**Connecticut Permanent Long-Term Bridge Monitoring
Network Volume 3: Monitoring of a Multi-Steel Girder
Composite Bridge – I-91 SB over the
Mattabesset River in Cromwell (Bridge #3078)**

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16. Abstract

This report describes the instrumentation and data acquisition for a multi-girder, composite steel bridge in Connecticut. The computer-based remote monitoring system was developed to collect information on the girder bending strains. The monitoring system was installed in 2004 to collect girder strains. The bridge is part of a network of bridges in a long-term research project to evaluate the performance of a variety of bridges in Connecticut. Data has been collected over a multi-year period using normal vehicular traffic. A series of papers has been generated to explore how the monitoring of this bridge can provide information of use to the Department of Transportation. The initial study involved the development of the data collection approach, used load tests and finite element analyses to describe the behavior, and used the data to make comparisons with the AASHTO Specification Requirements. The next study continued the development of the data from normal truck traffic to determine load and patterns and to propose guidelines for the long-term structural health monitoring of this bridge. The third study demonstrated that the monitoring system can also be used as a Bridge Weigh-In-Motion system. The monitoring system serves as a non-intrusive system to provide information on both the quantity and weights of trucks crossing the bridge. In the next study damage measures were developed for this bridge and compared to the inherent variability of actual bridge measurements to determine the minimum level of damage that can be detected by the system. The final study described in this report identifies and quantifies different data qualification measures needed for the structural health monitoring of this bridge.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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I-91 SB over the Mattabesset River in Cromwell (Bridge #3078)

INTRODUCTION

Researchers at the University of Connecticut and in the Connecticut Department of

Transportation have been using field monitoring to explore the behavior of bridges during the

past two and a half decades (Lauzon and DeWolf, 2003). This report is based on the research

project that was developed to place long-term monitoring systems on a network of bridges in

the state (DeWolf, Lauzon and Culmo, 2002; Olund and DeWolf, 2007; DeWolf, Cardini,

Olund and D'Attilio, 2009). The first system was installed in 1999, and since then five other

bridges have been added to the network. The bridges have been selected because they are

important to the state's highway infrastructure and because they are typical of different bridge

types. Each monitoring system has been tailored to the particular bridge, using a variety of

sensors, and all data is collected remotely. As with many of our busier highways, it is not

possible to close a bridge for monitoring, and thus all systems collect data from normal

vehicular traffic. The goal of this research has been to use structural health monitoring to

learn about how bridges behave over multi-year periods, to provide information to the

Connecticut Department of Transportation on the behavior of the state's bridges, and to

develop structural health monitoring techniques that can be used to show if there are major

changes in bridges' structural integrity.

The current four-year phase in this long-term project has focused on installation and implementation of monitoring systems on two new bridges, substantial upgrading of the monitoring equipment, with addition of video collection, and development of techniques for long-term structural health monitoring. Specifically for this bridge, during the current project the monitoring system was replaced, which included removal of the previous data acquisition system and replacement with National Instruments CompactDAQ hardware connected to a Small Form Factor PC. The new data acquisition system allows for enhanced capabilities, among which are improved sensor resolution, anti-aliasing of accelerometer signals, internet connectivity for viewing and archiving of data, and flexibility for future expansion, including installation of new temperature transducers connected to the system to help account for temperature effects. This new bridge monitoring system also underwent a full data qualification and error quantification. The finite element model was updated to quantify the changes in the various damage measures (DMs) for specific types of damage. The sensitivity of the DMs is quantified for the various damage cases in order to identify the most appropriate DM(s) for implementation for long-term monitoring. These efforts are documented within the report.

This report is for a three span, each simply supported, composite steel girder bridge over a river in Cromwell (Inventory Number 3078). The bridge serves the southbound traffic and has three lanes of traffic, with breakdown lanes on both sides. An aerial view of the bridge is shown in Figure 1. The bridge studied is the lower bridge in the figure, and the three transverse white lines indicate the support locations for the three spans. Figure 2 shows a side

view. A view from underneath the bridge, with the main girders and cross-bracing, is shown

in Figure 3. The bridge was selected for monitoring because it is typical of many multi-girder

steel bridges in the state interstate system and because it is subject to heavy traffic loading.

Monitoring began in 2004.

Figure 1. Aerial View of Steel Multi-Girder Bridge

Figure 2. Side Elevation

Figure 3. Bridge Superstructure

The bridge elevation is shown in Figure 4. The steel girders are simply supported at the interior supports, and the girders sit on bearings at the ends. Figure 5 shows a cross section. All girders in Spans 1 and 2 have a W36X194 section with a partial length cover plate in the central span areas. The girders in Span 3 have a W36X150 sections with a partial length cover plate in the central span areas. Diaphragms are located at the quarter points in Spans 1 and 2, and at the third points in Span 3. The concrete deck is 7.75 inches thick, with an additional 2.5 inch wearing surface.
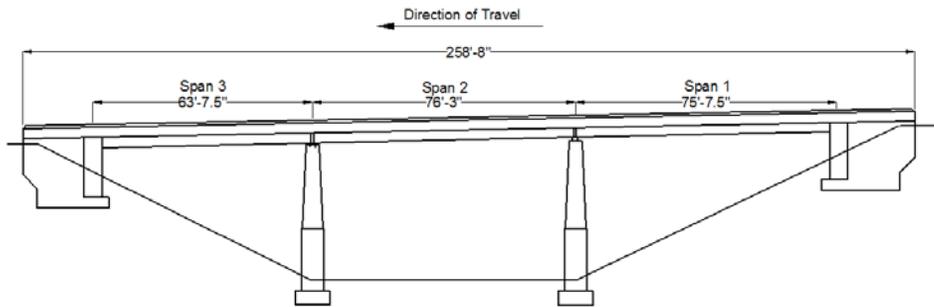
Figure 4. Elevation of Steel Multi-Girder Bridge
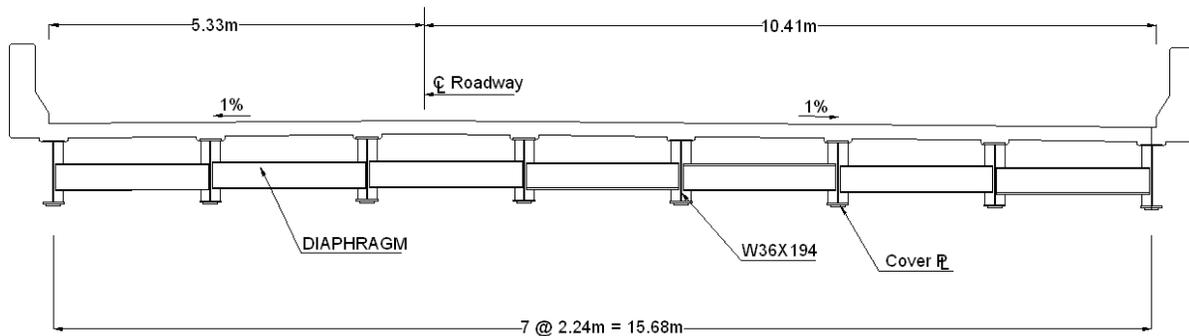
Figure 5. Bridge Cross Section

