Critical Tension-shear load of elastomeric seismic isolators: An experimental perspective

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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.

Key words: Isolation; rubber bearings; critical tension-shear load; horizontal shear strain; damage.

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 S et al[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 I 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. S.L. Burtscher et al [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 AD [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. D Cardone et al [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 Weisman et al [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.

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. F. L[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 5MPa. Yoshitaka Muramatsu et al[8] did some tensile experiments about natural rubber bearings with different diameter of 500mm, 800mm and 1200mm 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. James M. 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. Q.R. 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. Z. D. et al[11] researched the vertical stiffness of a new type isolator in 2012. James M. K. et al [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 M et al [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:

$$P_{crit,0} = \frac{\sqrt{2}\pi GAS_2 r}{T_r} \quad (1)$$

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):

$$P_{crit} = P_{crit,0} \frac{A_e}{A} \quad (2)$$

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]:

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

Here,

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

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 Equation (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.

2. Experimental tests

2.1 test specimens

Because each specimen would be tested for either damage or buckling in the condition of

1 tensioning or tension-shear, each specimen may be tested only for once time. In order to
2 measure the critical tension-shear load accompanied by different shear strain, five natural
3 rubber bearing specimens(ISO.A,B,C,D,E) with the same inner structure are selected. In the
4 literature[15], the first shape factor of the elastomeric bearings used in isolation building is
5 advised to be more than 15, the second shape factor of them is advised to be more than 5. In
6 this paper, the first shape factor and the second shape factor of the nature rubber bearing
7 specimens(ISO.A,B,C,D,E) is 16.667 or 4.583, the former is more than 15, the latter is close
8 to 5. The detailed geometrical parameters of the specimens are summarized in Table 1.

9 The basic mechanical properties of all specimens have been derived from a number of
10 standard cyclic tests prescribed in the Code[16]. For both the vertical stiffness and the
11 horizontal stiffness, the method of three circles was adopted, and the stiffness was gained
12 from the third circle. The frequency of vertical load in the vertical stiffness test was 0.1Hz,
13 and the frequency of horizontal displacement in the horizontal stiffness test was about 0.33Hz,
14 which was referenced from the 3s period of the most common isolated building. The basic
15 mechanical properties of all specimens were tested on the 10000kN compression-shear
16 equipment in the Earthquake Engineering Research & Test Center of Guangzhou University,
17 in China. Only compressive load can be imposed by the equipment. The maximum capacity
18 and frequency range of vertical load are about 10000kN and 0.01Hz~0.1Hz, respectively.
19 When the vertical compressive stiffness is tested, four additional displacement transducers
20 will be installed. The maximum capacity of horizontal load is about 500kN, the working
21 frequency of horizontal displacement is about 0.001Hz~0.8Hz, and the range of horizontal
22 displacement is about ± 200 mm. Fig.2 shows the elevation view of the test equipment. In

order to prevent the specimen from sliding during the horizontal test, an especial anti-sliding material was adopted.

After all five specimens were tested, the mean value was calculated, and the deviation of test result of each specimen versus the mean value was also taken out. Table 2 gives comparison of both the vertical compressive stiffness and horizontal stiffness of all specimens to the corresponding mean value. In the first column in this table, it can be seen that there are obvious deviations of the vertical compressive stiffness for specimens ISO. A and B, while there are minor deviations for bearings ISO. C, D and E. It can be found that the maximum deviation is about +18.2% for isolator ISO. B and the minimum value is about -15.8% for isolator ISO. A. All absolute values of deviations are less than 20% for the vertical stiffness. Compared with deviations of the vertical stiffness, those of the horizontal stiffness are less as listed in the second column in Table 2. It can be seen that the maximum value of deviation is about +7.6% for specimen ISO.C, and the minimum value is about -9.1% for specimen ISO. A. All absolute values of deviations are less 10%. According to the results, these five specimens can be considered approximately as a batch of specimens with the same mechanical property.

