

Study on the performance of lead rubber bearing considering vertical force correlation

Z Y Cheng^{1,2*}, Z D Hu², L Li²

1. School of architecture and materials engineering,
Hubei University of Education, Wuhan, China;

2. Hubei Key Laboratory of Control Structure, Huazhong
University of Science & Technology, Wuhan, China

ABSTRACT

To study the vertical force correlation of the lead rubber bearing, the pseudo static test of the bearing has been carried out, and the test shows that when the vertical force is small, the pre-yield stiffness and the yield shearing force of the bearing are increased with the increase of vertical force, while the post-yield stiffness is decreased with the increase of vertical force. When the vertical force is increased to a certain extent, the bearing parameters may be stable. The bearing parameter has been identified by the least square method, and then, the quantitative relation between the bearing parameter and the vertical force could be obtained. The calculation model and the motion equation of the isolation structure under the multi-dimensional earthquake excitation have been established, and the parameter iteration of bearing obtained from the test has been used for solving the motion equation, from which the seismic response of an isolation structure has been made available when the vertical force of the bearing is considered. The calculation of engineering examples shows that the displacement of the isolation layer will increase after the consideration of the vertical force correlation of the bearing, and the displacement of the upper structure will have a larger overall shifting.

1. INTRODUCTION

The lead rubber bearing not only has mechanical properties meeting requirements of seismic design and use, but also the good applicability, durability and economy [1]. So, it is widely used in all kinds of seismic isolation engineering. As a relatively mature isolation technology, it has been widely recognized by engineering and academic fields both at home and abroad [2, 3]. However, in the past study and application, the influence of vertical force on the isolation performance of lead rubber bearings has usually been ignored [4]. Kelly, Griffith and Aiken [5-7] proved the correlation between the mechanical property of the lead rubber bearing and the vertical force respectively through the experiments. With the increase of horizontal relative displacement, the effect of $P-\Delta$ became more and more significant. Ryan, Kelly and Chopra, et.al [8-9], obtained the variation rule of the yield shearing force of the bearing with the vertical pressure through the pseudo-static experiments of variable axis force, which means that the yield shearing force is zero as the bearing is very low in pressure, increases rapidly with the increase of pressure, and is stable at one point as the pressure is greater than

*Corresponding Author: chengzhiyuan2008@163.com

a certain limit. The above studies only have qualitatively proved that the mechanical properties of lead rubber bearing are correlated to the vertical force, but the quantitative relation between the mechanical parameter and the vertical force is not available. The Japanese Architectural Society has also pointed out that it is difficult to simulate the vertical force correlation of isolation of the rubber lead only with the mechanical theory. In regard to the study on the vertical force correlation of rubber lead isolation bearing, it is recommended that the actually measured data of the experiment shall prevail. Under the action of earthquake, the bearing not only bears the horizontal seismic action, but also the effect of the larger vertical earthquake. Then, the lead rubber bearing will bear the non-negligible vertical seismic force, and its physical and mechanical characteristics will change, thus affecting the seismic performance of the whole isolation structure. In this paper, based on the pseudo static test of the lead rubber bearing, the influence of the vertical force correlation on the isolation performance of the lead rubber bearing has been studied by parameter identification technology, and the quantitative relationship between the physical & mechanical property of the isolation bearing and the vertical force obtained.

2. VERTICAL FORCE CORRELATION TEST OF THE BEARING

2.1. Test equipment

The vertical force correlation test of the bearing has been completed in the Engineering Structure Inspection Center of Huazhong University of Science and Technology. The main test equipment used includes: CS2500/200 load-shear test machine and CZY500 lead rubber isolation bearing.

The CS2500/200 load-shear test system, as shown in Fig.1, mainly consists of the horizontal loading system, the vertical loading system and the data acquisition system. The horizontal loading capacity is $2 \times 10^3 \text{ kN}$, and the displacement stroke is $\pm 600 \text{ mm}$; the vertical loading capacity is $2.5 \times 10^4 \text{ kN}$, and the displacement stroke is $\pm 200 \text{ mm}$. The data acquisition system can complete the horizontal and vertical loading, force and displacement data collection, and display the hysteresis curve and so on.

The CZY500 lead rubber bearing is manufactured by a domestic manufacturer, and its theoretical values of physical and mechanical parameters are shown in Table 1. To reduce the error, two bearings in the same type (numbered CZY500-1 and CZY500-2 respectively) have been used for the parallel test in this test.

Table.1 CZY500 mechanical parameters of isolation bearing

pre-yield stiffness (kN/mm)	13.86
post-yield stiffness (kN/mm)	1.08
yield bearing force (kN)	64.37
$\gamma=100\%$ Equivalent stiffness (kN/mm)	1.75
$\gamma=250\%$ Equivalent stiffness (kN/mm)	1.34

