Study on Mechanical Property of Bridge Bearings under Eccentric Compression and Shearing

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***Abstract*—In order to obtain the mechanical properties of plate type elastomeric pad bearing in bridge engineering under non-ideal working conditions, eccentric compression-shear test is carried out, taking into account different rotation angle and shearing deformation of the bearing. Numerical analysis is carried out by ABAQUS software, to simulate the disengaging of bearing accurately. Disengaging factor is put forward based on the disengaging area of the bearing. The influence of loading direction to slipping property of bearing is also studied, and equivalent friction coefficient is put forward. Results show that the rotation angle of bearing under different shear deformation has a large influence on its mechanical properties, especially on the bearing stiffness, disengaging factor and equivalent friction coefficient.**

***Index Terms*—plate type elastomeric pad bearing, bridge engineering, mechanical property, eccentric compression**

I. Introduction

Plate type elastomeric pad bearings are used widely in bridge engineering. These bridge bearings connect the supper structure and substructure, transfer vertical load and horizontal load, and also make it possible that main girder can deform freely under normal service condition. However, it was found that these bearings may be in a state of eccentric compression and local disengaging in practice due to installation error as well as the deflection of the main girder and piers under horizontal loads, e.g., earthquakes [1].

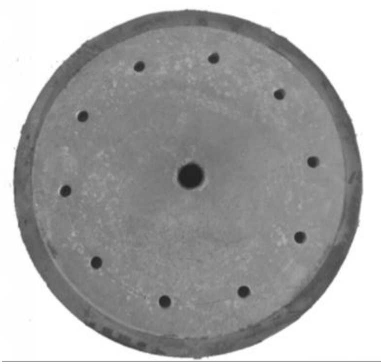
Results of shaking table test of a three-span concrete continuous beam bridge shows that the bearing begins slipping under the peak ground acceleration (PGA) of 200 gal, and to some degree play a role of isolator; with the PGA increases to 500 gal, the large deformation of the substructure makes the bearing to roll off and disengage from the main girder, and the bearing is under severe eccentric compression [2-3].

Existing research suggests that bearing is the weakest link in the bridge structure, and the mechanical properties of bearings has a great influence on the seismic response of the whole bridge structure. Most of the works are based on the mechanical properties of plate type elastomeric pad bearings under ideal condition [4-5], but they rarely involve in bearings under large deformation [6-7]. This paper will introduce the study on mechanical properties of the bearing under eccentric compression and shearing by both experiment and numerical analysis.

II. Eccentric Compression-shear Test

Plate type elastomeric pad bearing are not fixed between the superstructure and substructure. To study the mechanical properties of these bearing under eccentric compression and shearing, a fixed plate was connected to the upper surface of the test bearing so that we can focus on the slipping if bottom surface of the bearing.

Natural rubber bearing type D400 was adapted in the eccentric compression-shear test. Fig. 1 shows the profiles of the bearing. The basic geometrical and mechanical parameters of test bearing are shown in Table I.



(a) Top view of bearing

(b) 3-D view of bearing

Figure 1. Photos of test bearing

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TABLE I. PROPERTY PARAMETERS OF BEARING

Main parameter	Units	Type-D400
shear modulus of rubber G	N/ mm2	1.0
Correction factor κ	-	0.88
diameter of Internal steel plate D	mm	390
diameter of bearing D_0	mm	400
thickness of steel plate t_s	mm	3
numbers of steel plate	-	9
thickness of rubber layer t_r	mm	10
number of rubber layers n	-	10
Horizontal stiffness of bearing	kN/mm	1.19

The test studied the shearing property of the bearing under different loading angles. Bearings were connected to the loading equipment with by upper and bottom plates. The rotation angles of bottom plates were 0, 0.01, 0.02, 0.03 rad, respectively. Vertical load is 1200 kN, which is determined by the design pressure of the bearing. Horizontal load is controlled by a sine-wave cyclic displacement load at a frequency of 0.02Hz, and at an amplitude of 50% and 100% equivalent shear deformation, which is represented by letter *E*.

III. NUMERICAL ANALYSIS

Numerical analysis was carried out by ABAQUS software. A 3-D finite element model are established considering the material nonlinearity, geometrical nonlinearity and contact nonlinearity [8-9].

The concrete plates were considered as rigid body due to their large Young's modulus. Viscoelastic damper characteristics of bearings were considered by Maxwell model based on Prony series [10]. The contact property was defined by penalty friction model. Due to the large slipping displacement and deformation of rubber layers, geometrical nonlinearity was considered. Table II shows the parameters of this viscoelastic material.

