Experimental study on mechanical properties of high damping rubber bearing model

Yale Li¹²,a, Zhouhong Zong¹b, Xueyang Huang³,c, Jian Xia³,a,d and Lu Liu¹,e

¹School of Civil Engineering, Southeast University, Nanjing 210096, China; ²Jincheng college, Nanjing University of Aeronautics and Astronautics, Nanjing 211156, China; ³Fujian Academy of Building Research, Fuzhou 350025, China; ⁴Fujian Provincial Key Laboratory of Green Building Technology, Fuzhou 350025, China

E-mail: ¹812044475@qq.com; ²1600764796@qq.com; ³656469441@qq.com; ⁴811493133@qq.com; ⁵657174807@qq.com

Abstract. A high damping rubber bearing was designed and manufactured in order to reduce the seismic response of the bridge structure. The experimental study on its mechanical properties was carried out. The results show the horizontal equivalent damping ratio is 16.77% when the shear strain is 175%. If the shear strain is larger, the post yield stiffness will be smaller as well as the horizontal equivalent stiffness. However, the equivalent damping ratio and yield force will be larger. If the vertical compressive stress is greater meanwhile the loading frequency is faster, and number of repeated loading is smaller, the equivalent stiffness and the post yield stiffness will be larger as same as the equivalent damping ratio. Destruction didn’t occur if the shear strain was no more than allowable shear strain (250%), and the ultimate shear strain was 350%. Compression destruction came when pressure stress was 10MPa. In the case of failure, the bearing was stable, but had large, nonrecoverable vertical and horizontal deformation. The study results can be used as the basis for shaking table test of seismic isolated continuous girder bridge with high damping rubber bearing and the reference for relative seismic isolated bridge design.

1. Introduction

Vibration isolation rubber bearings include natural rubber bearing, lead rubber bearing, and high damping rubber (HDR) bearing. The lead rubber bearing has been widely used in the bridge structure at home and abroad due to its good damping effect[1-3]. It is worth noting that environmental pollution is unavoidable in the production of lead core. After experiments, it was found that the lead core which is the source of damping would be fatigue destroyed under low cyclic loading[4]. If the lead bearing rubber fails, pollution will be caused by lead core leakage. Therefore, scholars began to study on other isolation bearings such as HDR bearing. Bhuiyan et al. established the elastic viscoplastic rheological model of HDR bearing by the horizontal performance test[5]. Markou et al. established a non-linear rheological model to explain the Mullins effect HDR bearing[6]. Monzon et al. studied the seismic response of 1:4 steel plate bridge with HDR bearing by shaking table test[7].

HDR bearing is a new type of seismic isolation bearing developed in recent years. It sets the vertical bearing capacity, the level of restoring force and damping performance. Its initial elastic stiffness to resist wind load, is similar with laminated rubber bearings. The damping ratio is greater than 12% under large displacement[8], which is much higher than that of the plate rubber bearing and
less affected by temperature[4]. At present, HDR bearing with damping ratio greater than 20%, which is called super high damping rubber (SHDR) bearing, has been developed. SHDR bearings have been applied on Hong Kong-Zhuhai-Macao Bridge[9,10]. It can be predicted that there will be a large number of HDR isolated bridges in the future, so it is of practical significance to study the seismic performance of HDR isolated continuous girder bridges.

2. Bearing model design and test conditions

2.1. Design of bearing model
The size of HDR bearing model is smaller than the conventional bearing in bridge engineering, in order to be utilized for the shaking table test of two span continuous girder bridge model. The upper and lower connecting plates size is 24cm × 24cm and the rubber body is a cylinder with a diameter of 15cm. The inner part of the bearing is a laminated structure, which comprises 4 layers of 2mm steel plate and 4 layers of 5mm rubber, shown in figure 1.

![Figure 1. HDR bearing structure.](image)

2.2. Test condition
The test was carried out in the laboratory of Hengshui Taiwei New Materials Polytron Technologies Inc. The test equipment is 2000 ton electro-hydraulic servo dynamic pressure shear test machine produced by Ji’nan Sanyue Testing Instruments Co.Ltd, as shown in figure 2.

