EXPERIMENTAL STUDY ON MECHANICAL PERFORMANCE OF A NEW HYBRID LEAD VISCOELASTIC DAMPER

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Abstract

Passive control technology is an effective solution to alleviate structural response in earthquakes. In that solution, dampers are used to absorb the energy input from earthquake for reducing damage of building. A new hybrid lead viscoelastic damper (HLVD) is proposed in this paper. Dissipation of energy is provided for with the use of viscoelastic material that works in shear and of the multiple lead cores that act in shear. The prototype product of HLVD was designed and three identical damper specimens were fabricated. Each damper was subjected to harmonic loading to investigate the effects of strain amplitude, cyclic loading and loading frequency on the mechanical properties of HLVD. Hysteretic load-displacement curves for each specimen were recorded and plotted. The experimental results show that the developed HLVD has stable and plump hysteretic loops under cyclic loads. During 30 cycles of cyclic loading at 100% shear strain, the hysteretic curves shrink obviously in the first 5 cycles. Then it gradually stabilizes, and almost completely coincide in the last 10 cycles. Meanwhile, the mean maximum damping force ($\boldsymbol{P}_{\max}$), effective stiffness ($\boldsymbol{K}$) and absorbed energy ($\boldsymbol{E}$) of HLVD experienced a slow decline in that period. The hysteretic loops, $\boldsymbol{P}_{\max}$, $\boldsymbol{K}$ and $\boldsymbol{E}$ of HLVD at 100% shear strain has negligibly changed under loading frequencies of 0.02 Hz, 0.05 Hz and 0.1 Hz, which indicates that the mechanical properties of HLVD are basically insensitive to the loading frequency.

Keywords: passive control; damper; loading frequency; mechanical performance;

1. Introduction

In recent years, a demand on the earthquake resistant and protect system has been consistently increasing due to the occurrence of strong earthquakes that resulted in huge loss of life and property such as 2008 Wenchuan earthquake and 2013 Lushan earthquake in China. How to ensure the satisfactory seismic performance and resilience of buildings has become an urgent problem to be solved in the earthquake engineering field [1-3].

The passive control technique is to add additional damping to the structure to reduce the dynamic response of structure. It is proved that the passive control technology is efficient solution to reduce the structural damage and control the structural vibration in actual earthquakes [4]. The strategy to provide the extra damping force is to install dampers within the building. These damper can absorb the energy input from earthquake.

The existing dampers can be basically grouped into two broad categories: velocity-dependent dampers and displacement-dependent dampers. Viscoelastic damper, a kind of velocity–dependent damper made of elastomeric materials, can absorb energy at very small vibration amplitudes. What's more, due to the restorability of the elastomeric material, there is no residual deformation in the viscoelastic damper after earthquakes. However, the mechanical properties of viscoelastic dampers are greatly affected by displacement amplitude [5], loading frequency [6], and ambient temperature [7], which is disadvantageous for the design and application of building structures using viscoelastic dampers. Metallic damper, a sort of displacement–dependent damper, utilizes plastic deformation of metal materials to absorb seismic energy. Its advantage is that it can provide both greater additional stiffness and damping to the structure. But metallic dampers need be replaced after the earthquake because the cumulative plastic deformation of steel will cause failure of dampers. These works of replacement add to the cost of repairing buildings and lengthen the time making buildings into reuse. The concept of resilience puts forward a higher demand for damper characteristics.

Lead is an elastic-perfectly plastic metal material with remarkable energy-absorbing ability. It is worth noting that lead has a dynamic recrystallization ability that allows the properties of lead materials to return to its original state after undergoing plastic deformation. In other words, lead dampers can be reused after an earthquake and do not need to be replaced. The combination of viscoelastic and lead materials has become a notable idea for the research of high performance dampers. The most successful example is the lead rubber bearing (LRB) invented in New Zealand, an isolator that is widely used to protect buildings and bridges [8]. In this paper, a new hybrid lead viscoelastic damper (HLVD) is proposed. An experimental study was carried out to investigate the mechanical properties of HLVD.

