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Implementation of Structural Monitoring: Advantages and Limitations

I. Harik[1], and A. Peiris[1]

[1]University of Kentucky, Lexington, Kentucky, USA

ABSTRACT: Structural Health Monitoring of a number of bridges in Kentucky has proven to be an economical and effective method for extending the life of bridges and for providing the tools for immediate response and decision making. Three bridges are highlighted. The first bridge is on I-65 in Louisville where instrumentation, that continuously monitors the bridge, permitted the design of an economical retrofit. The second bridge is on I-64 over US60 where instrumentation continuously monitors the bridge for possible impact on the girders resulting from over height limit trucks. The third bridge is on US41 North over the Ohio River where instrumentation has been placed on the bridge piers to monitor for barge/flotilla impact. For the I-64 and US41 bridges, and in the case of an incident, selected personnel are notified via text messages on their cell phones along with e-mail messages. The messages identify the type of incident and its severity, and list the web site where the incident can be viewed along with data from the instrumentation on the bridge. Decisions can be made in minutes in regard to the course of action.

1 INTRODUCTION

Structural Health Monitoring (SHM), according to Farrar and Worden (2006), refer to the process of implementing a damage identification strategy for engineering infrastructure. The monitoring enables engineers to identify damages to bridge structures which could be material and/or geometrical. SHM of bridges has become extremely popular throughout the past decade. Recent technological advances facilitate the usage of more complex and accurate systems for evaluating the performance of both existing and new bridges. Ko and Ni (2005) identified some of the applications of SHM around the world for large bridges and summarized the technological developments in the field of bridge monitoring.

Typically, and depending on the desired final outcome, monitoring of bridges fall into three main categories: (i) Short-term monitoring, (ii) Long-term monitoring, and (iii) Extreme event monitoring. Short-term monitoring is carried out usually on bridges with suspected damage or deterioration in order to evaluate the degree of damage and possibly identify a practical retrofit measure. The same monitoring can be performed following repairs to evaluate the effectiveness of the repair technique. Long-term monitoring is carried out to identify behavior, loading patterns and deterioration rates, obtain data for possible future repairs and maintenance, evaluate operational safety, research and improve bridge designs, and identify possible damages following extreme events such as earthquakes. Extreme event monitoring may or may not gather information at regular time intervals as the other two categories. This type of monitoring is specially designed to identify events such as collisions or blasts at critical locations, and severe movements arising from phenomena such as earthquakes or hurricanes. The information is transmitted in real-time to inform engineers of possible damage to the structure in order to make swift decisions on potential bridge closures or postings and avoid catastrophic failures.

This paper presents the SHM of three bridges in Kentucky. The bridge on I-65 in Louisville utilized short-term monitoring where instrumentation, that continuously monitor the bridge, permitted the design of an economical retrofit. A combination of long term and extreme event monitoring is in place at the bridge on I-64 over US60 and US41 North over the Ohio River, where instrumentation continuously monitors the bridge for possible impact.

2 BRIDGE ON I-65 IN LOUISVILLE

2.1 *SHM Objective*

Estimate the degree of crack movement to identify the best retrofit measure. Following the retrofit, SHM is used to evaluate the effectiveness of the method.

2.2 *Project Description*

Interstate-65 (I-65) travels in a north-south direction through the city of Louisville. Several spans on I-65 between Jacob and Gray Streets were observed to have cracking in some of the precast prestressed concrete girders in the elevated spans of the expressway. The damaged section of I-65 is a parallel-bridge; each bridge carries three lanes of traffic in either northbound or southbound direction. A schematic of the damaged expressway is shown in Figure 1.