![Figure 2. Pressure shear test machine.](image)

3. Compression test of bearing model
Bearing model compression test was carried out by using the loading method specified in GB/T 20688.1-2007[11] 6.3.1.3, in accordance with the requirements of the JT/T 842-2012[8] 6.6.1. Loading of 3 cycles was from 0 to maximum design pressure to 0 and only the last cycle was calculated. Compression stiffness can be deduced by Eq.1:

$$K_v = \frac{P_2 - P_1}{Y_2 - Y_1}$$

(1)

Where $K_v$=Compression stiffness; $P_1$=26.55kN; $P_2$=106.2kN; $Y_1$, $Y_2$=the corresponding vertical compression displacement of $P_1$ and $P_2$. $K_v$ was calculated as 91.94kN/mm. Therefore, the modified elastic modulus $E_c$ of the bearing model is 103.9MPa.

4. Shear test of bearing model
In accordance with the requirements of the JT/T 842-2012[8] 6.6.3, bearing model horizontal shear test was carried out by using the loading method specified in GB/T 20688.1-2007[11] 6.3.2. The vertical stress is 6MPa and the shear strain is 175%. Loading frequency was set to 0.05Hz, in order to
ensure the test security. The average equivalent stiffness $K_h$ and equivalent damping ratio of the 2–11th cycle tests were obtained as test results after loading 11 cycles. $K_h$ is 0.924kN/mm and $\eta_{eq}$ is 16.77%.

5. Shear properties correlation test of bearing model

The horizontal shear performance test results were obtained by using certain vertical stress, shear strain, loading frequency and loading times. Performance indicators will be affected if any of the above 4 factors changes. Thus the shear performance of the bearing model was studied by correlation test.

5.1. Shear strain correlation

The compressive stress was 6MPa and the loading frequency was 0.05Hz. The maximum shear strain were 50%, 100%, 150%, 175%, respectively. The curves of horizontal equivalent stiffness, yield stiffness, yield force and equivalent damping ratio were calculated, as shown in figure 3. The larger the shear strain is, the smaller the equivalent stiffness and yield stiffness are, with greater yield force and equivalent damping force.

![Figure 3. Horizontal performance indicators under different shear strains.](image)

5.2. Vertical compression stress correlation

The horizontal shear performance was tested with different vertical compression stress which was 2MPa, 4MPa, 6MPa, respectively. The maximum shear strain was 175% and the loading frequency was 0.05Hz. Horizontal shear performance indicators were obtained under the third cycle loading (see table 1). The horizontal equivalent stiffness, the yield stiffness and the equivalent damping ratio will increasing, with less yield force as soon as the vertical compressive stress is greater.

| Vertical Stress (MPa) | $k_h$ (kN/mm) | $h_{eq}$ (%) | $k_d$ (kN/mm) | $Q_d$ (kN) |
|----------------------|----------------|-------------|----------------|--------------|
| 2                    | 0.935          | 16.834      | 0.594          | 12.016       |
| 4                    | 0.981          | 17.253      | 0.673          | 10.86        |
| 6                    | 1.053          | 17.494      | 0.764          | 10.184       |

5.3. Loading frequency correlation

The horizontal shear performance was tested with different loading frequency which is 0.02Hz, 0.05Hz, 0.1Hz, respectively. The maximum shear strain was 175% and the vertical compression stress was 6MPa. Horizontal shear performance indicators were obtained under the third cycle loading (see table 2). The horizontal equivalent stiffness, the yield stiffness, the yield force and the equivalent damping ratio are higher as soon as the loading frequency is faster.

