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METHOD OF ANALYSIS COMPARISON STUDY FOR A CURVED, STEEL GIRDER BRIDGE

FINAL REPORT

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UDOT RESEARCH & DEVELOPMENT REPORT ABSTRACT

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16. Abstract

Horizontally curved bridges are much more difficult to design than conventional straight bridges because the horizontal curve in the bridge adds torsional effects to the girders. Due to the uncertainties of the analysis methods currently being used by design engineers, the Federal Highway Administration (FHWA) is interested in knowing what level of analysis is required to obtain accurate results when analyzing horizontally curved bridges.

The FHWA contracted with Utah State University (USU) to test a horizontally curved bridge in Salt Lake City, Utah, which was scheduled for demolition. Loads were applied to the bridge by driving loaded dump trucks slowly across it. The strains and deflections were measured at key points on the girders.

Upon completion of the testing, several finite element models of the bridge were developed using Sap 2000. Due to the potential complexity of finite element models it is desirable to find other methods of analysis, or types of models, that are much less complicated, but are still able to give accurate enough results to use for analysis and design purposes.

This report contains a comparison of results for various types of finite element models and a form of hand analysis for curved girders. This comparison provides information as to the relative accuracy of the different types of finite element models and the hand analysis, along with an indication as to which types of analysis are appropriate.

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Abstract

Many horizontally curved, steel girder bridges have been built in the past and are still being built today. Horizontally curved bridges are much more difficult to design than conventional straight bridges because the horizontal curve in the bridge adds torsional effects to the girders. Due to the uncertainties of the analysis methods currently being used by design engineers, the Federal Highway Administration (FHWA) is interested in knowing what level of analysis is required to obtain accurate results when analyzing horizontally curved bridges.

The FHWA contracted with Utah State University (USU) to test a horizontally curved bridge in Salt Lake City, Utah, which was scheduled for demolition. USU and Bridge Diagnostics Inc. performed these tests and examined the strains and deflections of the bridge. Loads were applied to the bridge by driving full dump trucks slowly across it. The strains and deflections were measured at key points on the girders and plotted against the position of the truck to construct influence diagrams.

Upon completion of the testing, several finite element models of the bridge were developed using Sap 2000. These models were calibrated with the data obtained from the field-testing. The final model, called jr22, gives very good results, but the model is very complicated. Due to the potential complexity of finite element models it is desirable to find other methods of analysis, or types of models, that are much less complicated, but are still able to give accurate enough results to use for analysis and design purposes.

This report contains a comparison of results for various types of finite element models and a form of hand analysis for curved girders. This comparison provides information as to the relative accuracy of the different types of finite element models and the hand analysis, along with an indication as to which types of analysis are appropriate.

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Executive Summary

The purpose of this study is to examine different analysis strategies for curved, steel girder bridges. Ultimately, this boiled down to a comparison between the V-Load method, an approximate by hand analysis, and various levels of finite element models. The V-Load analyses were executed following guidelines contained in the Highway Structures Design Handbook, published by the National Steel Bridge Alliance. The finite element models were created and analyzed using SAP 2000 structural analysis software on a PC.

The baseline for comparison in this study consists of field data collected during the testing of a curved girder bridge in Salt Lake City in 1999. This bridge was a semi-composite (which made the analysis much more complicated), steel girder bridge about 25 years old. The bridge had three spans and was super-elevated, in addition to containing a vertical curve. It was slated for demolition after the testing, as part of the I-15 reconstruction project.

The finite element models utilized were of several levels of sophistication, from a flattened model using beam and shell elements to an extremely complicated model that utilized shell elements for all the major structural components, vertical beam elements to model the semi-composite nature of the bridge, springs to simulate the boundary conditions, and the super-elevation and vertical curvature were maintained.

Several types of comparisons were made between the field data and the outputs of the V-Load method and the finite element models. Percentages of error in strain were compared, influence diagrams were created for strain (this is the most useful comparison), and deflections were examined.

The fact that this report is based on the examination of a single bridge is an unavoidable weakness of this study; opportunities to test bridges in the field to the extent that this one was tested do not come along very often. However, there is some information to come out of this study that leads to some basic conclusions:

- The V-Load method, as implemented following the Highway Structures Design Handbook guidelines, was the most conservative approach, oftentimes to extremes.
- The semi-composite nature of the bridge and the condition of the bridge supports made modeling of the bridge difficult.
- The prediction of the bridge strains was in all cases better predicted by the analyses methods than were the displacements.
- Taking the vertical curve and super-elevation out of the models had a minimal impact on the outcomes of the models.
- The finite element models using shell elements throughout, customized boundary conditions using springs, and flexural connectors to simulate the semi-composite behavior provided the best predictions of bridge behavior (Shells Flat and jr22 Variable models).

- The beam flat model, using beam elements to model the girders rather than shells, provided the best prediction of bridge behavior among the simpler models.

The following overarching recommendation is made, in addition to those contained in the body of the report:

- Given the level of computer sophistication that engineers have today, especially new graduates, the lower costs of finite element software, and the efficiencies in design that can come from improved analyses, all curved, steel girder bridges should be analyzed using some form of finite element analysis. Approximate hand approaches, like the V-Load method, are suitable for the initial development of member sizes that can be used within a finite element model, but the end analysis, and the data used for design, should come from a finite element based modeling approach.

Contents

Contents (cont.)

List of Tables

List of Figures

Page

List of Figures (cont.)

Page

List of Figures (cont.)

Page

Introduction

Horizontally curved, steel girder bridges are often used in our modern road systems. The curve in the bridge allows for a smoother transition for traffic, which creates better road travel. The disadvantage to horizontally curved bridges is the fact that they are more difficult to analyze and design than conventional straight bridges. The horizontal curvature in the girders adds torsional effects, which can increase or decrease the strains in the girders.

Due to the difficulty in analyzing these bridges, a variety of approaches may be used. The appropriateness and relative accuracy of these different approaches needs to be determined. Engineers at the Federal Highway Administration (FHWA) are interested in knowing what types of analyses obtain accurate results when analyzing horizontally curved bridges.

The FHWA contracted with Utah State University (USU) to test a horizontally curved bridge in Salt Lake City, Utah, which was scheduled for demolition. USU along with Bridge Diagnostics Inc. (BDI) tested the bridge. Loads were applied to the bridge by driving fully loaded dump trucks, either singly (233 kN gross weight) or in tandem (the second towed by the first, 454 kN total gross weight) slowly across it [BDI, 1999]. The strains and deflections were measured at key points on the girders and plotted against the position of the truck to construct influence diagrams [Laursen, 1988]. Upon completion of the testing, several finite element models of the bridge were constructed using SAP 2000 [CSI, 1997]. The final model, named jr22, gives very good results, having been calibrated to the test results, but the model is very complicated. Due to the complexity of this model it was desirable to find other models and methods of analysis, including less complicated hand analysis methods which yield accurate enough results to use for design purposes.

Application

The practical application of this study will be an indication to practicing bridge engineers of how complicated a finite element model needs to be, or whether approximate hand methods are appropriate, in the analysis of curved girder bridges. The objective is to reach a suitable level of confidence in the stresses and/or strains predicted through analysis so that designs based on the analytically predicted behaviors of these curved girder bridges are appropriate, not over designed, and safe for the public.

The Bridge

The bridge tested for this study was a 3-span welded steel plate, curved girder bridge scheduled for demolition and replacement during the I-15 reconstruction project. The bridge was located in Salt Lake City, on the 6400 South interchange. It was ramp A-6, moving traffic from northbound I-15 to westbound I-215, over the I-215 eastbound lanes. The bridge was approximately 40 feet wide. The first and third spans were 41 feet 6 inches long and the middle span was 69 feet 3 inches. The bridge had a radius of 477.46 feet. The bridge deck was super-elevated at six percent. The bridge also followed a vertical curve which transformed from -1.47 percent to 6.06 percent in 350 feet. The bridge was constructed of five welded steel plate curved girders and behaved in a semi-composite manner. This bridge was fitted with 48 re-usable strain transducers at 136 unique locations and 15 string pot type deflection-measuring devices. Each of the strain gages was assigned a number, with the locations of the gages shown in the Figure 1. For the locations with just two gages, a gage was placed on the lower flange of the girder, just below the web, and the other was placed on the upper flange, just to the side of the web. Where four gages are shown, two were located on the bottom flange, one on each side of the web at the extreme edge of the flange; the other two gages were located on the upper flange, directly above those on the lower flange. At points where seven gages are listed, the additional three gages were placed up the web, distributed evenly between the flanges [BDI, 1999; Womack, et al. 2001].

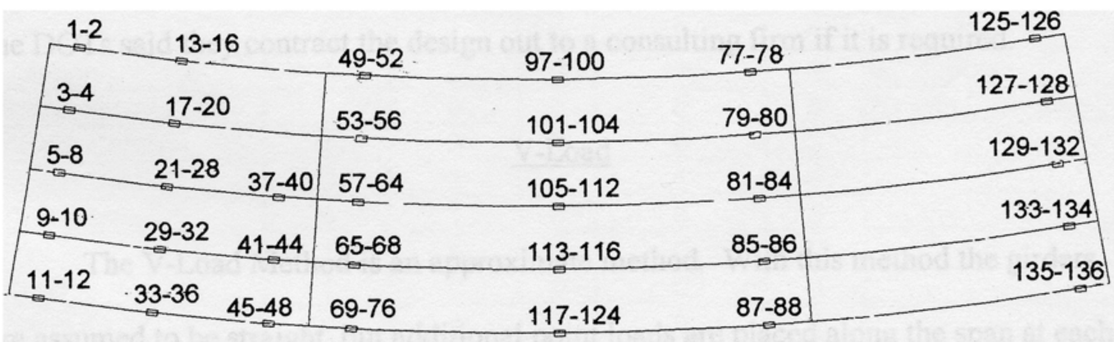

Figure 1. Gage locations.

Methods of Analysis

In order to determine which methods of analysis should be tested, thirty-six state departments of transportation (DOTs) were successfully contacted by phone. The majority of the DOTs use, for in house analysis, one of three methods: the V-Load method, Descus, or Finite Element methods. The method used by each of the states contacted is shown in Table 1. Within the table a "1" in a column indicates the use of that method and a "0" indicates no use. Some DOTs use more than one method to perform an analysis, with the most popular method being the V-Load method, which twenty-one of the thirty-six departments contacted use. Eleven of the departments use Descus, but in some cases the person responding did not understand what type of analysis Descus actually is. Six of the departments use some other form of finite element analysis. Another six of the departments said they don't design horizontally curved bridges. A few of the departments do not use horizontally curved bridges or the horizontal curves that they do use are so gradual that the curvature need not be considered. Other DOTs said they contract the design out to a consulting firm if it is required.

V-Load

The V-Load method is an approximate method of analysis. With this method the girders are assumed to be straight, but point loads are placed along each span at points where the diaphragm connects to the girders, simulating torsional loads imposed on the girder system. In this study the V-Load method was applied according to guidelines contained in the Highway Structures Design Handbook [NSBA, 1996].

In order to determine the magnitude of the extra point loads the moments at critical sections (typically diaphragm locations) along the girders are determined, as if the bridge were a normal, straight span. Then the V-Load is determined as the sum of the moments in all of the girders divided by two constants, C and K. The constant C is a function of the number of girders used on the bridge and can be looked up in the Highway Structures Design Handbook. The constant K is determined as the outside radius of the bridge times the distance between the girders divided by the distance between the diaphragms. Once the V-Load has been calculated the extra loads are applied to each of the girders. The value of the loads applied depends on the position of the girder. The loads placed on the outside girder are equal to the V-Load and are acting down. The loads applied to the inside girder are also equal to the V-Load, but are acting up. The loads added to the middle girders are calculated by assuming a straight-line variation from one side of the bridge to the other. For example, if a girder is located at the center of the bridge no V-Load will be added to it. With the V-Load method boundary conditions must be assumed which will allow evaluation by hand. According to the Highway Structures Design Handbook, in the V-Load method it is not practical to consider more than one span at a time.

For the bridge analyzed in this report there were 231 different load cases that had to be evaluated. This required repeating the V-Load process 231 times. This was not practical by hand, so a computer program was developed, using Microsoft Excel and Visual Basic, that uses the V-Load method to calculate the strains and displacements at the desired points along the span.

With the V-Load method three key assumptions had to be made to make it possible to apply the method to the tested bridge.

36 States Surveyed						
DOT	**V-Load**	**Descus**	**FE**	**Don't Do it**	**Other**	**Comment**
Alabama	1	1	0	0	0	
Arkansas	1	0	0	0	0	
California	0	0	0	1	0	
Colorado	1	1	0	0	1	Line Girder Program
Connecticut	1	0	1	0	0	
Delaware	0	0	0	1	0	
Florida	0	1	0	0	1	BSDI
Illinois	1	0	0	0	1	MDX Software
Kansas	1	0	0	0	0	
Kentucky	1	0	1	0	0	
Louisiana	0	1	0	0	0	
Maine	0	0	0	1	0	
Maryland	0	1	0	0	0	
Massachusetts	0	0	0	1	0	Contract Out
Minnesota	1	0	0	0	0	
Missouri	1	0	1	0	0	
Montana	1	0	0	0	0	
Nebraska	1	0	0	0	0	
Nevada	1	0	1	0	0	
New Hampshire	1	0	0	0	0	
New Jersey	1	0	0	0	0	
New Mexico	0	0	0	1	0	
North Carolina	0	1	0	0	0	
North Dakota	1	0	0	0	0	
Ohio	1	1	0	0	0	
Oklahoma	1	1	0	0	0	
Oregon	0	0	0	0	1	GT Strudel
Pennsylvania	0	0	1	0	0	3D with Plate Elem.
South Carolina	1	0	0	0	0	
South Dakota	0	0	0	1	0	
Tennessee	0	1	0	0	0	
Texas	1	1	0	0	0	
Utah	1	0	0	0	0	
Vermont	0	1	0	0	0	
West Virginia	0	0	1	0	0	
Wisconsin	1	0	0	0	0	
Total	**21**	**11**	**6**	**6**	**4**	

Table 1. Results of Survey of DOTs

First, it was necessary to decide the amount of load that would be transferred by the deck to each of the girders for each of the three load paths. It was assumed that the loads acted only on the girders that were on each side of, and under, the path. The load positions and girders are shown in Figures 2 and 3. To calculate strains it was assumed that the loaded truck following path Y1 was supported by girders one and two and that the other girders did not support any of the weight. Girders two, three and four supported the loaded truck along path Y2. Girders four and five supported the loaded truck on path Y3. The loads were distributed to each of the girders by using principles of static equilibrium. This made it possible to determine the moments in the girders with the bridge assumed to be straight. Then the V-loads were calculated using Highway Structures Design Handbook, and added to the girders at the appropriate locations.

