Comparative Study on Seismic Performance of Conventional RC Coupling Beams and Hybrid Energy Dissipative Coupling Beams used for RC Shear Walls

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SUMMARY:
Reinforced concrete coupling beams in a RC shear wall system are an important key structural element in that they provide additional stiffness and strength to cantilever-type RC shear walls. According to current seismic codes, RC coupling beams are required to be properly detailed with significantly complicated reinforcement arrangements in order to achieve stable cyclic response without strength degradation during strong ground motion. Recently, hybrid energy dissipative coupling beams for RC shear wall systems were developed to avoid such complicated details and to increase energy dissipating capacities. This study first discusses the mechanisms of the proposed hybrid energy dissipative coupling beams when subjected to cyclic loading. Experimental investigation is then described on the cyclic behavior of RC shear walls connected by the hybrid energy dissipative coupling beams whose comprise U-shaped steel plates and high damping rubbers. Experiment results show that RC shear walls connected by hybrid energy dissipative coupling beams presents excellent seismic response over conventional coupled RC shear walls. This is due to the controllable stiffness and yield strength of the hybrid energy dissipative coupling beams and consequently, the increased energy dissipating capabilities resulting from the yielding mechanism of U-shaped steel plates and material characteristics of high damping rubber.

Keywords: Reinforced concrete shear wall system, hybrid energy dissipative devices, high damping rubber, coupling beam, U-shaped steel plate

1. INTRODUCTION

Reinforced concrete (RC) shear wall systems are one of effective seismic lateral-force-resisting systems applicable to high-rise structures. RC coupling beams in a shear wall system are an important key structural element in that they provide additional stiffness and strength by the frame action achieved throughout coupling cantilever-type RC shear walls (Paualay and Priestly, 1992). To do this, coupling beams must be designed to provide structural integrity and to maintain the frame actions which are desirable characteristics for effectively resisting lateral forces such as wind and earthquake loads. Furthermore, even during very strong ground motion, stable cyclic response should be required for coupling beams (Harries et al., 2000).

According to current seismic codes such as ACI 318 (2011), significantly complicated reinforcement details are required to achieve such higher structural performance of coupling beams. The complicate reinforcement details in coupling beams are expected to be undesirable in terms of constructionability and ultimately, construction costs. To figure out these problems, this study proposes hybrid energy dissipative devices applicable to coupling beams to avoid such complicated details and to increase energy dissipating capacities. The proposed hybrid energy dissipative device consisting of visco-elastic high damping rubbers and U-shaped steel plates intends to be designed to effectively control structural vibration because of its additional stiffness and energy dissipation capacities.
This study experimentally investigates the cyclic behavior of hybrid dissipative device. Quasi-static tests were carried out to compare cyclic performance between structural wall systems with and without hybrid energy dissipative devices.

2. FORM AND HYSTRESIS OF HYBRID ENERGY DISSIPATIVE DEVICE

Figure 2.1 is a concept drawing of a hybrid damper designed to be installed at the mid-span of a coupling beam connecting shear walls and the deformed shape of the hybrid damper. The hybrid damper consists of a high damping rubber damper and a pair of U-shape steel dampers: the high damping rubber damper is made of two steel casings and high damper rubbers placed in between of the casings. The hybrid damper is designed to allow for accommodating shear deformations when drifts occur between floors of a building. The arrangement of wings of casing 1 and casing 2 alternately makes to deform two pieces of high damping rubber installed in between the wings. Such shape of the high damping rubber damper maximizes the stiffness and the dissipated energy by high damping rubber since, if shear deformations occurs, the same amount of shear deformations simultaneously occurs on the high damping rubber installed between the casings. Therefore, this type of shapes for the high damping rubber damper provides an advantage that the required stiffness and dissipation for damper are satisfied with the change of the number of high damping rubber layers (Suzuki et al., 2005).

