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A Tension-resistant Device in Base Isolation

Y. Zhou[1], P. Chen[2], X.L. Xu[3], X.H. Li[4]

[1] *Professor, Tongji University, yingzhou@tongji.edu.cn*
[2] *Graduate student, Tongji University, 100751@tongji.edu.cn*
[3] *Professor, Nanjing Technology University, njxuxiuli@163.com*
[4] *Professor, Nanjing Technology University, lixuehongnj@163.com*

Abstract

The elastomeric isolation system is not commonly adopted in high-rise construction and buildings with large aspect ratio, due to large overturning moment and subsequent development of tensile force at the base. Once tensile stress occurred in laminated rubber bearing, damage and cavities would expand inside the rubber which may lead to inestimable adverse effect on mechanical performance of isolators. A new type of tension restraining device to be used in conjunction with LRBs is proposed. This device aims to keep the tensile stress in the rubber under the limit value, while adapting to horizontal deformation of the rubber bearing. Numerical analysis and low-cycle load test of the prototype isolators with the tension-restraint device were carried out. And an analysis model for a high-rise frame-core tube isolated building using rubber bearings was established. Time history analysis results indicate that large tensile stress happen in isolators under maximum considered earthquake (MCE).And the tensile constraining effect was verified by analysis. Further, a shake table test of a 1:15 scale isolated structure in accordance with previous analysis model is presented to investigate the performance of the proposed device under seismic excitation. Experiment results illustrate that installation of the tension restraint device in isolation floor would not influence the horizontal shear behavior of the bearing and the global behavior of the isolated structure. The tension-restraint devices are promising systems to use in high-rise buildings and buildings with large aspect ratio.

Keywords: tension-restraint device, laminated rubber bearing, high-rise building, finite element analysis, experiment

1. Introduction

Many high-rise isolated buildings and large aspect ratio isolated buildings have been built in recent decades [1]. Although isolation technology has been proved to be a favorable method to mitigate seismic hazard, tension stress would appear in the isolators of those kinds of buildings [2, 3].

Base isolation has been widely used in low-rise buildings with fundamental periods shorter than 1s [4]. However, in recent decades, the number of high-rise isolated buildings keeps increasing, such as the 32-story Los Angeles City Hall and 18-story Oakland City Hall. Especially in Japan, between 1990 and 2002, one third of all the approved base-isolated (BI) buildings in Japan were taller than 40m, and 40% of all BI buildings after 1995 had an aspect ratio larger than two [5,6]. But the use of laminated rubber bearings remains uncommon in tall buildings worldwide owing to the potential tensile stress that may occur under the overturning moment. Due to insufficient tensile capacity, the rubber isolators may become damaged or even failed under earthquake [7]. Chen SC et al. proposed a theoretical model for analyzing the rubber bearing based on the theory of elasticity. And experiment was conducted to verify that the proposed stress and deformation expressions can be used to simulate the stress distribution and deformed pattern of rubber layer for laminated rubber bearings in elastic range, the crack energy method for predicting the failure mechanism is feasible [8, 9]. Yoshitake et al. studied the tension properties of laminated rubber bearings with different shape factors. Tests on rubber bearings with three diameters were carried out and results show that tensile deformation capacity of natural rubber bearings decreases with increasing diameter [10]. Dorfmann et al. investigated the damage mechanism of natural rubber. Once the cavitation initiates, the bulk modulus of the material significantly reduced [11]. Considering the adverse consequence caused by the cavitation in bearings, Kelly et al. proposed a procedure to predict the tensile buckling load of rubber bearing in the presence of cavitation [12]. Kelly et al. elaborated an analytical formulation to predict the instability of a rubber bearing affected by cavitation which is also a procedure to calculate buckling load in tension in the presence of cavitation for both long strip bearings and circular bearings [13]. Kumar et al. investigated the cavitation strength of rubber bearing and other corresponding mechanic properties of bearing under tensile load experiments [14]. And further, Kumar et al. proposed an advanced numerical model of elastomeric isolation bearings, this phenomenological models are presented to describe the behavior of elastomeric isolation bearing in tension, including the cavitation and post-cavitation behavior [15]. Yoshida et al. established a finite element model of a whole rubber bearing to study its overall tension and torsion performance. Results reveal that mechanic properties as tension stiffness, yield strength, yield strain and limit deformation are very crucial for the design and application of rubber bearing [16].

