Research and Application of Lead Viscoelastic Damper

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ABSTRACT:

A new type of energy dissipation device, lead viscoelastic damper(LVD), was introduced, and the principle, configuration, characteristics of LVD are illustrated.The LVD, which is consisted of lead core and viscoelastic materials, mainly dissipates energy through shear strains of the viscoelastic material and compressive deformation and shear deformation of the lead core, Therefore, it combines the characteristics of both displacement-dependent and velocity-dependent dampers. The experiments were done to study the performance of LVD. Experimental results show that the LVD have good seismic energy dissipation capabilities and performance of fatigue resistance, and shares many of the advantages of existing passive control devices. Based on relevant research results, the energy formula for LVD simulating with Bouc-wen model was presented, and the force model and design process of the LVD and the analysis method of structures with LVDs were studied. The calculating formula of equivalent damping ratio for the structures with LVDs was derived. Finally, some applications of the proposed LVD in seismic retrofit as well as new construction projects were presented in this paper. Analysis results of the projects indicate that the structural seismic behavior could be significantly improved due to the adoption of the structures with LVDs.
KEYWORDS: Lead viscoelastic damper(LVD), Energy dissipation, Hysteresis performance

1. INTRODUCTION

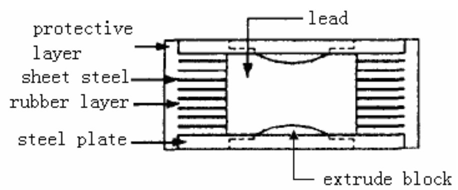
In recent years, considerable attention has been paid to researches and development of energy dissipation technology due to remarkable reduction effect of vibration, simple construction, low cost and maintenance convenience. Contrary to semi-active and active systems, there is no need for an external power supply for energy dissipation technology. In past several decades, many different types dampers have been developed, such as steel triangular plate energy dissipator, friction damper, Tapered steel energy dissipator, visco-elastic damper and viscous damper，lead shear damper etc, some have been used in the seismic retrofit as well as new construction projects, and the effects and economical benefits of those dampers have been studied by Pall A.S and Marsh C, etc(Pall A.S and Marsh C, 1981, Soong T.T andDargush G.F,1997, Cherry S and Filiatrault. A,1993, Skinner R.I, Kelly J.M and Heine A.J, 1975 , Tsai K.C, et al, 1993, Tyler R.G,1978 ,Robinson W.H and Greenband L.R,1976,Li H.N and Li G,2006,etc) .

The primary objective of adding energy dissipation devices to building structures is to dissipate energy during an earthquake, and to substantially reduce the seismic response of the gravity-load- resisting structure. However, the major of above-mentioned dampers only adopt one energy dissipation mechanism, and provide much confined damping force and ability of energy dissipation. In order to increase the effect of damper, the idea of amplifying the deformations and the force in passive control devices was utilized, such as toggle energy dissipation brace and composite damper(Constantinou MC, Tsopelas P,et al,1997, Sigaher A.N and Constantinou M.C,2003,OU J.P and Wu B,2001,Zhou Y and Liu J,1998). But the construction of the toggle energy dissipation was complex, therefore, the application of toggle energy dissipation brace was limited.

In the paper, A new type composite energy dissipation device——lead viscoelastic damper(LVD) was proposed. It is consisted of lead core and viscoelastic materials, and is of dual energy dissipation mechanism, and mainly dissipates energy through shear strains of the viscoelastic material and compressive deformation and shear deformation of the lead core. The experiments were done to study the performance of LVD. Experimental results show the LVD have good seismic energy dissipation capabilities and performance of fatigue resistance, and shares many of the advantages of existing passive control devices. The force model and design process of the LVD and the analysis method of structure with the LVDs were put forwarded. Finally, some applications of the proposed LVD in seismic retrofit as well as new construction projects are illustrated. Analysis results of the projects indicate that the structural seismic behavior could be obviously improved due to the adoption of the structure with the LVD.

2.The principle, configuration, characteristics of LVD

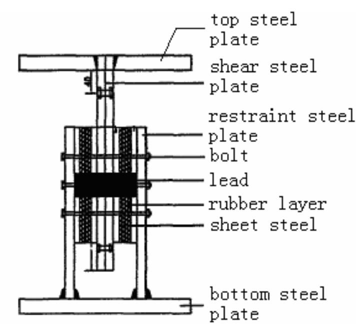
As illustrated in Figure 1, The LVDs are consisted of lead core, viscoelastic material (rubber) sheets , thin steel sheets, connecting steel plates, shear steel plates(extrusion head) and restraining steel plates(covering layer). In addition of the lead core, these components are connected together by vulcanization under high temperature and high pressure, a or several holes are made in advance to keep the damper in uniformly heating during vulcanization, then are filled with the lead. Obviously, the LVD is the combination of lead damper and viscoelastic damper, and it is combines the characteristics of both displacement-dependent and velocity-dependent devices.



