Mullins effect of High Damping Rubber: Experimental result and mathematical modeling

Saitama University Nguyen Anh Dung, Yoshiaki Okui
Suncoh Consultant Shinya Ishijima
Civil Eng. Research Institute for Cold Region Hiroshi Mitamura
Rubber Bearing Association Takashi Imai

I. Introduction

In the effort to mitigate hazards from destructive earthquakes, rubber bearings are widely adopted due to their efficiency. They can shift the natural period of structures so as to avoid the resonance with excitations. Besides, they can absorb energy by damping properties to improve the structures' damping performance.

Recently, the use of High damping rubber (HDR) bearing is increased due to their enhanced dissipation property. However, HDR is known to possess Mullins effect, which is stress-softening behaviour under cyclic loading. In seismic design codes for bridges, the bilinear model for HDR bearings is based on testing data after preloading to remove Mullins effect. However, HDR material recovers its virgin state with time, called healing effect. This phenomenon may influences the performance of structural ststems with HDR bearings

In the present study, Mullins effect is investigated to develop a mathematical model. In addition, the healing effect[1)] is investigated with a series of triangular wave loading tests.

II. Lap shear test

The experimental work was conducted on HDR specimens with a computer-controlled testing machine (Shimadzu, Autograph AG-100kNG) at room temperature. Fig. 1 shows the dimension of a HDR specimen. There are two rubber layers with 25x25 mm^2 area and 4mm thickness.

In order to investigate the effect of the strain amplitude on Mullins effect, a cyclic shear test with variable amplitude (CSVA) was carried out. Fig.2 presents the stress-strain responses of a CSVA test. At each strain amplitude, the stress response decreases after the first cycle, and then the stress-strain curve reaches to a stable loop.

The triangular wave loading tests with a constant strain amplitude of 100% were conducted on three HDR specimens. After predetermined retention periods, these specimens were loaded once again with the same strain history as the first test to examine the healing effect.

Fig. 3 shows a comparison of the stress responses in the first test and the second test after 1 week. The stress amplitude of the second test closely reaches to the stress amplitude of the first test. It means that the stress almost recovers to the initial level after 1 week from the first loading.

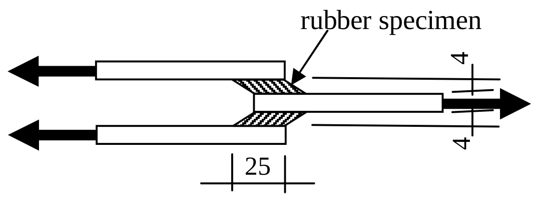

Fig. 1 Dimension of rubber specimen

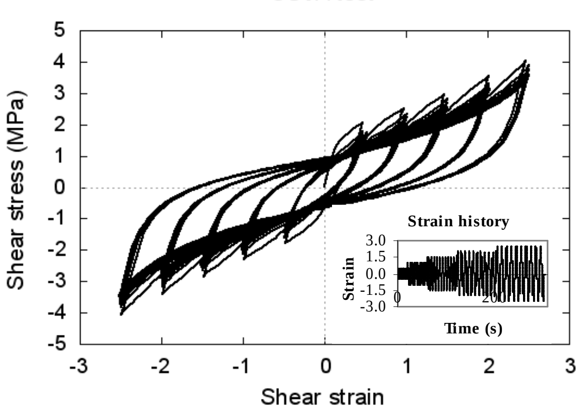

Fig. 2 Strain history and stress-strain curve of CSVA test

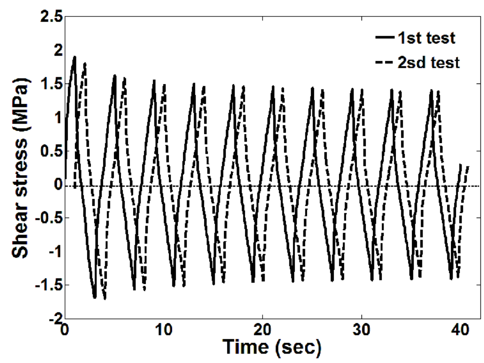

Fig. 3 Stress history of 1st test and 2nd test after 1 week from 1st test

III. Evolution equation for Mullins effect

The stress ratio r defined in Eq. (1) is employed to describe Mullins effect:

$$r = t_i / t_0 \qquad (1)$$

where τ_i is the stress amplitude at the i^{th} cycle, and τ_0 is the stress amplitude at the stable cycle.

