A New Experimental Manner to Determinate Design Parameters of High Damping Rubber Bearings

Nguyen Anh Dung, Quang Hung Nguyen

Abstract*: High damping rubber bearings (HDRB) is an efficient technique developed to prevent or minimize damage to buildings during earthquakes. HDRB with high flexibility and high damping capacity have been widely applied in Japan. The high flexibility will be able to move the structures' natural refequencies to shirk the resonance with excitation, while their high damping capability can reduce the corresponding displacement. In seismic design codes (AASHTO 2010, JRA 2004), the design parameters of HDRB are identified from a stress-strain loop of sinusoidal bearing experiment results. The specimens of HDRB are designed based on ISO 2005, however, the cost of these specimens is quite high. In this paper, a new test manner, namely lap shear tests with cheap cost is investigated to replace the bearing tests. The analytical results show that lap shear tests may be the alternative method for determination of design parameters of HDRB.

Keywords*: Earthquake resistance, Rubber bearing, Bearing tests, Lap shear tests.

I. INTRODUCTION

The base isolation systems are recognized as an efficient shock resistance solution for structures. There are some types of base isolation systems, above all, seismic design of bridges with using high damping rubber bearings (HDRB) spread widely in Japan. The performance of structures using HDRB is very good during earthquakes. The use of HDRB does not only bring the safety of the constructions but also the economic efficiency. High damping rubber (HDR) material is made by a special vulcanization process [1, 2], this process make HDR material has some superior properties such in strength and damping capacity. Some mechanical behavior of HDRB is similar to the behavior of other rubber bearings, for example, they are small deformation when subjected to vertical loads, but they can be large deformation when subjected to horizontal loads. Although HDRB have some special properties which are different from the properties of other rubber bearings. They perform high damping capacity, Marioni (1998) [3] defined that HDRB have to provide at least 10% of an equivalent viscous damping. In addition, HDR is high durable. Gu and Itoh (2006) [4] shown that the HDRB's equivalent stiffness is varied from 10% to 25% after 100 years. It means that HDRB does not demand the maintenance. In some current design standards [5-7], the complicated mechanical characteristics of HDRB are modeled by a bilinear model. Though some previous investigations [8-9] have indicated that the mechanical characteristics of HDRB strongly depend on loading rates, the design model could not describe this rate-dependent property. In order to improve the shortcoming of the design model of HDRB, Bhuiyan et al., 2009 [10] presented a model of HDRB considering the strain-rate dependence property. The design parameters of HDRB models have to be identified based on a stress-strain loop obtained from sinusoidal loading tests. In order to determine the design parameters from the test results, sinusoidal loading experiments with frequency of 0.5 Hz and some kind of tests are usually conducted on bearing specimens. The mechanical behavior of HDRB is very different from the standard elastomeric bearings' behavior. Therefore, HDRB specimens are quite expensive. The machine for bearing tests must be high loading capacity and the operation of this machine is complex. There is another way to get stress-strain cycles for determining design parameters of HDRB, namely lap shear tests which can be conducted on cheaper material specimens. Each material specimen consists of only two small rubber layers attached to the steel bars. Therefore, material specimens are much cheaper than bearing specimens and lap shear test procedure is also simple. In order to find an appropriate manner to determine the design parameters of HDRB in seismal analysis of structures, in this paper, lap shear tests are carried out on HDR material specimens. The lap shear test data are compared with the data of bearing tests in [10]. Moreover, the model parameters of [10] are determined based on lap shear tests and these parameters are used in numerical simulations of experimental results

II. EXPERIMENTAL SET UP

A. *Bearings tests on high damping rubber bearings l*

The HDRB specimens in the bearing tests are designed based on ISO 2005 [11]. The details of HDRB specimens are indicated in Table 1 and Fig. 1. Because of the presence of Mullins effect [12] in virgin rubber material, all HDRB specimens are preloaded by 11 sinusoidal loading cycles with frequency of 0.05 Hz before the real tests for detaching the Mullins effect from other mechanical behavior of HDRB.