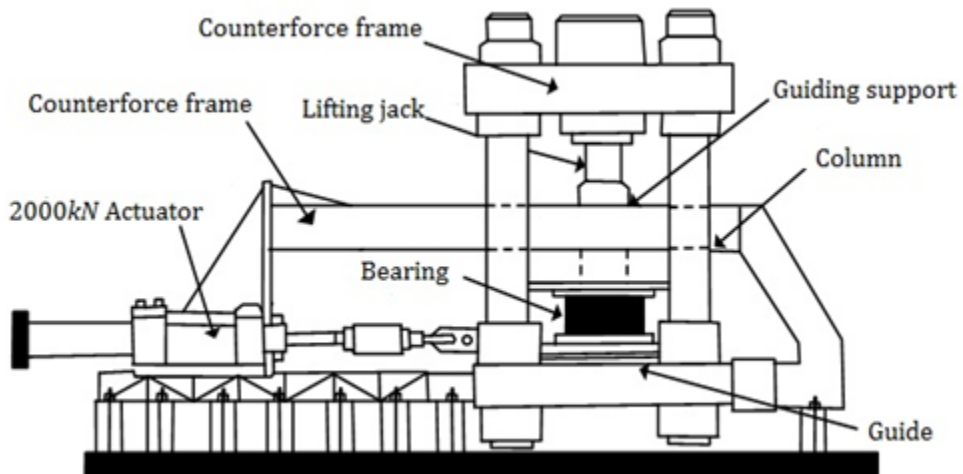
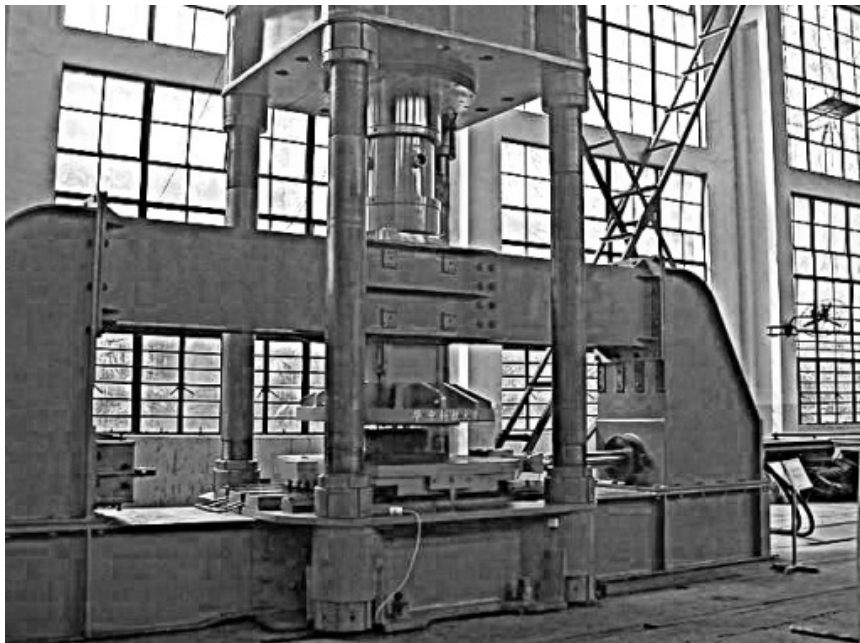


Fig.1 The CS2500/200 load-shear test system

The CZY500 lead rubber bearing is manufactured by a domestic manufacturer, and its theoretical values of physical and mechanical parameters are shown in Table 1. To reduce the error, two bearings in the same type (numbered CZY500-1 and CZY500-2 respectively) have been used for the parallel test in this test.

2.2. Test process

In the test process, the vertical force of the isolation bearing is graded and loaded with the equal step length, and the interval is 1MPa-22MPa and the step length is 1MPa. The specific test steps are as follows:

- a. According to the size of the CZY500 isolation bearing, the plate is installed on the CS2500/200 load-shear test machine, and then, the isolation bearing is fixed on the test machine platform to prevent from the slipping of bearing as the vertical loading force is small.
- b. The vertical loading system begins to make the pressurization, and when the pressure loaded is up to 1MPa, the hysteresis test of the mechanical performance of the bearing is carried out (where the horizontal displacement is $\gamma=100\%$), and each test shall be cycled for 3 times. See the National Code of China [10] for the specific requirements of the hysteretic test of the horizontal performance of bearing. No more detailed description for this.
- c. When the test machine begins to unload after completing the hysteresis test of horizontal performance, the test machine stops for about 30min, and the test bearing recovers to the normal temperature, so that the influence of temperature on the hysteresis performance of the bearing could be eliminated.
- d. Continue to complete the subsequent pressure loading and obtain the hysteretic curve of the bearing under different vertical pressure.

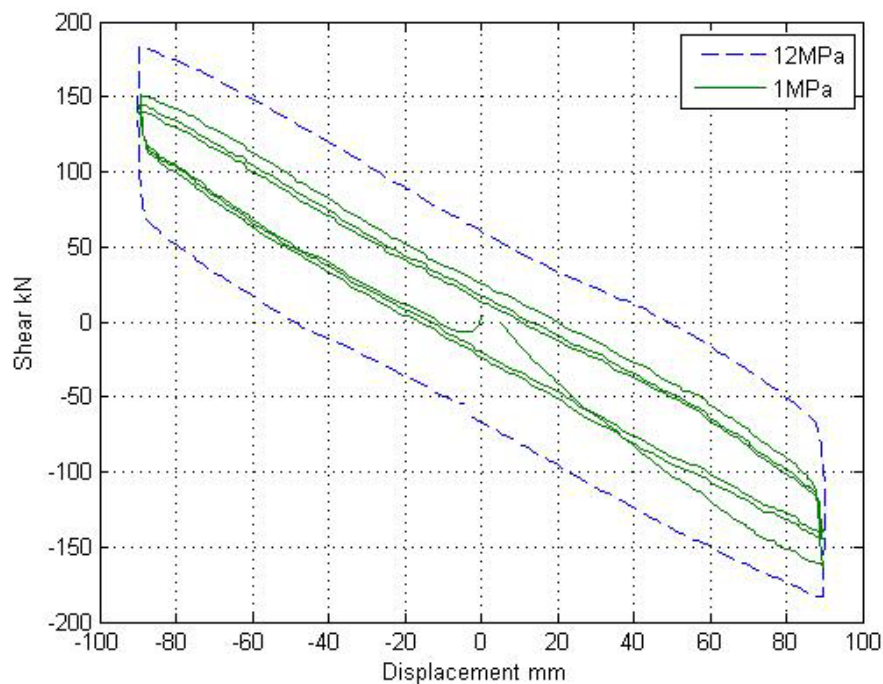
2.3. Test results

Refer to the hysteresis curve of the bearing at the vertical pressure of 12MPa, and the hysteresis curve of the CZY500 lead rubber bearing under the action of vertical load at all levels is shown in Fig.2. For the limitation of paper length, there are only hysteresis curves of the CZY500-1 bearing under the vertical forces of 1MPa, 3MPa, 5MPa, 7MPa, 18MPa and 22MPa drawn.

