2009

Evaluation of accelerated bridge construction methods and designs in the state of Iowa

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Evaluation of accelerated bridge construction methods and designs in the state of Iowa

by

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A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Civil Engineering (Structural Engineering)

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Iowa State University

Ames, Iowa

2009

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ABSTRACT

Accelerated bridge construction (ABC) is the general term given to a variety of approaches aimed at reducing construction durations of bridge projects. Using these approaches on bridge projects introduces a number of advantages including reduced traffic disruption and increased safety. This thesis is comprised of two papers that focus on a number of ABC projects completed in the state of Iowa in the last decade. The first paper highlights the construction aspects of these projects and gives an evaluation of the projects based on criteria related to rapid construction and gives a comparison of the project cost to non-ABC projects. A road user cost analysis is also presented to demonstrate the cost benefit of decreased traffic disruption. The paper closes with a collection of lessons learned from the projects and a look into the future of ABC technologies. The second paper focuses on the design of accelerated bridge projects and the progression of the bridge elements and connection details over time. The paper includes an evaluation of the design of these bridges.

CHAPTER 1. GENERAL INTRODUCTION

Background

The author of the following thesis document acted as a research assistant for a series of research projects while pursuing a Master of Science degree in Civil Engineering at Iowa State University. The projects were all similar in the respect that they were all related to accelerated bridge construction. These projects presented the opportunity to compile information about accelerated bridge construction technologies, present recommendations for future use of the technologies, and test an accelerated bridge project in the field. The information gathered from this research was then used to write two papers on the subject of accelerated bridge construction in the state of Iowa. These papers make up the majority of this thesis document.

Research Approach

A number of research opportunities were presented to the author to assist in the development of this thesis document. An outline of the projects the author has participated in and completed is given below.

Boone County Bridge Field Test

A field test was performed on a bridge in Boone County, Iowa on two separate occasions during the summers of 2007 and 2008 to evaluate the post-construction behavior of the structure. The bridge was chosen for analysis because it was constructed in an accelerated manner using precast concrete elements for both the superstructure and substructure. Strain and displacement gages were installed at strategic locations of the bridge and the data recovered from the test was interpreted. It was determined through both field tests that the behavior of the bridge was satisfactory based on AASHTO specifications. The report documenting this field test can be found in the Appendix B of this thesis.

SHRP2 R04 Innovative Bridge Designs for Rapid Renewal Project

Iowa State University and several bridge design consultants coordinated to perform the first phase of the Strategic Highway Research Program Project Number R04 (SHRP2 R04). The primary objective of this project was to develop rapid bridge replacement technologies that can significantly reduce total project time. The first phase of the project consisted of collecting data from accelerated bridge projects around the world and utilizing that information to create a list of possible rapid replacement technologies to be further examined.

The author conducted a comprehensive literature review in order to compile available rapid bridge replacement resources. All pertinent articles found in this search were considered for review. The most applicable information was summarized into a report. In addition to the literature review, a request for information was sent out to a number of contacts in the bridge field. These contacts were from a broad spectrum of bridge engineering disciplines and were located all around the world. This request yielded some useful information that was added to the report. Finally, interviews were conducted with five contractors from around the country.

This phase of the project was completed with a report that combined all of the information collected from the literature search. The report culminated with the selection of a number of promising ABC technologies and a decision matrix used to evaluate these alternatives.

Thesis Organization

A considerable amount of information regarding accelerated bridge construction technology was discovered during the comprehensive literature review completed for the SHRP2 R04 project. The literature review generated from this information is substantial and also very general making it an unsuitable document for this thesis. However, the information gathered in that work was utilized to create two papers regarding the evolution of accelerated bridge construction in the state of Iowa.

The first paper is titled “Accelerated Bridge Construction in the State of Iowa: Evolution of Construction Practices and Prognostication" and can be found in Chapter 2 of this thesis. This paper reviews five major accelerated bridge construction projects in the state of Iowa and evaluates them based on selected criteria. In addition to the evaluation, a road user cost analysis was completed and detailed to demonstrate the benefit of reduced traffic disruption. The paper also details a number of lessons learned from accelerated bridge projects in the state of Iowa and gives a description of some possible rapid replacement technologies of the future. The paper focuses on bridges that can be built with common construction equipment.

The second paper is titled “Accelerated Bridge Construction in the State of Iowa: Evolution of Design Practices, Procedures, and Specifications" and can be found in Chapter 3 of this thesis. This paper examines four bridges that have been built in Iowa using accelerated construction techniques. The focus of this paper is on the design of these bridges and how the designs have evolved over time. The bridge designs are then evaluated based on criteria related to the acceleration properties of the design and performance. The paper is then concluded with a look at the lessons learned from past accelerated bridge projects in the state of Iowa.

The appendix of this thesis contains two sections to supplement the body of this thesis. Appendix A contains the calculations and references used to develop the bridge performance matrix values in Chapter 2. Appendix B contains the field test report from the Boone County Bridge built using accelerated construction. This report has been added to this thesis because the bridge tested in this paper is evaluated in both Chapters 2 and 3 and this report was a significant part of the author's graduate work. Accelerated bridge designs are innovative and must be field tested to verify they will be capable of carrying the expected loads with the appropriate behavior.

CHAPTER 2. ACCELERATED BRIDGE CONSTRUCTION IN THE STATE OF IOWA: EVOLUTION OF CONSTRUCTION PRACTICES AND PROGNOSTICATION

A paper to be submitted to the *ASCE Journal of Construction Engineering and Management*

Matthew Becker, Terry Wipf, Brent Phares, Kelly Strong

Abstract

A number of construction methods have been used around the world to successfully accelerated bridge construction. These methods utilize a variety of innovative materials and techniques to accomplish reduced construction durations and traffic disruption. In the State of Iowa, bridges are typically located on low-volume roads, an environment in which little research has been conducted in the area of accelerated bridge construction. This paper presents experience from five bridges in the state of Iowa built using accelerated bridge construction (ABC) methods. The bridges were each built using unique bridge systems and materials. An evaluation of these projects based on several criteria is given. Included in the evaluation is a cost comparison to a typical non-ABC project and a road user cost analysis. The findings give evidence that ABC projects can be built economically using innovative methods. The paper concludes with a list of lessons learned from these projects and a look at the future of ABC technologies.

Introduction

Ever increasing traffic demands and resulting higher road user costs (RUC) have introduced new challenges to the bridge construction industry. In short, bridges must be built faster and with less traffic disruption in order to deal with these issues. Accelerated bridge construction (ABC) is the general term given to a variety of approaches aimed at solving these problems. ABC can be accomplished in many different ways using various materials, designs and construction methods. However, ABC is a relatively new concept throughout the United States and this can make its application quite costly. Fortunately, much work has been completed in the last decade to advance ABC technologies and methods with the intent of making them more economical.

There are many advantages to using ABC beyond the reduced construction duration and traffic disruption. Daily RUC accumulated over the course of the project are significantly reduced because of the condensed construction schedule. RUC are generally not considered in traditional construction estimates but can be substantial on projects impacting high traffic volumes. In addition, worker safety can be improved because construction crews are on-site for shorter time periods. Also, reduced construction durations correspond to less impact on the environment. Finally, ABC projects are often constructed using prefabricated components that are created in more controlled environments, making them more durable and long-lasting. This increased durability, in turn, lowers the overall life-cycle cost of the project.

The State of Iowa has contributed to the advancement of ABC technologies in recent years. Through a partnership between the Iowa Department of Transportation (Iowa DOT) and Iowa State University (ISU), a number of innovative ABC projects have been designed, constructed, and evaluated. Theses bridges were built using various bridge systems, materials and construction methods. The experience gathered from these projects has been vital to the development of more efficient, cost-effect bridge designs. However, there has been little systematic comparison of alternative ABC concepts to determine which techniques and designs offer the best potential for future development and standard adoption. The objective of the work described here is to compare five ABC projects representing different design concepts and construction methodologies to determine which approaches offer the greatest opportunities for the future.

The five bridges included in this research have been selected for study here based upon their innovative attributes and contribution to the development of ABC in Iowa. These five projects will be described in detail and subsequently be evaluated based on three criteria:

- Construction speed (feet constructed/day)
- Production (tonnage/day)
- Cost (total project cost/bridge deck area)

These criteria have been selected because they best exemplify the "construction" features of an ABC project. A RUC analysis will also be performed on two projects to demonstrate the magnitude of savings that can be realized by reducing traffic disruption. In addition to these quantitative measures, evaluation of effectiveness will be examined, through descriptions, of lessons learned from experience on ABC projects in Iowa. The lesson learned section will include issues and circumstances that are often overlooked on construction projects but are critical to the success of the project. Finally, suggestions and recommendations for possible future ABC technologies will be discussed.

Bridge Case Studies

The bridges selected for evaluation were all built in the State of Iowa and were built with the goal of furthering ABC technology. Components from all of the projects have been tested in the laboratory and most of the bridges have been field tested. The bridges have various span lengths and were built in locations of varying traffic volumes and conditions.

Boone County Bridge

The Boone County Bridge was built in 2006 and at its completion became the first prestressed, precast concrete bridge built in the United States. This three-span structure, shown in Figure 1, was built in a greatly accelerated manner using various prefabricated elements. The completed bridge, shown in Figure 1, features a full-depth precast superstructure as well as precast substructure components. The bridge system was developed by the Iowa DOT and laboratory and field tested by ISU (Bowers, et al 2007).

Figure 1. View of completed Boone County Bridge

The original plan for the Boone County Bridge was to build the entire structure with precast concrete components. It was later determined that precast piers would add a significant cost to the project with a very small savings in time. The Iowa DOT chose to use steel piles for the piers as an alternative to precast concrete. Steel piles provided the designers with an economical option that would not significantly decrease the efficiency of the project. Overall, precast components were used for the pier caps, abutments, girders and deck panels (Abu-Hawash, McDonald, et al, 2007).

The precast concrete abutment and pier caps are connected to the piles using a cast-in-place joint. This connection is illustrate in Figure 2. Blockouts are created in the abutment and pier caps at the location of each pile. After placement "over" the piles, these blockouts are filled with a high early strength grout. A high range water reducer (HRWR) was used in the grout mix to increase the slump to 7 inches; this ensured that the grout flowed completely into the reinforcement-congested blockouts (Bowers, et al, 2007).

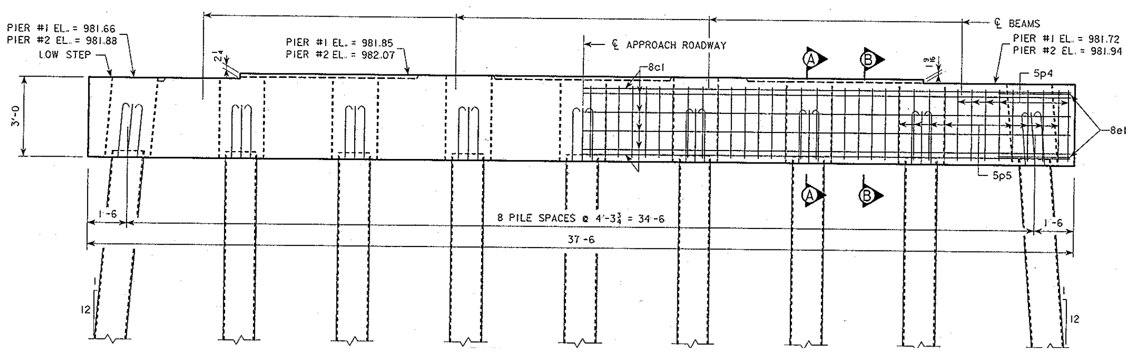

Figure 2. Boone County precast pier cap and pier layout

Four precast concrete girder lines carry the bridge deck. The beams used on the bridge were similar to the standard Iowa DOT five girder design with slight modification. The design used on the bridge was altered to allow for the removal of a girder line (Abu-

Hawash, McDonald, et al, 2007). The bridge deck is a full-depth, precast system made up of 36 panels which are shown in Figure 3. The deck panels are 16 ft wide in the transverse direction of the bridge and 8 ft long along the bridge length. This geometry allows for staged construction, with the deck panels covering half of the bridge width. Each panel is 8 in. thick and has two full-depth channels located over each beam line. After placement of the panels, post-tension strand is placed in the channels and tensioned. The channels are then grouted. A cross section of the bridge showing the deck panels and longitudinal channel layout is shown in Figure 4.

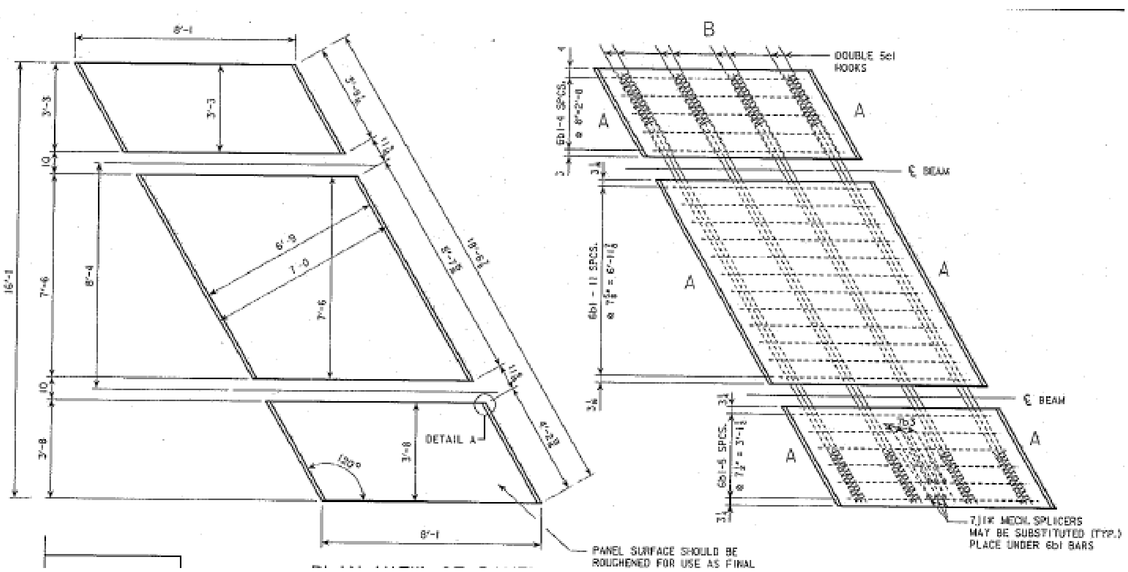

Figure 3. Boone County precast deck panel dimensions

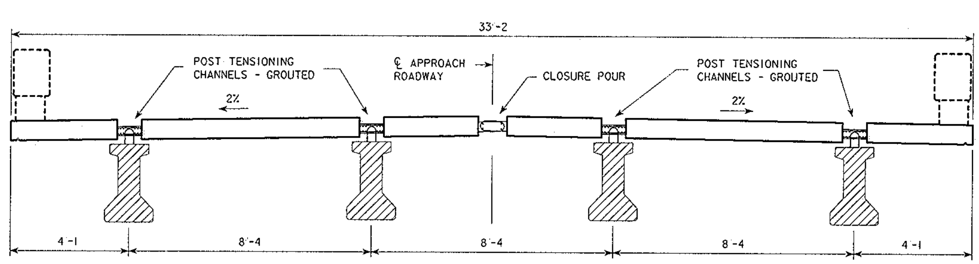

Figure 4. Boone County Bridge cross section including the longitudinal joints

The Boone County Bridge is located on a low volume road in northern Boone County. This type of bridge is typical of a large majority of the bridges in the state of Iowa with approximately 85% of the state's 26,000 bridges located on secondary roads (Klaiber and Wipf, 2004). Many of these bridges are in need of replacement by local agencies.

Construction of the new bridge began with the driving of the piles. Special care was taken during this process to meet the lateral end of driving tolerances. End of driving tolerances were small because the precast cap beams had to slip over the piles ends. After the cap beams were set in place, a high strength grout was used to quickly secure the joint by filling blockouts in the cap beams. A photo of one of the abutments being installed onto the piles is shown in Figure 5.

Figure 5. Placement of precast abutment cap onto H-piles

Placement of the girders took place in less than one day. The girders were delivered to the site early in the morning and were all in place just after noon. The following day deck panel delivery began. The panels were delivered to the site three at a time; half of the panels arrived the first day and the other half the next. Placement of the first half of the deck panels took one full day while installation of the other half only took half a day. This observation demonstrates a relatively steep learning curve sometimes associated with precast construction methods. A photo of a typical deck panel being installed is shown in Figure 6.

Figure 6. Installation of a precast concrete deck panel

The remainder of the construction activities began as soon as the last deck panel was placed and properly aligned. First, the transverse joints between panels were cast with a high early strength grout. While these joints were curing, post-tensioning (PT) strands were threaded down each of the longitudinal channels which are located directly over each girder. Each channel contains twelve 0.6 inch diameter strands. Once the strands were placed, the bridge was post-tensioned from one end in less than four hours. Concrete was then cast in the longitudinal joints and allowed to cure.

A theoretical work schedule was created for the Boone County Bridge project and compared to the actual schedule in the field. The actual bridge was completed on December 28, 2006 after 60 working days. The theoretical schedule, based on activity durations taken from the actual project, showed that the bridge could have been built in 12 working days. This schedule assumes that the existing structure was already removed and the abutment berms were complete prior to construction. The disparity between the theoretical and actual schedule can be attributed to the inexperience of the contractor with accelerated construction projects (Bowers, et al 2007) Despite the inefficiency of the project, the bridge was constructed in nearly half the time of a traditional bridge project of this magnitude.

The Boone County Bridge was constructed in an accelerated manner in order to quickly replace a deteriorated structure on a low volume road. Although this bridge was larger than most secondary road bridges, the project showed that this construction process could be used successfully and could possibly be used on higher volume bridges of this size.

FRP Temporary Bypass Bridges

Temporary bypass bridges are used in a number of construction applications. These bridges are generally small in size and are manufactured in more complete sections for easy assembly. Traffic disruption is reduced by using these bridges to create detour routes or to temporarily replace damaged existing bridges. For many years the Iowa DOT had employed the use of prefabricated steel bridges for these structures. In 2003, the Iowa DOT began research on the use of fiber-reinforced polymers (FRP) as a means of creating a lighter, more durable, and easier to construct bypass bridge. A photo of an FRP bridge being tested is shown in Figure 7.

Figure 7. Gravel truck applying load at test site

FRP is a composite material consisting of a polymer matrix and a reinforcing agent. The polymer is usually made up of resin, additives and fillers and the reinforcing agent is typically either glass or carbon. FRPs possess high-strength, low weight, and generally corrosion-resistant properties. FRPs are an ideal material for use on rapid construction bridge projects because they can be pre-manufactured into modular segments, much like concrete can. Composite materials have high strengths and, because of their low weight, can be placed quickly with very “small” equipment. The high durability of the material also makes it resilient to deicing salts and marine exposure conditions.

The FRP bypass bridge consists of two 13 ft and 6 in. wide by 39 ft and 10 in. long panels connected together to form two traffic lanes as shown in Figure 8. Each panel composed half of the overall bridge width and had a thickness of approximately 3 ft. A steel guardrail system was added in addition to an epoxy wearing surface (Wipf, et al, 2005).

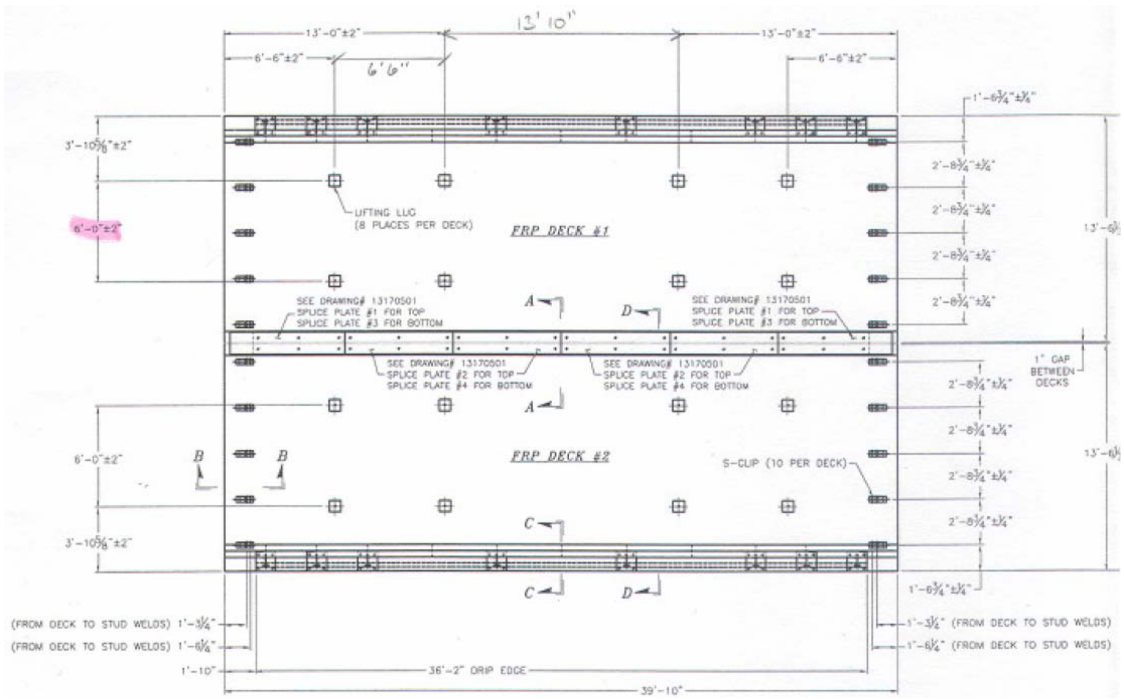

Figure 8. FRP panel layout for temporary bypass bridges

Fabrication of the FRP panels was both an innovative and complex process. Each exterior face of the panels is composed of seven layers, or plies, of FRP fabric. This external portion of the panels supplies bending resistance. The central portion of the panels is made up of 600 cylinders wrapped in FRP; these cylinders provide shear resistance. Fabrication was completed by filling the structure with a resin through a method known as vacuum injection (Wipf, et al,2005).

In March 2007, the panels were brought to a location near Ft. Atkinson, Iowa for installation. The panels were transported to the site, one on top of the other, on a standard semi-trailer bed as shown in Figure 9. Once on site, the panels were lifted from the truck and into their final location using a light crane. A pair of plates were installed at the top and bottom of the bridge deck centerline, bridging the longitudinal joint between the individual panels, and then connected by a threaded bar at regular spacings. A similar threaded bar connection was used to secure the guardrail to the bridge deck. Details of these two connections are shown in Figure 10. Once the abutments were constructed, the superstructure was constructed in less than two days and ready for traffic (Hosteng, et al, 2007).

Figure 9. FRP panels loaded onto truck trailer for delivery

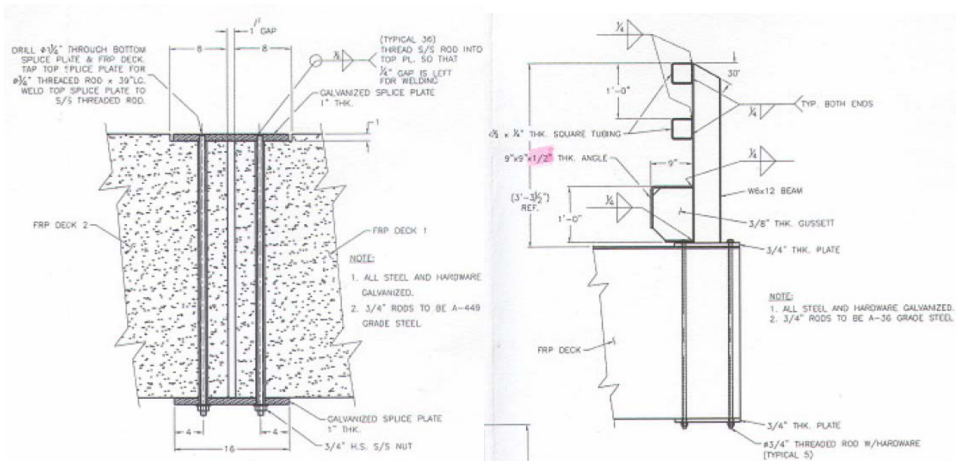

Figure 10. Panel connection detail (left) and girder connection detail (right)

Unfortunately, the panels were not placed properly and this has lead to serious degradation of the structure over time. Specifically, the panels were placed so that their edges projected above the approach pavement elevation. Over time, impact from traffic deteriorated this portion of the panels. This is a construction issue and could have been corrected with more stringent construction tolerances (Wipf, et al, 2005).

Black Hawk County Bridge

In 2007, Blackhawk County furthered the development of precast construction with the construction of its own bridge. This bridge was completed with the hopes of further advancing rapid low volume bridge replacement. The bridge system used on this project was developed by Blackhawk County and was based on a system that had been used in Iowa since the mid-1970s. The original system, the beam-in-slab bridge (BISB) system had been used on over 80 bridges in the state (Konda, el al, 2003). This design had been modified to make a more efficient section that allowed for longer spans. This modified system is known as the precast modified beam-in-slab bridge (PMBISB) system.

