FINAL
CONTRACT REPORT

CLASSIFICATION OF LONGITUDINAL WELDS IN AN ALUMINUM BRIDGE DECK

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ABSTRACT

An aluminum bridge deck (called ALUMADECK) has been developed by Reynolds Metal Company and is made of extruded aluminum sections welded together at the sides to form a bridge deck. The longitudinal welds used to connect the extrusions do not match any of the fatigue category details in the AASHTO LRFD Bridge Specifications. In order to classify these welds, two fatigue tests were performed on a two-span ALUMADECK section fabricated over "simulated" bridge girders. Certain locations on the longitudinal welds were tested at a constant amplitude fatigue stress of at least 13.8 MPa (equivalent to the 1994 AASHTO LRFD Bridge Specification Category C Detail) to determine if the welds could be conservatively classified as a detail category C.

The ALUMADECK was subjected to 10,000,000 cycles of fatigue loading. There was no sign of fatigue crack initiation during this loading. Once the fatigue loading was complete a residual strength test was performed. The residual strength of the ALUMADECK after fatigue loading was 33% greater than the ultimate strength of an earlier generation of the ALUMADECK.

From the data collected and observations made during the fatigue loading the longitudinal welds in the ALUMADECK can be conservatively classified as an AASHTO detail category C.

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INTRODUCTION

Reynolds Metals Company (Reynolds) has developed a lightweight aluminum bridge deck to be used as an alternative to conventional reinforced concrete bridge decks. The ALUMADECK provides several advantages over the use of conventional reinforced concrete bridge decks. The ALUMADECK weighs approximately 122 kg/m^2 compared to the reinforced concrete deck usually weighing over 488 kg/m^2. The live load limit of a bridge may be increased due to this decrease in deck weight or lighter girders may be used to support the deck. Also, the on-site construction time for an ALUMADECK bridge is less than that of a reinforced concrete bridge deck in that it is pre-fabricated and there is no need for form-work or time for curing of the concrete.

The ALUMADECK from Reynolds is made from 305 mm wide 6063-T6 extruded aluminum sections welded together at the sides. These welds are parallel to the direction of traffic in a deck-girder super-structure system. Two different multi-void extrusions have been developed, the first generation was a two-void shape and the second generation was a three-void shape. These two designs are shown in Figure 1.

A two-void bridge deck was used in a bridge on Route 58 in Mecklenburg County, VA. Field tests have been conducted on this bridge to evaluate the composite connection between the deck and girder; load distribution within the deck system; dynamic load allowance of the deck/girder system; and the distribution of stresses within the deck. In addition to these field tests, structural testing has been conducted at the Federal Highway Administration (FHWA) Turner-Fairbanks Research Center's Structures Laboratory. The tests at FHWA include loading of the deck panels with various support conditions and two load-to-failure tests. Based on the results of the FHWA tests, the two-void extruded shape was refined and the three-void system was developed.

An important question remains regarding the structural performance of the three-void system. The longitudinal welds connecting the extrusions do not match any of the detail classifications given in the American Association of State Highway Officials (AASHTO) LRFD Bridge Specifications (1994) for aluminum welded details. Therefore, the fatigue strength of these connections is not known. Fatigue testing of these longitudinal welds must be conducted in order to properly classify this connection detail.

OBJECTIVES AND SCOPE

The objectives of this project are:

1) Investigate the fatigue strength of the longitudinal welds joining the ALUMADECK extrusions.
2) Determine the residual strength of the ALUMADECK after fatigue testing.

These objectives were accomplished through the testing of a two-span section of the ALUMADECK under fatigue and static loads.

BACKGROUND

Two criteria were used to establish the stress range in the longitudinal welds for the fatigue test. The first criteria is the design fatigue stress in the Little Buffalo Creek Bridge in Mecklenburg County. The objective was to evaluate the design fatigue strength of this "in service" bridge. The second criteria was to establish a conservative fatigue category as per AASHTO LRFD specifications (1994). Once the longitudinal welds were subjected to fatigue loading, the bridge deck was tested to failure to determine its residual strength.

Longitudinal Weld Design

The design fatigue stress for the longitudinal welds from the design calculations for the aluminum bridge deck in the Route 58 bridge was 13.1 MPa (Modjeski and Masters, 1996). Since the bridge was designed before the three-void shape was developed the bridge uses the two-void shape. There are no design calculations available for the three-void shape since the three void shape has not been used in a bridge.

Detail Classification

In order to be used in a highway bridge structure, the ALUMADECK must comply with the AASHTO Bridge Specifications. One part of this specification deals with aluminum structures and the fatigue strength of their connection details. The longitudinal welds in the aluminum panels must be classified by their fatigue strength in accordance with the AASHTO Specifications.

The AASHTO LRFD Bridge Specification (1994) states that the components and details in aluminum structures shall be investigated and designed for fatigue. In order to do this AASHTO illustrates a number of examples of typical connection details and places them into 6 categories based upon their fatigue strength. The categories range from A to E with A being the highest strength detail and E being the lowest strength. The longitudinal welds in the aluminum deck do not exactly match any of these illustrative examples, the closest being a groove weld splice connection. This illustrative example can be found in Figure 2 and is taken directly from the AASHTO LRFD Bridge Specifications (1994).

This particular weld detail has a detail category of B and C depending on different weld characteristics. Since the longitudinal welds in the aluminum deck closely represents this detail category it is considered to be classified somewhere between a category B and C detail.

Based upon the different detail categories, AASHTO lists the constant amplitude fatigue thresholds. These fatigue thresholds are listed in Table 1 for the different detail categories. If a particular detail is subjected to loading with a stress range below this fatigue threshold the detail is considered to have an infinite life, or additional loading cycles will not propagate fatigue cracks (Barker and Puckett,1997). Considering the opposite, if a particular detail is subjected to loading with a stress range greater than the fatigue threshold, the detail is susceptible to initiation of a fatigue crack.

AASHTO reduces the fatigue threshold by 50% to obtain the nominal fatigue resistance of a weld, this accounts for the possibility that the heaviest truck to cross the bridge in the life of the structure could be as much as twice as heavy as the fatigue truck used in the design. Figure 3 compares the fatigue resistance of Category A, B, and C details over an infinite number of cycles. From Figure 3 it can be seen that the fatigue threshold for a detail Category C is 13.8 MPa and a Category B detail is 20.7 MPa.

In order to test the longitudinal weld at a constant amplitude stress range representative of actual field conditions (13.1 MPa) and representative of a conservative detail category (Category C at 13.8 MPa), a constant amplitude stress range of 13.8 MPa was selected for the fatigue tests.

Residual Strength

The residual strength of the aluminum deck will be determined after fatigue testing has been completed. The strength of the three-void deck system before fatigue loading is not known, however, test to failure of the two-void deck system were conducted at FHWA's Turner-Fairbanks Lab in December, 1996. The results of the FHWA tests will be compared with the residual strength test to get an indication of the affect of fatigue loading on residual flexural strength.

FHWA performed ultimate strength test on two 2.74 m by 3.66 m panels that where simply supported on the 3.66 m sides and unconstrained on the 2.74 m side with the load patch applied at the center of the panel. In the first ultimate load test at FHWA local buckling under the load patch occurred at 832 kN and at 881 kN "punching" failure occurred under the load patch. Total weld failure on the bottom of the panel occurred in the second ultimate load test at a combined load of 1441 kN when two load patches where used (Matteo et al, 1996).

TEST SPECIMEN

A two-span ALUMADECK section was fabricated over "simulated" bridge girders for testing. The deck consisted of 3 components:

1) two 2.44 m X 3.66 m full panels
2) two 0.30 m X 3.66 m partial panels
3) three magnesium grout joints connecting the full and partial panels over the girders

The complete test set-up is shown in Figure 7.

Two 2.44 m X 3.66 m panels of the aluminum deck were used in the testing program. The purpose of the welds in these panels is to connect the one foot aluminum extrusions together at the sides, providing continuity in the top and bottom flange (Matteo et al, 1996). Visual inspection of the welds revealed that they were of high quality with a minimum amount of flaws showing. Figure 4 is a diagram of how the welds connect two extruded sections.

The two 2.44 m X 3.66 m panels were connected together through the use of a mechanical splice encased in magnesium grout over the supporting girder. Figure 5 is a picture of the actual connection of the two panels before the magnesium grout is added. Aluminum splice plates were placed above and below the two "tongues" that extend out from the edge of the panels. Two aluminum bolts were placed through the "tongue" and two splice plates to connect the two panels. This connection is also used on the outside of the large panels to connect the 2.44m X 3.66 m panels to a partial panel which consisted of a single, one foot extrusion. Figure 6 shows a plan view of the test set-up.

With the two large panels connected and the partial panels connected on the outside of the large panels, the complete deck sat on three W27X146 beams. These beams were to simulate the support girders in a deck-girder bridge system. The girders were connected directly to the reaction floor so that bending would occur only within the deck system and not the within the girders. Figure 7 is a diagram of the complete test set-up. The deck system was placed on the girders so that the extrusions and the longitudinal welds ran parallel to the girders or the direction of traffic.

Shear studs were welded to the girders and two studs were spaced every six inches so that they extend up through the splice connection. The deck system sat 44.45 mm above the girders so that there was no contact between the steel girders and the aluminum panels. The area where the mechanical splice is located was filled with a magnesium grout so that composite action was developed between the deck and the girders.

As shown in Figure 7 the two large panels are designated Side A and Side B. Side B is coated with a 9.53 mm thick epoxy based wearing surface. There is no wearing surface applied to Side A so that strain gages could be applied to the top side of the panel.

INSTRUMENTATION AND DATA ACQUISITION

Load was applied during the fatigue tests using two 222 kN capacity MTS actuators. In accordance with the AASHTO LRFD Bridge Specifications a 203 mm X 508 mm tire patch was used to transfer the load from the actuator to the aluminum deck. Figure 8 and Figure 10 shows the orientation of the load patch on the aluminum panels for Fatigue Test One. Fatigue Test One used one actuator placed in the center of Side A. Fatigue Test Two involved two actuators, one placed in the center of Side A and the other placed in the center of Side B as shown in Figure 9 and Figure 11. The fatigue tests were conducted using displacement control where the stroke of the actuator went through a specified displacement regardless of the load being applied.

For the Residual Strength Test, a 1780 kN capacity load ram was used with a 2670 kN load cell. Some adjustments were made to the tire patch due to the increase in loads that were expected but the size remained 203 mm X 508 mm located in the center of the panel of Side A (the load arrangement used was identical to that used for Fatigue Test One shown in Figure 8 and 10).

In order to obtain the strain in the welds during testing, Micro-Measurement CEA-13-125UW-350 strain gages were used (3.175 mm gage length and a resistance of 350 ohms). The gages were placed at locations on the surface of the deck where the largest stresses were expected. Exact location of the gages for the different tests is discussed in the "Test Set-Up and Protocol" section. The largest noise levels within the wiring of the strain gages was recorded as +/- 10 micro-strains, or 0.7 MPa. In order to determine the stress at the gage locations, the strain values obtained during testing were multiplied by 69.6 GPa, the modulus of elasticity for 6063-T6 Aluminum.

Linear Voltage Displacement Transducers (LVDT's) were used to measure the vertical deflection of the deck panels at various locations during the two fatigue tests. For the Residual Strength Test wire pots were used to measure the vertical deflection of the deck panels.

The data acquisition system used was the Optum Megadac 3415 AC. The recording speed was set to 200 Hz for the fatigue tests and 10 Hz for the Residual Strength Test.

TEST METHOD

Three separate tests were performed on the ALUMADECK which include:

1) Single fatigue loading of Side A for 5 million cycles (Fatigue Test 1).
2) Simultaneous fatigue loading of Side A and B for 5 million cycles (Fatigue Test 2).
3) Static loading of Side A to failure (Residual Strength Test).

Test Set-Up and Protocol

Fatigue Test 1

The objective of Fatigue Test 1 was to evaluate the longitudinal welds at the bottom of the deck near midspan at a constant amplitude stress range of 13.8 MPa for 5 million cycles. Strain gages were placed on top of the deck around the load patch and on the underside of the deck at different locations along the welds and deck panels. The location of the gages used in this test can be found in Figures 12 and 13. Linear Displacement Transducers (LVDT) were placed at four locations around the test set-up to measure vertical deflection. The location of the LVDT's can be found in Figure 14.

An actuator was placed in the center of the deck (see Figures 8 and 10) and load was applied so that the maximum stress range in the welds was at least 13.8 MPa. This loading was applied in the form of a sine wave at a frequency of 2.4 Hz so that approximately 100,000 cycles of loading/unloading could be achieved every 12 hours.

Every 100,000 cycles the fatigue loading was interrupted so that observation of the welds could be conducted to check for fatigue crack initiation. At this time a sample of the fatigue loading data was recorded (strains, load, and deflection) and a stiffness test was performed. The stiffness test was a static test of the deck to 133 kN during which data from the strain gages and LVDT's was recorded. This process was repeated for every 100,000 cycles until five million cycles of dynamic loading was reached.

Evaluation Methods
In addition to visual examination of the welds during the fatigue test, data was recorded every 100,000 cycles to assist in determining if any fatigue cracks were forming. The strains were monitored to see if any significant changes was taking place at the different gage locations. Particular attention was given to the gages on the longitudinal welds and those with a stress range at or close to 13.8 MPa. A dramatic increase or decrease in any measured strain range during the test could signify that a fatigue crack was forming at or close to that particular gage location. If this was detected close attention would be given to the surrounding gages to check for an increase or decrease in strain which would signify that the stress was being redistributed.

Also, the stiffness tests of the aluminum deck were used to determine if a fatigue crack had initiated. A load versus deflection plot was recorded every 100,000 cycles to check for an increase in deflection signifying a loss of stiffness. If a loss of deck stiffness was to occur there should be a significant change in strains along the underside of the deck, this would possibly indicate that a fatigue crack was forming.

Fatigue Test 2
The objective of Fatigue Test 2 was to evaluate the ability of the deck/girder joint to resist repeated loads and subject the welds at the bottom of the deck on Side A near midspan to further cycles of a 13.8 MPa constant amplitude stress range. Strain Gages were placed at various locations along the longitudinal welds and were located at areas on the underside of the panels beneath the load patch. No gages were placed on the top side of Side B while gages were placed around the load patch on the top of Side A. Strain gages were also located on the welds on top of Side A near the middle deck girder joint. This was done so that the stress range in the welds that were subjected to negative bending could be monitored. A diagram of the gage locations can be found in Figures 15, 16, and 17.

Two actuators were used to apply a fatigue load that yielded a maximum stress range in any of the welds on the bottom of the deck of 13.8 MPa. The load was applied at a rate of 2.3 Hz so that approximately 100,000 cycles of loading/unloading took place every 12 hours. A sample of the cyclic loading was recorded every 100,000 cycles to check the stresses in the welds. Also at

100,000 cycle increments the dynamic loading was interrupted so that a stiffness test could be performed.

In order to perform a stiffness test using two actuators, data was recorded from the strain gages and the LVDT's when zero load was being applied to the deck. Once this data was recorded both actuators were used to apply a load of 45 kN to the deck and data once again was recorded. This process was repeated at loads of 89 kN and 133 kN. This process was repeated every 100,000 cycles for 5 million cycles.

Residual Strength Test

The Residual Strength Test consisted of loading Side A until failure of the deck occurred. A 1780 kN load ram was placed at midspan of Side A and strain gages were placed at various locations around the deck. The location of the gages can be found in Figures 18 and 19. Data was recorded as the deck was loaded and unloaded in 133 kN increments.

