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DESIGN, INSTALLATION, AND OPERATION OF A MONITORING SYSTEM FOR AN INTERSTATE HIGHWAY BRIDGE

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Abstract

A permanent long-term monitoring system is currently being installed on a typical three-span continuous, slab-on-steel girder bridge in New Castle County, Delaware. The bridge carries Interstate 495 around Wilmington, Delaware, and has a relatively high volume of truck traffic. The system will automatically measure strain, displacement, rotation, acceleration, and temperature at key locations on the bridge. Two types of data will be collected: "event" data, when heavy vehicles cross the bridge, and periodic "monitor" data. The purpose of the monitoring system is to provide near real-time, and long-term, data on the performance of this typical bridge. The system will also be used as a test bed for new sensors and sensor systems for bridge monitoring as they become available in the future. Presented in the paper is a brief overview of the design, installation, and operation of the monitoring system, and a discussion of some preliminary test results from the bridge.

INTRODUCTION

A program is currently in progress through the University of Delaware, Center for Innovative Bridge Engineering, to bring online a comprehensive monitoring system for a typical interstate highway bridge. The bridge is a three-span continuous, slab-on-steel girder design that carries northbound Interstate 495 around Wilmington, Delaware. The monitoring system was designed, (1) to provide near real-time, and long-term, data on the performance of this typical bridge, and (2) to be used as a test bed for new sensors and sensor systems for bridges as they become available in the future. Presented in the paper is a brief overview of the design, installation, and operation of the monitoring system, and a discussion of some preliminary test results from the bridge.

DESCRIPTION OF THE BRIDGE

Bridge 1-821 is a four-span bridge with one simply supported span and three continuous spans. A photograph of the bridge is shown in Figure 1. Only the continuous northbound spans have been instrumented; therefore, only spans two through four are discussed in the paper. A plan view of the continuous portion is shown in Figure 2. Concrete piers support spans two, three, and the left end of span four. A sloped abutment supports the right end of span four. The bottom of the steel girders sit about 50' above ground level at the non-sloped areas under the bridge. The bridge is at a slight skew of 5.2°. The total length of the continuous portion is approximately 200'.

Figure 1. Photograph of Bridge 1-821.

The center span is 76'- 7 5/8" and the back spans are 61'-3 3/4" each. The composite deck slab is supported by nine equally spaced steel girders. When the bridge was originally constructed, it had seven equally spaced girders supporting three lanes of traffic. Two girders were added to the east side of the bridge later when the highway was widened to four lanes of traffic. These are referred to as girders G8 and G9 on the plan shown in Figure 2. All nine girders are spaced 8'-0" on center. The deck slab is 69'-6" wide and has a parapet on each side.

The entire bridge is comprised of four different girder cross sections. The original seven girders vary longitudinally between three different cross sections due to the negative bending regions over the piers. The two new girders only vary between two different cross sections. Cross section one of girders one through seven consists of a W36x135 steel beam with an 8" composite concrete slab on top. Cross section two consists of a W36x150 steel beam with an 8" composite concrete slab on top. Cross section three consists of a W36x150 steel beam with 0.688"x10" cover plates on both the top and bottom flanges. The deck was designed as non-composite in the negative bending regions. The cross sections of girders G8 and G9 are W36x150 with the composite deck in the positive bending regions, and a W36x210 in the negative bending regions. There are also intermediate MC18x42.7 diaphragms located along the length of the bridge.

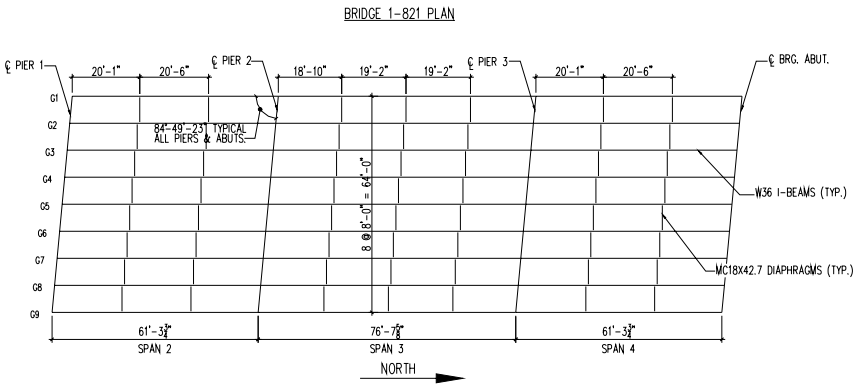

Figure 2. Plan view of Bridge 1-821.