Even with the fact that elastomeric bearing can sustain a moderate tension force level, tension in isolators is still supposed to be minimized. Building codes in many different countries including China and USA adopts limitation for maximum tensile stress in isolator considering the insufficient tensile resistant capacity [17]. These limitation ensure the safety of isolated building however the extension of laminated rubber isolation system in high-rise buildings is restricted. Numerical investigations of dynamic response of high-rise base-isolated buildings under multi-directional ground motions presented in Liu et al. show that while the tensile stress in the isolators fall within the code-prescribed limits under unilateral excitations, tensile stress in corner isolators significantly exceed those limits under bilateral shaking [18]. Former researchers including Griffith et al. and Logiadis et al. investigated various tension-restraint system to limit the uplift of the isolated structure and provide the isolators with tensile resistant capacity [19, 20]. Kasalanati et al. studied pre-stressed tendons in parallel with a variety of isolators [21]. Constantinou et al. used a block mechanism that resists tension as uplift prevention system for friction pendulum isolators [22]. Several projects in U.S. adopted “loose-bolt” connection to release tension force in isolators, such as LA City Hall retrofit, San Bernadino Medical Center and LAC/USC Medical center. Ryan KL et al. conducted time history analysis using an advanced bearing model that incorporates the relation between axial load and bearing response to estimate the peak axial force in base-isolated buildings include overturning. Rocking of the structure and bearing axial load effects are found to have little influence on the peak lateral bearing deformation [23]. Roussis P et al. investigate the effect of uplift-restraint for isolators using enhanced version of program 3D-BASIS-ME. The results demonstrate that tension in individual isolators and by extension the increase of isolation-system friction force, did not have any appreciable effect on either the total isolation system response or the superstructure response [24].

This paper presents a novel tension-restraint device (TRD) for laminated rubber bearing. The bearings installed with TRD are referred as tension-restraint lead bearing (TLRB). The mechanical properties of the device and its working mechanism under static and dynamic loads have been investigated via numerical simulation, cyclic load test of the prototype TLRB. And time history analysis for a calculation model established in commercial finite element software is employed. Under the excitation of MCE, tension stress occurs due to significant overturning effect which is not a favorable situation for isolated structure. Thus, in order to figure out the effectiveness of proposed device, shake table test of a scaled model employing the TLRB was conducted. It can be concluded from the experimental and numerical results that device can help keep the tensile stress of the bearings below the limits set forth in the design, while posing minimal effect on the horizontal shear properties of the rubber bearings and behavior of the isolators in compression. Due to the predominant tensile problem of isolator under overturning effect, the tension-restraint devices are attractive for use in high-rise isolated buildings with large aspect ratio to protect the isolators.

2. Basic working principle of tension resistant device

2.1 Design concept

The TLRB is comprised of six main parts. The schematic figure is shown in Fig.1. and Fig.2. below. Fig.3. shows the 3D model of the whole TLRB. The tension-restraint device is elaborately designed according to the corresponding elastomeric bearing. And it is installed along with the bearing in the isolation floor. Specifications for the designing details are listed: (1) One side of the active part is interlocked with the shackle bar and the other side pass through the opening of the fixed part. Enough length is supposed to be reserved considering the maximum horizontal deformation of the bearing. (2) In order to decouple the influence on the device caused by vertical deformation of bearing, a small gap is left in the interlock of which the height is equivalent to the height of the pre-determined maximum vertical force. (3) Shackle bar are connected to the upper plate under the bottom of superstructure. The fixed part is connected to the column of substructure. (4) All positions where sliding happens are lubricated with oil and curtain interspaces are set so as to ensure the smooth movement between active part and fixed part.

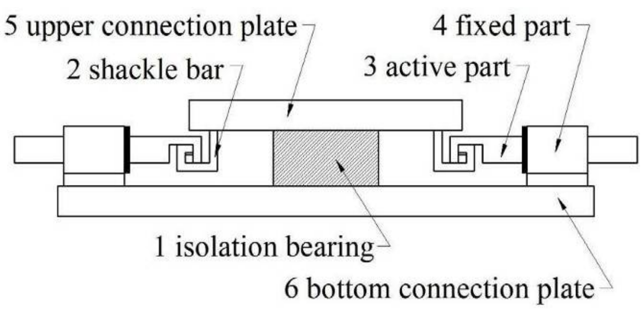


Fig. 1 Isolation bearing with TRD

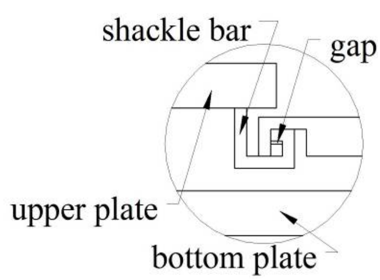


Fig. 2 Connection details in the interlock

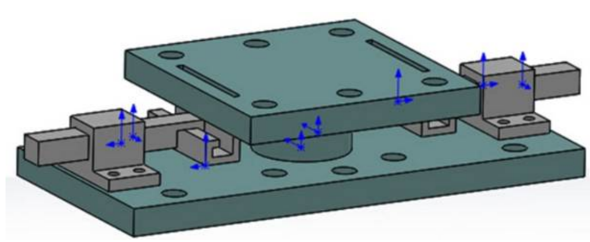


Fig. 3 Three dimensional model of TLRB

2.2 Restraint principles

The mechanic properties of TRD can be simply described as Fig.4. and Fig.5. In the vertical direction, the effect of TRD can be simplified as tensile arm with large stiffness set at the two sides. When the tensile force occurs, the arms are supposed to undertake most of the force to protect the bearing itself. Besides, maximum displacement restriction effect is also provided. In horizontal direction, the device can keep the shear deformation of bearing within safety scope. Damping buffers are set at maximum allowable position so as to slowly stop the moving bearing under excitation of earthquake.