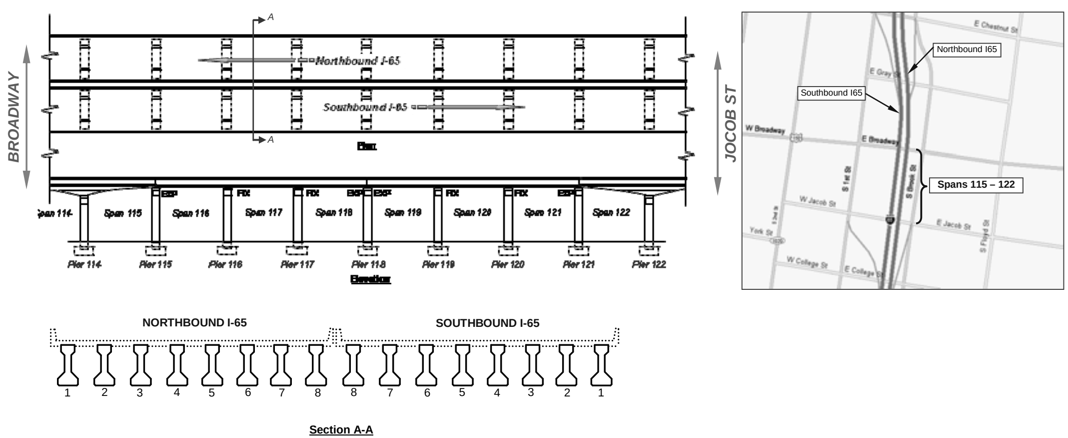


Figure 1. Schematic of prestressed concrete spans (106-113) between Jacob and Gray Streets.

The continuous precast prestressed concrete girder spans support a reinforced concrete bridge deck of varying thickness ranging from 200mm to 270 mm. The precast prestressed concrete girder spans were observed to have cracking to varying degrees at several locations. The cracking was particularly prevalent near or at fixed end locations where translational movement in the bridge direction is restricted. To investigate the liveliness of the cracks, two girders (Girders designated as Beam 6 and Beam 7) in Span 117 at Pier 117 were instrumented with linear variable displacement transducers (LVDTs) in the horizontal and vertical directions to measure the respective movements. The instrumentation was installed on February 16, 2004, and the maximum daily movement and temperature measured until June 27, 2005. The recoded data was used to design a simple retrofit to repair, strengthen and restore the capacity of the damaged prestressed concrete girders using carbon fiber reinforced polymer (CFRP) sheets, and once the repair was complete the LVDTs were attached again to evaluate the effectiveness of the retrofit as depicted in Figure 2(b). The monitoring confirmed that the volatile horizontal movement was stabilized due to the retrofit (Figure 3), while in the vertical direction the retrofit had stopped the vertical movement from increasing further.

(a) before retrofit (b) after retrofit

Figure 2. Instrumentation on Beam 6 and Beam 7 before and after strengthening with CFRP.

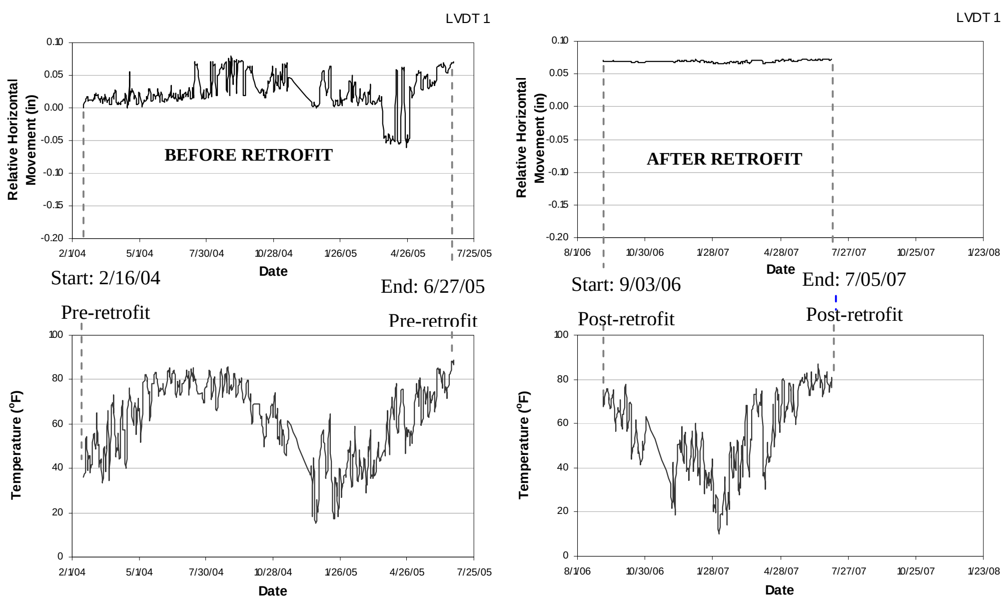


Figure 3. Relative horizontal movement measured at Beam 6 in Span 117.

