International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249-8958 (Online), Volume-8 Issue-5, June 2019

Self-Heating of High Damping Rubber Bearings: Experiments and Mathematical Modeling

Nguyen Anh Dung, Quang Hung Nguyen

***Abstract**: This paper is devoted to investigate the self-heating phenomenon inside high damping rubber bearings (HDRB). The rubber bearing tests were conducted at different ambient temperatures ranging from -30°C to 23°C in an environmental experimental chamber. A series of sinusoidal loading tests under a frequency of 0.5 Hz were carried out to investigate the rise of the inside temperatures in HDRB. The experimental results indicate that the temperatures inside HDRB are increased under sinusoidal loading, and these inside temperatures rise with the decrease in ambient test temperatures. Moreover, two mathematical equations are proposed to predict the inside temperatures of HDRB. The calculation of the equations is similar to the measured temperature in the center of HDRB.*

***Keywords**: high damping rubber bearings, self-heating, inside temperature, temperature dependence.*

I. INTRODUCTION

After the Kobe Earthquake 1995, the applications using rubber bearings for bridge structures were rapidly spread in Japan. Rubber bearings with high flexibility can lengthen the natural periods of structures to reduce the seismic response, while high damping capacity can control the relative displacement response. Recently, high damping rubber bearings (HDRB) has been widely employed due to its high seismic performance and durability. This technique is proven to be cost-effective and reliable. However, it is generally known that HDRB have complicated mechanical characteristics, such as temperature dependence, self-heating effect and, so on. These characteristics obviously influence the seismic response prediction of structures isolated by HDRB at seismal cold regions such as Hokkaido in Japan and Alaska in USA.

In current guide specifications [1, 2] for the seismic design of structures used HDRB, the mechanical behavior of HDRB is reproduced by a bilinear model. The current bilinear model cannot represent the self-heating effect, therefore, this model has a restriction in preproduction of mechanical behavior of HDRB. As a result, if the bilinear model for HDRB is used in analysis, the performance prediction of structures will be unreliable, especially at seismically active cold areas. An appropriated seismic design model considered the self-heating effect is required.

Manuscript published on 30 June 2019.
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Temperature dependence of mechanical behavior of HDRB is less investigated in current literatures [3]. Some previous works [4, 5] investigated the ambient temperature dependence and the exposure history on rubber's constitutive behavior. The ambient temperature history dependence of high damping rubber material due to crystallization effect and associated increase in relative shear modulus were reported in [5]. Imai et al [6] presented some experimental results that describe the temperature dependence of the stress-strain hysteresis loops. In recently, Nguyen et al. [3] performed an test program to study the mechanical characteristics of HDRB at room and low temperatures. On the basis of experimental results, a rate-dependent rheology model is proposed to preproduce the hysteresis loops of HDRB under cyclic loading. In the mentioned studies, the ambient temperature in a test chamber is assumed to equal the inside temperature of rubber bearings. However, when HDRB is stood by cyclic loading, the absorbed energy by HDRB is changed into heat after that the heat makes the temperatures inside rubber significantly increase. Takaoka et al. [7] shown that cyclic loading made the inside temperature increase by about 30ºC at room temperature, which leads that the yield load of bearings drops to about 80%, but this test only at room temperature. There is not research on self-heating behavior of HDRB at low temperatures. All these shortcomings obviously indicate the necessity of addressing the self-heating effect into a design model to predict the performance of the structures with HDRB, especially at cold area.

The final goal of the research project is to develop a design procedure of HDRB at low temperatures. As the first step, rubber bearing tests are conducted to investigate the mechanical behavior of HDRB at low temperatures. On the basis of the experimental results, the self-heating effect on the mechanical bahavior of HDRB is discussed. Moreover, two mathematical equations are proposed to predict the inside temperatures of HDRB.

II. EXPERIMENTAL STUDY

A. . Specimens

All HDRB specimens have square plan with sizes of 240x240 mm. A typical view of a specimen with layer details is shown in Fig. 1. The properties of the specimens are given in Table 1. These specimens follow ISO standard [8]. Due to the presence of Mullins effect [9] 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 behavior from other mechanical behavior of HDRB.