Fig. 4 Restraint principle in vertical direction

Fig. 5 Restraint principle in horizontal direction

3. Working performance analysis under static loads

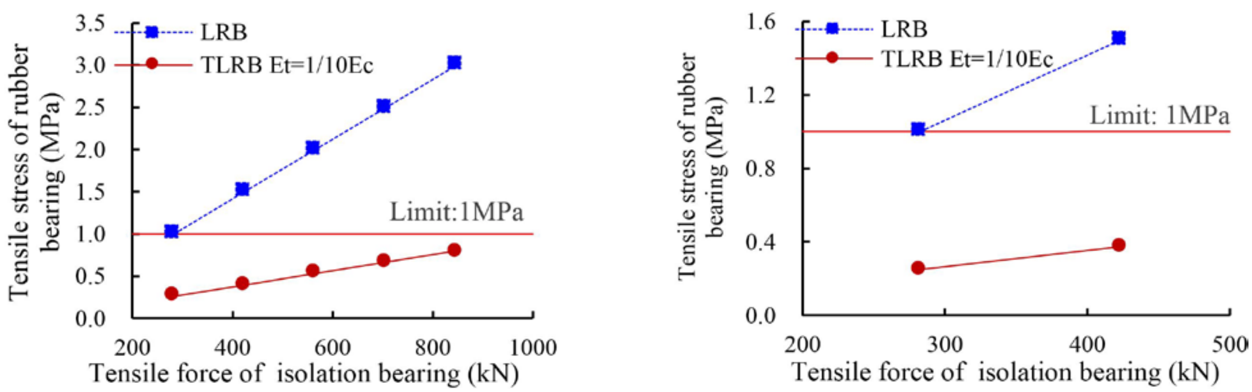
3.1 Size design of prototype TLRB

A lead rubber bearing with a commonly used size was adopted as test specimen. The outer diameter and inner diameter (lead core) of the bearing is 600mm and 110mm respectively. The detail size of TRD was determined according to pure tensile limit state and horizontal deformation limit state under the consideration of safety.

3.2 Numerical simulation

3.2.1 Tension restraint effect analysis

Commercial finite element software ANSYS was used to analyze the working performance of TLRB600 under pure tension state and shear tension state. A 3 dimensional solid finite element model was established considering the bilinear stiffness of elastomeric bearing. It is simulated using spring elements with assumption that tensile stiffness is about 1/10 of the compressive stiffness [7]. Analysis results are shown in Fig.6 accordingly. In the pure tensile analysis condition, when loaded with maximum vertical force 847.8kN, the elastomeric bearing experience 3MPa tensile stress which exceeds the 1MPa limitation in Chinese Code [17]. After installing TRD, however, under the same vertical force level, TRD undertake most of the tension force. The tension stress in the bearing is 0.8MPa which falls in the allowable range in the Code. Similar tension restraint effect can also be seen in shear-tensile analysis condition.



(a) pure tensile limit state

(b) horizontal deformation limit state（240mm）

Fig. 6 Tensile stress comparison of rubber bearings between LRB600 and TLRB600 under same tensile force

3.2.2 Ultimate strength check of TRD

In order to ensure the safety of TRD in the most unfavorable working condition, equivalent stress of the device was checked both in tensile limit state and horizontal deformation limit state. The maximum equivalent stress calculated in the analysis was 213MPa which is below the yield stress for the used steel Q345 of 276MPa.

3.3 Test verification of the prototype TRD

3.3.1 Test equipment

The static test were carried out in the experiment center of Wuxi Fuyo Co., Ltd. The loading equipment (Fig.7) for the test was imported from Japan with a maximum vertical compressive force of 20,000kN, a maximum vertical tensile force of 6,000kN, and a maximum horizontal displacement of 1m.

3.3.2 Test procedure

The components of TRD were fabricated and assembled with the LRB600 rubber bearing to form a tension-resistant bearing TLRB600, shown in Fig.8. The tests (LT, SC, and ST) were first conducted for TLRB600 specimen. After finishing these tests, the TRD components were removed from the LRB600 bearing, which was then subjected to the same series of tests.