For most cases, it is expected that the seismic performance of a structure will increase by sufficient stiffness and energy dissipation provided by high damping rubber dampers developed in this study. However, for the most current seismic and vibration control designs, it is required that the design of vibration control devices shall be operated effectively not only for design earthquakes, but for the maximum level of earthquakes. It may not be feasible to manufacture high damping rubber dampers to dissipate all vibration energy from every vibration source since their sizes may exceed the coupling beam's size. This causes problems in terms of economy and installation feasibilities. In order to address the problems and satisfy the requirements for coupling beams, this study introduces the hybrid energy dissipative devices using parallel connection of U-shaped steel hysteresis dampers with high damping rubbers to deliver additional stiffness and to maximize energy dissipation. The U-shaped steel dampers are welded to the top and the bottom of the high damping rubber damper to enable to accommodate relative displacements occurring in the longitude direction when a RC shear walls are laterally displaced.

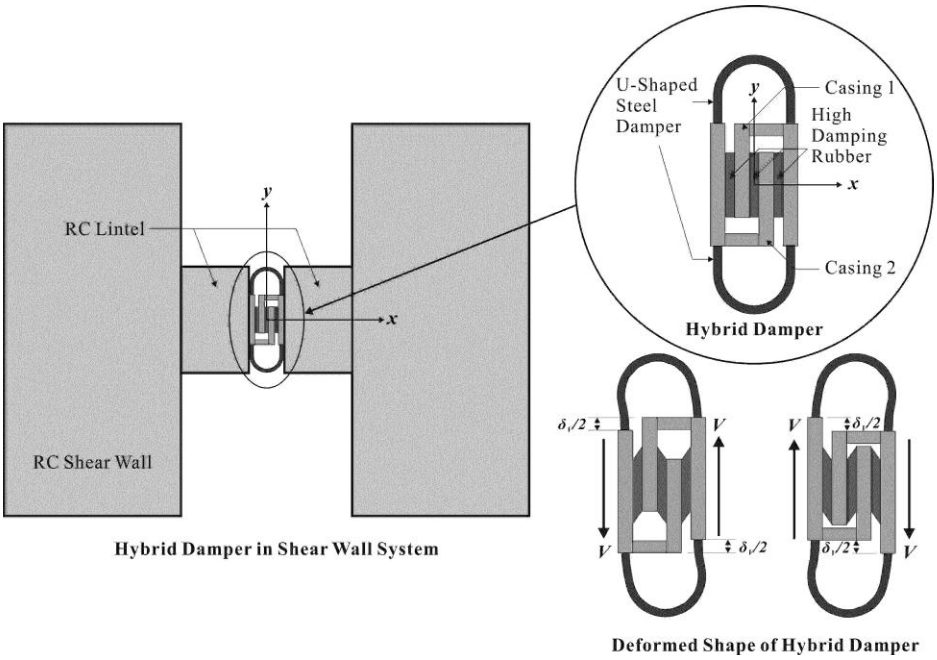


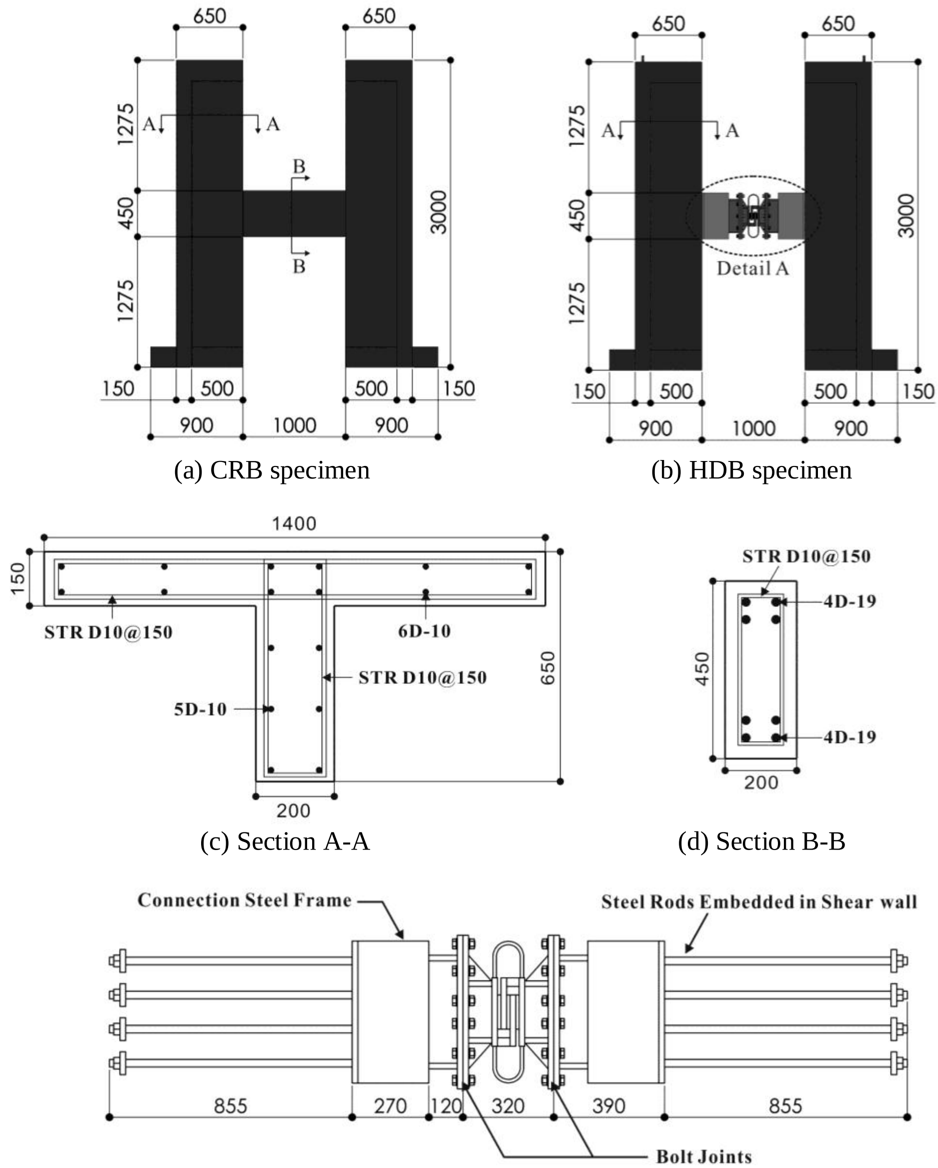
Figure 2.1 Schematic drawing of a hybrid damper embedded into a coupling beam connecting RC shear walls and the deformed shapes of a hybrid damper

The ideal deformation shapes of a hybrid damper are shown in the right bottom of Figure 2.1 when they are subjected to shear force *V*. The left displays the deformed shape when a drift angle is clockwise while the right shows the deformed shape of the damper under anti-clockwise shear forces. If a rotation is clockwise, the gap between casings widens whereas the gap shortens in anti-clockwise rotation. The vertical relative displacement δ_V between the right and the left coupling beams generates the relative displacement $\delta_V/2$ at the top and bottom faces of the casings while each layer's high damping rubber and the U-shaped steel damper have shear deformations in amount of δ_V.

3. QUASI-STATIC EXPERIMENTS

3.1. Specimens for Quasi-Static Tests

For quasi-static tests, total two actual-sized shear wall test specimens were designed and built. Figure 3.1 (a) shows RC shear walls with a conventionally reinforced coupling beam (CRB specimen: a RC shear wall specimen with a Conventional Reinforcement Beam). A HDB (RC shear walls with a Hybrid energy dissipative coupling beam) specimen is shown in Figure 3.1 (b). The RC shear walls of both specimens are the same size and reinforcement arrangements as the HDB specimen. In the HDB specimen, special details are employed in the RC coupling beams for easy replacing hybrid dampers.



