LONG-TERM TEMPERATURE MEASUREMENT OF RUBBER BRIDGE BEARING EXPOSED TO SOLAR RADIATION FOR AGING ESTIMATION

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ABSTRACT: Rubber bridge bearings have been used nationwide in Japan after the Hyogo-ken Nanbu earthquake in 1995. The equivalent shear stiffness of a rubber bridge bearing increases due to aging of rubber. It is currently assumed in the long-term performance prediction of rubber bridge bearings that rubber in the bearing has the same temperature as its surrounding ambient temperature because rubber bridge bearings are usually in the shadow as they are installed between the superstructure and the pier. However, in the actual environment, there are many bearings exposed to solar radiation that causes bearing temperature to increase. Since thermal oxidation is one of the major deterioration factors for rubber, temperature has a significant influence on the deterioration process of rubber in a bridge bearing. To accurately estimate a degree of rubber deterioration, the increase of bearing temperature due to solar radiation is necessary to be evaluated. To understand the solar radiation effect on long-term performance of rubber bridge bearing, internal bearing temperature, external bearing temperature, and global solar radiation were measured for one year for a bearing installed in outside environments in this study. Based on the measured data, an empirical relationship between solar radiation and the internal bearing temperature was obtained. In addition, the long-term increase of the equivalent shear stiffness of a rubber bridge bearing due to aging was estimated by including solar radiation effect on bearing temperature. The difference of 3% in the change of equivalent shear stiffness was found whether or not the effect of solar radiation was included.

1 INTRODUCTION

Rubber bridge bearings are to support a superstructure and to protect the structure from the earthquake. The rubber bearing is mainly classified into the isolation rubber bearing and the horizontal force distribution bearing. The isolation rubber bearing makes the fundamental natural period of the structure longer than the predominant period of ground motions so that seismic energy input into the structure can be reduced. The horizontal force distribution bearing is mainly used for a continuous multi-span bridge, and has a function that distributes the inertia force at the earthquake to two or more piers. Severe damage was seen in many bridges where steel bearings were used in the Hyogo-ken Nanbu earthquake in 1995, and advantages of the base-isolated bridge were recognized (Iemura, 1999). In Japan, rubber bridge bearings were developed in the 1970's (Ishibashi et al., 1984). It has been adopted in many bridges since then.

Aging of rubber material has been researched since the vulcanization method was discovered. Rubber bridge bearings used for a long term showed changes in their mechanical properties. Aging of rubbers can be caused by different factors including thermal oxidation, ozone, light, ultraviolet rays, and rainwater. Among these factors, the effect of thermal oxidation is found to be most significant in the case of rubber used in bridge bearings. Aging causes rubber to stiffen and its tensile strength and elongation at break to decrease. Rubber bearings also tend to increase their stiffness over time, resulting in the increase of the fundamental frequency of the isolated bridge from its design value. However, in the current Japanese Design Specifications of Highway Bridges (JRA 2002), performance change of rubber bearings due to aging is not considered.

The temperature of bearings is usually assumed to be close to the outside temperature because they are thought to be always in shadow under the superstructure. However, the actual bridge survey reveals that there are many bridge bearings exposed to solar radiation, and their surface temperatures are much higher than the ambient temperature during the day. To evaluate the aging of the rubber bearing for a long term accurately, it is important to understand the temperature of the rubber bearing in the installed environment.

In the present study, the internal temperature, the surface temperature of the rubber bearing, and solar radiation in the installed location were measured to examine how solar radiation affects the temperature of the rubber bearing during the day, and eventually to evaluate the long-term performance degradation of the rubber bearing. The surface and internal temperatures of the rubber bearing were measured for one year, and the temperature variation inside the bearing was examined. Based on the measurement data, the relationship between the internal temperature of the rubber bearing and the daily total solar radiation on the bearing was proposed. Finally, a long-term variation of an equivalent shear stiffness of the rubber bearing due to aging was estimated in consideration of the effect of solar radiation on the bearing temperature.