RESULTS AND DISCUSSION

The objective of the fatigue testing was to determine if the longitudinal welds in the aluminum deck could withstand a constant amplitude stress range of 13.8 MPa and hence could be classified as a Category C detail according to AASHTO LRFD Bridge Specifications (1994). Two fatigue tests of the aluminum deck were conducted:

1) Fatigue Test 1: Evaluated the longitudinal welds at the bottom of the deck on Side A near midspan at a constant amplitude stress range of 13.79 MPa for 5,000,000 cycles.
2) Fatigue Test 2: Evaluated the ability of the deck girder joint to resist repeated loads and subjected the longitudinal welds at the bottom of the deck of Side A near midspan to 5,000,000 more cycles of 13.8 MPa constant amplitude stress range.

To monitor the potential for damage during the fatigue tests, the fatigue tests were interrupted for stiffness tests every 100,000 cycles. Load, deflection, and strain data was recorded every 100,000 cycles during the fatigue loading and stiffness tests as well.

A static test to failure was conducted to check the residual strength on Side A of the aluminum deck after the longitudinal welds on the bottom side of the deck were subjected to 10,000,000 cycles of 13.8 MPa constant amplitude stress range.

Regression lines were used in plots of load versus strain and load versus deflection for the two fatigue test. The regression lines summarize the data points recorded and make it possible to distinguish between the data obtained at 100,000 cycle increments.

Fatigue Test 1 Results

More than 100 data files were recorded during the first fatigue test. Due to this large amount of data, the comparisons that follow will be made at one million cycle increments. Smaller increments will be investigated as the results warrant.

Fatigue Loading Results

Comparison of the load and deflection values obtained every one million cycles can be found in

Table 2. The maximum deflection range of the aluminum deck at midspan is in the last column of this table. These values were taken from the LVDT's located at midspan of Side A directly beneath the load patch.

Table 3 contains stress ranges at all 48 gages used during the first fatigue test. The stress ranges given were obtained by recording data for a period of two to three seconds while the aluminum deck was subjected to a constant amplitude fatigue load. From this data, five to seven load cycles were observed and the minimum strain was subtracted from the maximum strain in one cycle to obtain the strain range. The strain ranges were multiplied by the Modulus of Elasticity of the aluminum used in the ALUMADECK to obtain the given stress range.

A comparison plot of the load and deflection can be found in Figure 20. Based on the results given in Table 3, six gauge locations were chosen because of their high stress range during the fatigue loading; two gages each on the welds located beneath the load patch and one gage from each of the welds outside of the load patch. Figures 21 through 26 compare the fatigue load to the strain at these six gage locations on the longitudinal welds. The lines presented in these figures represent regression lines for one cycle of data. This was done so that a distinction could be made between the six sets of data. The load-deflection and load-strain ratio (given in the tables) is equal to the slope of these regression lines and will be used to determine any change in behavior of the deck. Comparisons are made every one million cycles for each sensor location.

Stiffness Test Results

The stiffness test took approximately one minute to perform. With the data collection rate set at 200 readings a second some of the stiffness test data files contained more than 15,000 data points for any particular sensor. In order to present this large amount of data a moving average of six data points was taken from the recorded data. Regression lines representing the data points collected were plotted for comparison and come from the load and strain and load and deflection graphs. The load-deflection plot can be found in Figure 27. The six gauge locations used for comparison in the Fatigue Test section for Fatigue Test 1 were used for comparison in this section. The six gauge locations represent the highest stress in the longitudinal welds during the stiffness test. The load versus strain plots for these six critical gage locations can be found in Figure 28 through Figure 33.

Table 4 compares the maximum load and deflection every one million cycles. The total deflection of the aluminum deck directly beneath the load patch can be found in the last column of this table. Since the maximum load was never exactly 133 kN during the stiffness test, the deflection values were multiplied by a normalization factor (a ratio of the maximum load obtained to 133 kN). Table 5 has the values of this normalized deflection.

This process of normalization was also performed on the maximum stresses obtained at the various gage locations. These maximum normalized stresses can be found in Table 6.

Fatigue Test 1 Discussion

Two sets of data, fatigue test data and stiffness test data were recorded during Fatigue Test 1. As shown in Table 2, an average load range of 118 kips was applied to Side A in a cyclic manner with a constant amplitude. The 118 kip load range was chosen so that a minimum stress range of 13.8 MPa could be achieved in Gage BH (the gage location with the highest strain of all gages located on the longitudinal welds) during this cyclic loading. During the stiffness test, data was recorded while load was applied from 0 to approximately 133 kN.

Fatigue Test Discussion

As shown in Table 3, the stress range at gage location BH was never less than 14.4 MPa, with an average stress range of 15.5 MPa during 5 million cycles of loading. This is 12.5% greater than the 13.8 MPa needed to classify the welded connection as a Category C detail. Two other gages within 1% of an average stress range of 13.8 MPa are gage locations BA and BC whose average stress range over 5 million cycles was 14.1 MPa and 13.7 MPa, respectively.

From Table 3, six gages (four on welds directly beneath the load patch and two one weld outside the load patch) with the highest stress range on each of the four welds around the load patch were chosen to compare the strains obtained during the dynamic loading with the load being applied. The gage locations used to make this comparison were gage locations AA, BA, BH, CF, CJ, and DA. The location of these sensors with respect to the load patch can be found in Figure 12. All of these gages are located on longitudinal welds on the bottom of the panel of Side A.

Gage Location AA

Located one weld to the right of the load patch, gage location AA had an average stress range of 7.2 MPa after 5 million cycles of loading on the load patch. This value is considerably less than 13.8 MPa but still important. It would be expected that if any fatigue cracks were to form, the stress around the crack would be redistributed within the deck. Figure 21 compares the load and strain at gage location AA. From this figure it can be seen that the load-strain ratio did not change significantly after 5 million cycles of loading. The standard deviation of the stress range is 0.2 MPa and was calculated from the values in Table 2 for gage location AA, approximately 3% of the total stress in the weld at that location.

Gage Location BA

Gage BA is located 102 mm from the edge of the load patch on a longitudinal weld that is located directly beneath the load patch. The average stress range for 5 million cycles at this gage location is 14.1 MPa. The stress range shows a slight increase every one million cycles when looking at Table 2. It should be noted that this level of increase of stress is approximately equal to the signal noise (+/- 0.7 MPa) and therefore not of concern. Figure 22 is a plot of the strain and load recorded during the dynamic loading. From this plot and the load-strain ratios, it is seen that there is not a significant change in either at this gage location during the 5 million cycles of loading. The standard deviation for the stress ranges in Table 2 is 0.5 MPa, approximately 3.6% of the average stress range, less than the signal noise of 0.7 MPa.

Gage Location BH

Gage BH is located on a longitudinal weld directly beneath the load. The stresses at this gage location were the highest among any stresses measured during fatigue test. If a fatigue crack were to form during loading this would be a probable location because of this high stress range. The average stress in this gage location during the 5 million cycles of load was 15.5 MPa. Figure 23 shows that even though the strains at this location are high, there is not a significant change in the slope of the load-strain line. With this information and visual observations of the welds, it was determined that no fatigue cracks had formed near this location. The standard deviation of the stress range values in Table 2 is 0.6 MPa, 4.0% of the average stress range, less than the 0.7 MPa from signal noise.

Gage Location CF
Gage CH is also located on a longitudinal weld directly beneath the load patch. Figure 24 shows the load-strain plot for 5 million cycles of loading at this location. Although the regression lines are not grouped together as tight as in the previous plots, Table 2 shows that the stress range at this location essentially remained constant. This can also be seen with the comparison of the load-strain ratios. The mean stress range was 12.2 MPa with a standard deviation of 0.4 MPa, only 3.6% of the total stress range.

Gage Location CJ
Figure 25 compares the strain due to the 5 million cycles of loading for gage location CJ. As discussed with the previous gage locations, the load-strain ratios show that there is insignificant change in strain during the 5 million cycles of loading. The average stress range for this gage location was 13.3 MPa with a standard deviation of 0.6 MPa, 4.1% of the total stress range.

Gage Location DA
Gage location DA is located one weld to the left of the load patch. Similar to gage location AA, a small stress range was achieved here compared to the stresses obtained on the welds directly beneath the load patch. The average stress range in this location over 5 million cycles of loading was 5.2 MPa with a standard deviation of 0.1 MPa. Figure 26 is a plot of the load and strain at this location, the load-strain ratios in this figure show that there is no significant change in strain at this location during fatigue test 1.

Load versus Deflection
In order to show that stiffness within the deck system did not change, a comparison was made between the load and deflection values recorded during the 5 million cycles of loading. Figure 20 is the load-deflection plot for the midspan of Side A. The lines in this graph show that there is little change in deflection during the 5 million cycles of loading. Table 2 compares the load range and deflection range at the midspan of Side A every one million cycles. It can be seen from this table that there is no significant change in the deflection range during this fatigue test.

Stiffness Test Discussion
The fatigue testing of the deck was interrupted every 100,000 cycles so that a stiffness test could be performed to check for any change in behavior of the deck. Through observation of deflection and strain data it can be shown whether or not the deck losses or gains stiffness. Table 6 compares the maximum normalized stresses at every gage location during this test. From this table, six gage locations (one each on the two welds outside of the load patch and two each on the two welds directly beneath the load patch) with the highest normalized stress were chosen to compare the load and strain during the 5 million cycles of loading. These are gage locations: AA, BA, BH, CF, CJ, and DA. Table 6 contains the average maximum normalized stress and standard deviation mentioned below. The zero cycle column (the second column) was not used during these calculations. Strains measured initially (at zero cycles) are approximately 10 to 20% higher than those measured after cyclic loading had begun. This is contributed to settlement within the load frame after approximately 100,000 cycles of fatigue loading was applied to the bridge deck.

Gage Location AA
The average maximum normalized stress at gage location AA was 7.9 MPa with a standard

deviation of 0.1 MPa. Figure 28 is a plot of the load and strain during the 5 million cycles of loading. Comparing the load-strain ratios in this figure, it is easily shown that there was no change in strain at this gage location during the 5 million cycles of loading.

Gage Location BA

The average maximum normalized stress at gage location BA was 15.6 MPa with a standard deviation of 0.1 MPa. This gage has the second largest stress of all gages located on the longitudinal welds, a possible point for a fatigue crack to form. The small change in maximum stress at this location during the 5 million cycles of loading indicates that it is not likely that fatigue cracks formed at or near this gage location. Figure 29 shows the load-strain plot at this gage location. Comparison of the load-strain ratio shows that after 5 million cycles of loading there was no change in stress at this location.

Gage Location BH

This gage location is of great concern since it is had the highest stress of any gages located on the longitudinal welds. The average maximum normalized stress at this location was 17.0 MPa with a standard deviation of 0.01 MPa, a deviation less than one percent of the total stress. Comparison of the load-strain ration in Figure 30 also shows that there is no change in stress after 5 million cycles of loading at this gage location.

Gage Location CF

The values in Table 6 show a little change in the maximum normalized stress at gage location CF. The average maximum normalized stress is 12.8 MPa with a standard deviation of 0.7 MPa for the 5 million cycles of loading. The standard deviation is higher than what has been previously shown at other gage locations but still insignificant since the noise in the sensors is approximately +/- 0.7 MPa. Comparison of the load-strain ratio in Figure 31 shows only a minor change of strain during the 5 million cycles of loading.

Gage Location CJ

The average maximum normalized stress at gage location CJ was 14.7 MPa with a standard deviation of 0.3 MPa during 5 million cycles of loading. This gage location has the third highest stress of any gages located on the longitudinal welds. It is interesting to note that the stress is the highest at the 3 million cycle mark, this is also true for all gages located on this particular weld. Comparison of the load-strain ratios in Figure 32 shows an insignificant change in strain at this gage location during the 5 million cycles of loading.

Gage Location DA

The average maximum normalized stress at gage location DA was 5.5 MPa with a standard deviation of 0.6 MPa. Similar to gage location CJ, the stress is the highest at the 3 million cycle point (shown in Table 6). Comparison of the load-strain ratios in Figure 33 shows that there is not a significant change in strain during the 5 million cycles of loading.

Deflection

Load and vertical deflection comparisons were made from a location directly beneath the midspan of the deck. Any change in deflection during the 5 million cycles of constant amplitude loading would signify a change in stiffness of the bridge system.

Table 4 shows the maximum load applied to the deck during the stiffness test. At the maximum load the deflection was recorded and can be found in the Maximum Deflection column of this table. The last column is the total deflection at midspan that the deck underwent. This deflection was normalized to equivalent values at 133 kN of load so that a direct comparison of 6 different stiffness tests can be made. The normalized deflection values can be found in Table 5. From this table it can be seen that the deflection did not change significantly for each million cycles of loading. The deflection at the start (neglecting 0 cycles) was 1.24 mm where the final deflection after 5 million cycles of loading was 1.30 mm, an increase in deflection of 0.06, only 3.7% of the maximum deflection.

Figure 27 also compares the load and deflection for every one million cycles. Comparison of the load-deflection ratios on this graph shows that there was not a significant change in deflection during the 5 million cycles of loading.

Significance of Results

As discussed in the Constant Amplitude Fatigue Loading section of Fatigue Test Results, the strain range for the gage locations along the welds remained consistent throughout the 5 million cycles of loading. This was shown by the values given in Table 3 and the load-strain ratios found in the load-strain graphs for six gage locations with the highest stress during this test.

The deflection at midspan during the stiffness test was used to compare the stiffness of the deck throughout the 5 million cycles of loading. As discussed above, the deflection did not vary significantly during this test. Also used to check for changes in stiffness was the strains at six gage locations along the longitudinal welds. There was no notable change in the strains during the 5 million cycles of loading.

This information indicates that no fatigue cracks initiated when the longitudinal welds on the bottom of the deck near midspan of Side A were subjected to a constant amplitude stress range of at least 13.8 MPa for 5,000,000 cycles.

Fatigue Test 2 Results

Similar to Fatigue Test 1, data was recorded every 100,000 cycles during this test. All of the strain gages used in this test were placed on the longitudinal welds around the two load patches and along the weld closest to the deck girder joint. Comparison of the results is made for every one-million cycles. Any significant change in data will result in closer observations around the discrepancy.

Fatigue Loading Results

Comparison of the load range and deflection range obtained every one-million cycles during dynamic loading can be found in Table 7. Two loads were applied to the test set-up, one load on Side A and the other on Side B. The reported deflection readings were taken at midspan directly beneath the load patch for their respective sides. Table 8 contains the stress range of all 40 gage locations used during the second fatigue test. Data was recorded for a period of three to five seconds while the aluminum deck was subjected to two constant amplitude fatigue loads. From this data five to seven cycles of load were observed and the minimum strain was subtracted from the maximum strain in one cycle to obtain the strain range. During this test a load range of approximately 133 kN was applied to both sides of the deck to ensure that a minimum 13.8 MPa stress range was achieved in Gage G4, the gage location with the highest stress among any of the longitudinal welds gage locations.

From the values in Table 8, eight gages were selected which had the highest stress range throughout the 5 million cycles. The data from these eight gages was used to compare the load being applied to the strain in the welds. These graphs can be found in Figure 34 through Figure 41. The data in these plots was recording during one cycle of loading and the loads used in the graphs are the loads that correspond to the side in which the specific gage is located. The lines in these figures represent the regression lines or a summary of the data points obtained during the fatigue loading. The load-strain ratios are equal to the slope of the regression lines.

Figure 42 and Figure 43 compares the load and deflection for Side A and Side B respectively. Deflections were recorded at midspan directly beneath the load patch for each side. Again, regression lines were used in these figures with the load-deflection ratios equal to the slope of the regression lines.

Stiffness Loading Results

In order to perform a static test using two actuators, data was recorded as 133 kN of load was applied in three equal increments. Table 9 compares the maximum normalized stress at 133 kN for all 40 gages, every one million cycles. In order to normalize the stresses, a ratio of 133 kN to the actual load applied on each side was calculated and multiplied by the maximum stress obtained at each sensor location. The maximum load applied to each side and the corresponding deflection can be found in Table 10. Table 11 has the measured deflections from Table 10 and normalizes them as described above.

Three gage locations for each panel were chosen from Table 9 based upon having the highest maximum normalized stress. For these seven gage locations, the load and strain were compared and presented in Figure 44 through Figure 50.

