# Seismic Behavior of High-Rise Concrete Shear-Wall Buildings with Hybrid Coupling Beams

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**SUMMARY:**
The coupling beam plays as the first protection in the reinforced concrete (RC) shear wall system. In order to dissipate more energy, a hybrid coupling beam is developed which consists of a metallic damper in series with the concrete coupling beam. The strength of the metallic damper is carefully selected so that the RC part of the coupling beam remains elastic, while all plasticity goes into the metallic damper. This mechanism protects the RC part from seismic damage. And the metallic damper can be quickly replaced once it is damaged. This significantly enhances the reparability of entire structure, making it possible to be immediately functional after earthquakes. One hybrid coupling beam and one traditional RC beam are experimentally examined. The seismic dissipation of the hybrid beam is approximately twice of the traditional beam. Finally, a high-rise building is designed. Preliminary analysis demonstrates the seismic performance is improved by 15%.

*Keywords: High-rise buildings, Hybrid coupling beam, Metallic dissipater*

## 1. INTRODUCTION

High rise buildings constructed with concrete shear wall systems are very popular in China because of their excellent seismic performance supplied by its dual seismic defense mechanism, i.e., the coupling beam and the shear walls (Cao, 2004). Coupling beams are commonly to be damaged first during an earthquake corresponding to the fortification level. The entire structural system becomes more flexible and the shear-bending deformation mode becomes to be bending-dominated deformation mode, thus preventing more seismic energy going into the superstructure.

As the major energy dissipation component, the coupling beam is expected to be ductile. This, however, is sometimes proved difficult, even followed the current seismic design code (MHURD, 2010). One reason is the length-to-height ratio of the coupling beam is commonly small to meet the architecture requirement. The other is the strengthening of steel rebar which results in the shear cracks throughout the coupling beam, lowering its energy dissipation capacity, and more important, making it very difficult to be repaired. To improve the ductility of the traditional RC coupling beam, a hybrid wall system was developed in the first decades of the $21^{st}$ century. Steel coupling beam is used instead of the RC beam, which is able to dissipate more energy (El-Tawil et al, 2002; Canbolat et al, 2005; Park et al, 2005, 2006). To improve the reparability, energy dissipation devices are incorporated with the steel beam (Shahrooz, 2001), which can be replaced after major earthquakes.

To this end, in order to improve the seismic performance of RC coupling beams, a hybrid coupling beam system was developed. It combines a metallic energy dissipater and the concrete coupling beam in series. The stiffness and the resistance of the concrete coupling beam are both slightly higher than the metallic dissipater, so that most deformation and energy were concentrated to the dissipater to protect the concrete portion. In this paper, a traditional RC coupling beam was designed following the Chinese seismic design code. Then a metallic dissipater was designed according to the strength and stiffness of the coupling beam and inserted at the mid-span. Both traditional and hybrid coupling beams were tested experimentally, demonstrating that the energy dissipation capacity of the hybrid beam was 1.3 to 2.2 times that of the traditional coupling beam, and cracks on the hybrid coupling beam were well controlled. Finally, a high-rise RC shear wall building with 50 stories is designed. The deformation is bending-domiated, so that the top 20 stories are installed with the metallic damper in the selected coupling beams. Preliminary analysis demonstrates that the displacement response of the structure is well controlled and the seismic performance is improved by 15-20%.

## 2. DESIGN OF TRADITIONAL RC COUPLING BEAMS

A thirty-four story RC shear wall building was designed following the typical Chinese seismic design procedure. The seismic fortification intensity is VIII, and the site type is II. Typical wall thickness is 200 mm. The natural period of the designed structure is 2.34 sec. Total mass is about 24,000 ton. One coupling beam with the length of 1.2 m and the height of 0.4 m is taken for the experiment. Four longitudinal HRB335 rebars are put into the coupling beam symmetrically. The diameters are all 20 mm. HPB300 steel was used for the stirrups with the diameter of 10 mm and the distance between stirrups is 100 mm throughout the coupling beam. Two steel meshes are set in each shear wall. The diameter of horizontally distributed steel rebars is 8 mm with the distance of 200 mm, while the diameter of vertical steels is 10 mm with the distance of 200 mm. The grades of all distributed steel rebars are HPB300. Note that there is a boundary constraint element in each piece of shear wall, which is directly connected to the coupling beam. The function of the boundary constraint element is to prevent compressive local failure. Six longitudinal rebars of HRB335 with diameter of 14 mm are put along the wall, similar as a column. HPB300 stirrups with diameter of 8 mm and distance of 100 mm are used in the boundary constraint region.

