Thermal Effects in Long-term Monitoring of ASR-Affected PC Gelber Hinge Bridge

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Abstract—**Crack expansion behavior due to temperature changes has a significant influence on the soundness of reinforced concrete bridges. In this study, the expansion of cracks by Alkali-Silica Reaction (ASR) was investigated using long-term remote monitoring on a four-span pre-stressed concrete (PC) rigid-frame bridge. To evaluate the workability of a deteriorated bridge, instead of only focusing on the deformation of cracks under external loads, the consideration of environmental temperature factor is also needed. By analyzing the relationship between temperature changes and displacement behaviors over time, the ASR-induced crack expansion trend had been obtained. After that, the prediction of ultimate status of this bridge under extreme and normal working conditions was discussed. The monitoring results showed that the ASR-induced cracks are getting wider over time. Furthermore, the results of the study also supported that since the objective bridge is designed with Gelber hinges, there are spaces for deformation between two spans, which make displacement easier to occur throughout the year, from spring to summer in particular. Finally, this study provides information about the relationship between the behavior of a typical ASR-deteriorated PC bridge and environmental thermal effects at a specific time of the year.**

Index Terms—**Long-term, Gelber Hinge, Thermal, ASR**

I. INTRODUCTION

During high economic growth, in order to motivate the development of the country, Japan has built numerous infrastructures such as bridges, roads, airports, and buildings [1]. However, as time flies, under surrounding environmental impact and human's usage, infrastructures -especially bridges which are subjected directly to daily, seasonally environmental thermal effects-have been deteriorating, this is the problem occurring all around the world [2][3]. Nowadays, Japan has lots of bridges whose quality is getting degraded days after days [4]. Alkali-silica reaction (ASR) is one of the popular reasons of bridge deterioration in Japan because of the existence of many reactive aggregates throughout the country. Especially ASR is known for causing the deterioration of bridges in Noto Region, where the main cause for ASR: andesite, is widely distributed [5]. The reaction between the highly alkaline cement paste and the reactive non-crystalline silica, forms the gel of alkali silicate hydrate. This gel increases in volume by absorbing water, which leads to an expansive pressure inside the structures, resulting in spalling, cracking and failure of the concrete [6][7].

Furthermore, Japan is located in a temperate zone with four seasons: spring, summer, autumn, and winter, thus temperature amplitude is varying from hot to cold, continuously changing throughout the year. This is a perfect condition for promoting ASR growing process [8]. The changes in structural temperature and temperature distribution in a bridge lead to movements and deformations of cracks or slabs, which seriously affect the workability of concrete structures. In fact, structural behavior of bridges is more significantly affected by environmental thermal actions than by external loading factors [9]. With all the geological and environmental thermal conditions that the bridges in Japan are facing, it is necessary to continuously observe their deformations and estimate the developing trends of cracks. Then, use the deformation trend for proposing the most appropriate repair technique to prevent damaged structures from future deterioration.

Reinforced concrete bridges are designed to maintain their service and function over long periods of time. During their service life, the concrete is exposed to many aggressive influences, including external loading and vibration, rough weather conditions, the presence of chlorides near marine environments or frost damage, which cause adverse effects to structural health [10]. Therefore, the responses of a structure are extremely important for early detection and the most economic maintenance strategy (Life Cycle Benefit/ Cost Analysis) [11].

Many studies have proved that these responses are extraordinarily difficult to comprehend and are affected both by thermal and loading effects [12] [13]. However, not so many researchers have considered temperature change factor for this type of the concrete bridge in their studies yet. A study of evaluating the current status of hinges and bearings on 77 years-service, steel cantilever

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Chousei Bridge by carrying out a static loading field test was conducted by Khanh et al. [14]. Another study conducted by Miyashita et al. aimed to evaluate the present performance for planning future maintenance strategies [15]. The evaluation was done by short-term monitoring of a cantilever steel truss bridge. Besides, a study of a large-scale testing program on ASR-affected concrete structural members in nuclear power plants was presented by Hayes et al [16]. Three concrete specimens, designed to experience a free expansion rate of approximately 0.15% per year were fabricated and placed within a controlled environmental chamber (38 ± 1℃ (100 ±2 ℉) and 95 ±5% relative humidity. Among many studies about the behaviors of ASR-induced cracks under thermal effects, no study has used remote long-term monitoring for the Gelber Hinge-typed bridge in advanced.

