HISTORY OF

CONNECTICUT'S SHORT-TERM STRAIN PROGRAM

FOR EVALUATION OF STEEL BRIDGES

July 2009

John T. DeWolf
University of Connecticut

Report No. CT-2251-F-09-6

Connecticut Department of Transportation

Bureau of Engineering and Construction
Research and Materials

James M. Sime, P.E.
Manager of Research

Ravi V. Chandran, P.E.
Division Chief, Research and Materials

A Project in Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Technical Report Documentation Page

1.Report No. CT-2251-F-09-6	**2. Government Accession No.**	**3. Recipients Catalog No.**
4. Title and Subtitle History of Connecticut's Short-term Strain Program for Evaluation of Steel Bridges		**5. Report Date** July 2009 **6. Performing Organization Code** SPR-2251
7. Author(s) John T. DeWolf, Ph.D., P.E.		**8. Performing Organization Report No.** SPR-2251
9. Performing Organization Name and Address University of Connecticut Connecticut Transportation Institute Storrs, CT 06269-5202		**10. Work Unit No. (TRIS)** **11. Contract or Grant No.** CT Study No. HPR-2251 **13. Type of Report and Period Covered** Final Report 7/1/2006 to 6/30/2009
12. Sponsoring Agency Name and Address Connecticut Department of Transportation 2800 Berlin Turnpike Newington, CT		**14. Sponsoring Agency Code** HPR-2251
15. Supplementary Notes This study conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration		

16. Abstract

Non-destructive strain monitoring has been used for two decades on Connecticut's bridges to supplement visual field inspections. These studies have addressed a wide range of problems, including fatigue cracking in diaphragm connections, cracked secondary connections, main girder cracking, load ratings, over-load conditions, and concerns with movable bridges involving drive mechanisms and counter-weight supports. Monitoring has often shown that repairs are not necessary, and when necessary, the data collected in the monitoring has been used to provide information on how best to design the repair. The benefit from the monitoring program during the past two decades has saved the State of Connecticut millions of dollars, well below the cost of implementing the monitoring program.

17. Key Words	**18. Distribution Statement**
Bridge monitoring, testing, steel bridges, instruments for measuring specific phenomena, strain gages for stresses	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA. 22161

19. Security Classif. (Of this report)	**20. Security Classif.(Of this page)**	**21. No. of Pages**	**20. Price**
Unclassified	Unclassified	29	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

DISCLAIMER

The contents of this report reflect the views of the author who is responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Connecticut Department of Transportation or the Federal Highway Administration. The report does not constitute a standard, specification or regulation.

Acknowledgements

The University of Connecticut, the Connecticut Transportation Institute, and the Connecticut Department of Transportation are acknowledged for their joint participation in the ongoing bridge monitoring program, with funds provided over the years by both the Connecticut Department of Transportation and the U. S. Federal Highway Administration. This work could not have been carried out without the effort of many talented graduate students, some of whom are listed in the references.

Over the years, four research engineers in the Research Office at ConnDOT have been my co-principal investigators on much of the research summarized in this report. They are:

Robert G. Lauzon, Ph.D., P.E.

Eric G. Feldblum

Paul F. D'Attilio

Alireza Jamalipour, P.E.

Executive Summary

During the past two decades, the Connecticut Department of Transportation and the University of Connecticut have been using strain monitoring to provide information needed in the management of the bridge infrastructure in the State. These studies have been carried out when there have been questions about the performance of the State's bridges. The information has been used determine if repairs or replacements are needed. Often, as has been shown from these studies, repairs have not been needed, resulting in substantial savings in both costs and time.

The table on the following page summarizes the studies done on 18 bridges in Connecticut during the past two decades. The results indicate the benefits of carrying out strain monitoring, with estimated savings in costs where available.

Portable Strain Monitoring System Applications

Bridge Number	Town	Type of Bridge (s)	Problem/Concern	Outcome	Results
1	Bridgeport	Multi-girder bridges on I-95	Cracked diaphragm elements	Replace selected diaphragm elements	Design information
2	Bridgeport	Multi-girder bridges on I-95	Cracked diaphragm connections	Fewer repairs	Saved $2,000,000
3	Wethersfield	Bridge over Connecticut River	Cracked connections	Repair not required	Saved $250,000
4	Norwalk	Two Span girder bridge	Fatigue Cracking	Repair not required	Saved $50,000
5	Westport	Steel girder bridge on Parkway	Fatigue Cracking	Repair not required	Saved $50,000
6	Trumbull	Multi-girder bridge	Girder Strength	Repair not required	Saved $25,000
7	Seymour	Multi-span bridge	Cracked connections	Repair not required; length of project reduced by one year	Saved $250,000
8	North Haven	Skewed multi-girder bridge	Cracked Girders	Repair not required	Saved $10,000
9	New Haven	Moveable bridge	Counter weight hanger	Immediate repair verified	Safety
10	South Norwalk	Bascule bridge	Drive mechanism study	Provided designers with information needed for repairs	Design information
11	Mystic	Bascule bridge	Member forces	Provided designers with information needed for repairs	Design information
12	East Haddam	Swing truss bridge	Drive mechanism; Member forces	Provided designers with information needed for repairs	Design information

