Demonstration Smart Timber Bridge – Glulam Timber Bridge on Geo-synthetic Reinforced Soil (GRS) Abutments

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Abstract

Recently, Buchanan County, Iowa, cooperated with the U.S. Federal Highway Administration (FHWA), USDA Forest Service, Forest Products Laboratory (FPL), and Iowa State University's Bridge Engineering Center (ISU–BEC) and the National Center for Wood Transportation Structures (NCWTS) on a project involving the construction and monitoring of a glued-laminated (glulam) timber bridge superstructure on geosynthetic reinforced soil (GRS) integrated bridge system (IBS) abutments. The research team installed sensors within the substructure, at the girder bearings, and on the superstructure. Together, the system creats an autonomous structural health monitoring system that remotely transmits continuous data. Long-term monitoring enables researchers to evaluate GRS–IBS system performance with respect to variables of time, ambient conditions, and loading.

1. Introduction

This Demonstration Smart Timber Bridge, see Figure 1, is one of the first timber bridge superstructures to be installed on geosynthetic reinforced soil (GRS) abutments in the United States, and provided the opportunity to collect key performance data using an array of sensors integrated into a structural health monitoring (SHM) system. The process of monitoring smart timber bridges is described in Phares et al. The project detailed herein is a joint effort between the USDA Forest Products Laboratory (FPL), Iowa State University's Bridge Engineering Center (ISU–BEC), and the Federal Highway Administration (FHWA). This paper provides an overview of the design and construction phases, installation of sensors for SHM of the substructure and superstructure systems, and a review of the preliminary monitoring data collected to date.

Figure 1 Demonstration Smart Timber Bridge on GRS Abutments, Buchanan County, Iowa

2. Substructure Monitoring

The stability and constructability of GRS abutment are two of its most valuable characteristics. Movement of any abutment is critical, and potentially detrimental to any superstructure. To date, monitoring of the movement of GRS–IBS abutments has come from manual surveying and are typically collected only at intervals of days, weeks, or months. Specific areas of interest within the GRS abutment targeted for monitoring include: movement or tilting of the back wall and wing walls, settlement at the superstructure sill and approach roadway joint, lateral soil movement within the GRS abutment, and soil pressure in high stress areas of the GRS abutment.

To gain a better understanding of the stability of a GRS abutment, sensors were place within the layers of the GRS. The monitoring sensors installed within the abutment are shown in Figure 2. The cross section shown was adapted from the abutment design plans for the site and used with permission from Buchanan County, Iowa. The sensors include tilt meters, moisture and temperature sensors, extensometers, earth pressure cells, and soil profile sensor arrays.

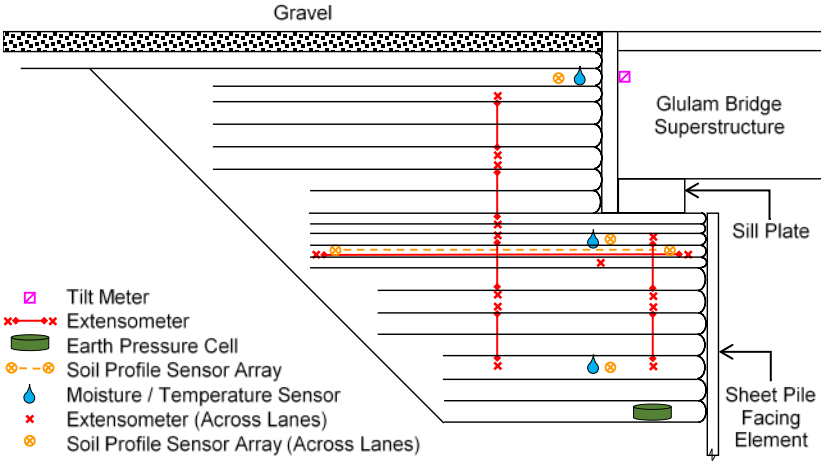

Figure 2. Sensor placement within GRS abutment. Adapted from site design plans prepared by Buchanan County, Iowa, and used with permission