An assembly including two coupling beams and two boundary constraint elements of shear walls at both sides was constructed. The two coupling beams respectively represent the beam at two consecutive stories. The slab effect is not considered in this study. At the external side of each boundary constraint element, the connecting zone is designed to connect the specimen to the loading frame. In this study, the specimen is loaded horizontally. Therefore, the coupling beams are turned 90 degrees, as shown in Fig.2.1 (a). They are treated as the traditional RC coupling beams.

## 3. DESIGN OF HYBRID COUPLING BEAMS

The hybrid coupling beams have similar geometry as the traditional coupling beams. The only difference is that the coupling beam is broken at the mid-span, and a metallic damper is installed. The configuration of the metallic damper is shown as Fig.3.1 (a), similar as the ADAS devices used by Latour et al. (Latour et al, 2012). It constitutes of embedded plates, clampers, constraint plates, dissipaters, post-tension bolts and connecting bolts. It is an assembling modular damper. The number of dissipaters can be freely selected based on the demanded force. The dissipater is machined as Fig.3.1 (b). When being deformed, plasticity would be developed throughout the whole triangular plate, thus maximizing the energy dissipating capacity.

Fig.3.2 (a) shows the real damper to be inserted in the specimen. Before installation, the anchor rebars shall be welded perpendicularly to the embedded plates, as shown in Fig.3.2 (b). The anchor length shall be long enough to resist shear force and moment that would be generated by the damper. Then the damper is put into concrete framework, as shown in Fig.3.2 (c). The anchor rebars shall be securely connected to the longitudinal rebars of the coupling beam. Finally, the concrete is casted.

## 4. EXPERIMENTAL SCHEME

The two specimens are loaded using a frame as shown in Fig.4.1. The specimen is connected to the foundation beam and the loading beam by bolts. A four-link mechanism is employed to avoid rotation.

The actuator with one end securely pinned to the strong reaction wall and the other to the loading beam is used to load the specimen horizontally. An L-shaped loading beam is used to enforce the loading axis pass through the mid-span of the coupling beams, so that the coupling beams are loaded in a pure-shear mode. The specimens after set up under the loading frame are shown in Fig.4.2 (a) and (b), respectively.