Production of the panels and the abutment caps was completed by Blackhawk County using only county forces during the winter of 2007. This technique allowed work to be accomplished during the offseason and also ensured the bridge elements were ready in advance of the initiation of construction. The abutment caps were fabricated by laying a steel W-section on its side and casting concrete around the upper half. The deck panels consisted of steel W-section girders encased in concrete as shown in Figure 11. The majority of "tension" concrete in between each girder line was removed using curved PVC forms. This created an arched shaped on the bottom of the panels in between each girder. Precast abutment backwalls were also produced for the bridge (Wineland, Klaiber, and Schoellen 2007).

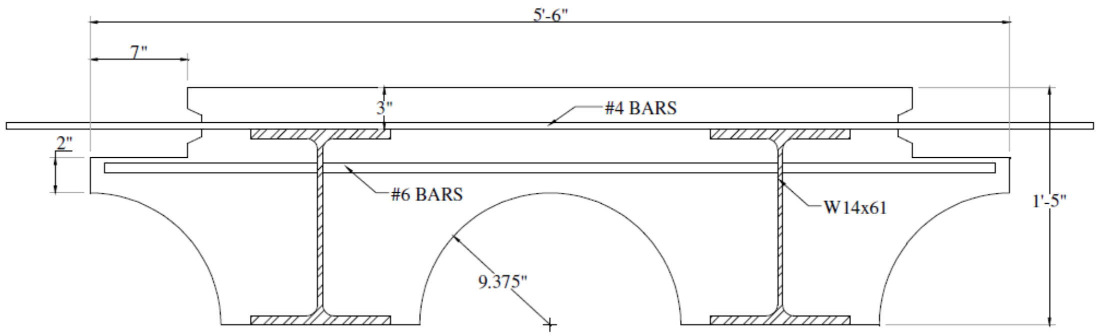

Figure 11. PMBISB deck panel cross-section

Construction of the bridge began with the installation of steel H-piles at each abutment; the H piles were arranged for strong axis bending. Once pile installation was complete, the abutment caps were placed. The abutment caps were placed so that the W-section in the cap sat directly on the H-piles as seen in Figure 12. This connection provided a degree of lateral restraint to the abutment cap.

Figure 12. Precast concrete abutment cap supported by steel H-piles

The deck panels were transported to the site and placed on the abutment caps after the completion of the substructure. When all six panels were in place, reinforcement was installed in the longitudinal closure joints. Concrete was then placed in the joints to complete the superstructure. The completed bridge deck, shown in Figure 13, had a span length of 40 ft and a width of 32 ft. Total on-site construction time for the superstructure was less than 40 hours (Wineland, Klaiber and Schoellen, 2007).

Figure 13. Black Hawk County Bridge near completion

24th Street Bridge in Council Bluffs

At the time, the replacement of the 24th Street Bridge in Council Bluffs combined more innovative and accelerated construction and design components than any other bridge constructed in the State of Iowa. The bridge, shown in a conceptual drawing in Figure 14, was built in 2008 by the Iowa DOT with funding from a variety of sources. Construction time was reduced from an estimated two construction seasons to one using accelerated methods while at the same time maintaining traffic on at least three lanes at all times (Abu-Hawash, Khalil, et al 2007).

Figure 14. Conceptual drawing of the 24th Street Bridge

The 24th Street Bridge is a two-span bridge with a 354 ft total length and a 105 ft width. Steel girders and a full-depth, precast concrete deck system makes up the superstructure. A typical precast concrete deck panel used on the bridge is shown in Figure 15. Steel girders were chosen for the superstructure to allow for longer span lengths. The bridge is part of a major improvement project on the Council Bluffs Interstate System (CBIS). The new six-lane, two span bridge replaces a four-lane, four span bridge. Accelerated contract methods, phased construction, and prefabricated elements were used to make this ABC project a success (Abu-Hawash, Khalil, et al 2007).

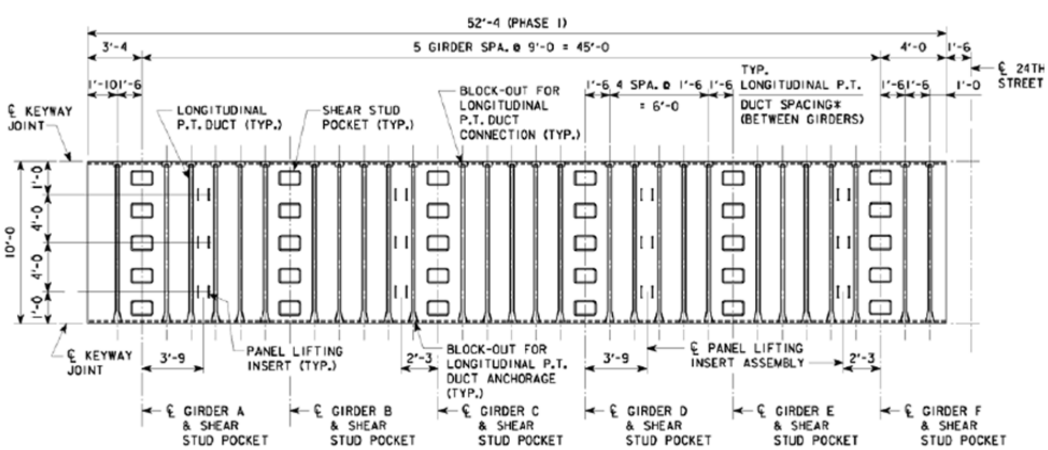

Figure 15. Typical precast deck used on 24th Street Bridge

The Iowa DOT helped to ensure the bridge would be built rapidly by using A+B contracting methods. The winning bidder for this contract type is decided by multiplying the number of construction days by an estimated daily user cost and adding that amount to the bid price. In this way, construction duration becomes a part of the decision-making.

A staged construction approach was used by the contractor to maintain three lanes of traffic at all times. Construction activities were divided into two primary phases. The first phase involved the removal of one lane of the existing bridge and the construction of the southbound half of the new bridge. During this phase, traffic was maintained on the remaining three lanes of the existing bridge. The next phase of construction involved the removal of the remaining portion of the existing bridge and the construction of the northbound half of the new bridge. During this phase, traffic was maintained on the southbound half of the new bridge. A diagram of each construction phase is shown in Figure 16.

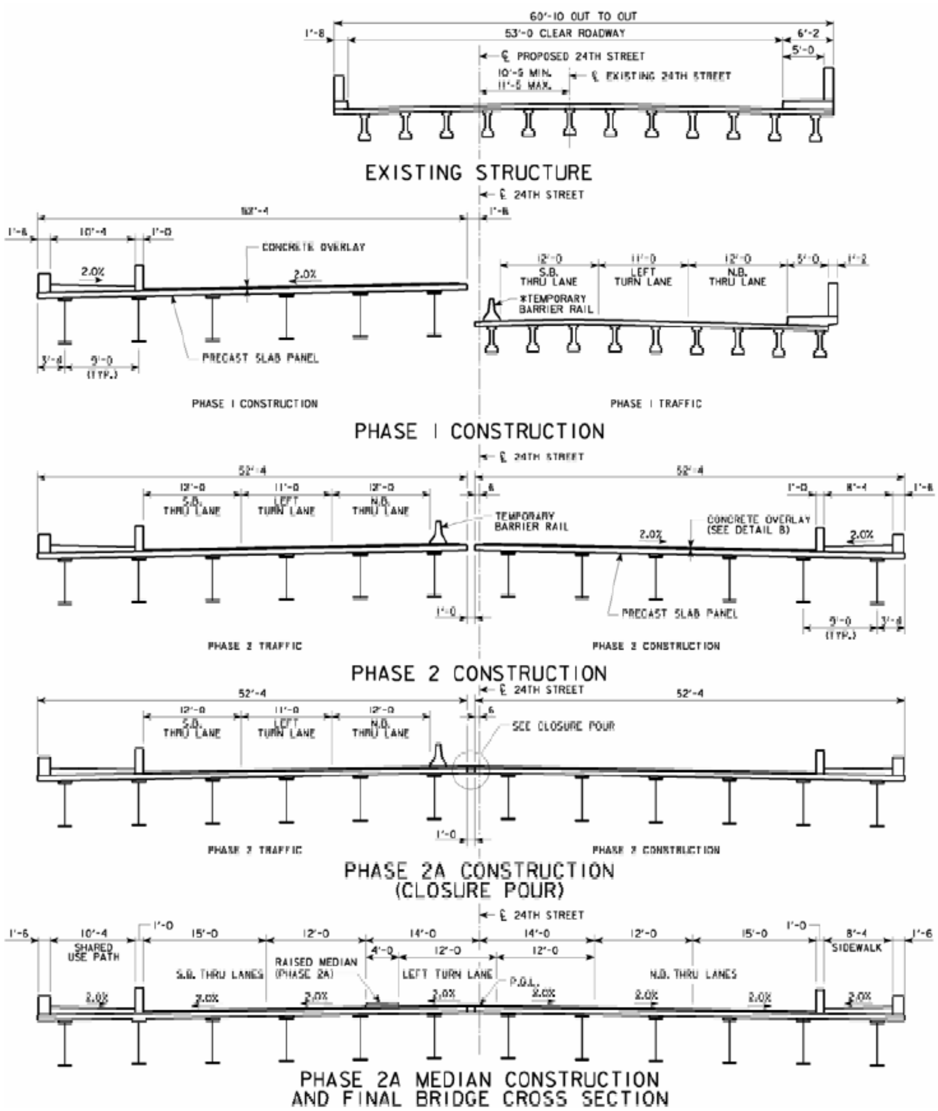

Figure 16. Staged construction phases of 24th Street Bridge project

Construction of the superstructure was completed using a variety of prefabricated elements. Once the abutments and pier were completed, the steel girders were installed. High performance steel was used in the top and bottom flanges to produce a lighter cross-section. The deck panels were then placed on the girders. Each panel spanned half of the total deck width and measured 10 ft along the bridge length. Keyway joints were provided at the transverse edges of the panels and were grouted immediately after all panels had been placed. Longitudinal post-tensioning was completed as soon as the transverse joints reached the required strength. Grout was also used in shear pockets to provide composite action between the deck and the girders. Finally, after both phases were complete, the two bridge halves were connected using a longitudinal closure pour (Abu-Hawash, Khalil, et al, 2007).

Buchanan County Bridge

The Buchanan County Bridge was completed in 2008 and was built using ultra-high performance concrete (UHPC) in its main span. This was the second experience working with UHPC bridge elements in the State of Iowa (and the United States). The Buchanan County Bridge is unique because it features a pi-girder full-depth deck cross section. This was the first time this bridge system was used in the state of Iowa.

UHPC exhibits some outstanding qualities that make it an attractive product to designers and contractors. The most apparent advantage of using UHPC is that it is significantly stronger than conventional concrete. This allows smaller sections which results in the reduction of weight and depth of bridge components. UHPC also demonstrates very high durability with very low permeability, which lowers the overall life cycle cost of the product.

The Buchanan County Bridge consists of three spans with a 115 ft total length. The 51 ft center span is composed of three precast concrete pi-girder beams. Each beam measures 8 ft 4 in. in width. A cross section of the final pi-section used on the project is shown in Figure 17. The substructure is made up of steel H-piles supporting integral abutments and pier caps (Keierleber, et al 2008).

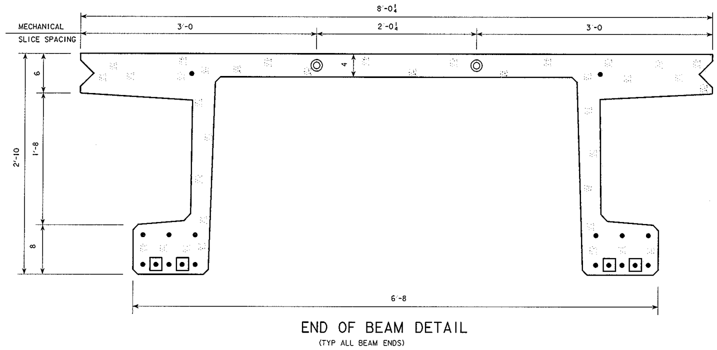

Figure 17. Buchanan County pi-girder cross-section

Construction of the Buchanan County Bridge was not a complete accelerated bridge project because only the middle span was prefabricated. The main purpose of the project was to advance the use of UHPC as an innovative material, not to evaluate UHPC as an accelerated component. However, the benefits of UHPC in accelerated construction were evident on this project. Construction of the middle span was completed in two days. The beams were installed on the first day and grout was placed in the longitudinal joints on the second day. Photos showing the transportation and installation of the pi-girder cross-sections are shown in Figures 18 and 19, respectively.

Figure 18. Delivery of a precast concrete pi-girder

Figure 19. Installation of precast concrete pi-girder

Despite all the benefits of UHPC and other innovative materials, there are some potential concerns with using these materials. Generally, the initial cost of innovative materials is very high. This has impeded the widespread use of these products. Research has been performed at a number of universities, including ISU, to learn more about UHPC. With UHPC, there is also some concern as to how it will respond to deicing agents and also to its compatibility with other materials. In order to increase the use of UHPC, a proper code needs to be developed, designs for the product must be standardized for use, and more producers have to be available.

UHPC shows much promise for use on accelerated bridge projects. UHPC has high strength properties that make it an interesting material for bridge components

Evaluation

The five bridge projects described in this paper have been evaluated based on a performance matrix developed based on three accelerated construction criteria:

- Cost per square foot of bridge deck ($/ft^2)

- Daily work progress (ft/day)
- Daily quantities (tons/day)

These criteria have been chosen because they can be used to compare the accelerated qualities of ABC projects. The construction costs, durations and tonnages were determined using papers, plan sets, and contract documents. The calculations for the performance matrix values and their references can be found in Appendix A. In addition to the performance matrix evaluation, savings resulting from RUC have been calculated for the Boone County Bridge and 24th Street Bridge projects. A savings in RUC can offset the premium sometimes introduced by ABC projects.

Performance Matrices

The performance measures for each bridge project discussed previously are shown in Tables 1 and 2. Table 1 provides information regarding the entire project duration and entire bridge structure. Table 2 provides information related to the bridge superstructure alone and the associated construction time required for its construction.

Table 1. Performance matrix for total bridge project

Bridge	Final Construction Cost	Total Construction Duration, (days)	Bridge Deck Area, (ft^2)	Structural Tonnage (tons)	Cost per Sq. Ft. of Bridge Deck, ($/ft^2$)	Daily Quantities (tons/day)
24th Street	$5,375,000	185	29028	5180	$185.17	28.0
Black Hawk County	N/A	22	1280	190	N/A	8.6
Boone County	$509,173	110	5007	534	$101.69	4.9
Buchanan County	$1,000,000	-	1266	-	$789.89	-
FRP Bypass	$240,300	-	1053	-	$228.21	-

Table 2. Performance matrix for superstructure portion of bridge projects

Bridge	Superstructure Construction Duration, (days)	Total Span Length, (ft)	Structural Tonnage (tons)	Daily Work Progress (ft/day)	Daily Quantities (tons/day)
24th Street	122	358.5	3170	2.94	26.0
Black Hawk County	2	40.0	160	20.00	80.0
Boone County	36	151.3	294	4.20	8.2
Buchanan County	2	51.0	68	25.50	34.0
FRP Bypass	2	39.0	48	19.50	24.0

Cost Evaluation

The cost evaluation method most commonly used on bridge projects is the cost per square foot of bridge deck. The advantage of this method is that it allows one to compare the costs of varying sizes of bridges. The cost used for the evaluation presented herein is the final total construction cost of the bridge. This cost does not include any research-related costs or miscellaneous cost such as aesthetics.

Prior to evaluation of the individual bridge costs, the cost of a traditional low volume road bridge was determined to allow for comparison between ABC and non-ABC projects. According to Abu-Hawash (2005), a bridge representative of a typical Iowa low volume road bridge was let at a cost of $114 per square foot of bridge in 2004. Using yearly inflation values presented by Buechner (2007), this value was estimated to be a 2007 cost of approximately $150 per square foot of bridge. This cost was verified to be an accurate approximation based on figures showing that a low volume road bridge in Florida in 2007 had a cost of $160 per square foot of bridge (Florida DOT).

Several conclusions can be drawn from this cost comparison. The most noticeable values in the table are the high costs of both the Buchanan County and FRP Bypass Bridges. These bridges utilized very high-cost, innovative materials. Using ultra-high performance concrete (UHPC) and fiber-reinforced polymers (FRP) in bridge construction provides the benefits of increased strength and light weight but comes with this added premium. From these projects it could be concluded that using innovative materials may not be economical on a first-cost basis. In time, though, as the material is used more widely in the industry, the cost of these materials may become more economical.

From the overall analysis further conclusions can be made by comparing the ABC bridge costs to a non-ABC project cost. It was found that the Boone County Bridge was built at a significantly lower cost than a non-ABC bridge. This disproves the belief that ABC projects cannot be completed at a rate competitive with non-ABC projects. It is the authors' opinion, however, that ABC projects cannot be competitive without the use of innovative designs and construction methods.

A slightly higher cost was realized on the 24th Street Bridge in relation to the Boone County Bridge. This cost increase is most likely attributed to the cost of maintaining traffic throughout the project duration. On projects constructed in high traffic volume areas, costs like these are like to by incurred to ensure traffic is maintained at an adequate level.

Road User Costs Analysis

Road user costs are those associated with the loss experienced by the travelling public due to construction disruption. As stated earlier, these costs are not generally included in an overall project cost. Higher traffic volumes and the need to maintain traffic has increased the importance of these costs.

Two projects, the 24th Street project and the Boone County project, were evaluated using RUC to discover the savings that could be realized by using ABC methods. Both of these projects were constructed using a bridge system that can be constructed in a traditional, non-ABC manner. In these two cases the use of accelerated construction methods decreased the amount of time that the construction crews were on site. The 24th Street project further reduced traffic disruption by maintaining three lanes of traffic at all times during construction. The Iowa DOT calculates RUC using a simple formula:

RUC = (equivalent vehicles)/2 * detour distance * cost/mile * # of construction days

The formula has the following assumptions:

- One truck equals three cars
- Only half of the traffic will use the designated detour route
- Cost per mile = $0.36 per mile

The traffic conditions used in both situations are shown below in Table 3. For the 24th Street Bridge, existing traffic conditions on the project were used. In the case of the Boone County Bridge, existing traffic conditions were not used because the bridge is located on a very low volume gravel road. In order to replicate a more representative environment, average traffic volumes for a typical highway in Iowa were used. These data correspond to 2007 traffic on Highway 69 just north of Ames, Iowa.

Table 3. Traffic conditions for RUC analysis

	24th Street	Boone County
Design Year Traffic	15,000	4340
Design Year % Trucks	19	10

Estimated construction times were developed for non-ABC construction of these bridge types based on past experience. The Boone County Bridge was completed in approximately 60% less time than a traditional, non-ABC project of its kind. This corresponds to a value of 183 days. The 24th Street Bridge was completed in a single construction season as opposed to the typical two construction season duration for a project of its magnitude (equivalent to a duration of 550 days). Traffic disruption durations for both the ABC and non-ABC versions of each project are shown below in Table 4.

Table 4. Traffic disruption durations for the RUC analysis projects

	24th Street		Boone County	
	ABC	non-ABC	ABC	non-ABC
Traffic Disruption Days	0	550	110	183

RUC were calculated for each of the four projects using the Iowa DOT. These data are portrayed in Table 5. An assumed detour distance of 3 miles was assumed for all three projects.

Table 5. RUC and RUC savings for each project

	24th Street		Boone County	
	ABC	non-ABC	ABC	non-ABC
Savings	$0.00	$6,147,900.00	$309,355.20	$514,654.56
Total Savings	**$6,147,900**		**$205,299.36**	

The benefit of using accelerated construction methods for each of the two projects is clear after observing the savings in RUC. If the premium of using accelerated construction on a project is less than the savings obtained from RUC, then the use of ABC may be justified.

Productivity Evaluation

The daily work progress criterion is based on the length of bridge constructed per day. The longitudinal length used is the total length of the bridge and the construction duration is the time for superstructure assembly. This criterion is useful for ABC projects because it demonstrates the speed at which the superstructure is constructed. On the other hand, the daily quantities criterion is based on the average tonnage of bridge material placed in a given day. This criterion has been determined for both the entire bridge structure and the superstructure alone.

It is evident from the performance matrices of Tables 1 and 2 that ABC projects exhibit high productivity rates. Furthermore it can be observed that productivity is increased with the use of larger structural components. However, these components may not be appropriate for all sites.

Lessons Learned

Many lessons have been learned from experiences with ABC in the State of Iowa. The case study projects described herein have been analyzed to identify problems or issues that could significantly increase the efficiency of future projects. Outlined below are six recommendations to improve the effectiveness of future ABC projects:

- **Effective Communication**

One of the most important factors for a successful ABC project is proper communication. Communication is easily neglected, however timely and accurate communication of information can have a significant impact upon the success of an ABC endeavor. There are many forms of communication that can be used during a project. Pre-construction meetings held between all parties directly involved in the project (e.g., designers, prime contractor, sub-contractor, etc.) ensure that all parties have a common understanding of the project goals and the overall design intent and that each partner knows what is expected of them. Public meetings and announcements should be used to keep the public informed travel impacts. Announcements can be made on all forms of media including the internet, newspaper, radio, and road signs.

- **Timely Procurement**

Delivery of prefabricated components to the site can be an important aspect contributing to the speed of construction. Procurement and delivery of bridge components should be coordinated with the actual construction schedule to increase the efficiency of the project. Delivery delays can contribute significantly to the cost of the project and can put a contractor at risk of losing incentives. It is obviously beneficial to have the prefabrication site as close to the project as possible. In some cases, a temporary site may prove to be economical.

- **Efficient Detours**

Bridge replacement can be best expedited if traffic can be redirected, but this is dependant on the availability of effective detour routes. Even when bridges are replaced under traffic, minimizing disruption of traffic during an ABC project is a critical component of project success. ABC is more effective if, prior to construction, an efficient detour can be made available to the existing traffic on the route. This route should be advertised to the public in a clear, accessible manner. In many cases, more than one detour may be necessary to accommodate existing traffic.

- **Adequate Equipment**

Using the right equipment and having contingency plans can greatly increase the success of the project. If the appropriate equipment is not used, projects can be significantly delayed. Even if the delay is minimal, thousands of dollars can be realized in RUC. Before construction begins it is important to understand what equipment is most efficient for the individual project. In addition to having the right equipment on hand, it is crucial to have a contingency plan in case of equipment malfunction.

- **Local Competition**

In order to make ABC more economical, it is important to design a bridge that can be constructed by more than one likely-to-bid contractor. Designing to the abilities of local contractors permits more competition, subsequently lowering the final construction cost.

- **Repetitive Projects**

The Boone County Bridge project demonstrated that a bridge could be built in a very short time duration using almost entirely prefabricated components. It was also apparent that there is a steep learning curve on projects of this nature. A great deal of time was spent to become familiar with the new construction techniques. However it was observed that when a particular activity was repeated, it was completed in a fraction of the original time. It is essential to the success of future ABC projects that this be acknowledged.

Future of ABC

The future of ABC is full of possibilities. Many of the accelerated bridge placement techniques are being improved and construction times continue to be reduced. This is beneficial to the advancement of ABC technology. However, it is crucial that new technologies continue to be developed. There are numerous construction techniques and materials being researched and developed for use on ABC projects. However, little comparative research has been done to identify which ABC techniques are most effective and efficient, especially for rural bridge replacements.

For example, one piece of equipment that shows much promise for success on ABC projects is the self-propelled modular transporter or SPMT. An SPMT is a computer-controlled vehicle that is used to move and lift very heavy objects. This machine is extremely useful for rapid construction because a bridge superstructure can be removed and replaced in as little as one night. An individual SPMT is made up of 4 or 6 axles, each axle composed of 4 wheels. A pair of SPMT vehicles are shown in Figure 20 transporting a bridge. These vehicles have been used in Europe, but have seen limited use in the United States. The major downfall of using SPMTs is that they are very expensive to use and can only be used in areas where a clear delivery path is provided from the erection site to the bridge (Ralls, Tang and Russell, 2005). Such an approach to ABC for rural bridge would not be feasible.

Figure 20. SPMTs used to transport an entire bridge superstructure

Another promising ABC placement technique that was developed for use on bridges in more congested areas is a top down gantry system. This system requires the erection of falsework on both sides of the bridge span and rolling out gantry cranes to place precast deck panels. This system has been used effectively on ABC projects but tends to be costly, making it impractical for use on rural bridge replacements.

These technologies show much promise for the accelerated construction of "signature" or "major" bridges but do not seem to be feasible alternatives for use on more typical overpass-type structures. In these cases, it is critical that the ABC technology employed on the project can be utilized by smaller contractors using lighter construction equipment. For this reason, it is valuable to develop materials that are lighter and have greater spanning capabilities.

The benefits of using high performance materials such as FRP and UHPC have already been demonstrated. These materials show much promise as light weight materials with high strength properties but seemingly have practical limitations when it comes to fabrication and cost. In order to alleviate these limitations, the materials need to be further researched and used more extensively. It is likely that as the materials are used to a greater extent, they will become more economical. It is essential to keep in mind that at one time many materials, such as precast concrete, were thought of as too costly for widespread use and are now used commonly around the world.

Even more innovative materials exist that may be looked at in the future. One specific concept involves the use of long-fiber carbon tubes that can be filled with pressurized air for temporary self-support, with some cells then filled with resin or post-tensioning strand after erection. Differential air pressure could be used to control camber. The carbon tubes would be sealed in a composite material that could be sprayed or troweled. Another possibility is to combine ultra-high strength concrete chemistry with geofoam technology to develop an expanding, high strength concrete material that could essentially be spray-applied.

