Field Strain Monitoring to Evaluate Unexpected Cracking in a Non-Redundant Steel Plate Girder Bridge

July 2009

Report No. CT-2251-2-09-4

Gino P. Troiano Jr., Graduate Research Assistant
Department of Civil & Environmental Engineering
University Of Connecticut, Storrs, CT, 06269.

John T. DeWolf, Professor
Department of Civil & Environmental Engineering
University Of Connecticut, Storrs, CT 06269.

Connecticut Department of Transportation
Bureau of Engineering and Construction
Research and Materials

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

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

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

Technical Report Documentation Page

1.Report No. CT-2251-2-09-4	**2. Government Accession No.**	**3. Recipients Catalog No.**
4. Title and Subtitle Field Strain Monitoring to Evaluate Unexpected Cracking in a Non-Redundant Steel Plate Girder Bridge		**5. Report Date** July 2009 **6. Performing Organization Code** SPR-2251
7. Author(s) Gino P. Troiano, Jr. and 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** 7/1/2006 to 7/2009
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
This study was carried out to evaluate fatigue cracking in tie plates in a multi-span, non-redundant, steel plate-girder bridge. The plates are needed to provide continuity for the transverse floor beams. Repairs have been on-going, and the goal was to explain the cause of cracking and provide guidelines for those responsible for designing the repairs to assure that there would be no further cracks. The designers expected that these bolted plates would act in simple tension, which is a reasonable assumption based on the plans and actual bridge. Field monitoring has demonstrated however that the plates are acting as bending members, with bending occurring in the horizontal plane. The field testing, combined with a finite element analysis, have been used to explain the behavior causing bending and to provide guidance on how best to make the repairs.

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	19	

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

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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 funded by the Connecticut Department of Transportation and the U. S. Federal Highway Administration. Also acknowledged are the efforts of many graduate students who have participated in the past research, some of whom are listed in the references. We recognize the efforts of Connecticut Department of Transportation engineer Alireza Jamalipour, our partnering researcher in bridge monitoring. We are especially grateful to Paul D'Attilio, Connecticut Department of Transportation, Bridge Safety & Evaluation, who organized and assisted with the field monitoring for the Route 190 bridge and to Josh Olund, graduate student at University of Connecticut, for his assistance with the field monitoring and initial analysis of the results.

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)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		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)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		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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ABSTRACT

This study was carried out to evaluate fatigue cracking in tie plates in a multi-span, non-redundant, steel plate-girder bridge. The plates are needed to provide continuity for the transverse floor beams. Repairs have been on-going, and the goal was to explain the cause of cracking and provide guidelines for those responsible for designing the repairs to assure that there would be no further cracks. The designers expected that these bolted plates would act in simple tension, which is a reasonable assumption based on the plans and actual bridge. Field monitoring has demonstrated however that the plates are acting as bending members, with bending occurring in the horizontal plane. The field testing, combined with a finite element analysis, has been used to explain the behavior causing bending and to provide guidance on how best to make the repairs.

INTRODUCTION

The bridge studied is a forty-three year-old plate girder bridge that crosses the Connecticut River. The non-redundant bridge has two main longitudinal girders set back from the edges. There are transverse floor beams, both between the longitudinal girders and that cantilever out from the longitudinal girders. The top flange of the longitudinal girders is connected with tie plates, originally designed to as tension connectors. Fatigue cracking in the tie plats has raised concerns that the tie plates are being subjected to stresses that are significantly different than those assumed in design.

As a result of cracks, emergency repairs were mandated in 2005. Continued inspection has shown that cracks are continuing to develop in additional tie plates. Strain monitoring along with a detailed finite element analysis were carried out to provide designers with an explanation of the cause of cracking and to provide information needed for renovations.

LITERATURE REVIEW

For over two decades, the University of Connecticut and the Connecticut Department of Transportation have been conducting both short-term and long-term structural health monitoring on approximately three dozen bridges throughout the State (*1*). Short-term studies in Connecticut have involved strain monitoring on a variety of bridges ranging in age, construction type, and usage *(2-8)*. These strain monitoring studies have been a useful tool in assessing the behavior and structural integrity of a variety of bridges in the State's infrastructure. The results have provided information needed for repairs and renovations, often demonstrating that repairs are not needed.

