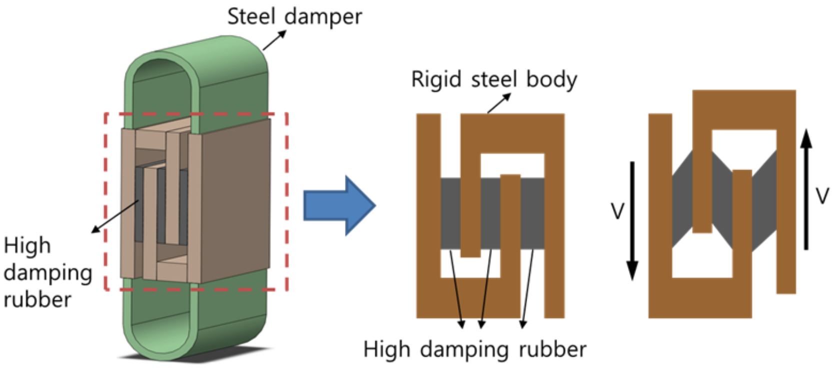


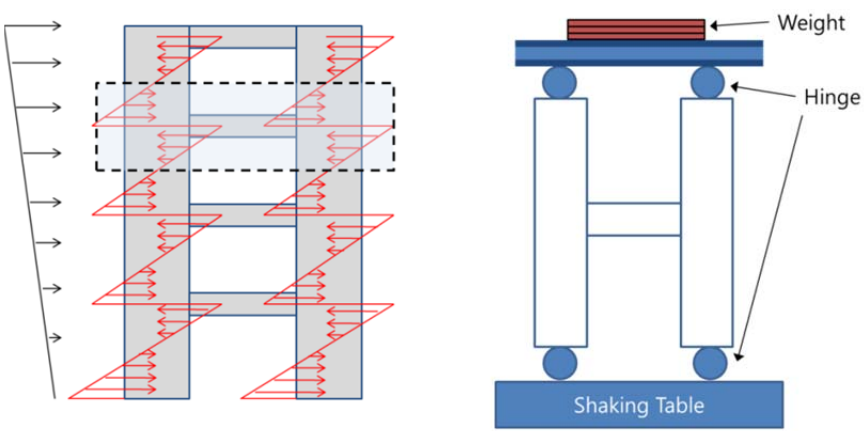
Figure 2. Shape of Hybrid Energy Dissipative Device

3. EXPERIMENTAL VALIDATION OF HYBRID ENERGY DISSIPATIVE DEVICE

3.1. Test specimens

Figure 3 shows the moment distribution of RC shear walls when a lateral load is applied. The maximum moment occurs at the connections with the coupling beam while zero moment is developed at the mid-span of the coupling beam and the mid-height of the shear walls. The specimen for the dynamic tests is based on the moment distribution. Considering the capacity of a shake-table, two RC shear walls with one story-height connected by a coupling beam were used for the test specimen, as shown in Figure 3. The test specimen represents the RC shear wall system encased by dotted lines in Figure 3 (a). Hinges at the top and the bottom of the specimen, as shown in Figure 3 (b), were installed to properly represent the moment distribution of the shear walls coupled by beams and to prevent from developing any unexpected moment.

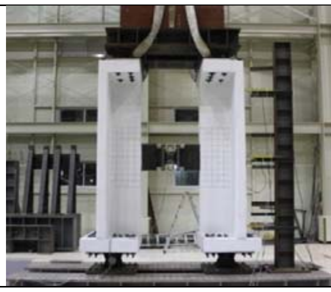
Two different specimens are designed for the shear walls coupled by a conventional RC beam (after therein denoted by ECS) and the shear walls connected by a proposed hybrid energy dissipative device (denoted by HCS). The dimensions of each specimen are shown in Figure 4. Considering the available seismic weight of 70 kN, the capacity of the shake-table and safety during tests, the dimensions of structural members in each specimens were determined. HCS specimen includes additional anchoring steel bars to use energy dissipative device. For the shake-table test, concrete with compressive strength of 24MPa, high-strength reinforcement bar, HD400 with the tensile yield strength of 400 MPa and steel material SS400 with the yielding strength of 240 MPa and the nominal tensile strength of 400 MPa were used. The details on the specimens are summarized in Table 1.