Concluding Remarks

It can be seen by evaluating a sample of Iowa's accelerated bridge projects that innovations in ABC have made this general approach to construction less expensive to use and more efficient. In some cases ABC projects can be equal to or lower than the cost of non-ABC projects with the added benefits of reduced construction time and traffic disruption. It is also apparent from Iowa's bridge projects that no one bridge system is the optimum solution for every situation. Different traffic, environmental, and geometric conditions influence the type of design, material, and construction that will be most efficient. Utilizing experience from past projects will contribute to the success of future projects.

The future of ABC is limitless with a number of innovative technologies already being developed. These technologies may be costly to implement at first but their benefits can be great. With continued use and understanding, these alternatives can become more feasible and economical. However, it appears that for the foreseeable future, the use of precast concrete as the primary component of an ABC project is the best solution.

The advancement of accelerated technologies in bridge construction is vital to the future of the nation’s infrastructure. The experience the State of Iowa has gained through a number of these projects has given the opportunity for improvement and progression in this area. The willingness to experiment with new and innovative materials has also helped keep the state at the forefront of rapid replacement technology. It is continued experience and the willingness to experiment that are necessary to advance ABC techniques.

CHAPTER 3. ACCELERATED BRIDGE CONSTRUCTION IN THE STATE OF IOWA: EVOLUTION OF DESIGN PRACTICES, PROCEDURES, AND SPECIFICATIONS

A paper to be submitted to the *ASCE Journal of Bridge Engineering*

Matthew Becker, Terry Wipf, Brent Phares, Kelly Strong

Abstract

In the last decade, accelerated bridge construction (ABC) has become more widely used as the need for reduced construction durations and fewer traffic disruptions has increased. Over time, designs have evolved to decrease both the construction duration and the cost of these projects. In the state of Iowa, bridges are typically located on low-volume roads, an environment in which little research has been conducted in the area of ABC. This paper presents the design of four bridges in the state of Iowa built using ABC methods. The bridges were each built using unique bridge systems and materials. The evolution of the bridge systems and specifically the connections employed is the main focus of the first part of the paper. An evaluation of these projects based on the a number of design-based criteria is also presented. These criteria include constructability, traffic disruption, cost, durability and span length. The findings of the evaluation show that no one bridge design is appropriate for all bridge projects. The most favorable bridge systems are then selected for different construction environments.

Introduction

Ever increasing traffic demands and rising road user costs (RUC) have introduced new challenges to the bridge construction industry. Bridges must be built faster and with less traffic disruption in order to deal with these issues. Accelerated bridge construction (ABC) is the general term used to describe a variety of approaches to solving these problems. ABC can be accomplished in many different ways using various materials, designs and construction methods. However, ABC has not been used extensively throughout the United States and this can make its application quite costly. Fortunately, many research projects have been completed in the last decade that have advanced ABC technologies and methods to make them more economical.

The State of Iowa has been designing bridges for use in accelerated projects for over a decade. These bridges were designed using a wide range of bridge system types and a variety of different materials. In addition, the majority of these designs have been tested, both in the lab and in the field, and improved upon. Because a large percentage of the road bridges found in Iowa are located on rural roads, it is critical for the state to focus on bridge designs that can be constructed by local or county crews with lighter construction equipment. This sets the ABC focus of Iowa apart from other areas of the nation that concentrate on bigger systems that utilize heavy construction equipment more appropriate for high-volume roads in urban settings.

This paper focuses on the development of efficient bridge systems for ABC in the State of Iowa and the progression of the designs over time. To accomplish this, four specific projects will be highlighted and critiqued. Designs for these bridges were originally based on conventional approaches that had been used in the state for years. The adaptation of these designs to be compatible with accelerated construction has significantly reduced traffic disruptions and increased the number of bridges that can be built in an individual construction season. The bridge systems will be evaluated based on the following characteristics:

- Constructability
- Traffic disruption
- Cost
- Durability
- Span length

Bridge Case Studies

The bridges selected for evaluation were all built in the State of Iowa and were constructed with the intention of furthering ABC technology. The following case studies will focus on the design of each bridge system and the evolution of the connection details. Components from all of the projects have been tested in the laboratory and most of the bridges have been field tested to prove they are structurally adequate. The bridges have various span lengths and were built in locations with varying traffic volumes and types.

Black Hawk County Beam-In-Slab Bridge System

The first bridge reviewed here was built in Black Hawk County using a beam-in-slab system. The beam-in-slab bridge (BISB) system was developed in the 1970s for use on low volume roads. There are over 80 of these bridges currently in use in the state with the first one built in Benton County. The design is useful for rural bridges because it can be built without specialized equipment (Konda, et al, 2003). Since its conception, the system has undergone a number of modifications to increase its efficiency. The system has gone from a cast-in-place design for use on low-volume roads to the current precast design.

The original BISB system, shown in Figure 21, was comprised of longitudinal steel I-girders placed at 24 inches on center with unreinforced concrete filling the spaces between them. Steel straps were welded at the quarter points to provide lateral restraint between the girders and plywood was placed between adjacent bottom flanges to act as formwork. This design was well-suited for county construction crews because it could be installed with light equipment and was shown to provide a cost savings of 20% with respect to traditional systems. However, due to the large self weight of the structure and the lack of composite action between the concrete and steel, the span length of the system was limited (Konda, et al, 2003).

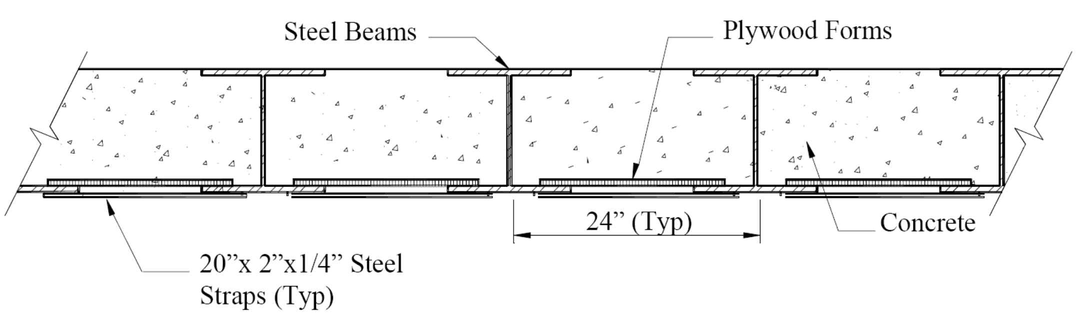

Figure 21. Original BISB system

Researchers found two ways to make the system significantly more efficient. The first modification was to introduce composite action between the concrete and steel. This was accomplished by placing holes into the web of the girders at 3 inches on center. The second modification was to remove the ineffective regions of concrete from the tension zones of the section. In order to remove this area, a corrugated steel system was used as the formwork between the girders (Konda, et al, 2003).

This modified beam-in-slab bridge (MBISB) design, illustrated in Figure 22, increased the possible span lengths significantly. A demonstration bridge was built in Tama County to determine the ease of construction and to investigate the behavior of the bridge due to loading. This bridge had an overall span length of 70 ft. The bridge was built with a cost savings of 10% relative to the average bridge at the time (Konda, et al, 2003).

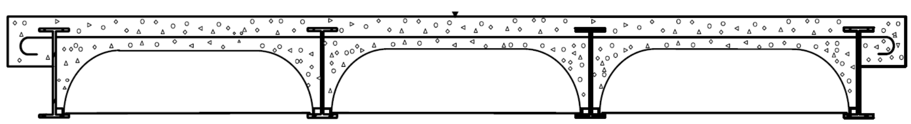

Figure 22. MBISB system

In 2007, the Black Hawk County bridge was constructed using a design expanded from the MBISB system. This system is known as the precast modified beam-in-slab bridge (PMBISB) system and is portrayed in Figure 23. A photo of one of the precast deck panels in the field is shown in Figure 24. The major difference between the PMBISB and MBISB systems is the use of precast components. This drastically minimizes the overall construction duration. The design was developed by Black Hawk County and was tested by Iowa State University (Wineland, et al, 2007).

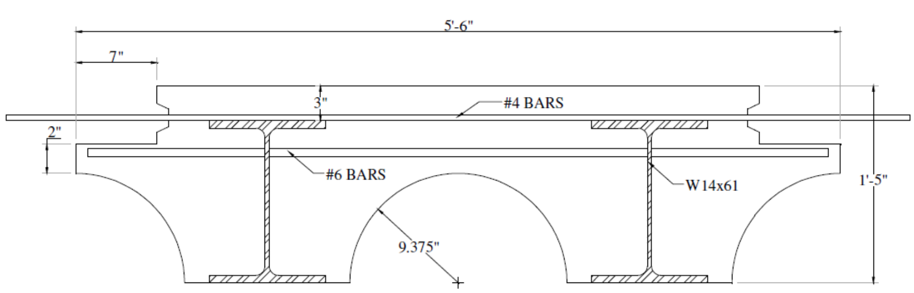

Figure 23. PMBISB system

Figure 24. PMBISB system deck panel used on Black Hawk County Bridge

The bridge, known as the Mt. Vernon Road Bridge, spans a total of 40 ft with a width of 32 ft. Six precast beam-in-slab deck panels make up the superstructure. The design is similar to the previous BISB types but has some slight modifications. One of these changes is the utilization of 18” PVC pipe to create the arch between the girders (Wineland, et al, 2007).

A precast abutment cap was developed for this project to further increase the speed of construction. The abutment cap is made up of a W steel section on its side with concrete cast around its upper half. This configuration takes advantage of the properties of both materials and also uses the downward protruding steel flanges as a connection between the abutment and abutment cap. Two views of the abutment cap placed on the pier can be seen in Figure 25. A W12x65 section was used on the Mt. Vernon Road Bridge project. A series of tests were performed at Iowa State University (ISU) to determine the adequacy of this steel section. These tests revealed that the section could be reduced to a lighter and more economical W12x29 section and still provide sufficient capacity (Wineland, et al, 2007).

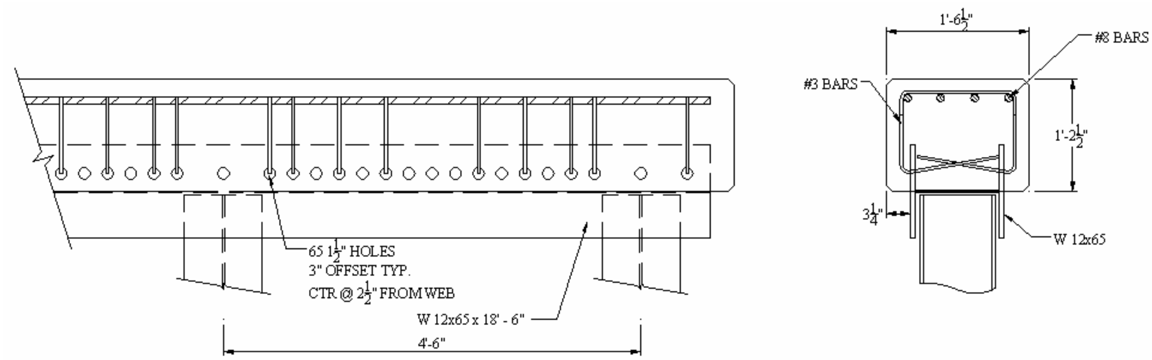

Figure 25. Precast abutment cap used on Mt. Vernon Road Bridge

The abutment used on the Mt. Vernon Road Bridge was made up of a series of H-piles. However, a precast concrete abutment backwall was developed for use on future projects. The backwall is a 14 ft by 4.25 ft reinforced concrete slab with reinforcement varying with depth. It was determined from testing that this segment could adequately carry the expected lateral earth pressures. The flanges of the precast abutment cap act as lateral bracing along the abutment backwall adding additional capacity (Wineland, et al, 2007).

A great deal of research was devoted to the connection between adjacent precast deck panels. The panels come together to essentially form a longitudinal channel (or closure pour). This channel requires some form of reinforcement in addition to grout in order to provide sufficient strength. Three different connection details were tested and evaluated on the basis of strength and ease of assembly (Wineland, et al, 2007). All three connection types are shown in Figure 26.

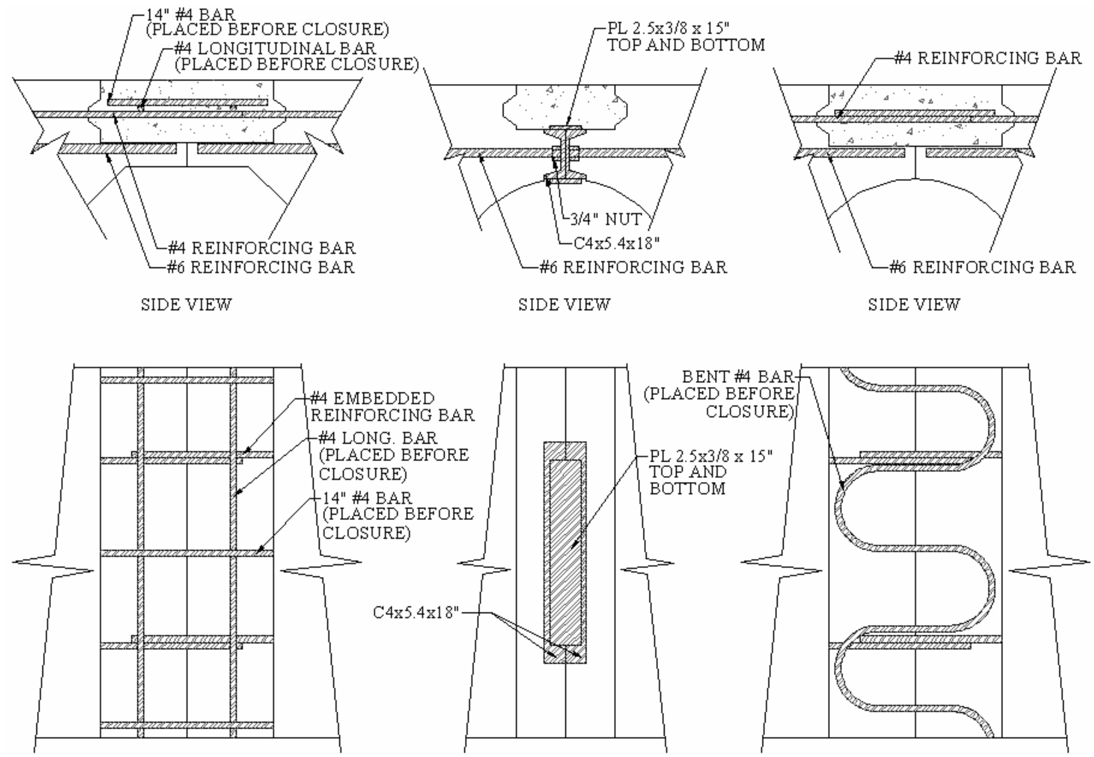

Figure 26. Connection details evaluated for Black Hawk County Bridge

The Type 1 connection (left in figure) consisted of regular #4 reinforcing steel placed longitudinally in the channel. The Type 2 connection (center in the figure) was comprised of a steel plate that was welded to steel channel sections on the adjoining deck panels. The last connection, Type 3 (right in the figure), consisted of reinforcing steel bent in an S-shape. After testing, it was determined that the Type 2 connection was by far the strongest connection but was also the most difficult to fabricate. The Type 3 connection was the easiest to construct but provided the lowest bending capacity. The optimum joint detail was Type 1 because it had a sufficient moment capacity and is relative easy to install. The Mt. Vernon Road Bridge utilized a Type 1 joint detail (Wineland, et al, 2007).

Construction of the Mt. Vernon Road Bridge was completed successfully in an accelerated manner using the PMBISB system. The precast components of the bridge were cast in the winter and were ready for placement shortly after the construction season began. Using this design, the superstructure of the bridge, shown completed in Figure 27, was completely constructed in less than 40 on-site hours. The total project duration was 22 days. Another advantage of this design was that the entire project was completed with light equipment using small crews. At completion, the bridge was field tested and the behavior observed was satisfactory (Wineland, et al, 2007).

Figure 27. Black Hawk County Bridge near completion

The beam-in-slab system used in Black Hawk County effectively accelerated the construction of bridges on low volume roads by using a traditional county bridge design and incorporating precast concrete components. However, this design utilized a bulky cross section that did not have significant span lengths. In order to solve this problem, the Iowa Department of Transportation (DOT) set out to research and construct a bridge with a longer span with similar accelerated construction attributes.

Boone County Full-Depth Precast Deck System

The Boone County Bridge, shown in Figure 28, was built in the late part of 2006 as part of the Innovative Bridge Research and Construction (IBRC) Program and became the first prestressed, precast concrete bridge built in the United States. This three-span structure was built in a much accelerated manner using various prefabricated elements. The bridge features a full-depth precast superstructure as well as precast substructure components. The bridge system was developed by the Iowa DOT and tested by ISU (Abu-Hawash, McDonald, et al, 2007).

Figure 28. Completed Boone County Bridge

The original plan for the Boone County Bridge was to build the entire structure with precast concrete components. It was later determined that precast piers would add a significant cost to the project with a very small savings in time. The Iowa DOT chose to use steel piles for the piers as an alternative to precast concrete. Steel piles provided the designers with an economical option that would not significantly slow down the efficiency of the project. Overall, precast components were used for the pier caps, abutments, girders and deck panels (Abu-Hawash, McDonald, et al, 2007).

The precast concrete abutment and pier caps are connected to the piles using a cast-in-place joint. This connection is shown in Figures 29 and 30. Blockouts are created in the abutment and pier caps at the location of each pile. These blockouts were filled with a high early strength grout to speed up construction time. A high range water reducer (HRWR) was used in the grout mix to increase the slump to 7 inches. This slump level ensured that the grout flowed completely into the congested blockouts. The precast substructure caps were each installed in fifteen minute time periods and grouted the following day (Bowers, et al, 2007).

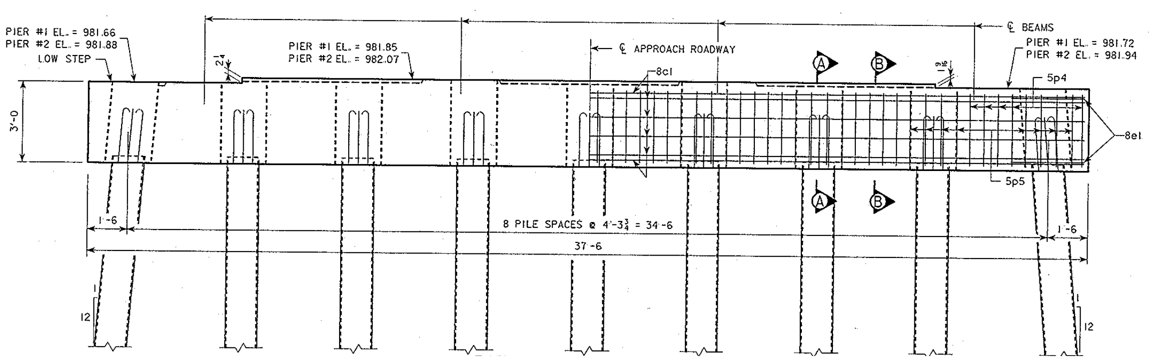

Figure 29. Boone County precast pier cap and pier layout

Figure 30. Installation of precast pier cap at Boone County Bridge

Four precast concrete girder lines carry the bridge deck. The beams used on the bridge were similar to the standard Iowa DOT five girder design with slight modification. The design used on the bridge was altered to allow for the removal of a girder line. Installation of the girders was completed in less than a day (Abu-Hawash, McDonald, et al, 2007).

The bridge deck is a full-depth, precast system made up of 36 panels which are shown in Figure 31. The deck panels are 16 ft wide in the transverse direction of the bridge and 8 ft long along the bridge length. This orientation allows for staged construction, with the deck panels covering half of the bridge width. A photo of the deck panels midway through construction is shown in Figure 32. The panels are 8 in. thick and have two full-depth channels located over the beam lines.

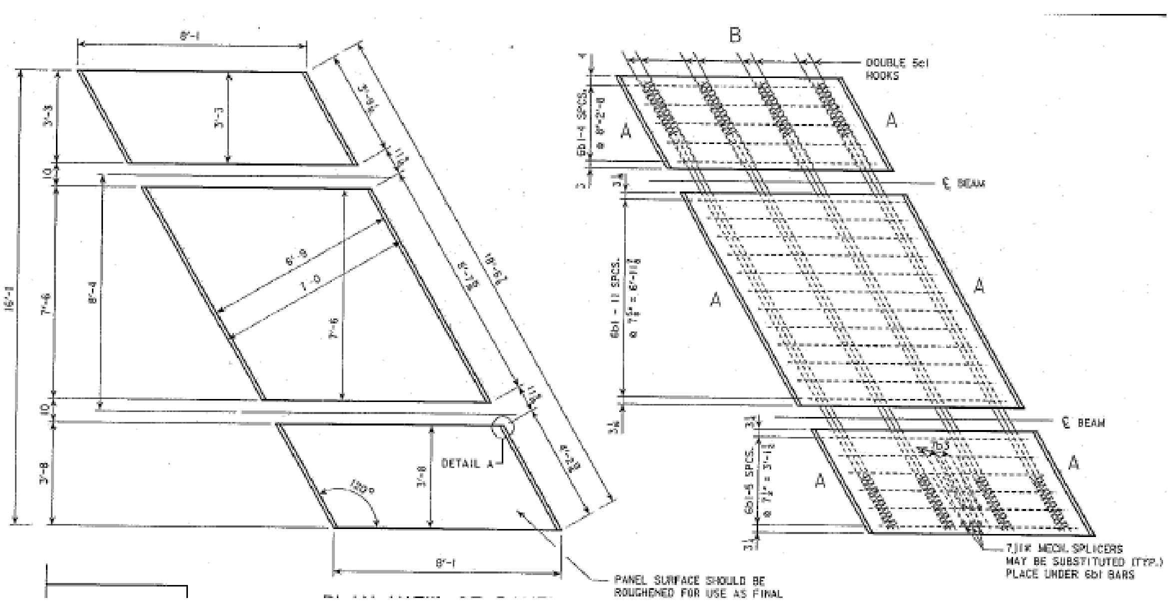

Figure 31. Boone County precast deck panel dimensions

Figure 32. View of precast deck panel installation at Boone County Bridge

The connection detail between panels on the Boone County Bridge was much more complex than the Black Hawk County connection. Panels came together to create a longitudinal joint over each girder line as shown in Figure 33. This allowed the top flange of the girders and the sides of the deck panels to act as a form for the placement of grout. A number of reinforcing details are located within this joint. Double hook bars extend from the deck panels into the joint to promote lateral load transfer. Additional reinforcement protrudes from the girders into the joint to achieve composite action between the deck and the girders. Finally, twelve post-tensioning strands are threaded along each joint. A photo of the joint in the field prior to grout placement can be seen in Figure 34.

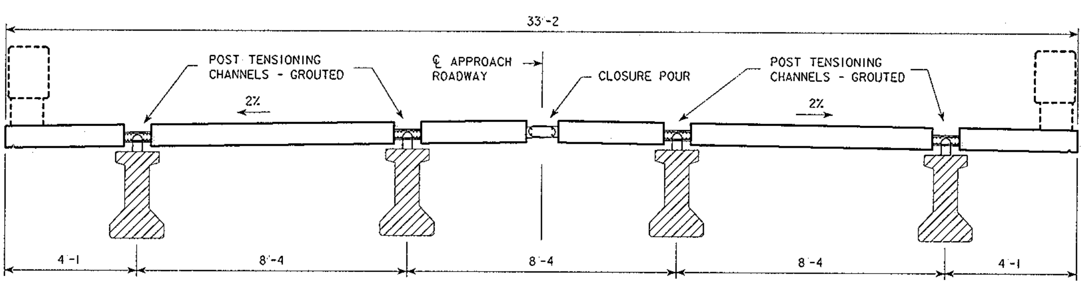

Figure 33. Boone County Bridge cross-section including the longitudinal joints

Figure 34. Longitudinal joint congestion on Boone County Bridge

The combination of all these reinforcing details creates a very congested joint. This gives this connection a much higher strength capacity than the system in Black Hawk but is much more complex to install. This can add critical hours to the length of the project and ultimately elevate the cost of the project.

Laboratory testing was conducted at ISU on several parts of the Boone County Bridge system. The tests were completed prior to construction of the bridge in order to verify that the system could carry the loads (Bowers, et al, 2007).

The actual construction required a total of 90 working days for completion. Following the project, it was determined that the bridge could have been built in a mere 12 days with improved organization and additional experience. With further use and understanding, this full-depth precast bridge system could be used to significantly accelerate bridge construction.

Madison County Deck Beam System

In 2005, Madison County was faced with the task of replacing a 21 ft timber bridge that had been in service on a secondary road for over 60 years. The bridge was in need of replacement because the slopes supporting the abutments were continually eroding resulting in repeated maintenance costs. The county decided to use an innovative accelerated design for the replacement of the bridge (Abu-Hawash, et al, 2007). The completed bridge is shown below in Figure 35.

Figure 35. Completed Madison County Bridge

The final bridge design selected by Madison County utilized precast concrete abutments supported by steel H-piles along with a precast concrete superstructure/deck system. The replacement bridge extended the span length to 46 ft 8 in. and provided a 24 ft roadway width (Abu-Hawash, et al, 2007).

