Results of Field Measurements on the Williamsburg Bridge Orthotropic Deck, Final Report on Phase III

Robert J. Connor

John W. Fisher

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on the
Williamsburg Bridge Orthotropic Deck
Final Report on Phase III

by

Robert J. Connor
and
John W. Fisher

ATLSS Report No. 01-01
PIN# 84193BRM912
FA# X751.55.122

January 2001

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on Advanced Technology for Large Structural Systems

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Results of Field Measurements on the
Williamsburg Bridge Orthotropic Deck

Final Report on Phase III

by

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January 2001
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Executive Summary

The third and final phase of a comprehensive research program which studied the behavior of a steel orthotropic deck system has been completed. The first two phases of research, Phase I and Phase IIA & IIB involved laboratory static and fatigue testing of full-scale multi-span sections of the cantilevered roadways. Through these studies, it was found that the diaphragm/bulkhead connection detail, located at floorbeams, is particularly sensitive to fatigue. As a result of the Phase I Laboratory Studies, recommendations intended to improve the fatigue resistance of this detail were made prior to construction. These changes were incorporated into the final design of the south roadway fabrication and are currently in service. In order to assess the effectiveness of these improvements, additional laboratory fatigue testing (Phase IIA & IIB) was conducted which subsequently verified the improved fatigue resistance.

Phase III, the results of which are the focus of this report, involved an in-depth field instrumentation and testing program on the Williamsburg Bridge in New York City, NY.

The field testing was conducted in order to:
1. Verify the laboratory test program as related to loading and overall behavior.
2. Determine the proportions of in-plane and out-of-plane stresses adjacent to the cutout.
3. Determine the effects of the wearing surface.
4. Develop stress-range histograms at critical details.
5. Compare the measured stress range spectrum to the stress range predicted analytically and to the design assumptions.
6. Better characterize the behavior of this complex structural system subjected to wheel loads.

The south roadway cantilever field instrumentation began during July of 1997 and was completed in January of 1999 and consisted of two phases. The first phase consisted of controlled load tests utilizing trucks of known load and dimensions. During these tests, over 80 crawl and dynamic tests were conducted with both single and tandem-axle trucks. The second phase involved long-term remote monitoring for a period of four months during the fall of 1998. Instrumentation consisted of 114 strain gages that were installed within a two span section (2 @ 20ft) at three floorbeams of the cantilevered southern roadway.

In addition to the measurements made on the cantilevered portion of the southern roadway, 20 channels were installed on the diaphragm plate on floorbeam 64E on the inner roadway as a pilot study. The data were collected to gain information pertaining to the behavior of the inner roadway as well as the characteristics and distribution of the stress range spectrum. The results of the measurements made on the inner roadway are discussed in Appendix A of this report.

Finally, a proposed inspection manual was developed to be used during routine inspection of the steel orthotropic deck. This manual alerts inspectors to details where fatigue cracking could be expected based on the laboratory tests and is included as Appendix D of this report.
The following observations were made upon completion of the testing program:

1. The general behavior of the diaphragm plate at floorbeams, as observed in the laboratory, is consistent and in good agreement with the behavior observed in the field.
2. For similar loading conditions, proportions of in-plane and out-of-plane stresses measured in the diaphragm plate during the laboratory and field testing programs are in good agreement. Typically, the in-plane stress component dominates the stress-range cycle.
3. Tests were conducted before and after the application of the wearing surface. These tests demonstrated the following:
   3.1. The wearing surface has no influence on the global behavior of the deck system. Thus, there is no significant composite action being developed between the steel deck and the wearing surface on the Williamsburg Bridge.
   3.2. The wearing surface has no effect on the local behavior of the individual ribs.
   3.3. Stresses in the diaphragm plate are only influenced by the wearing surface immediately adjacent to the deck plate/diaphragm weld. Stresses near the bottom of the diaphragm plate (i.e., adjacent to the cutout) are unaffected by the addition of the wearing surface.
   3.4. Stress ranges in the deck plate itself were decreased between 25% to 50% after the addition of the wearing surface. These decreases appear to be due to spreading of the individual wheel loads resulting in greater local load distribution. The decreases do not appear to be caused by the composite action between the steel deck plate and the wearing surface.
4. Comparison of measurements made during crawl and dynamic speed runs indicate that there is little dynamic amplification generated. This is attributed to the new condition of the wearing surface and gently curving profile of the roadway. If the wearing surface degrades and begins to unravel, considerable increases in dynamic amplification of the wheel loads would be expected.
5. The passage of the single and tandem-axle test trucks produces one stress cycle in the floorbeams, ribs and diaphragm plate. However, each individual axle produces a single stress cycle in the deck plate and rib/deck connection,
6. The peak stress range in the diaphragm plate adjacent to the cutout is primarily influenced by the heavy rear axle or heavy rear axle group (i.e., a tandem) and not the total weight of the truck.
7. Long-term remote monitoring of the Williamsburg Bridge orthotropic deck diaphragm indicated that the variable amplitude stress-range spectrum has a wider band than assumed in the AASHTO LRFD specifications. As a result, a number of stress cycles exceed the constant-amplitude fatigue limit for Category C, which was found to be applicable to the rib-to-diaphragm welded joint at the cutouts. Measured stress range histograms indicate that the fatigue-limit-state truck (i.e., 2xHS-15) assumed in the AASHTO LRFD may not be conservative for design of certain details of an orthotropic deck, (i.e., diaphragm cutouts). The CAFL of the rib-to-diaphragm welded joint at the cutouts was exceeded up to 3% of the time as a result of this fact.
The laboratory and field testing programs have demonstrated that several of the cutouts are likely to sustain fatigue damage should the current distribution of truck traffic continue or increase at some point in the future. Fortunately, the estimated remaining fatigue life of these details is greater than 75 years. In order to make inspectors aware of potential locations where fatigue cracking could be anticipated, a field inspection guideline has been prepared and is included as Appendix D to this report.

Recommendations for additional instrumentation and future monitoring of the Williamsburg Bridge orthotropic deck are included for use by the New York City DOT.
### Summary of laboratory and field testing programs for Williamsburg Bridge rehabilitation

<table>
<thead>
<tr>
<th>Phase</th>
<th>Purpose of Test</th>
<th>Test Loading</th>
<th>Test Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Estimate and compare the fatigue resistance of weld Options “A” and “B”. Option “A” as recommended by Steinman, Option “B” as recommend in the 1994 AASHTO LRFD Bridge Design Specifications</td>
<td>Simulated the passing of one HS15 fatigue truck in each lane with an additional 30% more load to account for impact in the outer lane. Tested for 8.5 million cycles</td>
<td>Weld Option “A”, along with other design improvements, implemented into production replacement panels installed on the south inner and outer roadways on the Williamsburg Bridge</td>
</tr>
<tr>
<td>IIA</td>
<td>Assess the fatigue performance of the as-built design that included weld Option “A” and other design improvements</td>
<td>Simulated the passing of one HS15 fatigue truck in each lane with an additional 30% more load to account for impact in the outer lane. Tested for 5 million cycles.</td>
<td>Design improvements effective on as-built specimen that exhibited good fatigue performance under the test loading that was consistent with AASHTO LRFD Bridge Design Specifications</td>
</tr>
<tr>
<td>IIB</td>
<td>Produced as much fatigue cracking as possible to determine more accurately and under higher stress ranges, the fatigue resistance of weld Option “A”. Assess effectiveness of two rib-to-diaphragm connection repair weld options.</td>
<td>Simulated the passing of one truck in outer lane at the 3.1xHS15 load level (equivalent to two HS20 design trucks with an additional 15% for impact per truck). Tested for 2 million cycles.</td>
<td>Sufficient cracking resulted and was adequate for assessing the fatigue resistance of welded connection. Fatigue resistance of weld Option “A” define by the AASHTO Category C resistance curve and superior to Weld Option “B” defined by Category “E”</td>
</tr>
<tr>
<td>III</td>
<td>Better understand the behavior of the orthotropic deck system and to verify the laboratory test program. Determine the effect of the wearing surface &amp; percent of dynamic amplification. Develop stress range histograms at critical locations from the random amplitude traffic spectrum.</td>
<td>Test trucks weighing just less than an H15 were positioned in the inside &amp; outside lanes as well as side-by-side positions. (GVW = 26.5 kips) Both crawl and dynamic tests were conducted. A second series of tests were conducted using a heavier truck corresponding to an H35. (GVW=69.2 kips). Only dynamic tests were conducted with this truck.</td>
<td>Laboratory test accurately simulated the behavior of the deck. The wearing surface had little effect on the stress range at the cutout and little dynamic amplification was observed. Stress range histograms indicate that heavy vehicles regularly cross the bridge and the CAFL of the cutout is exceeded up to 3.5% of the time. The heaviest trucks correspond to about 3 times the HS15 fatigue truck</td>
</tr>
</tbody>
</table>
1.0 INTRODUCTION

As part of an ongoing research program on the Williamsburg Bridge being conducted at Lehigh University, an in-depth field study of the orthotropic deck system has been completed. Instrumentation and testing of the south outer roadway cantilever began during July of 1997 and was completed in January of 1999 and consisted of two tasks. The first task included controlled load tests utilizing trucks of known load and dimensions. During these tests, over 80 crawl and dynamic tests were conducted with both single and tandem-axle trucks. The second task involved long-term remote monitoring of the outer roadway which began in August of 1998 and continued for a period of six months. During the long-term monitoring portion, data were collected remotely via phone modems and consisted of both stress-range histograms and time histories. Instrumentation consisted of strain gages that were installed within a two-span section (2 @ 6.1m (20 ft)) of the cantilevered southern roadway near midspan.

All testing was conducted by personnel from Lehigh University’s Center for Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center located in Bethlehem, Pennsylvania.
2.0 BACKGROUND

The Williamsburg Bridge located in New York City, NY is currently undergoing a major rehabilitation (see Figures 2.1a and 2.1b). A significant portion of this project involves the replacement of the existing concrete-filled deck on both the inner and outer roadways with a steel orthotropic deck. The orthotropic deck is composed of prefabricated panels approximately 12.2m (40ft) long and 6.1m (20ft) wide. The panels are made continuous with a combination bolted and welded transverse splice detail in the deck plate and ribs.

Figure 2.1a – Photograph of North Face of the Williamsburg Bridge. Manhattan Tower Shown (8/6/98)

Orthotropic bridge decks have been used extensively throughout the United States and Europe. Unfortunately, some of these systems have often exhibited fatigue cracking after being placed into service [1,2]. In order to minimize the possibility of fatigue cracking on the Williamsburg Bridge, fatigue testing of a full-scale prototype panel which incorporated two details was conducted. One of the details was developed by Steinman and was different than that required in the 1994 AASHTO LRFD Bridge Design Specification. This detail consisted of a combination groove/fillet weld at the rib-to-diaphragm connection. This testing was conducted at Lehigh University and was the first phase of this comprehensive study. Through that study it was found that the diaphragm/bulkhead connection detail, located

Figure 2.1b – South Face of Williamsburg Bridge. Manhattan Tower Shown
at floorbeams, is particularly sensitive to fatigue damage and the improved details did
indeed offer superior fatigue resistance [3]. Recommendations intended to improve the
fatigue resistance of this detail were made prior to construction. These changes were
incorporated into the final design and are currently being used on the orthotropic deck
panels. In order to assess the effectiveness of these improvements, additional laboratory
fatigue testing was also conducted as Phase II of the research. The results and findings of
Phase II are summarized in ATLSS Reports #98-04 and #99-02 [3,4].

In addition to the full-scale laboratory testing conducted during Phases I and II,
Phase III consisted of an in-depth field instrumentation and testing program. Both
controlled and uncontrolled tests were conducted in the area of panel points (PPTs) 63E,
64E, and 65E. The results of Phase III are the subject of this report.

Though not the focus of this report, 20 strain gages were also installed at
floorbeam 67E by Lehigh University personnel as part of a separate research program.
Sixteen of the gages were installed on the diaphragm plate and were located identical to
those installed adjacent to the diaphragm cutouts at floorbeam 64E. The other four
remaining gages were installed on floorbeam 67E and positioned like those on floorbeam
64E. This additional instrumentation and testing was performed in order to investigate
the effects of a misalignment between the centerline of the diaphragm plate and the
centerline of the floorbeam web. The results of this study can be found in a separate
report entitled Evaluation of the Effects of Diaphragm Offset at Panel Point 67E on the
South Outer Roadway - ATLSS Report 98-07 [5]. However, that report only discusses the
results of controlled load testing which was conducted during August of 1997. One of
the recommendations of that report was to monitor a few gages installed adjacent to
selected ribs during the remote long-term monitoring program. This task was undertaken
during the third monitoring period when four of the strain gages installed at this location
were monitored and stress-range histograms were developed. Since these data were
collected after ATLSS Report 98-07 was written and finalized, the, stress-range
histogram data collected at floorbeam 67E are discussed in Appendix B of this report.

In addition to the measurements made on the cantilevered portion of the south
outer roadway, 20 channels were installed on the diaphragm plate on floorbeam 64E on
the south inner roadway. These data for this pilot study were collected to gain
information pertaining to the behavior of the south inner roadway and to determine if
future measurements on the inner roadway (to be conducted by New York City DOT)
were necessary. Sufficient data were collected to establish the magnitude and
distribution of the stress range spectrum. It should be noted that no controlled load tests
were conducted on the south inner roadway. The results of the measurements made on
the inner roadway are discussed in Appendix A of this report.
3.0 INSTRUMENTATION

The following section describes the instrumentation plan used during the field testing. Because the City of New York is to continue monitoring the orthotropic deck, a detailed discussion pertaining to the instrumentation and data acquisition system used, especially for the remote monitoring portion can be found in Appendix C.

3.1 Strain Gage Plan

“As built” strain gage plans from diaphragms 63E, 64E, and 65E are presented in Figures 3.1 to 3.6, respectively. All figures are oriented looking west. Channel numbers shown in parentheses are on the far or west side of the diaphragm. Strain gages were placed at locations known to be fatigue sensitive from the laboratory studies. At several locations, strain gages were installed on both faces of the diaphragm so that axial and bending strain components could be calculated.

Using the gage plan of the Phase I laboratory testing program as a template, the field strain gage plan was developed. A great deal of information was collected regarding the appropriate positions for strain gages for this type of structural system during the Phase I laboratory testing. Strain gages installed on the test panel studied during the Phase II laboratory testing were also positioned to match those installed in the field.

The original proposal for the Phase III field testing called for a total of 80 strain gages. However, 30 additional gages were added after discussions between NY City DOT, Steinman, and Lehigh. During the remote long-term monitoring, four more strain gages were installed on the deck plate perpendicular to the rib walls near rib 5 (see details below). Thus, the total number of strain gages installed on the south cantilever roadway was 114.
Figure 3.1 – General Plan of Instrumented Section of Williamsburg Bridge Cantilever Roadway.
Figure 3.3 – Gage Plan at Floorbeam 64E (Detail D).

Uniaxial Gage (Typ.)

Uniaxial Gage East Face (Typ.)

Bi-Axial Rosette East Face (Rib 5 Only)

Wires Cut on All Bulkhead Gages

Uniaxial Gage on West Face Near Cape Hole
Ribs 5, 6, & 7 (6 Channels)

Gages at Rib 6
Located as in Lab

Gages at Rib 5
Located as in Lab

Gages at Rib 7
Located as in Lab

$\frac{1}{6}$ from Weld Toe (Typ.)

$\frac{1}{8}$ (Typ.)

$\frac{5}{8}$ (Typ.)

Detail D
Diaphragm Strain Gage Layout
(Floorbeam 64E - Looking West)
(Total of 28 Strain Gage Channels)

---

Bulk-Head Gages are Measurements Group
CEA-06-W250B-120 Gage Factor is 2.075

Diaphragm Gages are Measurements Group
LWK-06-W250B-350 Gage Factor is 2.02

Bi-axial Gages are Measurements Group
CEA-06-125WT Gage Factor is 2.07
Figure 3.4 – Gage Plan at Floorbeam 6SE (Detail E).

Detail E
Diaphragm Strain Gage Layout
(Floorbeam 6SE - Looking West)
(Total of 18 Strain Gage Channels)

Gages @ Rib 5
Located as in Lab

Uniaxial Gage West Face (Typ.)

Wires Cut on All Bulkhead Gages

$\frac{1}{4}''$ from Weld Toe

$1''$

Bulk-Head Gages are Measurements Group
CEA-06-W250B-120 Gage Factor is 2.075

Uniaxial Gages are Measurements Group
LWK-06-W250B-350 Gage Factor is 2.02

* V or H Denotes Longitudinal Axis of Gage
(V=Parallel to Rib, H=Perpendicular to Rib)

* "ll" Denotes Gages on Opposite Face

* All Bulk-Head gages were installed During Panel Fabrication

Field Gage Plan
Williamsburg Bridge - Phase III
New York City NY

Prepared by Lehigh University
Becchtem PA

Date - 7/3/97 Rev. - 6/22/99
Design - RJC Drawn - RJC 6 of 6
Figure 3.5 – Strain Gage Plan at Transverse Weld Near Floorbeam 65E

Uniaxial Gages are Measurements Group
LWK-06-W250B-350 Gage Factor is 2.02

Plan of Gages at Transverse Weld
(Total of 8 Strain Gage Channels)

Detail A

Transverse Weld

Gages Placed Along Rib Wall

See Detail at Right
Midway Between Ribs (Typ.)

© Bulkhead & Floorbeam

Backin Bar

13/8" (Typ.) 3" 13/8" (Typ.)

© Rib 5

Edge of Cope

Prepared by Lehigh University
Bethlehem PA

Field Gage Plan
Williamsburg Bridge - Phase III
New York City NY

Date - 7/3/97 Rev. - 6/22/99
Design - RJC Drawn - RJC 2 of 6
Figure 3.6 – Strain Gage Locations on Shear Plate, Longitudinal Rib Gages, and Transverse Deck Gages
The rationale behind the selected strain gage locations is presented below.

1. **Floorbeam Gages** – Strain gages were installed on the flanges of the floorbeams near the connection to the truss (see Figure 3.7). The gages installed at the top of the floorbeam were installed on the tie plate which passes through the lower chord of the main truss and connects to the top flange of the floorbeam supporting the inner roadway. Strain gages installed at the bottom of the floorbeam were installed on the portion of the floorbeam bottom flange which extends to the bottom flange of the inner floorbeam. Gages were positioned to capture and measure the overall bending moments at the fixed end of the floorbeam.

The locations of the gages installed on the floorbeams in the field were nearly the same as those in the laboratory. However, the details of the bolted connection used in the laboratory are quite different. Thus, a direct comparison of the laboratory and field data cannot be made for this detail.

![Figure 3.7a - Photograph of Typical Strain Gage Installation Bottom Flanges of Floorbeam (Floorbeam 64E Shown)](image)

Figure 3.7a - Photograph of Typical Strain Gage Installation Bottom Flanges of Floorbeam (Floorbeam 64E Shown)
Figure 3.7b - Photograph of Typical Strain Gage Installation Bottom Flanges of Floorbeam (Floorbeam 64E Shown)
2. **Transverse Deck Gages** – Some orthotropic decks have experienced problems with longitudinal deck plate cracking along the rib walls. Therefore, in order to measure the stress ranges generated by passing wheel loads, gages were applied transverse to the rib wall on the underside of the deck. (See Figure 3.8 and Figures 3.1 & 3.6). These were designated as channels 87D through 90D. The “D” denotes that the gage was located on the Deck plate. Later, during the third setup of long-term monitoring, four channels adjacent to CH-87D through CH-90D, were added to the Rib walls and are denoted by CH-87R through CH-90R, hence the “R”. The axis of the gages placed on the rib walls was oriented vertically.

![Figure 3.8 - Photograph of Instrumentation Installed on the Deck Plate Transverse to the Rib Wall](image)

Figure 3.8 - Photograph of Instrumentation Installed on the Deck Plate Transverse to the Rib Wall
3. **Longitudinal Rib Gages** – Strain gages were applied to the bottom of several ribs to provide information pertaining to transverse load distribution. (See Figure 3.9) In order to locate the neutral axis, gages were also installed on the deck plate adjacent to the rib wall at two ribs. (See Figure 3.1 and 3.6, Detail B)

Figure 3.9 - Photograph of Instrumentation Installed on the Deck Plate Parallel to the Rib Wall.
4. **Shear Plate Gages** – Strain gages were applied on the top and bottom of the shear plate between PPTs 63E and 64E in order to determine in and out of plane stresses in the plate. (see Figure 3.10 and Figure 3.6, Detail G). The axis of the gages was oriented transverse to the ribs. These gages were subsequently destroyed during later phases of construction.

![Image of Shear Plate Gages](image-url)

**Figure 3.10** - Photograph of Instrumentation Installed on the Bottom of the Shear Plate Between at Floorbeam 63E and 64E. Lower Chord of the Main Truss is to the Right.
5. **Transverse Groove Weld Gages** – Four gages were installed on the deck plate adjacent to each cope hole in the wall of rib 5 near PPT 65E. The copes in the rib wall are required to make the transverse groove weld in the deck plate. These gages were placed on both sides of the weld along side the exterior walls of rib 5 and were oriented in the longitudinal direction. These gages were intended to measure stresses generated from the passage of wheel loads at the transverse weld. (See Figure 3.11 and Figure 3.5, Detail A). Some orthotropic decks have had problems with cracking of this detail [7, 8].

![Figure 3.11 - Photograph of Instrumentation Installed at Transverse Groove Weld in the Deck Plate at Floorbeam 65 E.](image)
6. **Diaphragm and Bulkhead Gages** – Gages were installed on the diaphragm and bulkhead plates to measure actual service stresses at this critical detail (See Figure 3.12a & b and figures 3.2, 3.3, and 3.4). The gages were oriented perpendicular to the rib wall. Most of the gages installed adjacent to the cutout on the diaphragm plate were positioned identically to those installed in the laboratory. Thus, these data could also be compared to data collected during the laboratory testing program. However, a few gages were offset at 25mm (1in) instead of 6.5mm (0.25in). The measurements made at these locations are not discussed in this report for consistency.

![Figure 3.12a - Photograph of Typical Instrumentation Installed at Diaphragm](image-url)
Figure 3.12b - Photograph of Instrumentation Installed at Diaphragm. (Note the Wires from Strain Gages Installed on the Bulkhead Plate)
3.2 Data Acquisition System

Two different data acquisition systems were used during the Phase III field testing at the Williamsburg Bridge. Both systems were digital data acquisition systems and are described in detail in Appendix C of this report.
4.0 Field Testing Plan - General

The following is a description of the testing program conducted during 1997 through 1999. A total of 114 strain gages were monitored in the area of panel points 63E, 64E, and 65E. Both controlled load tests and uncontrolled long-term monitoring were carried out. (The details related to the controlled load tests conducted at FB67E in August of 1997 are discussed in ATLSS Report 98-07, Evaluation of the Effects of Diaphragm Offset at Panel Point 67E on the South Outer Roadway [5].)

Two different sets of controlled load tests were conducted. First, a set of crawl tests (<5mph) were conducted prior to the placement of the wearing surface using single-axle dump trucks provided by the New York City DOT. Second, a series of crawl and dynamic tests were conducted after the application of the wearing surface. For these tests, two different trucks were used. During September of 1997, crawl and dynamic tests were conducted using single-axle dump trucks provided by the City. However, it was observed that the gross vehicle weight (GVW) of the single-axle trucks was rather low, about 117.9kN (26.5kips). Therefore, in order to obtain data using loads more representative of actual traffic, additional dynamic testing was conducted during March of 1998. For this set of tests, a tandem-axle dump truck with a GVW of about 311kN (70kips) was utilized. Detailed information pertaining to axle load and geometry of each truck is presented hereafter.
4.1 Test Trucks

4.1.1 Single-Axle Truck

Figure 4.1 is a photograph of a typical single-axle test truck and is representative of all of the single-axle trucks used. The GVW of this truck was rather low compared to other types of vehicles, but not unreasonable for single-axle type trucks. Tables 4.1 and 4.2 provide information pertaining to the axle load and geometry of the test trucks.

![Figure 4.1 - Photograph of Single-Axle Test Truck Used During August of 1998 Testing](image)

It should be noted that there was considerable difficulty in obtaining accurate GVW and axle load data for each of the single-axle trucks and it was not possible to obtain individual axle load data. The drivers provided weight slips indicating the GVW of the test trucks was 164kN (36.8kips). However, when these same trucks were used after the wearing surface was applied, (one week later) the GVW indicated on the weight slips was 112kN (25.2kips). Visual inspection revealed that the amount of the payload was essentially the same.

Therefore, in order to establish what the true axle loads and GVW were, one of the test trucks was loaded and weighed while personnel from Steinman were present. These measurements could only be made after all of the testing using the single-axle trucks was completed. The GVW of the test truck measured during this subsequent weighing was equal to 117kN (26.5kips). It was decided to assume that the GVW and axle loads measured during the weighing performed by Steinman were representative of all tests conducted with the single-axle trucks.

In terms of GVW and geometry, this truck most closely resembles the H-15 design vehicle. A comparison between the single-axle test truck and the H-15 Design Truck can be found in Table 4.1. The axle spacing of the test truck and H-15 Design truck are 4.59m (15’-1”) and 4.27m (14’-0”) respectively. Although the GVW is also similar, (117kN vs 133kN), the load distribution to the individual axles is quite different.
The rear axle of the test truck only weighed 83.2kN (18.7kips) while the H-15 rear axle weighs 106.7kN (24kips), almost 30% heavier. However, it should be noted that the rear axles of all AASHTO LRFD design trucks actually represent a tandem in order to simplify design [26].

### 4.1.2 Tandem-Axle Truck

Figure 4.2 is a photograph of the tandem-axle test truck. This truck had a GVW of 308kN (69.2kips). A private contractor provided the tandem-axle truck in order to obtain a heavier load and more accurate measurements of axle weights. Tables 4.1 and 4.2 provide information pertaining to axle load and geometry of the tandem-axle test truck.

![Figure 4.2 - Photograph of Tandem-Axle Test Truck](image)

The overall geometry of this truck was also similar to that of the H-15 design vehicle. The distance from the centerline of the front axle to the centerline of the rear tandem is 4.59m (15'-1”). (Note that this is the same distance from the centerline of the front axle to the rear axle of the single-axle truck.)

As planned, the GVW and individual axle loads of the tandem-axle test truck are larger than those on the H-15 design vehicle, as shown in Table 4.1.
Test Description | Rear Axle | Front Axle Load kN (lb.) | First Rear Axle Load kN (lb.) | Second Rear Axle Load kN (lb.) | GVW kN (lb.) | Date of Tests
--- | --- | --- | --- | --- | --- | ---
Crawl Runs - W/O Wearing Surface | Single | 34.7 (7,800) | 83.2 (18,700) | N/A | 117.9 (26,500) | August of 1997
Crawl Runs - W/ Wearing Surface | Single | 34.7 (7,800) | 83.2 (18,700) | N/A | 117.9 (26,500) |
Dynamic Runs - W/ Wearing Surface | Single | 34.7 (7,800) | 83.2 (18,700) | N/A | 117.9 (26,500) |
Dynamic Runs - W/ Wearing Surface | Tandem | 66.1 (14,860) | 118.9 (26,720) | 122.7 (27,580) | 307.7 (69,160) | March of 1998

**H-15** | Tandem | 26.7 (6,000) | 53.4 (12,000) | 53.4 (12,000) | 133 (30,000) | -

**Notes**
1. Weight measurements made of a single-axle dump truck on September 19th 1997. This truck was identical to those used during the August 1997 testing.
3. Rear axle of AASHTO design trucks actually represents a tandem.

**Table 4.1 - Test Truck and H-15 Axle Load Data**

<table>
<thead>
<tr>
<th>Rear Axle</th>
<th>L1 mm (in.)</th>
<th>L2 mm (in.)</th>
<th>Wf mm (in.)</th>
<th>Wr mm (in.)</th>
<th>A1,2 mm (in.)</th>
<th>B1 mm (in.)</th>
<th>C1 mm (in.)</th>
<th>D1,2 mm (in.)</th>
<th>E1 mm (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>4597 (181)</td>
<td>N/A</td>
<td>2083 (82)</td>
<td>1829 (72)</td>
<td>229 (9)</td>
<td>191 (7.5)</td>
<td>514 (20.25)</td>
<td>278 (9.75)</td>
<td>191 (7.5)</td>
</tr>
<tr>
<td>Tandem</td>
<td>4470 (154)</td>
<td>(54)</td>
<td>2083 (82)</td>
<td>1829 (72)</td>
<td>203 (8)</td>
<td>267 (10.5)</td>
<td>546 (21.5)</td>
<td>260 (10.25)</td>
<td>203 (8)</td>
</tr>
<tr>
<td>H-15</td>
<td>4270 (168)</td>
<td>-</td>
<td>1829 (72)</td>
<td>1829 (72)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Notes**
1. For single-axle trucks this dimension is average of several measurements taken from different trucks.
2. Only the actual longitudinal length in bearing. Does not include portion of tire that is lightly touching the deck plate.

**Table 4.2 - Test Truck and HS-15 Geometry Data**
4.2 Testing Program

Field testing began in August of 1997 with the controlled load tests and was completed in March of 1999 with the conclusion of the long-term remote monitoring. A tremendous amount of data were collected during the program.

Each of the single-axle controlled load tests were repeated two to four times in order to ascertain the variability associated with the behavior of the structural system. In this report for each set of tests (e.g., tests conducted at 48 km/h, truck in outside lane), a “typical” response data set was used which best represents that set of tests. The specific test selected is indicated with **bold text** in Tables 4.4, 4.5, and 4.6. These data were selected based on an in-depth review and comparison of data from duplicate tests. The data were found to be repeatable and consistent. These test results are discussed in Chapter 5. The transverse positions of the truck axles are illustrated in Figure 4.4

4.2.1 Crawl Tests

Prior to the application of the wearing surface, a series of crawl tests were conducted using single-axle test trucks (see Figure 4.1 and Table 4.4). Crawl tests were conducted in order to measure the response of the orthotropic deck system to rolling loads. Since the speed of the test truck was less than 8 km/h (5 mph), dynamic effects were minimized and the complex behavior of the system can be more easily understood. In addition, there are several gages located on the deck plate where the stresses are produced by the direct application of wheel loads, with little if any influence due to the global response of the structural system. For example, stress ranges measured at the transverse deck groove weld are sensitive to individual wheel loads. Measurements made at these locations were expected to be more sensitive to dynamic effects of the wheel load than other locations.

Two transverse positions were considered. The positions were located in the predetermined travel lanes used by day-to-day traffic (i.e., lanes 7 and 8). Additional tests were conducted with one truck positioned in each lane (i.e., two trucks, side by side (see Figure 4.3)). As is apparent from Figure 4.3, there is barely enough room for the two trucks to pass safely. According to NYC DOT and our own visual observations, trucks do not typically cross side by side due to the limited clearance along the span and the more narrow width at the towers. Thus, this load case is considered to be unlikely.
After the application of the wearing surface, a series of crawl tests identical to those on the bare deck were conducted. The same transverse positions were used. By comparing these data, the effect of the wearing surface on the behavior of the deck could be established.

Several other miscellaneous crawl tests were also conducted, both with and without the wearing surface. For these tests, the test trucks were positioned in other transverse locations. These tests are also identified in Tables 4.4 and 4.5. Several tests were conducted with one of the rear wheels of the single-axle test truck first positioned over rib 5 and then between ribs 5 and 6. In this latter position, the stresses produced at the transverse groove weld splice were maximized. Another test was conducted in which the trucks were positioned in one lane with one truck just a few feet behind the other. This test simulated conditions that could potentially occur during a traffic jam.