(a) CRB specimen (b) HDB specimen

(c) Section A-A (d) Section B-B

(e) Detail A

Figure 3.1 Dimensions and connection details of test specimens

The nominal compressive strength of concrete used for the specimens is 21MPa and the nominal yield strength of reinforcement SD400 is 400Mpa. Figure 3.1 (c) and (d) display the dimensions of the RC shear walls and coupling beams, respectively. Also, the reinforcement arrangement can be found in the figure. For the CRB specimen, the shear strength, flexural yielding moment and ultimate bending moments of the coupling beam are, respectively, 230kN, 138kN□m, and 179kN□m. The shear walls of CRB and HDB specimen have the yielding bending moment, 85kN□m and the maximum bending moment strength, 126kN□m. The special details consisting of several rods and bolts are introduced for the connection between the hybrid damper and the shear wall. This connection is conceived to develop similar stiffness to the conventionally reinforced coupling beam used for the CRB specimen. The hybrid damper is designed to allow for the maximum shear displacement of 30mm which is equivalent to approximately 1.5% story drift angle. It is also designed to prevent the yield of RC shear walls at the same shear force level.

The hybrid damper developed in this study limits the yield of the U-shaped damper against winds. In order to reflect this, the U-shaped steel damper is designed to yield when a drift angle reaches to more than 0.2% of the story height (1/500) which is commonly accepted for the absolute roof drifts of a building. The positions of displacement measuring instrument are shown in Figure 3.2 with the concept drawing of the HDB test specimen. The top and the bottom of the concrete shear wall are connected to supporting hinges while only the bottom is fixed on the floor. The top hinge is connected to the loaded beam while displacements are controlled with the actuator connected to the loaded beam. A series of LVDTs are installed to measure more accurate drift angles during the experiment. Loading history prescribed in AISC (2005) and Darwin and Nmai (1986) for beam-to-column connection tests was used for the tests. The CRB specimen were laterally loaded from 0.375% Drift up to 2% Drift with loading speed of 0.01hz, as shown in the right part of Figure 3.2. Quasi-static tests with the HDB specimen were carried out from 0.2% Drift up to 2% Drift to observe if the yield displacement of the U-shaped steel dampers is observed.

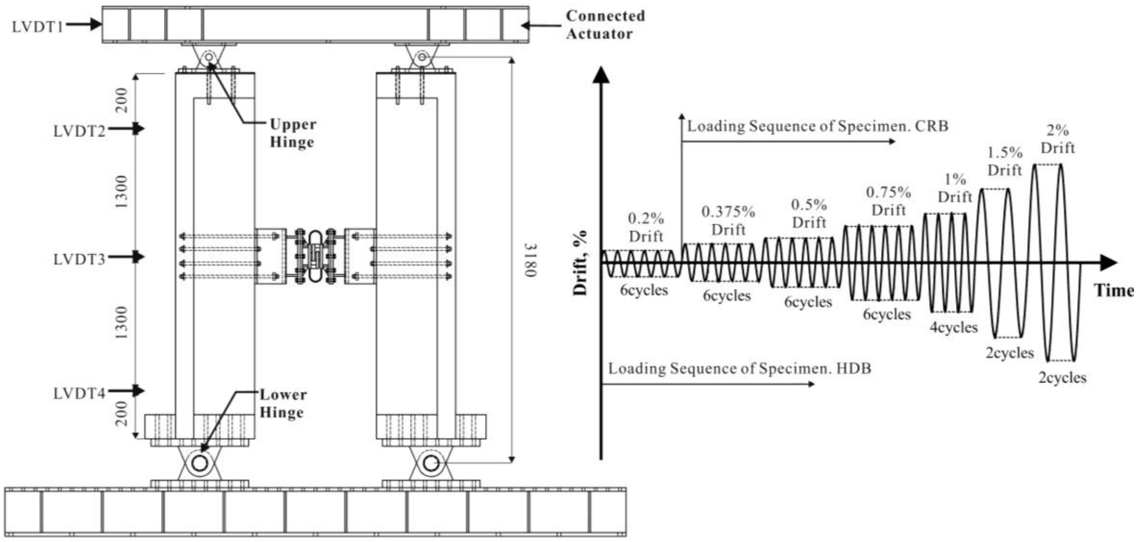
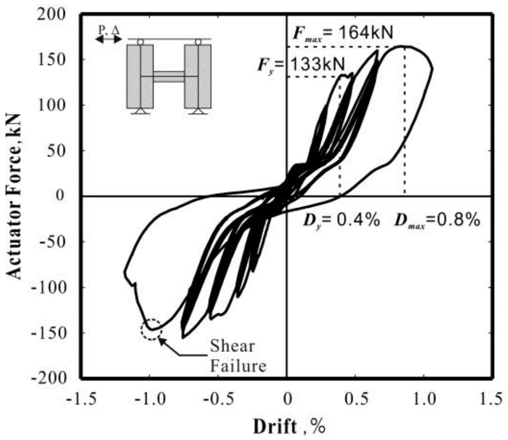