OBJECTIVES AND SCOPE OF STUDY

This bridge was selected as part of a research project, designed to implement long-term monitoring systems on a network of different bridges in Connecticut, using different bridge types and sensor combinations. This bridge was added to the project because it is typical of many smaller interstate bridges in Connecticut, and because it is on one of the state's busiest highways, with a large volume of automobile and truck traffic.

The monitoring system is designed to provide information on load histories, to learn about the distribution of the loads to the eight girders, and to evaluate the deck/girder composite action. This information is to be used to develop structural health monitoring techniques that could be used on similar bridges to determine if there are significant changes in the structural behavior, ones that would be indicative of major damage in either the girders or the deck.

At the end of the initial monitoring period, it became clear that another feature worth exploring was the evaluation of the system for use as a non-intrusive bridge weigh-in-motion monitoring system. This was then added to the objectives for the second part of the study.

INSTRUMENTATION AND DATA ACQUISITION

The monitoring system was designed with 20 strain gages, for live load monitoring. In the first phase of the project, 16 gages were located at the center of the end span entered by the

traffic, and four gages were located close to the interior support to check for continuity. As
explained below, the four gages located close to the interior span were moved to the second
span after the initial study. The initial location of the gages is shown on a plan of the bridge in
Figure 6. Pairs of gages were placed at the midspan of each girder, one is two inches below
the bottom of the top girder flange, and one is two inches above the bottom of the top girder
flange.
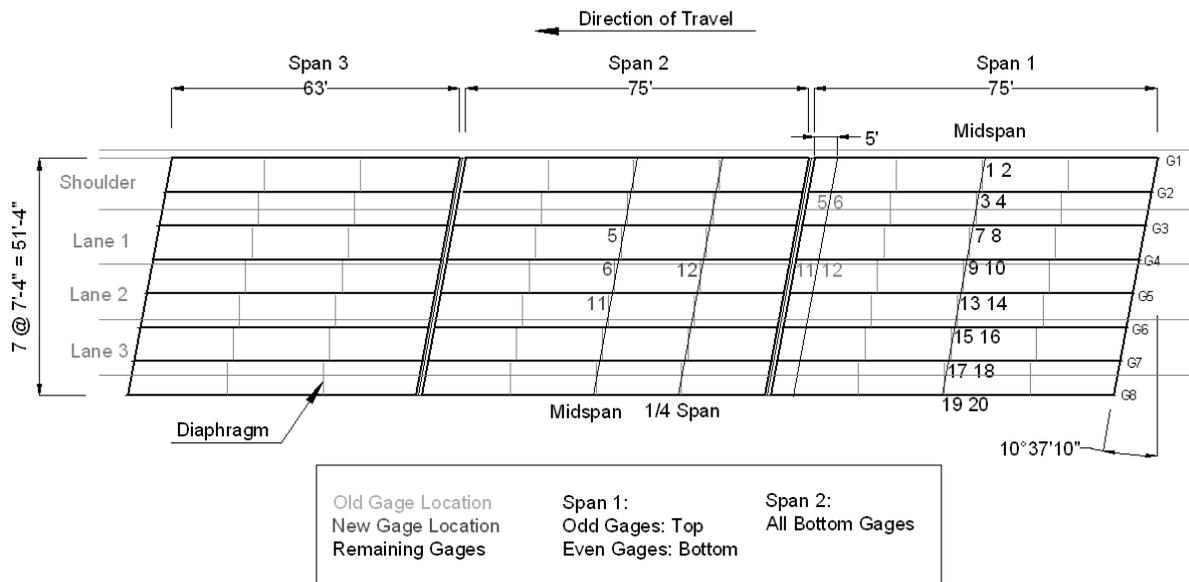
Figure 6. Location of Sensors on Plan View of Bridge

A photo of one of the strain sensors, applied on the web of a girder near the bottom, is shown
in Figure 7. The sensor is on the right. A photo with a pair of sensors, one near the top and
one near the bottom, is shown in Figure 8.
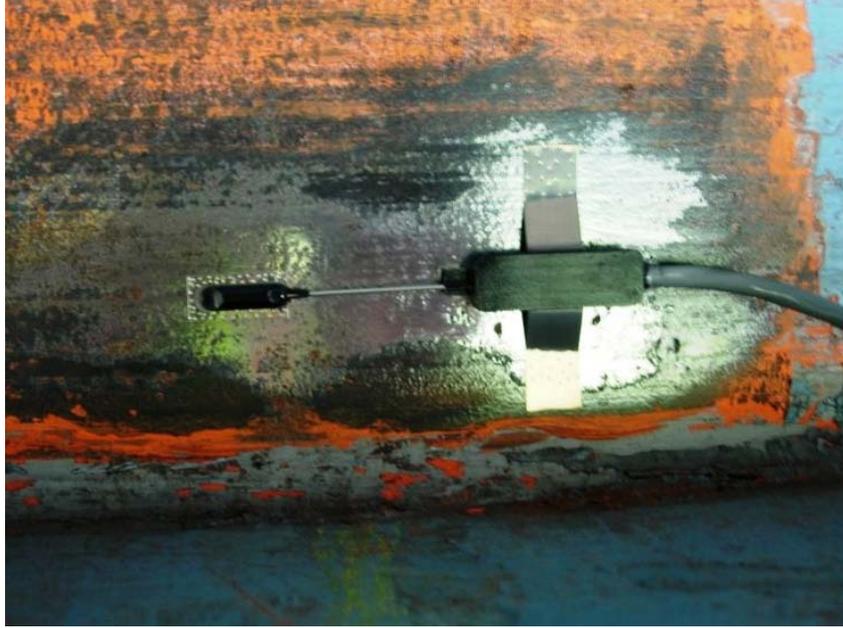
Figure 7. Strain Sensor

Figure 8. Strain Sensors Located Near Top and Bottom of Girder

The strain gages are connected to an on-site computer located in a weatherproof box, located

underneath the bridge on the closest abutment, shown in Figure 9.