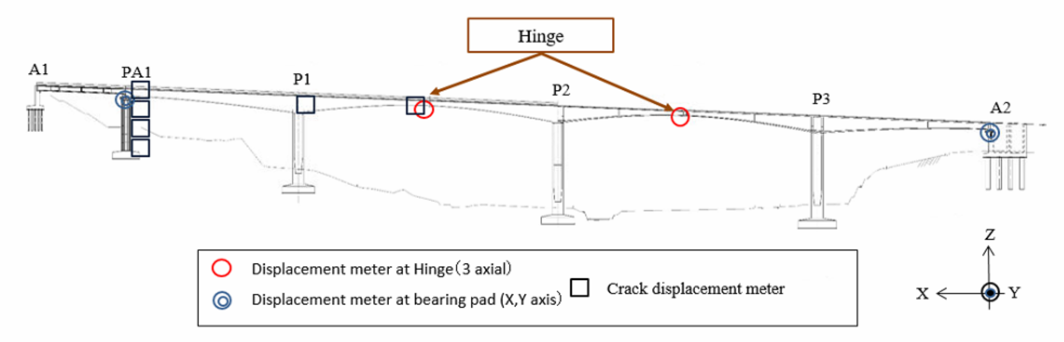

Figure 1. Measurement positions and types for long-term monitoring

Thus, this study will propose a new way to investigate the response of structure in terms of temperature changes, by using the long-term remote monitoring method. The attempt of this study is to evaluate the effects of temperature change on pre-stressed concrete (PC) bridges having severe cracks due to ASR deterioration. Located in Noto region, the objective bridge of this study is a part of an important road network. It is used not only for travel needs of the native people but also for emergency situations. When a natural disaster such as an earthquake occurs, this road provides a connection between two regions, make it easier for the relief operation. After the Noto Peninsula Earthquake, seismic reinforcement was implemented. At the same time, the monitoring activities were conducted to observe the effectiveness of reinforcement for cracks caused by ASR. This bridge is designed with Gelber Hinge form, which is simple to construct but have weak resistance against earthquake. Therefore it is necessary to understand the healthiness or the behavior of the bridge under various circumstances. By applying long-term remote monitoring, the displacement changes and cracks expansion due to environmental temperature effects of the objective bridge can be clarified daily.

II. OBJECTIVE BRIDGE

In this study, the objective bridge is a four-span PC rigid-frame bridge with 2 hinges, one is between P1 and P 2, other are for the connection between P2 and P3. The overview image of this bridge and position of hinges are shown in Figs. 1 and 2. This bridge was constructed in 1978 with the design of Gelber hinges, which is simple to design and elaborate. However as seismic activities in the Pacific Ring of Fire occur more frequently, the risk of earthquakes is increasing sharply. Therefore it is necessary to estimate the behavior of this bridge under seismic activities to figure out the most appropriate maintenance strategies. As mentioned above, the ASR-induced cracks occurred in many positions both at superstructure and substructure of the bridge. The leaking water from the expansion device, along with the spraying of the anti-freezing agent in the winter created a suitable environment for ASR phenomenon. After the Noto Peninsula Earthquake in 2007, the concrete jacketing method has been executed on both piers to increase the structure's endurance ability against earthquake and further cracks expansion [17].

Figure 2. Overview of objective bridge

Figure 3. Concrete Jaketing

The cracks occurring in this objective structure can be seen on both piers and box girders. The deterioration is happening severely both outside and inside of the structure as shown in the Figs. 3-5. Fig. 3 shows that the reinforced concrete jacketing layer has some significant cracks due to the leaking water from the surface of the bridge. Moreover, inside the box girder, there are numerous thin cracks on the walls along the longitudinal direction (Fig. 5). There are also some damaging points at the joints (Fig. 4), which is believed to be the result of a collision between two girders at the hinge due to structural extension caused by temperature change.