The deflection at midspan for each side was compared to the load for that respective side and is plotted in Figure 51 for Side A and in Figure 52 for Side B.

Fatigue Test 2 Discussion

The purpose of Fatigue Test 2 was to evaluate the ability of deck girder joint to resist repeated loads and subject the longitudinal welds at the bottom of the deck near midspan to further cycles of 13.8 MPa constant amplitude stress range. Two loads were used during this test one located at midspan of Side A and the other at midspan of Side B. The loads went through the same displacement at the same time during the loading which was in the form of a sine wave. Similar to Fatigue Test 1, the dynamic loading of the deck was interrupted every 100,000 cycles so that a stiffness test could be conducted.

Two main sets of data, stiffness data and fatigue test data, were recorded during Fatigue Test. All strain gages used during this fatigue test were located on the longitudinal welds.

The load range for the first 500,000 cycles was 114 kN and the stress range in gage G4 was 13.2 MPa. At this point the decision was made to increase the stress range at gage location G4 to 13.8 MPa. The load range was increased to an average 126 kN in order to achieve this. Because of this the stress ranges and deflection range for the first 500,000 cycles is slightly less than the values obtained after this change was made. The values from 0 cycles will be left out when calculating the average stress range, average maximum normalized stress, and standard deviation calculations.

Fatigue Test Discussion
Load was applied to the deck system so that the stress range at gage location G4 would be a minimum of 13.8 MPa. Gage location G4 was chosen since it had the highest stress range during Fatigue Test 1. From Table 7, the average load range for Side A was 127 kN and the average load range for Side B was 126 kN during this fatigue test.

Table 8 shows the stress range for every gage location used during this test. Data is presented at one million cycle increments. From the 40 gages listed in Table 8, the eight gage locations with the highest stress ranges (two per weld located beneath each tire patch) were selected to compare the load and strain recorded for the 5 million cycles of this test. The gages used in this comparison include: B2, B5, C3, C4, F3, F4, G1, and G4. The location of these eight gages can be found in Figure 15 and Figure 17.

The deflection of each side at midspan was measured to determine if there were any change in stiffness of the deck during the fatigue test.

Gage Location B2
The average stress range at gage location B2 was 10.3 MPa during the 5 million load cycles with a standard deviation of 0.34 MPa. Comparing the load-strain ratio in Figure 34 it can be seen that there is little variation in the strain at this location during the dynamic loading of this test.

Gage Location B5
Gage location B5 has the highest stress range for any gage locations on Side B. The average stress range for the 5 million cycles of loading was 11.2 MPa with a standard deviation of 0.3 MPa. Figure 35 also compares the load and strain at this gage location. The load-strain ratios found in this figure show that there was not a significant change in strain during the 5 million cycles of loading. If a fatigue crack was to form on Side B this would be an ideal location because of the high stress range, no evidence of a fatigue crack was found through visual observation or through changes in stress.

Gage Location C3
The average stress range at gage location C3 was 9.5 MPa with a standard deviation of 0.3 MPa. The load-strain ratios in Figure 36 show little variation throughout the 5 million load cycles.

Gage Location C4
The average stress range at gage location C4 was 9.7 MPa with a standard deviation of 0.41 MPa during the 5 million cycles of loading. Figure 37 is a plot of the load and strain at this location, little variation can be noticed from this plot and seen in the load-strain ratios.

Gage Location F3
Gage location F3 which is located on Side A had an average stress range of 12.1 MPa and a standard deviation of 0.3 MPa during the 5 million cycles of loading. As shown in Table 8 all gage locations on Side A have a higher stress range than those located on Side B. Even with the higher stress range, little variation of the load-strain ratio can be seen in Figure 38.

Gage Location F4

The average stress range at gage location F4 was 10.8 MPa with a standard deviation of 0.2 MPa during the 5 million cycles of loading. Little change in the stress range is shown in Figure 39 where the load-strain ratio does not change significantly during this second fatigue test.

Gage Location G1

Gage location G1 has the second largest stress range of any gage locations in this fatigue test with an average stress range of 13.7 MPa with a standard deviation of 0.4 MPa during the 5 million cycles of loading. This high stress range could promote the possibility of fatigue crack formation, looking at Figure 40 there is no evidence of this occurring.

Gage Location G4

Gage location G4 had the highest stress range of any of the gage locations in this fatigue test. During the testing it would be insured that this gage location would have at least a 13.8 MPa stress range, this location would also be monitored closely for the possibility of fatigue crack formation. The average stress range from Table 8 for this gage location was 14.6 MPa with a standard deviation of 0.3 MPa; little variation in the stress as the weld was subjected to 5 million cycles of loading. Comparison of the load-strain ratios in Figure 41 shows that there was little if no change throughout the 5 million cycles of loading.

Deflection

If a fatigue crack was to form it would be expected that there would be an increase in the deflection of the deck near midspan. The deflection range for every one million cycles can be found in the last column of Table 7 for the midspan of Side A and Side B. The deflection range for 0 Cycles is less than the other cycles due to the lower load range used. The deflection of Side A during the 3 million cycles of loading also are off from the average and is contributed to problems with the LVDT during this part of testing.

Considering these two errors in data, the deflection range does not change significantly during this fatigue test. This can also be seen in Figure 42 and Figure 43, load-deflection plots for Side A and Side B. The load-deflection ratios in these two figures do show some change during the 5 million cycles of loading but this can be expected since it is dynamic loading and the load range although close is not the same every one million cycles.

Stiffness Test Discussion

The dynamic loading of the deck was interrupted every 100,000 cycles so that a stiffness test could be performed to check for damage and loss of stiffness within the deck. In order to perform a stiffness test using two actuators data was recorded in four increments. First data was recorded for all sensors at zero load. Then approximately 44 kN was applied to both sides of the deck and data once again was recorded for a few seconds. This process was repeated at 89 kN and 133 kN. From this data the strains at all gage locations can be compared along with the deflection at midspan for both sides.

Since only four points are used to compare the strains and deflection, there will be a greater variation in the load-deflection ratio and the load-strain ratio. In order to visually interpret the result, regression lines will not be used in the graphs, rather the actual data points will be plotted.

Table 9 compares the maximum normalized stress at all gage locations used in Fatigue Test 2 (gage layout in Figures 15, 16 and 17). From this table three gage locations from each side with the highest maximum normalized stress were chosen to compare and check for loss of stiffness within the deck. These gage locations chosen include: B3, B5, C5, F3, G1, and G4.

The deflection recorded every one million cycles will also be compared to check for changes in stiffness for both sides.

Gage Location B3
The average maximum normalized stress at gage location B3 was 10.4 MPa with a standard deviation of 0.7 MPa. This is a higher deviation than what was observed in the constant amplitude fatigue loading but still equal to the +/- 0.7 MPa error due to the noise in the gages. Figure 45 compares the four data points for every one million cycles along with the load-strain ratios. The variation in the load-strain ratio is due to only having four data point to use when calculating the slope of the lines. The variation however is not significant enough to mean that stiffness within the deck is changing.

Gage Location B5
The average normalized stress at gage location B5 was 11.2 MPa with a standard deviation of 0.6 MPa during the 5 million cycles of loading. From Table 9 there is no significant change in the stress during the stiffness test at this gage location. Figure 46 compares the four data points and the load-strain ratios for every one million cycles at this gage location. Little change in strain can be seen can be seen in the data points except for the 2 million cycle data point. This variation in strain has to do with the way the gage was balanced during the test, the load-strain ratio shows that the 2 million data points is relative to the other five million cycles.

Gage Location C5
Gage location C5 had an average maximum normalized stress of 9.5 MPa with a standard deviation of 0.3 MPa during the 5 million cycles of loading in Fatigue Test 2. Figure 47 shows that there is not a significant change in the load-strain ratio at this gage location.

Gage Location F3
The average maximum normalized stress at gage location F3 was 12.1 MPa with a standard deviation of 0.3 MPa during the 5 million cycles of loading. Figure 48 compares the four data points for every one million cycles of loading, from this figure it can be seen that the load-strain ratio does not change significantly during Fatigue Test 2.

Gage Location G1
Gage location had the second highest normalized stress with an average stress of 13.58 MPa and a standard deviation of 0.28 MPa during the 5 million cycles of loading. Figure 49 shows that there was not a change in the strain at this gage location throughout the fatigue loading. This is also shown through comparison of the load-strain ratios.

Gage Location G4
Gage location G4 was used to control the load that was applied to the deck throughout the dynamic loading of Fatigue Test 2. This gage location has the highest stress out of any of the gage locations used in this test. The average maximum normalized stress was 14.9 MPa with a standard deviation of 0.01 MPa. Figure 50 compares the four data points for the 5 million cycles of loading, no significant change in stress is shown in this figure. Also, the load-strain ratios are within less than 1% percent of each other. No significant change took place at this gage location.

Deflection
Comparing the deflection of both sides every one million cycles will help to determine if stiffness was lost within the deck system. Table 10 presents the load and deflections for both sides every one million cycles. Since the maximum load was never exactly 133 kN the deflection values were normalized, these values can be found in Table 11. From this table the average deflection of Side A at midspan was 1.13 mm, the variation in values every one million cycles is never greater than 2% of this values. For Side B the average deflection was 1.03 mm for 133 kN of loading. The variation in deflection values for Side B was never greater than 1.1% of the average deflection.

As discussed in the Deflection section of the Constant Amplitude Fatigue Loading for Fatigue Test 2, there was a problem with the LVDT on Side A around 3 million cycles of loading, this is why the deflection value in Table 11 for Side A at 3 million cycles is lower than the other values.

This error in the LVDT can also be seen in Figure 51, a plot of the load and deflection for Side A. Neglecting this error, all data points for the 5 million cycles of loading are relatively close to each other and there is not significant change in the load displacement ratios. This is also true for Side B and can be seen in Figure 52.

Deck Girder Joint Discussion
The ability of the deck girder joint to withstand 5 million cycles of loading was one concern for Fatigue Test 2. With load being applied to Side A and Side B simultaneously the deck girder joint was subjected to negative bending and the welds near this location were of concern. Gages T1, T2, and T3 were located on the weld closest to the deck girder joint. With an average dynamic load of 126 kN (this is in excess of AASHTO HS20 design axle load) applied to both sides, the gages locations along this center weld had an average stress of 5.52 MPa. This is significantly less than the stresses that have been discussed along the bottom side of the deck.

Figure 44 compares the stress at gage location T2 every one million cycles of loading. From the load-strain ratios in this figure it can be shown that there was no change in behavior of the deck at this location. Through visual observations it was also noted that there was no apparent damage to the magnesium grout during the 5 million cycles of loading in Fatigue Test 2. The offset of the data points in Figure 44 can be contributed to re-balancing of the sensors throughout the testing.

Significance of Results
Through visual observation and data reduction, no evidence of initiation of fatigue cracks during this second fatigue test was found. This was apparent when the stress range of the gage locations remained consistent during the fatigue loading for 5 million cycles. It was expected that had a fatigue crack formed there would be some increase or decrease in strain along the longitudinal welds. The stress range at gage location G4 was never less than 14.2 MPa during the dynamic loading of the aluminum deck, this is greater than the required 13.8 MPa needed in order to classify the weld detail as an AASHTO detail category C.

The stiffness of the deck did not change significantly during this second fatigue test. This was shown when the load, deflection, and strain values for every one million cycles were compared above. In addition, the load and strain values from the stiffness test were compared for three gage locations on Side A and Side B. This comparison showed that none of the gage locations had any significant increase or decrease in strain during the 5 million cycles of loading.

One interesting observation was that the average deflection at 133 kN for Side A was 1.13 mm while the average deflection on Side B was 1.03 mm. The 10% greater deflection on Side A has been contributed the 9.53 mm thick epoxy wearing surface on Side B. Side B was considered to have a greater stiffness than Side A because of this wearing surface.

The deck girder joint was unaffected by the 5 million cycles of load applied during this fatigue test. There were no visual defects in the magnesium grout of this joint after the loading. Also the stress in the weld closest to this joint showed no change throughout the loading.

Residual Strength Test

Side A was loaded to failure during the residual strength test. The deck was loaded and unloaded to 133 kN during the first loading phase, after this the process was repeated adding 133 kN to the maximum load each time until failure occurred. Nine separate loads were applied until failure within the deck occurred. Data was recorded during these nine loadings and Figure 53 is a plot of load and deflection values for all nine load applications. The maximum load an deflection for each load cycle can be found in Table 12 and a plot of these values is found in Figure 54.

Static Test to Failure

After the welds on the bottom of Side A were subjected to a constant amplitude stress range of 13.8 MPa, Side A was loaded to failure to determine the residual strength of the deck. Although the three-void deck system was not tested to failure before the fatigue loading began, the results from the failure test can be compared to previous failure test of the two-void deck system conducted at FHWA.

Load was applied in 133 kN increments until failure of the deck occurred. Nine load cycles were required before failure of the deck was achieved. The maximum load applied was 1170 kN with a 13.8 mm deflection at midspan. Maximum load and deflection values for all nine load cycles can be found in Table 12. Figure 53 is a plot of the load and deflection at midspan for all nine loading stages. By the end of the fourth loading phase (534 kN) the deck began to show some plastic behavior.

In order to better see this Figure 54 was created which is a plot of the maximum load and deflection values for all nine loading stages. The blue line on this graph represents the theoretical elastic response of the deck. Between 445 kN and 556 kN the deck begins to behave in a plastic manner.

The failure of Side A was considered to be a local buckling failure of the web truss beneath the load patch. A picture of a buckled web can be found in Figure 55 and the location of the eight webs that buckled can be found in Figure 56. This failure is similar to the first failure test that was conducted by FHWA. Both ultimate load tests experienced local buckling under the load patch. This type of failure is significant in that even after 10 million cycles of constant amplitude loading of Side A it was not the welds that failed but rather the truss system in the web of the deck. This further supports the observation that fatigue cracks did not form along the longitudinal welds during the fatigue loading that took place in Fatigue Test 1 and Fatigue Test 2.

When compared to the test conducted by FHWA the ultimate strength of the three void bridge deck was 33% greater (1169.0 kN ultimate load for three void shape and 880.7 kN ultimate load for two void shape) than the ultimate load of the two void bridge deck. This increase in ultimate load capacity was also after Side A had been subjected to 10,000,000 cycles of a fatigue load.

CONCLUSIONS

The conclusions of this research are:

1. With no fatigue crack formation in the longitudinal welds, the 13.8 MPa weld fatigue design strength is adequate value to use.
2. The longitudinal welds in the aluminum deck can be conservatively classified as an AASHTO detail category C.
3. Ten million cycles of loading on Side A did not affect the residual strength of the aluminum deck when an ultimate load was applied. The three-void deck shape had a 33% greater ultimate strength than the ultimate strength of the two-void shape even after fatigue loading.

RECOMMENDATIONS

The AASTHO Detail Classification for the longitudinal welds in the ALUMADECK is conservatively a detail category C. Further testing would be required in order to determine if the bridge deck could withstand fatigue loading for a detail category B. A test similar to the one conducted for this report would be adequate to make the decision.

