EXPERIMENTAL INVESTIGATION OF LAMINATED RUBBER BEARINGS AND THEIR MODELING: HIGH DAMPING RUBBER BEARING

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1. INTRODUCTION

The concept of base isolation, which is rapidly gaining wide acceptance, is one in which flexibility and high damping property are provided by a specially designed isolation system that is placed between the superstructure and the foundation. High damping rubber bearings have been increasingly used as a dissipating device in structural systems in terms of controlling the structural response under earthquake loads. In current practice of the design of highway bridges in Japan, bilinear model has been employed for seismic analysis of rubber bearings. However, this model cannot be successfully applied in the case of high damping rubber bearings due to having the inherent highly nonlinear, viscoplastic constitutive property in it. To address such complex behaviors of rubber bearings and implement into the seismic analysis of bridge, a rheology model based on the experimental investigations is proposed in this study.

2. EXPERIMENT

In this study, three types of rubber bearings (HDR, NR and LRB) were experimentally investigated. Two types of each of NR and LRB and three types of HDR bearing were used in this study. The experimental scheme was composed of simple relaxation test (SR test), simple shear test (SS test) and multi-step relaxation test (MSR test). There was a specific purpose for each test to carry out in this work; the SR test was carried out to identify the viscosity property, the SS test for rate-dependency phenomena and the MSR test to determine the rate independent response parameters of the bearings. Due to the page limitation in this paper some typical test results of HDR-S2 are given and all others are skipped. (See Bhuiyan et al. 2007 for details). The dimension of the specimen is shown in Figure 1. The details of the specimens are presented in Table-1. In order to study rate dependence, rubber bearing specimens were subjected to simple shear test with constant strain rates. The strain rates applied in these tests were calculated in terms of the initial dimension of the specimen measured just before the respective test. Figure 2 shows the shear stress- shear strain responses as obtained form HDR-S2 under shear deformations. Throughout this paper, the stress corresponds to the nominal shear stress determined by dividing the horizontal shear force by plan area of the bearing and the strain by dividing the shear deformation by the total thickness of the rubber layers. Four tests were carried out with particular strain rate. The monotonic responses as visible from the tests are found to strongly nonlinear with strain levels. The comparison of the stress response indicates the strongly pronounced rate dependent behavior during loading whereas a much weaker rate dependent behavior is observed during unloading. In addition, the presence of hysteresis is also observed.

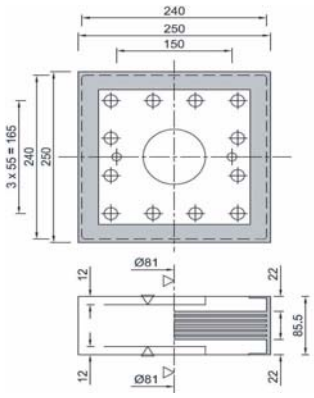

Figure 1. Plan and side view of the specimen

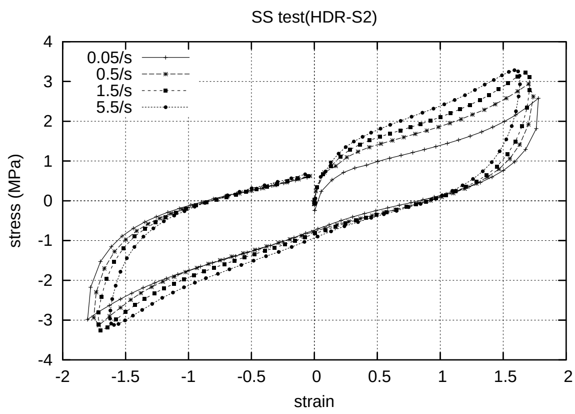

Figure 2. SS test result of HDR-S2

Table 1: Details of the specimen

Type of bearing	High damping rubber bearing			Natural rubber bearing		Lead rubber bearing	
Abbreviated designation	HDR-S1	HDR-S2	HDR-S3	RB1	RB2	LRB1	LRB2
Cross-section (mm)		240X240		240X240		240X240	
Number of rubber layers		6		6		6	
Thickness of one rubber layer (mm)		5		5		5	
Thickness of one steel layer (mm)		2.3		2.3		2.3	
Diameter of lead plug (mm)		-		-		81	
Nominal shear modulus (MPa)		G12		G12		G12	

The stress responses obtained from simple shear test at different strain rates have presented strong rate-dependent behavior during loading and weak rate dependence during unloading. This rate dependence phenomenon can be attributed to the viscosity effect of the material. To investigate this phenomenon, an experimental investigation of rubber bearing is needed. To this end, the relaxation behavior of the bearing is investigated through simple relaxation and multi-step relaxation tests (Figures 3 and 5) and these are shown in Figures 4, and 6. The relaxation period in SR test was 1800 sec and that in MSR test 1200 sec at each strain level. At the end of each relaxation period the stress response becomes time independent and this state of response is regarded as the equilibrium response in an asymptotic sense. The difference between the current stress and the corresponding equilibrium stress is the so-called overstress. Figure 6 shows the equilibrium response as obtained from the MSR test results.

