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Development of Displacement Sensor for Detecting Seismic Damage of Bearing at Railway Structure

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Abstract

In order to resume the operation after a large quake, it is necessary to investigate the degree of damage of railway structures. Labors and time are needed to inspect structures, in particular, the inspection of bearings needs to great labors because the around of bearings is high and narrow place. In the 2016 Kumamoto earthquake, the inspection of structures was one of the significant factors to delay the resumption of railway operation. Thus, it is important to shorten the inspection time for an early resumption of operation.

A non-contact displacement sensor that detects the deformation of bearing was proposed in this study. The target bearing is a pad type rubber bearing, and the horizontal displacement of slip of the rubber pad and the vertical displacement of settlement of girder can be measured by the sensor. The displacement might influence the running safety of trains. This sensor also can be adjusted to the steel type bearing that has a significant correlation between seismic damage and displacement. A limit sensor is also installed in this sensor, which notify if the displacement of bearing reaches a threshold displacement. It is possible to detect the damage of side block of steel type bearing by limit sensor.

The displacement is measured at intervals of 10 minutes, and the sensor can be run for more than 8 years by one battery. Furthermore, the measured data of displacement are automatically transmitted to the Internet server via gateway by wireless, and so it is possible to monitor the deformation of bearing quickly after an earthquake in a remote place by access the Internet server.

In addition, the relationship between the slip displacement of bearing and the running safety of the train was investigated by numerical analysis. As a result, it was found out that the running safety would not be satisfied if the slip displacement of bearing exceeds more than 30% of side length of the rubber pad. Moreover, it was proved by a simple experiment that it was possible to confirm whether the performance of running safety was impaired by the developed sensor.

In this paper, ongoing performance verification tests including shaking table test and atmospheric exposure test are introduced.

Keywords: Displacement sensor, Bearing, Seismic damage, Damage detection method

1. Introduction

When a large earthquake occurs and trains stop emergently, it is necessary to inspect the degree of damage of railway structures in order to resume the railway operation. In the 2016 Kumamoto earthquake, a lot of structures were damaged in a wide area [1, 2, 3], so labors and time were needed to inspect a large number of structures. In particular, the inspection of bearings needed great labors, because the bearing was typically located at high and narrow place as shown in Fig. 1. In the 2016 Kumamoto earthquake, not only restoration of derailed cars, but also terms for inspection of structures significantly affected the number of days before resuming train operation.

In this study, the relationship between the damage of bearing and the running safety of the train was investigated to find a limit degree of damage that inspection might be required. According to the result, a non-contact displacement sensor that detect the damage of bearing that influence on the running safety was developed for the purpose of quick inspection and supporting early resumption of railway operation.

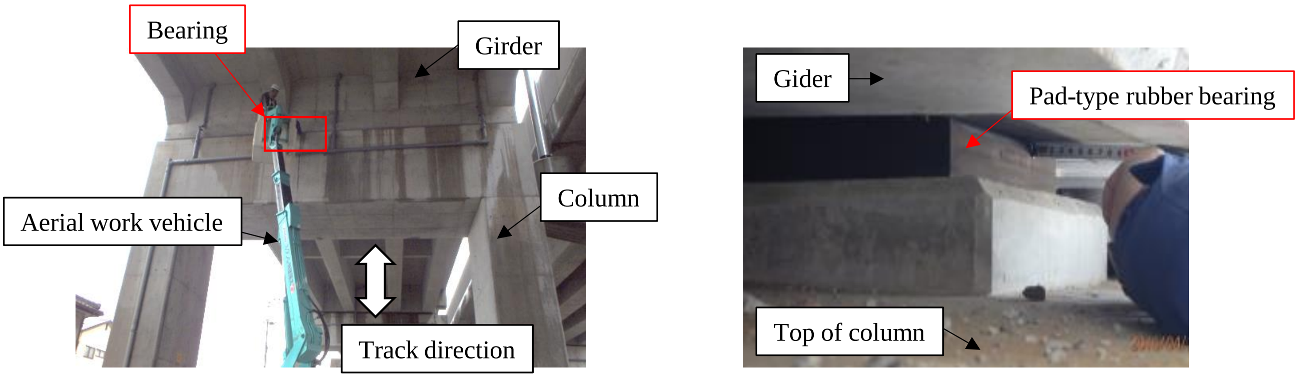


Fig. 1 – Inspection of bearing after an earthquake

2. Target bearing

Based on the damage case of the 2016 Kumamoto earthquake, a pad-type rubber bearing was selected as target bearing to be monitored, which has been generally installed to the railway rigid frame viaducts. In the Kumamoto earthquake, about 2,100 bearings were installed in Kyushu Shinkansen, so a lot of bearings needed to be inspected visually by using the aerial work vehicle [3]. It took 4 days for all bearings before all inspections were completed.

