A MULTI-LAYER THERMAL COUPLED HYSTERETIC MODEL FOR HIGH DAMPING RUBBER BEARINGS AT LOW TEMPERATURE

Kyoto University Student Member ○Jie Shen
Kyoto University Regular Member Akira Igarashi
Saitama University Regular Member Ji Dang
Kawakin Core-Tech Non-Member Yuki Hamada
Kawakin Core-Tech Regular Member Takehiko Himeno
Kawakin Core-Tech Regular Member Hiroshi Shinmyo
Chodai Regular Member Nobuyuki Nabeshima

1. INTRODUCTION

The high damping rubber (HDR) bearing is one of the most effective isolation devices for mitigating the seismic damage of structures. Temperature is a critical factor that affects the performance of HDR bearing. The initial stiffness and strength of rubber bearing significantly increase at low ambient temperature, and this phenomenon should be taken into consideration in engineering design. The self-heating effect during energy dissipation in HDR bearing results in a reduction of its stiffness and characteristic strength. Thermo-mechanic coupling model was proposed by some researchers to consider the effect of temperature on the hysteretic behavior of bearings.

However, the previous studies only considered the interior of the bearings as a single temperature point, which could not explain the heat transform within the rubber. A more accurate model with thermal mechanism is proposed in this paper to predict the hysteretic behavior and temperature distribution of each rubber layer within the HDR bearing.

2. A THERMAL COUPLED HYSTERETIC MODEL

In order to take the temperature effects on the restoring force into consideration, a hysteretic restoring force model combined with a heat transfer model is developed in this research. The proposed model is referred to as the temperature-dependent Bouc-Wen model (T Bouc-Wen model). The relationship between restoring force, $F(t)$, shear displacement, $d(t)$ and temperature, $T(t)$ at time t, can be expressed as:

$$F(t) = \alpha K d(t) e^{m\times\frac{T(t)-23}{100}} + (1 + b\varepsilon(t)^2)(1-\alpha) K Z e^{n\times\frac{T(t)-23}{100}} \quad (1)$$

$$\dot{Z} = A\dot{d}(t) - \beta\left|\dot{d}(t) Z\right| Z - \gamma \dot{d}(t) Z^2 \quad (2)$$

$$\beta = \frac{1}{2d_y^2}, \gamma = s\cdot\beta \quad (3)$$

where K is the initial stiffness, $\varepsilon(t)$ is the shear strain defined as the displacement divided by the thickness of a single rubber layer, $Z(t)$ is the hysteretic components of the restoring forces, α is the post-yielding stiffness ratio, c and ds are the parameters describing temperature dependence, constant A (equals to 1), β, γ, b and s are dimensionless parameters of the hysteresis curve, d_y is the yield displacement.

In the heat transfer model, an independent temperature value is assigned to each rubber layer. The heat is generated by the loading and transferred externally based on heat conduction mechanisms. The time derivative of temperature ($\dot{T}$) for each rubber layer can be expressed as:

$$\dot{T} = (\dot{E} + \dot{Q})\lambda \quad (4)$$

where $E(t)$ is the dissipated energy during the loading, calculated by Eq. (5), $Q(t)$ is the heat through conduction within the bearing, calculated by Eq. (6), λ is the heat capacity of rubber or steel layers.

$$E(t) = \int_0^t F(\tau)\dot{d}(\tau)d\tau \quad (5)$$

$$\dot{Q}(t) = \frac{kA}{d}(T_{in} - T_{ex}) \quad (6)$$

where k is the thermal conductivity of material, A is the cross-sectional area, d is the thickness of the layer, T_{in} and T_{ex} are the internal and external temperatures.