Bridge 1-821 was selected for permanent monitoring for several reasons. First, it is located on a heavily traveled interstate highway, thus it has a high Average Daily Traffic (ADT) count and a high Average Daily Truck Traffic (ADTT) count. Second, it is a continuous, slab-on-steel girder bridge, which is typical of many bridges in Delaware and the United States. Finally, it is convenient to the University of Delaware.

OVERVIEW OF THE MONITORING PROGRAM

The goal of the monitoring system is to provide data that can be used to study the short- and long-term performance of the bridge to repeated loadings from the site specific traffic, and its degradation due to environmental factors. Data will be used to study the behavior of the bridge to individual loading events, to study the statistical characteristics of multiple loading events, and to study the long-term performance, i.e., degradation, of the bridge due to repeated loadings and environmental factors.

The term “performance” is used here in a general sense to mean the manner in which the bridge performs its structural function. More specifically, the data from the monitoring program will be used to study: (1) longitudinal and transverse load distribution, (2) composite behavior, (3) support fixity, (4) fatigue of the girders and critical connections, (5) impact, (6) natural frequencies, mode shapes and damping ratios, and (7) thermally induced stress and deformation. The key environmental factor to be directly measured is temperature: of the bridge at selected locations and air temperature. Other environmental factors such as humidity, rain fall and snow will be collected from local weather stations. Records of salting during ice and snow storms will be gathered from the highway agency.

A total of 61 sensors have been permanently mounted on the bridge. Sensors have been installed to measure the strain, displacement, rotation, and acceleration of selected girders, as well as air temperature, girder temperature, and deck temperature. In the future, video cameras may be added, as well as weigh-in-motion sensors. Data will be recorded on-site using a high-speed data acquisition system that is remotely accessible via the Internet. Two different types of datasets will be collected: “event” data and “monitor” data. When a heavy vehicle crosses the bridge, the system will be triggered to capture a high speed “event” record. Single event records will be used to study in detail the response of the bridge to that particular load. Ensembles of event records will be used to study the response in a statistical sense. Issues such as load distribution, support fixity, composite action, influence of non-structural elements, and multiple-presence can be studied using the event data. Over time, changes in the event response should be indicators of some change in the bridge itself, or changes in the traffic on the bridge.

The monitor data will consist of short samples taken on the hour, every hour. With monitor data, researchers will be able to study the actual performance of the bridge to factors such as sustained load, temperature variations, and environmental influences. Monitor data will be used to track changes that might occur over much longer time periods.

Bridge 1-821 will also be used as a test bed for new sensors and sensor systems as they become available. Allowances have been made to incorporate other sensors into the monitoring system, so that the data they provide and their performance characteristics can be compared to that of the conventional sensors that are on the bridge.

These new sensors and systems can be deployed temporarily on the bridge and the results compared to the historic data collected from the permanent monitoring system. This will hopefully aid in the development, testing, and verification of sensors for bridge applications.

INSTRUMENTATION PLAN

Sensors

A total of 61 sensors are mounted to the bridge. This included 32 resistive foil strain gages, 4 vibrating wire strain gages, 9 cable potentiometers to measure deflections and rotations, 6 accelerometers, 5 thermocouples, and 3 resistance temperature detectors (RTDs). The sensors were arranged on the bridge to provide the greatest possible spatial distribution, with the fewest number of sensors, and to provide information along key longitudinal and transverse lines. The sensors can be seen in the gage layout in Figure 3.

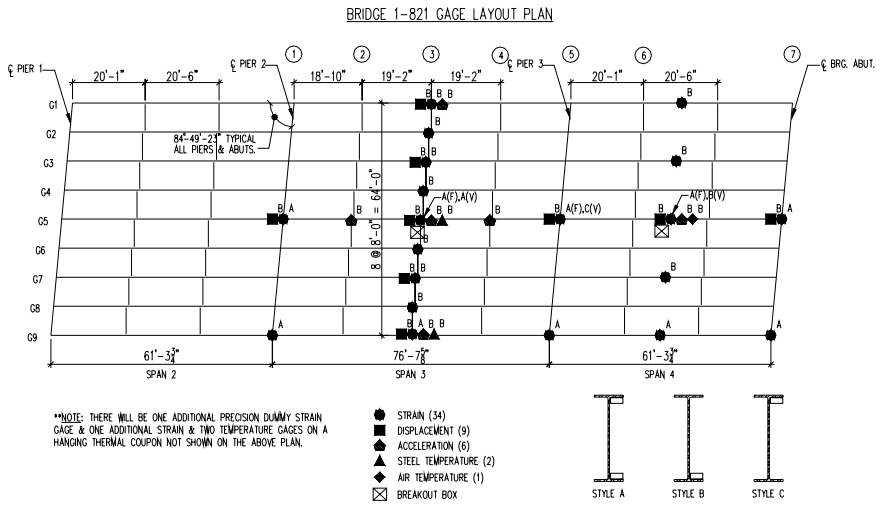

Figure 3. Instrumentation layout.