The precast concrete abutment footings, shown in Figure 36, were designed based on Iowa DOT standards and were similar to the abutments used on the Boone County Bridge. The 27 ft 4 in. wide footings have a height of 3 ft 6 in. and a thickness of 3 ft and are reinforced with mild steel. Corrugated metal pipe was installed at the pile locations to create a void for the abutment to pile connection. Shear studs were welded to the H-piles to enhance composite action. This void was then grouted to secure the connection (Abu-Hawash, et al, 2007).

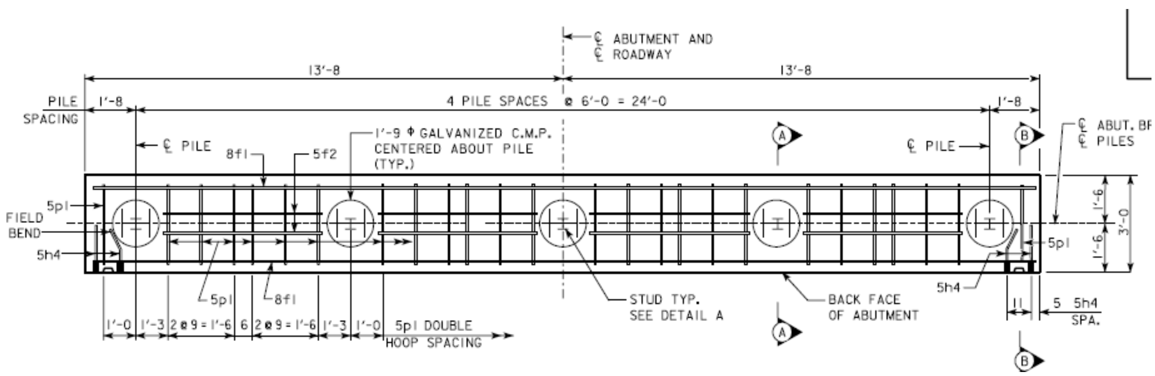

Figure 36. Madison County precast abutment in plan view

A box beam design was selected for use as the bridge superstructure/deck system. Six beams were used, with each beam measuring 4 ft wide and having a depth of 2 ft 3 in. The beams were principally connected together by a longitudinal keyway that was grouted after installation of all six beams. These connections allowed for load transfer between the beams (Abu-Hawash, et al, 2007). A cross section of the box beam can be seen in Figure 37 and a diagram of the bridge cross section, including the longitudinal joints is shown in Figure 38.

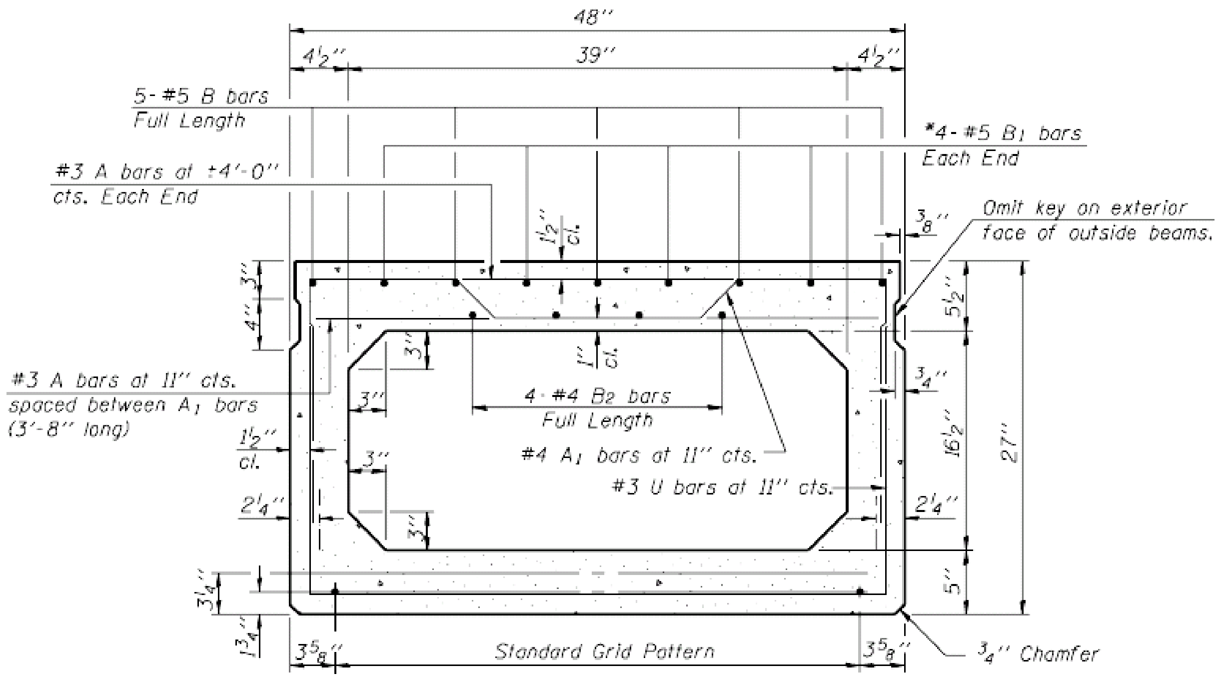

Figure 37. Madison County precast box beam cross-section

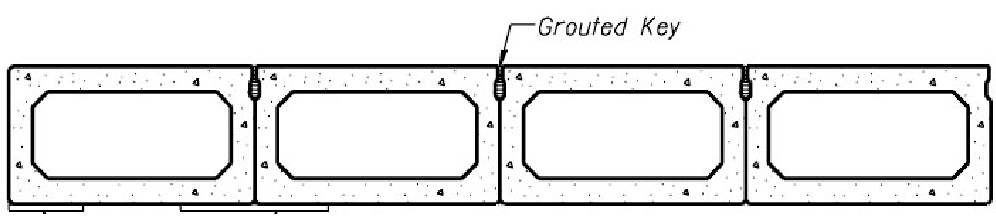

Figure 38. Madison County Bridge cross-section including longitudinal joints

The longitudinal joint connection used on the Madison County Bridge was relatively simple to install. Adjacent box beam sections came together and created a longitudinal channel. This connection was completed with the placement of a high slump grout into the joint. The absence of reinforcing steel in the joint reduced the complexity of the connection, making installation much faster and more efficient.

On December 4, 2006, the construction crew moved onto the site to begin removal and excavation tasks. This schedule was carefully coordinated to coincide with the near completion of the prefabricated elements. The contractor was able to lift and place each beam without difficulty as shown in Figure 39. In a 90 minute interval, all six girders were installed in their proper locations. Work was then halted for the remainder of the winter season and resumed again in March. The bridge was completed and opened to traffic on April 10, 2007. The actual time the contractor spent on the site amounted to only four and a half weeks. This is a significant reduction in time compared to the two month duration typical of a similar project of this size (Abu-Hawash, et al, 2007).

Figure 39. Installation of precast box beam at Madison County Bridge

After the successful completion of the bridges in Black Hawk, Boone and Madison counties, accelerated construction on low volume roads became a clear reality. The focus of these rapid replacements was the development of systems that could be quickly constructed. Of principal importance was the continual refinement of precast element connections. The next evolutionary step was to design a bridge for use on a high volume road. The system was developed after drawing upon the previous experiences and modifying the design details as appropriate.

24th Street Bridge System

In 2008, the Iowa DOT completed a bridge project in Council Bluffs, Iowa that featured a full-depth, post-tensioned deck supported on high performance steel girders. The project was part of a major rehabilitation of the Council Bluffs Interstate System. High traffic volumes and congested roadways in the corridor required limiting the project duration to one construction season. The final design, shown in Figure 40, developed by the Iowa DOT met this constraint by using prefabricated elements and innovative materials (Abu-Hawash, Khalil, et al, 2007).

Figure 40. Conceptual drawing of 24th Street Bridge

The new 24th Street Bridge, concept shown in Figure 40, replaced a four-span bridge that crossed the I-80/I-29 interstate. The spans of the bridge were increased in both length and width to accommodate higher traffic volumes on the bridge and an expanded roadway below. The new two-span bridge now spans 12 interstate lanes with a total length of 354 ft and a width of 105 ft. The bridge carries six lanes of traffic, a sidewalk and a multi-use trail (Abu-Hawash, Khalil, et al, 2007).

Steel girders were chosen to support the deck for a variety of reasons. For one, steel increases the span length capability of the bridge. This allowed the bridge to be constructed with only two spans, minimizing the number of piers in the roadway below. Steel also allowed for a more slender profile creating a greater vertical clearance and a more aesthetically pleasing design. Twelve girder lines spaced at 9 ft on center were used to carry the deck panels. Designers made use of high performance steel at high moment regions of the bridge. The high strength properties of this material permitted the profile to remain shallow throughout the entire length (Abu-Hawash, Khalil, et al, 2007).

The connection details utilized on the 24th Street Bridge were much more elaborate than those of its predecessors. Due to the high number of precast panels and connection points, careful planning was necessary to design a system that could be installed quickly and easily. Connection points of interest include the girder-to-panel connection, transverse panel connection and longitudinal panel connection.

The girder-to-panel connection was provided in this system by way of a number of shear pockets located throughout the bridge deck. Every two feet along the girder lines, a group of shear studs was installed. The precast panels were designed to accommodate these shear studs by square openings at the location of each group of shear studs. The location of these pockets on each panel can be seen in Figure 41. These pockets were grouted after all the panels were placed to ensure a complete connection between the deck and the girders (Abu-Hawash, Khalil, et al, 2007).

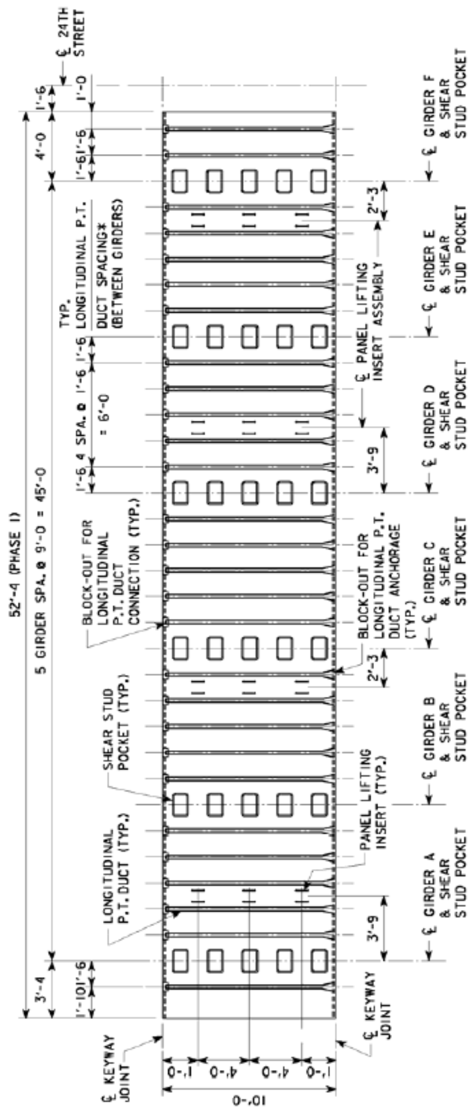

Figure 41. Typical precast deck used on 24th Street Bridge

The panels were designed to create a keyway joint at the transverse edges. This joint was grouted to create continuity along the length of the bridge. The Iowa DOT recommends using this type of joint for precast panels with longitudinal post-tensioning. This design is easy to install and eliminates problems associated with damaged or poorly fabricated panel edges (Abu-Hawash, Khalil, et al, 2007).

A longitudinal closure pour located on the centerline of the bridge was used to provide a connection between the two stages of construction. Reinforcement located within this joint included double hook bars extending from the panel edges and longitudinal bars along the length of the joint. A diagram of the longitudinal joint is shown in Figure 42. As one can clearly see, this is yet another evolutionary step of the closure joints used in the previously described designs.

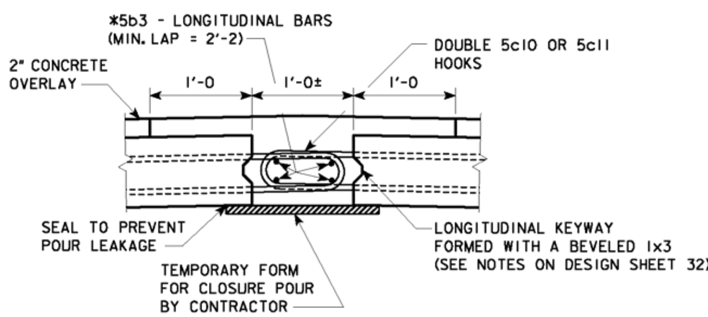

Figure 42. Longitudinal closure joint detail

A total of seventy precast concrete panels were used to make up the deck. Each panel had a thickness of 8 inches with a length of 10 ft and a width of 52 ft 4 in. The panels were pretensioned in the transverse direction and were post-tensioned in the longitudinal direction. A photo of one of these panels being placed in the field is shown in Figure 43. The width of these panels matched half of the width of the bridge creating an opportunity for the bridge to be constructed in two stages.

Figure 43. Installation of precast deck panel at 24th Street Bridge

The first stage of construction consisted of the assembly of one half of the bridge as traffic remained on the existing bridge. Stage two then advanced with the removal of the existing bridge and construction of the remaining half of the new bridge while traffic moved to the first half of the new bridge. The longitudinal closure pour was used to link the two bridge halves together to complete construction. In this way, traffic was maintained in three lanes at all times significantly reducing congestion in the area (Abu-Hawash, Khalil, et al, 2007).

The bridge was completed in November of 2008 after a single construction season. The full-depth concrete deck design in combination with the high performance steel girders provided a product that could be installed rapidly with no disruption to traffic below. The two stage design also allowed for preservation of traffic across the bridge at all times.

Evaluation

The evaluation of the four bridges was completed by comparing the bridges under the criteria outlined previously: constructability, traffic disruption, cost, durability, and span length.

Constructability

One of the most important criteria of a successful ABC project is the constructability of the bridge. ABC projects are relatively new to construction crews, particularly local contractors that work on smaller bridges. Designing a bridge with constructability in mind may be the most important factor in reducing the construction duration of a project. Reducing the time a construction crew is on site leads to other improvements such as reducing disruption to traffic and impact on the environment. In this case, the criterion for constructability is evaluated by the actual time required to completely install individual deck pieces. A rating of 5 corresponds to a deck system that cannot realistically be installed any faster and a rating of 1 corresponds to a deck system installed with no acceleration.

All four ABC projects investigated significantly increased the constructability relevant to a traditional project of its kind. The Madison County deck system was the most efficient, however, because it required the installation of no steel in the longitudinal joints. The deck beams were installed in their locations, the joints were grouted, and the deck was complete. For this reason, the Madison County Bridge was given a rating of 4. The Black Hawk County Bridge was slightly more complex with the addition of reinforcing steel in the longitudinal joints. For this reason, this bridge is given a rating of 3. The 24th Street and Boone County Bridges were given a rating of 2 because the longitudinal joints of these bridges were highly congested and difficult to install, containing both longitudinal reinforcing steel and post-tensioning steel.

Traffic Disruption

Traffic disruption is notably reduced on an ABC project because there are fewer construction days on the site. However, traffic will clearly be disrupted during that time and will have to find alternate routes. This issue is especially critical in high volume situations or in areas where the length of a detour is not practical. To solve this problem, a bridge can either be built alongside an existing bridge or it can be built in stages. Traffic disruption durations for each bridge project are shown in Table 6. A rating of 5 corresponds to a project that maintains traffic at all times and a rating of 3 corresponds to a bridge that, although accelerated, does not maintain traffic flow. A rating of 1 indicates severe traffic disruption.

Table 6. Traffic disruption durations for each bridge project

Bridge	Total Traffic Duration, (days)
24th Street	0
Black Hawk County	22
Boone County	110
Madison County	27

The 24th Street Bridge in Council Bluffs is the only bridge of the four that does not disrupt traffic at any time during construction. It receives a 5 rating because it maintained three lanes of traffic at all times. The Boone County Bridge design was given a rating of 4 because although this specific project did not allow construction under traffic, future projects using this design could be built while maintaining traffic. The other projects are given ratings of 3 because other than using accelerated techniques, they do not alleviate traffic disruption issue and require the use of a detour.

Cost

The cost of a bridge project is traditionally the most important factor when choosing the ideal alternative. Unfortunately, ABC projects are generally higher cost than projects built using conventional methods. Because the bridges are of various sizes, they will be evaluated by cost/square foot of deck area. These cost values for each bridge are shown in Table 7. The cost used for evaluation is the total cost of all preliminary work, materials and construction.

Table 7. Cost comparison of bridges

Bridge	Final Construction Cost, ($)	Bridge Deck Area, (ft^2)	Cost per Sq. Ft. of Bridge Deck, ($\$/ft^2$)
24th Street	$5,375,000	29,028	$185.17
Black Hawk County	N/A	1,280	N/A
Boone County	$509,173	5,007	$101.69
Madison County	$131,478	1,120	$117.38

A typical non-ABC project constructed in the state of Iowa in 2007 has a cost of approximately $155 per square foot of bridge deck. Two bridges, the Boone and Madison County Bridges were built at a much lower cost than this traditional bridge cost. This fact shows that an ABC project can be completed at or below the cost of a non-ABC project. This is possible because of innovative designs and a reduction in labor costs. A rating of 4 is given to these two projects because they were built at a cost below the average non-ABC project.

The 24th Street Bridge, however, was built at a cost slightly higher than the non-ABC cost of $155 per square foot of bridge deck. This higher cost stems from the fact that it can be costly to maintain traffic during construction. A rating of 2 is given to this bridge because it is more expensive to build than a traditional non-ABC project. Cost data were not available for the Black Hawk County Bridge and are therefore not evaluated.

Durability

The durability of the structure is possibly the most overlooked characteristic of a bridge project. A product with a high durability can last years longer, significantly reducing the overall life cycle of the project. Durability can be achieved by using high quality materials and careful construction methods. A rating of 5 is given to a bridge that is most durable. A rating of 1 corresponds to a typical cast-in-place concrete product.

All four of the bridges reviewed possess higher durability properties than traditional cast-in-place concrete bridges because they were prefabricated in a controlled setting. This ensures that the concrete cures appropriately and is formed correctly. However, the box beam design used on the Madison County Bridge is known to have a high potential for strand corrosion due to water retention within the girder. Because of this, the Madison system is given a 2 rating. The other three bridges are given a rating of 4 because they should have a significantly longer life cycle than a traditionally cast-in-place concrete bridge.

Span Length

Different bridge systems and materials offer various bridge span lengths. It is beneficial for a bridge to have longer spans for a number of reasons. The major benefit of longer spans is that they require fewer intermediate piers to support them. Fewer intermediate piers correspond to fewer bridge components and connections to install. This can contribute to the acceleration of the project. A smaller number of piers is especially useful on bridges crossing over a congested roadway or an environmentally sensitive area. The bridges have been evaluated based on the utilized span lengths. The span lengths of each bridge system are shown in Table 8. A rating of 5 corresponds to the system with the best spanning capacity and a rating of 1 relates to a bridge with poor spanning capacity.

Table 8. Span lengths of bridge projects

Bridge	Span Length, (ft)
24th Street	178.5
Black Hawk County	40.0
Boone County	56.5
Madison County	46.7

The 24th Street Bridge is given a rating of 5 for its superior spanning capacity in relation to the other bridges reviewed. Steel girders were used to increase the span of this bridge to nearly 180 ft. A large span was necessary on this project to reduce the number of piers in the congested interstate below. The Boone and Madison Bridges both provide spans near 50 ft. This span length is equal to an average bridge span and is therefore given a rating of 3. Finally, the Black Hawk County Bridge is given a 2 rating because it was designed for use as a short span county road bridge.

Summary

The results of the bridge design evaluation are shown below in Table 9. All four of the bridge systems reviewed showed an improvement over traditional bridge systems. The incorporation of precast concrete into non-ABC designs was the most significant improvement on acceleration. The additional improvement and evolution of the deck cross section and the longitudinal joint brought about further advancements.

Table 9. Evaluation matrix for selected bridges

	Constructability	Disruption	Cost	Durability	Span Length
24th Street	2	5	2	4	5
Black Hawk County	3	3	-	4	2
Boone County	2	4	4	4	3
Madison County	4	3	4	2	3

It is clear that all five of these projects were successful ABC projects in one or more ways. Unfortunately, it is impossible to choose a specific system as the optimum alternative to be used in all situations. The geometry of the bridge, the characteristics of the construction site and the traffic conditions all play a significant part in the determination of the appropriate construction technology used.

Low volume roadways require a simpler design with less attention devoted to aesthetics. The Black Hawk and Madison County Bridges perform well in low volume situations. These bridges were constructed simply and quickly using county construction crews and are expected to have a long operational life. On the other hand, the Boone County Bridge system should be used on low volume roads with longer span needs. The less efficient constructability of this design is counteracted by its greater lengths.

High volume roads, although less common in the state of Iowa, involve the use of a more complicated system that can be built with little or no disruption to traffic. For this reason, the 24th Street Bridge system is the most effective for use on high volume roadways. This system was constructed much faster than a traditional project of its size and maintained traffic at all times using a staged construction method. It is important to mention that the Boone County Bridge could also be used on a project of this kind if a staged construction method was utilized.

Concluding Remarks

The increasing number of deteriorating bridges and the need for replacement of these bridges with minimal traffic disruption has brought about much attention to accelerated bridge construction. The design of rapid replacement bridges not only accelerates construction but also improves worker safety and reduces the environmental impact. The State of Iowa is one that has experience working with projects of this nature.

Four bridges built in the state of Iowa that were designed for accelerated construction were reviewed and evaluated. A clear progression was found from one project to the next as more experience was gained. This confirms that a commitment to the research and development of accelerated bridge technologies will produce more efficient designs that can be used to resolve the problem of the failing infrastructure.

CHAPTER 4: GENERAL CONCLUSIONS

Over the course of this thesis, six accelerated bridge construction (ABC) projects were investigated in detail and afterward evaluated based on a number of criteria. The first paper focused on the construction aspect of these projects. The goal of this paper was to evaluate the economics and production rates of the individual projects. The cost analysis revealed that bridges can be built in an accelerated manner without a cost premium if the innovative methods and designs are used. A road user cost (RUC) analysis, although not usually considered on traditional projects, established the significant impact traffic disruption can have on the general public. The second paper followed four bridge projects and the evolution of the bridge elements and connections over time. These projects were evaluated, with a numbered matrix, using criteria based on performance, cost and constructability. No one bridge system was chosen as the ideal option for all projects but it was apparent that different systems are appropriate for different environments. The major conclusions from these papers are summarized in the following paragraphs.

Cost Analysis

In the first paper, the five bridges evaluated were compared based on total cost per square foot of bridge deck. This method was used because it allows for simple comparison between bridges of different sizes. The cost used in this analysis was the total cost for design, materials and construction of the project. As a review, the bridges and their respective costs are shown below in Table 10.

Table 10. Cost comparison of selected ABC projects

Bridge	Final Construction Cost	Bridge Deck Area, (ft^2)	Cost per Sq. Ft. of Bridge Deck, (/ft^2)
24th Street	$5,375,000	29028	$185.17
Black Hawk County	N/A	1280	N/A
Boone County	$509,173	5007	$101.69
Buchanan County	$1,000,000	1266	$789.89
FRP Bypass	$240,300	1053	$228.21

Several conclusions can be drawn from this cost comparison. The most noticeable values in the table are the high costs of both the Buchanan County and FRP Bypass Bridges. These bridges utilized very high-cost, innovative materials. Using ultra-high performance concrete (UHPC) and fiber-reinforced polymers (FRP) in bridge construction provides the benefits of increased strength and light weight but comes with this added premium. From these projects it could be concluded that using innovative materials may not be economical on a first-cost basis. In time, though, as the material is used more widely in the industry, the cost of these materials may become more economical.

From the overall analysis further conclusions can be made by comparing the ABC bridge costs to a non-ABC project cost. It was found that the Boone County Bridge was built at a significantly lower cost than a non-ABC bridge. This disproves the belief that ABC projects can not be completed at a rate competitive with non-ABC projects. It is the authors' opinion, however, that ABC projects can not be competitive without the use of innovative designs and construction methods.

A slightly higher cost was realized on the 24th Street Bridge in relation to the Boone County Bridge. This cost increase is most likely attributed to the cost of maintaining traffic throughout the project duration. On projects constructed in high traffic volume areas, costs like these are likely to be incurred to ensure traffic is maintained at an adequate level.

Road User Cost Analysis

After discovering the added cost associated with reduced traffic disruption, it was desired to analyze the cost benefits associated with the maintenance of traffic flow. The cost savings connected to reduced traffic disruption are called road user costs (RUC) and can be calculated using a variety of methods. In this thesis, the RUC was calculated using a simple equation employed by the Iowa DOT. This equation is used on projects to determine the benefits of using ABC construction methods as opposed to non-ABC methods. RUC is traditionally not considered on construction projects because this cost is never realized by the owner. However, with rising traffic volumes and the need to reduce traffic disruption, this cost has become more important.

Two bridges, the 24th Street and Boone County Bridges, were analyzed using the RUC equation. These bridges were related to comparable bridges constructed using non-ABC bridge methods. The RUC and the savings associated with using ABC methods are shown in Table 11. This savings from RUC is the premium an owner could spend on ABC methods without a loss. Both projects realized substantial amounts in savings.