Other researchers have also used strain monitoring to evaluate bridges. Nowak, Sanli, and Eom (*9*) analyzed steel multi-girder bridges and determined that the American Association of State Highway and Transportation Officials (AASHTO) load distribution factors are conservative. Shenton, Jones, and Howell (*10*) developed a web-based system for measuring live load strain in bridges that was used for load rating, fatigue assessment, and permit vehicle monitoring. Bhattacharya, Li, Chajes, and Hastings (*11*) used a strain monitoring system to determine load ratings using in-service data from normal traffic loading. Chajes and Shenton (*12*) conducted controlled load tests in order to determine load ratings.

BRIDGE DESCRIPTION

The bridge discussed in this report was built in 1964 and carries four lanes of traffic of a major state route over the Connecticut River and an AMTRAK Railroad. It is located in the Windsor area and is shown in Figure 1. The Average Daily Traffic on the bridge is 25,500, of which 6 % are trucks. The bridge also carries gas and water pipes, as well as communication and data cables. It is a non-redundant structure with two travel lanes in each direction, as well as a pedestrian walkway on the northern side. There are 8 spans, with an overall length of 1345 feet and a maximum span length of 200 feet. A typical cross-section of the structure is shown in Figure 2. The width is 49.5 feet. All elements of the structure below the bridge deck are symmetrical. Note that the centerline of traffic does not coincide with the centerline of the structure. There are five simply supported spans at the ends and a continuous three-span segment in the center portion over the river. The fatigue cracks are occurring in the tie plate connections on the transverse floor beam connections located at the ends of the simple spans.

FIGURE 1 Aerial View of Bridge.

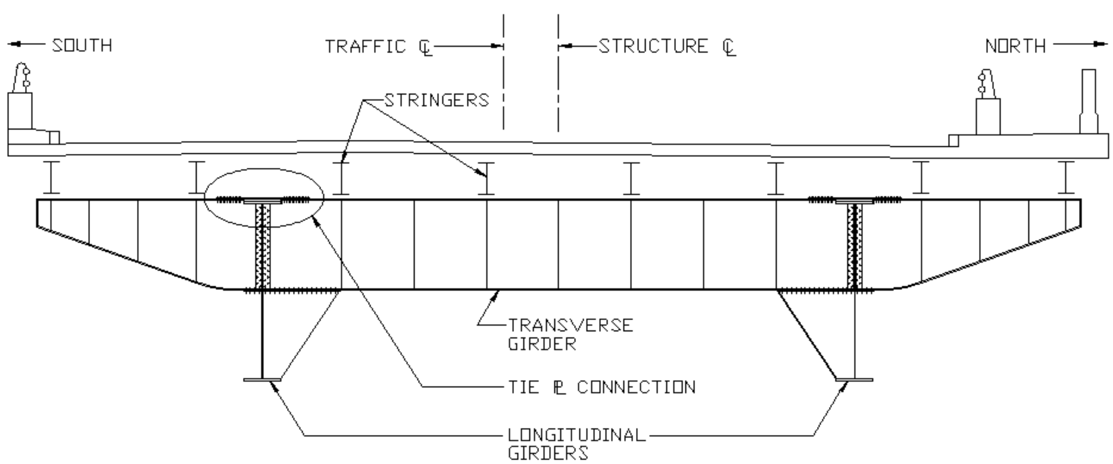

FIGURE2 Typical cross-section of bridge structure for simple spans.

Each simply supported span consists of two main, welded longitudinal steel plate girders that support seven equally spaced transverse welded steel plate-girder floor beams. The transverse floor beams span the interior between the longitudinal plate girders with cantilevers exterior to the longitudinal girders on each side. The elevation of the top flange of the transverse floor beams is approximately 1.25 inches above that of the top flange of the longitudinal girders. The transverse floor beams support longitudinal W21x68 stringers that are non-composite with the concrete deck slab. The stringers are continuous across three spans of the transverse floor beams. The bottom flange of the interior portion of the transverse floor beam is braced in the horizontal direction using a WT7x37.5. There is no lateral bracing on the cantilevered portion of the transverse floor beam. All original structural steel had a yield stress equal to 36 ksi.