Portable Strain Monitoring System Applications - Continued

Bridge Number	Town	Type of Bridge (s)	Problem/Concern	Outcome	Results
13	Derby	Curved bridge	Deflection higher than expected in new bridge	Confirmed that design stresses not exceeded	Opened bridge on time
14	Willington	Multi-girder bridge	Corroded beam in multi-girder bridge	Renovation not required	Repairs not needed
15	East Granby	Multi-girder bridge	Subject to Overload vehicles	Stresses below design values	Safety
16	Devon	Old steel truss bridge for railroad	Aging	Provided designers with information needed for repairs	Design information
17	Stonington	Steel bridge overpass	Weight of paving equipment	Confirmed that design stresses not exceeded	Safety
18	Enfield	Bridge over Connecticut River	Cracking in tie plates	Provided designers with information needed for repairs	Safety

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)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°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)		
°C	Celsius	1.8C+32	Fahrenheit	°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)

Table of Contents

List of Figures

Chapter 1

Introduction

Structural problems in the bridge infrastructure system are generally attributable to aging, increased traffic volumes and increased vehicle weights. Those responsible for managing the infrastructure must balance the increasing number of problems with available resources. The decision to use limited resources depends on answers to a series of questions. Should a bridge be closed? Should a bridge be load-rated? How should repairs be made so that they are economical and so that the bridge will not continue to have problems during its remaining life? Are repairs even needed?

While analytical tools and modern design guides are helpful when problems are identified, they do not always provide all details necessary to make a final decision on both the need for repair and how to make the repair. Analysis using computer models cannot attempt to mimic the variation in the stress ranges experienced by a bridge. There are many approximations involved in even the best analytical models, including estimates based on loads, load patterns, distribution of loads, impact and fatigue. Even modern finite element models are normally unable to provide accurate stress ranges because of the difficulty in fully modeling the material properties and connections. The AASHTO design was developed with conservative simplifying assumptions, and thus it does not accurately represent actual conditions. The only way to obtain precise information, especially for localized details, is to conduct field monitoring. This is particularly beneficial for determining stress levels in connections, evaluating how loads are distributed to different components, determining deformational induced behavior and providing fatigue predictions.

This document reports on a twenty year program to use non-destructive field monitoring to evaluate a wide variety of structural steel bridges that have been reported to have problems based on visual inspections or have raised concerns about load effects. The approach has involved short-term strain monitoring to supplement analytical evaluations. This program has provided the Connecticut Department of Transportation with guidance on whether repairs are needed, and if needed, how they can be implemented economically, both with respect to costs and time (1).

Strain Monitoring

During the twenty-year period for the studies reported in this paper, there have been major advances in electronics, and this has led to vastly improved capabilities for data collection, involving speed, field evaluations and data storage for later use (2, 3). The initial monitoring began with a portable computer developed for automobile testing. It was necessary to adapt this for strain monitoring, involving extensive software development and design in-house of signal conditioning modules for strain measurements. The development of durable laptops and portable signal conditioning equipment has greatly simplified testing, and it has often provided the opportunity for full evaluation in the field.

The keys to selection of equipment used I this work have been: (1) The equipment must be portable for ease of implementation; (2) Power should be provided by batteries, either internal or from vehicles; (3) The equipment should be easy to set up and remove in a variety of field locations: (4) Results should be displayed in the field to assure that the data being collected is useful and reliable; (5) As much as possible, field evaluation should include preliminary results so that it is clear when monitoring can cease; (6) The learning curve to learn how to use the equipment should be minimized so that those new to the monitoring projects can get up to speed as quickly as possible.

The general testing procedure has typically involved from 1 to 3 days. Most studies have involved not more than 8 strain gages. A few have used 100 or more gages, and these are noted in the reviews below. Weldable strain gages have proven to be the best choice for these short-term studies of steel bridges. Testing has generally been carried out using normal traffic, with histograms developed to obtain information on the truck traffic.

Extensive software has been written to use during both the strain monitoring and in the postprocessing of the data. One of the goals has been the automation of the data analysis for evaluation of the remaining fatigue life. A program has been developed to calculate the effective stress range from data collected in the filed and to process this to determine the remaining fatigue life of the structural element (2, 3). The fatigue evaluations are based on the *Guide Specification for Fatigue Evaluation of Existing Steel Bridges* of the American Association of State Highway and Transportation Officials (4). This involves developing a histogram from the random truck passages during testing and using Miner's rule to produce the constant effective stress range, needed for the evaluation of the remaining fatigue life.

Chapter 2

Strain Monitoring Studies

Brief descriptions of the bridges and the problems are given in the following, followed by the monitoring approach used and how the results were used to aid in the management of the infrastructure. References to more detailed papers are included when the material is readily available elsewhere. The studies are presented in historical order, with the earliest studies first. When available, approximate cost savings from the strain monitoring are given.

1 - Cracking in Diaphragm Elements in Multi-Girder Bridge

This study, the first in the program, involved the determination of the influence of diaphragms on the overall performance in a typical composite multi-steel girder bridge in the interstate system (2, 5). The bridge, part of the interstate system, had been constructed in the mid 1950s. The study was designed to determine the cause of cracking in diaphragms and to provide information useful for making repairs. A typical cross section is shown in Figure 1, and the two diaphragm types are shown in Figure 2.

