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Assessing the Structural Integrity of Concrete Half-joints Using Sensor Data

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Abstract

Half-joints in concrete bridges are known to exhibit an increased rate of degradation. Their main vulnerability is situated in the re-entrant corner, buried deep inside the joint. This makes visual inspection nearly impossible. A Structural Health Monitoring (SHM) system offers a promising alternative, but interpretation of the half-joint status from SHM data is not straightforward. The study presented in this paper is a case study of the SHM system on the Naardertrekvaart bridge in the Netherlands. Analysis of SHM data revealed a dependence of the movement of the bridge on a seasonal temperature cycle, presumably caused by hindered thermal contraction of the half-joints. This phenomenon offered no reliable estimation of the half-joint status. In addition, from the movement of the lower half-joint nibs under traffic loads, a stiffness parameter was devised, used as an estimation of the half-joint status. The study indicated that a high-frequency approach can increase effectiveness of the SHM system.

Keywords: half-joint; concrete bridge; structural health monitoring; data analysis; finite element modelling.

1 Introduction

The half-joint, also known as the Gerber saddle or Gerber joint, was first introduced by Heinrich Gottfried Gerber, a German Engineer [1,2]. It is a type of joint that can frequently be found in concrete bridges. This type of joint consists of a lower nib connected to the support, and an upper

nib connected to the span, as shown in Figure 1. Loads are generally transferred from the upper nib to the lower nib. This type of joint gained some popularity between 1960 and 1970, mainly due to its ability to facilitate a more slender design of the superstructure. Currently, over 100 of the bridges in the Netherlands in possession of Rijkswaterstaat contain half-joints [3].

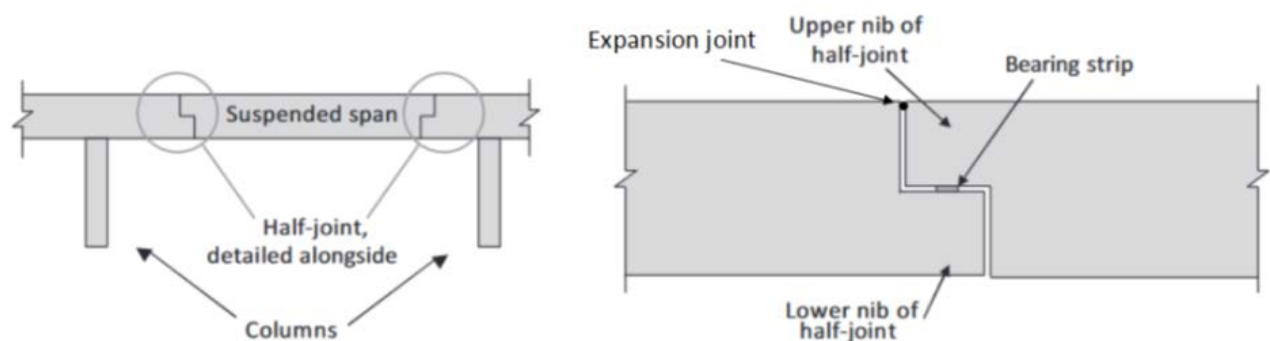


Figure 1: Half-joint principle for reinforced concrete bridges, edited [15]

