Study on the seismic performance of X-added damping and stiffness energy dissipation device

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SUMMARY:
A X-added damping and stiffness energy dissipation device(X-damper) is designed with the soft steel. In order to study performance parameters and energy dissipation capacity of the X-dampers, the performance experiment of the design X-damper models are conducted under low cyclic and reciprocal loading. The test results show that: (1) hysteretic curve of the X-damper is stable and repeatable, the X-damper has good seismic energy dissipation capabilities. (2) The X-shaped plate can yield almost entirely along their length in shear deformation due to the appropriate design. Based on the test results, with the use of PERFORM 3D software, the models of the structure with and without X-dampers are built, and nonlinear time history analysis under frequently and rarely occurred earthquake are conducted. The analysis results show that: (1) the X-damper can yield ahead to dissipate energy under strong earthquake action, the member plastic damage of the structure with X-dampers can be reduced. (2) The X-dampers is more efficient to protect the member in main structure under strong earthquake.

Keywords: added damping and stiffness (ADAS) energy dissipation device   energy dissipation hysteretic performance seismic response plastic deformation

1. INSTRUCTIONS

The research and development of passive energy dissipation control technique against wind and earthquake excitation have achieved significant progress over the last several decades. Various kinds of energy dissipation devices have been studied by scholars at home and abroad. A number of these devices have been installed in new construction as well as seismic retrofit projects for the energy dissipation under earthquake or strong wind action (Soong T T, Dargush. G F,1997, Pall A.S and Marsh C ,1981, Cherry S and Filiatrault A ,1993, Skinner R.I, Kelly J.M and Heine A.J.,1975, Tsai K.C ,1993, Tyler R.G ,1978, Robinson W.H and Greenbank L.R,1976, Li H.N and Li G ,2006, Zhou Y,2006a, b,c,d). Added damping and stiffness (ADAS) energy dissipation device has been developed by Whittaker etc (Whittaker, A S.,Bertero,V.V and Thomposon C L, etal,1989), it is consisted of X-shaped steel plates and connection plates. These X-shaped steel plates were designed to work primarily in double curvature, which makes their layout more efficient as these elements yield almost entirely along their length. The ADAS damper is an assemblage of several sheet X-shaped steel plates that is designed for installation in a building frame such that the relative story drift causes the top connecting steel plate of the damper to move horizontally relative to the bottom connecting steel plate. By yielding a large volume of steel, the ADAS damper can dissipate substantial energy under earthquake or strong wind. Khe-Chyuan Tsai et al carried out the triangular-shaped steel plate energy absorbers (TPEA).The comparative experimental study of the TPEA was conducted, and the force model of the TPEA and design method of structure with the TPEAs was given (Tsai K.C,1993). Based on the research results of the ADAS damper, the H-ADAS damper was investigated by Ching Shyan Chen et al. A number of projects study results shown that the use of the H-ADAS damper is one of the feasible ways to dissipate the earthquake energy and to control the seismic response of structure (Xing S.T, Guo X ,2003, Li D.W ,2005, LI S.Y ,2005, Xu C.E ,2008, Wang Y Y,Chen Q X,Xue Y T ,2004).

The objective of this research was to study the hysteretic performance of X-damper with made in soft steel. The performance experiment of the design model of the X-damper is conducted under low cyclic and reciprocal loading. Based on the test results, the performance parameters and energy dissipation capacity of the damper are investigated. With the use of PERFORM 3D software, the structure with and without X-dampers structure are built, and nonlinear time history analysis under frequently and rarely occurred earthquake are conducted to study the control effect of the X-damper.

2. PERFORMANCE TEST

2.1 Damper design

The X-dampers were made of soft steel with nominal yield strength fy=160Mpa, tensile strength fu=250 Mpa. The corresponding measured values are illustrated in **Table.1**. The average values of yield strength and tensile strength are 173.3 Mpa and 253.3 Mpa, respectively. The specifications of Dampers for Vibration Energy Dissipation of Buildings required that fy/fu be equal to or less than 0.8 and that elongation rate be equal to or more than 60%, both these criteria were mat.

