Seismic requirements for laminated elastomeric bearings and test protocol for verification

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Abstract

Laminated elastomeric rubber bearings have been widely used after 1995 Kobe, Japan, earthquake, and no severe damage had been observed before the 2011 earthquake. However, some of laminated elastomeric rubber bearings, including those designed according to the post-1995 design specifications, suffered severe damage such as rupture or deep crack into rubber by the 2011 earthquake. Considering the significance of the damage of laminated elastomeric rubber bearings during the 2011 Great East Japan earthquake, the seismic design specifications for highway bridges, which were revised in spring, 2012, included requirements for seismic structural members including bearings. This paper introduces the requirements for seismic structural members and the test protocols, which were recently proposed by the authors, for laminated elastomeric rubber bearings in order to verify the requirements.

Introduction

The 2011 Great East Japan earthquake caused the catastrophic damage by the huge tsunami and the strong ground shaking in the Tohoku and Kanto regions. Although many road bridges were washed away in the coastal areas by the tsunami, structural damage caused by the strong ground shaking was relatively less. This is because the seismic retrofit projects have been performed to highway bridges and the retrofitted bridges performed well under the strong ground excitation. Relatively old but unretrofitted bridges suffered relatively larger damage.

In terms of damage of bearings caused by the 2011 earthquake, steel bearings of bridges that were designed according to pre-1980 design specifications but had not been retrofitted suffered severe damage. Failure of side stopper of fixed bearings, failure of side blocks, fracture of set bolts were observed after the event as shown in Photo 1. On the other hand, minor damage, which did not have significant effect on its structural function, was observed in steel bearings designed according to post-1995 design specifications.

Laminated elastomeric rubber bearings have been widely used after 1995 Kobe, Japan, earthquake, and no severe damage had been observed before the 2011

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earthquake. However, some of laminated elastomeric rubber bearings, including those designed according to the post-1995 design specifications, suffered severe damage such as rupture or deep crack into rubber by the 2011 earthquake as shown in Photo 2. Although neither deck unseating nor collapse of bridges occurred due to this damage, this had a significant impact on the reliability of the rubber bearings.

(a) Movable bearing (b) Fixed bearing

Photo.1 Damage of steel bearings designed according to pre-1980 design specifications

(a) Rupture of rubber bearing (b) Crack of rubber bearing

Photo.2 Damage of laminated elastomeric rubber bearings designed according to post-1995 design specifications

Although the causes of this damage have still been under investigation, one of the causes could be the insufficient original capacity of the rubber bearing. In fact, not only the seismic performance of design level excitation but also the behavior up to failure had not been verified through a series of experiments considering seismic loading before the 2011 earthquake.

Considering the significance of the damage of laminated elastomeric rubber bearings during the 2011 Great East Japan earthquake, the seismic design specifications for highway bridges, which were revised in spring, 2012, included requirements for seismic structural members including bearings. In particular, seismic isolation bearings in seismic isolation bridges (Menshin bridges) have fundamental functions to ensure the seismic performance of the bridges, and thus, the isolation bearings are one of the most important members in Menshin bridges.

This paper introduces the requirements for seismic structural members and the test protocols, which were recently proposed by the authors, for laminated elastomeric rubber bearings in order to verify the requirements.

Requirements for seismic structural members

The 2012 seismic design specifications for highway bridges require experimental verification for members which are significantly affected by the seismic effect as followings:

1) Failure mode shall be clear, and sufficient safety margin for the failure should be ensured,

2) Stable behavior under cyclic loading for the design level ground motion shall be ensured, and

3) An analytical modeling of mechanical properties such as nonlinear force versus displacement relation shall be clarified.

The conditions for application, such as range of temperature, axial force, structural details, etc., shall also be determined based on the conditions of the corresponding experiment. These requirements are intended to be used to verify newly developed material, structural design, structural members, devices, etc. in order to encourage the introduction of these new technologies in the performance-based design concept.

For bearings, the following is also required in addition to the above listed requirements.

4) Bearings shall be simple in mechanism to ensure its full function under seismic excitation.

This is because manufactured bearings consist of various parts for various functions such as transmitting loads to substructure, flexibility for displacement of superstructure, resisting uplift force, etc., and thus, complicated mechanism might be likely developed.