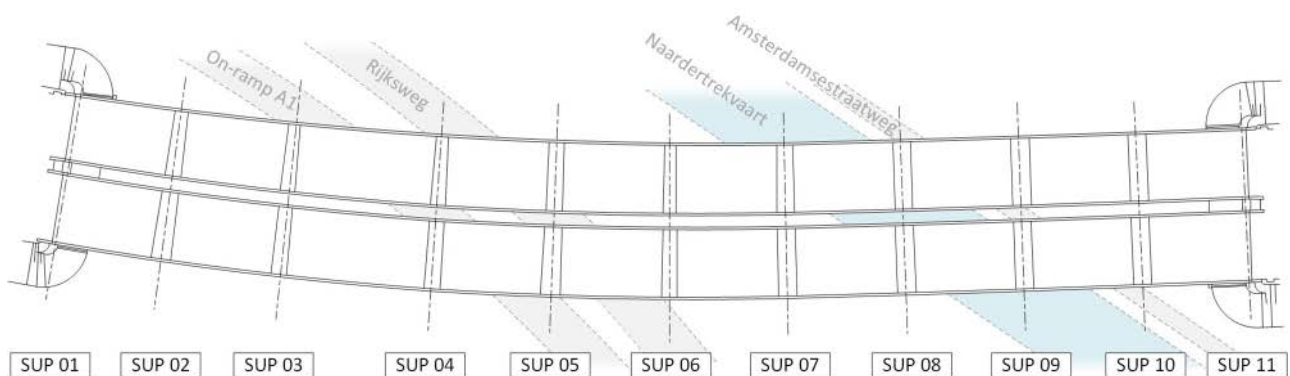


Figure 2: Top view schematic of the Naardertrekvaart bridge

Before 1970, engineers did not have code provisions to rely on regarding designing of half-joints. Back then, the reinforcement of the half-joints was generally detailed similarly to corbels, despite the load transfer mechanism being significantly different. Later research showed the importance of the implementation of hanger reinforcement or diagonal reinforcement bars near the half-joint [4–8]. The improper reinforcement detailing, can lead to lower bearing capacity of the half-joints than they were initially designed for. In addition, owing to the geometry of the design, a diagonal crack in the re-entrant corner of the half-joint is always expected. In combination with water seepage into the joint, the diagonal crack results in a higher susceptibility risk of corrosion of the reinforcement across the re-entrant corner. The parts of the half-joint that are most prone to degradation, the re-entrant corners, are often buried deep inside the joint, making inspection and maintenance very difficult. All these problems lead to higher risk of failure for half-joint bridges across the world [9,10], occasionally resulting in collapse [11,12].

This research aims to gain more insight on how to use the measurements from a conventional SHM system to assess the structural integrity of concrete half joints. This is done through a case study of a typical half-joint bridge.

2 The Monitored Structure

The Naardertrekvaart bridge was constructed in 1969, and is part of the A1 highway in the Netherlands. It consists of two separate bridges, a northern and a southern bridge. A schematic top view of the bridge can be found in Figure 2. Both

bridges contain 11 supports and 10 spans, of which 9 standard spans and 1 divergent span between support 3 and 4. Both bridges are slightly slanted [3]. Each span of the bridge is composed of 11 prefabricated, prestressed longitudinal girders, which are connected to the supports using half-joints. The supports are composed of a column and a platform, as can be seen in Figure 3.



Figure 3: Street view image of support 5 of the southern Naardertrekvaart bridge (Google Maps)

Multiple inspections during the lifetime of the bridge showed signs of degradation of the half-joints. Water damage below the joints indicated that water was able to seep into the joint, which increases the susceptibility of the reinforcement to corrosion. Additionally, electric potential measurements of the reinforcement bars close to the re-entrant corners indicated that some corrosion was taking place, but measurements were taken by selective sampling across the bridge and the results were inconclusive [13]. As a result, the exact condition of the half-joints of the bridge are yet unknown.

3 The Monitoring System

The uncertainty of the state of the half-joints led to the placement of an SHM system in 2022. This monitoring system takes measurements of the rotation and vertical displacement of the lower nib of the four half-joints at support 5 and 6, visible in Figure 2. Measurements are taken at multiple locations along the width of the bridge. The measurement sensors are intrinsically thermally compensated. It also takes temperature measurements to enable filtering out the thermal influences on the measurement data. Figure 4 shows the SHM setup at one measurement location. The inclinometers are mounted directly onto the concrete, while the displacement sensors are installed on a metal rod, mounted to the support column. The thermometers measure the temperature of the metal rod, and the temperature of the concrete on the sides of the bridge. The total setup of the SHM system can be found in Figure 5.

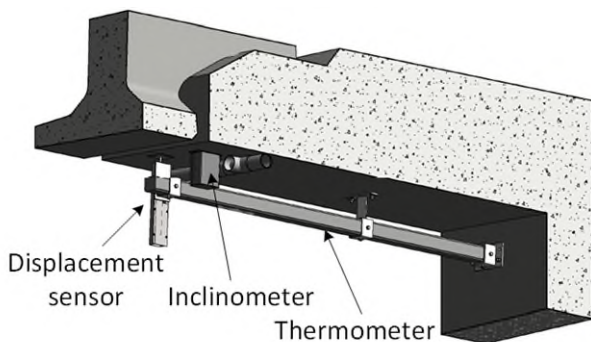


Figure 4: Sensor setup at a measurement location [16]