Figure 3.2 Testing setup, instrumentation and loading sequence

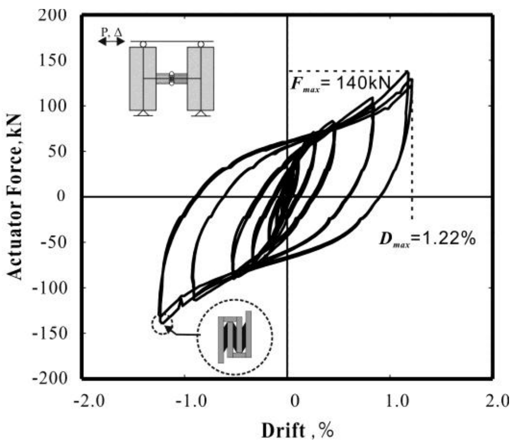
3.2. Experiment Results

As shown in Figure 3.3, the CRB and HDB specimens show major cracks after the quasi-static tests. The maximum load, the maximum drift angle and other results of the experiment are summarized in Table 3.1. In the CRB specimen the cracks were initially observed around the connection region between a RC beam and a shear wall at the drift angle 0.23% soon after the test had been started. The number of cracks propagated from the connection region to the center of the coupled beam with the increase of the applied drift angle. Diagonal shear cracks were observed at the center of the coupling beam at 0.4% of the drift angle and strength degradation was examined at the drift angle of 0.8% soon after the occurrence of major cracks on the shear wall at 0.75% of the drift angle. At the drift angle of 1%, notable falling of cover concrete occurred on the coupling beam and its stirrup was exposed, which resulted in brittle shear failure. Major cracks occurred around the connection of the shear wall at the drift angle of 0.75% propagated to overall shear wall.

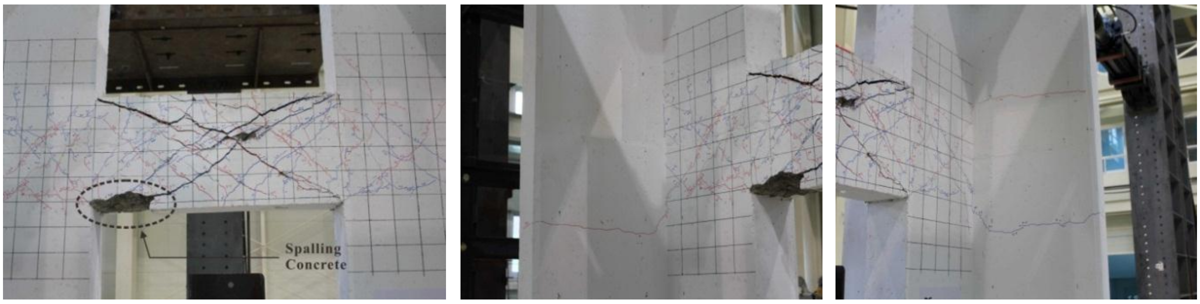
For the HDB specimen, the load – drift angle relation of Figure 3.3 (b) shows a stable hysteresis behavior without considerable structural damages on the structural members except the hybrid energy dissipative devices. Compared to CRB specimen, the HDB specimen developed more ductile behavior with significantly large energy dissipation. Since the proposed hybrid damper has lower yield strength than conventional reinforced concrete coupling beams, the deformations are concentrated on the damper and the load – drift angle relation of the HDB specimen is mainly dependent on the hysteresis of hybrid damper. As shown on the hysteresis curve, it is also noted that the tangent stiffness at the drift angle more than 0.5% increases due to the high damping rubber's hyper-elastic property (Dall'Asta and Ragni, 2006; Fujino et al. 2004). On 0.5% drift angles, the cracks were observed in parallel with the embedded steel bars and propagated to the flange area of the shear wall as the drift angle increases. However, any strength degradation due to these cracks is not found during the test.