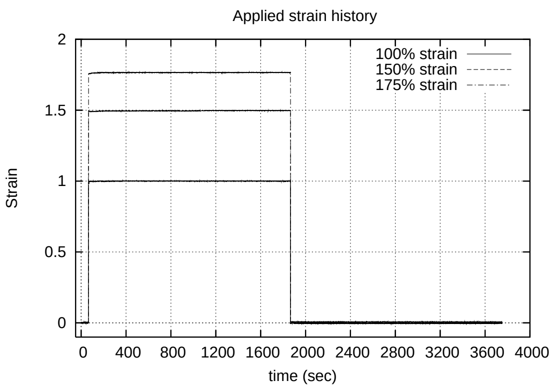

Figure 3. Strain history applied in SR test

3. RHEOLOGY MODEL

On the basis of the experimental findings, the objective of the following Section is to design a one dimensional rheology model, which provides a qualitative description of the mechanical behavior of rubber bearings. The basic ideas of the model are the additive stress and corresponding strain decompositions which are illustrated in Figure 7. As shown in Figure 7, the total stress τ decomposes into a rate independent equilibrium stress τ_{eq} and a rate dependent overstress τ_{oe}.

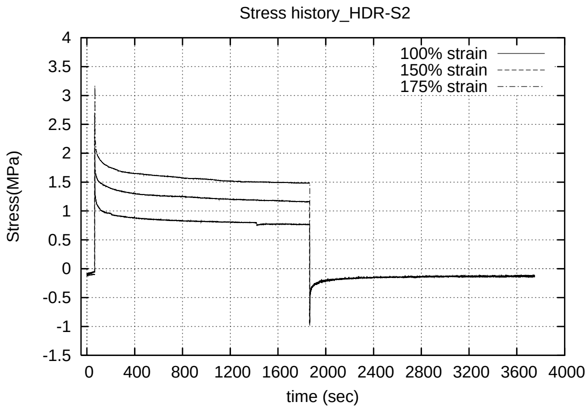

Figure 4. Stress history (HDR-S2) obtained from SR test at different strain levels.

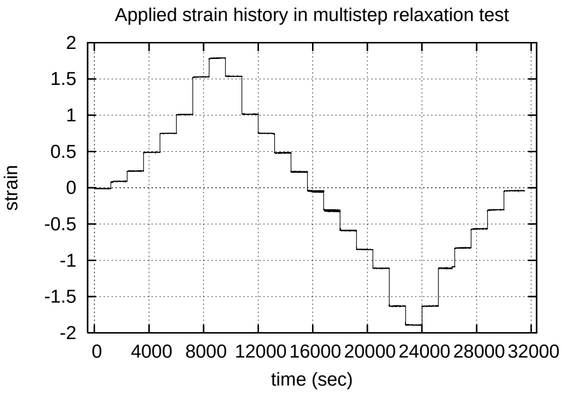

Figure 5. Applied strain history in MSR test

The equilibrium stress τ_{eq} itself is a sum of two terms: the first term τ_{ee} is nonlinear function of total strain γ, and the second term τ_{ep} is rate independent function of the strain,

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

In addition to the stress decomposition, the strain decomposition is now introduced. They are defined by