2 MEASUREMENT PROGRAM OF BEARING TEMPERATURE

2.1 *Bearing for measurement*

The bearing is a high dumping rubber (HDR) bearing of 420 mm x 420 mm x 134 mm, manufactured by Tokai Rubber Industries, Ltd., the size of which is in the minimum class produced for the bridge use. The dimensions of the bearing are shown in Figure 1. The bearing has six rubber layers with a thickness of 9 mm, end steel plates with a thickness of 32 mm, five inner steel plates with a thickness of 3.2 mm, and surface rubber with a thickness of 10 mm. It is covered with natural rubber (NR) with a thickness of 10 mm. By using thermocouples inserted from the top of the bearing, and the internal temperature was measured at the 1st, the 4th, and the 6th rubber layers.

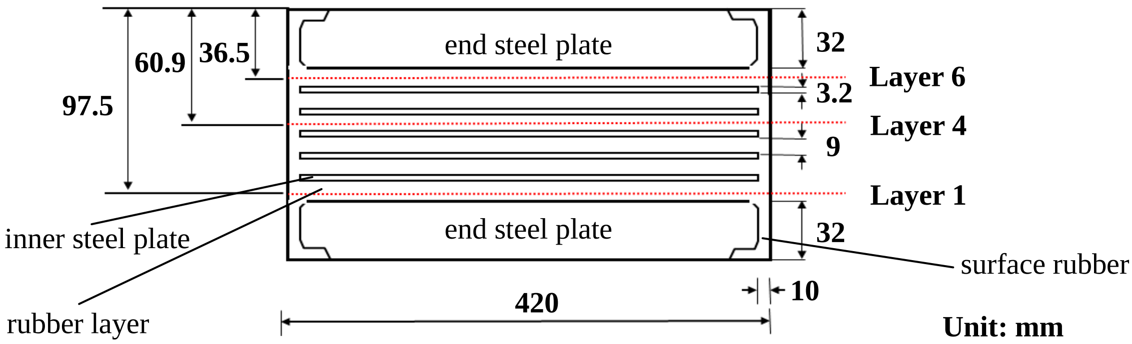
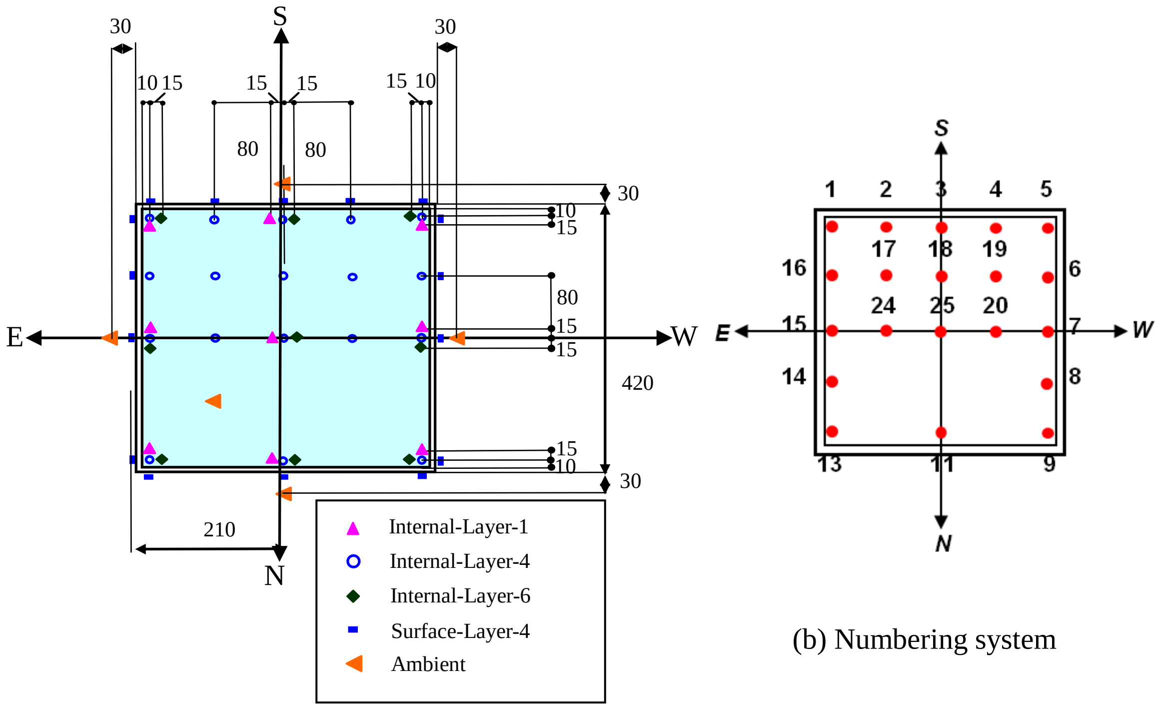