The specimens were subjected to varying displacement under a displacement-control procedure and the resisting forces were logged for each step. The following summarize the test procedures for the two isolator types:

(1) LT condition: These tests were aimed at determining the tensile properties of the LRB and TLRB specimens. The loading consisted of imposing purely vertical displacements with amplitudes controlled by the laboratory equipment displacement capacity. For TLRB, the ultimate vertical load was 848.2kN (resulting in 3MPa of tensile stress in LRB) with a maximum vertical displacement of 10.27 mm.

(2) SC condition: The specimens were subjected to a constant compressive force of 4241.2kN (corresponding to a normal compressive stress of σ=15MPa in the LRB). Lateral displacement of bearing was a sinusoidal function containing 5 fully reversed cycles with displacement amplitudes of: 60mm, 120mm and 240mm (corresponding to rubber shear γ = 50%, 100%, 200%) and velocities of 0.0265 mm/s, 0.0133 mm/s, and 0.0066 mm/s respectively.

(3) ST condition: The specimens were subjected to a constant tensile force of 282.7kN (corresponding to a normal tensile stress of σ =1MPa in the LRB). Because the loading equipment did not include the auto-load system for this condition, the horizontal displacements were manually input in 30mm increments for 5/4 reversed deformation cycles with amplitude of 240mm (rubber bearing shear strain of γ = 200%).

Fig. 7 Test loading equipment

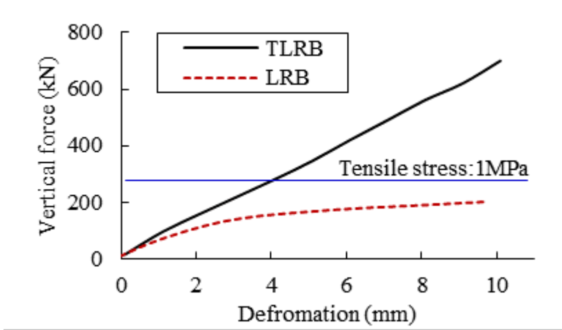
Fig. 8 Model of TLRB600

3.3.3 Results

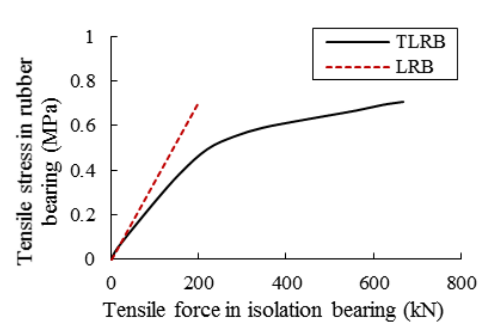
In limit tensile test condition, the tensile-resistant capacity was investigated by comparison. The main results of tensile experiment were listed in table1. And force-deformation curves of TLRB600 and LRB600 are compared in Fig.9. With the vertical deformation start to increase rapidly, the tensile resistant capacity of LRB600 asymptotically approached a limit of approximately 200kN (equivalent to 0.7MPa tensile stress in rubber bearing). If tensile force demand for LRB600 exceeds this value, overturning failure might happen for the superstructure which may lead to a disaster. By contrast, tension force for TLRB600 increase linearly with the increasing vertical displacement resulting an elastic force-displacement curve. When the vertical force reaches the peak at 700kN, the tensile stress of the bearing in TLRB600 is approximately 0.7MPa which is below the limitation in the Code. However, if the LRB600 sustained same vertical load, the tensile stress would far beyond the limitation, at 2.25MPa. By Comparison, it is verified that TRD was successfully engaged reducing the risk of damage and failure of the rubber bearing under tensile force.

Table 1 – Results of LRB and TLRB under tensile experiment condition

Tensile stress	0.5MPa	1.0MPa	1.5MPa	2.0MPa	2.5MPa
LRB displacement	2.9mm	--	--	--	--
TLRB displacement	2.0mm	4.3mm	6.3mm	8.3mm	10.5mm



(a) Tensile force and bearing deformation



(b) Tensile stress in rubber and tensile force

Fig. 9 Tensile property comparison for LRB and TLRB

LRB600 and TLRB600 were tested and analyzed in SC load condition and ST condition separately. The mechanic property comparison are listed in table2 and table3 below. *Kh* represents the initial stiffness of bearing, *Kd* represent the equivalent stiffness of bearing (related to the maximum horizontal deformation) and *Qd* is the yield force.