Figure 9. Instrument Cabinet with On-Site Computer

The monitoring system was purchased as a package, including all sensors and field equipment.

The system records the strain at 0.02 second intervals (50 Hz) at a 1 micro-strain resolution.

While this is sufficiently accurate to capture peek strain values for trucks crossing the bridge,

it is not sufficiently accurate to get full dynamic effects, i.e. to determine impact loads. The

computer is linked remotely to a computer at the University of Connecticut, where data

collection can be managed and saved.

The system works continuously, though only data associated with larger vehicles is saved using a trigger approach. When one of the strain gages at the bottom of the girders, directly under the outside lane used by trucks, exceeds a set level, data is saved for all strain gages, beginning with a time just before the strain level is reached until a time just after the strain level is reached. This assures that all data is saved for the full passage of the truck. Typically, data associated with trucks weighing 20 kips or larger is saved.

After the first three studies were completed, the system was upgraded, as explained below.

DATA ANALYSIS FOR STUDIES PRIOR TO UPGRADING OF MONITORING SYSTEM

There has been a series of studies using the extensive data collected over multi-year periods from this bridge. The initial study involved the development of the data collection approach, and it used load tests and finite element analyses to fully describe the behavior. There were two sets of load tests using known five-axle trucks. Comparisons were made with the AASHTO Specification Requirements. The next study continued the development and study of the data, based on use of normal truck traffic, both to refine the determination of load patterns and to propose guidelines for the long-term structural health monitoring of this bridge type. The third study demonstrated that the monitoring system can also be used as a bridge weigh-in-motion system. The monitoring system serves as a non-intrusive system to provide information on both the quantity and weights of the trucks crossing the bridge. Following

these three studies, the monitoring system was upgraded and expanded to include video monitoring. The system is currently being used with a finite element model to explore the use of the structural health monitoring system to determine if there are significant changes in the structural behavior that would be indicative of major damage to either the girders or the deck.

Development of Data Collection Approach

The implementation of the system and development of the data collection approach began with Chakraborty's research as reported in his thesis (2005) and reported by Chakraborty and DeWolf (2005, 2006). The monitoring was initially set up to collect information on the loading from large vehicles and use this to evaluate the behavior of the bridge. Areas of interest included the number of vehicles using the bridge, the distribution of strains in the different girders, the shift in the neutral axis and the distribution of the loads to the different girders.

The background for the strain monitoring of this bridge is based on a number of short-term strain monitoring studies carried out during the past 20 years to address specific concerns on the in-service steel bridges' behavior in Connecticut, reviewed by DeWolf, Lauzon, and Culmo (1998) and by Sartor, Culmo, and DeWolf (1999). Similar studies include those by Chajes and Shenton (2005), Barr, Eberhard and Shenton (2001), Wang, Liu, Huang and Shahawy (2005) and Yakel and Azizinamini (2005).

The primary objective of this monitoring system was to collect data associated with large vehicles, i.e. trucks, and a study of the initial data demonstrated that a threshold at 20 micro-strain for the lower strain gages would serve this purpose. This is associated with trucks weighing 20 kips or larger. Girder G4, located under the lane normally used by trucks, was selected to trigger the data collection. The field monitoring data was used to study the strain distribution across the eight girders, the location of the neutral axis in the beams that was designed to be composite with the slab, and the live load distribution factors. Examples from this research are given below.

Figure 10 shows a typical plot of the strains in a girder due to the passage of a truck across the span. The solid line is the tensile strain at the bottom of the web, and the dashed line is the compressive stress at the top of the web, which is near the neutral axis. The two peaks in the tensile strain are distinct and a function of the multi axles.
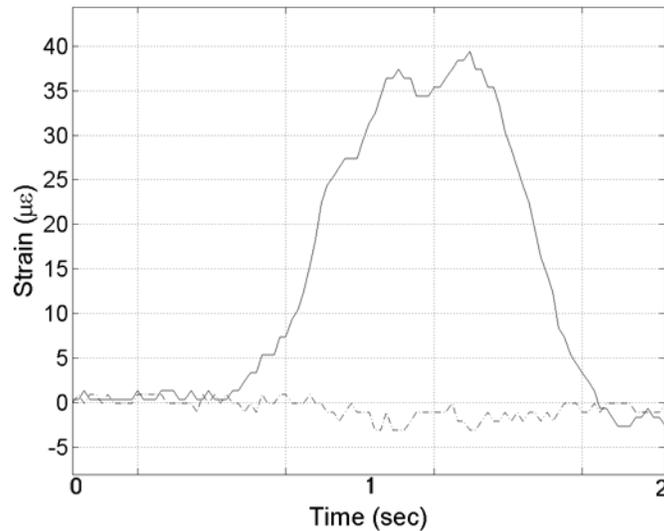
Figure 10. Strain at Top and Bottom of Girder G4

The location of the neutral axis was determined using the strains at the top and bottom of the web, using linear elastic behavior. Figure 11 shows the position of the neutral axis for girder G4 as a truck crosses the bridge. The dashed line corresponds to the calculated neutral axis determined using the properties of the composite section. The small extension of the neutral axis into the slab is due to a dynamic effect since it occurs over a very short time.
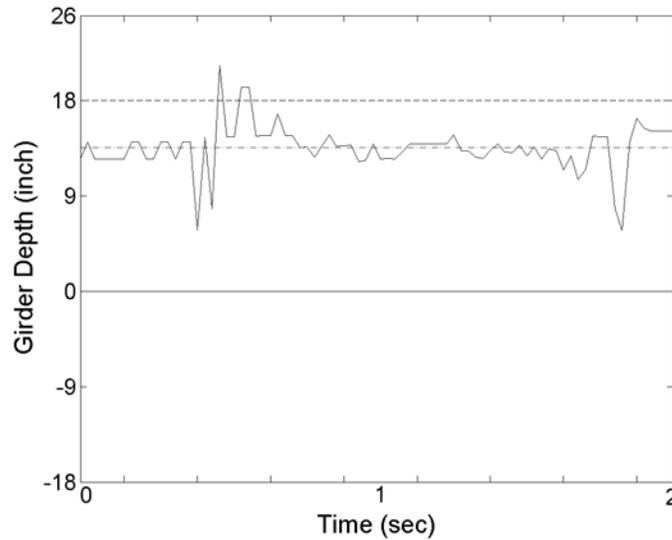
Figure 11. Position of Neutral Axis for Girder G4