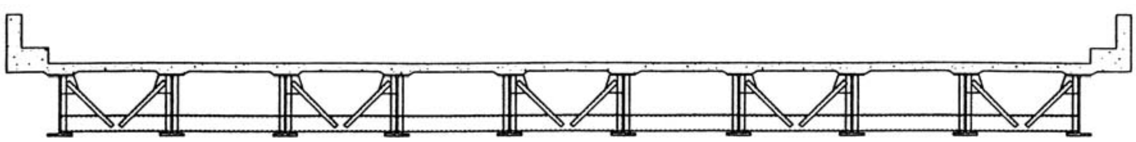

Figure 1 Bridge cross section

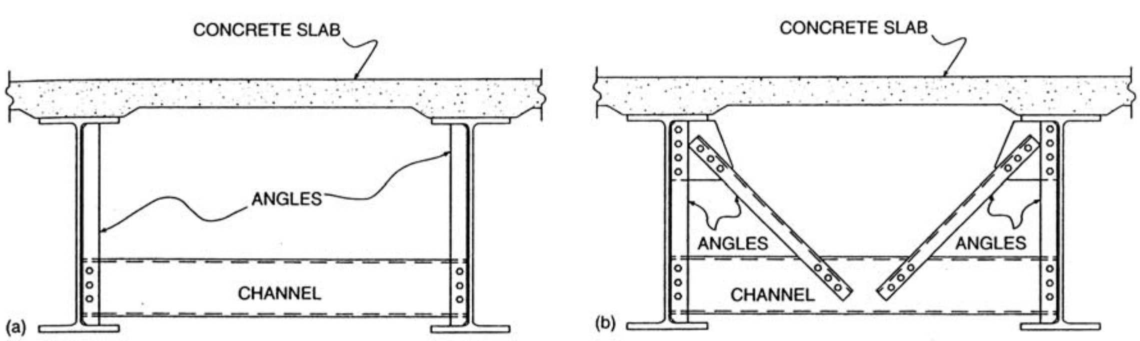

Figure 2 Diaphragm types

Strain gages were placed on the angle legs used to connect the diaphragms to the stringer webs. The field data, using a detailed finite element analysis for comparison, demonstrated that the stress levels in the diaphragm angles exceeded design levels, thus explaining the cracks noted during the visual inspections. The high stress levels were attributed to the inability to adequately evaluate the three-dimensional behavior of the structural system when the bridge had been designed in the 1950s. The study was also used to explore the contribution of the diaphragms to the overall performance of the bridge system. The conclusion was that the diaphragms were not making substantial contributions to the overall lateral load distribution to the different girders. Thus it was concluded that the cracking was due to differential deflections between the adjacent girders, and as a result this should not cause long-term problems. Nevertheless, the diaphragm angles with the higher stress levels were replaced with tee sections. The primary benefit from this study, conducted nearly 20 years ago, was that it demonstrated the feasibility of supplementing visual inspections and analytical studies with field strain monitoring.

2 - Fatigue Cracking in Diaphragm Connections in Multi-Girder Bridge

This bridge is another part of the elevated bridges reported in the previous study. The bridge is a multi-girder, multi-span structure, simply supported at all supports with diaphragms located at the quarter points, and the typical details are as shown in Figures 1 and 2. Fatigue cracking in the mid-span diaphragm connections angles was noted during visual inspections. The cracking was primarily associated with the stringer bays under the low speed lanes, and the initial plan was to replace all diaphragms. Connection angles were strain gaged to review the behavior inducing the cracking and to determine if repairs were needed for the diaphragms at the quarter points. The field monitoring demonstrated that the fatigue cracking was distortion induced, caused by differential deflection between the adjacent stringers. This resulted in bending stresses in the leg of the angle in the diaphragm as the connection angle pulled away from the stinger web. The testing demonstrated that the actual stresses were small and that the angles were failing due to out-of-plane bending. The results indicated that the cracking does not compromise the structural integrity of the bridge since the strains were low and since the cracking could not propagate into stringer webs and flanges. The decision was made to rehabilitate only mid-span connection angles, saving approximately two million dollars in early 1990 costs.

3 - Deformational Fatigue Cracking in Connections between Transverse and Main Girders

The bridge studied was built in 1958 (2, 6). The 14-span, non-redundant bridge crosses the Connecticut River. The interior spans are continuous, with simple spans at the ends. The problem studied occurred in the simple spans. The two main longitudinal girders are non-composite with the deck. The transverse beams have their top flange above the composite beams, and they are composite with the deck slab. The connection is shown in Figure 3.