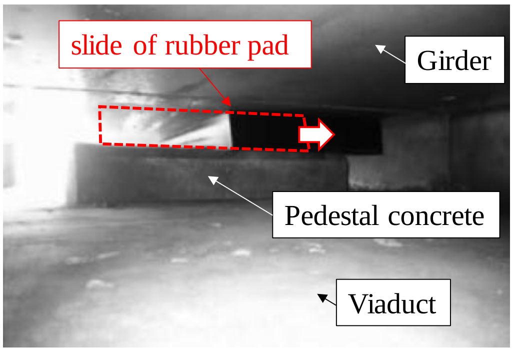


Fig. 2 – Target damage of bearing

Fig. 2 shows the typically damage case of bearing at the Kumamoto earthquake. The rubber pad of bearing set on the pedestal concrete slipped in track or transverse direction.

The running safety or structural safety might be affected due to the slip of rubber pad, because it reduces the effective area to bears against the vertical load such as dead, track and impact load. Therefore, the slide of rubber pad, which is considered to have the greatest effect on the running safety and structural safety, was to be monitored by a sensor in this study.

First, the effect of the amount of slide displacement of rubber pad on the running and structural structural safety was evaluated by numerical analysis, and the limit of the slide displacement of rubber pad that satisfies the running and structural safety was obtained. Seconds, a sensor that measures the slide displacement of rubber pad was developed. This sensor also can transmit the measured data to the Internet server via a gateway, and that data can be obtained at remote locations. Finally, several performance verification tests of the developed sensor were performed.

3. Limit of damage

In order to arrange the limit of slide displacement of rubber pad that satisfies the running and structural safety, a numerical analysis was performed. The outline of the analysis is shown in Fig. 3.

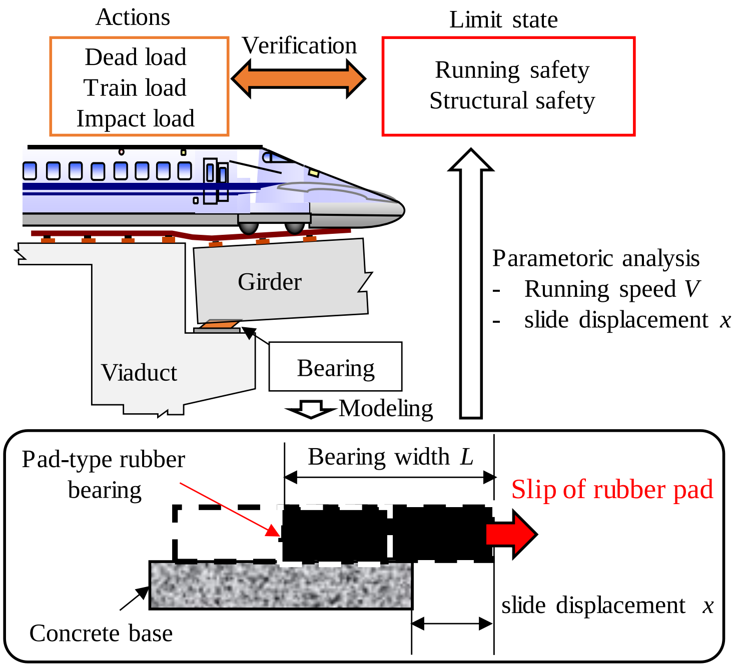


Fig. 3 – Outline of analytical study

3.1 Structure model

The adjacent two railway rigid frame viaducts of Shinkansen and a connecting girder between both viaducts were modeled. The span of the girder was 9.3 m, and the pad-type rubber bearings were set under the girder.

