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RECENT ADVANCES OF PASSIVE STRUCTURAL CONTROL AND ITS APPLICATION IN MAINLAND CHINA

Xilin LU [1] and Bin ZHAO [2]

SUMMARY

The recent developments of theoretical researches, model tests and engineering applications of passive structural control in Mainland China are reviewed in this paper. As the passive structural control is an effective and economical technology for reducing the seismic response of the civil engineering structures and dissipating the input energy from an earthquake event, an increasing amount of attention to the theoretical research and engineering implementation has been given by the researchers and engineers during the recent years, and the state-of-the-art of passive structural control shows that the passive control methods have been developed into matured stage in China. As a result of the research and technological development, the passive control technology has been used in the new built structures as well as the seismic retrofitting of the existing buildings. Finally, the future research initiatives of passive structural control in civil engineering are presented.

Keywords: state-of-the-art review, civil engineering, passive structural control, engineering application

INTRODUCTION

The research in structural control as an earthquake resistant technology for structural systems in China began in the early 1980's. During the past twenty years, an increasing amount of attention has been given by the researchers and engineers to theoretical research and engineering implementation of structural control, and significant progress has been taken in the field. As a result of the research and technological developments, the passive structural control technology has been put into actual application in China, both in new built buildings and the seismic retrofitting of the existing buildings. In this paper, the recent developments of theoretical researches, model tests and engineering applications of the passive structural control in Mainland China are reviewed, and some possible future research directions of passive structural control in civil engineering are also presented.

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[1] Professor and presenting author, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, 200092, P. R. China. Email: lxlst@mail.tongji.edu.cn

[2] Associate professor, State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, 200092, P. R. China. Email: binzh@mail.tongji.edu.cn

ANALYSIS MODEL OF PASSIVE ENERGY DISSIPATION DAMPERS

Viscous dampers and viscoelastic dampers

The structure and performance of clearance hydro cylinder dampers are studied by Ou [1]. Based on the constitute relationship of fluid and model test results, the output force of the clearance hydro cylinder dampers are derived.

The calculating models of lead viscoelastic damper are studied by Zhou [2]. Both the bilinear model and the bilinear-Ramberg-Osgood model are used to simulate the restoring force model of the lead viscoelastic damper. The results indicate that the bilinear-Ramberg-Osgood model is more effective than the bilinear model for simulating the hysteretic energy dissipation behavior of the lead viscoelastic damper.

Based on the constitutive model of Kelvin-Voiget, the influential function of vibration frequency, environmental temperature and shear strain on the shear modulus and shear loss modulus of viscoelastic damper, shown as Fig. 1, are researched by Zou [3]. The temperature-rised fatigue model of viscoelastic damper is derived from the first law of thermodynamics.

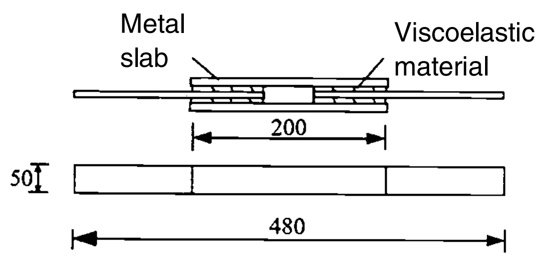


Fig. 1 Viscoelastic damper

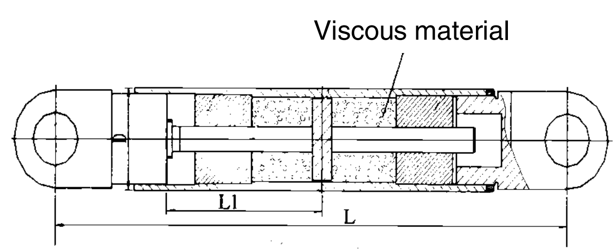


Fig. 2 Viscous damper

Based on the pseudo-static test results, the calculating model and property of energy dissipation of the viscous damper, shown as Fig. 2, are studied by Weng [4]. The stiffness of the damper support is also considered in the presented model.