Table 11. RUC and savings realized by using ABC methods

	24th Street		Boone County	
	ABC	non-ABC	ABC	non-ABC
Savings	$0.00	$6,147,900.00	$309,355.20	$514,654.56
Total Savings	**$6,147,900**		**$205,299.36**	

Design Evolution

The second paper highlights the advances in design of specific details and components of bridge systems. In the state of Iowa alone, the advances in ABC bridge systems has been apparent. For one, the complexity of connections has increased. This is due to the incorporation of post-tensioning steel and other reinforcement to strengthen the structure. These connections have proved to significantly increase the efficiency of the structure but have complicated the construction process. The development of a simpler connection with equal structural capacity is necessary to increase the constructability of these connections.

Conclusion

The papers of this thesis have revealed some valuable information about ABC projects in the state of Iowa. It was found that ABC bridges can be built economically using innovative methods. It was also discovered that RUC associated with a reduced construction time can add considerable savings to the traveling public. In addition, the design of these structures was accounted from the early stages of ABC in Iowa to a major bridge project built over an interstate without disrupting traffic. When analyzing these projects it was clear that no one bridge system was the best option for all projects. Before beginning an ABC project it is important to discover which system type works best for a given situation. And finally, the use of innovative materials to significantly increase the construction efficiency may be an answer, but not without continued research and use.

APPENDIX A. BRIDGE PERFORMANCE REFERENCES

Costs

24th Street Bridge

- **$537,000**

Iowa Department of Transportation Contract Data

Black Hawk County Bridge

- **N/A**

Boone County Bridge

- **$509,173**

Nelson, Jim. “Boone and Madison County IBRC projects: ABC using precast elements”. Iowa Department of Transportation. PowerPoint. 23 August 2007.

Buchanan County Bridge

- **$1,000,000***

LaFarge North America Bid Proposal Document

* The total cost used for this project was estimated using the fabrication and delivery bid document from the project. The total cost of precast UHPC pi-girder elements and the delivery of these elements was $900,000. An estimated construction cost of $100,000 was then assumed for the erection of these elements and assumed piers.

FRP Bypass Bridge

- **$240,300**

Iowa Department of Transportation Contract Data

Madison County Bridge

- **$131,478**

Abu-Hawash, A., N. L. McDonald, J. S. Nelson, S. Nielsen, and A. Samuelson. 2007. Accelerated construction in Iowa. Paper presented at the 2007 PCI National Bridge Conference, Phoenix, Arizona.

Construction Durations

24th Street Bridge

- Total Construction Duration: <u>185 days</u>
- Superstructure Construction Duration: <u>122 days</u>

Strong, K. and M. Kaewmoracharoen. 2009. Creating 3-D models from 2-D documents to simulate work zone constraints: A test of perceived benefit to cost. Proce*edings of the 2009 International Transportation Management Conference*, Orlando, Florida.

Black Hawk County Bridge

- Total Construction Duration: <u>22 days</u>
- Superstructure Construction Duration: <u>2 days</u>

Abu-Hawash, A., N. L. McDonald, J. S. Nelson, S. Nielsen, and A. Samuelson. 2007. Accelerated construction in Iowa. Paper presented at the 2007 PCI National Bridge Conference, Phoenix, Arizona.

Boone County Bridge

- Total Construction Duration: <u>110 days</u>
- Superstructure Construction Duration: <u>36 days</u>

Landau, Cole Joseph. “Transportation construction administration”. (MS Thesis, Iowa State University, 2007).

Buchanan County Bridge

- Total Construction Duration: N/A
- Superstructure Construction Duration: 2 days

Keierleber, B. Telephone interview. 30 January 2009.

FRP Bypass Bridge

- Total Construction Duration: N/A
- Superstructure Construction Duration: 2 days

Wipf, T. J., B. M. Phares, and T. K. Hosteng. 2005. Field testing of an FRP temporary bypass bridge. Paper presented at the 2005 Mid-Continent Transportation Symposium, Ames, Iowa.

Madison County Bridge

- Total Construction Duration: 27 days
- Superstructure Construction Duration: 2 days

Abu-Hawash, A., N. L. McDonald, J. S. Nelson, and A. Samuelson. 2007. Accelerated construction in Iowa. Paper presented at the 2007 PCI National Bridge Conference, Phoenix, Arizona.

Span Lengths and Deck Area

24th Street Bridge

- Span: 354 ft (178.5 ft, 175 ft)
- Deck Area: 354 ft x 82 ft = 29,028 ft^2

Abu-Hawash, A., H. Khalil, P. Schwarz, B. Phares, and N. McDonald. 2007. Accelerated design and construction for the 24th street bridge in Council Bluffs, Iowa. Paper presented at the 2007 Mid-Continent Transportation Research Symposium, Ames, Iowa.

Black Hawk County Bridge

- Span: 40 ft
- Deck Area: 40 ft x 32 ft = 1280 ft^2

Wineland, V. W., F. W. Klaiber, and T. P. Schoellen. 2007. Laboratory and field testing of precast bridge elements used for accelerated construction. Paper presented at the 2007 Mid-Continent Transportation Research Symposium, Ames, Iowa.

Boone County Bridge

- Span: 151.33 ft (47.42 ft, 56.5 ft, 47.42 ft)
- Deck Area: 151.33 ft x 33.083 ft = 5006.6 ft^2

Bowers, R., S. Kevern, R. Kieffer, F. W. Klaiber, C. Landau and J. S. Nelson. 2007. Construction and testing of an accelerated bridge construction project in Boone county. Paper presented at the 2007 Mid-Continent Transportation Research Symposium, Ames, Iowa.

Buchanan County Bridge = 51.167 ft

- Span: 51.167 ft
- Deck Area: 51.167 ft x 24.75 ft = 1266.4 ft^2

Keierleber, B., D. Bierwagen, T. Wipf, and A. Abu-Hawash. 2008. Design of Buchanan County, Iowa bridge using ultra high-performance concrete and pi-girder cross section. Paper presented at the 2008 PCI National Bridge Conference, Orlando, Florida.

FRP Bypass Bridge

- Span: 39 ft
- Deck Area: 39 ft x 27 ft = 1053 ft^2

Wipf, T. J., B. M. Phares and T. K. Hosteng. 2005. Field testing of an FRP temporary bypass bridge. Paper presented at the 2005 Mid-Continent Transportation Research Symposium, Ames, Iowa.

Madison County Bridge

- Span: 46.67 ft

- Deck Area: 46.67 ft x 24 ft = 1120.08 ft^2

Abu-Hawash, A., N. L. McDonald, J. S. Nelson, S. Nielsen, and A. Samuelson. 2007. Accelerated construction in Iowa. Paper presented at the 2007 PCI National Bridge Conference, Phoenix, Arizona.

Structural Tonnage Calculations

Quantities for all materials used in the bridge projects studied in this thesis were gathered from the final plan documents for each respective bridge.

A number of assumptions were made regarding the unit weights of each of the materials:

- High performance concrete: 160 lb/ft^3
- Regular concrete: 145 lb/ft^3
- Steel: 490 lb/ft^3
- Fiber-reinforced polymer: 30 lb/ft^3

24th Street Bridge

Superstructure

- Precast concrete panels
    - Panel A (2)
        - 11.6 CY of H.P. Concrete = 50,112 lb
        - 2375 lb of reinforcing steel
        - 104,974 lb = 52.49 tons
    - Panel B (33)
        - 11.6 CY of H.P. Concrete = 50,112 lb
        - 1741 lb of reinforcing steel
        - 1,711,150 lb = 855.58 tons
    - Panel C (2)
        - 11.6 CY of H.P. Concrete=50,112 lb
        - 2364 lb. of reinforcing steel
        - 104,952 lb = 52.48 tons

- Panel D (2)
    - 11.6 CY of H. P. Concrete = 50,112 lb
    - 1730 lbs of reinforcing steel
    - 1,710,790 lb = 855.4 tons
- Reinforcing steel in superstructure: 63,649 lb = 0.428 tons
- H. P. concrete in superstructure: 1,220,830 lb = 610.42 tons
- Structural steel in superstructure: 1,485,189 lb = 742.6 tons
- Total Superstructure = 3,169.4 tons

Total Structure

- Structural steel: 1,485,189 lb = 742.6 tons
- Reinforcing steel: 164,433 lb = 82.22 tons
- H. P. Concrete: 10822 CY = 4,701,020 lb = 2,350.5 tons
- Concrete: 96.2 CY = 376,623 lb = 188.3 tons
- Panels: 1815.95 tons
- Total Structure = 5,179.6 tons

Boone County Bridge

Superstructure

- Precast concrete beams
    - 2 @ 7.7 tons = 15.4 tons
    - 4 @ 11.9 tons = 47.6 tons
- Diaphragm Steel: 2942.6 lb = 1.47 tons
- Interior Panels (32)
    - 2.9 CY of concrete: 11,353.5 lb = 5.68 tons
    - 1283 lb of reinforcing steel = 0.64 tons

- Total interior panels = 202.2 tons

- Exterior Panels (4)
  - 3 CY of Concrete: 11,745 lb = 5.87 tons
  - 1686 lb of reinforcing steel
  - Total exterior panels = 26.86 tons
- Total Superstructure = 293.53 tons

Total Structure

- Superstructure: 293.53 tons
- Concrete in substructure: 56.8 CY = 222,372 lb = 111.19 tons
- Reinforcing steel in substructure: 15,019 lb = 7.5 tons
- Abutment footings (2)
  - 15.6 CY of concrete: 61,074 lb = 30.54 tons
  - 3171 lb of reinforcing steel = 1.59 tons
  - Total abutment footings = 64.25 tons
- Pier caps (2)
  - 13.8 CY of concrete: 54,027 lb = 27.01 tons
  - 2732 lb of reinforcing steel = 1.37 tons
  - Total pier caps = 56.76 tons
- Total Structure = 533.83 tons

Black Hawk County

Superstructure

- Deck panels

- 71.47 CY of concrete: 289,440 lb = 144.72 tons
- Steel W Sections: 30,140 lb = 15.07 tons
- Total Superstructure = 159.8 tons

Total Structure

- Superstructure = 159.8 tons
- Abutment caps (2)
  - Concrete = 5.75 tons
  - Steel = 1.35 tons
- Total Structure = 174.8 tons

Buchanan County Bridge

Superstructure

- Pi girder beams(3 @ 22.2 tons) = 66.6 tons
- Beam diaphragms: 1287 lb = 0.64 tons
- Dowels: 370 lb = 0.185 tons
- Total Superstructure = 67.43 tons*

- The superstructure of the Buchanan County Bridge was the only ABC part of the project. For that reason, only the superstructure tonnage is calculated and evaluated.

FRP Bypass Bridge

Superstructure

- 3,159 ft^3 * 30 lb/ft^3 = 94,770 lb = 47.39 tons*

* The FRP Bypass Bridges does not have an accelerated substructure portion. Therefore, the superstructure is the only portion of the structure to be analyzed.

Madison County Bridge

Superstructure

- Precast concrete box beams (6)
  - 9.1 CY of H.P. Concrete = 39,312 lb = 19.57 tons
  - 1218 lb of reinforcing steel = 0.609 tons
- Total Superstructure = 121.59 tons

Total Structure

- Box Beams: 121.50 tons
- Abutment footings (2)
  - 11 CY of H. P. Concrete: 47,520 lb = 23.76 tons
  - 1267 lb of reinforcing steel = 0.63 tons
- Abutments
  - 6.4 CY of H.P. Concrete: 27,648 lb = 13.82 tons
  - 725 lb of reinforcing steel = 0.36 tons
- Total Structure = 184.57 tons

APPENDIX B. FIELD TESTING OF A PRECAST CONCRETE BRIDGE

PRECAST CONCRETE ELEMENTS FOR ACCELERATED BRIDGE CONSTRUCTION:
FIELD TESTING OF A PRECAST CONCRETE BRIDGE, BOONE COUNTY BRIDGE

Final Report
January 2009

Principal Investigator
Terry J. Wipf, Director, Bridge Engineering Center
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Sponsored by
the Iowa Highway Research Board (IHRB Project TR-561)
and Boone County, Iowa, through the Federal Highway Administration's
Innovative Bridge Research and Construction Program

Preparation of this report was financed in part through funds provided by
the Iowa Department of Transportation through its research management agreement with
the Center for Transportation Research and Education (CTRE Project 06-262).

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Acknowledgments

The authors would like to thank the Iowa Highway Research Board, the Iowa Department of Transportation, Boone County and the Federal Highway Administration for providing funding, design expertise, and research collaboration for this project. Special recognition is give to the following individuals for their significant contributions to the research: Ahmad Abu-Hawash, Jim Nelson, Stuart Nielsen, and many other staff from the Office of Bridges and Structures at the Iowa Department of Transportation; Curtis Monk, Iowa Division, Federal Highway Administration; Dave Anthoney (recently retired), Bob Kieffer and Scott Kruse, Boone County; and Doug Wood, Iowa State University along with numerous graduate and undergraduate students, including Ryan Bowers, Matt Goliber, Dustin Gardner and Nathan Hardisty.

Executive Summary

A full-depth precast deck bridge was built in Boone County in 2006 as a replacement for an existing bridge. The bridge was constructed in an accelerated manner using precast concrete components. A series of laboratory tests were completed by Iowa State University on individual segments of the bridge. Detailed description and analysis of these tests can be found in sections 1 and 2 of Volume 1.

This third and final section of Volume 1 documents the field testing portion of this project. Two field tests were carried out on the Boone County Bridge. The first took place the summer following construction and the second took place one year later. A summary of the testing process, instrumentation plan, and analysis of data are located in this report.

1. BACKGROUND

The world moves at a constantly increasing pace. Traffic volumes rise along with the number of bridge construction projects. In this fast-paced world, it can be difficult for construction crews to keep up. It also is critical to keep impact on transportation at a minimum. This means getting construction crews in and out of a job as quickly as possible. Much work has been done to find a way to speed up the construction process of bridges in Iowa. A variety of rapid construction techniques can be used to accelerate the construction of bridges and minimize disruption to traffic.

The importance of rapid construction technologies has been recognized by the Federal Highway Administration (FHWA) and the Iowa Department of Transportation (DOT). It was decided that a bridge would be built in Boone County, Iowa to test accelerated bridge construction techniques. Construction began on July 17, 2006 and concluded December 28, 2006. This bridge underwent extensive tests during construction, in the laboratory, and in the field. Funding for the design, construction, and evaluation of this project was provided by the FHWA-sponsored Innovative Bridge Research and Construction (IBRC) Program. Funding for the laboratory testing was provided by the Iowa DOT and the Iowa Highway Research Board; funding for the documentation and the post-tensioning monitoring and verification was provided by the FHWA and Boone County.

In the Boone County Bridge project, construction was accelerated using precast bridge elements. Precast bridge components are cast off-site, allowed to cure, and transported to the site. Once at the scene of construction, individual pieces of the bridge can be put together in a quick and efficient manner. This process has advantages for the public, the owner, and the environment.

The most obvious advantage of rapid construction is time saved. Highways have higher daily traffic volumes than ever before. It is important to shorten the length of construction in order to reduce the impact on traffic flow. Traditional bridge construction processes require time to set up forms, pour concrete, and allow concrete to cure. By using precast bridge elements, time on the site is greatly reduced. Rapid construction is also less harmful to the environment than traditional methods. This is especially apparent on bridges that cross bodies of water. Less time on the site means fewer occurrences of pollution.

One disadvantage of rapid construction is that the initial cost of precast elements is more costly than traditional construction methods. This extra cost can be offset by a reduction in labor costs. Less time on the job site corresponds with a lower cost for labor.

The location selected for this bridge is in the northern part of Boone County. The bridge crosses Squaw Creek on 120th Street. The original bridge on this site was called the Marsh Arch Bridge. The Marsh Arch Bridge is shown in Figure 1.1. The new bridge is a continuous, four-girder, three-span bridge with a full-depth, precast deck and can be seen in Figure 1.2. The bridge is 151 ft - 4 in long with a width of 33 ft - 2 in. Deck panels are 8-inches thick, half the width of the bridge, and pre-stressed in the transverse direction. Each panel had two full-depth channels, located over the pre-stressed girders, for post-tensioning. Once the panels were erected, the entire bridge deck was post-tensioned in the longitudinal direction, after which the post-tensioning channels were grouted. Precast pier caps and precast abutments were also used in the bridge substructure.

Figure 44.1 Marsh Arch Bridge originally on 120th St

Figure 1.45 Completed replacement bridge on 120th St

Extensive testing was performed on this bridge. Three stages of testing took place: construction, laboratory, and field testing. During construction, strain gages were attached to the post-tensioning bars in the bridge deck panels. These gages were monitored during the post-tensioning process. The gages remain in the bridge deck and can be monitored at any time. The laboratory portion of testing took place at the Iowa State University Structures lab. The individual bridge elements that were tested in the lab were the precast abutments, pier caps, and bridge deck panels. Finally, two field tests were performed using strain and deflection gages. The tests were conducted in the summers of 2007 and 2008. The field tests consisted of static and rolling cases using standard tandem-axle gravel trucks. These trucks were provided by Boone County.

2. FIELD TEST

2.1 Introduction

The initial field test was performed on June 28, 2007. A combination of static and rolling loads were used to create critical load cases on the bridge. These loads were simulated by typical tandem-axle gravel trucks. During the test, strains and deflections were measured by transducers located at critical sections of the bridge. Installation of the instrumentation and all runs of the test vehicles were completed in one day. For descriptive purposes, the three spans are numbered 1 through 3 from east to west. This makes Span 1 the first span crossed by the truck and Span 3 the last span crossed by the truck. The four girders are numbered 1 through 4 from south to north and the two piers are described as east and west piers.

In addition to the strain and displacement transducers, vibrating wire gages were also monitored. These vibrating wire gages were originally installed during construction to measure strains during the post-tensioning process. The gages remain in the bridge and can be used to monitor strains in bridge during field tests. The gages were monitored during the static test by a switch-and-balance system.

2.2 Strain and Displacement Instrumentation Description

Instrumentation was installed on the bridge in order to determine maximum loading stresses and deflections on the bridge. Flexural strains in the concrete girders and guardrail were measured by strain transducers while string potentiometers measured deflections along the mid-span of the central span. A total of 36 strain transducers and 9 deflection transducers were used during the test. The instrumentation layout of these gages can be seen in Figure 2.1.

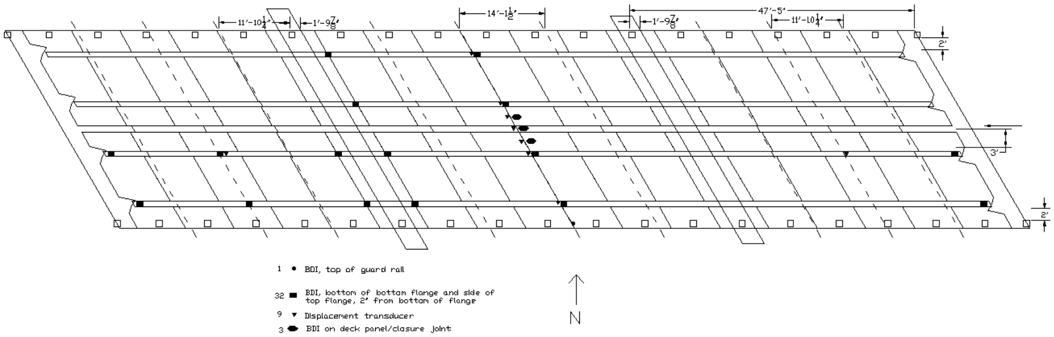


Figure 2.1 Final instrumentation layout used for first field test

Gage installation was completed on the morning of the test. Strain transducers were applied to top and bottom flanges of specific girders or on the bottom of the bridge deck. The locations of the strain gages on top and bottom flanges are shown in Figure 2.2. Deflection transducers were secured to a level platform near ground level and connected to the bridge superstructure with piano wire. A tripod system was set up below the bridge to provide a level surface for the string potentiometers. This tripod system can be seen in Figure 2.3.

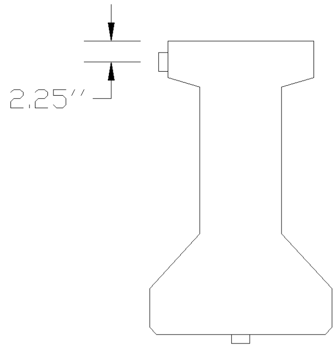


Figure 2.2 Typical strain gage locations on concrete girders

Figure 2.3 Tripod system used to support displacement transducers

The mid-span of Span 2 was a heavily instrumented area due to the potential for maximum deflections and strains. At this location, each girder was instrumented with a deflection gage and a top and bottom flange strain gage. In addition to the girders, the closure joint at mid-span was instrumented to check for significant deflection and strain differential between the sides of the joint. The gage configuration at the closure joint is shown in Figure 2.4. Along with the mid-span, the east side of the west pier had strain gages at all four girders. These strain gages were used to analyze negative moment conditions at this pier.

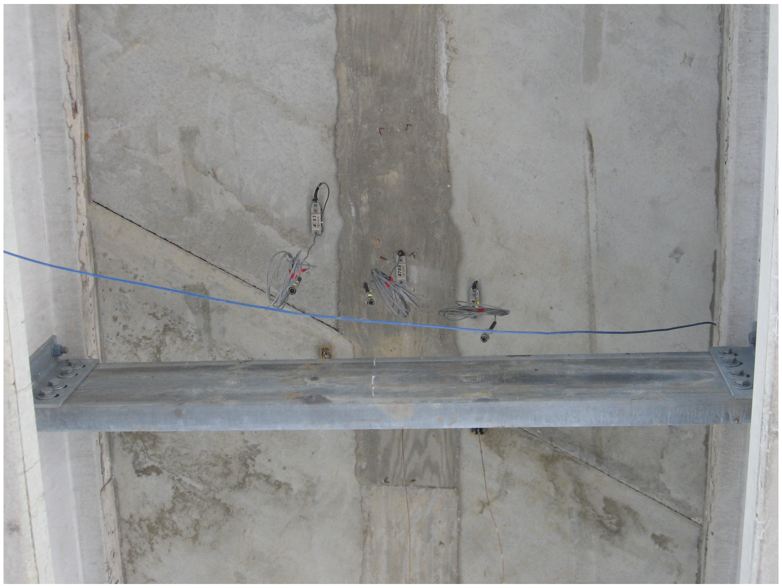


Figure 2.4 Instrumentation layout at closure joint

Span 3 also contained a significant amount of instrumentation. At this span, Girders 1 and 2 had strain gages at the west abutment, mid-span and west side of the west pier. All strain gages located at abutments and piers are installed a distance of 32” (girder depth) from the abutment or pier. In addition to the strain gages, one deflection transducer was installed on Girder 2 at mid-span. A tripod system was not needed for the transducer at this location. Instead, the string potentiometer was fixed to a board and secured to the rip-rap below on the ground.

Instrumentation was less concentrated at Span 1. At this location, strain gages were installed on Girders 1 and 2 at the east abutment. These strain gages were used to compare behavior of east and west abutments. In addition to the strain gages, a deflection transducer was installed on Girder 2 at mid-span. The location and set up of this gage is identical to the deflection gage at Span 3.

The final element monitored during the test was the guardrail. A single strain transducer was applied directly to the top of the south guardrail at the mid-span of Span 2. This gage was used to determine behavior of the guardrail during rolling tests.

2.3 Vibrating Wire Instrumentation Description

Vibrating wire gages were installed within the deck panels prior to concrete placement in order to monitor strains during the post-tensioning process and additional field tests. Twelve vibrating wire gages were installed in four of the deck panels. The deck panels were labeled A, B, C and D and can be seen highlighted in Figure 2.5. These gages were concentrated near the southern-most post-tensioning channel. A different number of gages were located at each panel. Each deck panel consisted of four gage locations as shown in Figure 2.6. A gage located at deck panel C and location 2 is therefore designated as Gage C2. Each panel contained gages at different locations. The gage locations at each panel can be seen in Table 2.1.

