Performance test of steel damper and its application in seismic mitigation of bridges

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ABSTRACT: The applications of E-shaped and X-shaped steel dampers in seismic mitigation of bridges are introduced in this paper. Seismic performance tests were firstly conducted to investigate the energy-dissipation behaviours of these dampers. Then the proper constitutive model of steel dampers is developed and discussed based on the test results. Furthermore, two practice applications of these dampers in seismic mitigation of small to medium-span or long-span bridges are introduced. It is concluded that (1) both the E-shaped and X-shaped steel dampers exhibit powerful energy-dissipation capacities through cyclic plastic deformations; (2) the steel dampers with proper design parameters are proved to be quite efficient in seismic control of bridges, especially for those where restrained connections between superstructures and substructures are required for service-level loadings, while flexible and high damping connections are desired during earthquake event; (3) The economic steel dampers provide a concise and stable solution for seismic retrofit of bridges.

1 INTRODUCTION

Currently fluid viscous dampers and yielding steel dampers are widely used in seismic mitigation of bridges (Feng 2009; Infanti 2004). The fluid viscous damper is velocity-dependent, and its damping force is largely dominated by the movement velocity. The damping force of the viscous damper is not prone to be developed under service-level loadings, such as thermal movement. While during an earthquake, the viscous dampers will result in considerable damping forces which provide effective restraints or bridge superstructures. The viscous dampers have been applied in large numbers of long-span cable stayed or suspension bridges, to control the longitudinal girder displacements, especially in earthquake event. However, the viscous damper is weak in providing the recentering stiffness for the whole bridge structure, which may lead to the significant permanent deformation of bridges (Guan 2009; Ye 2007). Different from a viscous damper, a yielding steel damper is displacement-dependent, dissipating earthquake energy through the yielding of steels. Besides, a yielding steel damper can provide lateral restraint for the bridges through its initial elastic stiffness, which is quite important and beneficial in service-level conditions. After the steel damper yields, the post-yielding stiffness or strain-hardening effect of the damper can also help enhance the self-centering capacities of the whole structure (Li 2016; Xiang 2016). Compared with a fluid viscous damper, a yielding steel damper is simple and cost-effective, which will be widely used as a viable alternative for seismic protection of bridges.

In this paper, two types of yielding steel dampers are introduced and tested for their hysteretic properties, and then proper constitutive models are discussed. Finally, practice applications of these dampers in bridges are presented.

2 STEEL DAMPER CONFIGURATION AND HYSTERESIS TESTS

2.1 E-shaped steel damper

An E-shaped damper is cut from a thick mild steel plate, as shown in Figure 1. It is optimized in shape so that plasticization is almost uniformly distributed over the volume, while the localization and deformation concentration are prevented. When the middle leg and outer legs are individually hinge-connected to different elements and undergo relative displacements, it would be forced to deform unsymmetrically. Since the legs are designed to be elastic, the energy dissipation occurs only in the transverse beams which are subjected to nearly constant flexural moments. Both the flexural moments and the axial forces have opposite directions in the two parts of the beam, and this will neutralize the effect of geometry changes. The geometry changes for increasing numbers of cycles would cause the strain hardening or softening behaviour, and/or asymmetry of the hysteretic curves.

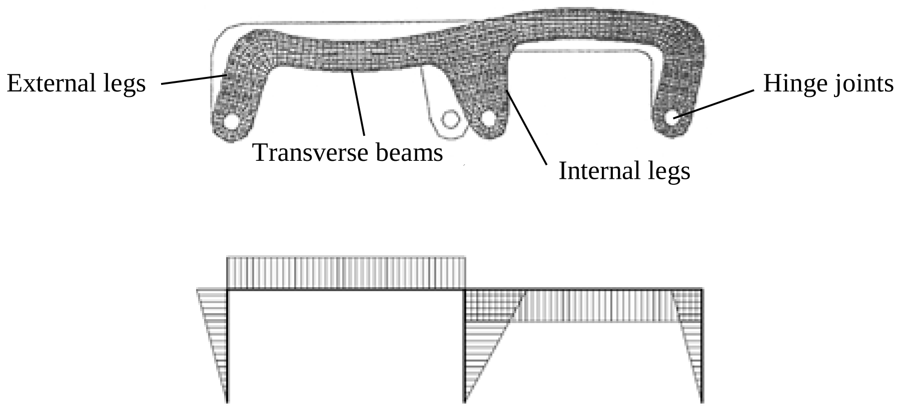


Figure 1. E-shaped steel damper and moment diagram

The E-shaped steel dampers are either used individually or in company with some other devices, etc. sliding steel bearings, as shown in Figure 2. This type of bearing is named of Energy Dissipation Bearing (EDB). A EDB provides lateral resistance during an earthquake as well as gravity loads support. The E-shaped steel dampers can also be united into a damper group which is usually installed between the superstructure and the substructure, as shown in Figure 3.