2.2 Test set-up

Because the above-mentioned 10000kN compression-shear equipment can't do tension or tension-shear test, all of specimens would be done on another 3000kN/5000kN tension/compression-shear equipment in the laboratory as shown in Fig.3. The test apparatus constitutes a self-balanced system designed for testing specimen in the vertical direction and the horizontal direction. The shear force of the specimen is exerted by horizontal actuator, and

the vertical load is applied by vertical actuator. Because there are two or more jacks between the horizontal sliding track and the test platform under the isolator specimen, tension load and/or compression load can be realized easily by the equipment. The maximum displacement for the horizontal actuator is about $\pm 800\text{mm}$, the maximum force is about 1100kN , and the working frequency range is about $0.001\text{Hz}\sim 1\text{Hz}$. In the vertical direction, the maximum compression and tension load can reach 5000kN and 3000kN , respectively, and the maximum displacement is about 1000mm .

The shear force and the vertical force acting on the isolator specimen were measured by the two dimensional load cell directly. All test data were recorded automatically by control computer. The loading frequency was about 0.001Hz , and the sampling frequency was about 10Hz in order to prevent test data overflowing,

2.3 Test procedure

There were three kinds of test, that is, tension-shear test and only axial tension test as well as purely shear test. When tension-shear test was done, the vertical force acting on the isolator was zero at first, and then the horizontal displacement would be applied slowly. After the horizontal displacement reached the target value, then the vertical tensile displacement would be applied slowly. If only axial tension was done, the horizontal displacement was constant while only vertical displacement was applied. If only purely shear test was done, the vertical force would be kept zero. Table 3 gives the test arrangement for each isolator specimen respectively.

2.4 test results

2.4.1 test curves

When tension-shear test was carried out, all data including the horizontal displacement, the vertical displacement and the vertical force could be recorded automatically at the same time. Fig.4 gives the variation of the tensional force with the increase of vertical displacement, for each test performed at a given shear deformation 0, 100%, 200%, 300% and 483%. The critical load at the different horizontal shear strain level can be identified. When the horizontal strain is kept zero, the curve of tension force-displacement relationship shows that there are three phases during the whole testing process, that is, the elastic phase, the yielding phase and the hardening phase. The duration in the elastic phase is the shortest, while the duration in the yielding phase is the longest. In this curve, the yielded tension force is about 22kN, and the corresponding displacement is about 10mm. The failure load is about 237.6kN, and the corresponding displacement is about 241.4mm. Then the ratio of the yielded force to the failure load is about 1/11, and the ratio of yield displacement to failure one is about 1/24, which means that there is a very large gap between the yielding phase and the tension failure phase. When the horizontal strain is kept 100%, the curve shows that there are two apparent phases including the elastic phase and the hardening phase. The yielding phenomena can be found, but the yielding platform is very short. In this curve, the yielding tension displacement of about 3.8mm is very small, and the corresponding yielding force is about 50kN. But the ultimate displacement is about 155mm, and the corresponding ultimate tension force is about 121kN. Then the ratio of the yielding to ultimate displacement is about 1/41, and the ratio of the yielding force to the ultimate load is about 1/2.42. So a large gap between the yield and failure phase is observed again. When the horizontal strain is kept zero or 100%, the tension force-displacement relationship curves show the same damage

phenomena, that is, tension damage, a type of brittle fracture. But when the horizontal strain is 200%, the curve shows a different failure pattern-buckling damage. In this horizontal strain state, the yield and buckling displacement is about 2.1mm and 32.8mm, and the corresponding yield and buckling tension force is about 32kN and 60.9kN, respectively. The ratio of the yield displacement versus the buckling displacement is about 1/16, which is larger than 1/24 at the zero horizontal strain and 1/41 at the 100% horizontal strain. Therefore, the duration between yielding and damage will be shortened with the increase of horizontal strain. When the horizontal strain is kept 300%, the buckling damage also occurs, which is similar to the state of 200% horizontal strain. Because the unloading process was followed after the buckling point appears, the descending stage didn't emerge. When the horizontal strain is kept 483%, one point is shown in this figure because the real experiment is a horizontal ultimate test with zero vertical force. As a whole, when the constant horizontal strain is small, such as shear strain of zero and 100%, apparent tensile break appears. With the increase of horizontal displacement, buckling failure will appear. However, when the vertical force is kept zero, shear failure will emerge.