Second, the girders were assumed to be pinned at the abutments and fixed at the intermediate supports, with the center span fixed at both ends; and, third, it was assumed that no moment was passed from span to span.

In order to apply the V-Load method it was also necessary to take out the super- elevation and make the grade change zero.

A similar process was followed to calculate deflections. As can be seen from Figure 3, either girders two and three or three and four took the bulk of the load, depending on the position of the loaded truck. Deflections were only reported in the spans when the loads were applied in that span.

With the V-Load method it was not possible to consider the semi-composite action of the concrete deck and the girders, so the strains and deflections determined using this method should be greater than those measured in the field.

Descus

Negotiations with the company that distributes the Descus software were unfruitful and a copy of the software was not obtained for this study. Therefore, this method of analysis was not included in this study.

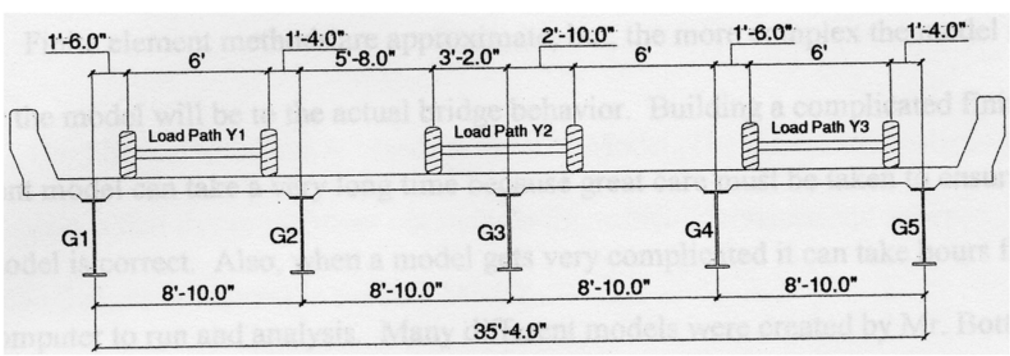

Figure 2. Load and girder positions for V-Load method to find strains.

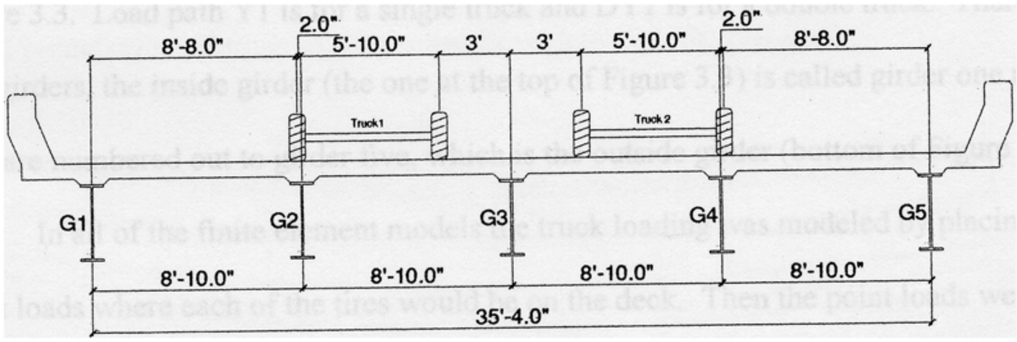

Figure 3. Load and girder positions for deflection calculations.

Finite Element Method

Finite element analyses are approximate, however, the more complex the model is the closer the model will be to the actual bridge behavior. Building a complicated finite element model can take a very long time because great care must be taken to ensure the correctness of the model. Also, when a model gets very complicated it can take hours for a computer to run an analysis.

Many different finite element models were created, based on the bridge testing, by Stephen Bott using SAP 2000 [Bott, 2002]. Each of Mr. Bott's models that were used in this study are explained in the following sections. In each of the models there are three load paths, which are shown in Figure 4. Load paths Y1, Y2 and Y3 are for a loaded single truck (233 kN), DY1 and DY2 are for a double truck load (454 kN). The trucks drove from south to north along the bridge, left to right on Figure 4. There are five girders, the inside girder (the one at the top of Figure 4) is labeled girder one and they are numbered out to girder five, which is the outside girder (bottom of Figure 4).

In all of the finite element models the truck loading was modeled by placing point loads where each of the tires would be on the deck. Then the point loads were incrementally moved along the load paths. Doing this produced 231 load cases to be evaluated for each of the models.

<u>Model jr22</u>

Model jr22 was calibrated using the field test data and served as the baseline, along with the field data, for comparing the other models against the behavior of the bridge. Model jr22 is a very complicated model with over eleven thousand nodes. It is not the type of finite element model that would typically be used to analyze a bridge on the interstate system. The girders, deck and diaphragms are constructed out of shell elements. The parapets are of solid elements. The deck is attached to the girders with beam elements, which are called link elements. The connections between the beams and the supports are quite complicated; they vary between fixed and simple by the use of springs.

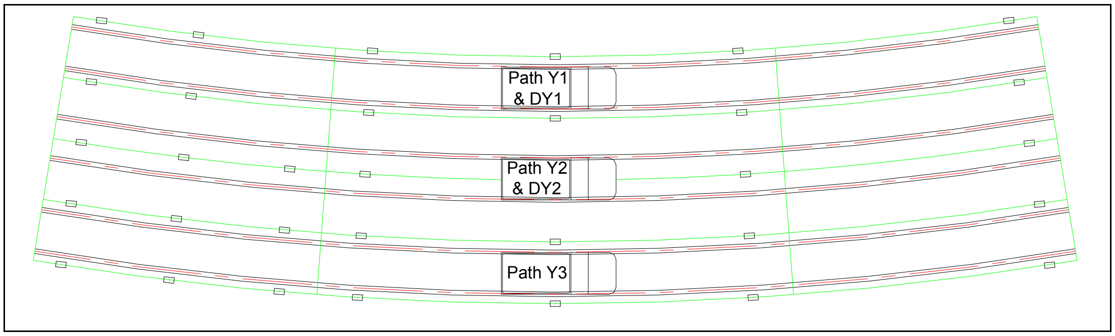

Figure 4. Load paths.

Shells Standard Boundary

This model is a variation of Model jr22 that uses standard pinned, fixed or roller boundary conditions, as opposed to Model jr22 that attempts to simulate the actual boundary conditions of the bridge through the use of springs.

Shells Flat

The Shells Flat Model is based on Model jr22. The difference being that this model does not include the vertical curvature and super-elevation that are contained in Model jr22.

Jr22 Variable

Model jr22 was modified slightly to account for the varying composite action between the girders and the concrete deck. Due to the greater shear at the supports, and the minimal shear at the mid-spans, there was more composite action at the centers of the spans than there was near the supports. In this model the beam link elements, which connect the deck to the girders, had varying moments of inertia along the span in order to simulate the varying composite action.

Beam

The Beam model is much simpler than the models that use shell elements to construct the girders. In this model the girders were constructed of beam elements with a deck of shell elements. Using beam elements, rather than shells, for the girders reduced the complexity of the model greatly. This model has 3,330 nodes compared to Model jr22 that has over eleven thousand nodes.

The Beam model is still super elevated with the vertical curvature. The boundary conditions are standard connections, either pinned, roller or fixed. The concrete deck is fixed in all directions from movement and rotation at the abutments. The girders are fixed against translation in all directions and rotation about the vertical and transverse axes at the abutments. This model is designed to be completely non-composite.

Beam Flat

The Beam Flat model is similar to the Beam model, except the super elevation and vertical curve are removed. With the super elevation taken out this model was very simple to construct.

Field Data

Field data was obtained from test data files that were provided by Bridge Diagnostics, Inc. [BDI, 1999]. As trucks were driven across the bridge strains were measured and recorded with the position of the truck. These strains were measured at much smaller increments than were used in the finite element models. Field data measurements were not necessarily taken at the same points as were produced by the models. Because of this, field data from BDI were interpolated to provide strains at the same points as were calculated by the models. Using this interpolated field data gives a more accurate picture of how well the models predict the bridge behavior. Removing field data points that were not considered within the models made the plots of the strains from the field data much smoother and easier to compare to outputs from the models.

Methods of Comparison

Four methods were used to compare the results from the different models and the field data. The first method used the maximum average percent deviation from the maximum actual strain. With this method the maximum singular value of strain was found for each span on each girder, the percent that this maximum strain for each of the models deviated from the maximum field data strain was determined, then the percent error was calculated for each model.

The second comparison method utilized percent error diagrams, which show a maximum strain at each gage location, rather than a maximum strain for an entire span. On the percent error diagrams the percent error between the maximum strains for two different data sets (models or field data) is placed over each gage location.

Influence diagrams were the third method of comparison. These are plots of the strain at a gage versus the position of the truck. All of the different analytical methods plus the field data can be plotted on the same plot, but this would be very confusing. Plotting the output of a model that gives very bad results with output from other models can hide the actual results of the better models, so caution must be taken when developing these diagrams. It is best to compare just one or two models to the field data.

The fourth method used compared the deflections at the centers of the spans. To do this charts were produced with the percent error in the deflection of each of the models compared to the field data. The deflections were only checked for the three load cases where two fully loaded trucks were parked at the center of each of the three spans.

General Observations

The first three methods of comparison compare the accuracies of the strain data. The semi-composite action of the girders and the concrete deck had a greater effect on the strain results at the top of girders, especially in regions of high positive bending moments, than it did on the bottom of the girders. In almost every case the strains obtained from the field data for the bottom of the girder are much larger, and should be considered more critical for comparison, than those from the top of the girder.

For comparison purposes if a gage was not placed at the center of a girder flange, directly in line with the web, the strain at this point was determined through interpolation of the field data strains across the flange.

There was a very large amount of data to compare, so as part of this study a program was developed that generates any percent error graph or influence diagram that is desired, for this study bridge. This program is explained in more detail in Appendix A and is contained on the CD that accompanies this report. A graph can be produced for any of the different gage locations for whichever methods one would like to compare. The program also allows the generation of any percent error diagram that one would like. There are thousands of different combinations of graphs and charts that could be produced, but only a small number of typical graphs and charts that support the conclusions of this report are shown.

The results for span three, though contained in portions of this report, are not discussed nor used for comparison due to the fact that the span had only one gage per girder at a distance of only four feet from the end abutment (due to time constraints of the freeway closure). With such few strain gages reasonable comparisons are difficult to make.

Maximum Strain in Span Comparison

Table 2 shows the largest micro-strain for each of the models on each of the spans at the bottom of each girder. Table 3 shows the percent error for each method compared to the field data for each of the girders in each of the spans. A negative percent indicates that the model under predicts the strain.

Based on a review of Tables 2 and 3, models jr22 Variable (shown as jr22V in the tables) and Shells Flat are the most accurate models compared to the field data. This does not include Model jr22 which was calibrated to the field data. However, in the process of analyzing these methods of analysis a consideration of how complicated the model is, which relates to the difficulty in creating the model, must be considered in addition to the accuracy of the model; models as complicated as jr22, jr22 Variable, and other shell models would rarely, if ever, be used for a typical interstate bridge.