An example of the distribution of the truck load over the eight girders is shown in Figure 12. This shows the strains at the bottom of each of the girder webs.
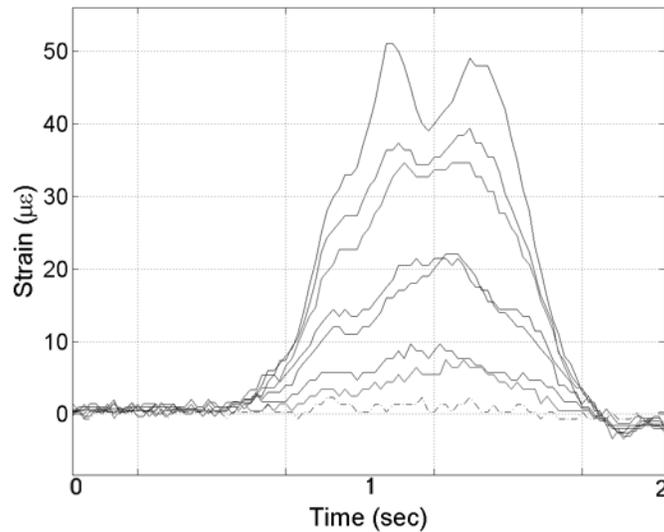
Figure 12. Tensile Strains at Bottom of Eight Girders

The field data was also compared to the design value from the AASHTO Specification

Requirements, using the specification in place when the bridge was designed. As shown by

Chakraborty (2005) and Chakraborty and DeWolf (2006), the maximum stresses obtained

from the field data were typically less than half that used in the design of the bridge, based on

the largest truck allowed by the AASHTO Specification. This demonstrates that the live load

stresses required by the specification are significantly higher than routine live load values.

This is due to a greater distribution of the truck load over more girders, redundancies in the

bridge due to constraints that were not modeled in the analysis, and the fact that the bridge

does not experience maximum truck weights on a regular basis.

As a further check of the field data, two sets of load tests were conducted, each using a truck

of known weight. One was a larger truck that was fully loaded and the other was a smaller

truck. The results of these load tests were compared to those from a finite element analysis.

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The finite element model was based on modeling the deck slab with 4-noded, 6-degree of freedom shell elements and the girders were modeled with 2-noded, 6-degree of freedom beam elements. Following the approach used by Chan and Chang (1999) and Chung and Sotelino (2005), the beam elements were connected to the slab using rigid links modeled with beam elements. Figure 13 shows the strains at the bottom of girder G5 for the larger truck, using the field data and the finite element model. The field data is the dashed line and the finite element data is the solid line. A study of the correlation between the two sets of data shows a correlation coefficient of 0.92.
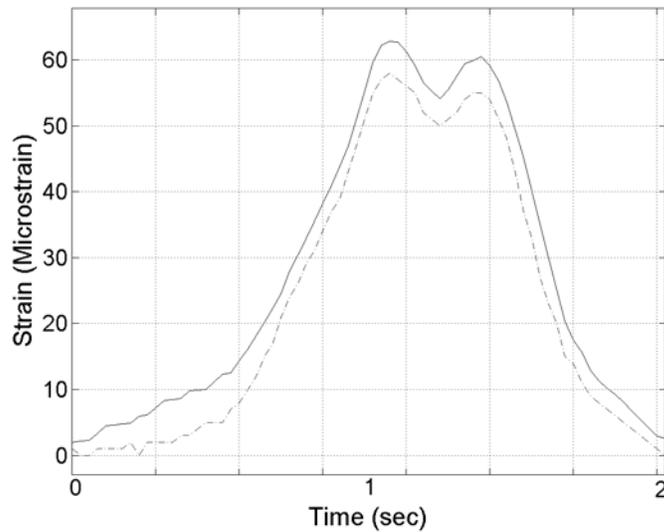
Figure 13. Tensile Strain in Girder G5 for Test Truck –
Field Data and Finite Element Analysis

The strains obtained from the finite element analyses are typically higher than those obtained from the load tests. One reason for this is the fact that the small stiffening effect of the parapets was not included in the finite element model. In addition, there are always

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constraints in real bridges that are often difficult to model in a finite element analysis. As an example, actual supports are never perfectly pinned. The maximum difference between these two results was 8% for all girders, for all tests. In addition, the finite element model was used by Chakraborty and DeWolf to look at other comparisons.

Development of Basis for Structural Health Monitoring

A review of the literature on strain monitoring has shown that field strain monitoring studies have been used for load rating, damage evaluation, and comparison of field results with design guide values (Shenton, Jones, and Howell, 2004; Nowak, Sanli, and Eom, 1999; Bhattacharya, Li, Chajes, and Hastings, 2004). These studies have each addressed specific concerns in an existing bridge.

The goal of the research reported in this section (Cardini, 2007; Cardini and DeWolf, 2009 – Structural Health Monitoring Journal) was to use the long-term strain monitoring data to develop an approach for continuous long-term structural health monitoring. Of interest was the ability to determine if there is a significant change in the structural integrity. Changes in structural integrity could include large cracks in one of the girders or significant degradation of the concrete deck. As an example, the collapse of a Rhode Island Interstate Bridge was averted when a passerby observed a severe crack at midspan in the exterior steel girder in a multi-girder bridge (Shores, 1988). The bridge had been inspected approximately six months prior to the appearance of this crack. Another example of girder cracking is the Hoan Bridge

in Wisconsin (NCHRP, 1999). In either of these examples, continuous monitoring could have provided information that there were significant changes in the structural integrity.

At the beginning of this study, the data from the four gages placed near the interior support in the first span was used to show that there is no continuity at the interior support; thus the gages were moved to the second span (See Figure 6). Placing these four gages in the second span provided a basis to determine speed and ultimately vehicle weights, discussed in the next section in this report.

A review of the continuing field data and further finite element analyses was used to categorize the data into areas that were felt useful for long-term structural health monitoring. Three areas were proposed: (1) distribution factors can be used to verify that truck loads are distributed to the eight girders as designed, and are necessary to determine if there is damage either to a specific girder or the deck in the region of the girder; (2) peak strains can be used to check fatigue life and potential girder failure; (3) the neutral axis location can be checked to see if large tension stresses are developing in a girder, indicating that there may be problems with the deck durability. The following briefly reviews these three approaches.