Friction dampers

The behaviors of two different energy dissipation dampers based on friction are studied by Zhou [5]. The test results show that the friction dampers are quite effective in energy dissipation with stable hysteretic behavior.

Steel plate yielding dampers

The membrane effects in steel plate energy dissipaters are analyzed by Wu [6]. The results indicate that the membrane effects in steel plate energy dissipaters cannot be ignored. A calculating method of membrane effects under the fatigue loads and corresponding fatigue design criteria considering the membrane effects is set up. The method can be used for parameter design of steel plate yielding energy dissipaters.

Some new energy dissipation dampers, shown as Fig. 3, are presented by Zhou [7]. The comparative experiment of new energy dissipaters with different design parameters under low cyclic reversed loading is conducted. The test results show that the friction dampers are very effective in energy dissipation and the working behavior is quite stable.

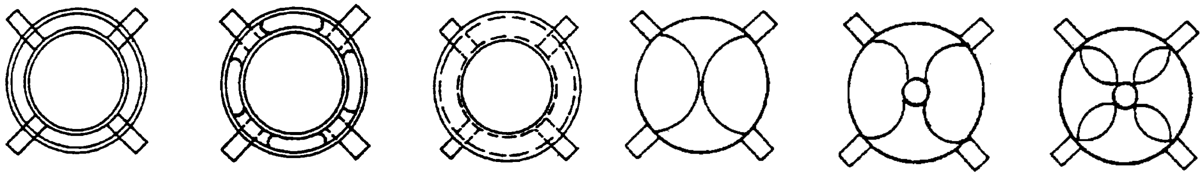


Fig. 3 New energy dissipation dampers

SHAKING TABLE TEST OF STRUCTURES EQUIPPED WITH DAMPERS

The series shaking table test of a 3-story steel frame structure equipped with the lead rubber bearing damper and the combined energy dissipation system consist of lead rubber bearing damper and oil damper are carried out by Lu [8]. The shaking table test is shown as Fig. 4. The test results show that the dampers can increase the damping ratio and stiffness of the whole system. The frequencies and damping ratios of the model structure are listed in Table 1.

Table 1 Frequencies and damping ratios of the model structure

Dissipation device	Frequency	Damping ratio
Rubber damper	1.953	0.081
Rubber & viscous damper	2.344	0.346
Without damper	1.074	0.010

Fig. 4 Model of 3-story frame with dampers

Fig. 5 Adjacent building model linked by fluid dampers

The shaking table test for the seismic adjacent buildings with linking fluid dampers, shown as Fig. 5, are carried out by Yang [9]. The experimental results show that the installation of fluid dampers can significantly reduce the seismic responses of both buildings. Another shaking table test for the two adjacent buildings linked by high efficient damper, one kind of steel damper, are carried out by Yan [10]. The test results also indicated that the dampers could efficiently reduce the seismic response of both sub-structures.