Fig.5 shows the relationship between the ultimate tension and horizontal shear strain from the experimental result and theoretical solution derived from equation (2). It can be seen that the maximum ultimate tension appears at axial tension test without horizontal shear strain, and the corresponding ultimate tension strength is about 6.25MPa, which exceeds the required value 1MPa in literature[17]. From zero to shear strain of 200%, the ultimate tension strength decreased linearly with horizontal shear strain increasing. the strength at the shear strain of 100% and 200% are 4.08MPa and 1.6MPa, respectively. From 200% to 483%, the rule is

1 nonlinear. At the shear strain of 300%, the strength is about 0.5MPa. From tension strength of
2 0.5Mpa to 0, the undergoing shear strain of isolator is about 183%. Comparing the test results
3 with the theory ones, there are some errors at the same horizontal shear strain and the theory
4 value is higher than the test value in most cases. For example, at zero shear strain, the theory
5 value of ultimate tension strength is about 9.15MPa exceeding 46% to the test value. At 100%
6 shear strain, the theory value is about 6.63MPa, exceeding 62% to the test value. At 200%
7 shear strain, the theory value is about 4.23MPa, over 164% to the test value. At 300% shear
8 strain, the theory value is about 2.11MPa, over 321% to the test value. The tendency shows
9 that, the more the horizontal shear strain is, the more the relative error is in most cases. It also
10 means that equation (2) overestimates the capability of elastomeric seismic isolators in most
11 cases. Although there is large difference of ultimate tension strength between test values and
12 theory ones, the slope of line of the theory values is very close to that of linear part of the test
13 values.

14 Fig.6 shows the relation between ultimate tension strain and horizontal shear strain for
15 test value. Similar to Fig.5, the maximum tension strain also appears at zero shear strain, the
16 corresponding ultimate tension strain is about 503%, which means the maximum deformation
17 can reach more than five times total thickness of inner rubber before rubber bearing is tensile
18 break. If the test specimen is taken as an example, total thickness of inner rubber is 48mm,
19 and the maximum tension displacement is about 241mm, which exceeds the maximum
20 horizontal shear displacement of 232mm under purely shear state. From zero to 200% shear
21 strain, the ultimate tension strain also decreased linearly with horizontal shear strain
22 increasing. At the 100% and 200% shear strain, the ultimate tension strain is about 252% and

about 68%, respectively. From 200% to 300% shear strain, the change of ultimate tension strain with horizontal shear strain increasing falls into nonlinear phase. At the 300% shear strain, the ultimate tension strain is about 21%. From 300% to 483% shear strain, the ultimate tension strain decreases from 21% to zero. From Figs.5 and 6, it can be seen that the similar variation appears in these two figures. On the whole, both the ultimate tension and the ultimate tension strain vary nonlinearly with the horizontal shear strain. The status of 200% shear strain can be considered as a divide. When the shear strain of isolator is less than 200%, either the ultimate tension or the ultimate tension strain is linear function of shear strain. While the shear strain is larger than 200%, the relation is nonlinear between either the ultimate tension or the ultimate tension strain and shear strain. The varies of the ultimate tension strength as a function of the ultimate tension strain were shown in Fig.7.

The specimen ISO.A was stretched while the horizontal shear strain was remained 300%, only crack could be found apparently. When the maximum tension load appears and the tension force decreases, test was unloaded quickly by hand. In order to test the residual strength of rubber bearing, the specimen ISO.A was tested again while the horizontal shear strain was kept 100%, and the test ends until the specimen damaged thoroughly. The tension force-displacement relation curves at 300% and 100% shear strain for specimen ISO.A and at 100% shear strain for specimen ISO.E are plotted in Fig. 8. Test results show that there is still residual strength of rubber bearing after buckling damage at large constant horizontal shear strain. The buckling strength is 24.394kN for specimen ISO.A at constant 100% horizontal shear strain state, and the corresponding buckling displacement is about 40.713mm. This buckling strength for specimen ISO.A is larger than that at constant 300% horizontal shear

1 strain state, while it is less than that for specimen ISO.E with only one time test. Moreover,
2 the destruction forms also change. It is buckling failure not tension fracture, which is true for
3 specimen ISO.E, when specimen ISO.A is tested at the second time at constant 100%
4 horizontal shear state.