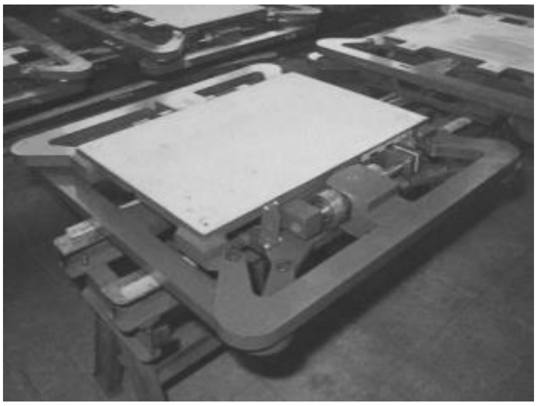


Figure 2. Energy Dissipation Bearing (EDB)

Figure 3. E-shaped steel damper group

To investigate the hysteretic behaviours of EDB and E-shaped damper group, both these two types of devices were tested at Tongji University. The loading system is pseudo-dynamic, with a maximum horizontal loading capacity of 2000 kN and a displacement excursion of 500 mm. The imposed force is measured by dynamometer which is placed on the jack head of the actuator, and the displacement of dampers is measured by displacement transducers. The loading protocols are cyclic, with a series of increasing-amplitude cycles. The tested force-displacement hysteretic curves of these two dampers are plotted in Figure 4 and Figure 5, respectively. Seen from the hysteretic curves, the EDB and E-shaped damper group appear quite stable till failure, and exhibited powerful energy dissipation. It can also be seen that there are slightly softening segments in the hysteretic curves of damper group when the force reaches nearly to zero. This may be due to the gap or buffer material at the hinge joints.

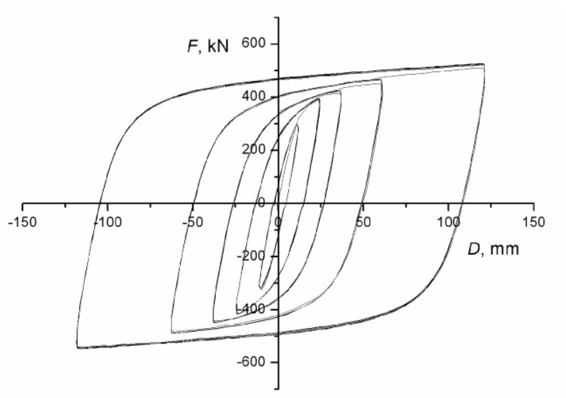


Figure 4. Hysteric curves of EDB

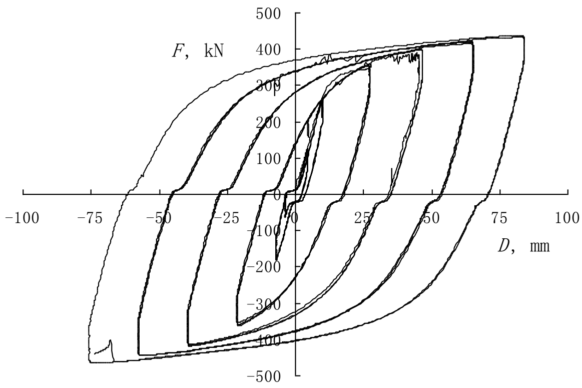


Figure 5. Hysteretic curves of damper group

2.2 **X-shaped steel damper**

The X-shaped steel dampers are also cut from thick mild steel plates and united in parallel as a group with common fixed endings (Fig. 6). In the past decades, the X-shaped steel dampers have been widely used in building structures as energy dissipation devices. Many studies have also been done, showing that a X-shaped steel damper is stable, of high damping, and insensitive to the environmental condition, and requires low maintenance (Kelly 1972; Whittaker 1991; Raúl 2004).