		Maximum micro-Strains							
		Models							
		Field	jr22	jr22 V	Shell Flat	Shells SB	Beam	Beam Flat	V-Load
Girder 1	Span1	59	63	66.2	65.8	42.1	98	98.1	106
	Span 2	86.3	78.7	80.7	79.7	-104	233	135	-138
	Span 3	17.8	13.8	18.8	14.3	-25.9	26.9	26	61.7
Girder 2	Span1	65.1	68.4	67.8	71.6	49.7	75.6	75.6	123
	Span 2	81.9	78.3	73.7	79	-93.5	174	101	-168
	Span 3	22.5	21.7	24.9	22.2	-30.2	21.3	20.6	72.1
Girder 3	Span1	90.3	93.6	87.5	95.8	62.7	-75.2	75	152
	Span 2	103	91.3	84.1	92.9	-115	155	89.4	-208
	Span 3	39.7	24.5	34.5	30.5	-45.2	22.4	21.7	89.6
Girder 4	Span1	65	66.3	63.8	69	-51.4	69.6	69.4	92.4
	Span 2	73.7	62.4	60.5	64.1	-63.1	153	76.1	-104
	Span 3	25.9	20.4	22.6	21.8	-30.3	18	17.4	38.6
Girder 5	Span1	-36.1	54.6	56.7	56.7	-44.5	89.1	88.7	107
	Span 2	64	66.8	66.9	67.7	-71.8	208	103	-119
	Span 3	17.1	14.5	15.7	15.1	-19.4	23	22	44.9

Table 2. Maximum micro-strains, bottom of girders

		Models						
		jr22	jr22 V	Shell Flat	Shells SB	Beam	Beam Flat	V-Load
Girder 1	Span1	6.78%	12.20%	11.53%	-28.64%	66.10%	66.27%	79.66%
	Span 2	-8.81%	-6.49%	-7.65%	20.51%	169.99%	56.43%	59.91%
	Span 3	-22.47%	5.62%	-19.66%	45.51%	51.12%	46.07%	246.63%
Girder 2	Span1	5.07%	4.15%	9.98%	-23.66%	16.13%	16.13%	88.94%
	Span 2	-4.40%	-10.01%	-3.54%	14.16%	112.45%	23.32%	105.13%
	Span 3	-3.56%	10.67%	-1.33%	34.22%	-5.33%	-8.44%	220.44%
Girder 3	Span1	3.65%	-3.10%	6.09%	-30.56%	-16.72%	-16.94%	68.33%
	Span 2	-11.36%	-18.35%	-9.81%	11.65%	50.49%	-13.20%	101.94%
	Span 3	-38.29%	-13.10%	-23.17%	13.85%	-43.58%	-45.34%	125.69%
Girder 4	Span1	2.00%	-1.85%	6.15%	-20.92%	7.08%	6.77%	42.15%
	Span 2	-15.33%	-17.91%	-13.03%	-14.38%	107.60%	3.26%	41.11%
	Span 3	-21.24%	-12.74%	-15.83%	16.99%	-30.50%	-32.82%	49.03%
Girder 5	Span1	51.25%	57.06%	57.06%	23.27%	146.81%	145.71%	196.40%
	Span 2	4.38%	4.53%	5.78%	12.19%	225.00%	60.94%	85.94%
	Span 3	-15.20%	-8.19%	-11.70%	13.45%	34.50%	28.65%	162.57%

Table 3. Percent error for micro-strains, bottom of girders

Examining these tables for a combination of model simplicity and accuracy would show the Beam Flat model to be the best combination of simplicity and accuracy. Though certainly not as accurate as the shell element based models, it provides a suitable level of performance when simplicity of the model is combined with accuracy.

Percent Error Diagrams Comparison

The maximum strains examined in the previous section were created by the double truck loading. For consistency, this section will examine only double truck loads. The single truck loading tended to result in small strains, which make percentage comparisons difficult because a small difference in strain causes a large percentage difference. However, by utilizing the comparison program on the CD contained in the Appendix, percent error diagrams may be created for the single truck loading.

Load Path DY1

The percent error diagrams show the maximum strain for the bottom of the girders at a specific gage location compared to the maximum strain predicted from a model, and the percent difference of the two strains. The top number of a cluster of three numbers is the percent error of the model, the other numbers are the strain from the field data over the model predicted strain.

Figures 5 through 10 show these error diagrams for each of the five finite element models that were not calibrated to the field data, and the V-Load method.

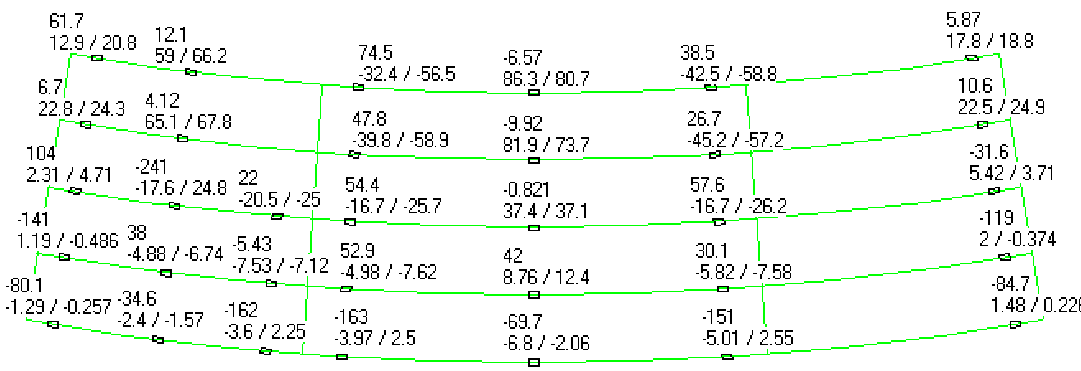

Figure 5. Percent error in maximum strain at the bottom of the girders for load case DY1, jr22 Variable and field data.

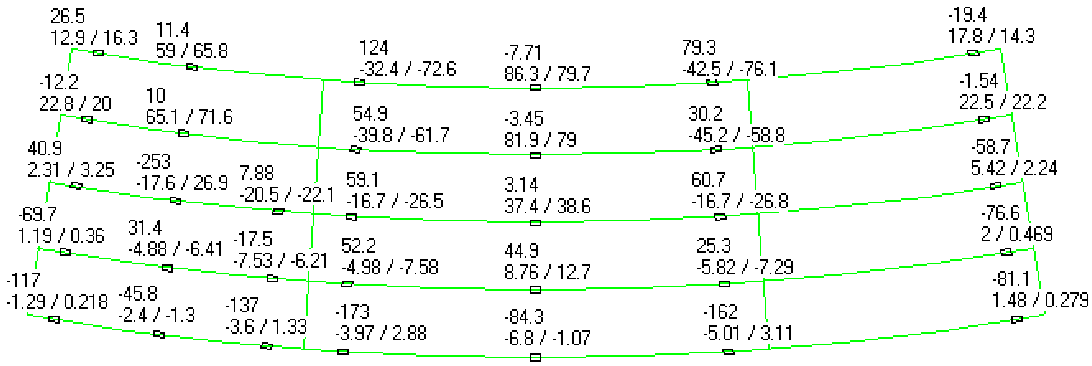

Figure 6. Percent error in maximum strain at the bottom of the girders for load case DY1, Shells Flat and field data.

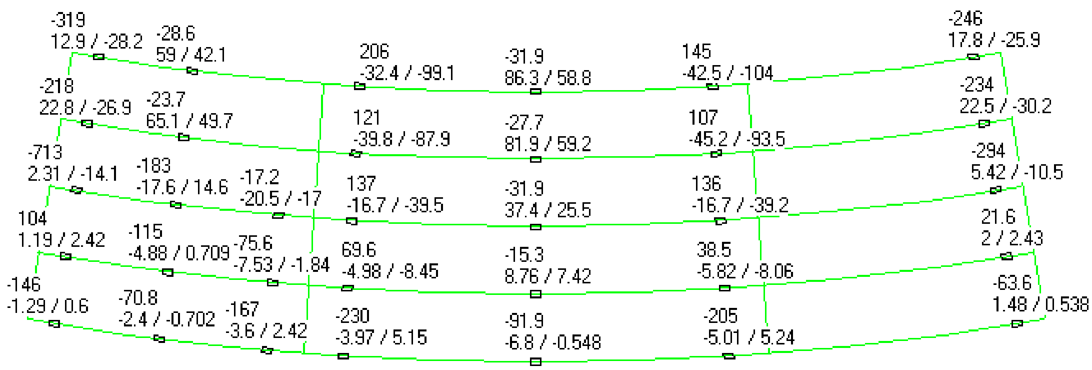

Figure 7. Percent error in maximum strain at the bottom of the girders for load case DY1, Shells Standard and field data.

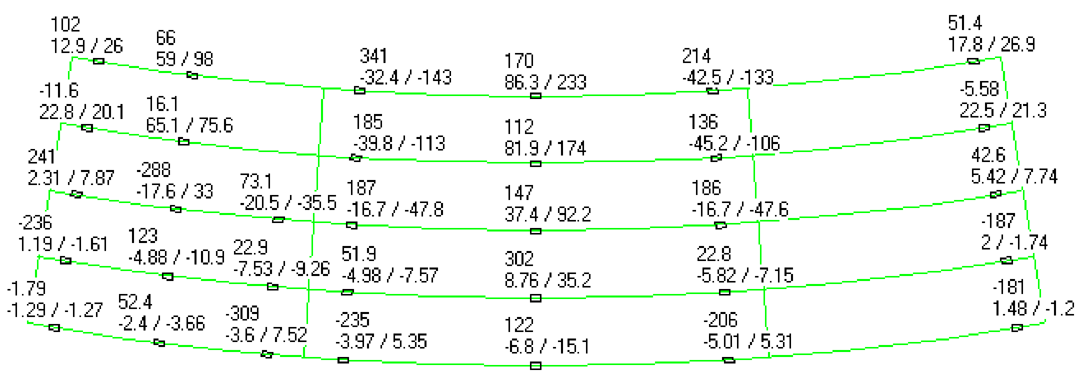

Figure 8. Percent error in maximum strain at the bottom of the girders for load case DY1, Beam and field data.

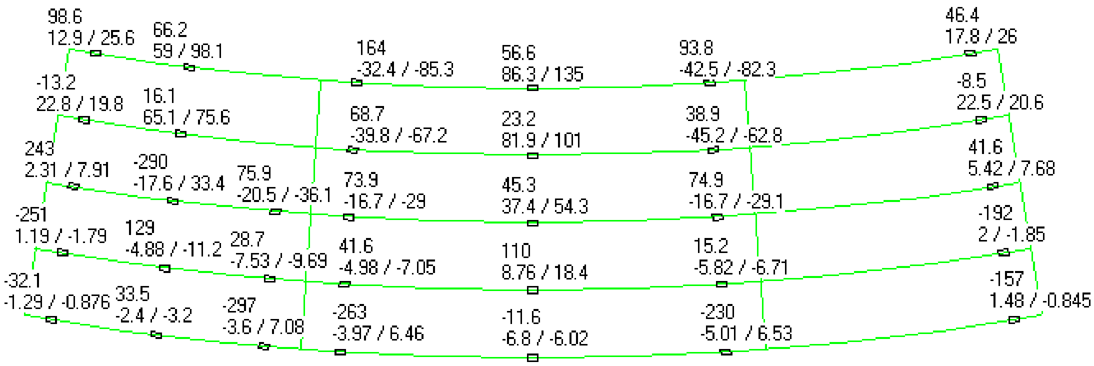

Figure 9. Percent error in maximum strain at the bottom of the girder for load case DY1 for Beam Flat and field data.

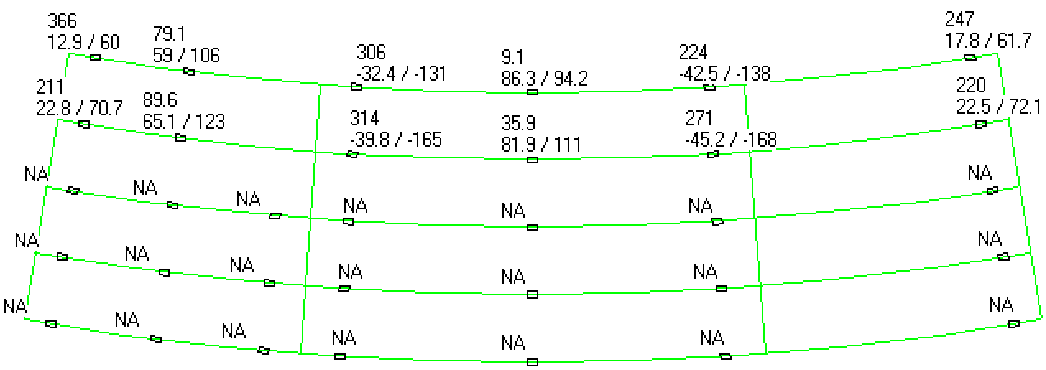

Figure 10. Percent error in maximum strain at the bottom of the girders for load case DY1, V-Load and field data.

The term "NA" as shown in Figure 10 indicates that due to the distribution of load utilized in the V-Load method, those girders did not support enough of the truck load to make a valid comparison.

<u>Load Path DY2</u>

Figures 11 through 16 show these error diagrams, for loads traveling along path DY2, for each of the five finite element models that were not calibrated to the field data, and the V-Load method.

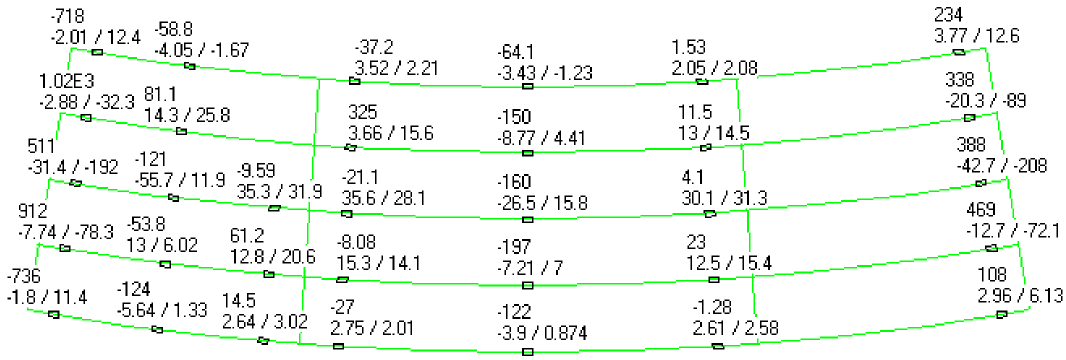

Figure 11. Percent error in maximum strain at the top of the girders for load case DY2, jr22 Variable and field data.