A simple grid nomenclature was developed to designate the sensors. The girders are numbered one through nine with one starting at the west side of the bridge. The girder numbers serve as a y-axis for the grid. There are also numbers running left to right at pier and diaphragm locations that serves as an x-axis for the grid. The grid number locations and all gages are shown in Figure 3. The sensor designation is made up of four characters (the fourth character is not always used). The first character represents the type of measurement, the next two characters represent the x-y grid location on the bridge, and the last character designates top or bottom of flange, or one of two other indicators.

Both weldable electrical resistive foil strain gages and vibrating wire strain gages are used to measure flexural strain in the girders. Thirty-two weldable foil strain gages have been installed on the bridge. These gages are located on the top or bottom flange of the girder, and are uniaxial, quarter bridge sensors. To minimize noise pick-up, the Wheatstone bridges are completed at the gage site. The resistive strain gages will measure slow changes in strain, and higher rate changes due to vehicles and vibration. Four Geokon Model 4100 vibrating wire strain gages are used to measure the flexural strain in the girders at slow sample rates (i.e., only monitor data). The sensor has a gage length of 51 mm and has a standard measurement range of 3000 microstrain. Resistive foil strain gages are co-located with the vibrating wire strain gages, to provide a comparison between the two readings. Both types of strain gages are environmentally protected. The vibrating wire gages come with a stainless steel cover and appropriate sealants. The foil strain gages are first encased in a strong silicone sealant; a small rectangular plastic enclosure with a small hole for the conductor is then placed over each foil gage and sealed with the same sealant.

Nine Unimeasure HX-P510 cable potentiometers are used to measure global deflections and rotations of the girders. The transducer can function in a variety of environments including exposure to rain or wash down. The transducer

has a range of two inches and a resolution of 0.001". The locations of these sensors can be seen in the gage layout in Figure 3.

To measure the vertical girder deflection the potentiometers are mounted to the girders at the locations where deflections are to be measured. The stationary reference for the deflection measurement is a 0.063" diameter nylon coated stainless steel cable that is strung between the piers on span three, and the pier and abutment on span four. To maintain tension in the cable, the cable is connected to a spring, which in turn is attached to a turnbuckle that is anchored to the pier. The spring will account for any thermal expansion or contraction in the steel wire and the turnbuckle will allow for manual tightening or loosening of the cable. The end of the potentiometer cable remains stationary, while the transducer moves with the girder it is attached to. Vertical displacements are measured during events and monitored over the long term.

Six Crossbow accelerometers are mounted to the bridge to capture dynamic effects during event recording. Four of the six accelerometers are single axis CXL01LF1 series sensors measuring acceleration in only the vertical direction. The remaining two are tri-axial CXL01LF3 series accelerometers that are oriented to measure vertical and transverse vibrations (acceleration in the longitudinal direction is not recorded). The accelerometers have an input range of ± 1g and a sensitivity of 2 Volts/g. They are encased in a nylon enclosure and can withstand a temperature range from –400°C to +85°C. The accelerometer layout can be seen in Figure 3.

There are eight temperature sensors deployed on the bridge. Of the eight gages there are three resistance temperature detectors (RTD's), two standard thermocouples, and three surface temperature thermocouples. The RTD's measure steel temperature in three locations. Two will measure the temperature of an interior girder and an exterior girder. The last RTD will measure the temperature of a steel coupon that will be hung from the bridge. The purpose of the interior and exterior gage temperature measurements is to look at the temperature difference of the steel between a shaded and non-shaded girder and the effects the differential has on strain and deflection in the girder. The steel coupon with temperature sensor will serve as a control specimen, since the steel is free to expand and contract with temperature changes.