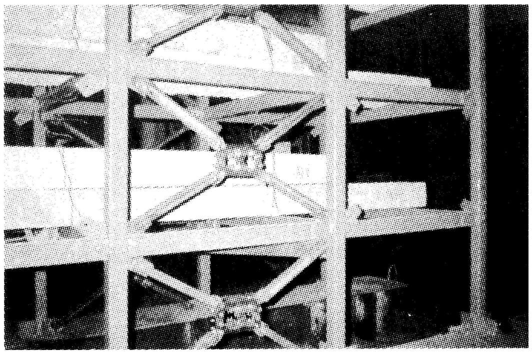


Fig. 6 Steel frame model with dampers

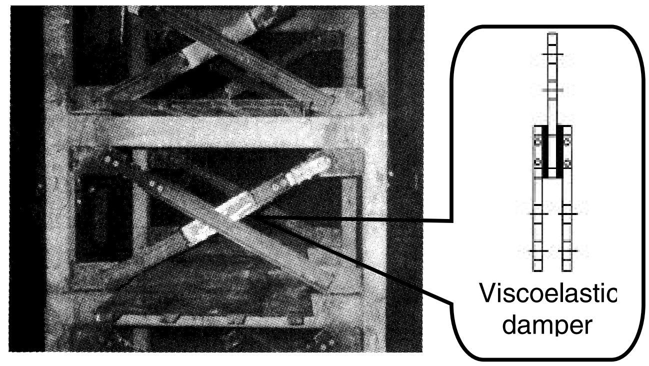


Fig. 7 RC frame model with viscoelastic dampers

The shaking table test of a 16-story steel tall building equipped with the steel plate yielding energy dissipaters, shown as Fig. 6, are performed by Ou [11]. The test results show that the steel plate yielding energy dissipaters have good vibration absorption effect.

The shaking table test of a 3-story RC frame structure with viscoelastic dampers, shown as Fig. 7, are carried out by Xu [12]. The test results show that the dampers can increase the damping ratio and stiffness of the model system, and the viscoelastic dampers are more effective in displacement reduction than accelerator reduction.

The Shaking table test for damage identification of RC frame and seismic retrofitting of damaged RC frame, shown as Fig. 8, are carried out by Li [13]. The test results show that the retrofitted frame possesses roughly the same earthquake resistant capacity as that of the original frame, and the frictional energy dissipation device is effective in reducing structural vibration.

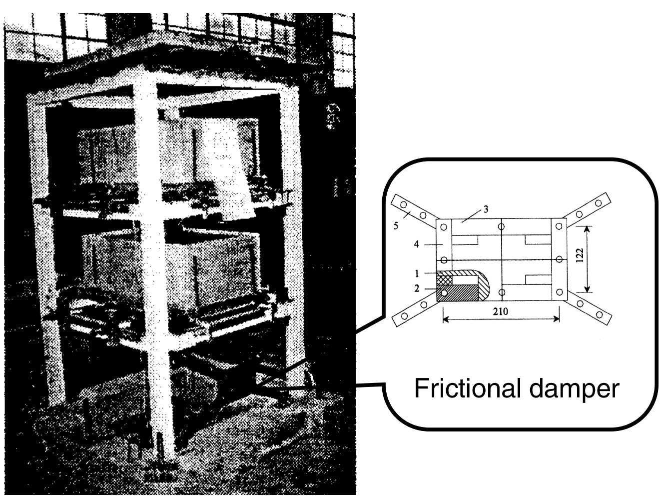


Fig. 8 Seismic retrofit using frictional dampers

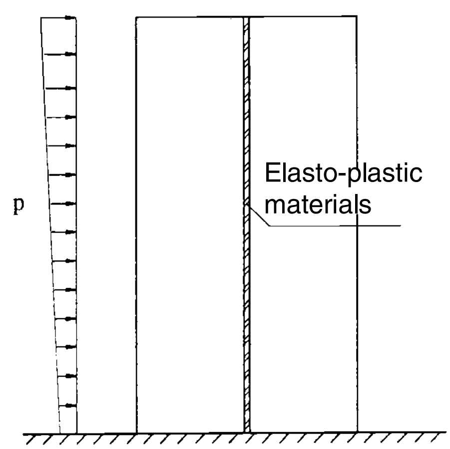


Fig. 9 Slit wall with elasto-plastic materials

TEST AND ANALYSIS OF ENERGY DISSIPATION SHEAR WALL

A passive structural control system for seismic resistance of shear wall structures, which is called the vertically slit shear wall system, shown as Fig. 9, is proposed by Lu [14, 15, 16]. The force-displacement skeleton curve of the energy dissipating devices in the vertical slit is presented by the shear-friction tests of the energy dissipating devices and the static-cyclic load test of one-story slit shear wall. In order to verify the seismic control effect of the slit wall, the shaking table test of two 10-story slit wall models are carried out with different kinds of energy dissipating devices. The test results indicate that the slit shear walls have favorable seismic performance. The above-mentioned slit wall with rubber belts was applied in a tall building located at Shanghai, China, in 1997, and the thickness of the slit is about 30mm.