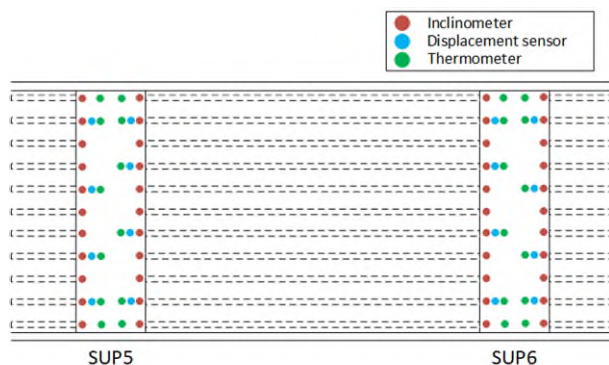


Figure 5: Locations of the sensors of the SHM system

The SHM system takes measurements at a frequency of 10Hz. By default, the average of every 30s of measurements is then uploaded to the cloud, resulting in a measurement storage frequency of 1/30 Hz. As a result of this storage system, most of the dynamic effect on the data are filtered out, and the dataset contains only the quasistatic behaviour of the bridge. In addition to this dataset, a 24 hour dataset with the original, high-frequency measurements is obtained to analyse the dynamic behaviour of the structure.

At the time of this research, an early warning system was continuously monitoring the measurement data for anomalies. This system, capturing mostly the static behaviour of the bridge, was unable to effectively identify occurrences of degradation.

4 The Measurement Data

For this research, two datasets were acquired using the SHM system described above. The first dataset contains two years of low-frequency measurements, while the second dataset contains 24 hours of high-frequency measurements. These datasets are described in the following sections.

4.1 Long-term Measurement Data

The long-term measurement dataset, with a measurement frequency of 1/30Hz, is first analysed to discover any traits that can be used for inference of the structural integrity of the half-joints. Inference of this structural integrity is performed in the subsequent section.

4.1.1 Data Analysis

The graph in Figure 6 shows the long-term rotation of the lower half-joint nibs. The measurement data exhibit a slight downward trend. The cause of this downward trend is likely related to the inaccuracy of the measurement system. In addition to the downward trend, the measurement data exhibit a noticeable annual fluctuation. Analysis of the correlation plot in Figure 7 reveals a clear positive correlation between the outside temperature and the observed rotation of the lower half-joint nibs.

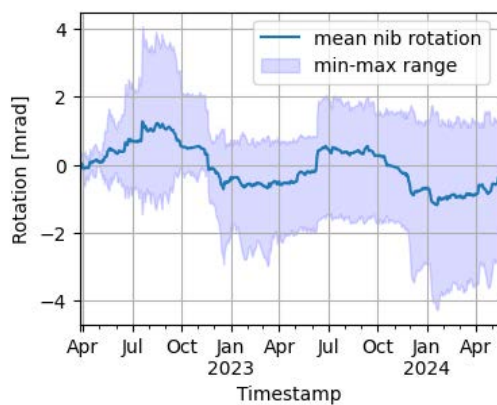


Figure 6: Overall rotational behaviour observed by the inclinometers

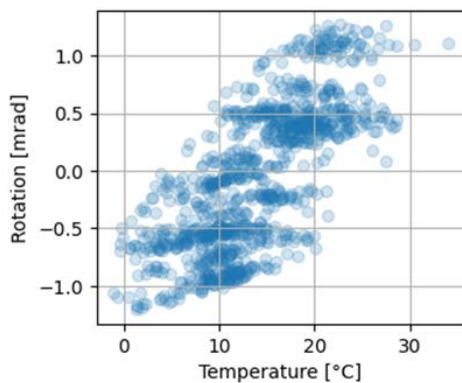


Figure 7: Correlation plot of the rotation and temperature data

This observation suggests that the lower nibs of the half-joints rotate upwards during periods of high temperatures, and rotate downwards during periods of low temperatures. The inference of the status of the half-joints from the dependence of the nib rotation on temperature is described in the following section.

4.1.2 Inference of Half-joint Status

To explain the fluctuating behaviour of the rotation of the lower half-joint, multiple phenomena were investigated. Only one of these phenomena seemed promising in doing so [3]. This phenomenon is characterised by the presence of a contact surface inside of the half-joint. In a conventionally designed half-joint bridge, elastomeric bearings are placed between the girders and the support platforms. These bearings are implemented to facilitate free horizontal movement between the two structural components and should therefore be the only point of contact between the spans and the supports. However, inspections of the physical structure have indicated that there is insufficient vertical space between the transversal end-beams and the lower half-joint nib. A schematic of the situation is shown in Figure 8. Direct contact between the elements can result in the buildup of a horizontal friction force between them when temperature changes cause thermal expansion or contraction. This friction force would result in a downward bending moment on the lower half-joint nib during times of low temperatures. The magnitude of the developed friction force is difficult to accurately estimate due to simultaneous dependence on vertical load on the joint, conditions of the contact surfaces and state of the reinforcement bars close to the re-entrant corner.