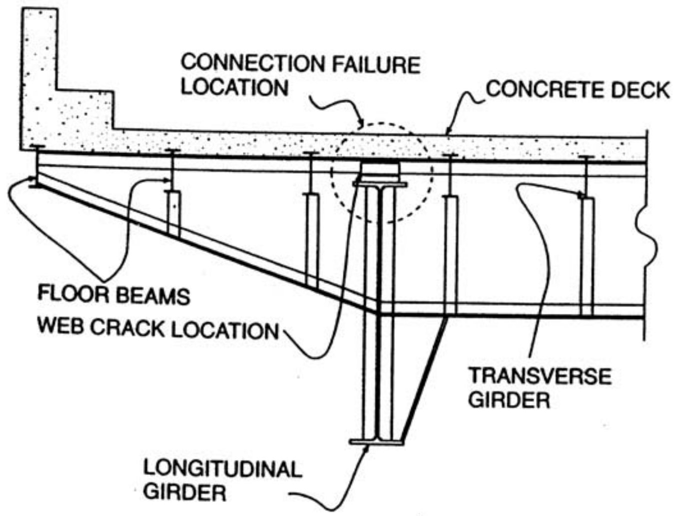

Figure 3 Connection between longitudinal and transverse beam

The connection angles used to connect the transverse beams to the longitudinal beams exhibited fatigue cracks, and some of the bolts had fractured. Strain gages were placed on the angles and the flanges of the longitudinal girders. In addition, strain gages were installed on bolts to measure the bolt tension force. The bolts were then placed in the angle connections, located at the quarter point locations. Normal traffic loading was used, and the data was then processed into histograms for use in fatigue life predictions. The results demonstrated that the angles were subject to bending, confirming that they were subject to fatigue cracking. The strains in the bolts that were gaged were also at the fatigue limit. Finite element analyses for the full span and for the connection angle were used to corroborate the stress levels. The research demonstrated that the top flange of the longitudinal girder should not be connected to the transverse beam at the abutment and quarter points. Removing these connections allowed rotational shear deformations, with no loss in overall capacity. It was estimated that the savings in costs over full repair of all cracked connections was $250,000.

4 - Cracking in Girder Flange at Interior Support

Visual inspection noted that there were cracks near the central support in a two-span girder bridge (3). The cracks were in the welds connecting the plates at the top of the bearing stiffeners to the top flange of the girder web, shown in Figure 4.

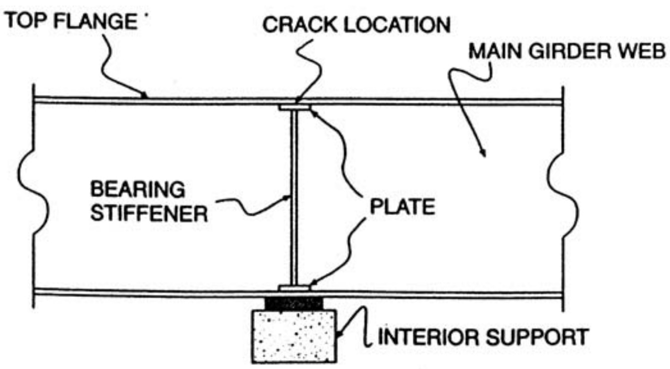

Figure 4 Cracking in girder flange at interior support

The concern was that the crack, aligned in the longitudinal direction, could propagate and lead to fracture. This design predated much of what has been learned about fatigue details, and the detail involved use of a plate so that welding would not be needed directly between the stiffener and the girder flange. The strain monitoring demonstrated that the stresses, combined with the low volume of truck traffic, would not lead to propagation of the cracks or to further cracking. The most likely cause of the original cracks was due to poor quality welding during fabrication. As a result of the monitoring, approximately $50,000 was saved because it was determined that field repairs were not needed.

5 - Non-Prismatic Steel Girder with Varying Flange Thicknesses

There are changes in the flange thickness at approximately the third points in this multi-girder composite bridge (3). Groove welds are used to join the flanges. A detail is shown in Figure 5.

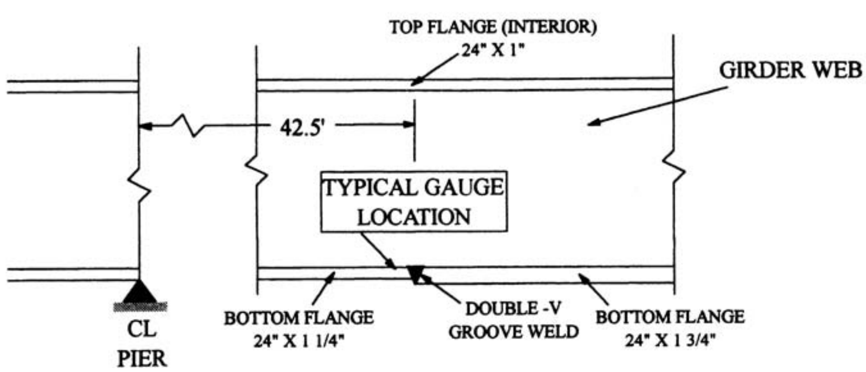

Figure 5 Change in flange thickness

Field inspection showed that there are defects in the groove-type welds. Field monitoring was used to demonstrate that the cracks in the welds would not propagate due fatigue.

Consequently repairs were not needed, saving approximately $50,000 in anticipated renovation costs.

6 - Multi-Girder Bridge with Smaller Middle Girder

This skewed multi-girder bridge was scheduled for a deck overlay. Analytical calculations, based on standard design code distribution factors, indicated that the middle girder, which is smaller than the others, would be overstressed. This would require expensive strengthening of the middle girder. Strain monitoring was used to determine the actual distribution factors. The deck plan is shown in Figure 6, and strain gages were applied to the middle girder, beam 4, and an adjacent girder.

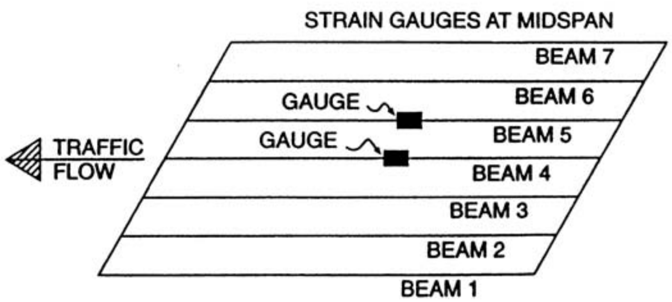

Figure 6 Plan for multi-girder bridge with smaller middle girder

Field testing demonstrated that the design distribution factors are conservative. As a consequence, it was not necessary to strengthen the middle girder. This saved the approximately $25,000 for the field strengthening.