Figure 6. X-shaped steel damper

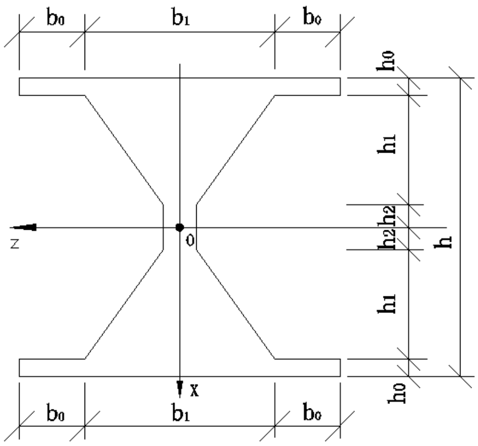
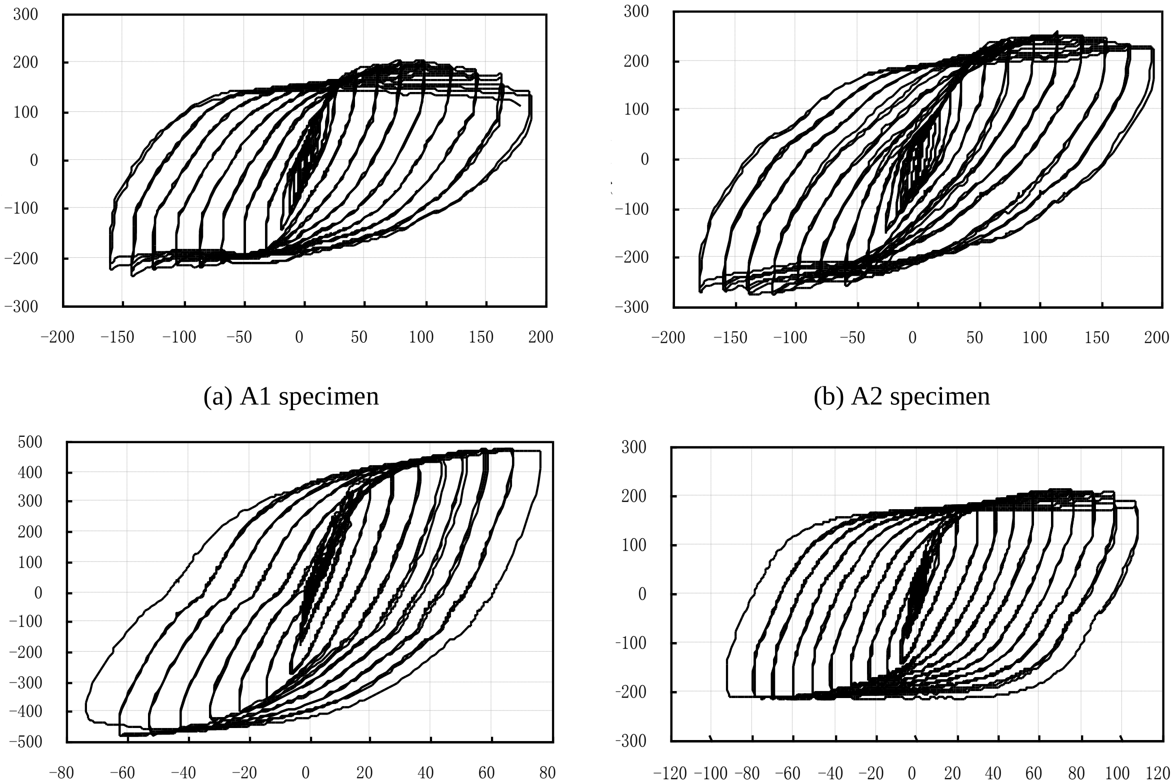


Figure 7. Dimension of X-shaped steel plate

Table 1. Summary of the tested specimen dimension details.

Specimen	h_1 (mm)	h_2 (mm)	t (mm)	Number of steel plates
A1	300	60	300	30
A2	300	60	300	30
B1	150	30	240	30
B2	150	30	240	20

In this study, four sets of X-shaped dampers were tested in the laboratory. The design details of the tested damper specimens are shown in Figure 7 and Table 1. Test results of the specimens are shown in Figure 8. It can be seen that the stable and good energy dissipation capacities are displayed, which is quite consistent with the previous studies. Moreover, test results also indicate that a higher and thinner specimen will always leads to a larger ultimate displacement, but smaller initial stiffness and yield strength. A desired or expected design parameters of the X-shaped steel damper can be easily achieved by adjusting the plate number and dimensions.