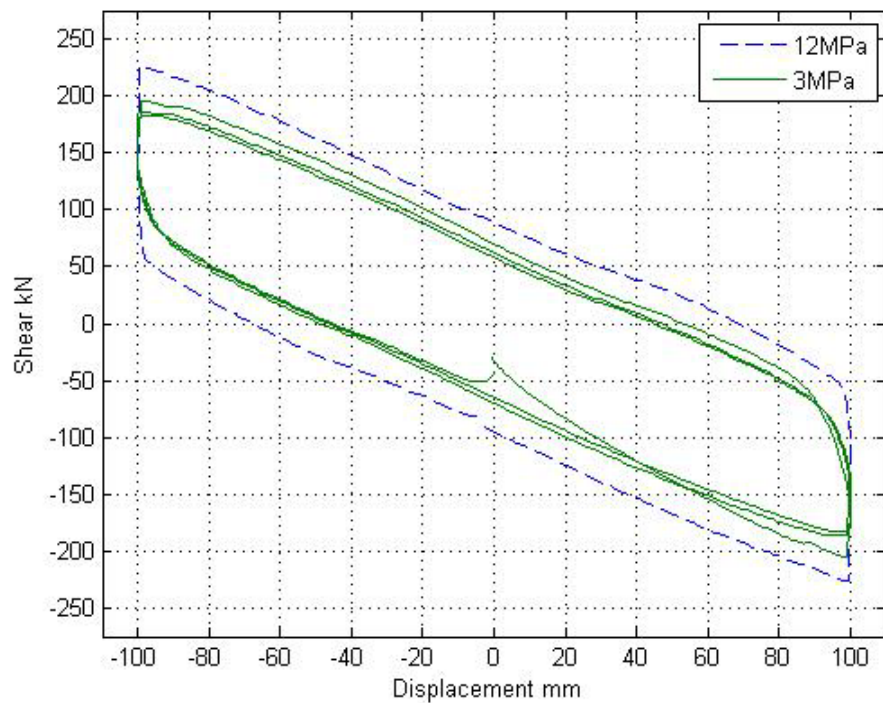
From Fig.2, it can be seen that when the vertical pressure of the lead rubber bearing is relatively small (less than 5MPa), the hysteresis curve is obviously shrinking, and the hysteresis area of the bearing is smaller. When the vertical pressure of the lead rubber bearing is relatively large (greater than 7MPa), the hysteresis curve is little influenced by the vertical pressure, and the hysteresis performance tends to be stable.

2.4. Identification and analysis of bearing parameters

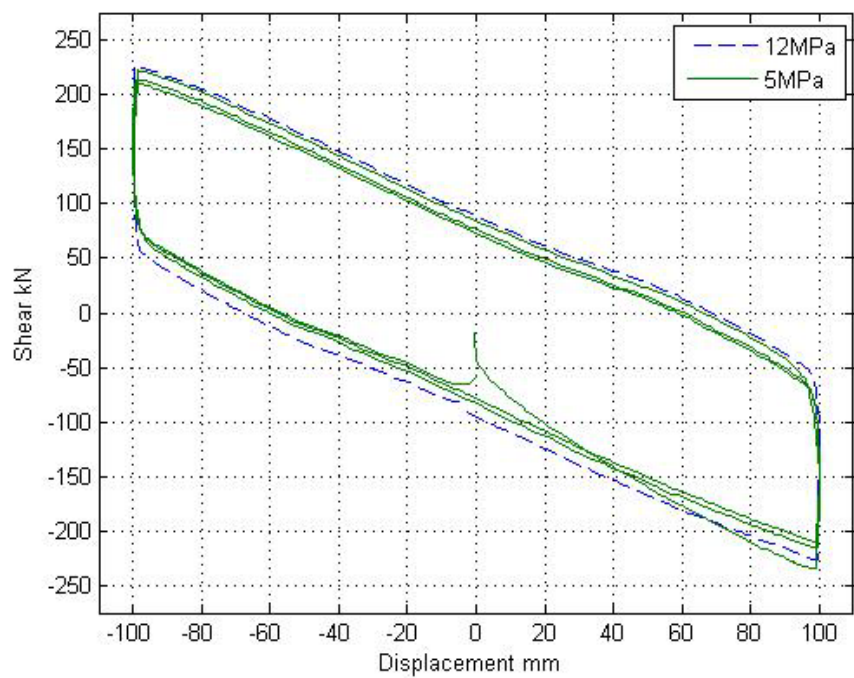
Parameter identification is to determine a set of parameter values based on the test data and the established model, so that the numerical results obtained from the calculation of model could best fit the test data (for the curve fitting problem), and it is commonly used in structural health monitoring and test [11-12]. The least square method is the most widely-used parameter identification method. Its criterion is to find the best function matching [13] of data by minimizing the error sum of squares. Therefore, the least square method is used in this paper for the parameter identification of the isolation bearing for test results. The pre-yield stiffness, the post-yield stiffness and the yield shearing force of the bearing under different vertical loads are quantified, and the regression analysis is used to fit the change curve of the bearing parameter with the vertical load, as shown in Fig.3.