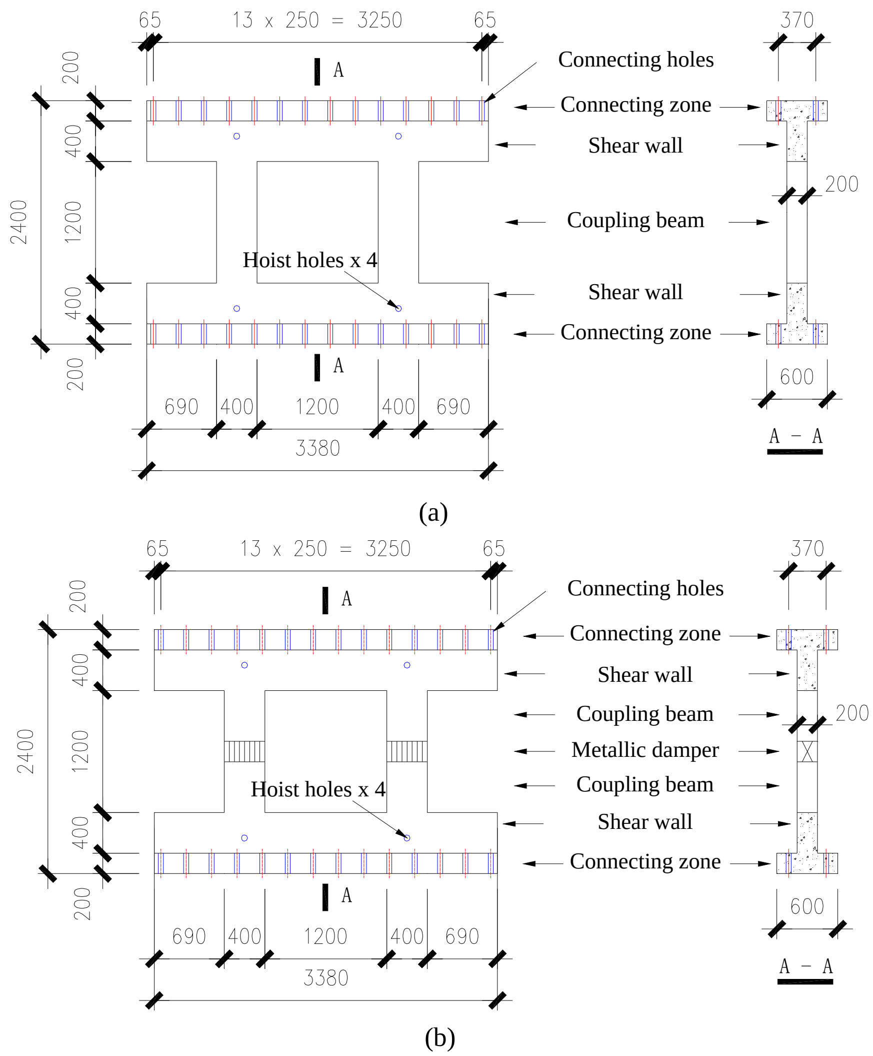



**Figure 2.1** Specimens: (a) Traditional coupling beam; (b) Hybrid coupling beam

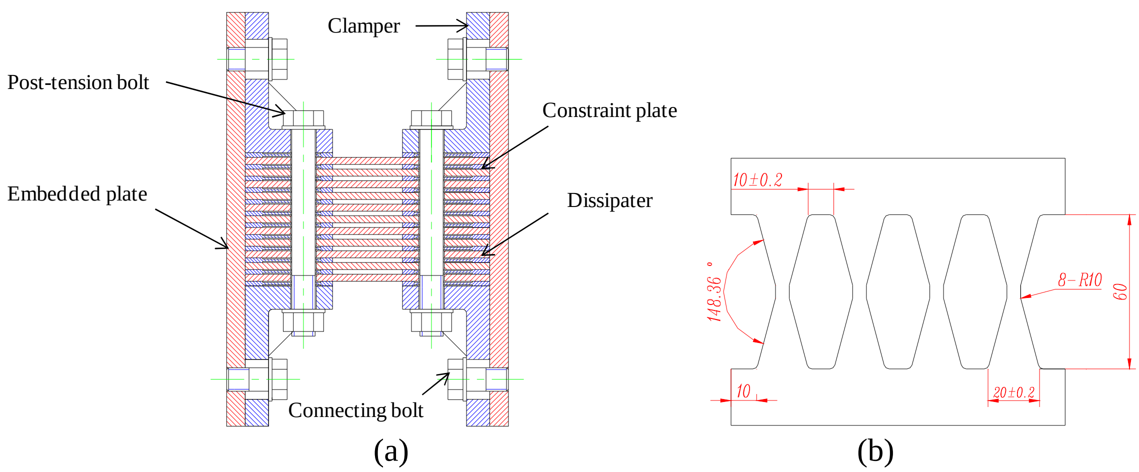


**Figure 3.1** Metallic damper: (a) Assembling modular damper; (b) Configuration of dissipater

(a) (b) (c)