Vertically oriented extensometers (VE), referred to as borehole extensometers, measure abutment settlement. There are six sets of VE in the abutment: four sets of two VE are positioned under the beam seat, two sets of four VE are positioned within the roadway approach to the superstructure. Horizontally oriented extensometers (HE), referred to as soil extensometers, measure lateral soil movement. Four HE are used in total: one set of two HE are positioned parallel to the roadway and placed near the midpoints of each of the two driving lanes, and one set of two HE are positioned perpendicular to the driving lanes below the interface between the bridge and the approach. Soil profile sensor arrays (SPA), also referred to as shaped accelerometer arrays, involve a series of accelerometers connected by 0.5 m segmented rods. The accelerometers monitor relative movement at each of the connection points, providing internal soil profile information. Two sizes of SPA were used, 3 m and 7 m: two 3-m SPA were placed parallel to the roadway and near the midpoints of each of the two driving lanes, and three 7-m SPA were placed perpendicular to the driving lanes. Three moisture–temperature sensors were placed at the midpoint of the roadway 15 cm adjacent to each of the 7-m SPA. Two earth pressure cells were placed at the bottom of the abutment, near the midpoints of each of the driving lanes and directly under the beam seat. Two sets of two tilt meters were affixed to the abutment back wall to measure the angle of tilt of the back wall parallel and perpendicular to the driving lanes. Several ambient condition sensors were mounted in and around the abutment for monitoring wind speed, wind direction, solar radiation, and precipitation. Temperature and relative humidity are also measured on site, both above the level of the abutment and below the superstructure. Data are collected from the abutment and ambient conditions sensors every 30 minutes by a CR1000 datalogger (Campbell Scientific, Inc., Logan, UT) and the data are transmitted via cellular connection for processing and permanent storage.

3. Superstructure Monitoring

The foundation of the instrumentation plan and monitoring system for the glulam superstructure is a modification of the BECAS (Lu, et al.) monitoring system developed by ISU–BEC. The system was first modified and tested on a glulam girder superstructure in Delaware County, Iowa, in 2012 (Boechler et al). After monitoring and fine-tuning that system for several years, minor changes and improvements were made prior to implementing the system on the bridge of this project.

The two main objectives of the SHM system on this bridge were to (1) collect structural performance data from the bridge and (2) provide real-time, continuous load rating of the superstructure for damage and deterioration detection. The SHM system for the GRS timber bridge consists of 36 strain gages installed on the glulam girders, six strain gages installed on the underside of the transverse glulam deck panels, three moisture sensors (two in the girders and one in the deck) (Pence et al), and two temperature sensors. All 47 of these sensors are connected to, and monitored by, a CR9000X datalogger (Campbell Scientific). Figure 3 illustrates the instrumentation layout for the GRS timber bridge. An on-site desktop computer collects the data from the data logger and pushes them wirelessly via cell modem and router to the BEC main servers at the home office in Ames, IA. After the data are received by the servers, they are filtered and reduced, separating out data files with a detected truck event for further analysis and evaluation.