Cracking has occurred in the top plate used to make the interior transverse floor beam continuous with the exterior cantilevered transverse floor beam. The web is made continuous through the longitudinal girder using bolted double-angle connections. The bottom flange of the transverse floor beam is also made continuous through the longitudinal girder using a bolted seat connection. The top flange of the transverse floor beam is not rigidly connected to the top flange of the longitudinal girder. A tie plate is used to make the top flange of the transverse floor beams continuous over the top of the longitudinal girder, as shown in Figure 3. A filler plate exists between the tie plate and the top flange of the longitudinal girder. Significant corrosion is present between the tie plate and the filler plate at the end joints in the concrete deck, located at the ends of the simple spans. The corrosion has caused an upward vertical deformation of the tie plate with respect to the top of the longitudinal girders, with magnitudes up to approximately ¾ inch (1.91 cm).

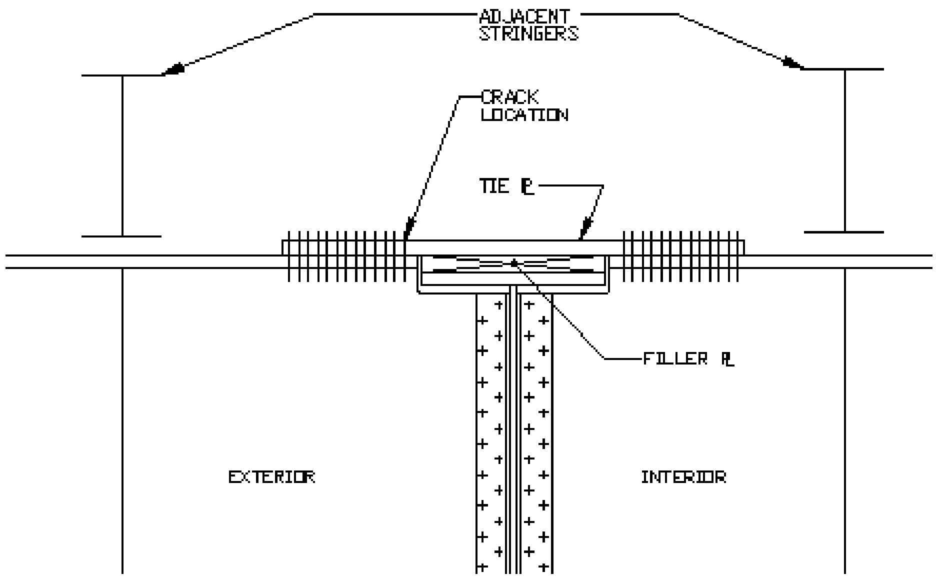

FIGURE 3 Detail of tie plate connection between interior transverse floor beam and exterior cantilevered transverse floor beam.

Prior to this study, eight tie plates on the transverse floor beams at the ends of each simply supported span exhibited fatigue cracks. The cracks occurred on the edge of the tie plate, on the interior side of the longitudinal girders. All cracks were on the interior side of the tie plate. Each crack developed adjacent to the first bolt of the bolted connection to the top flange nearest the longitudinal girder. The cracks have occurred in similar locations on each tie plate, but only on the southern side of the bridge, towards which the centerline of traffic is shifted. A small crack was also noted on the leading edge of the connection of the bottom flange of the transverse floor beam, located on the exterior of the longitudinal girder. The crack at the bottom flange of the transverse floor beam was only noted on one of the girders. This crack was repaired.

The first set of cracked tie plates were repaired two years prior to this study. The repair design consisted of removing the cracked tie plate and filler plate, and replacing only the tie plate. The filler plate was not replaced because it was believed that the rust between the filler plate and the original tie plate was a major contributor to the cause of the crack. The new tie plate had the same dimensions as the one it replaced, but it was made using steel with a yield stress of 50 ksi, whereas the original tie plates had a yield stress of 36 ksi. A recent inspection revealed a crack on a tie plate that was not previously replaced. This is what prompted the strain monitoring reported in this study. This report presents the findings of two sets of strain gage monitoring. Monitoring was first conducted to collect strain data from two original tie plates, one with a crack and one without a crack. Additional monitoring was carried out to collect data from a recently repaired tie plate.