(a) Details of lead-rubber damper


(b) Phtot of rotundity lead-rubber damper

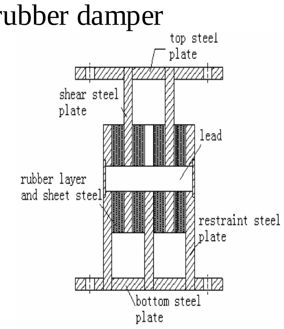

(c) Phtot of square lead-rubber damper



(d) Details of combined lead-rubber damper


(e)Phtot of combined lead-rubber damper


(f) Phtot of lead- viscoelastic damper



(g) Details of composite lead-viscoelastic damper


(h) Phtot of composite lead-viscoelastic damper

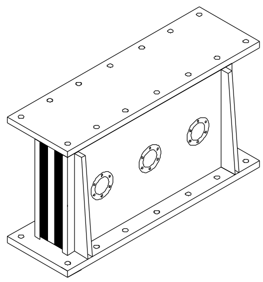

(i) Multi-lead viscoelastic damper

Figure 1 Lead viscoelastic damper

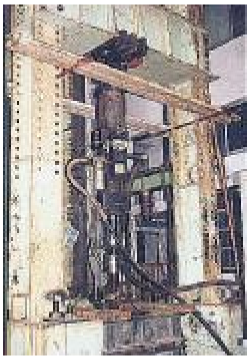
In most cases, the damper should be placed between the stories or the adjacent buildings. During earthquake and strong wind, the top steel plate and bottom steel plate of the damper displace relatively, the strains of the viscoelastic material is kept a nearly uniformly ,at the same time, the lead core is subjected to shearing and compressive forces. So the energy is dissipated by the viscoelastic materials and
lead core.

Compared with other energy dissipation devices（dampers）, this damper has some special characteristics, shown as follow(Zhou Y,2000).
(1) holds two kinds of energy dissipation mechanism——the lead yielding energy dissipation and viscoelastic material hysteresis energy dissipation. So, the LVD energy dissipation is more efficient.
(2) The damper combines two common dampers, so it simplify the manufacture process and installation process, then the cost is reduced.
(3) The damper can dissipate energy in two directions, and the performance of the damper will not be affected by the vertical deformation of the members of the structure.
(4) It can be widely used to control responses of vibration of high-rise buildings, bridges etc under earthquake and wind actions.
(5) The performance of the damper can be regulated by only adjusting the diameter of the lead core to meet different requirements, so it is easily industrialized.

3.The hysteresis performance and force model of LVD

Four types of dampers, lead-rubber damper, combined lead-rubber damper, lead viscoelastic damper and composite lead- viscoelastic damper, are tested to research the hysteresis performances, in the paper, the performances of only one specimen for each type of dampers are illustrated, and the parameters are given in table 3.1.The experimental setups are shown in Figure 2. The force-displacement loops of the dampers are shown in Figure 3. The results show that the hysteresis curves of the dampers are smoothly, and are of good energy dissipation capability. It is evident that the dampers can provide large initial-stiffness and small plastic-stiffness, and have good performance of fatigue resistance and hysteresis(Xue Z.D,2001, Liu B,Zhou Y, Deng X.S,et al.,2002,Zhou Y, Deng X.S, Xu Z.D,2001).