The tables also list whether the test was conducted during the first or second wiring set-up. Because of the large number of channels being monitored, two separate set ups were required for each test (See Appendix C for details). The tables also identify whether a commuter train was passing during the test.
Figure 4.4 – Locations of Test Trucks and Wheel Loads.
### Table 4.4 – Crawl Tests Prior to the Application of the Wearing Surface at Panel Point 63E, 64E, and 65E

<table>
<thead>
<tr>
<th>File Name</th>
<th>Channels Recorded</th>
<th>Truck Position</th>
<th>Speed (mph)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>In1-1x.idw</td>
<td>First Set-up</td>
<td>Inside Lane</td>
<td>Crawl</td>
<td>No Trains Passing</td>
</tr>
<tr>
<td>In2-1x.idw</td>
<td>First Set-up</td>
<td>Inside Lane</td>
<td>Crawl</td>
<td>No Trains Passing</td>
</tr>
<tr>
<td>Out1-1x.idw</td>
<td>First Set-up</td>
<td>Outside Lane</td>
<td>Crawl</td>
<td>No Trains Passing</td>
</tr>
<tr>
<td>Out2-1x.idw</td>
<td>First Set-up</td>
<td>Outside Lane</td>
<td>Crawl</td>
<td>No Trains Passing</td>
</tr>
<tr>
<td>Out3-1x.idw</td>
<td>First Set-up</td>
<td>Outside Lane</td>
<td>Crawl</td>
<td>No Trains Passing</td>
</tr>
<tr>
<td>Out4-1x.idw</td>
<td>First Set-up</td>
<td>Outside Lane</td>
<td>Crawl</td>
<td>No Trains Passing</td>
</tr>
<tr>
<td>Both1-1x.idw</td>
<td>First Set-up</td>
<td>One Truck in Each Lane</td>
<td>Crawl</td>
<td>Train Passed @ About 20 sec,</td>
</tr>
<tr>
<td>Both2-1x.idw</td>
<td>First Set-up</td>
<td>One Truck in Each Lane</td>
<td>Crawl</td>
<td>Train Passed @ About 20 sec,</td>
</tr>
<tr>
<td>In1-2x.idw</td>
<td>Second Set-up</td>
<td>Inside Lane</td>
<td>Crawl</td>
<td>No Trains Passing @ Start</td>
</tr>
<tr>
<td>In2-2x.idw</td>
<td>Second Set-up</td>
<td>Inside Lane</td>
<td>Crawl</td>
<td>Train Passed @ About 60 sec,</td>
</tr>
<tr>
<td>In3-2x.idw</td>
<td>Second Set-up</td>
<td>Inside Lane</td>
<td>Crawl</td>
<td>No Trains Passing</td>
</tr>
<tr>
<td>In4-2x.idw</td>
<td>Second Set-up</td>
<td>Inside Lane</td>
<td>Crawl</td>
<td>No Trains Passing</td>
</tr>
<tr>
<td>Out1-2x.idw</td>
<td>Second Set-up</td>
<td>Outside Lane</td>
<td>Crawl</td>
<td>No Trains Passing</td>
</tr>
<tr>
<td>Out2-2x.idw</td>
<td>Second Set-up</td>
<td>Outside Lane</td>
<td>Crawl</td>
<td>No Trains Passing</td>
</tr>
<tr>
<td>Out3-2x.idw</td>
<td>Second Set-up</td>
<td>Outside Lane</td>
<td>Crawl</td>
<td>No Trains Passing</td>
</tr>
<tr>
<td>Out4-2x.idw</td>
<td>Second Set-up</td>
<td>Outside Lane</td>
<td>Crawl</td>
<td>No Trains Passing</td>
</tr>
<tr>
<td>Both1-2x.idw</td>
<td>Second Set-up</td>
<td>One Truck in Each Lane</td>
<td>Crawl</td>
<td>Train Passing at Start Only</td>
</tr>
<tr>
<td>Both2-2x.idw</td>
<td>Second Set-up</td>
<td>One Truck in Each Lane</td>
<td>Crawl</td>
<td>Train Passed at End of Test</td>
</tr>
<tr>
<td>Both3-3x.idw</td>
<td>Second Set-up</td>
<td>One Truck in Each Lane</td>
<td>Crawl</td>
<td>No Trains Passing</td>
</tr>
<tr>
<td>Both4-2x.idw</td>
<td>Second Set-up</td>
<td>One Truck in Each Lane</td>
<td>Crawl</td>
<td>No Trains Passing</td>
</tr>
<tr>
<td>Tr1-2x.idw</td>
<td>Second Set-up</td>
<td>One Truck</td>
<td>Crawl</td>
<td>Truck Wheel Located Over Rib 5 in Order to Investigate the Stress Ranges at the Transverse Weld (Trains for Parts of Tests of 1 &amp; 2)</td>
</tr>
<tr>
<td>Tr2-2x.idw</td>
<td>Second Set-up</td>
<td>One Truck</td>
<td>Crawl</td>
<td>Truck Wheel Located Between Ribs 5 &amp; 6 in Order to Investigate the Stress Ranges at the Transverse Weld (Train Came at End of Test 2)</td>
</tr>
</tbody>
</table>

Notes:
1. The speeds during the crawl tests were less than 8km/h (5mph).
Table 4.5 – Crawl Tests After the Application of the Wearing Surface at Panel Point 63E, 64E, and 65E

4.2.2 Dynamic Tests

A series of dynamic tests were conducted after application of the wearing surface. Dynamic tests were not conducted prior to the application of the wearing surface for safety reasons. Trucks were located in the same transverse positions used during the crawl tests. Target speeds of 24 and 48 km/h (15 & 30 mph) were desired, however, due to site and vehicle limitations, the maximum speed attained was only about 42 km/h (26 mph). Dynamic tests were not conducted with the test trucks positioned side by side for safety reasons and because such an event is unlikely. Table 4.6 summarizes the dynamic tests conducted using the single-axle truck at panel points 63E, 64E and 65E and list the actual speed of the truck during the test.

Dynamic tests were not conducted with the test truck positioned to maximize stresses in the transverse splice. It was believed that the crawl tests would provide sufficient (and more useful) data at this location. Two other tests were conducted in
which the driver of the truck applied the brakes over the instrumented floorbeams. The speed of the truck was about 40km/h (25mph) for these tests. No unusual stresses were produced and there were no negative effects observed in the wearing surface as a result of these tests. A similar series of tests were conducted using the tandem-axle test truck.

The table also lists whether the test was conducted during the first or second set-up.

<table>
<thead>
<tr>
<th>File Name</th>
<th>Channels Recorded</th>
<th>Truck Position</th>
<th>Speed (mph)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1_15WS1.idw</td>
<td>First Set-up</td>
<td>Inside Lane</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>I2_15WS1.idw</td>
<td>First Set-up</td>
<td>Inside Lane</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>I3_15WS1.idw</td>
<td>First Set-up</td>
<td>Inside Lane</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>O1_15WS1.idw</td>
<td>First Set-up</td>
<td>Outside Lane</td>
<td>17</td>
<td>-</td>
</tr>
<tr>
<td>O2_15WS1.idw</td>
<td>First Set-up</td>
<td>Outside Lane</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>O3_15WS1.idw</td>
<td>First Set-up</td>
<td>Outside Lane</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>O1_30WS1.idw</td>
<td>First Set-up</td>
<td>Outside Lane</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>O2_30WS1.idw</td>
<td>First Set-up</td>
<td>Outside Lane</td>
<td>26</td>
<td>-</td>
</tr>
<tr>
<td>O3_30WS1.idw</td>
<td>First Set-up</td>
<td>Outside Lane</td>
<td>26</td>
<td>-</td>
</tr>
<tr>
<td>I1_15WS2.idw</td>
<td>Second Set-up</td>
<td>Inside Lane</td>
<td>15+</td>
<td>-</td>
</tr>
<tr>
<td>I2_15WS2.idw</td>
<td>Second Set-up</td>
<td>Inside Lane</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>I3_15WS2.idw</td>
<td>Second Set-up</td>
<td>Inside Lane</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>I1_30WS2.idw</td>
<td>Second Set-up</td>
<td>Inside Lane</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>I2_30WS2.idw</td>
<td>Second Set-up</td>
<td>Inside Lane</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>I3_30WS2.idw</td>
<td>Second Set-up</td>
<td>Inside Lane</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>O1_15WS2.idw</td>
<td>Second Set-up</td>
<td>Outside Lane</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>O2_15WS2.idw</td>
<td>Second Set-up</td>
<td>Outside Lane</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>O3_15WS2.idw</td>
<td>Second Set-up</td>
<td>Outside Lane</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>O1_30WS2.idw</td>
<td>Second Set-up</td>
<td>Outside Lane</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>O2_30WS2.idw</td>
<td>Second Set-up</td>
<td>Outside Lane</td>
<td>25</td>
<td>-</td>
</tr>
<tr>
<td>O3_30WS2.idw</td>
<td>Second Set-up</td>
<td>Outside Lane</td>
<td>22</td>
<td>-</td>
</tr>
<tr>
<td>Br1-2wx.idw</td>
<td>Second Set-up</td>
<td>One Truck</td>
<td>20</td>
<td>Braking Test</td>
</tr>
<tr>
<td>Br2-2wx.idw</td>
<td>Second Set-up</td>
<td>One Truck</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.6 – Dynamic Tests After the Application of the Wearing Surface at Panel Point 63E, 64E, and 65E
4.2.3 Remote Long-Term Monitoring

Measurements were made at selected locations while normal daily traffic crossed the Williamsburg Bridge. The uncontrolled monitoring of the outer roadway (lanes 7 & 8) began on August 4th 1997 and was completed on January 22nd 1999 (i.e., a period of about six months). Although the structure was open to all traffic, the measurements are not entirely representative of what they will be when the rehabilitation is completed. During the monitoring period, there were many times when lane 7 or 8, (or both) were closed to provide access for construction workers, typically between 9:00am and 3:00pm.

As originally proposed, monitoring was to be carried out by Lehigh University for a minimum period of three months. After that time, remote monitoring was to be taken over by NYC DOT with guidance and suggestions provided by Lehigh. Specific details and recommendations for future monitoring are discussed in Section 8.

Rather than collect data at a limited number of locations for the entire monitoring period, three different groups of 20 channels were monitored for a minimum of one month each. Thus, data were collected at more locations than originally proposed. The data collected during each one-month period were sufficient to establish useful stress-range histograms at each location. Four “control” channels were monitored during all three setups. Specifically, channels 27 & 29 adjacent to rib 5 and channels 45 & 46 adjacent to rib 7 on floorbeam 64E. These channels are located beneath lanes 8 and 7 respectively. This provided continuity between the measurements and permitted an assessment of any change in the traffic patterns during these periods.

The specific channels and the data collected during each setup are summarized in the Tables 4.7, 4.8 and 4.9. See Section 6 for additional details pertaining to the remote long-term monitoring.
First Monitoring Period

Table 4.7, lists the channels recorded during the first period of monitoring. Monitoring began on August 5th 1998 and continued through September 3rd 1998. As shown, 18 of the channels were located on the diaphragm plate and 2 were located on the flanges of floorbeam 64E where it connects to the truss.

<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Actual Channel Number</th>
<th>Chan. on “Vishay”</th>
<th>Comments - Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CH-27</td>
<td>1</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 5 S.E. Corner</td>
</tr>
<tr>
<td>2</td>
<td>CH-29</td>
<td>2</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 5 N.E. Corner</td>
</tr>
<tr>
<td>3</td>
<td>CH-45</td>
<td>3</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 7 S.E. Corner</td>
</tr>
<tr>
<td>4</td>
<td>CH-46</td>
<td>4</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 7 N.E. Corner</td>
</tr>
<tr>
<td>5</td>
<td>CH-1</td>
<td>5</td>
<td>Rainflow Hist. Only - Diaphragm @ FB63E Rib 5 S.E. Corner</td>
</tr>
<tr>
<td>6</td>
<td>CH-2</td>
<td>6</td>
<td>Rainflow Hist. Only - Diaphragm @ FB63E Rib 5 N.E. Corner</td>
</tr>
<tr>
<td>7</td>
<td>CH-5</td>
<td>7</td>
<td>Rainflow Hist. Only - Diaphragm @ FB63E Rib 5 S.W. Corner</td>
</tr>
<tr>
<td>8</td>
<td>CH-6</td>
<td>8</td>
<td>Rainflow Hist. Only - Diaphragm @ FB63E Rib 5 N.W. Corner</td>
</tr>
<tr>
<td>9</td>
<td>CH-35</td>
<td>9</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 5 S.W. Corner</td>
</tr>
<tr>
<td>10^1</td>
<td>CH-36</td>
<td>10^1</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 5 N.W. Corner</td>
</tr>
<tr>
<td>11</td>
<td>CH-39</td>
<td>11</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 6 S.E. Corner</td>
</tr>
<tr>
<td>12</td>
<td>CH-40</td>
<td>12</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 6 N.E. Corner</td>
</tr>
<tr>
<td>13</td>
<td>CH-41</td>
<td>13</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 6 S.W. Corner</td>
</tr>
<tr>
<td>14</td>
<td>CH-42</td>
<td>14</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 6 N.W. Corner</td>
</tr>
<tr>
<td>15</td>
<td>CH-51</td>
<td>15</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 7 S.W. Corner</td>
</tr>
<tr>
<td>16</td>
<td>CH-52</td>
<td>16</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 7 N.W. Corner</td>
</tr>
<tr>
<td>17</td>
<td>CH-55</td>
<td>17</td>
<td>Rainflow Hist. Only - Diaphragm @ FB65E Rib 5 S.W. Corner</td>
</tr>
<tr>
<td>18</td>
<td>CH-56</td>
<td>18</td>
<td>Rainflow Hist. Only - Diaphragm @ FB65E Rib 5 N.W. Corner</td>
</tr>
<tr>
<td>19</td>
<td>CH-101</td>
<td>19</td>
<td>Rainflow Histogram Only - FB64E West Side of Top Flange</td>
</tr>
<tr>
<td>20</td>
<td>CH-102</td>
<td>20</td>
<td>Rainflow Histogram Only - FB64E West Side of Bottom Flange</td>
</tr>
</tbody>
</table>

Notes:

1. This channel would not balance. It is believed that the reason is due to the wiring at the Vishay and not the channel itself. In order to prevent any possible problems arising from having an open sensor, the input from channel 35 (9 on Vishay) was “jumpered” to this location.

Table 4.7 – Channels Included in First Monitoring Period. (August 5th and Through September 3rd 1998)

Most of the channels monitored during the first period were located on the diaphragm plate adjacent to the rib/diaphragm weld near the cutout. During the laboratory tests, this detail was identified as being subjected to the highest stress range with the greatest potential for fatigue damage. Thus, the first monitoring period focused on the behavior at this detail at as many locations as possible.

The response of the floorbeam is much less sensitive to “local” response than the gages installed on the diaphragm or deck plates. Therefore, a pair of gages installed on the flanges of floorbeam 64E provided data pertaining to global load distribution and to compare with measurements made on the diaphragm plate. Specifically, channel 101, which was installed on the top flange, and channel 102, which was installed on the bottom flange.

Stress-range histograms were developed at all twenty locations. Typically, triggered time histories were only recorded at channels 27 & 29 and 45 & 46. However, using channels 27 & 29 as triggers, a few time histories were also recorded for all twenty channels. Based on the results of the controlled load tests, it was determined that a
sampling rate of 100Hz adequately captured the response of the diaphragm plate to moving wheel loads.

**Second Monitoring Period**

Table 4.8 lists the twenty channels monitored during the second monitoring period. Monitoring began on September 27th and continued through November 27th 1998. Monitoring of eight channels included with the first setup, continued during the second setup. Four of these were channels 27 & 29 and 45 & 46. The other four channels were installed on the flanges of floorbeam 64E (i.e., CH-101 and CH-102) and adjacent to rib 5 at floorbeam 63E (i.e., CH-1 and CH-2).

The remaining 12 channels were located on the deck plate. Eight of these channels were located at the transverse weld near floorbeam 65E, specifically channels 91 through 98. Interestingly enough, the root opening of this weld and cope length, was the largest of all the splices on the southern cantilever roadway. The remaining four channels were located adjacent to the longitudinal weld joining the ribs and the deck plate. Specifically, channels CH-87D through CH-90D. (The “D” denotes that the gage was located on the Deck plate.) The axis of these gages was oriented perpendicular to the longitudinal axis of the ribs.

Based on the results of the measurements made during the controlled load tests and random traffic, it was determined that in order to accurately capture the response of the deck plate, a sampling rate of 200Hz was required. Thus, for the second setup, the sampling rate was increase to 200Hz for all channels. As during the first setup, stress-range histograms were developed at all twenty locations and triggered time histories were recorded at channels 27 & 29 and 45 & 46.
<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Actual Channel Number</th>
<th>Chan. on “Vishay”</th>
<th>Comments - Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1′</td>
<td>CH-27</td>
<td>1</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 5 S.E. Corner</td>
</tr>
<tr>
<td>2′</td>
<td>CH-29</td>
<td>2</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 5 N.E. Corner</td>
</tr>
<tr>
<td>3′</td>
<td>CH-45</td>
<td>3</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 7 S.E. Corner</td>
</tr>
<tr>
<td>4′</td>
<td>CH-46</td>
<td>4</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 7 N.E. Corner</td>
</tr>
<tr>
<td>5′</td>
<td>CH-1′</td>
<td>5</td>
<td>Rainflow Hist. Only – Diaphragm @ FB63E Rib 5 S.E. Corner</td>
</tr>
<tr>
<td>6′</td>
<td>CH-2′</td>
<td>6</td>
<td>Rainflow Hist. Only – Diaphragm @ FB63E Rib 5 N.E. Corner</td>
</tr>
<tr>
<td>7</td>
<td>CH-87D</td>
<td>7</td>
<td>Rainflow Histogram Only - Transverse to South Side of Rib 6</td>
</tr>
<tr>
<td>8</td>
<td>CH-88D</td>
<td>8</td>
<td>Rainflow Histogram Only - Transverse to South Side of Rib 5</td>
</tr>
<tr>
<td>9</td>
<td>CH-89D</td>
<td>9</td>
<td>Rainflow Histogram Only - Transverse to South Side of Rib 5</td>
</tr>
<tr>
<td>10′</td>
<td>CH-90Df</td>
<td>10′</td>
<td>Rainflow Histogram Only - Transverse to South Side of Rib 4</td>
</tr>
<tr>
<td>11</td>
<td>CH-91</td>
<td>11</td>
<td>Rainflow Histogram Only - Transverse Weld Near FB 65E</td>
</tr>
<tr>
<td>12</td>
<td>CH-92</td>
<td>12</td>
<td>Rainflow Histogram Only - Transverse Weld Near FB 65E</td>
</tr>
<tr>
<td>13</td>
<td>CH-93</td>
<td>13</td>
<td>Rainflow Histogram Only - Transverse Weld Near FB 65E</td>
</tr>
<tr>
<td>14</td>
<td>CH-94</td>
<td>14</td>
<td>Rainflow Histogram Only - Transverse Weld Near FB 65E</td>
</tr>
<tr>
<td>15</td>
<td>CH-95</td>
<td>15</td>
<td>Rainflow Histogram Only - Transverse Weld Near FB 65E</td>
</tr>
<tr>
<td>16</td>
<td>CH-96</td>
<td>16</td>
<td>Rainflow Histogram Only - Transverse Weld Near FB 65E</td>
</tr>
<tr>
<td>17</td>
<td>CH-97</td>
<td>17</td>
<td>Rainflow Histogram Only - Transverse Weld Near FB 65E</td>
</tr>
<tr>
<td>18</td>
<td>CH-98</td>
<td>18</td>
<td>Rainflow Histogram Only - Transverse Weld Near FB 65E</td>
</tr>
<tr>
<td>19′</td>
<td>CH-101</td>
<td>19</td>
<td>Rainflow Histogram Only - FB64E West Side of Top Flange</td>
</tr>
<tr>
<td>20′</td>
<td>CH-102</td>
<td>20</td>
<td>Rainflow Histogram Only - FB64E West Side of Bottom Flange</td>
</tr>
</tbody>
</table>

Notes:
1. These channels were recorded during first period of monitoring program.
2. This channel would not balance. It is believed that the reason is due to the wiring at the Vishay and not the channel itself. In order to prevent any possible problems arising from having an open sensor, the input from channel 89 (9 on Vishay) was “jumpered” to this location.

Table 4.8 – Channels Included During Second Monitoring Period.
(September 27th and Through November 27th 1998)
Third Monitoring Period

Table 4.9 lists the channels monitored during the third monitoring period. Monitoring began on December 13th, 1998 and continued through February 16th, 1999.

Just prior to beginning the third monitoring period, four channels were installed on the rib wall, perpendicular to the deck plate. These channels are denoted as CH-87R through CH-90R. Thus, eight channels were located at the rib/deck connection at four different locations. In order to develop stress-range histograms for the ribs, four gages that were located on the bottom of the ribs 5 and 7 were monitored, specifically; channels 75 & 76 located on rib 5 and channels 81 and 82 located on rib 7. As indicated in Table 3.9, these gages were installed just west of floorbeam 64E.

<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Actual Channel Number</th>
<th>Chan. on “Vishay”</th>
<th>Comments - Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CH-27</td>
<td>1</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 5 S.E. Corner</td>
</tr>
<tr>
<td>2</td>
<td>CH-29</td>
<td>2</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 5 N.E. Corner</td>
</tr>
<tr>
<td>3</td>
<td>CH-45</td>
<td>3</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 7 S.E. Corner</td>
</tr>
<tr>
<td>4</td>
<td>CH-46</td>
<td>4</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 7 N.E. Corner</td>
</tr>
<tr>
<td>5</td>
<td>CH-1</td>
<td>5</td>
<td>Rainflow Hist. Only - Rib 5 of FB 67E N.W. Corner</td>
</tr>
<tr>
<td>6</td>
<td>CH-3</td>
<td>6</td>
<td>Rainflow Hist. Only - Rib 5 of FB 67E N.W. Corner</td>
</tr>
<tr>
<td>7</td>
<td>CH-5</td>
<td>7</td>
<td>Rainflow Hist. Only - Rib 5 of FB 67E N.W. Corner</td>
</tr>
<tr>
<td>8</td>
<td>CH-7</td>
<td>8</td>
<td>Rainflow Hist. Only - Rib 5 of FB 67E N.W. Corner</td>
</tr>
<tr>
<td>9</td>
<td>CH-87R</td>
<td>9</td>
<td>Rainflow Hist. Only - South Side of Rib 6 Trans. To Deck Plate</td>
</tr>
<tr>
<td>10</td>
<td>CH-88R</td>
<td>10</td>
<td>Rainflow Hist. Only - North Side of Rib 5 Trans. To Deck Plate</td>
</tr>
<tr>
<td>11</td>
<td>CH-89R</td>
<td>11</td>
<td>Rainflow Hist. Only - South Side of Rib 5 Trans. To Deck Plate</td>
</tr>
<tr>
<td>12</td>
<td>CH-90R</td>
<td>12</td>
<td>Rainflow Hist. Only - North Side of Rib 4 Trans. To Deck Plate</td>
</tr>
<tr>
<td>13</td>
<td>CH-87D</td>
<td>13</td>
<td>Rainflow Hist. Only - Transverse to South Side of Rib 6</td>
</tr>
<tr>
<td>14</td>
<td>CH-88D</td>
<td>14</td>
<td>Rainflow Hist. Only - Transverse to North Side of Rib 5</td>
</tr>
<tr>
<td>15</td>
<td>CH-89D</td>
<td>15</td>
<td>Rainflow Hist. Only - Transverse to South Side of Rib 5</td>
</tr>
<tr>
<td>16</td>
<td>CH-90D</td>
<td>16</td>
<td>Rainflow Hist. Only - Transverse to North Side of Rib 4</td>
</tr>
<tr>
<td>17</td>
<td>CH-75</td>
<td>17</td>
<td>Rainflow Hist. Only - Bot. of Rib 5 1ft. W. of FB64E (Neg. Mom. Reg.)</td>
</tr>
<tr>
<td>18</td>
<td>CH-81</td>
<td>18</td>
<td>Rainflow Hist. Only - Bot. of Rib 5 8ft. W. of FB64E (Pos. Mom. Reg.)</td>
</tr>
</tbody>
</table>

Notes:
1. These channels were also recorded during the first and second setups of monitoring program.

Table 4.9 – Channels Included During Third Monitoring Period. (December 13th and Through February 16th, 1999)
During the third period, four channels previously installed at floorbeam 67E were monitored. As discussed in Section 2.0, this additional instrumentation and testing was performed in order to investigate the effects of a misalignment between the centerline of the diaphragm plate and the centerline of the floorbeam web. The results of this study can be found in a separate report entitled *Evaluation of the Effects of Diaphragm Offset at Panel Point 67E on the South Outer Roadway - ATLSS Report 98-07* [5]. Specifically, channels 1, 3, 5, and 7, which are located adjacent to rib 5 near the cutout, were monitored. Table 4.10 relates the gages installed at floorbeam 67E to the corresponding gages installed at panel points 63E, 64E, and 65E.

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Location on Diaphragm</th>
<th>Panel Point 63E (Fig. 3)</th>
<th>Panel Point 64E (Fig. 4)</th>
<th>Panel Point 65E (Fig. 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH-1</td>
<td>Near Rib 5 @ S.E. Corner</td>
<td>1</td>
<td>27</td>
<td>N/A</td>
</tr>
<tr>
<td>CH-3</td>
<td>Near Rib 5 @ N.E. Corner</td>
<td>2</td>
<td>29</td>
<td>N/A</td>
</tr>
<tr>
<td>CH-5</td>
<td>Near Rib 5 @ S.W. Corner</td>
<td>5</td>
<td>35</td>
<td>55</td>
</tr>
<tr>
<td>CH-7</td>
<td>Near Rib 5 @ N.W. Corner</td>
<td>6</td>
<td>36</td>
<td>56</td>
</tr>
</tbody>
</table>

Table 4.10 – Channels at Floorbeam 67E that were Monitored During the Third Setup and Corresponding Channels at Floorbeams 63E, 64E and 65E.
5.0 Results of the Controlled Tests

Results of the controlled load testing are discussed in this section. The effects of vehicle speed, wearing surface, and vehicle position on the behavior of the deck are considered.

5.1 Floorbeam Response

As shown in Figures 3.1 and 3.7, strain gages were installed on the flanges of floorbeams 63E, 64E, and 65E. Recall that the gages installed at the top of the floorbeam were located on the tie plate, which passes through the lower chord of the main truss and connects to the top flange of the interior floorbeam. Strain gages installed at the bottom of the floorbeam were installed on the portion of the floorbeam bottom flange that extends to the bottom flange of the inner floorbeam. The connection of the cantilever floorbeam to the main truss is a rather complicated combination bolted and riveted connection. As a result, the exact stress path is not entirely clear. Nevertheless, the gages were positioned to capture and measure the overall bending moments at the fixed end of the floorbeam. Prior to placing the strain gages, the connections were studied and final locations selected in order to minimize local effects (due to bolt holes, etc). Overall, the stress ranges measured in the floorbeams were small and the data were consistent and repeatable.

The locations of the gages installed on the floorbeams in the field were nearly the same as those in the laboratory. However, the details of the bolted connection used in the laboratory are quite different. Thus, a direct comparison of the laboratory and field data cannot be made.

Figure 5.1 – Typical Floorbeam Response During a Crawl Run (FB64E)  
(Single-Axle Test Truck Located in the Outside Lane Headed West)
5.1.1 Floorbeam Response - Crawl Tests

Table 5.1 and Figure 5.1 presents the response at floorbeam 64E during a crawl run in which the test truck was positioned in the outside lane and was traveling west, towards Manhattan. The data are from gages mounted on the east and west sides of the top and bottom flanges. As seen in the plot, the stress range in the bottom flange is somewhat less than in the top flange tie plate (CH102 & CH104). In addition, the stress range in the bottom flange appears to be almost equal on the east and west face of the flange plate and therefore, predominantly in-plane. However, the response of the tension tie plate is not as uniform.

![Figure 5.2 – In and Out-of-Plane Stress Components in Tension Tie Plate on Floorbeam 63E Response During a Crawl Run (Single-Axle Test Truck Located in the Outside Lane Headed West)](image)

Table 5.1 – Comparison of Stress Ranges Measured at Floorbeams 63E, 64E, and 65E for all the Controlled Tests

<table>
<thead>
<tr>
<th>Location</th>
<th>Chan #</th>
<th>Crawl Tests (MPa)</th>
<th>Dynamic Tests° (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Inside</td>
<td>Outside</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inside</td>
<td>Outside</td>
</tr>
<tr>
<td>FB63 Top E</td>
<td>99</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>FB63 Top W</td>
<td>100</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>FB64 Top W</td>
<td>101</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>FB64 Bot W</td>
<td>102</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>FB64 Top E</td>
<td>103</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>FB64 Bot E</td>
<td>104</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>FB65 Top E</td>
<td>105</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>FB65 Top W</td>
<td>106</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>

Notes 1. Speed of Truck was 48km/h (30mph).
For all tests in which the truck was headed west, the peak stress in each floorbeam tie plate always occurs on the east face first. Figure 5.2 shows the in-plane and out-of-plane stress components in the tie plate as the test truck passes over floorbeam 63E. (This out-of-plane stress can also be thought of a lateral horizontal in-plane stress). It is clear that there are measurable (although small) out-of-plane bending stresses being generated in the top flange tie plates. Note in Figure 5.2 the stress reversal in the out-of-plane components. Table 5.2 lists the maximum measured in and out-of-plane stress ranges measured at each tie plate for this test. The out-of-plane stresses are slightly less at floorbeam 64E. (It should be noted that during the dynamic tests, the trucks were several hundred feet away from the instrumented section of roadway prior to and after a given dynamic test, due to the additional distance required for acceleration and deceleration, the same response was observed. Thus, the lower proportion of out-of-plane stress at floorbeam 64E is not attributed to the position of the test truck or symmetry.) As expected, during tests in which the truck was traveling in the opposite direction (i.e., headed east), the peak stress first occurred on the west face (see Figure 5.6).

<table>
<thead>
<tr>
<th>Floorbeam</th>
<th>In Plane Stress MPa (ksi)</th>
<th>Out of Plane Stress</th>
<th>% Out-of-Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>63E</td>
<td>9.0 (1.3)</td>
<td>2.5 (0.4)</td>
<td>28</td>
</tr>
<tr>
<td>64E</td>
<td>9.0 (1.3)</td>
<td>2.2 (0.3)</td>
<td>24</td>
</tr>
<tr>
<td>65E</td>
<td>9.2 (1.3)</td>
<td>2.4 (0.4)</td>
<td>26</td>
</tr>
</tbody>
</table>

Table 5.2 – Comparison of In and Out-of Plane Stress Ranges Measured at Floorbeam 63E, 64E, and 65E (Test Truck in the Outside Lane at a Crawl Speed Headed West)

This response is similar and consistent with the behavior observed in floorbeams of girder bridges. In fact, out-of-plane bending stresses (or lateral horizontal in-plane bending stresses) have been found to dominate the response of tie plates in several highway bridges [9, 10]. Although the specific details of the structural system are different, the actual mechanics of the behavior of the two deck systems is actually quite similar. In either system, the deck is a relatively stiff with respect to vertical in-plane bending. The cantilever floorbeam web is a simple web-angle connection that offers little resistance to horizontal forces. The tie plate, which is bolted to the top flange of the floorbeam and the truss chord is quite stiff. As vehicles pass, a shear force (and therefore a relative horizontal displacement) occurs between the deck and the floorbeam. This horizontal force is resisted by the stiff tie plate. The fact that the effect is less in the bottom flange is also consistent with the behavior observed in girder bridges.

Measured stresses are compared in Figure 5.3 for channel 102, which is located on the west face of the bottom flange of floorbeam 64E, for the following three cases:

1. One truck located in the inside lane.
2. One truck located in the outside lane.
3. Both trucks side by side.
As expected, Figure 5.3 indicates that peak stresses (moments) increase as the truck moves to the outside lane due to the increase in the moment arm. Also, peak stresses increase when two trucks are placed side by side. It is interesting to note that by superimposing the peak stress of 2.7 MPa obtained for a single truck located in the inside lane with that of 7.0 MPa obtained for a single truck in the outside lane, the expected stress for two trucks side by side would be 9.7 MPa. This is identical to the measured stress of 9.7 MPa for the case when two trucks are located side by side. Similar observations were made at the other floorbeams. Any variation or discrepancy can most likely be attributed to the variability in truck position and weight (the GVW of the two test trucks was not identical). It is also important to note that the test truck generates only one cycle per passage. This will be discussed further below.

Figure 5.3 – Effect of Truck Position on Measured Stress Range in Bottom Flange. Floorbeam 64E Shown, Test Trucks Headed West (CH 102)

The Williamsburg Bridge carries two tracks of commuter rail traffic down the middle of the structure. During the controlled load test program, commuter trains often passed. Figure 5.4a presents measured stresses at floorbeam 64E during a typical crawl test with the truck in the outside lane. However, during this test a commuter train passed. The effect is seen as a smaller magnitude sinusoidal response riding on the primary cycle. A dashed line is added to indicate that the cycles are essentially in phase in both the bottom and top flange.

It was initially thought that the passing commuter train was exciting the suspension of the test truck. However, a close look at the time history revealed that this could not be the case since the period of the cycle is about 2.5 seconds (0.4Hz), which exceeds the natural period of the truck suspension. It is believed to be the direct
influence of the “trucks” or wheels on each of the commuter cars. As the cars pass, the
deflection of the interior floorbeam (which supports the tracks) is applying deformations
through the truss floorbeam connection into the cantilever floorbeam. The effect is
observed in each floorbeam consecutively. This is seen in Figure 5.4b. The response of
channels 100, 101, and 106, all of which are located on the west side of the floorbeam tie
plates, are plotted as a train is passing.

Figure 5.4b compares the response from time t=6 to 20 seconds. (It should be
noted the time histories were adjusted in Figure 5.4a to start near 0 MPa at the beginning
of the time history for clarity). The effect first occurs at floorbeam 63 (CH99), then is
observed at floorbeam 64E (CH103), and finally at floorbeam 65E (CH105). The
opposite response was observed as the train left the instrumented area. Thus, the train is
headed west, to Brooklyn.

![Figure 5.4a – Effect of Passing Commuter Train on Floorbeam Response During a
Typical Crawl Test (Floorbeam 64E Shown, Test Truck Headed West in Outside Lane)](image-url)
The mean response at channel CH101 is also shown in Figure 5.4a. This corresponds to the response that would be expected if the train were not passing. A comparison with the results shown in Figure 5.1 indicates that the passing train has little effect on the mean response of the floorbeam. The amplitude of the sinusoidal curve produced by the train is only about 7MPa (1ksi). Thus, the maximum increase in stress range is only 3.5MPa (0.5ksi). Because the magnitude of the additional stress is so small, it is considered negligible at this location.

It is also worth noting that there are two trains passing in Figure 5.4a. The first is headed west (between 10 and 35 seconds) while the second is headed east (between 40 and 75 seconds). The magnitude of the stress range increases as the eastbound train passes, since the eastbound track is the south track and therefore closer to the south truss and strain gages. In addition, the time between peaks is greater, indicated the train was traveling at a slightly lower speed. Each train in Figure 5.4a produces 9 sub-cycles.
Although not discussed in detail, other observations on the response of the floorbeams were made during the controlled load tests. These are listed below.

1. Two tests were conducted in which the tests trucks were slowly driven across the deck following one another in the outside lane to simulate a truck grouping during heavy traffic conditions. The measured response of the floorbeam indicated that the passage of both trucks still produced a single stress cycle. However, the peak stress range was 40% to 50% greater in magnitude.