MONITORING SYSTEM DESCRIPTION

A portable strain measuring system was utilized to obtain strain data from the structure under normal vehicular traffic loading. A detailed description of the system and its capabilities is given by Sartor, et. al (*2*).

The initial monitoring was carried out with 2 strain gages located on an un-cracked tie plate and 2 gages located on a cracked tie plate. Neither tie plate had been replaced during repairs to the bridge. The cracked tie plate was on a transverse floor beam located at the end of a simple span. The crack developed on the interior edge of the plate, located on the interior side of the longitudinal girder. The un-cracked tie plate was on the girder adjacent to the girder with the cracked tie plate. The location of the gages is shown in Fig. 4.

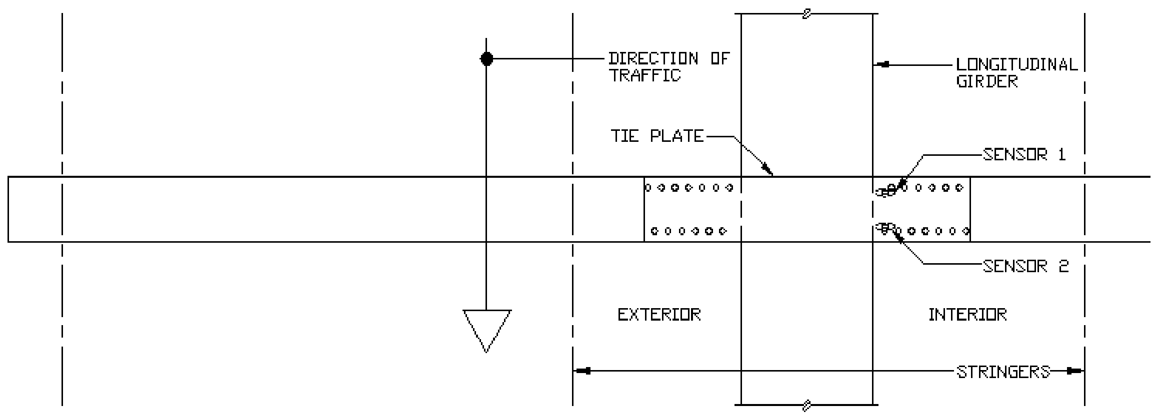

FIGURE 4 Strain gage layout for the first stage of strain monitoring, with gages located both on an uncracked tie plate and a cracked tie plate.

As noted, the initial tests raised a number of questions, resulting in a second set of monitoring tests. This second set used 8 strain gages, 4 on a repaired tie plate, 2 on the top flange of the cantilevered portion of the transverse floor beam, and 2 on the bottom flange of the cantilevered portion of the transverse floor beam. Gages were placed on each edge of the tie plate to determine if the tie plate is acting in axial tension, as anticipated from the design, or if there is some other type of action. In the second set of tests, half of the gages were installed on the flanges of the exterior cantilever to monitor the behavior observed in the first set of data collection. The location of the gages is shown in Fig.5.

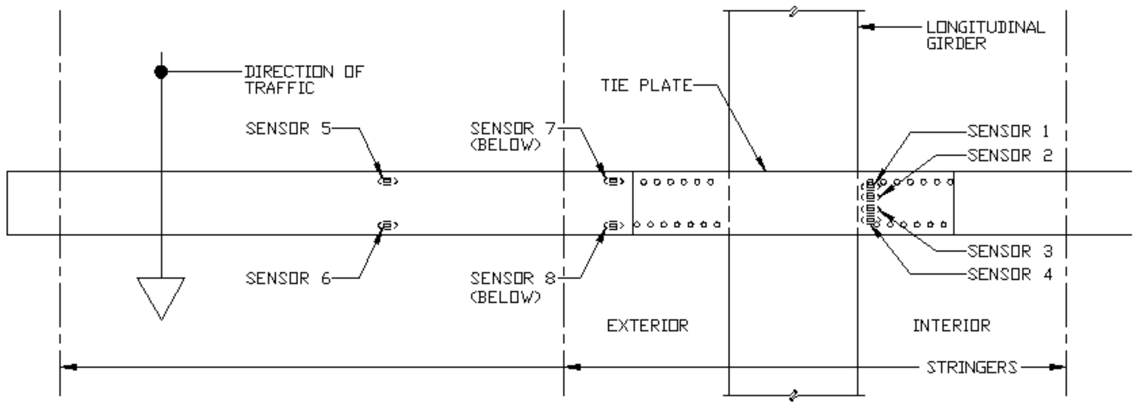

FIGURE 5 Strain gage layout for the second stage of strain monitoring, with gages located on a repaired tie plate and on the flanges of the cantilevered portion of the transverse floor beam.