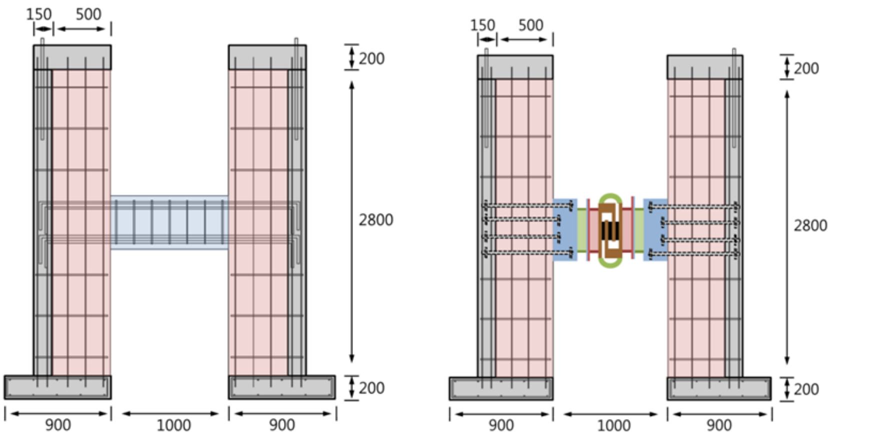


(a) Moment in Shear wall (b) Specimen Shapes

Figure 3. Test Specimen Shapes

Table 1. Test Specimens Chart

Division	Existing Coupling Beam Shear Wall Specimen	Hybrid Coupling Beam Shear Wall Specimen
Specimen Name	ECS	HCS
Test Setting		
Variable	Reinforced Concrete Coupling Beam	Hybrid Coupling Beam
Shear Wall Thickness	200mm	200mm
Remarks	Beam's Section : 450x200	Damper's Yielding Strength : 100kN



Unit : mm

(a) **ECS** (b) **HCS**

Figure 4. Specimen Drawings

The seismic wave with NS element (PGA=817.7gal, duration=42.24sec) of Kobe's earthquake, as shown in Figure 5, was selected as a basic wave-form to be applied to the test specimens. The selected wave-form are scaled in the order of step1, step2, step3 and step 4 for ECS specimen while HCS specimen is applied in the order of step 1, step 2 and step 2.5. Table 2 summarizes scale factors, peak ground acceleration (PGA), energy-equivalent velocity V_E and V_E/V_{EM} of each step. The energy-equivalent velocity can be obtained from:

$$V_E = \sqrt{\frac{2E}{M}} \ , \ \left(E = \frac{MV_E^2}{2}\right) \qquad \text{Equation 1}$$

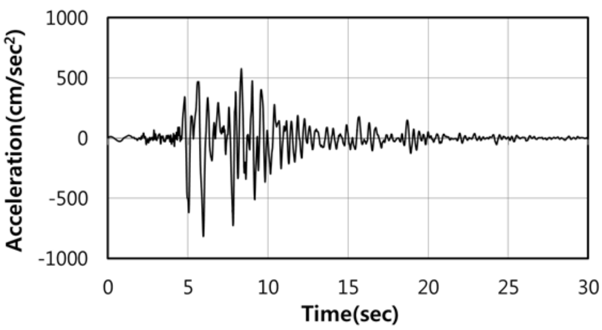


Figure 5. Inputted Earthquake Waves

where M is total mass and E is seismic energy. The symbol of V_{Em} is design energy-equivalent velocity which is usually determined by the maximum energy-equivalent velocity of ground motions considered with safety factors. After a test of each step, the dynamic characteristics of each specimen and structural damages were checked to determine the next vibration application step's scale.

The HCS specimen was tested up to the 2.5 step because the high damping rubber was failure due to bad workmanship. During manufacturing high damping rubber, it was exposed to instantaneously extremely high heat and the quality of rubber itself and the adhesive between rubber and steel plate is questionable.

Table 2. Vibration Application Step Information

Step	Scale facor (%)	PGA(cm/sec^2)	$V_E(cm/s)$		V_E/V_{EM}(%)	
			ECS	HCS	ECS	HCS
1 step	10%	81.7	2.1	9.0	7.6	19.3
2 step	50%	408.9	18.1	40.0	65.0	0.87
2.5 step	70%	571.9	-	81.1	-	136.4
3 step	100%	817	51.9	-	157.8	-
4 step	130%	1063.0	134.0	-	264.1	-