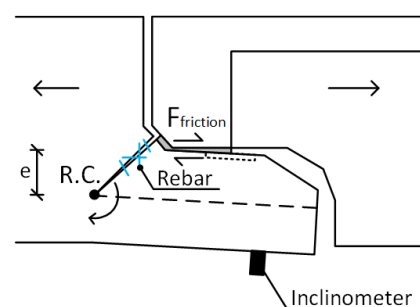


Figure 8: Schematic of nib rotation as a result of hindered thermal contraction of the structural elements

An estimation of the effect of this horizontal friction force on the rotation of the lower half-joint nib can be acquired by using a very simplified model of the half-joint system. The model simulates the connection between the lower half-joint nib and the platform as a linear elastic

rotational spring. Its stiffness is estimated based on a previously conducted FEM calculation by Ingenieursbureau Kok & Van den Heuvel [14]. It was assumed that the horizontal contact faces between the lower half-joint nib and the transversal beam do not slip. The predicted effect of friction force development on the rotation of the lower half-joint nibs in combination with the average rotation observed by the inclinometers can be found in Figure 9. Comparison of the observed and predicted effect shows that the prediction is an overestimation, but follows the same pattern. Although this is an indication that this phenomenon is taking place in the half-joints, the simplicity of the model of the half-joint makes it unfitting as an indicator of the structural integrity of the half-joints.

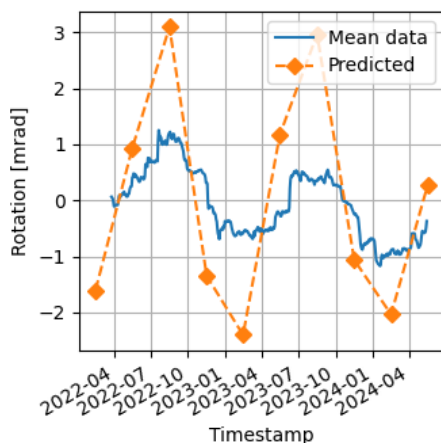


Figure 9: Predicted effect of hindered thermal contraction of the structural elements on rotation measurements, compared to the observed rotation

In contrary to analysis of the quasistatic behaviour of the bridge, analysis of dynamic behaviour could offer a better opportunity for inference of the structural integrity of the half-joints. Following from this, the next section will discuss the analysis of a high-frequency measurement dataset.

4.2 High-frequency Measurement Data

The previous section described the analysis of the long-term, low-frequency dataset acquired by the SHM system. This section covers the dataset containing 24 hours of high-frequency measurements. The measurement data is first analysed to discover any traits that can be used for

inference of the structural integrity of the half-joints. Inference of this structural integrity is performed in the subsequent section.

4.2.1 Data Analysis

The high-frequency measurement data of the Naardertrekvaart contains the dynamic behaviour of the bridge, which the long-term dataset filtered out. The dynamic behaviour can be characterised by its power spectral density (PSD), which reveals the dominant vibration frequencies. The average PSD of all inclinometers is displayed in Figure 10. A clear peak can be observed at a frequency of approximately 2.2Hz. Repetitive traffic loading at a constant frequency could cause a visible peak in the PSD. However, as the average frequency of passing traffic during rush hour does not exceed 1.4Hz, the peak is likely to be caused by vibrations of the bridge system in one of its natural frequencies.

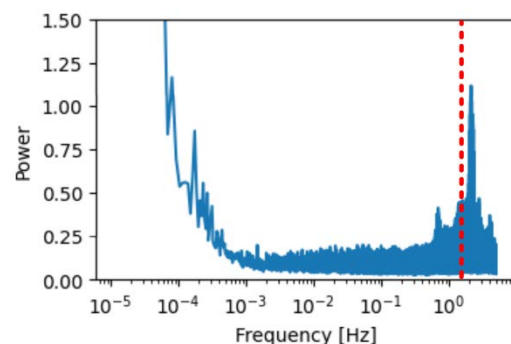


Figure 10: Average power spectral density of all inclinometers

The rotation observed by the inclinometers is a superposition of the following possible components, displayed in Figure 11.