As shown in Fig. 4, the space frame model of the structures was composed. The columns, upper beams and slabs were modeled, while the underground beams and piles were not modeled, and the bottom of columns were fixed to the base. All structural members were modeled with elastic beam elements. In order to assume the damage caused by the earthquake, an equivalent stiffness after cracking was given to columns.

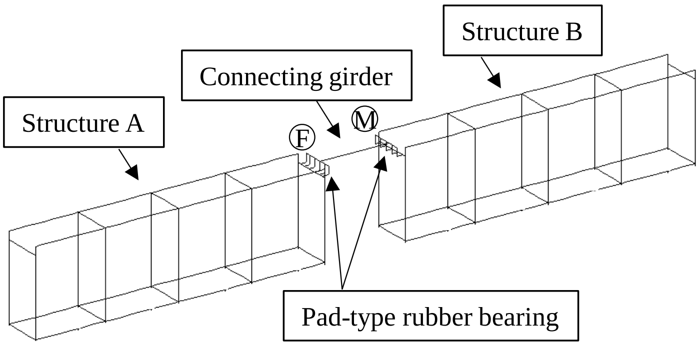


Fig. 4 – Structural model

The rubber pad was modeled by vertical and horizontal spring elements, these values of stiffness was calculated by Japanese design standards [4]. In addition, the sliding friction of rubber pad was also considered. The modeling method of bearing is shown in Fig. 5.

3.2 Parameters

The sliding ratio and running speed of vehicle were set to a parameter. Here, the sliding ratio α is determined as Eq. (1).

$$\alpha = x / L \tag{1}$$

Where x is a slide displacement of rubber pad caused by the earthquake, and L is the width of rubber pad. The vertical stiffness of rubber pad was reduced according to the slide ratio α.

The slide ratio α was set to 11 cases in 5% increments from 0% to 50%. The running speed V was set to 5 cases as follows: 80 km/h, 130 km/h, 160 km/h, 260 km/h and 300 km/h. The impact load by the vehicle was calculated according to the Japanese standards [5]. These parameters are shown in Table 1.

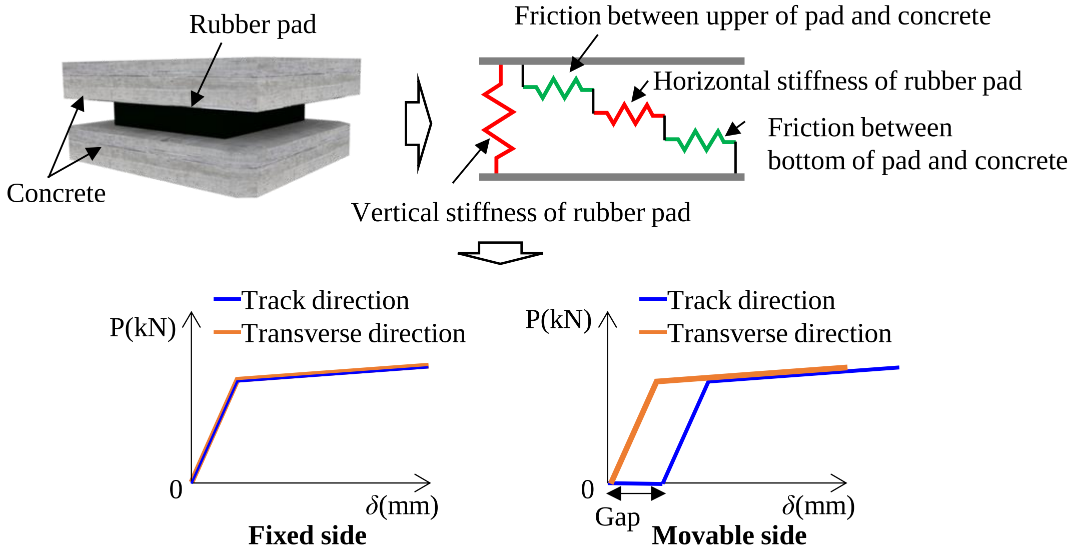


Fig. 5 – Bearing model

Table 1 – Parameters of analysis

α (%)	**V (km/h)**	**Impact load**
0 to 50 in 5 increments	80, 120, 160, 260, 300	Calculated by *V*

3.3 Result and discussion

A static analysis was performed to calculate the stress of rubber pad and displacement of girder at each cases and performances such as restorability of bearing, deflection of girder and vertical misalignment at joint were checked by the corresponding verification indices. The performance demand would be met if the verification index is lower than unity.