5 *2.4.2 Test damage phenomena*

6 When tension-shear test was going on, the whole process was recorded. Fig.9 gives
7 some test photos at zero horizontal shear strain state for specimen ISO.D, including photos
8 before damage, after damage, and damage characteristic. Because there is no cover rubber
9 around the specimen, deformation of inner rubbers and inner steels can be seen clearly during
10 testing. The bloating part is inner steel, and the sunken part is inner rubber. When rubber
11 bearing is compressed axially, due to the restriction from inner steels adjacent to them, inner
12 rubber will bloat, which makes rubber bearing good compressive capability. When it is
13 tensioned axially, inner rubber will elongate in the vertical direction. But the inner rubber is
14 constrained by inner steel adjacent to it, then the mid height part of each piece of inner rubber
15 will be sunken. With the increase of vertical tensile displacement, the crossing section area of
16 the mid height part of each piece of inner rubber will reduce, which makes the concentrated
17 tension be larger. Finally, the inner rubber will suffer tensile fracture. It can also be found that
18 due to tension some inner steel layers (seeing the red circle in Fig. 9(a)) are inclined, which
19 are also the final failure region as shown in Fig.9 (b). In Fig.9(b), a large void part, whose
20 length may be some times of diameter of bearing, occurs between two failure parts of bearing,
21 which means that there is a very good axial tensile capability before rubber bearing breaks.
22 Fig.9 (c) shows two breaking rubber sections.

Fig.10 gives some test photos at the different test stages when the horizontal shear strain is kept 100% for bearing ISO.E. After tension force is exerted, it can be seen that an obvious necking phenomenon occurs on the whole specimen as shown in Fig.10 (a), which is different from axial tension test. It seems that the crossing section area at the mid height of bearing becomes the minimum. With the increase of tensile displacement, out of plane deformation appears on some parts of inner steels as shown in Fig. 10(b) marked with red circle, which is also the final failure region as shown in Fig.10 (c). The remaining inner steel with large out of plane deformation can be seen clearly in Fig. 10(c). Fig. 10(d) shows that only broken rubber is left after bearing is failure.

Fig.11 gives some test photos at the different test stages when the horizontal shear strain is kept 200% for bearing ISO. C. From Figs. 15(a) and Fig.11(b), it can be seen that necking phenomena occurs once tension force is applied. The first crack appears in the inner rubber near the bottom of bearing. Then, with the vertical tensile displacement increasing, the crack gradually deepens inside of the layer of inner rubber as shown in Fig.11(c). Finally, the whole layer of inner rubber is tensioned to disrupt and becomes a very smoothing fracture crossing section as shown in Fig.11(d). It is also concluded that only broken rubber is left after bearing is failure as seen in Fig.11(e).

Fig.12 gives some test photos at the different test stages when the horizontal shear strain is kept 300% for bearing ISO.A. In Fig.12 (a), one apparent crack, which locates near the bottom of rubber bearing, can be seen again. Because the test was unload when the buckling load reached the maximum load at 300% horizontal shear state, Fig.12 (b) is the damage phenomena of isolator under the tension shear test state in which 100% constant shear strain

1 is loaded again and kept to be constant. The fracture section also shows only rubber breaking
2 can be found.

4 **3. Conclusions**

5 In this paper, the critical tension-shear behavior of a series of elastomeric seismic bearing
6 has been experimentally evaluated at different horizontal strain amplitudes ranging from zero
7 to 483%, including axial tension and purely shear. A batch of natural rubber bearings with
8 approximately same basic properties were selected to test in order to find the effect of
9 horizontal shear strain on the critical load of elastomeric seismic isolators. During these tests,
10 the horizontal displacement of the specimens was held at a specified value while the vertical
11 tension load was progressively raised up to ultimate load or buckling load. The isolator was
12 considered to be in critical state when the vertical tension force reached the maximum value
13 or the tensile break occurred. Based on the results of these experiments study, the following
14 conclusions can be drawn:

