AMERICAN SOCIETY FOR
ENGINEERING EDUCATION

Paper ID #36014

Technical Survey and Literature Review on Bridge Joint Monitoring Practices

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Bridge Joint Monitoring Literature Survey and Practices in New England States

ABSTRACT

Expansion joints are essential components for maintaining the stability of numerous bridge types by accommodating and absorbing the movements of a bridge. Various factors cause bridge movement, including thermal expansion, weather variations, vehicle movement, and strain from different loads. To minimize damage and maintenance costs, joint monitoring is utilized to detect any changes or deterioration to the joint. Current methods of joint monitoring are man-power intensive, costly, and time-consuming; creating a demand for new processes that can alert the engineer before the damage becomes extensive. Recently, joint monitoring efforts have been implemented around the world. In Europe and Asia, many studies of temperature and thermal effects have been conducted on highways, suspension bridges, and cable-stayed bridges. However, there are not many joint monitoring applications in the United States. This paper focuses on the needs of the bridges in the Northeastern United States, by presenting the current joint monitoring practices adopted by the six Department of Transportation in New England as a technical survey. This survey on bridge joint monitoring provided details about the impacts on the expansion joint caused by certain factors such as structural movement at the joint, traffic loading, joint design, and the materials used. By understanding the effects of the surrounding elements on the bridge joint, a better process for long-term monitoring of expansion joints can be developed, which is beneficial for the safety and stability of the bridge.

INTRODUCTION

In transportation infrastructure, bridges play an important role in providing access between land regions, major cities, and bodies of water. Bridges also function as networks, providing people access to work opportunities, goods and services, and different recreational activities. It is essential that bridges are operating properly, as they are a fundamental component of society. Because of its numerous uses, bridges are constantly exposed to dead and live loads, as well as various environmental factors. Different loads caused by vehicle or pedestrian traffic, and environmental factors such as heat and precipitation can cause movement of the bridge. Although bridges are designed to accommodate for some movement, excess movement can lead to deterioration of the structure, and in some extreme cases the collapse of the bridge. Bridge behavior ranges, but it is common for bridges to expand because of heat exposure. When a bridge becomes heated, the road expands, but when the bridge cools, the road will retract. These variations in the bridge may seem insignificant, however, constant temperature fluctuations can alter bridge length. As a result, the bridge may become warped or damaged.

Bridges are designed with expansion joints to safely absorb these movements. It is standard practice to specify a sealed joint to block debris and water from passing through the joint, which can result in damage to the joint and the bridge [1]. A silicone foam sealant was developed for small-movement bridge expansion joints and has proven to be resistant to traffic and weather in the bridge expansion joints across the Northeast [2]. However, the foam can still collect debris due to some cracking and splitting when the sealant loses its bonding. This poured sealant can be a good temporary solution to protect the joint, however in the long term, this method requires a lot of maintenance and the joint can still become damaged.

Without proper maintenance of the bridge or its joints, it can fail the structure and compromise the safety of the public. A study by the Technical Studies Department of French Highways (SETRA) estimated that the cost of maintaining expansion joints is between 7% and 8% of the total maintenance cost of bridges [3]. As key elements in the transportation system, it is beneficial to use an inspection process that can monitor any deficits before the damage becomes extensive. Using bridge monitoring systems can help detect any negative changes early, but also useful in validating design assumptions and parameters, as well as providing real-time information for safety assessments [4]. Expansion joint monitoring is one method that can be used to monitor any defects or changes to the expansion joint. This system has been used on different types of bridges and integrated with other technologies to create a more accurate and time-efficient approach to monitor any changes. Europe and Asia have recently used and developed joint monitoring systems.

In this paper, recent joint monitoring practices have been summarized via literature review and survey of New England DOTs. The first part provides joint monitoring efforts in Europe, Asia, and North America, including countries such as Portugal, China, and the United States. The joint monitoring methods can be categorized in terms of theoretical methods, sensor systems, and the correlation between temperature and displacement. In addition, the current joint monitoring practices are provided based on the email survey to six Departments of Transportation in New England. The detailed survey questionnaire, results, and discussion are discussed. Utilizing previous and current joint monitoring practices can allow for a better understanding of what factors affect bridge joints, which can aid in developing a more efficient long-term monitoring system of expansion joints.

INTERNATIONAL JOINT MONITORING PRACTICES IN RECENT YEARS

Theoretical Methods

There have been many reports of successful performances of joint health monitoring systems on bridges. Recent approaches tend to involve statistical analysis of data and analyzing correlation patterns between temperature and displacement measurements. In addition to statistical analysis, various models and theoretical studies have been implemented in addition to an SHM system to ensure the accuracy of the system.