2. The passage of a single-axle test truck produced one stress cycle. The effects of individual axles cannot be distinguished in the time histories of floorbeam response.

3. There was no measurable change in the response of the floorbeams due to the addition of the wearing surface.
5.1.2 Floorbeam Response - Dynamic Tests

Figure 5.5 compares the response at channels located at floorbeam 64E for both 24 and 48km/h (15 & 30mph) dynamic tests conducted with the single-axle test truck. The test truck was located in the outside lane during both of these tests. From Figure 5.5, it is clear that there is little difference in the measured response from each test. The dynamic test also produced a single dominant cycle as the test truck crossed the panel.

Although each truck passage produces one dominant stress cycle, it is apparent a smaller higher frequency vibration was also introduced. The magnitude of these cyclic stresses is very small, less than 3.4Mpa (0.5ksi). A Fast Fourier Transformation (FFT) of the response indicates a free vibration of about 5Hz. The same frequency response was observed in both the 24km/h (15mph) and 48km/h (30mph) tests. Table 5.1 summarizes the peak response stress-range data.

Figure 5.6 presents measured stresses in the top flange tie plate and bottom flange of floorbeam 64E during the passage of the tandem-axle test truck (see Table 5.1). The truck was headed east and the speed was approximately 48km/h (30mph). The peak stress range was doubled to 18MPa and 22MPa for channels 101 and 104, respectively. The same out-of-plane response was observed in the top flange tie plate as the tandem-axle truck passed. Note though, that the peak stress occurs on the west side (CH101) before the peak stress on the east side (CH103) of the top flange. This is opposite of what was observed when the single-axle truck passed because the single-axle truck was headed west and the tandem-axle truck was headed east. This is consistent with the previous discussion regarding the tie plate behavior. The response in the bottom flange was almost purely in plane.
In Figure 5.7, only channels 101 and 102 are plotted for clarity. The two peaks in the time history correspond to the front and rear axles of the truck and are identified in Figure 5.7 by the vertical lines. Note, that the front and rear axle group of the tandem-axle truck however, produces a single, larger peak. (Throughout this report, the term *axle group* refers to a set of 2 or more closely spaced axles.) The individual axles of the single-axle truck were not observable. Presumably because the GVW of the single-axle test truck was considerably less than the tandem-axle truck and the rear axle weight was not as great.

![Figure 5.6 –Response of Floorbeam 64E Due to Tandem-Axle Test Truck (48km/h (30mph) Test Truck Headed East)](image_url)
Figure 5.7 – Response of Floorbeam 64E Due to Tandem-Axle Test Truck. Note the Individual Peaks Due to the Front and Rear Axles (48km/h (30mph) Test Truck Headed East)
5.2 Longitudinal Rib Response

Strain gages were installed on the bottom flange of several longitudinal ribs at two different transverse sections (see Figure 3.1). One section was located in the negative moment region, approximately 0.3m (1ft) west of floorbeam 64E. The other section was located in the positive moment region, approximately 2.44m (8ft) west of floorbeam 64E. In addition, gages were also installed on the deck plate adjacent to ribs 5 and 7 in order to determine the effect (if any) of the wearing surface on the location of the neutral axis.

5.2.1 Longitudinal Rib Response - Crawl Tests

Figure 5.8 presents measured strains in the positive moment region as a single-axle test truck passed in the inside lane prior to the application of the wearing surface. Data are plotted for all gages located on the bottom of the ribs. It is clear that ribs 6, 7, and 9, located in the inside lane, directly beneath the truck, are the most highly stressed. The individual effects of the front and rear axles can be seen in these ribs. As expected, stresses produced in ribs 1, 2, and 5, located toward the outside of the cantilever, are considerably less. In addition, the response is more “global” at ribs 1 and 2, as the effects of the individual axles cannot be distinguished. (See Figure 4.4 for locations of wheels.)

![Figure 5.8 – Response of Floorbeam 64E Due to Single-Axle Test Truck Located in the Inside Lane. Note the Individual Peaks Due to the Front and Rear Axles (Crawl Speed, Test Truck Headed West, With Out Wearing Surface)](image)

Figure 5.9 illustrates the response in the same ribs as shown in Figure 5.8, but for a test in which the truck was located in the outside lane prior to the application of the wearing surface. As expected, the ribs located toward the outside of the cantilever are the

50
highest stressed. The peak stress in ribs 2 and 5 is higher for this load case than for ribs 6, 7, and 9 when the test truck was located in the inside lane.

![Figure 5.9](image)

Table 5.2 compares the maximum stress ranges measured in the positive moment region for tests conducted with the test truck placed in the inside lane, outside lane, and side by side, with and without the wearing surface.

<table>
<thead>
<tr>
<th>Chan #</th>
<th>Rib #</th>
<th>Without Wearing Surface (MPa)</th>
<th>With Wearing Surface (MPa)</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td>Inside Lane</td>
<td>Outside Lane</td>
</tr>
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<td>15</td>
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</tr>
<tr>
<td>82</td>
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<td>17</td>
<td>9</td>
</tr>
<tr>
<td>86</td>
<td>9</td>
<td>14</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 5.2 – Maximum Stress Ranges Measured on the Bottom of Ribs in the Positive Moment Region

The data in Table 5.2 indicates that the greatest decrease in stress range, after the wearing surface was applied, was about 4MPa (0.6ksi). This decrease is small and some
of the difference is attributed to variations in GVW and transverse position of the test trucks. Nevertheless, there is a slight decrease in the peak stress range for the gages installed directly on the deck plate since the stresses at this location are the result of both global bending and direct wheel loads. Figure 5.10 compares data from gages on Rib 5 and the deck plate, immediately adjacent to the rib wall (see Figure 4.4 for wheel locations). The gages on the deck plate (channels 77 & 78) are directly loaded by passing wheels and some local effects could be expected. The gages installed on the deck plate indicate that it is acting as a top (i.e., compression) flange with almost no stress reversal. However, it is apparent that the neutral axis is near the deck plate and the magnitude of the stress is small.

The results in Table 5.2 and Figures 5.8 and 5.9 suggest that there is greater load distribution taking place among the ribs when the truck is in the outside lane. However, when the truck is located in the inside lane, the ribs located near the tip of the cantilever, carry less load. This is because the interior ribs are subjected to more curvature and more rigidly supported on the cantilever floorbeam. The deck is “pulled down” with the deflecting floorbeam, most notably when the truck is in the outside lane.

![Figure 5.10](image.png)

**Figure 5.10 – Comparison of Measured Response in Rib and Deck Plate Before and After the Application of the Wearing Surface in Positive Moment Region (Crawl Speed, Single-Axle Test Truck Headed West in the Outside Lane, Rib 5)**
Figures 5.11 and 5.12 and Table 5.3, compare measurements made on the ribs in the negative moment region. These gages are located 0.3m (1ft) west of floorbeam 64E. The load response characteristics observed in the negative moment region are quite different. In both figures it is apparent that the bottom flange of rib 1 experiences a tensile stress range, regardless of truck position. However, at the interior ribs, a stress reversal is developed when the wheel is over the rib. This indicates that the exterior ribs are following the deflected shape of the floorbeam due to compatibility and therefore undergo a positive bending moment. Again, the deck is “pulled down” with the deflecting floorbeam. This effect is most easily observed in rib 1 where, regardless of truck position, a negative moment is never produced adjacent to the floorbeam (Compare Figures 5.11, 5.12, and 5.13). (This is discussed further in Section 5.2.3)

When the truck is in the outside lane, the effect is most pronounced since the curvature and deflection of the floorbeam is greatest for this load case. This observation reinforces and partially explains the apparent decrease in load distribution among the exterior ribs when the truck is in the inside lane, as discussed above. The individual effects of the front and rear axles are also apparent in the ribs that are most heavily loaded.

Table 5.3 compares measurements made before and after the application of the wearing surface for all three load cases in the negative moment region. There is no significant difference in measurements made before and after the application of the wearing surface. It should also be noted, that, similar to the response of the floorbeam, adding the results obtained from inside and outside lane positions yields the measured response during the test in which both trucks were side by side. Again, the best agreement occurs in the measurements made after the application of the wearing surface, though it is unlikely these two factors are related.
Figure 5.11 – Comparison of Measured Response in Rib Before the Application of the Wearing Surface in the Negative Moment Region
(Crawl Speed, Single-Axle Test Truck Headed West in the Inside Lane)

Figure 5.12 – Comparison of Measured Response in Rib Before the Application of the Wearing Surface in the Negative Moment Region
(Crawl Speed, Single-Axle Test Truck Headed West in the Outside Lane)
<table>
<thead>
<tr>
<th>Chan #</th>
<th>Rib #</th>
<th>Without Wearing Surface (MPa)</th>
<th>With Wearing Surface (MPa)</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
<td>Inside Lane</td>
<td>Outside Lane</td>
</tr>
<tr>
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<td>1</td>
<td>7</td>
<td>9</td>
</tr>
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<td>7</td>
<td>10</td>
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<td>85</td>
<td>9</td>
<td>12</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5.3 – Maximum Stress Ranges Measured on the Bottom of Ribs in the Negative Moment Region

5.2.2 Longitudinal Rib Response - Dynamic Response

Figure 5.13 presents stresses measured in the positive moment region of the ribs due to the single-axle test truck located in the outside lane. Table 5.4 lists the maximum stress ranges produced in each of the ribs in the positive moment region.

Figure 5.13 – Comparison of Measured Response in Rib After the Application of the Wearing Surface in the Positive Moment Region (48km/h, Single-Axle Test Truck Headed East in the Outside Lane)
A comparison of the data in Table 5.4 reveals that there is no difference in the stress range produced during crawl or dynamic tests. This is attributed to the smoothness of the newly placed wearing surface and the gently curving profile of the roadway.

Figure 5.14 presents stresses measured in the positive moment region of the rib due to the tandem-axle test truck located in the outside lane. It is clear, as expected, that the tandem-axle truck generates a considerably greater stress range, although the shape of the response curves are similar (i.e., Figure 5.14 vs. 5.13). At locations where the stress was of a significant magnitude (>7Mpa (1ksi)), the stress range produced by the tandem-axle truck was divided by the stress range produced by the single-axle truck. The ratio in the measurements were found to average about 2.8 for both lane positions, which is comparable to the ratio of the rear axle weights of the test trucks, which was 2.9 (243kN/83kN=2.9). This confirms the fact that it is the heavy axle(s) that have the greatest effect on the magnitude of the peak stress range during a vehicle passage.

In the positive moment region the load distribution characteristics were independent of the type of truck. However, in the negative moment region the contributions to the stress-range cycle were significantly different in the vicinity of the floorbeam. Lighter vehicles like the single-axle test truck caused more stress reversal than the heavier tandem-axle test truck. These characteristics are apparent in Figures 5.11 through 5.14.

<table>
<thead>
<tr>
<th>Chan #</th>
<th>Rib</th>
<th>Crawl Tests&lt;sup&gt;2,4&lt;/sup&gt; (MPa)</th>
<th>Dynamic Tests&lt;sup&gt;1,2&lt;/sup&gt; (MPa)</th>
</tr>
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<td></td>
<td></td>
<td>Inside</td>
<td>Outside</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inside</td>
<td>Outside</td>
</tr>
<tr>
<td>72</td>
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<tr>
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<tr>
<td>86</td>
<td>9</td>
<td>11</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5.4 – Comparison of Maximum Stress Ranges on the Bottom of the Ribs in the Positive Moment Region During Crawl and Dynamic Tests

1. Speed of truck was 48km/h (30mph).
2. Tests conducted after application of wearing surface.
3. Test truck headed east.
4. Test truck headed west.
Figure 5.14 – Comparison of Measured Response of Ribs After the Application of the Wearing Surface in the Positive Moment Region (48km/h, Tandem-Axle Test Truck Headed East in the Outside Lane)

Table 5.5 – Comparison of Maximum Stress Ranges on the Bottom of the Ribs in the Negative Moment Region During Crawl and Dynamic Tests

Table 5.5 compares the maximum stress ranges from the crawl and dynamic tests in the negative moment regions of the ribs. As in the positive moment region, there is no observable difference in the measurements that would suggest there is any significant dynamic amplification.

Tests with the tandem-axle truck located in the inside lane suggest that a considerable amount of load was distributed to the exterior ribs. For example, the highest...
stress range was measured at channel 71, which is located at rib 1, near the cantilever tip. In almost every other test in which the truck was in the inside lane, the stresses in rib 1 are the lower than other ribs. (Some of this is attributed to the transverse position of the test truck. During testing it was apparent that the transverse position of the test truck was shifted to the south (i.e., not entirely in the inside lane).)

Figure 5.15a – Comparison of Measured Response of Ribs After the Application of the Wearing Surface in the Negative Moment Region
(48km/h, Tandem-Axle Test Truck Headed East in the Inside Lane)

The time history for the test truck in the inside lane is shown in Figure 5.15a. It can be seen that the bottom of ribs 1 and 2 (CH71 and CH73) are entirely in tension as the tandem-axle truck passes in the inside lane. This response is similar to the response shown in Figure 5.11. In addition, the stress reversals in ribs 5 and 6 are small as the heavy tandem-axle truck passed. A similar response was observed when the tandem-axle test truck was positioned in the outside lane, as shown in Figure 5.15b.

Since the floorbeam is flexible, tensile stresses could be expected in the bottom of ribs 1 and 2 due to the deflection of the floorbeam. Consider the example of a continuous beam (rib) on elastic supports. If a point load were applied directly over the centerline of the support (floorbeam), a positive moment would be produced in the beam (rib) over the support (floorbeam). However, on the deck, the load is moving and is directly over the floorbeam for only an instant. At all other load positions, a negative moment and a positive moment (due to the deflection of the floorbeam) are generated in the beam (rib). The addition or superposition of these two moments produces the final stress condition in the rib. For the lighter single-axle truck, the GVW and proportion of axle loads is such that rib curvature (and therefore negative moment), is low and does not dominate. As a result, a positive moment is produced in the rib due to the deflection or “settling” of the
floorbeam. However, for the heavy tandem-axle truck, the GVW and proportion of axle loads is such that the rib curvature dominates the response and the effect of the deflecting floorbeam is overshadowed. Only small stress reversals are produced. This behavior further illustrates the very complex interaction between the orthotropic deck and supporting system. (This behavior, and in particular the influence on the response of the diaphragm plate is discussed in Section 5.4.1.4).

Figure 5.15b – Comparison of Measured Response of Ribs After the Application of the Wearing Surface in the Negative Moment Region (48km/h, Tandem-Axle Test Truck Headed East in the Outside Lane)
5.3 Response at Transverse Groove Weld

5.3.1 Transverse Groove Weld - Crawl Tests

A total of 8 strain gages were installed on the deck plate near the transverse groove weld. These gages were oriented in the longitudinal direction (see Figures 3.1 & 3.5).

Table 5.6 - Measured Stress Ranges at Gages Installed on the Deck Plate at the Transverse Deck Splice Prior to the Application of the Wearing Surface

Table 5.6 lists the maximum stress range produced by the rear axle at each gage for each transverse position prior to the application of the wearing surface. Only the stress range produced by the rear axle is listed since it dominates the response (see Figure 5.16). The peak stress ranges were produced when the truck was located in the outside lane.

Table 5.7 - Measured Stress Ranges at Gages Installed on the Deck Plate at the Transverse Deck Splice After the Application of the Wearing Surface

Table 5.7 lists the maximum stress range produced by the rear axle at each gage for each transverse position after the application of the wearing surface. Note that individual wheels were placed over rib 5 or between ribs 5 and 6 for some tests (see Figure 3.5). A comparison of Tables 5.6 and 5.7 shows that both decreases and increases were observed after the application of the wearing surface at these locations. Some variability was expected due to variations in the transverse position of the wheels and
because the magnitudes of the wheel loads which were not well defined (see Section 4.1.1).

Table 5.7 indicates that the maximum stress range in the deck plate at the cope was always less than 10MPa (1.4ksi). The maximum occurred when the test truck was placed in the outside lane. For this case, the peak stress range on each side of the rib splice (channels 95 & 97 or 92 & 94), were almost identical across the splice (see Table 5.7). This is due to the symmetry of the connection and identical geometry on each side of the splice.

Figure 5.16 illustrates a typical response from a crawl test with one of the wheels of the test truck positioned directly over rib 5 (see Figures 3.5 & 4.4). For clarity, only the response from channels 95, 96, 97, and 98 are shown. The response due to both the front and rear wheels can be identified and are shown on the plot. It should be noted that the peak response of channels 95 & 98 are slightly out-of-phase with channels 96 & 97 since these gages are at different longitudinal positions on the deck plate.

![Diagram of stress response](image)

**Figure 5.16 – Comparison of Measured Response Near Transverse Weld After the Application of the Wearing Surface in the Negative Moment Region (Crawl Test, Single-Axle Test Truck Headed West, Rear Wheel Centered Over Rib 5)**

Although, tests were not conducted with the tandem axle truck positioned directly over the instrumented portion of the welded splice, the effects can be estimated. As shown in Figure 5.16, each axle produces a unique stress peak as the single-axle truck passed. It was observed that each of the rear axles of the tandem-axle truck also produce individual peaks. (This observation was also apparent from measurements during the uncontrolled monitoring and will be discussed later.)
It is reasonable to assume that the stresses produced by the heavier axles of the tandem-axle truck are proportional to the axle loads. The ratio of the rear axle loads is about 1.5 (see Tables 4.1 & 4.2). Therefore, the stresses produced by the tandem-axle truck could be estimated as about $1.5 \times 9\text{MPa}$ or about $13.5\text{MPa}$ ($2.0\text{ksi}$), which are also quite low. Tests were not conducted with the tandem-axle truck positioned directly over the instrumented portion of the welded splice.

### 5.3.2 Transverse Groove Weld - Dynamic Tests

Table 5.8 summarizes and compares measurements at the transverse deck weld made during results of crawl and speed runs. As can be seen, there is no appreciable difference in the measurements, thereby suggesting there is no dynamic amplification. Again, this is attributed to the new condition of the wearing surface.

<table>
<thead>
<tr>
<th>Chan. #</th>
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<th>Truck Position</th>
<th>Inside Lane</th>
<th>Outside Lane</th>
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<tbody>
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<td></td>
<td></td>
<td></td>
<td>Crawl Run MPa (ksi)</td>
<td>48km/h Lane MPa (ksi)</td>
</tr>
<tr>
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<td>Btwn. Ribs 4&amp;5</td>
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<td>1 (0.1)</td>
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<td>2 (0.3)</td>
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<tr>
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<td>Btwn. Ribs 4&amp;5</td>
<td>Inside Lane</td>
<td>1 (0.1)</td>
<td>1 (0.1)</td>
</tr>
<tr>
<td>94</td>
<td>Near Cope</td>
<td>Inside Lane</td>
<td>2 (0.3)</td>
<td>2 (0.3)</td>
</tr>
<tr>
<td>95</td>
<td>Btwn. Ribs 5&amp;6</td>
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<td>3 (0.4)</td>
<td>3 (0.4)</td>
</tr>
<tr>
<td>96</td>
<td>Near Cope</td>
<td>Inside Lane</td>
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<td>2 (0.3)</td>
</tr>
<tr>
<td>97</td>
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<td>Inside Lane</td>
<td>3 (0.4)</td>
<td>3 (0.4)</td>
</tr>
<tr>
<td>98</td>
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<td>Inside Lane</td>
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<td>2 (0.3)</td>
</tr>
<tr>
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<td>Outside Lane</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Crawl Run MPa (ksi)</td>
<td>48km/h Lane MPa (ksi)</td>
<td>Crawl Run MPa (ksi)</td>
</tr>
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<td>91</td>
<td>Btwn. Ribs 4&amp;5</td>
<td>Outside Lane</td>
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<td>Near Cope</td>
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<td>2 (0.3)</td>
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<tr>
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<td>3 (0.4)</td>
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<td>Outside Lane</td>
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<td>2 (0.3)</td>
</tr>
</tbody>
</table>

Table 5.8 - Comparison of Crawl and Dynamic Stress Ranges at Gages Installed on the Deck Plate at the Transverse Deck Splice After the Application of the Wearing Surface
5.4 Diaphragm Response

The response and behavior at the rib/diaphragm connection was the primary focus of the field and laboratory measurements. Because the response of this connection is quite complex, the general behavior of the rib/diaphragm connection as observed in the field will be discussed first. This will then be followed by detailed discussions pertaining to the effect of wearing surface, effect of vehicle speed; in-plane and out-of-plane stress components, and the effect of vehicle position.

5.4.1 Diaphragm Response - Crawl Tests

5.4.1.1 General Behavior

Typical time history data measured at a diaphragm and bulkhead plate located adjacent to rib 5 of floorbeam 64E are presented in Figures 5.17a and 5.17b. This crawl test was conducted after the application of the wearing surface with the single-axle test truck positioned in the outside lane. The most obvious observation is that the area near the cutout is subjected to the greatest stress range and peak stress (CH27 & 29 and CH35 & 36). Stresses on the internal bulkhead are lower at corresponding locations. As shown in the detailed gage plans (Figures 3.2, 3.3, & 3.4), the bulkhead gages were located 25mm (1in) away from the weld toe and are oriented horizontally and not perpendicular, to the rib wall in order to avoid damage to the gage during welding. Both of these factors contribute to the lower stress ranges measured. In both the laboratory and field tests, it was observed that the response at rib 5 is most often larger and typical of the behavior of most ribs. Therefore, the behavior of rib 5 will be the focus of this section.

Figure 5.17a – Typical Response at Diaphragm Plate at Rib/Diaphragm Connection After the Application of the Wearing Surface
(Crawl Speed, Single-Axle Test Truck Headed West in the Outside Lane)
Figure 5.17b – Typical Response at Back-to-Back Gages Installed on the Diaphragm Plate at Rib/Diaphragm Connection After the Application of the Wearing Surface (Crawl Speed, Single-Axle Test Truck Headed West in the Outside Lane)

Behavior, similar to that shown in Figures 5.17a and 5.17b, was observed in the diaphragm plates at other floorbeams and other ribs. This general behavior and the most significant observations can be characterized as follows:

1. Typically, the highest stresses were observed when one test truck was positioned in the outside lane or when the trucks were placed side-by-side. For these load cases, tension stresses were measured near the cutout in the diaphragm plate on the south or “cantilever” side of the rib (i.e., CH27 & 35) while compression stresses were measured at gages located on the north or “fixed” side (i.e., CH29 & 36).

2. Effects of individual front and rear axles could be observed in the time history data measured near the cutout. The effect of each axle was more pronounced in gages on the diaphragm plate that were closer to the deck plate (compare the response of channels 25 & 26 with channels 27 & 29 in Figure 5.17a). The effect of the two individual rear axles of the tandem-axle truck was not apparent.

3. Stresses at the top of the diaphragm plate and perpendicular to the rib wall were less than those near the cutout (compare the response of channels 25 & 26 with channels 27 & 29). As a result, the response at the top of the diaphragm plate will not be discussed further.
4. The magnitude of stresses in diagonally opposite bulkhead gages were of the same sign and typically lower in magnitude at the bottom of the bulkhead plate throughout the stress cycle (see Figure 5.17b). Although these gages were oriented horizontally, the data suggests the presence of a tension diagonal stress field as observed in the laboratory testing [4]. The lower bulkhead gages were typically compatible with the response of the adjacent gages on the diaphragm plate.

5. At locations where strain gages were placed back-to-back on the diaphragm plate adjacent to the cutout, both in-plane and out-of-plane stresses were calculated. The magnitudes and proportions of the in-plane and out-of-plane stresses at a given rib were affected by the position of the test truck.
5.4.1.2 Effect of Wearing Surface

Figure 5.18 compares measurements at channels 27 and 29 before and after the application of the wearing surface. These gages are located adjacent to the cutout on the east face of the south and north sides of rib 5, respectively. The data indicate that there is only a small difference between the two tests. Some of the difference can be attributed to the variations in transverse position and the GVW of the test trucks. The stresses in the diaphragm plate are primarily influenced by in-plane forces, from shear and bending, as well as out-of-plane bending caused by rotation of the ribs. These force effects are essentially independent of the wearing surface. Thus, a smooth wearing surface will not have any significant influence on behavior at this location.

Figure 5.18 – Comparison of Measured Response on Diaphragm Plate Near Cutout Before and After the Application of the Wearing Surface (Crawl Speed, Single-Axle Test Truck Headed West in the Outside Lane)
Table 5.9 compares data taken before and after the application of the wearing surface at gages installed near the rib cutouts. Data from all three transverse positions are listed. Both increases and decreases were observed reinforcing the fact that the wearing surface has no effect at this location.

<table>
<thead>
<tr>
<th>Chan #</th>
<th>Rib # /Flrbm</th>
<th>Without Wearing Surface</th>
<th>With Wearing Surface</th>
</tr>
</thead>
<tbody>
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<td></td>
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<td>Outside Lane</td>
</tr>
<tr>
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</tr>
<tr>
<td>56</td>
<td>5/65E</td>
<td>5</td>
<td>29</td>
</tr>
</tbody>
</table>

Table 5.9 - Comparison of Measured Response on Diaphragm Plate Near the Cutout
Before and After the Application of the Wearing Surface
(Single-Axle Test Trucks Only, Crawl Speed)
5.4.1.3 Effect of Vehicle Speed

Dynamic speed runs were conducted with the test truck positioned in each lane. Table 5.10 compares the response at ribs 5 and 7 for a crawl run and a 48km/h (30mph) dynamic test. These data are from tests conducted after the application of the wearing surface. The data collected during the 24km/h (15mph) tests were found to be in agreement with the 48km/h (30mph) tests and are therefore not listed in the table. The measured stress ranges are about the same for each test, confirming there is negligible dynamic amplification.

<table>
<thead>
<tr>
<th>Chan. #</th>
<th>Gage Location Rib/floorbeam</th>
<th>Inside Lane</th>
<th>Outside Lane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crawl Run MPa (ksi)</td>
<td>48km/h Lane MPa (ksi)</td>
<td>Crawl Run MPa (ksi)</td>
</tr>
<tr>
<td>1</td>
<td>5/63E</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>5/63E</td>
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<tr>
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<td>7</td>
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</tr>
<tr>
<td>56</td>
<td>5/65E</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

Notes
1. These data are from a 24km/h test. A maximum speed of 24km/h was limited for safety reasons.
5.4.1.4 In-Plane and Out-of-Plane Stress Components

At locations where gages were placed back-to-back on the diaphragm plate, the proportions of the in-plane and out-of-plane components could be calculated. Back-to-back gages were only installed near the cutouts since this was identified as the critical location in the laboratory tests.

Figure 5.19 – Comparison of In and Out-of-Plane Stresses at Diaphragm Plate Near Cutout After the Application of the Wearing Surface. Channels 27 and 35 Shown (Crawl Speed, Single-Axle Test Truck in Outside Lane Headed West)

In-plane stresses were calculated as the average of measurements made at back-to-back strain gages. The out-of-plane stress components were then calculated as the difference between the in-plane stress component and the actual gage measurement. Resulting time histories from two typical tests, one with the single-axle and one tandem-axle test truck, each positioned in the outside lane, are presented in Figures 5.19 and Figures 5.20, respectively.

Tables 5.11 and 5.12 list the magnitude of the in-plane and out-of-plane stress ranges due to the passage of the single and tandem-axle test trucks respectively. The out-of-plane stress range is also expressed in terms of the percentage of the in-plane stress range. Note that the out-of-plane stress range component clearly dominates the cycle when the single-axle test truck is positioned in the inside lane. However, the proportion of the out-of-plane stress-range drops significantly when the test truck passes in the outside lane, although the magnitude often increases.
The time histories presented in Figures 5.19 and 5.20 are very similar in shape. The out-of-plane stress cycle is also similar for each truck, although the second sub-cycle is more pronounced for the tandem-axle truck. This is attributed to the greater axle loads and different distribution of loads with the tandem-axle truck. The out-of-plane response of channels 27 and 35 or 29 and 36 is different in each figure due to the different travel directions of the test trucks. The most important observation is that the stress-range cycle is dominated by the in-plane stress component and a single truck passage produces a single dominant stress cycle.
Table 5.11- Calculated In and Out-of-Plane Stress Ranges in Diaphragm Plate Adjacent to Cutout (Single-Axle Truck, Crawl Speed)

The large increase in the proportion of the out-of-plane stress range in the diaphragm plate is related to the rotation of the longitudinal ribs. Whether a rib is located toward the fixed or free end of the cantilever, the amount each rib is rotated is about the same when subjected to the same load. This is because the relative stiffness and boundary conditions for each closed rib is essentially the same. It was previously stated that ribs directly under a wheel load rotate nearly the same amount at the floorbeam regardless of the transverse position of the rib. Since the diaphragm plate is attached to the rib at the floorbeam, it is also forced to rotate with the rib and produce out-of-plane stresses consistent with the magnitude of the rotation. Comparing the response of the ribs listed in Table 5.4, it can be seen that the magnitude of the stress range in each rib is about the same for the same loading conditions. This implies that the bending moment and rotation would also be similar. However, the in-plane stress component in the diaphragm plate at rib 5 decreased considerably as the truck is positioned in the inside lane. Thus, although the magnitude of the out-of-plane stress range actually remains about the same, its contribution in the total stress-range cycle increases.

The results summarized in Tables 5.11 and 5.12 demonstrate that when the lighter single-axle vehicle is in the inside lane, the horizontal shear in the diaphragm is decreased at ribs 5 & 6 and the rotation of the rib dominates the stress range in the diaphragm plate. The heavier tandem-axle truck results in much larger in-plane bending
effects as seen in Table 5.12, with the truck in the inside lane. Both vehicles resulted in much higher in-plane stresses when they were in the outside lane and a substantial decrease in the out-of-plane response of the diaphragm plate.

<table>
<thead>
<tr>
<th>Stress Component</th>
<th>Location</th>
<th>Channel</th>
<th>Inside Lane</th>
<th>Outside Lane</th>
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</thead>
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<tr>
<td></td>
<td></td>
<td></td>
<td>MPa</td>
<td>%&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>In-Plane</td>
<td>Rib 5</td>
<td>CH1 &amp; CH5</td>
<td>34</td>
<td>-</td>
</tr>
<tr>
<td>Out-of-Plane</td>
<td>FB63E</td>
<td>CH1</td>
<td>18</td>
<td>53</td>
</tr>
<tr>
<td>In-Plane</td>
<td>Rib 5</td>
<td>CH5</td>
<td>18</td>
<td>53</td>
</tr>
<tr>
<td>Out-of-Plane</td>
<td>FB63E</td>
<td>CH2 &amp; CH6</td>
<td>48</td>
<td>-</td>
</tr>
<tr>
<td>Out-of-Plane</td>
<td>Rib 5</td>
<td>CH2</td>
<td>21</td>
<td>44</td>
</tr>
<tr>
<td>Out-of-Plane</td>
<td>FB63E</td>
<td>CH6</td>
<td>21</td>
<td>44</td>
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<tr>
<td>In-Plane</td>
<td>Rib 5</td>
<td>CH27 &amp; CH35</td>
<td>47</td>
<td>-</td>
</tr>
<tr>
<td>Out-of-Plane</td>
<td>FB63E</td>
<td>CH27</td>
<td>20</td>
<td>43</td>
</tr>
<tr>
<td>Out-of-Plane</td>
<td>FB64E</td>
<td>CH35</td>
<td>20</td>
<td>43</td>
</tr>
<tr>
<td>In-Plane</td>
<td>Rib 5</td>
<td>CH29 &amp; CH36</td>
<td>59</td>
<td>-</td>
</tr>
<tr>
<td>Out-of-Plane</td>
<td>FB64E</td>
<td>CH29</td>
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<td>42</td>
</tr>
<tr>
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<td>FB64E</td>
<td>CH36</td>
<td>25</td>
<td>42</td>
</tr>
<tr>
<td>In-Plane</td>
<td>Rib 6</td>
<td>CH39 &amp; CH41</td>
<td>26</td>
<td>-</td>
</tr>
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<td>CH39</td>
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</tr>
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<td>19</td>
<td>73</td>
</tr>
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<td>Rib 6</td>
<td>CH40 &amp; CH42</td>
<td>32</td>
<td>-</td>
</tr>
<tr>
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<td>63</td>
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<td>CH45 &amp; CH51</td>
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<td>CH45</td>
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<td>CH51</td>
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<td>FB64E</td>
<td>CH52</td>
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<td>74</td>
</tr>
</tbody>
</table>

Notes:
1. Ratio of the out-of-plane stress range to the in-plane stress range expressed as a percent.
2. The test truck was partially in the outside lane (i.e., lane 8) during this test, thus the data are slightly skewed due to this. It was difficult for the driver to get as close to the parapet during this 48km/h (30mph) test as compared to the tests conducted with the single-axle test truck.

Table 5.12- Calculated In and Out-of-Plane Stress Ranges in Diaphragm Plate Adjacent to Cutout (Tandem-Axle Truck, 48km/h)
5.4.1.5 Effect of Transverse Position of Test Truck

The overall response of the diaphragm plate to the single-axle and tandem-axle test trucks was similar. Each vehicle produced a single primary stress-range cycle as it passed over a floorbeam and the heavy rear axle(s) dominated the response. Table 5.13 summarizes the measured stress ranges for the single-axle and tandem-axle test trucks. With the exception of the data shown for the single-axle trucks located in both lanes, all data presented in Table 5.13 are from dynamic tests. No crawl tests were conducted using the tandem-axle test truck.