2. Hybrid lead viscoelastic damper

HLVD products, consisting of multiple lead cores, laminated rubber and steel plates, are shown in Figure 1. The viscoelastic composite vulcanized from a layer of rubber and thin steel plate is sandwiched between the shear and restrain plates. The lead rods are put into the reserved holes and sealed by the close plates. The limit block is fixed to the top plate by high strength bolts. Meanwhile, a friction plate is sandwiched between the limit block and the restrain plate. The top and bottom plates transmit relative drift between upper and lower floors.

In order to comprehensively investigate the mechanical properties of HLVD, three identical damper specimens were manufactured based on prototype product and tested under different loading conditions. In particular, shear tests under harmonic loading were performed to study the strain amplitude and frequency dependency of the damper response. In addition, the effect of cyclic loading on the mechanical properties of HLVD were examined. The numbering and corresponding test contents of three specimens are summarized in Table 1.

Table 1 - Specimen number and research content

Number of specimens	Test contents
1#	Strain amplitude dependency
2#	Effect of cyclic loading
3#	Loading frequency dependency

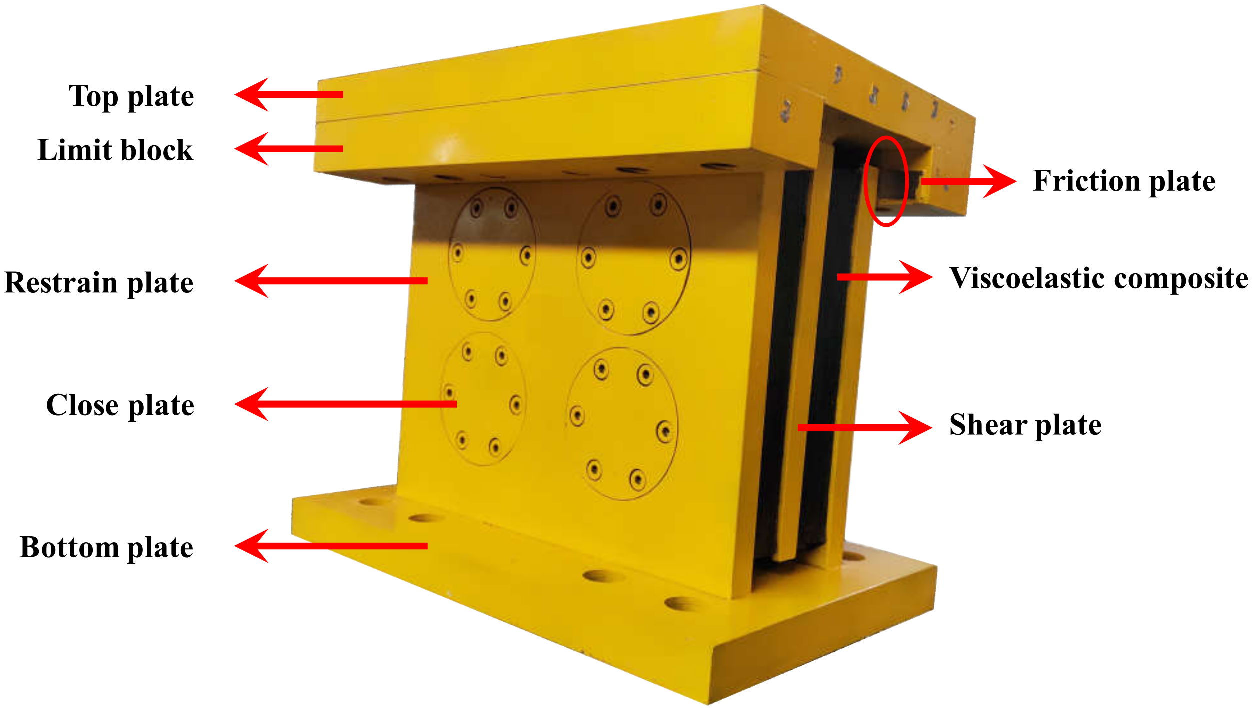


Figure 1 - Prototype of HLVD

3. Experimental program

3.1 Specimen design

The total thickness of the laminated rubber in a viscoelastic composite excluding the thin steel plate is 30 mm. The plane size of a sheet rubber is 400 mm × 300 mm. The diameter of the lead core is 70mm. Steel plates of various thicknesses were mild steel grade Q345. The thickness of the top and bottom plates was 40 mm, which can provide enough strength to apply loading and enough stiffness to eliminate the effect of the deformation of the steel plate.