The damper is consisted of 15 sheet X-shaped steel plates and two sheet connection plates. The outline dimension of the X-damper is 1350×180×220mm, as shown in **Figure.1**. The X-shaped plates were flame cut form single plate elements using numerically controlled equipment. The X-shaped edge is ground to achieve a smooth finish with no visible notching. The dimensions of the X-shaped edge is 180×150mm, and the width of the mid-location is 30mm, as shown in **Figure.1**. The design X-damper photo is shown in **Figure.2**. Based on the material test results and the correlative equation, the performance parameters of the X- damper can be drawn: yield force Fy=18.3t, elastic stiffness K_1=14820.99t/m, yield displacement △y=1.3mm.

Table.1 Parameters of the soft steel

No	Yield strength (MPa)	Tensile strength (MPa)	Yield ratio	Elongation rate (%)	Elastic modulus(GPa)
1	175	255	0.686	65.5	211
2	165	245	0.673	66.0	
3	180	260	0.692	62.0	
Average	173.3	253.3	0.684	64.5	

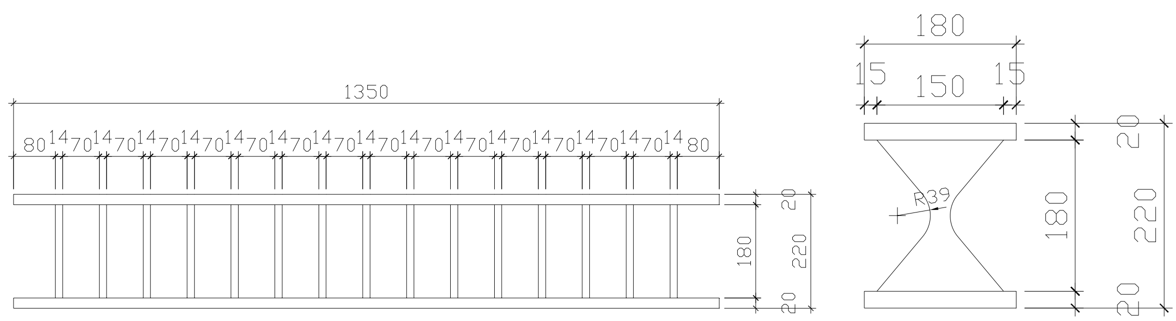


Figure.1 Construction of the X-ADAS

Figure.2 Photo of the X-ADAS

2.2 Test setup and loading program

The test setup adopted the electro-hydraulic servo loading system that comprised a self-balanced reaction frames and a hydraulic actuator, as shown in **Figure.3**. The test specimens were loaded via 1000kN actuator with in-line load cell. The hydraulic actuator had a displacement capacity of ±600mm, horizontal maximum speed capacity of 1500mm/s and working frequency of 0.001Hz～5Hz. The control displacement via a linear variable displacement transducer mounted on the actuator. The actual displacement of the specimen in test process is measured by off-site displacement transducer of the capacity of ±150mm.

The two specimens were subjected to a loading program consisting of increasing amplitude elastic and post yield cycles of displacement based on the specifications of Dampers for Vibration Energy Dissipation of Buildings, The damper loading program for the two specimens were given in **Table.2**.