(a) A1 specimen (b) A2 specimen

(c) B1 specimen (d) B2 specimen

Figure 8. Force-displacement hysteretic curves of tested X-shaped steel damper specimens

2.3 Constitutive model

A bilinear hysteretic model is usually adopted to simulate the mild steel dampers (Manuel 2006). However, in most commercial FEM software, such as SAP2000 and Midas etc., the Wen model is adopted instead because it has a rapid and stable convergence in nonlinear analysis (Wen 1976).

The force-displacement relationship of the Wen model can be described as follows:

$$F = r \cdot k \cdot d + (1-r)\, F_y \cdot z \tag{1}$$

where F = lateral force; F_y = yield strength; k = initial stiffness; r = ratio of post-yield stiffness to initial stiffness; d = relative displacement; and z = internal hysteresis variable. This variable has a range of $|z| \leqslant 1$, with the yield surface represented by $|z| = 1$. The initial value of z is zero, and it evolves according to the differential equation:

$$\dot{z} = \frac{k}{F_y} \begin{cases} \dot{d}(1-|z|^{\xi}) & \text{if } \dot{d} \cdot z > 0 \\ \dot{d} & \text{otherwise} \end{cases} \tag{2}$$

According to the test results, parameters for the Wen model were obtained by regression analysis, as shown in Table 2. It can be seen that the ratio r and the exponent ξ can take constant values, 0.025 and 1.5, respectively.

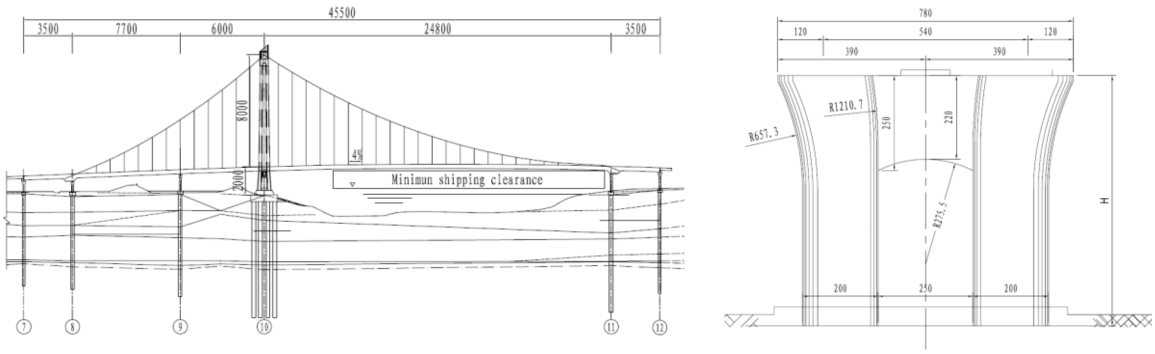
Table 2. Summary of parameters in Wen model.

Specimen	Initial Stiffness ***k*** **(kN/mm)**	**Ratio *r***	**Yield Strength** F_y **(kN)**	**Exponent**
EDB	35.5	0.025	400	1.5
E-shaped damper group	35.5	0.025	400	1.5
A1	12.0	0.025	150	1.5
A2	16.0	0.025	200	1.5
B1	48.0	0.025	360	1.5
B2	16.0	0.025	160	1.5

3 PRACTICE APPLICATIONS IN BRIDGES

3.1 EDBs used in the Nanjing Jia River Bridge

The EDBs have been used in seismic mitigation of a long-span bridge, the Nanjing Jia River Bridge, in both longitudinal and transverse directions. The Nanjing Jia River Bridge is a self-anchored suspension bridge with a single tower and an asymmetric span arrangement, as shown in Figure 9a. Two parallel girders connected by tie beams are located at the two sides of the tower. Steel girders are adopted for the main span and concrete girders for the secondary spans to balance the dead loads due to the asymmetric span arrangement. Two separate frame piers are adopted for both the auxiliary piers and the transition piers, as shown in Figure 9b. Cast-in-place piles, 60 to 80m long, 2.0 to 2.5m in diameter, are used for all piers and tower foundations.



(a) Elevation (b) Frame pier

Figure 9. Elevation of the Nanjing Jia River Bridge (unit: cm)

Figure 10 shows the detail arrangement of the EDBs. It can be seen that the EDBs are applied in seismic control both in longitudinal and transverse directions. In the longitudinal direction, two EDBs with a yielding strength of 2000 kN are adopted at the tower location. Compared with the fixed tower-girder connection, the base shear force of the tower is reduced to 29.3%, while compared with the floating tower-girder connection the longitudinal girder displacement is reduced to 19.2%. Therefore, it offers an optimum balance between displacement demands and inner-force reactions. Moreover, a static analysis show that the maximum lateral shear force on each EDB under functional loads such as wind, temperature and vehicle braking forces, is no more than 993 kN; therefore fixed connection can be provided between the main girder and the tower in service conditions and consequently unexpected vibration in the longitudinal direction can be prevented.