7 - Weld Cracks in Diaphragm Connections

This multi-span bridge was 36 years old, when it was noted during renovation of the deck that there were some cracks in welds that connect the diaphragm to the top flange of the girders (2, 7). The typical connection and crack location are shown in Figure 7.

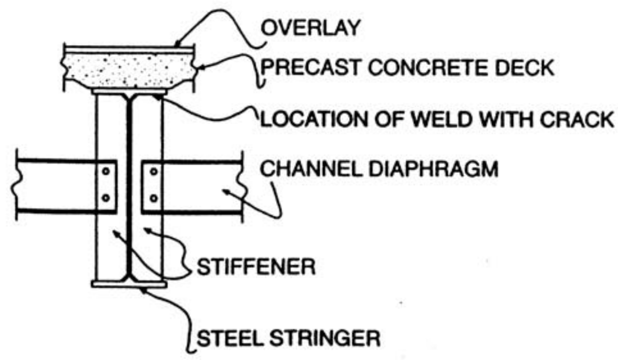

Figure 7 Weld crack in diaphragm connection

Since there were 882 locations in which this connection was used, each with the potential of developing similar cracks, field monitoring was used to determine the cause of the cracks, the stress levels and provide information for potential corrections. The stress levels determined from monitoring during normal vehicle traffic were low, and it was determined that the cause of cracking was due to poor quality welds during the initial construction. Since repairs were not needed, the estimated savings was $250,000. Had repairs been needed, the renovation would have required approximately an additional year.

8 - Fatigue Cracking in Webs at Diaphragm Locations

This skewed bridge had cracks in the web adjacent to the diaphragms in two different locations (2, 7). The diaphragm connection plates were welded to the top flange and the web of the plate girders, but not to the bottom tension flanges. The crack location is shown on the detail in Figure 8.

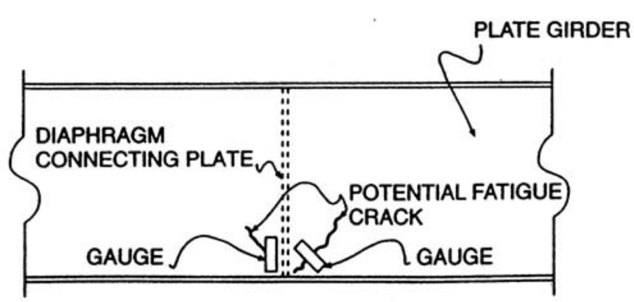

Figure 8 Cracking in web adjacent to diaphragm

The proposed repair was to weld the connection plates to the lower flange. However, a computer generated analysis indicated high stress levels in some of the girder tension flanges adjacent to the diaphragms, and this could result in fatigue cracking if the connection plate was welded to the lower flange. Strain monitoring was used to determine the actual stress levels. The analysis of the field data, using a histogram to make fatigue life predictions, demonstrated that the actual stress levels are significantly lower than the analytical values. The data from the field monitoring was also used to determine what type of repair would be needed. One option was to bolt the connection plate to the lower flange and another was to weld the connection plate directly to the lower flange. The first would provide better a fatigue life prediction, but it would be more costly to accomplish in the field. Based on use of actual field stress levels, the second was found to be suitable, saving approximately $200,000.

9-11 - Evaluation of Critical Components in Movable Bridges

Three different short monitoring studies were conducted to get answers to questions on specific elements in movable bridges.

9 - A bascule bridge, scheduled for replacement, had significant corrosion problems (3). Inspectors were concerned that the hanger supports for the large counter weight had reduced cross-sections because of the corrosion. The hangers were designed for axial force only. There were also concerns that wear and friction in the bearings, due to aging, was further reducing the hanger load capacity. The hangers were monitored during opening and closing of the bridge, confirming that failure could occur. Immediate repair was carried out, and the bridge continued to operate until the new replacement bridge was in place.

10 - In another bascule bridge study, monitoring was used to determine the actual stresses in a drive mechanism (2). The bridge was scheduled for renovation, and this required adding weight to the lifted portion. The designers were concerned that this would then over-stress the main drive shaft during opening and closing. Strain monitoring was used to determine the actual torsional stresses in the drive shaft. This information then was used to plan the renovations.

11 - Strain monitoring was used in another bascule bridge with truss supports (2). The bridge was scheduled for renovation. The magnitude of the forces in the different members was not readily determined from an analysis, due to complexities in the truss elements and the varying weight distributions to the different elements during opening and closing. In this study, 24 strain gages were used. The testing provided information needed by the designers.

12 - Large Historical Swing Bridge

The bridge, approximately 80 years old, was scheduled for renovation (2). It is shown in Figure 9.

Figure 9 Historical swing bridge

Two major problems were investigated. The center pivot bearing was designed to take the full gravity load during opening and closing. However, over the years problems were occurring in the drive mechanism and the outriggers used to balance the bridge during this displacement. Strain gages were used to provide the designers with better information on this behavior. The other concern involved the truss members, which are multiple eyebars. In an earlier renovation, the bridge deck was replaced, increasing the overall weight. Additional eyebars were added to truss members, and there were concerns that these additional bars were not carrying their share of the load. An extensive strain monitoring program, using 100 gages, verified that not all eyebars were fully effective, and this information was provided to the designers.