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Table1. Dimension and material properties of HDR

Specification	HDRB
Plan of the specimen (mm2)	240x240
Rubber layer number	6
Rubber layer thinkness (mm)	5
Steel layer thinkness (mm)	2.3
Nominal shear modulus (MPa)	1.2

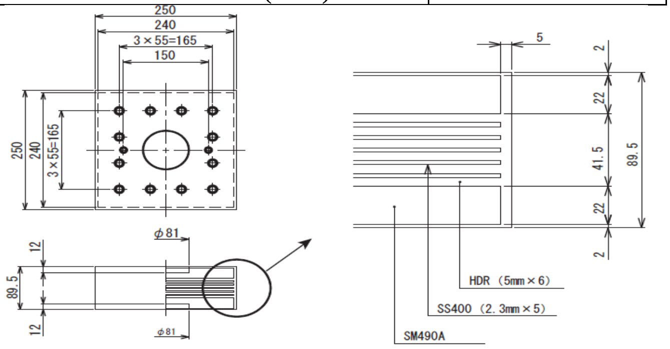
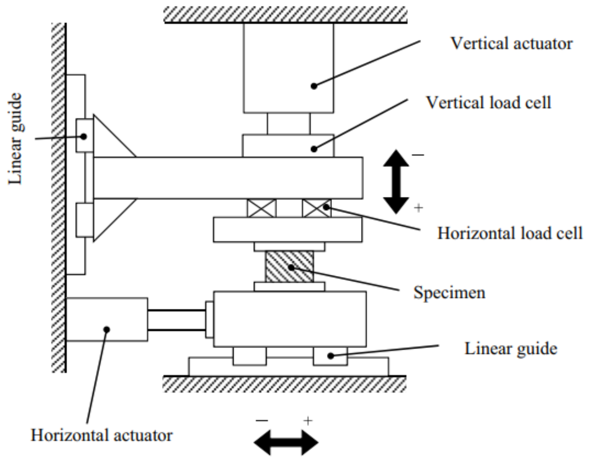


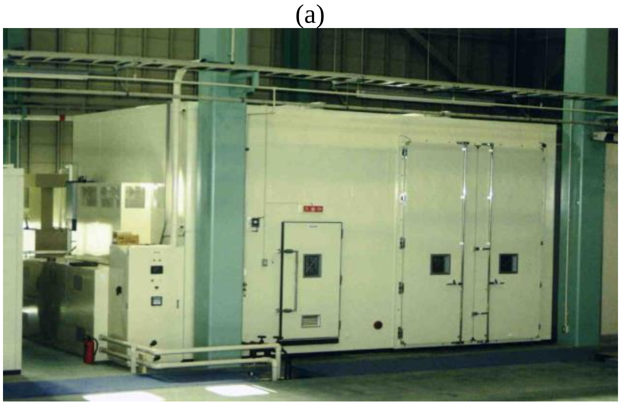
Figure 1. HDRB specimens (dimensions in mm)

B. Test set-up

The rubber bearing tests were carried out by a servo-hydraulic testing machine in an experimental room. The test ambient temperatures are -30°C, -20°C, and 23°C. All specimens are conducted under a constant vertical compression stress of 6 MPa in order to consider the effect of vertical load. A personal computer is used to record the output data. This test set-up is shown in Fig. 2, which is same as the experimental set-up in [3].



(a)



(b)

Figure 2. Experimental set-up: (a) testing machine, (b) testing room [3]

In order to measure the temperatures inside the specimens, the thermocouples are installed inside of these specimens. The positions of temperature measurement in the central section are shown in Fig. 3. Eleven sinusoidal loading cycles were applied on the specimens with a shear strain amplitude and frequency of 1.75 and 0.5Hz, respectively. The strain history applied in sinusoidal loading tests is indicated in Fig. 4.

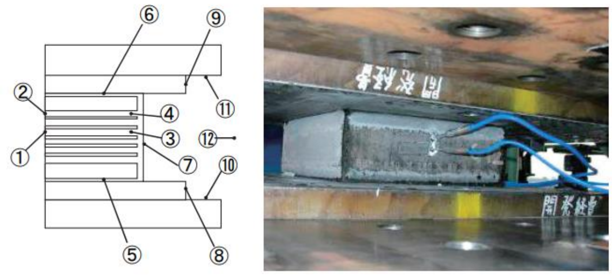


Fig.3. Measure points of temperatures (Japan Rubber Bearing Association)