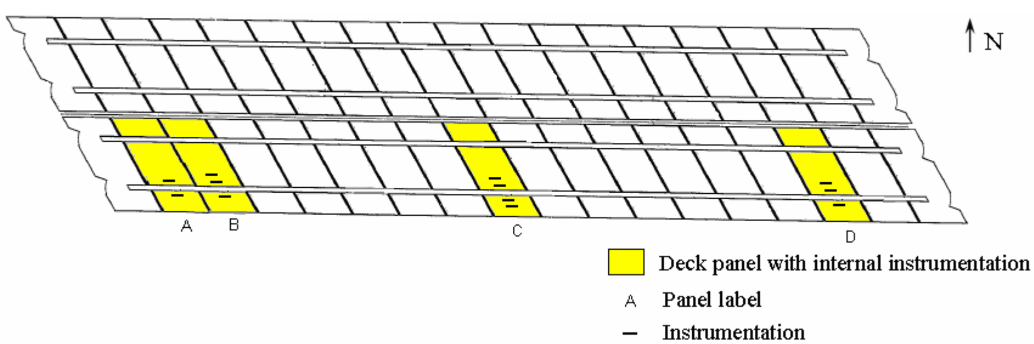


Figure 2.5 Deck panels instrumented with vibrating wire gages

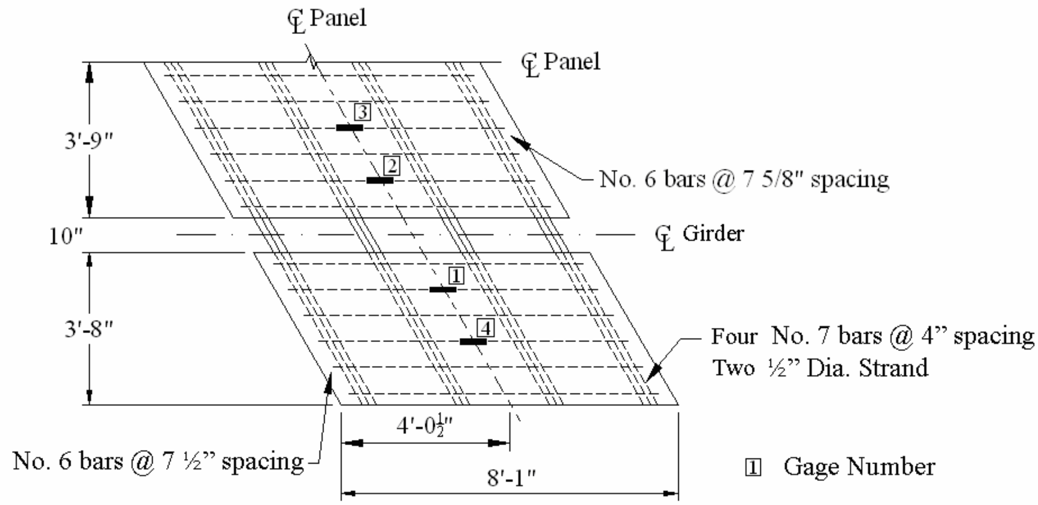


Figure 2.6 Typical VWG locations in deck panels

Table 2.1 Gage numbers and locations in each deck panel

Deck Panel	No. of Gages	Gage Location
A	2	A1, A2
B	3	B1, B2, B3
C	4	C1, C2, C3, C4
D	3	D1, D2, D3

An additional seven vibrating wire gages were installed on post-tensioning strands throughout the bridge. These gages were labeled 1 through 7 and their locations can be seen in Figure 2.7. All seven gages were monitored during the post-tensioning process. At the conclusion of this procedure, gages 1, 2 and 4 were removed. The remaining four gages were left in place for use during field tests. As a result, strains in each of the four longitudinal joints can therefore be monitored at the middle of the bridge.

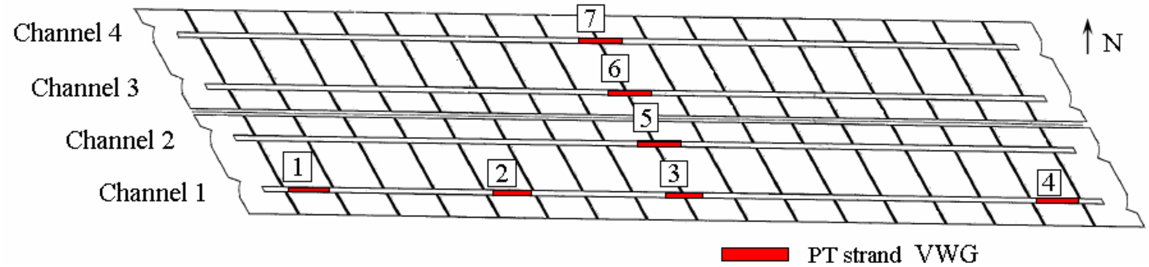


Figure 2.7 Post-tensioning vibrating wire gage locations

Some issues with the vibrating wire gages prevented the monitoring of a few of the gages during the field test. Gages B1 and B2 were not recorded because they did not read on the switch-and-balance system. Also, gages in Deck Panel C were not recorded because their wires were too short to reach the switch-and-balance machine.

2.4 Load Vehicles

The two test vehicles used to simulate traffic loads were standard tandem-axle gravel trucks, which were provided by Boone County. The trucks were loaded and axle weights and gross weights were recorded as shown in Table 2.2. An assumption has been made that the rear axle load is split evenly between the two axles. The critical lengths of each vehicle were recorded prior to the test. The two trucks had identical dimensions which are shown in Figure 2.8.

Table 2.2 Test vehicle loads

Truck #	Front Axle	Rear Axle	Gross Weight
29	17.46	18.16	53.76
31	17.22	18..16	53.52

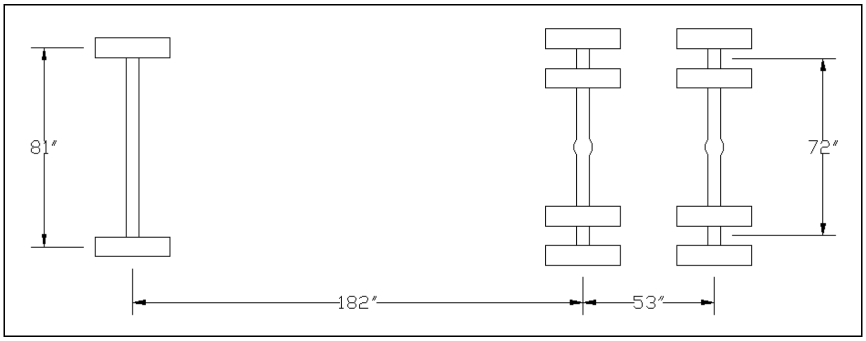


Figure 2.8 Test vehicle dimensions

2.5 Test Lanes

The field test was run on five different traffic lanes as shown in Figure 2.9. These lanes were chosen to produce maximum effects on the bridge. The trucks followed the lane line with the left tire for Lane 1 and the right tire for Lanes 2 through 5. Lane 1 is located 2 feet north of the south guardrail. Lane 2 is positioned 3 feet south of the centerline. Lane 3 is directly on the centerline. Lane 4 is 3 feet north of the centerline and Lane 5 is two feet south of the north guardrail. Lanes 1 and 5 are used to evaluate exterior loads and can be used in comparison of symmetry. Lane 4 is use to place the truck over the center of the bridge. Lanes 2 and 3 are used to evaluate load transfer as the truck is shifted across the bridge width. The test vehicle can be seen driving on Lane 3 in Figure 2.10.

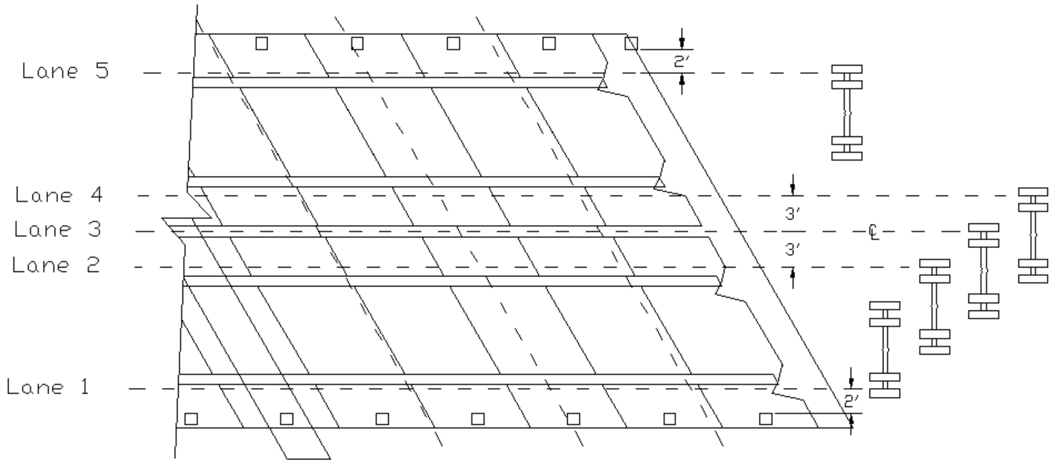


Figure 2.9 Lane configurations for static and rolling tests

Figure 2.10 Test vehicle in Lane 3 position

2.6 Static Tests

Static load tests were conducted on the bridge to evaluate maximum load cases on the bridge. Three different load cases were devised to produce maximum effects at a certain point of interest. Each of these three load cases was performed on Lanes 1, 2 and 4. Load

Case 1 was made up of Truck 31 at the mid-span of Span 2 and Truck 29 at the mid-span of Span 1 as shown in Figure 2.11. This load case produced a maximum negative moment at the east pier. Load Case 2 was made up of Truck 31 at the mid-span of Span 3 and Truck 29 at the mid-span of Span 1 as shown in Figure 2.12. This produced the greatest maximum moment in Span 2. Load Case 3 was made up of Truck 29 at the mid-span of Span 2 as shown in Figure 2.13. This produced a maximum moment at Span 2. The center of the rear tandem axles was used as the position point on the truck. The truck layout for each load case can be seen in Figure 2.14. The traffic lanes used in these tests are shown in Figure 2.9.

Figure 2.11 Static test (Load Case 1)

Figure 2.12 Static test (Load Case 2)

Figure 2.13 Static test (Load Case 3)

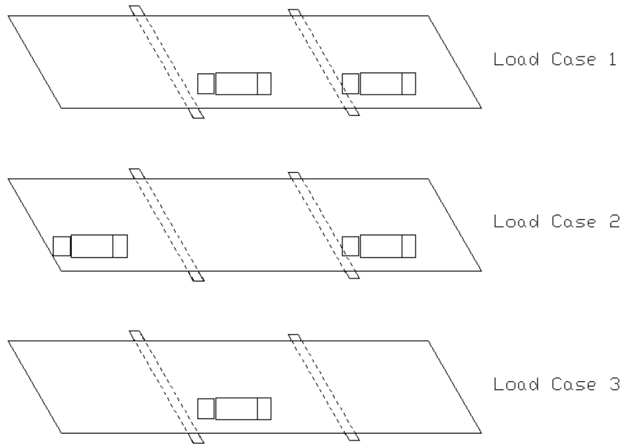


Figure 2.14 Load cases for static tests

The static test procedure was as follows. The data acquisition system was activated and Truck 31 was led to the mid-span of Span 2. As soon as Truck 31 was set, Truck 29 was placed at the mid-span of Span 1 to make Load Case 1. After a significant amount of data was taken, Truck 29 was brought to the mid-span of Span 3. Truck 31 remained in its position at the mid-span of Span 1 to make Load Case 2 complete. For Load Case 3, Truck 31 continued off of the bridge and Truck 29 moved to the mid-span of Span 2. The static tests for Lanes 2 and 4 were a repetition of this procedure.

2.7 Rolling Tests

Rolling tests were conducted after the static tests. A rolling test consists of one single truck slowly moving across the bridge along a single lane. The truck speed in maintained at approximately 5 mph. A rolling test was performed twice on each of the five traffic lanes. Three trials were done on Lane 1 because of a communication error on test 1.1. Duplicate tests were performed in order to compare tests and account for any irregularities. A drawing of the five driving lanes used for the rolling tests can be reviewed in Figure 2.10.

A total of fifteen marks were drawn across the bridge at certain positions. These marks are used to allow the position of the truck to be found in relation to the data. A mark was made at all abutments, quarter spans, mid spans, third-quarter spans, and piers. In addition to these bridge marks, a beginning mark was made 10 feet before the east abutment and an ending mark was made 20 feet beyond the west abutment. The positions of the first and last mark ensure that data is taken before the truck on the bridge until it is completely off. During the test, the operator of the data acquisition system made a note each time the rear axle of the testing vehicle crossed a mark. This allows the researcher to approximate where the truck was at any specific moment during the test.

The rolling test data was acquired using the same equipment as in the static tests. The truck was lined up with the appropriate lane and brought to a halt at about 20 feet before the east abutment. The data acquisition system was then switched on and the truck began across the bridge at a constant crawling speed. Marks were taken as the rear axle of the testing vehicle passed each mark on the bridge. When the truck passed the last mark, the data acquisition system was turned off.

3. DATA ANALYSIS

Strain and displacement data were analyzed bridge performance. Several graphs from the field test data are presented. These graphs were chosen because they best describe the behavior of the bridge. The bridge experienced very little displacement or strain during the test. Upon examination of the data, it was determined that two of the displacement gages were not operational. Later in the report, these two gages are pointed out and values are assumed for these locations. Errors in the test can be attributed to the small values, gage malfunctions, and gage vibrations. Marks were taken each time the right rear axle reached a quarter-span line.

3.1 MS 2 Analysis

Strains and displacements at MS 2 were recorded as the truck moved across the bridge. This process was replicated for all five lanes. Figure 3.1a and Figure 3.1b show the displacement and strain profiles, respectively, at MS 2 when the right rear axle of the truck was located at MS 2.

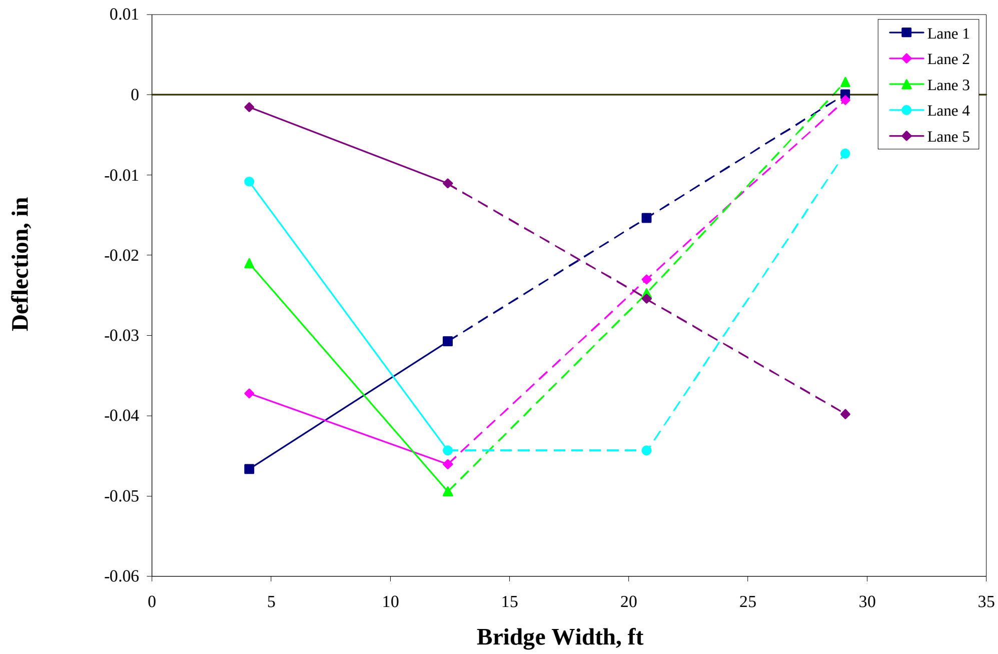
MS 2 Deflection Profiles

The deflection profiles shown in Figure 3.1a portray the movements of the girders due to the weight of the truck. It is important to note that the displacement gage located on Girder 3 was not operating during the test. Values have been assumed to complete the profiles on the graph. Trend lines to and from this point have been dashed to indicate this assumption. Lanes 1 and 5 illustrate the activity at the midspan when the truck is at each guardrail. Both profiles are most displaced at the nearest girder and go to zero at the far girder in a fairly straight line. As expected, the profiles created by Lanes 1 and 5 are nearly symmetric. Lane 4 gives the deflection profiles with the truck is on the bridge centerline. The displacement profile in this traffic lane is symmetric about the centerline as anticipated. The profiles of Lanes 2 and 3 are almost identical. The greatest deflection occurred on Girder 2 when the truck was in Lane 3.

MS 2 Strain Profiles

The strain profiles shown in Figure 3.1b reveal forces in the girders at MS 2 when the rear axle was located at MS 2. Lane 1 shows the high tension forces in the girder nearest the truck with a straight line trend to zero at the other side. Lane 5 is symmetric to Lane 1 except for the gage at Girder 4. It is possible that this gage also was not working at the time. Lane 4 depicts the strain profile when the truck is on the bridge centerline. The profile is symmetric about the centerline. Lanes 2 and 3, as with the deflection profiles, are quite similar. Lane 3 once again has the higher value of strain.

(a) **Deflection Profile**



(b) Strain Profile

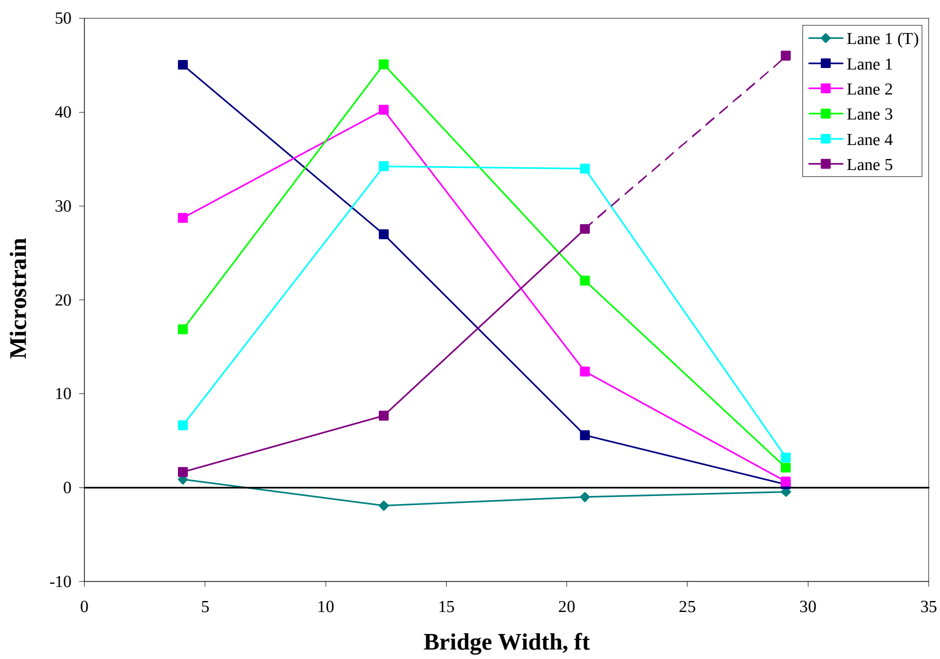


Figure 3.1 MS 2 Deflection and Strain (Lanes 1-5)

MS 2 Profiles from Static Loading

Midspan 2 Profiles were analyzed for both strain and deflection when the trucks were in Load Cases 1 through 3. The deflection profiles are in Figures 3.2a, 3.3a, and 3.4a. The strain profiles are in Figures 3.2b, 3.3b, and 3.4b. The truck loading case is shown above each set of Figures.

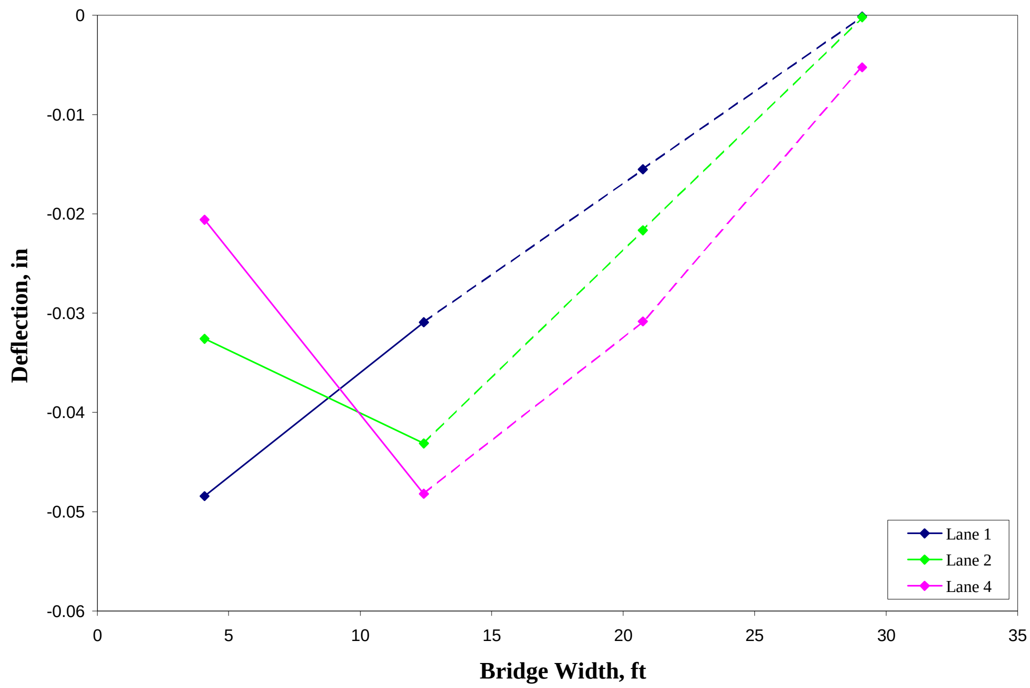
MS 2 Deflection Profiles

Load Case 1 and 3 created almost identical deflection profiles at the midspan of Span 2. The load pattern in Lane 1 created a straight-line deflection profile from Girder 1 to Girder 4 with Girder 1 having a maximum deflection of -.05 inches. Lanes 2 and 4 generated the greatest deflection at Girder 2. Loading in Lane 4 did not produce a symmetric profile about the centerline as expected. This unanticipated behavior can be attributed to the problem with the gage on Girder 3. Load Case 2 produced a very small amount of deflection with a maximum deflection of .008 inches. The bridge deflected slightly upward as would be expected.

MS 2 Strain Profiles

Load Cases 1 and 3 produce very similar strain profiles. Lane 1 loading creates a straight-line strain profile from Girder 1 to Girder 4 with Girder one having a maximum strain of approximately 45 microstrains. Lanes 2 and 4 produce very similar strain profiles. Maximum strain occurs in Girder 2 in these cases. Load Case 3 creates very little strain in the Midspan 2 profile. Maximum strain in this case is approximately -8 microstrains.

(a) Deflection Profiles



(b) Strain Profiles

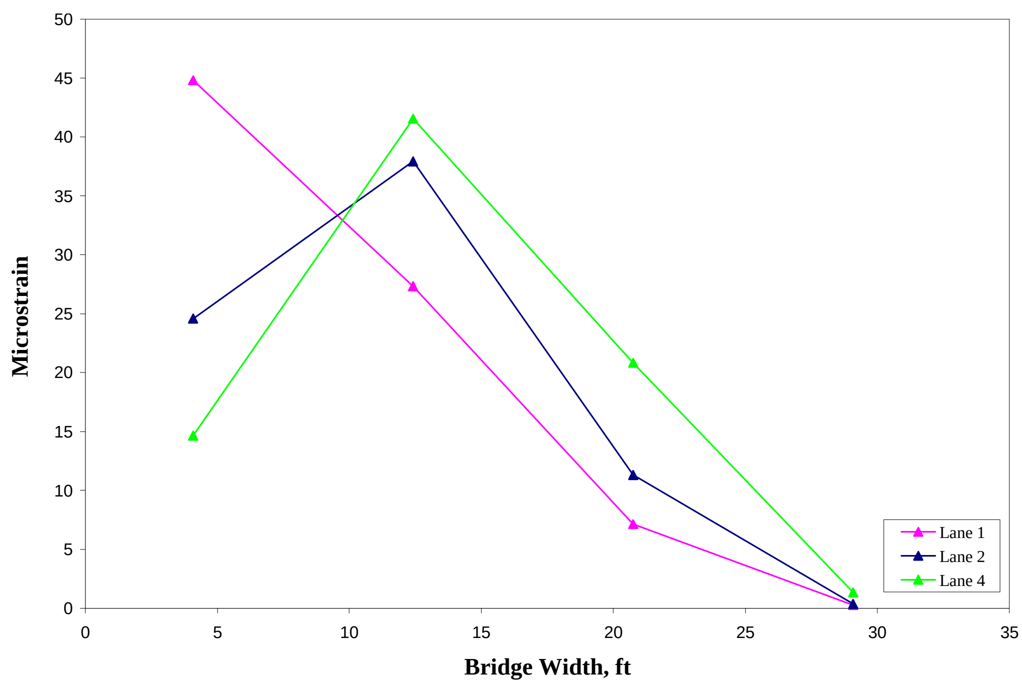
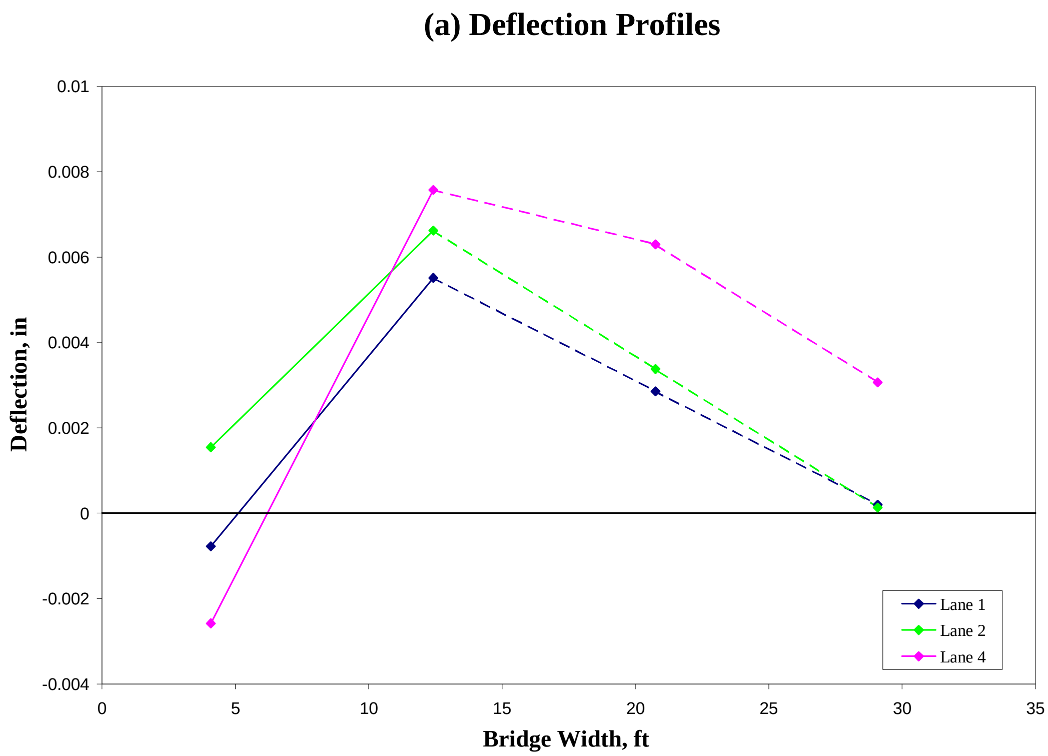