Table 2 – Comparison of mechanic property of LRB and TLRB in SC condition

	Shear deformation	*Kh*(kN/mm)	*Kd*(kN/mm)	*Qd*(kN)
LRB	50%	2.600	1.121	88.757
TLRB		2.547	1.084	87.777
Deviation		-2.0%	-3.3%	-1.1%
LRB	100%	1.555	0.810	89.417
TLRB		1.548	0.831	85.991
Deviation		-0.5%	2.6%	-3.8%
LRB	200%	1.108	0.728	91.145
TLRB		1.116	0.747	88.539
Deviation		0.7%	2.6%	-2.9%

Table 3 – Comparison of mechanic property of LRB and TLRB in ST condition

	Shear deformation	*Kh*(kN/mm)	*Kd*(kN/mm)	*Qd*(kN)
LRB	200%	1.097	0.955	34.178
TLRB		1.475	1.032	106.422
Deviation		34.5%	8.1%	211.4%

3.4 Summary

Summary can be made according to analysis and experiment for prototype specimen as follows: (1) After installing the TRD, tensile capacity can be significantly improved. (2) Installation of TRD barely affect horizontal hysteretic properties of isolator on working condition (compression state) and it can well protect the isolator from degradation and reduction of energy absorption ability under tensile state. Two main summary above clearly demonstrate that TRD has a satisfactory tension restraint effect on bearing and present a feasible design solution in bearings that need to sustain significant tension force.

4. Working performance analysis under dynamic loads

A calculation model for a high-rise isolated building was established in commercial finite element software and time history analysis was conducted to find tension force in corner isolators. Further, a shake table test of a 1:15 scaled model in accordance with the analyzed model was carried out to study the working performance of TRD under dynamic loads.

4.1 Time history analysis

The test model was designed based on a high-rise frame-core tube concrete structure in an intensity degree 9 earthquake zone according to a Chinese building code, with a peak ground acceleration of 0.4g under MCE level. The calculation model is shown in Fig.10. The height of super-structure is 58.3m. A total of 42 elastomeric bearing were used in the design of isolation floor. The information of seismic records used in the analysis is listed in table 4. And the spectrum of each wave and the average spectrum is compared in Fig.11. In order to figure out whether there would exist tensile force in isolators, the magnitude of the seismic input was set as MCE. Results indicate that tensile stress occur in the four corner bearings. Maximum tensile stress reaches 1.72MPa which is over the limitation in the Chinese Code. The main reason for the over tensile stress may lies in the bidirectional overturning effect. Configuration of bearings and the maximum calculated tensile stress is presented in Fig.12.

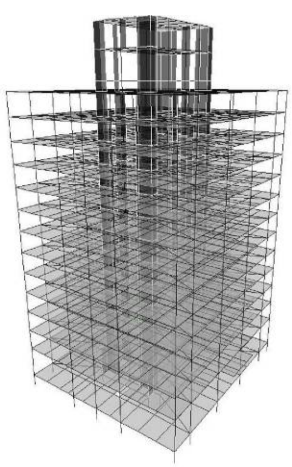


Fig. 10 3D view of Calculation model

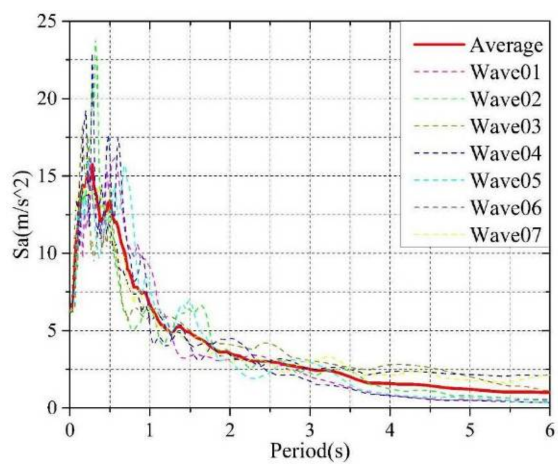


Fig. 11 Spectrum of the seismic waves

Maximum tensile force value in corner bearings significantly higher than limitation. To control the tensile stress and overturning effect, the tension-restraint effect of TRDs are considered in the side bearings. And maximum tension force comparison and maximum vertical deformation comparison for corner bearing before and after consideration of TRD are shown in Fig.13 and Fig.14. Though the total tension force increases due to the larger vertical stiffness, significant reduction on tensile stress in bearings and vertical displacement can be easily observed.

Table 4 – List of earthquake waves for analysis

Number	Name	Time	Duration
WAV01	ELCENTRO	1940	30s
WAV02	NGA_no_2958_CHY054	1999	74.99s
WAV03	NGA_no_187_H	1979	39.32s
WAV04	CPC_TOPANGA CANYON	1994	55.56s
WAV05	NGA_no_949_ARL	1994	39.94s
WAV06	Artificial wave	-	30.00s
WAV07	Artificial wave	-	30.00s