Long-term distribution factor monitoring is based on the use of the range of distribution factors determined for each girder. The distribution factor is the percentage of the total load that is resisted by a specific girder. This calculation uses the peak strains associated with each truck crossing. A range of acceptable distribution factors is produced from a sample of normal truck traffic and is checked periodically for changes. The first step in determining the

range of acceptable distribution factors is to determine if the truck is traveling in Lane 1 or 2, which can be done with a review of the peak strain values. As an example, the distribution factors from multiple trucks crossing Girder G3 in the outer lane are shown in Figure 14.
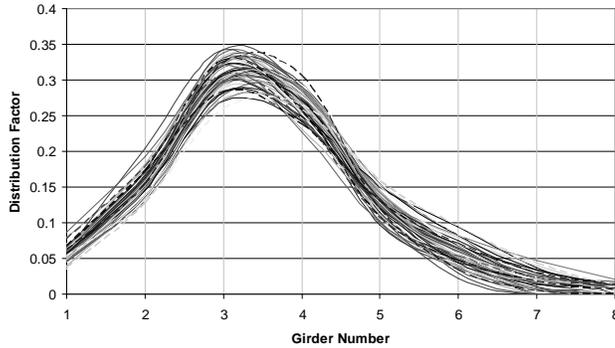
Figure 14. Plot of Distribution Factors for Trucks Crossing in Outer Lane

Figure 15 shows the envelope for the distribution factors for trucks crossing in both the outer lane and the middle lane. Under a wide variety of trucks, at different speeds, individual distribution factors should fall within the two curves shown in this figure. Should one or more girders begin to fail, plots of some of the distribution factors will drift outside this envelope.
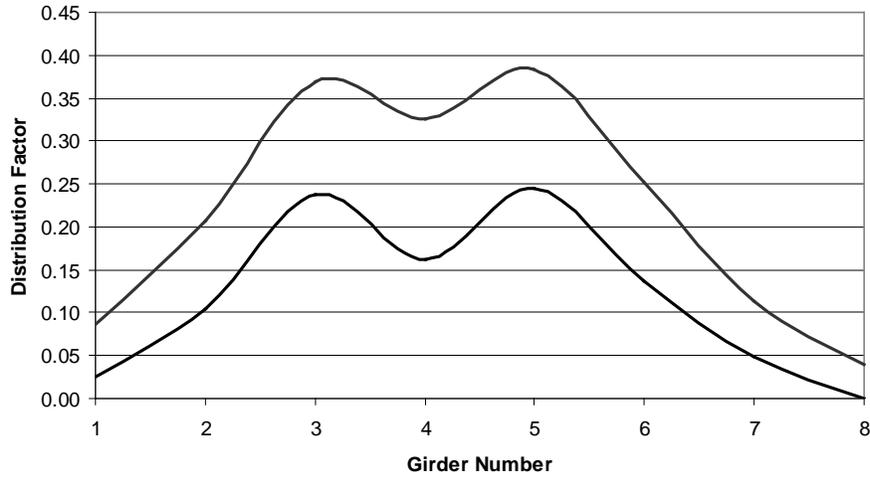
Figure 15. Distribution Factor Envelope – Outer and Middle Lane

A second proposed area is to check for peak strains. The peak strains for trucks over a typical 24-hour period are plotted in Figure 16. There are a few outlying trucks with strains above these levels. Typically, these are either over-weight trucks or permit trucks. For long-term structural health monitoring, the truck peak strain data should be checked periodically to ensure that large peak strains are not occurring on a frequent basis.
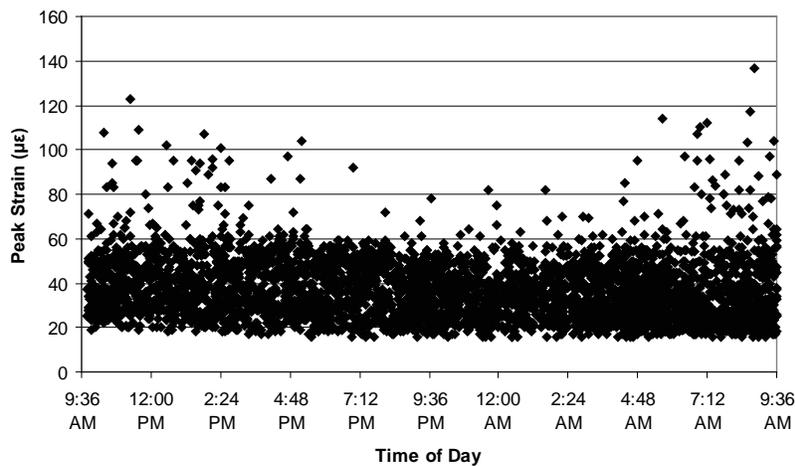
**Figure 16. Peak Strains from Truck Traffic over 24 Hour Period –
Outer and Middle Lane**

The third proposed area is to evaluate the neutral axis location in each girder. If the neutral axis moves downward on a regular basis, there is some type of failure in either the concrete deck or in the shear connection. If the neutral axis moves upward into the concrete deck, there could be problems with the girder. Figure 17 shows a plot of the neutral axis versus the peak strain.
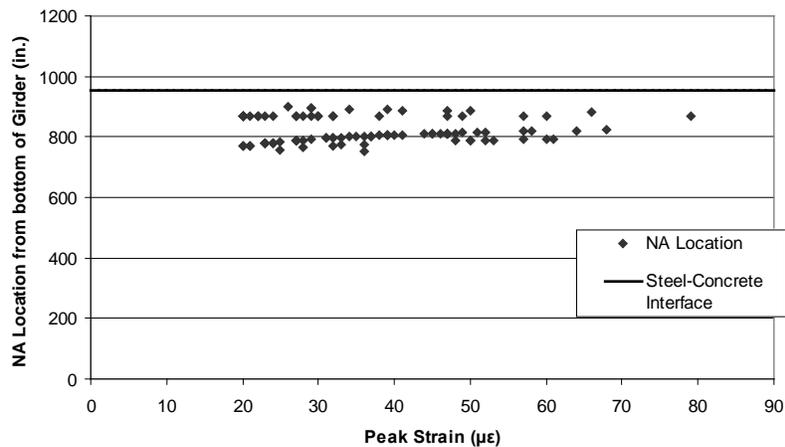
Figure 17. Neutral Axis Location versus Peak Strain

Use of Monitoring System for Bridge Weigh-In-Motion

A study of the all of the data collected with this bridge demonstrated that the monitoring system could be used as a bridge weigh-in-motion system. The applied system has the advantage of not using any axle detectors in the roadway; instead all analyses are performed using strain gages attached directly to the steel girders, providing for a long-term monitoring system with minimal maintenance. This study was carried out by Cardini (2007) and Cardini and DeWolf (2009 – ASCE Bridge Journal). The goal was to show that the field data can be

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readily applied to gain important information on the quantity and weights of the trucks crossing the highway bridge.