All data was collected at a sampling rate of 30 Hz. The data collection was triggered manually and recorded in 10-20 minute scans, each with 3 to 5 truck events creating peak strains from 30 $\mu\varepsilon$ to a maximum of 120 $\mu\varepsilon$. Shorter scans were conducted for random single truck events using an observer on the bridge to note when monitoring should begin. Additional tests were conducted using a fully loaded, known-weight test truck.

The strain data revealed that the strains in the tie plates varied, with tensile strains on one side and compressive strains on the other side as the vehicle approached the monitored location. The tests demonstrated that the tie plate, located on the trailing edge of the longitudinal girder span, is subjected to loading any time the vehicle is in the longitudinal girder span.

Figure 6 shows a truck event recorded during the initial set of tests. Gage 2 is on the leading edge, i.e. it is located on the same side of the tie plate as the approaching vehicle. This side is the interior side with respect to the end support. Gage 1 is on the trailing edge of the tie plate, i.e. on the side opposite to the leading edge. Gages were placed on both sides of the tie plate because the cracks always seemed to be aligned on one side with respect to the direction of traffic crossing, even though the tie plates were expected to be in uniform axial tension resulting from the continuity of the transverse floor beams. The tests demonstrated that there is significant bending in the horizontal plane.

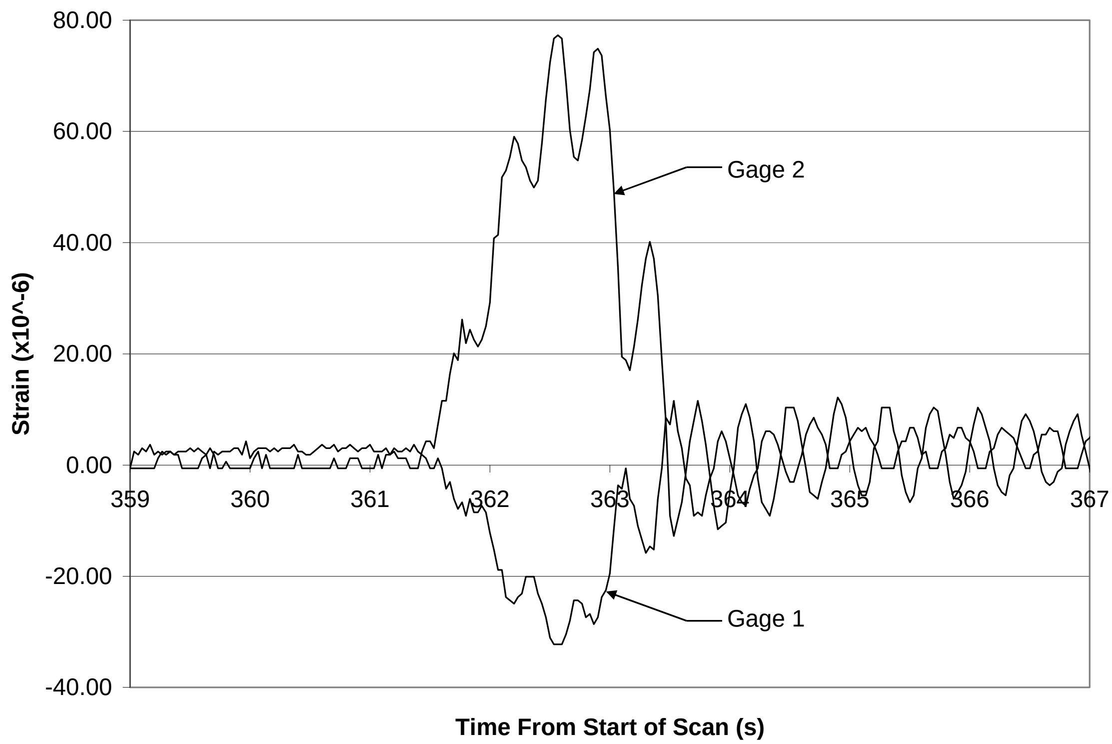

FIGURE 6 Strain data from a truck event on a cracked tie plate.