Figure 3.2 MS 2 Strain and Deflection Profiles (Load Case 1)



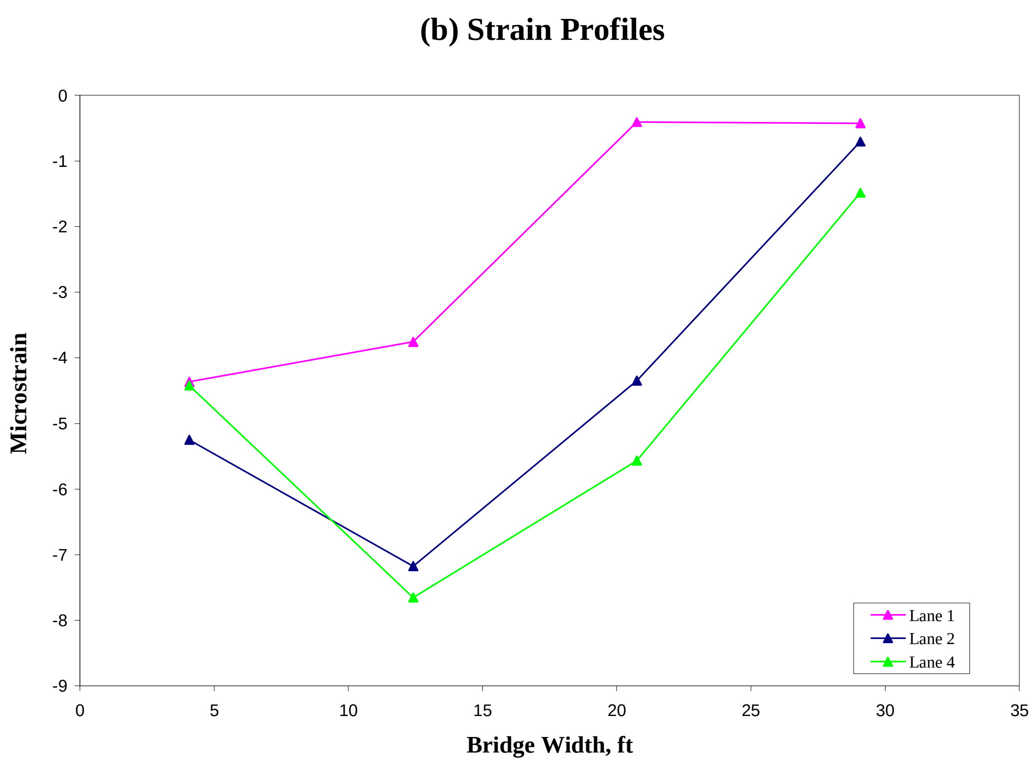
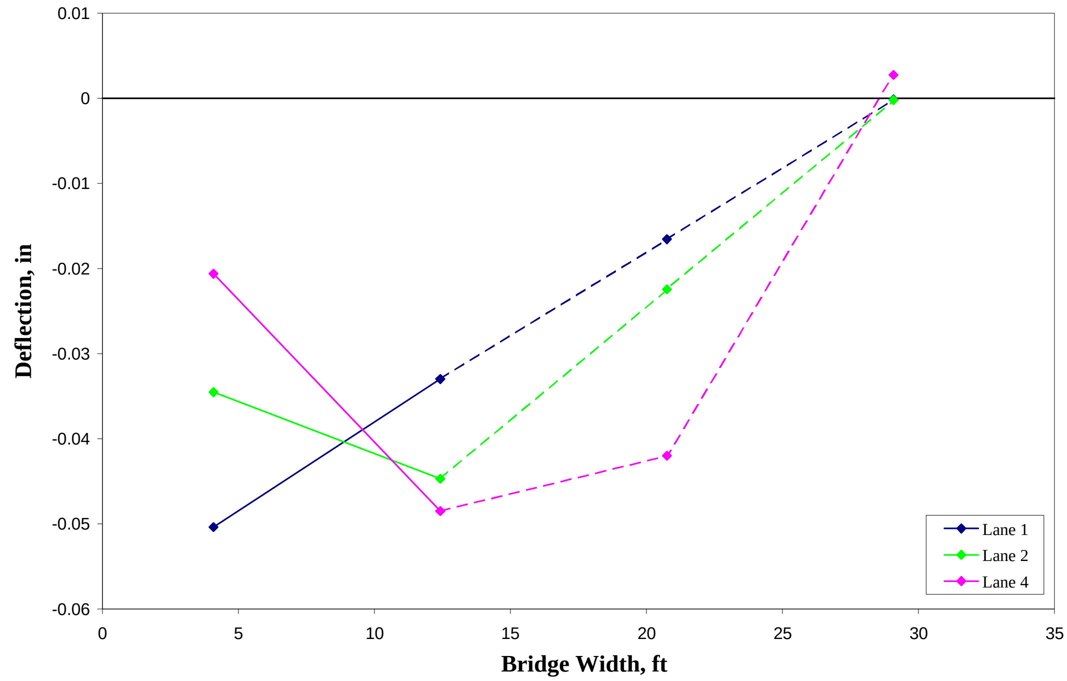


Figure 3.3 MS 2 Strain and Deflection Profiles (Load Case 2)

(a) Deflection Profiles



(b) Strain Profiles

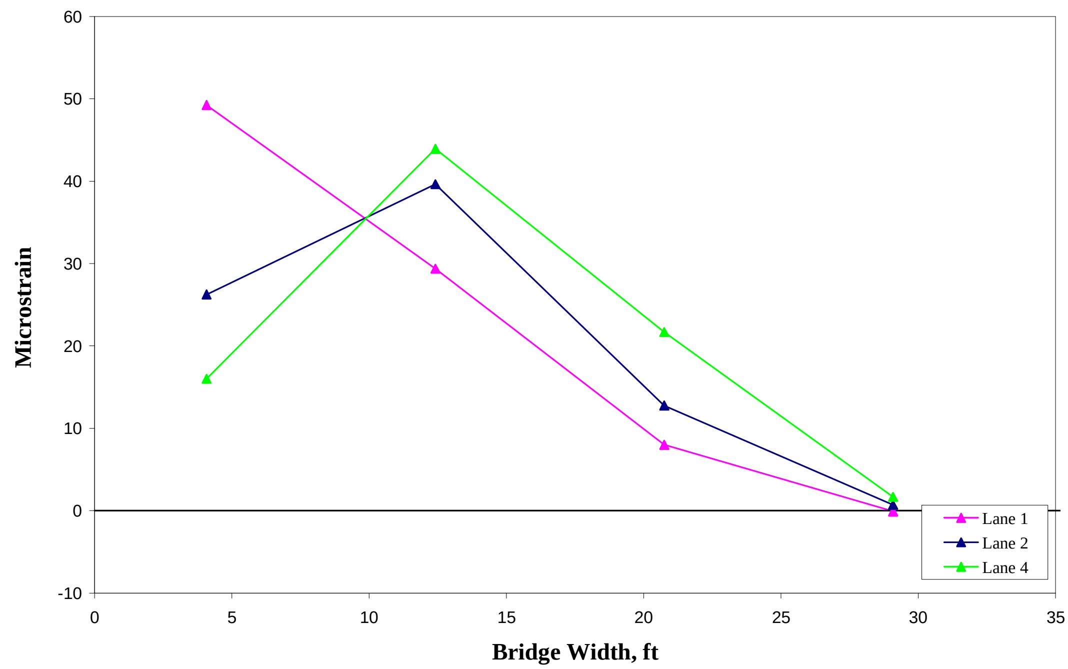


Figure 3.4 MS 2 Strain and Deflection Profiles (Load Case 3)

3.2 Girder 2 Analysis

The behavior of Girder 2 was also analyzed. Girder 2 is a full-length precast concrete girder. Deflection gages were applied on the midspans of each span in order to get a general idea of the deflection profile. These deflections are the main focus of analysis for this element of the bridge.

Girder 2 Deflection Profiles

The Girder 2 deflection profile is shown below in Figure 3.5. This profile corresponds with the rear axle positioned over MS2. All five traffic lane conditions are included. A maximum deflection of -.05 inches was found when the truck was in Lane 3. Lanes 2 and 4 were very similar with slightly less deflection than Lane 3. As expected, the Lane 5 condition created the least amount of deflection. The transducer at MS 1 was not working correctly, so it was assumed that MS 1 values were equal to MS 3 values.

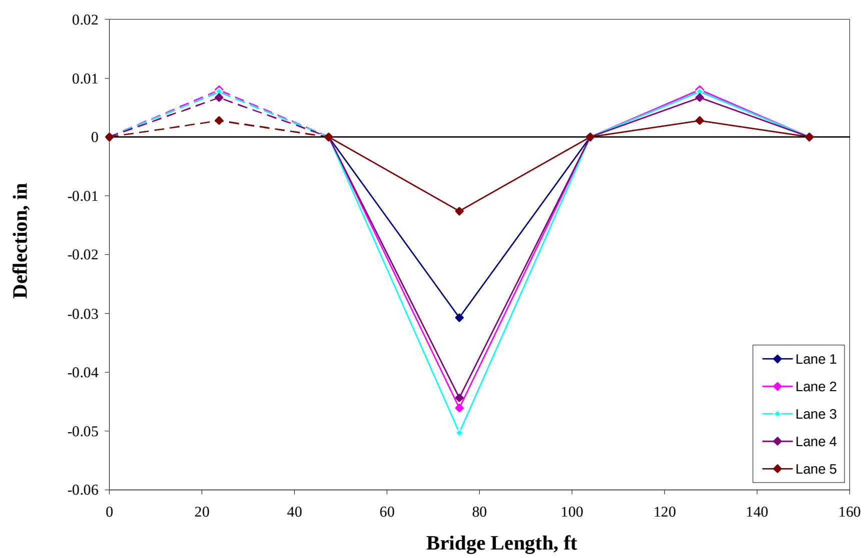
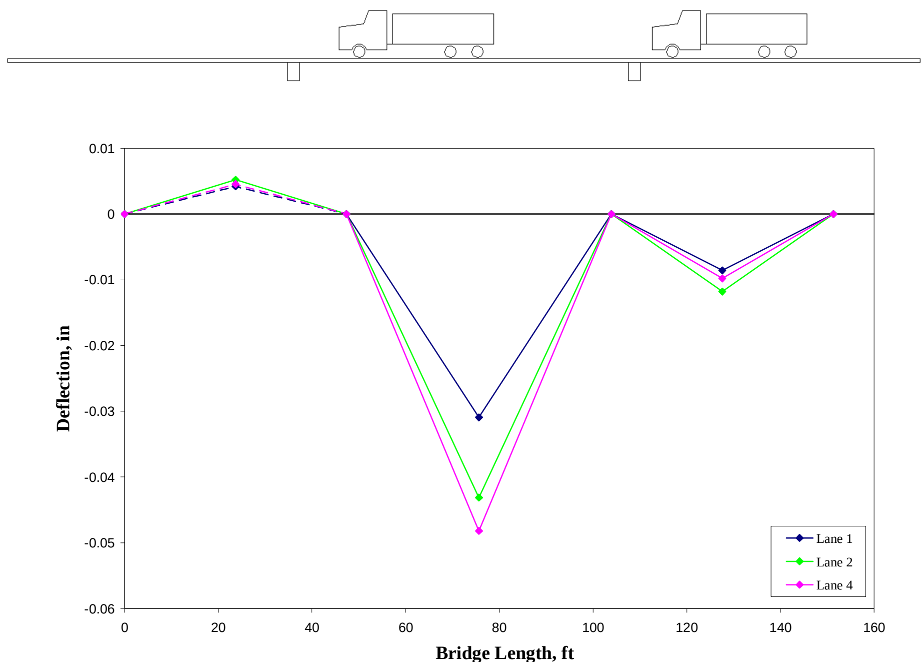


Figure 3.5 Girder 2 Deflection Profile (Lanes 1-5)

Girder 2 deflection profiles were also monitored during each static load test. The data is presented in Figures 3.6a through 3.6c. Load Case 1 and 3 produce the greatest deflection at MS 2. Very small displacements were recorded at MS 1 and MS 3. This can be attributed to the fact that they are end spans and have shorter span lengths. As stated above, MS 1 was assumed due to faulty testing equipment.

Load Case 1



Load Case 2

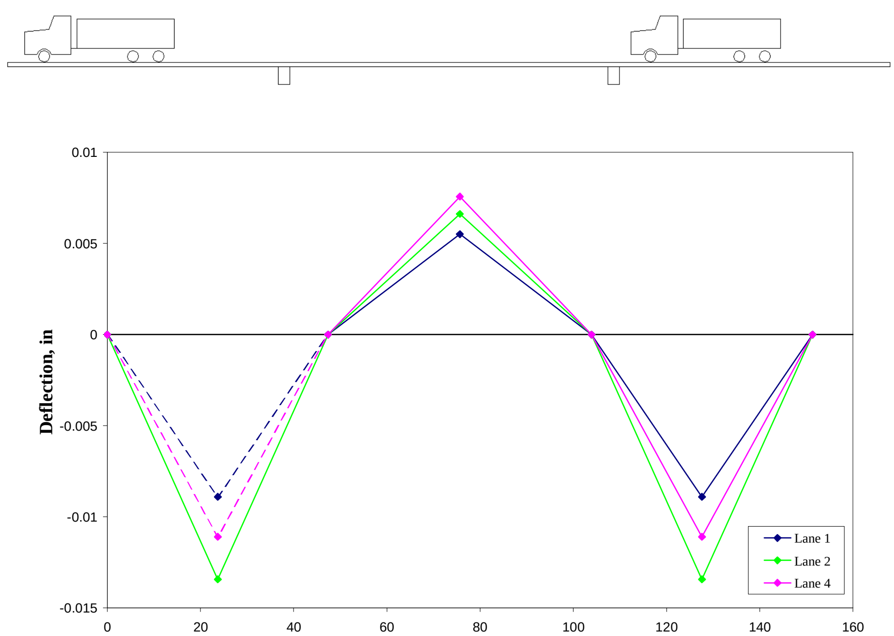


Figure 3.6 Girder 2 Deflection Profiles (Load Cases 1-3)

Load Case 3

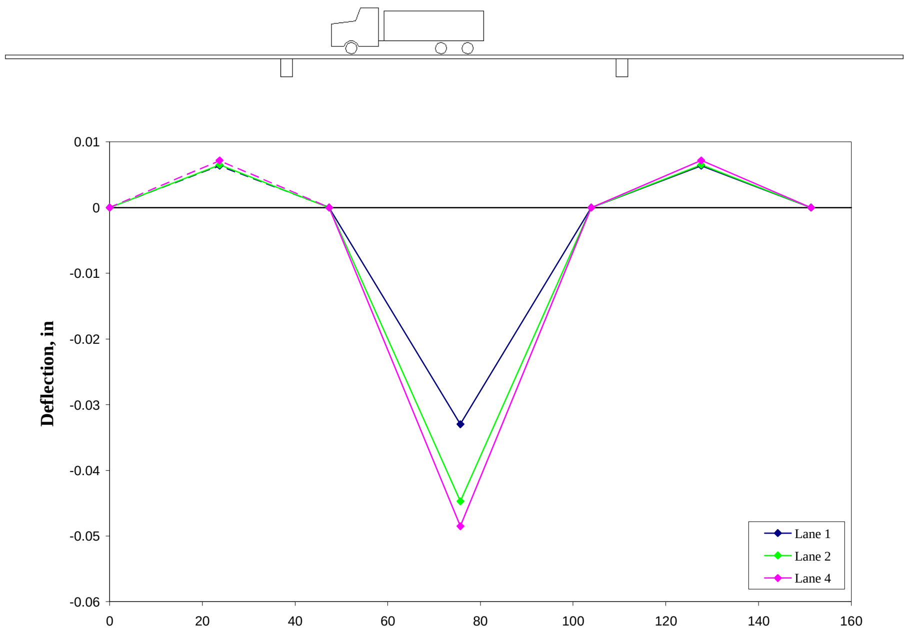
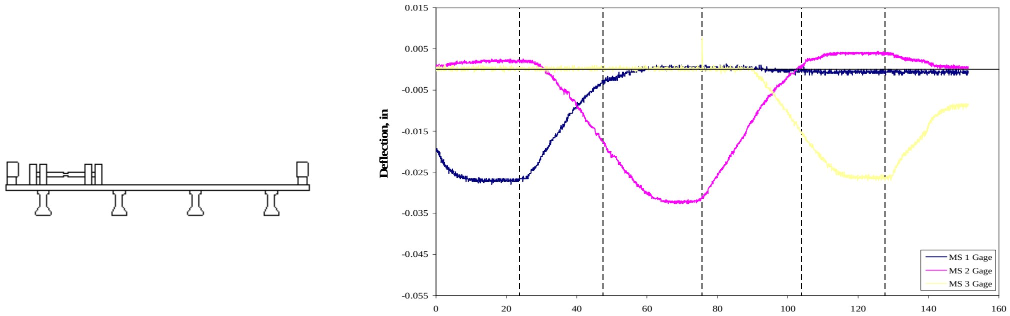
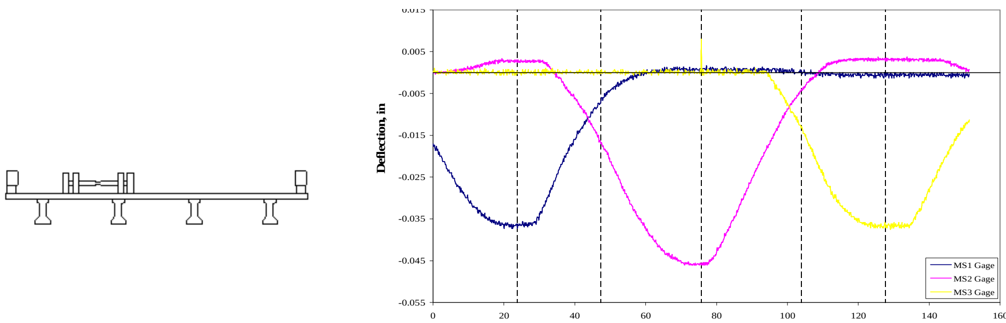


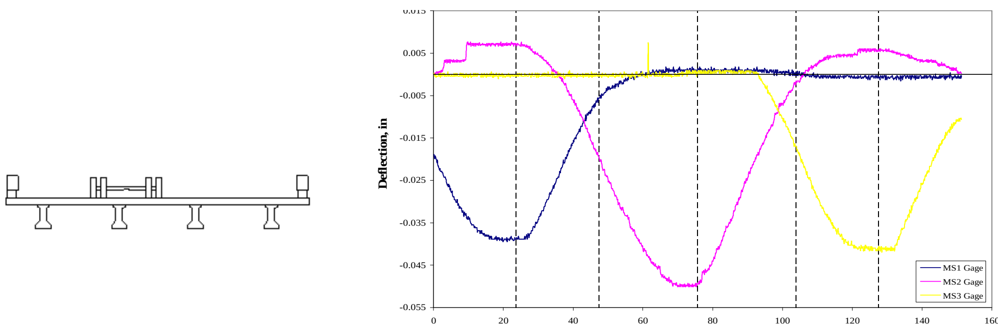
Figure 3.6 Girder 2 Deflection Profiles (Load Cases 1-3)

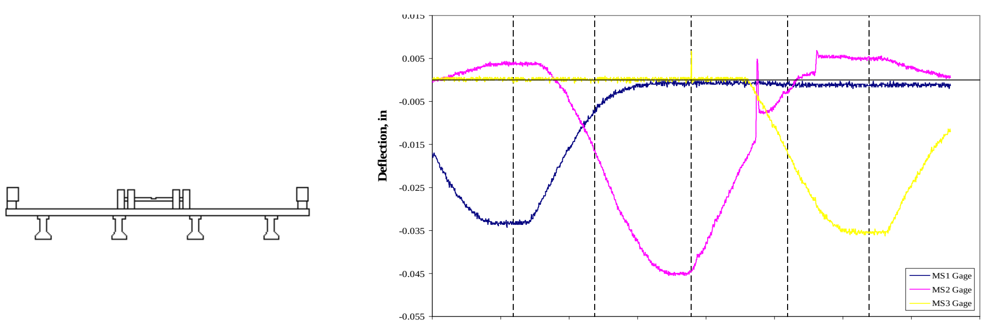
Girder 2 Deflection History

Deflection gages were recorded as the truck traversed the bridge. Figures 3.7a - 3.7e show data from the gages along Girder 2 during this time. Gages were located at the MS of each span. The graphs show that MS 2 consistently deflected more than MS 1 and MS 3. These graphs verify earlier graphs by showing greatest deflection occurring when the truck was in Lane 3. Once again, Lanes 2 and 4 produced slightly less deflection than Lane 3 and Lane 5 produces the smallest amount of deflection. MS 1 and MS 3 deflected a maximum distance approximately equal to 80% of the maximum deflection experienced at MS 2.


Deflection, in
MS 1 Gage
MS 2 Gage
MS 3 Gage


Deflection, in
MS1 Gage
MS2 Gage
MS3 Gage


Deflection, in
MS1 Gage
MS2 Gage
MS3 Gage


Deflection, in
MS1 Gage
MS2 Gage
MS3 Gage

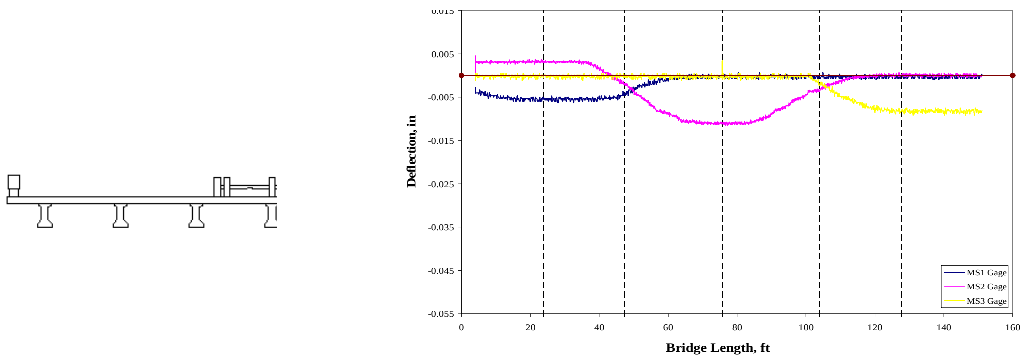


Figure 3.7 Girder 2 Deflection History (MS Gages)

3.3 East Side of West Pier Strain Profiles

Strain gages were installed at the east side of the west pier in order to evaluate strain at this location. It was possible to investigate the strain profile at this location at anytime during each of the five traffic lane tests. Figure 3.8 shows the strain profiles at the east side of the west pier for each traffic lane when the rear axle was at MS 1. A maximum compression of 15 $\mu\epsilon$ occurred when the truck was in Lane 2. The maximum negative condition could be attained by placing a truck at MS 1 and MS 2. The maximum negative strain condition at the pier can therefore be assumed to be twice the maximum strain from one truck, or 30 $\mu\epsilon$. Virtually no strains were generated when the truck was in Lane 4.

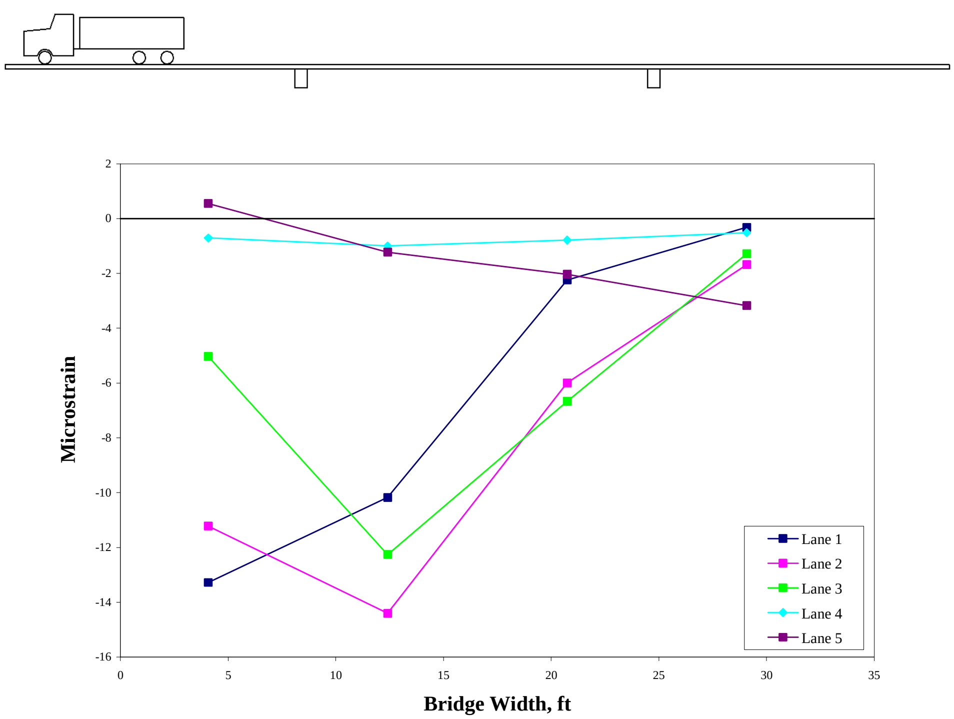


Figure 3.8 East Side of West Pier Strain Profile (Rear Axle at MS 1)

3.4 South Guardrail Strain History

A strain gage was located on the top of the south guardrail at MS 2. This strain gage was monitored as the truck traversed the bridge in each of the five traffic lanes. Figure 3.9 illustrates the strain in this guardrail relative to the position of the truck on the bridge. A maximum negative strain of 32 $\mu\varepsilon$ occurred in the guardrail while the truck was in Lane 1. This significant amount of strain establishes the fact that the guardrail contributes to the stiffness of the bridge. Strain in the guardrail lessens as the truck passes further from the south side of the bridge. Strain in the south guardrail is virtually zero when the truck is in Lanes 4 and 5.