**Figure 3.2** Installation: (a) Sample damper; (b) Anchor rebars; (c) Installation in the framework

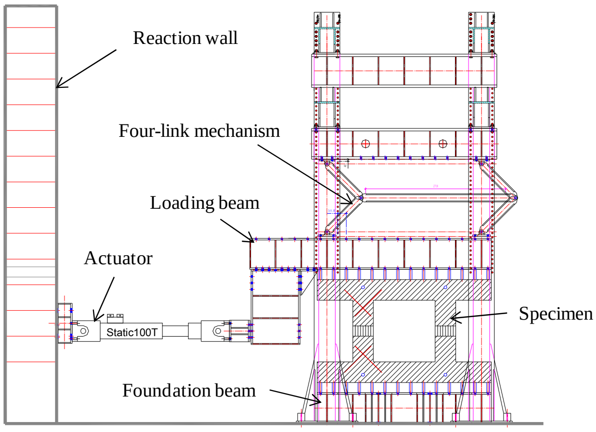


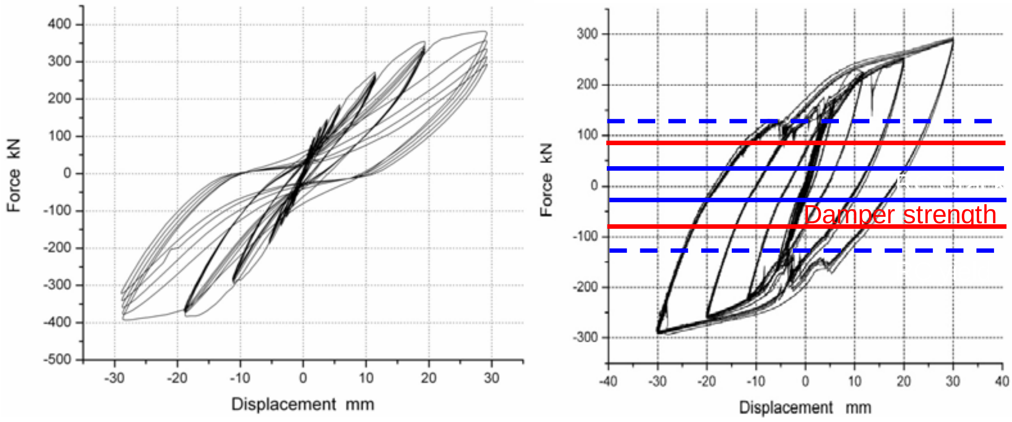

**Figure 4.1** Loading frame

(a) (b)

**Figure 4.2** Specimens under loading frame: (a) Traditional RC coupling beam; (b) Hybrid coupling beam

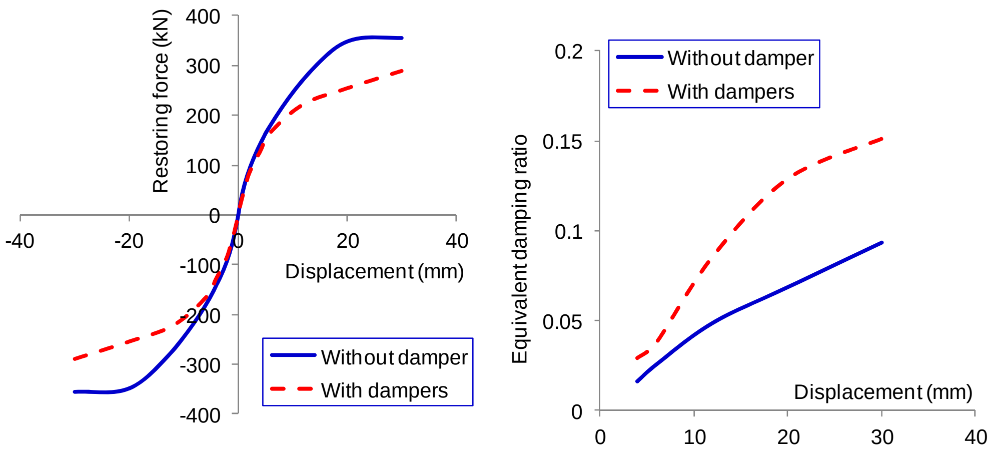
## 5. EXPERIMENTAL RESULTS

A quasi-static cyclic test was conducted for each specimen. To compare their behaviour, the same loading pattern was used. The hysteretic curves are shown in Fig.5.1 (a) and (b) respectively for the traditional RC coupling beam and the hybrid coupling beam, respectively. Obviously, the hysteretic curve of the hybrid coupling beam is fatter than the traditional one, implying a higher energy dissipating capacity. Significant pinching effect was observed on the traditional specimen. From Fig.5.2 (a), the strength of the hybrid coupling beam is lower than the traditional one because the strength of the metallic damper is relatively smaller than the traditional coupling beam. The strength is thus controlled by the metallic damper. However, for the hybrid coupling beam, the equivalent damping ratio, an index to indicate the energy dissipating capacity, is 1.3 to 2.2 times of that of the traditional one. More important, the damage of the hybrid specimen was well controlled. Only one bending crack was observed at the end of each half coupling beam, as shown inFig.5.3 (b), while the damage of the traditional coupling beam distributed along the whole beam.