The relationship between the slide ratio *α* and the verification index with respect to the maximum vertical stress of bearing according to each running speed *V* is shown in Fig. 6. The maximum vertical stress of bearing was the greatest effect on the running safety. As shown in Fig. 6, in case the slide ratio *α* is 15% or more, the running safety is not satisfied when the running speed *V* is 300 km/h. In case the *α* exceeds 30%, the running safety is not satisfied when the *V* is 80 km/h or more.

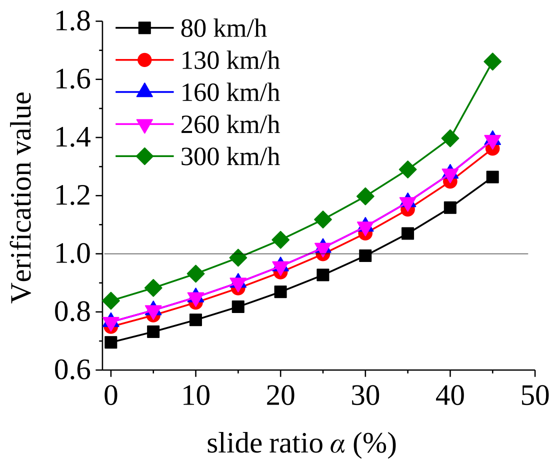


Fig. 6 – Relationship between *α* and check value of vertical stress of bearing

From the above, it is possible to determine the allowable maximum running speed according to the amount of damage of pad bearing after the earthquake.

4. Development of detective sensor

Since it was found that the sliding displacement of the rubber-pad bearing took an important role in evaluating the running safety of trains, a sensor that detects the slide displacement of rubber pad installed at high and narrow place of structures was developed.

Table 2 – Required performant of sensor

Measurement target	Size	Accuracy	Power supply	Communication
Slide displacement of rubber pad	To be installed around the bearing	About 1 mm	To run for at least 5 years	To obtain the measurement data from a remote location by wireless communication

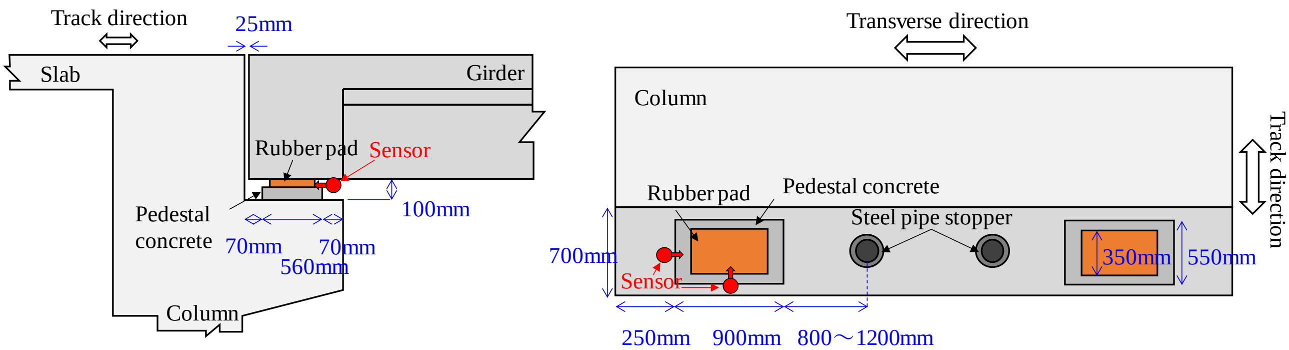


Fig. 7 – Dimensions around the bearing

4.1 Required performance

The required performance of the sensor is shown in Table 2. In order to arrange the sensor, the available space around the typically pad-type rubber bearing were investigated. These values are shown in Fig. 7. The sensor shall be small enough to be installed between the girder and the top of column as shown in Fig. 7.

As for the measurement method, an inspection method that only determines whether the displacement exceeds the threshold can be considered, so, not only a measurement sensor, a limit sensor that detects that something touches it was also developed.