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TABLE 1. Constant Amplitude Fatigue Threshold (AASHTO LRFD 1994)

Detail Category	Threshold (MPa)
A	65.5
B	41.4
C	27.6
D	20.7
E	13.8
F	11.0

TABLE 2. Fatigue Test 1 - Fatigue Loading - Load and Deflection Values

Cycles	Maximum Load (kN)	Minimum Load (kN)	Load Range (kN)	Midspan Deflection Range (mm)
0	126	4	107	1.19
1,000,000	133	4	117	1.05
2,000,000	133	3	120	1.19
3,000,000	136	3	121	1.18
4,000,000	137	3	122	1.20
5,000,000	138	4	123	1.20

TABLE 3. Fatigue Test 1 - Fatigue Loading - Stress Ranges

Gages	Stress Range (MPa) per million cycles					
	0	1,000,000	2,000,000	3,000,000	4,000,000	5,000,000
TD-01	5.0	5.2	5.4	5.5	5.5	5.5
TD-02	12.5	14.3	14.8	14.1	14.5	14.8
TD-03	13.7	16.1	16.1	17.8	176.4	18.1
TD-04	40.5	38.2	39.4	36.1	36.3	35.8
TD-05	28.3	27.6	30.3	21.1	25.9	19.2
TD-06	20.5	23.6	23.6	27.0	26.5	26.5
TD-07	14.5	16.5	17.0	15.1	16.6	16.5
TD-08	6.8	8.0	8.1	3.6	8.4	8.1
AA	7.0	7.0	7.2	7.2	7.4	7.4
AB	5.7	5.7	5.9	5.7	5.7	6.0
AC	5.7	6.0	6.3	6.1	6.1	6.2
BA	13.2	14.0	14.2	14.3	14.3	14.6
BB	8.7	10.8	10.9	11.0	11.3	10.9
BC	12.9	13.4	13.9	13.9	14.1	14.1
BD	1.4	1.2	1.2	1.0	1.0	1.2
BE	8.8	9.4	9.0	9.4	9.8	9.8
BF	11.0	11.4	11.7	11.8	11.9	11.9
BG	8.0	8.8	9.1	9.0	9.1	9.0
BH	14.4	15.2	15.4	15.7	16.1	16.1
BJ	12.4	13.2	13.2	13.2	13.4	13.4
CA	10.0	11.0	11.0	11.2	11.6	11.4
CC	12.2	12.8	13.2	13.2	13.4	13.2
CD	15.9	17.5	17.9	17.9	18.5	18.3
CE	9.6	10.5	11.0	11.0	11.4	11.2
CF	11.6	11.8	12.8	12.2	12.4	12.2
CG	2.2	1.9	1.9	1.7	1.7	1.7
CH	16.5	16.5	17.1	17.1	17.5	17.5
CI	13.9	14.6	14.8	14.8	15.0	15.2
CJ	12.4	12.8	13.4	13.4	13.7	13.9
CK	11.6	12.2	12.6	12.4	12.8	12.6
CM	13.8	14.4	14.8	14.8	15.0	14.9
CN	10.8	11.2	11.7	11.7	11.9	11.9
CO	8.0	8.3	8.6	8.6	8.7	8.7
DA	5.0	5.0	5.1	5.2	5.3	5.3
DB	6.8	7.2	7.4	7.5	7.7	7.7
DC	8.5	9.0	9.4	9.4	9.6	10.0
DD	7.1	7.3	7.3	7.5	7.7	8.1
DE	4.9	5.0	5.1	5.1	5.2	5.2
DF	0.8	0.8	0.9	1.0	0.9	0.8
DG	5.5	5.7	5.9	6.0	6.3	6.1

[shaded box] Designates gages located on welds.

TABLE 4. Fatigue Test 1 - Stiffness Loading - Load and Deflection Values

Cycles	Maximum Load (kN)	Minimum Load (kN)	Load Range (kN)	Midspan Deflection (mm)
0	137	-0.1	138	1.57
1,000,000	140	-0.1	140	1.31
2,000,000	136	-0.4	136	1.32
3,000,000	135	0.0	135	1.31
4,000,000	135	-0.2	135	1.32
5,000,000	135	-0.1	135	1.31

TABLE 5. Fatigue Test 1 - Stiffness Loading - Normalized Load and Deflection Values

Cycles	Measured Deflection (mm)	Normalization Factor	Normalized Deflection (mm)
0	1.57	0.970	1.52
1,000,000	1.31	0.951	1.24
2,000,000	1.32	0.982	1.30
3,000,000	1.31	0.990	1.30
4,000,000	1.32	0.991	1.31
5,000,000	1.31	0.989	1.30

TABLE 6 - Fatigue Test 1 - Stiffness Test - Maximum Normalized Stresses

Gages	Maximum Normalized Stress (MPa) per million cycles					
	0	1,000,000	2,000,000	3,000,000	4,000,000	5,000,000
TD-01	-6.3	-6.1	-6.4	-5.5	-6.5	-6.4
TD-02	-14.7	-15.5	-15.8	-13.9	-15.3	-15.2
TD-03	-16.1	-17.0	-17.0	-17.9	-18.8	-18.7
TD-04	-58.6	-51.6	-51.1	-45.2	-46.5	-46.1
TD-05	-39.8	-44.6	-45.7	-22.5	-40.9	-32.4
TD-06	-23.0	-24.5	-24.0	-27.5	-27.9	-27.3
TD-07	-15.9	-17.4	-17.6	-15.2	-16.1	-16.1
TD-08	-8.1	-9.6	-18.1	-2.1	-14.8	-11.8
AA	8.2	7.9	7.9	7.9	7.7	8.0
AB	6.5	4.8	0.7	9.9	2.8	4.1
AC	7.0	6.5	6.3	6.8	6.3	6.4
BA	16.1	15.5	15.6	15.7	15.5	15.6
BB	9.7	6.5	0.1	16.9	4.5	7.1
BC	15.9	15.2	15.2	15.2	15.0	15.1
BD	1.0	-1.7	14.5	11.7	-8.7	-4.6
BE	10.3	10.1	10.0	10.1	9.7	9.7
BF	13.3	12.8	12.7	12.9	12.5	12.7
BG	9.7	6.8	4.6	13.1	6.0	7.5
BH	17.6	17.0	17.2	17.1	17.0	16.9
BJ	15.4	14.5	14.8	14.5	14.3	14.3
CA	12.4	10.1	9.0	14.9	9.9	10.7
CC	14.8	14.3	14.5	14.7	14.1	14.3
CD	19.9	18.2	15.4	22.5	17.2	17.7
CE	11.2	9.1	6.6	13.9	8.5	9.4
CF	14.4	13.2	12.5	13.7	12.1	12.3
CG	3.7	2.5	2.2	3.2	1.4	1.6
CH	0.6	19.0	18.5	19.3	18.3	18.7
CI	17.2	16.5	15.8	17.5	15.7	15.9
CJ	15.6	14.7	14.5	15.3	14.3	14.5
CK	14.4	13.5	13.4	14.5	12.9	13.1
CM	17.2	16.5	16.1	17.2	16.0	16.2
CN	13.6	12.8	12.5	13.7	12.5	12.8
CO	10.0	9.3	9.0	10.3	9.1	9.3
DA	6.1	5.4	5.0	6.4	5.1	5.5
DB	8.4	7.9	7.7	9.0	7.7	8.0
DC	10.5	9.5	9.0	11.3	9.1	9.4
DD	8.7	7.9	8.0	9.0	7.7	7.7
DE	6.2	5.4	5.4	6.0	5.3	5.6
DF	0.8	-3.6	-20.0	14.8	-11.7	-5.8
DG	7.0	4.8	213.7	10.5	3.9	5.4

Designates gages located on welds.

TABLE 7. Fatigue Test 2 - Fatigue Loading - Load and Deflection Values

Cycles	Maximum Load (kN)		Minimum Load (kN)		Load Range (kN)		Midspan Max. Deflection (mm)		Midspan Min. Deflection (mm)		Midspan Deflection Range (mm)	
	Side A	Side B	Side A	Side B	Side A	Side B	Side A	Side B	Side A	Side B	Side A	Side B
0.0E+00	137	135	22	21	115	114	4.82	8.76	3.88	7.90	0.94	0.86
1.0E+06	145	145	19	22	127	123	4.94	8.82	3.88	7.87	1.06	0.94
2.0E+06	153	153	20	20	132	133	5.02	8.77	3.90	7.71	1.11	1.05
3.0E+06	146	147	17	17	129	130	4.18	12.73	3.30	7.77	0.88	1.13
4.0E+06	144	144	13	17	131	127	6.48	9.12	5.37	8.14	1.12	0.98
5.0E+06	145	144	17	17	128	127	7.28	9.09	6.13	8.11	1.14	0.98

TABLE 8 - Fatigue Test 2 - Fatigue Loading - Stress Ranges

Gages	Stress Range (MPa) per million cycles					
	0	1,000,000	2,000,000	3,000,000	4,000,000	5,000,000
T1	4.6	41.9	4.9	4.8	4.8	5.0
T2	5.2	5.4	5.6	5.4	5.5	5.5
T3	5.2	5.4	5.8	0.5	5.7	5.6
T4	3.4	4.1	4.1	4.0	4.1	3.9
T5	13.3	15.2	15.9	15.3	15.7	15.8
T6	16.1	18.5	19.2	18.1	18.5	18.5
T7	22.3	25.7	25.9	24.7	24.6	24.1
T8	13.9	15.9	17.0	16.3	17.1	16.1
A1	4.9	5.2	5.7	5.6	5.5	5.5
A3	4.7	5.2	5.5	5.4	5.2	5.4
A5	4.8	5.1	5.4	5.2	5.2	5.2
B1	8.9	9.7	10.5	10.3	10.0	10.2
B2	9.1	9.9	10.8	10.5	10.3	10.3
B3	9.2	10.1	10.5	10.5	10.4	10.3
B4	9.0	9.8	10.0	9.9	9.9	9.9
B5	9.9	10.7	11.7	11.3	11.1	11.2
C1	8.5	9.2	9.9	9.8	9.4	9.7
C2	8.1	8.8	9.6	9.2	9.0	9.0
C3	8.3	9.0	9.9	9.7	9.2	9.4
C4	8.5	9.1	10.2	9.8	9.5	9.5
C5	8.2	9.1	9.9	9.6	9.4	9.4
D1	2.4	2.6	3.0	3.0	2.8	2.9
D3	2.1	2.2	2.6	2.6	2.5	2.8
D5	0.5	0.7	0.9	0.8	0.8	0.8
E1	3.2	3.4	3.9	3.4	3.9	4.3
E3	3.7	3.4	3.7	3.9	3.7	3.9
E5	3.7	4.3	4.3	4.3	4.1	4.3
F1	8.5	10.0	10.0	9.8	10.3	10.0
F2	9.6	10.5	10.5	10.3	11.0	10.3
F3	10.8	11.8	12.2	12.2	12.4	11.8
F4	9.4	10.5	10.8	10.8	11.0	11.0
F5	6.9	7.7	7.9	8.1	8.1	7.9
G1	11.8	13.2	14.2	13.7	14.1	13.4
G2	12.0	13.0	14.1	13.2	13.4	13.4
G3	9.8	10.8	11.2	11.2	11.6	11.4
G4	13.2	14.4	15.0	14.6	14.8	14.2
G5	11.2	12.4	12.8	13.0	13.0	12.8
H1	6.5	6.5	7.3	6.7	6.9	6.9
H3	4.9	5.1	5.5	5.5	5.5	5.5
H5	4.9	5.9	6.1	6.5	6.5	6.5

TABLE 9 - Fatigue Test 2 - Stiffness Test - Maximum Normalized Stresses

Gages	Stress Range (MPa) per million cycles					
	0	1,000,000	2,000,000	3,000,000	4,000,000	5,000,000
T1	5.1	-0.1	4.2	4.8	5.3	4.4
T2	5.9	6.5	5.1	5.7	6.1	5.2
T3	5.9	6.4	5.1	0.1	6.1	5.4
T4	-3.7	-3.7	-5.0	-4.0	-3.9	-4.7
T5	-14.5	-13.9	-15.7	-14.8	-14.3	-15.0
T6	-17.5	-17.8	-18.3	-17.3	-16.7	-17.3
T7	-24.7	-24.5	-25.5	-24.3	-23.5	-24.5
T8	-13.4	-13.4	-17.9	-14.3	-14.5	-14.4
A1	5.6	5.9	5.5	5.5	5.8	5.2
A3	5.0	5.7	3.7	5.3	5.6	5.2
A5	5.1	5.9	5.3	5.2	6.3	6.6
B1	10.0	10.6	9.2	10.3	10.6	10.1
B2	10.3	10.7	9.3	10.5	10.8	10.3
B3	10.2	11.0	9.1	10.3	10.9	11.0
B4	9.9	11.0	9.7	9.5	11.3	11.9
B5	11.0	11.7	9.9	11.4	11.7	11.2
C1	9.3	10.1	8.6	9.4	10.0	9.8
C2	8.7	9.4	8.3	9.0	9.2	8.9
C3	9.2	9.7	8.5	9.2	9.5	9.0
C4	9.2	9.9	8.5	9.5	9.7	9.2
C5	9.3	9.9	9.3	9.4	9.7	9.1
D1	2.0	2.8	1.2	2.4	2.6	2.1
D3	1.9	2.4	1.4	2.1	2.3	1.7
D5	-0.1	4.7	10.8	-0.2	11.0	16.6
E1	3.0	3.6	2.6	3.4	3.6	3.2
E3	3.0	3.4	2.4	3.2	3.4	3.0
E5	3.7	5.4	4.0	4.0	5.9	5.9
F1	9.5	10.8	9.0	9.7	10.8	11.3
F2	10.5	10.6	10.3	10.3	10.9	11.3
F3	12.0	12.5	11.7	12.3	12.2	11.9
F4	10.4	11.1	9.9	10.8	10.9	10.5
F5	7.5	7.9	7.2	7.8	8.0	7.5
G1	13.5	13.8	13.7	13.7	13.7	13.5
G2	13.1	13.4	13.2	13.4	13.4	13.4
G3	10.9	11.1	11.3	11.0	11.2	11.2
G4	14.8	15.1	14.7	15.0	15.0	14.8
G5	12.3	12.7	12.5	12.7	12.6	12.5
H1	6.5	6.8	6.6	6.6	6.5	6.7
H3	4.9	6.0	7.1	5.2	7.2	8.8
H5	5.3	5.7	5.5	5.5	5.4	5.4

TABLE 10 - Fatigue Test 2 - Stiffness Loading - Load and Deflection Values

Cycles	Max Load (kN)		Min Load (kN)		Load Range (kN)	
	Side A	Side B	Side A	Side B	Side A	Side B
0.0E+00	134	134	0.0	0.0	134	134
1.0E+06	134	134	0.1	0.0	134	134
2.0E+06	134	134	0.2	0.1	134	134
3.0E+06	137	136	0.0	0.0	137	136
4.0E+06	134	134	0.0	0.1	134	134
5.0E+06	134	134	0.1	0.1	134	134

Cycles	Max Delfection (mm)		Min Deflection (mm)		Deflection Difference (mm)	
	Side A	Side B	Side A	Side B	Side A	Side B
0.0E+00	4.79	8.75	3.68	7.74	1.12	1.01
1.0E+06	4.85	8.74	3.73	7.71	1.12	1.03
2.0E+06	4.85	8.62	3.72	7.58	1.14	1.04
3.0E+06	4.12	8.74	3.23	7.69	0.89	1.05
4.0E+06	6.40	9.05	5.24	8.01	1.16	1.04
5.0E+06	7.17	9.01	6.02	7.98	1.15	1.04

TABLE 11. Fatigue Test 2 - Stiffness Loading - Normalized Deflection Values

Cycles	Deflection Difference		Normalization Factor		Normalized Delfection	
	Side A	Side B	Side A	Side B	Side A	Side B
0.0E+00	1.12	1.01	0.993	0.993	1.11	1.00
1.0E+06	1.12	1.03	0.997	0.997	1.12	1.03
2.0E+06	1.14	1.04	0.997	0.997	1.13	1.03
3.0E+06	0.89	1.05	0.977	0.980	0.87	1.03
4.0E+06	1.16	1.04	0.993	0.997	1.15	1.04
5.0E+06	1.15	1.04	0.997	0.997	1.14	1.03

TABLE 12. Residual Strength Test - Maximum Load and Deflection Values

Load Number	Max Load (kN)	Max Delfection (mm)
1	135	1.22
2	271	2.41
3	400	3.59
4	535	4.78
5	669	6.23
6	802	7.77
7	936	9.58
8	1119	12.70
9	1168	13.85