ANALYSIS AND DESIGN OF STRUCTURES EQUIPPED WITH DAMPERS

Based on the performance experiments and numeric research results of passive energy dissipation systems, a uniform aseismatic design method of structures with energy dissipation devices is presented by Ou [17]. The method can be directly used for the design of structures equipped with passive energy dissipation devices.

The dynamic responses of frame equipped with friction dampers and the friction dampers in series with viscous fluid dampers are analyzed by Lu [18] and Zhou [19]. The effect of some parameters, such as initial slip force of friction dampers, brace stiffness and the viscous fluid dissipation coefficient, are also studied. The reduction effects are compared between energy dissipation systems only with friction dampers and the series connection with friction dampers and viscous fluid dampers. The numerical results indicate that he friction dampers in series with viscous fluid dampers are more effective in reducing the acceleration responses of the model structure.

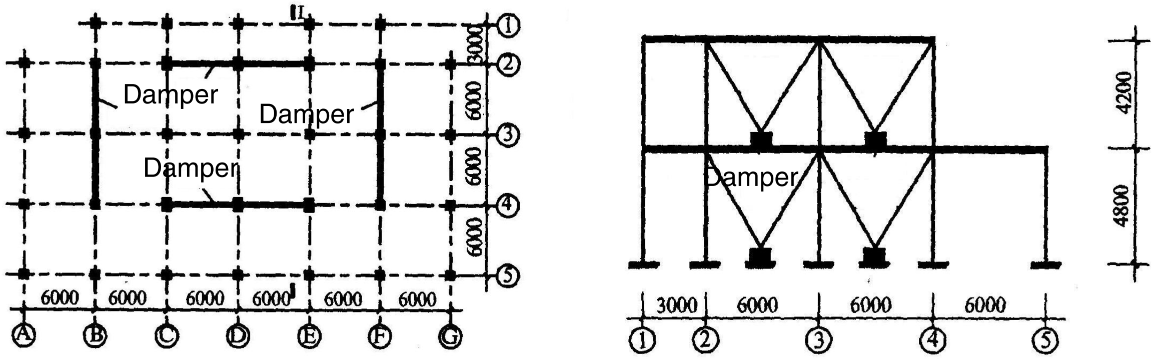
The calculation methods of viscoelastic damper for controlling the nonlinear earthquake responses of multistory damper and steel brace is established by Wei [20]. A fluid viscous damper with double guide bars is developed, and the structural vibration energy dissipation analysis of a frame structure with the fluid viscous dampers is carried out by Ye [21]. The results indicate that both the viscoelastic damper and the fluid viscous dampers are quite effective in reducing the dynamic responses of the structures.

The design parameters of structures equipped with energy dissipation dampers are studied by Weng [22]. The energy dissipation property of damping device hysteretic model is derived. The design curves of equivalent damping ratio to the brace stiffness, and the ratio of maximum damping force of the damping device to the inter-story yield shear force of the structure are proposed. The presented design method is also verified by one pseudo-static test and shaking table test of energy dissipation structures.

ENGINEERING APPLICATIONS

New Buildings

The energy dissipation technology was used in a new built Dining-room and a Chemistry Lab Building of Zhenrong Middle School, Yunnan province Ou [23, 24]. Two kinds of the energy dissipation dampers, the friction dampers and the viscoelastic dampers, are used in the Dining-room and Chemistry Lab Building respectively. The dynamic responses of the original building and the building equipped with energy dissipation dampers are carried out by both response spectra method and time history analysis method. The analysis results show that the seismic capacity of the structure is improved by using the energy dissipation dampers. The location of the energy dissipation dampers of the Dining-room of Zhenrong Middle School are shown in Fig. 10.