3.2 Test setup

An electro-hydraulic servo compress-shear testing machine was used to apply horizontal load (***P***) to the specimens. In the horizontal direction, the maximum force and displacement that the machine can reach are 1500 kN and 600 mm, respectively. The vertical load of the machine remained at 0 kN throughout the horizontal loading process. The actual test site is shown in Figure 2.

The ***P*** was measured by a load sensor installed inside the machine. The relative displacement (***D***) between the up and bottom plates was monitored by an external displacement sensor. The frequency of data acquisition was 20 Hz. In other words, 20 data were acquired in 1 second.

Figure 2 - Test setup

3.3 Test protocol

Table 2 summarizes the loading protocol for three specimens. All tests were conducted using a harmonic loading protocol at ambient temperature. In order to investigate the effects of strain amplitude dependency on the response of HLVD, the 1# specimen was tested at 50%, 100% and 250% shear strain (γ) of rubber. These tests were carried out at a loading frequency (f) of 0.02 Hz for four cycles. The 2# specimen was tested at 100% shear strain for a total of 30 cycles to study the effect of cyclic loading. The frequency dependency of HLVD was investigated by applying the horizontal displacement corresponding to the shear strain of 100 % for three different levels of frequency such as 0.02 Hz, 0.05 Hz and 0.1 Hz.

The horizontal displacement imposed by the testing machine is determined by the target of shear strain. For example, because the total thickness of the laminated rubber is 30 mm, the lateral displacement for the shear strain of ±100 % is ±30 mm.

Table 2 - Test protocol

specimen	**Shear strain γ (%)**	**Loading frequency f (Hz)**	**Number of loading cycles N**
1#	50, 100, 250	0.02	4
2#	100	0.02	30
3#	100	0.02, 0.05, 0.1	4

4. Test results

4.1 1# specimen

In order to study the effects of strain amplitude on the HLVD's behavior, shear tests were conducted on the 1# specimen at shear strains of 50%, 100% and 250%.

During the increase of horizontal deformation, uniform shear deformation of viscoelastic composite can be clearly observed. At the γ = 50% and 100%, no abnormality was found in the appearance of the damper. However, at the γ = 250%, it was found that the laminated rubber was partly peeled off from the shear plate, as shown in Figure 3.

The hysteretic curve of 1# specimen is shown in Figure 4. It can be seen that the hysteretic curve of HLVD is plumper with the increase of horizontal deformation, which also means that HLVD was absorbing more and more energy. At the same time, the coincidence of hysteretic curves for four cycles at the same rubber shear strain is very high, which indicates that the hysteretic property of HLVD is stable. The ultimate deformation capacity of this prototype product exceeds rubber shear strain of 250%.