1. Rotation of the support base on its foundation.
2. Bending of the support column.
3. Torsional rotation of the support platform.
4. Rotation of the lower half-joint nib relative to the support platform.

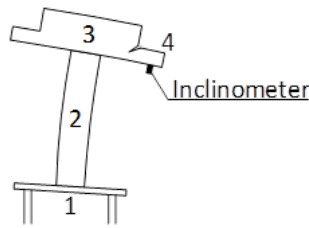


Figure 11: Schematic of the different components of the observed rotation

For the purpose of assessing the structural integrity of the half-joints, the only relevant component is component 4. By estimating and filtering out the effect of components 1 to 3, the effect of component 4 can be estimated. The combined effect of component 1 and 2 is estimated as the average rotation of all inclinometers connected to the corresponding support. The average rotation of opposing sensors in longitudinal direction gives an indication of the effect of component 3. However, this indication becomes inaccurate when the opposing measurement locations behave asymmetrically. Therefore, the effect of component 3 is estimated by fitting a least squared estimation of a linear line through the average rotation of opposing sensors, over the width of the bridge. An estimate for the effect of component 4 is attained by, for every datapoint, subtracting the estimated effect of components 1, 2 and 3 from the measurement data of the inclinometers.

4.2.2 Inference of Half-joint Status

As described before, the rotation of the lower half-joint nib relative to the support platform could be associated with the structural integrity of the half-joint. To acquire an actual indicator, the dynamic behaviour needs to be related to the load on the half-joint. A straightforward, but time-consuming approach would be to develop a sophisticated digital twin of the support, and run a non-linear analysis to find the response of the half-joint to traffic loading at multiple stages of degradation. Model results can then be compared to the observed response. This approach lies outside the scope of this research, which is the development of a universal monitoring-based assessment method for half-joint bridges. A more suitable approach is to devise a parameter that functions as an indicator for the structural integrity of the half-joints. For this

research, a stiffness parameter was chosen, which relates the estimated vertical load on the half-joint directly to the amplitude of the vibrations observed by the inclinometers.

The weight of the vehicles crossing the bridge is unknown. Therefore, an estimation must be made of the average load on the lower half-joint nib per hour of the day. To make this estimation, a simulation is run using Python. This simulation pushes realistic axle loads over an influence line, representing the portion of the load on a bridge span that is being transferred to one of the half-joints. Realistic traffic loads are sampled from the database of the Bridge Weigh-in-Motion (WIM) system on the Moerdijkbrug, which is part of the A16 highway in the Netherlands. The amount of sampled vehicles is based on average hourly traffic intensity measurements by Rijkswaterstaat. The hourly traffic intensity measurements are shown in Figure 12, split up into three different weight classes. The definition of the three weight classes can be found in Table 1.

