Monitoring the Performance of Timber Bridges over the Long Term

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ABSTRACT

Timber bridges are often viewed by engineers as less durable than steel or concrete structures. However, they remain a durable and economical option along secondary roads in many rural areas of the country. With well over 75,000 bridges listed by the Federal Highway Administration's National Bridge Inventory as having timber superstructures as of 2002, they represent about 15% of the nation's highway bridges. Many of these timber bridges have been in service for more than 50 years. Knowledge of their long-term performance characteristics will allow maintenance and repair practices to be optimized and for future designs to incorporate improved design details for extending the service life of timber bridges. This paper will discuss long-term data collection goals, overview current work, and outline sensor types/features needed for obtaining reliable data required to successfully monitor timber bridges.

Key words: bridge—moisture—performance—sensors—timber—vibration—wood

INTRODUCTION

The Federal Highway Administration (FHWA) recently studied the effectiveness of the bridge inspection program within the National Bridge Inventory (NBI) (Phares et al. 2001). The NBI bridge condition data have been largely based upon visual assessment techniques which have been shown to be highly variable and subjective. These visual bridge inspection techniques have served as the basis for prioritizing bridge rehabilitation and replacement funds for the past 35 years. With the nation's highway bridges getting older and their deteriorated condition diminishing their level of service, focus has shifted towards repair and strengthening techniques that extend service life. When bridge replacements are considered, there is a need for greatly improved bridge condition data to support the greater allocation of funds.

Subsequently, the FHWA initiated its Long-Term Bridge Performance Program (LTBPP) in order to gain a better understanding of the relative deterioration rates for highway bridges. The introduction of the LTBPP program signals a major shift from the routine NBI (2-year interval) inspections towards a more proactive approach employing continuous data collection of in-service bridge structures. In order to generate the required health-monitoring data, key bridge performance parameters will be tracked using state-of-the-art sensing technologies on hundreds of instrumented bridges over a 20-year period. The goal is to generate more quantitative and more reliable condition and performance data (over extended periods of service) that can better support decisions for bridge repair and replacement.

The focus of this paper will be data collection strategies to support the long-term monitoring aspects of timber highway bridges. Timber highway bridges comprise about 15% of the approximately 575,000 highway bridge in the FHWA NBI. They provide vital transportation links mainly along secondary roadways in rural areas of the country. This paper will discuss data collection goals, overview past field monitoring work, and propose data collection strategies for long-term performance monitoring of timber highway bridges.

LONG-TERM FIELD MONITORING GOALS

Acquiring reliable quantitative data pertaining to the condition of the main structural components of timber bridge systems can potentially provide insight into the performance and deterioration characteristics of the components with respect to load and environmental conditions. Knowledge of these performance and deterioration characteristics can lead to forecasting the decay and wear of the structure as well as the degradation of load capacity. If structural integrity weakening can be forecast, then preventative maintenance and inspection schedules can be developed to identify and correct the deficiencies of the timber bridge structure prior to major deterioration and/or catastrophic failure.

Sensor Attributes

Some of the key attributes for data sensors suitable for long-term timber bridge monitoring are as follows:

Low Cost. The unit cost of sensors should be relatively low to support usage on a variety of timber bridge structures, including long-span trusses/arches and shorter span timber bridges. Cost will be a factor in embedding a number of sensors in a single structure also.

Environmentally Durable. The sensors must be sufficiently rugged to withstand the rigors of outdoor exposure including effects of temperature, precipitation, and sunlight.

Reliable and Accurate. The sensors must maintain their reliability and remain sufficiently accurate in measuring various performance parameters under exposed conditions. The sensors will need to be designed to undergo a large range of temperatures and precipitation. Also, the sensors will need to have a high signal to noise ratio. The primary goal for sensors is that they remain reliable and accurate for at least 20 years.

Placement of sensors will also be an important factor in developing a successful timber bridge monitoring system. Initially, a limited number of sensors will be placed in specific locations the earliest signs of distress typically occur. A secondary goal is development of miniaturized sensors that can be embedded into bridge members built of engineered wood composites. A large array of embedded sensors will provide a global (vs. localized) indication for each data parameter. In order to achieve this goal, the sensors will need to have the following attributes in addition to those listed above.