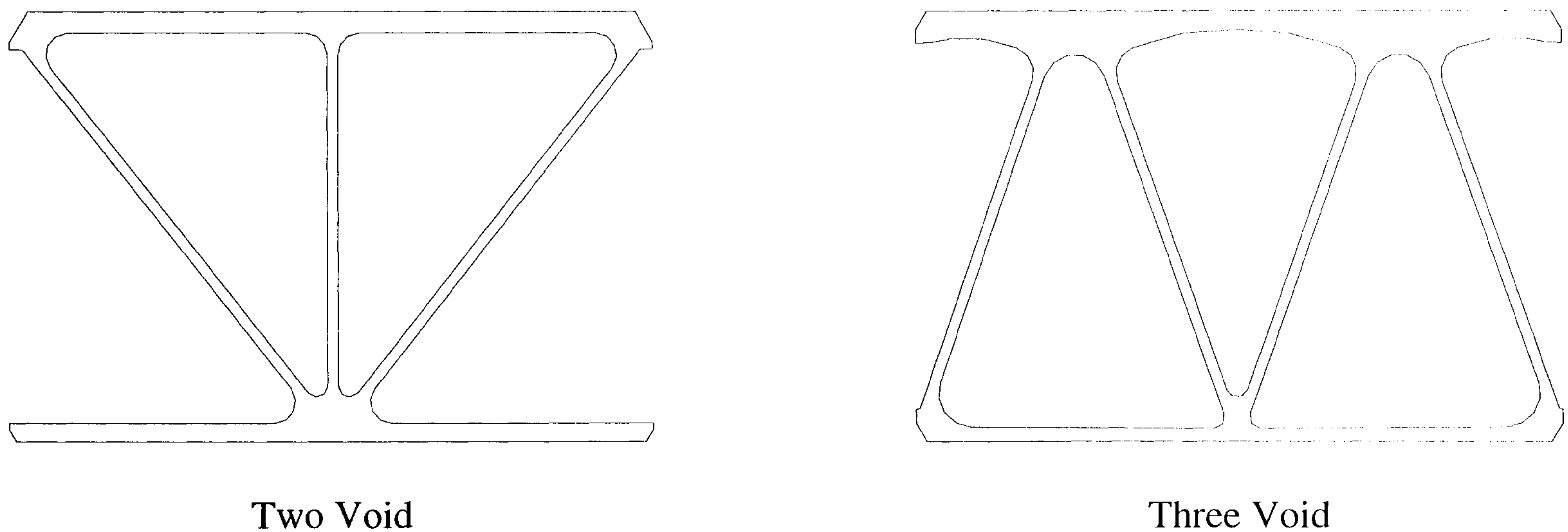

FIGURE 1. Two-Void and Three-Void Extrusion

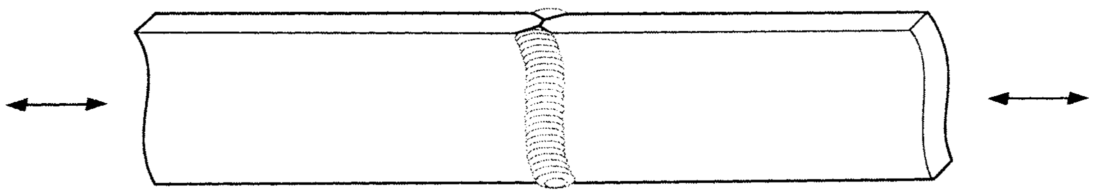

Figure 2. Groove Weld Splice Connection, AASHTO LRFD Bridge Specification (1994)