Experimental protocol for verification of mechanical properties of laminated elastomeric rubber bearings

The experimental verification is employed not only for verification of the requirements but also for determination of the design limit values. For such purpose, it is necessary to determine an experimental protocol and verification methods for the requirements described in previous chapter. Quasi-static cyclic loading tests are selected as a standard experimental method in this purpose because they are suitable to examine the damage progress due to increment of deformation, dynamic strength, ductility and energy dissipation capacity, and the effects of number of cycles on cyclic behavior.

For laminated elastomeric rubber bearings, the design limit strain shall be determined based on experiments verifying the requirements of items 1) and 2) listed in previous chapter, which verifies the ultimate failure mode and stable behavior under seismic excitation.

To verify the ultimate failure mode, a cyclic loading of 2 cycles with amplitude of the ultimate limit displacement (as plotted A in Figure 1) is required, and a safety factor of 1.2 shall be considered to determine the design limit strain from the displacement at Point A. After this loading, a monotonic loading is performed up to the deformation in which the bearing loses its function due to rupture or buckling of the bearing.

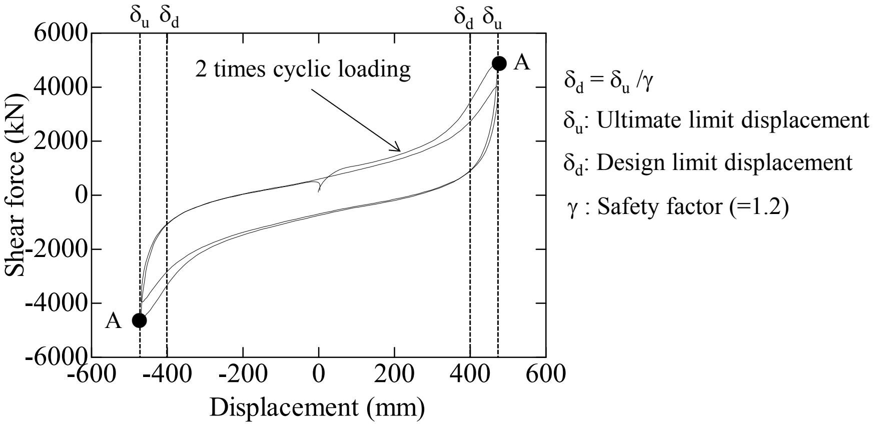


Fig.1 Hysteretic loop at the ultimate limit displacement

To verify the stable behavior under seismic excitation, a cyclic loading of at least 5 cycles with amplitude of the design limit displacement is required as shown in Figure 2. The degradation of equivalent stiffness and energy dissipation capacity is evaluated through the cyclic loading test.

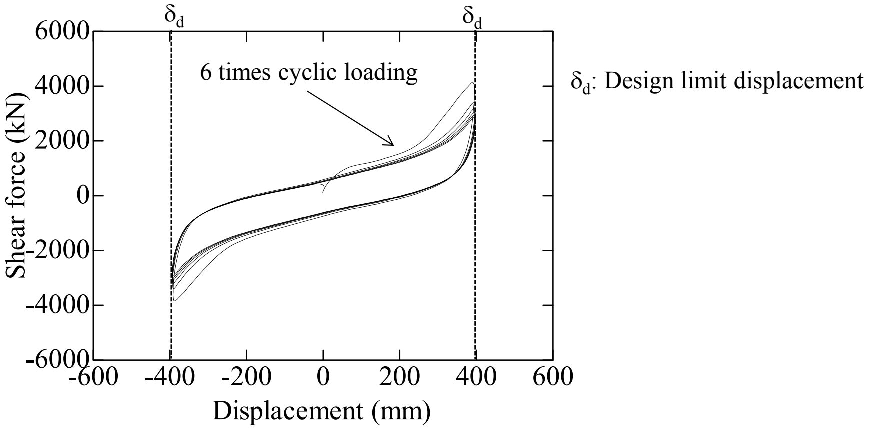


Fig.2 Hysteretic loop at the design limit displacement

The number of cycles in the loading test employed for verifying the stable behavior of the bearing was determined based on the analytical seismic response of bridges with isolation bearings or elastomeric bearing under design ground motions. A series of nonlinear dynamic response analyses was conducted with input ground motions for both the interplate earthquake and the near-fault earthquake. Figure 3 shows the number of times exceeding 90% of the maximum response displacement. For both the bridges with isolation bearings and those with elastomeric bearings, the maximum number of times exceeding 90% of the maximum response displacement is 4, and thus, by considering 5 as the number of cyclic loading in the experimental verification, the stable behavior of the bearings can be ensured during seismic response of the bridge under a strong excitation.