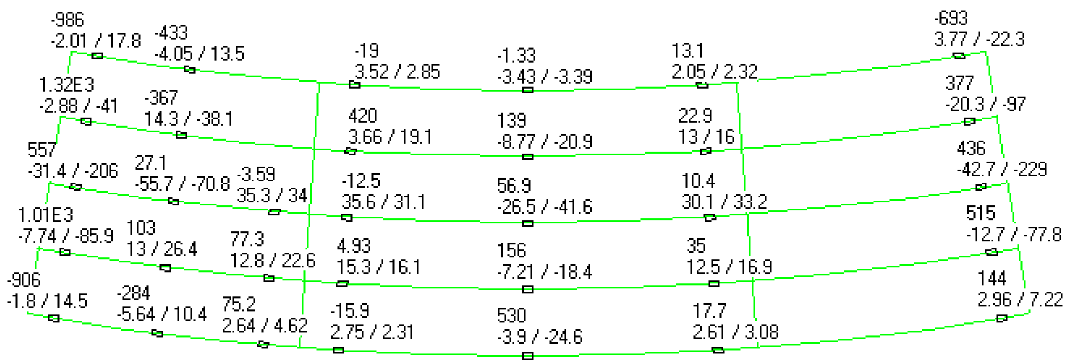

Figure 12. Percent error in maximum strain at the top of the girders for load case DY2, Shells Flat and field data.

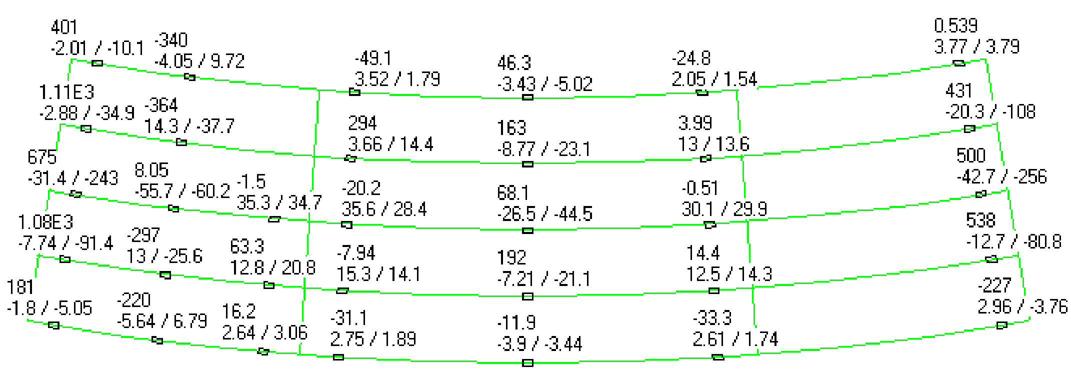

Figure 13. Percent error in maximum strain at the top of the girders for load case DY2, Shells Standard Boundary and field data.

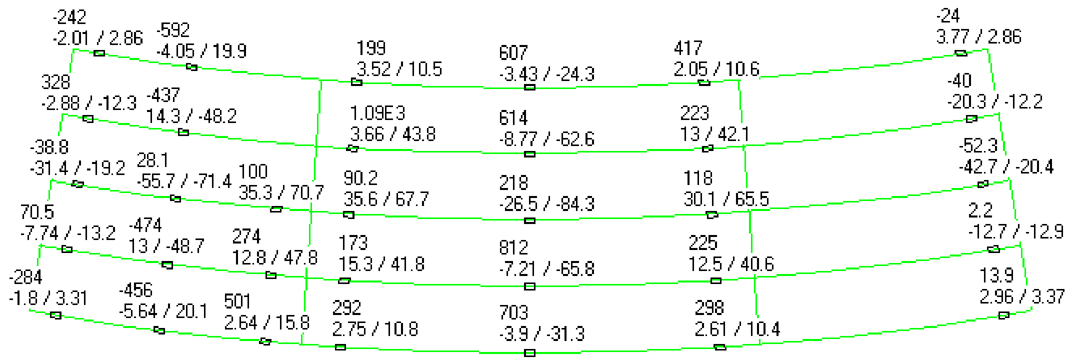

Figure 14. Percent error in maximum strain at the top of the girders for load case DY2, Beam and field data.

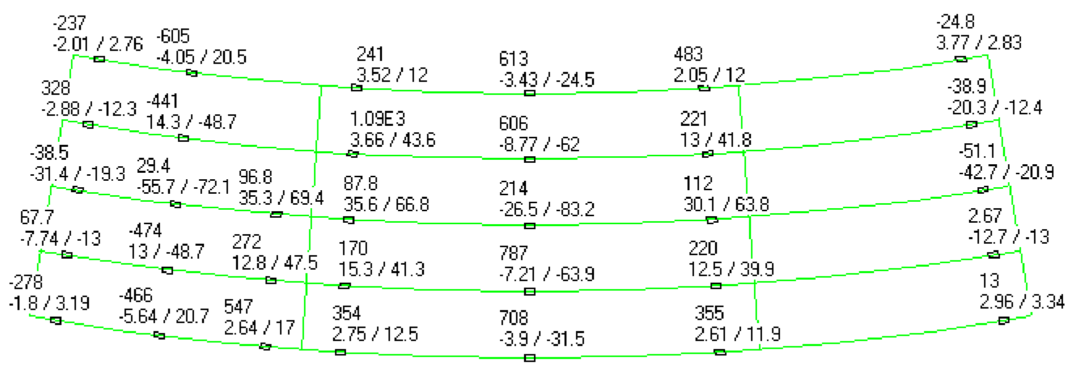

Figure 15. Percent error in maximum strain at the top of the girders for load case DY2, Beam Flat and field data.

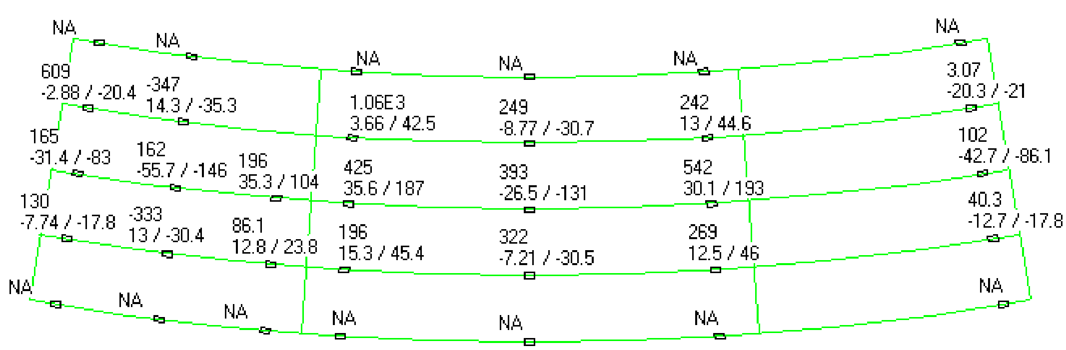

Figure 16. Percent error in maximum strain at the top of the girders for load case DY2, V-Load method and field data.

Load Path DY3

The running of two dump trucks in series across the bridge on load path DY3 was not possible because of a pier supporting a new bridge, therefore, comparisons for this load path are not shown in the body of this report. However, utilizing the CD contained with this report, any type of analysis diagram seen in this report may be produced for load path Y3, the single truck load.

Percent Error Diagrams, Conclusions

A review of the Percent Error Diagrams reveals the following:

- The modeling of boundary conditions is critical for models that utilize shell elements to construct the girders. The two models (jr22 Variable, Shells Flat) that use springs to simulate the actual boundary conditions provide much better results than the model that uses standard pinned, fixed or roller boundary conditions (Shells Standard Boundary).
- The models utilizing shell elements to construct the girders and springs for the boundary conditions perform better than the models that utilize beam elements for the girders.
- The models without the super-elevation and vertical curve of the bridge performed better than the models that included the super-elevation and vertical curve.
- Though not the equal of the shell element models, the Beam Flat model does compare favorably with the more complicated models.
- The Beam model and V-Load analysis tend to have the largest errors. The Beam model tends to be more conservative, overestimating the strains. The V-Load method, however, contains some large errors in underestimating strains.

Utilizing the Percent Error Diagrams to indicate what types of analyses would be appropriate to use for predicting the behavior of a curved, steel girder bridge (based on the analysis of this single bridge), it would appear that a finite element model using shell elements throughout the model and springs to approximate the actual boundary conditions provides the best prediction of bridge behavior. However, given the very complicated nature of such a shell model, it should be noted that the model utilizing beam elements for the girders, with standard pinned, fixed or roller boundary conditions, and no super-elevation or vertical curvature predicts the behavior of the bridge quite well. In terms of efficiency, the beam element model would have to be considered more efficient, given its simpler nature and results.

Influence Diagrams Comparison

An influence diagram is generated from the recorded strain at one particular point on a bridge as a load moves across the bridge. In the case of this study the strains at various locations on the bridge are recorded using strain gages and the moving load is induced by the loaded dump trucks crawling slowing across the bridge. Therefore, an influence diagram is a plot of strain at a specific location on the bridge verses the position of the moving trucks.

The following influence diagrams show graphically, and in a much better way than the Percent Error Diagrams, the performance of the various analysis methods as compared to the field data, and each other. Influence diagrams from each span will be shown and discussed.

Span 1 (South Span)

Mid-span Gage Positions

The following eight influence diagrams show the strains at the bottom of girders resulting from the truck movements along the three distinct load paths, considering the girders most influenced by each path.

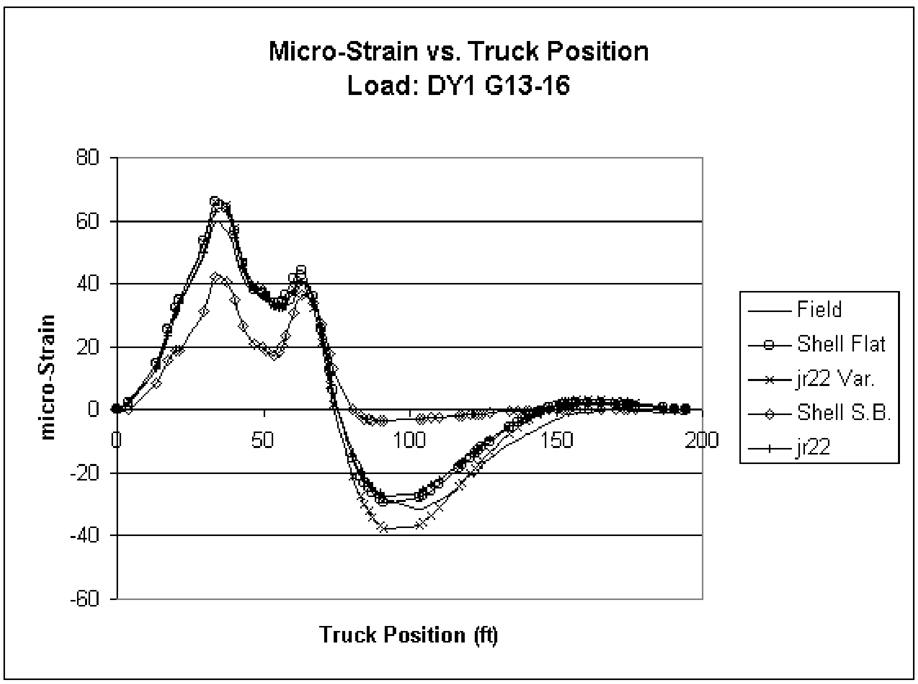

Figure 17. Micro-strain vs. truck position, shell models on bottom of girder at position of gages 13-16.

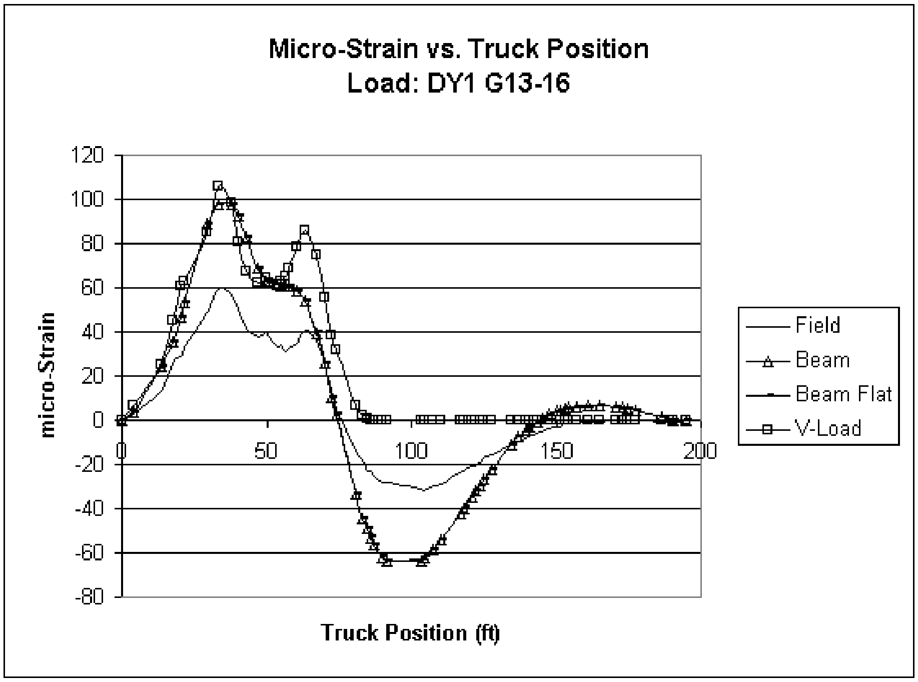

Figure 18. Micro-strain vs. truck position, beam models and V-Load method on bottom of girder at position of gages 13-16.