Figure 1. Vertical cross section of bearing for measurement

2.2 *Location of measurement and measuring method*

The locations of the temperature measurement points and their numbering system are shown in Figure 2. Internal temperatures were measured at Pts. 1, 2, 3, 4, 5, 6, 7, 9, 11, 13, 15, 16, 17, 18, 19, 20, 24, and 25 at Layer 4, and Pts. 1, 3, 5, 7, 9, 11, 13, 15, and 25 at Layers 1 and 6.

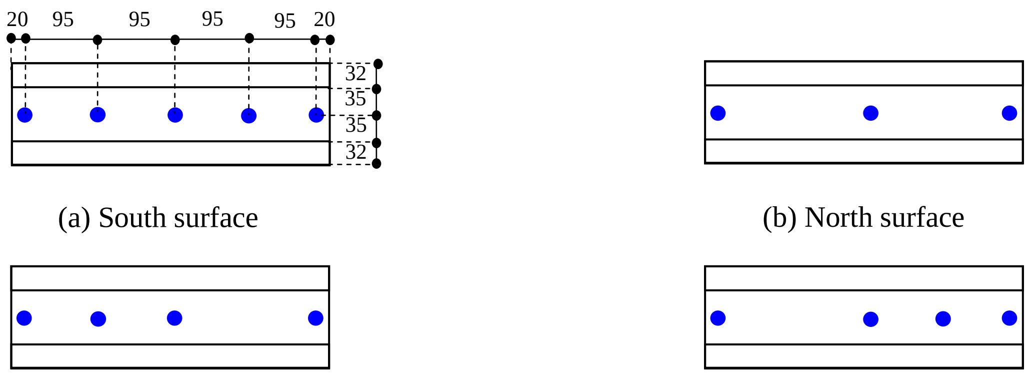


(a)Plan view

(b) Numbering system

Figure 2. Measurement positions and numbering system for internal measurement

Surface bearing temperature was measured on all sides by using standard T-type thermocouples at the same height as Layer 4 of internal measurement points. The measurement locations of surface temperature are shown in Figure 3. There were five points of surface measurement positions on the south side, four points on the west and east sides, and three points on the north side. In addition, solar radiation was measured on the south side using a pyranometer with sensitivity of 7 mV/kW/m^2 for wave lengths of 305-2800 nm.



(a) South surface

(b) North surface

(c) East surface

(d) West surface

Figure 3. Measurement positions for surface bearing temperatures

2.3 *Measurement condition*

The measurement was carried out on the roof of a four-story building in Nagoya University, Japan. Styrofoam sheets of 30mm in thickness were used as heat insulator at the top and the bottom of the bearing to prevent the heat transfer.

In this study, all four sides of the bearing are able to receive solar radiation, and Figure 4 shows the measurement conditions. Surface and internal temperatures of the bearing were measured every ten minutes for one year from February 9, 2010.

Figure 4. Measurement condition

3 TEMPERATURE OF BEARING EXPOSED TO SOLAR RADIATION

3.1 *Measurement results*

Ambient temperature, internal bearing temperature and global solar radiation data from the measurement are shown in Figures 5 and 6. There were some days when data were not obtained due to data checking and charging batteries. Only the days that have full one day data are shown in Figures 5 and 6.