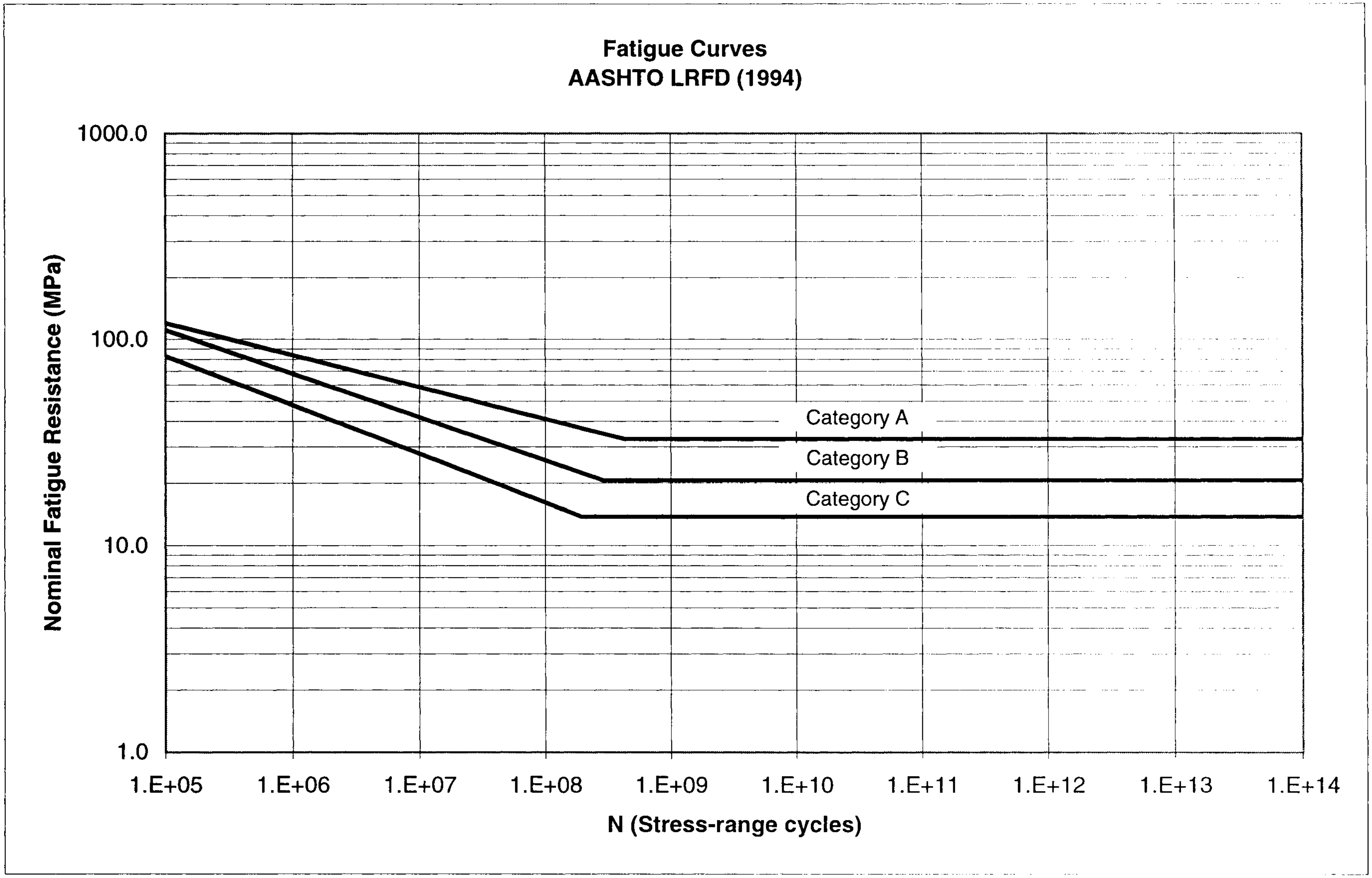

FIGURE 3. Fatigue Resistance Details

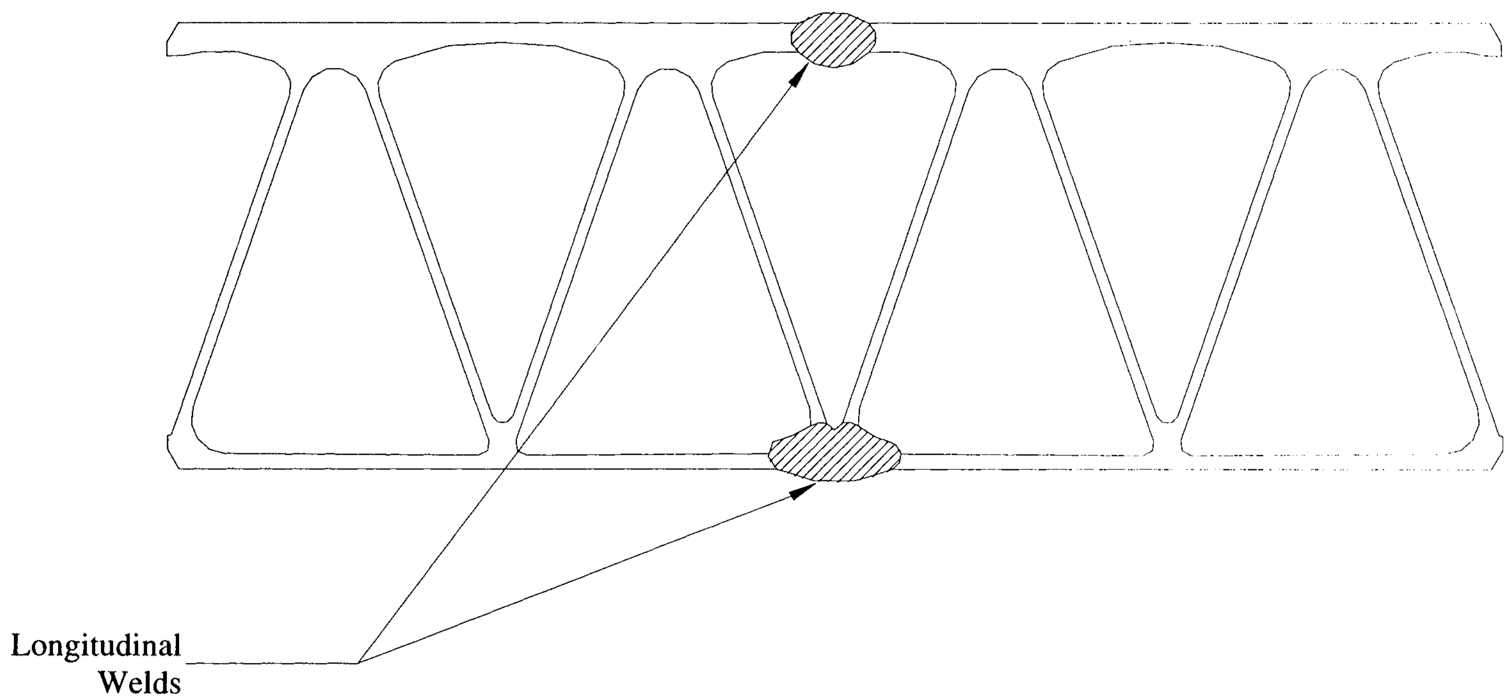

FIGURE 4. Extrusion Weld Connection

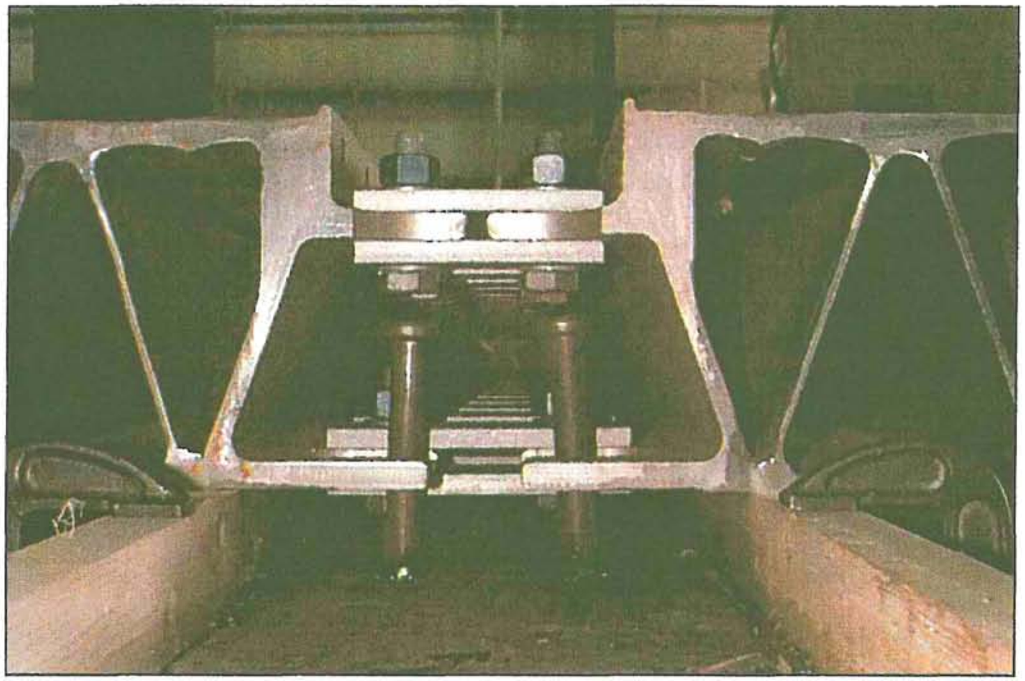

FIGURE 5. Mechanical Splice Connection

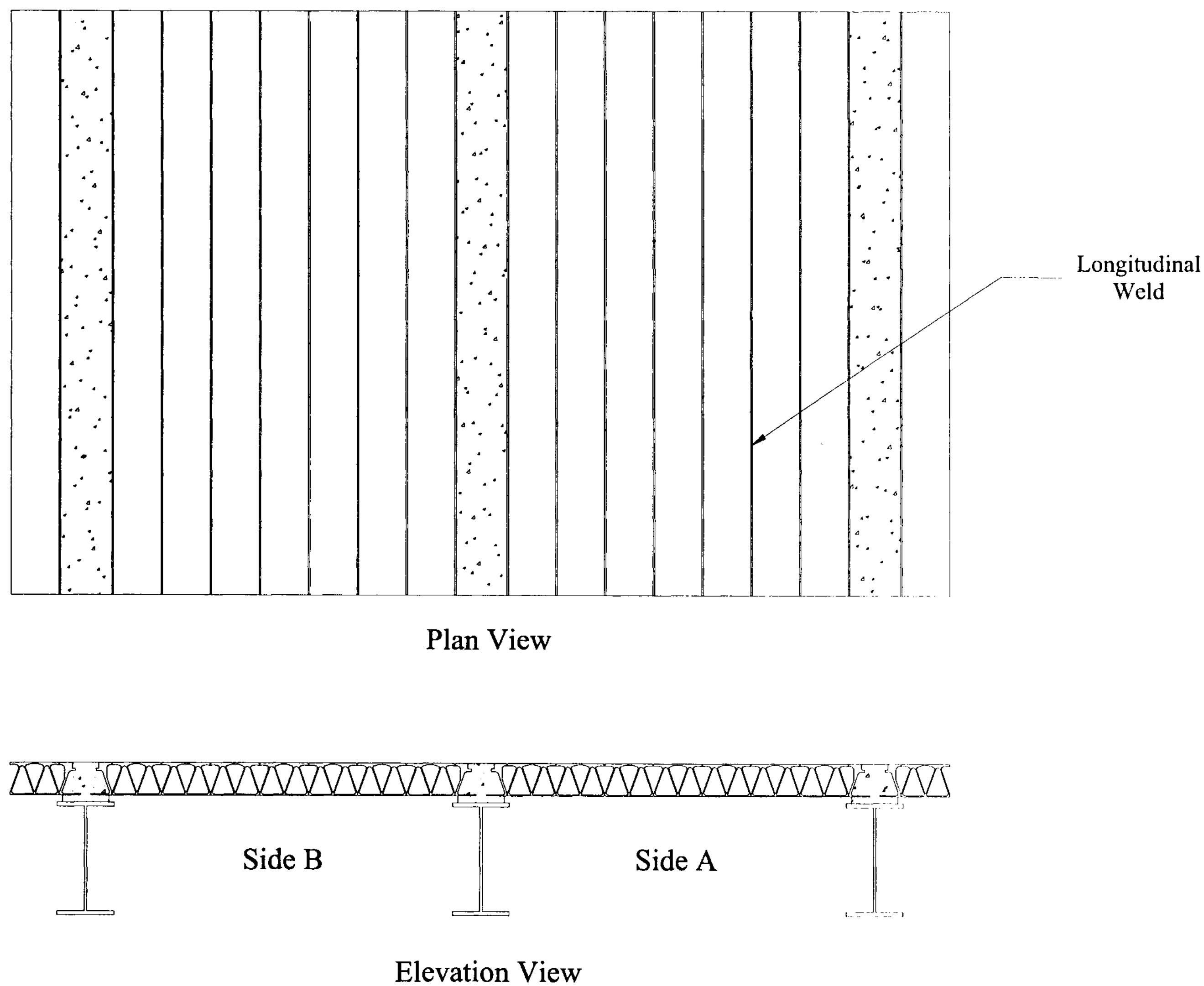

FIGURE 6. Plan and Elevation View of Test Set-Up

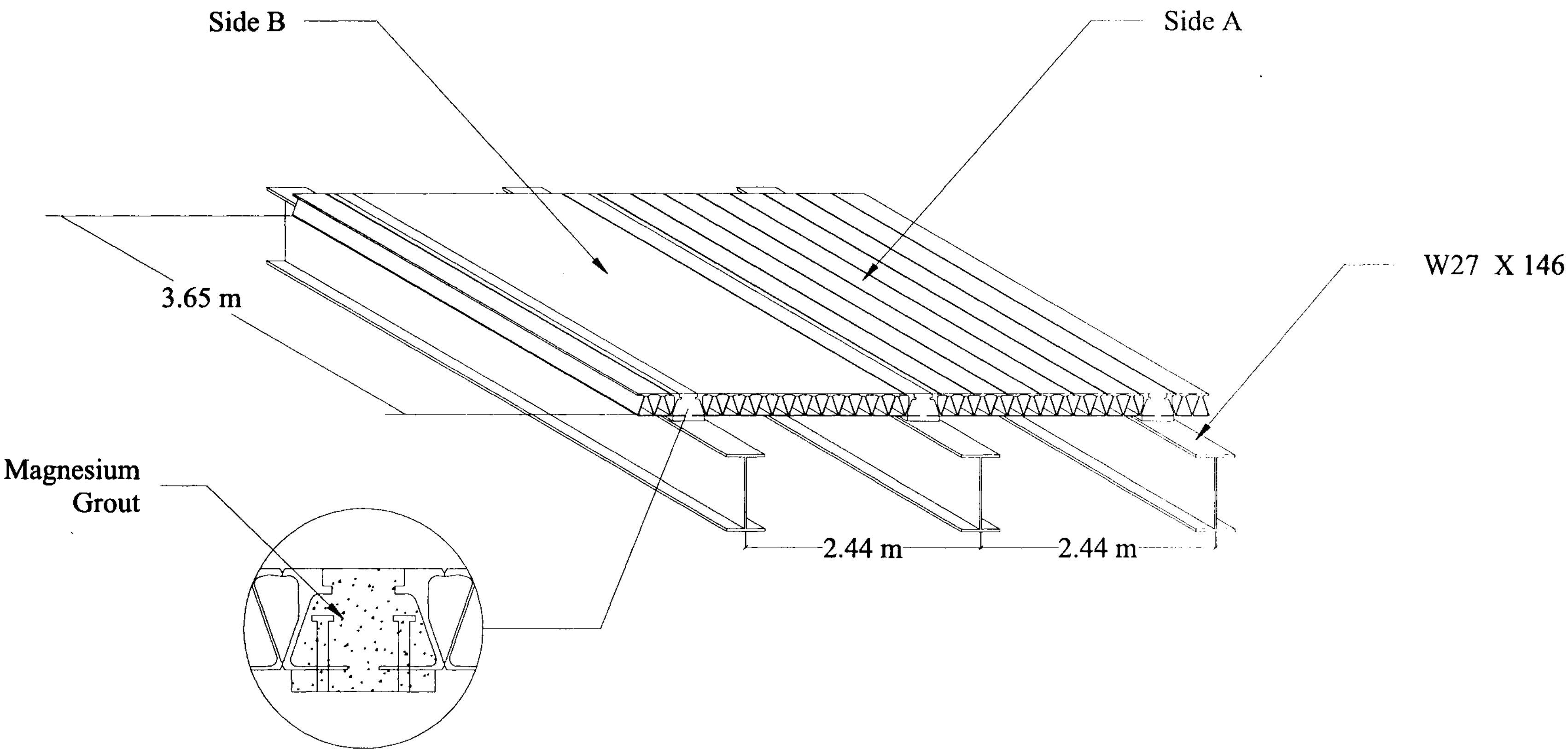

FIGURE 7. Complete Test Set-Up

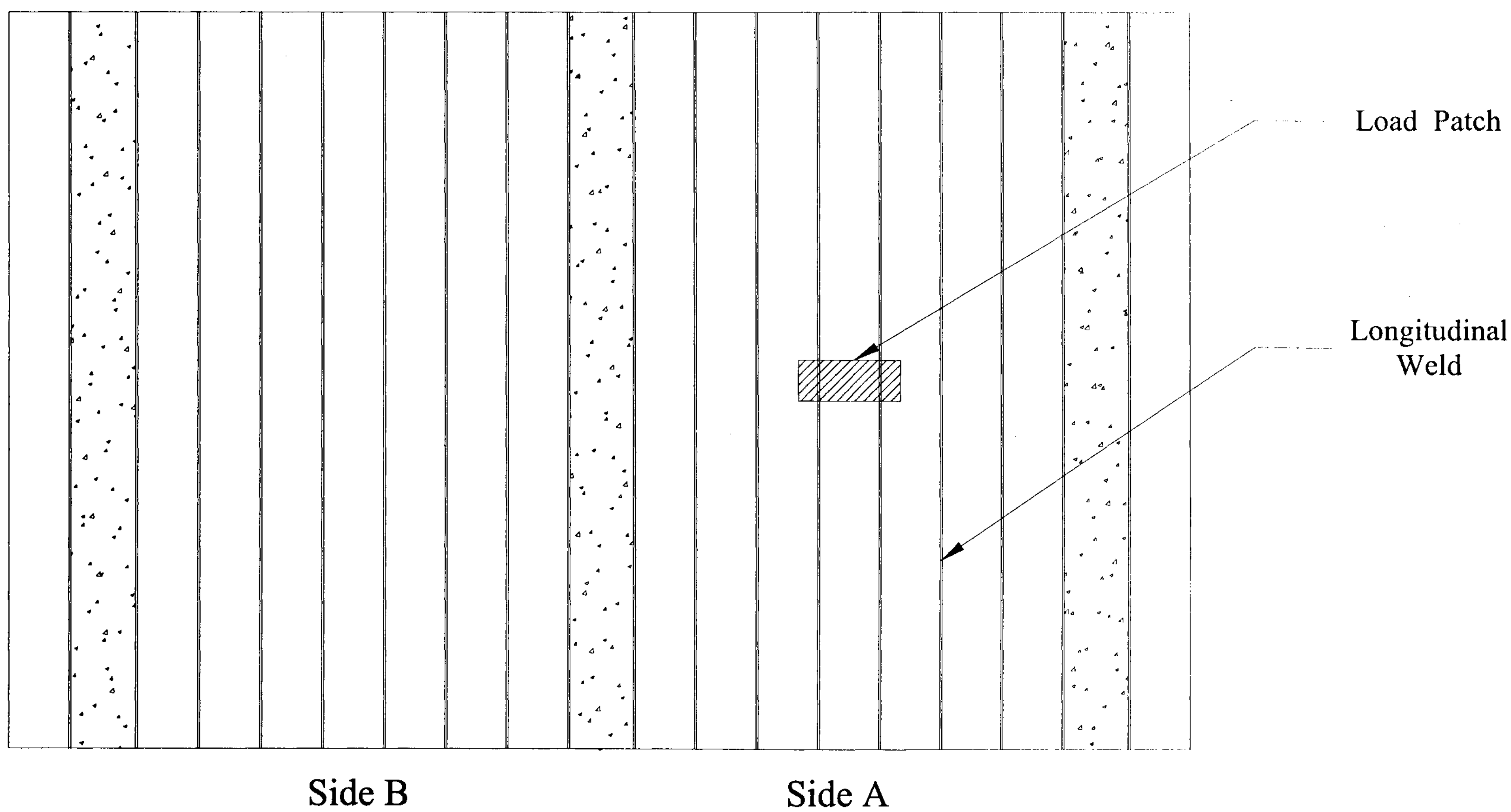

FIGURE 8. Location of Load Patch for Fatigue Test 1 and Residual Strength Test