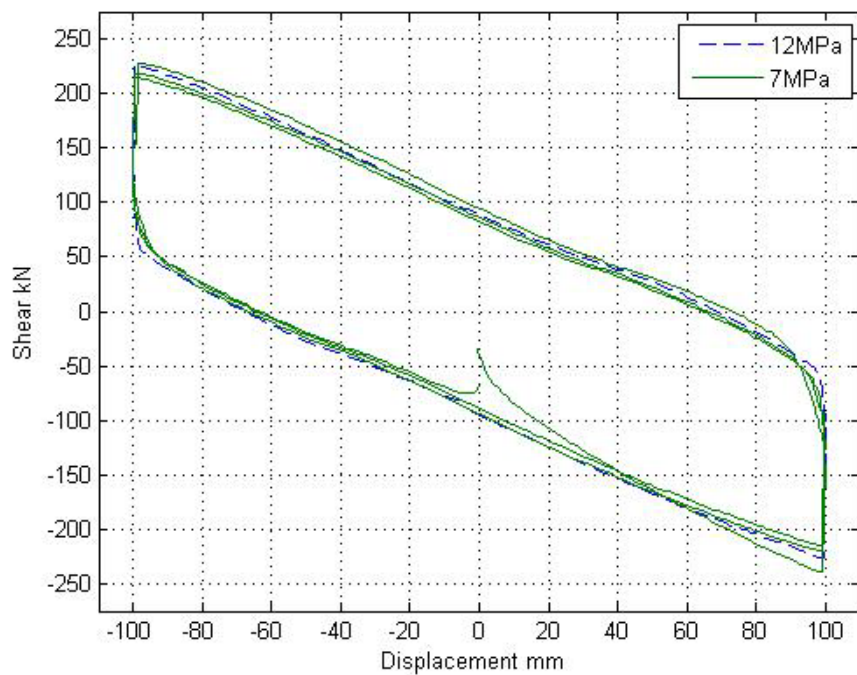
(a)



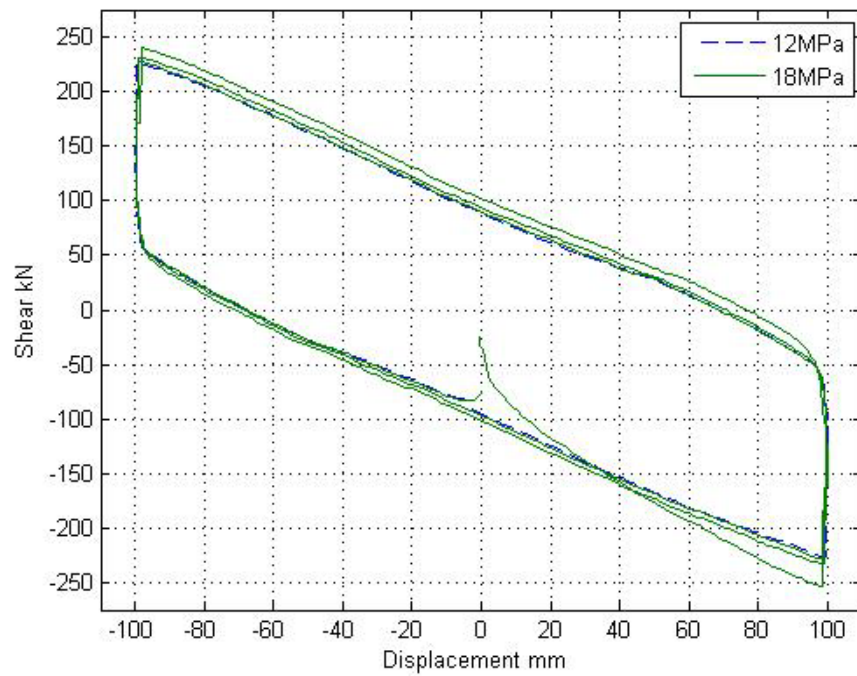
(b)



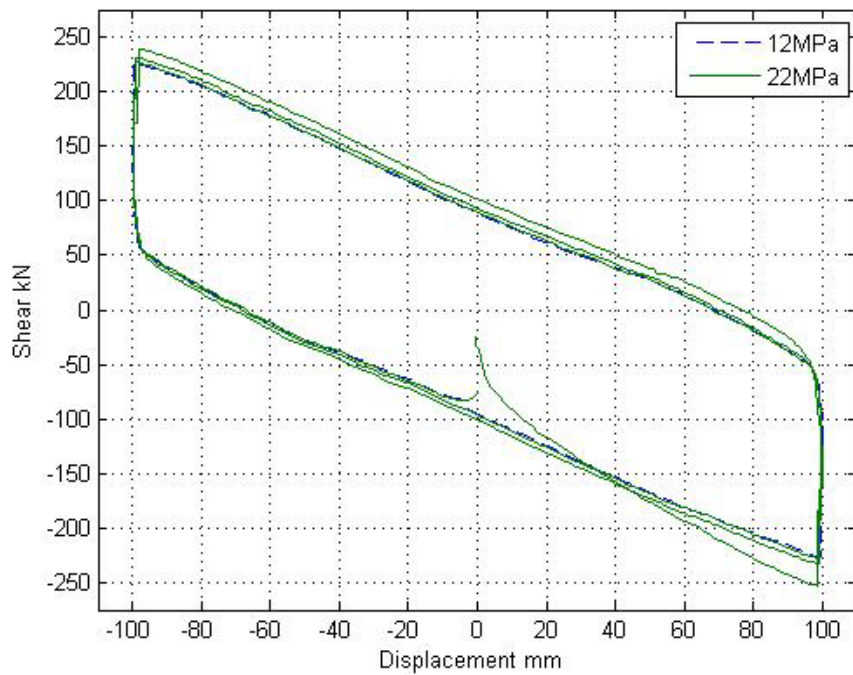
(c)



(d)