(a) Press-shear test equipment

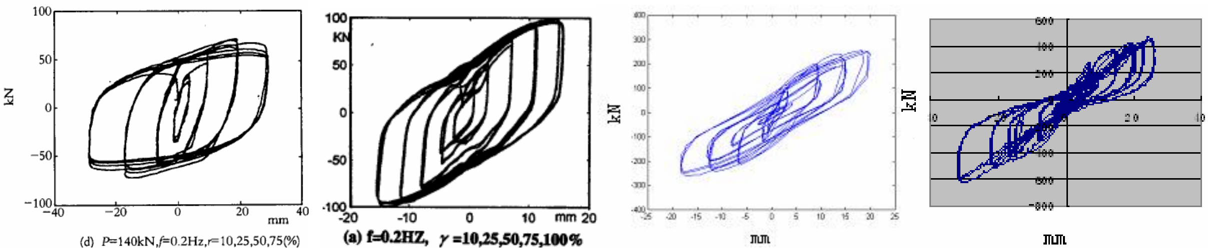


(b) Pull-press test equipment

Figure 2 Experimental setup of model

Table 3.1 The parameters of dampers

Damper type	The area of visco-elastic (rubber) layers（mm^2）	The thickness of viscoelastic (rubber) layers（mm）	The number of viscoelastic (rubber) layers	The number of steel layers	The sticknes s of steels（mm）	Lead core diameter（mm）	loading frequency（Hz）
Lead-rubber damper	30925	42	10	10	1	80	0.2
Combined lead-rubber damper	17680	32	8	3	1.5	60	0.2
Lead-viscoelastic damper	84974	24	8	3	3	80	0.1
The composite lead-viscoelastic damper	100830	72	12	3	3	100	0.02



(a) Lead-rubber damper (b)Combined lead-rubber damper (c) Lead-viscoelastic damper (d) Composite lead-viscoelastic damper

Figure 3 Hysteresis curve of the difference type dampers

The force model of LVD is more complex than other dampers because of combined characteristics of lead damper and viscoelastic damper. It is very important to set up a simple and accurate force modal. At present, the bilinear model, bilinear-RO model and Bouc-Wen model are normally used to simulate the non-linear hysisteresis behavior of LVD.

Bouc-Wen hysteresis model that depends on four parameters was proposed by Bouc.R, and was modified by Wen(Bouc R,1967,Wen Y.K,1976).

The Bouc-Wen hysteresis model is expressed as:

$$P(d,z)=\gamma K_y d+(1-\gamma)K_y z \tag{3.1}$$

$$\dot{z}=A\dot{d}-\alpha|\dot{d}|z|z|^{n-1}-\beta\dot{d}|z|^{n} \tag{3.2}$$

Where z is inelastic displacement, α, β, A and n are the parameters to control the shape of hysteresis curve , respectively; γ is rigidity ratio(the ratio of plastic-stiffness K_d to initial stiffness K_y, $0<\gamma<1$).

Based on the Bouc-Wen model, programs are developed to stimulate hysteresis behavior of the composite lead-viscoelastic damper using the MATLAB software(Wu C.X,2007), the parameters α, β, γ and n are 0.4,-0.4,0.253and 1, respectively. The factor A is a exponential function that have relation with the maximum displacement d_0, and can be estimated by linear regression method. As shown in Figure 4, the hysteretic curves using numerical method are in good agreement with those of experimental results. Normally, the displacement of dampers are controlled below 25mm, when the displacement of dampers exceeds the value, there will be much large gap between the numerical results and experimental data during the unload process, because of the slipping movements of the lead core.

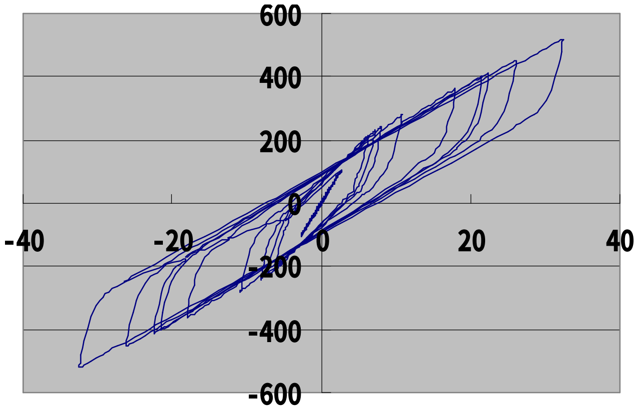


Figure 4 Hysteretic curve of numerical stimulation

4.Analysis methods of structures with LVD

In the structures with LVD, the additional stiffness and damping of LVD has great influences on the dynamic properties and seismic responses of structures. The analysis method of structures with LVD is more complicated than common structures due to the strong non-linear characteristics of LVD under strong earthquake actions. So the non-linear time history and static elastic-plastic analysis method are adopted in the analysis process of structures with LVD. Sometime, the mode-superposition method is used to analyze the structures in order to simplify the compute process.

The motion equation of structures with LVD given is:

$$M\ddot{X}+(C_s+C_d)\dot{X}+(K_s+K_d)X=-MI\ddot{X}_g \tag{4.1}$$

Where M, K_s and C_s are the mass, stiffness and damping coefficient matrices of original structure, respectively. K_d and C_d are stiffness and damping coefficient matrices of LVD. respectively. X, $\dot{X}$, $\ddot{X}$ and $\ddot{X}_g$ are the displacement, velocity and acceleration of structure with LVD and ground acceleration, respectively. I is unit column vector.