$$\gamma = \gamma_a + \gamma_s = \gamma_c + \gamma_d \tag{2}$$

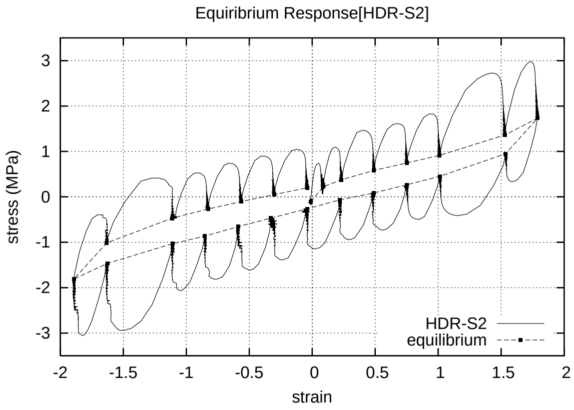

Figure 6. Equilibrium response obtained from MSR test

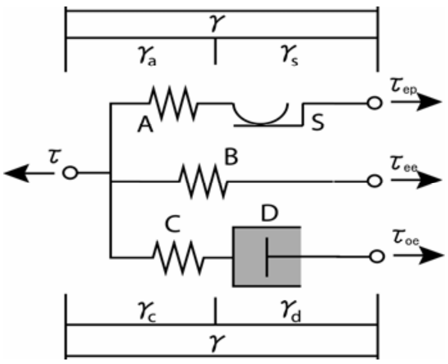

Figure 7. Rheology model

The first decomposition is related to the hysterestic part of the equilibrium stress, and the inelastic strain γ_s of the friction element, whereas the second decomposition corresponds to the overstress, and the inelastic strain γ_d of the nonlinear dashpots element. The construction of the model of each element is described below.

Element A corresponds to the elastic spring and the stress-strain relation can be expressed as

$$\tau_{ep} = C_1 \gamma_a \tag{3}$$

where C_1 is a constant and γ_a stands for the strain of the spring A.

Element S is a friction slider. The friction slider will be active when the stress level in the slider reaches a critical value of the stress, τ_{cr} i.e.

$$\begin{cases} \dot{\gamma}_s \neq 0 & \left|\tau_{ep}\right| = \tau_{cr} \\ \dot{\gamma}_s = 0 & \left|\tau_{ep}\right| < \tau_{cr} \end{cases} \tag{4}$$

Element B corresponds to a nonlinear elastic spring and the stress-strain relation can be stated as:

$$\tau_{ee} = C_2 \gamma + C_3 \left|\gamma\right|^m \operatorname{sgn}(\gamma) \tag{5}$$

where C_2, C_3, C_4 and m are constants and

$$\operatorname{sgn}(x) = \begin{cases} 1 & : \quad x > 0 \\ 0 & : \quad x = 0 \\ -1 & : \quad x < 0 \end{cases}$$

Element C corresponds to the elastic spring and the stress-strain relation can be expressed as:

$$\tau_{oe} = C_4 \gamma_c \tag{6}$$

where C_4 is a constant.

Element D is a nonlinear dashpot, whose stress and strain rate relation can be expressed based on the experimental results obtained form MSR and SR tests. From the SS test results at different strain rates (Figure 2) strong rate dependence during loading and relatively weak rate dependence during unloading has been observed. This type of behavior of the bearing can be attributed to the viscosity property of it. The relaxation behavior induced by the viscosity at different strain levels was examined in detail through SR and MSR tests (Figures 3 and 5 and see Bhuiyan et al. 2007 for details). One typical test result obtained form MSR test at strain level 150% is demonstrated in Figure 8 where a clear correspondence between overstress and dashpot strain rate is observed. The similar correspondence was also observed at all other strain levels. From this experimental investigation it is seen that viscosity property of rubber bearings varies with the sign of $\frac{d}{dt}\left|\gamma_d\right|$. Depending on the sign of this mathematical quantity the loading and unloading conditions are set and this convention will be used throughput this paper. This condition can be expressed as:

For loading: $\frac{d}{dt}\left|\gamma_d\right| > 0$, unloading: $\frac{d}{dt}\left|\gamma_d\right| < 0$ (7, a, b)

Finally the stress and strain rate relation for the dashpot can be expressed as:

$$\tau_{oe} = A_l \exp\left(q\left|\gamma\right|\right)\left|\frac{\dot{\gamma}_d}{\dot{\gamma}_o}\right|^n \operatorname{sgn}(\dot{\gamma}_d) \quad \text{Loading} \tag{8a}$$

$$\tau_{oe} = A_u \left|\frac{\dot{\gamma}_d}{\dot{\gamma}_o}\right|^n \operatorname{sgn}(\dot{\gamma}_d) \quad \text{Unloading} \tag{8b}$$

where $\dot{\gamma}_o = 1$ (sec^{-1}) is a reference strain rate of the dashpot, A_l, A_u, q and n are viscosity parameters.