Toughness. Sensors will need to be rugged enough to withstand manufacturing methods and be compatible with waterproof adhesives.

Power Consumption and Communication. Sensors should have very low-power requirements and be capable of transmitting data to an onsite computer control system using wireless technologies.

Key Data Parameters

The following data variables should be the primary focus of a successful timber bridge monitoring system. These monitoring data sets should be able to provide an early warning of bridge deterioration due to physical or biological factors.

Moisture Content. The moisture content of wood is the best predictor for conditions conducive to incipient (early) decay. There is a threshold level of wood moisture (approximately 22% to 24%) below which decay cannot sustain itself. Brown rot is one type of decay organism that is commonly found in timber bridge structures and can significantly reduce load carrying capacity of bridge structural members prior to exhibiting visual signs of deterioration. For glulam bridges, where the initial moisture content is less than 15%, the development of sensors that will trigger warnings as the threshold moisture content is surpassed. For sawn lumber bridges, many structures are installed with internal moisture contents in excess of 30%, and sensors should be designed to trigger warnings as they drop below fiber saturation levels.

Deflection/Strain. The behavior of a timber bridge under heavy trucks, whether static or dynamic loading, gives the best system performance data. When typical service loads are used, deflection and strain data collected a various locations can provide an indication of load distribution levels.

Vibration Characteristics. Measuring the vibration characteristics of timber bridges can provide a measure of the overall stiffness of the bridge system, without the time delay of live load testing. Forced and free vibration techniques isolate the key frequencies that can be correlated to bridge superstructure stiffness.

Bridge Distortions. Because timber bridge materials are hygroscopic, they shrink and swell as their moisture content changes. When exposed to the elements, they can undergo significant moisture-related distortions that can adversely affect the overall structural performance.

Prestressing Bar Forces. The structural integrity of stress-laminated bridges is predicated on the maintenance of sufficient force in the prestressing bars. If bar forces drop below minimum design levels, various modes of failure can potentially take place. Active monitoring of these bar forces will give a key indication of the structural performance of the bridge. In addition, some rehabilitated longitudinal deck bridges employ stress-laminated techniques which increase load capacity and these prestressing bar forces deserve similar attention.

PREVIOUS FIELD MONITORING EFFORTS

Previous efforts with regard to performance monitoring of timber bridges focused primarily on two timber bridge superstructure types: stress-laminated and sawn-timber-girder timber bridges.

Automated Data Acquisition Systems

During the 1990s, the National Timber Bridge Monitoring Program was conducted by the U.S. Department of Agriculture (USDA) Forest Service, Forest Products Laboratory (FPL) in conjunction with the FHWA. Nearly 100 timber bridge structures were evaluated in the field during their initial two to five years in-service. Most of the field bridges were of the new stress-laminated deck design and the field data helped support the acceptance of a guide specification by the American Association of State Highway Transportation Officials (AASHTO). A subset of approximately 12 bridges from FPL/FHWA monitoring program were instrumented with automated data acquisition systems (Table 1). A remote data acquisition system was installed at each bridge site to monitor key performance parameters for stress-laminated decks that included temperatures, relative humidity, and stress-laminating compression forces. Field data was continuously collected over 24- to 48-month periods using a Campbell-Scientific datalogger and various sensors (Figure 1). A Vaisala temperature and humidity probe was used to measure the ambient conditions beneath the superstructure. Thermocouple wires were used to measure ambient and internal bridge deck thermal variations. Hollow-core steel load cells were custom manufactured at FPL and then encapsulated within an environmentally rugged PVC casing.