The measurement was carried out with a non-contact method by using 'Time-Of-Flight (TOF)' sensor. The accuracy of the measurement sensor was set to 1 mm.

The battery life was set to 5 years or more so that the battery could be replaced during the periodic inspection of structures. In order to ensure the battery life, an interval measurement method was adopted. This is because, for the inspection after an earthquake, it is not always necessary to monitor the dynamic behavior under an earthquake, it is only necessary to monitor the static state after an earthquake.

In addition, in order to monitor the seismic damage of the bearing from a remote location without visual inspection after an earthquake, the data measured by the sensor should be transmitted to the Internet by wireless communication.

4.2 System

The sensor that satisfies all required performance was developed. The outline of system is shown in Fig. 8. The system of sensor was composed of the following elements:

– A sensor node that measures slide displacement and transmit the data to the gateway

– A gateway that connect the sensor node and the cloud sever

– A cloud sever that store the measured data

– A mobile device such as smart phone or laptop that access to the cloud sever

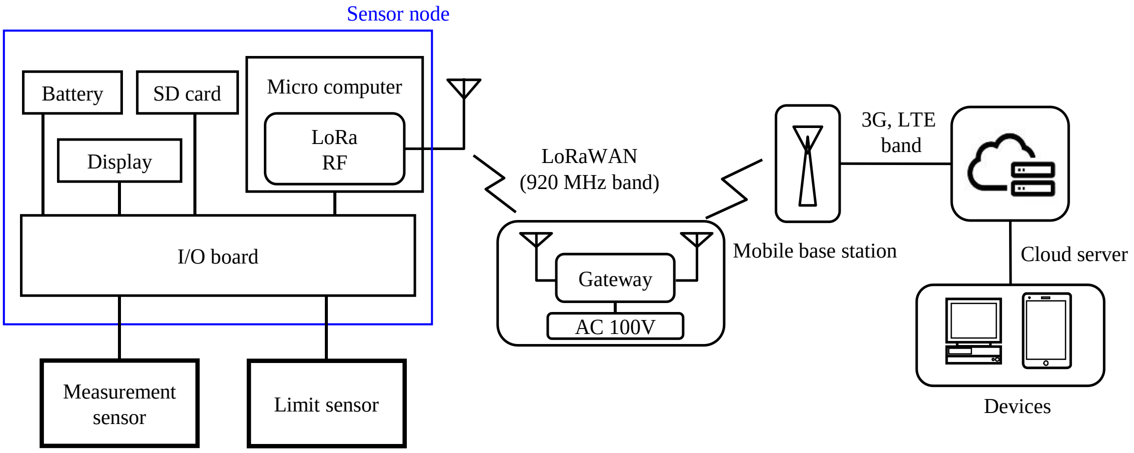


Fig. 8 – System of the sensor

4.3 Sensor node

A sensor node is composed of a Battery, a microcomputer, an I/O board, a three-axis measurement sensor and a limit sensor as shown in Fig. 9. The measurement sensor is composed of an integrated combination of CMOS image sensor and IR-LED. This is adopted the triangulation method and outputs digital (I^2C) data. The size of sensor device is 16.9 mm × 11.0 mm × 5.2 mm.

The limit sensor is composed of a waterproof switch and a neodymium magnet. The switch would be turned off if the switch comes off from the magnet.

4.4 Network

The sensor node measures the slide displacement of rubber pad at 10-minute intervals and transmits the data to the gateway by 920 MHz band. The gateway transmits the data to the cloud server by 3G or LTE band.

When the measurement and transmission are not performed, the system would change to the power saving mode. At the set time, the system starts up and operates the transmission establishment, measurement and data transmission. The measurement data are stored on the cloud server. The stored data can be browsed and downloaded by devices such as a laptop or a smartphone via Internet.