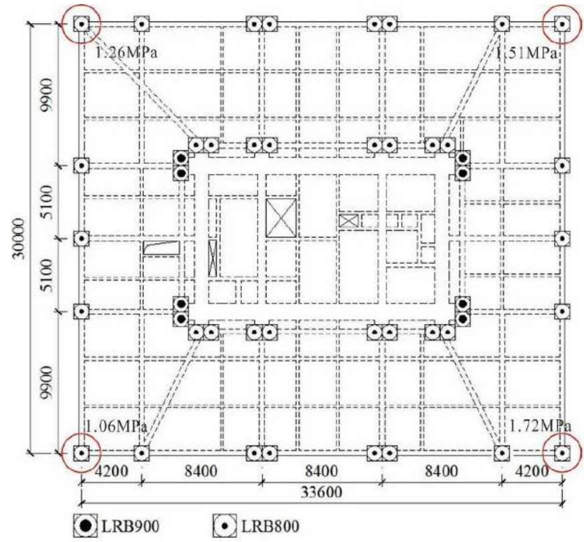


Fig. 12 Configuration of isolation floor and maximum tensile stress in isolators

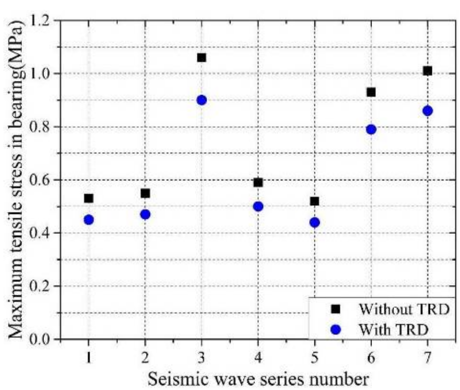


Fig.13 Maximum tension stress in bearing

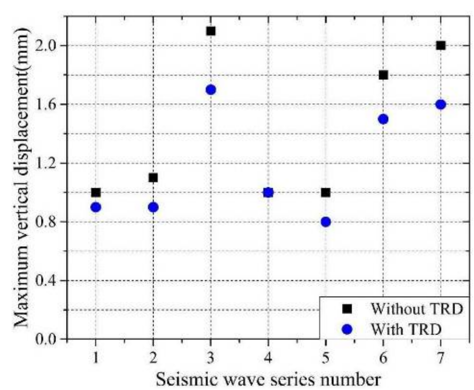


Fig. 14 Maximum vertical displacement

4.2 Building model and model isolators

The model structure was designed strictly according to the similitude law. Scaling factor was chosen as 1/15 considering the size of shaking table. The height of small scaled model is 3.89m with a floor plan size of 2.24m×2.00m. The model was constructed with micro concrete and galvanized steel wires. A total of 6 model bearings were used in the isolation layer for test model The test model was constructed in State Key Laboratory of Disaster Reduction in Civil Engineering of Tongji University as shown in Fig.16.

The test bearings were designed according to the stiffness and yield force scaling factor of isolation layer. Considering the minimum fabrication size of the rubber bearings, the diameter of model bearing was chosen as 100mm and with a diameter of 14mm lead core in the center. Besides, TRD devices were fabricated to accommodate the reduced-scale LRB100 bearings. And TLRB100 were designed to be arranged at the 4 corner position where tensile force are most easy to occur. Layout of the model isolation floor is shown in Fig.17.

4.3 Bearing testing

Series static cycle load tests were conducted to study the mechanic property of LRB100 and TLRB100. And comparison has been made between LRB100 and TLRB which is similar to the previous study on prototype bearing in section 3. Small scaled model bearing with TRD is shown in Fig.15 below.

4.3.1 Test equipment and procedure

The loading equipment for test constituted of an electro-hydraulic servo loading system with 1000kN maximum horizontal axial force of 630kN maximum horizontal tangential force, a data acquisition system and an analysis system.

The load condition are similar as prototype test, a total of 3 loading conditions were conducted including limit tensile (LT) condition, shear-compression (SC) condition and shear-tensile (ST) condition for both LRB100 and TLRB100.

4.3.2 Model bearing testing results

Static experiment results correlate the results of the prototype isolators well indicating that model TRDs are supposed to achieve the expected design purpose to protect the elastomeric bearing from tensile force in seismic excitation.

Fig. 15 Small scaled model bearing with TRD

Table 5 – List of earthquake waves for test

Number	Name	Time	Duration
Northridge	Northrige-01	1994	39.94s
Chichi	Chi-chi, Taiwan-05	1999	74.98s
AW	Artificial wave	--	40.00s

4.4 Shake table test

4.4.1 Earthquake excitation and amplitude

Two sets of historical ground motion records (Northrige and Chi-Chi) and one set of artificially generated ground motion record (shorted as AW) were selected as the excitation input. The spectrum comparison of input waves (MCE level) is shown in Fig.18. The information of the seismic waves used in the shake table test is listed in table 6. Three levels of amplitude of the input ground motions were fed to the specimen: frequent intensity, basic design intensity and rare intensity, with the corresponding spectral acceleration amplitudes of 0.21g, 0.61g and 0.95g respectively. In order to satisfy the similitude laws, the original time step of 0.02s of all ground motions needed to be scaled to 0.21 of its original value resulting in 0.0042s time step. First series of shaking table tests was performed on a base isolated structure with six lead rubber bearings without TRDs. Subsequently, the TRD components were installed at four corner isolators and the tests were repeated.