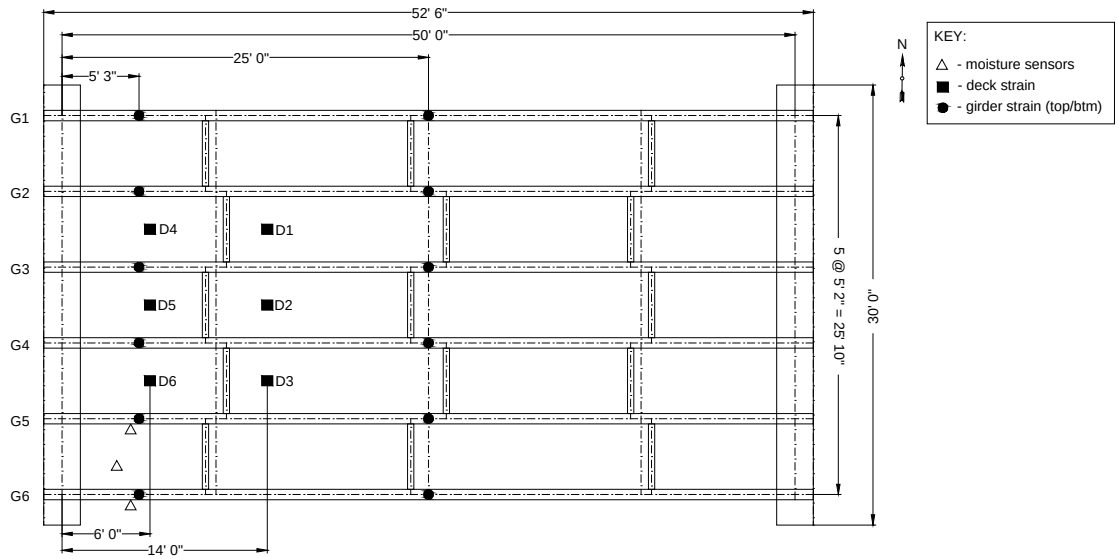

Figure 3. Superstructure instrumentation layout.

Girder strains are used for multiple analyses of the structure, including but not limited to, the neutral axis, peak tensile strain, girder end rotation, transverse load distribution, and various truck detection–evaluation calculations. Deck strains are collected at key locations, using the same shim gage configuration discussed previously, to obtain vehicle information as well as deck performance measures. The deck gages allow the BECAS system to not only detect the presence of a vehicle, but determine the speed of the vehicle, the transverse position of the vehicle on the bridge, the number and spacing of axles on the vehicle, as well as assess glulam deck performance. The raw strain data collected in the SHM system are continuously stored in the database as 1- minute data files. Truck events are identified using the deck strains; data files not found to have a truck event are discarded, and only data files representing truck events are further analyzed. A typical strain three-axle truck response is shown in Figure 4, which allows for calculation of vehicle speed along with number and spacing of axles.

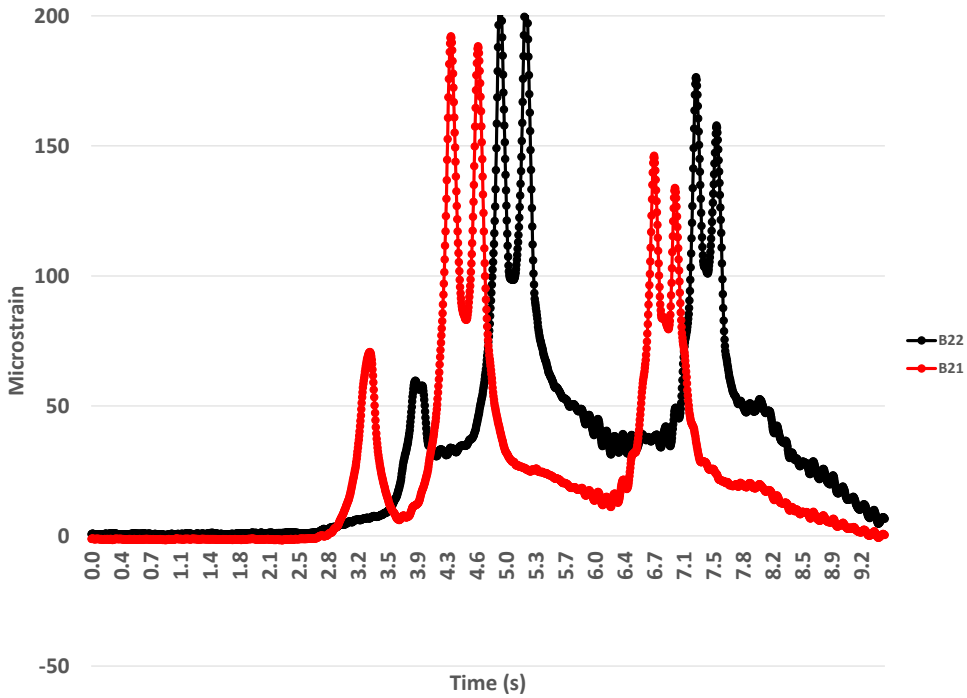

Figure 4. Truck strain response from deck gages.