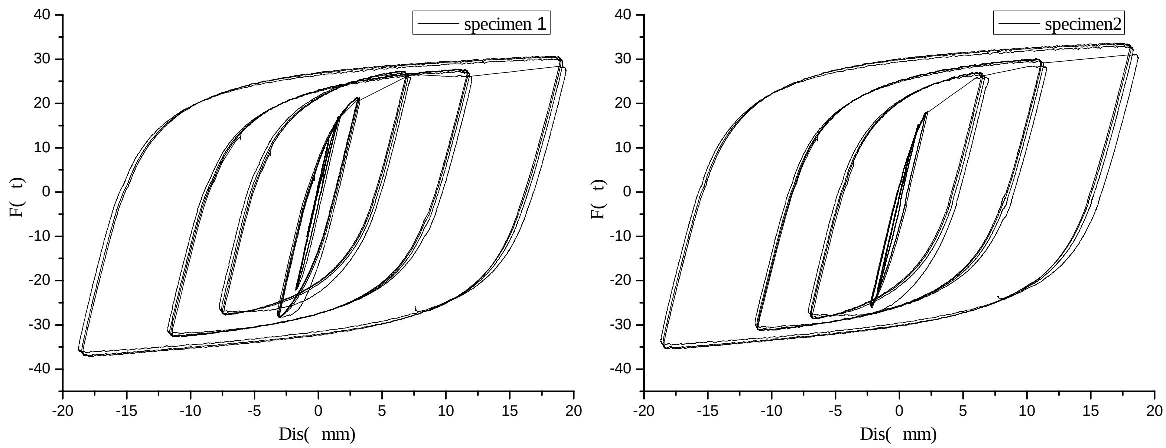
Figure.3 The test setup

Table.2 Loading program

NO	Control displacement/mm	frequency /Hz	Cyclic number
1	±0.84	0.04	
2	±1.6	0.02	
3	±3.08	0.015	4
4	±7.22	0.01	
5	±11.63	0.007	
6	±18.72	0.005	

2.3 Test results

Figure.4 presents the measured damping force-displacement hysteretic curves for two specimens. Specimens behaved in a very similar manner, with stable and repeatable hysteretic response and steadily increasing resistance over the entire test process. No visible damage could be observed until completion of the tests, except that the paint in the X-shaped plate surface crack on large deformation case, however the weld joint location no crack. The test photo of large deformation of the damper was shown in **Figure.5**. It is evident that the X-shaped plate can yield almost entirely along their length, and the strength of weld joint can meet the design requirement.



(a)Specimen 1 (b) Specimen 2

Figure.4 Hysteretic curve

Figure.5 Test photo

Based on the obtained experimental curves, the maximum and minimum damping force were obtained on the different displacement, which is plotted in **Figure.6.** The yield displacement, yield force and plastic stiffness can be obtained by the Fig.6 and the correlative equations, the results are shown in table.3.

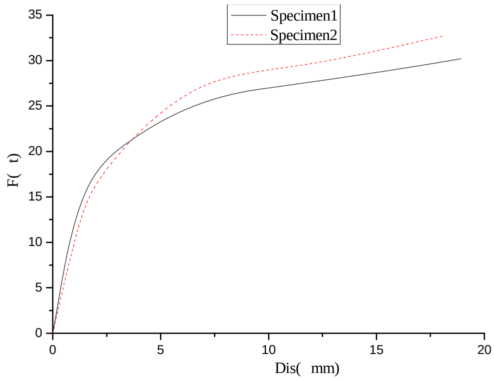


Figure.6 Skeleton curves

Table.3 Analysis results

No	Elastic stiffness (kN/mm)	Yield force (kN)	Yield displacement (mm)	Plastic stiffness (kN/mm)
Specimen 1	126.1	181.5	1.44	3.23
Specimen 2	122.74	176.8	1.44	3.78
Average	124.4	179.2	1.44	3.51
Error (%)	-14	-0.5	+9.7	—

The performance parameters error between the design parameters and the experimental results was shown in table.3. It appears that test elastic stiffness of the specimens was much lower than the design value, and the yield displacement was more than the design value. But the error doesn't exceed 15%, which can meet the design requirement of the Code for Seismic Design of Buildings. The cause of the lower elastic stiffness and large yield displacement obtained from the bolt slippage in test.