Table 1. Timber bridges instrumented with automated data acquisition systems for two- to five-year monitoring periods

State	Bridge name	Nearest City	Year built
WI	Pine River	Richland Center	1991
	Moose River	Clam Lake	1996
MN	Ciphers	Warroad	1989
IA	Deans Bottom	Moulton	1993
OH	McCurdy Road	Butler	1995
PA	Dutch Hill Road	City of Titusville	1992
	Brookston Road	Howe	1992
	Laurel Run	Jackson	1992
	Jacobs	Todd	1991
	Millcross Road	East Lampeter	1992
	Dogwood Lane	West Brunswick	1993
	Birch Creek	Cherry	1992

The field performance data from many of these instrumented bridges has been reported previously. From 1991 through 1993, the Ciphers Bridge was documented in the extreme weather conditions in Northern Minnesota (Wacker et al. 1998). From 1993 through 1995, the Deans Bottom bridge performance was monitored in southern Iowa. From 1997 to 2002 the FPL acquired data from seven hardwood demonstration timber bridges that were constructed by the Pennsylvania Department of Transportation using hardwood bridge materials (Wacker et al. 2004). The comprehensive data set from all 12 stress-laminated decks further characterized the trend in bar force levels in these bridges.

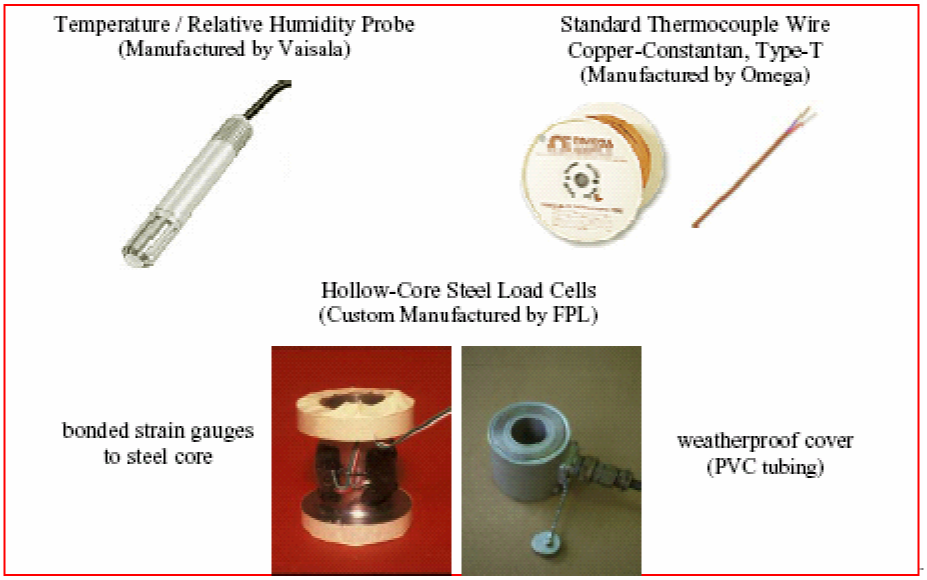

Figure 1. Typical sensors used in previous two- to five-year field monitoring studies

This data also was used to characterize any effects of cold (winter) temperatures on their structural performance. The sensors that were used in these field studies yielded acceptable data but required periodic recalibrations and other adjustments during the monitoring period.

Forced Vibration Inspection Technique

Several single-span timber bridges comprised of longitudinal sawn timber stringers with a transverse plank deck were evaluated in the field: 5 timber bridges from the Ottawa NF in Michigan's Upper Peninsula (Wang et al. 2005) and 12 timber bridges from St. Louis County, MN, (Wacker et al., in progress) were evaluated in service using dynamic testing techniques and compared with static live load test results.

A forced-vibration technique was used to identify the first bending mode frequency of the bridge structures. This method is a purely time domain method and was proposed because it eliminates the need for modal analysis. An electric motor with a rotating unbalanced wheel is used to excite the structure which creates a rotating force vector proportional to the square of the speed of the motor. Placing the motor at mid-span ensured that the simple bending mode of structure vibration was excited. A single piezoelectric accelerometer, also at mid-span, was used to record the response in the time domain. To locate the first bending mode frequency, the motor speed was slowly increased from rest until the first local maximum response acceleration was located. The period of vibration was then estimated from ten cycles of this steady-state motion. Because the primary goal of this work was to relate the vibration characteristics of the timber bridge structures to a measure of structural integrity, the bridges were also evaluated with the established method of static load–deflection field testing. Stiffness of bridge superstructure (*EI* product) could then be estimated from the field test results.