Figure 5 shows the average internal temperature over 18 measurement points of the 4th layer and the ambient temperature. Because differences in the internal bearing temperatures among three layers are found to be small, Figure 5 only shows the internal temperature of the 4th layer. From Figure 6, it can be seen that solar radiation in January, February, November, and December shows the smaller values, while the higher values occur in May-August. When solar radiation of the day is small, internal bearing temperature tend to be close to the ambient temperature. On the other hand, for sunny days, internal bearing temperatures are higher than ambient temperature. The larger the solar radiation, the larger the difference between internal and ambient temperatures becomes. The maximum differences between the internal and ambient temperatures of in a month are about 7˚C, 6˚C, 7˚C, 7˚C, 9˚C, 8˚C, 7˚C, 7˚C, 7˚C, 7˚C, 3˚C, and 4˚C for February, March, April, May, June, July, August, September, October, November, December, and January, respectively.

In the measured one-year period, May has the highest average value of daily total solar radiation. As it can be seen in Figure 6, the number of cloudy and rainy days in May is less than other months. The highest value of daily average ambient temperatures occurred in July. However, the highest value of monthly average ambient temperature occurred in August.

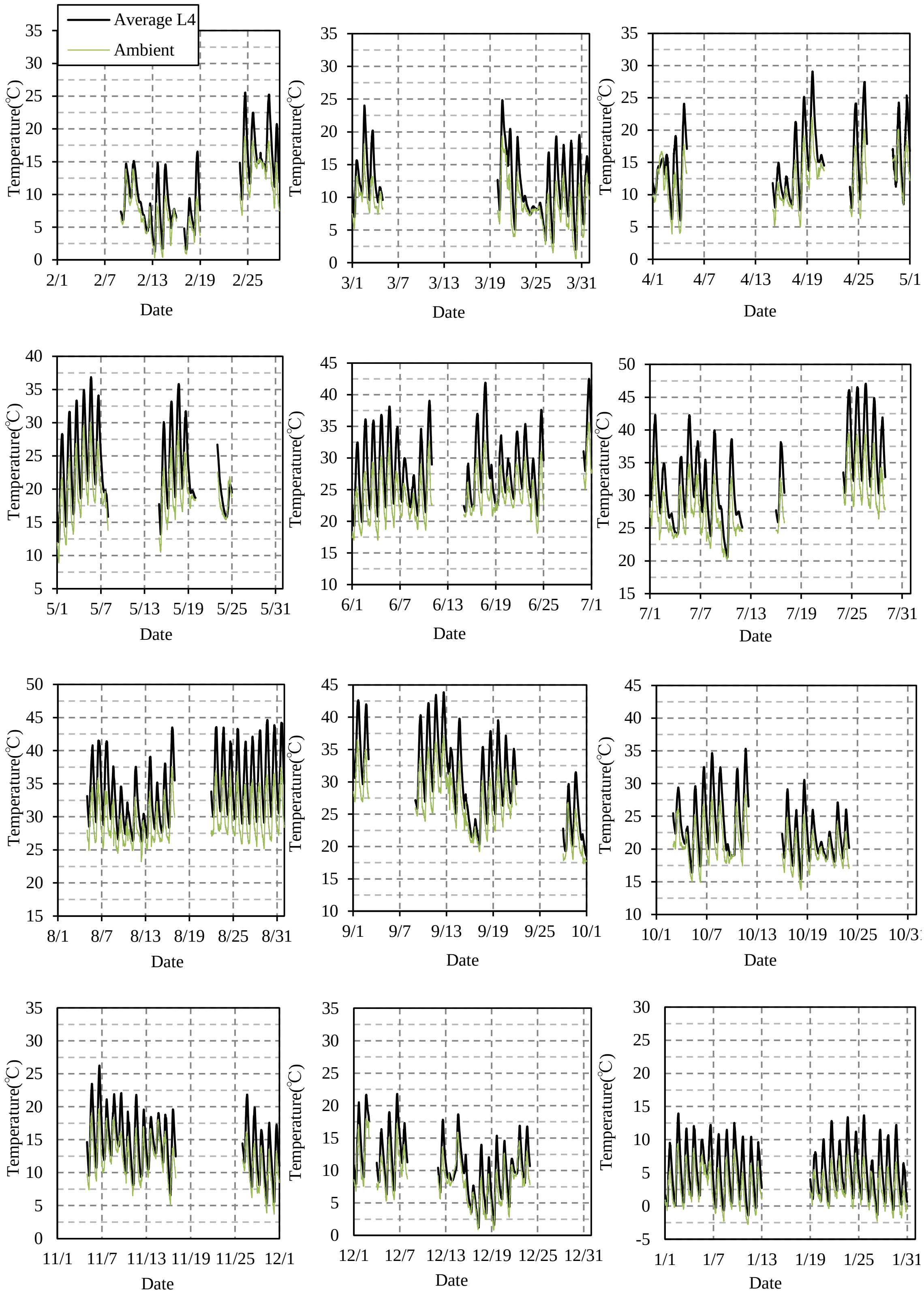


Figure 5. Internal bearing temperature data

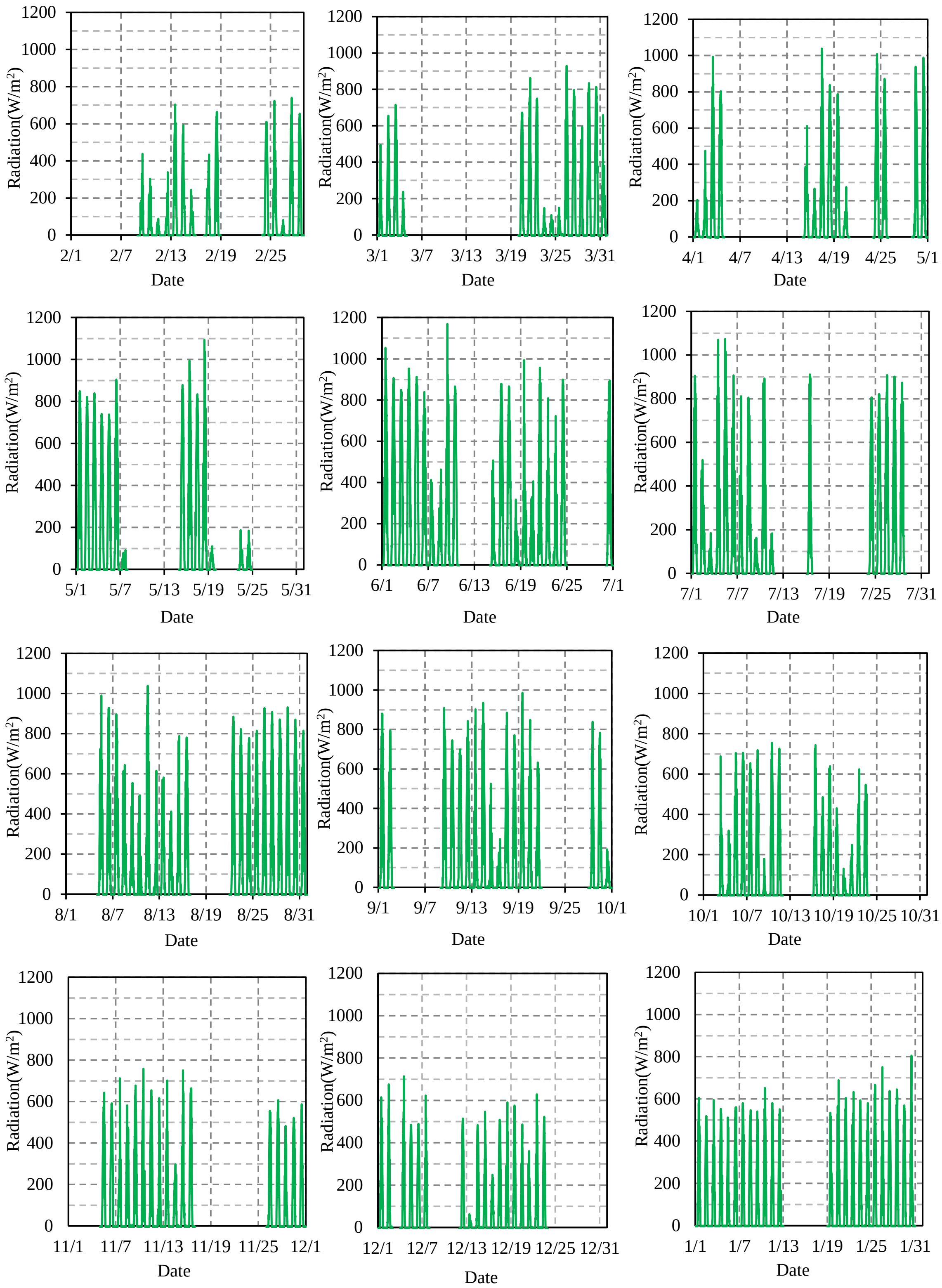


Figure 6. Global solar radiation data

3.2 *Temperature variation inside bearing*

Temperature variations in Layer 4 on the center lines along E-W and N-S directions on a sunny day of May 2, 2010 are shown in Figures. 7 and 8, respectively. Five different time instances are examined: (1) the center of bearing (at Pt 25 in Layer 4, L4-25) becomes the highest temperature of the day, (2) L4-25 becomes the lowest temperature of the day, (3) ambient temperature becomes the highest of the day, (4) ambient temperature becomes the lowest of the day, and (5) the surface bearing temperature becomes the highest of the day. As it can be seen in Figures. 7 and 8, solar radiation affects the temperature variation inside the rubber bearing. However, a large temperature variation inside the bearing occurs only within about 20 mm from the bearing surface. Temperature is almost uniform beyond that depth, where the variation is only about 2-3˚C. The largest variation in the 20 mm region occurs when the surface reaches the highest temperature as