Of the two standard thermocouples, one will provide general air temperature and the other will measure the concrete deck temperature. The gage measuring deck temperature was grouted into a small hole that was drilled into the underside of the concrete deck. The purpose of installing a gage in the concrete deck is to examine the temperature gradient between the deck, which is directly exposed to sunlight, and the bottom of an interior steel girder, which is constantly shaded. A bondable surface thermocouple is mounted next to each RTD.

Data Acquisition

Data acquisition is provided by a Campbell Scientific CR9000X data logger. The CR9000X is intended for applications requiring slow speed recording, and rapid scan rates, of up to 4.5 kHz. The system can be configured with a wide selection of input modules, to accommodate different types of sensors. The CR9050 5 Volt Analog Input Module provides fourteen input channels. One CR9060 Excitation Module can provide up to sixteen channels of 5 Volts excitation. Of the sixteen channels there are six continuous and ten switched excitation channels. The system has 128 MBytes of memory available for internal program and data storage; a 256 MByte PC card provides additional data storage space. The PC9000 Support Software, which is based on the BASIC programming language, allows for straightforward program generation and also has different types of triggering capabilities. Communication with the CR9000X can either be done through a direct serial connection or via the internet through an ethernet connection. Once at the site, the system can be remotely accessed and configured, and data can be downloaded via the internet. The system can be configured to automatically download data at a predefined time of the day.

The data acquisition system is housed in a 40" x 33" x 14", NEMA4 rated enclosure. The enclosure is secured to the concrete pier that supports spans three and four. Services at the enclosure include 110 Volts AC power and a telephone line for high-speed internet access. Also housed in the enclosure is an uninterruptible power supply (UPS), DSL modem, and other peripherals.

Wiring

From the data acquisition system/enclosure, seven multi-conductor trunk cables run to two junction boxes located on Girder 5. One junction box is located at mid-span of span three, and the other is located at mid-span of span four. From the junction boxes, conductors for individual sensors are run to the sensor site.

The junction box on span three is denoted as the south junction box and the box on span four as the north junction box. Each trunk cable contains twenty-five twisted conductor pairs. Three trunk lines run to the north junction box and four run to the south junction box. The junction boxes are 27" x 21" x 10" NEMA4 rated enclosures that are secured to the bottom flange of the girder with metal frames and beam clamps. The trunk cables feed into the one

side of the junction box and the sensor wires feed into the opposite side of the box, each through nylon water tight fittings. Inside the junction box are terminal strips where the connections are made between the trunk cables and the sensor conductors.

Additional conductors have been provided to each junction box through the trunk cables, so that in the future additional sensors can be added very easily to the system. When a new sensor is added, a conductor for the sensor only needs to be run back to the closest junction box, where excitation is provided through the trunk cable, and the signal connection is be made back to the data acquisition system. The system has been setup to add an additional ten four-wire sensors.

All of the cables are supported and secured in zinc plated steel cable trays that are secured to the pier or girders. Four inch by two inch deep trays are used for the trunk cables and locations where there are a large number of sensor wires coming out of the junction box. Two inch by two inch deep trays are used in areas where there are fewer sensor cables. Individual cables are secured to the cable trays with "zip-ties."

RESULTS OF PRELIMINARY DIAGNOSTIC TESTS

Two diagnostic tests were conducted on Bridge 1-821 as part of the planning for the permanent monitoring system. A static test was conducted in the summer of 2004 and an ambient vibration survey was conducted in the summer of 2006. The details and key results of those tests are summarized below.

Static Test

For this test, the bridge was instrumented with a total of twenty-eight quick mount strain transducers. The sensors were concentrated along the transverse mid-span of span three, and along girder 3. Two loaded dump trucks made five passes at a crawl speed across the bridge and the resulting strains were recorded. Ambient traffic strains were also recorded for three minutes.

The overall response of the bridge to the semi-static loads was as would be expected for a continuous three span bridge. The peak tensile strain occurred at midspan of the bridge where maximum positive bending would be expected. The maximum compressive strain occurred over pier two in a negative bending region. The center of the main span experienced negative bending when the test truck was on one of the back spans.

The peak tensile strain for a single truck pass was 160 με, which corresponds to a live load stress of 5.53 ksi. The peak compressive strain for a single truck pass was -57 me, which corresponds to a live load stress of -1.96 ksi. The peak tensile strain for a side-by-side (multiple presences) truck pass was 210 με, which corresponds to a live load stress of 7.23 ksi. The peak compressive strain for a side-by-side truck pass was -58 με, which corresponds to a live load stress of -2.0 ksi. The peak tensile strain recorded during the short period of monitoring ambient traffic was 205 με, which corresponds to a stress of 7.07 ksi.