a. Plan view of first floor b. Cutaway view of I-I section

Fig. 10 Dining-room of Zhenrong Middle School

Recently, the fluid dampers have been applied to an actual 60-story ultra-tall building with 10-story large podium connected by Lu [25] to reduce their torsional seismic response. An extensive analysis on the structure and a serious of experiment on the fluid dampers have been carried out to get the optional parameters for the fluid dampers, and to achieve the best structural performance under various seismic excitations. Finally, 40 fluid dampers with maximum capacity of 600kN were used to connect the podium structure to the main building at different floor levels on and below the roof of podium structures, so as both the podium structure and the main building can meet the seismic design requirements for low and higher intensity of earthquake actions. The layout of the fluid dampers is shown in Fig. 11, and the perspective picture of this building is shown in Fig. 12.

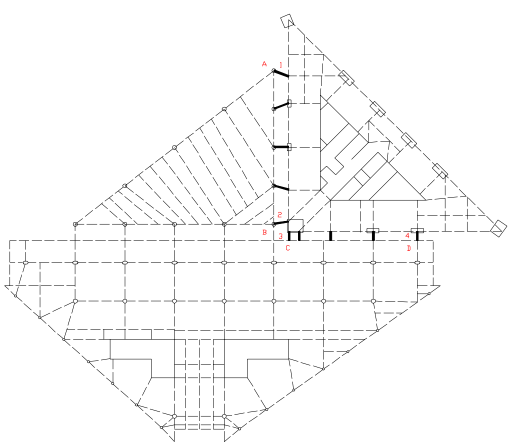


Fig. 11 Plane layout of the fluid dampers

Fig. 12 Perspective picture of the building

Seismic retrofitting

The energy dissipation technology was used for seismic retrofitting of some key buildings in Beijing such as the Beijing Hotel, the Beijing Railway Station, the Revolution and History Museum of China and the Beijing Exhibition Hall by Wang [26] and Ou [27]. The seismic structural analyses and design are carried out by means of response spectrum and time history analysis methods for calculating the strength and deformation of the original structures under minor and major earthquake design levels respectively. The energy dissipation dampers (Jarret model made in France) with a specified hysteretic model are used in the principal and detailed design of the retrofitting. The time history responses of the structure equipped with dampers are analyzed by a nonlinear analysis program based on Wilson'θ approach, and the elasto-plastic deformation of the structure, the buckling of steel bracing, the nonlinear features of the rigidity and damping of the energy dissipation bracing were also considered in the seismic design. The numerical results indicate that the energy dissipation dampers will upgrade the seismic capacity of retrofitted building structures. Some in site dampers for the retrofitted buildings and the energy dissipation systems are shown as Fig. 13 and Fig. 14.

The energy dissipation technology was also used for seismic retrofitting of the buildings in Shenyang by Wu [28] and Shanghai by Weng [29]. Some in site dampers for a Shanghai office building retrofitting are shown as Fig. 15.

Fig. 13 Dampers of the Beijing Exhibition Hall

Fig. 14 Dampers of the Beijing Railway Station

Fig. 15 Dampers of a Shanghai Office Building

Broadcast and TV tower

The pendulous tank, which can be taken as tuned mass damper, was used for reducing the dynamic