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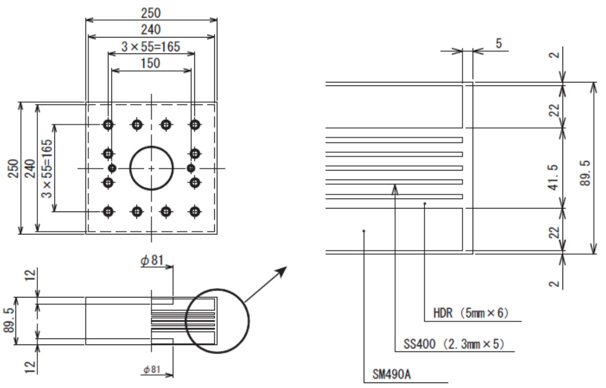


Fig. 1: Size of specimens in bearing tests

***Tab. 1.* Details of HDRB specimens**

Specification	HDRB
Specimen's plan (mm2)	240x240
Rubber layer number	6
Rubber thickness (mm)	5
Steel thickness (mm)	2.3
Nominal shear modulus (MPa)	1.2

In order to consider the effect of vertical load, all the bearing tests are carried out under a vertical presure of 6 MPa. The machine used in bearing tests is in Fig. 2, all HDRB specimens used in these tests are new. All bearing experiments are conducted at room temperatures and test data are recorded by a computer.

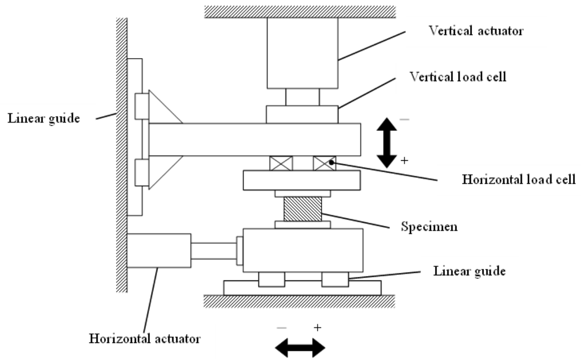


Fig. 2: The testing machine for bearing tests

B. *Lap shear tests on HDR material.*

The dimensions of the lap shear test specimens were presented in Fig. 3, there were two rubber layers with 25x25 mm2 are and 4 mm thickness. All specimens in lap shear tests are also preloaded before the real tests to cut out the Mullins softening behavior. The experimental work of lap shear tests is carried out on these specimens with a computer-controlled testing machine that is presented in Fig. 4 and these experiments are conducted at room temperature.

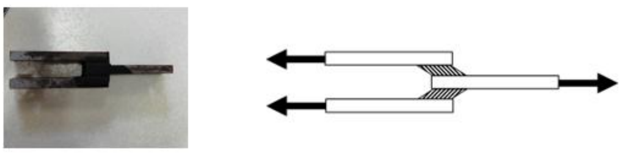


Fig. 3: Lap shear test specimen

Fig. 4: The testing machine for lap shear tests.

III. RESULTS AND DISCUSION

The test program was implemented in this paper following the same testing methods and same HDR materials as presented in [10]. The experimental schedule is included by three types of tests: multi-step relaxation (MSR) tests, simple shear (SS) tests, and simple relaxation (SR) tests. The purpose of implementing MSR, SS, and SR tests is to determine the rate-independent equilibrium behavior, rate-dependent behavior, and viscosity behavior of HDR, respectively.

A. *The experimental results and discussion*

1) *Equilibrium response obtained from MSR tests*

The equilibrium responses obtained from two test methods are presented in Fig. 5. There is some difference at high strain level (175%), the stresses of bearing tests are higher than the stresses of lap shear tests. This difference can be explained by the work of steel layers together with rubber layers in bearing specimens. The appearance of steel layers in bearings make the strain hardening larger in bearing tests. However, the two results are quite similar to each other.

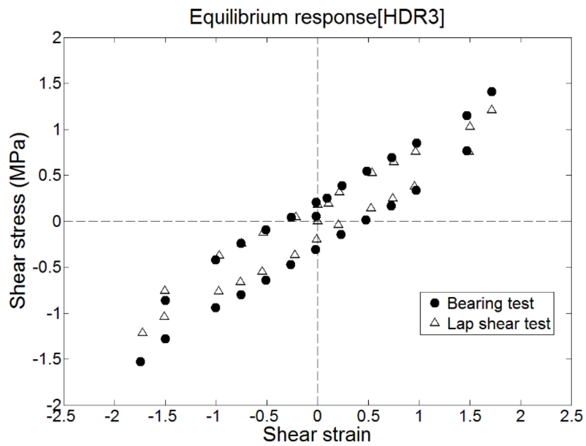


Fig. 5. Equilibrium responses obtained from bearing tests and lap shear test

Viscosity behavior obtained from SR tests

Fig. 6 describes the comparison of SR test results obtained from bearing tests and lap shear tests. Similar to MSR tests, the difference of stress responses rises with the increase in strain level. However, the SR test results obtained from bearing tests are same as the SR test results obtained from lap shear tests.