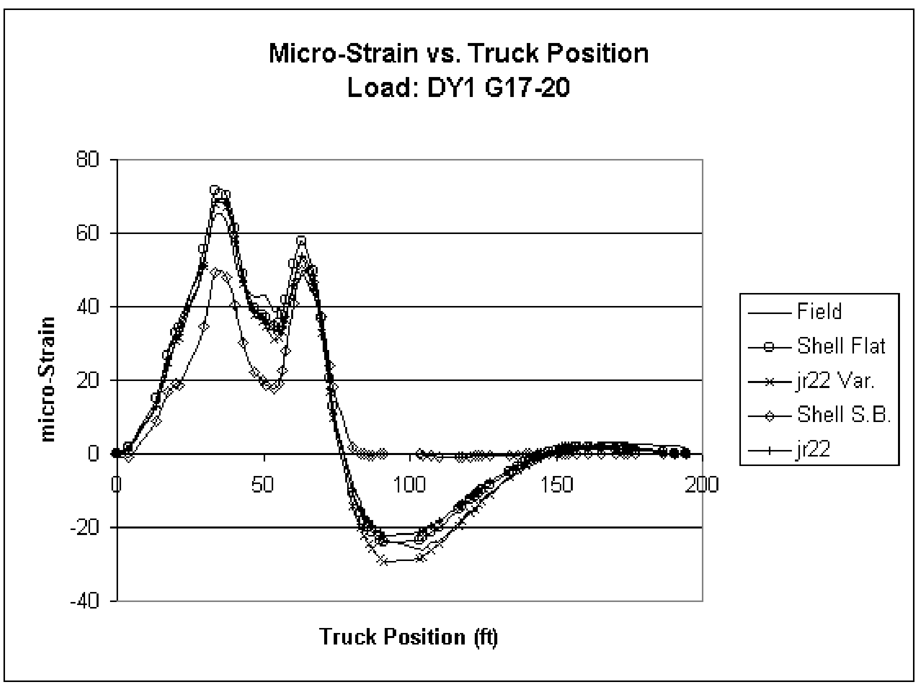

Figure 19. Micro-strain vs. truck position, shell models on bottom of girder at position of gages 17-20.

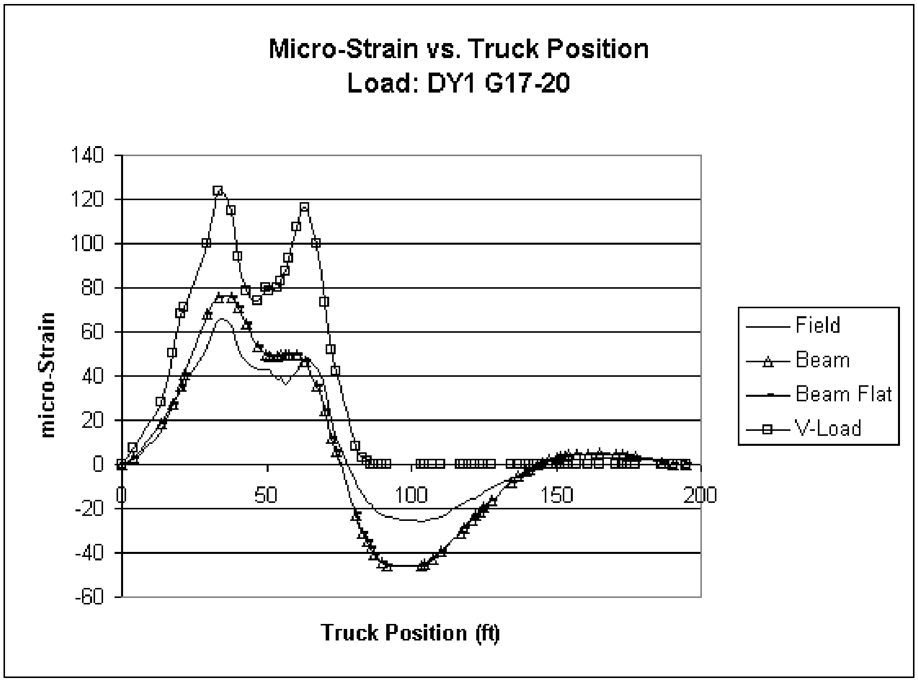

Figure 20. Micro-strain vs. truck position, beam models and V-Load method on bottom of girder at position of gages 17-20.

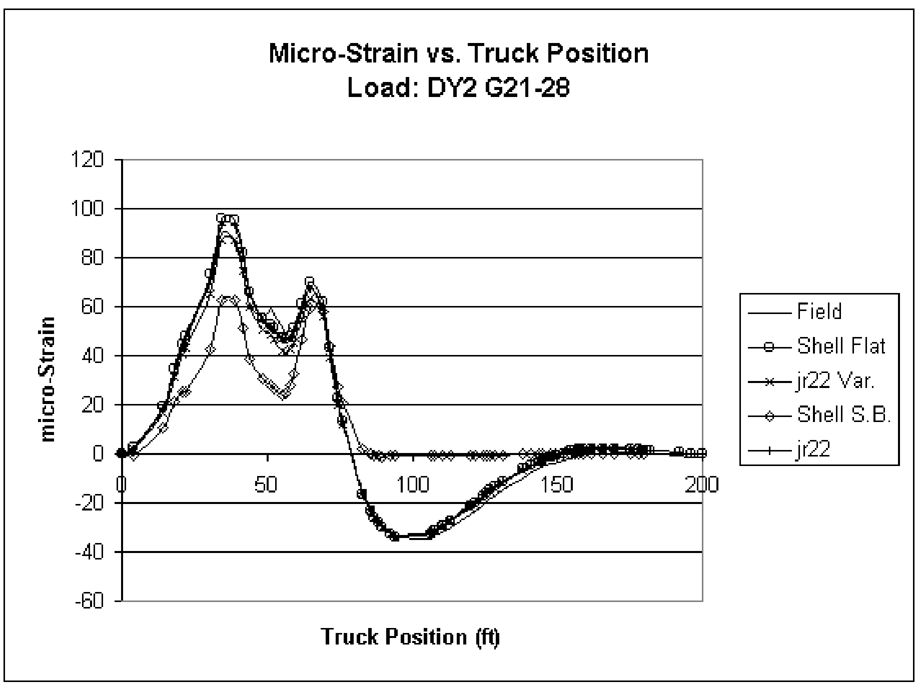

Figure 21. Micro-strain vs. truck position, shell models on bottom of girder at position of gages 21-28.

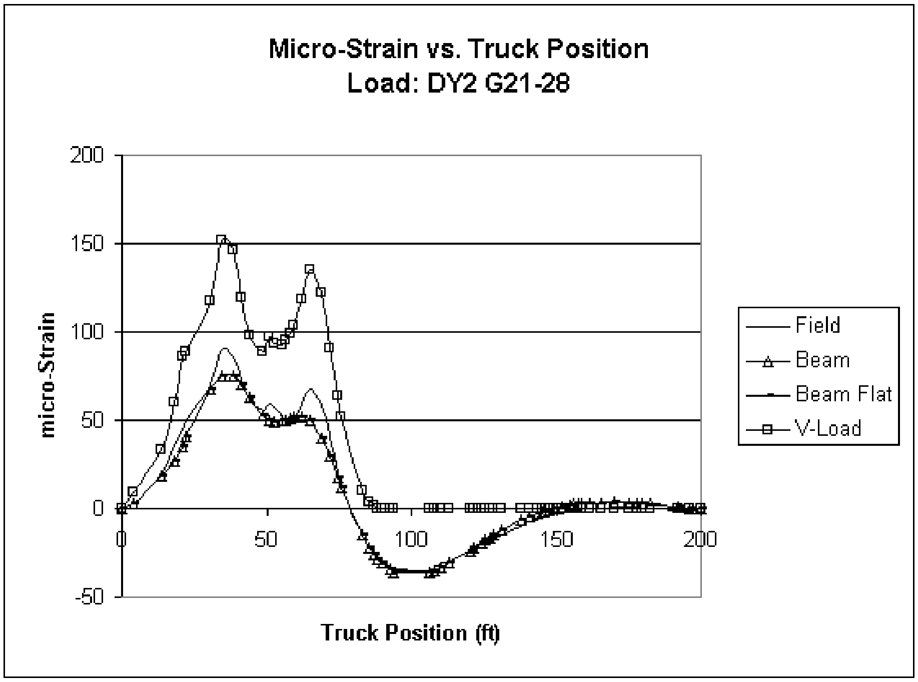

Figure 22. Micro-strain vs. truck position, beam models and V-Load method on bottom of girder at position of gages 21-28.

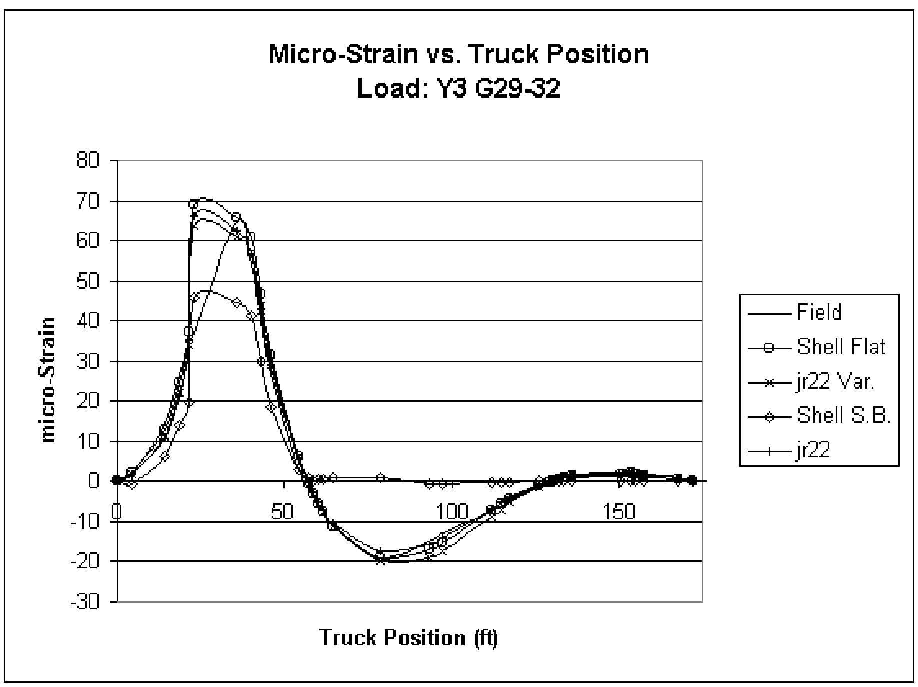

Figure 23. Micro-strain vs. truck position, shell models on bottom of girder at position of gages 29-32.

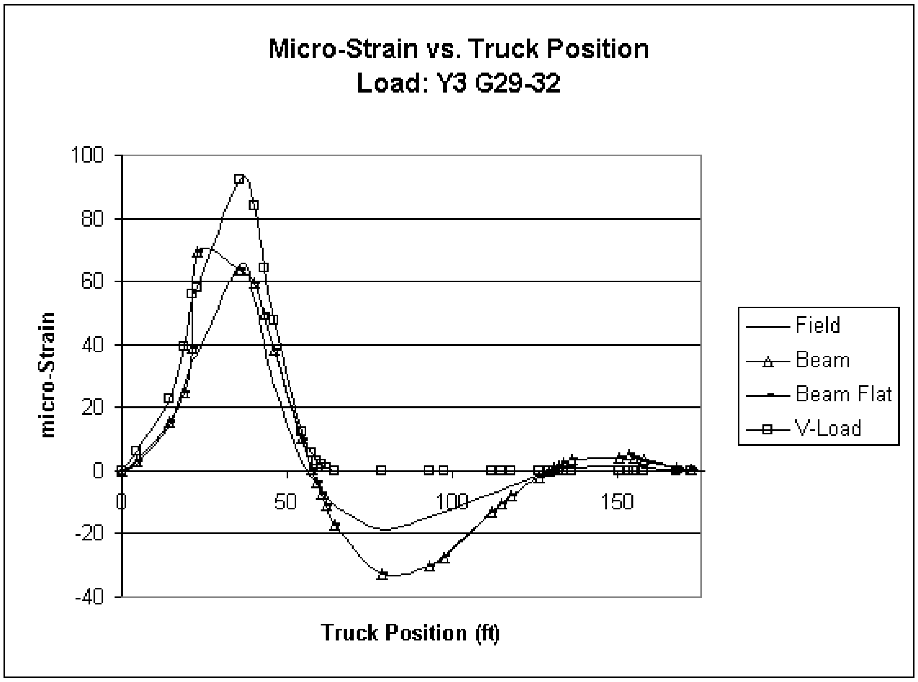

Figure 24. Micro-strain vs. truck position, beam models and V-Load method on bottom of girder at position of gages 29-32.

Figures 17 through 24 show the results of the jr22 Variable and Shells Flat models to be extremely accurate compared to the field data. In most cases the influence lines from these two models lay right on top of the field data. (Recall that the jr22 model was calibrated using the field data, so it is not reasonable to use this model within the comparison.) The Beam and Beam Flat also do well in predicting the behavior of the bridge, though they both tend to be somewhat conservative their qualitative predictions are excellent.

As for which models are most efficient in terms of effort to create and accuracy of results the Beam Flat and Beam models are not so conservative, particularly in the regions of highest positive moment, as to negate their efficiency given their ease to construct. However, if extreme accuracy is of the utmost importance without concern for time spent in creating a model, this situation not being the usual case, then the Shells Flat model would be the best to use, based on this comparison.