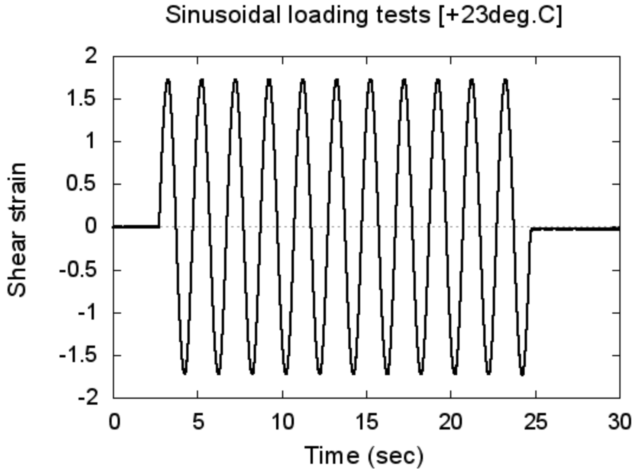


Fig. 4. Applied strain history in sinusoidal loading tests at +23°C

III. EXPERIMENTAL RESULTS

The stress-strain loops obtained from the tests are presented in Fig. 5. The experimental results shown that the 1st stress-stress cycle is much different from the other cycles, and this difference increases with the reduction of the ambient temperatures. The difference of the cycles can be explained by self-heating effect. The temperature rise inside HDRB makes their stiffness become smaller and the stresses decrease. This stress softening behavior is much larger ta low temperatures. It means that the self-heating effect on the mechanical characteristics of HDRB increases with the decrease in the ambient temperatures. According to experimental results in Fig. 6, it is found that the inside temperature rising at low temperature is also larger than at room temperature. Inside temperature rising at -30°C (ambient temperature) is approximately 27°C, and inside temperature rising at -20°C is approximately 24°C, whereas inside temperature rising at 23°C is about 12°C. This temperature rise and the stress softening behavior show that the stress-strain hysteresis loops of HDRB strongly depend on the inside temperature of HDRB, not only ambient temperatures.

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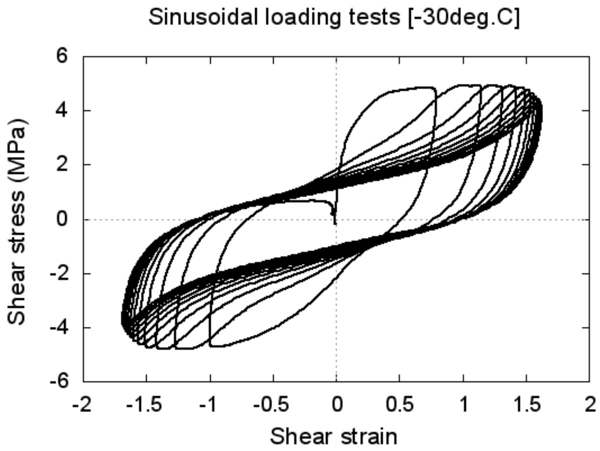
When the design parameters of design models are determined from the stress-strain loops, the rise of the inside temperatures of HDRB should be considered in a design procedure of structures used HDRB, especially at low temperatures.



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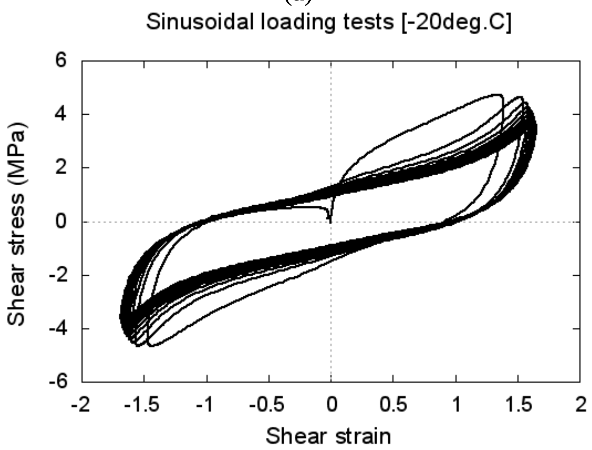