Instantaneous response obtained from SS tests

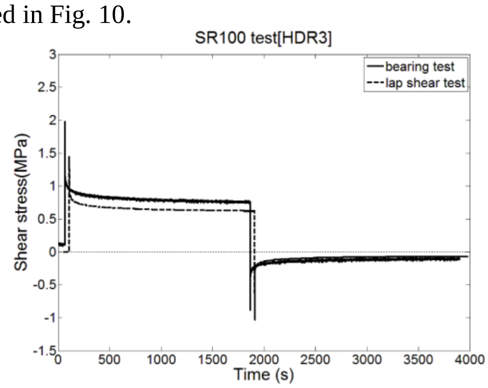
Fig. 7 indicates the instantaneous responses obtained from the two testing methods. The stresses of bearing tests are higher than the stresses of lap shear tests because of the work of steel layers together with rubber layers.

2) The comparison of design parameters of the rheology model in Bhuiyan (2009) [10]

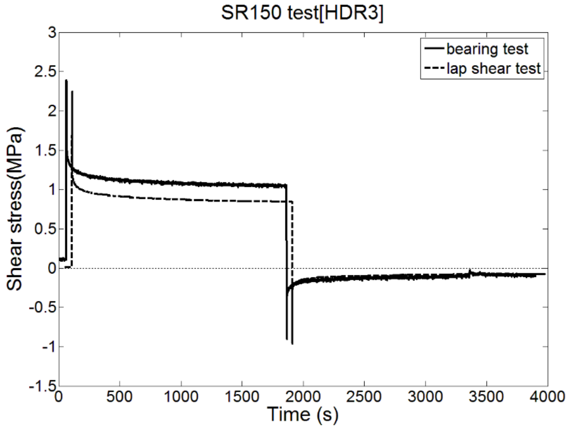
In order to study the application of lap shear tests into practical design of HDRB, experimental data obtained from lap shear tests are used to identify the model parameters of the rheology model of [10], then these obtained parameters are used to simulate sinusoidal loading test data.

The rheology model [10] is illustrated in Fig. 8, where τ is the average shear stress of HDR layers and γ is the shear strain of HDR layers. In the rheology model, the total shear force is divided into three parts that are the elasto-plastic force in the first branch, the nonlinear elastic force in the second branch and the viscosity over-force in the third branch. The mathematical equations of this model are shortly shown in Eq. (1).

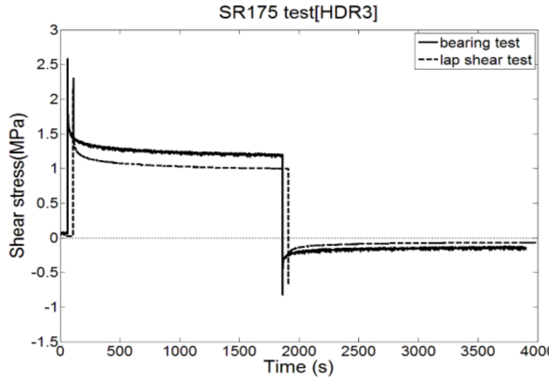
The model parameters obtained from lap shear tests are compared with those obtained from bearing tests and are presented in Table II, III, IV. These parameters are used to simulate sinusoidal loading data, the simulation results are shown in Fig. 9. For comparison, the simulation results used parameters obtained from bearing tests in [10] are again presented in Fig. 10.



(a)

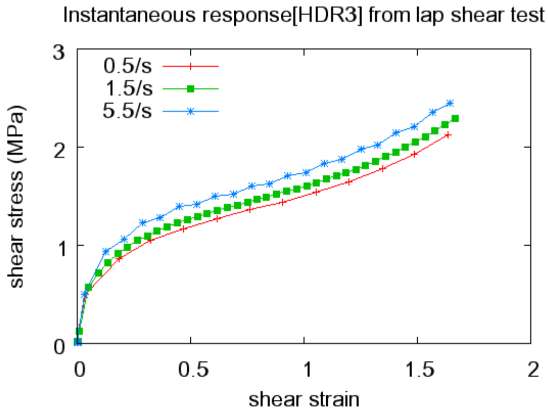


(b)

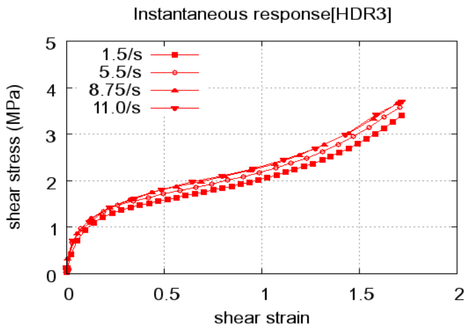


(c)

Fig. 6. SR tests obtained from bearing tests and lap shear tests at strain level: (a) 100% (b) 150% (c) 175%



(a)



(b)