Fig.16 1:15 scale base isolated building

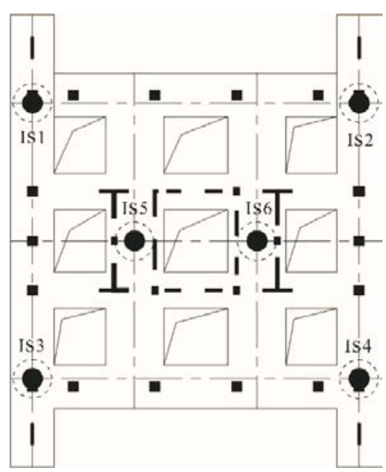


Fig.17 Isolation layer arrangement

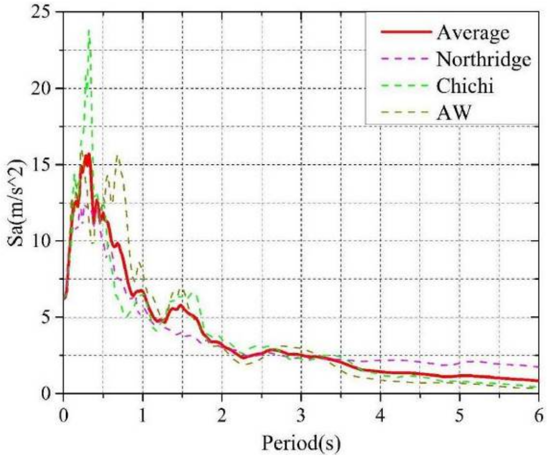


Fig.18 Spectrum of seismic waves in shake table test

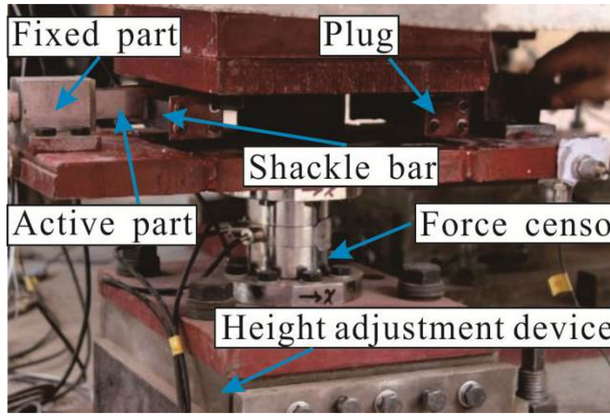


Fig.19 Installation details of isolation floor with TRD

4.4.2 Arrangement of the isolation floor

To fulfill the requirement of the experiment, the design of isolation floor need elaborate consideration. The time history force data was obtained via three directional force censor. They are installed under each isolator. During the test, gravitational load on each isolator should be balanced. So that a kind of height adjustment device is introduced in the test. The details of configuration of isolation floor is presented in Fig.19.

4.4.3 Results

Tension restraint effect of the TRD was studied by comparing the vertical displacement of rubber bearings. For record AW under rare earthquake ground shaking, the isolator experienced the uplift. Taking IS1 (see Fig.17) isolator with TRD installed as an example, tensile force measured in the isolator during a unilateral excitation under AW ground motion scaled to a rare event is plotted in Fig.20. Vertical deformations between the upper plate and the bottom plate reflecting the axial deformation of the rubber bearing of LRB and TLRB isolators in same conditions are compared in Fig.21. While the isolators were under compression, vertical deformations of the rubber bearing between LRB and TLRB were nearly the same. However, during the time when the bearings were subjected to tensile force, the amplitude of the vertical deformation of the rubber bearing in TLRB was reduced compared to the LRB implying that the tensile stress of the rubber bearing decreased.

The influence of TRD on isolation effect was analyzed in different conditions. When the tensile stresses occurred in the bearings, the hysteretic behavior of LRB and TLRB isolators are similar (see Fig.22(a)), which is different from the trends observed in a cyclic test in ST conditions. The inconsistency is mainly attributed to the transient and almost instantaneous occurrence of tensile state during the ground motion as opposed to a constant application of tensile force in the earlier tests. Although the friction force generated between the TRD components has a small influence on the shear performance of isolators in tensile state, the device has little impact on the observed hysteretic behavior of isolators during the ground motion shaking, because the isolators mainly remain in compression. For the test runs during which the tension did not occur in the bearings, hysteretic performances of TLRB fitted well to the results of LRB both in unilateral and bilateral excitations as shown in Fig.22(a, b). The observation indicates that TRDs have less influence on the shear performance of isolators in compressive state and is consistent with the results from the tests with isolators under compression presented in Section 3.