3.2. Test Results

Dynamic Characteristics of Specimens

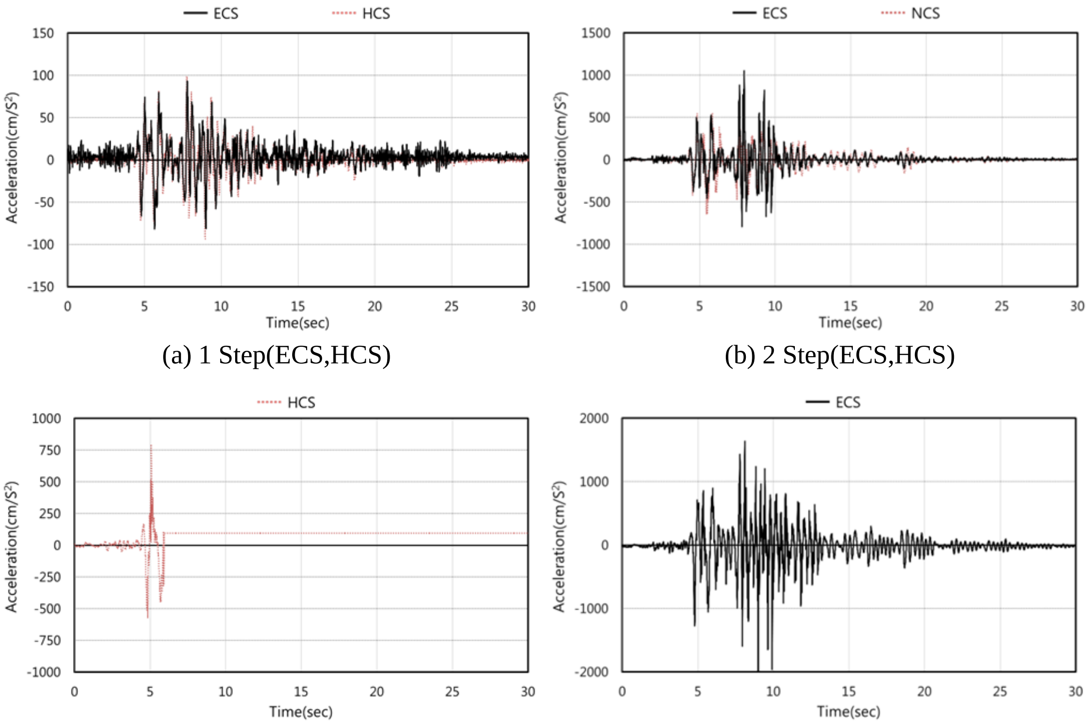
The natural periods, natural frequencies, energy equivalent velocities and design energy equivalent velocity (V_{Em}) are obtained from the shake-table tests summarized in Table 3. The specimen's natural periods are measured before the each step of the test. On the step 1, both of the two specimens are in elastic. It is observed at the test step 1 that the natural periods as well as the values of V_{Em} of both specimens increase. The plastic mechanism of both specimens is activated from input shaking intensity of the test step 1. The elongation of natural periods and increase of V_{Em} are more pronounced with the increase of shaking intensities.

Table 3. Response Characteristic of Specimens

Specimens	Step	Natural Period	Natural Frequency	V_E	V_{EM}	V_E/V_{EM}
ECS	1	0.140	7.275	2.1	27.90	7.6
	2	0.140	7.275	18.1	27.90	65.0
	3	0.162	6.164	51.9	32.92	157.8
	4	0.250	3.999	134.0	50.74	264.1
HCS	1	0.230	4.355	9.0	41.53	19.3
	2	0.230	4.355	40.0	41.53	87.
	2.5	0.293	3.411	81.1	52.31	136.4

Acceleration Response

The maximum response acceleration in each vibration application step presents in Table 4 while Figure 6 displays each time-history acceleration response that was obtained from the acceleration sensor attached to the top of the specimens. From all specimens, the maximum response is increasing as the shaking intensities are increased. In the test step 1, the maximum acceleration of the HCS specimen is larger than that of the ECS specimen. However, in the test step 2, the acceleration response of the HCS specimen is lower than that of the ESC specimen. During the tests, the entered acceleration and the output acceleration have 5~10% difference due to errors of testing machines. Figure 7 shows the relation between the maximum acceleration response and energy-equivalent velocity V_E of both specimens. From both specimens, the maximum acceleration response increases with the increase of V_E. The maximum acceleration and energy-equivalent velocity measured in the HCS specimen is much lower than those of the ECS specimen.