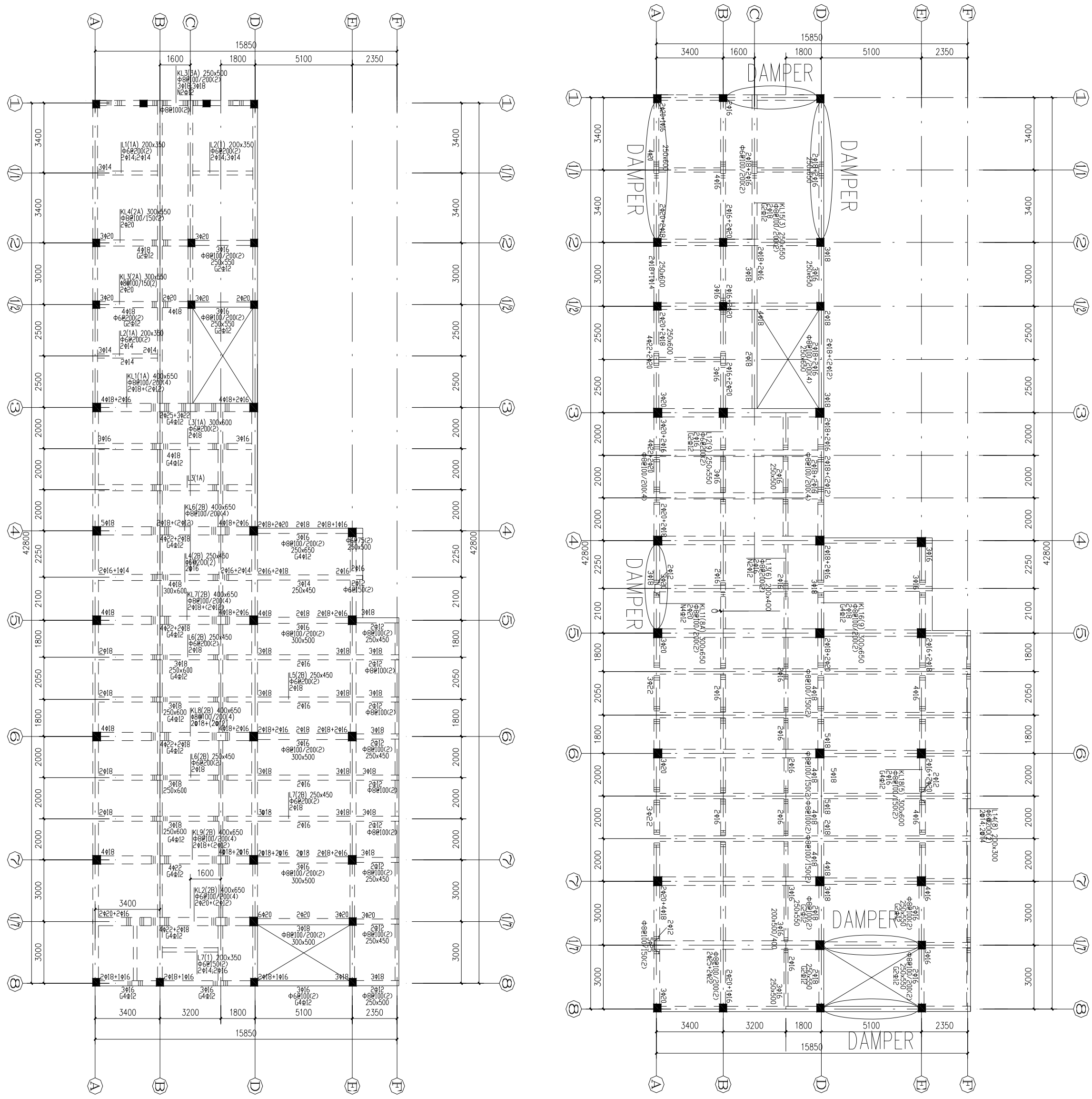
3. STRUCTURAL ANALYSIS

3.1 Structural introduce

The project was three-story with stairhood on the top office building of reinforced concrete frame. The total height is 13.75m, which the first and second story height are 3.6m， the third story height is 3.9m and stairway height is 2.65m. The length is 42.8m and width is 15.82m. The plan configuration of the building is given in **Figure.7**.

The column cross-section sizes of the first story are 600×600mm , and other story are 500×500mm. All column reinforcement is 12Φ22. The beam cross-section sizes and reinforcement of the building were given in **Figure.7**. The floor slab is 90mm thick. Concrete with a grade C30 is adopted in all members.

According to requirement of the Code for Seismic Design of Buildings, the building is asymmetric-plan structure, so it is suggested to adopt X-dampers to control seismic response, especially to reduce torsional response of the structure. The X-dampers were installed from first story to third story, the installed locations in plan were shown in Fig.7. All dampers are set up in the form of 人-brace system, as shown in **Figure.8**. The damper parameters were listed in **Table.3.**



(a) transverse beam (b) longitudinal beam

Figure.7 Section size and Reinforcement of beam

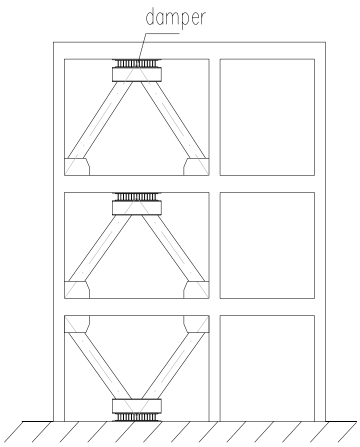


Figure.8 Installation from of the damper

3.2 Analytical model

In order to study the seismic performance of the structure with and without the X-dampers, three dimensional mathematical models were prepared using program PERFORM 3D. The analysis on structure with energy dissipation devices is very convenient to adopt the program, because it has several element types, such as beam, column, wall, seismic isolator, viscous damper, etc (COMPUTERS&STRUCTURES INC,2006).