A typical set of strain data collected for a truck in the second set of tests is shown in Fig. 7. The strain data was collected in the second set of testing on a repaired plate, which, as noted before, no longer had a filler plate. As shown, the strains increased approximately linearly during the initial loading stage, i.e. in the first half of the event. Strain gages 1 and 2 are on the leading edge. Strain gages 3 and 4 are located on the trailing edge. As shown, strain gages 1 and 2 recorded linearly increasing tensile strains while strain gages 3 and 4 recorded linearly increasing compressive strains. All strains were approximately at their respective peaks at the same time during the event. Based on the time period for the full event, it is clear that the vehicle is approximately in the middle of the span when the strains are at their highest peaks. The magnitude of the strains then decreases as the truck approaches the monitored girder, at the end of the span.

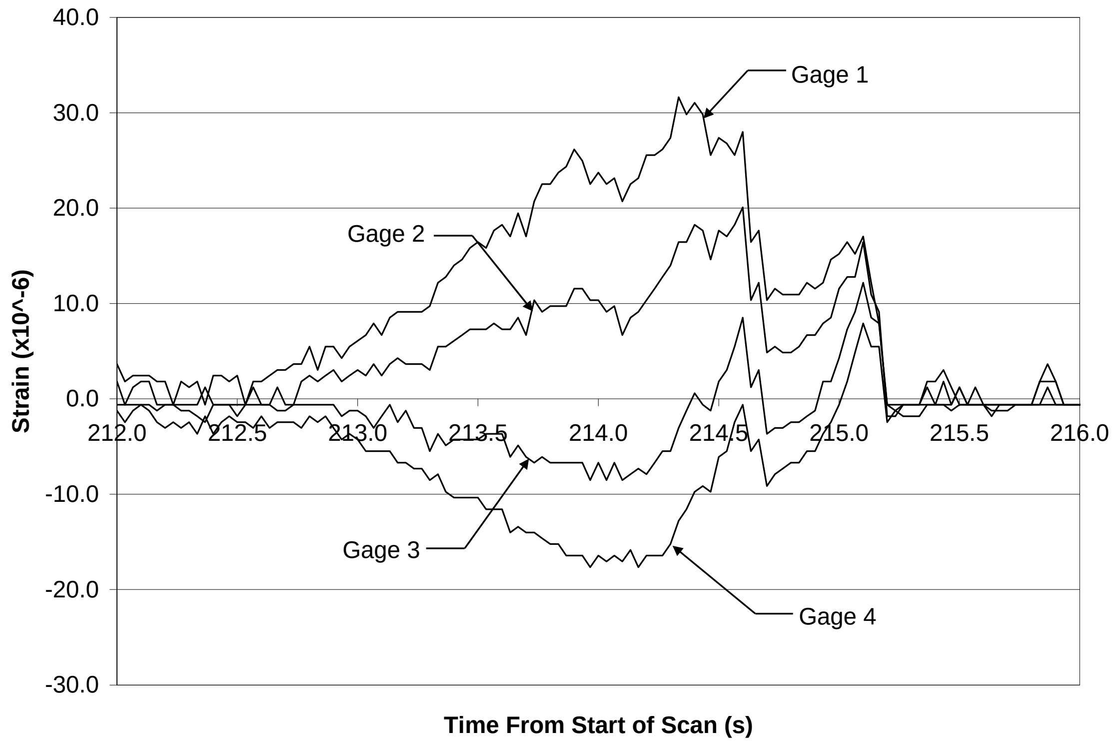

FIGURE 7 Strain data from truck event on a repaired tie plate.