- 15 (1) The critical load decreases nonlinearly with the horizontal shear strain increasing;
- 16 (2) The ultimate tension damage appears when the horizontal shear strain is less than or equal
17 to 100%, in these situation, some parts of inner steel undergoing out of plane deformation
18 is the final failure region. The buckling damage appears when the horizontal shear strain is
19 greater than or equal to 200%, in these conditions, crack will appear in the inner rubber
20 near the bottom of bearing.
- 21 (3) There are still some remaining strength for rubber bearing after buckling damage occur at
22 large horizontal shear strain state.

(4) The theory formula excessively estimates the ultimate tension strength of elastomeric seismic isolators in most cases. Since this point is derived from the test results of only five specimens, in the future, more specimens, including different shape factors and/or different rubber thickness, will need to be tested in order to verify its correctness.

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1 **Caption for Tables**

2 Table 1 Elastomeric bearings (Specimen ISO.A,B,C,D,E) details

3 Table 2 Deviations of test results of all specimens relative to the mean value

4 Table 3 Arrangement of test for each isolator specimen

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Caption for Figures

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

Fig.2 Elevation view of the equipment used in testing the basic property of isolators;

Fig.3 The tension-shear test set-up

Fig.4 Tension force vs tension displacement curves of all specimens

Fig.5 Tension strength vs horizontal shear strain curve of ultimate property of rubber bearing

Fig.6 Ultimate tensile strain vs horizontal shear strain curve of ultimate property of rubber bearing

Fig.7 Tension strength vs ultimate tensile strain curve of ultimate property of rubber bearing

Fig.8 Comparison of ultimate curves to different shear strain state

Fig.9 test photos for ISO.B at 0% horizontal shear strain state

Fig.10 test photo for ISO.E at 100% horizontal shear strain state

Fig.11 test photos for ISO.C at 200% horizontal shear strain state

Fig.12 test photo for ISO.A at 300% horizontal shear strain state

Table 1 Elastomeric bearings (Specimen ISO.A,B,C,D,E) details

Shear modulus of inner rubber	$G(\text{MPa})$	0.392
Outer diameter	D' (mm)	220
Inner diameter	D (mm)	220
Diameter of core	d_0 (mm)	20
Thickness of one rubber layer	t_r (mm)	3
Number of rubber layers	n_r	16
Thickness of steel shim	t_s (mm)	1
Number of steel shims	n_s	15
Total thickness of rubber	T_r (mm)	48
The first shape factor	S_1	16.667
The second shape factor	S_2	4.583

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Table 2 Deviations of test results of all specimens relative to the mean value

Specimen No.	Kv-error	Kh-error
ISO.B	+18.2%	-4.8%
ISO.E	+5.2%	+6.8%
ISO.C	-6.4%	+7.6%
ISO.A	-15.8%	-9.1%
ISO.D	-1.2%	-0.5%

Note: the value of error is relative to the meaning value of five specimens

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Table 3 Arrangement of test for each isolator specimen

Specimen No.	Horizontal direction/shear strain	Vertical direction
ISO.B	0%	Ultimate
ISO.E	100%	Ultimate
ISO.C	200%	Ultimate
ISO.A	300%	Ultimate
ISO.D	Ultimate	0

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

(b) effective cross section area

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Fig.3 The tension-shear test set-up

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Fig.4 Tension force vs tension displacement curves of all specimens

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Fig.5 Tension strength vs horizontal shear strain curve of ultimate property of rubber bearing

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Fig.6 Ultimate tensile strain vs horizontal shear strain curve of ultimate property of rubber bearing

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Fig.8 Comparison of ultimate curves to different shear strain state

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Fig.9 test photos for ISO.B at 0% horizontal shear strain state

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Fig.10 test photo for ISO.E at 100% horizontal shear strain state

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Fig.11 test photos for ISO.C at 200% horizontal shear strain state

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(a) damage occurring

(b) damage characteristic

Fig.12 test photo for ISO.A at 300% horizontal shear strain state

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