Figure 3 – 1# specimen

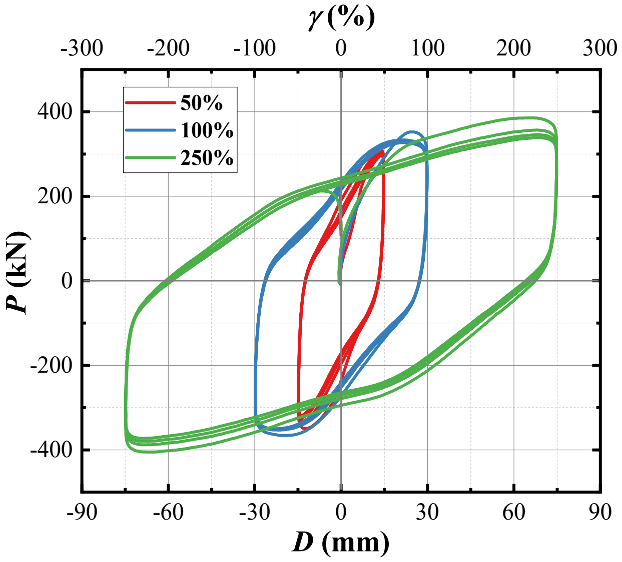


Figure 4 - Hysteretic curve of 1#

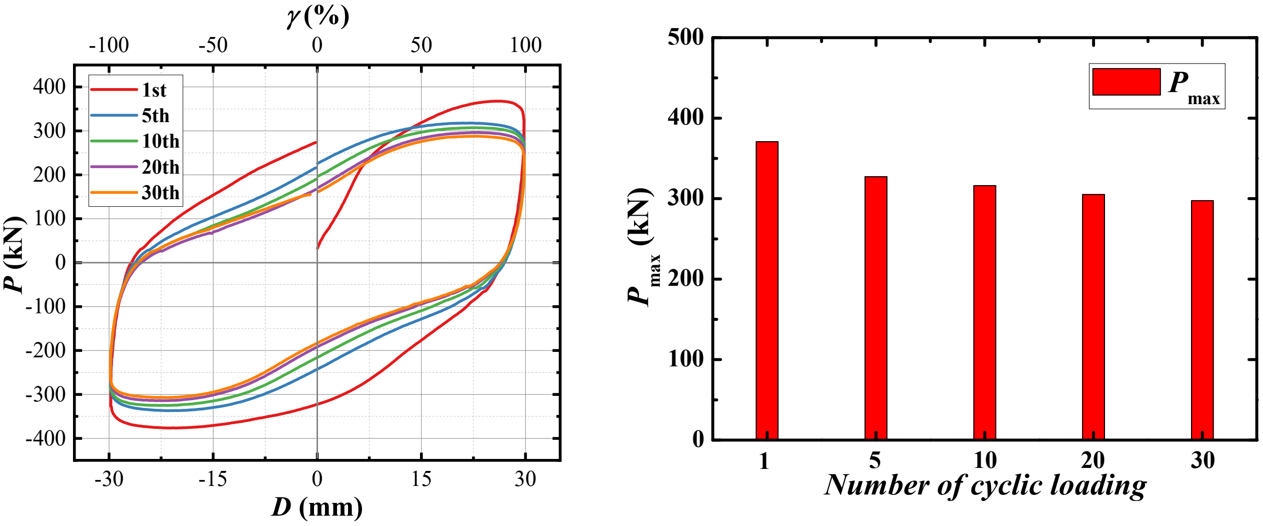
4.2 2# specimen

For evaluate the effects of cyclic loading on HLVD, a total of 30 loading cycles at shear strain of 100% were applied to the 2# specimen at a loading frequency of 0.02 Hz.

In order to clarity, the hysteretic curve of 2# specimen at the 1st, 5th, 10th, 20th and 30th cycles is drawn in Figure 5 (a). As the increase of number of cyclic loading, the hysteresis loop of damper shrinks continuously, especially the first five cycle, which indicates that the damper performance has a certain decline. However, the hysteretic curves from the 20th to the 30th cycle have changed inconsiderably.