No-bulking trilinear steel model is used to model the reinforcement in the RC frame. The yield strength is 300N/mm^2, limit strength is 335 N/mm^2, elastic modulus is 200000N/ mm^2 and limit strain is 0.2 of the H335. Mander concrete model is used to describe the stress-strain relation of the confined concrete in uniaxial compression. Based on the Code for Design of Concrete Structures, the strength design value of C30 is 14.3Mpa, limit stress is 17.9Mpa and limit strain is 0.02. The X-damper can be well described by using the trilinear seismic isolator model (Wu C.Y, Wu C.X, Zhou Y,2010).

The program ETABS and Perform-3D have been used for a comparative analysis, so to ensure the reliability of models. The model analysis results are shown in **Table.4**.

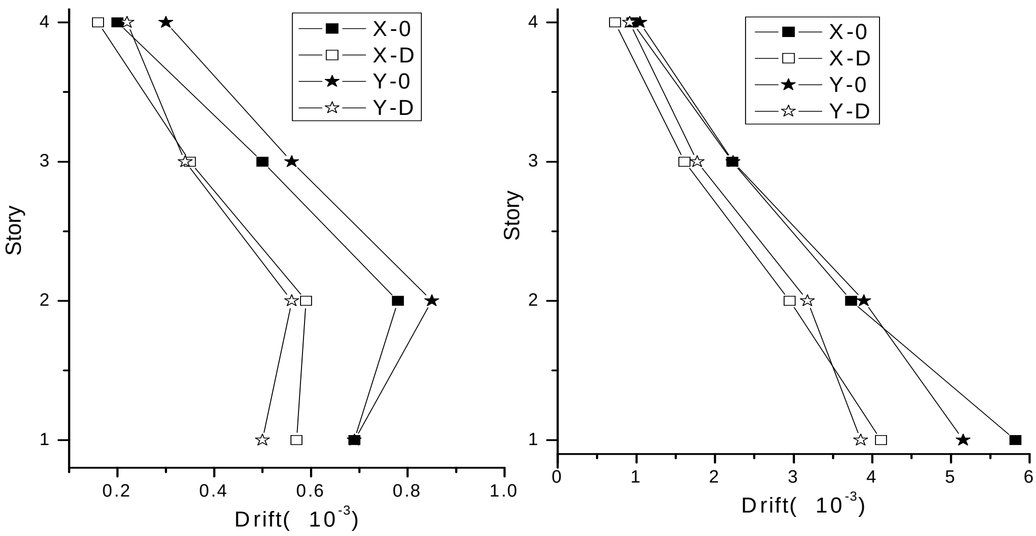
Table 4 Comparison of structural period and mass

	1ST(s)	2 ST (s)	3 ST (s)	Mass (T)
ETABS	0.52029	0.45578	0.42253	2122
PERFORM 3D	0.5155	0.448	0.406	2097

Nonlinear time history analysis under frequently occurred earthquake and rarely occurred earthquake are carried after ensure the reliability of the models. Two natural seismic waves (Northridge wave and Kobe wave) used in analysis process. The amplitude of each earthquake input record is adjusted to correspond to frequently occurred earthquake and rarely occurred earthquake. The corresponding acceleration amplitudes are 55gal and 310gal (PGA), respectively.