Abutment Gage Positions

Figures 25 through 30 show the influence diagrams for strains near the southern abutment of Span 1, on both the top and bottom of girders, as predicted by the finite element models and V-Load method, and as compared to the field data. These diagrams are very typical, both quantitatively in terms of the magnitudes of the strains and qualitatively with respect to the signs of the strains, for the strains recorded near the abutments and supports. These figures do a very good job of showing how difficult it is to model the small strains near supports, especially the strains on the top of the girders. Only the most sophisticated (and complicated) of the finite element models, Shells Flat and jr22 Variable, did a good job of predicting strains and even those models were extremely conservative on the upper flange of the girders.

In this case, the need for extreme accuracy in the prediction of these small strains must be examined. Is it critical to predict accurately, both qualitatively and quantitatively, these strains? Or, is the ability to accurately predict the maximum strains in the girders sufficient? If the answer to the first question is yes, then only the accuracy of models like Shells Flat or jr22 Variable will do, along with the effort required to produce such models. However, if the second question can be answered yes, then the beam models, Beam and Beam Flat, are sufficient. They model the maximum values of strain well, and though they struggle a bit with the qualitative prediction of strains near supports, they still do a satisfactory job of predicting the maximum strains in areas of low strain, i.e. near abutments.

<u>Span 2 (Middle Span)</u>

Mid-span Gage Positions

Figures 31 through 36 compare the performance of the models and V-Load method to the field data for double dump truck loads along paths 1 and 2, at the bottom of the girders, center of the middle span. Both the Shells Flat and jr22 Variable models show up as excellent predictors of the bridges behavior at these points. Of the less complicated models the beam flat is shown to do the best, though at times conservative, job of predicting the strains in the bridge.

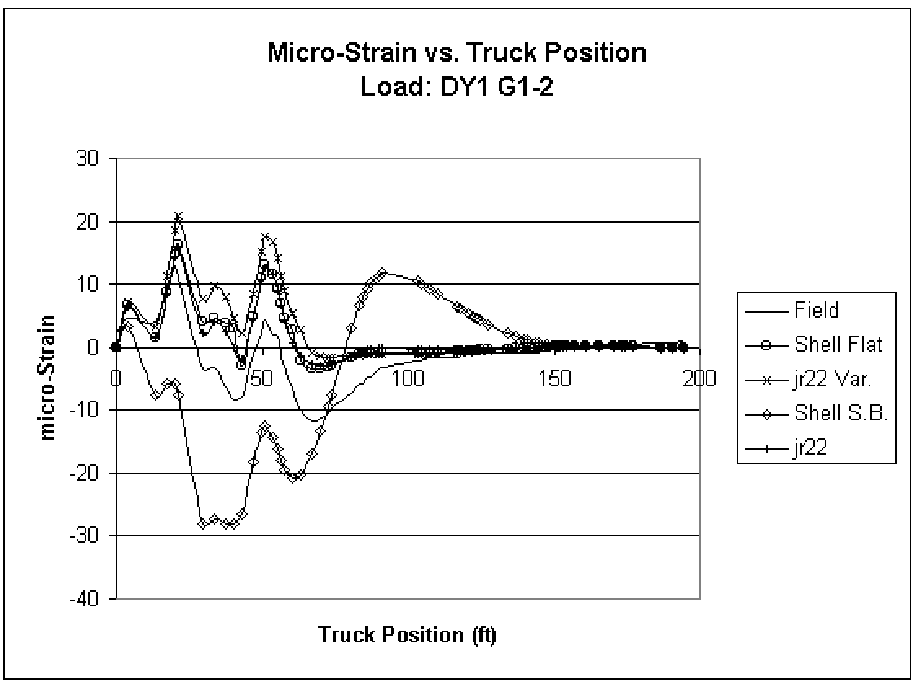

Figure 25. Micro-strain vs. truck position, shell models on bottom of girder at position of gages 1-2.

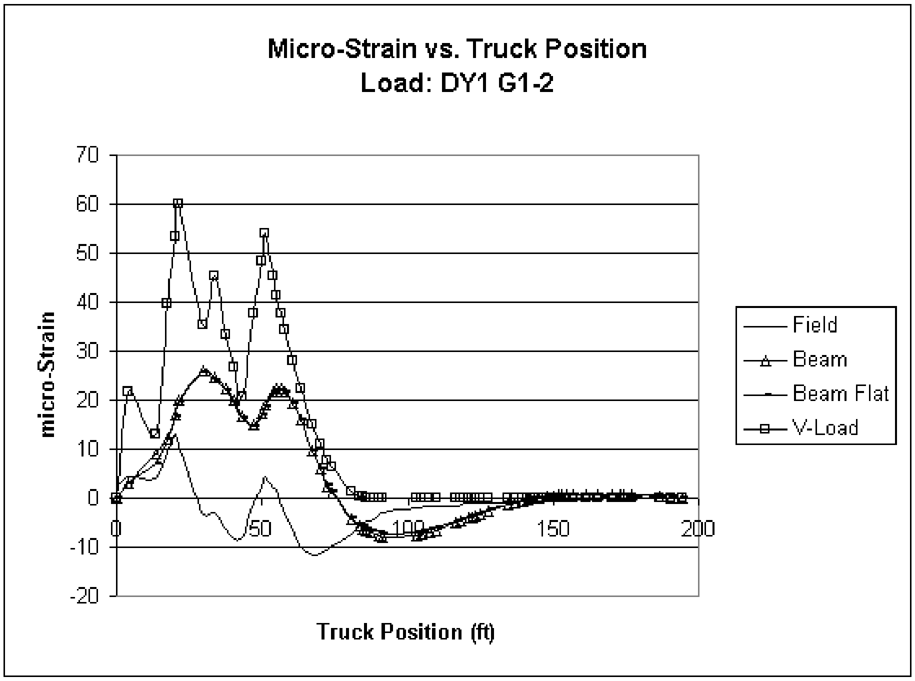

Figure 26. Micro-strain vs. truck position, beam models and V-Load method on bottom of girder at position of gages 1-2.

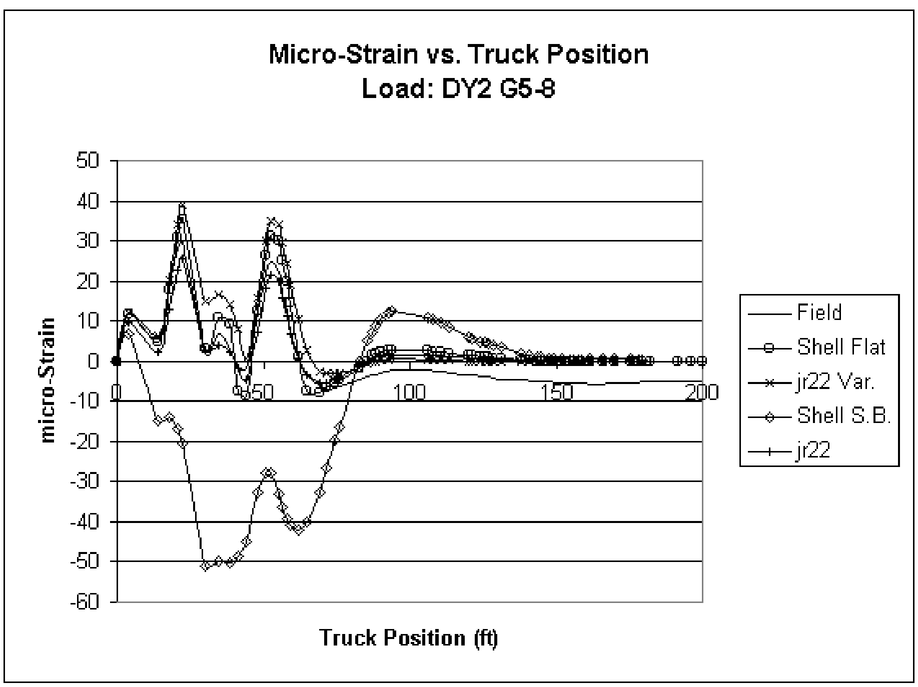

Figure 27. Micro-strain vs. truck position, shell models on bottom of girder at position of gages 5-8.

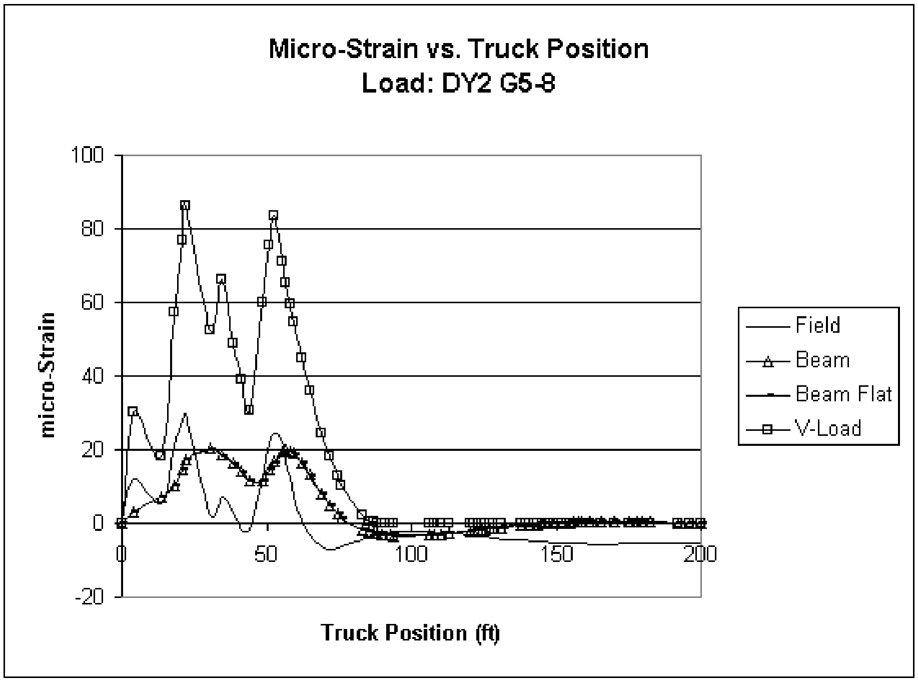

Figure 28. Micro-strain vs. truck position, beam models and V-Load method on bottom of girder at position of gages 5-8.

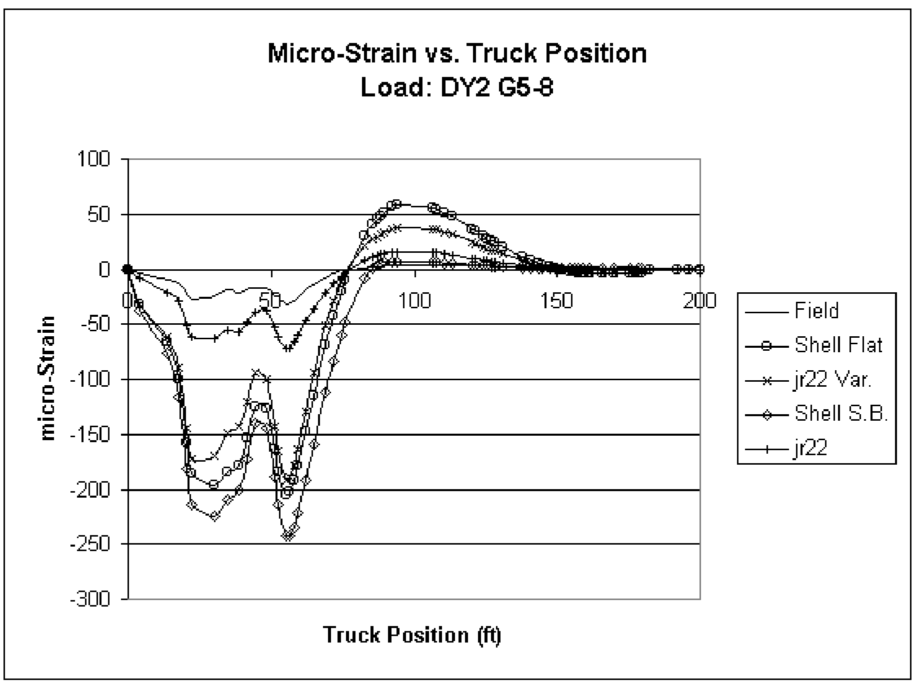

Figure 29. Micro-strain vs. truck position, shell models on top of girder at position of gages 5-8.

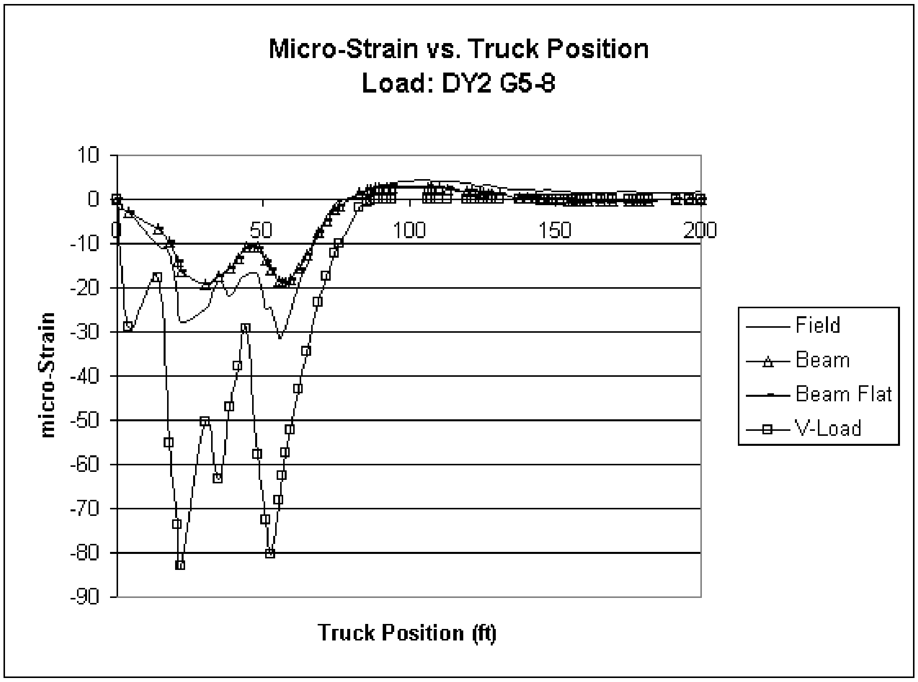

Figure 30. Micro-strain vs. truck position, beam models and V-Load method on top of girder at position of gages 5-8.