<table>
<thead>
<tr>
<th>Chan #</th>
<th>Rib # /Flrbm</th>
<th>Single-Axle Test Truck MPa (ksi)</th>
<th>Tandem-Axle Test Truck MPa (ksi)</th>
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<td>Outside Lane¹</td>
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<td>5/63E</td>
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<td>5/63E</td>
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<td>56</td>
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<td>6</td>
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</tbody>
</table>

Notes
1. These data are from a dynamic test.
2. These data are from a crawl test. Two trucks were not positioned side by side for dynamic tests for safety reasons.

Table 5.13 - Comparison of Measured Stress Range in Diaphragm Plate Near the Cutout for the Single-Axle and Tandem-Axle Test Trucks

The data in Table 5.13 for single-axle test trucks in the inside and outside lanes indicate that direct superposition is sometimes at variance with the test results with two single-axle test trucks crossing side by side. Some of this can be attributed to variation in truck position. On average, the agreement is worst at ribs 5 and 6. This observation is not surprising since vehicles that are directly above a given rib most heavily influence stresses at the cutout.

It can also be seen that a truck placed in the inside lane has a relatively small effect on rib 5. In fact, the stress ranges produced with a single test truck in the outside lane are nearly equal to the stress ranges produced by trucks in both lanes.

A review of the time history data from individual tests provides insight as to why the stress range is over estimated when the results from the inside and outside lanes are
superimposed. Figure 5.17b illustrated the response adjacent to the cutout at rib 5 of floorbeam 64E as the single-axle test truck passed in the outside lane. When the test truck was positioned in the inside lane, a different response was produced. Figure 5.21 compares the response at the cutout at FB64E for channels CH27 and CH29 for two test runs; one with the single-axle test truck located in the inside lane and one with it in the outside lane. With the test truck positioned in the outside lane, the response at channels CH27 & CH29 is approximately equal in magnitude and opposite in sign. However, when the test truck is positioned in the inside lane, the stress cycles produced at CH27 and CH29 are significantly reduced.

![Figure 5.21 - Comparison of Measured Stress Range in FB64E Diaphragm Plate Near the Cutout for the Single-Axle Test Truck in the Inside and Outside Lanes. (Crawl Speed)](image)

Although the magnitude of the stress produced by the single-axle test truck at channels CH27 & CH29 is small, it indicates that the peak stress and stress range at a given rib produced by trucks placed side-by-side can be less than that produced by one truck in the outside lane. The effect is most notable at north side of rib 5 (CH27 of rib 5). Simply superimposing the measured stress range for a given channel (i.e., adding the data in the 3rd and 4th columns in Table 5.13) does not consider if the cycle was a tensile or compressive cycle. However, if the magnitude of the stress is considered, the small increases and even slight reductions in stress range shown in Table 5.13 for ribs 5 and 6 are apparent. For rib 7, which is located beneath the inside lane, the effect is less pronounced. It is clear that simple superposition of the results from tests with the trucks placed in the inside and outside lanes overestimates the actual measured stress range when both trucks cross side by side.
This effect was not as apparent during tests utilizing the tandem-axle test truck. Often, the tandem-axle test truck was not entirely centered in the inside lane. Thus, the effect would be expected to be less pronounced. Nevertheless, although tests were not conducted with tandem-axle test trucks placed side by side, it is reasonable to assume that the same trend in behavior, as illustrated in Table 5.13, would occur with the tandem-axle truck.

Figure 5.22- Compressive Stress at Channel 27 Due to a Random Truck Passing in the Inside Lane

Compressive stresses were also observed on both sides of rib 5 during remote monitoring. Figure 5.22 presents a time history which illustrates this behavior from a random truck located in the inside lane. The response of channels CH45 and CH46 (rib 7) is as expected; approximately equal in magnitude and opposite in sign. However, the response of channels CH27 & CH29; located on rib 5 in the outside lane, indicates that both sides of the rib go into compression with some reversal in CH29. In this case, the magnitude of the compressive stress at channel CH27 is about -25MPa (-3.6ksi). Hence, with two trucks placed side-by-side, superposition using the test data in Table 5.13 would reduce the stress range at channel CH27. Clearly then, a single heavier truck in the outside lane results in a higher stress range. This observation and the test results presented in Table 5.13 indicate that the “project specific” design criteria do not produce the maximum effects at all locations in the diaphragm plate. This observation will be discussed more fully below.
The results presented in Table 5.14 are from tests conducted using the single-axle test truck. Also included are calculated values assuming a single heavy truck weighing twice the test truck was located in the outside lane. Comparing the measured and calculated results, it is clear that a single truck weighing twice the test vehicle would produce considerably greater stresses in ribs 5, 6, and 7 than two individual trucks passing side-by-side.

Table 5.14 confirms that a single heavy truck in the outside lane produces greater stresses than two lighter trucks passing side-by-side. Since the roadway is narrow on the south outer roadway, it is more likely to have a single heavy truck pass in one lane than two trucks side-by-side.

Data collected during the laboratory Phase IIB testing [4] also verified this observation. During Phase IIB, a simulated truck with a total GVW of 3.1xHS-15 (including impact) was used for the test. Hence, the loading position used in the Phase IIB laboratory test accurately and conservatively simulated in service conditions.

<table>
<thead>
<tr>
<th>Chan #</th>
<th>Rib # /Flrbm</th>
<th>Single-Axle Test Truck MPa (ksi)</th>
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<th>Both Lanes²</th>
<th>2 x Outside Lane³</th>
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<td></td>
</tr>
</tbody>
</table>

Notes
1. These data are from a dynamic test.
2. These data are from a crawl test. Two trucks were not positioned side by side for dynamic tests for safety reasons.
3. Calculated value obtained by multiplying the stress range measured with the test truck located in the outside lane by 2.0.

Table 5.14 – Comparison of effects of test trucks in the outside lane (measured) and the effect of doubling the weight of the truck (calculated). Note for the single axle test truck, doubling the weight of the truck in the outside lane almost always produces a greater stress range.
6.0 Results of Remote Long-Term Monitoring

Remote long-term monitoring of selected strain gages was conducted continuously over a period of six months beginning in early August of 1998 and ending in late January of 1999. The long-term monitoring program produced a large volume of time history data at several locations. In addition, stress-range histograms were developed at 44 different locations.

The results of the long-term monitoring are discussed in this chapter. The data from the triggered time histories and stress-range histograms will be presented for each element monitored. However, data from other channels and elements may be referenced in each section in order to fully describe a given point or aspect of behavior. The interpretation of the results of the long-term monitoring program can be found in Chapter 7. Strain gages that were inoperative are not included in the tables.

<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Channel Number</th>
<th>COMMENTS - LOCATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CH-27</td>
<td>Triggered Time History/ Rainflow - FB64E Rib 5 S.E. Corner</td>
</tr>
<tr>
<td>2</td>
<td>CH-29</td>
<td>Triggered Time History/ Rainflow - FB64E Rib 5 N.E. Corner</td>
</tr>
<tr>
<td>3</td>
<td>CH-45</td>
<td>Triggered Time History/Rainflow - FB64E Rib 7 S.E. Corner</td>
</tr>
<tr>
<td>4</td>
<td>CH-46</td>
<td>Triggered Time History/ Rainflow - FB64E Rib 7 N.E. Corner</td>
</tr>
<tr>
<td>5</td>
<td>CH-1</td>
<td>Rainflow Histogram Only - FB63E Rib 5 S.E. Corner</td>
</tr>
<tr>
<td>6</td>
<td>CH-2</td>
<td>Rainflow Histogram Only - FB63E Rib 5 N.E. Corner</td>
</tr>
<tr>
<td>7</td>
<td>CH-5</td>
<td>Rainflow Histogram Only - FB63E Rib 5 S.W. Corner</td>
</tr>
<tr>
<td>8</td>
<td>CH-6</td>
<td>Rainflow Histogram Only - FB63E Rib 5 N.W. Corner</td>
</tr>
<tr>
<td>9</td>
<td>CH-35</td>
<td>Rainflow Histogram Only - FB64E Rib 5 S.W. Corner</td>
</tr>
<tr>
<td>11</td>
<td>CH-39</td>
<td>Rainflow Histogram Only - FB64E Rib 6 S.E. Corner</td>
</tr>
<tr>
<td>14</td>
<td>CH-42</td>
<td>Rainflow Histogram Only - FB64E Rib 6 N.W. Corner</td>
</tr>
<tr>
<td>15</td>
<td>CH-51</td>
<td>Rainflow Histogram Only - FB64E Rib 7 S.W. Corner</td>
</tr>
<tr>
<td>16</td>
<td>CH-52</td>
<td>Rainflow Histogram Only - FB64E Rib 7 N.W. Corner</td>
</tr>
<tr>
<td>17</td>
<td>CH-55</td>
<td>Rainflow Histogram Only - FB65E Rib 5 S.W. Corner</td>
</tr>
<tr>
<td>18</td>
<td>CH-56</td>
<td>Rainflow Histogram Only - FB65E Rib 5 N.W. Corner</td>
</tr>
<tr>
<td>19</td>
<td>CH-101</td>
<td>Rainflow Histogram Only - FB64E West Top Flange</td>
</tr>
<tr>
<td>20</td>
<td>CH-102</td>
<td>Rainflow Histogram Only - FB64E West Bottom Flange</td>
</tr>
</tbody>
</table>

Table 6.1 – Channels Included in First Monitoring Period (August 5th to September 3rd 1998)
6.1 Details of Monitoring Program

As stated in Chapter 3, three different groups of channels were monitored during this portion of the field testing. Tables 6.1, 6.2, and 6.3 list the specific channels considered during each monitoring period.

<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Channel Number</th>
<th>COMMENTS - LOCATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CH-27(^1)</td>
<td>Triggered Time History/ Rainflow – FB64E Rib 5 S.E. Corner</td>
</tr>
<tr>
<td>2</td>
<td>CH-29(^1)</td>
<td>Triggered Time History/ Rainflow - FB64E Rib 5 N.E. Corner</td>
</tr>
<tr>
<td>3</td>
<td>CH-45(^1)</td>
<td>Triggered Time History/Rainflow - FB64E Rib 7 S.E. Corner</td>
</tr>
<tr>
<td>4</td>
<td>CH-46(^1)</td>
<td>Triggered Time History/ Rainflow - FB64E Rib 7 N.E. Corner</td>
</tr>
<tr>
<td>5</td>
<td>CH-1(^1)</td>
<td>Rainflow Histogram Only - FB63E Rib 5 S.E. Corner</td>
</tr>
<tr>
<td>6</td>
<td>CH-2(^1)</td>
<td>Rainflow Histogram Only - FB63E Rib 5 N.E. Corner</td>
</tr>
<tr>
<td>7</td>
<td>CH-87D</td>
<td>Rainflow Histogram Only – On Deck Perp. to South Side of Rib 6</td>
</tr>
<tr>
<td>8</td>
<td>CH-88D</td>
<td>Rainflow Histogram Only – On Deck Perp. to North Side of Rib 5</td>
</tr>
<tr>
<td>9</td>
<td>CH-89D</td>
<td>Rainflow Histogram Only – On Deck Perp. to South Side of Rib 5</td>
</tr>
<tr>
<td>11</td>
<td>CH-91</td>
<td>Rainflow Histogram Only - Transverse Weld Near FB 65E</td>
</tr>
<tr>
<td>14</td>
<td>CH-94</td>
<td>Rainflow Histogram Only - Transverse Weld Near FB 65E</td>
</tr>
<tr>
<td>15</td>
<td>CH-95</td>
<td>Rainflow Histogram Only - Transverse Weld Near FB 65E</td>
</tr>
<tr>
<td>16</td>
<td>CH-96</td>
<td>Rainflow Histogram Only - Transverse Weld Near FB 65E</td>
</tr>
<tr>
<td>17</td>
<td>CH-97</td>
<td>Rainflow Histogram Only - Transverse Weld Near FB 65E</td>
</tr>
<tr>
<td>18</td>
<td>CH-98</td>
<td>Rainflow Histogram Only - Transverse Weld Near FB 65E</td>
</tr>
<tr>
<td>19</td>
<td>CH-101(^1)</td>
<td>Rainflow Histogram Only - FB64E West Top Flange</td>
</tr>
<tr>
<td>20</td>
<td>CH-102(^1)</td>
<td>Rainflow Histogram Only - FB64E West Bottom Flange</td>
</tr>
</tbody>
</table>

Table 6.2 – Channels Included for Second Period of Monitoring (September 27\(^{th}\) to November 27\(^{th}\) 1998)
### Table 6.3 – Channels Included for Third Period of Monitoring (December 13\textsuperscript{th} 1998 to January 22\textsuperscript{nd} 1999)

<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Channel Number</th>
<th>COMMENTS - LOCATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CH-27\textsuperscript{1}</td>
<td>Triggered Time History/ Rainflow – FB64E Rib 5 S.E. Corner</td>
</tr>
<tr>
<td>2</td>
<td>CH-29\textsuperscript{1}</td>
<td>Triggered Time History/ Rainflow - FB64E Rib 5 N.E. Corner</td>
</tr>
<tr>
<td>3</td>
<td>CH-45\textsuperscript{1}</td>
<td>Triggered Time History/Rainflow - FB64E Rib 7 S.E. Corner</td>
</tr>
<tr>
<td>4</td>
<td>CH-46\textsuperscript{1}</td>
<td>Triggered Time History/ Rainflow - FB64E Rib 7 N.E. Corner</td>
</tr>
<tr>
<td>5</td>
<td>CH-1</td>
<td>Rainflow Histogram Only - FB67E Rib 5 S.E. Corner</td>
</tr>
<tr>
<td>6</td>
<td>CH-3</td>
<td>Rainflow Histogram Only - FB67E Rib 5 N.E. Corner</td>
</tr>
<tr>
<td>7</td>
<td>CH-5</td>
<td>Rainflow Histogram Only - FB67E Rib 5 S.W. Corner</td>
</tr>
<tr>
<td>8</td>
<td>CH-7</td>
<td>Rainflow Histogram Only - FB67E Rib 5 N.W. Corner</td>
</tr>
<tr>
<td>9</td>
<td>CH-87R</td>
<td>Rainflow Histogram Only – On South Side of Rib 6 Perp. to Deck</td>
</tr>
<tr>
<td>10</td>
<td>CH-88R</td>
<td>Rainflow Histogram Only – On North Side of Rib 5 Perp. to Deck</td>
</tr>
<tr>
<td>11</td>
<td>CH-89R</td>
<td>Rainflow Histogram Only – On South Side of Rib 5 Perp. to Deck</td>
</tr>
<tr>
<td>12</td>
<td>CH-90R</td>
<td>Rainflow Histogram Only – On North Side of Rib 4 Perp. to Deck</td>
</tr>
<tr>
<td>13</td>
<td>CH-87D</td>
<td>Rainflow Histogram Only – On Deck Perp. to South Side of Rib 6</td>
</tr>
<tr>
<td>14</td>
<td>CH-88D</td>
<td>Rainflow Histogram Only – On Deck Perp. to North Side of Rib 5</td>
</tr>
<tr>
<td>15</td>
<td>CH-89D</td>
<td>Rainflow Histogram Only – On Deck Perp. to South Side of Rib 5</td>
</tr>
<tr>
<td>16</td>
<td>CH-90D</td>
<td>Rainflow Histogram Only – On Deck Perp. to North Side of Rib 4</td>
</tr>
<tr>
<td>17</td>
<td>CH-75</td>
<td>Rainflow Histogram Only – Bot of Rib 5 305mm(1ft) West of FB64#</td>
</tr>
<tr>
<td>18</td>
<td>CH-76</td>
<td>Rainflow Histogram Only – Bot of Rib 5 2438mm(8ft) West of FB64#</td>
</tr>
<tr>
<td>19</td>
<td>CH-81</td>
<td>Rainflow Histogram Only – Bot of Rib 7 305mm(1ft) West of FB64#</td>
</tr>
<tr>
<td>20</td>
<td>CH-82</td>
<td>Rainflow Histogram Only – Bot of Rib 7 2438mm(8ft) West of FB64#</td>
</tr>
</tbody>
</table>

#### Notes:
1. These channels also were recorded during first and second periods of the monitoring program.

**6.2 Floorbeam Response to Random Traffic**

During the first and second monitoring periods, two gages mounted on the flanges of floorbeam 64E were monitored. Specifically, CH101, which is located on the tension tie plate, and CH102, which is located on the bottom flange (see Tables 6.1 and 6.2). For locations of these gages see Figures 3.1, 3.7a, and 3.7b.

Compared to data collected at the other locations on the orthotropic deck, the response of the floorbeams is always more “global” in nature. In addition, the behavior of cantilevered floorbeams in general is well understood and is relatively unbiased by the local effects of the orthotropic deck.

**6.2.1 Triggered Time Histories - Floorbeam**

Figures 6.1, 6.2 and 6.3 illustrate the response of floorbeam 64E to three different types of truck configurations. In addition to channels CH101 and CH102, these figures also contain time history data from CH89D, mounted on the deck plate 1524mm (5ft) west of FB64E. Channel CH89D is very sensitive to individual wheel loads. Thus, it can be used to accurately identify the axle configuration of the truck crossing the structure.
Figure 6.1 – Response at Channels 101 and 102 of Floorbeam 64E During the Passage of a Random Three-Axle “H” Series Truck

Figure 6.1 illustrates the response at the floorbeam during the passage of a typical 3 axle “H” series truck. Because the longitudinal positions of the strain gages mounted on the deck are known, the axle spacing and the speed of the truck can be estimated quite accurately. The estimated axle spacing and speed of the truck are listed in Table 6.4.
### Table 6.4 – Estimated Speed and Geometry of Three Random Trucks Recorded During Long-Term Remote Monitoring

<table>
<thead>
<tr>
<th>Figure</th>
<th>Truck Type / Total Truck Length</th>
<th>Estimated Speed km/h (mph)</th>
<th>L1 mm (in)</th>
<th>L2 mm (in)</th>
<th>L3 mm (in)</th>
<th>L4 mm (in)</th>
<th>L5 mm (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>3 Axle “H” Series / 5.79m (19’-0&quot;)</td>
<td>40 to 43 (25 to 27)</td>
<td>4370 (172)</td>
<td>1420 (56)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6.2</td>
<td>6 Axle “HS” Series 12.63m (41’-5&quot;)</td>
<td>42 to 45 (26 to 28)</td>
<td>4190 (165)</td>
<td>1475 (58)</td>
<td>4290 (168)</td>
<td>1345 (53)</td>
<td>1345 (53)</td>
</tr>
<tr>
<td>6.3</td>
<td>5 Axle “HS” Series 15.0m (49’-3&quot;)</td>
<td>21 to 24 (13 to 15)</td>
<td>3505 (138)</td>
<td>1500 (59)</td>
<td>8790 (346)</td>
<td>1220 (48)</td>
<td>-</td>
</tr>
</tbody>
</table>

**Figure 6.2 – Response at Channels 101 and 102 of Floorbeam 64E During the Passage of a Random Six-Axle Short “HS” Series Truck**
Figure 6.3 – Response at Channels 101 and 102 of Floorbeam 64E
During the Passage of a Long Random 5-Axle “HS” Series Truck

The overall shape of the floorbeam time history curve shown in Figure 6.1 is the same as that discussed previously in Chapter 5 (see Figures 5.6 & 5.7). This is expected since the overall geometry of this random 3-axle truck is very similar to the geometry of the tandem-axle test truck. The response to the 6-axle HS truck shown in Figure 6.2 and described in Table 6.4 is similar to that shown in Figure 6.1. This is because the “clear” distance between the heavy axle groups (i.e., L3 in Table 6.4) is relatively short, about 4.3m (14’-0”).

The response shown in Figure 6.3 clearly demonstrates the effect of increasing total vehicle length beyond the 6.1m (20ft) spacing of the floorbeams. The clear distance between the heavy axles (i.e., L3 in Table 6.4) is estimated to be 8.8m (28’-10”). As can be seen in Figure 6.3, there are two small distinct stress peaks produced by the passage of this truck. The tractor, which appears slightly heavier, produces the first and the second is produced by the trailer.

More important however, is that there is only one major stress cycle produced per truck. The total length between axles of the truck response shown in Figure 6.3 is about 15m (49’-3”), which is approaching the maximum legal length for an HS truck. Thus, a truck would have to be considerably longer to produce more than one primary stress cycle.
6.2.2 Stress-Range Histograms - Floorbeam

Table 6.5 summarizes the data collected during the first and second monitoring periods. The effective stress range for each channel was calculated and is shown Table 6.6. The effective stress range was calculated by excluding all stress-range cycles less than 20MPa. (The rationale for this procedure is discussed in detail in Section 7.4.) Also shown in the table is the number of cycles that exceeded the constant amplitude fatigue limit (CAFL) of the detail. The percent exceedence is also provided. Table 6.6 also lists the maximum stress range taken directly from the rainflow cycle count. Prior to calculating the effective and maximum stress ranges, the data were reviewed. Data contained in the rainflow tables were compared to triggered time histories for CH101 & CH102 and other channels in order to establish if the data were consistent. The data in the rainflow tables were also compared to the results of the controlled load tests. After this review, the maximum stress range was then determined.

Table 6.5 – Summary of Stress-Range Histograms for CH101 & CH102 of Floorbeam 64E Collected During the First and Second Monitoring Periods

<table>
<thead>
<tr>
<th>Bin #</th>
<th>Bin Range MPa</th>
<th># Cycles CH101</th>
<th># Cycles CH102</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20-25</td>
<td>2050</td>
<td>2305</td>
</tr>
<tr>
<td>2</td>
<td>25-30</td>
<td>595</td>
<td>880</td>
</tr>
<tr>
<td>3</td>
<td>30-35</td>
<td>175</td>
<td>374</td>
</tr>
<tr>
<td>4</td>
<td>35-40</td>
<td>73</td>
<td>207</td>
</tr>
<tr>
<td>5</td>
<td>40-45</td>
<td>49</td>
<td>145</td>
</tr>
</tbody>
</table>

Table 6.6 – Maximum and Effective Stress Ranges for CH101 & CH102 of Floorbeam 64E

<table>
<thead>
<tr>
<th>Channel / Location</th>
<th>First Period¹ &amp; Second Period²</th>
<th></th>
<th></th>
<th>Total # Cycles¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_{max}$ MPa (ksi)</td>
<td># Cycles &gt; CAFL³</td>
<td>$S_{reff}$ MPa (ksi)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$S_{max}$ MPa (ksi)</td>
<td>$#$</td>
<td>$%$</td>
<td></td>
</tr>
<tr>
<td>101/FB64E T.F.</td>
<td>43 (6.2)</td>
<td>0</td>
<td>0.00%</td>
<td>25 (3.6)</td>
</tr>
<tr>
<td>102/FB64E B.F.</td>
<td>43 (6.2)</td>
<td>0</td>
<td>0.00%</td>
<td>27 (3.9)</td>
</tr>
</tbody>
</table>

Notes
1. The first monitoring period covered 1 month - August 5th - September 3rd 1998.
2. The second monitoring period covered approximately 2 months - September 27th to November 27th 1998.
3. Assumes Category B, see Chapter 7.

Table 6.6 – Maximum and Effective Stress Ranges for CH101 & CH102 of Floorbeam 64E

The fatigue resistance of the bolted tension tie plate and the bolted bottom flange correspond to Category B details. There were no cycles that exceeded the CAFL of this detail. It is apparent that the maximum stress range is small compared to the CAFL for
6.3 Transverse Groove Weld Response to Random Traffic

Some orthotropic decks have developed fatigue cracks adjacent to this detail. Cracks have been observed to develop in the deck plate and are similar to those developed from out-of-plane web gap distortion in plate girders. However, there is little data on in-service stresses at the deck plate detail. Six channels installed near the transverse groove weld deck splice were included in the second monitoring period. Triggered time histories were collected at selected intervals and stress-range histograms were developed for all six channels.

Although eight gages were installed, CH92 and CH93 were very noisy and no meaningful data were collected.

6.3.1 Triggered Time Histories - Transverse Groove Weld

Figure 6.4 illustrates the response at channels CH91 and CH95, which are adjacent to the transverse deck weld during the passage of two random trucks (See Figure 3.6 for locations). The response produced by the first truck indicates that one line of the wheels was located very near to CH95, which is installed adjacent to the cope. However, the same truck has a minimal influence on the response at CH91, which is located between ribs 4 and 5. This implies that the wheel footprint was shifted toward rib 6. Although not shown in Figure 6.4, the response at gages CH96 and CH98 are also consistent with this observation. The stress range produced by the second truck is primarily tensile at CH91. However, the stress range at CH95 is rather small, implying that the wheel footprint was between ribs 4 and 5.

Table 6.8 also lists the maximum stress range for each gage. Prior to calculating the effective and maximum stress ranges, the data were reviewed and compared to
triggered time histories for these six channels as well as other channels in order to establish if the data were consistent. The data in the stress-range histograms were also compared to the results of the controlled load tests. The maximum stress range was determined after assuring that no stray signals were present in the data. From Table 6.8 it can be seen that no cycles exceeded the CAFL, which is assumed to be Category C, as discussed in Chapter 7.0.

Figure 6.4 – Response at Channels 91 and 95 Located Near Rib 5 Adjacent to the Deck Plate Transverse Groove Weld During the Passage of Two Random Trucks
<table>
<thead>
<tr>
<th>Bin #</th>
<th>Bin Range MPa</th>
<th># Cycles CH91</th>
<th># Cycles CH94</th>
<th># Cycles CH95</th>
<th># Cycles CH96</th>
<th># Cycles CH97</th>
<th># Cycles CH98</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20-25</td>
<td>687</td>
<td>142</td>
<td>1826</td>
<td>458</td>
<td>458</td>
<td>762</td>
</tr>
<tr>
<td>2</td>
<td>25-30</td>
<td>105</td>
<td>83</td>
<td>519</td>
<td>83</td>
<td>83</td>
<td>255</td>
</tr>
<tr>
<td>3</td>
<td>30-35</td>
<td>42</td>
<td>60</td>
<td>137</td>
<td>18</td>
<td>18</td>
<td>98</td>
</tr>
<tr>
<td>4</td>
<td>35-40</td>
<td>20</td>
<td>40</td>
<td>66</td>
<td>4</td>
<td>11</td>
<td>31</td>
</tr>
<tr>
<td>5</td>
<td>40-45</td>
<td>15</td>
<td>37</td>
<td>32</td>
<td>2</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>45-50</td>
<td>7</td>
<td>23</td>
<td>26</td>
<td>1</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>7</td>
<td>50-55</td>
<td>4</td>
<td>10</td>
<td>10</td>
<td>1</td>
<td>1</td>
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<td>8</td>
<td>55-60</td>
<td>-</td>
<td>2</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes
1. Channels CH92 and CH93 were not operational and are not listed.

Table 6.7 – Summary of Stress-Range Histograms for Channels Adjacent to the Transverse Groove Weld Near Floorbeam 65E

<table>
<thead>
<tr>
<th>Channel / Location</th>
<th>Second Period1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( S_{\text{max}} ) MPa (ksi)</td>
</tr>
<tr>
<td>91/FB65E Btwn. Ribs 4&amp;5.</td>
<td>52 (7.6)</td>
</tr>
<tr>
<td>94/FB65E Near Cope.</td>
<td>58 (8.4)</td>
</tr>
<tr>
<td>95/FB65E Btwn. Ribs 4&amp;5.</td>
<td>58 (8.4)</td>
</tr>
<tr>
<td>96/FB65E Near Cope.</td>
<td>52 (7.6)</td>
</tr>
<tr>
<td>97/FB65E Btwn. Ribs 4&amp;5.</td>
<td>52 (7.6)</td>
</tr>
<tr>
<td>98/FB65E Btwn. Ribs 4&amp;5.</td>
<td>48 (6.9)</td>
</tr>
</tbody>
</table>

Notes
1. Second period covered approximately 2 months of monitoring; September 27th to November 27th 1998.
2. Assumes Category C, see Chapter 7.

Table 6.8 – Maximum and Effective Stress Ranges for Channels Adjacent to the Transverse Groove Weld Near Floorbeam 65E
6.4 Longitudinal Rib Response to Random Traffic

During the third monitoring period, four gages on longitudinal ribs 5 and 7 were monitored. Specifically, CH76 and CH82, located in the positive moment region between FB64E & FB65E and CH75 and CH81, located in the negative moment region near FB64E. Triggered time histories were collected during selected intervals throughout the monitoring period. In addition, stress-range histograms were developed for all four gages.

6.4.1 Triggered Time Histories – Longitudinal Ribs

Figure 6.5 illustrates the response of ribs 5 and 7 during the passage of a random truck. The gages located near the negative moment region demonstrated that stress reversals occur. Gages located on the deck plate indicated that this truck was a three-axle “H” type truck, similar in overall geometry to the tandem-axle test truck. The response is similar to the controlled load tests and was typical for most trucks. However, occasionally an atypical response was also observed. Figure 6.6 illustrates such a response that was recorded on Saturday, December 12, 1998 at 5:24PM. The response of rib 7, shown in Figure 6.6, is considerably different than that shown in Figure 6.5 and what was observed during the controlled load tests. The gages on rib 5 were not as different.

![Figure 6.5](image)

Figure 6.5 – Response at Channels on Ribs 5 and 7 in the Positive and Negative Moment Region During the Passage of a Random Truck

The gages installed on the deck plate and diaphragm plate indicated that the vehicle crossed the bridge in the inside lane (lane 7). It was also observed that this vehicle was traveling slower than most other trucks. Although the exact axle configuration of this truck is unknown, review of all the gages suggests that this vehicle...
had several closely spaced axles (note CH81 and CH82). The vehicle is thought to be a slow moving heavy vehicle (like a crane) traveling in the inside lane. Since the vehicle is moving slower than normal traffic, the driver likely kept the vehicle very near the gutter line of the inside lane to allow faster moving traffic to pass. Hence, the response of rib 7 would likely be affected the most, as illustrated in Figure 6.6. Other passing trucks or commuter trains could also have an influence this atypical behavior.

![Figure 6.6 – Atypical Response at of Ribs 5 and 7 in the Positive and Negative Moment Region During the Passage of a Random Truck](image)

It should be noted that it is not important that the exact vehicle type and axle configuration be identified for this vehicle. Although in many cases accurate estimates can be made, there is no way of knowing precisely what the exact geometry and GVW is for any random truck. What is important is that the measurements show that the in-service response of the deck system is complex and that unusual stress cycles and stress reversals will occur in both the positive and negative moment region.
6.4.2 Stress-Range Histograms – Longitudinal Ribs

Table 6.9 summarizes the data collected from gages installed on the longitudinal ribs. The effective and maximum stress range for each channel was calculated and is listed in Table 6.10. Also included in Table 6.10 are the number of cycles exceeding the CAFL and the percent exceedence. The effective stress range was calculated by excluding all stress-range cycles less than 20MPa. Data contained in the stress-range histograms were also compared to the triggered time histories for these 4 channels and to other channels. The data were also compared to the results of the controlled load tests. Only after a comprehensive review of the data was made were the histograms completed.

<table>
<thead>
<tr>
<th>Bin #</th>
<th>Bin Range MPa</th>
<th># Cycles CH75 Rib 5 Neg. Mom.</th>
<th># Cycles CH76 Rib 5 Pos. Mom.</th>
<th># Cycles CH81 Rib 7 Neg. Mom.</th>
<th># Cycles CH82 Rib 7 Pos. Mom.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20-25</td>
<td>2072</td>
<td>6416</td>
<td>1865(^1)</td>
<td>5777</td>
</tr>
<tr>
<td>2</td>
<td>25-30</td>
<td>489</td>
<td>3607</td>
<td>325(^1)</td>
<td>3162</td>
</tr>
<tr>
<td>3</td>
<td>30-35</td>
<td>128</td>
<td>1659</td>
<td>85</td>
<td>1077</td>
</tr>
<tr>
<td>4</td>
<td>35-40</td>
<td>66</td>
<td>873</td>
<td>35</td>
<td>457</td>
</tr>
<tr>
<td>5</td>
<td>40-45</td>
<td>22</td>
<td>453</td>
<td>20(^1)</td>
<td>228</td>
</tr>
<tr>
<td>6</td>
<td>45-50</td>
<td>20</td>
<td>235</td>
<td>34</td>
<td>89</td>
</tr>
<tr>
<td>7</td>
<td>50-55</td>
<td>7</td>
<td>105</td>
<td>16</td>
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<tr>
<td>8</td>
<td>55-60</td>
<td>6</td>
<td>39</td>
<td>5</td>
<td>22</td>
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<tr>
<td>9</td>
<td>60-65</td>
<td>2</td>
<td>23</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>10</td>
<td>65-70</td>
<td>1</td>
<td>9</td>
<td>2</td>
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<tr>
<td>11</td>
<td>70-75</td>
<td>-</td>
<td>11</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>75-80</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes
1. The data for channel 81 contained several noise spikes that artificially increased the number of cycles in the lower bins. As a result, the number of cycles in the lower bins was calibrated to the other channels and "cleaned" as required.

![Stress-Range Histograms](image-url)

Table 6.9 – Summary of Stress-Range Histograms for Gages on Longitudinal Ribs
From Table 6.9, it can be seen that channels CH76 and CH82, located in the positive moment region, are in good agreement with respect to the number of cycles in each bin and the total number of cycles accumulated over the period. The cycle count data for channel CH81 originally contained a large number of “noise spikes” in the lower bins, as noted in Table 6.9. After a thorough review of the triggered time history data and comparison to the data from the other channels, the noise spikes were removed. As can be seen in Table 6.10, the data for channel CH81 compares well with CH75. The proportion of cycles between channels CH75 and CH82 is similar to that between CH76 and CH82.