13 - Curved Access Ramp

The measured deflections were much greater than expected in a new curved access ramp (2). Prior to opening the ramp, strain monitoring was used to determine if the problem was in the computer analysis or due to construction problems. Data was collected when a large truck of known weight was placed on the bridge. This confirmed that the bending and torsional stresses were as expected from the design. The engineers used the measured strains to reanalyze the bridge, confirming that the original deflection was not a problem. The bridge was then opened without delay.

14 - Multi-Girder Steel Bridge with Corroded Beam

The first interior girder on one side of this ten-girder bridge, built in 1914, was severely corroded, and there were concerns that this girder could be overloaded. The other girders, including the exterior, larger girders were in good condition. All girders are built into the supports. Additionally, the bridge was not designed as composite bridge. Testing indicated that the bridge is behaving compositely, that the girders are behaving closer to fixed than pinned for truck loading. Based on the field data, it was concluded that the bridge is performing acceptably and thus renovation is not needed.

15 - Bridges Subject to Superload Permit Vehicles

A multi-girder bridge was tested twice, for two different superload vehicles. The larger vehicle weighed approximately a million pounds. Testing demonstrated that for both loads, the strains were significantly smaller than estimated from detailed analyses. This is because analyses are often based on conservative distribution factors, and because they do not fully account for composite action and partial fixity in joints. More information on superload vehicles is given by Culmo, DeWolf and DelGrego (8, 9).

16 - Century-Old Railroad Truss Bridge

This study was carried out to evaluate the structural behavior and the influence of aging on multi-span century-old railroad truss bridges, with separate bridges for each direction (10, 11). The truss elements are made of built-up members, with either multiple eyebars or laced channel sections. The truss bridge is shown in Figure 10, and a typical cross-section is shown in Figure 11.

Figure 10 Truss bridge

Figure 11 Truss bridge cross-section

Field monitoring for 16 trains, using a data logger with 96 channels and a total of 372 strain gages, was carried out over a two week period. This study was developed to provide designers with information needed for renovation. In addition, researchers used the data from testing to evaluate the live load distribution throughout the bridge. The results showed that the actual live load distributions are significantly different than expected from conventional analytical approaches. The live load distribution in multiple eyebar elements is far from uniform, and the distribution of shear through indeterminate panels is significantly different than obtained from a normal truss analysis. There was significant out-of-plane bending in the trusses due to floor beam end rotations, causing problems with the pins. The study demonstrated the need to use field monitoring to better understand the behavior of older bridges.

17 - Monitoring Bridges Subject to Large Paving Machines

This study was developed to evaluate bridge strains when loaded with a new paving machine. The loads from the new paving machine were much higher than obtained from earlier machines, and the combination of the paving machine and the trucks needed to load the machine with pavement complicated the determination of the overall loading on the bridge. In addition, it was necessary to keep traffic on the bridge at the same time as the paving operation. Two different bridges in the interstate system were monitored (12). The paving operation is shown in Figure 12. The study also provided the opportunity to evaluate the bridges when loaded with a vibratory roller following paving.

Figure 12 Paving operation

The strains were recorded at 30 times a second to capture both the static and dynamic stress components, providing estimations of the impact level. The monitoring confirmed that the paving equipment, with the tri-axle trucks, did not exceed the design stress levels, even when other trucks crossed the bridge during paving. The data collected for the vibratory roller, normally not allowed on bridges because of concerns that the concrete deck might be compromised during rolling, did not exceed the strains induced by the paving operation.

18 - Cracking in Tie Plates in Non-Redundant Plate Girder Bridge

This study was carried out to explain the cause of fatigue cracking in tie plates in a multi-span, non-redundant, steel plate-girder bridge (13). Repairs have been on-going, and in addition to explaining the cause of cracking, engineers needed guidelines on how best to make repairs. The bridge cross-section is shown in Figure 13. The tie plate with the cracking connects the tension flanges of the transverse girder at the top of the longitudinal girder. A plan view of the tie plate is shown in Figure 14. The cracking occurs in the tie plate on the side opposite to the cantilevered transverse girder.