3.3 Analysis results

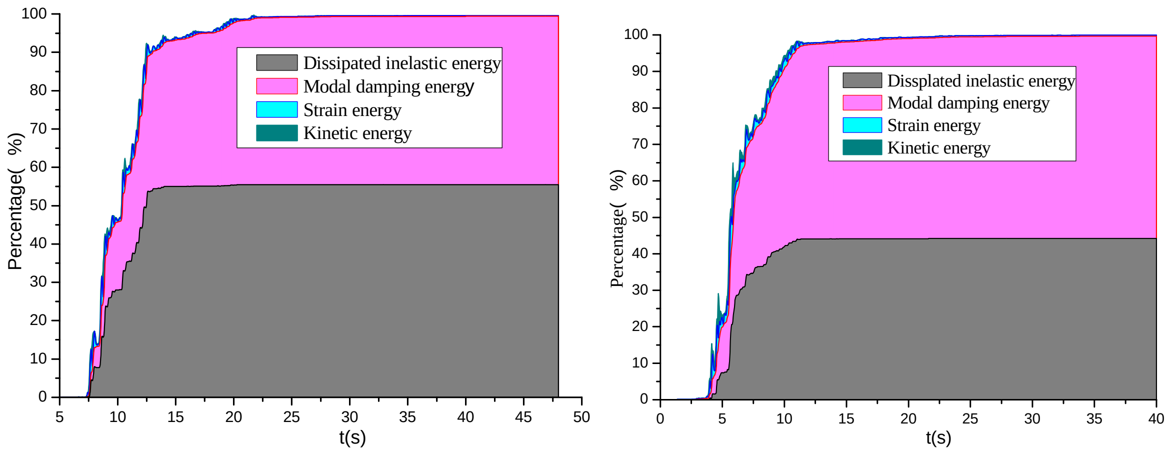
The average value of inter-story drift of structure with and without X-dampers under frequently occurred earthquake and rarely occurred earthquake were given in **Figure.9**. The results show that the maximum inter-story drifts of structure without X-damper under frequently occurred earthquake were 1/1280 in X-direction and 1/1176 in Y-direction, and were 1/1690 in X-direction and 1/1785 in Y-direction of the structure with X-dampers. Compared the maximum inter-story drift of the structure with X-dampers with the structure without X-damper, it can be reduced by 30%. The maximum inter-story drifts of structure without X-damper under rarely occurred earthquake were 1/171 in X-direction and 1/193 in Y-direction, and were 1/243 in X-direction and 1/259 in Y-direction of the structure with X-damper, which can be reduced by 25%.



(a) Frequently occurred earthquake (b) Rarely occurred earthquake

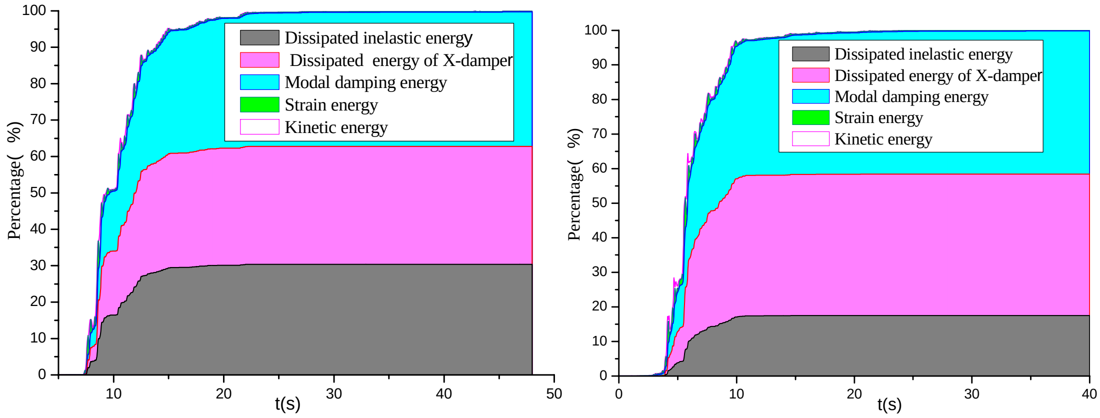
Figure.9 Structural inter-story drift

The results of the members dissipated energy of structure with and without X-dampers under rarely occurred earthquake were given in **Figure.10** and **Figure.11**. The results show that: the earthquake input energy of the structure without X-damper were dissipated by the column and beam members damage, and were dissipated by X-dampers of the structure with X-dampers that the deformation response and damage of structure can be reduced. About 55% the input total energy be dissipated by the beam and column members inelastic deformation of the structure without X-dampers under Kobe wave action of PGA=310gal, while the percentage is about 44% under Northridge wave. While about 30% the input total energy were dissipated by the beam and column members inelastic deformation and about 32% energy were dissipated by X-dampers of the structure with X-dampers under Kobe wave action of PGA=310gal, about 17% the input total energy be dissipated by the beam and column members inelastic deformation and about 41% energy dissipated by X-dampers under Northridge wave action.