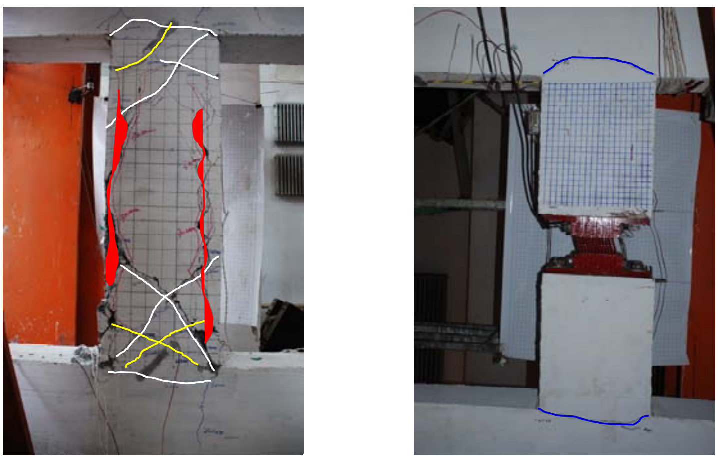

(a) (b)

**Figure 5.1** Hysteretic curves: (a) Traditional RC coupling beam; (b) Hybrid coupling beam




(a) (b)

**Figure 5.2** Behavior comparison: (a) Skeleton curves; (b) Equivalent damping ratios



(a) (b)

**Figure 5.3** Damage distribution: (a) Traditional RC coupling beam; (b) Hybrid coupling beam

## 6. APPLICATION EXAMPLE

A 50-story RC shear wall building is designed using the proposed hybrid coupling beams. It is located in an area with the seismic intensity of VII, and the PGA of the design basis earthquake is 0.1g, with the exceedance probability of 10% in 50 years. Fig.6.1 shows the typical plan view of the building. Considering the deformation mode is bending dominated, implying a larger story drift can be observed in the top stories, the metallic dampers are installed in the top 20 stories. The distribution of dampers is shown in Fig.6.1. Three types of metallic dampers are used, each of which with different stiffness and yielding forces. To examine the seismic performance of the building, finite element models were built using PKPM, a design software used in China, ETABS, a finite element software developed by University of California at Berkeley, and a general-purposed finite element program, ABAQUS. Only those results from ABAQUS are discussed in this paper. In this model, the dampers are modelled by a link element with a bilinear kinematic hardening model. The shear wall system is modelled by shell elements using the damage plasticity model for concrete simulation. The vibration modes are first examined between models using different software. The first ten vibration modes are listed in Table 6.2, and the first vibration period is about 2.7 s.

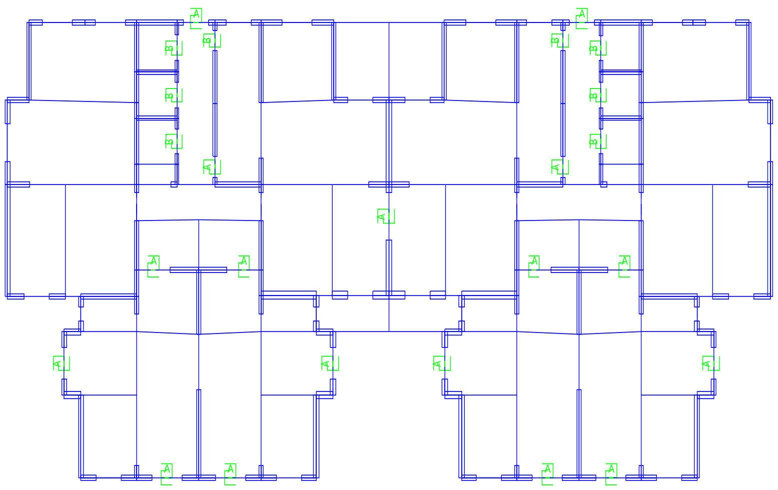


**Figure 6.1** Standard plan view and damper distribution

**Table 6.1** Parameters of employed dampers

| Type | Stiffness (kN/mm) | Yielding force (kN) | Post-yielding stiffness (kN/mm) |
|---|---|---|---|
| A | 400 | 300 | 4 |
| B | 80 | 60 | 0.8 |
| C | 560 | 420 | 5.6 |