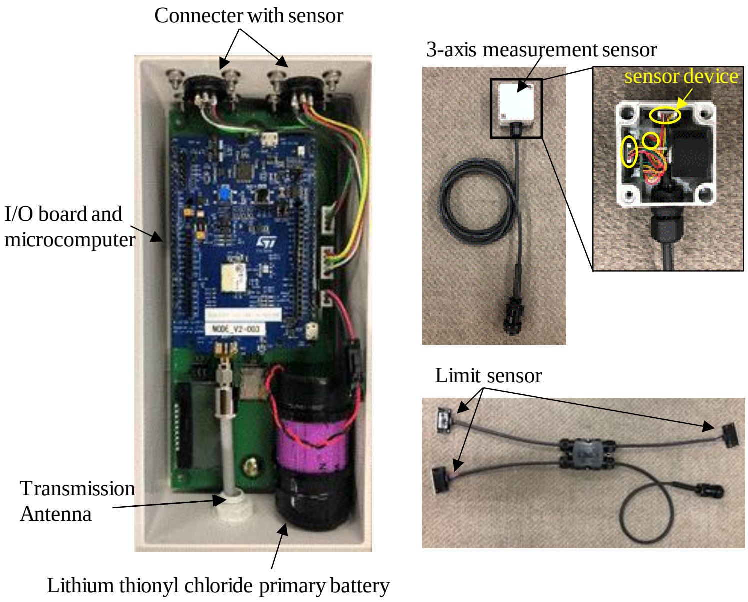


Fig. 9 – System of the sensor

Table 3 – Measurement accuracy of sensor

Measurement range (mm)	**Maximum error (mm)**
40 ～ 70	0.27
80 ～ 100	0.71
100 ～ 150	1.03
150 ～ 250	1.97
250 ～ 400	2.88

5. Performance verification

5.1 Accuracy

The accuracy of the measurement sensor is shown in Table 3. It was evaluated by using other high precision sensor. As shown in Table 3, the accuracy varies due to the measurement distance, the shorter the measurement distance, the better the accuracy. When the measurement range is from 40 mm to 150 mm, the accuracy satisfies the required performance shown in Table 2.

5.2 Temperature resistance

In order to confirm the stability of the measurement accuracy against the temperature fluctuation under the exposure environment, the test using thermostat was conducted. The measurement sensor was set in the thermostat. After setting, the distance between the sensor and the object was fixed at 50 mm and the temperature in the thermostat was changed from 25 ℃ to 60 ℃. Then, the measured displacement was recorded every 5 ℃.

The result is shown in Table 4. It was confirmed that the variation of displacement was only ±0.16 mm with respect to the temperature fluctuation. Therefore, it was found that the accuracy of sensor is less dependent on the temperature.

5.3 Vibration resistance

The vibration resistance of the developed sensor was verified by a shaking table test. The developed sensor and the high precision sensor for verification were both set on the structural model, and excited to the extreme acceleration level, up to 1300gal.

Table 4 – Measured displacement at the temperature fluctuation test

Step.	Room temperature (℃)	measured displacement (mm)	Step.	Room temperature (℃)	measured displacement (mm)	Step.	Room temperature (℃)	measured displacement (mm)
1	25	50.00	**11**	-25	50.16	**21**	15	50.16
2	20	50.00	**12**	-30	50.16	**22**	20	50.16
3	15	50.00	**13**	-25	50.16	**23**	25	50.00
4	10	50.00	**14**	-20	50.16	**24**	30	50.00
5	5	50.00	**15**	-15	50.16	**25**	35	50.00
6	0	50.16	**16**	-10	50.16	**26**	40	50.00
7	-5	50.16	**17**	-5	50.16	**27**	45	50.00
8	-10	50.16	**18**	0	50.16	**28**	50	49.84
9	-15	50.16	**19**	5	50.16	**29**	55	49.84
10	-20	50.16	**20**	10	50.16	**30**	60	49.84