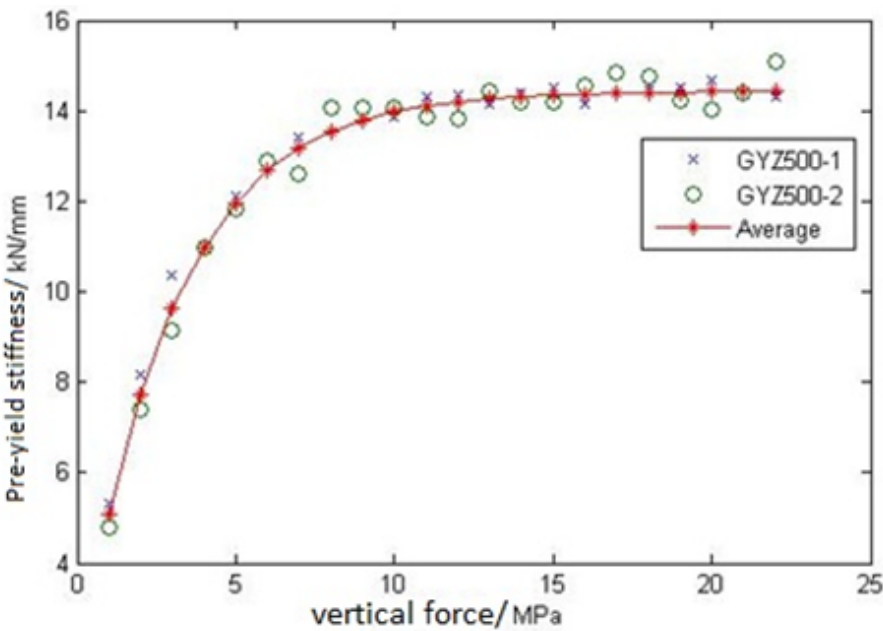


(e)

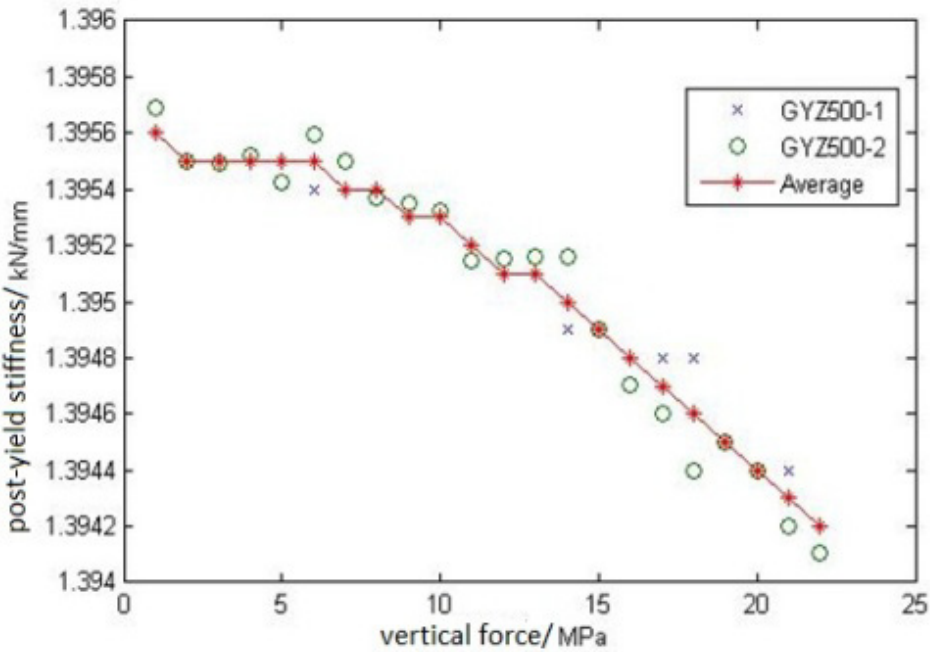


(f)

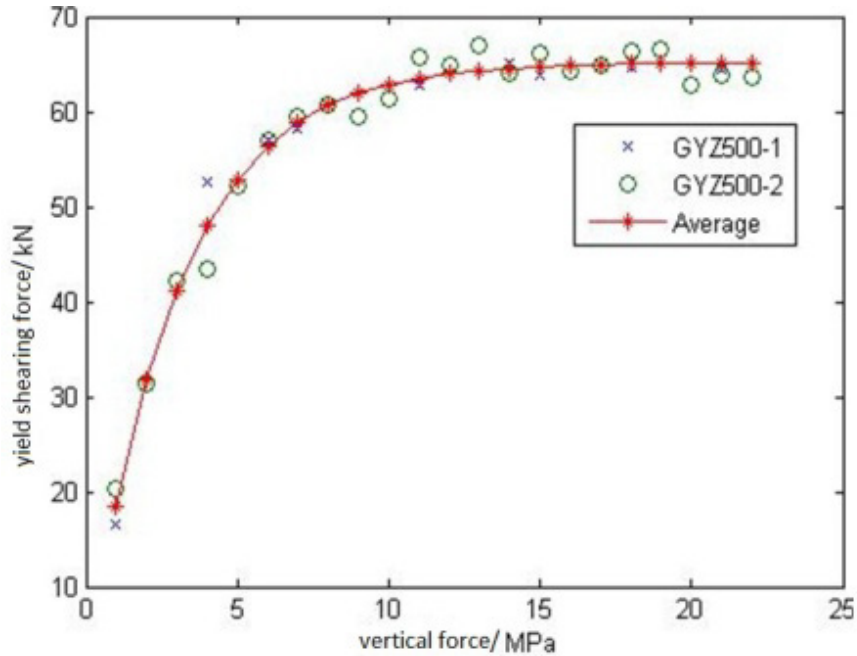
Fig. 2 Hysteretic curves of GZY500 lead rubber bearing under vertical forces at All Levels



(a) Pre-yield stiffness



(b) Post-yield stiffness



(c) Yield shearing force

Fig.3 Bearing parameter identification results of lead rubber bearing under different vertical pressure

From Fig.3, it can be seen that: ① the pre-yield stiffness and the yield shearing force of the lead rubber bearing are greatly influenced by the vertical force. When the vertical force is relatively small, the value increases with the increase of the vertical force, and as the vertical force is further increased, the value tends to be stable. ② the post-yield stiffness is also affected by the vertical force, but its overall trend is decreasing. This is because of the enhancement of $p - \Delta$ effect of the bearing for the increase of vertical force. However, it also can be seen that the post-yield stiffness of the bearing varies little. For the CZY500 bearing, the change range is only between 1.393 and 1.395.