Fig. 1 shows the detailed heat-transfer mechanism of the model. Due to the symmetry of the rubber bearing consisting of six rubber layers, the upper three rubber layers are taken into analysis. The multi-layer heat transfer model considers the heat transfer within the rubber and steel layers. Note that the horizontal heat transfer is ignored, while the vertical heat transfer is considered in this model. The selected temperature simulation points are the top (T_{1a}, T_{2a}, T_{3a}), middle (T_1, T_2, T_3) and bottom (T_{1b}, T_{2b}, T_{3b}) points of rubber layers, as well as the top point of the steel ending plate (T_0, assumed as the ambient temperature). It is assumed that heat is generated at the middle point inside the rubber layer during loading and is transferred outward along the height based on thermal conduction. Specifically, the temperature of the middle point of each rubber layer (take T_1 as the example) can be derived as:

$$T_{1,i} = T_{1,i-1} + \lambda_r dE_1 + \lambda_r \frac{k_r A}{0.5d_r}(T_{1b,i-1} - T_{1,i-1})dt - \lambda_r \frac{k_r A}{0.5d_r}(T_{1,i-1} - T_{1a,i-1})dt \quad (7)$$

where i is the time step of loading. For other temperature points, the calculating equation is similar to Eq. (7), but without the heat generating term ($\lambda_r dE$).

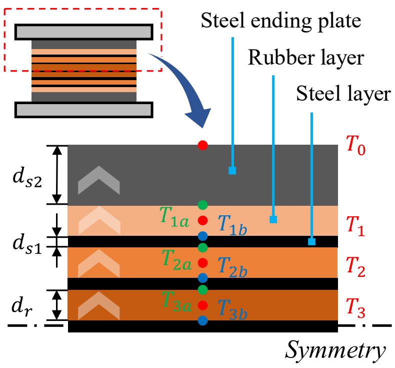

Fig. 1 Heat-transfer mechanism of the model.

Keywords: HDR bearing, Restoring force model, Multi-layer temperature, Thermal coupling, Self-heating effect
Contact address: Kyoto University, Gokasho, Uji, Kyoto, 611-0011, Japan, Tel: 0774-38-4135

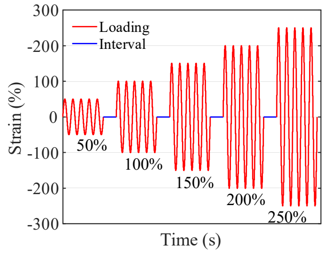

Fig. 2 Loading pattern.

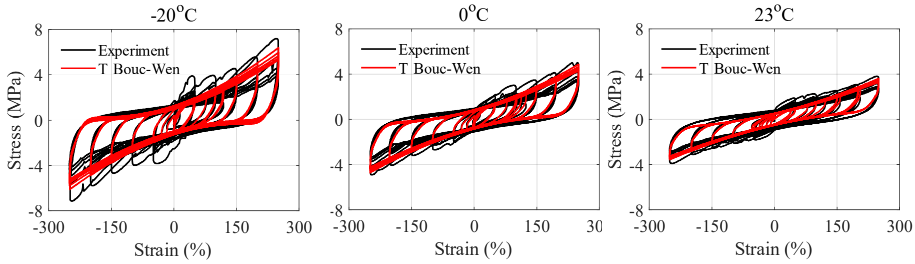

Fig. 3 Hysteresis loops at 23°C, 0°C, and −20°C of BoucWenT model compared with experimental results.