**Table 6.2** Parameters of employed dampers: Units (s)

| Mode | PKPM Model | ETABS Model | ABAQUS Model |
|---|---|---|---|
| 1 | 2.854 | 2.666 | 2.711 |
| 2 | 2.372 | 1.918 | 1.877 |
| 3 | 1.759 | 1.383 | 1.216 |
| 4 | 0.769 | 0.635 | 0.648 |
| 5 | 0.706 | 0.603 | 0.607 |
| 6 | 0.567 | 0.457 | 0.428 |
| 7 | 0.419 | 0.323 | 0.311 |
| 8 | 0.340 | 0.301 | 0.302 |
| 9 | 0.300 | 0.248 | 0.264 |
| 10 | 0.285 | 0.219 | 0.241 |

Time history analysis then conducted using El-Centro ground motion. Following the typical design procedure of China, a ground motion with the exceedance probability of 2% in 50 years was used to examined the structural performance when sustaining a rare earthquake. The PGA of the ground motion is scaled to 0.4 g. The maximum story drifts are shown in Fig.6.2 and 6.3 for the longitudinal and lateral directions, respectively. In the longitudinal direction, the maximum story drift is 1/381 for the building with hybrid coupling beams. Compared with the original model with the maximum story drift of 1/312, the displacement response is reduced by 18%. In the lateral direction, the maximum story drift is 1/304 for the building with hybrid coupling beams. Compared with the original model with the maximum story drift of 1/256, the displacement response is reduced by 15%. The hysteretic curve of a typical damper is given in Fig.6.4.