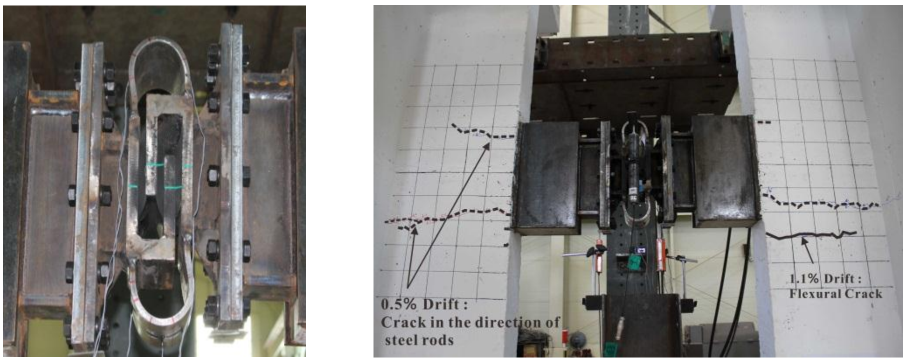
(a) Load – drift angle curve of CRB specimen



(b) Load – drift angle curve of HDB specimen



(c) Crack patterns for CRB specimen



(d) Deformed shape of hybrid damper and crack patterns for HDB specimen

Figure 3.3 Force-displacement results and deformed shapes of test specimens

Table 3.1 Summary of Test Results

Specimen	Yielding Force F_y (kN)	Max. Force F_{max} (kN)	Yielding Drift D_{max} (%)	Max. Drift D_{min} (%)
CRB	130	164.3	0.4	0.8
HDB	-	140	-	1.22

The maximum shear displacement which might occurs at the hybrid damper used in this study is 30mm. Any displacement exceeding the value has a possibility that steel casings attached with high damping rubber directly contacts each other as shown in Figure 3.3 (b). If this happens, stiffness of the damper will increase rapidly to cause abrupt failure of the shear wall system. For this reason, the test with the HDB specimen was terminated.

To assess supplement damping provided by the hybrid energy dissipating device, effective stiffness k_{eff}, equivalent viscous damping ratio ζ_{eq} and dissipation energy amount E_D of the CRB and HDB specimens are compared (Chopra, 2001; Christopoulos and Filiatrault, 2007; Shen et al. 1995). The effective stiffness and equivalent viscous damping ratios are, respectively, calculated from:

$$k_{eff} = \frac{F_{max}-F_{min}}{d_{max}-d_{min}} \tag{4.1}$$

$$\zeta_{eq} = \frac{E_D}{2\pi k_{eff} d_{max}^2} \tag{4.2}$$

where d_{max} represents the measured lateral maximum displacement at the top of the shear wall and E_D is dissipated energy measured by the area encased by the load-drift angle hysteresis curve. Figure 3.4 shows the effective stiffness, the equivalent viscous damping ratio and the dissipation energy amount according to the drift angles of the CRB and HDB specimens. The figures are obtained from average values of k_{eff}, ζ_{eq} and E_D calculated from each cycle except the first and the last cycles.