The Eq(4.1) is non-linear equation. The general method such as the modal analysis method is used to solve the Eq(4.1),in which equivalent linear is needed for C_d and K_d in Eq(4.1). The matrix C_d and K_d will be replaced the effective damping and stiffness matrix of the LVD. The effective damping and stiffness of the LVD when the Bouc-wen ($\alpha=-\beta$, $n=1$) model is utilized can be calculated by(Wu C.X,2007):

$$\begin{cases} K_e=\dfrac{\gamma K_y d_{max}+(1-\gamma)K_y A(d_{max}-d_1)}{d_{max}} \qquad C_e=\dfrac{TW_d}{2\pi^2 d_{max}^2} \\ W_d=(1-\gamma)K_y A[(d_1+d_{max})^2-\dfrac{2}{\alpha-\beta}(d_{max}-d_1)+\dfrac{2e^{2(\beta-\alpha)d_1}-2e^{(\beta-\alpha)(d_{max}+d_1)}}{\alpha-\beta}] \end{cases} \tag{4.2}$$

Where d_{max} is the maximum displacement of the LVD, d_1 is the displacement of the LVD at z=0 in Equation (3.2); T is the period of structure with the LVD, W_d is hysteretic energy of the LVD.

The dampers must be uniformly distributed in buildings and the added damping ratio can't be too big in order to ensure the analysis precision of the modal analysis method. But the distribution of dampers in practical engineering is often limited, therefore, the time-history method is used to analyze the dynamic response of the structure with the LVD. In the time-history method, the member model or storey model——bilinear model is adopted for the original structure, and Bouc-wen model is adopted for the LVD. Both models are superposed for the restoring-force model of structure with the LVD.

The time-varying damp and stiffness matrix are introduced into Eq(4.2),then the earthquake responses(displacement, velocity and acceleration) of structures with LVDs at any point of time during the whole time course can be calculated by Wilson-θ method or other methods. But the time-history analysis method also have some disadvantages, for instance, the method need a lot of computing time and the results possible appear in macro-deviation owing to the random selection earthquake waves. Therefore, the static elastic-plastic analysis method is usually adopted. The damping of original structure, added damping and stiffness of the LVD may influence the main factor of analytical results in the static elastic-plastic analysis method. Because the static analysis method do not reflecting on the behavior of energy dissipation of the LVD. The structure with the LVD damping ratio can calculated by:

$$\begin{cases} \text{Structure in elastic condition:} \\ \xi_e=0.05+\dfrac{\sum_{j=1}^{m} lW_{dj}}{\dfrac{2\pi^2(1-\rho+\rho\mu)}{\mu T^2}\sum_{i=1}^{n}(\dfrac{w_i}{g})\delta^2\varphi_{i1}^{\ 2}} \\ \text{Structure in elastic-plastic condition:} \\ \xi_e=0.05+0.2(1-\dfrac{1}{\sqrt{u}})+\dfrac{\sum_{j=1}^{m} lW_{dj}}{\dfrac{2\pi^2(1-\rho+\rho\mu)}{\mu T^2}\sum_{i=1}^{n}(\dfrac{w_i}{g})\delta^2\varphi_{i1}^{\ 2}} \end{cases} \tag{4.3}$$

Where ρ and μ are post-yield stiffness ratio and displacement ductility factor of original structure, respectively. l is the number of the LVD in j th story. m is the number of story with the LVD. W_{dj} is dissipation energy of one LVD in j th story, it can be calculated by Eq(4.2).

5.Design of LVD

Based on the code for seismic design of building(GB50011-2001), The LVD should work to absorb earthquake energy in frequently occurred earthquake (elastic structure), therefore, yield displacement of LVD is first calculated in the LVD design procedure, and other parameters of LVD are confirmed by the following analysis. In this section the procedure for design method of LVD is introduced.

(1) According to Eq.12.3.6-2 of the code for seismic design of building(GB50011-2001) and the structural parameters, the yield displacement of LVD d_y is calculated. That is: $\frac{d_y}{d_{sy}} \leq \frac{2}{3}$,where , d_{sy} is structural elastic inter-story drift value.

(2) Based on the research results (Zhou F.L,1996), the thickness of viscoelastic material h_V can be approximated as $h_V = d_y/0.05$.

(3) The percent of energy dissipaters bearing shear force need less than 30% total inter-story shear force in structure with displacement-dependent damper, therefore, yield force of LVD can be express as: $P_y \leq 0.3V_i$,where, V_i correspond to the i th story total inter-story shear force.