Just prior to the end of the event, all gages show a smaller tensile values, with a much smaller variation in the strain magnitudes. This is believed to be the point at which the truck is directly over the transverse floor beam being monitored. At this time during the event, the transverse cantilevered girder is behaving approximately in simple bending, with the tie plate acting in nearly uniform tension. It is assumed that the variation in the tensile strains is attributable to the fact that the actual truck has multiple axles.

Fig. 7 also shows that the magnitude of the tensile strains at the end of the event are not as large as the peak strains that occur when the truck is approximately in the center of the longitudinal span. This suggests that the cantilever action that is expected to control the loading on the tie plate is not the worst case loading. The worst case for the tie plate is, in fact, while the truck is in the center of the longitudinal girder span.

Looking at all events, the maximum recorded strain in the tie plate was approximately 120 $\mu\varepsilon$ in tension, recorded during normal vehicular traffic on the cracked tie plate. Typical truck events yielded peak tensile strains ranging from approximately 30 to 85 $\mu\varepsilon$, with peak compressive strains ranging from approximately 35 to 60 $\mu\varepsilon$. Each respective peak occurred while the truck was approximately in the center of the longitudinal girder span. When the truck crossed directly over the transverse floor beam being monitored, the strains dropped significantly, with magnitudes equal to approximately 40 to 60% of the peak strain recorded for the strain gage when the truck was located approximately in the center of the longitudinal girder span.

An additional reason for conducting the second set of tests was to determine how the transverse cantilever beams were actually deforming. The strain gages on the leading edge of the top flange and the leading edge of the bottom were both in tension when the truck was approximately in the center of the span. The strain gage on the trailing edge of the top flange was in compression. The data recorded by the three strain gages demonstrated that the exterior, transverse cantilevered girder was bending about a vertical axis in the longitudinal direction of the bridge away from traffic, i.e. the end of the cantilever moved horizontally away from the center of the span. This is opposite to what would normally be expected for the deformations of this bridge. Thus, the next phase of the research was to conduct a finite element analysis to fully explore this behavior and to better explain how to make repairs.

FINITE ELEMENT ANALYSIS

The finite element analysis model consisted of approximately 37,000 elements, representative of all aspects of the structure, including lateral bracing members and stiffeners. The longitudinal girders, transverse floor beams, girder stiffeners, stringers, and concrete deck slab were modeled with shell elements. The lateral bracing members for the transverse floor beams were modeled with beam elements. Figure 8 shows a three-dimensional rendering of the finite element model, including mesh lines used in the analysis.

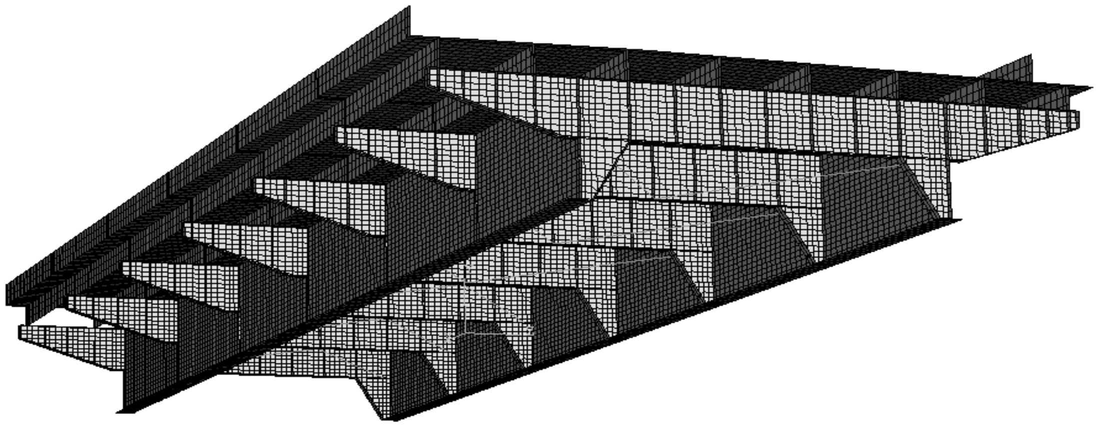

FIGURE 8 Three-dimensional finite element model.

The analysis involved stepping a static load across the deck, designed to model a typical semi-truck. Figure 9 shows an exaggerated deflected shape of the structure when the load is in right lane in the center of the simple span.