2.3 *SHM Advantages and Limitations*

The SHM showed that the cracks, though active, were not growing and were within acceptable limits. This allowed for the simple strengthening using CFRP laminates versus the more expensive alternatives of extending the pier cap support or construction of new piers. No limitations of SHM were identified in this project.

3 BRIDGE ON I-64 OVER US60

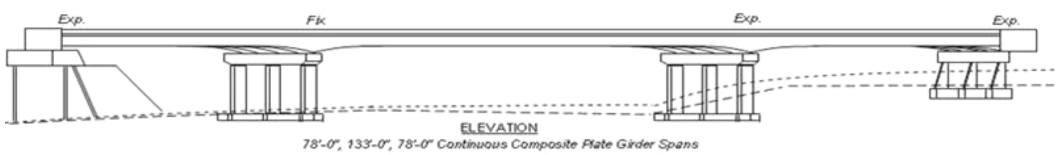
3.1 SHM Objective

Provide immediate knowledge of truck impact to selected state and other transportation officials, and identify over height limit trucks.

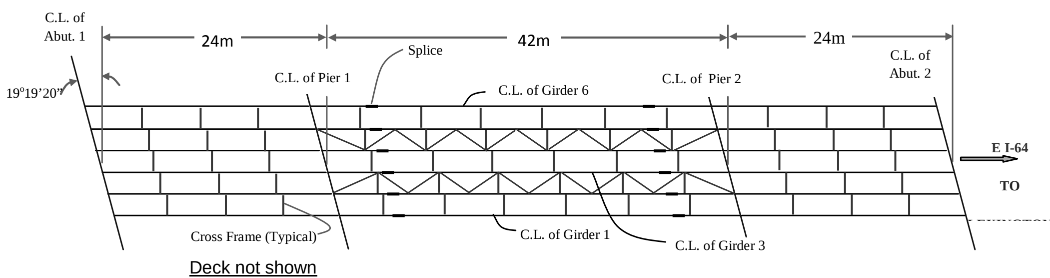
3.2 *Project Description*

The I-64 Bridges over US60 are located in Franklin County, KY. The parallel bridges, Eastbound and Westbound, are of composite steel-concrete type, with an overall length of 90 m. As depicted in Figure 4, the bridges have three spans of lengths 24 m, 42 m, and 24 m, respectively.The 190 mm thick concrete deck of the bridge is supported by six continuous plate girders of varying-and-constant depth type. The underside of an exterior girder [Girder 1 in Figure 4(b)], which has the least height-to-ground distance, of the eastbound bridge has shown signs of impact. It is suspected that the impact is caused by certain truck types traversing on the eastbound route of US60 beneath the bridge. Remote sensing technology, that can monitor the behavior and response of the I-64 Bridges over US60 from potential impact, was set up at various locations on the bridge. The data is to be transmitted to a computer at the University of Kentucky to be analyzed, compared, and viewed, in elapsed or real time.

Although potential impact of trucks is only anticipated to occur to the exterior girder in the eastbound bridge due to approaching traffic, remote sensing technology was implemented to both westbound and eastbound bridges that are parallel to each other. Due to the similar nature of both bridges in terms of dimensions and expected loading, the effects from the potential impact on the eastbound bridge (i.e., the subject) can therefore be compared to the westbound bridge (i.e., the base). Figure 5 shows the different devices that are being employed in this project: strain gauges, temperature gauges, infrared sensors, ultrasonic height detectors, accelerometer, and video cameras.



(a) Elevation view



(b) Top view of the eastbound I-64 Bridge over US60

Figure 4. Schematics of I-64 Bridge over US60.

Eleven locations are implemented with strain and temperature gauges (indicated as SG-#). Five strain gauges are in the westbound I-64 bridge, and the remaining ones are in the eastbound bridge. The strain effects due to potential impacts are studied through SG-9 to SG-11. SG-10 – SG-11 are in the middle span of the eastbound I-64 bridge. The two infrared sensors are denoted as IR-1 and IR-2 in Figure 5. The infrared sensors serve as a detector of trucks, which travel in the eastbound US60, that would result in an impact to Girder 1 in the eastbound I-64 Bridge. When the infrared mechanism is interrupted, presumably due to a truck, the sensor will simultaneously trigger its adjacent ultrasonic height detector and video camera to measure the truck height and to capture images of the truck, respectively. In this project, a single accelerometer is also employed, oriented along the centerline of the bridge. The accelerometer is coupled with SG-11 to form Impact Detector (ID), as shown in Figure 5. The unit is continuously operational in order to take measurements of acceleration and vibration, whether Girder 1 in the eastbound I-64 bridge is impacted or not.

