Hysteretic restoring force model of HDRB including thermo-mechanical coupling effect and verifications by hybrid simulation

Kyoto University, Student Member, ○Yuqing Tan
Kyoto University, Member, Akira Igarashi
Kawakin Core-Tech, Yuki Hamada
Saitama University, Student Member, Keizo Terachi
Saitama University, Member, Ji Dang
Kawakin Core-Tech, Member, Takehiko Himeno
Office U-Tech, Member, Yoshifumi Uno

1. INTRODUCTION

It has been known that high damping rubber bearings (HDRBs) exhibit significant stiffening due to low-temperature effects, while the stiffness of HDRBs decreases under cyclic loading due to self-heating as shown in the experimental study by Okui et al. (2017). For modeling of the restoring force characteristics of HDRBs, consideration of the inner temperatures can greatly improve the accuracy of the model.

In this study, a restoring force model of HDRBs at low temperatures including the self-heating effect is developed based on the modified Park-Wen model. The validity of the developed model is investigated by a comparison with the result of the hybrid simulations under controlled environmental temperature.

2. INNER TEMPERATURE DEPENDENCE

Let $T(t)$ be the inner temperature of a bearing at time t. The time derivative of $T(t)$ can be expressed by

$$\dot{T} = \left(\dot{E} - \dot{Q}\right)\lambda \tag{1}$$

where $E(t)$ is the dissipated energy due to the hysteretic force-displacement response of the bearing during shear deformation, $Q(t)$ is the energy loss caused by the heat radiation and conduction from the bearing contact surfaces, λ is a constant determined by heat capacity of rubber and steel layers in the bearing, and the dot symbol denotes the time derivative. The dissipated energy $E(t)$ and energy loss $Q(t)$ are calculated by

$$E(t) = \int_0^t F(\tau)\delta(\tau)d\tau \quad , \quad \dot{Q} = Ah\left(T - T_a\right) \tag{2}$$

where $F(t)$ and $\delta(t)$ are the restoring force and shear displacement of the bearing, respectively at time t, A is the cross sectional area of the shear key (the heat energy is assumed to escape from the bearing to the shear key), h is the convective heat transfer coefficient given by $W/(m^2 \cdot K)$, in which W, m, K are the convective heat, length and temperature, respectively, and T_a is the ambient temperature. In the case of cyclic loading, increase of $E(t)$ per cycle corresponds to the area of the hysteresis loop. Using the inner temperature T as an internal variable, a hysteretic restoring force model of high damping rubber bearings is developed based on the modified Park-Wen model proposed by Dang et al. (2016). The restoring force of the bearing $F(t)$ is expressed by

$$F = \alpha K_1 \delta e^{d \times \frac{T-23}{100}} + \left(1 + b\varepsilon^2\right)\left(1-\alpha\right)K_1 Z e^{c \times \frac{T-23}{100}} \tag{3}$$

$$\dot{Z} = A\dot{\delta} - \beta\left|\dot{\delta}Z\right|Z - \gamma\dot{\delta}Z^2 \tag{4}$$

where $Z(t)$ is the original internal variable representing the hysteretic component in the restoring force, ε is the shear strain defined by the the displacement $\delta(t)$ divided by the total rubber layer thickness, α is the post-yield stiffness ratio, K_1 is the elastic stiffness. A, β, γ and b are dimensionless parameters for hysteresis curve. The symbols c and d are newly introduced parameters describing the temperature dependence. Cyclic loading tests of high damping rubber bearing specimens were conducted at ambient temperatures of 23°C, 0°C and −20°C, with shear strain amplitudes between 50% and 250%. The model parameters are identified from the cyclic loading test results as shown in Table 1.

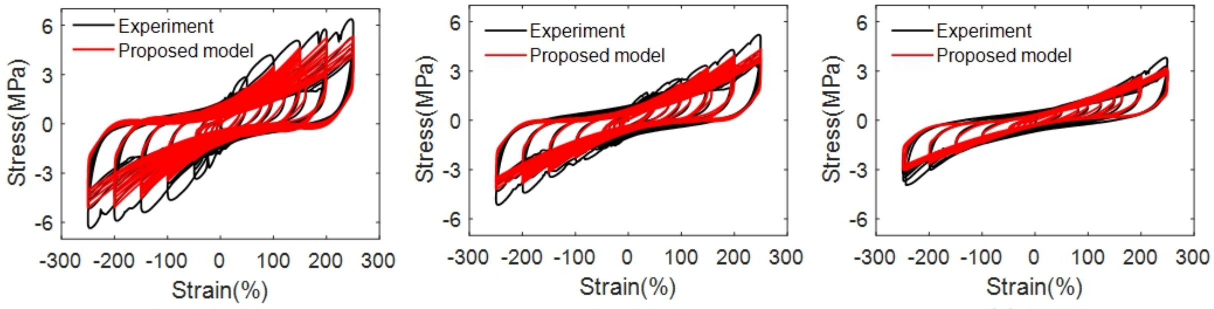
Table 1. Identified parameters

α	K_1(*KN/mm*)	A	β	γ	b	c	d
0.380	4.292	1	0.200	-0.192	0.667	-2.457	-1.132

The hysteresis loops obtained by the cyclic loading tests and simulated results by the proposed restoring force model are shown in Fig. 1. The inner temperature dependence in a low temperature range and stiffness reduction with repeated cycles as well as nonlinear hysteretic response involving strain hardening are successfully expressed by the model.