3. ISOLATION STRUCTURE ANALYSIS CONSIDERING VERTICAL FORCE CORRELATION

Ground motion has both horizontal and vertical components during the earthquake. It can be known from the previous test that the parameters of the lead rubber bearing are correlated to the vertical force, and when the vertical force changes, the mechanical properties of the bearing will also change, which means that the bearing parameters are no longer constant. The mechanical properties of lead rubber bearing directly affect the seismic response of isolation structure. Therefore, to study the influence of the lead rubber bearing on the seismic performance of the whole structure after the consideration of the vertical force correlation, the seismic response analysis model and the corresponding motion equation which could consider the vertical earthquake action should be established first, and the vertical force correlation model of the bearing is embedded into it; then, the iterative solution for the motion equation

could be carried out. Finally, the influence of the lead rubber bearing on the isolation structure under the consideration of the vertical force correlation is obtained.

3.1. Calculation model

Generally speaking, the seismic analysis model of the building structure can be shear type [14], where the quality of the wall is concentrated on each floor, as shown in Fig.4(a):

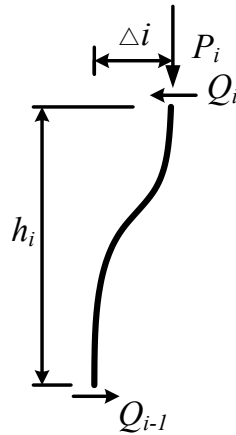
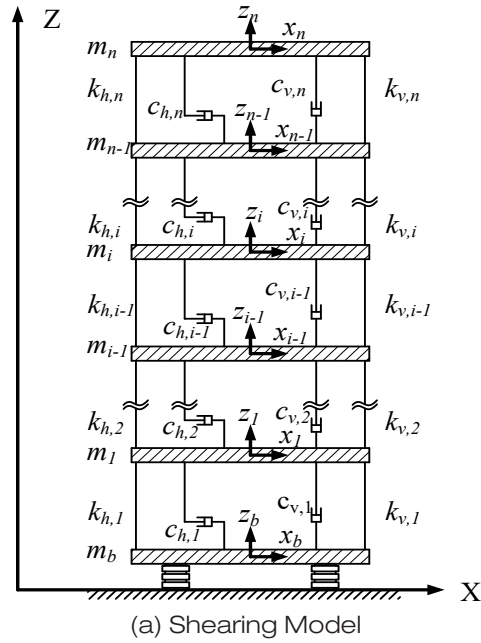


Fig.4 Seismic analysis model of the building structure

$m_1, m_2 \cdots m_n$ is the concentrated mass of each layer of the upper structure; m_b is the quality of the isolation layer; $k_{h,1}, k_{h,2} \cdots k_{h,n}$ is the horizontal stiffness of each layer; $k_{v,1}, k_{v,2} \cdots k_{v,n}$ is the vertical stiffness of each layer; $c_{h,1}, c_{h,2} \cdots c_{h,n}$ is the horizontal damping of each layer, and $c_{v,1}, c_{v,2} \cdots c_{v,n}$ is the vertical damping of each layer. Considering the second moment effect (P- Δ effect) of each layer of the structure (that is, the horizontal and vertical geometric nonlinear couplings as shown in Fig.4(b), the shear Q_i of the i^{th} layer column can be expressed as:

$$Q_i = k_{h,i} (x_i - x_{i-1}) + \frac{P_i \Delta_i}{h_i} \quad (1)$$

Where, x_i is the horizontal displacement of the i^{th} layer column; h_i is the height of the i^{th} layer column; p_i is the axial force of the i^{th} layer column, and it can be calculated by the following formula.

$$P_i = k_{v,i} (z_i - z_{i-1}) - m_i g \quad (2)$$

3.2. Motion equation

According to the dynamic analysis model of the isolation structure shown in Fig.4, the motion equations of the isolation layer, the standard layer and the top layer of the isolation structure can be directly established. The motion equation of the seismic isolation layer is shown in (3) and (4); that of the standard layer in (5) and (6), and that of the top layer in (7) and (8).

$$m_b \ddot{x}_b + c_{h,1} (\dot{x}_2 - \dot{x}_1) - c_{h,b} (\dot{x}_1 - \dot{x}_b) + k_{h,1} (x_1 - x_b) + \frac{P_1 (x_1 - x_b)}{h_1} - \sum f_{bh,i} = -m_b \ddot{x}_g \quad (3)$$

$$m_b \ddot{z}_b + c_{h,1} (\dot{x}_2 - \dot{x}_1) - c_{v,b} (\dot{z}_1 - \dot{z}_b) + k_{v,1} (z_1 - z_b) - \sum f_{bv,i} = -m_b \ddot{z}_g \quad (4)$$

$$m_i \ddot{x}_i + c_{h,i} (\dot{x}_i - \dot{x}_{i-1}) - c_{h,i-1} (\dot{x}_{i-1} - \dot{x}_{i-2}) + k_{h,i} (x_{i+1} - x_i) + \frac{P_{i+1} (x_{i+1} - x_i)}{h_{i+1}} - k_{h,i-1} (x_i - x_{i-1}) - \frac{P_i (x_i - x_{i-1})}{h_i} = -m_i \ddot{x}_g \quad (5)$$