| Loading Frequency (Hz) | $k_h$ (kN/mm) | $h_{eq}$ (%) | $k_d$ (kN/mm) | $Q_d$ (kN) |
|-----------------------|---------------|-------------|----------------|--------------|
| 0.02                  | 1.017         | 17.366      | 0.744          | 9.595        |
5.4. Loading times correlation
The horizontal shear performance was tested with 50 times. The maximum shear strain was 175%. Loading frequency was 0.05Hz and the vertical compressive stress was 6MPa. Shear force-shear displacement hysteresis curves of the 1, 3, 5, 10, 20, 30, 50th cycles are plotted in figure 4. The surrounded areas of the hysterisis curves decreased while curves gradually elongated and had the clockwise rotation (see figure 4). The horizontal shear performance changed with the increase of loading times. Horizontal equivalent stiffness $K_h$ and the yield stiffness $K_d$ in figure 5 had a downward trend. The yield strength $Q_y$ decreased with the increase of loading times. The descent speeds of the 1–5th cycles were fast and afterwards the speeds were stable (see figure 6). Horizontal equivalent stiffness $K_h$ and surrounded area of the hysteresis curve $W_d$ were relevant to equivalent damping ratio $h_{eq}$. $W_d$ decreased rapidly of the 1–10th cycles then slowed down. $K_h$ declined faster than $W_d$ in the 10–20th cycles, so $h_{eq}$ increased in the short term. After 20 times, $W_d$ continued to decline and $K_h$ tended to be stable, so $h_{eq}$ decreased but not significant (shown in figure 7).

![Figure 4. Shear force-shear displacement hysteresis curves.](image)

![Figure 5. Horizontal equivalent stiffness and the yield stiffness.](image)

![Figure 6. Yield strength.](image)

![Figure 7. Equivalent damping ratio.](image)

6. Ultimate shear test of bearing model

6.1. Large deformation shear test
The allowable shear strain was 250%, and the vertical compressive stress was 6MPa. The loading repeated for 3 times with frequency of 0.05Hz. Post test phenomenon is shown in figure 8. The position of the inner steel plate of the bearing model was dislocated, and the surface of the rubber protective layer was marked by steel plates with a small amount of wore surface. But there was no structural damage such as tensile shear failure.

![Figure 8. Large deformation shear test phenomena.](image)

6.2. Ultimate shear test
The vertical compressive stress was 6MPa, and the loading frequency was 0.05Hz. Failure occurred when the ultimate shear strain was 350%. Surface wore (see figure 9(a)), 1 of 4 connecting screws for connecting steel plates and rubber body was cut (see figure 9(b)). The rubber body could not recover.
completely after unloading, and the residual deformation occurred (see figure 9(c)). Measured ultimate shear performance curve is illustrated in figure 10. Failure shear force was 92.3kN. It can be seen from figure 10 that the horizontal stiffness is large when the shear displacement is small, which is suitable for resisting wind load. The horizontal stiffness is small when the shear displacement is large, which means bearing displacement will alleviate bridge seismic response on the condition of the small and medium earthquakes. When the shear displacement is too large, the hardening of the bearing will improve the horizontal stiffness, which is beneficial to controlling the relative displacement between the bridge and the infrastructure.

![Figure 9. Ultimate shear failure.](image)

7. **Ultimate compression test of bearing model**

The vertical compression test was carried out to test the ultimate compressive strength. The bearing model ringed to severe bulging under 10MPa compression stress (see figure 11). The horizontal residual deformation of the support was 6mm and vertical residual compression deformation was 3.2mm after unloading. It could be seen that inner rubber was extruded to the original hollow rubber body when the connecting steel plate was invisible, as shown in figure 12.

![Figure 11. Permanent deformation of rubber.](image)

8. **Conclusions**

In order to test the mechanical properties of the high damping rubber bearing model used in the shaking table test of the continuous beam bridge model, the following conclusions are drawn:

The horizontal equivalent damping ratio is 16.77%, which means the model is HDR bearing.
The larger the shear strain is, the smaller the equivalent stiffness and yield stiffness are, with greater yield force and equivalent damping force. The horizontal equivalent stiffness, the yield stiffness and the equivalent damping ratio will increasing, with less yield force as soon as the vertical compressive stress is greater.

The horizontal equivalent stiffness, the yield stiffness, the yield force and the equivalent damping ratio are higher if the loading frequency is faster.

The larger the number of repeated loading is, the smaller the yield force, the horizontal equivalent stiffness and the yield stiffness are. Besides, the equivalent damping ratio also shows a downward trend.

The bearing model will not be destroyed if shear strain is less than 250%. The ultimate shear strain was 350%.

The ultimate compressive stress was 10MPa. When the model was damaged, the bearing was stable though had vertical and circumferential residual compression deformation.

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