Bridge Weigh-In-Motion systems were first proposed by Moses (1979). Further work was carried out by Moses and Ghosn (1983), Moses,et al. (1985, 1986, 1986), Snyder et al. (1985), Ghosn and Xu (1988), Kim, Sokolik, and Nowak (1996), Znidaric, Lavric, and Kalin (2002), Znidaric, Kalin, and Lavric (2002), Gonzalez and O'Brien (2002), Quilligan, Karoumi, and O'Brien (2002), Dunne, O'Brien, Basu, and Gonzalez (2005), Ojio and Yamada (2002, 2005), Jacob and O'Brien (2005), O'Brien, Znidaric and Ojio (2005), and Yakel and Azizinamini (2005).

The review of the literature has shown that there are different approaches for bridge weigh-in-motion methods. The factors that need to be considered in the selection of a method include pavement smoothness, calibration procedure, superstructure type, span and support conditions, and bridge geometry. These are reviewed in the references by Cardini. Based on the bridge type, the method used by Ojio and Yamada (2002) was selected for study. This method works where the individual axle peaks are not important, as long as groups of axles are detected. The method computes the gross vehicle weight (GVW) by integrating the strain response curve. It relates the speed to the weight of the truck, using a truck of known weight to calibrate the system. An example of a strain response curve is shown in Figure 18. The general principle is that as a load passes over a bridge at a certain speed it produces an influence area recorded by strain readings. The influence area is the area under the strain curve, multiplied by the speed. In this study, the speed is determined by measuring the time

between the peak strains determined from two strain gages separated in the direction of travel. As an example, if the truck is in lane 1, gages 8 and 5 are used as a basis. The method requires data from a load test where the speed and weight of the truck are known.
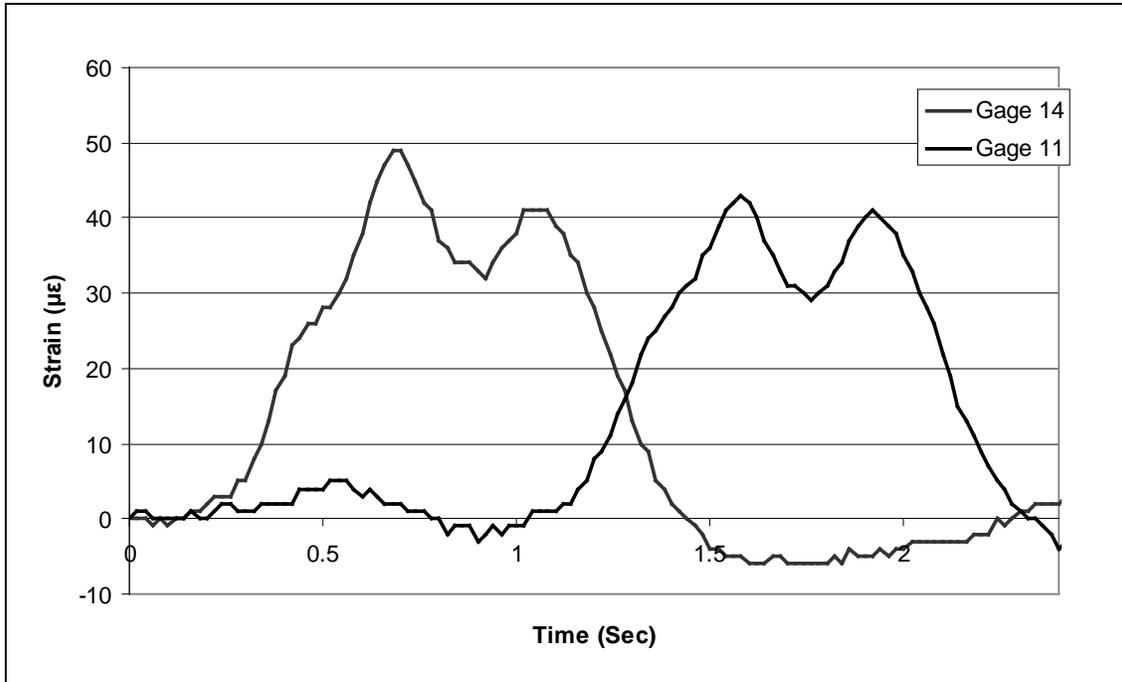
Figure 18. Strain versus Time for a Typical Truck for Gages 14 and 11

This method is based on having only one truck on the bridge at a time. Moses and Ghosn (1983) developed an algorithm to separate weights of multiple trucks; but for the bridge in this study, there were not sufficient examples where two trucks were on the bridge span simultaneously to test their algorithm. The bridge is relatively short, and vehicles typically cross the bridge in a little less than one second. Using this approach, the results from a typical

weekday over a 24-hour period are plotted in Figure 19. This shows a histogram of trucks crossing the bridge, with their estimated weights.
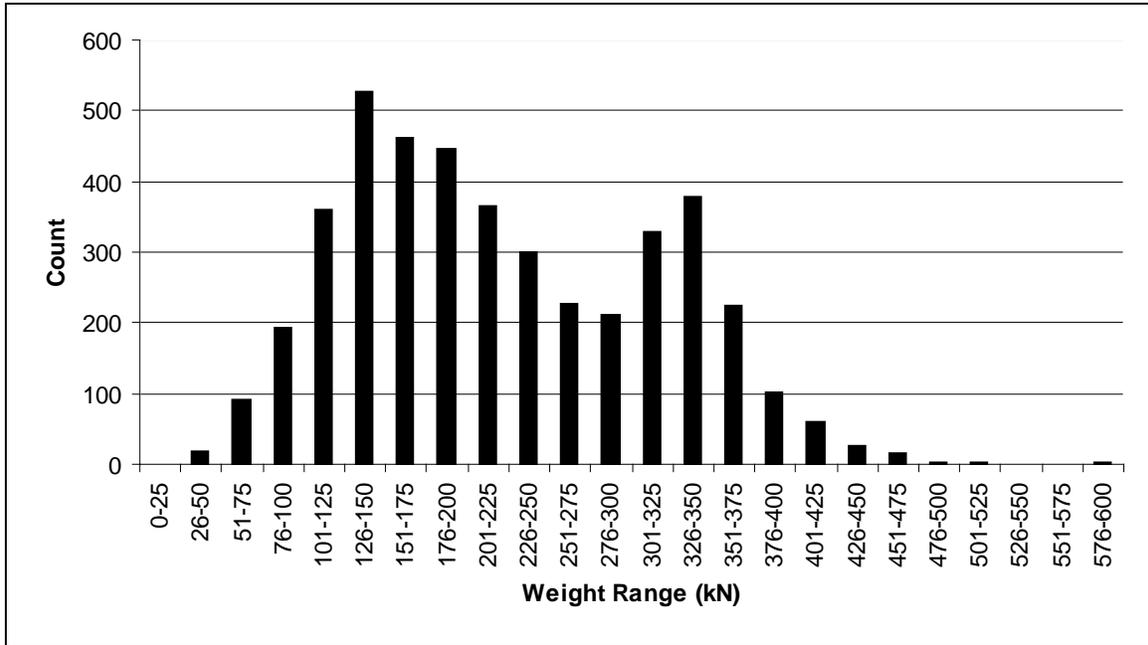
Figure 19. Range of Truck Weights over 24-Hour Period