The change of the strain response caused by creep, shrinkage, and temperature changes within a 1- minute period are considered negligible and can be neglected during the data process, which was also discussed by Doornink et al. and Lu. The baseline strain for each sensor can be identified by finding the mode of the sensor data, which represents the value most frequently occurring in the 1-minute data collection. The raw strain data of each sensor can then be zeroed with respect to the baseline strain to eliminate the creep-, shrinkage-, and temperature-induced strain components.

The approach taken for monitoring the superstructure dynamic behavior is to consider that the superstructure is a black box composed of structural governing equations with unknown parameters that takes in first-order inputs in the form of forces and yields displacements as first-order outputs. Forces are measured using two LBM-20K load cells (Interface, Inc., Scottsdale, AZ) capable of measuring up to 89.0kN under each end of the six glulam stringers. The use of two load cells per stringer end ensures static equilibrium and facilitates measuring stringer torsion. Load cell signals are conditioned and digitized using six-input LabJack T7 Pro multifunction DAQ devices; four LabJack devices are utilized in all. Force measurement data are transferred from the LabJack via USB to a Raspberry Pi 2 single-board computer, which transmits the information to the remote server for archiving. The displacement output of the bridge is measured by fixed reference frame cameras monitoring the movement of infrared laser LEDs. The infrared laser LEDs have a divergence of 2° and are imaged using the camera settings as a white dot in a black background. The centroid of this dot is tracked in real time to monitor the movement of the bridge with subpixel accuracy. Two types of cameras are used to monitor the bridge; a Raspberry Pi NoIR Camera, which is attached to each of the four Raspberry Pis and converts the image of the LED to a digital coordinate; and the Pixy CMUcam5 which utilizes an embedded microcontroller to calculate the image to coordinate conversion onboard at 50Hz. The

displacement data is sent with the force data to the server. An additional Raspberry Pi is utilized to act as a master to coordinate the timing between the four data acquisition Pis and to serve as a gateway between the locally networked Pis.

The generated force displacement data will be utilized to inversely solve for the unknown superstructure parameters by satisfying the governing system of equations. Each vehicle becomes an excitation to the system that adds to the behavior space for which to characterize the black box and which to subsequently compare against for indications of degradation.

4. Conclusions

In total, approximately 100 sensors have been installed in or on the substructure and superstructure of the Demonstration Smart Timber Bridge in Buchanan County, Iowa. Independent systems power, collect data, monitor the bridge, and transmit collected data back to servers for additional processing 24 hours a day, 7 days a week. Both the substructure and superstructure systems continue to be actively monitoring data from the GRS abutments and the bridge superstructure. The continuous monitoring is and will continue to be helpful in assessing the overall health of the bridge and furthermore improving the long-term performance of the structure, above and below the ground, by detecting structural deficiencies and/or triggering timely maintenance actions.

In addition to the long-term structural monitoring being conducted by the SHM system, routine short-term live-load tests are included in the program for this structure. The initial load test was conducted in the spring of 2017, with subsequent tests to follow every 6 to 12 months for a period of 2 to 3 years. Data from the live-load testing will be used to validate strains collected from the SHM system, verifying vehicle recognition parameters for the system, and provide additional structural performance information on the structure. In addition to the structural-related measurements, moisture readings will be taken during the live-load testing using typical moisture meters to validate moisture readings collected by the SHM system.

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