The actual transverse load distribution for bending of the bridge was compared to values calculated using AASHTO standard specifications. According to AASHTO the distribution factors are 1.14 for a single truck and 1.45 for side-by-side vehicles. The values calculated using the measured strains were, 0.86 for the single truck and 1.4 for side-by-side trucks. Data on transverse load distribution was used in deciding on the density of strain gages along the transverse centerline of the bridge for the permanent monitoring system.

The test data was also used to demonstrate composite action of the deck. This helped to determine the number of gage locations where both top and bottom flanges are instrumented in the permanent system.

A final parameter that was analyzed from the static data was the percent fixity of the end restraints. The ends of the bridge are considered to be free rotating, or have zero percent fixity. However, there may be some restraint to rotation due to the nature of the bearings. The percent fixity was calculated by taking the ratio of the strain at the abutment to the strain at midspan of span four. The percent fixity of the bridge was calculated to be approximately 26%. As a result of this finding, the permanent monitoring program includes a few strain measurements on the top and bottom flanges at the abutments.

Dynamic Test

An ambient vibration survey of the bridge was conducted in the summer of 2006. Six single axis accelerometers were placed on the steel girders to measure vertical acceleration due to ambient excitations. Three accelerometers were placed across the transverse midspan of the center span, one was placed at the quarter point and one at the three-quarter point of the center span, and one accelerometer was placed at the quarter point of span four. Two ten minute windows of ambient data were recorded at a rate of 40 samples-per-second.

MatLab was used to do the spectral analysis of the data. Power spectra were created for each sensor, along with cross-spectra for different gage combinations. A sample power spectrum for one sensor is shown in Figure 4.

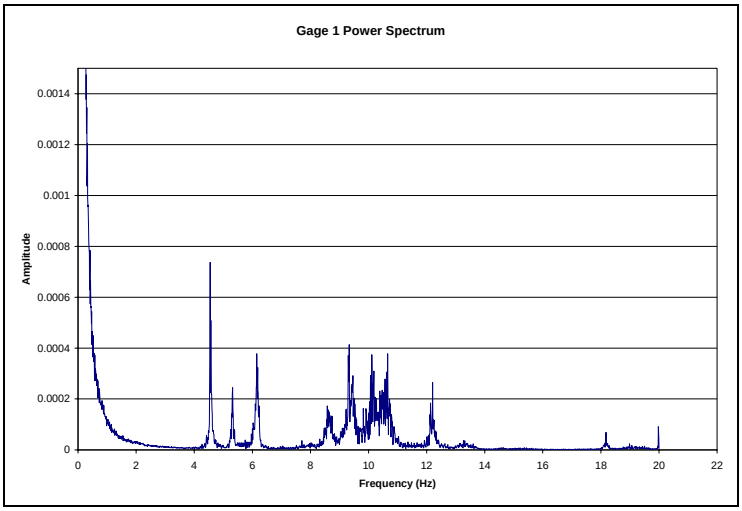

Figure 4. Sample power spectra from ambient vibration survey of Bridge 1-821.

The peaks in the spectra correspond to the natural frequencies of the bridge. The first three natural modes of vibration were identified with confidence. Mode one, which occurs at a frequency of 4.6 Hz, is the fundamental vertical mode of a three-span system, with the back spans moving out of phase with the center span. Mode two, which occurs at a frequency of 5.3 Hz, is a predominate torsional mode, with each span twisting along the longitudinal axis of the bridge. Mode three, which occurs at a frequency of 6.1 Hz, is similar to mode one, only the center of each span is moving out of phase with both edges.

These results, along with the results of finite element analyses of the bridge, weighed heavily in the final decision of the number and location of accelerometers that were installed in the permanent monitoring system.

CONCLUSIONS

A permanent long-term monitoring system has been designed and installed on a typical highway bridge in New Castle County, Delaware. The purpose of the system is to provide data on the performance of the bridge, and how it behaves under live loads and environmental influences. The system will automatically gather structural response data from key locations on the bridge, as heavy vehicles cross the bridge, and periodically under “no-load” conditions. The system has also been designed so that new, alternative sensors can be integrated into the system. The data from the new sensors can be compared with the historical data from the conventional sensors on the bridge. In this way, the system can serve as a testbed for new advanced sensors for bridge monitoring.

At the time of writing this paper, the final sensors were being installed on the bridge, and initial data was being collected. Future papers will report on the data and results obtained from the monitoring system.

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