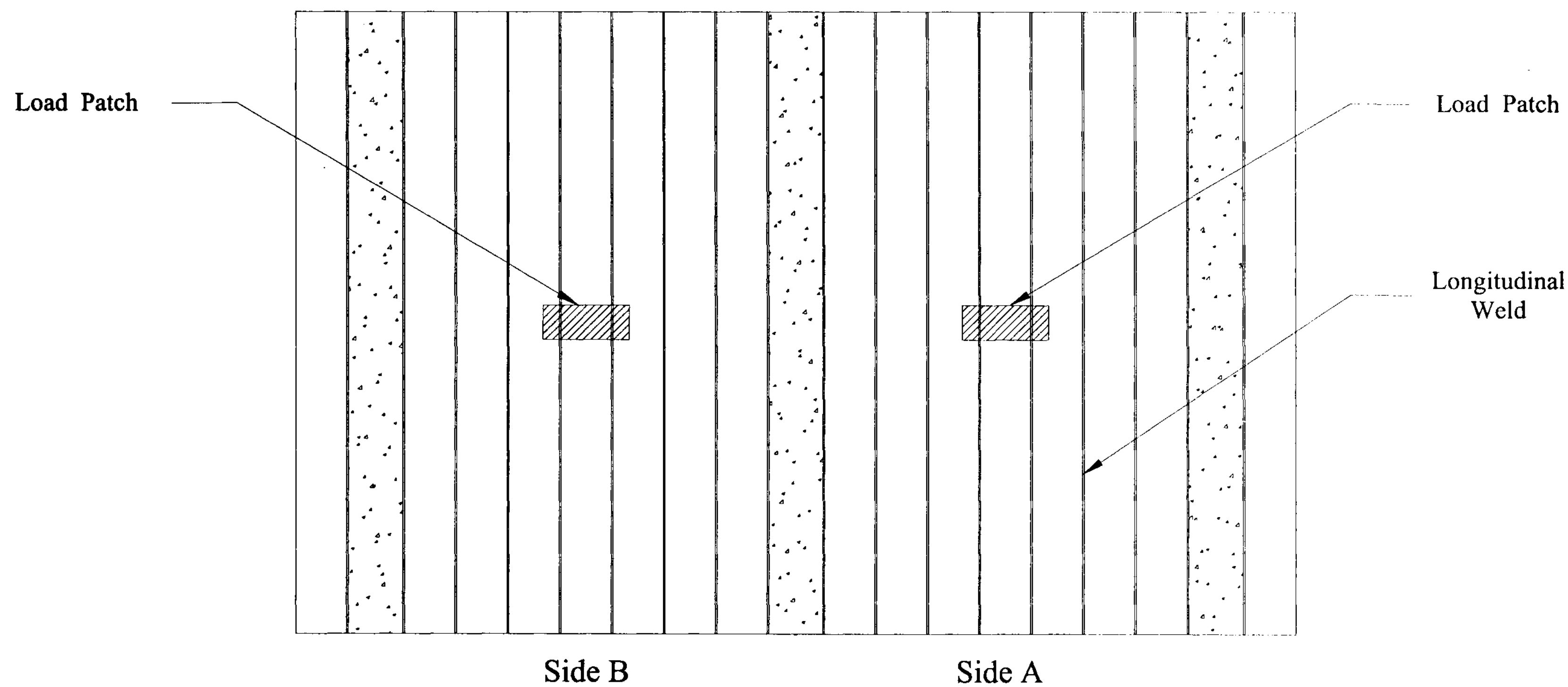

FIGURE 9. Location of Load Patch for Fatigue Test 2

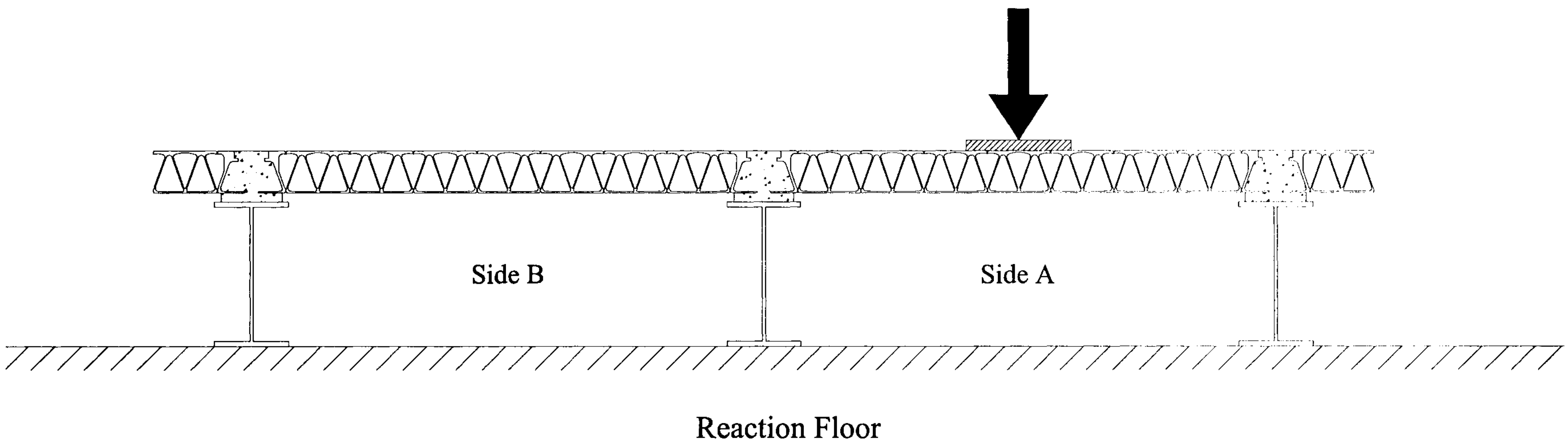

FIGURE 10. Fatigue Test 1 and Residual Strength Test Load Set-Up

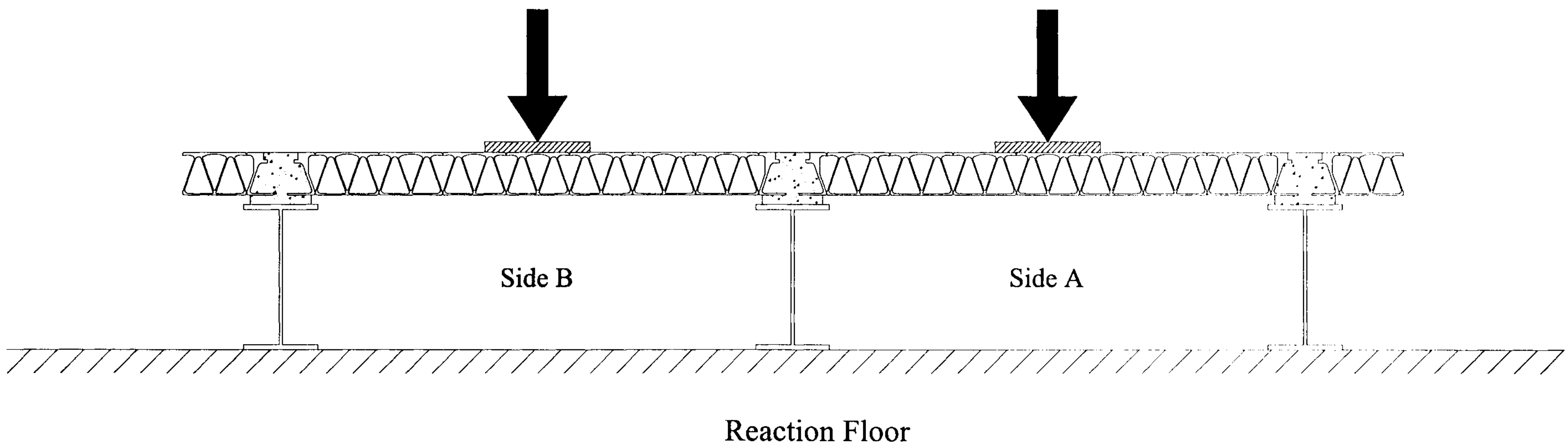

FIGURE 11. Fatigue Test 2 Load Set-Up

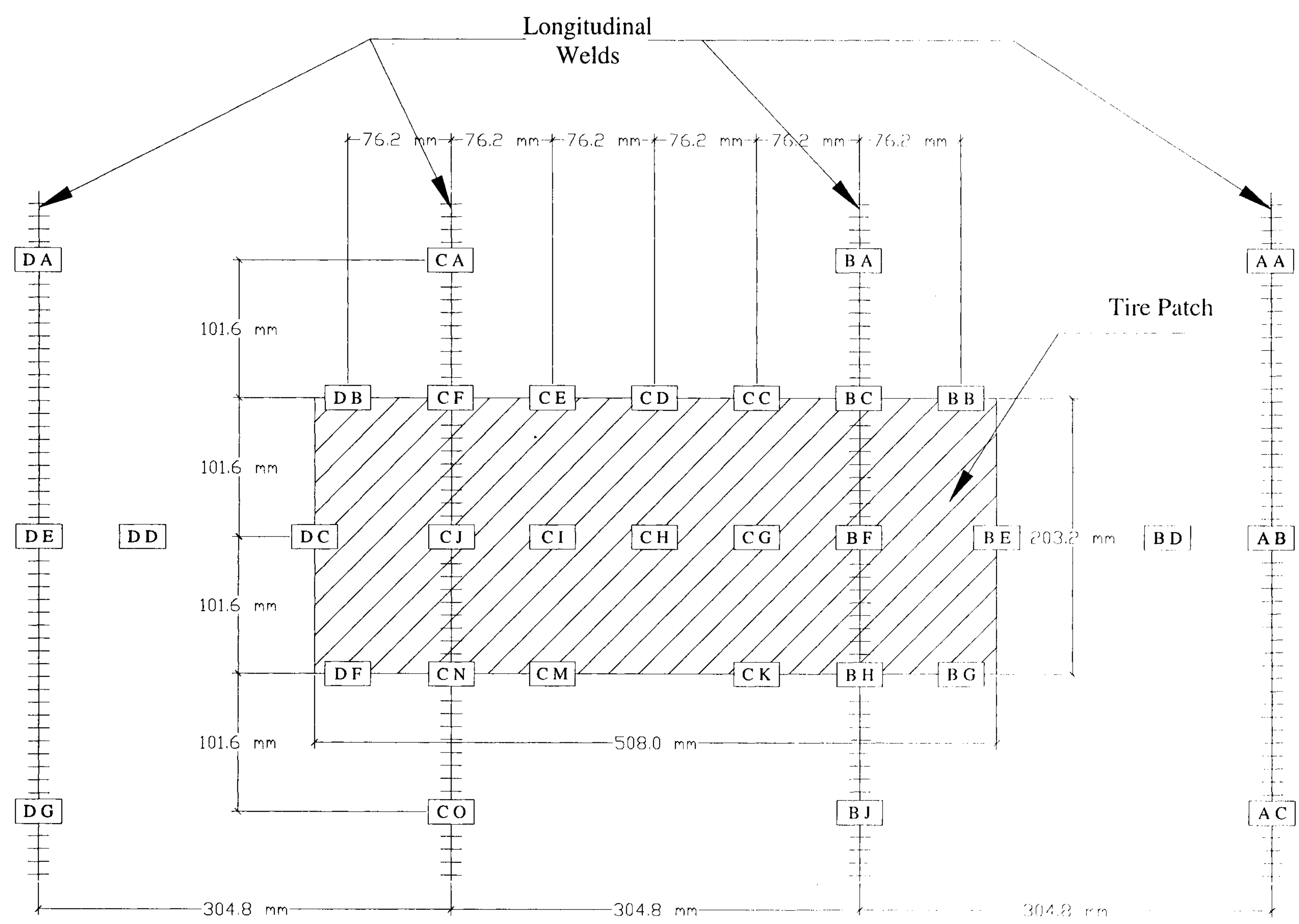

FIGURE 12. Fatigue Test 1 Gage Layout, Bottom of Side A

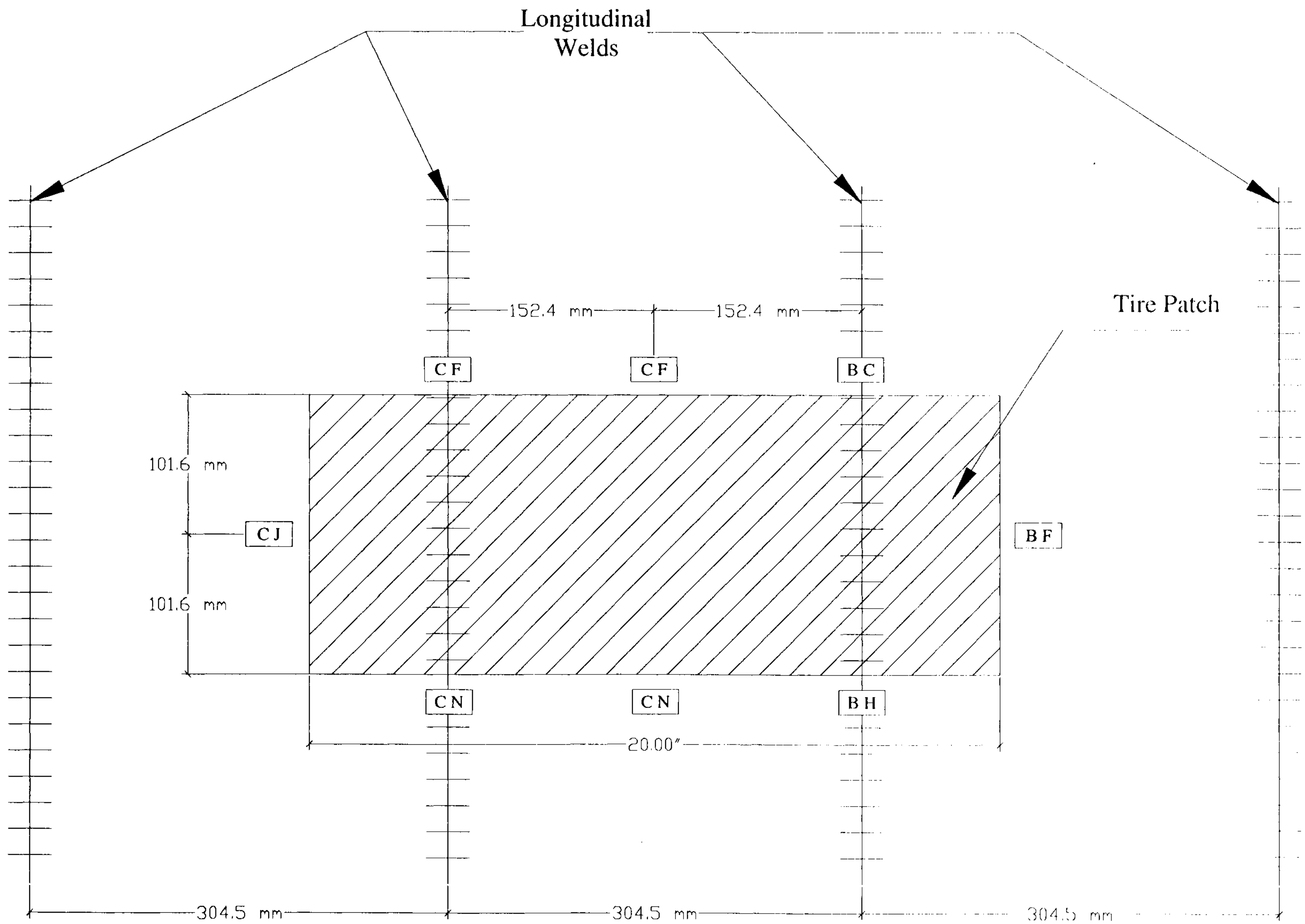

FIGURE 13. Fatigue Test 1 Gage Layout, Top of Side A

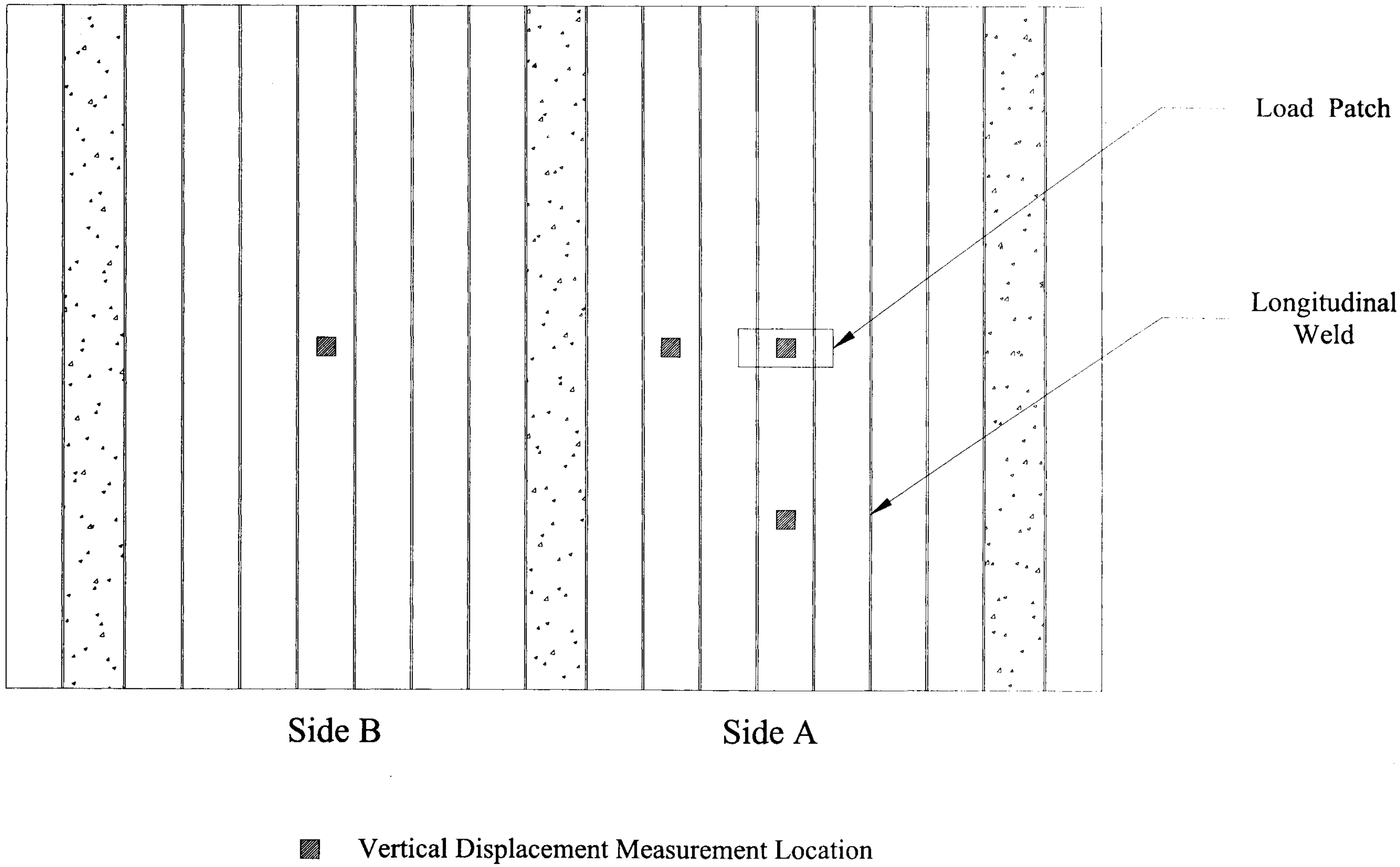