(a) 1 Step(ECS,HCS)

(b) 2 Step(ECS,HCS)

(c) 2.5 Step(HCS)

(d) 3 Step(ECS)

Figure 6. Response Acceleration

Table 4. The Maximum Response Acceleration

Step	ECS		HCS	
	V_E	Acc(cm/s^2)	V_E	Acc(cm/s^2)
1	2.1	89.9	9.0	98.6
2	18.1	1048	40.0	732.3
2.5	-	-	81.1	796.5
3	51.9	1980	-	-
4	134.0	2319	-	-

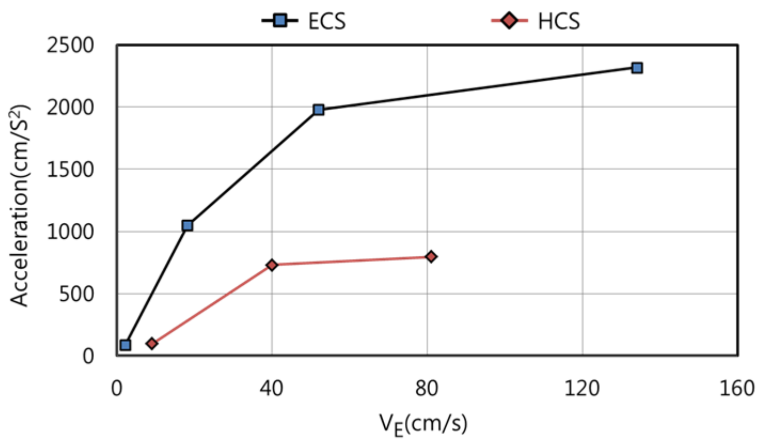
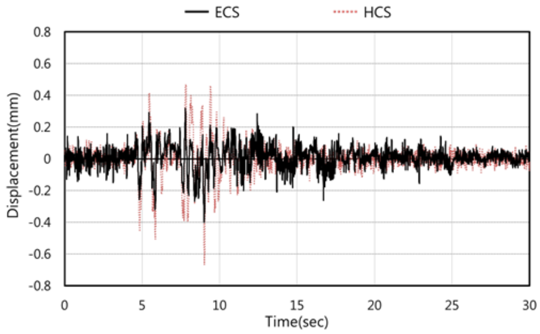


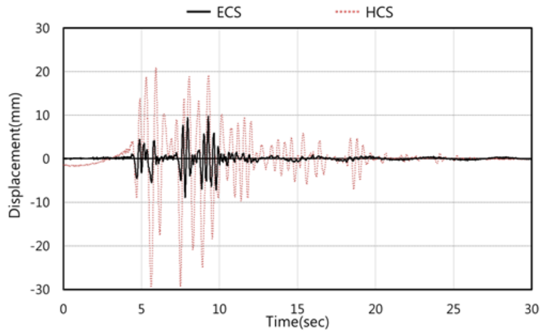
Figure 7. The Relation between acceleration and energy-equivalent velocity

Displacement Response

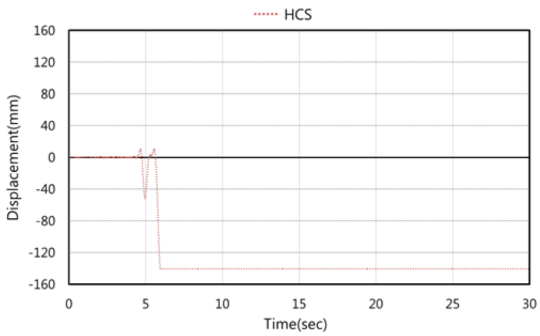
Figure 8 shows the displacement time-history of each step test which is measured by LVDTs installed at the top of the specimen. The measured maximum displacements are summarized in Table 5. The maximum displacements of both specimens are increased with the increase of shaking intensities. The measured displacement of the HCS specimen is much larger than that of the ECS specimen since the lower stiffness of HCS specimen.