5. Acknowledgements

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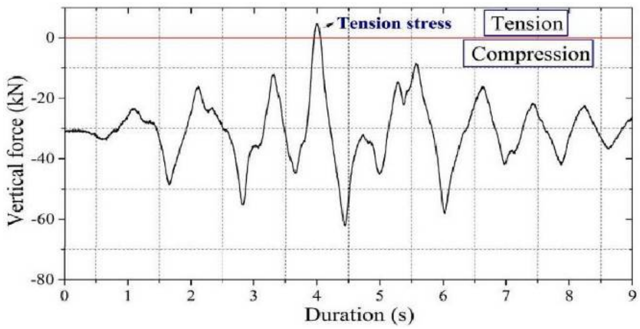


Fig.20 Force time history of LRB (unilateral excitation of AW wave scaled to a rare intensity earthquake level)

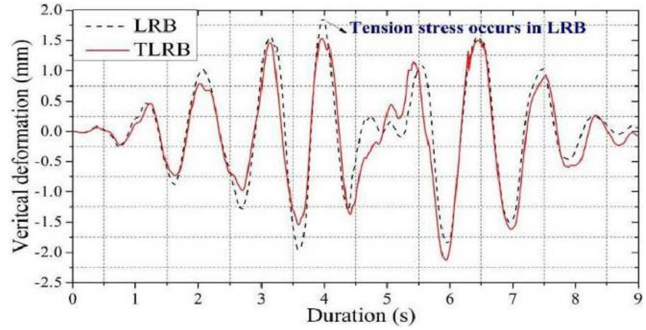
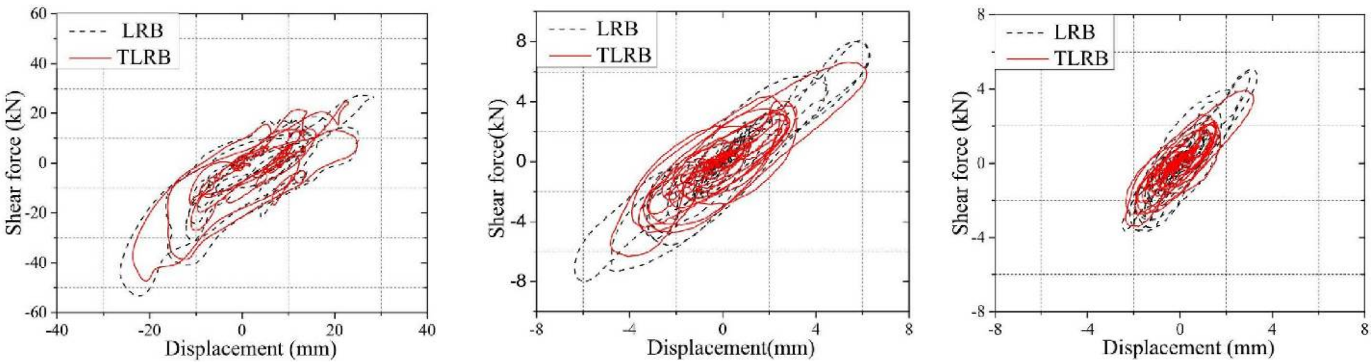


Fig.21 Vertical displacement comparison of LRB and TLRB (unilateral excitation of AW wave scaled to a rare intensity earthquake level)



(a) Rare intensity level (b) Basic design level (c) Frequent intensity level

Fig.22 Hysteretic comparison of LRB100 and TLRB100

6. Conclusion

Based on laminated rubber isolation technology, a novel tension-restraint device is proposed to address a significant uplift problem of rubber bearings in base isolated high-rise buildings and buildings with large aspect ratio.

(1) Tension-restraint devices can improve the tensile capability of isolators and protect the rubber bearings from damage and/or failure under the tensile force by restricting the vertical deformation of the rubber bearings and keep the bearing tensile stresses below the maximum design capacity.

(2) The installation of TRD are proved to help avoid degradation in horizontal shear performance and energy absorption capacity of the isolators in tensile condition. The tension-resistant bearings were shown to have met the expected performance requirements under the tension, the shear-tension and the shear-compression conditions. Meanwhile, it barely affect the regular working performance under compression state.

(3) According to results of time history analysis, large tensile force are prone to occur in corner bearing, and considering the restraint effect of TRD, the tensile force can be well controlled.

(4) Working performances of the device under seismic excitation was verified by shake table test, in which the device can protect bearing from tensile stress. And it is proved that installation of TRD would not affect the basic mechanic properties of rubber bearing.

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