Since the energy dissipation characterizes the behavior of HDR bearing, the dissipated energy under cyclic loading is adopted as a parameter describe Mullins

Keyword: Mullins effect, Stress-softening, High damping rubber, Healing effect, Dissipated energy.
Address: Civil and Environmental Engineering, Saitama University - 225Shimo-Okubo, Sakura, Saitama, 38-8570, Japan

effect. Based on CSVA test data, the relationship between the stress ratio and the accumulated dissipated energy D is obtained as shown in Fig. 4. The stress ratio decreases with increasing the accumulated dissipated energy. In addition, if the experienced maximum strain γ_{max} is increased, the stress ratio takes a larger value than that at the previous γ_{max}.

The gradient of r-D curves is calculated, and based on the relationship between this gradient and the stress ratio, an evolution equation is proposed in the following form:

$$\frac{dr}{dD}\left(g_{\max}\right)^{m}=c\left(r-1\right)^{n} \qquad (2)$$

where: m, n, and c are constants and they are determined by least square method.

The Eq. 2 is fitted with the experimental results for determining the parameters m, n, and c and the fitting result: m=1.442, c=-0.2877, and n=1.249.

The relationship between the gradient and the stress ratio obtained using the proposed equation with the identified parameters, and the experimental results are presented in Fig. 5.

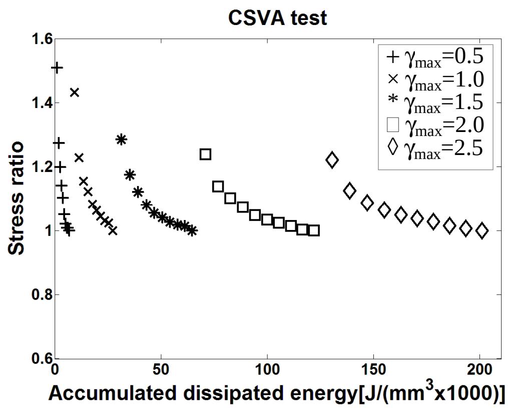

Fig. 4 Relationship between stress ratio and accumulated dissipated energy for different max. experienced strain

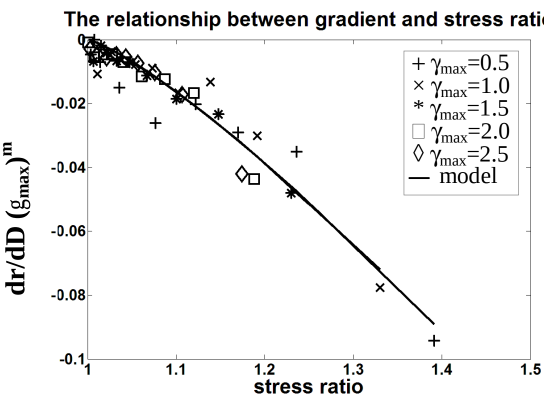

Fig. 5 Comparison between evolution equation with experimental data

IV. Healing effect

In this paper, healing effect is investigated by introducing three parameters: the stress amplitude, the equivalent damping constant h_B, and the equivalent shear modulus G_{eq}.

The ratio of the stress amplitude of the 2nd test to the 1st test can describe the healing effect.

The second parameter h_B is calculated from

$$h_B=\frac{\Delta W}{2pW} \qquad (3)$$

where ΔW is the dissipated energy per cycle, and W is the elastic strain energy. The recovery of h_B is evaluated by the ratio of h_B at the 2nd test to the 1st test.

Finally, the third parameter G_{eq} is given as

$$G_{eq}=\frac{t^{+}_{\max}-t^{-}_{\max}}{g^{+}_{\max}-g^{-}_{\max}} \qquad (4)$$

where $t^{+}_{\max}$ and $t^{-}_{\max}$ are the maximum positive and negative shear stresses, respectively; and $g^{+}_{\max}$ and $g^{-}_{\max}$ are the maximum positive and negative shear strains, respectively.

Table 1 shows the recovery of the parameters. These three ratios stand for the ratio of individual parameter in the 2nd test to that in the 1st test.

Table 1: Healing effect, Recovery of parameters.

Parameter’s recovery	Test-1day	Test-1week	Test-3weeks
Stress amp. ratio (%)	88.90	94.81	97.43
h_B ratio (%)	82.69	84.50	90.34
G_B ratio (%)	86.64	97.98	98.64

V. Conclusions

A CSVA test was performed in order to investigate Mullins effect. Based on the experimental result, an evolution equation of the stress ratio is proposed. This equation can describe the dependence of the stress ratio on the accumulated dissipated energy and the experienced maximum strain.

The three introduced parameters are recovered by more 80% after 1 day. This indicates that Mullins effect can be recovered in a short period (1 day). However, they are still recovered after 3 weeks.

References

Dall’ Asta, A., Ragni, L.: Experimental tests and analytical model of high damping rubber dissipating devices, Engineering Structures 28, 2006, pp. 1974-1884.