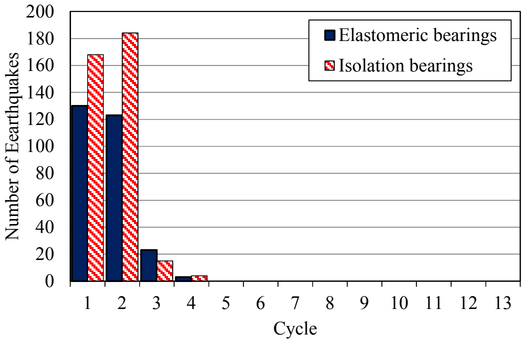
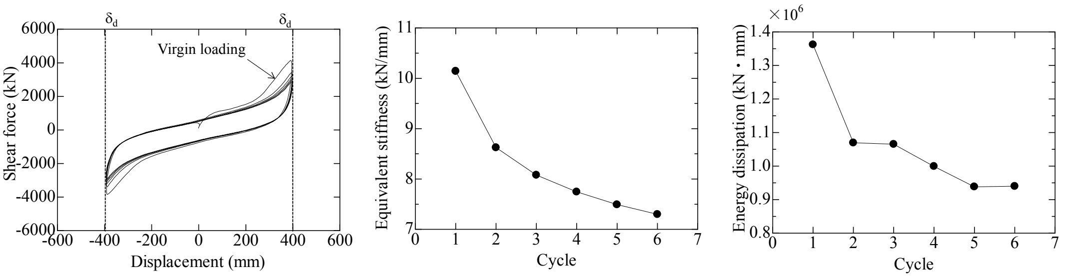


Fig.3 The number of times exceeding 90% of the maximum response displacement

Figure 4 shows an example of lateral force versus displacement relation and plots of the degradation of equivalent stiffness and energy dissipation capacity. As cyclic loading is applied with the same displacement, equivalent stiffness and energy dissipation capacity decrease, but the degree of decrement at each cycle decrease, which means behavior of bearing becomes more stable under cyclic loading. Table 1 summarizes the requirements for verifying the stable behavior under cyclic loading. The virgin loading can be ignored in this evaluation because the hysteresis of virgin loading excursion shows apparently different behavior from the hysteresis of the 2nd and the following cycle.



(a) Hysteretic loop at the design allowable displacement

(b) Equivalent stiffness at each cycle

(c) Energy dissipation at each cycle

Fig.4 Example of lateral force versus displacement relation and plots of the degradation of equivalent stiffness and energy dissipation capacity

Table 1 Requirements for the stable behavior of laminated elastomeric rubber bearing under cyclic loading

Items	Engineering indexes for evaluation	Criteria
1	Degradation ratio of equivalent stiffness at the 6th cycle loading to the 2nd cycle loading	Less than 30%
2	Degradation ratio of energy dissipation capacity at the 6th cycle loading to the 2nd cycle loading	Less than 30%
3	Degradation ratio of equivalent stiffness in each loading cycle (2nd to 6th cycle loadings)	Less than 10%
4	Degradation ratio of energy dissipation in each loading cycle (2nd to 6th cycle loadings)	Less than 15%

Modeling method of mechanical properties of laminated elastomeric rubber bearings

It is essential to model mechanical properties such as nonlinear force versus displacement relation appropriately because the accuracy of seismic response evaluated by not only nonlinear dynamic analyses but also nonlinear static analyses highly depends on the reliability of the idealization of mechanical properties. In particular, since seismic isolation bearings in Menshin bridges have fundamental functions to ensure the seismic performance of the bridges as described above, the accurate idealization of mechanical properties of isolation bearings is needed.

The design specifications recommend employing an appropriate analytical model of lateral force versus lateral displacement relation based on a series of cyclic loading tests. As shown in Figure 5, lateral force at the maximum displacement decreases as cyclic loading is repeated with the same displacement, which suggests that the analytical model shall be set to represent the behavior of the 5th cycle loading at the design limit displacement as shown in Figure 5. This is because the model developed based on this concept results in conservative estimation of the seismic energy dissipation and the seismic response of bridge.