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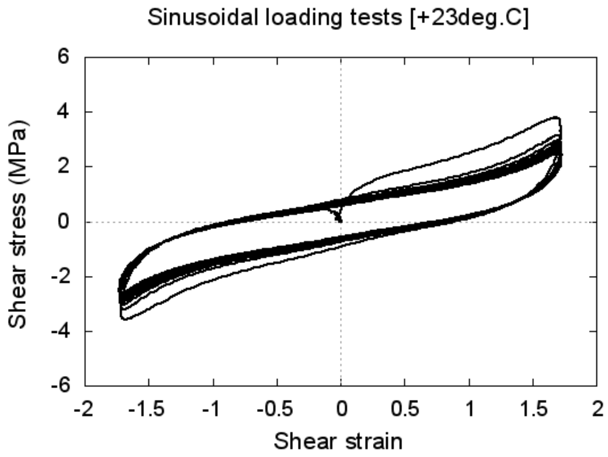
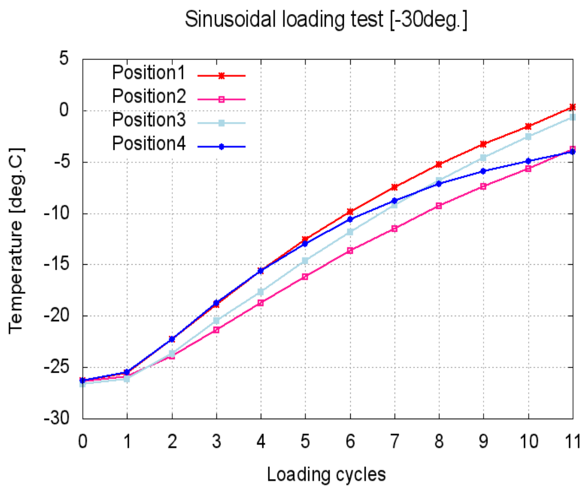


(c)

Fig. 5. Experimental results of stress-strain relationships at ambient temperature (a) -30ºC, (b) -20ºC, and (c) 23ºC



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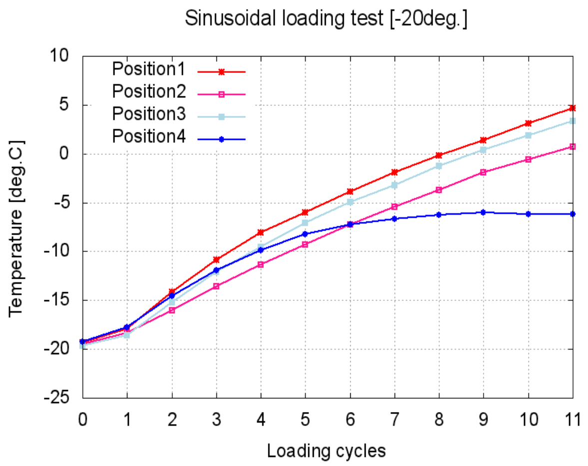

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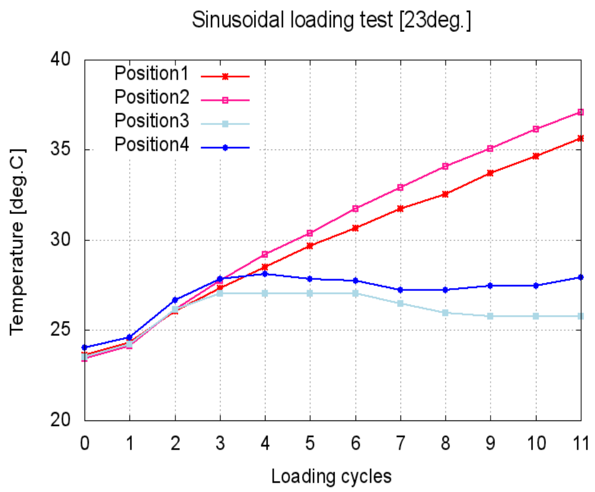

(c)

Fig. 6. Experimental results of inside temperature at ambient temperature (a) -30ºC, (b) -20ºC, and (c) 23ºC

IV. MATHEMATICAL MODELING

The cumulative dissipated energy density is calculated by

$$D = \sum_{i=1}^{11} D_i \qquad (1)$$

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where D_i is the absorbed energy density of the i^{th} cycle, and this energy density equals the close area of a stress-strain loop for one cycle. The temperature inside HDRB varied under sinusoidal loading tests are presented in Fig. 5. The experimental results indicate that the rise of the temperature inside HDRB and the absorbed energy of HDRB increase when the ambient temperatures decrease. All absorbed energy density is assumed to be changed into the heat, and this hear make temperatures inside HDRB increase under the adiabatic condition.

Case 1: Considering HDRB including only rubber material in the temperature rise process, after that the temperature rise ΔT of HDRB under cyclic loading tests would be estimated by Eq. (2).

$$DV_r = C_{pr} m_r \Delta T \quad (2)$$

where C_{pr} is the rubber's specific heat; m_r and V_r are the rubber's mass and rubber's volume, respectively.