For example, the Ting Kau Bridge in Hong Kong, China used a normal correlation pattern between effective temperature and thermal movement to predict the expansion joint displacements under the design maximum and minimum temperatures. This is then compared with the design allowable values, which is beneficial because an accurate estimate of the cumulative displacements provides a solid foundation for calculating a reasonable interval for expansion joint inspection or replacement [4]. This approach created a regression model using previous measurement data of expansion joint displacements to establish a normal correlation pattern, which can be used to detect any anomalies. Analysis from the Ting Kau bridge application showed that the effective temperature on a deck cross-section should be estimated by using only the temperatures in structural components [4]. This research is beneficial in providing a process for verifying design and assessing the conditions of bridge expansion joints, using conditions and measurements collected from the expansion joints and the bridge temperature.

Another example of a theoretical approach used in joint monitoring would be the I-35W St. Anthony Falls Bridge in Minneapolis, Minnesota. To monitor the expansions for rapidly growing anomalies, the monitoring technique employs two independent anomaly-detection routines: quickly developing and slowly developing anomaly-detection [5]. The quickly developing anomaly-detection routine used Bayesian Regression to integrate the uncertainties in the time-dependent deflection predictions, while the slowly developing anomaly-detection routine used the rates of the recorded time-dependent behavior about the Arrhenius-adjusted age to track degradation. Although both anomaly-detection methods were successful in identifying anomalies to a certain extent, there are still several limitations that should be considered when extending this procedure to other systems or structures. But these issues are adjustable from structure to structure, so this methodology can be applied to any type of measured data that is heavily influenced by temperature and time-dependent variables.

In addition to data analysis methods, the Zhangjiang Bay Bridge in South China used a finite element (FE) model to compare the measured data values and checked for any additional abnormalities [6]. The FE model was created based on the assumption that when subjected to equivalent loads, an accurately constructed model should behave and move in the same way at the structure it represents. The predicted displacement values from this model were compared to the observed values from the actual bridge. This model is beneficial in providing accurate data to be compared with the measured data and has the ability to account for any missing data with simple adjustments to the model. Because this method is efficient in analyzing the relative errors between measured and calculated displacements, it may be able to construct a more complex model in addition to an SHM system that can offer greater accuracy estimates of the missing bridge conditions.

Finally on the suspension bridge over the Yangtze River in Jiangsu, China, a theoretical study was conducted on the thermal performance analysis to determine the structural longitudinal and vertical displacements, and the induced internal forces [7]. To calculate longitudinal displacements, the stresses at each deck section were averaged. Because the displacement derived from the temperature-induced strain and the displacement calculated from the DIS sensors were similar, this calculation is effective. The calculations for vertical deflections were done using temperature-induced strain and the stresses recorded on the deck. The collected data was used to compute the structural curvatures, and the results indicate an acceptable bias. These computations are beneficial for SHM systems as they are another way to verify the data obtained from the sensors on the bridge in use.

Joint monitoring systems vary from application to application as seen in the previous examples, but they prove to be beneficial in validating measurement data collected from the studies, as well as providing real-time information on the conditions of the bridge.

Sensor Systems Used on Current SHM Methods

A joint monitoring system can have many sensors that are installed at different locations on the bridge to monitor data. Below is a summary of the sensors installed on each bridge investigated in Portugal, China, and the United States. The number of sensors varies from bridge to bridge, depending on the scope of work.

For the Ting Kau Bridge, more than 230 sensors were installed [4]. This system included anemometers, accelerometers, displacement transducers, temperature sensors, strain gauges, weigh-in-motion sensors, and global positioning systems (GPS). The displacement transducers were installed to measure the displacement of the expansion joint at each end of the bridge. In addition, 83 temperature sensors were installed at different locations to measure the temperature of the steel girder and tower legs, interior temperature of the concrete deck and asphalt pavement, as well as the atmospheric temperature.

For the I-35 W St. Anthony Falls Bridge, the monitoring system included thorough instrumentation including vibrating wire strain gauges, resistive strain gauges, fiber-optic strain gauges, thermistors, accelerometers, linear potentiometers, and corrosion sensors [8]. However, only the 12 potentiometers, which measured the longitudinal movement at the expansion joint, and the 42 thermistors were relevant for the development of the anomaly-detection routines [5].

For the Zhangjiang Bay Bridge, the SHM system uses many various sensors to monitor the daily temperature effects on the cable-stayed bridge [6]. The sensors included GPS rovers, strain gauges, thermometers, and electromagnetic (EM) sensors. The GPS rovers were used to measure the displacement at the top of the towers, as well as at the center of the main girder.