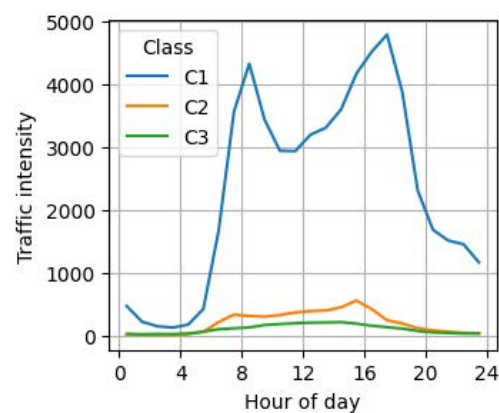


Figure 12: Average hourly traffic intensity on the Naardertrekvaart bridge

Table 1: Vehicle classes of the traffic intensity measurements

Vehicle class	Weight
C1	Lightweight
C2	Medium-weight
C3	Heavyweight

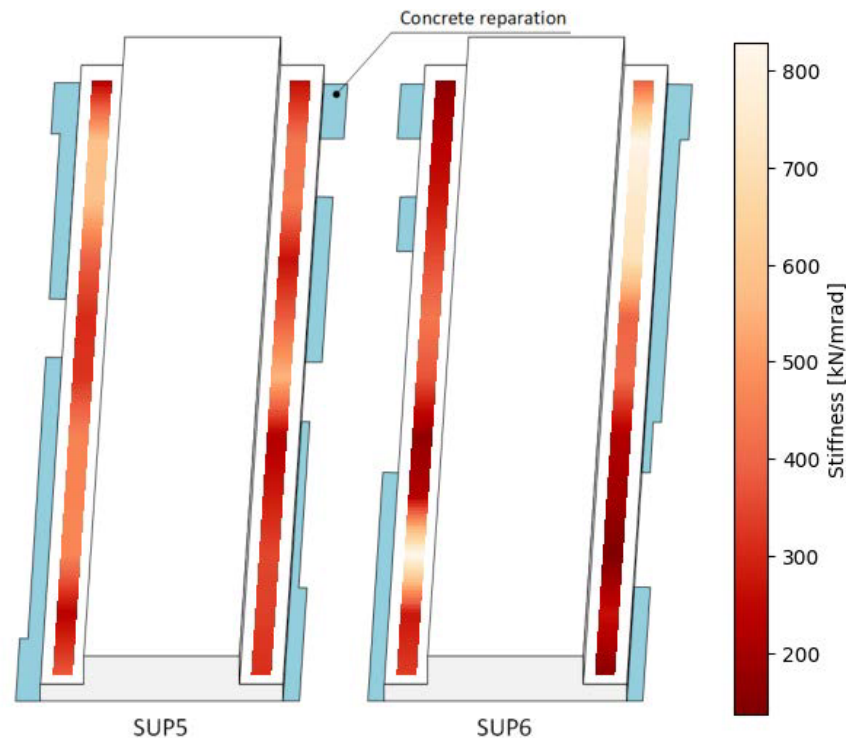


Figure 13: Values of the estimated stiffness values of the platform. The blue planes represent the location and degree of repairs that have been done to the concrete of the platforms.

Plotting the estimated hourly average vertical load on the half-joint against the hourly averaged amplitude of the vibrations observed by the inclinometers, generates a graph which characterises the stiffness of the connection between the lower half-joint nib to the support platform. The slope of a linear line through the origin of these graphs, fitted through the datapoints, represents the stiffness of the connection. The lower this stiffness, the higher the degree of degradation that has taken place. Figure 13 displays the results for the stiffness parameter at the different measurement locations, where estimations for the stiffness between the measurement locations have been obtained through linear spatial interpolation. The figure gives an indication of the structural integrity of the half-joints of support 5 and 6. To confirm the functionality of the devised stiffness parameter as an indicator of the structural integrity of the half-joint, its results must be verified with experimental data of the bridge.

5 Review of the Monitoring System

This research underpins the difficulty of using an SHM system to assess the structural integrity of half-joint bridges. This difficulty originates from the complex effect of damage on half-joint behaviour, along with the strong dependence of the behaviour of the bridge on temperature differences. The degradation of bridges like the Naardertrekvaart bridge, with a lower half-joint nib that is continuous over the width of the bridge, are exceptionally difficult to assess, as force redistribution should be accounted for.

SHM systems are, however, more useful in identifying changes in the structural state of half-joint bridges, when they monitor changes in oscillatory response. As a result of even the slightest damage to the bridge, oscillatory amplitudes and natural frequencies of the elements can change. This approach needs little understanding of the behaviour of the bridge and thereby mitigates the need for development of a digital twin.

The functionality of the stiffness parameter proposed in this research is yet to be verified. With further investigation, a universal parameter can be developed for the purpose of the assessment of half-joint status.

6 Conclusions

This research aimed to use the measurement data of the SHM system on the Naardertrekvaart bridge to assess the structural integrity of its half-joints. The SHM system was installed after concerns of the formation of a diagonal crack in the re-entrant corner of the lower part of the half-joint. Analysis of the long-term, low-frequency measurement data revealed a slight downward trend and a clear thermal dependence. Thermal dependence is expected to originate from hindered thermal contraction of the half-joints, due to insufficient vertical spacing between the horizontal faces of the half-joint. This phenomenon provided insufficient possibility for inference of the structural integrity of the half-joints. Analysis of 24 hours of high-frequency measurement data revealed more

promising opportunities. Estimated rotation of the lower half-joint nibs relative to the support platforms was obtained by estimating and filtering out the effects of other phenomena. This relative rotation was used to devise a stiffness parameter, which could prove useful in the assessment of the structural integrity of the half-joints. The functionality of this parameter has yet to be confirmed by physical experiments on the bridge.

The results of this research indicate that conventional SHM systems are ineffective in locating and quantifying the structural degradation of half-joints. Instead, a dynamic approach can be taken, which, combined with additional knowledge of the magnitude of traffic loads, can yield more useful results.

7 Acknowledgment

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