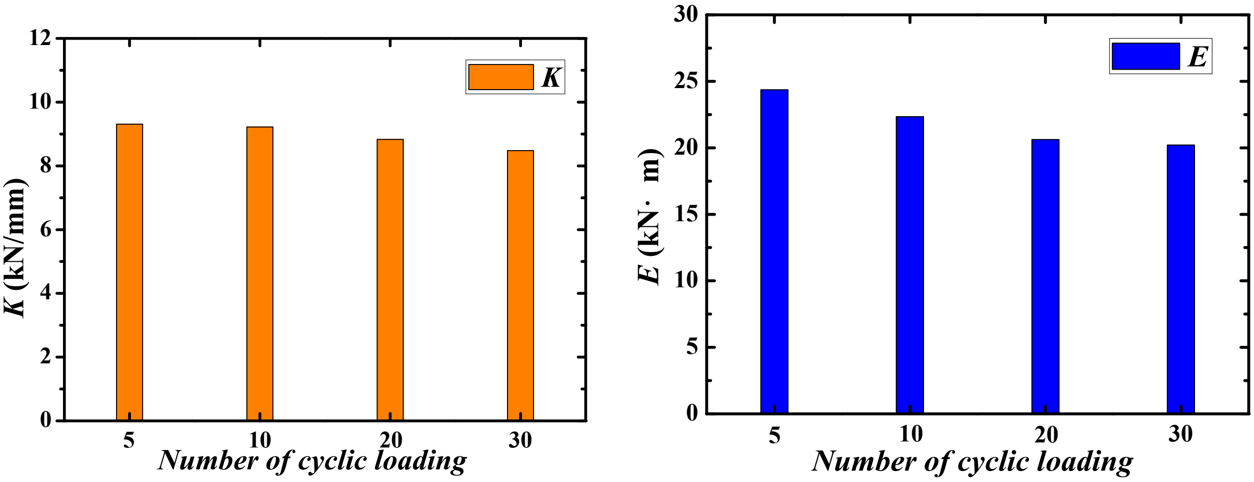
Figure 5 (b) – (d) show the results about mean maximum damping force (**$P_{\max}$**), effective stiffness (**K**) and dissipated energy (**E**) of HLVD. The **$P_{\max}$**, **K** and **E** experienced a slow decline during the process of cyclic loading. In particular, the **K** and **E** decreased from 9.31 kN/mm and 24.36 kN·m at the 5th cycle to 8.48 kN/mm and 20.21 kN·m at the 30th cycle, respectively.

The test results indicate that HLVD has good anti-fatigue performance and the hysteretic behavior and mechanical properties do not continue to deteriorate but remain gradually stable with the increase of the number of loading cycles.



(a) Hysteretic curve

(b) Maximum damping force



(c) effective stiffness

(d) Dissipated energy

Figure 5 – Test results of 2# specimen

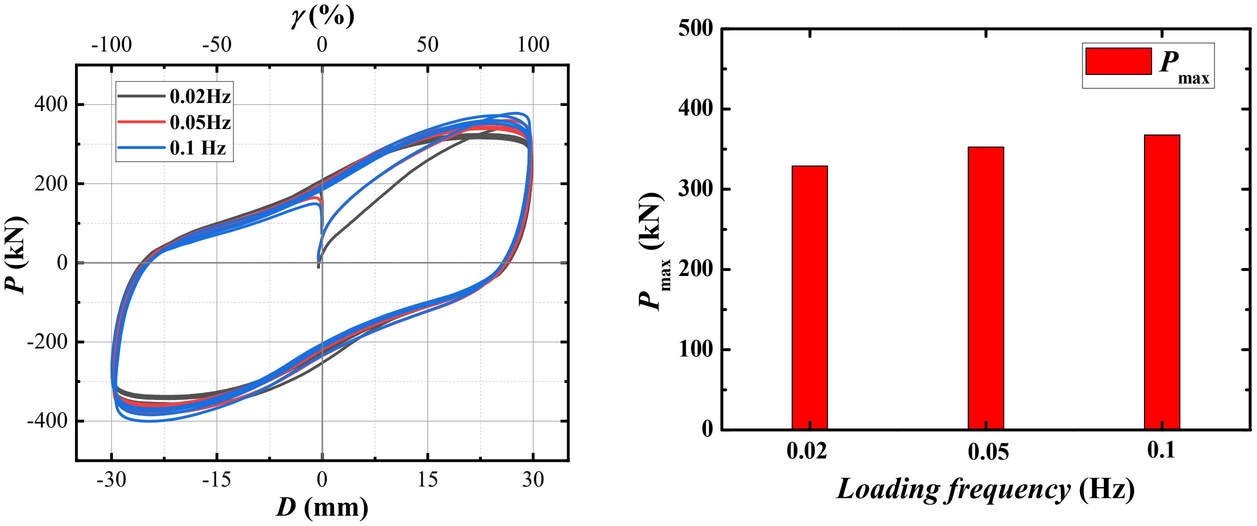
4.3 3# specimen

In order to investigate the effects of loading frequency on the mechanical properties of HLVD, 3# specimen was tested at different loading frequencies of 0.02 Hz, 0.05 Hz and 0.1 Hz under shear strain of 100%.