As shown, there were no cycles that exceeded the CAFL, which is assumed to be Category A, on the base metal of the longitudinal ribs. However, it should be noted that gages located in the negative moment region were not placed adjacent to the rib/diaphragm or bulkhead/rib welds. The transverse weld at this location is a Category C detail (CAFL=69MPa (10ksi)). At midspan, the weld connecting the intermediate diaphragm and the rib is also a Category C detail. The controlled load tests confirmed that the neutral axis is near the top of the rib due to the deck plate action as a top flange. Thus, stress ranges are most likely low at these details.

<table>
<thead>
<tr>
<th>Channel/Location</th>
<th>$S_{\text{max}}$ MPa (ksi)</th>
<th>Cycles $&gt;CAFL^2$</th>
<th>$S_{\text{eff}}$ MPa (ksi)</th>
<th>Total # Cycles$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH75/Rib 5 @ Neg. Mom Region</td>
<td>68 (9.9)</td>
<td>0</td>
<td>26 (3.7)</td>
<td>2813</td>
</tr>
<tr>
<td>CH76/Rib 5 @ Pos. Mom Region</td>
<td>78 (11.3)</td>
<td>0</td>
<td>30 (4.3)</td>
<td>13432</td>
</tr>
<tr>
<td>CH81/Rib 7 @ Neg. Mom Region</td>
<td>68 (9.9)</td>
<td>0</td>
<td>26 (3.7)</td>
<td>2388</td>
</tr>
<tr>
<td>CH82/Rib 7 @ Pos. Mom Region</td>
<td>68 (9.9)</td>
<td>0</td>
<td>28 (4.0)</td>
<td>10858</td>
</tr>
</tbody>
</table>

Notes
2. The data for channel 81 contained several noise spikes that artificially increased the number of cycles in the lower bins. As a result, the number of cycles in the lower bins was calibrated to the other channels and “cleaned” as required.
3. Assumes Category A, see section 7.

Table 6.10 – Maximum and Effective Stress Ranges for Gages on Longitudinal Ribs
6.5 Deck Plate/Rib Wall Response to Random Traffic

Prior to beginning the third period of monitoring, four (4) strain gages were added to the rib walls (See Section 3.1). These gages were oriented vertically and perpendicular to the deck plate. Each gage was placed in-line with the existing gages (i.e., CH87D through CH90D) mounted on the deck plate. Some orthotropic decks have experienced cracking at the rib/deck plate connection [11, 12]. However, there is little information pertaining to actual in-service stress ranges at this connection. Stress-range histograms were developed for all 8 of these channels for the entire third monitoring period.

6.5.1 Triggered Time Histories – Deck Plate/Rib Wall

Triggered time histories were recorded for all channels mounted at the deck plate/rib wall connection on two occasions during the third monitoring period.

A review of the time history data revealed that there was considerable variability in the stress range produced by a passing wheel load. For gages mounted on the deck plate or rib wall, stresses were either tension or compression, depending on the transverse position of the wheel load. Figure 6.7 illustrates such behavior during the passage of two random trucks for CH90R adjacent to Rib 4. Note that each truck produces a different stress cycle; the first truck produces a tension stress range, while the second truck produces a compression stress range. The small stress cycle after the first truck is believed to be a passenger car.

![Figure 6.7 – Response at CH90R Adjacent to Rib 4 Due to the Passage of Two Random Trucks](image-url)

(Note that the first truck produces a tension stress range while the second truck produces a compressive stress range)
In Figure 6.7, the first and second trucks produce 32MPa (4.6ksi) and 25MPa (3.6ksi) stress ranges, respectively. However, for fatigue evaluation, it is the stress range that is of importance. As a result, the peak and valley produced by each truck is added and would result in a stress range of 57MPa (8.3ksi). The stress ranges in the upper bins of the histogram shown in Table 6.10, are likely the result of adding positive and negative stress cycles from adjacent vehicles and are not necessarily produced by individual trucks.

An extensive review of the triggered time history data was made to gain insight into the behavior of the connection, since controlled load data were unavailable for CH87R to CH90R. From this review, it was apparent that the behavior of this connection is very sensitive to the transverse position of the wheel footprint. Nevertheless, some general trends in the data were observed and are discussed.

For CH88R and CH89R, installed on opposite sides of rib 5, the stress at CH88R was mainly in tension while at CH89R it was mainly compression. This behavior is illustrated in Figure 6.8. All three of the passing trucks produced positive stress in CH88R and negative stresses in CH89R. The magnitude of the stress range at each location for each truck is roughly about the same. However, the behavior was not always this consistent. Rib 5 is the only location in which gages were installed on each side of a rib. Although it is assumed that this behavior would be observed at other interior ribs, it could not be verified with the current instrumentation.

![Figure 6.8 – Response at CH88R and CH89R Adjacent to Rib 5 Due to the Passage of Three Random Trucks](image_url)
For most events, each axle of a passing truck produces an individual stress cycle, as illustrated in Figure 6.9. The response at CH90R and CH90D at Rib 4 for a typical HS truck demonstrates that each axle produces an individual stress range cycle. This response is characteristic of deck elements directly beneath the wheel load.

This indicates that the passing wheel loads dominate the vertical stresses measured on the rib wall. This was also true for transverse gages mounted on the underside of the deck plate. Therefore, direct effects of the wheel load and not “global” transverse bending of the ribs and deck plate dominate the stress cycles in the rib wall and deck plate at the rib/deck connection.

Figure 6.9 – Response at CH90R and CH90D as Random HS Type Truck Passed
Note that Each Axle Produces an Individual Stress Cycle
The speed of the truck shown in Figure 6.9 was estimated to be 48km/h (30mph). Assuming each tire footprint of the heavy axles is about 228mm (10in) long and a speed of 48km/h (30mph), then the wheel is located above a given gage for only 0.017 seconds. Thus, in order to accurately capture the peak stress, high data acquisition sampling rates are required. Based on calculations and a trial and error process, it was determined that for gages located on the deck plate (including the transverse weld) and on the rib wall adjacent to the deck plate or the upper diaphragm gages, a sampling rate of 200Hz adequately captured the response induced by individual truck wheel loads. Cars and small trucks can cross the span at higher rates of speed than heavy trucks. In order to capture the response of faster moving vehicles, higher sampling rates may be required for gages located on the deck plate. For all other gages, a sampling rate of 100Hz proved to be sufficient.

6.5.2 Stress-Range Histograms – Deck Plate/Rib Wall Connection

Stress-range histograms were developed for all gages mounted on the deck plate and rib walls. With the exception of channel CH87D, all gages were operational and relatively noise free throughout the entire third monitoring period. Tables 6.11 & 6.12 and Figures 6.10 & 6.11 summarize the stress-range histogram data collected during the third period of monitoring. Table 6.12 also lists the number of cycles that exceeded the CAFL of the detail as well as the percent exceedence. As can be seen there were about 24 cycles that exceeded the CAFL at channel CH90R, about 0.54%. The implication of this will be discussed further in Chapter 7.

It should be noted that channel CH90, which did not work properly during the second monitoring period, was subsequently repaired during the third monitoring period. There were no addition problems with this gage and it functioned properly for the remainder of the monitoring program.

<table>
<thead>
<tr>
<th>Bin #</th>
<th>Bin Range MPa</th>
<th># Cycles CH87R</th>
<th># Cycles CH87D</th>
<th># Cycles CH88R</th>
<th># Cycles CH89D</th>
<th># Cycles CH89R</th>
<th># Cycles CH90D</th>
<th># Cycles CH90R</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>1328</td>
<td>928</td>
<td>1954</td>
<td>420</td>
<td>2224</td>
<td>846</td>
<td>2347</td>
</tr>
<tr>
<td>2</td>
<td>25-30</td>
<td>427</td>
<td>362</td>
<td>933</td>
<td>134</td>
<td>996</td>
<td>273</td>
<td>1107</td>
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<tr>
<td>3</td>
<td>30-35</td>
<td>141</td>
<td>127</td>
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<td>50</td>
<td>373</td>
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<td>419</td>
</tr>
<tr>
<td>4</td>
<td>35-40</td>
<td>46</td>
<td>57</td>
<td>159</td>
<td>21</td>
<td>178</td>
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<td>78</td>
<td>7</td>
<td>109</td>
<td>13</td>
<td>100</td>
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<td>45-50</td>
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<td>28</td>
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<td>25</td>
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<tr>
<td>11</td>
<td>70-75</td>
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<td>1</td>
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<td>12</td>
<td>75-80</td>
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<td>-</td>
<td>1</td>
</tr>
</tbody>
</table>

Notes
1. Channel 90D, which did not work properly during the second monitoring period, was subsequently repaired during the third monitoring period.

Table 6.11 – Summary of Stress-Range Histograms for Gages on Longitudinal Rib Walls Near the Rib/Deck Weld

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Figure 6.10 – Stress-Range Histogram for Channels 88D, 89D, and 90D Installed on the Deck Plate

Figure 6.11 – Stress-Range Histogram for Channels 87R, 88R, 89R, and 90R Installed on the Ribs

95
### Channel / Location

<table>
<thead>
<tr>
<th>Channel / Location</th>
<th>$S_{\text{max}}$ MPa (ksi)</th>
<th>$S_{\text{ref}}$ MPa (ksi)</th>
<th>Total # Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH87R/S. Side Rib6 on Rib Wall</td>
<td>63 (9.1)</td>
<td>26 (3.8)</td>
<td>1976</td>
</tr>
<tr>
<td>CH88D/N. Side Rib5 on Deck Plate</td>
<td>73 (10.6)</td>
<td>28 (4.1)</td>
<td>1539</td>
</tr>
<tr>
<td>CH88R/N. Side Rib5 on Rib Wall</td>
<td>68 (9.9)</td>
<td>28 (4.1)</td>
<td>3579</td>
</tr>
<tr>
<td>CH89D/S. Side Rib5 on Deck Plate</td>
<td>58 (8.4)</td>
<td>27 (3.9)</td>
<td>645</td>
</tr>
<tr>
<td>CH89R/S. Side Rib5 on Rib Wall</td>
<td>73 (10.6)</td>
<td>30 (4.3)</td>
<td>4071</td>
</tr>
<tr>
<td>CH90D/N. Side Rib4 on Deck Plate</td>
<td>73 (10.6)</td>
<td>29 (4.2)</td>
<td>1299</td>
</tr>
<tr>
<td>CH90R/N. Side Rib4 on Rib Wall</td>
<td>83 (12.0)</td>
<td>31 (4.5)</td>
<td>4430</td>
</tr>
</tbody>
</table>

### Notes

1. Third period covered the period from December 13th to January 22nd 1999.
2. Channel 90D, which did not work during the second monitoring period was repaired during the third monitoring period.
3. Assumes Category C, see Chapter 7.

Table 6.12 – Maximum and Effective Stress Ranges for Gages Installed Transversely to Deck Plate and Longitudinal Ribs
6.6  Diaphragm Plate Response to Random Traffic

The response of the diaphragm plate to random variable loading was the primary focus of the long-term monitoring portion of the field testing program. For control, triggered time histories were collected for channels, CH27, CH29, CH45, and CH46 for the entire monitoring period of the southern outer roadway. In addition, stress-range histograms were developed for these four gages for the entire period. Time histories and stress-range histograms were developed for 11 other locations on the diaphragm plate for shorter periods of time.

Figure 6.12 – Detail of Triggered Time History - Triggers Set at +50MPa and –50MPa for CH27 and CH29 Located at Rib 5, Respectively
(Note Two Second Pre-trigger and Five Second Post-trigger)

6.6.1 Triggered Time Histories – Diaphragm Plate

The diaphragm plate is subjected to both in-plane and out-of-plane forces. Gages installed on the north and south sides of the rib, adjacent to the cutout, typically undergo nearly equal and opposite stress cycles. This characteristic response of the diaphragm plate was used to an advantage during the monitoring portion. Software triggers were set to recognize this behavior. When the criteria were met, the data acquisition system recorded the event. Figure 6.12 is a portion of a triggered time history and illustrates the concept. For this file, the trigger thresholds were set at +50MPa for CH27 and –50MPa for CH29. Thus, a time history was recorded only when both criteria were met and only for trucks producing stress ranges greater than 50MPa. When the conditions were met for CH27 and CH29 at rib 5, data were also collected on CH45 and CH46 at rib 7 as part of the same file. The same algorithm was used with CH45 and CH46 as the trigger
channels and with CH27 and CH29 recorded concurrently in the same file. Thus each triggered time history consists of data from all four gages.

Each event was recorded for a specified interval of time (a total of seven seconds as illustrated in Figure 6.12). The data acquisition system was programmed to maintain a buffer so that the first two seconds prior to the actual trigger condition being met were included as part of the data file. The system then continued recording data for a predetermined period (5 seconds in Figure 6.12). As a result, each event occurred for 7 seconds creating a series of small events joined together in one file. However, individual events may have occurred minutes or hours apart.

The triggered time histories provided a means for verifying the stress-range histograms and establishing the behavior of the diaphragm plate adjacent to the cutout under random variable loading.

![Figure 6.13 – Detail of Response on Diaphragm Plate Due to Passage of a Short Random 5-Axle HS Series Truck](image)

The response of the diaphragm plate to trucks with different axle configurations, such as the HS series vehicles, was evaluated. Figure 6.13 presents the response of the diaphragm plate to a short, heavy 5-axle HS type of truck. Also included for reference in Figure 6.13 is CH88D, which is located on the deck plate and is sensitive to wheel loads. One of the most important observations is that the truck produces a single large stress cycle in the diaphragm plate at the cutout. The effects of the individual axles are small compared to the global response to the truck. In addition, the effects of the individual axles of the tandem-axles can’t be distinguished adjacent to the cutout and produce a single peak response. Overall, the HS truck response is very similar to that produced by the single and tandem-axle test trucks.
Figure 6.14 illustrates the response of the diaphragm plate to a longer HS type truck (this is the same truck shown in Figure 6.3). The increased length of the truck changes the response of the diaphragm plate. There are clearly defined peaks as the tractor and the trailer pass. However, the unloading is only partial, as the stresses never return to zero between the two peaks.

Throughout the monitoring program, there were occasional periods when the inside or outside lanes of the outer roadway were temporarily shutdown during the day for maintenance. These closures could be identified in the triggered time histories. Figure 6.15 presents the response of ribs 5 and 7 during a shut down of the outer lane (lane 8) of the cantilevered roadway. Channels CH45 and CH46, adjacent to rib 7, were the trigger channels while CH27 and CH29, adjacent to rib 5, were the “slave” channels. While all lanes were open, heavy vehicles crossed in the inside and outside lanes in random transverse positions. Although it was the trigger conditions for CH45 and CH46 that were met, the actual transverse position of a given truck was not confined to the inside lane. As a result, the magnitude of the response of CH27 and CH29 was often similar to that of CH45 and CH46.
Once the outside lane was closed (indicated by the vertical dashed line in Figure 6.15), all vehicles were *forced* to travel in the inside lane since traffic cones were in place. A marked decrease in stresses in CH27 and CH29 is clearly evident in Figure 6.15. However, the response of CH27 and CH29 adjacent to rib 5 are *both* compressive with negative peaks of up to 25 MPa. This phenomena was discussed in Chapter 5, it is again mentioned here to reinforce the fact that it is the result of trucks passing in the inside lane and to demonstrate the complex behavior of the orthotropic deck system. Since triggered time histories were only developed for ribs 5 and 7 under these loading conditions, it is probable that ribs 2, 3, and 4 experienced the global behavior observed at rib 5 as well.
One of the largest stress ranges produced by an individual truck during the monitoring program is presented in Figure 6.16. Also shown in Figure 6.16 is the response from a somewhat lighter truck for comparison (first truck). Although the exact axle configuration for this truck is not known, based on the characteristics of the response, it is believed to be either a tandem or tri-axle H series truck or a very short HS series truck. Since the response of channels CH27 and CH29 are greater than channels CH45 and CH46, it indicates that the truck was in the outer lane.

The event shown in Figure 6.16 occurred on Monday, August 27th 1998 at 11:44AM. Thus, it was not an overloaded truck crossing the bridge in the early morning hours to avoid detection. Review of all the data revealed that there was no correlation between time of day and the passage of heavy vehicles.

Figure 6.16- Response at Ribs 5 and 7 of Floorbeam 64 E
Due to the Passage of a Very Heavy Truck
### 6.6.2 Stress-Range Histograms – Diaphragm Plate

Stress-range histograms were developed for several of the gages mounted on the diaphragm plate. All of these gages were located adjacent to the cutout near the weld toe. The gages were operational and relatively noise free throughout the entire monitoring period. Table 6.13 summarizes the channels monitored during all three monitoring periods. The histogram data for all gages mounted on the diaphragm plate are included in Appendix E.

<table>
<thead>
<tr>
<th>Channel #</th>
<th>Location</th>
<th>Period Monitored</th>
<th>Total Time Monitored</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
</tr>
<tr>
<td>CH1</td>
<td>FB63E Rib 5 S.E. Corner</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>CH2</td>
<td>FB63E Rib 5 N.E. Corner</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
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<td>FB63E Rib 5 S.W. Corner</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>CH6</td>
<td>FB63E Rib 5 N.W. Corner</td>
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<td>NO</td>
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</tr>
<tr>
<td>CH27</td>
<td>FB64E Rib 5 S.E. Corner</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>CH29</td>
<td>FB64E Rib 5 N.E. Corner</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>CH35</td>
<td>FB64E Rib 5 S.W. Corner</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>CH39</td>
<td>FB64E Rib 6 S.E. Corner</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>CH42</td>
<td>FB64E Rib 6 N.W. Corner</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>CH45</td>
<td>FB64E Rib 7 S.E. Corner</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>CH46</td>
<td>FB64E Rib 7 N.E. Corner</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>CH51</td>
<td>FB64E Rib 7 S.W. Corner</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>CH52</td>
<td>FB64E Rib 7 N.W. Corner</td>
<td>YES</td>
<td>NO</td>
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</tr>
<tr>
<td>CH55</td>
<td>FB65E Rib 5 S.W. Corner</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>CH56</td>
<td>FB65E Rib 5 N.W. Corner</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
</tr>
</tbody>
</table>

Table 6.13 Summary of Diaphragm Gages Included in the Long-Term Monitoring Program
Tables 6.14, 6.15, and 6.16 summarize the results for each of the three monitoring periods for each channel. The effective and maximum stress range for each channel was calculated by excluding all stress-range cycles less than 20MPa (2.9ksi). Also listed are the number of cycles exceeding the CAFL of the detail and percent exceedence. Prior to calculating the effective and maximum stress ranges, the data were carefully reviewed and compared to the triggered time histories for all available channels and data from the controlled load tests. This eliminated the inclusion of stray signals.

<table>
<thead>
<tr>
<th>Channel/Location</th>
<th>First Period (30 Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_{\text{max}}$ MPa (ksi)</td>
</tr>
<tr>
<td>CH1 / FB63E Rib 5 S.E. Corner</td>
<td>107 (15.6)</td>
</tr>
<tr>
<td>CH2 / FB63E Rib 5 N.E. Corner</td>
<td>118 (17.1)</td>
</tr>
<tr>
<td>CH5 / FB63E Rib 5 S.W. Corner</td>
<td>118 (17.1)</td>
</tr>
<tr>
<td>CH6 / FB63E Rib 5 N.W. Corner</td>
<td>147 (21.4)</td>
</tr>
<tr>
<td>CH27 / FB64E Rib 5 S.E. Corner</td>
<td>152 (22.1)</td>
</tr>
<tr>
<td>CH29 / FB64E Rib 5 N.E. Corner</td>
<td>152 (22.1)</td>
</tr>
<tr>
<td>CH35 / FB64E Rib 5 S.W. Corner</td>
<td>138 (20.0)</td>
</tr>
<tr>
<td>CH39 / FB64E Rib 5 S.E. Corner</td>
<td>127 (18.5)</td>
</tr>
<tr>
<td>CH42 / FB64E Rib 6 N.W. Corner</td>
<td>123 (17.8)</td>
</tr>
<tr>
<td>CH45 / FB64E Rib 7 S.E. Corner</td>
<td>112 (16.3)</td>
</tr>
<tr>
<td>CH46 / FB64E Rib 7 N.E. Corner</td>
<td>127 (18.5)</td>
</tr>
<tr>
<td>CH51 / FB64E Rib 7 S.W. Corner</td>
<td>101 (14.6)</td>
</tr>
<tr>
<td>CH52 / FB64E Rib 7 N.W. Corner</td>
<td>118 (17.1)</td>
</tr>
<tr>
<td>CH55 / FB65E Rib 5 S.W. Corner</td>
<td>138 (20.0)</td>
</tr>
<tr>
<td>CH56 / FB65E Rib 5 N.W. Corner</td>
<td>152 (22.1)</td>
</tr>
</tbody>
</table>

Notes:
1. Stress Cycles that exceed 20 MPa (2.9ksi).
2. Assumes Category C, see Chapter 7.

Table 6.14 - Maximum and Effective Stress Ranges for Gages Installed on the Diaphragm Plate for the First Monitoring Period (30 Days Total)
<table>
<thead>
<tr>
<th>Channel/Location</th>
<th>$S_{\text{max}}$ MPa (ksi)</th>
<th>Cycles $&gt;CAFL$</th>
<th>$S_{\text{eff}}$ MPa (ksi)</th>
<th>Total # Cycles</th>
<th>Cycles$^1$ per Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH1 / FB63E Rib 5 S.E. Corner</td>
<td>107 (15.6)</td>
<td>323 1.59%</td>
<td>34 (5.0)</td>
<td>20,308</td>
<td>333</td>
</tr>
<tr>
<td>CH2 / FB63E Rib 5 N.E. Corner</td>
<td>107 (15.6)</td>
<td>344 1.16%</td>
<td>34 (5.0)</td>
<td>29,765</td>
<td>488</td>
</tr>
<tr>
<td>CH27 / FB64E Rib 5 S.E. Corner</td>
<td>138 (20.0)</td>
<td>1168 3.12%</td>
<td>39 (5.7)</td>
<td>37,384</td>
<td>613</td>
</tr>
<tr>
<td>CH29 / FB64E Rib 5 N.E. Corner</td>
<td>143 (20.7)</td>
<td>1456 3.40%</td>
<td>40 (5.8)</td>
<td>42,878</td>
<td>703</td>
</tr>
<tr>
<td>CH45 / FB64E Rib 7 S.E. Corner</td>
<td>152 (22.1)</td>
<td>970 2.45%</td>
<td>39 (5.7)</td>
<td>39,563</td>
<td>649</td>
</tr>
<tr>
<td>CH46 / FB64E Rib 7 N.E. Corner</td>
<td>178 (25.8)</td>
<td>1385 3.16%</td>
<td>41 (5.9)</td>
<td>43,808</td>
<td>718</td>
</tr>
</tbody>
</table>

Notes:
1. Stress Cycles that exceed 20 MPa (2.9ksi).
2. Assumes Category C, see Chapter 7.

Table 6.15 - Maximum and Effective Stress Ranges for Gages Installed on the Diaphragm Plate for the Second Monitoring Period (61 Days Total)

<table>
<thead>
<tr>
<th>Channel/Location</th>
<th>$S_{\text{max}}$ MPa (ksi)</th>
<th>Cycles $&gt;CAFL$</th>
<th>$S_{\text{eff}}$ MPa (ksi)</th>
<th>Total # Cycles</th>
<th>Cycles$^1$ per Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH27 / FB64E Rib 5 S.E. Corner</td>
<td>138 (20.0)</td>
<td>241 2.56%</td>
<td>38 (5.5)</td>
<td>21154</td>
<td>529</td>
</tr>
<tr>
<td>CH29 / FB64E Rib 5 N.E. Corner</td>
<td>138 (20.0)</td>
<td>834 3.22%</td>
<td>39 (5.7)</td>
<td>25887</td>
<td>647</td>
</tr>
<tr>
<td>CH45 / FB64E Rib 7 S.E. Corner</td>
<td>128 (18.5)</td>
<td>623 2.33%</td>
<td>39 (5.7)</td>
<td>26750</td>
<td>669</td>
</tr>
<tr>
<td>CH46 / FB64E Rib 7 N.E. Corner</td>
<td>138 (20.0)</td>
<td>899 2.99%</td>
<td>40 (5.8)</td>
<td>30035</td>
<td>751</td>
</tr>
</tbody>
</table>

Notes:
1. Stress Cycles that exceed 20 MPa (2.9ksi).
2. Assumes Category C, see Chapter 7.

Table 6.16 - Maximum and Effective Stress Ranges for Gages Installed on the Diaphragm Plate for the Third Monitoring Period (40 Days Total)

Comparing Tables 6.14 through 6.16, it can be seen that the effective and maximum stress ranges are consistent for similar channels during the three periods. Because each of the three monitoring periods were of different length, the number of cycles were normalized for a daily average. The truncated cycles per day are in very good agreement for similar channels. Figure 6.17 illustrates the stress-range histogram for CH27 that was developed from data collected during the second monitoring period. The “tail end” of the data are plotted in the upper right corner of the histogram at expanded scale. The stress-range spectrum for CH27 was found to be consistent throughout the monitoring program. The stress-range spectrum for other locations is very similar to the results shown in Figure 6.17. The stress-range histogram data are included in Appendix E for all channels.
Figure 6.17 – Summary of Stress-Range Histogram for CH27 Located on FB64E Adjacent to the Cutout. Data Collected During the Second Monitoring Period
7.0 Summary and Interpretation of Results

Both the controlled load tests and the remote long-term monitoring phases of the field-testing program have demonstrated that the in-service behavior of the orthotropic deck is very complex. In addition, the peak stress ranges produced by the random variable-amplitude load-range spectrum are higher than anticipated by the AASHTO Specifications for certain elements and details of the orthotropic deck system.

7.1 Summary of Controlled Load Tests

A comprehensive controlled load test program has been completed using test trucks of known load and geometry. The results of these tests can be summarized as follows:

1. The general behavior of the diaphragm plate at floorbeams in the laboratory is consistent and in good agreement with the behavior observed in the field.

2. For similar loading conditions, proportions of in-plane and out-of-plane stresses measured in the diaphragm plate during the laboratory and field-testing programs are comparable. Typically, the in-plane stress component dominates the stress-range cycle.

3. Tests conducted before and after the application of the wearing surface demonstrated the following:
   3.1. The wearing surface has no influence on the global behavior of the deck system. Thus, there is no significant composite action being developed between the steel deck and the wearing surface on the Williamsburg Bridge.
   3.2. The wearing surface has no effect on the behavior of the individual ribs.
   3.3. Stresses in the diaphragm plate are only influenced by the wearing surface immediately adjacent to the deck plate/diaphragm weld. Stresses near the bottom of the diaphragm plate (i.e., adjacent to the cutout) are unaffected by the addition of the wearing surface.
   3.4. Stress ranges in the deck plate itself were decreased between 25% and 50% after the addition of the wearing surface. These decreases appear to be primarily due to spreading of the individual wheel loads. This results in greater local load distribution. The decreases do not appear to be caused by composite action between the steel deck plate and the wearing surface.

4. Comparison of measurements made during crawl and dynamic speed runs indicate that there is little dynamic amplification generated. This is attributed to the new condition of the wearing surface and gently curving profile of the roadway. If the wearing surface degrades and begins to unravel, considerable increases in dynamic amplification of the wheel loads would be expected.

5. The passage of the single and tandem-axle test trucks produces one stress-range cycle in the floorbeams, ribs and diaphragm plate. Each individual axle produces a single stress-range cycle in the deck plate and rib/deck connection.

6. The peak stress range in the diaphragm plate adjacent to the cutout is primarily influenced by the heavy axle or heavy axle group (i.e., a tandem) and not the total weight of the truck.

7. The maximum stress range adjacent to the cutout occurs when a single heavy truck is positioned in the outside lane. Two lighter trucks placed side-by-side do not generate as large a stress range.
7.2 Summary of Long-Term Monitoring

The long-term monitoring of the south cantilever (outer) roadway continued for 6 months, beginning in Early August of 1998 and ending in late January of 1999. An extensive volume of data were collected. Both time histories and stress-range histograms were developed from the data. The results of these tests can be summarized as follows:

1. The calculated effective stress range, developed from the measurements, is below the constant amplitude fatigue limit (CAFL) for all locations on the orthotropic deck system where instrumentation was installed.
2. Several locations on the floorbeam diaphragm adjacent to the cutout for the longitudinal ribs experience stress ranges that are greater the CAFL. These large stress ranges comprise up to 3.5% of the spectrum.
3. The estimated GVW of the heaviest trucks in the load spectrum is consistent with the upper bound estimates of other studies.
4. The existing AASHTO LRFD Bridge Design Specifications may result in and unconservative estimate of the effective stress range at the floorbeam diaphragm cutout. However, the Specifications appear adequate for other components of the orthotropic deck system.

7.3 Interpretation of the Data

7.3.1 Strain Gage Measurements

Some variability in test data, especially that collected during field testing, occurs because of the variation in vehicle weight, geometry and the randomness of the live loads. Other variables contributing to these deviations include variations in vehicle position as well as variations in fabrication and material tolerances. After a reviewing the data, these factors were determined to be small.

7.4 Stress-Range Histograms

The stress-range histogram data collected during the uncontrolled monitoring permitted the development of a random variable-amplitude stress-range spectrum for each strain gage. It has been shown that a variable-amplitude stress-range spectrum can be represented by an equivalent constant-amplitude stress range equal to the cube root of the mean cube (rmc) of all stress ranges (i.e., Miner’s rule) [13,14] (i.e., $S_{\text{reff}} = [\Sigma \alpha_i S_i ]^{1/3}$).

Several methods can be used to convert a random-amplitude stress-range response into a stress-range histogram. During the long-term monitoring program, stress-range histograms were developed using the rainflow cycle counting method [15]. The rainflow cycle counting method is widely used and accepted for use in most structures. The rainflow analysis algorithm was programmed to ignore any stress range less than 1.5MPa (0.2ksi (7µε)). For all steel details, a cut-off or threshold is appropriate and necessary.

The effective stress ranges presented for each channel in Chapter 6 were calculated by ignoring all stress-range cycles less than 20MPa (2.9ksi) (about ¼ the constant amplitude fatigue limit (Category C) for the diaphragm detail). This threshold was selected for two reasons.
Previous research has demonstrated that stress ranges less than $\frac{1}{4}$ the CAFL have little effect on the cumulative damage at the detail [16]. It has also been demonstrated that as the number of random variable cycles of lower stress range levels are considered, the predicted cumulative damage provided by the calculated effective stress range becomes asymptotic to the applicable S-N curve. A similar approach of truncating cycles of low stress range is accepted by researchers and specifications throughout the world [17].

Figure 7.1, shows the effect of calculating the effective stress range for several levels of truncation using test data collected from CH27 during the second monitoring period. The data are also listed in Table 7.1. Data below the cut off of 20MPa (2.9ksi) are shown in italics for clarity.
As the truncation level decreases, the effective stress range and corresponding number of cycles plotted approaches the slope of the S-N curve for Category C, which is also plotted in Figure 7.1 (i.e., a slope of –3 on a log-log plot). As long as the cut off level selected is consistent with the slope of the fatigue resistance curve, considering additional stress cycles at lower truncation levels does not improve the damage assessment and can therefore be ignored.

Equally important is that the load spectrum assumed in the AASHTO LRFD for design was developed by only considering vehicles greater than about 90kN (20kips) [18]. Thus the AASHTO LRFD design also truncates and ignores stress ranges generated by lighter vehicles and vibration [14]. The observed frequency of stress cycles obtained from traffic counts is also consistent with the frequency of vehicles measured.

<table>
<thead>
<tr>
<th>Cut Off (MPa)</th>
<th>Number Cycles &gt; Cut Off Value</th>
<th>$S_{\text{eff}}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>941,322</td>
<td>15</td>
</tr>
<tr>
<td>10</td>
<td>148,657</td>
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<tr>
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<td>37,384</td>
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<td>30</td>
<td>14,110</td>
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<td>40</td>
<td>7,160</td>
<td>61</td>
</tr>
<tr>
<td>50</td>
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<td>125</td>
</tr>
<tr>
<td>130</td>
<td>4</td>
<td>135</td>
</tr>
</tbody>
</table>

Table 7.1 – Calculated Effective Stress Ranges Using Different Stress Range Cut Off Levels. Data is from CH27 for the Second Monitoring Period

The maximum stress ranges listed in the tables developed in Chapter 6 were determined from the rainfall count. According to rainfall cycle counting procedures, the peak and valley that comprise the maximum stress range may not be the result of a single loading event and may in fact occur hours apart. In other words, an individual truck did not necessarily generate the maximum stress range shown in the tables. In many cases, it was possible to identify this maximum stress range with a specific vehicle passage, but in other cases, the maximum rainfall stress range exceeded the maximum stress range from any individual vehicle. However, the individual trucks producing the peak stress ranges listed for CH27, CH29, CH45 and CH46, which are located on diaphragm/floorbeam 64E, could almost always be traced back to an individual truck through the triggered time histories.
7.4.1 Stress-Range Histograms – Floorbeams
The stress-range histograms developed at the tension tie plate and bottom flange of the floorbeam covered a period of three months (91 days). Both the top and bottom flanges are connected to the lower chord of the truss by means of a high strength bolted connection. The fatigue resistance of this detail is Category B with a CAFL 110MPa (16ksi). The calculated effective stress range ($S_{\text{reff}}$) for the top and bottom flanges was 25MPa (3.6ksi) and 27MPa (3.9ksi) respectively. The peak stress range from the rainflow count was only 43MPa (6.2ksi), which is well below the fatigue limit for the detail as shown in Table 6.6.

Both the controlled load tests and the long-term monitoring confirmed that no fatigue damage would occur at the floorbeam connections.