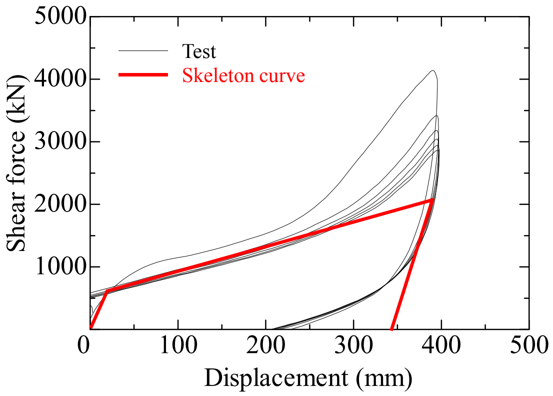


Fig.5 Hysteretic loop and skeleton curve at the design limit displacement

The hysteresis of 1st cycle of laminated elastomeric rubber bearings shows quite different from those after 2nd cycle as shown in Figure 5. Lateral force of 1st cycle at the maximum displacement is 21% larger than that of 2nd cycle. This large lateral force could cause damage at its attachment of bearings. Therefore, this large lateral force shall be considered into the design of the attachment and the member attached with bearing.

Example of experimental verification for laminated elastomeric rubber bearings

This chapter exemplifies results of the lateral loading test of lead rubber bearing conducted for verification of the seismic requirements. Table 2 shows dimensions and properties of the test specimen. The dimension of the rubber is 1020 mm, the layer thickness of rubber is 39mm, the shear stiffness is 1.2N/mm^2, the primary shape factor is 5.99, and the secondary shape factor is 6.41. The bearing contains 4 circular lead plugs with diameter of 144mm.

The lateral loading test was conducted with vertical pressure of 6N/mm^2. The test specimen was loaded at laboratory temperature with the loading rate of 15mm/sec.

Table 2 Dimensions and properties of test specimen

Specimens dimension	Longitudinal		A	mm	1020
	Lateral		B	mm	1020
	Total rubber height		T	mm	314
Design dimension	Plane Dimension	Longitudinal	a	mm	1000
		Lateral	b	mm	1000
	Laminated-rubber	Layer thickness	t_e	mm	39
		Number of Rubber layers	n	—	4
		Total layer thickness	Σte	mm	156
	Lead shape	Lead diameter	DP	mm	144
		Number of lead plug	NP	—	4
Properteies	Primary shape factor		S1	—	5.99
	Secondary shape factor		S2	—	6.41
	Rubber Shear Modulus		G	N/mm^2	1.2
	Vertical stiffness		E	N/mm^2	324

Table 3 lists a series of loading sequence of the experimental verification. Step 1 is the test conducted for quality control. 11 times cyclic loading at effective design displacement, which corresponds to 0.7 times design limit displacement, was applied to the specimen in Step 1. In this test, the effective design displacement was determined to be 280mm.

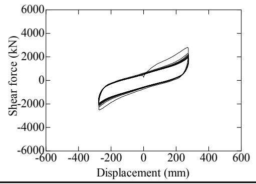
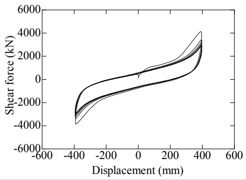
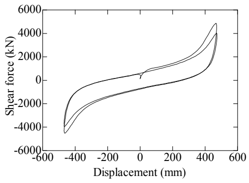
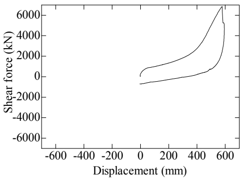
Table 3 Series of loading sequence of the experimental verification