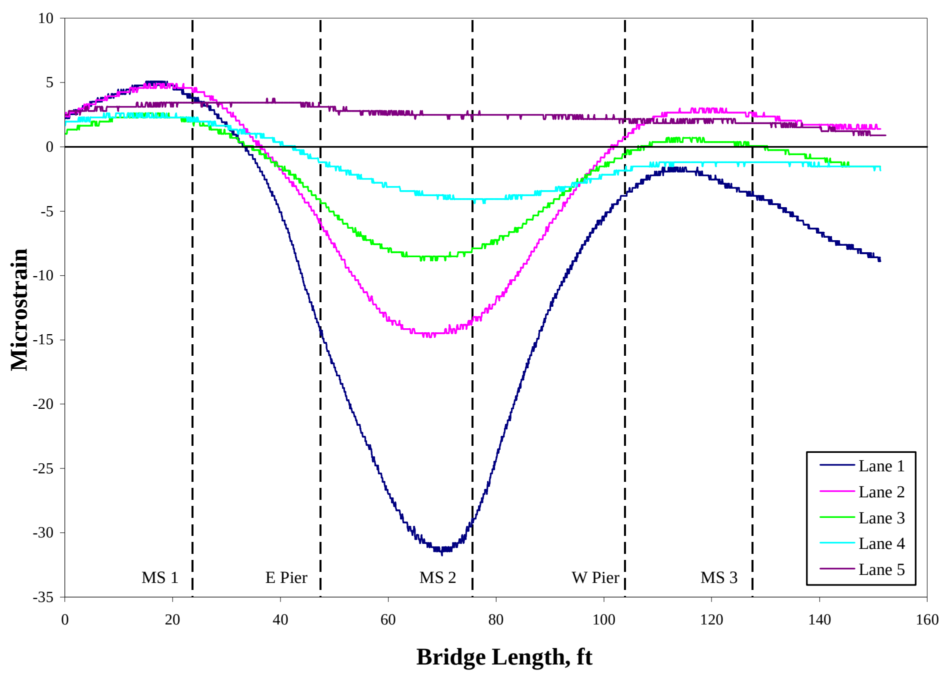
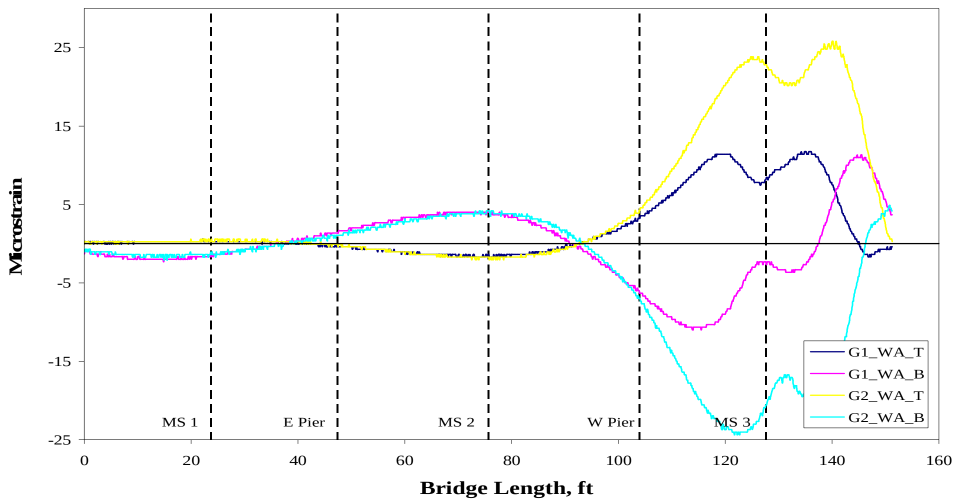


Figure 3.9 South Guardrail Strain History

3.5 Abutment Strains

Strain transducers at both abutments were monitored during each of the five traffic lanes. Data from the west abutment and east abutment are shown in Figures 3.10a and 3.10b, respectively. The Lane 2 loading condition was used for these graphs because it was the maximum strain condition for the abutments. Strains on the graphs are shown relative to the position of the truck on the bridge.

(a) West Abutment



(b) East Abutment

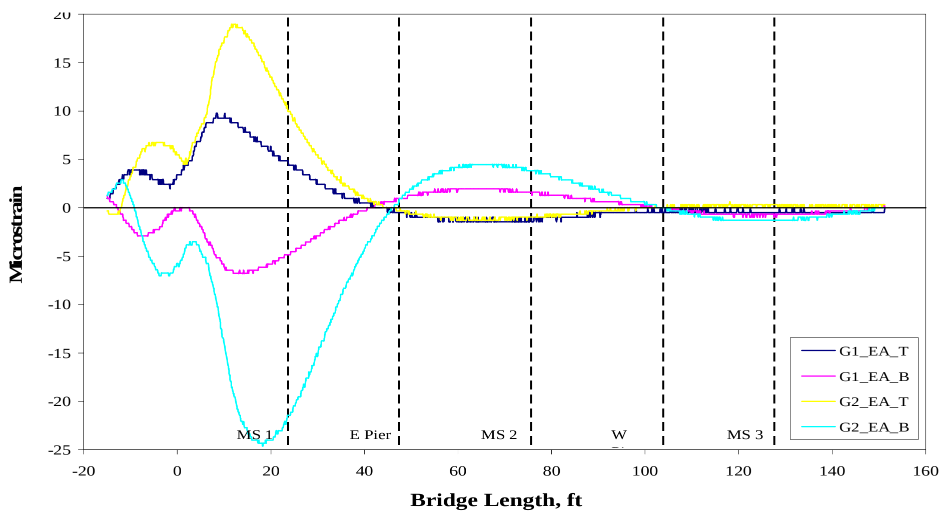
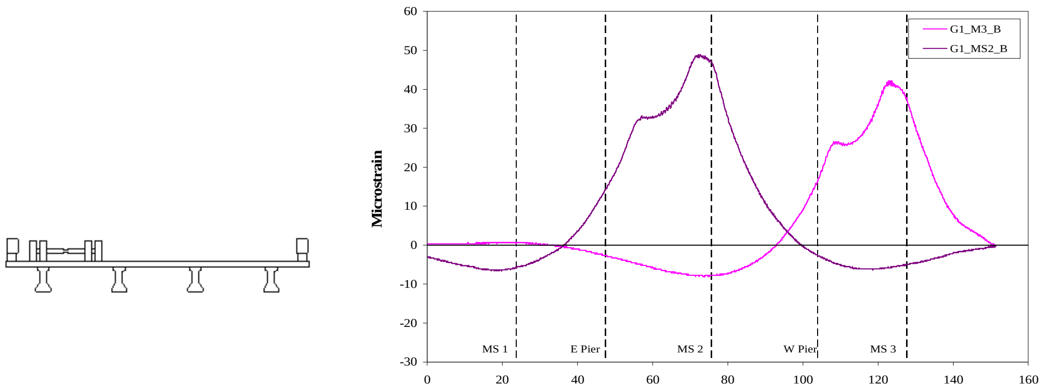


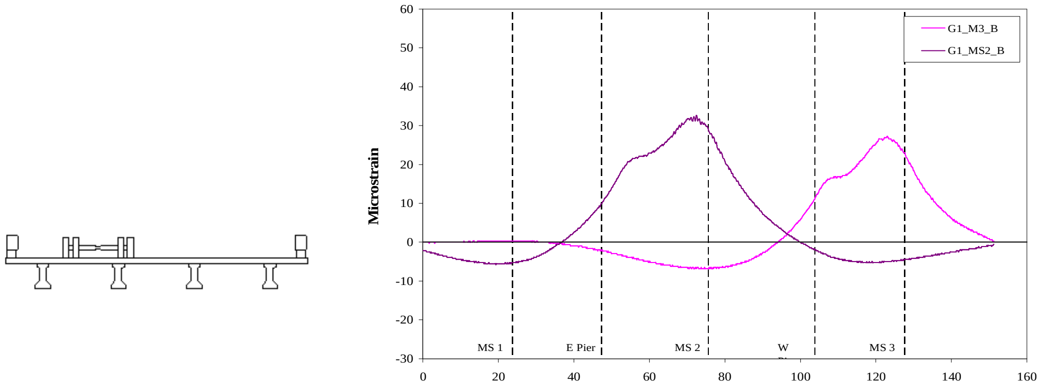
Figure 3.10 Abutment Strain History

3.6 Girder 1 Strain History

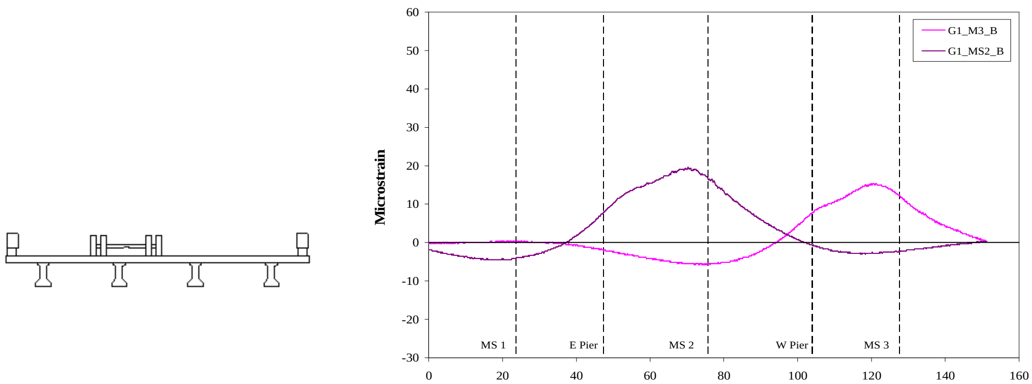
Strain transducers were located on the bottom flange of Girder 1 at the midspan of spans 2 and 3. Strains in these locations relative to the position of the truck can be seen in Figures 3.11a-3.11e. The five graphs each represent data from a different traffic lane loading condition. As expected, the greatest strains occurred when the truck was in Lane 1. Strains decreased with each successive lane. Lane 5 is not included in the report due to the lack of significant strain values. Strain gages were not located at the MS 1 location. MS 3 had a maximum strain equal to approximately 80% of the maximum strain of MS 2. This was determined using Lanes 1, 2 and 3. Lane 4 data was too insignificant to compare.



Microstrain
G1_M3_B
G1_MS2_B
MS 1
E Pier
MS 2
W Pier
MS 3
60
50
40
30
20
10
0
-10
-20
-30
0
20
40
60
80
100
120
140
160



Microstrain
G1_M3_B
G1_MS2_B
MS 1
E Pier
MS 2
W
MS 3
60
50
40
30
20
10
0
-10
-20
-30
0
20
40
60
80
100
120
140
160



Microstrain
G1_M3_B
G1_MS2_B
MS 1
E Pier
MS 2
W Pier
MS 3
60
50
40
30
20
10
0
-10
-20
-30
0
20
40
60
80
100
120
140
160

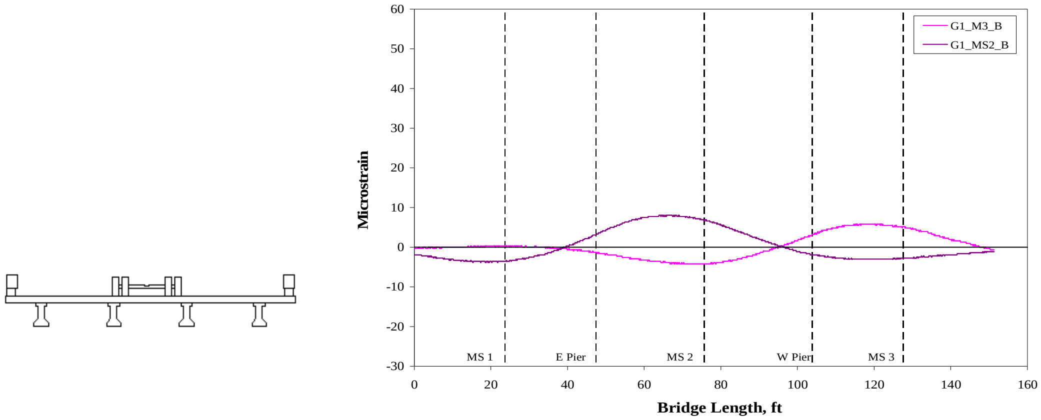


Figure 3.11 Girder 2 Strain History (Lanes 1-4)

3.7 Composite Behavior Analysis

Composite behavior was analyzed at each girder location of MS 2. Three strain locations were used: top flange, bottom flange and post-tensioning strand. Strains at the top and bottom flange of each girder were grouped with the strains from the corresponding post-tensioned strand to make a strain depth profile. Strain depth profiles for each girder during LC 1.1 are shown in Figures 3.12a through 3.12d. A structure experiencing composite behavior should exhibit a straight-line strain profile along its depth. It was found that Girders 2 and 3 consistently demonstrate straight-line strain depth profiles throughout each load case. Girders 1 and 4, however, do not show evidence of straight-line strain behavior. This is most likely due to defective instrumentation on the bridge. It is believed that the VWG at Girders 1 and 4 are damaged. This may be due to over straining of the gages during the post-tensioning process. In addition, the strain BDI gage at the bottom flange of Girder 4 is assumed to be faulty.

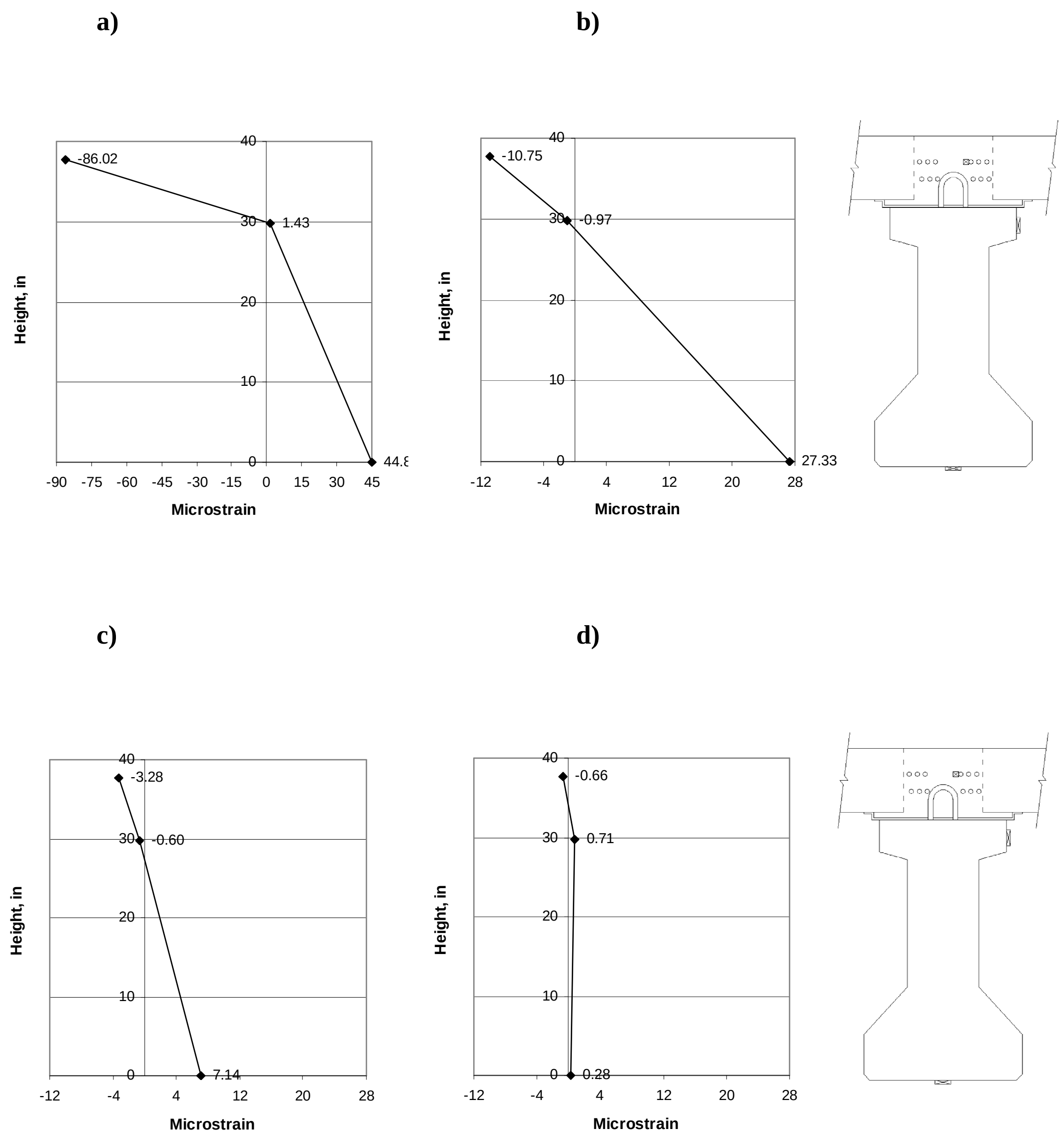


Figure 3.12 Strain Depth Profile (Girders 1-4)

The top and bottom flange strains were used to calculate a theoretical strain at the level of the post-tensioned strand. The actual strains were then compared to the theoretical strains. The theoretical strains calculated further enforce the possibility that VWG at Girders 1 and 4 are not working. Data for LC 1.1 can be seen in Table 3.1. PT_C and PT_A correspond to the calculated theoretical post-tensioning strain and the actual post-tensioning strain during the test. The difference between these two values is given as ΔPT. Theoretical strain was calculated using a straight line interpretation along the girder-deck cross section.

Table 3.1 Strain Depth Data

	G1	G2	G3	G4
ΔPT	76	2	1	1
PT_C	-10.24	-8.58	-2.68	0.83
PT_A	-86.02	-10.75	-3.28	-0.66
TF	1.43	-0.97	-0.60	0.71
BF	44.80	27.33	7.14	0.28

3.8 Girder Distribution Factor

Load distribution across the bridge was determined using a girder distribution method. Distribution of the load to each girder can be found by calculating the moment in each girder. This can be done using the relationship $\sigma = \frac{Mc}{I_x}$. In this equation, σ is stress, M is moment, c is the distance from the x axis, and I_x is the moment of inertia about the x axis. It was assumed that I_x and c were identical at each girder location. This simplifies the equation to $\sigma = M$. Furthermore, using the equation $\sigma = \varepsilon E$, and for a constant E, it can be assumed that the strain is proportional to the moment in the girder. The load distribution was then evaluated using the strain at the bottom flange of each girder.

Load distribution at each girder was then calculated by taking the strain at each individual girder divided by the total strain of all four girders. This data was plotted for Lanes 1 through 5 for the case when the truck was positioned at MS 2. These graphs are shown in Figures 3.13. The AASHTO design load distribution factor, S/14, was added to the graphs for comparison. In all cases, load distribution at each girder stays below this design value. As stated earlier, the strain BDI at Girder 4 was not working. This caused the data for Lanes 4 and 5 to be incorrect.

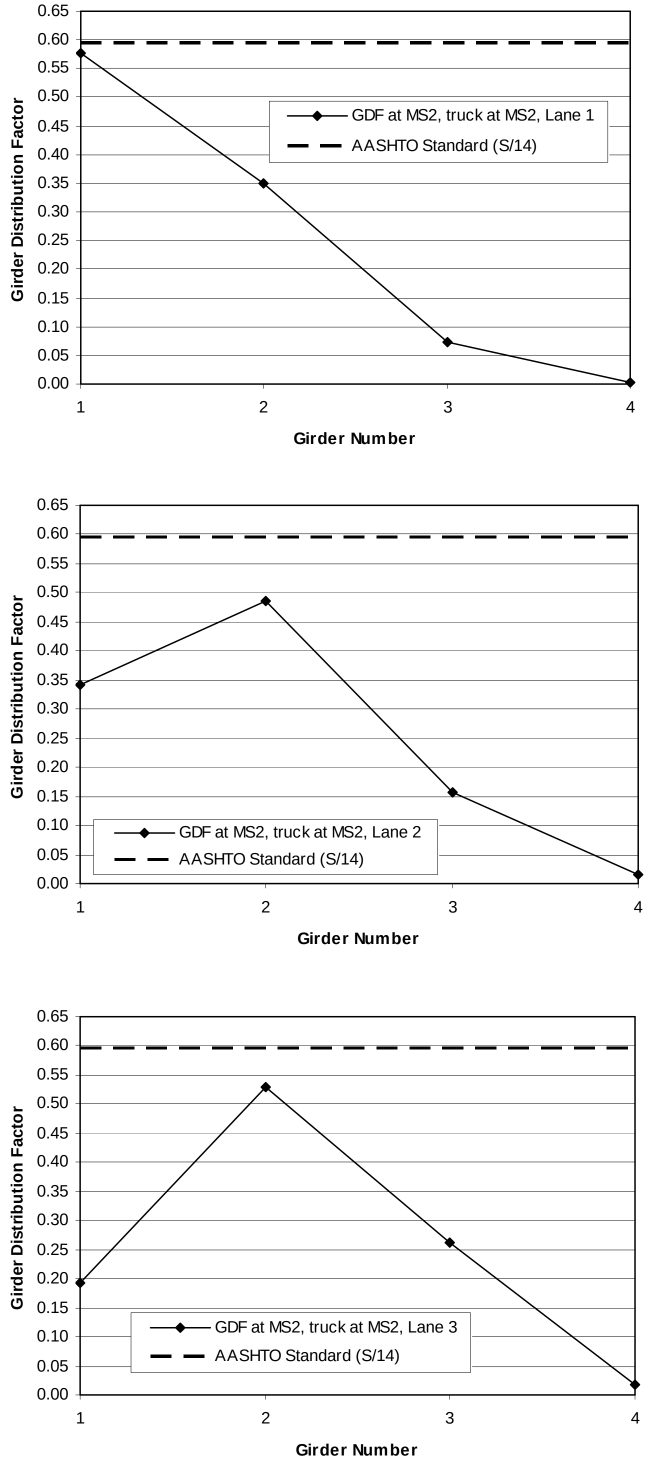
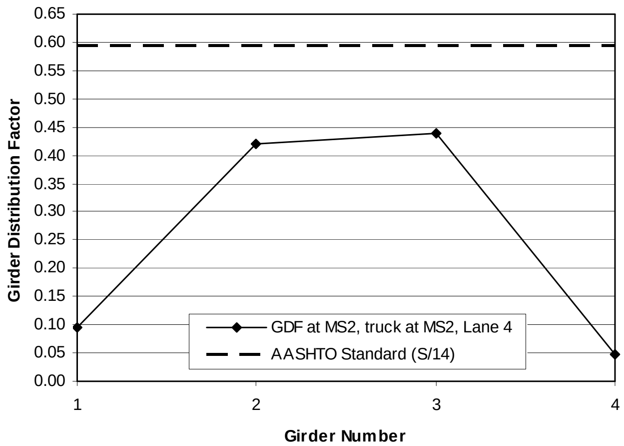


Figure 3.13 Load Distribution at MS 2 (Lanes 1-5)



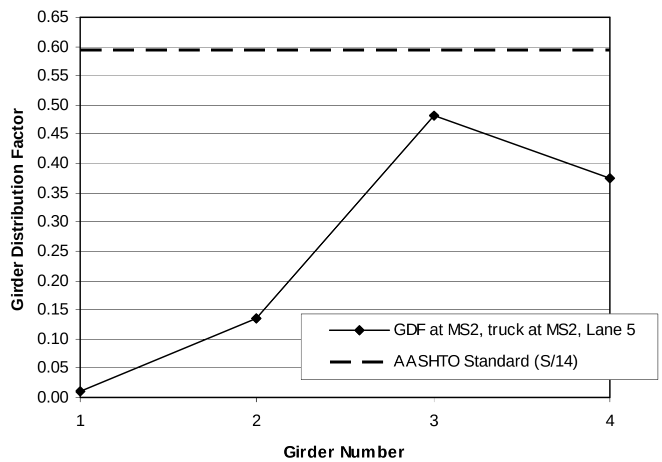


Figure 3.13 Load Distribution at MS 2 (Lanes 1-5)

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