For the suspension bridge over the Yangtze River, the SHM system included roughly 165 sensors including fiber Bragg grating sensors (FBGs), uniaxial accelerometers, GPS Model GX1230 receivers, displacement sensors, and triaxial ultrasonic anemometers [7]. The FBGs were installed to measure the strain and temperature across the main span of the bridge, while the displacement sensors were installed on the 2 expansion joints to monitor the longitudinal deflection of the girder.

For the cable-stayed bridge in Ningbo China, the SHM system contains 350 sensors, including temperature sensors and displacement transducers [9]. Of the many sensors, 4 displacement transducers were installed on the two expansion joints to measure longitudinal displacement, and 57 temperature sensors were installed to measure air and concrete temperatures across the bridge.

SHM systems consists of a variety of sensors, however, as seen in the previous bridges, it is common for bridge joint monitoring systems to use displacement and temperature sensors. Although these five bridges were fully instrumented, the practice was still extensive and time-consuming for joint monitoring. Many bridges in the world are not equipped with any sensors to monitor the expansion joint and its surrounding environment. This can be because sensor system supplies are limited and costly. Therefore it is important to develop cost-effective sensors for joint monitoring to ensure that all bridges are safe for operation.

Temperature and Joint Displacement Correlation

Based on the data collected by numerous sensor systems and provided by many joint monitoring systems, there is a correlation between temperature and displacement of the expansion joint. This movement is common with temperature variations, as different materials expand and contract depending on the temperature in their environment. When structural thermal expansion is constrained, internal forces can occur which can cause tension and compression that can ruin or damage the framework of the bridge [6].

For example, from the SHM system of the Ting Kau Bridge, the study reported that the movements of the expansion joints and the measured effective temperatures are highly correlated [4]. The displacement measurements and temperature data were plotted for comparison, and the curves were very similar to each other. As a result of the good correlation, it was determined that temperature fluctuation accounts for the majority of the expansion joint movement.

Data collected from the SHM system on the Zhangjiang Bay Bridge also show temperature patterns affecting bridge behavior [6]. Displacement measurements show that in the early mornings, the longitudinal displacement of the girder is restored to nearly zero, when the ambient temperature is at its lowest. However, in the early afternoon, the west tower and girder reached their greatest maximum displacement when the ambient temperature was at its highest. The sun rising and setting in the east and west causes these components to experience greater temperatures at different times of the day, which accounts for the early and late afternoon displacements of the east and west towers.

Finally, the results from the analysis on the long-span suspension bridge over the Yangtze River showed that temperature variations are also a major cause of deformity of the bridge [7]. Based on the displacement sensors that are located on both sides of the main girder, the longitudinal expansion has the same trend as the temperature. The correlated displacement measurements from the obtained strain data also suggest that temperature is a major factor in expansion joint movement.

Although these SHM models have demonstrated that there is a correlation between temperature and displacement of the expansion joints, the Ting Kau Bridge, the Zhangjiang Bay Bridge, and the suspension bridge over the Yangtze River are all located in China. There are fewer studies of bridges in the United States. This is crucial to why there needs to be additional monitoring performed in the United States. Across the United States, the weather varies significantly from coast to coast, but temperature also fluctuates in a single region from season to season. These constant changes in weather and temperature can cause damage to the bridge components, which iterates the importance and necessity of bridge joint monitoring.

CURRENT BRIDGE JOINT MONITORING PRACTICES OF NEW ENGLAND

Since temperature variation is a major cause of joint movement, and because New England's climate varies from season to season, it is important to monitor the structural changes in the bridge and its joints in this region. In this environment, a bridge's lifespan can be reduced due to high levels of thermal expansion, and the expansion joints may be weakened because of the various damaging factors during the long winter season. A survey was prepared to investigate the expansion joint monitoring methods of six Departments of Transportation (DOTs), including Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont. This survey will be useful in determining the future needs of joint monitoring systems and practices.

Survey Questionnaire

The survey questionnaire consists of the following questions in Table 1.

Table 1. Joint Monitoring Practice Survey Questionnaire
How often do you conduct bridge inspections? a. Biannual (twice a year) b. Annual (once a year) c. Biennial (every two years) d. Other
Does your team currently engage in long-term monitoring of expansion joints? To what level? a. Yes - we have an internal system to monitor during our inspections b. Yes - we have a designated research group or point people working on field applications c. No - we do not currently engage in long-term bridge monitoring because we do not see value in it d. No - we do not currently engage in long-term monitoring because we do not have the funds/resources to do it e. No - but we are interested in engaging
What benefits do your team see to long-term monitoring of expansion joints?
What does your team see as potential limitations to long-term monitoring of bridge expansion joints?

Survey Results

The survey focuses on the joint monitoring practices in each of the six DOTs. From the first question of 'How often do you conduct bridge inspections', the most frequent response was biennial inspections which were answered by 5 DOTs, followed by 1 annual inspection. This result is also represented in Figure 1.