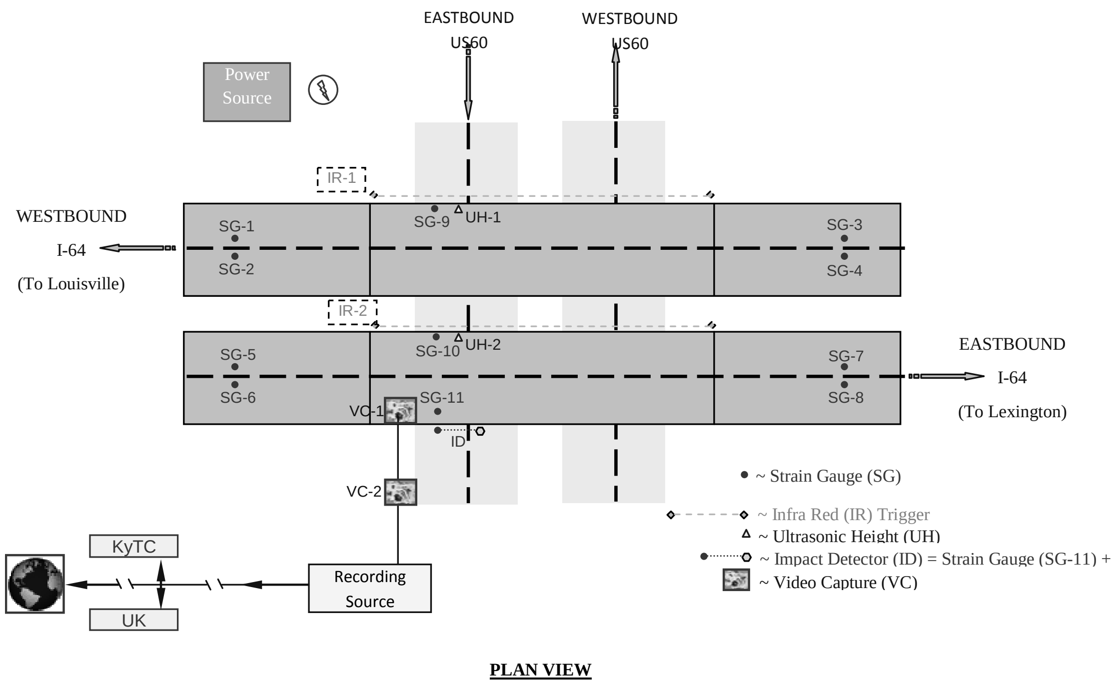


Figure 5. Gauge layout of I-64 Bridge over US60.

The two video cameras (VC) – VC-1 and VC-2 – employed in this project are designed such that they serve as a surveillant device that is able to transmit '*live*' feeds from the bridge site; some delay is expected due to relay of live images from the site to the remote station situated in the Kentucky Transportation Center, at the University of Kentucky. IR-1and UH-1 as a group forms Detector 1 while Detector 2 is comprised of IR-2, UH-2, VC-1 and VC-2.

3.3 SHM Advantages and Limitations

Before the implementation of SHM on the I-64 over US60 bridge, truck impacts went undetected unless informed by the public or recognised by a transportation official. The present setup provides a safer alternative where damge can be quickly identified and repaird. The cost of the equipment as well as the constant maintenance has been one of the disadvantages of the project.

4 BRIDGE ON US41 NORTH OVER OHIO RIVER

4.1 SHM Objective

Provide immediate knowledge of barge impact to selected state and other transportation officials. Update website with required information to take immediate urgent action when necessary.

4.2 *Project Description*

In Kentucky, there are approximately 1,800 km of navigable waterways. The Ohio River constitutes close to 70 percent of the waterways. To transport and receive goods, barges are the primary means of transportation in these waterways. With the amount of waterways traffic, accidents caused by barge impacts at times are inevitable. While barges travel in a slower speed (< 3.09 meter per second), the size of barges that travel collectively can be enormous [31 m in width by 183 m or 366 m in length] making maneuvering often time challenging.