Fig. 7. SS test results obtained from (a) lap shear test (b) bearing test

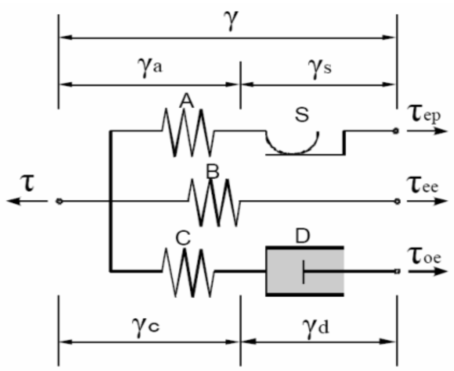


Fig. 8. Rheology model for HDRB in Bhuiyan (2009) [10]

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$$\tau = \tau_{ep}(\gamma_a) + \tau_{ee}(\gamma) + \tau_{oe}(\gamma_c) \quad (1a)$$

$$\tau_{ep} = C_1 \gamma_a \quad (1b)$$

$$\text{with} \quad \begin{cases} \dot{\gamma}_s \neq 0 & \text{for} \quad |\tau_{ep}| = \tau_{cr} \\ \dot{\gamma}_s = 0 & \text{for} \quad |\tau_{ep}| < \tau_{cr} \end{cases}$$

$$\tau_{ee} = C_2 \gamma + C_3 |\gamma|^m \operatorname{sgn}(\gamma) \quad (1c)$$

$$\tau_{oe} = A \left| \frac{\dot{\gamma}_d}{\dot{\gamma}_o} \right|^n \operatorname{sgn}(\dot{\gamma}_d) \qquad \tau_{oe} = C_4 \gamma_c \quad (1d)$$

$$\text{with} \quad A = \frac{1}{2}\left(A_1 \exp(q|\gamma|) + A_u\right) + \frac{1}{2}\left(A_1 \exp(q|\gamma|) - A_u\right) \tanh(\xi \tau_{oe} \gamma_d)$$

***Tab. 2.* Equilibrium parameters**

Test method	C_1 (MPa)	C_2 (MPa)	C_3 (MPa)	C_4 (MPa)	τ_{cr} (MPa)	m
Bearing test	2.101	0.595	0.0024	2.653	0.296	7.423
Lap shear test	2.100	0.595	0.0024	2.653	0.2024	6.421

***Tab. 3.* Viscosity parameters**

Test method	A_1 (MPa)	A_2 (MPa)	q	n	ξ
Bearing test	0.783	0.781	0.276	0.190	1.242
Lap shear test	0.521	0.501	0.431	0.178	1.242

***Tab. 4.* Viscosity parameters for simulation of stress-strain cycle**

Test method	A_1 (MPa)	A_2 (MPa)	q	n	ξ
Bearing test	0.402	0.241	0.353	0.213	1.242
Lap shear test	0.481	0.272	0.431	0.178	1.242

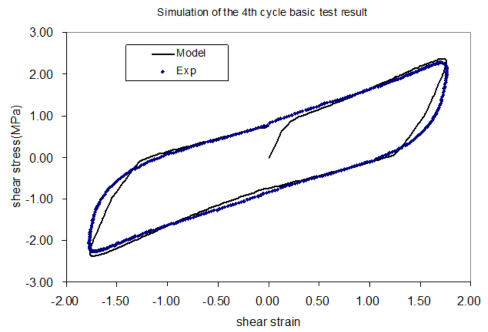

FIG. 9: SIMULATION OF THE STRESS-STRAIN CYCLE RESPONSE OF BEARING USING THE MATERIAL PARAMETERS OBTAINED FROM LAP SHEAR TESTS

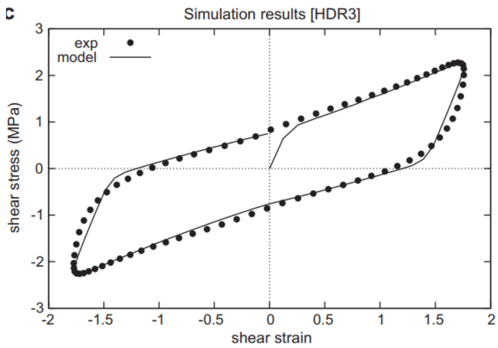

Fig. 10. Simulation of the stress-strain cycle response of bearing using the material parameters obtained from bearing tests in [10]

IV. CONCLUSION

A lap shear test program was carried out to find an appropriate method to determine the design parameters of HDRB in seismic analysis of structures. A detail comparison between lap shear test results and bearing test results has been conducted. The comparison results show the similarity in the two test methods. Moreover, a comparison conducted between the simulations and the test data indicates that lap shear tests could be used to determine the design parameters of HDRB in seismic analysis of structures.

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