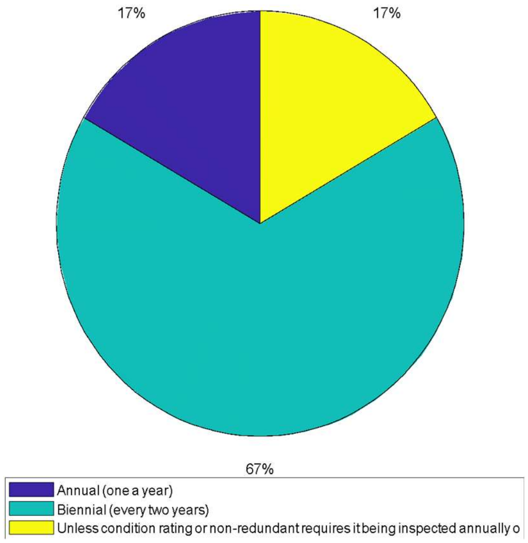

Figure 1. Frequency of Bridge Inspections

In addition to inspections, the engagement level in long-term monitoring of the expansion joints was also reported. The survey showed that a majority of the DOTs were not engaged in joint monitoring. As shown in Figure 2, 4 out of the 6 DOTs reported lacking funding while 1 reported not seeing the value in joint monitoring yet. Therefore, only 1 out of the 6 DOTs is actively monitoring the joints during their inspections.

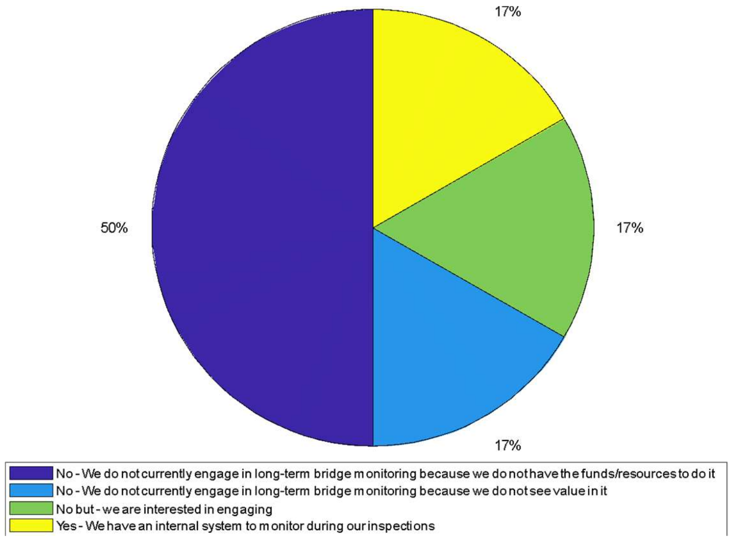

Figure 2. Engagement Level in a Long-Term Monitoring of Expansion Joints

In addition, benefits and potential limitations of long-term monitoring were requested from the experts of each DOT to further understand the reasoning behind the level of engagement. The benefits include: (i) Further understanding of the impacts of heavy trucks on joints and bridges for the development of better bridge maintenance plans, (ii) The effectiveness and durability of joint designs and joint materials, (iii) The temperature range and product conditions. The limitations included: (i) Funding, (ii) Resources, and (iii) Moving to greater use of asphalt plug joints which are replaced on a routine cycle or when the conditions warrant. This insight is important, as it shows that there is potential for the development of more joint monitoring practices for the benefits listed once the limitations are resolved.

CONCLUSION

Expansion joint monitoring systems have proved to be very helpful in detecting any negative changes to the bridge early on. Some extensive bridge monitoring performed in Europe and Asia has shown that there is a correlation between temperature and displacement of the expansion joints. Although there have been some practices in the United States of expansion joint monitoring, further investigations were conducted to understand the demands for joint monitoring systems and practices in the future. A survey was conducted of the six New England Departments of Transportation (DOTs) to obtain information regarding current bridges and expansion joint monitoring practices within this region. Responses received showed that there are many benefits to joint monitoring, including the development of better bridge maintenance plans, better understanding of the effectiveness and durability of joint designs and joint materials, as well as the temperature range and the status of product conditions. However, because of funding and resource limitations, a majority of the six DOTs were unable to engage in long-term monitoring. This survey provided key insight for the research team that there is a need for a joint monitoring system that is convenient and cost-effective. The information from this survey is also extremely helpful for the research team in their goal of developing a real-time wireless sensor system capable of continuously monitoring the displacement of bridge expansion joints. This research has added meaning to New England bridges as the region's weather changes drastically from season to season and structural components can expand and retract due to temperature fluctuations giving rise to various amounts of joint movements.

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