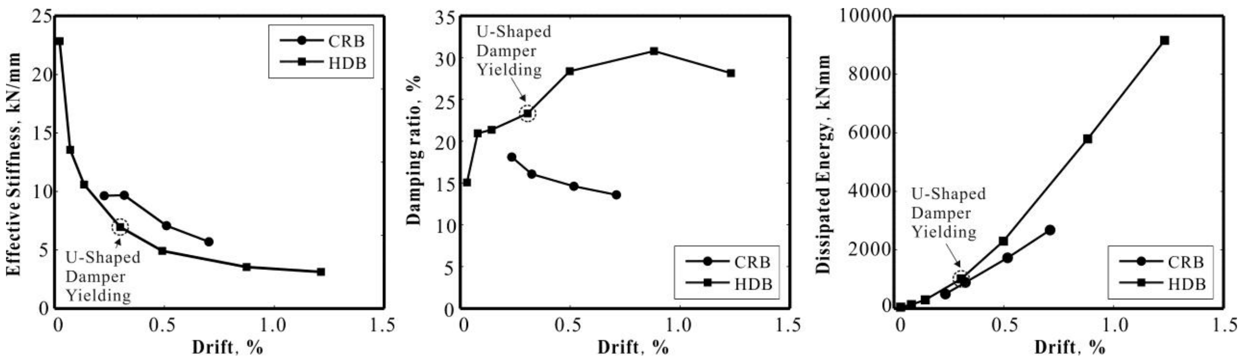


Figure 3.4 Comparison of seismic performance indexes

The effective stiffness of the CRB specimen has been maintained 9.6kN/mm prior to the coupling beam's shear yield, and becomes gradually decreased by the yielding of the coupling beam after the drift angle becomes equal to or larger than 0.325%. After the HDB specimen develops the maximum effective stiffness of 23.2kN/mm at the initial 0.03% drift angle, its effective stiffness decreases with the increase of the drift angles. In overall, 85% reduction in effective stiffness is measured while the reduction rate in effective stiffness of the HDB specimen gradually decreases with the increase of the drift angles. This phenomenon is resulted from the unique property of high damping rubbers being greatly dependent to the strain-amplitude when cyclic loading is applied. In general, while high damping rubbers have the high effective stiffness on the cyclic loading of low shear deformation rate, the effective stiffness reduces gradually as the amplitude becomes larger (Dall'Asta and Ragni 2006). For dissipating energy, both CRB and HDB specimens dissipated approximately 947kN□mm energy, at drift angle less than 0.3% when the U-shaped steel damper initially starts to yield. Especially, at the drift angles lower than 0.3%, the energy has been dissipated by the visco-elastic behavior of the high damping rubber. While the shear walls and coupling beam of HDB specimens are in elastic, the similar amount of energy is dissipated with CRB specimen due to the hybrid damper. On the other hand, at the drift angle larger than 0.3%, the energy dissipation of the HDB specimen increases rapidly due to the yield of the U-shaped steel damper and the specimen dissipates energy of 9161kN□mm at the maximum drift angle of 1.22%. For the CRB specimen, the dissipated energy seems to increase due to the coupling beam's plastic behavior but it does not dissipate more energy because of shear failure of coupling beam.

The equivalent viscous damping ratios also increase with the increase of drift angles of the HDB specimen. Especially, at the drift angles between 0.3% and 0.5% the damping ratios increase a great deal because of the yielding of the U-shaped steel damper. The maximum equivalent viscous damping ratio of the HDR specimen reaches to 31% which is significantly larger than that of the CRB specimen.

4. CONCLUSION

In this study, a hybrid damper consisting of high damping rubber and U-shaped steel dampers is proposed to improve the seismic performance of reinforced concrete shear wall systems. The hybrid energy dissipative device can provide the following improvements on structural seismic performance.

First, the hybrid energy dissipative device can minimize damages of structural elements with inducing and concentrating plastic hinges into the devices. Second, it, even at significantly large drifts, maintains structural integrity resulting from increasing indeterminacy due to retaining frame action. Third, it improves energy dissipation capacity that can reduce oscillation amplitudes of structural systems. Also, the proposed energy dissipating devices helps for constructionability and construction cost since complicated seismic connection details on coupling beams are avoided.

For real applications of the proposed hybrid dampers, more researches on the development of design procedure are required in the future along with more through experimental validation to demonstrate the their dynamic response to actual earthquakes.

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