Table 5 – Measured displacement at the shaking table test

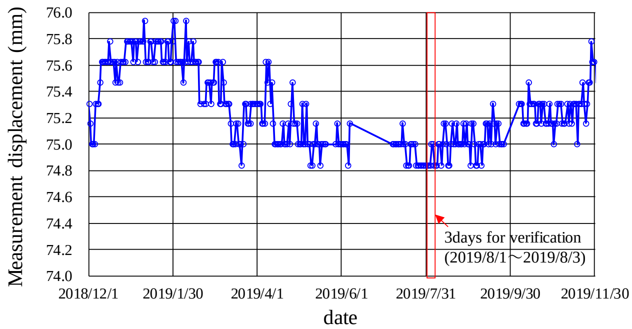
Case No.	Input acceleration (cm/s^2)	developed sensor		high precision sensor		Error	
		initial (mm)	residual (mm)	initial (mm)	residual (mm)	initial (mm)	residual (mm)
1	100	0.00	0.00	0.20	0.22	-0.20	-0.22
2	200	-1.25	0.00	0.28	0.26	-1.53	-0.26
3	300	0.00	0.00	0.31	-0.07	-0.31	0.07
4	400	0.00	-1.25	-0.06	-0.40	0.06	-0.85
5	500	-1.25	-1.25	-0.37	-0.57	-0.88	-0.68
6	600	-1.25	-1.25	-0.45	-0.47	-0.80	-0.78
7	800	-1.25	-2.50	-0.47	-0.91	-0.78	-1.59
8	1000	-1.25	-8.91	-0.89	-9.00	-0.36	0.09
9	1100	-8.91	1.25	-9.01	-0.30	0.10	1.55
10	1100	1.25	8.59	0.32	8.91	0.93	-0.32
11	1100	8.59	10.93	9.70	10.89	-1.11	0.04
12	1100	13.28	5.00	13.53	5.50	-0.25	-0.50
13	1300	7.34	103.12	7.97	101.46	-0.63	1.66
14	800	104.37	106.09	102.87	105.08	1.50	1.01
15	800	106.72	108.43	105.57	107.93	1.15	0.50

The residual displacement of the structural model was measured and compared. The result is shown in Table 5. The measurement error of developed sensor was up to 1.66mm when the residual displacement was about 100 mm at 13th case. Therefore, it was found that even under strong motion, the accuracy is the same as the accuracy verified statically, and the data transmission is also secured.

5.4 Durability

Several developed sensors were installed at the bearing on the test line at Railway Technical Research Institute and a long-term durability test under exposure environment was performed. The test has been carried out since November 2018.

The result for one year from the start of the test and for 3 days are shown in Fig. 10. As shown in this figure, it is confirmed that the daily and seasonal fluctuation due to the temperature expansion of girder were measured without malfunctions. It consequently followed that the long-term continuous measurement was possible while maintaining the accuracy and the data transmission stability even under exposure environment.



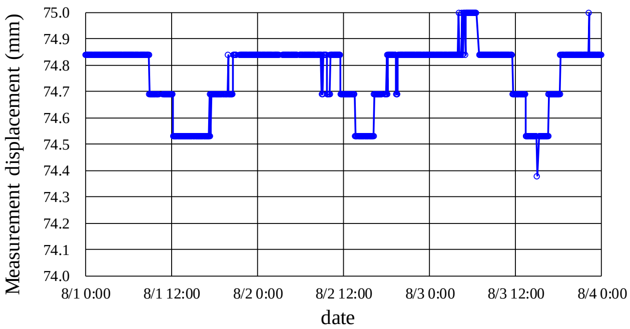


Fig. 10 – Measured displacement in the long-term durability test

6. Conclusion

In order to support the resumption of railway operation after a large quake, a limit state of pad-type rubber bearing after an earthquake was evaluated and a damage detective method using sensor was developed.

The slide displacement of rubber pad was decided to the detective target based on the 2016 Kumamoto earthquake. The limit state of slide displacement was evaluated by numerical analysis. Then, the limit state of slide ratio α was arranged with respect to the running speed of vehicle. As the result, it was found that in case the slide ratio α is 30 % or more, running safety of vehicle over 80 km/h does not satisfy.

The sensor detects the slide displacement of rubber pad was developed. Two different sensors, measurement sensor and limit sensor, were proposed to detect the occurrence and its quantity of the severe damage of pad bearing. The sensors were driven by a long-term battery (at least 5 years) and measures three-axis displacement in the accuracy 1 mm. The measurement data is transmitted to the Internet server via a gateway and be browsed and downloaded from the server.

Several performance verification tests were conducted as follows: an accuracy verification test, a temperature resistance test, a vibration resistance test and a durability test. As the result it was confirmed that the developed sensor is satisfied the required performance for detecting the damage of bearing after an earthquake.

The long-term durability test will be continuously conducted. Furthermore, the Installation test to the actual railway structures will be conducted.

7. References

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