This vibration technique was intended to complement routine bridge inspections by providing an indication of the structural performance of the superstructure system. However, several factors have limited this technique for field inspection application. Focus has now shifted towards a fully automated system to measure vibration characteristics as part of a measurement and control system mounted onsite.

Figure 2. Measuring the response of a single-span timber bridge to forced vibration testing

DEVELOPMENT OF LONG-TERM PERFORMANCE MONITORING SYSTEM

Preliminary proof-of-concept laboratory studies have been completed towards the development of two sensors that measure the moisture content of wood beams. In addition, a field study to develop a fully automated, forced-vibration measurement and control system for timber bridges is underway. These new sensor systems are intended to be fully integrated with fully automated health monitoring systems mounted on a bridge.

Moisture Content of Bridge Members

Methods of acquiring the moisture content of wood beams have been explored. A freshly cut 8 in. birch log was cut into a 5 in. x 5 in. x 48 in. beam. A center line was drawn along the grain and six digital relative humidity/temperature sensors (SH-7) manufactured by Sensirion, were embedded in the birch beam and monitored over a 60-day period (Figure 3). Sensor #1 (E1) was embedded 4 in. from the edge at a depth of 2 3/4 in.. Sensor #2 (E2) was embedded 12 in. from the edge at a depth of 1 3/4 in. Sensor #3 (E3) was embedded 20 in. from the edge at a depth of 1 1/4 in. Sensor #4 (E4) was embedded 28 in. from the edge at a depth of 2 3/4 in. Sensor #5 (E5) was embedded 36 in. from the edge at a depth of 1 3/4 in. Sensor #6 (E6) was embedded 44 in. from the edge at a depth of 1 1/4 in.

To embed the sensors, a 3/8 in. diameter hole was drilled to 1/4 in. short of the sensor depth. A 3/8 in. diameter ribbed plastic sleeve with a light coating of silicon sealant was inserted into the hole. The sleeve was driven in the hole until it reached the 1/4 in. stop. Then a 5/32 in. diameter hole was drilled to the full sensor depth. The SH-7 sensors were then inserted into the sleeve until the head of the sensor passed the plastic sleeve and rested in the wood void 1/4 in. past the sleeve. A small amount of silicon sealant was placed over the top of the sleeve to keep the sensor in place and to restrict the introduction of ambient conditions into the sensor cavity.

In addition to the embedded sensors, a remote wireless resistance pin sensor, manufactured by Omnisense, was installed on the surface of the beam and monitored over the same 60-day period (Figure

4). The pin sensor measured the resistance between the pins that were threaded 1/4 in. into the beam along the center line, 24 in. from the edge. The wireless sensor is powered by a single 3/6v lithium battery. The sensor communicated with a receiver located approximately 100 ft. away in an adjacent office. The receiver is connected to the Internet, and the data transmitted from the sensor is sent to the Omnisense server where it is stored and prepared for display.

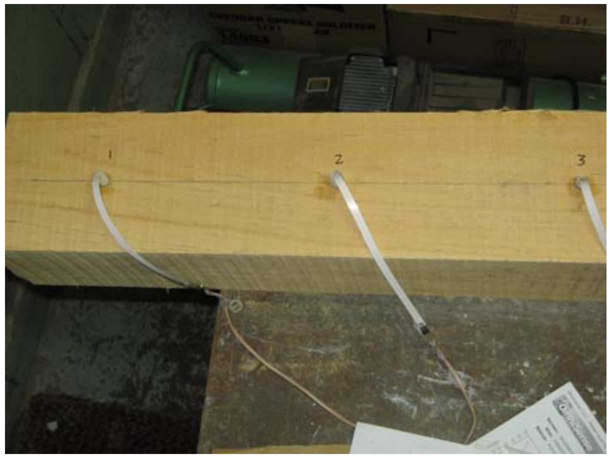

Figure 3. Embedded and surface-mounted sensors for measuring wood moisture

Figure 4. Omnisense wireless resistance pin sensor

The birch beam was placed in a controlled environment with a temperature of 70^{o} F and relative humidity of 12%. As a control reference the birch beam was placed on a digital scale, and the constant weight of the specimen was recorded for the 60-day period. The initial weight of the beam was measured and recorded, and upon completion of the test period, the beam was placed in a drying oven to obtain a dry weight.