In the transverse direction, EDBs with different yield strength are designated according to parameter analysis and the key responses are listed in Table 3. For comparison, the key seismic demands with conventional fixed girder-pier connections in the transverse are also analysed and the results are listed in Table 4. It can be seen that the shear forces of the bearings in the fixed connecting system are too large to design for since the frame piers with such a low ratio of shear span to section height (1.3-2.9) can hardly present any ductile behaviour. Besides, the moments at the base of the piers, the maximum axial force and bending moment of the most critical pile at each pier location decrease by up to 75%, 63% and 59%, respectively. Similarly, the EDBs will remain in elastic state under service conditions, presenting essential constraint connections in the transverse direction and avoid any unexpected vibrations.

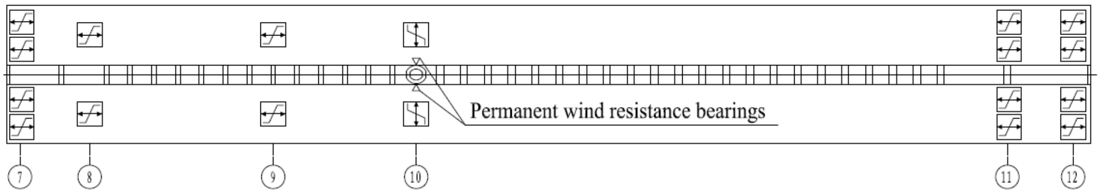


Figure 10. Arrangement of EDBs in the bridge

Table 3. Key responses of the proposed scheme in the transverse direction.

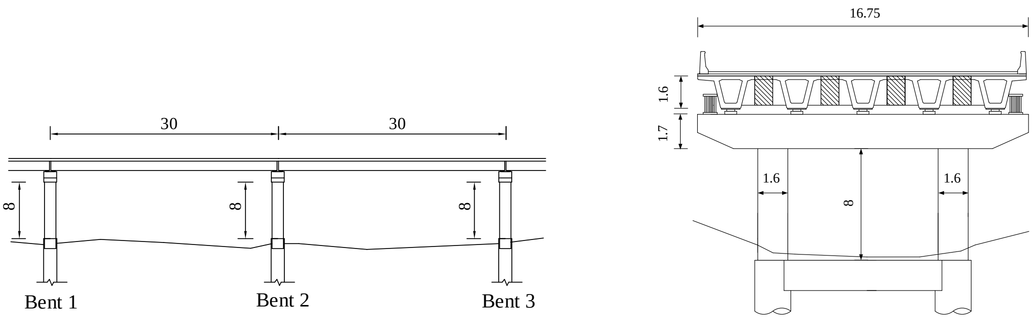
Key Responses	7#	8#	9#	10#	11#	12#
Yield strength of a single EDB (kN)	400	800	800	-	800	800
Shear force of a EDB under service conditions (kN)	267	439	698	-	520	426
Lateral deformation of a EDB under earthquake (mm)	91	74	47	-	84	100
Moment at the base of piers under earthquake (kN.m)	9300	2723	5042	-	7659	11877
Maximum seismic axial force of the pile (kN)	7575	5126	7016	24241	7219	8147
Maximum seismic moment of the pile (kN.m)	7473	4262	3447	20068	7263	6871

Table 4. Key responses of conventional fixed connecting scheme in the transverse direction.

Key Responses	7#	8#	9#	10#	11#	12#
Shear force of bearings (kN)	10664	14517	7696	18468	11868	6282
Bending moment at the base of piers (kN.m)	20581	27564	23427	772988	36015	16226
Axial force of pile under dead loads (kN)	4434	5553	8509	22344	16271	5551
Maximum seismic axial force of the pile (kN)	16730	38050	26060	21559	19740	11500
Maximum seismic moment of the pile (kN.m)	17090	20390	10180	18674	22770	8145
Shear force of bearings (kN)	10664	14517	7696	18468	11868	6282

3.2 X-shaped steel dampers used in Rongjiang Bridge

X-shaped steel dampers have been applied in Rongjiang Bridge as transverse unseating-prevention devices, just in place of conventional concrete shear keys. The Rongjiang Bridge is a multi-span simply supported bridge with continuous slab. The bridge superstructure consists of five 1.6m-height precast box girders which are supported by double-column concrete bents through several laminated-rubber bearings. The bents have an equal height of 8.0m and a column diameter of 1.6m. The laminated-rubber bearing has a plan dimension of 600mm in diameter and a height of 130mm. There are in total ten bearings installed in each bent. The foundations of the bridge are shaft foundations with a diameter of Figures 11a-b plot the elevation and cross-section view of the bridge.