7.4.2 Stress-Range Histograms – Transverse Weld
Stress-range histograms were developed at six locations adjacent to the transverse groove weld in the deck plate at floorbeam 65E. Instrumentation was located between ribs (three locations) and adjacent to the cope in the rib wall (three locations). As was noted previously, the deck splice at this detail has one of the largest root openings of any splice on the south outer roadway.

There are two locations where fatigue cracking is a concern and each should be considered separately. First, is *throat cracking* of the deck plate weld when the backing bar is left in place at the full-penetration transverse groove weld. Second is *toe cracking* of the deck plate at the end of the longitudinal weld between the deck plate and the rib wall. Both of these details are subjected to a complex combination of in-plane and out-of-plane stresses.

![Figure 7.2 – Detail at Transverse Groove Weld Illustrating the Two Types of Potential Cracking that Can Occur (Deflected Shape is Exaggerated)](image-url)
The full-penetration groove weld is continuous across the width of the deck and is subjected to the vertical forces applied from individual wheel loads. It was demonstrated by both the controlled load tests and the uncontrolled monitoring that each axle produces a single cycle. Each passing wheel produced local out-of-plane bending stresses in the deck plate. However, the deck plate is also subjected to longitudinal in-plane stresses generated by the longitudinal bending of the orthotropic deck panel between floorbeams and the global response of the suspended span. Of these three stress components, the local out-of-plane bending stress was observed to dominate the stress cycle. In the time history data, the effects of the global forces (i.e., the longitudinal bending of the orthotropic deck panel between floorbeams and the global response of the suspended span) are very small with respect to the local out-of-plane bending stresses.

Figure 7.2 indicates the orientation of potential crack growth at the weld toe termination near the cope hole. Also indicated in Figure 7.2 is the exaggerated deflection of the deck plate due to wheel loads. The deck plate in this region acts as a beam with a span equal to the clear distance between the ends of the rib cope holes. At the edges of the cope hole, restraining moments are developed. The stresses produced by these moments dominate the stress cycle and may ultimately produce cracking at the weld toe if the fatigue limit is exceeded.

The weld toe at the edge of the cope hole is a Category E detail with respect to the in-plane (longitudinal) stress ranges. However, the out-of-plane bending stress field is dominant as demonstrated by the field measurements. Although the actual fatigue resistance of this detail has not been established through testing, it can reasonably be considered a Category C detail with respect to out-of-plane bending stresses at the weld toe based on tests conducted on stiffeners subjected to out-of-plane deformation [19].

The gage with highest stress ranges located near a cope hole, was CH94 (see Table 6.8). Stress-range histograms were developed during the second monitoring period for a total of 61 days at CH94. The peak effective stress range and maximum stress range measured at CH94 were of 33MPa (4.8ksi) and 58MPa (8.4ksi) respectively. Thus, for the instrumented ribs, fatigue cracking is not expected to be a concern at this detail since all stresses are well below the CAFL of 69MPa (10ksi) for Category C. Although only a very limited area was instrumented, this location is believed to conservatively represent all other locations since this splice had one of the largest root openings and is considered a worst case based on studies in Japan which demonstrated that the stress range decreases with decreasing cope length [7].

The fatigue resistance of the deck plate splice subjected to in-plane stresses, without the backing bar removed, is classified as a Category D detail in the most recent revisions of the AASHTO LRFD [20]. This is consistent with full-scale fatigue testing of very similar details on beams containing cope holes at splices with backing bars [21]. However, the fatigue strength of this detail subjected to out-of-plane bending stresses has not been well established. It is important to note that in the field, these welds were inspected using NDT methods thereby insuring the quality of the weld. Therefore, when subjected to out-of-plane bending stresses, it is reasonable to assume that the fatigue resistance of this detail is between Category D and C. Even if the fatigue resistance is conservatively assumed to be Category E and the stress-range data for CH94 is used, the remaining life can be estimated. If all cycles are at the peak stress range of 58MPa (8.4ksi) and the observed 43 cycles/day (2,617 cycles/61 days (CH94 2nd monitoring
period) are used to estimate the fatigue life, it would take over 100 years to develop a crack. Since the effective stress range is only 4.8ksi, no fatigue damage is expected during the useful life of the deck.

7.4.3 Stress-Range Histograms – Longitudinal Rib/Deck Weld

This connection is made using a single-bevel partial-penetration weld with 80% penetration into the rib wall. Cracking of this detail may initiate from either the weld toe or the root due to stresses produced by wheel loads or by out-of-plane transverse bending of the deck plate.

Stress-range histograms were developed at seven locations adjacent to the longitudinal rib/deck weld. The centerline of each gage was positioned 19mm (¾ in.) away from the opposite plate as shown in the gage plans. This stress range can be used to determine if there is potential for weld toe cracking. CH90R, located on the rib wall, exhibited the greatest effective stress range and peak stress range during the long-term monitoring. The greatest effective stress range and peak stress range at CH90R were 31MPa (4.5ksi) and 83MPa (12.0ksi) respectively.

For weld toe cracking at the deck plate or rib wall, the weld toe condition is analogous to a Category C detail, which has a CAFL of 69MPa (10ksi). Considering the maximum effective stress range of 31MPa (4.5ksi) measured at CH90R and the number of cycles per day was 148 (4,430cycles/30days (CH90R 3rd monitoring period)), fatigue cracking of the deck plate is not expected to occur at this detail.

The measured stress range was the result of transverse bending. During the laboratory testing, heavy load prints, which simulated the effects of wheel loads, were positioned directly over some of the ribs. The magnitude of the applied loading conservatively represented upper-bound wheel loads. At the end of the Phase IIB laboratory-testing program, a thorough investigation was conducted and no fatigue cracking was detected at any rib/deck weld [4]. Overall, the quality of this weld was good and there was tight fit-up between the deck plate and the rib (in the laboratory specimen). Thus, whatever the loading condition, the field measurements and the laboratory test results indicate that fatigue cracking of this detail is not likely.

7.4.4 Stress-Range Histograms – Diaphragm Plate Cutouts

Stress-range histograms were developed for 15 gages located on the diaphragm plate adjacent to the cutout at floorbeams. This detail was the primary focus of the laboratory and field studies.

Immediately after the long-term monitoring began, it became apparent that large stress ranges were being measured at the cutout. These large stress ranges were observed in both the triggered time histories and the stress-range histograms. However, the largest stress ranges were found in the histograms. It was previously noted that when using the rainflow cycle counting method to develop stress-range histograms, the peak stress ranges are not necessarily the result of a single truck. Thus, in order to estimate what type of truck was causing the high stresses, only the triggered time histories can be used. The characteristics of these heavy trucks are discussed in Section 7.5.
7.4.4.1 Comparison of Laboratory and Field Testing Programs

During the Phase IIA laboratory fatigue test, the project specific loading consisted of placing two trucks side-by-side on the cantilevered outer roadway. The magnitude of the loads used during Phase IIA was established based on the results of the Phase I test program and a simple analytical model [3]. In reality, the Phase I and II laboratory specimens were three-dimensional structures possessing significant transverse load distribution characteristics comparable to the constructed deck in the field. The laboratory loading scheme was developed considering trucks with variable axle spacing to determine the peak effects. The maximum effects were combined into a single loading event or “truck”. However, this “truck” does not actually exist in the in-situ traffic spectrum. Because of these simplifications and assumptions, the stress ranges measured during the Phase IIA and IIB laboratory tests are believed to be conservative estimates of the effective stress range in the diaphragm.

During Phase IIB, loading was only applied to the outside lane and was intended to simulate 310% of the HS-15 fatigue truck, including impact, in order to produce fatigue cracking in a reasonable period of time. According to the AASHTO LRFD Specification, the effective stress range \( S_{\text{eff}} \) generated by the fatigue truck is assumed to result in the equivalent cumulative damage produced by the variable amplitude stress range spectrum. In other words, the effective stress range produced by a single HS-15 truck represents the cumulative damage from all trucks.

The long-term monitoring program yielded stress range histograms at several locations on the diaphragm plate adjacent to the cutout. Using the field data, the effective stress range was calculated at each location. Because the structure is open to random traffic, field measured stress-range histograms are obviously comprised of a variable amplitude stress range spectrum (i.e., all trucks). Rather than compare the effects of individual trucks, it is more appropriate to compare the effective stress range \( S_{\text{eff}} \) produced in the laboratory with the effective stress range measured in the field. Although the laboratory data are believed to be conservative, a reasonable comparison can be made

(\text{It should be noted that without a rigorous analysis, a direct or “one-to-one” comparison between the laboratory and controlled load test data cannot be made. Such an analysis has not been completed to date and is out of the scope of this project. Hence, a direct comparison between the laboratory results and the results of the controlled load test data will not be made.})

In order to estimate the effective stress range produced in the laboratory by a single HS-15 fatigue truck in the outside lane, the results from Phase IIB must be adjusted. Assuming linear elastic behavior of the laboratory specimen, it is reasonable to assume that the stress range produced by one HS-15 fatigue truck with 15% impact can be estimated from the results of Phase IIB by using the following relationship:

\[
1.15 \times HS15 = \frac{1.15}{3.1} \times (\text{PhaseIIB Stress Range})
\]

Using this relationship, the effective stress ranges were calculated for various locations and are listed in Table 7.2 for gages installed adjacent to the cutout on the laboratory specimen.
<table>
<thead>
<tr>
<th>Location (Lab)</th>
<th>Phase IIB MPa (ksi)</th>
<th>Adj Phase IIB (HS15+I) MPa (ksi)</th>
<th>Field S_e MPa (ksi)</th>
<th>Phase IIB 2(HS-15+I) MPa (ksi)</th>
<th>Phase IIA HS15 +(HS-15+30%)</th>
<th>Field S_{rmax}</th>
</tr>
</thead>
<tbody>
<tr>
<td>D3-N8</td>
<td>69 (10.0)</td>
<td>26 (3.8)</td>
<td>-</td>
<td>52 (7.5)</td>
<td>47 (6.8)</td>
<td>-</td>
</tr>
<tr>
<td>D3-S-8</td>
<td>92 (13.4)</td>
<td>34 (4.9)</td>
<td>-</td>
<td>68 (9.9)</td>
<td>66 (9.6)</td>
<td>-</td>
</tr>
<tr>
<td>D5-N8</td>
<td>116 (16.8)</td>
<td>43 (6.2)</td>
<td>39 (5.7)</td>
<td>86 (12.5)</td>
<td>41 (6.0)</td>
<td>152 (22.1)</td>
</tr>
<tr>
<td>D5-S-8</td>
<td>194 (28.2)</td>
<td>72 (10.4)</td>
<td>37 (5.4)</td>
<td>144 (20.9)</td>
<td>88 (12.8)</td>
<td>138 (20.0)</td>
</tr>
<tr>
<td>D5-N-19</td>
<td>179 (26.0)</td>
<td>66 (9.6)</td>
<td>40 (5.8)</td>
<td>132 (19.2)</td>
<td>92 (13.4)</td>
<td>152 (22.1)</td>
</tr>
<tr>
<td>D5-S-19</td>
<td>160 (23.2)</td>
<td>59 (8.6)</td>
<td>-</td>
<td>118 (17.1)</td>
<td>68 (9.9)</td>
<td>-</td>
</tr>
<tr>
<td>D6-N-8</td>
<td>125 (18.1)</td>
<td>46 (6.7)</td>
<td>39 (5.7)</td>
<td>92 (13.4)</td>
<td>52 (7.5)</td>
<td>127 (18.4)</td>
</tr>
<tr>
<td>D6-S-8</td>
<td>117 (17.0)</td>
<td>43 (6.2)</td>
<td>37 (5.4)</td>
<td>86 (12.5)</td>
<td>-</td>
<td>123 (17.9)</td>
</tr>
<tr>
<td>D6-N-19</td>
<td>152 (22.1)</td>
<td>56 (8.1)</td>
<td>-</td>
<td>112 (16.3)</td>
<td>101 (14.7)</td>
<td>-</td>
</tr>
<tr>
<td>D8-N-8</td>
<td>39 (5.7)</td>
<td>14 (2.0)</td>
<td>-</td>
<td>28 (4.1)</td>
<td>28 (4.1)</td>
<td>-</td>
</tr>
<tr>
<td>D8-S-8</td>
<td>97 (14.1)</td>
<td>36 (5.2)</td>
<td>-</td>
<td>72 (10.4)</td>
<td>70 (10.2)</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes:
1. Phase IIB loading – 3.1 x HS-15 in outside lane only = 2.7 x (HS-15 +15% Impact). Data taken from Table 4.1 in Phase IIB Final Report [4].
2. Adjusted Phase IIB loading – 1.0 x (HS-15 + 15% Impact) in outside lane only (i.e., one fatigue truck with 15% impact).
3. Gage designations based on Phase IIA and Phase IIB.

Table 7.2 – Calculated Effective Stress Range Using Phase IIB Laboratory Data
It should be noted that the results presented for ribs 5 and 6 in Table 7.2 are the only locations of concern since measured stress ranges were highest at these locations. (A direct comparison of data from rib 7 is not available due to modifications made to the geometry of the cutout at rib 7 at the end of Phase IIA.) In addition, the small stresses measured at ribs 3 and 8 are not important as the stress ranges were low for both locations.

7.4.4.2 Rib/Diaphragm Welded Connection

Based on the laboratory studies, the rib/diaphragm weld can be considered a Category C detail in the region where the full penetration weld is used [4]. In this case, weld toe cracking will be the mode of crack propagation. Thus, the field strain gage measurements can be used directly to estimate the fatigue life of the detail. Table 7.3 lists the estimated fatigue life for each of the 15 locations on the diaphragm plate that were instrumented. The estimated life is presented for each of the monitoring periods separately. As can be seen, the calculated lives are quite consistent and in good agreement for each of the three periods where common gages existed.

<table>
<thead>
<tr>
<th>Channel / Location</th>
<th>$S_{\text{max}}$ MPa (ksi)</th>
<th>% of Cycles &gt; CAFL</th>
<th>$S_{\text{ref}}$ MPa (ksi)</th>
<th>Cycles per Day</th>
<th>Est. Life in Years (Cat C)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First Monitoring Period (30 days)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH1 / FB63E Rib 5 S.E. Corner</td>
<td>107 (15.6)</td>
<td>0.81%</td>
<td>34 (4.9)</td>
<td>291</td>
<td>352</td>
</tr>
<tr>
<td>CH2 / FB63E Rib 5 N.E. Corner</td>
<td>118 (17.1)</td>
<td>1.38%</td>
<td>36 (5.2)</td>
<td>444</td>
<td>193</td>
</tr>
<tr>
<td>CH5 / FB63E Rib 5 S.W. Corner</td>
<td>118 (17.1)</td>
<td>1.07%</td>
<td>34 (5.0)</td>
<td>391</td>
<td>247</td>
</tr>
<tr>
<td>CH6 / FB63E Rib 5 N.W. Corner</td>
<td>147 (21.4)</td>
<td>2.99%</td>
<td>39 (5.7)</td>
<td>563</td>
<td>116</td>
</tr>
<tr>
<td>CH27 / FB64E Rib 5 S.E. Corner</td>
<td>152 (22.1)</td>
<td>3.17%</td>
<td>39 (5.7)</td>
<td>583</td>
<td>112</td>
</tr>
<tr>
<td>CH29 / FB64E Rib 5 N.E. Corner</td>
<td>152 (22.1)</td>
<td>3.60%</td>
<td>40 (5.8)</td>
<td>648</td>
<td>95</td>
</tr>
<tr>
<td>CH35 / FB64E Rib 5 S.W. Corner</td>
<td>138 (20.0)</td>
<td>1.78%</td>
<td>37 (5.3)</td>
<td>441</td>
<td>184</td>
</tr>
<tr>
<td>CH39 / FB64E Rib 6 S.E. Corner</td>
<td>127 (18.5)</td>
<td>2.95%</td>
<td>39 (5.6)</td>
<td>476</td>
<td>144</td>
</tr>
<tr>
<td>CH42 / FB64E Rib 6 N.W. Corner</td>
<td>123 (17.8)</td>
<td>1.96%</td>
<td>37 (5.4)</td>
<td>514</td>
<td>149</td>
</tr>
<tr>
<td>CH45 / FB64E Rib 7 S.E. Corner</td>
<td>112 (16.3)</td>
<td>2.43%</td>
<td>39 (5.6)</td>
<td>571</td>
<td>120</td>
</tr>
<tr>
<td>CH46 / FB64E Rib 7 N.E. Corner</td>
<td>127 (18.5)</td>
<td>2.86%</td>
<td>40 (5.8)</td>
<td>623</td>
<td>99</td>
</tr>
<tr>
<td>CH51 / FB64E Rib 7 S.W. Corner</td>
<td>101 (14.6)</td>
<td>1.75%</td>
<td>37 (5.3)</td>
<td>468</td>
<td>173</td>
</tr>
<tr>
<td>CH52 / FB64E Rib 7 N.W. Corner</td>
<td>118 (17.1)</td>
<td>2.21%</td>
<td>39 (5.7)</td>
<td>539</td>
<td>121</td>
</tr>
<tr>
<td>CH55 / FB65E Rib 5 S.W. Corner</td>
<td>138 (20.0)</td>
<td>1.67%</td>
<td>36 (5.2)</td>
<td>437</td>
<td>196</td>
</tr>
<tr>
<td>CH56 / FB65E Rib 5 N.W. Corner</td>
<td>152 (22.1)</td>
<td>3.44%</td>
<td>40 (5.8)</td>
<td>691</td>
<td>89</td>
</tr>
<tr>
<td><strong>Second Monitoring Period (61 days)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH1 / FB63E Rib 5 S.E. Corner</td>
<td>107 (15.6)</td>
<td>1.59%</td>
<td>34 (5.0)</td>
<td>333</td>
<td>290</td>
</tr>
<tr>
<td>CH2 / FB63E Rib 5 N.E. Corner</td>
<td>107 (15.6)</td>
<td>1.16%</td>
<td>34 (5.0)</td>
<td>488</td>
<td>198</td>
</tr>
<tr>
<td>CH27 / FB64E Rib 5 S.E. Corner</td>
<td>138 (20.0)</td>
<td>3.12%</td>
<td>39 (5.7)</td>
<td>613</td>
<td>106</td>
</tr>
<tr>
<td>CH29 / FB64E Rib 5 N.E. Corner</td>
<td>143 (20.7)</td>
<td>3.40%</td>
<td>40 (5.8)</td>
<td>703</td>
<td>88</td>
</tr>
<tr>
<td>CH45 / FB64E Rib 7 S.E. Corner</td>
<td>152 (22.1)</td>
<td>2.45%</td>
<td>39 (5.7)</td>
<td>649</td>
<td>100</td>
</tr>
<tr>
<td>CH46 / FB64E Rib 7 N.E. Corner</td>
<td>178 (25.8)</td>
<td>3.16%</td>
<td>41 (5.9)</td>
<td>718</td>
<td>82</td>
</tr>
<tr>
<td><strong>Third Monitoring Period (40 days)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH27 / FB64E Rib 5 S.E. Corner</td>
<td>138 (20.0)</td>
<td>2.56%</td>
<td>38 (5.5)</td>
<td>529</td>
<td>137</td>
</tr>
<tr>
<td>CH29 / FB64E Rib 5 N.E. Corner</td>
<td>138 (20.0)</td>
<td>3.22%</td>
<td>39 (5.7)</td>
<td>647</td>
<td>101</td>
</tr>
<tr>
<td>CH45 / FB64E Rib 7 S.E. Corner</td>
<td>128 (18.5)</td>
<td>2.33%</td>
<td>39 (5.7)</td>
<td>669</td>
<td>97</td>
</tr>
<tr>
<td>CH46 / FB64E Rib 7 N.E. Corner</td>
<td>138 (20.0)</td>
<td>2.99%</td>
<td>40 (5.8)</td>
<td>751</td>
<td>82</td>
</tr>
</tbody>
</table>

Table 7.3 – Estimated Total Fatigue Life at the Rib/Diaphragm Weld Based on Stress-Range Histograms Developed During the Long-Term Monitoring Period
Although all locations have fatigue lives greater than 75 years, the location with the lowest estimated life is CH46 located at rib 7 of floorbeam 64E. This location consistently had the highest effective stress range and was also observed to have the highest measured maximum stress range. The fatigue life estimates in Table 7.3 are based on the fatigue resistance determined during the laboratory testing. “Failure” of this detail is not easily established in such a structure. During the laboratory tests, cracks lengths ranged from about 8.8mm (0.34in) to 34.1mm (1.34in) at the end of the test. However, cracking was first detected much earlier, as is characteristic of all fatigue details. Thus, cracking may initiate in less time in the field. From the laboratory tests, a reasonable lower bound estimate of the life at which cracking may first become observable varied between Category D and Category B. Using the fatigue resistance curve for Category D, a lower bound estimated life at which cracking may be first observed can be calculated using the data provided in Table 7.3 (See figure 4.11 of Phase IIB report [4]). The critical location is at rib 7 of floorbeam 64E, CH46, where the lower bound estimated life until crack initiation is predicted to be 41.

A comparison of the effective stress range \(S_{\text{eff}}\) listed in Tables 7.2 and 7.3 confirms that the laboratory and field measurements are in reasonable agreement for similar locations and ribs. The values of the maximum stress range \(S_{\text{max}}\) listed in Table 7.3 exceed the effective stress range \(S_{\text{eff}}\) by a factor of about 3.5. It is important to note that the maximum stress range \(S_{\text{max}}\) was obtained using the rainflow cycle counting method and an individual truck did not necessarily generate the peak stress range.

The AASHTO Specification states that the stress range \(S_{\text{eff}}\) produced by placing a single fatigue truck with 15% impact on the structure in a single lane is to be compared to one half the CAFL [22,24] to establish if the fatigue limit is exceeded. The “one half” factor is intended to account for the fact that the actual fatigue-limit-state truck is assumed to weigh twice the gross weight of the effective truck (i.e., the HS-15 with 15% impact). The ratio of the effective gross vehicle weight (GVW) to the GVW of the fatigue-limit-state truck in the measured spectrum is referred to in the literature as the “alpha factor” [25]. The LRFD Specifications imply that alpha equals 0.5 and that the fatigue-limit-state truck is about an HS-30 with 30% impact. In other words, the same fatigue design would result by placing a single HS-30 (i.e., 2xHS-15) in one lane of the structure and comparing the calculated stresses to the CAFL of a given detail. However, the measured peak stress range is larger than twice the effective stress range. Comparing the data in Table 7.3 to the data in tables for other locations in Chapter 6, it is clear that stress ranges measured at the diaphragm have the highest percent exceedence compared to the other details. This suggests that the variable amplitude stress-range spectrum at this detail has a wider bandwidth than assumed in the AASHTO LRFD [22,24].

The percentage of trucks exceeding the CAFL is also presented in Table 7.3. As is apparent in Table 7.3, a significant number of stress cycles exceed the constant-amplitude fatigue limit for category C, which is applicable to the diaphragm/rib welded joint at the cut-outs [4]. For most locations, the CAFL was exceeded up to 3% of the time during this study.

The load spectrum currently assumed in the AASHTO LRFD for fatigue design was developed and calibrated for global bridge members (i.e. main girders, floorbeams, etc). The assumption that the fatigue-limit-state load is twice the weight of the fatigue truck appears valid for these members, as indicated by the measurements made on the
deck plate and floorbeam (see summary tables in Chapter 6). However, the measured data suggest that the existing fatigue design approach in the AASHTO LRFD may not be conservative for some of the orthotropic deck elements such as the diaphragm to rib welded connections at floorbeam cutouts.

Other studies have also indicated that the fatigue-limit-state load may be closer to 3 times the GVW of the AASHTO Fatigue Truck [14,18,26]. For example, in NCHRP Report 299 this finding was based on a reliability analysis, comparison with the original AASHTO fatigue limit check, review of nationwide WIM data, and a study of peak ratio (peak/effective) measured stress spectra. According to the statistics of the GVW spectra, at 3xHS-15 fatigue-limit-state truck has only a 0.023 percent probability (about 1 in 5,000) of exceedence, which is reasonably consistent with the recommendation from NCHRP 354, which suggested that the fatigue-limit-state stress range have an exceedence of less than 1:10,000 [16]. The HS-30 fatigue-limit-state truck implied by the AASHTO LRFD provisions clearly has a much higher probability of exceedence, particularly for the floorbeam diaphragm. (The number of cycles exceeding the CAFL of the welded rib/diaphragm connection also exceeds 0.023 percent.)

Again, it must be emphasized that other elements, which are subjected to global behavior, such as the floorbeams and associated tie plate, and the longitudinal ribs, were not subjected to such high stress ranges. The ratio between the effective stress range and the peak stress range were more compatible with the assumptions in the AASHTO LRFD Specifications.

Obviously, some of the largest measured stress ranges are the direct result of overloaded vehicles and not due to deficiencies in the Specification. The New York City DOT does not prevent heavy vehicles from crossing the Williamsburg Bridge nor does it enforce restrictions (except on the Brooklyn Bridge).

7.4.4.3 Rib/Internal Diaphragm (Bulkhead) Connection

Stress-range histograms could not be developed for the strain gages installed on the internal diaphragm or bulkhead plate since construction workers cut the signal wires. However, based on the laboratory-testing program, estimates of the fatigue life of this detail can be made.

Because the bulkhead plate is located inside of the rib, out-of-plane stresses cannot be developed. This was verified by measurements made during the Phase IIB laboratory tests [4]. Thus, when the rib rotates, the bulkhead plate simply rotates with it.

The fatigue resistance of the as-built rib to bulkhead weld has been estimated to be Category E for initiation and Category D for life [4]. This fillet-welded connection can be idealized as a cruciform connection as shown in the AASHTO LRFD Specification [22]. For this case, root cracking and not weld toe cracking will control. As a result, it is not appropriate to use the maximum “surface” stresses obtained by the strain gages but rather, the in-plane stress component.

The laboratory tests demonstrated that the magnitude of the in-plane stress range immediately adjacent to the rib wall was approximately the same on both sides of the rib wall. Therefore, in order to estimate the fatigue life of the internal diaphragm, the in-plane stress range was estimated using gages located on the outside of the rib. The in-plane stress range cannot be directly calculated for all bulkheads since gages were not mounted on both faces of the diaphragm plate at all locations.
In order to make a rational estimate of the fatigue life of the rib/bulkhead connection, in-plane stress ranges were conservatively estimated at the locations where gages were placed back to back. Knowing the proportion of the in-plane stress range to the surface stress range, an adjustment factor Beta “β” can be calculated which can be used to adjust the stress-range histogram data. The beta factor is the ratio of the in-plane stress range to the larger surface stress range at a given set of back-to-back gages. A review of several time histories and all channels where gages were installed back-to-back resulted in the beta factors listed in Table 7.4.

Table 7.4 – Estimated Minimum Fatigue Life at the Rib/Bulkhead Weld Based on Modified Stress-Range Histograms Developed During the Long-Term Monitoring Period

<table>
<thead>
<tr>
<th>Location</th>
<th>Chan. of Max. Stress Range</th>
<th>β Factor</th>
<th>S_{ref}</th>
<th>βS_{ref}</th>
<th># Cycles per Day</th>
<th>Est. Life (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FB64E Rib 5 CH27 &amp; CH35</td>
<td>CH27</td>
<td>0.84</td>
<td>5.7</td>
<td>4.8</td>
<td>613</td>
<td>89</td>
</tr>
<tr>
<td>FB64E Rib 7CH45 &amp; CH51</td>
<td>CH51</td>
<td>0.98</td>
<td>5.3</td>
<td>5.2</td>
<td>468</td>
<td>92</td>
</tr>
<tr>
<td><strong>FB64E Rib 7CH46 &amp; CH52</strong></td>
<td><strong>CH46</strong></td>
<td><strong>0.88</strong></td>
<td><strong>5.9</strong></td>
<td><strong>5.2</strong></td>
<td><strong>718</strong></td>
<td><strong>60</strong></td>
</tr>
<tr>
<td>FB63E Rib 5CH1 &amp; CH5</td>
<td>CH5</td>
<td>0.87</td>
<td>5.0</td>
<td>4.3</td>
<td>391</td>
<td>194</td>
</tr>
<tr>
<td>FB63E Rib 5CH2 &amp; CH6</td>
<td>CH6</td>
<td>0.81</td>
<td>5.7</td>
<td>4.6</td>
<td>563</td>
<td>110</td>
</tr>
</tbody>
</table>

Table 7.4 also lists the estimated fatigue life for the rib/bulkhead connection in years for the locations where gages were placed back-to-back. The in-plane effective stress range in the bulkhead was conservatively obtained by multiplying the maximum effective surface stress range on the diaphragm for a given channel by the appropriate beta factor. The total number of cycles per day was assumed to remain constant over the life of the structure, as was the case at other joints. As expected, CH46 (shown bold) located adjacent to the bulkhead at rib 7 of FB64E, is the location with the shortest estimated life.

It should be noted that cracking of the bulkhead plate would not be visible. The consequence of the joint failure will be the introduction of out-of-plane bending stresses in the rib wall at the diaphragm plate weld end. This may eventually result in crack development into the rib wall. This will likely require 10 or more additional years to develop based on experience at the Westgate Bridge in Australia [23].

7.4.5 Summary of Fatigue Life Estimates

The estimates of fatigue life provided in Table 7.3 and 7.4 assume that traffic patterns remain the same over the life of the structure. Obviously, increases in truck weight and/or volume will result in shorter life estimates. The life estimates assume that toe or throat cracking (depending on the detail) are the controlling modes of crack growth.
7.5 Characteristics of the Trucks Producing High Stress Ranges

The data presented in Chapter 6 suggest that most of the trucks crossing the Williamsburg Bridge are typical for a large river crossing located in a major metropolitan area. However, a small percentage of these vehicles produced high to very high stress ranges at all cut out locations on the diaphragm plate. Although a percentage of the large stress ranges are believed to be due to underestimates of the fatigue-limit-state load provided in the AASHTO LRFD Specification, some heavily overloaded trucks were observed in normal traffic. Using the triggered time history data, the characteristics of these overload vehicles have been estimated.

7.5.1 Geometry of Trucks Producing High Stress Ranges

Using the triggered time history data, the geometry of very heavy trucks could be calculated quite accurately. This included the number of axles, the spacing of axles, and the speed of random trucks. This information required data from gages located on the floorbeams, deck plate, or diaphragm plate at two known cross sections. Occasionally, this information was not always available. Fortunately, the required data were collected as some of the heaviest trucks crossed the instrumented portion of the bridge.

Trucks of unusual geometry did not produce the greatest stress ranges observed in the triggered time histories. This was determined by comparing data collected at different locations as an individual heavy truck passed.

The data indicate that the geometry of these trucks is not unreasonable. The spacing of the rear axles varies between 1.22m and 1.52m (4ft to 5ft). A reasonable average value of 1.37m (4.5ft) can be assumed for most trucks. For “H” type trucks, the distance between the first (front) and last axle is typically 6.1m to 7.62m (20 to 25ft), depending on whether the truck has two or three rear axles. For the “HS” type trucks, the distance between the first and last axle is usually less than 15.24m (50 ft) with three axles on the trailer. HS trucks that are longer than this tend to produce lower stress ranges since the load is spread out further. Hence the effect on a given floorbeam diaphragm is less.

7.5.2 Estimated Axle Loads of Trucks Producing High Stress Ranges

By comparing the data from the controlled load tests with the triggered time history data, the GVW and axle loads of the heavy trucks were estimated. The concept of using the response of a structure to known loads to estimate the weight and configuration of an unknown vehicle is well established [27]. The procedure is commonly referred to as weigh-in-motion (WIM) and has been used in the development of current live-load models found in the Specifications. The method provides a reasonable upper-bound estimate of the configuration and GVW of heavy trucks crossing the structure.

In order to estimate the characteristics of unknown vehicles, the following assumptions were also made:

1. The rear axle(s) are the primary load producing the peak stress range at a given location on the diaphragm plate. As noted in Chapter 5, the data from the controlled load tests indicate that this is the case for both the single and tandem-axle test trucks. Therefore, only the weight of the heavy rear axles will be estimated from the measurements.
2. The controlled load tests used both single and tandem-axle “H” series trucks. Based on the long-term remote monitoring program, it became clear that similar “H” or very short “HS” series trucks produced the peak stress ranges. Nevertheless, because controlled load data are only available for “H” series trucks, only the characteristics of similar “H” trucks will be estimated.

3. Although the exact transverse position of the vehicle can only be estimated, it is assumed that the vehicle was located in the outside lane. The peak stress ranges were always produced at rib 5 when the test vehicles were located in the outside lane as discussed above. By comparing the data from rib 5 and rib 7, this assumption could be verified.

Table 7.5 summarizes measurements made at four channels located adjacent to the cutout on the diaphragm plate during the controlled tests. Also shown are data measured during the passage of a random tandem-axle truck during the remote long-term monitoring program.