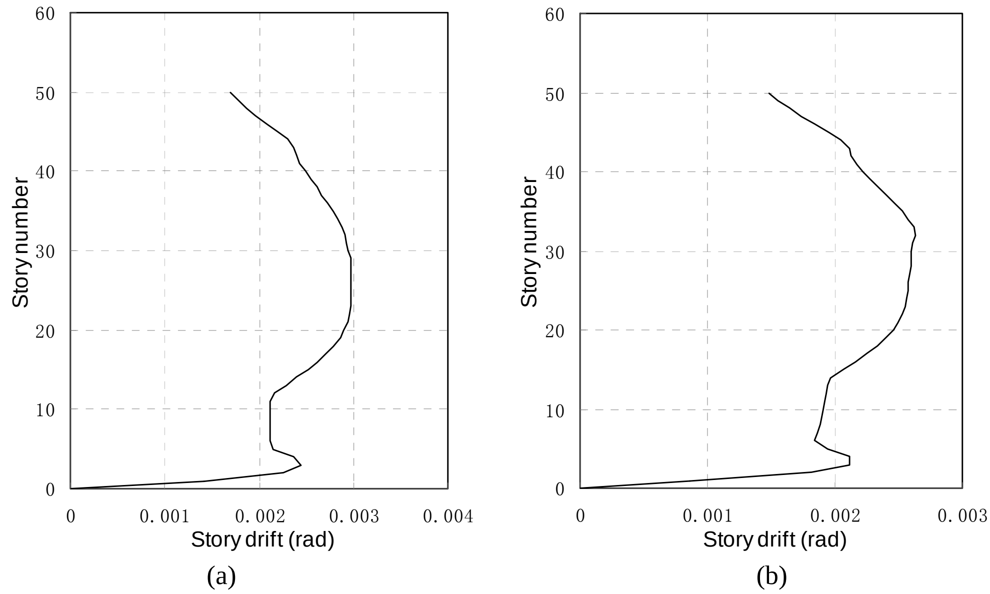



**Figure 6.2** Maximum responses in longitudinal direction: (a) Original structure; (b) Structure with hybrid beams

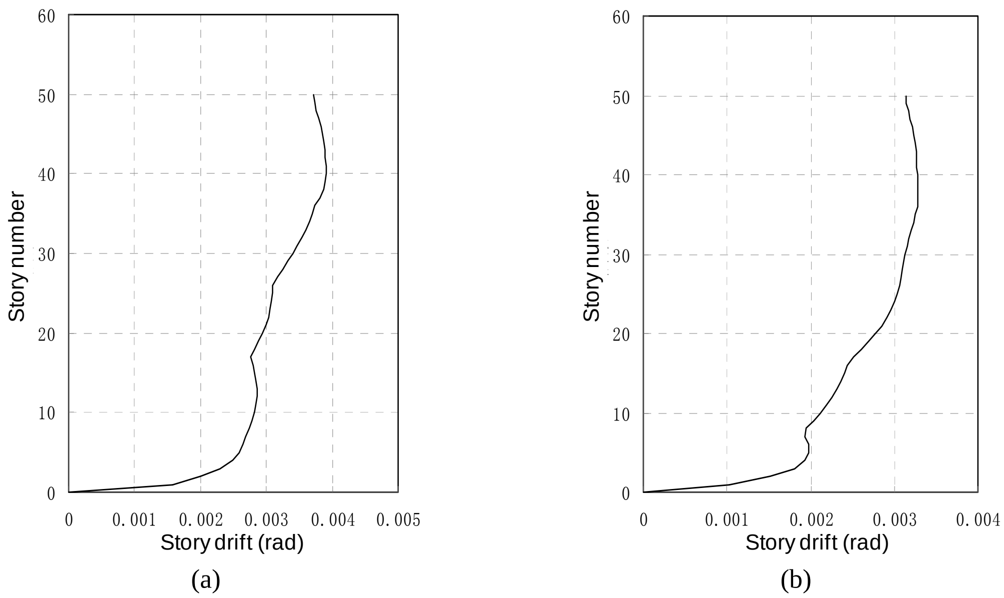



**Figure 6.3** Maximum responses in lateral direction: (a) Original structure; (b) Structure with hybrid beams

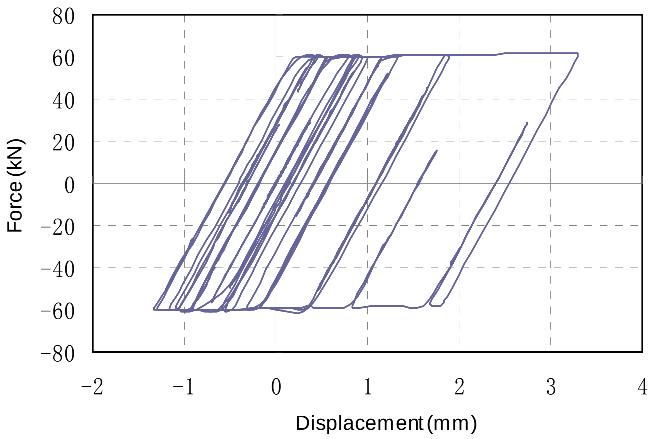



**Figure 6.4** Hysteretic curve of a typical damper

## 7. CONCLUSIONS

The proposed hybrid coupling beam was experimentally explored and compared with the traditional RC coupling beam. A lower strength was assigned to the hybrid beam by carefully selecting the design strength of the metallic damper. The installation of the metallic damper is constructively easy. Experimental demonstration indicates that the proposed hybrid coupling beam is more efficient in dissipating seismic energy. The RC part of the hybrid beam is well protected by concentrating the damage on the metallic damper. The metallic damper is installed by bolts on the embedded steel plates, thus being easily replaced. These features render the shear wall structure higher seismic performance, particularly for those buildings requiring immediate occupancy after an earthquake. A preliminary design and analysis of a high-rise building employing the proposed hybrid coupling beam demonstrate the effectiveness of the idea. However, the quantification of the design strength and stiffness of the damper, the effect of RC slab, and the distribution of the damper need further study.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