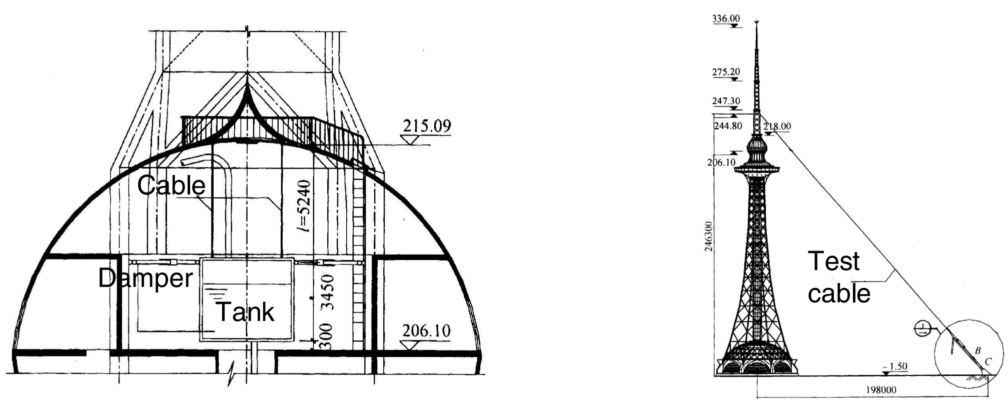


Fig. 16 Pendulous tank system and its site test

responses of the 336m high Heilongjiang Broadcast and TV steel tower by He [30]. The Vibration reduction effects of the pendulous tank system are measured on the site. The results indicate that this vibration control method is economical and effective. The pendulous tank system and the in site measurement are shown as Fig. 16.

DESIGN CODE

The new edition of Code for seismic design of buildings (GB50011-2001), published by Ministry of Construction of P. R. China and General Administration of Quality Supervision, Inspection and Quarantine of P. R. China, added a special chapter (Chapter 12) dealing with the base isolation and passive energy dissipation design methodologies, which will certainly speed up the application of the passive structural control technologies.

DISCUSSIONS ON THE FUTURE DEVELOPMENT

Based on the discussion presented in the preceding sections, the following topics are recommended to be given high priority in the future research activities in passive structural control.

1) Development of new efficient passive control devices
2) Large-scale structural model tests and site tests
3) Effective design method for structures with passive control devices
4) Development of design code and regulations
5) Engineering application

REFERENCES

1. Ou JP, Ding JH. “Theory and performance experiment of viscous damper of clearance hydro cylinder”. Earthquake Engineering and Engineering Vibration 1999; 19(4): 82-89.
2. Zhou Y, Xu ZD, Deng XS. “Calculating models of lead viscoelastic damper”. Earthquake Engineering and Engineering Vibration 2000; 20(1): 120-124.
3. Zou XY, Ou JP. “Parametric effects on restoring force model of viscoelastic damper”. Journal of Vibration Engineering 2001; 14(1): 81-84.
4. Weng DG, Lu ZH, Xu B, Zou HW, Xia Y. “The experimental study on property of energy dissipation of viscous liquid damper”. World Information on Earthquake Engineering 2004; 18(4): 30-34.
5. Zhou Y, Liu J. “Comparative experimental study on the behavior of two different energy dissipation brace based on friction”. Earthquake Engineering and Engineering Vibration 1997; 17(1): 40-48.
6. Wu B, Ou JP. “Analysis of membrane effects in steel plate yield energy dissipaters”. Earthquake Engineering and Engineering Vibration 1997; 17(1): 40-48.
7. Zhou Y, Liu J. “Development and study of new energy dissipaters (Dampers)”. Earthquake Engineering and Engineering Vibration 1998; 18(1): 71-79.
8. Lu, X.L. and Zhou, Q. “Dynamic Analysis Method of A Combined Energy Dissipation System and Its Experimental Verification,” Earthquake Engineering and Structural Dynamics 2002; 31(6): 1251-1265.
9. Yang Z, Xu YL, Lu XL. “Experimental study of seismic adjacent buildings with fluid dampers”. Journal of Structural Engineering 2003; 129(2): 197-205.
10. Yan WM, Lu YQ, Peng LY. “Experimental study of adjacent buildings linked by high efficient damper system”. Earthquake Engineering and Engineering Vibration 2003; 23(3): 160-169.
11. Ou JP, Wu B. “Experiment study on behavior of composite steel plate yield energy dissipaters and its effectiveness on absorbing seismic vibration of steel tall buildings”. Journal of Building Structures 2001; 22(1): 26-32.