Figure 4. Joints's broken tracks

III. LONG-TERM MONITORING

Long-term monitoring in this study consists of three categories, which are the deformation of the expansion joint, the displacement of bearing pad at abutment, and the expansion of cracks caused by temperature change effects. The evaluating method of this research was performed since April 2015. The positions of measurement devices are displayed in Fig. 1. As expressed in the figure, the displacement meters are at the Gelber hinge places (between P1-P2, P2-P3) and bearing pads, and crack width meters are installed inside the box girder along the bridge and PA1.

Figure 5. Cracks inside box girder

The equipment used is shown in the following Table 1. In this study, displacement meters (CDP-10) are set at hinges and bearing pads, and crack width meters (KG-5A) are installed on the walls inside the box girder (Fig. 5). All devices are provided by Tokyo Measuring Instruments Laboratory Co., Ltd. The crack width meter (Fig. 6) is attached on the walls inside the box girder used to measure the width of cracks as shown in Fig. 7.

TABLE I. EQUIPMENT AND QUANTITY

Name	Code	Numbers
Displacement Meter	CDP-10	20
Crack Width Meter	KG-5A	11

To inspect the development of cracks, monitoring was performed and the data is sent via email once every hour to the laboratory. Specifically, its results will be sent via data logger TDS-150, and can be observed continuously anytime.

Figure 6. Crack Width meter

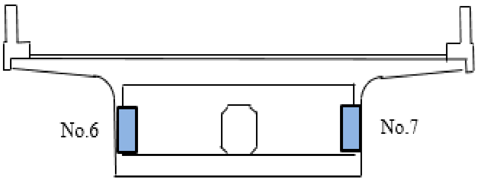

Figure 7. Crack Width Meter near P1-P2 hinge

IV. LONG-TERM MONITORING RESULTS

A. Cracks Width at Pier

The first observation points in this study are at pier PA1. The positions of sensors are shown in Fig. 8, spreading from top to bottom of the pier. Figs. 9 and 10 show the correlation between temperature change and the width of cracks near the top and at the middle of the pier PA1. As shown in Fig. 9 the crack in the middle of the pier is continuously increasing its width throughout the years. The width increases significantly at high temperature around 30 ^{0}C to 35 ^{0}C, where the data has a vertical development trend. When temperature changes from summer to winter and winter to summer, the width keeps increasing but with more slightly gradation. Observing the ascending trend of width development, it can be seen that by the winter of 2018-2019, the width is expected to increase above 0.16 mm.

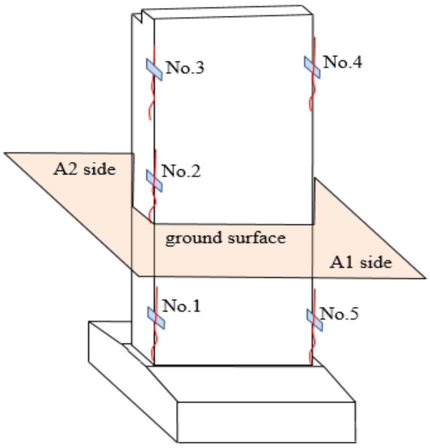

Figure 8. Crack width meter locations in PA1

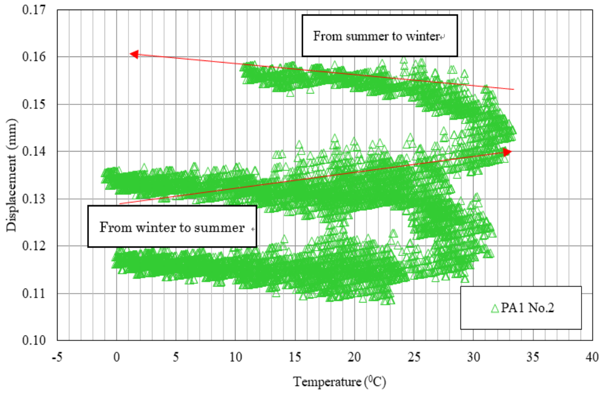

Figure 9. Relation between temperature and crack width at PA1 (No.2)