(a)Kobe wave (b) Northridge wave

Figure.10 Energy dissipation of structure without X-damper



(a)Kobe wave (b) Northridge wave

Figure.11 Energy dissipation of structure with the X-damper

4. CONCLUSION

The hysteretic performance of the X-dampers and seismic performance of the structure with and without X-dampers were studied in this paper. Based on the results, it can be concluded that:

(1) The hysteretic curve of the X-damper is stable and repeatable. The X-dampers has good seismic energy dissipation capabilities.

(2) The X-shaped plate can yield almost entirely along their length in shear deformation when the X-shape plate is reasonable designed.

(3) Structural plastic damage of the structure with X-dampers can be reduced. The X-dampers is more efficient to protect the member in main structure under earthquake.

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REFERENCES

Cherry S and Filiatrault A.(1993). Seismic response control of buildings using friction dampers. Earthquake Spectra.,**9:3**,447-466

COMPUTERS&STRUCTURES INC.(2006) The computer programs Perform -3d user guide. University avenue Berkeley, California

Li D.W. (2005). An experimental research on performance and application of a new type of mild steel damper added damping and stiffness .Haerbin: Harbin Institute of Technology.(in Chinese)

Li H.N and Li G.(2006). Experimental study of structure with “dual function” metallic dampers. Engineering structures ,**28:10**,1-12

LI S.Y. (2005).Analytical research on performance and application of the mild steel damper with the diamond-shaped opening and added damping and stiffness.Haerbin: Harbin Institute of Technology.(in Chinese)

Pall A.S and Marsh C.(1981).Friction-Damped Concrete Shear walls. ACI,**7:3**,87-193

Robinson W.H and Greenbank L.R. (1976).An extrusion energy absorber suitable for the protection of structures during an earthquake. Earthquake Engineering and Structural Dynamics,**4**,251-259

Skinner R.I, Kelly J.M and Heine A.J.(1975). Hysteresis Dampers for Earthquake-Resisstant Structures. Earthquake Engineering and Structural Dynamics,**3**,287-296.

Soong T T, Dargush. G F.(1997).Passive energy dissipation on systems in structure engineering. John Wiley& Sons.Ltd, New York

Tyler R.G..Tapered Steel.(1978). Energy Dissipators for Earthquake Resistant Structures. Bulletin of The New Zealand National Society for Earthquake Engineering , **11:4**,282-294.

Wang Y Y,Chen Q X,Xue Y T.(2004). The Application of HADAS in Seismic Strengthening Structure.The First Acadamic Forum on Earthquake Resistant Engineering and Retrofitting. KunMin.2004,279-285(in Chinese)

Whittaker, A S.,Bertero,V.V and Thomposon C L, etal.(1989) Earthquake Simulator Testing of Steel Plate Added Damping and Stiffness Elements ,Earthquake Engineering Research Center ,University of California ,Berkeley ,CA

Wu C.Y, Wu C.X, Zhou Y. (2010). Study and application on restoring force model of the notch-type triple-steel-tube buckling- restrained brace (TST-BRB).China civil engineering journal, **43:SUP**,397-402(in Chinese)

Xing S.T, Guo X.(2003). Study on mechanical behavior and effectiveness of a new type of mild steel damper. Earthquake Engineering and Engineering Vibration, **23:6**,179-186(in Chinese)

Xu C.E. (2008). Study on energy dissipation and seismic mitigation performance of HADAS damper . Shanghai: Tongji University.(In Chinese)

Zhou Y.(2006a) Design of Metallic Energy Dissipation Structure. Wuhan University of Technology Press, Wuhan(in Chinese)

Zhou Y.(2006b). Design of Friction Energy Dissipation Structure. Wuhan University of Technology Press, Wuhan(in Chinese)

Zhou Y.(2006c). Design of Viscoelastic Damping Structure. Wuhan University of Technology Press, Wuhan(in Chinese)

Zhou Y.(2006d).Design of Viscous Damping Structure. Wuhan University of Technology Press, Wuhan(in Chinese)