TABLE II. VISCOELASTIC MATERIAL PARAMETERS

Num.	g_i	t_i
1	0.499	0.1612
2	0.4598	0.0044

It is very important to adapt proper element type in finite element analysis. For instance, C3D8H is quite suitable for hyper-elastic materials, which is incompressible or almost incompressible, like rubber, however the commonly used one C3D8 will not be suitable. Table III lists main element types used in the finite element model.

TABLE III. FEM ELEMENT TYPES

Part	Element type
concrete plate	Rigid
rubber layer	C3D8H
steel shim	C3D8R

FEM simulation was divided into three analysis steps. The first step is to establish the contact relationship between the bearing and the concrete plate, which is good to the convergence of the FEM model. In the second step, vertical load was applied to the upper connecting plate. In the third step, the cyclic horizontal load was applied to the bottom plate. Fig. 2 shows the sketch map of bearing under eccentric compression, from which an obvious bearing disengaging can be seen.

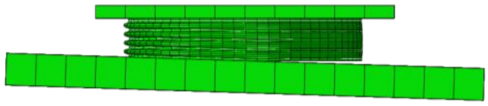


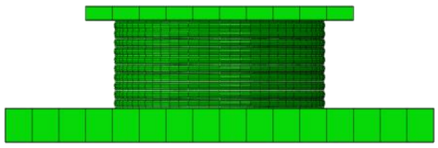
Figure 2. Bearing under eccentric compression

IV. RESULTS AND DISCUSSION

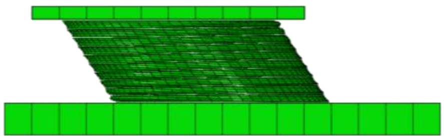
A. *Results of Bearing under Eccentric Compression*

Hysteretic curves are obtained from the eccentric-shearing test, which can reflect the mechanical property of bearings under cyclic loads. Fig. 3 shows the deformation of the bearing with plates of 0 rad rotation and 0.03 rad rotation under vertical load and 100 E horizontal load. Fig.4 shows the hysteretic curves of the bearing from the results of test and numerical analysis. The numerical results matches well with the results of eccentric-shearing tests.

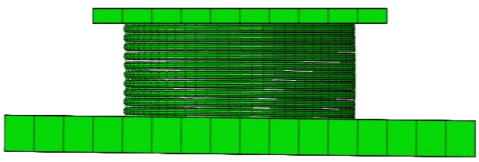
Shear stiffness of the bearing is a very important parameter in bridge bearing design. Table IV and Table V show the equivalent shear stiffness of both experimental results and FEM results of bearings under the forward and reverse loading under 50% *E* and 100%*E*. Stiffness increases as the rotation angle increases



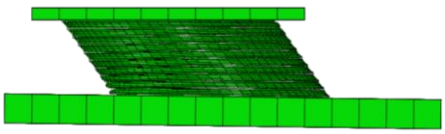
(a) E=0, Angle=0 rad



(b) *E*=50%, Angle=0.03 rad

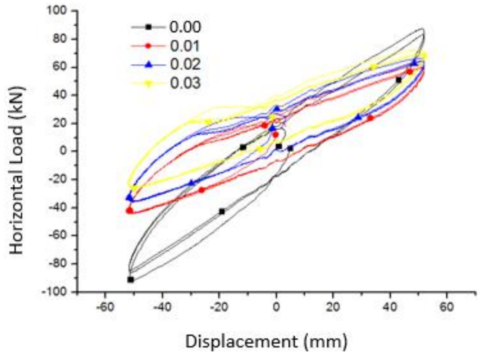


(c) E=0, Angle=0 rad

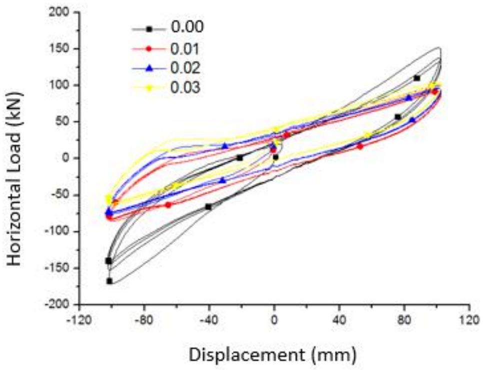


(d) *E*=50%, Angle=0.03 rad

Figure 3. Bearing deformation under eccentric compression and shearing



(a) E=50%



(b) E=100%

Figure 4. Comparison between FE analysis and test results

TABLE IV. EQUIVALENT SHEAR STIFFNESS OF 50%E（KN/MM）

Rotation（rad）	TEST		FEM	
	Positive Loading	Negative Loading	Positive Loading	Negative Loading
0	1.724	1.750	1.598	1.597
0.01	1.122	1.005	1.687	1.465
0.02	1.057	0.993	1.616	1.450
0.03	0.999	0.970	1.551	1.357

TABLE V. EQUIVALENT SHEAR STIFFNESS OF 100%E（KN/MM）

Rotation（rad）	TEST		FEM	
	Positive Loading	Negative Loading	Positive Loading	Negative Loading
0	1.714	1.520	1.649	1.652
0.01	0.981	0.855	1.698	1.588
0.02	0.926	0.833	1.658	1.580
0.03	0.872	0.827	1.623	1.537

B. Area of Bearing Disengaging

Bearing disengaging is a common damage in bridges, which is usually caused by the rotation of main girder and pier. The disengaging level of bearing is related to the surface pressure and horizontal loads, which can be defined by index k, the ratio of the area of disengaging and the area of total surface of the bearing, as shown in (1).

$$k = \frac{AREA_{\text{disengaging}}}{AREA_{\text{total}}} \times 100\% \tag{1}$$

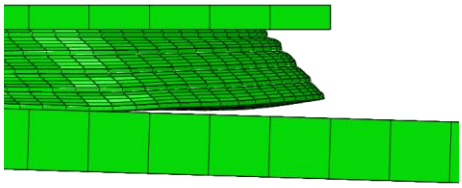


Figure 5. Local disengaging of bearing

Fig. 6 shows the disengaging ratio k of the type-D400 bearing at different rotation angles and different shearing deformation.

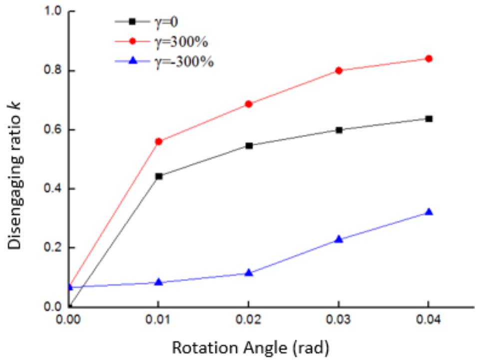


Figure 6. The influence of rotation angle on disengaging ratio

We can indicate that: the disengaging ratio k increases as the shearing deformation increases at the same plate rotation; k increases as the plate rotation increases at the same shearing deformation; k of positive horizontal load is bigger than that of negative horizontal load, so it is necessary to study the effect of horizontal loading direction to the bearing property, which will be discussed in next part C of this paper.

C. Equivalent Friction Coefficient

The effect of horizontal load direction will be introduced in this part. Positive loading and negative loading will lead to different results. The mechanical schematic diagram of bearing are shown in Fig. 7, in which rectangle represents the bearing, and triangle slope represents the plates with a rotation angle.

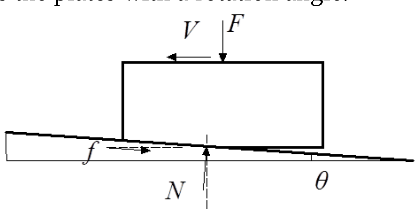


Figure 7. Force analysis of bearing

The equivalent friction is defined by (2),

$$\mu_{eq} = \frac{V}{F} \tag{2}$$

where V is the horizontal load at the top surface, F is the vertical load at the top surface.

When the lower plate is applied in the positive direction, we have (3).

$$\begin{aligned} F &= N\cos\theta - f\sin\theta \\ V &= N\sin\theta + f\cos\theta \end{aligned} \tag{3}$$

According to Coulomb's law of friction (4),

$$f = \mu N \tag{4}$$

the equivalent friction coefficient for positive loading direction can be rewritten as (5).

$$\begin{aligned} \mu_{\mathrm{eq}} = \frac{V}{F} &= \frac{N\sin\theta + f\cos\theta}{N\cos\theta - f\sin\theta} \\ &= \frac{\mu + \tan\theta}{1-\mu\tan\theta} \\ &= \tan(\varphi+\theta) \end{aligned} \tag{5}$$

where φ is the friction angle, which satisfies $\mu = \tan\varphi$.

When the lower plate is applied in the negative direction, we have:

$$\begin{aligned} F &= N\cos\theta + f\sin\theta \\ V &= -N\sin\theta + f\cos\theta \end{aligned} \tag{6}$$

Subscribing (4) and (6) to (2), the equivalent friction coefficient for negative loading direction is showed in (7).

$$\begin{aligned} \mu_{\mathrm{eq}} = \frac{V}{F} &= \frac{-N\sin\theta + f\cos\theta}{N\cos\theta + f\sin\theta} \\ &= \frac{\mu - \tan\theta}{1+\mu\tan\theta} \\ &= \tan(\varphi-\theta) \end{aligned} \tag{7}$$

Fig. 8 shows the relation between rotation angle and equivalent friction coefficient μ_{eq}. μ_{eq} increases as the Coulomb's friction coefficient μ increases. μ_{eq} decreases as the rotation angle increases. When rotation angle reaches 0.03 rad, μ_{eq} decreases to about 70% of that at 0.00 rad when μ=0.1, which must be considered cautiously in bridge bearing seismic design.

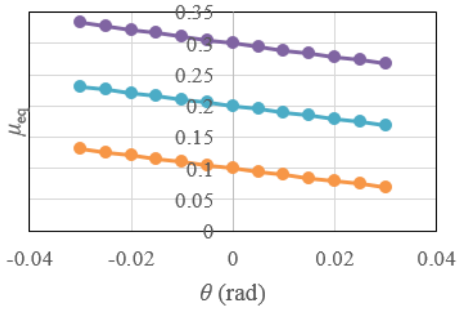


Figure 8. Relation between rotation angle and equivalent friction coefficient

V. Conclusion

1) Eccentric compression and shearing of plate type elastomeric pad bearings will lead to large shearing deformation and additional moments to bridge bearings, which has a huge influence on the mechanical property of bridge structure.

2) The disengaging level of bearing can be described by parameter k, the ratio of the area of disengaging and the area of total surface of the bearing. The ratio k is effected by the rotation angle, the shearing deformation of bearing and the loading direction.

3) Horizontal loading direction has a significant influence on slipping of plate type elastomeric pad bearings. The equivalent friction coefficient of positive loading is bigger than that of negative loading.

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References

[1] T. Wang, "Study on failure mechanisms of elastomeric pad bearing bridge with strong earthquake," M.S. thesis, Nanjing Tech University, China, 2016.(in Chinese)

[2] K. Wang, "Multi-level performance control and index research of seismic isolation bridge under large earthquake," Ph.D. dissertation, Nanjing Tech University, China, 2018. (in Chinese)

[3] L. Jian-zhong, H. Tang, and Z. G. Guan, "Shake table test and numerical analysis of a bridge model supported on elastomeric pad bearings," *Journal of Earthquake Engineering*, vol. 21, no. 4, pp. 604-634, 2017.

[4] M. Imbimbo and A. D. Luca, "FE stress analysis of rubber bearings under axial loads," *Computers & Structures*, vol. 68, no. 1-3, pp. 31-39, 1998.

[5] S. C. Chen, et al. "Modeling and analysis of laminated rubber bearings under axial tensile loading," *Materials and Structures*, vol. 47, no. 6, pp. 987-997, 2014.

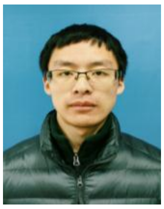
[6] Nguyen, H. Hieu, and J. L. Tassoulas, "Directional effects of shear combined with compression on bridge elastomeric bearings," *Journal of Bridge Engineering*, vol. 15, no. 1, pp. 73-80, 2009.

[7] Steelman, S. Joshua, et al. "Shear and friction response of nonseismic laminated elastomeric bridge bearings subject to seismic demands," *Journal of Bridge Engineering*, vol. 18, no. 7, pp. 612-623, 2012.

[8] Abaqus, Ver. "6.14 Documentation." Dassault Systemes Simulia Corporation 651 (2014).

[9] H. Weiguo, et al. "Numerical simulation of steel-laminated bearing considering friction slipping," *International Journal of Engineering and Technology*, vol. 10, no. 2, (2018).

[10] L. He, "Dynamical analysis of viscoelastic materials using Prony series and GHM viscoelastic models," M.S. thesis, Tsinghua University, China, 2013.



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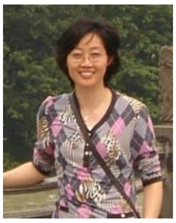

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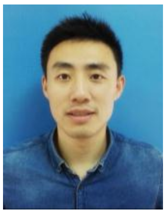

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