12. Xu ZD, Zhao HT, Shen YP, Zhang XH. "The Shaking table test of viscoelastic structure". Journal of Building Structures 2001; 22(5): 6-10.
13. Li HQ, Lu XL. "Experimental research on the earthquake damage identification of RC frame and retrofit of damaged RC frame using passive energy device". Journal of Building Structures 2001; 22(3): 9-14.
14. Lu XL, Jiang HJ, Wu XH, Lu L. "A passive structural control system for seismic resistance of shear wall structures with application". Proc. 2nd Word Conf. On Struc. Control; Kyoto, Japan. 1998(2): 1705-1714,
15. Lu XL, Jiang HJ. "Research on structural seismic control and energy dissipation with experiment and application", Journal of Vibration Engineering 1999; 12(2): 210-217.
16. Lu XL, Jiang HJ. "Hysteretic analysis of a new type of energy dissipation shear walls". Earthquake Engineering and Engineering Vibration 2000; 20(1): 112-149.
17. Ou JP, Wu B, Long X. "Seismic Design approaches of passive energy dissipation systems". Journal of Vibration Engineering 1999; 12(2): 202- 209.
18. Lu XL, Zhou Q. "Dynamic analysis of energy dissipation system with friction dampers in series with viscous fluid dampers". Earthquake Engineering and Engineering Vibration 2001; 21(1): 123-130.
19. Zhou Q, Lu XL. "Dynamic analysis of frame structures with friction energy dissipation devices". Earthquake Engineering and Engineering Vibration 2001; 21(2): 136-144.
20. Wei WH, Qu WL, Chen ZH. "Viscoelastic damper in control of earthquake responses on nonlinear buildings". Earthquake Engineering and Engineering Vibration 1999; 19(4): 95-101.
21. Ye ZQ, Li AQ, Cheng WR, Yang GH, Ding YL. "Study on vibration energy dissipation design of structures with fluid viscous dampers". Journal of Building Structures 2001; 22(4): 61-66.
22. Weng DG, Lu XL. "Study on design parameters of energy dissipation structures with experiment verification". Earthquake Engineering and Engineering Vibration 2004; 24(2), in press.
23. Ou JP, Zou XY, Long X, Wu B, Pan KY, Wang FX, Zhang JM. "Seismic analysis and design for dining-room structure of Zhenrong middle school with energy dissipaters", Part I: Response spectra method. Earthquake Engineering and Engineering Vibration 2001; 21(1): 109-114.
24. Ou JP, He Z, Long X, Wu B, Zou XY. "Seismic analysis and design for dining-room structure of Zhenrong middle school with energy dissipaters", Part II: Seismic damage performance control design. Earthquake Engineering and Engineering Vibration 2001; 21(1): 115- 122.
25. Lu XL, Jiang HJ. "Earthquake Engineering Research in Shaking Table Testing Laboratory of Tongji University, Shanghai, China", The First International Conference on Urban Earthquake Engineering 2004; Yokohama, Japan.
26. Wang YY, Xue YT, Ou JP, Wu B, Long X, Cheng MK, Wang ZG. "Structural analyses and design of seismic retrofitting with energy dissipation dampers for Beijing Hotel and other key buildings in Beijing". Journal of Building Structure 2001; 22(2): 35-39.
27. Ou JP, Wu B, Long X, Wang YY, Xue YT, Cheng MK, Wang ZG. "Analysis and design of seismic retrofit of Beijing Hotel with energy dissipaters: time history method". Earthquake Engineering and Engineering Vibration 2001; 21(4): 82-87.
28. Wu Bo, Li H, Lin LY, Shan M. "Strengthening the earthquake resistance of a building using friction dampers". Journal of Building Structure 1998; 19(5): 28-36.
29. Weng DG, Lu ZH, Ren XS, Lu XL, Yang JY, Xu B, Zhou HW. "Retrofit design for RC frame using viscoelastic dampers". Structural Engineers 2001, Suppl: 157-166.
30. He MJ, Ma RL. "Measurements and analysis of the vibration of Heilongjiang broadcast and TV steel tower controlled by pendulous tank". Journal of Building Structures 2001; 22(1): 39-41.