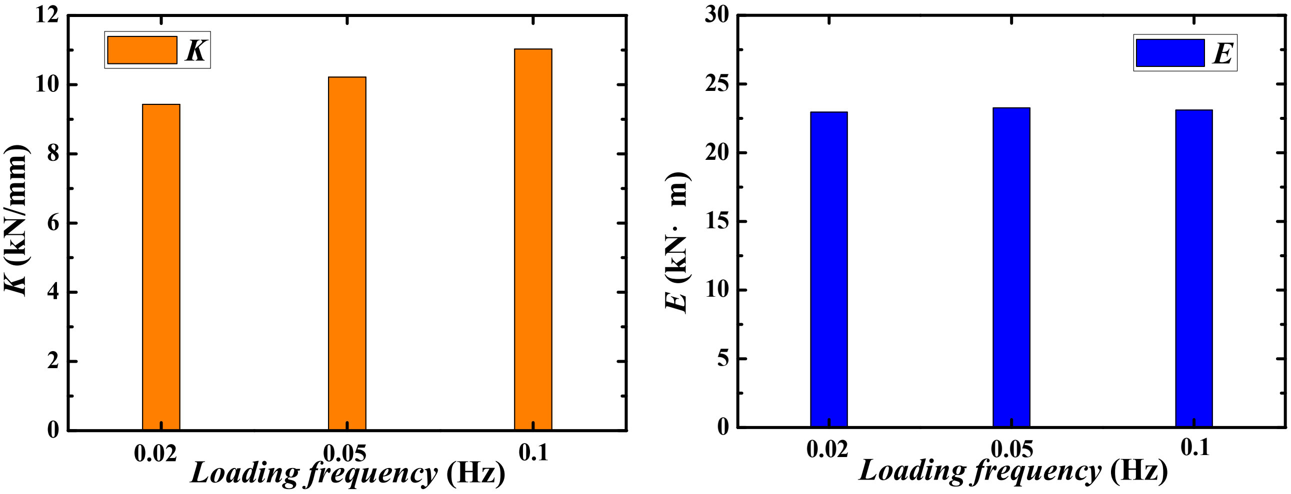
The hysteretic curve of 3# specimen at 100% rubber shear strain in different loading frequency is show in Figure 6 (a). There is no significant change in the hysteretic curves of different loading frequencies, which proves that the performance of HLVD is insensitive to the loading frequency.

As shown in Figure 6 (b) – (d), the range of loading frequencies from 0.02 Hz to 0.1 Hz has witnessed a slight rise in $\boldsymbol{P}_{\max}$ and $\boldsymbol{K}$ of 3# specimen, increasing from 328.97 kN and 9.43 kN/mm at 0.02 Hz to 367.68 kN and 11.03 kN/mm at 0.1 Hz, respectively. The energy consumed of 3# specimen at the 0.02 Hz, 0.05 Hz and 0.1 Hz loading frequencies is 22.95 kN·m, 23.26 kN·m and 23.1 kN·m, respectively.

The test results indicate that the hysteretic response and mechanical properties of HLVD are basically insensitive to the loading frequency from 0.02 Hz to 0.1 Hz.



(a) Hysteretic curve (b) Maximum damping force



(c) effective stiffness (d) Dissipated energy

Figure 6 –Test results of 3# specimen

5. Conclusions

A new hybrid lead viscoelastic damper (HLVD), is proposed in this paper. The construction and principle of HLVD are introduced. The mechanical properties of HLVD were investigated by test. The following conclusions can be drawn from the experiment:

(1) Hysteretic performance of HLVD is stable and excellent. its energy dissipation capacity is strong. The deformation capacity of HLVD is up to over 250% shear strain.

(2) The test results indicate that HLVD has good anti-fatigue performance and the hysteretic behavior and mechanical properties do not continue to deteriorate but remain gradually stable with the increase of the number of loading cycles.

(3) The hysteretic response and mechanical properties of HLVD are basically insensitive to the loading frequency from 0.02 Hz to 0.1 Hz.

6. Conclusions

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