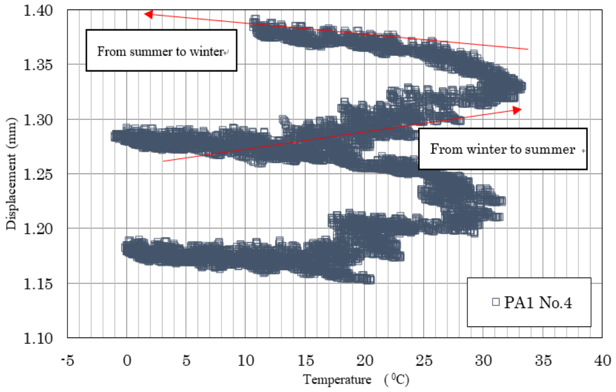

Figure 10. Relation between temperature and crack width at PA1 (No.4)

The width of crack near the top of the pier is shown in Fig. 10. The development of crack width at the middle and the top has nearly the same formation. Therefore, it can be concluded that temperature changes caused severe influences to the width of cracks in pier PA1. Furthermore, the value is much higher for the width at No. 4, about 1.4 mm in comparison with just 0.16 mm at No. 2. It presented that the width near the top is sharply more serious than ones in the middle of PA1. The crack development trend is the same at No. 3 and No. 4 near the top of the pier. Moreover, according to the intensive increasing trend of width development as shown in Fig. 10, the cracks near the top are the weakest points of the PA1, which caused negative effects to the soundness of pier. Piers hold an important role for sustaining the workability of whole bridge structures, thus early maintenance methods are highly considered for this viaduct.

B. Displacement at Hinges and Bearing Pad

Fig. 11 shows the displacement at the hinge of P2 and P3 in three dimensions under the temperature change. During nearly 4 years of measurement, the temperature was highest at about 35 ^{0}C in the summer, and lowest at about -2 ^{0}C in the winter within a year. The displacement of the longitudinal direction (X direction) is at its highest, approximately 40mm as the temperature decreases lower than 0 ^{0}C, and smallest, nearly 0 mm as the temperature in the range from 25 ^{0}C to 35 ^{0}C. It presents that in the winter, as the temperature gets lower, the structure was contracted, which makes the gaps between two slabs was widest. On the contrary, in the summer, Fig. 11 also presents some value which is slightly lower than 0 mm, which means that the collision between two sides of girders occurred. This result proved the assumption for the damaged tracks at hinges as shown above. For another two dimensions (Y and Z direction), there are minor changes in displacement under temperature effect, the value remains from about 1 mm to 3 mm at all temperature. Therefore, when making strategies for overcoming the damage at hinges, it is necessary to focus on longitudinal displacement. Moreover, the results obtained at the hinge of P1-P2 are the same as ones at P2-P3 respectively.