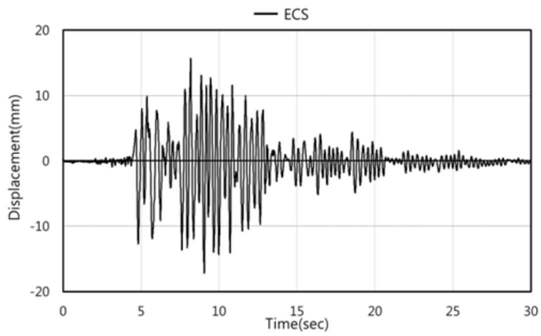
(a) 1 Step(ECS,HCS)



(b) 2 Step(ECS,HCS)



(c) 2.5 Step(HCS)



(d) 3 Step(ECS)

Figure 8. Response displacement

Table 5. The maximum Response Displacement

Step	ECS		HCS	
	V_E	Displacement, mm	V_E	Displacement, mm
1	2.1	0.40	9.0	0.67
2	18.1	9.78	40.0	29.5
2.5	-	-	81.1	-
3	51.9	17.22	-	-
4	134.0	-	-	-

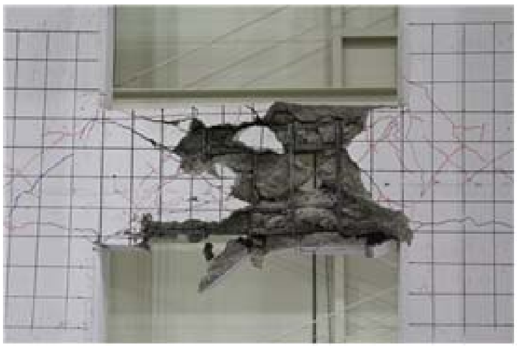
Observation of Structural Damage

During the step 1 test, no structural damage was found on shear walls or coupling beam in the both specimens although very minor cracks were observed in both specimens. After the step 2, several major cracks were found on shear walls and connection area with the coupling beam. The major cracks in the ECS specimen were progressed in the step 3. In the test step 4, shear failure was occurred at the RC coupling beam while the major cracks on the shear walls were more progressed. After the test step 4, the structural damages observed in the ECS specimen are presented in Figure 9.

Figure 10 shows the deformation and structural damages observed in the HSC specimen after the test step 2.5. During the test step 1 and 2, any structural damage is not found on the shear walls and coupling beam with the hybrid energy dissipative dampers. As mentioned before, during the test step 2.5, the attached high damping rubber to the steel plate was fractured and the specimen was, as shown in Figure 10, displaced due to the sudden stiffness reduction. Although the test was stopped, there was not observed structural damages on the shear walls. This means that the proposed hybrid energy dissipating dampers can protect RC shear walls from seismic attack provided that more cautions had been made during the manufacturing process of high damping rubber dampers and the fracture, as shown in Figure 10, can be prevented. In order to validate this assumption, additional shaking table tests will be performed with the hybrid energy dissipated dampers manufactured by strict quality control.

(a) The Whole

(b) Shear Wall and Coupling Beam

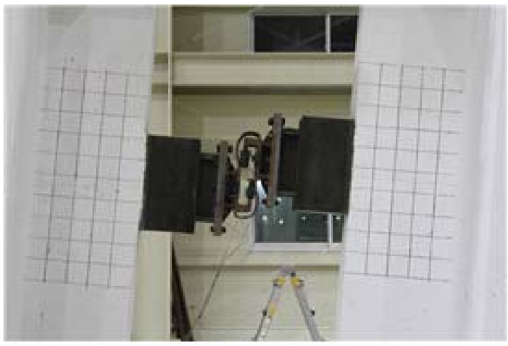


(c) Coupling Beam – Front

(d) Coupling Beam - Back

Figure 9. Damage Status of ECS Specimen

(a) The Whole



(b) Shear Wall and Coupling Beam

(c) Hybrid Damper

(d) Enlarged Damper

Figure 10. Damage Status of HCS Specimen

4. CONCLUSION

This study proposes a hybrid energy dissipative device consisting of two components; high damping rubber damper and U-shaped steel damper to secure a building's elastic stiffness and to increase deformation capacity and energy dissipation, and to prevent structural damages on other structural members such as RC shear walls. A series of the shake-table tests was performed and the results are following;

1) The test results show the reduction in acceleration response due to the introduction of a hybrid energy dissipative device.

2) Even in the relatively lower level of shaking intensity, there are many major cracks observed in the ECS specimen. The coupling beam of ECS specimen was destroyed during the test step 4. In the meanwhile, the test with the HCS specimen was stopped due to the fracture of high damping rubber during the test step 2.5. However, there is no structural damage on the coupling beam and shear walls.

3) It is found that the application of hybrid energy dissipative devices will reduce acceleration response, which would prevent structural damages on RC shear walls. If more careful product quality control is made during manufacturing hybrid energy dissipative devices, dissipated energy and ductility capacity of the system will be increased so that its seismic performance would be improved. This will be validated from shake-table tests in near future.

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