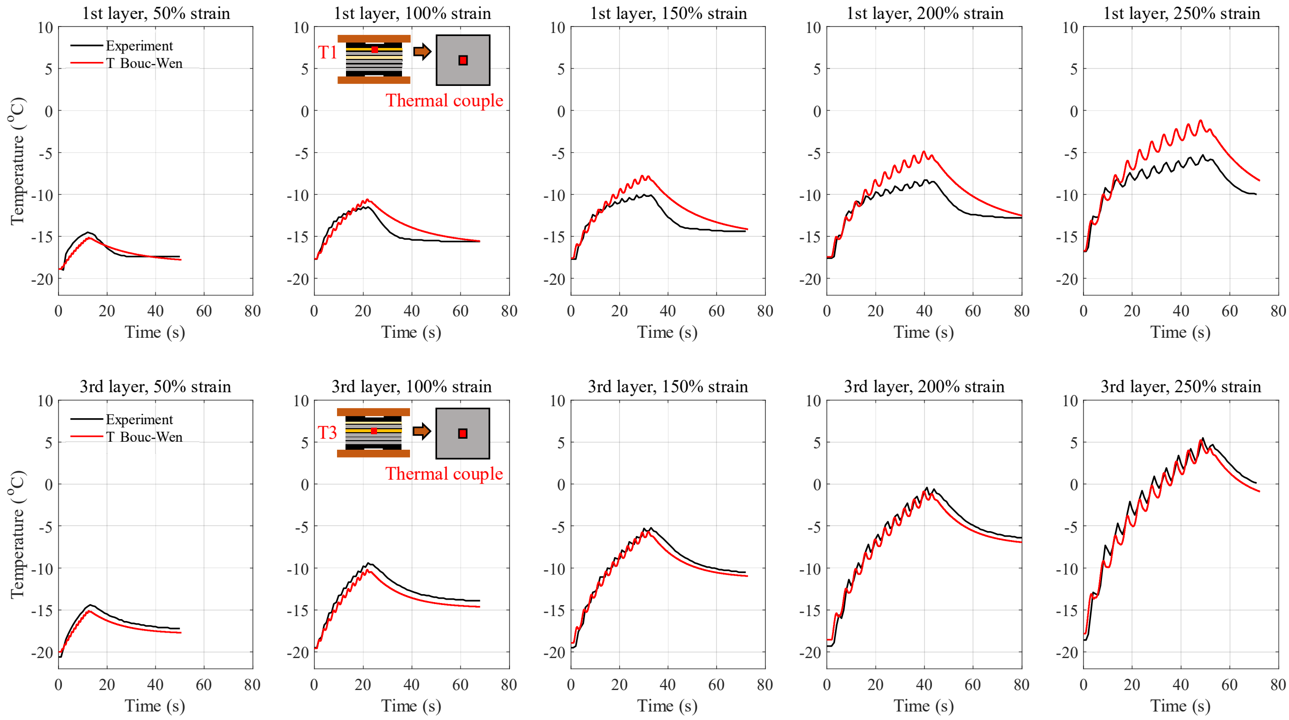

Fig. 4 Temperature prediction of first and third layers of HDR bearing at −20°C with BoucWenT model.

Table 1 Input identified parameters of BoucWenT model.

α	K	s	d_y	b	m	n
0.3	30	0.9	0.3	0.3	-2.1	-0.5

3. RESULTS

Cyclic loading of a HDR bearing was numerically simulated using in the proposed model, and compared with test results. Axial load corresponding to 6 MPa was applied to the HDR specimens in the tests. Shear strain amplitudes of 50%, 100%, 150%, 200%, and 250% were applied with 5 cycles for each amplitude, as shown in Fig. 2. The ambient temperatures of 23°C, 0°C, and −20°C were considered to test the behavior of bearing not only for the room temperature, but for the cold areas. The input simulated parameters were listed in Table 1.

Fig. 3 shows the hysteretic loops of the T Bouc-Wen model compared with experimental results. The results indicated a good coincidence of hysteretic loops between the proposed model and the cyclic loading tests. Moreover, the stiffness degradation was obvious under the loading of different cycles within the same strain level.

The low-ambient temperature and self-heating effect would significantly affect the initial stiffness and characteristic strength of the HDR bearings. The computed temperatures at the center points of the first and third rubber layers compared with temperatures measured by thermocouples in the specimens during the tests are shown in Fig.4. A good agreement between the numerical and experimental results can be seen, and the difference of temperatures depending on the rubber layers is also simulated with an acceptable accuracy.

4. CONCLUSIONS

A restoring force model coupled with thermal mechanics is proposed to investigate the hysteretic behavior and multi-layer temperature distribution affected by the low-ambient temperature and self-heating effect. This model showed a good agreement of hysteretic behavior of restoring force and displacement relationship and stiffness degradation. Since the multi-layer temperature distribution produced by the model was shown to well match with the experimental result, it is suggested that the proposed restoring force modeling technique combined with the thermal mechanics is a promising approach.

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