3. COMPARISON WITH HYBRID SIMULATION TEST RESULTS AND DISCUSSION

Keywords: High damping rubber bearing, restoring force model, temperature effect, self-heating, hybrid simulation
Contact address: Kyoto University, Gokasho, Uji, Kyoto, 611-0011, Japan, Tel: 0774-38-4135



(a) −20°C (b) 0°C (c) 23°C

Fig. 1 Hysteresis loops of high damping rubber bearings computed by the proposed model and comparison with cyclic loading test result

Loading tests of high damping rubber bearings using the hybrid simulation technique were carried out to evaluate the seismic response of a girder bridge, assuming ambient temperatures of 23°C, 0°C and −20°C. The bridge model and test framework is shown in Fig. 2. The natural period of the hypothesized isolated bridge is 1.498 sec, and the assumed ground motion is Level 2, Type II, ground type-II accelerogram 1, specified in Design Specification of Highway Bridges (Japan Road Association, 2017). The detail of the hybrid simulation test is described in Tan et al. (2021).

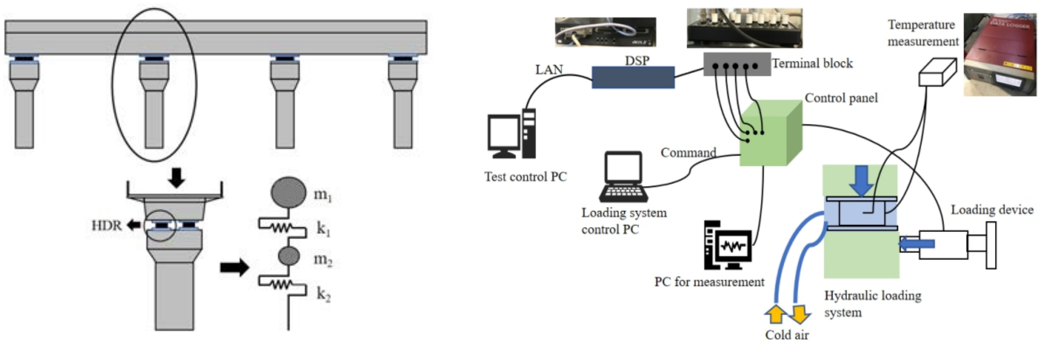
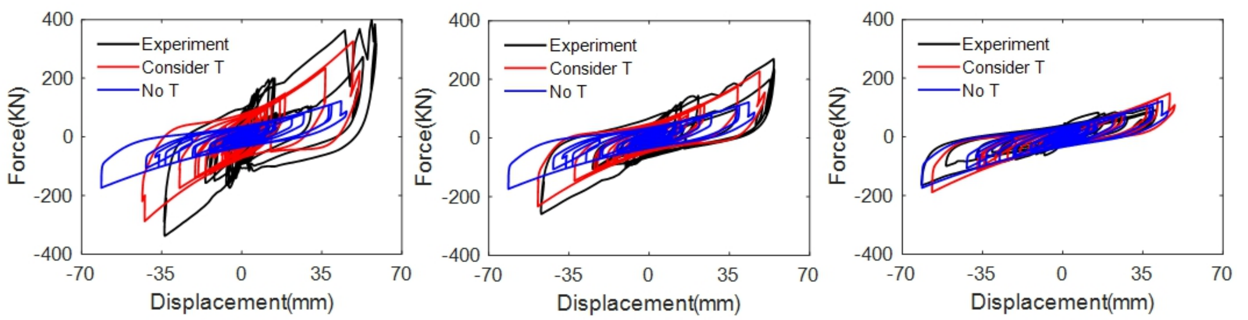


Fig. 2 Bridge model (the left) and test framework (the right)

Comparison of hysteresis loops obtained by hybrid simulation and that of the proposed model is shown in Fig. 3. An acceptable agreement between the model and test results are observed at the temperatures of 23°C and 0°C under those non-cyclic seismic loading conditions. Improvement of accuracy in −20°C is yet to be explored in future research.



(a) −20°C (b) 0°C (c) 23°C

Fig. 3 Comparison between experimental and analytical hysteresis loops at different temperatures in hybrid simulation

REFERENCES

Okui, Y., Onoue, Y., Sato, T., and Imai, T.: Temperature Dependence of Mechanical Behavior of High Damping Rubber Bearings Considering Self Heating, J. JSCE Ser. A1, Vol.73(1), 2017, pp. 165-173. (In Japanese)

Dang, J., Igarashi, A., and Murakoshi, Y.: Development of Hysteretic Model for High-damping Rubber Bearings under Bi-directional and Large Strain Domain Loading, J. JSCE Ser. A1, Vol.72(2), 2016, pp. 250-262. (In Japanese)

Tan, Y., Dang, J., Igarashi, A., Himeno, T., Hamada, Y., and Uno, Y.: Low Temperature Hybrid Simulations for High Damping Rubber Bearings, 第 23 回橋梁等の耐震設計シンポジウム講演論文集, JSCE, 2021, pp. 215-221.