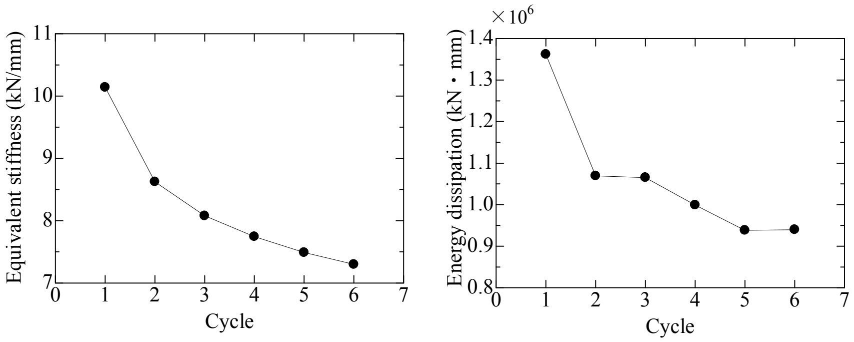
STEP	Displacement	Number of times to repeat	Purpose
1	Effective design displacement（0.7×δa）	11	Quality control
2	Design limited displacement（δa）	6	Verification of stable behavior
3	Ultimate limited displacement（1.2×δa）	2	Verification of behavior at the ultimate limit state
4	Rupture displacement	Monotonic loading	Verification of safety margin for failure

Step 2 is the test for verification of stable behavior at the design limit displacement. 6 times cyclic loading was applied to the specimen in Step 2. The amplitude of this loading is 400 mm. Step 3 is the test for verification of behavior at the ultimate limit state. 2 times cyclic loadings at the ultimate limit displacement (480 mm), which corresponds to 1.2 times design limit displacement, was applied to the specimen in Step 3. And then, monotonic loading was applied up to the deformation in which the bearing loses its function due to rupture or buckling in Step 4.

Table 4 shows shear force versus displacement relation at each step and photos at maximum shear deformation. Figure 6 shows change of equivalent shear stiffness and energy dissipation capacity, respectively.

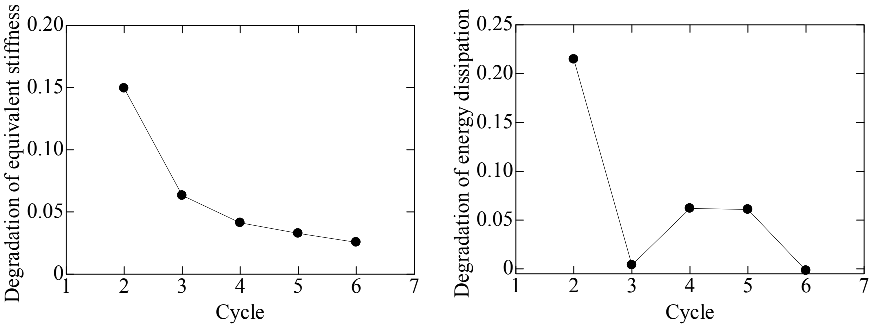
Table 4 Shear force versus displacement relation at each displacement

Step and Conditions	Shear force versus displacement relation	Photo at maximum deformation
Step1: Effective design displacement Shear strain: 175% Cyclic times: 11times		
Step2: Design limit displacement Shear strain: 250% Cyclic times: 6times		
Step3: Ultimate limit displacement Shear strain: 300% Cyclic times: 2times		
Step4: Up to rupture Shear strain: 370% Monotonic loading		



(a) Equivalent stiffness at each cycle

(b) Energy dissipation at each cycle



(c)Degradation of equivalent stiffness at each cycle

(d)Degradation of energy dissipation at each cycle

Fig. 6 Change of equivalent shear stiffness and energy dissipation capacity

Although the lateral force at the 1st cycle is significantly large, stable behavior after the 2nd cycle can be observed during cyclic loading at the design limit displacement. In the cycles at the ultimate limit displacement, stable behavior can be still observed although noticeable hardening behavior can also be observed. After loading at Step 3, lateral displacement was applied monotonically and the force increased up to 6852kN, which corresponds to 1.7 times larger than the lateral force at the design limit displacement, and finally ruptured.

Concluding remarks

This paper summarized the seismic requirements for bearings of bridge and test protocols for verification for the limit state and stable behavior under cyclic loading were proposed, so that mechanical properties such as the nonlinear relation between force and displacement were appropriately modeled in the seismic analysis of bridge.

It has been over 15 years since laminated elastomeric bearings widely used. Stock of old laminated elastomeric bearings will increase in the near future. On the other hand, though only 15 years passed, damage of laminated elastomeric rubber bearings are observed due to seismic force or deterioration due to environmental effects. Therefore, PWRI has just kicked off a collaborative research project with highway companies on investigation of change of mechanical and material properties of not only laminated elastomeric bearing but also steel bearings in order to evaluate mechanical properties, residual capacity and diagnostic technic of existing bearings in bridges.

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