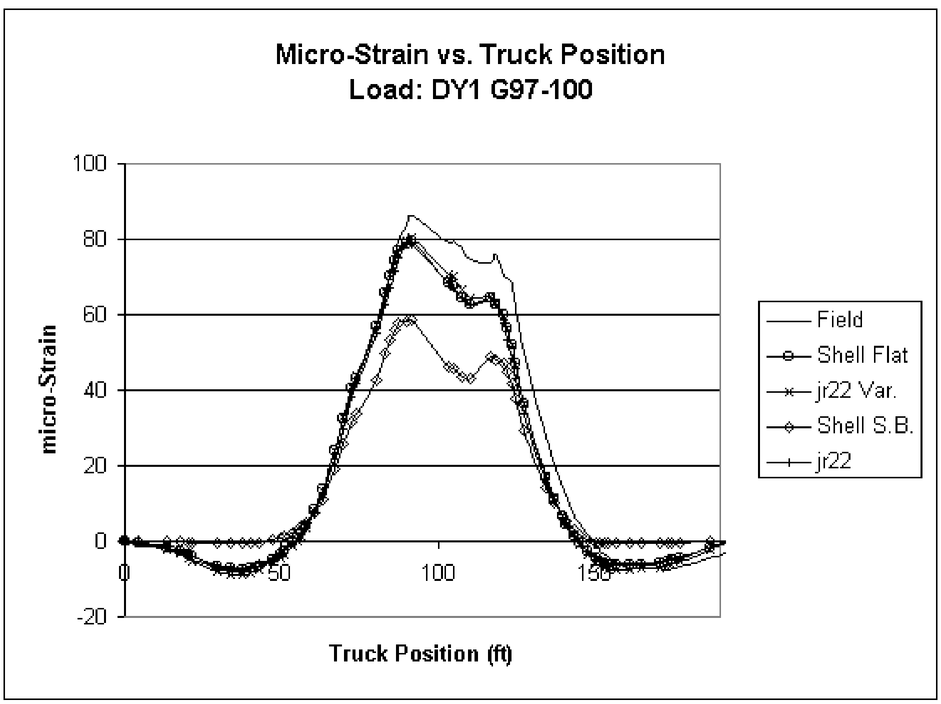

Figure 31. Micro-strain vs. truck position, shell models on bottom of girder at position of gages 97-100.

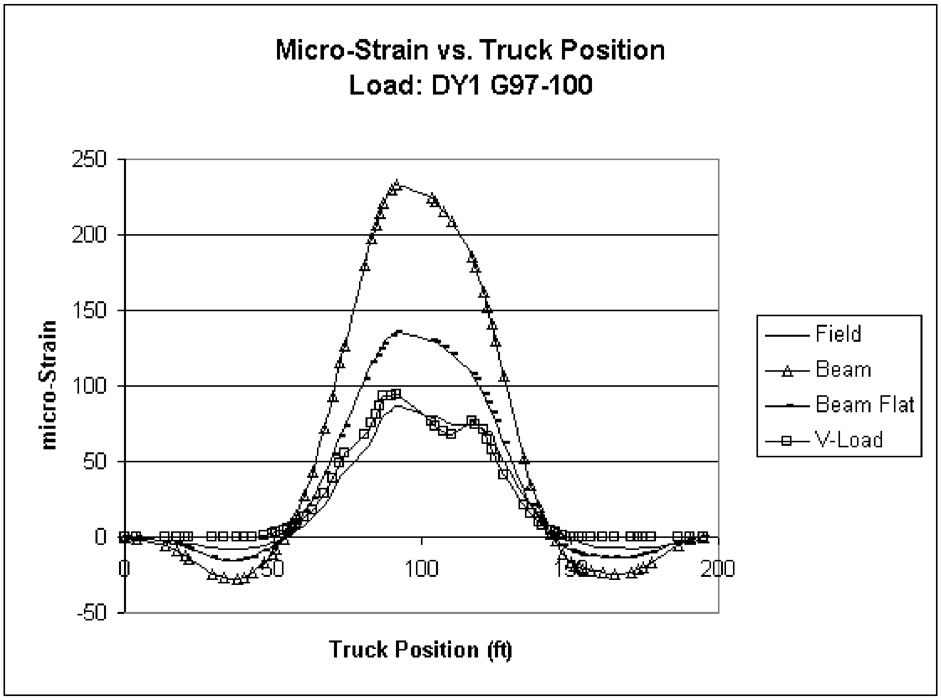

Figure 32. Micro-strain vs. truck position, beam models and V-Load method on bottom of girder at position of gages 97-100.

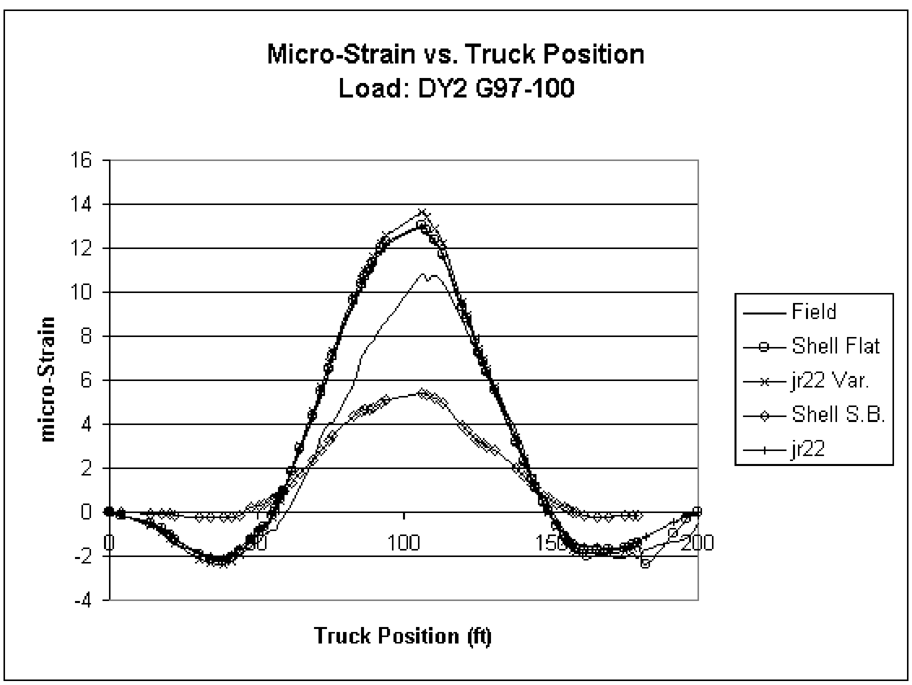

Figure 33. Micro-strain vs. truck position, shell models on bottom of girder at position of gages 97-100.

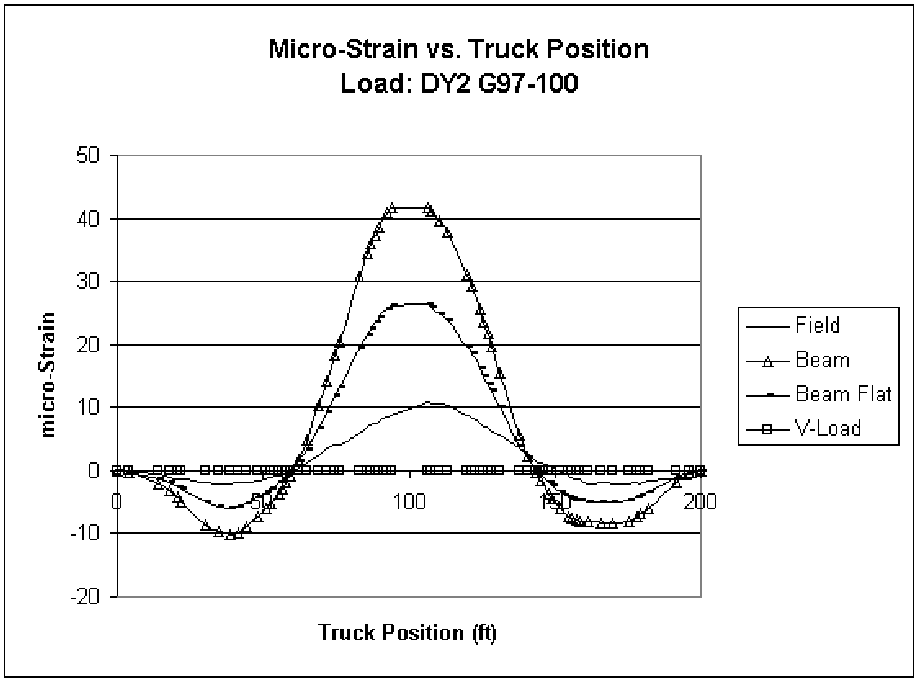

Figure 34. Micro-strain vs. truck position, beam models and V-Load method on bottom of girder at position of gages 97-100.

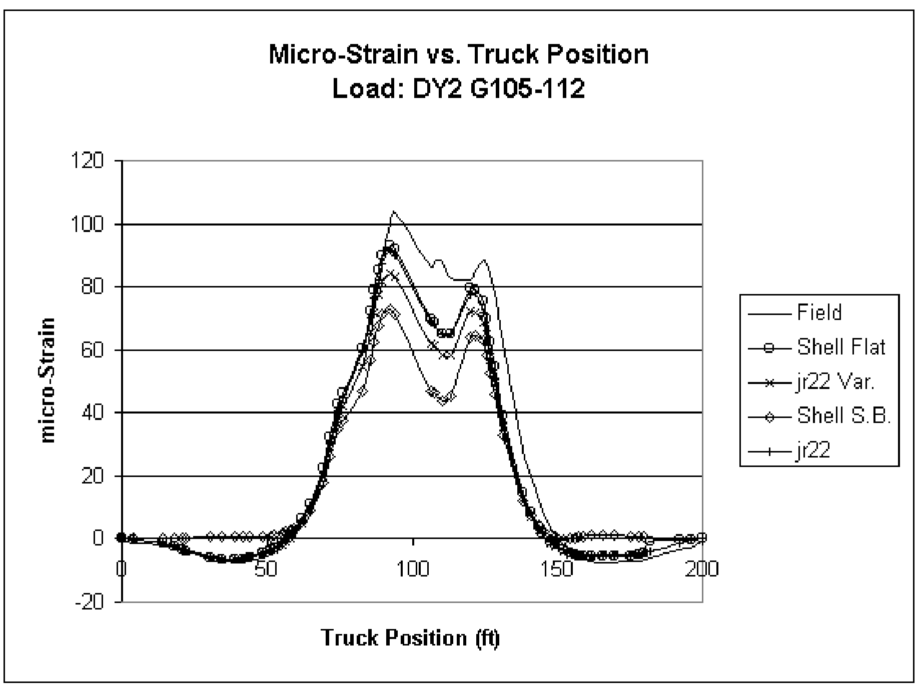

Figure 35. Micro-strain vs. truck position, shell models on bottom of girder at position of gages 105-112.

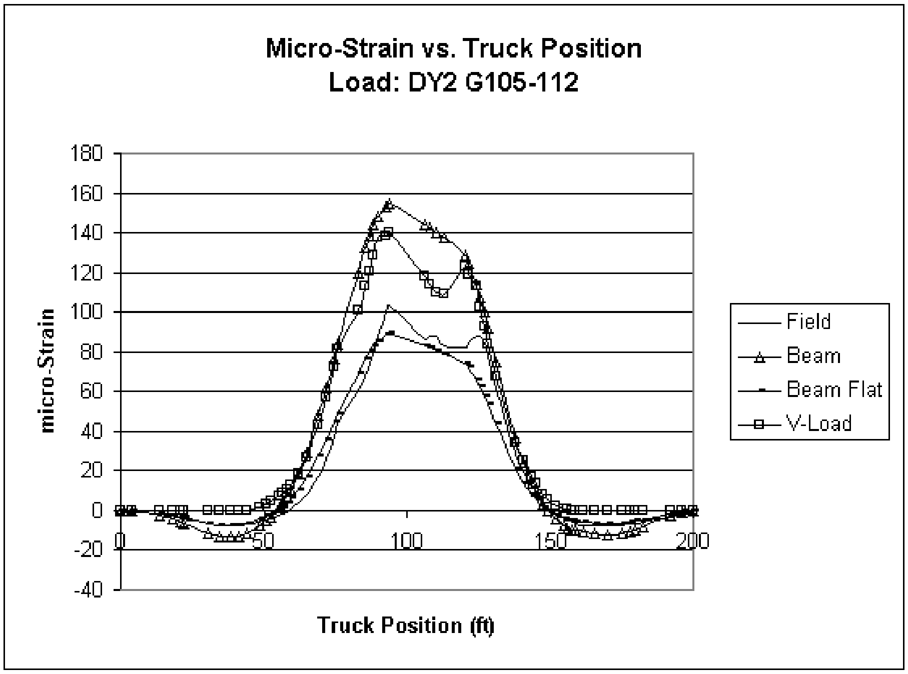

Figure 36. Micro-strain vs. truck position, beam models and V-Load method
on bottom of girder at position of gages 105-112.