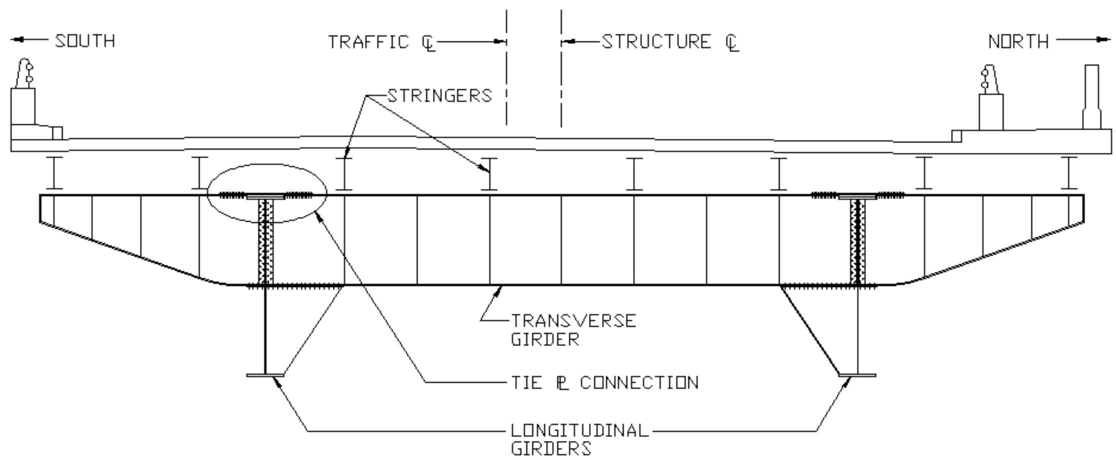

Figure 13 Bridge cross-section

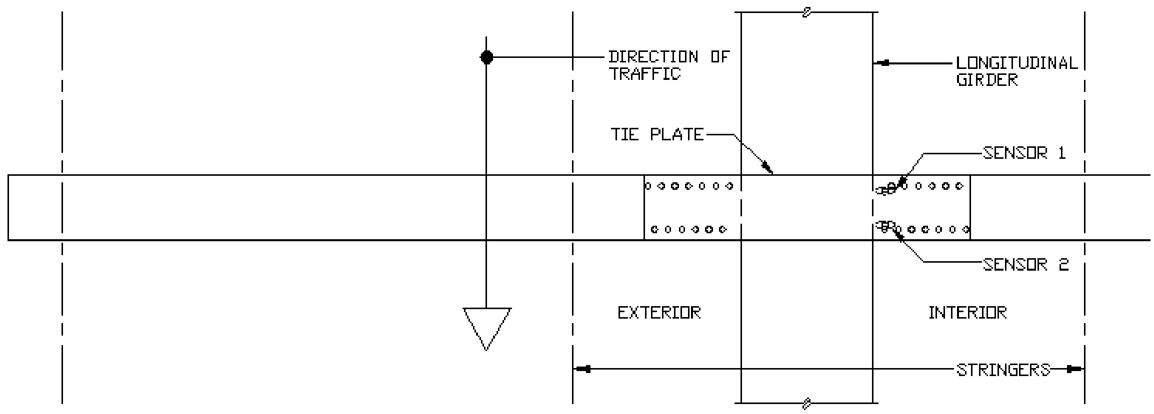

Figure 14 Plan view of tie plate subject to cracking

While similar studies of tie plates have been carried previously, this study incorporated a detailed three-dimensional finite element analyses with the field data to fully explain the behavior and provide guidelines on both where and how to renovate the tie plates. It was shown that most tie plates do not need replacement, and where replacement is needed, information was given on how to modify the original design.

Chapter 3

Conclusions

As the bridge infrastructure continues to age, it is increasingly important to use non-destructive evaluations to supplement both visual inspections and analytical studies. These evaluations can be used to obtain measurable and quantifiable information regarding the existing structural conditions which then can be used to determine the structural resistance and to provide information needed in the overall management of the bridge infrastructure.

The field monitoring examples presented in this paper have directly impacted to the maintenance and replacement program for Connecticut’s bridges. Often, as has been shown, the experience has been that problems, perceived in visual inspections, do not require repairs when investigated using non-destructive strain monitoring. When repairs have been recommended, it has been because non-destructive monitoring has verified the need for repair. In these cases, field data has been used to provide guidance on how best to make the repair, both economically and so that the remaining service life is not impacted by the initial problem.

The work reported in this paper has demonstrated the value of using non-destructive testing to supplement both conventional visual inspections and analytical studies. As the study shows, structural health is best evaluated with data from testing.

References

1. R.G. Lauzon and J.T. DeWolf. 2003. Connecticut's Bridge Monitoring Program – Making Important Connections Last. TR News, January/February No. 24:46-47.

2. J.T. DeWolf and M.P. Culmo. 1998. Nondestructive Evaluation of the Steel Bridge Infrastructure. Technology, Law and Insurance. Vol. 3, No. 4:251-260.

1. R. Sartor, M.P. Culmo and J.T. DeWolf. 1999. Short Term Strain Monitoring of Bridge Structures. Journal Bridge Engineering, American Society of Civil Engineers, Vol. 4, No. 3:157-164.

2. AASHTO. (1990, 1993 Revision) Guide Specification for Fatigue Evaluations of Existing Steel Bridges. The American Association of State Highway and Transportation Officials, Washington, DC.

3. T.J. Descoteaux and J.T. DeWolf. 1993. Influence of Diaphragms on the Overall Performance of Bridges. Structures Congress 93, American Society of Civil Engineers, Irvine, CA, pp. 963-968.

4. K.J. Bernard, M.P. Culmo and J.T. DeWolf. 1997. Strain Monitoring to Evaluate Steel Bridge Connections. Structures Congress XV, American Society of Civil Engineers, Portland, Oregon, pp 919-923.

5. J.T. DeWolf, T.R. Lindsay and M.P. Culmo. 1997. Fatigue Evaluations in Steel Bridges Using Field Monitoring Equipment. Structures Congress XV, American Society of Civil Engineers, Portland, Oregon, pp 26-30.

6. M.P. Culmo, J.T. DeWolf and M.R. DelGrego. 2004. Behavior of Steel Bridges under Superload Permit Vehicles. Annual Meeting of Transportation Research Board, Washington, D.C., 21 pages.

7. M.P. Culmo, J.T. DeWolf and M. R. DelGrego. 2004. Behavior of Steel Bridges Under Superload Permit Vehicles. Transportation Research Record: Journal of the Transportation Research Board, No. 1892, TRB, National Research Council, Washington, D.C., pp. 107-114.

8. M.R. DelGrego, M.P. Culmo and J.T. DeWolf. 2004. Monitoring of Century-Old Railroad Truss Bridge. Annual Meeting of Transportation Research Board, Washington, D.C., 20 pages.