Case 2: HDRB is considered as composite of steel and rubber in the temperature rise process, and the temperature in rubber is assumed to be same as the temperature in steel. Then the temperature rise ΔT can be estimated by Eq. (3).

$$DV_r = \left[C_{pr} f + C_{ps} \left(1 - f\right) \right] m_r \Delta T \quad (3)$$

where C_{ps} is the steel's specific heat;
$m = m_r + m_s$ stands for the total mass;
m_s is the steel's mass;
$f = m_r / m$ is the mass fraction of rubber.

In this paper, the specific heats for rubber and steel are selected in Unita et al. (2004) [10].

The comparison of measured temperature with calculated temperature is presented in Fig. 7. The estimated temperature by Eq. (3) is similar to the measured temperature at position 1 in the center of the HDRB, the result of Eq. (3) is more accurate than the result of Eq. (2). Although, the estimated temperatures are higher than the measured temperatures at other positions because some heat transfers from the specimen to the ambient environment in the measurement.

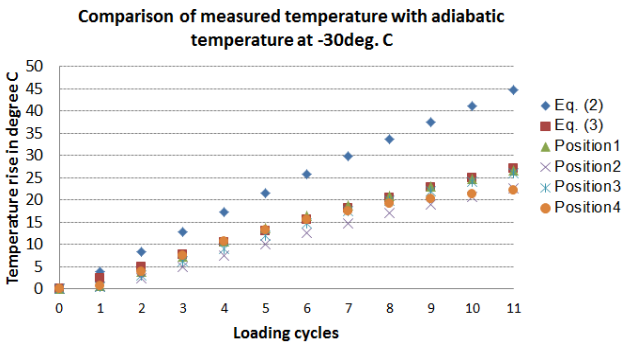

Fig.7. Comparison of measured temperature with theoretical temperature at -30°C ambient temperature

The comparison shows that Eq. (3) can accurately predicts the temperature rising in the center of HDRB. It means that all absorbed energy assumed to be converted into the heat energy and HDRB considered as as composite of rubber and steel are correct at the center. The ability of Eq. (3) is an important step for developing a design procedure of HDRB at low temperatures. For example, we can propose a relationship between the temperature rise in the center of HDRB with the stress-strain hysteresis loops of HDRB. This work can help to predict the performance of the structures with HDRB at seismically active cold regions.

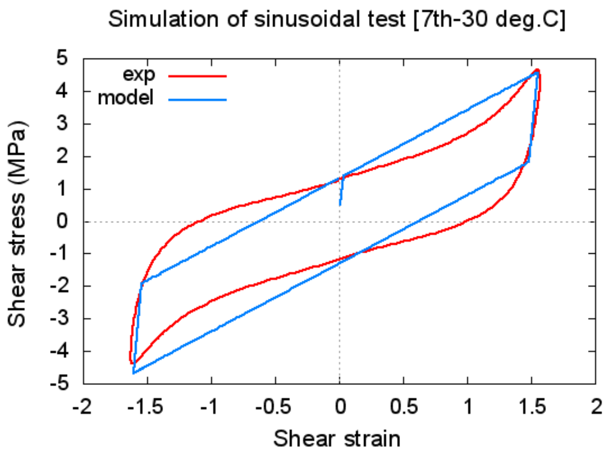

Fig.8. The comparison of the bilinear model with experimental result at -10°C inside temperature

The parameters of the design bilinear model are determined based on a stress-strain cycle obtained from sinusoidal loading tests at -10°C inside temperature. Then the model is used to simulate the test data, fig. 8 shows the comparison of the bilinear model with the sinusoidal test result. The experimental result shows significant hardening at a high strain level, but the bilinear model cannot represent this feature. This is the limitation of the bilinear model at lower temperatures.

V. CONCLUSIONS

The temperatures inside HDRB are increased by cyclic loading, and the increase in the inside temperature of HDRB becomes larger at lower ambient temperatures.
In order to propose a calculation procedure of temperature rise during an arbitrary strain history, the inside temperature rise of HDRB in a sinusoidal test is calculated from the dissipated energy density under a simple adiabatic assumption. The estimated temperature with considering HDRB as composite of rubber and steel is similar to the measured temperature at the center of the HDRB. Since the hardening in the stress-strain relationship of HDRB becomes significant at low temperatures of -20°C and -30°C, the bilinear model is not well representation of HDRB' behavior at low temperatures.

ACKNOWLEDGMENTS

The testing works were support by Japan Rubber Bearing Association and Prof. Okui in Saitama university, Japan. Authors sincerely give them the acknowledgements and gratefulness.

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