an effect of solar radiation, where there is a difference of 20˚C between the surface and the depth of 20 mm. As the bearing has a 10 mm thick NR surface rubber, there is about 10 mm of internal rubber thickness that experiences a large temperature increase as a result of solar radiation.

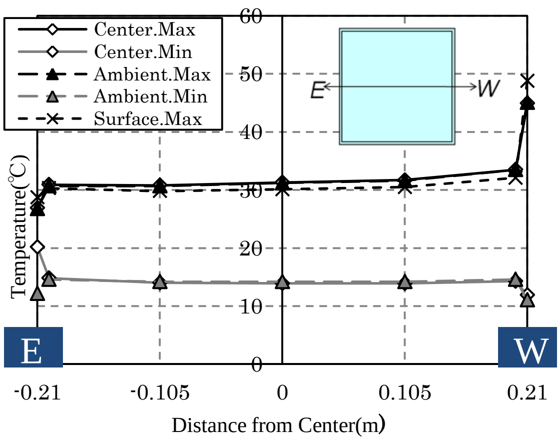


Figure 7. Internal bearing temperature variation along the E-W centerline in Layer 4

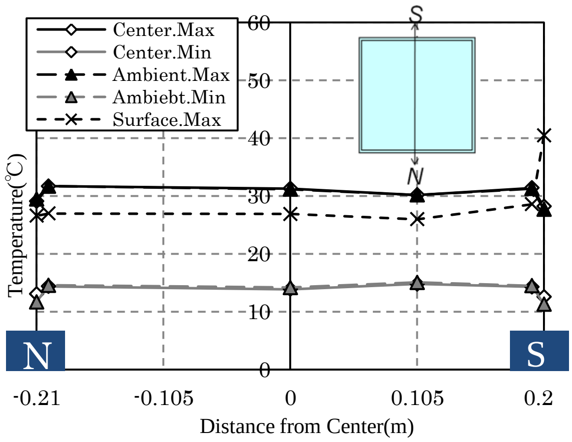


Figure 8. Internal bearing temperature variation along N-S centerline in Layer 4

4 LONG-TERM PERFORMANCE OF RUBBER BEARING CONSIDERING SOLAR RADIATION

4.1 *Bearing temperature prediction*

To investigate the effect of solar radiation on long-term performance of rubber bearing, bearing temperature is one of the key parameters. In this study, the internal of bearing temperature is estimated based on the temperature measurement results. As it can be concluded from the measurement results, the difference between daily average temperatures of the internal bearing and ambient is affected by the solar radiation of the day. By comparing the daily averages of the ambient and internal bearing temperatures, a relationship between the temperature difference and daily total radiation on bearing is examined as shown in Figure 9.