The US41 Northbound (US41N) bridge over the Ohio river in Henderson County, Kentucky, is a cantilever through-truss bridge. The total length of the bridge including approach spans is 1950 m. The length of the four-span main bridge is 699 m. The plan and elevation of the main bridge are shown in Figure 6. The bridge is a through-truss type with suspended spans, fixed spans, anchor arms and cantilever arms. The US41N bridge was equipped with sensing technology to monitor the piers from afar (i.e., monitoring station will be housed in the Kentucky Transportation Center approximately 320 km from the bridge site) for impact from a barge or barge flotilla. The impact monitoring is achieved under two phases where certain objectives were achieved under each phase.

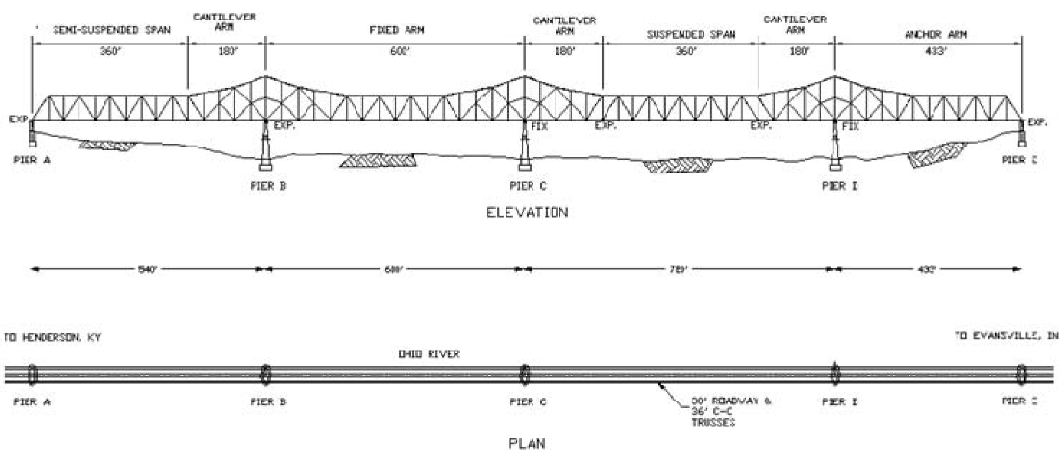


Figure 6. Plan and elevation of US41N over Ohio river.

4.3 Phase 1 – Objective 1: Damage Identification

The basic instrumentaion used in this project for detecting and measuring impacts is the accelerometer. Accelerometers were mounted on the top of Piers B, C, and D. In addition, linear variable displacement transducers (LVDTs) were also mounted at the expansion bearings on top of Pier B. Various acceleration and displacement limits or thresholds were set to identify ‘severe’ and/or ‘critical’ impacts. A ‘severe’ impact is defined as the limit or threshold of impact that would cause ‘possible’ damage to the piers in question. A ‘critical’ impact is defined as the limit or threshold of impact that would not only cause damage to the pier, but the type of impact that would also require the closure of the bridge for further inspection. A plot of typical maximum hourly vertical acceleration data collected at Pier D is shown in Figure 7.