9. M.R. DelGrego, M.P. Culmo and J.T. DeWolf 2008. Performance Evaluation through Field Testing of Century-Old Railroad Truss Bridge. Journal of Bridge Engineering, American Society of Civil Engineers. Vol. 13, No. 2:132-138.

10. E.G. Feldblum, P.F. D'Attilio and J.T. DeWolf. 2005. Strain Monitoring of Bridges During Paving Operations. Annual Meeting of Transportation Research Board, Washington, D.C. 19 pages.

11. G.P. Troiano, P. D'Attilio, J.K. Olund and J.T. DeWolf. 2008. Field Strain Monitoring to evaluate Unexpected Cracking in a Non-Redundant Steel Plate Girder Bridge. Annual Meeting of Transportation Research Board, Washington, D.C., 21 pages.

Appendix A – Publications Developed Based on this Research

The following publications have been based and related to research conducted during this project and on the theses of graduate students working on the project:

T.J. Descoteaux and J.T. DeWolf. 1993. Influence of Diaphragms on the Overall Performance of Bridges. Structures Congress 93, American Society of Civil Engineers, Irvine, CA, pp. 963-968.

J.T. DeWolf and R.G. Lauzon. 1995. Application of Monitoring Technology to Bridge Assessment. Fifth International Conference on Structural Failure, Product Liability and Technical Insurance, Technical University of Vienna, Vienna, AUSTRIA, pp. 413-423.

J.T. DeWolf. 1995. Bridge Deterioration. Structural Stability and Research Council on Stability Problems Related to Aging, Damaged, Deteriorated Structures, Kansas City, MO, pp. 163-173.

R.G. Lauzon and J.T. DeWolf. 1996. Bridge Monitoring and Instrumentation in Connecticut. Research-to-Practice Symposium on Repair and Rehabilitation of Bridges and Pavements, Warwick, Rhode Island.

J.T. DeWolf, T.R. Lindsay and M.P. Culmo. 1997. Fatigue Evaluations in Steel Bridges Using Field Monitoring Equipment. Structures Congress XV, American Society of Civil Engineers, Portland, Oregon, pp 26-30.

K.J. Bernard, M.P. Culmo and J.T. DeWolf. 1997. Strain Monitoring to Evaluate Steel Bridge Connections. Structures Congress XV, American Society of Civil Engineers, Portland, Oregon, pp 919-923.

J.T. DeWolf, M.P. Culmo and R.G. Lauzon. 1997. Assessment Program for Bridge Infrastructure. Conference on Infrastructure Condition Assessment: Art, Science, and Practice, American Society of Civil Engineers, Boston, Massachusetts, pp. 101-110.

J.T. DeWolf, M.P. Culmo and R.G. Lauzon. 1998. Connecticut's Bridge Infrastructure Monitoring Program for Assessment. Journal Infrastructure Systems, American Society of Civil Engineering, Vol. 4, No. 2:86-90.

J.T. DeWolf and M.P. Culmo. 1998. Nondestructive Evaluation of the Steel Bridge Infrastructure. Technology, Law and Insurance. Vol. 3, No. 4:251-260.

R. Sartor, M.P. Culmo and J.T. DeWolf. 1999. Short Term Strain Monitoring of Bridge Structures. Journal Bridge Engineering, American Society of Civil Engineers, Vol. 4, No. 3:157-164.

J.T. DeWolf. 1999. Strain and Acceleration Assessment of Bridge Performance. Structural Engineering in the 21st Century, Structural Engineering Institute, American Society of Civil Engineers, New Orleans, LA, pp. 719-722.

J.T. DeWolf, R.G. Lauzon and M.P. Culmo. 2002. Monitoring Bridge Performance. Structural Health Monitoring Journal. Vol. 1, No. 2:129-138.

R.G. Lauzon and J.T. DeWolf. 2003. Connecticut's Bridge Monitoring Program – Making Important Connections Last. TR News, January/February No. 24:46-47.

M.R. DelGrego, M.P. Culmo and J.T. DeWolf. 2004. Monitoring of Century-Old Railroad Truss Bridge. Annual Meeting of Transportation Research Board, Washington, D.C., 20 pages.

M.P. Culmo, J.T. DeWolf and M.R. DelGrego. 2004. Behavior of Steel Bridges under Superload Permit Vehicles. Annual Meeting of Transportation Research Board, Washington, D.C., 21 pages.

M.P. Culmo, J.T. DeWolf and M. R. DelGrego. 2004. Behavior of Steel Bridges Under Superload Permit Vehicles. Transportation Research Record: Journal of the Transportation Research Board, No. 1892, TRB, National Research Council, Washington, D.C., pp. 107-114.

E.G. Feldblum, P.F. D'Attilio and J.T. DeWolf. 2005. Strain Monitoring of Bridges During Paving Operations. Annual Meeting of Transportation Research Board, Washington, D.C. 19 pages.

G.P. Troiano, P. D'Attilio, J.K. Olund and J.T. DeWolf. 2008. Field Strain Monitoring to evaluate Unexpected Cracking in a Non-Redundant Steel Plate Girder Bridge. Annual Meeting of Transportation Research Board, Washington, D.C., 21 pages.

M.R. DelGrego, M.P. Culmo and J.T. DeWolf. 2008. Performance Evaluation through Field Testing of Century-Old Railroad Truss Bridge. Journal of Bridge Engineering, American Society of Civil Engineers. Vol. 13, No. 2:132-138.