Embedded and ambient temperature, relative humidity and dew point data was collected automatically at 30-minute intervals over the entire 60-day test period. The Omnisense surface mount wireless sensor also collected temperature, relative humidity, and dew point data, and it was collected continuously. Accessing the Sensor Activity Analysis display the data collected can be viewed over selected time periods. Daily averages obtained from the Omnisense website were used to graph the sensor's data. During testing, embedded Sensor #4 provided unreliable initial data and then failed completely. After 10 days Sensor #4 was disconnected, and no further data was collected from this point.

Analysis of the data collected indicates that the moisture content recorded by the sensors varied with the depth of the sensor. Readings from the sensors that were mounted at 2 3/4 in. and 1 3/4 in. tracked along the same trend line, and the sensors that were mounted at 1 1/4 in. also tracked together and paralleled the deeper sensors at a lower value. The values recorded by the wireless pin sensor were more linear but within the range of the values obtained from the embedded sensors.

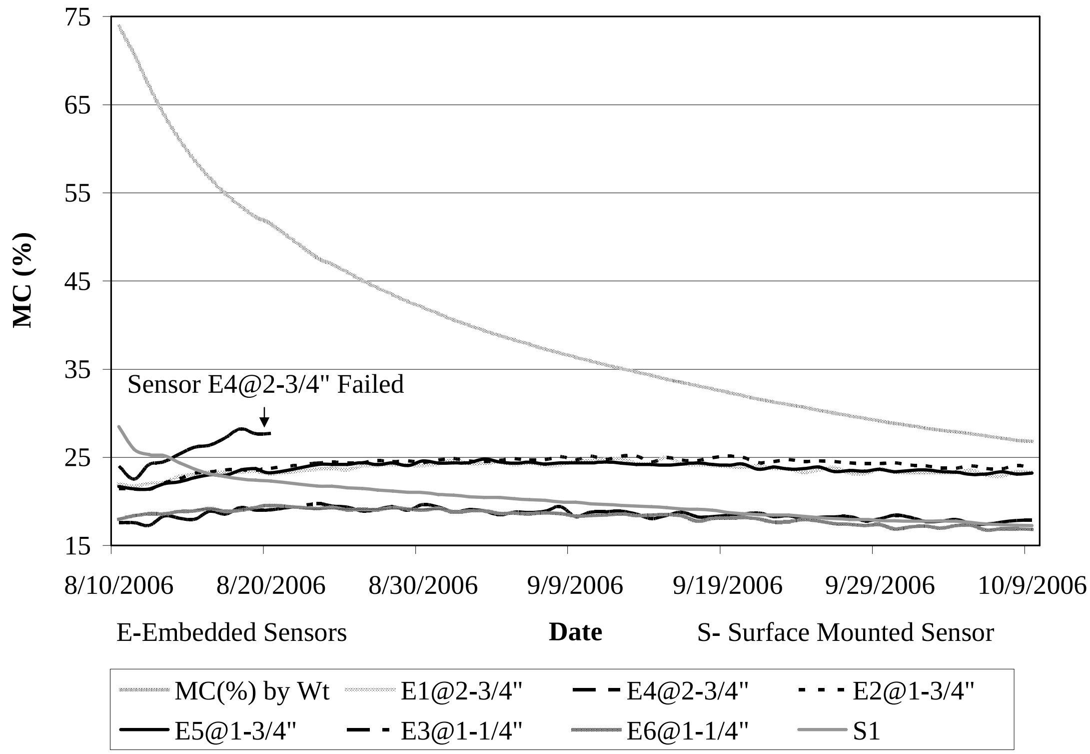

Figure 5. Average moisture content trends of embedded Sensirion SH-7 Temp/RH sensors and surface-mounted Omnisense Temp/RH sensor