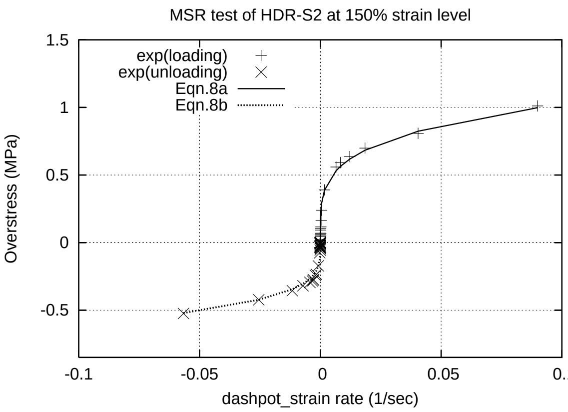

Figure 8. Identification of viscosity parameters

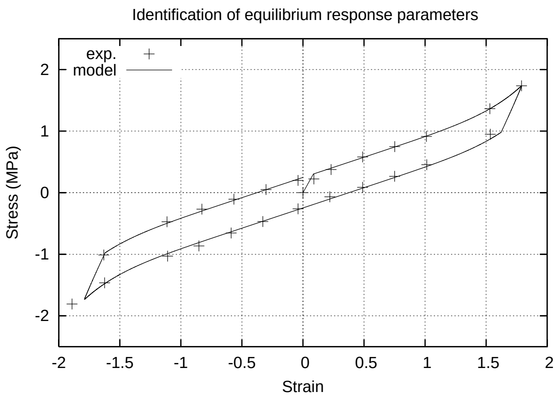

Figure 9. Identification of equilibrium response parameter

4. PARAMETER IDENTIFICATION

Eqn. (1) to (8) show that a number of parameters are required for a complete representation of the rheology model. All the parameters can be determined from direct experimental observations following a specific method. As a result, the experimental observations of HDR-S2 as shown in Figure 8 and 9 were used to determine the elasticity and viscosity parameters using the nonlinear least square method. Table 2 and 3 present the elasticity and viscosity parameters for HDR-S2 (See for details, Bhuiyan et al. 2007).

5. NUMERICAL SIMULATION

The 4th cycle of the basic test (Sinusoidal loading test with 0.5 Hz and 175% strain) in order to remove the Mullins' effect is considered for the simulation purpose. Using the parameters as shown in Table-2 and 3 a numerical simulation of the 4th cycle stress-strain response is carried out using the modified and earlier versions of the rheology model. The earlier version of the rheology model proposed by the authors (Bhuiyan et al. 2007) correspond to the model where nonlinear viscosity property has been considered the same in both loading and unloading directions .i.e Equation 8(a) has been used as the overstress expression for loading and unloading conditions. On the other hand the modified version of the model corresponds to the model where different viscosity behaviors i.e. the different overstress expressions for loading (Eqn. 8a) and unloading (Eqn.8b) are considered. The simulation result shows (Figure 10) a better agreement with the experimental results in compared with the earlier version of the rheology model (Bhuiyan et al. 2007) with a sharp shifting of the response from loading to unloading direction.

Table 2: Elasticity parameters

	C_1 MPa	C_2 MPa	C_3 MPa	C_4 MPa	τ_{cr} MPa
HDR-S2	2.6	0.66	0.006	3.25	0.24

Table 3: Viscosity parameters

	A_l MPa	A_u MPa	q MPa	n MPa
HDR-S2	0.35	0.27	0.41	0.26

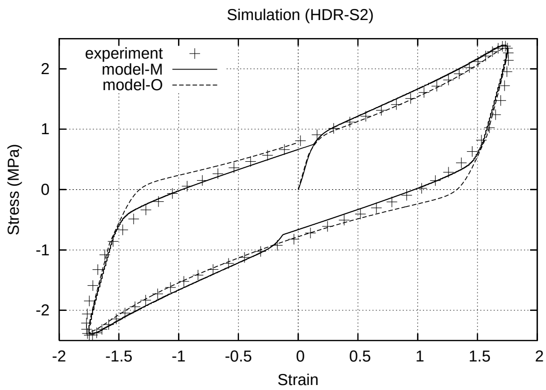

Figure 10. Numerical simulation of 4th cycle stress-strain response of basic test

6. CONCLUDING REMARKS

To overcome the various limitations of the current bilinear model for rubber bearing, a rheology model is proposed by considering the nonlinear rate dependence and equilibrium hysteresis in addition to the nonlinear elasticity behavior. From the results of numerical simulation it can be stated that the proposed rheology model with the parameter identification scheme is adequately applicable to the seismic analysis of bridge. Moreover, a further study might be needed to improve the modified model to have a smooth shifting of the stress-strain response from loading to unloading.

7. REFERENCES

Mullins, L., Softening of rubber by deformations. *Rubber Chem. Technology*, Vol. 42, pp. 339-362, 1969

Bhuiyan, A.R, Okui,Y., Mitamura, H and Imai, T., "A rheology model of rubber bearing for seismic analysis of bridges" 62nd JSCE Annual Conference , Hiroshima, 2-14 September, 2007