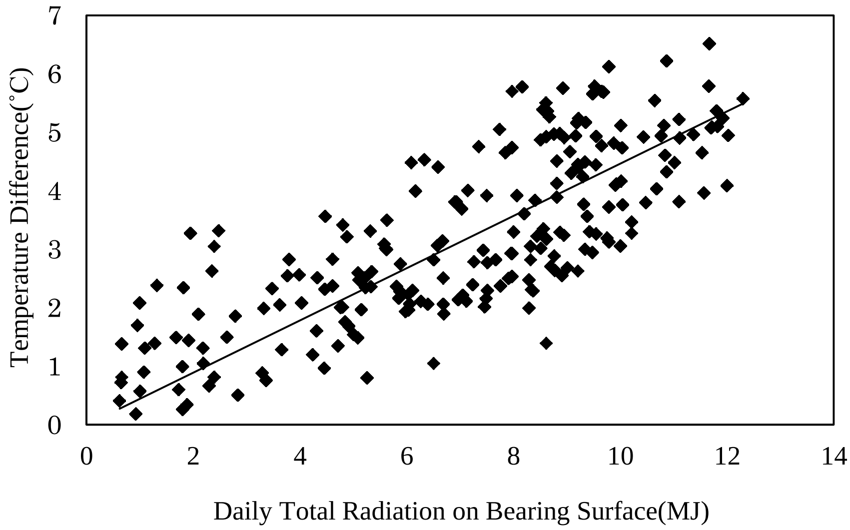


Figure 9. Relationship between daily total radiation on bearing surface and difference of internal bearing and ambient temperatures

By assuming that internal temperature is uniform in the bearing, the heat used to increase bearing temperature from solar radiation can be calculated by the following equation:

$$\Delta Q = c\rho V\Delta T = c\rho V\left(T_2 - T_1\right) \tag{1}$$

where, ΔQ represents the difference between heat from solar radiation and heat lost by the bearing through convection and radiation, c is specific heat, ρ is the density, V is the bearing volume, and ΔT is the temperatures difference before and after the bearing receiving solar radiation. T_1 and T_2 are bearing temperatures before and after the bearing receives solar radiation, T_1 and is assumed to be equal to the ambient temperature. In Equation 1, it is assumed that ΔQ has a linear relationship with the temperature difference ΔT between T_1 and T_2. In this study, by assuming $S \propto \Delta Q$, where S is daily total radiation on bearing surface, a relationship between solar radiation and the temperature difference ΔT was examined (Paramashanti et al. 2010). A regression analysis found the following linear function to estimate the temperature difference ΔT between daily average internal bearing and ambient temperatures from the daily total radiation on bearing surface S is obtained as follows:

$$\Delta T = 0.446S \tag{2}$$

Since the daily total global solar radiation and the daily average of ambient temperature of the day can be obtained from Japan Meteorological Agency (JMA), daily average internal bearing temperature can be estimated from Equation 2 for any location.

Based on JMA database, yearly average ambient temperature of Nagoya is 16.6˚C, and yearly average daily total radiation on bearing surface calculated from data of daily total global solar radiation of Nagoya is 8.2MJ in 2010. By using these data, in Equation 2, the yearly average internal bearing temperature is calculated as 20.2˚C. This value matches the yearly average internal bearing temperature from the measurement results.