<table>
<thead>
<tr>
<th>Channel/Location</th>
<th>Controlled Load Tests</th>
<th>Random Tandem Axle(s) Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single-Axle MPa (ksi)</td>
<td>Tandem-Axle MPa (ksi)</td>
</tr>
<tr>
<td>CH1 / FB63E Rib 5 S.E. Corner</td>
<td>19 (2.8)</td>
<td>55 (8.0)</td>
</tr>
<tr>
<td>CH2 / FB63E Rib 5 N.E. Corner</td>
<td>21 (3.0)</td>
<td>56 (8.1)</td>
</tr>
<tr>
<td>CH27 / FB64E Rib 5 S.E. Corner</td>
<td>25 (3.6)</td>
<td>83 (12.0)</td>
</tr>
<tr>
<td>CH29 / FB64E Rib 5 N.E. Corner</td>
<td>28 (4.1)</td>
<td>82 (11.9)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Estimated using Figure 7.3 from data from all four channels

Table 7.5 – Comparison of Measurements Made During the Controlled Load Tests and a Random Tandem-Axle Truck

The data in Table 7.5 for rib 5 are plotted in Figure 7.3 for the single and tandem-axle test trucks only. A linear regression of the data for each gage was performed and is also plotted in Figure 7.3. The weight of the rear axles of the random truck can be estimated from the assumed linear relationship. Based on the data from CH27 alone, the estimated weight is about 337kN (76kips). Using data from CH1, CH2, and CH29, similar weights were estimated. The average weight of the rear axles for this truck, considering all the data, was estimated to be about 350kN (79kips).

Conservatively assuming that the front axle accounts for about 1/5th of the total GVW (See Table 4.1), it is estimated that the front axle weighed about 88kN (19.8kips), which is not unreasonable.

Assuming that the rear axle group consists of two axles implies that each rear axle carries about 178kN (40kips). Although this is a rather large load, it is not unreasonable. Tests conducted at the ATLLSS Center have demonstrated that properly inflated tires (dual wheels) can carry axle loads of 156kN (35kips), at least statically, without excessive...
deflection [28]. Hence, individual axle loads of 178kN (40kips) are not unreasonable for tandem axles. However, if it is assumed that the total rear axle load of 350kN (79kip) is spread to three rear axles, the maximum axle load is reduced to 117kN (26.3kips). In either case, this results in a truck with a GVW of about 445kN (100kips) possessing axles spaced according to Section 7.5.2, as shown in Figure 7.6.

This procedure can be used to estimate the weight for other heavy axles or axle groups when the stress range is known. Knowing the stress range at any one of the four gages on rib5 of FB63E or FB64E, the stress range at the other three locations can be estimated. For example, during the third phase of monitoring, a triggered time history of a very heavy truck in the outside lane was recorded and is shown in Figure 7.4 for CH27, CH29, CH1, and CH2. From Figure 7.4 it can be seen that the stress range produced in CH27 is about 128 MPa (18.6ksi). The stress range at the other three locations and the average weight of the heavy axles was estimated from Figure 7.3. These results are compared in Table 7.6 with the actual measured stress ranges observed in rib 5 of FB64E and FB65E. There is good agreement between the measured and estimated stress ranges for all three locations using the regression relationships. The average estimated weight of the rear axles for this truck is 388 kN (87kips). Considering the magnitude, it is likely that three axles carried this load.

Figure 7.3 – Plot of Data in Table 7.5 and Linear Regression of Data. Only Data from Controlled Load Tests are Plotted and Included in the Regression
Figure 7.4 - Measured Stress Ranges from a Random Truck

<table>
<thead>
<tr>
<th>Location</th>
<th>Estimated Stress Range MPa (ksi)</th>
<th>Actual Stress Range MPa (ksi)</th>
<th>Estimated Rear Axle Weight (W&lt;sub&gt;r&lt;/sub&gt;) kN (kips)</th>
<th>Equation of Regression Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH27 (Rib 5 FB64E)</td>
<td>-</td>
<td>128 (18.6)</td>
<td>388 (87)</td>
<td>S&lt;sub&gt;r&lt;/sub&gt;=0.3302x(W&lt;sub&gt;r&lt;/sub&gt;)</td>
</tr>
<tr>
<td>CH29 (Rib 5 FB64E)</td>
<td>129 (18.7)</td>
<td>134 (19.4)</td>
<td></td>
<td>S&lt;sub&gt;r&lt;/sub&gt;=0.3321x(W&lt;sub&gt;r&lt;/sub&gt;)</td>
</tr>
<tr>
<td>CH1 (Rib 5 FB63E)</td>
<td>93 (13.5)</td>
<td>94 (13.6)</td>
<td></td>
<td>S&lt;sub&gt;r&lt;/sub&gt;=0.2394x(W&lt;sub&gt;r&lt;/sub&gt;)</td>
</tr>
<tr>
<td>CH2 (Rib 5 FB63E)</td>
<td>91 (13.2)</td>
<td>93 (13.5)</td>
<td></td>
<td>S&lt;sub&gt;r&lt;/sub&gt;=0.2341x(W&lt;sub&gt;r&lt;/sub&gt;)</td>
</tr>
</tbody>
</table>

Notes:
1. Determined using Figure 7.3

Table 7.6 - Comparison of Estimated and Actual Stress Ranges for the Random Truck Shown Figure 7.4.

Assuming that the front axle accounts for about 1/5<sup>th</sup> of the total GVW, it is estimated that the front axle weighed about 97kN (22kips) and the GVW was 485kN (109kips). This estimate is compatible with extreme loads established in 1981 and 1987 field measurements (27). Figure 7.5 is reproduced from Reference 27 (Figure #68 in Ref 27). As can be seen, the “tail end” of the distribution is good agreement with the upper bound GVW estimated using the measured data. This reinforces the argument that the alpha factor for the diaphragm cut out region is greater than assumed by the AASHTO LRFD Specification. However, as stated earlier, the Specification appears adequate for other global elements, such as the floorbeam and longitudinal ribs.
Although individual trucks occasionally produced stress ranges higher than those discussed above, the exact configuration of these trucks is unknown. The frequency of occurrence of these trucks is also very small. It is recognized that the monitoring program only included about six months of data and that heavier trucks may cross the structure once all phases of construction are completed. Although the frequency of occurrence is low, it is believed that 485kN (109kips) is a reasonable upper bound estimate of the GVW for H series trucks crossing the Williamsburg Bridge.

For the “H” series trucks it is most likely that the rear axle load of 387kN (87kips) is carried on three axles of 129kN (29kips). The estimated configuration of the heaviest trucks (H and HS) given is in Figure 7.6. For HS series trucks, the GVW is most likely greater since there are more axles to carry the load. However, it is unlikely that the GVW of these trucks (i.e., those with five heavy axles) is 729kN (164kips) (5axles x 129kN/axle + 84kN front axle = 729kN). Considering this limit, it is more probable that the maximum axle load is around 98kN (22kips), since there is a practical limit to the GVW that a single tractor can pull. Assuming rear axles of 98kN (22kips) and a front axle load of 40kN (9kips) results in a truck with a GVW of 529kN (119kips). It must be noted that this is a very conservative upper bound estimate of the “HS” series trucks crossing the Williamsburg Bridge (See Figure 7.6).
Figure 7.6 – Estimated Geometry and Upperbound Axle Loads of Heavy “H” and “HS” Series Trucks Crossing the Williamsburg Bridge.
Using the above relationships, the stress range for various levels of the rear axle of an H-15 fatigue truck can also be estimated from the field data. (*It is recognized that the Specifications require the use of the HS-15 truck for fatigue design and not the H-15 truck. However, because it has been demonstrated that it is primarily the heavy rear axles that produce the peak stress range in the diaphragm plate, a comparison to the rear axles of the H-15 truck provides a reasonable comparison to the requirements in the Specification.*) The estimated stress range for 100%, 200%, and 300% of the H-15 rear axle plus 15% impact are listed in Table 7.7. The data from the controlled load tests and the random heavy truck described in Table 7.5 are also listed for comparison. Note the similarity between the effects of the random heavy truck and the estimated stress for 300% of the HS-15 rear axle load. The estimated axle load for this random truck is 350kN (78.6 kips), as discussed above, which is about 10% less than three times the H-15 rear axle load (including impact) of 368kN (83 kips).

<table>
<thead>
<tr>
<th>Channel and Location</th>
<th>Measured(^3)</th>
<th>Estimated Stress Ranges from Various H-15 Trucks(^{1,2})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single-Axle</td>
<td>Tandem-Axle</td>
</tr>
<tr>
<td>CH1 / FB63E Rib 5 S.E. Corner</td>
<td>19 (2.8)</td>
<td>55 (8.0)</td>
</tr>
<tr>
<td>CH2 / FB63E Rib 5 N.E. Corner</td>
<td>21 (3.0)</td>
<td>56 (8.1)</td>
</tr>
<tr>
<td>CH27 / FB64E Rib 5 S.E. Corner</td>
<td>25 (3.6)</td>
<td>83 (12.0)</td>
</tr>
<tr>
<td>CH29 / FB64E Rib 5 N.E. Corner</td>
<td>28 (4.1)</td>
<td>82 (11.9)</td>
</tr>
</tbody>
</table>

Notes:
1. Estimated using Figure 7.3 and equations in Table 7.6. Values include 15% impact.
2. Assumes truck is in the outside lane.
3. Measured data from trucks located in the outside lane listed in Table 7.5.
4. As required by AASHTO LRFD fatigue design.

Table 7.7 – Estimated Effects at Selected Locations of Various Levels of the H-15 Truck

It should also be noted that the estimated effects of a truck that weighs twice the H-15 truck produces peak stress ranges that are reasonably consistent with the Category C CAFL of 69MPa (10ksi), which is applicable to the rib/diaphragm welded cutout detail. For example, the estimated stress range at channels CH27 & CH29 are both 81MPa (11.8ksi). This suggests that even though the project specific design loading was different than the AASHTO LRFD Specification, stress ranges produced by the design vehicle are within allowable limits on the structure.

This observation also reinforces the fact the laboratory data cannot be compared to the field measurements directly. The field measurements provided stress cycles caused by single vehicles and not by two trucks in adjacent lanes as tested in the laboratory. For example, comparing the laboratory measured stress range produced by twice the HS-15 truck plus impact in the outside lane at rib 5, found in Table 7.2, with the data in Table 7.7, confirms that the laboratory tests over estimates the stress range at the cutout.
8.0 Future Field Measurements and Studies

The controlled and uncontrolled monitoring program has produced valuable information related to the behavioral characteristics and in-service stress ranges of the orthotropic deck on the south outer roadway of the Williamsburg Bridge. As originally proposed, additional monitoring of selected locations was to be completed by the New York City DOT. This chapter suggests areas where additional field measurements are desirable.

8.1 Additional Measurements on the South Outer Roadway

A significant amount of data have been collected on the south outer roadway at floorbeams 63E, 64E, 65E, and 67E. The stress-histograms that have been developed are believed to accurately represent and characterize the current traffic conditions for the entire southern outer roadway. However, some additional instrumentation and monitoring is suggested at floorbeam 64E.

Measurements made on the inner roadway revealed that the highest stresses and stress ranges were measured at ribs 16 and 17, where the diaphragm is the shallowest and the curvature of the floorbeam is greatest (see Appendix A). For similar reasons, it is recommended that 4 uniaxial gages be installed on the diaphragm plate adjacent to the cutouts at ribs 8 and 9 at floorbeam 64E (8 gages total). These gages should be positioned identical to those installed adjacent to the cutouts at rib 5 on floorbeam 64E. Monitoring of selected gages should be conducted for a minimum period of one month. It may also be prudent to collect random data during the replacement and subsequent closures of the north roadways for periods of one month, depending on traffic patterns.

With the north roadway still under construction, additional monitoring at other floorbeams along the southern outer roadway is not likely to provide any new information. (Collecting additional data prior to the completion of all construction is of little value since the traffic patterns are temporary and effects on fatigue life would be very small.) However, after all phases of construction are completed, gages installed at floorbeam 64E, on the south outer roadway, should be monitored. The data will establish if any significant changes in traffic patterns have taken place since the initial monitoring program completed in 1999. Within six months after all construction is completed, it is suggested that data be collected for a period of one to two months. Monitoring should be then be conducted every five (5) years for periods of one or two months in order to determine any changes in behavior and traffic patterns (i.e., stress range histograms). If significant changes in behavior are observed, it may be prudent to conduct controlled load tests using a truck similar to the tandem-axle test truck utilized during the March 1998 tests. This truck can be “mixed” in with normal traffic and lane closures would not required.

The following locations should be monitored simultaneously:

**Outer Roadway**
- Gages on the diaphragm plate adjacent to the cutout at ribs 5, 7, 8, and 9 at FB 64E
- Gages on the top and bottom flanges of FB 64E

**Inner Roadway (Discussed Below)**
- Gages on the diaphragm plate adjacent to the cutout at ribs 12 through 18 at FB 64E
- All gages on the top and bottom flanges of FB 64E beneath the inner roadway
8.2 Additional Measurements on the Inner Roadway

Details pertaining to the measurements made on the inner roadway are summarized in Appendix A of this report along with recommendations for additional research. Those recommendations are repeated here for convenience.

The measurements made on the orthotropic deck system on the inner roadway have revealed some unexpected and interesting aspects of behavior that require further study. The limited stress-range histograms that were developed provide valuable information regarding in-service stresses. However, these measurements were limited in scope and duration. Additional field testing is desirable and should include ribs 12 and 18.

Specifically, the following additional fieldwork is suggested:

1. Install uniaxial gages at ribs 12 and 18. The measured stress ranges were highest in the northern most ribs (i.e., rib 17). However, no gages were installed at ribs 12 and 18. The gages should be positioned identical to those on ribs 13 through 17.

2. Install gages on the top and bottom flanges of floorbeam 64E near the southern connection to the truss, at the centerline of the inner roadway and adjacent to or between (i.e., midspan) the rail lines to better characterize the curvature of the floorbeam under truck and train loading. A gage should also be placed on the diaphragm plate adjacent to the deck plate at each section to establish the degree of composite action and the assumption that plane sections remain plane (see Figure 8.1).

3. Conduct remote monitoring of selected gages to better define the random-amplitude stress-range spectrum for the inner roadway (as stated above).
4. Make measurements using a loaded test truck of known weight and dimensions. Tests should be conducted with the truck positioned in lane five and six, similar to the tests carried out with the tandem-axle vehicle on the lanes 7 and 8. *These tests could be conducted concurrently with those described above and lane closures are not required.*

5. Monitor selected gages to establish the frequency of occurrence of the observed truck/train interaction and its influence on the random-amplitude stress-range spectrum.
References:

2. Wolchuk, R., Steel Orthotropic Decks and Their Applications in Bridge Engineering, Lehigh University, Civil Engineering Seminar, Bethlehem, PA, April, 1992.


ACKNOWLEDGMENTS

This work was sponsored by the FHWA US DOT, New York State DOT, and New York City DOT. In addition, the technical support and assistance with coordination of the field testing program provided by Dyab Khazem, Brian Gill, and Jamey Barbas from Steinman Consulting Engineers in New York City was invaluable. Thanks are also due to the New York City DOT and Yonkers Construction for providing the test tucks.

The authors would like to recognize Lehigh University graduate students Kevin Johns, Brian Metrovich, and Paul Tsakopoulos for their efforts during the field instrumentation and testing phase of this project. In addition, ATLSS Instrumentation Specialists Ed Tomlinson and Russ Longenback provided valuable assistance during the field activities.
APPENDIX A

Summary of Measurements Made on the

   Inner Roadway

   of the

Williamsburg Bridge Orthotropic Deck
A1.0  Background

Though not part of the original scope of work, 20 additional strain were installed on the inner roadway by Lehigh University at floorbeam 64E in March of 1999. The five interior ribs (ribs 13 through 17) were each instrumented with four strain gages. Data were collected from March 18th to April 26th 1999. The data consisted of triggered time histories and stress-range histograms.

Although the amount of data collected on the inner roadway are limited (i.e., there is no data from controlled tests), valuable information was gained regarding the behavior of the inner roadway. The results of this “pilot study” are discussed in this Appendix.

A2.0  Instrumentation Plan

Figure A2.1 shows the strain gage layout used on the diaphragm at floorbeam 64E on the inner roadway. The gage locations and the data collected are summarized in Table A2.1. Figure A2.2 is a cross section of the Williamsburg Bridge at floorbeam 64E. As can be seen in Figure A2.1, the gage layout is comparable to that used on the outer roadway, for rib 5 of floorbeam 64E. Gages were installed on both sides of the diaphragm plate adjacent to the cutout. No gages were installed on the floorbeam, deck plate, or ribs. The wires for these 20 channels are located in the steel box mounted to floorbeam 64E which housed the data acquisition system.

Figure A2.1 - Strain Gage Layout on the Diaphragm at Floorbeam 64E on the Inner Roadway
Figure A2.2 – Half Section of Williamsburg Bridge
<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Actual Channel Number</th>
<th>Comments - Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CH-1</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 13 S.W. Corner</td>
</tr>
<tr>
<td>2</td>
<td>CH-2</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 13 S.E. Corner</td>
</tr>
<tr>
<td>3</td>
<td>CH-3</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 13 N.W. Corner</td>
</tr>
<tr>
<td>4</td>
<td>CH-4</td>
<td>Trig. Time Hist./Rainflow - Diaphragm @ FB64E Rib 13 N.E. Corner</td>
</tr>
<tr>
<td>5</td>
<td>CH-5</td>
<td>Rainflow Hist. Only – Diaphragm @ FB64E Rib 14 S.W. Corner</td>
</tr>
<tr>
<td>6</td>
<td>CH-6</td>
<td>Rainflow Hist. Only – Diaphragm @ FB64E Rib 14 S.E. Corner</td>
</tr>
<tr>
<td>7</td>
<td>CH-7</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 14 N.W. Corner</td>
</tr>
<tr>
<td>8</td>
<td>CH-8</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 14 N.E. Corner</td>
</tr>
<tr>
<td>9</td>
<td>CH-9</td>
<td>Rainflow Hist. Only – Diaphragm @ FB64E Rib 15 S.W. Corner</td>
</tr>
<tr>
<td>10</td>
<td>CH-10</td>
<td>Rainflow Hist. Only – Diaphragm @ FB64E Rib 15 S.E. Corner</td>
</tr>
<tr>
<td>11</td>
<td>CH-11</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 15 N.W. Corner</td>
</tr>
<tr>
<td>12</td>
<td>CH-12</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 15 N.E. Corner</td>
</tr>
<tr>
<td>13</td>
<td>CH-13</td>
<td>Rainflow Hist. Only – Diaphragm @ FB64E Rib 16 S.W. Corner</td>
</tr>
<tr>
<td>14</td>
<td>CH-14</td>
<td>Rainflow Hist. Only – Diaphragm @ FB64E Rib 16 S.E. Corner</td>
</tr>
<tr>
<td>15</td>
<td>CH-15</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 16 N.W. Corner</td>
</tr>
<tr>
<td>16</td>
<td>CH-16</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 16 N.E. Corner</td>
</tr>
<tr>
<td>17</td>
<td>CH-13</td>
<td>Rainflow Hist. Only – Diaphragm @ FB64E Rib 17 S.W. Corner</td>
</tr>
<tr>
<td>18</td>
<td>CH-14</td>
<td>Rainflow Hist. Only – Diaphragm @ FB64E Rib 17 S.E. Corner</td>
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<tr>
<td>19</td>
<td>CH-15</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 17 N.W. Corner</td>
</tr>
<tr>
<td>20</td>
<td>CH-16</td>
<td>Rainflow Hist. Only - Diaphragm @ FB64E Rib 17 N.E. Corner</td>
</tr>
</tbody>
</table>

Table A2.1 – Channels Monitored on Inner Roadway  
(March 18th to April 26th 1999)
A3.0 Results of Monitoring

The triggered time histories indicate that the overall response of the diaphragm plate to random truck loading is very similar to that of the outer roadway. Figure A3.1 shows the response due to a random truck headed east for CH13, CH14, CH15, and CH16 on rib 16. As on the outer roadway, there is a single dominant stress cycle produced per truck.

![Figure A3.1 – Response at Rib 16 Due to Passage of a Random Eastbound Truck](image)

Channels CH13 and CH14 are placed back to back on the diaphragm plate on the south side cutout, CH15 and CH16 on the north side. Stress levels on each side of the rib (i.e., north vs. south) are opposite in sign, similar to the response of the outer roadway. However, the stresses are reversed to those observed on the outer cantilevered roadway. On the outer roadway, gages on the north side of the rib (i.e., fixed end of the floorbeam) were in compression while the gages on the south side (i.e., free end of the floorbeam) were in tension. Channels CH13 and CH14 are located on the south side of rib 16 and are in compression as shown in Figure A3.1. This indicates that the curvature of the floorbeam on the inner roadway is opposite that of the cantilever, as expected.

During the monitoring period, a limited amount of time history data was collected for all 20 channels. It became apparent that the highest stress ranges were consistently occurring at the northern most ribs 16 and 17. In order to investigate this further, triggered time histories were collected at channels CH17 though CH20 for a short interval of time. These data verified that the highest stresses were being generated at these ribs. (The stress-range histograms also confirmed this observation, as discussed in Section A4.)
This behavior is believed to result from the enforced compatibility between the deck and the floorbeam. The live-load moments in the floorbeam are higher at rib 17 than at rib 13. Hence, the curvature of the floorbeam is also greater at rib 17 than at rib 13. Since the deck is not fully composite with the floorbeam, it is forced to follow the deflected shape of the floorbeam. Although not shown, the proportions of in-plane and out-of-plane stresses were comparable to that observed on the outer roadway. This results in a large horizontal deformation in the diaphragm plate at rib 17 as the curvature between the floorbeam and the deck is enforced. This results in higher horizontal shear forces in the diaphragm plate near the end of the deck which in turn results in higher cyclic stresses at the cutouts.

A3.1 Effects of the Commuter Rail Lines

The floorbeam supporting the inner roadway is continuous across the width of the structure. This floorbeam also supports two commuter rail lines which pass through the center portion the Williamsburg Bridge (see Figure A2.2). Passing trains were observed to influence the response of the orthotropic deck on the outer roadway as noted in Section 5. The effect of the trains was much greater on the inner roadway since the floorbeam curvature was greater.

Figure A3.2 –Response of Diaphragm Plate Adjacent to Rib 17 on Diaphragm Plate During Passage of Commuter Train (The Train was Headed East)
Figure A3.2 shows the response at rib 17 as a commuter train passed. The response is similar to that observed during the control tests on the outer roadway as trains passed. However, the magnitudes of the stresses are higher and each pair of adjacent axles of the units of the train produces a cycle of about 9 to 10 per train.

Note that there is a positive stress produced in channels CH17 and CH19 as the train approaches the floorbeam. However, as the train passes, the stress becomes negative at these two channels. The opposite is observed at channels CH18 and CH20. Hence as the train approached, the east face of the diaphragm plate was in tension while the west face was in compression. A similar response was produced by eastbound heavy trucks as they crossed the floorbeam (see Figure A3.3) on the inner roadway. This suggests that the train was also headed east, toward Brooklyn.

These stresses are a result of the continuity of the orthotropic deck across the floorbeams and the “global” response of the suspended span. The global bending of the suspended span is apparent because the effects of the train are observed at floorbeam 64E about 30 seconds prior to (and after) the train reaches and passes the floorbeam. Assuming the train is traveling at 20mph, it is estimated that it was almost 900 feet (about 45 panel points) away when the effects of the train were first observed at floorbeam 64E.
Figure A3.4 shows the response of the same gages for a different train. Note that the gages on the west face (CH18 and CH20) are in tension while the gages on the east face (CH17 and CH19) go into compression, which is opposite of what was observed in Figure A3.2. Since the response is opposite of the eastbound train, it indicates that this train was headed west, toward Manhattan. It should also be noted that the magnitudes of the stresses are less than those measured for the eastbound train. Since the westbound trains are on the northern track the floorbeam curvature is less at rib 17.
Ribs 16 and 17 are closer to the commuter rail lines than the other ribs (see Figure A2.2). As a result, passing trains have a greater influence on the measured stresses at these ribs. Figure A3.5 compares the response for channels CH1 (rib 13) and CH19 (rib 17) as a commuter train passed. The influence of the train at CH19 is clearly greater than at CH1. In fact, each pair of adjacent axles of the train produces a stress-range cycle as that averages about 28MPa at CH19. The stress range produced at CH1, which is further away from the train, is only about 6 MPa.

![Figure A3.5 - Response of Diaphragm Plate at CH1 (Rib 13) and CH19 (Rib 17) as a Commuter Train Passed](image)

While on site, it was observed that commuter trains cross the Williamsburg Bridge frequently. The probability that a train will cross at the moment a heavy truck is crossing is high. In order to assess these events, channel CH20 on rib 17 was monitored for a few days.

Figure A3.6 presents an event recorded on March 13th 1999 in which a train and a heavy truck were crossing floorbeam 64E at the same time. The wheels of the truck and train appear to be in phase as they cross the floorbeam. Had the truck crossed the floorbeam by itself, the peak stress and stress range would have been about 75MPa (10.9ksi) at CH19. However, the superposition of the two responses results in a peak stress of almost 90 MPa (13.1ksi). The stress range is seen to increase from 75MPa (10.9ksi) to about 125MPa (18.1ksi). This is roughly a 2/3 increase in stress range due to the two vehicles crossing the floorbeam simultaneously.
Whenever a train and a truck are on the bridge and headed in toward each other, they must pass at some point. Because the train spans several floorbeams, the probability that the axle loads of both vehicles will both be over a floorbeam is high. The time history data indicate that it is not uncommon for trucks and trains to cross floorbeam 64E at the same time. Obviously, not all of the trucks in these events were as heavy as the one illustrated in Figure A3.6. Nevertheless, the data demonstrate that these loading events take place with some frequency. (As will be discussed in Section 4, the trains had a substantial effect on the number of cycles counted in the stress-range histograms.)

Figure A3.6 - Response of Diaphragm Plate at CH19 (Rib 17) as a Random Heavy Truck and a Commuter Train Passed Over Floorbeam 64E
A4.0  Stress-Range Histograms for the Inner Roadway Diaphragm Plate

Stress-range histograms were developed for all of the gages mounted on the diaphragm plate. All of these gages were located adjacent to the cutout near the weld toe. With the exception of channel CH10, all gages were operational and relatively noise free throughout the entire monitoring period. During the monitoring of the inner roadway, an electrical short in the power supply line created significant noise in a portion of the data. (This short eventually shut off the data logger.) As a result, only the data from the latter half of the monitoring program was considered. The portion of time covered is from March 29th to April 16th, 425 hours. Although the monitoring period is considerably less than on the outer roadway, the data were consistent and believed to reasonably represent the random-amplitude stress-range spectrum. Additional measurements should be made on the inner roadway as described in Section A5.

<table>
<thead>
<tr>
<th>Channel/Location</th>
<th>$S_{\text{eff}}$ MPa (ksi)</th>
<th>$S_{\text{max}}$ MPa (ksi)</th>
<th>Total # Cycles</th>
<th>Cycles/ per Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH-1 / FB64E Rib 13 S.W. Corner</td>
<td>28 (4.2)</td>
<td>97 (14.2)</td>
<td>3,587</td>
<td>203</td>
</tr>
<tr>
<td>CH-2 / FB64E Rib 13 S.E. Corner</td>
<td>30 (4.4)</td>
<td>83 (12.0)</td>
<td>3,155</td>
<td>178</td>
</tr>
<tr>
<td>CH-3 / FB64E Rib 13 N.W. Corner</td>
<td>28 (4.0)</td>
<td>58 (8.4)</td>
<td>4,035</td>
<td>228</td>
</tr>
<tr>
<td>CH-4 / FB64E Rib 13 N.E. Corner</td>
<td>26 (3.8)</td>
<td>93 (13.4)</td>
<td>6,707</td>
<td>379</td>
</tr>
<tr>
<td>CH-5 / FB64E Rib 14 S.W. Corner</td>
<td>27 (3.9)</td>
<td>98 (14.2)</td>
<td>5,045</td>
<td>285</td>
</tr>
<tr>
<td>CH-6 / FB64E Rib 14 S.E. Corner</td>
<td>28 (4.0)</td>
<td>98 (14.2)</td>
<td>3,801</td>
<td>215</td>
</tr>
<tr>
<td>CH-7 / FB64E Rib 14 N.W. Corner</td>
<td>28 (4.0)$^{x}$</td>
<td>68 (9.9)$^{x}$</td>
<td>4,095$^{x}$</td>
<td>465$^{x}$</td>
</tr>
<tr>
<td>CH-8 / FB64E Rib 14 N.E. Corner</td>
<td>26 (4.0)</td>
<td>93 (13.4)</td>
<td>5,703</td>
<td>322</td>
</tr>
<tr>
<td>CH-9 / FB64E Rib 15 S.W. Corner</td>
<td>28 (4.0)</td>
<td>83 (12.0)</td>
<td>8,498</td>
<td>480</td>
</tr>
<tr>
<td>CH-10 / FB64E Rib 15 S.E. Corner</td>
<td>BAD CHANNEL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH-11 / FB64E Rib 15 N.W. Corner</td>
<td>32 (4.6)</td>
<td>123 (17.8)</td>
<td>33,681</td>
<td>1,903</td>
</tr>
<tr>
<td>CH-12 / FB64E Rib 15 N.E. Corner</td>
<td>32 (4.6)</td>
<td>128 (18.6)</td>
<td>32,568</td>
<td>1,840</td>
</tr>
<tr>
<td>CH-13 / FB64E Rib 16 S.W. Corner</td>
<td>30 (4.4)</td>
<td>118 (17.1)</td>
<td>36,248</td>
<td>2,048</td>
</tr>
<tr>
<td>CH-14 / FB64E Rib 16 S.E. Corner</td>
<td>32 (4.6)</td>
<td>123 (17.8)</td>
<td>27,244</td>
<td>1,539</td>
</tr>
<tr>
<td>CH-15 / FB64E Rib 16 N.W. Corner</td>
<td>31 (4.5)</td>
<td>123 (17.8)</td>
<td>34,186</td>
<td>1,931</td>
</tr>
<tr>
<td>CH-16 / FB64E Rib 16 N.E. Corner</td>
<td>33 (4.8)</td>
<td>138 (20.0)</td>
<td>44,807</td>
<td>2,531</td>
</tr>
<tr>
<td>CH-17 / FB64E Rib 17 S.W. Corner</td>
<td>35 (5.1)</td>
<td>133 (19.2)</td>
<td>30,433</td>
<td>1,719</td>
</tr>
<tr>
<td>CH-18 / FB64E Rib 17 S.E. Corner</td>
<td>35 (5.1)</td>
<td>138 (20.0)</td>
<td>38,628</td>
<td>2,182</td>
</tr>
<tr>
<td>CH-19 / FB64E Rib 17 N.W. Corner</td>
<td>39 (5.6)</td>
<td>168 (24.3)</td>
<td>55,005</td>
<td>3,108</td>
</tr>
<tr>
<td>CH-20 / FB64E Rib 17 N.E. Corner</td>
<td>39 (5.6)</td>
<td>158 (23.0)</td>
<td>54,416</td>
<td>3,074</td>
</tr>
</tbody>
</table>

Notes:
1. Only includes stress cycles that exceed 20 MPa (2.9ksi).
2. Only includes data collected between March 29th, 1999 to April 7th, 1999 due to noise problem. The total time was eight days and 19 1/2 hours.

Table A4.1 - Maximum and Effective Stress Ranges for Gages Installed on the Diaphragm Plate of the Inner Roadway for the Fourth Monitoring Period (17 Days 17 Hours Total)
Table A4.1 summarizes the stress-range histogram data for each channel. The effective and maximum stress range for each channel was calculated by excluding all stress-range cycles less than 20MPa (2.9ksi). Prior to calculating the effective and maximum stress ranges, the data were reviewed and compared to the triggered time histories for all available channels to minimize the inclusion of random noise signals.

As shown in Table A4.1, the calculated effective stress range is reasonably consistent for all channels. However, there is a considerable variation in the peak stress range and the number of cycles. As previously discussed, the time history data indicated that the largest stress ranges were measured on the north ribs (ribs 15, 16, and 17). In addition, the effects of the trains were also greatest at these ribs. The significant increase in the number of cycles at ribs 15, 16, and 17 is attributed to two factors.

First, when a truck passes, a larger stress range is produced at the northern ribs, as was shown by the time history data. A considerable number of trucks produce cycles that are greater than 20MPa, which was selected as the cutoff. Second, as shown in Figure A3.5, each pair of axles of a commuter train produce a stress cycle that is typically greater than 20 MPa at rib 17. Assuming 200 trains per day (100 each way) and ten cycles per train, an additional 2000 cycles are produced each day by the passing trains.

In order to verify that the commuter trains were responsible for the increase in the number of cycles, the effective stress range and corresponding number of cycles was recalculated ignoring all cycles less than 30MPa (4.4ksi). Since the axles of the trains produced cycles that were generally between 20MPa (2.9ksi) and 30MPa (4.4ksi), ignoring all cycles less than 30MPa (4.4ksi) should remove the effects of the trains axles from the data.

<table>
<thead>
<tr>
<th>Channel/Location</th>
<th>$S_{\text{eff}}$ (MPa (ksi))</th>
<th>$S_{\text{max}}$ (MPa (ksi))</th>
<th>Total # Cycles</th>
<th>Cycles per Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH-13 / FB64E Rib 16 S.W. Corner</td>
<td>44 (6.6)</td>
<td>118 (17.1)</td>
<td>6,704</td>
<td>379</td>
</tr>
<tr>
<td>CH-14 / FB64E Rib 16 S.E. Corner</td>
<td>47 (6.8)</td>
<td>123 (17.8)</td>
<td>6,250</td>
<td>353</td>
</tr>
<tr>
<td>CH-15 / FB64E Rib 16 N.W. Corner</td>
<td>46 (6.7)</td>
<td>123 (17.8)</td>
<td>6,986</td>
<td>395</td>
</tr>
<tr>
<td>CH-16 / FB64E Rib 16 N.E. Corner</td>
<td>49 (7.1)</td>
<td>138 (20.0)</td>
<td>9,389</td>
<td>530</td>
</tr>
<tr>
<td>CH-17 / FB64E Rib 17 S.W. Corner</td>
<td>50.5 (7.3)</td>
<td>133 (19.2)</td>
<td>8,081</td>
<td>457</td>
</tr>
<tr>
<td>CH-18 / FB64E Rib 17 S.E. Corner</td>
<td>52 (7.6)</td>
<td>138 (20.0)</td>
<td>9,049</td>
<td>511</td>
</tr>
<tr>
<td>CH-19 / FB64E Rib 17 N.W. Corner</td>
<td>54 (7.8)</td>
<td>168 (24.3)</td>
<td>16,866</td>
<td>953</td>
</tr>
<tr>
<td>CH-20 / FB64E Rib 17 N.E. Corner</td>
<td>53 (7.7)</td>
<td>158 (23.0)</td>
<td>16,913</td>
<td>956</td>
</tr>
</tbody>
</table>

Notes:
1. Only includes stress cycles that exceed 30 MPa (4.4ksi).