Influence Diagrams, Conclusions

The information provided by the influence diagrams contained in this report leads to the following conclusions:

- The Shells Flat and jr22 Variable models are the best predictors of bridge behavior, both quantitatively and qualitatively.
- The Beam Flat model is the best predictor of the simpler models/methods. It does well from a qualitative point of view, though at times is conservative from a quantitative point of view.
- All the models/methods predicted best the large strains at the mid-span points, where there is no shear and the bridge behaved in a more composite manner.
- None of the models did a very good job of predicting strains near the supports (in areas of small strains). The shell type models did well qualitatively, but were very conservative from a quantitative point of view. Neither the beam type models nor the V-Load method did well near the supports.

Deflection Comparison

During the testing of the bridge deflections were measured on each of the girders at the centers of each of the spans due to a load in the middle of each of the spans. To create this type of loading two loaded dump trucks were used (454 kN total gross weight) with the first rear axle of each truck placed on the centerline of the span, causing the trucks to face in opposite directions. This created a maximum load at the center of the span. The two trucks were spaced approximately 1.8 meters apart, on either side of the longitudinal center line of the bridge [Womack, et al. 2001]. The results from the field tests are shown in Table 4.

After the deflections were determined by each analysis method they were compared to the field data by calculating the percent error for each predicted displacement. This percent error was calculated as the predicted deflection from a model minus the actual deflection measured from the field data, that difference divided by the field deflection and multiplied by 100. For example, if the predicted deflection were 0.05 inches and the actual deflection was 0.1 inches, the error for the prediction would be a -50%; the negative sign indicating that the model underpredicts the deflection and the magnitude of the percent showing the amount of error off of the actual displacement.

These percent errors for each of the finite element models and the V-Load method are reported in Tables 5 through 10. It must be noted that the deflections measured in the field were very small, the largest being 0.167 inches. With such small deflections it did not take much of a change in a predicted displacement to result in a large change in the percent error for that prediction, and all the models were very sensitive in predicting displacements. Very slight changes in the models resulted in significant changes to the predicted displacements, though not the predicted strains.

The results of all this is that utilizing a comparison of displacements, predicted to actual, as a method of determining the performance of an analysis approach is not very meaningful. The displacements are just too small and the models too sensitive to make this type of comparison useful.

If there is anything to be gained, at least from a qualitative point of view, from this comparison it is that the jr22 Variable, Shells Flat and Shells Standard Boundary Models all tended to under predict displacements. While the Beam Model, the Beam Flat Model, and the V-Load method all tended to over predict displacements.

Deflection due to load in span 1 (in)					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	-0.026	-0.093	-0.095	-0.078	-0.023
Span 2	0.011	0.022	0.027	0.02	0.009
Span 3	-0.001	-0.003	-0.003	-0.002	-0.004
Deflection due to load in span 2 (in)					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	0.005	0.015	0.028	0.026	0.008
Span 2	-0.064	-0.166	-0.203	-0.167	-0.067
Span 3	0.009	0.022	0.029	0.022	0.004
Deflection due to load in span 3 (in)					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	-0.004	-0.007	0	0.006	0.001
Span 2	0.012	0.023	0.027	0.02	0.011
Span 3	-0.022	-0.083	-0.099	-0.083	-0.029

Table 4. Deflections from Field Measurements.

Percent error due to load in span 1					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	-9	-114	-98	3	-194
Span 2	-127	-502	-8	-116	-840
Span 3	-2742	3	545	-740	-37
Percent error due to load in span 2					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	154	-535	-54	-8	-2022
Span 2	-136	-116	-11	-116	-134
Span 3	-1749	5	-52	-406	335
Percent error due to load in span 3					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	-56	-262	-5332	-152	1678
Span 2	-701	-114	-8	-548	-124
Span 3	-195	-13	-98	-116	-10

Table 5. Percent Error in Deflections from jr22 Variable.

Percent error due to load in span 1					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	-30	-104	-100	-9	-126
Span 2	-96	-444	-76	-98	-731
Span 3	-776	-116	370	-258	-110
Percent error due to load in span 2					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	-29	-414	-88	-75	-1787
Span 2	-109	-104	-20	-104	-109
Span 3	-1549	-69	-87	-318	31
Percent error due to load in span 3					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	-105	-145	-3859	-93	367
Span 2	-616	-98	-75	-486	-96
Span 3	-126	-24	-100	-105	-32

Table 6. Percent Error in Deflections from Shells Standard Boundary.

Percent error due to load in span 1					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	0	-113	-98	17	-197
Span 2	-125	-564	-3	-115	-949
Span 3	-2826	-4	616	-717	-44
Percent error due to load in span 2					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	146	-552	-56	-3	-2247
Span 2	-138	-117	1	-118	-135
Span 3	-1944	11	-54	-419	327
Percent error due to load in span 3					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	-62	-255	-5786	-149	1737
Span 2	-781	-113	-3	-617	-122
Span 3	-200	-0	-98	-116	-2

Table 7. Percent Error in Deflections from Shells Flat.

Percent error due to load in span 1					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	165	58	83	70	177
Span 2	381	210	168	232	467
Span 3	1348	368	322	525	216
Percent error due to load in span 2					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	998	439	207	197	632
Span 2	196	99	89	94	196
Span 3	541	263	204	232	1458
Percent error due to load in span 3					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	159	71	3478	323	1074
Span 2	310	192	168	234	356
Span 3	195	75	75	60	123

Table 8. Percent Error in Deflections from Beam.

Percent error due to load in span 1					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	177	64	89	78	197
Span 2	407	223	180	251	515
Span 3	1373	386	297	494	247
Percent error due to load in span 2					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	1059	459	219	212	695
Span 2	223	113	102	111	234
Span 3	576	311	172	168	2056
Percent error due to load in span 3					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	163	72	-3504	-329	-1108
Span 2	333	204	179	253	397
Span 3	208	116	41	-17	621

Table 9. Percent Error in Deflections from Beam Flat.

Percent error due to load in span 1					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	-116	34	33	63	-67
Span 2	N/A	N/A	N/A	N/A	N/A
Span 3	N/A	N/A	N/A	N/A	N/A
Percent error due to load in span 2					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	N/A	N/A	N/A	N/A	N/A
Span 2	-192	189	150	221	10
Span 3	N/A	N/A	N/A	N/A	N/A
Percent error due to load in span 3					
	Girder 1	Girder 2	Girder 3	Girder 4	Girder 5
Span 1	N/A	N/A	N/A	N/A	N/A
Span 2	N/A	N/A	N/A	N/A	N/A
Span 3	-114	51	27	52	-76

Table 10. Percent Error in Deflections from V-Load method.

Conclusions

The analyzed data and comparisons with field data that have come out of the testing of the curved girder bridge utilized in this project and the analysis methods examined herein have resulted in the following conclusions:

- The use of strain influence diagrams is the best way to compare the predictive abilities of various analytical methods and field data.

- Due to the semi-composite nature of the bridge it was difficult to model. The best results from the models and V-Load method occur at the centers of the spans, where shear is zero and behavior is composite-like. The worst predictions of strain by the models and V-Load method are near the abutments and supports, where shear is a maximum and behavior is non-composite.

- The conditions of the bridge supports also made modeling difficult. Some supports were welded, some rusted frozen and others had shifted off their base; they were definitely not “pins” and “rollers” which made the simulation of them difficult.

- The prediction of bridge displacements by the various analysis methods was poor. The magnitudes of predicted displacements were very sensitive to changes in the finite element models.

- The prediction of bridge strains by the various analysis methods was quite good. The strains predicted by the models were much less sensitive to changes in the models, than were the deflections.

- Taking the vertical curve and super-elevation out of the finite element models (using flat models) did not have a detrimental effect on the determination of bridge behavior by the models. Frequently the flat models better predicted the strains in the bridge than did the more complicated models with super-elevation and vertical curvature.

- The finite element models using shell elements throughout, customized boundary conditions using springs, and flexural connectors to simulate the semi-composite behavior provided the best predictions of bridge behavior (Shells Flat and jr22 Variable models).

- The beam flat model, using beam elements to model the girders rather than shells, provided the best prediction of bridge behavior among the simpler models.

- The V-Load method was by far the most conservative analysis approach, oftentimes to extremes.

- The ability of any of the finite element models to predict the behavior of a new, or soon to be built, bridge will be improved over the models' ability to predict the behavior of the bridge tested in this project. The fact that the supports on a new bridge will behave as "pins", "rollers" or fixed ends will allow the models to use standard boundary conditions to effectively predict the bridge behavior. In addition, a new bridge is most likely to be composite in nature which will also allow the models to provide more accurate predictions of bridge behavior.

Application and Recommendations

How the information provided through this report may be applied by practicing bridge engineers is simple, direct and contained in the following bullet points:

- Though the V-Load is simple and applicable by hand, resulting in an easy and inexpensive analysis process, it is extremely conservative and will lead designers to significantly over design bridges based on the strains predicted by this method. The dollars saved through this simple analysis will be spent many times over in the cost of a bridge that is built based on this analysis approach. This method could be a suitable preliminary analysis tool, but bridge designs should not be based on analyses utilizing this method.

- In general, a finite element based model, either a commercially available bridge analysis package that is based on finite elements or a general purpose finite element package, should be used to analyze curved girder bridges. The cost of suitable finite element software is less than $10,000 today, the time it takes to create a satisfactory beam and shell elements model is hours, and the time to run the analysis on a computer is minutes. The little bit of extra time it takes to perform this type of analysis, over an approximate hand method, is well worth the investment given that a bridge design based on this type of analysis will be much more efficient and, as a result, the bridge will be less costly.

- Unless there is a special instance where an analysis must be extremely accurate throughout an entire bridge, there really isn't a need to go to the lengths of modeling a bridge using shell elements to model the girders. This type of analysis is very complicated and time consuming (days to create the model and hours to run on a computer), and the return on the effort, in terms of analytical information for a designer to use, is not significant enough to justify the additional time and cost.

- In most cases, where the values of maximum strain (stress) are needed from an analysis in order to proceed with a design and where some conservativeness is desired, finite element models utilizing beam elements for the girders and shells for the deck are satisfactory. This type of model, based on the data examined in this project, appears to be the best combination of model efficiency and results.

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Appendix

Analysis Viewer Program

<u>Setting up the Program</u>

In order to use the program "Analysis Viewer", all of the files in the "Anlsviewer" folder on the enclosed CD must be copied to a folder on a hard disk drive. After the files have been transferred to the disk drive, the status of the Data files must be changed. To do this, right click on the "Anlsviewer" folder and select properties. A window will pop up which will allow a change in the status of the folder, which is originally marked as read only. Unselect the read only box, click OK, apply the change to the folder only, and click OK again. Then go into the folder and apply the same process to change the read only status of the GraphMakeInfo.bgd, LineGrp.dat, and Results.mdb files. Make sure that the above mentioned files and the BendingStrain.wmf file are all in the same folder with Anlsviewer.exe. Now the program is ready to be run.

<u>Using the Program</u>

This program is capable of generating any Percent Error Diagram or Influence Diagram based on the test data discussed in this report. The data from the models and field tests are stored in an Access data base file. The Access data file is named Results.mdb.

Start the program by double clicking on the "Anlsviewer" icon. Once the program has started the data must be accessed. On the window that popped up when the "Anlsviewer" icon was hit click on the "File" menu and then click on the "Open" button. In the window that pops up double click on the "Results" file icon. This will load the data into the window that comes up after activating "Anlsviewer". Now select the view menu, which will give you the choices of an Error Graph or a Line Graph.

The "Error Graph" corresponds to the Percent Error Diagrams, the "Line Graph" is for the Influence Diagrams. To generate a Percent Error Diagram, click on the "Error Graph" button under the "View" menu. This will bring up the Percent Error Diagram generator window. Place a name for the diagram in the appropriate window, using the "New" button for a new diagram or selecting an existing diagram from the drop down menu. Select a load case from the drop down menu in the "Load Case" box, and the location on the girders of the strain calculations from the "Strain" box. In the "Methods" box select the two methods (or field data) for comparison in the diagram. The percent error will be calculated as the results from the second method of analysis minus the results from the first analysis method, the difference divided by the results from the first method of analysis and the total multiplied by 100 to get a percent value. In the "Gauge Locations" box select the locations on the bridge for which the percent error is to be calculated. It is normally best to select all the gauge locations for this type of comparison.

There are three options for the types of results to be output: 1) the percent difference calculated as explained above, named "Diff"; 2) the maximum micro-strain determined by the first method divided by the maximum micro-strain from the second method, named "1 over 2"; and, 3) the "Both" option, which will place the results from both the first and second options on a diagram.

Finally the Percent Error Diagram may be produced by clicking on the "Generate" button. A window will pop up with the diagram, which may be saved by clicking on the "Save" button, then selecting where to save the diagram and giving it a name. These diagrams will only be saved as a bitmap image.

To generate an influence diagram select the "Line Graph" button under the "View" menu of the initial window. As discussed earlier, a name must be selected or given to a new diagram, the Load Case selected, and the location on the girders for the calculation of strain chosen. Then the methods of analysis to be compared are selected (too many make a messy diagram), and the gauge locations picked. Choosing multiple gauge locations will result in multiple diagrams, as only one gauge position can be plotted per influence diagram. Again, these diagrams may be saved by clicking on the "Save" button.