Figure 5 displays the graphical representation of the MC trends for the 60-test period. The results showed that a definite trend exists based on the depth of the embedded sensors. Sensirion Sensors #1 and #4 were embedded at a depth of 2 3/4 in., Sensors #2 and #5 were embedded at a depth of 1 3/4 in., and Sensors #3 and #6 were embedded at a depth of 1 1/4 in. The laboratory results of this test indicate that depending upon the depth of the sensor there is a trend to the calculated %MC. However, sensor values are limited in the upper range by the fiber saturation point of the birch beam. The following equation from the *Wood Handbook* (FPL 1999) was utilized for calculating the equilibrium moisture content:

$$M = 1800/W\ [KH / (1-KH) + (K_1KH + 2K_1K_2K^2H^2) / (1 + K_1KH + K_1K_2K^2H^2)] \quad (1)$$

where,

M = moisture content (%)
T = temperature (^oF)
H = relative humidity (%)

and

$W = 330 + 0.452T + 0.00415T^2$
$K = 0.791 + 0.000463T - 0.000000844T^2$
$K_1 = 6.34 + 0.000775T - 0.0000935T^2$
$K_2 = 1.09 + 0.0284T - 0.0000904T^2$

Bridge Vibration Characteristics

A timber bridge in Minnesota has been instrumented with vibration motor (mounted underside) along with an onsite computer control system. The system is programmed to initiate vibration and collect pertinent data on a regular basis. The data collection is ongoing, and more details and results will be available soon.

SUMMARY

The key components of a long-term timber bridge performance monitoring program, including a description of the key performance indicators and a few data collection strategies, are presented.

Preliminary work has been completed with regard to development of wood moisture content and forced vibration measurement sensors and controls. Two electrical-resistance type sensors (one wired/embedded and one wireless/surface-mounted) were reliable and reasonably accurate in measuring the moisture content of a birch beam in the laboratory. Further study of the effectiveness of these moisture content sensors when exposed to the outdoors is ongoing. A reliable and accurate measure of the wood moisture content will predict when internal conditions of key bridge members are conducive to the development of decay deterioration.

Field studies are also currently underway to investigate the potential of an active bridge vibration measurement and control system. A viable system that measures the key vibration variables has been shown to be a good indicator of stiffness of the bridge superstructure. In addition, it may also provide key information for improving the reliability of estimating residual strength of the bridge system.

Further investigation into the use of fiber optic–based sensors is also underway. They have an advantage of minimal noise interference, which makes them a strong candidate for long-term performance monitoring applications.

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REFERENCES

FPL. 1999. *Wood Handbook: Wood as an Engineering Material*. Gen. Tech. Report FPL-GTR-113. Madison, WI: USDA Forest Service, Forest Products Laboratory.

Hilbrich Lee, P.D., M.A. Ritter, S. Golston, and K. Hinds. 1997. *Field performance of timber bridges: 14. Dean, Hibbsville, and Decatur stress-laminated deck bridges*. Res. Pap. FPL–RP–564. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Phares, B.M., D.D. Rolander, B.A. Graybeal, and G.A. Washer. 2001. Reliability of visual bridge inspection. *Public Roads*, 5 (March/April).

Wacker, J.P., C. Carlito, Jr., L.E. Hislop, P.D. Hilbrich Lee, and J.A. Kainz. 2004. *Long-term performance monitoring of hardwood timber bridges in Pennsylvania*. Res. Pap. FPL-RP-612. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Wacker, J.P., J.A. Kainz, and M.A. Ritter. 1998. *Field performance of timber bridges: 17. Ciphers stress-laminated deck bridge*. Res. Pap. FPL–RP–572. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Wacker, J.P., X. Wang, B.K. Brashaw, and R.J. Ross. 2007. *Structural Evaluation of Minnesota Timber Bridges Using Forced-Vibration Techniques*. In Progress. Res. Pap. FPL-RP-XXX. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.

Wang, X., J.P. Wacker, G. Morison, R.J. Ross, B.K. Brashaw, R. Vatalaro, and J. Erickson. 2005. *Nondestructive Evaluation of Single Span Timber Bridges using a Vibration Method*. Res. Pap. FPL–RP–627. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory.