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Critical tension–shear load of elastomeric seismic isolators: An experimental perspective

Chao-yong Shen *, Ping Tan, Jie Cui, Yu-hong Ma, Xiang-yun Huang

Earthquake Engineering Research & Test Center, Guangzhou University, Guangzhou 510405, China

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ABSTRACT

When the height-width ratio of isolated high-rise building is excessive large, elastomeric isolators may suffer from tension accompanying with large horizontal shear strains under strong earthquake excitations. It may be not safe if only considering isolators suffering from purely tension without considering horizontal shear strain.

In order to investigate the critical behavior of isolator under tension–shear load, five linear natural rubber bearings with the same inner structure have been experimentally evaluated at different horizontal strain amplitudes, ranging from zero to 483%, including axial tension and purely shear. At the same time, test results have been compared with the theory results.

Test results show that the critical load decreases nonlinearly with the increase of horizontal shear strain, which reveals that it is unreasonable to define the threshold value of tension independent of amount of horizontal shear strain. Comparing with test results of five rubber bearings, the theory results overestimate the ultimate tension strength of elastomeric seismic isolators in most cases. The photos of damage show isolator may occur in different damage pattern at different shear strains, 100% shear strain can be thought as the dividing line. All of the before-mentioned conclusions are drawn by only five isolators, more researches needs to be done in the future.

1. Introduction

An isolation rubber bearing is made up of a number of rubber and steel layers, which are mutually vulcanized together at a very high temperature. Because the steel layers constrain the horizontal deformation of rubber, the rubber bearing can have very high pressure stiffness in the vertical direction. Meanwhile, due to the low stiffness in the horizontal direction and good deformation capacity of rubber, the rubber bearing can have large deformability in the horizontal direction while supporting pressure. This will prolong the period of the isolated building and then reduce the earthquake force applied on the structure. However, for the high-rise isolated building with large height-width ratio, the isolators placed at the two opposite corners along the length direction of the structure will support huge vertical pressure and tension force accompanied by large horizontal deformation due to overturning moment.

There are some literatures for the analysis of isolator loaded by the vertical pressure force with large horizontal deformation. Nagarajaiah and Ferrell [1] did some research about stability of elastomeric seismic isolation bearings in 1999, and found that the critical load of the bearing reduced with increasing horizontal displacement and the horizontal stiffness reduced with increasing horizontal displacement and axial load. Buckle et al. [2] experimental studied on stability of elastomeric isolation bearings in 2002. It shows that the critical load decreased with increasing horizontal displacement or shear strain and the approximate formula was not conservative at smaller displacements and overly conservative at larger displacements. Burtscher and Dorfmann [3] did some compression and shear tests of high damping rubber bearings in 2004, and pointed out that the horizontal stiffness would decrease with the increase of horizontal displacement. Lanzo [4] did research on elastic beam models for stability analysis of multilayered rubber bearings in 2004. He thought that the stability analysis could not be confined to the determination of the critical load but needed an exact evaluation of the post-critical behavior. Cardone and Perrone [5] did some experimental test on critical load of slender elastomeric seismic isolator in 2012, and found that the current design approaches were overly conservative for slender elastomeric seismic isolators. Jared and Gordon [6] verified that the overlapping area method underestimated the critical load capacity of this bearing in comparison with the experimental results by means of some experimental test and finite element analysis in 2013.

* Corresponding author.

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In the most of above-mentioned literatures, research results show that the vertical load capacity of isolators may significantly reduce or isolators are easier to be bulking with the horizontal deformation of isolators increasing. However, in these literatures, few researches about the anti-tension capacity of isolators are mentioned.

How is the anti-tension capacity of isolators accompanied by large deformation? Zhou [7] did some anti-tension tests about rubber bearings in 1994. The vertical force-vertical deformation curve without shear strain showed a good nonlinear characteristic, the maximum anti-tension strength of specimen without shear strain could achieve about 5 MPa. Yoshitaka et al. [8] did some tensile experiments about natural rubber bearings with different diameter of 500 mm, 800 mm and 1200 mm respectively in 2001. Test results showed that the larger the diameter of bearing was, the less the ultimate tensile strength and the tensile strain was. Kelly [9] analyzed tension buckling in multilayer elastomeric bearing in 2003 and proposed the theoretical formula for the tension–shear strength of elastomeric bearing. Besides, it was also given that the influence of vertical load on horizontal stiffness and vertical displacement of the top of bearing as well as vertical displacement. Yang et al. [10] systemically researched the tension stiffness and the deformation model of rubber bearing in 2010. Based on the origin tensile stiffness and offset tension origin stiffness, theoretical solution related to purely tensile state and tension–shear state of isolated bearing were established to calculate deformation, respectively. Xu et al. [11] researched the vertical stiffness of a new type isolator in 2012. James and Maria [12] investigated the effect of cavitation on tension buckling in rubber bearings and proposed an estimation of the critical load of an infinite strip bearing affected by cavitation in 2013. Toshihisa and Ingbert [13] researched the tensile stiffness of elastomeric bearings at different vertical displacement in 2015, and shown that the tensile stiffness would be softening with the vertical displacement increasing. However, in the above research, test researches are only related in the axis tension or the tensile stiffness, up to now, few critical experiment curves about tensile buckling accompanied by different shear strain can be referred to in literatures. Although Kelly [9] gave the formula of tension buckling, there are few experiment to verify it.

According to the literature [9], the critical tension load without shear strain is given:

$$P_{crit,0} = \frac{\sqrt{2}\pi G A S_2 r}{T_r} \tag{1}$$

where G is the shear modulus of inner rubber, A is the area of rubber bearing, S_2 is the second shape parameter, r is the radius of gyration, which was equal to $\frac{D}{4}$ for a circle cross section with the diameter of D, T_r is the thickness of total inner rubbers.

For the above mentioned formulation, the critical load at the target shear displacement (δ) is evaluated as a function of the ratio between the effective area of the inner steel (A) and the overlap area of the displaced bearing (A_e) (see Fig. 1):

$$P_{crit} = P_{crit,0}\frac{A_e}{A} \tag{2}$$

where P_{crit} is the critical tension load accompanied by shear strain.

For circular bearings, for instance, the overlap area at the target displacement is given by [14]:

$$A_e = 2\left\{\frac{\alpha D^2}{8} - \frac{\delta_h}{2}\left[\sqrt{\left(\frac{D}{2}\right)^2 - \left(\frac{\delta_h}{2}\right)^2}\right]\right\} \tag{3}$$

Here,

$$\alpha = 2\arccos\left(\frac{\delta_h}{D}\right) \tag{4}$$

In this paper, the critical tensile load of a couple of rubber bearing used in isolation building is experimentally investigated, at first, test set-up and experimental program are presented in detail. Then, the experiment results about the curves of critical tension–shear load of elastomeric isolators will be discussed, at the same time, the test results will be compared with the theory result refereed by Eq. (2). At last, the characteristic of damage of isolators at different horizontal shear strain will be discussed. The intention of this paper is to testify the theory results, on the other hand, it will help engineers to comprehend the safety of isolators under the condition of shear-tension.

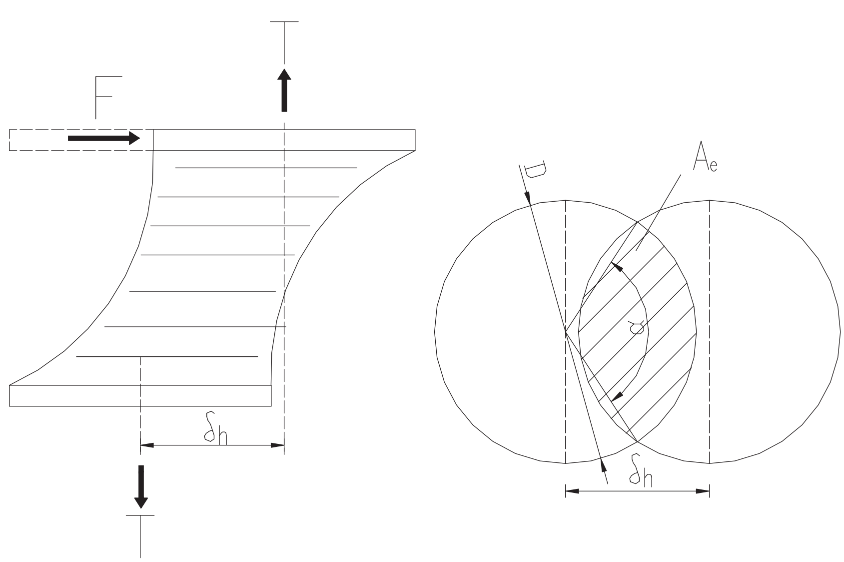

Fig. 1. Schematic deformed shape of an elastomeric bearing subjected shear and tension (a) elevation view; (b) effective cross section area.