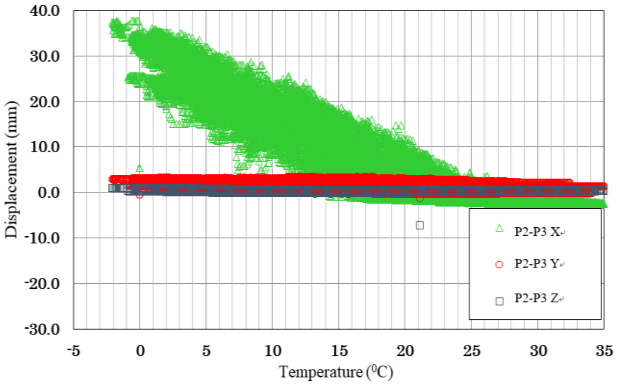

Figure 11. Displacement of Hinge at P2-P3

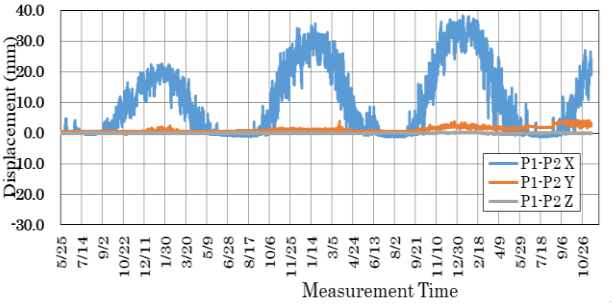

Figure 12. Displacement at P1-P2 hinge over time

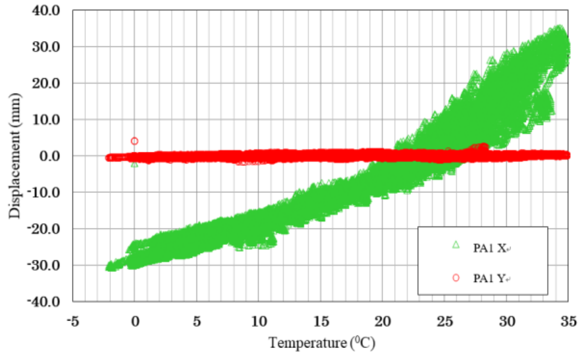

Figure 13. Displacement at PA1 (X Y axis)

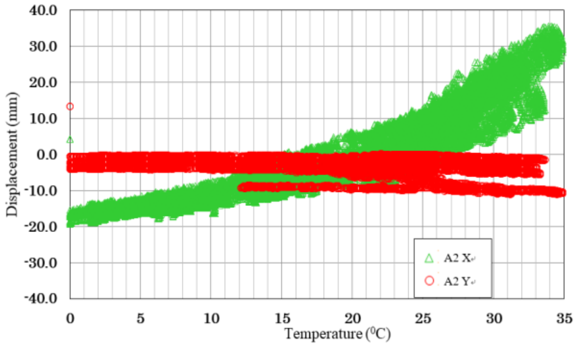

Figure 14. Displacement at A2 (X Y axis)

As shown in Fig. 12, the peak value of displacement on longitudinal direction at P1-P2 has an increasing trend annually. On January 2015, the peak displacement is about 20 mm, this value has increased to 40 mm in January 2018, and expect to be higher than 40 mm in January 2019. The trend of annually increasing displacement occurs not only at hinges P1-P2, but also the same as the bearing pads PA1, A2, and P2-P3 hinge. It presents that the stability of the entire structure is not decent, and future failure can be predicted.

The relationship between temperature change and displacement at bearing pad PA1 is shown in Fig. 13. As shown in Fig. 13, the displacement of the perpendicular direction with the longitudinal direction of the bridge(Y direction) has nearly 0 mm value at all temperature. On the other hands, the amplitude in the longitudinal direction of PA1's displacement is spreading from -30 mm to 35 mm. It shows that the upper structure of the bridge is sliding on bearing pad forward and backward, corresponding to seasons. At the temperature of 35 ^{0}C, the displacement has positive value, it means that the structure moves from A2 toward PA1. This is correspondent to displacement at P2-P3 hinge at the same temperature.

As presented in Fig. 14, the displacement at A2 has significant differences in comparison to those measured at PA1, especially on the Y direction. Especially, in the X direction, the displacement has the lowest value at about -20 mm, lower than ones at PA1, which is approximately -30 mm. Generally, the displacement trend on longitudinal direction is the same both at PA1 and A2. On the contrary, in the Y direction, the displacement at some point of temperature has decreased to -15 mm. This behavior not only occurs at high temperature but also at a low temperature, at a wide range from 12 ^{0}C to 35 ^{0}C. However, at this range of temperature, there are also minor displacements, which show that the displacement at A2 is unstable and need further serious inspections for the more accurate conclusion.