$$m_i \ddot{z}_i + c_{v,i+1} (\dot{z}_{i+1} - \dot{z}_i) - c_{v,i} (\dot{z}_i - \dot{z}_{i-1}) + k_{v,i+1} (z_{i+1} - z_i) - k_{v,i} (z_i - z_{i-1}) = -m_i \ddot{z}_g \quad (6)$$

$$m_n \ddot{x}_n + c_{h,n} (\dot{x}_n - \dot{x}_{n-1}) + \left[k_{h,n} + \frac{k_{v,n} (z_n - z_{n-1}) - m_n g}{h_n} \right] (x_n - x_{n-1}) = -m_n \ddot{x}_g \quad (7)$$

$$m_n \ddot{z}_n + c_{v,n} (\dot{z}_n - \dot{z}_{n-1}) + k_{v,n} (z_n - z_{n-1}) = -m_n \ddot{z}_g \quad (8)$$

In the formula (3) and the formula (4), $f_{bh,i}$ and $f_{bv,i}$ are respectively the horizontal shear and the vertical axial force of the i^{th} lead rubber bearing in the isolation layer, and could be solved by the time history analysis of seismic wave based on the earthquake excitation [15-16]. The horizontal stiffness $k_{h,i}$ of the isolation bearing is evaluated for value according to the results fitted in Fig.3. The vertical stiffness $k_{v,i}$ of each layer is evaluated for value according to the structural mechanics method based on the material used and is a constant. In this way, the seismic response of the structure can be obtained by solving the above motion equations iteratively.

4. ENGINEERING EXAMPLE

To study the influence of the isolation bearing on the seismic performance of the building structure under the consideration of the vertical force correlation, this paper takes a student apartment building in a school as an example. The project includes a five-storey frame structure with the height of 3.6m, the horizontal stiffness of each layer of $k_{h,i} = 11 \times 10^4 \text{ kN/m}$ and the vertical stiffness of $k_{v,i} = 101 \times 10^4 \text{ kN/m}$. The first-floor underground is the isolation layer, and the lead rubber bearing is used for the base isolation. The isolation bearings belong to CZY500, and there are 12 bearings, with the height of 1.8m. Before the isolation, the horizontal natural vibration period is $T_h = 0.578 \text{ s}$, while the vertical natural vibration period is $T_v = 0.06 \text{ s}$. After the isolation, the periods of them are $T'_h = 1.343 \text{ s}$ and $T'_v = 0.05 \text{ s}$ respectively. Seismic wave is *El-Centro* wave selected, and the horizontal peak acceleration is $a_{h,\max} = 4 \text{ m/s}^2$, while the vertical peak acceleration is $a_{v,\max} = 2.67 \text{ m/s}^2$. The motion equations of the above formulas (3)-(8) are solved iteratively, and the seismic response of each layer under *El-Centro* wave excitation can be obtained. The time history curve of displacement of the isolation layer is shown in Fig.5.

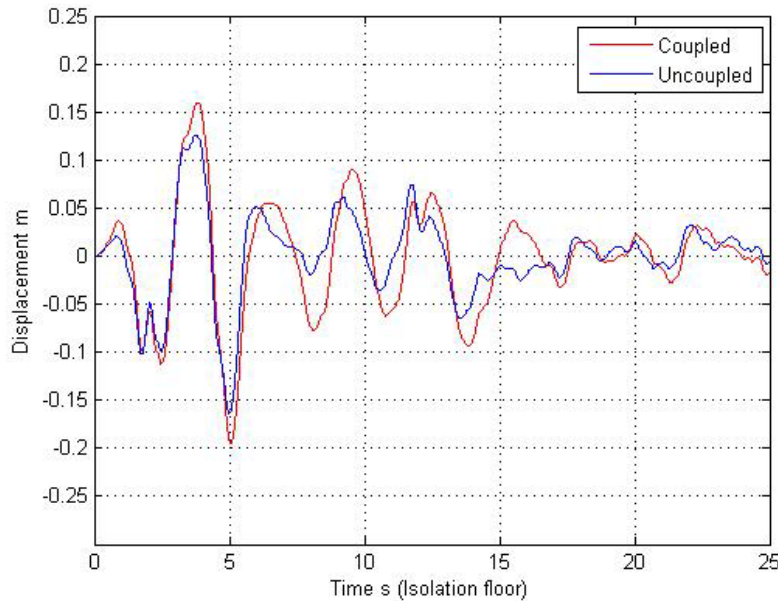


Fig.5 Displacement time curve of isolation layer

The peak displacement of each floor is shown in Fig.6.

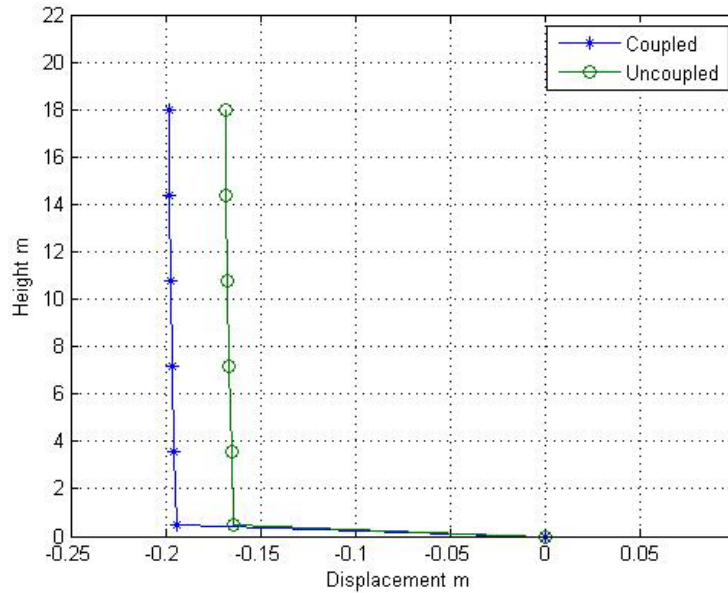


Fig.6 Comparison of peak displacements of each floor

From Fig.5 and Fig.6, it can be seen that under the same earthquake excitation, the isolation structure with lead rubber bearing as the vertical force correlation has been considered and that as no vertical force correlation has been considered both have similar motion laws, but the displacement peak of the former is larger than that of the latter. Simultaneously, for the upper layers, the displacement of the former is equivalent to the whole migration on the basis of the latter, which is in accordance with the previous rules of the study[17].