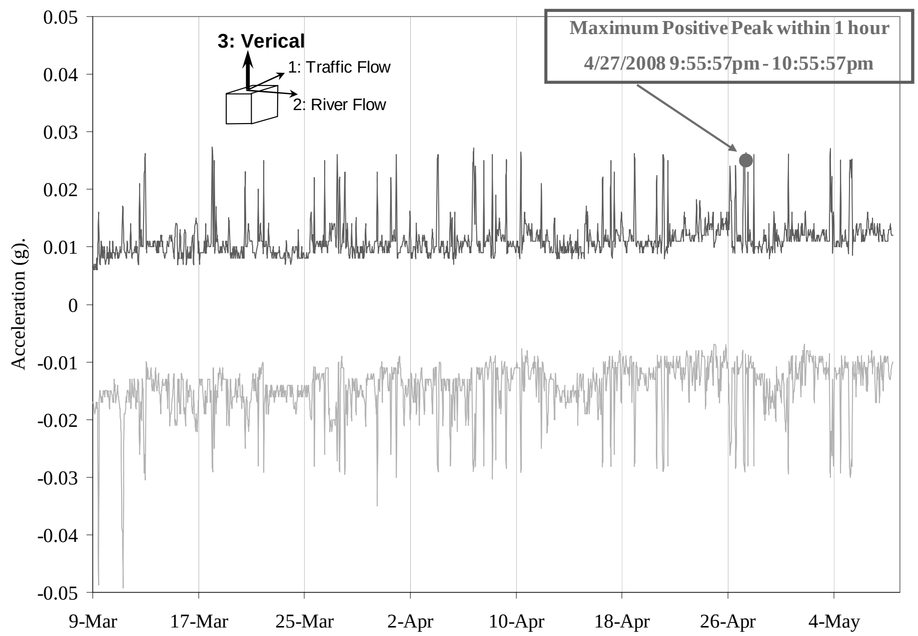


Figure 7. Maximum hourly vertical acceleration data at Pier D.

4.4 Phase 1 – Objective 2: Damage Notification

Once ‘severe’ and ‘critical’ impacts have been identified, the system automatically proceeds to notify related personnel members in the Transportation Operation Center in the Kentucky Transportation Cabinet, the US Coast Guard and other selected personnel. Three types of notification are established for the monitoring system: (1) text message – immediately after a ‘severe’ or ‘critical’ impact, the instrumentation will send text messages to specific cell phones, including information such as impacted pier, date and time, type of impact (‘severe’ or ‘critical’), (2) similar to text message, an email message will be sent to addresses containing information related to the type of impact, and (3) web site - Notified personnel should be able to visit a web site to view in real time the two expansion supports at top of Pier B, the eastern faces of Piers B, C and D, and the surrounding areas of Piers B, C and D. Video and/or photographic records is to be stored for at least 10 minutes prior to the event and 10 minutes following the event.

4.5 Phase 1 – Objective 3: Vessel Identification

The bridge is equipped with video equipments to make and record visual evident of vessels, barges, or flotilla, impacting the pier during any ambient condition (day, night, rain, fog, etc.).

4.4 Phase 1 – Objective 4: Data Collection

Typical data to be collected includes acceleration, displacement, and visual (video and still) records. A plot of the time history for the accelerations and displacements immediately prior to (~ 2 to 5 seconds) and following the impact (~15 to 30 seconds) as well as maximum hourly acceleration and displacement data should be accessible through the web site. The time histories should be stored and catalogued.

4.5 Phase 2: Bridge Closure for Critical Impacts

If 'critical' impacts have been detected, the bridge will be closed automatically by a system set up in the process. The system contains a gate, similar to the ones employed at a railroad crossing, and flashing light warning and turning away any traffic. The bridge will remain closed until inspection has been performed and bridge is clear of no further danger.

4.6 SHM Advantages and Limitations

The Kentucky transportation cabinet is required by law to investigage each and every barge impact on every bridge accross the Ohio river. Most often, this requires lane closures and sometimes even bridge closure. The present SHM helps quantify impacts and transmit information regarding the degree of impact via text message, email and internet uploads to the Transportation Operation Center in the Kentucky Transportation Cabinet, the US Coast Guard and other selected personnel. Decisions can be made in minutes in regard to the course of action. With the current SHM system only identified major impacts need to be investigated and the system also has the capability of closing the bridge automatically when 'critical' impacts are detected. Although the system may be cost effective, the constant maintenance and replacement of equipment has been a limitation of this project.

5 CONCLUSIONS

Structural Health Monitoring of three bridges in Kentucky was highlighted in this paper. The short term monitoring of the bridge on I-65 in Louisville enabled researchers to quantify the degree of movement in the damaged spans, both horizontally and vertically. This aided in determining the best retrofit measure for the cracked beams and also with the monitoring immediately following the strengthening, the effectiveness of the retrofit was quantifiably measured and compared with the movements before the repair.

Before SHM was implemented at the I-64 Bridge over US60 and US41N Bridge over the Ohio River, damage due to impacts went unnoticed until periodic bridge inspections or until collisions were reported and Transportation personnel were deployed to evaluate the damage. Inspecting large bridges over waterways like the US41N Bridge after every impact is costly as well as time consuming. Identifying damage and being able to quantify the damage in real-time significantly improves the capability of avoiding catastrophic failures. The SHM carried out on bridges in Kentucky has proven to be an economical and effective method for extending the life of bridges and for providing the tools for immediate response and decision making.

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