(4) The lead core area A_L and the viscoelastic material area A_v of LVD can be confirmed by Eq. $P_y = \tau A_L + \frac{GA_v}{h_v} d_y$,where, G is shear modulus of the viscoelastic material.

(5) The rigidity ratio can be calculated by: $\gamma = (\frac{GA_v}{h_v})/(\tau A_L/d_y + \frac{GA_v}{h_v})$.

(6) The design dampers will be distributed in the structure, and calculate the additional damping ratio. it need greater than the expectation value.

The design process of the LVD is shown in Figure 5.

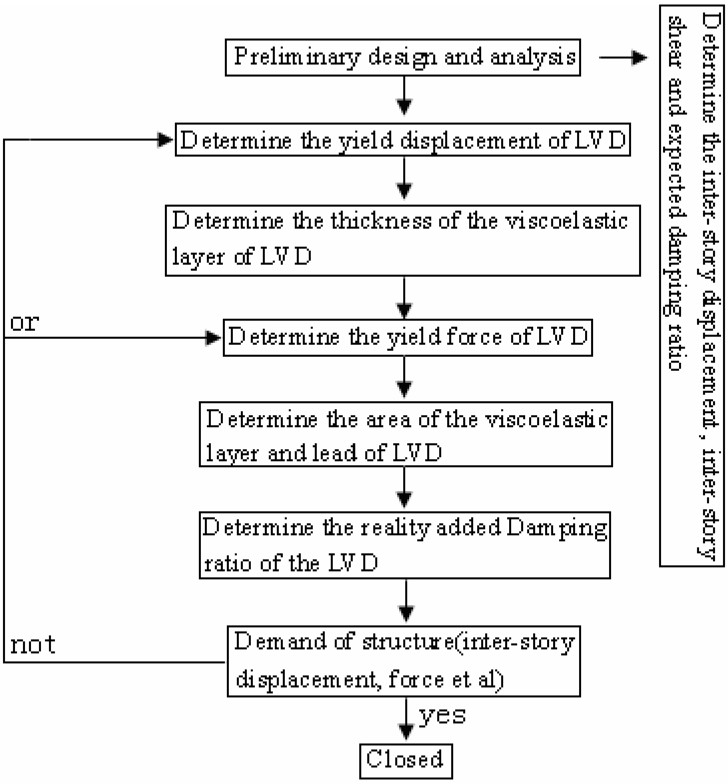


Figure 5 The LVD design process

6.Application of LVD

With the rapid development of energy dissipation technology, more and more projects utilities it to improve seismic behaviors of the buildings. The LVDs were used in Chaoshan-Xinhe Building and Dongshang-Jinxuan Building (Zhou Y,2006-1,2,3). The original design scheme of the Chaoshan-Xinhe Building is 22 floors above ground and one basement floor, the total floor area is about 27976.8m^2,and the plan of typical floor is elliptical shape, shown in Figure 6. A reinforced concrete core tube and concrete filled steel tube(CFST) frame structure is designed for the building. However, the owner wanted to increase three floors in construction procedure, so totally 28 pieces of LVD were installed in the building in order to meet the seismic performance requirements which was determined by seismic code. Figure 7 shows the construction site of LVD.

The Dongshan-Jinxuan Building is located at the Nonglin-Xia Road of Guangzhou, the building area is 7956m^2,and is 28 floors above ground and 3 basement floors. The whole project consists of two-residential-towers structure, which are from the 8-story to 28-story and a large commercial podium structure (Figure 8), Therefore the building needs to adopt different structural form. In the project, the stories stiffness, shear and path of force transferring change sharply near the transfer stories because the transfer floor located at a higher level in the 7-story of the building. The structure seismic performance is impacted by the above factor, therefore , 24 pieces of LVDs in total are installed in the building. Figure 9 shows the construction site of LVD.

Figure 6 Chaoshan-Xinhe Building

Figure 7 Construction site of LVD

Figure 8 Dongshan-Jinxuan Building

Figure 9 Construction site of LVD

6.Conclusion

LVD is a new dissipation energy device, which has strong ability of energy dissipation , stable performance and simple fabrication etc. The LVD combines the characteristics of both displacement-dependent and velocity-dependent dampers. It can be used in the seismic retrofit as well as new construction projects. Analysis results indicate that the structural seismic behavior could be obviously improved due to the adoption of the structure with the LVD, and the seismic response of structure with LVD obviously is reduced, because shear deformation of lead core and viscoelastic material could absorb energy during the earthquake, then the damage of structure can be reduced or during the earthquake. With the characteristics and advantages of the above summery, the LVD has a optimistic application future.

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