5. CONCLUSION

In the traditional lead rubber isolation bearing, the influence of the vertical force correlation on the performance of the bearing is not considered in the design, which causes that the seismic performance of the isolation structure is not in conformity with the actual situation, especially in the few floors and the small initial vertical force of the bearing, this error is more obvious. Therefore, in the design of lead rubber isolation bearing, especially under the action of vertical strong earthquake, the influence of the vertical force correlation on the performance of lead rubber bearing should be fully considered. This correlation is mainly reflected in the following two aspects:

- The influence of geometric nonlinearity. When the lead rubber bearing has a larger horizontal displacement, the $p - \Delta$ effect from the vertical force cannot be ignored, which means that in a certain range, the horizontal stiffness of the isolation bearing will decrease with the increase of the vertical force.
- The influence of material nonlinearity. The yield shearing force of the bearing is related to the vertical force. When the bearings are in the same horizontal displacement, the hysteresis areas increase with the increase of the vertical force in a certain range, which means that the yield shearing force of the bearing increases with the increase of the vertical force.

ACKNOWLEDGMENTS:

This paper is supported in part by the National Natural Science Fund (51508168), Technology Creative Project of Excellent Middle & Young Team of Hubei Province (No. T201620), Research Start-up Funding of Hubei University of Education Grant (NO. 8).

REFERENCES

- [1] Jong Wan Hu, Seismic analysis and parametric study of SDOF lead-rubber bearing (LRB) isolation systems with recentering shape memory alloy (SMA) bending bars [J]. *Journal of Mechanical Science and Technology*, 2016, 30 (7), 2987-2999.
- [2] C.P.Providakis, Effect of LRB isolators and supplemental viscous dampers on seismic isolated buildings under near-fault excitations [J]. *Engineering Structures*, 2008,30(5): 1187-1198.
- [3] Donghun Lee, Michael C. Constantinou. Further results on the heating of single and multi-core lead-rubber bearings and dampers [J]. *Bulletin of Earthquake Engineering*, 2016, 14 (4):999-1016.
- [4] WANG Jian-qiang, SHEN Xu, LI Zheng,et al. Influence of vertical load on mechanical properties of lead-rubber bearings [J]. *World Earthquake Engineering*, 2015,31(2):143-147. (in Chinese)
- [5] Aiken, I. D., Kelly, J. M., Tajirian, F. F. Mechanic of low shape factor elastomeric seismic isolation bearings. UCB/EERC-89/13[R]. Berkeley, 1989.
- [6] Clark, P. W., Aiken, I. D., Kelly, J. M. Experimental studies of the ultimate behavior of seismically-isolated structures. UCB/EERC-97/18[R]. Berkeley, 1997.
- [7] Griffith, M. C., Kelly, J. M., Coveney, V. A. Experimental evaluation of medium-rise structures subject to uplift. UCB/EERC-88/02[R]. Berkeley, 1988.
- [8] Ryan, K., Kelly, J. Experimental observation of axial load effects in isolation bearings[C]. *Proceedings of the 13th World Conference on Earthquake Engineering*, Canada. Vancouver, 2004.
- [9] Ryan, K. L., Kelly, J. M., Chopra, A. K. Nonlinear Model for Lead-Rubber Bearings Including Axial-Load Effects[J]. *Journal of Engineering Mechanics*, 2005, 131(12): 1270-1278.
- [10] GB20688.1-2007. First parts of rubber bearing: Test method for rubber isolation bearing [S]. Beijing: China Standard Press,2007. (in Chinese)
- [11] Zghal M, Mevel L, Moral P D. Modal parameter estimation using interacting Kalman filter[J]. *Mechanical Systems & Signal Processing*, 2014, 47(s1-2): 139-150.
- [12] Liu Y C, Loh C H, Ni Y Q. Stochastic subspace identification for output-only modal analysis: application to super high-rise tower under abnormal loading condition[J]. *Earthquake Engineering & Structural Dynamics*, 2013, 42(4): 477-498.
- [13] TANG Xu-qing. Numerical calculation method [M]. Beijing: Science Press,2015. (in Chinese)
- [14] Yildirim S E, Turgut K, Cihan D, Seismic analysis and investigation of damage mechanism of 57th infantry regiment memorial using finite-discrete element method[J]. *Bulletin of Earthquake Engineering*, 2017, 5(4):1397-1424.

- [15] Jangid R S. Optimum lead-rubber isolation bearings for near-fault motions [J]. Engineering Structures, 2007, 29(10): 2503-2513.
- [16] LU Hong-shan. Disaster risk analysis based on ground motion parameters [D]. Beijing: Institute of Geophysics, China, Earthquake Administration, 2004. (in Chinese)
- [17] Fabio Mazza, Alfonso Vulcano. Effects of near-fault ground motions on the nonlinear dynamic response of base-isolated RC framed buildings [J]. Earthquake Engineering and Structural Dynamics, 2011, 41(2): 211-232.