4.2 *Long-term performance of bearing considering solar radiation effect*

Itoh et al. (2007) proposed the estimation method of long-term performance of HDR bearing. The long-term performance is estimated based on the assumption that bearing temperature is constant over the aging time. In the estimation method, material degradation of rubber is estimated first based on the given bearing temperature, and stiffness change over aging time is then predicted. To investigate the effect of solar radiation on the long-term performance of HDR bearings the yearly average ambient temperature and the yearly internal bearing temperature were used to calculate bearing stiffness change.

The yearly average of measured ambient temperature is 16.9˚C, and the yearly average of measured internal bearing temperature is 20.2˚C. By using these temperature values, the change of bearing's shear stiffness of an HDR bearing with the size of 420 mm x 420 mm x 134 mm for 100 years can be calculated as shown in Figure 10. As can be seen in Figure 10, the application of the yearly average of measured internal bearing temperature results in a larger change of equivalent shear stiffness when compared to the application of yearly average measured ambient temperature. After 100-year aging time, the shear stiffness of HDR bearing increases by 19% when the yearly average measured ambient temperature is used, while it increases by 22% when the yearly average measured internal bearing temperature is used.

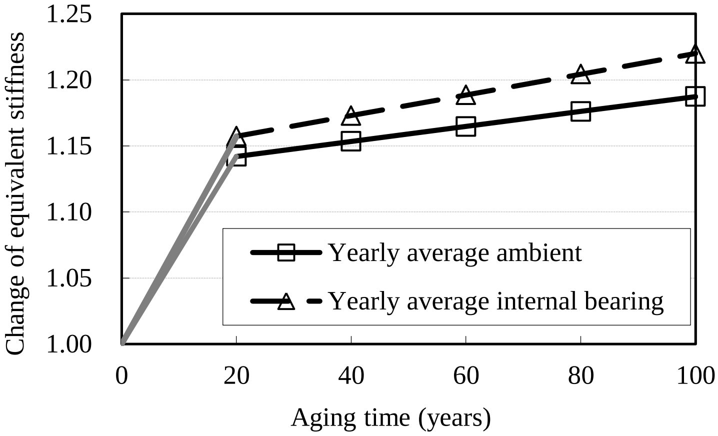


Figure 10. Long-term performance of 420 mm x 420 mm x 134 mm HDR bearing in Nagoya

5 SUMMARY AND CONCLUSIONS

In this study, temperature measurements of a bearing were carried out to understand the effect of solar radiation on bearing temperature and a temperature variation in a bearing. A long-term measurement for one year was performed to investigate bearing temperature variation in a year. Based on the measurement results, an empirical formula to estimate internal bearing temperature from the solar radiation was proposed. By using estimated bearing temperature, the long-term performance of HDR bearing exposed to solar radiation was predicted and compared to the one based on the yearly average ambient temperature. The conclusions are summarized as follows:

1) Daily average bearing internal temperature becomes higher than the daily average ambient temperature when the bearing is exposed to solar radiation during the day. For a 420 mm x 420 mm x 134 mm HDR bearing exposed to solar radiation, the maximum difference can be as large as 9˚C.
2) Bearing surface temperatures are significantly higher than the ambient temperature when the surface is exposed to solar radiation. The maximum difference from the ambient temperature can be larger than 30˚C.
3) From measurement results, the relationship between daily total radiation on bearing surface and the difference in daily average temperatures between the internal bearing and ambient was proposed for the bearing of this study.

4) For the bearing exposed to solar radiation, solar radiation increases bearing temperature, resulting in a faster rate of aging of rubber and a larger change of the equivalent shear stiffness of bridge rubber bearing over time. The use of yearly avearage internal bearing temperature in a case of bearing exposed to solar radiation provides a larger aging effect than the case where yearly average ambient temperature is used as bearing temperature. The difference between those two estimations in terms of bearing equivalent shear stiffness change after 100 years is about 3%. For a base-isolated bridge that does not have much redundancy in the seismic design, the effect of solar radiation on long-term performance of rubber bearing may have a significant effect on its seismic response. Therefore, it is necessary to examine the effect of solar radiation on the long-term performance of bridge rubber bearings.

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