C. *Crack Width inside Box Girder*

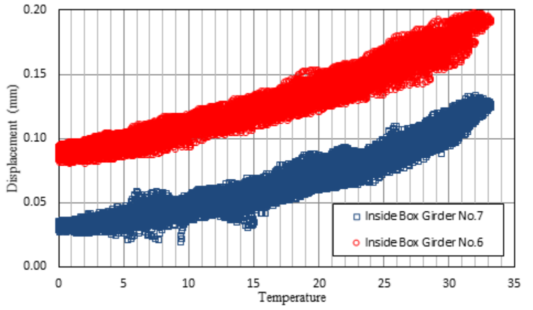

Figure 15. Cracks width on Box girder's walls

The correlations between the width of cracks and the temperature effect are demonstrated in Fig. 15. Even though the width is different on each side of the wall, it has the same deformation trend. It has the highest value of 0.20 mm and 0.13 mm at 34 ^{0}C, and lowest 0.09 mm and 0.04 mm at 0 ^{0}C for No.6 and No.7 respectively. This indicates that the width of ASR-induced cracks increases along with the growing of the temperature. Cracks are the condition for the development of aggressive aggregates to intrude. Thus it can be pointed out that at the higher temperature, in other words, in the summer, the ASR process takes place more simply than in the winter. The difference of width in the same box also indicates that the behavior of structure in terms of thermal actions is various, and difficult to comprehend. Furthermore, Fig. 16 showed that besides the change of width correspondents with the change of temperature throughout the years, the peak width remains stable through the years. Nevertheless, a minor change has occurred in 2018. Since the beginning of monitoring, the peak width remains the same around 0.17-0.18 mm at No.6 and 0.11 mm at No.7, but in summer of 2018, the highest value has slightly increased to 0.20 mm and 0.13 mm respectively. It can be concluded that the width of cracks is ascending extensively, and the bridge has entered the time when maintenance needs to be considered more seriously.

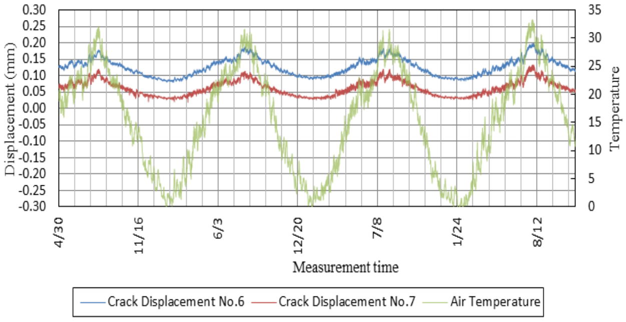

Figure 16. Crack development trend near P1-P2 hinge

V. CONCLUSION

In this study, to evaluate the behavior of the bridge under environmental thermal actions, the displacement of slabs, hinges and the displacement of cracks caused by ASR effects have been investigated by applying remote long term monitoring method. It is essential to perform measurement for a long period of time with the modern, high reliability device to get the most accurate results for proposing the most appropriate maintenance strategies. The results drawn from this study are expressed as followings.

(1) Long-term monitoring showed that the relationship between the temperature change and the expansion of cracks due to ASR, and the variability of width trend monthly had been obtained.

(2) The damaging points at the joints were caused by the collision due to deformation of hinges. It is confirmed that the extension due to the increase of temperature or the bend due to thermal actions between two girders is the reason for this collision. These tracks will become more severe as the displacement of slabs is increasing annually. The damage at the joints leads to the harmful effect to the healthiness of the structure. Therefore it is necessary to suppress the displacement before it gets out of control.

(3) Even though this is a curved-form bridge, the displacement at the joints position was insignificant on both sides of the slabs. Specifically, at 20 ^{0}C, the displacement of longitudinal direction on the left side at joint P1-P2 and P2-P3 are the same, which are both 20mm. When described on the graph, it can be seen that two figures have nearly the same distribution at all the temperature.

(4) Long-term monitoring proved that the thermal actions have significant effect on the responses of the whole structure, as well as the expansion performance of ASR-induced cracks in the bridge. In particular, the gap of hinges between two girders is widest in the winter and narrowest in the summer, with a considerable difference at appropriately 40 mm. For bearing pad, the displacement is oscillating from -30 mm to 35 mm throughout the year.

(5) The displacement and the width of ASR-induced cracks gotten from measurement results are getting higher and higher annually, which means that the objective bridge is confronting more and more seriously deterioration. Accordingly, considering the maintenance strategies is essential. Even though overcome such harsh built environment is not a simple wok.

As time flies, under environmental and temperature effects, the monitor equipment are deteriorated and need periodical inspection. The monitoring work will be carried on for nearly two more years for meeting the demand for deeper analysis and accurate-increased results.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

All authors conducted research, analyzed the data and wrote the paper. All authors had approved the final version.

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