Table A4.2 - Maximum and Effective Stress Ranges for Gages Installed on the Diaphragm Plate of the Inner Roadway for the Fourth Monitoring Period Using a Ignoring all Stress-Range Cycles Less than 30 MPa (17 Days 17 Hours Total)

Table A4.2 lists the calculated effective stress range and corresponding number of cycles when all cycles less than 30 MPa are ignored for ribs 16 and 17. The resulting number of cycles are in much better agreement with those shown in Table A4.1 for ribs 13, 14, and 15. The total number of cycles is still greater at ribs 16 and 17, since random trucks produce larger stress ranges (and therefore additional cycles) at ribs 16 and 17, as
previously discussed. This verifies the influence of the commuter trains on the effective stress range and corresponding number of cycles at ribs nearest the rail lines.

**A5.0 Summary of Measurements Made on the Inner Roadway**

A pilot study was conducted on the inner roadway orthotropic deck of the Williamsburg Bridge during the Spring of 1999. Instrumentation consisted of 20 strain gages installed adjacent to the cutouts at ribs 13 through 17. Data collected included time histories and stress range histograms for random traffic. No controlled load tests were conducted.

The measurements indicated the following:

1. Maximum measured stresses adjacent to the cutout are similar in magnitude to those observed on the outer roadway. The overall response of the diaphragm plate is also similar to that observed on the outer roadway.

2. The proportions of in-plane and out-of-plane stresses are comparable with that observations on the outer roadway.

3. The curvature of the floorbeam under the inner roadway is opposite of the cantilever. Thus, the distribution of stresses adjacent to the ribs is opposite to that observed on the outer roadway.

4. Trucks produce the largest stress ranges at ribs 16 and 17, which are located toward the center of the bridge.

5. The effects of the commuter trains is greater on the inner roadway, particularly adjacent to cutouts nearest the rail lines.

6. The individual axles of the trains produce stress cycles as high as 22MPa (3.2ksi) adjacent to the cutout. Thee additional cycles are a substantial proportion of the random-amplitude stress-range spectrum.
### A6.0 Additional Measurements on the Inner Roadway

The measurements made on the orthotropic deck system on the inner roadway have revealed some unexpected and interesting aspects of behavior that require further study. The limited stress-range histograms which were developed provide valuable information regarding in-service stresses. However, these measurements were limited in scope and duration. Additional field testing is desirable and should include ribs 12 and 18. Specifically, the following additional field work is suggested:

1. Install uniaxial gages at ribs 12 and 18. The measured stress ranges were highest in the northern most ribs (i.e., rib 17). However, no gages were installed at ribs 12 and 18. The gages should be positioned identical to those on ribs 13 through 17.

2. Install gages on the top and bottom flanges of floorbeam 64E near the southern connection to the truss, at the centerline of the inner roadway and adjacent to or between (i.e., midspan) the rail lines to better characterize the curvature of the floorbeam under truck and train loading. A gage should also be placed on the diaphragm plate adjacent to the deck plate at each section to establish the degree of composite action and the assumption that plane sections remain plane (see Figure A6.1).

3. Conduct remote monitoring of selected gages to better define the random-amplitude stress-range spectrum for the inner roadway (as stated above).

4. Make measurements using loaded test trucks with know weight and dimensions. Tests should be conducted with the truck(s) positioned in lane five and six, similar to the tests carried out with the tandem-axle vehicle on the lanes 7 and 8. *These tests could be conducted concurrently with those described above and lane closures are not required.*

5. Monitor selected gages to establish the frequency of occurrence of the observed truck/train interaction and its influence on the random-amplitude stress-range spectrum.

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*Figure A6.1 – Suggested Gage Locations on Floorbeam Beneath Inner Roadway*
APPENDIX B

Summary of Long-Term Remote Monitoring of Selected Channels at Floorbeam 67E on the South Outer Roadway of the Williamsburg Bridge Orthotropic Deck
B1.0 Background

During routine construction inspection, it was observed that an offset of up to 12mm (½ in) existed between the centerline of the diaphragm and the floorbeam web of PPT 67E. Due to concerns of possible detrimental effects resulting from the diaphragm offset, it was decided that field instrumentation and testing at PPT 67E was necessary to determine if remedial measures were required. A test program which included controlled crawl and dynamic load tests was completed. The results of these tests are discussed in detail in the report; Evaluation of the Effects of Diaphragm Offset at Panel Point 67E – Final Report on the South Outer Roadway [5]. That report suggested that a select number of channels be included in the long-term remote monitoring portion of the field testing program. As a result, during the third monitoring period, four channels installed at floorbeam 67E were monitored. Specifically, channels 1, 3, 5, and 7, which are located adjacent to rib 5 near the cutout. Data were collected from December 13th through February 16th 1999 and consisted of triggered time histories and stress-range histograms. This appendix summarizes the results of the long-term monitoring. Information related to the controlled load tests can be found in reference 5.

All testing was conducted by personnel from Lehigh University’s Center for Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center located in Bethlehem, Pennsylvania.
**B2.0 Instrumentation Plan**

Figure B2.1 shows the strain gage layout used on the diaphragm at floorbeam 67E on the outer roadway. The gages selected for the long-term monitoring program are listed in Table B2.1. Table B2.2 relates these gages to the corresponding gages installed at panel points 63E, 64E, and 65E. As can be seen in Figure B2.1, the gage layout is identical to that used on the outer roadway, specifically at rib 5 of floorbeam 64E. Gages were installed on both sides of the diaphragm plate adjacent to the cutout at all locations. No gages were installed on the floorbeam, deck plate, or ribs. The signal wires for these 20 channels are located in the steel box mounted to floorbeam 64E which housed the data acquisition system.

<table>
<thead>
<tr>
<th>Reference Number</th>
<th>Actual Channel Number</th>
<th>Chan. on “Vishay”</th>
<th>Comments - Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>CH-1</td>
<td>5</td>
<td>Rainflow Hist. Only - Rib 5 of FB 67E S.E. Corner</td>
</tr>
<tr>
<td>6</td>
<td>CH-3</td>
<td>6</td>
<td>Rainflow Hist. Only - Rib 5 of FB 67E N.E. Corner</td>
</tr>
<tr>
<td>7</td>
<td>CH-5</td>
<td>7</td>
<td>Rainflow Hist. Only - Rib 5 of FB 67E S.W. Corner</td>
</tr>
<tr>
<td>8</td>
<td>CH-7</td>
<td>8</td>
<td>Rainflow Hist. Only - Rib 5 of FB 67E N.W. Corner</td>
</tr>
</tbody>
</table>

Table B2.1 – Channels Monitored at floorbeam 67E of the Outer Roadway (December 13th and Through February 16th 1999)

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Location on Diaphragm</th>
<th>Panel Point 63E (Fig. 3)</th>
<th>Panel Point 64E (Fig. 4)</th>
<th>Panel Point 65E (Fig. 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH-1</td>
<td>Near Rib 5 @ S.E. Corner</td>
<td>1</td>
<td>27</td>
<td>N/A</td>
</tr>
<tr>
<td>CH-3</td>
<td>Near Rib 5 @ N.E. Corner</td>
<td>2</td>
<td>29</td>
<td>N/A</td>
</tr>
<tr>
<td>CH-5</td>
<td>Near Rib 5 @ S.W. Corner</td>
<td>5</td>
<td>35</td>
<td>55</td>
</tr>
<tr>
<td>CH-7</td>
<td>Near Rib 5 @ N.W. Corner</td>
<td>6</td>
<td>36</td>
<td>56</td>
</tr>
</tbody>
</table>

Table B2.2 – Channels at Floorbeam 67E Included in the Third Monitoring Period and Corresponding Channels at Floorbeams 63E, 64E and 65E.
Figure B2.1 - Strain Gage Layout on the Diaphragm at Floorbeam 67E

Diaphragm Strain Gage Layout
(Floorbeams 67E - Looking West)
(Total of 16 Strain Gage Channels)

Diaphragm Gages are Measurements Group
LWK-06-W250B-350 Gage Factor is 2.02

Bulk-Head Gages are Measurements Group
CEA-06-W250A-120 Gage Factor is 2.075

Note: Gage numbers in ( ) are on far or West side of diaphragm
B3.0  Stress-Range Histograms –Floorbeam 67E of the South Outer Roadway

Stress-range histograms were developed for four of the gages mounted on the diaphragm plate. All of these gages were located adjacent to the cutout near the weld toe. All gages were relatively noise free throughout the entire monitoring period. The portion of time covered is from December 13th and through February 16th 1999, for a total of 40 days.

The stress-range histograms were developed using the same procedures used throughout the long-term remote monitoring program (see Section 7.4).

<table>
<thead>
<tr>
<th>Channel/Location</th>
<th>$S_{\text{eff}}$ MPa (ksi)</th>
<th>$S_{\text{max}}$ MPa (ksi)</th>
<th>Total # Cycles 1</th>
<th>Cycles per Day 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH-1 / Near Rib 5 FB 67E @ S.E. Corner</td>
<td>36 (5.2)</td>
<td>118 (17.1)</td>
<td>18,764</td>
<td>469</td>
</tr>
<tr>
<td>CH-3 / Near Rib 5 FB 67E @ N.E. Corner</td>
<td>34 (4.9)</td>
<td>113 (16.4)</td>
<td>14,708</td>
<td>368</td>
</tr>
<tr>
<td>CH-5 / Near Rib 5 FB 67E @ S.W. Corner</td>
<td>35 (5.1)</td>
<td>123 (17.9)</td>
<td>20,551</td>
<td>514</td>
</tr>
<tr>
<td>CH-7 / Near Rib 5 FB 67E @ N.W. Corner</td>
<td>36 (5.2)</td>
<td>108 (15.7)</td>
<td>18,808</td>
<td>470</td>
</tr>
</tbody>
</table>

Notes:
1. Only includes stress cycles that exceed 20 MPa (2.9ksi).

Table B3.1 - Maximum and Effective Stress Ranges for Gages Installed on the Diaphragm Plate of FB67E on the South Outer Roadway During the Third Monitoring Period (40 Days Total)

Comparing the data listed in Table B3.1 with the results presented in Tables 6.12, 6.13, and 6.14 for similar gages installed at floorbeams 63E, 64E, and 65E, indicates that the measured stress-range histograms are comparable at all four locations. Thus, the diaphragm offset does not appear to have any negative influence on the measured stress-range histograms.

B4.0  Summary of Measurements Made at FB67E

The results of the long-term monitoring of selected gages at FB67E indicate the following:

1. Maximum measured stresses adjacent to the cutout produced by random trucks are essentially identical in magnitude and distribution to those observed at floorbeams 63E, 64E, and 65E.

2. The diaphragm offset has no significant influence on the behavior of the diaphragm plate subjected to random variable loading.

3. No additional field studies or measurements are needed at this location. In addition, no special attention is required during routine inspection of the orthotropic deck system.
APPENDIX C

Strain Gage Details
Data Acquisition
Modem Configuration
Remote Control of the CR9000
Strain Gages

The only type of sensors used were strain gages, of both the bondable and weldable type. All strain gages were wired as quarter-bridge circuits using a three-wire configuration and driven with an excitation voltage of 5 Volts. Both uniaxial and biaxial rosettes were used.

All uniaxial gages installed in the field were produced by Measurements Group Inc. and were type LWK-06-W250B-350. These gages are a weldable, fully temperature-compensated uniaxial strain gage. The grid is composed of modified Karma (K-alloy), encapsulated in a fiberglass-reinforced epoxy-phenolic. This strain gage exhibits good fatigue life (>10^7 cycles) and excellent stability. This type of gage is preferred for accurate strain measurements over long periods of time (months to years). K-alloy gages also offer a much flatter thermal output curve than typical Constantan alloy gages [6]. Weldable type strain gages have been selected due to ease of installation. The gage resistance of 350Ω and the excitation voltage of 5 Volts was selected for the following reasons:

1. Decreased lead wire effects, such as circuit desensitization due to lead wire resistance.
2. Decreases in unwanted signal variations caused by lead wire resistance changes caused by temperature fluctuations.
3. Improved signal to noise ratio, an important consideration in field instrumentation.

The weldable gages were installed on the ribs, deck plate and diaphragms of the south cantilever roadway during July of 1997. (See Figures 3.1, through 3.6 for locations.) Bondable biaxial rosettes were installed at only two locations on the east face of the diaphragm at PPT 64E near rib 5. These two rosettes were also installed during July of 1997. These gages were also produced by Measurements Group Inc. and are type CEA-06-125WT-120 (120Ω).

During fabrication of the panels under investigation, Lehigh University personnel installed resistance strain gages on the bulk-head plates at ribs 5 and 7 at PPTs 63E, 64E and 65E, as shown in Figures 3.1 to 3.6. These gages were bondable uniaxial strain gages produced by Measurements Group Inc. and are type CEA-06-W250A-120 (120Ω).

It should be noted that great care was taken in protecting the strain gages that were installed on site. All gages were protected with a multi-layer system and then sealed with a silicon type agent. All wire connections were soldered, electrically insulated with heat shrink tube and then protected with the same multi-layer and silicon sealing process. At the time of this report, no gages were lost to environmental exposure.

However, several gages were destroyed by construction workers during the fall of 1997. The gages that were destroyed or damaged are noted on Figures 3.2, 3.3, 3.4, & 3.6. Wires that were attached to the internal bulk-head gages ran inside the ribs and exited in the gap between ribs at the splices at PPTs 63E and 65E. Unfortunately, the wires attached to all internal bulk-head gages were cut by construction workers who were attaching the hand-hole covers near the rib splices. These wires were cut sometime after September of 1997 and before February of 1998. Thus, these gages could not be included during the March 1998 controlled load testing or the remote long-term monitoring program.
Data Acquisition

Controlled Load Tests Conducted During 1997

For all tests conducted during August of 1997, data were acquired using analog to digital (A/D) data acquisition boards produced by Keithley Instruments Inc. Due to system limitations, the maximum number of channels which could be recorded at one time was 64. As a result, two hook ups were required for each test. In order to compare data between like runs, a group of 18 channels were selected and recorded for all tests. Thus, for a given test during the first hook up, 46 channels plus 18 common channels were connected and recorded (46+18=64). (The 18 common channels are listed below.) For the second hook up, 46 different channels were connected along with the 18 common channels, thus totaling 110 channels (46_{1st \text{ SET}} + 46_{2nd \text{ SET}} + 18_{COMMON} = 110). The sampling rates used were 20 and 200 samples per second per channel for crawl and dynamic tests (up to 48 km/h) respectively. Strain gage conditioning was provided by Vishay Model 2100 signal conditioning Systems. All data were stored on a laptop computer at the site.

Common Channels for Each Setup

| CH77  | North side of Rib 5 at midspan between FB 64 and FB 65 on deck plate. |
| CH78  | South side of Rib 5 at midspan between FB 64 and FB 65 on deck plate. |
| CH80  | Bottom surface of C.L. Rib 6 at midspan between FB 64 and FB 65. |
| CH82  | Bottom surface of C.L. Rib 7 at midspan between FB 64 and FB 65. |
| CH83  | North side of Rib 7 at midspan between FB 64 and FB 65. |
| CH84  | South side of Rib 7 at midspan between FB 64 and FB 65 on deck plate. |
| CH86  | Bottom surface of C.L. Rib 2 at midspan between FB 64 and FB 65 |

| CH99  | Floorbeam 63 East face top flange |
| CH100 | Floorbeam 63 West face top flange |
| CH101 | Floorbeam 64 West face bottom flange |
| CH102 | Floorbeam 64 East face top flange |
| CH103 | Floorbeam 64 East face bottom flange |
| CH104 | Floorbeam 65 East face top flange |
| CH105 | Floorbeam 65 West face top flange |
| CH72  | Bottom surface @ C.L. of Rib 1 at midspan between FB 64 and FB 65. |
| CH74  | Bottom surface of C.L. Rib 2 at midspan between FB 64 and FB 65. |
| CH76  | Bottom surface of C.L. Rib 5 at midspan between FB 64 and FB 65 |

Note:
1. See Figures 3.1 through 3.6 for locations of channels.


Tests Conducted During March 1998

For all tests conducted during March of 1998, data were collected using a Campbell Scientific CR9000 data logger. This system is a high-speed multi-channel digital data acquisition system with 16 bit resolution. During these tests, data were collected on 82 strain gages simultaneously at sampling rates as high as 200Hz. Only 82 of the 110 channels installed at that time were recorded because 24 were damaged, as discussed in Section 3.1. In addition, a review of the data collected during 1997 indicated that there was no need to record the 4 channels installed on the shear plate since the measured stresses were very small. Thus, a total of 28 channels were not recorded for this set of tests.

The CR9000 system does not require external signal conditioning. Thus for the tests conducted during March of 1998, data were recorded without external signal conditioning. All data were temporarily stored on PCMCIA cards installed in the data logger and subsequently copied to the laptop at the end of each test for processing and back-up.

Remote Long-Term Monitoring

Data were also collected during the remote long-term monitoring portion of the project using the CR9000 Data Logger. In order to ensure a more stable, noise-free signal, Vishay Model 2100 signal conditioners were used. Control of the CR9000 was conducted remotely from Lehigh using modems. Program upload and data download was achieved using two U.S. Robotics 56k Faxmodems specially configured by Lehigh researchers. (For a more detailed discussion of the modem configurations, see Appendix C) One modem was placed at the site, the other in an office at the ATLSS Laboratory. The data were downloaded to a desktop PC every one to 14 days. Modem communication speeds were reasonably fast and robust. Fortunately, the data files were downloaded in binary format, thus dramatically decreasing the actual file size (by about a factor of 3). The entire data acquisition system was stored in a steel box that was bolted to the west face of floorbeam 64E (See Figures C-1a and C-1b).

Figures C-1a and C-1b – Photographs of the Steel Box which Contained the Data Acquisition System During the Long-Term Monitoring Program.
It should be noted that the remote monitoring was to have begun during the Spring of 1998. However, due to difficulties in securing a suitable and stable power supply for the data acquisition system and delays in the installation of a telephone line, this phase of the project could not begin until August 3, 1998. During this portion of Phase III, three groups of 20 channels were monitored for periods of four to five weeks each. Specifically, the following data were recorded:

1. Time histories for 2 channels (CH_27 and CH_29) located on the east face of the diaphragm on the north and south sides of rib 5 at floorbeam 64E. These channels were located beneath the outer lane (lane 8). It should be noted that these time histories were not continuously recorded. Rather, the data acquisition system began recording when the stresses induced by live loads exceeded predetermined levels (i.e., triggers). Two to four seconds of data were recorded prior to the trigger event (i.e., a 2 to 4 second buffer was maintained). Once the stresses fell below these levels, the data acquisition system recorded for 5 additional seconds and then stopped. Thus, each event recorded was a minimum of 7 to 9 seconds. In addition, CH_45 and CH_46 were also recorded when the trigger conditions were met for CH_27 and CH_29. These channels are essentially located beneath the inner lane (lane 7) and provided useful data for estimating the transverse position of the vehicle which caused the trigger event. It should be noted that channels 27 and 29 were automatically re-zeroed (digitally) on the whole and half hour. Sampling rates were 100Hz for the first and second set ups. A sampling rate of 200 Hz was used for the third set up.

2. Time histories for 2 channels (CH_45 and CH_46) located on the east face of the diaphragm on the north and south sides of rib 7 at floorbeam 64E. These channels are essentially located beneath the inner lane (lane 7). The same triggering method described above was also used for these two channels. Similar to above, CH_27 and CH_29 were also recorded when the trigger conditions were met for CH_45 and CH_46. These channels are essentially located beneath the outer lane (lane 8) and also provided useful data for estimating the transverse position of the vehicle which caused the trigger event. It should be noted that channels 45 and 46 were also automatically re-zeroed (digitally) on the whole and half hour. Sampling rates were 100Hz for the first and second set ups. A sampling rate of 200Hz was used for the third set up.

3. Stress-range histograms were also generated using the rainflow cycle counting method. The stress-range histograms were generated continuously and do not operate on triggers, thus all cycles were counted. A total of 20 channels were selected during each period for monitoring. (Specifically, the four channels mentioned above plus 16 other channels.) The rainflow table was updated every 10 minutes. Thus, in the event of system failure, say due to loss of power, a minimum amount of data would be lost.
Modem Details and Remote Control of CR9000

Land-line modems were used to upload programs and download data to and from the CR9000 Data Logger. A great deal of time was spent “fine tuning” the modems in order to maximize the communication speed. However, increasing communication speed (i.e., baud rate) can sacrifice the robustness of the connection.

The details pertaining to the configuration of the modems and the data logger will be discussed. The user is strongly urged to become familiar with basic modem terminology and programming. In addition, a basic understanding of the operation and programming of the CR9000 is also required.

The CR9000 is produced by Campbell Scientific, Inc., located in Logan, Utah.

Company Information
Campbell Scientific, Inc.
815 W. 1800 N.
Logan, Utah 84321-1784
Phone: (435) 753-2342
Fax: (435) 750-9540
Web http://www.campbellsci.com

Modems
Although there are many different manufacturers of analog modems, those used during the remote monitoring program were produced U.S. Robotics/3Com. Identical modems were used on each end of the connection (i.e., one in the lab and one on the bridge). Using identical modems at each side of the connection guarantees that modem “hand shaking” will take place and a robust connection can be established. The specific model was a U.S. Robotics/3Com 56k Faxmodems. Both modems were external modems. It is strongly suggested to use external modems since they are easier to configure and are more compatible with “Windows” software. The phone number during the testing period at the Williamsburg Bridge was 718-302-1744. This phone number may or may not be in service at this time.

Configuring the Modem at the Bridge
The following initialization strings were used for the modem placed at the Williamsburg Bridge. Other strings may work, but these were found to work very well.

Initialization String
ATY3
This initialization string puts the modem in a state that, if the modem is reset or turned on and off, it will go into a factory default of hardware flow control.

Dip Switches

<table>
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<th>5</th>
<th>Up</th>
</tr>
</thead>
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<tr>
<td>4</td>
<td>Up</td>
<td>8</td>
<td>Down</td>
</tr>
</tbody>
</table>
Configuring the Modem at the Office

The following initialization strings were used for the modem at the ATLSS Laboratory. Other strings may work, but these were found to work very well.

**Initialization String**

\[
\text{ATY2S10=255}
\]

*This initialization string puts the modem in a state that, if the modem is reset or turned on and off, it will go into a factory default of hardware flow control.*

**Dip Switches**

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<td>6</td>
<td>Up</td>
</tr>
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<td>7</td>
<td>Down</td>
</tr>
</tbody>
</table>

Configuring the CR9000

The PC9000 software which is used to control the CR9000 must be configured to communicate with the modems. Note that the appropriate cables between the CR9000 and TL-925 must be used. These cables are available from Campbell Scientific.

In general, the PC9000 software help screens are useful and informative regarding the specifics of modem communications. However, the following additional information is provided:

1. Remove the cover of the TL-925 and set “jumpers” for 19,200 baud. If this does not work, set the jumpers to “Auto Baud” (Note the TL-925 is located at the bridge and not the office.). **Only change the jumpers on the TL-925 when unplugged from the modem and the CR9000.**
2. Under “communications setup” in the PC 9000 software, set the I/O port to the appropriate communication port (e.g., Com 2). Then set the connection button to modem. The phone number and local modem initialization can now be input. The baud rate may need to be set at 19,200 in PC9000.
3. Set “Max Packet Size” to 2048. Occasionally, during peak usage, this may need to be reduced in order to increase the robustness of the connection.
4. Set the “Extra Response Time” to 20.
APPENDIX D

Field Inspection Guidelines for the

Orthotropic Deck on the Williamsburg Bridge
D1.0 Summary

The laboratory and field testing programs conducted by Lehigh University have identified specific locations on the floorbeam diaphragms that will be susceptible to fatigue cracking. These locations experience high stress ranges at the cutouts in the diaphragms of the orthotropic deck. As a result of the research, specific areas are identified for examination during future routine field inspections. No cracking is expected to be detected on the outer roadway of the Williamsburg Bridge orthotropic deck for at least 40 years.

Limited measurements on the diaphragm plate on the inner roadway adjacent to the cutouts of selected ribs indicated that high stress ranges also occur at these locations. However, these limited inner roadway measurements should only be considered as a “pilot” study. Further measurements should be made to establish the magnitudes of maximum stress ranges at the inner roadway. Additional instrumentation should be installed to permit a more thorough assessment of the of the inner roadway.

D1.1 Inspection - General

Assuming that the current truck traffic continues with the same loading distribution and frequency, no detectable fatigue cracking is likely to develop at any of the details listed below. These details require no special attention and should be inspected similar to any common welded or bolted detail.

1. Floorbeam tie plates
2. Transverse deck plate groove weld (deck plate splice)
3. Longitudinal rib to deck plate weld
4. Intermediate diaphragms
D1.2 Rib-to-Diaphragm Connection and Internal Bulkhead

The connection of the longitudinal rib to the diaphragm plate and the connection between the internal bulkhead and diaphragm plate were identified as sensitive to fatigue cracking during the laboratory testing. Both details are sensitive to heavy single or tandem-axles loads. The laboratory and field testing programs have demonstrated that several of the cutouts are likely to sustain cumulative fatigue damage should the current distribution of truck traffic continue for the next 40 years.

D1.2.1 Rib-to-Diaphragm Weld at Cutout

The diaphragm plate at the rib cutouts is subjected to a complex stress cycle comprised of both in-plane and out-of-plane components. Field and laboratory measurements have indicated that cracking of this detail is most likely to occur first at ribs 5, 6, and 7 in the cantilevered roadway. First crack detection or observation is not likely to occur for at least 40 years, assuming the truck weight distribution and frequency remains the same. Any potential cracks will initiate at the weld toe in the lower portion of the connection. Figure D1.1 is a photograph of a crack in the laboratory specimen and is provided to illustrate this type of crack.

The instrumentation installed near the cutout was focused on ribs 5, 6, and 7 of the cantilever roadway for both the laboratory and field studies. These locations were observed to have the highest stress ranges. Instrumentation was also installed on other ribs in the laboratory. The stress ranges measured at ribs 3, 4 and 8 were always less than that at ribs 5, 6, and 7. Hence inspection should be focused on ribs 5, 6, and 7.

Figure D1.1 – Photograph of a Typical Fatigue Crack at the Combination Groove/Fillet Welded Connection (This Photograph is Taken at a Fatigue Crack Observed in Laboratory the Fatigue Test)
The interior surface of the cutout is supposed to be ground smooth in order to eliminate notch-like defects or grooves in the base metal of the diaphragm plate produced during flame cutting. However, one such defect resulted in premature cracking adjacent to the cutout of rib 7 in the laboratory specimen. This crack is illustrated in Figures D1.2 and D1.3. The crack initiated at a flame-cut notch located 6.4mm (1/4in) from the rib-to-diaphragm weld toe and extended parallel to the weld toe as shown in Figure D1.2. Upon inspection, a similar but smaller defect was found at the inside top surface of rib 5, which was subjected to a compressive stress range. It did not develop a crack during the entire laboratory test program. The laboratory study demonstrated that the fatigue resistance of these notches correspond to a Category C detail.

This type of defect could be located anywhere along the periphery of any cutout. Therefore, inspectors should also examine the cutouts for evidence of similar notch like defects. These defects may be difficult to identify because the steel is painted with a multi-layer coating system which can easily hide them. However, if discovered, they can be easily repaired by grinding parallel to the perimeter of the cutout until the defect is removed and the surface is smooth.

Figure D1.2 – Photograph of a Fatigue Crack which Initiated at a Notch Defect in the Base Metal at the Cutout. This Notch was Made During Flame Cutting (This Photograph is Taken at a Fatigue Crack Observed in the Laboratory Fatigue Test)
Figure D1.3 – Photograph of a the Notch Shown in Figure A1.2. The View is Looking “Up” at the Cutout after it was Removed from the Diaphragm Plate
(This Photograph is Taken at a Fatigue Crack
Observed in the Laboratory Fatigue Test)
D1.2.2 Rib-to-Bulkhead Weld

The internal bulkhead is connected to the rib wall using back-to-back fillet welds and offers a lower fatigue resistance than the combination weld used to connect the diaphragm to the rib wall. Cracking can occur at the bottom and/or top portion of this connection. These cracks will not be visible on the outside of the rib. Toe cracks in the rib wall at the exterior combination weld at the only indicator that cracks in the internal bulkhead connection may exist.

Cracking at the Bottom of the Bulkhead

Throat cracking of the fillet weld at the bottom of the bulkhead plate has been observed in the laboratory tests after saw cuts exposed the inner ribs, as illustrated in Figure D1.4a. As this crack propagates, the bulkhead becomes ineffective and results in out-of-plane distortion (i.e., “oil canning” of the rib wall). This out-of-plane distortion eventually results in cracking of the rib wall which is illustrated in figure D1.4b. (It must be noted that the crack simulated in D1.4b was drawn in for illustrative purposes and is not a real crack.) Although cracking was found at the bottom of a few bulkhead plates in the laboratory, no cracks resulting from out-of-plane distortion had developed in the rib wall at the end of the test.

These cracks will only be detected if they progress through the rib wall, since there is no way to inspect this detail from the outside. Cracking is not expected to grow through the rib wall for at least 65 years, assuming the truck weight distribution and frequency remains the same.
Cracking at the Top of the Bulkhead

Figure D1.5 illustrates a crack that has developed in the throat of the fillet weld at the top of the bulkhead in the laboratory specimen. These cracks will continue to grow along the weld or into the base metal of the bulkhead until the entire connection is severed. Once the connection is severed, oil canning of the rib wall may occur and cracks will eventually develop in the rib wall as illustrated in Figure D1.4b.

![Figure D1.5 - Crack at Top of Bulkhead](image)
(This Photograph is Taken at a Fatigue Crack Observed in the Laboratory Fatigue Test)

Figures D1.6a and D1.6b illustrate another type crack which developed at the top end of the bulkhead in the laboratory. These cracks initiated at the weld toe and propagated through the rib wall (the crack is darkened for emphasis). The driving force for these cracks is a combination of in-plane stress in the bulkhead and diaphragm plate plus vertical stresses in the rib wall. (These photographs were taken after the lab test was completed and the specimen disassembled.) The laboratory test results suggest that it will be at least 65 years before such cracking would be detectable in the rib wall and diaphragm.
D2.0 Summary

The steel orthotropic deck installed on the Williamsburg Bridge has been the subject of a comprehensive laboratory and field testing program. Areas susceptible to fatigue cracking have been identified. The inspection of the orthotropic deck can be included with the regularly scheduled inspection program. No detectable cracking is expected for at least 40 years.

It is worth noting that orthotropic deck systems provide a considerable level of structural redundancy. Thus, if fatigue cracking is observed, it will have little influence on the overall behavior and load distribution characteristics of the deck system. Experience with other structures and the laboratory tests have demonstrated that repairs can be made while the structure remains in service. This will not present any danger to the motoring public and emergency repairs should not be required.
APPENDIX E

Stress-Range Histograms

for

Diaphragm Gages Adjacent to Cutouts
Stress-Range Histograms for Diaphragm Gages Adjacent to Cutouts

The following tables contain stress-range histogram data for each gage installed on the diaphragm plate adjacent to the cutout. Only the gages included in the Remote Long-Term Monitoring Program are presented. The data contained in each table are described below in the partially reproduced table.

<table>
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<th>Lower Lim of Bin</th>
<th>Upper Lim of Bin</th>
<th>Avg. of Bin</th>
<th>CH_27 # Cycles</th>
<th>CH_29 # Cycles</th>
<th>CH_45 # Cycles</th>
<th>CH_46 # Cycles</th>
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<td>524</td>
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</table>

► **Lower Limit of Bin** is equal to the minimum value of stress range cycle to be included in the given bin. The units are MPa.
► **Upper Limit of Bin** is equal to the maximum value of stress range cycle to be included in the given bin. The units are MPa.
► **Average of Bin** is equal to the numerical average of the lower limit value and upper limit value for a given bin. The units are MPa. This value is used in conjunction with # of Cycles in calculating the effective stress range (S_{eff}).
► **# of Cycles** is equal to the number of cycles counted between a given lower and upper limit of stress ranges. In other words, the number of cycles in the given bin. This value is used in conjunction with Average of Bin in calculating the effective stress range (S_{eff}).

The heavy line drawn between bin averages of 17.5MPa and 22.5MPa designates the “cutoff” of 20MPa. Note that in the calculation of the effective stress range, all cycles less than 20MPa were disregarded, as discussed in the Report.

The dates for each of the long-term monitoring periods were as follows:

**Period 1**  
August 5th to September 3rd 1998

**Period 2**  
September 27th to November 27th 1998

**Period 3**  
December 13th 1998 to January 22nd 1999
First Monitoring Period
August 5th to September 3rd 1998
Second Monitoring Period
September 27th to November 27th 1998
Third Monitoring Period
December 13th 1998 to January 22nd 1999