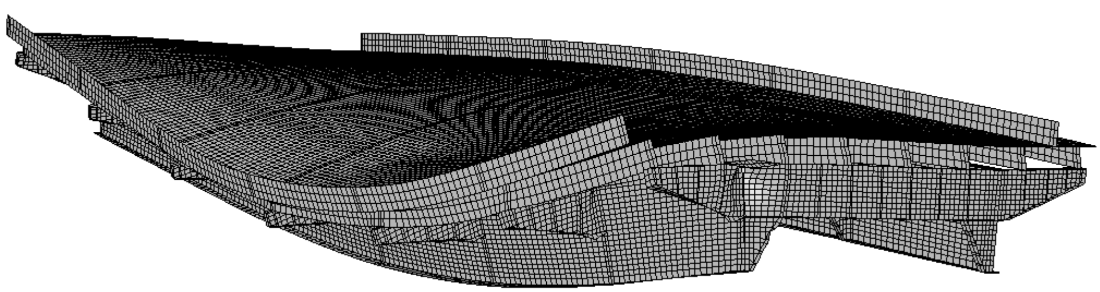

FIGURE 9 Three-dimensional finite element model in deformed shape.

A study of the deformations shown in this deflected shape confirms qualitatively that the tie plate is bending in the horizontal plane, and that these deformations are consistent with the field strain data. Figure 9 shows that the longitudinal girder deflects in simple bending when the load is in the center of the simple span. This deflection causes the end of the girder to rotate toward the center of the span, about the bearing located at the bottom flange of the girder. As the longitudinal girder rotates inward, the top of the transverse floor beam's web, which is connected via bolted double angles to the longitudinal girder, is pulled toward the center of the span. The stringers, which are connected to the top flange of the transverse floor beam, provide lateral bracing restraint and resist the inward movement of the transverse floor beam. This forces the tie plate to bend in the horizontal plane, creating tension on the leading edge of the tie plate and compression on the trailing edge of the tie plate.

The behavior is described in more detail in the M.S. thesis of the first author (*13*). As shown, the deflection of the longitudinal girder decreases as the load is stepped across the last transverse floor beam and away from the center of the span. Thus, the end rotation of the longitudinal girder is lessened, reducing the horizontal bending of the tie plate. When the load is directly over the last transverse floor beam of the span, the girder is subjected to simple cantilever action that causes near uniform tension in the tie plate. The tension caused in the tie plate from the cantilever action is much lower than the tension caused by the bending forces in the tie plate when the load is in the center of the simple span. This behavior reinforces the fact that the first, and highest, peak of the strain data collected occurs when the truck is in the center of the span, which is where the longitudinal girder is at its largest deflection, and therefore, it largest end rotation.

CONCLUSION

This report documetns a strain monitoring study to determine the cause of cracking in key tie plates of a non-redundant steel plate-girder bridge. The tie plates provide continuity for transverse floor beams that cantilever beyond the main supporting longitudinal girders.

Continuing field inspections noted the development of fatigue cracks in the tie plates, and the study began with strain monitoring to develop guidelines for use in repairs. All cracks developed at similar locations on the tie plates that were clearly designed as simple tension members to provide continuity to the top flange of the transverse floor beam. An initial strain monitoring study demonstrated that: 1) the tie plates are subject to bending in the horizontal plane; 2) the bending is not consistent with potential torsional deformations of the transverse floor beam that would be expected from bending of the longitudinal stringers; 3) the largest tension strains occurred when trucks are in the middle of the span and not directly over the cantilever, when maximum strains of the cantilever would be expected.

Additional field monitoring was used to better understand the cause of the large strains inducing cracks and to explain the behavior. The field data was correlated with a three dimensional finite element model to fully explain how deformations were occurring and to provide in sight into potential repairs.

The study demonstrated that repairs were only necessary for tie plates at the ends of the spans, greatly reducing the cost of the initial plan to replace all tie plates in the bridge. The field strain levels and an explanation of the behavior of the structure were used to provide the designers with guidelines on determining the dimensions of the replacement tie plates.

The information provided by this study is being used to maintain the structural integrity of the bridge and provide for an increased service life of this aging part of the State's infrastructure.

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