(a) Elevation (b) Cross-section

Figure 11. Configurations of Rongjiang Bridge (unit: m)

The X-shaped steel dampers were installed between the superstructure and the substructure in the transverse direction. The sum of the yield strength of steel dampers in each bent was designed as 10% of the dead load vertical reaction at the bent. The yield displacement and the post-yield stiffness ratio were set as around 0.02m and 10%, respectively. Table 5 lists the design parameters of steel dampers at each bent.

Table 5. Design parameters of X-shaped steel dampers at each bent.

Design Parameters	Yield Strength (kN)	Yield Displacement (m)	Initial Stiffness (kN/m)	Post-Yield Stiffness Ratio (%)
Steel damper	450	0.02	22500	10

The bridge model was subjected to two levels of earthquake excitation, which correspond to a 75-year recurrence and a 2000-year recurrence earthquakes at the bridge site. The ground motions were input into the bridge model only in the transverse direction. Two restraint cases were considered in this study:

Case 1: The superstructure is transversely restrained by concrete shear keys, and fix constraints are assumed between the superstructure and the substructure in transverse direction in the analysis model.

Case 2: The bridge prototype is just as same as the bridge in Case 1 except that the concrete shear keys are replaced by X-shaped steel dampers.

Table 6. Comparison of responses for different restraint cases.

Seismic Responses	75-year recurrence			2000-year recurrence		
	Case 1	Case 2	(C1-C2)/C1	Case 1	Case 2	(C1-C2)/C1
Bent axial force (kN)	1836	1665	9.3%	8612	5726	33.5%
Bent shear force (kN)	429	414	3.5%	1887	1402	25.7%
Bent moment (kN.m)	7253	6316	12.9%	32282	22000	31.9%
Foundation axial force (kN)	3557	3015	15.2%	15862	10253	35.4%
Foundation shear force (kN)	106	124	-17.0%	404	442	-9.4%
Foundation moment (kN.m)	2630	2229	15.2%	11722	7587	35.3%
Bent displacement (m)	0.133	0.091	31.6%	0.594	0.347	41.6%

Table 6 lists the comparison of seismic responses of the bridge for Case 1 and Case 2. It can be seen from the table that the seismic demands of the bridge can be greatly mitigated when concrete shear keys are replaced by the X-shaped steel dampers, especially during large earthquakes. For instance, compared with the case with conventional concrete shear keys, the moment of the bent reduces 12.9% and 31.9% for 75-year recurrence and 2000-year recurrence earthquakes respectively, for the case with X-shaped steel dampers. The reduction ratios of foundation moment are 15.2% and 35.3% for the two earthquake levels. The installation of X-shaped steel dampers also decreases the bent displacement by 31.6% and 41.6%. The yielding of X-shaped steel dampers during an earthquake will effectively limit the build-up of the inertial forces of the superstructure, protecting the substructures from severe damages. Besides, the hysteretic deformations of the steel dampers can also dissipate substantial earthquake energy, which will decrease the seismic demands of the bridge.

4 CONCLUSIONS

Two types of yielding steel dampers were introduced and tested in this study. Based on the test results, proper constitutive model was then proposed and calibrated. Tests proved that both these two steel dampers displayed stable and powerful energy dissipation capacities.

Two practice applications of the yielding steel dampers were introduced. One is the application of EDBs in the Nanjing Jia River Bridge, a long-span self-anchored suspension bridge, to mitigate the seismic demands both in longitudinal and transverse direction. Another is the application of X-shaped steel dampers in Rongjiang Bridge, a medium-span simply supported girder bridge, to reduce the transverse seismic response of the structure. Analysis results showed that both these two bridges with yielding steel dampers performed well during earthquake events. The biggest advantage of yielding steel dampers is that they can provide stable lateral restraints for the bridge structure to prevent unexpected vibration in service conditions, as well as powerful energy dissipation in an earthquake event.

5 ACKNOWLEDGEMENTS

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