Figure 19 demonstrates the use of the bridge-weigh-in motion system as adapted for the bridge studied. This provides useful statistical information on the volume and weights of trucks using this bridge.

DESIGN OF NEW MONITORING SYSTEM

Consistent with efforts to upgrade the monitoring systems and capabilities on other bridges in the project, the monitoring system was replaced in 2010. This included removal of the

previous data acquisition system and replacement with National Instruments CompactDAQ hardware connected to a Small Form Factor PC. This CompactDAQ has four modules installed that provide power to the sensors and collect data measurements from the sensors previously installed on the bridge. These modules not only support the input of RTDs, but they can measure resistance, voltage, and current as well. This combined with the remaining four expansion slots on the CompactDAQ will enable researchers to add a wider variety of sensors on the bridge for the purposes of structural health monitoring. The updated bridge monitoring system at the Cromwell Bridge provides:

- improved resolution of the sensor measurements with the 24-bit system;

- connectivity to the Connecticut Department of Transportation computer network over the internet, allowing for full access to the bridge monitoring computers;

- potential for real-time remote viewing of the bridge monitoring data from any PC on the CTDOT network using a java-based Real-Time Data Viewer (RDV);

- capability for automated data archival to an offsite FTP server; and

- flexibility to expand the current system to new sensors.

FURTHER DATA ANALYSIS WITH UPGRADED MONITORING SYSTEM

Plude (2011) updated the finite element model to quantify the changes in the various damage measures (DMs) for specific types of damage. The sensitivity of the DMs is quantified for the various damage cases in order to identify the most appropriate DM(s) for implementation for long-term monitoring.

Previous research has identified four damage measures (DMs) for this composite steel girder bridge (Cardini and DeWolf, 2009). The DMs considered are fundamental natural frequency, peak strain, strain distribution, and neutral axis location. While environmental and operational variability of bridge structures can affect their dynamic properties and response, it is assumed in this study that any variability is appropriately accounted for, as done by Scianna et al. (Scianna and Christenson, 2009).

A new finite element model was used to identify the appropriate DMs to use for specific failure modes. The bridge is modeled using approximately 50,000 plate elements to best capture the local crack behavior and global structural changes. The bridge model is loaded using the five-axle truck from Cardini and DeWolf (2009).

There are many different types of damage a composite steel girder bridge might experience. For this paper, three types of damage are considered: fatigue cracking due to truck traffic, impact of a truck passing under the bridge, and deterioration of the bridge deck. Cases 1 and 2 represent fatigue related damage to the bridge. Cases 3 and 4 capture potential damage as the result of a truck impacting the exterior girder of the bridge. The fifth damage case represents damage to the bridge deck. The first three damage cases are shown in Figure 20.
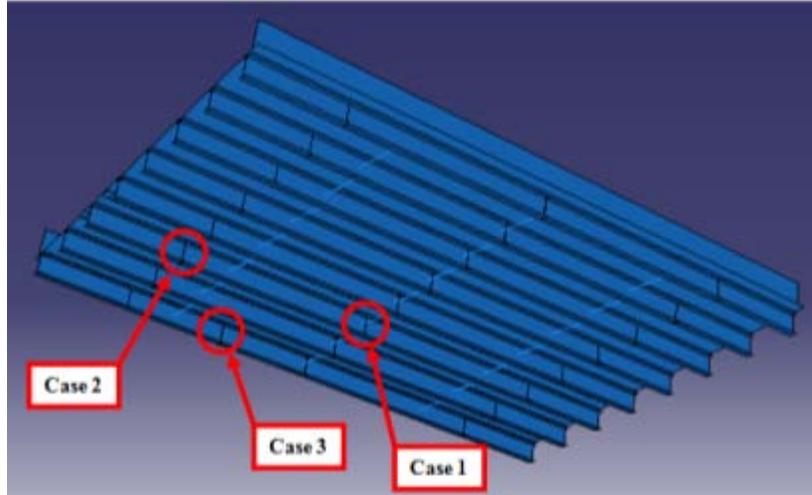
Figure 20. Assumed Damage Locations

For damage cases 1 through 3 where cracking of the girder is involved, a total of four levels

of damage were used to model the progression of a 3/8-inch-wide crack, as in Farrar and

Jauregui (1997).   Figure 21 shows a drawing of the cross section of the G3 girder for all four

damage levels.
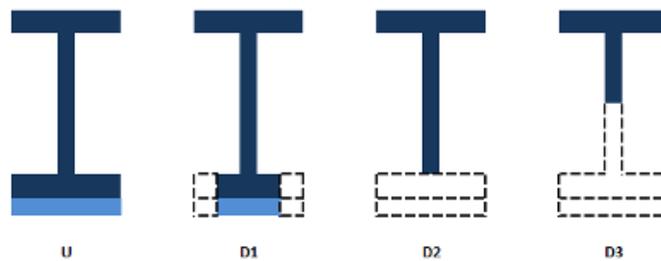
Figure 21. Cross-Section Levels of Damage

Results of Finite Element Analysis

The results of the finite element analysis indicate that for this bridge, fatigue cracks at the midspan of a girder are best identified by peak strain, strain distribution, or neutral axis for the damaged girder (G3 for this study). The fatigue crack located at the end of the coverplate is best identified by peak strain for the two girders immediately adjacent to the damaged girder (G2 and G4 for this study) or strain distribution of the damaged girder (G3 for this study). Locating additional sensors at the ends of the coverplates would provide more sensitive measurements and help better identify the damaged girder. The fatigue crack in the exterior girder initiated by impact loading at the 1/3 span is best identified by peak strain or neutral axis of the damaged girder. The general conclusion is that the sensitivity of the damage measures to fatigue cracking is dependent on the distance between the damage location and the sensor location. By placing sensors at or very near the location of damage, the sensitivity of the damage measures is increased and becomes isolated to the damaged girder. While midspan and the ends of the coverplates are obvious areas of high stress, placing additional strain sensors in locations where impact loading has occurred is also suggested to monitor the initiation of fatigue cracking at these locations.

Noncomposite behavior between the deck and the girder can be identified using all of the damage measures; however, it is particularly sensitive to the natural frequency and neutral axis damage measures with the neutral axis of the damaged girder being the most sensitive. Therefore, given the unique sensitivity of the natural frequency damage measure, if a change

in the peak strain and strain distribution damage measures *as well as* the neutral axis and natural frequency is observed, noncomposite behavior can be identified.

The initiation of bridge deck deterioration is not readily observed by the strain sensors located on the steel girders. Considering the previously discussed damage measures, deck deterioration has been difficult to detect. Of the four damage measures discussed here, neutral axis exhibits the most change, albeit a small change, and is making it the most likely damage measure to indicate problems with the deck.

DATA QUALIFICATION AND QUANTIFICATION

Recent work (Trivedi, 2009; Trivedi and Christenson, 2009; Prusaczyk, et al., 2011; and Prusaczyk, 2011) proposed a data qualification procedure for bridge monitoring and provided data qualification for this bridge. Data qualification is an area that has not previously been addressed in field monitoring studies on bridges. This is one of the key areas addressed as part of the upgrade of the bridge monitoring systems in the current phase of this research. The quality of measured data is of critical importance in drawing reliable conclusions from data analysis in bridge monitoring. Data qualification categorizes the quality of measured data. There is currently no formalized quality certification system in place for data qualification in bridge monitoring. Data qualification as proposed for bridge monitoring is divided into identification of data anomalies and error and noise quantification. The results of the data qualification for the upgraded bridge monitoring system on the Cromwell highway bridge are shown in Figure 22.

Bridge: Cromwell
Location: Cromwell, CT
Highway: I-91
NBI #: 03078

Sensor Information		Signal Clipping	Intermittent Noise Spikes	Signal Dropouts	Spurious Trends	Periodicy	Aliasing	Quantization Error (%)	Working SNR (dB)
Sensor	Sensor Type								
1	Strain Gage	--	--	--	--	x	--	7.0E-09	4.93
2	Strain Gage	--	--	--	--	x	--	7.0E-09	10.01
3	Strain Gage	--	--	--	--	x	--	6.9E-09	19.26
4	Strain Gage	--	--	--	--	x	--	7.0E-09	25.03
5	Strain Gage	--	--	--	--	x	--	6.9E-09	24.22
6	Strain Gage	--	--	--	--	x	--	7.0E-09	26.10
7	Strain Gage	--	--	--	--	x	--	7.0E-09	10.98
8	Strain Gage	--	--	--	--	x	--	7.0E-09	29.18
9	Strain Gage	--	--	--	--	x	--	7.0E-09	13.46
10	Strain Gage	--	--	--	--	x	--	6.9E-09	30.61
11	Strain Gage	--	--	--	--	x	--	7.0E-09	27.30
12	Strain Gage	--	--	--	--	x	--	6.9E-09	30.78
13	Strain Gage	--	--	--	--	x	--	7.0E-09	5.48
14	Strain Gage	--	--	--	--	x	--	7.0E-09	30.49
15	Strain Gage	--	--	--	--	x	--	7.0E-09	11.67
16	Strain Gage	--	--	--	--	x	--	7.0E-09	29.59
17	Strain Gage	--	--	--	--	x	--	7.0E-09	12.27
18	Strain Gage	--	--	--	--	x	--	6.9E-09	26.76
19	Strain Gage	--	--	--	--	x	--	7.0E-09	7.74
20	Strain Gage	--	--	--	--	x	--	7.0E-09	20.08

Figure 22. Results of Data Qualification for Cromwell Bridge Monitoring System

There are no signal clipping, intermittent noise spikes, signal dropouts or spurious trends observed in the measured sensor data. There is a periodicity observed, a ground loop, at 60 Hz. This periodicity is well above the sensor's effective bandwidth of 0-20 Hz and is addressed through filtering. No aliasing is present in the measurements. The quantization error is negligible. The working signal-to-noise ratio (SNR) ranges from approximately 5 dB (signal is 1.78 times larger than the noise floor) to 30 dB (signal is 31.63 times larger than the noise floor). The lower SNRs are for the strain sensors located at the top of the girders where strains are near the neutral axis and smaller in magnitude. The strain sensors at the bottoms of the girders have acceptable SNRs.

CONCLUSIONS

Use of the strain monitoring system has been used to gain a better understanding of the actual behavior of this multi-girder steel concrete bridge. Three separate studies have been conducted with the initial monitoring system, and one is currently underway with the upgraded monitoring system.

The first study set up the monitoring basis, and it included load tests with known vehicle weights. This study demonstrated that the actual strain and stress levels are typically well below those used in the design process. The study included a detailed finite element study to gain further information on the actual bridge behavior.

Structural health monitoring approaches were studied in the second study. The goal is to provide warning of major changes in the structural integrity, such as failure of a beam or significant deterioration of the deck slab. The proposed structural health monitoring approach is based on continual evaluation of the following:

- monitoring of the distribution factors for the girders, based on using an envelope of distribution factors;
- monitoring of the peak strain values for each of the girders; and
- monitoring of the neutral axis location.

The third study describes the use of the monitoring system for use as a long-term bridge weigh-in-motion system that can be readily applied to multi-girder interstate bridges. The system is a feasible alternative to traditional weigh-in-motion systems since it non-intrusive; i.e., it is not necessary to install sensors in the roadway pavement. The data produced by this system can be used for traffic planning, load rating, and structural health monitoring.

The fourth study, using the upgraded bridge monitoring system, demonstrates that the sensitivity of the damage measures to fatigue cracking is dependent on the distance between the damage location and the sensor location. By placing sensors at or very near the location of damage, the sensitivity of the damage measures is increased and becomes isolated to the damaged girder. Furthermore, by examining multiple DMs it is possible to identify specific types of damage, such as noncomposite behavior between the deck and the girder.

The fifth study, again using the upgraded bridge monitoring system, developed and applied a data qualification procedure to the upgraded bridge monitoring system on this bridge. The data anomalies and error quantification is provided in this report. The upgraded bridge monitoring system is shown to provide high quality sensor data for use as a basis for long-term structural health monitoring on this bridge.

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