FIGURE 14. Fatigue Test 1 LVDT Location

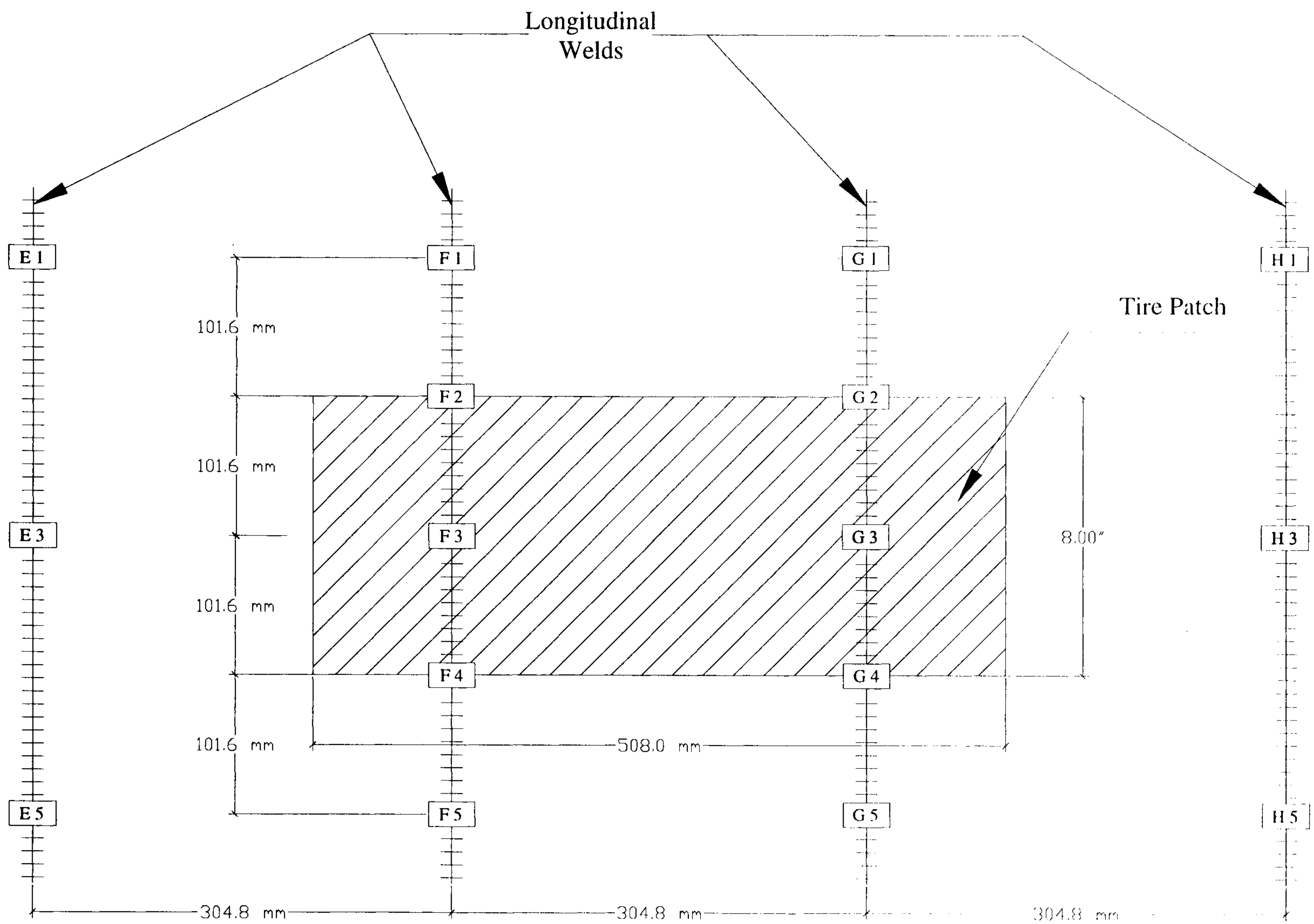

FIGURE 15. Fatigue Test 2 Gage Layout, Bottom of Side A

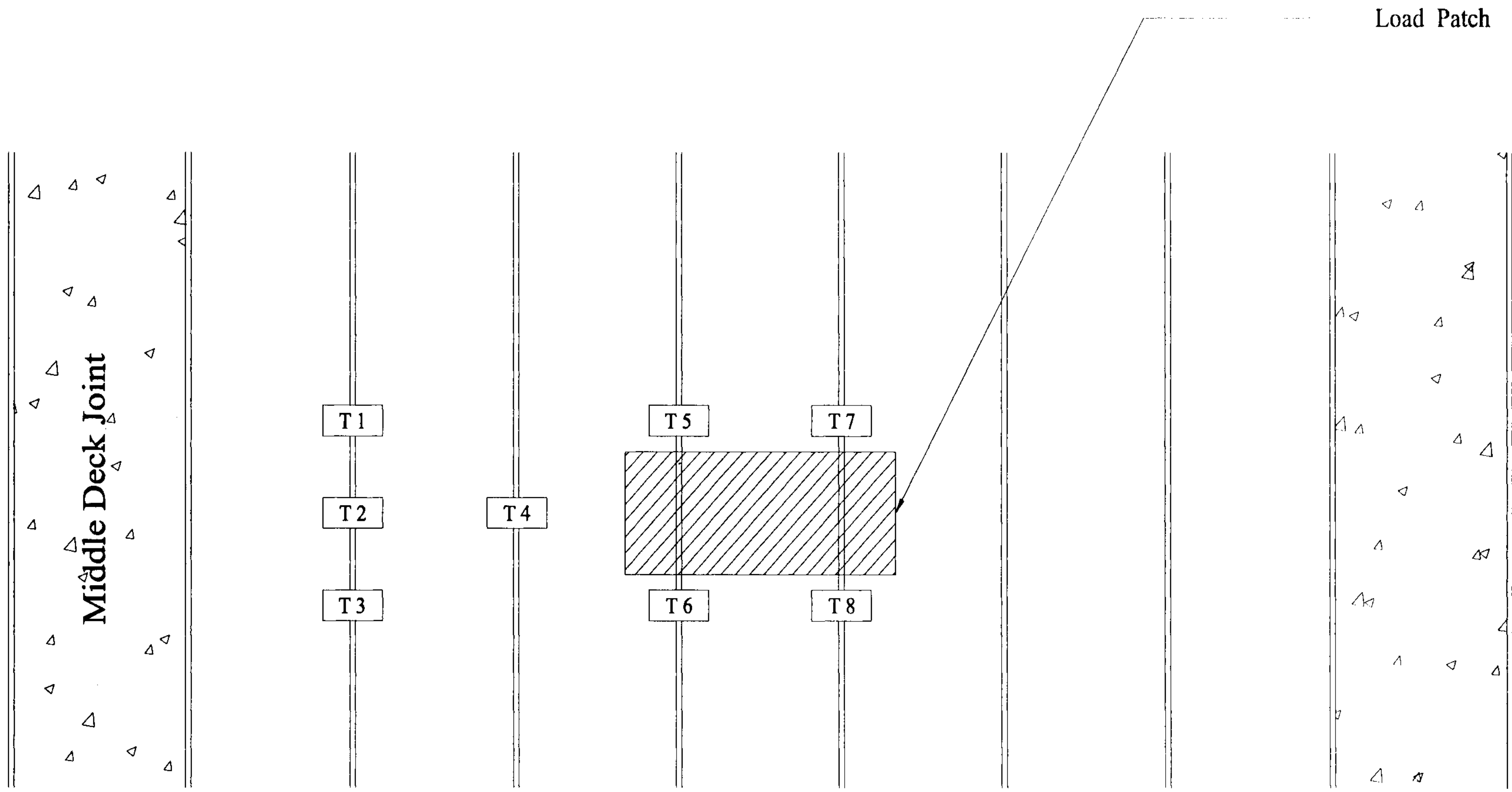

FIGURE 16. Fatigue Test 2 Gage Layout, Top of Side A

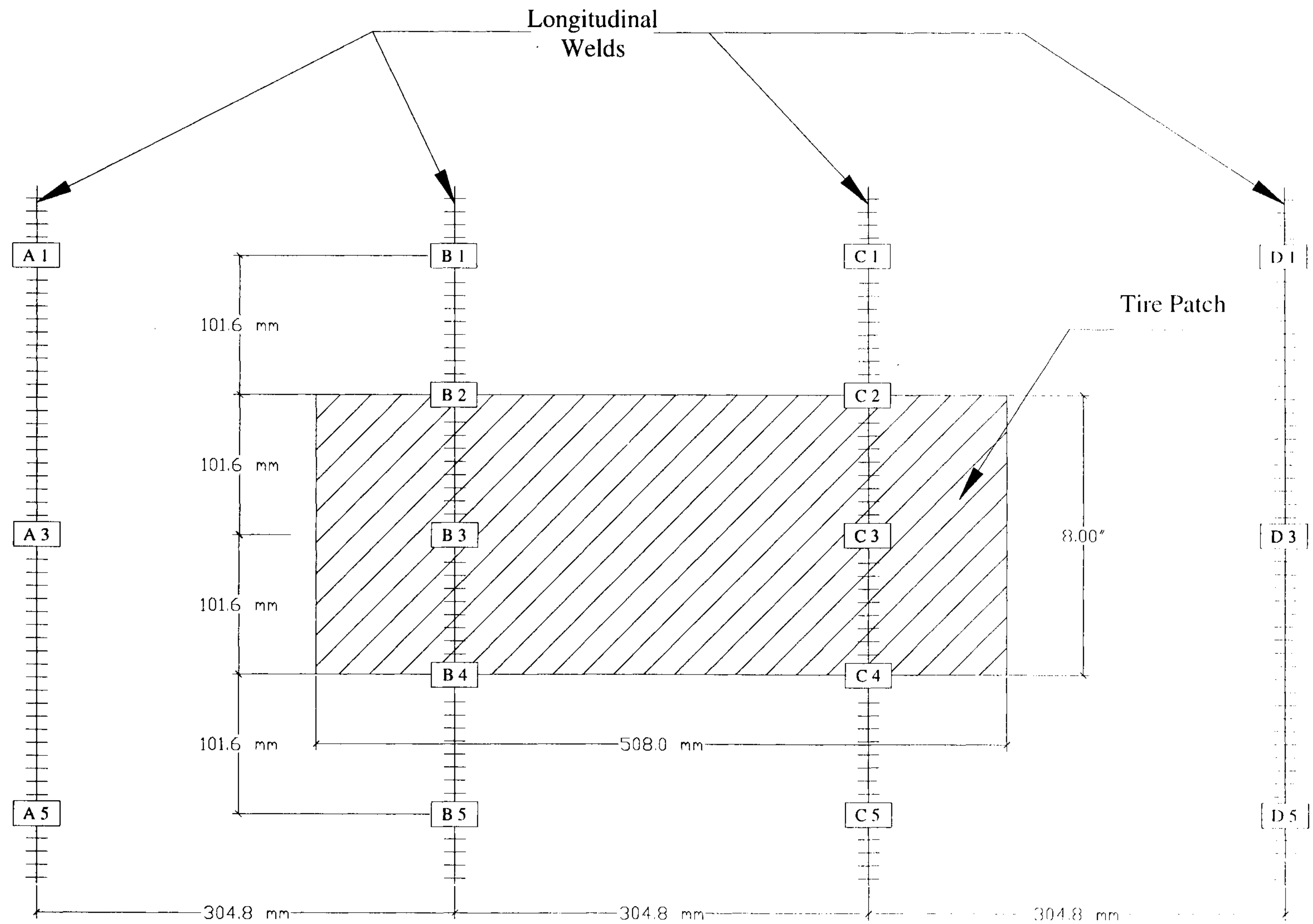

FIGURE 17. Fatigue Test 2 Gage Layout, Bottom of Side B

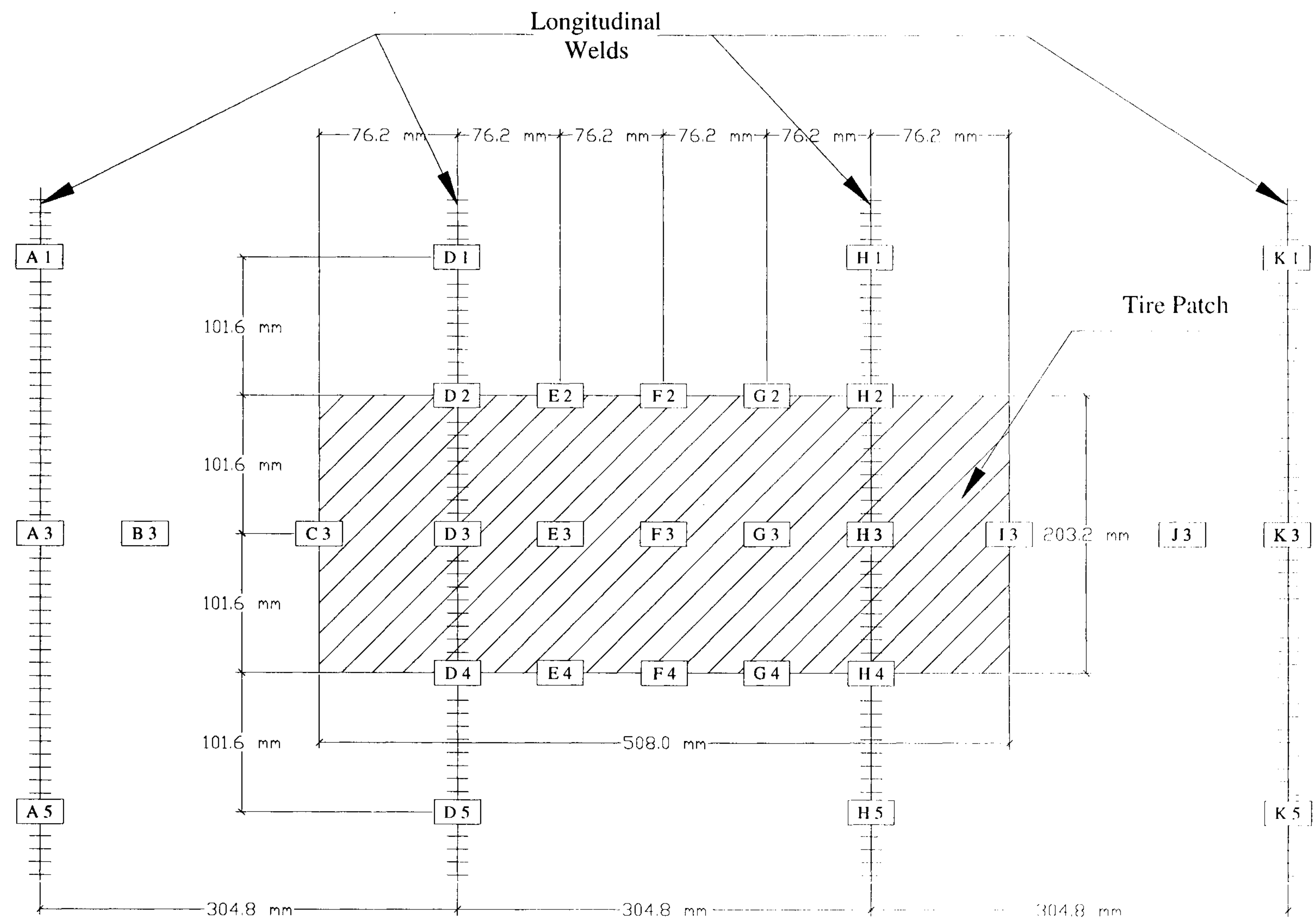

FIGURE 18. Failure Side A Gage Layout, Bottom of Side A

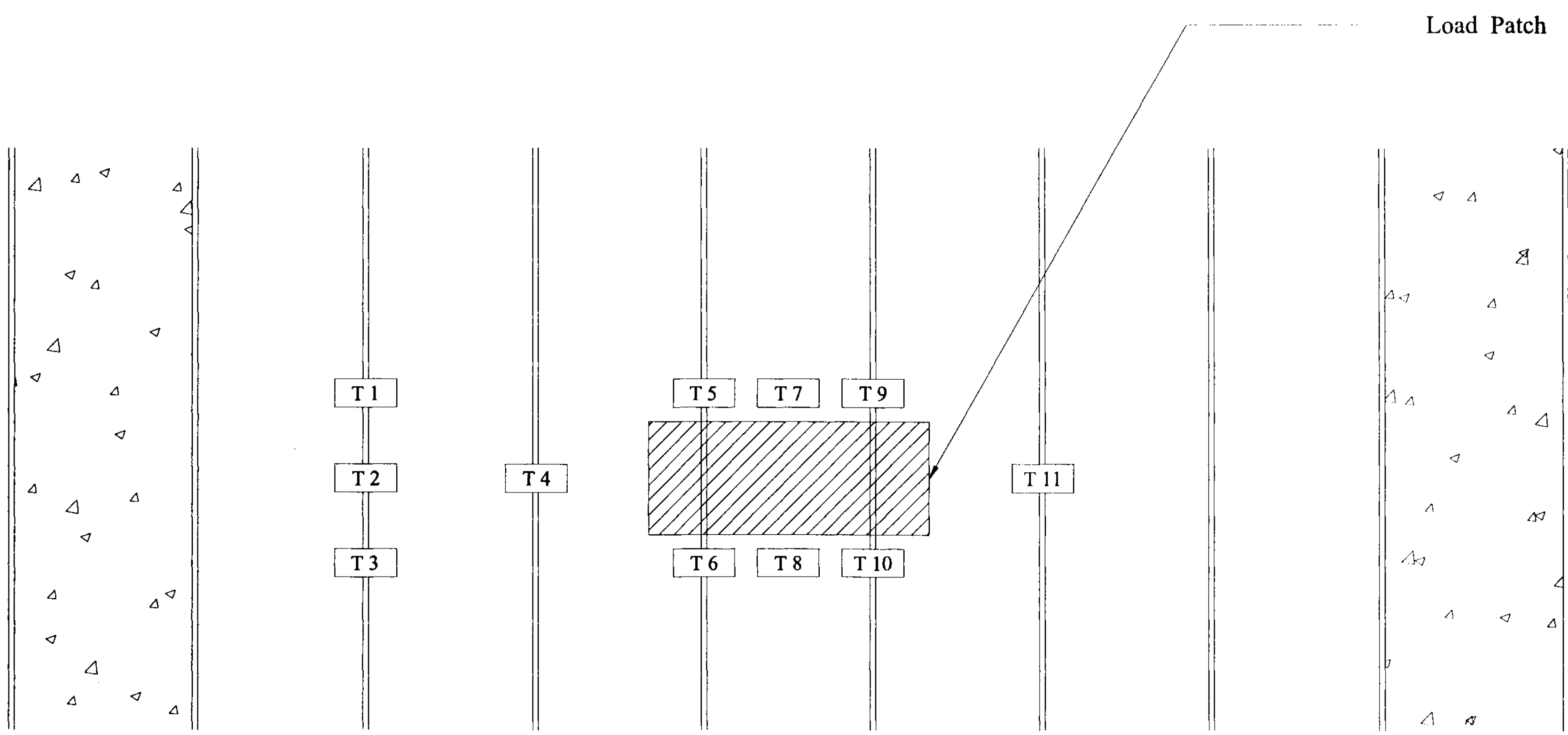

FIGURE 19. Failure Side A Gage Layout, Top of Side A

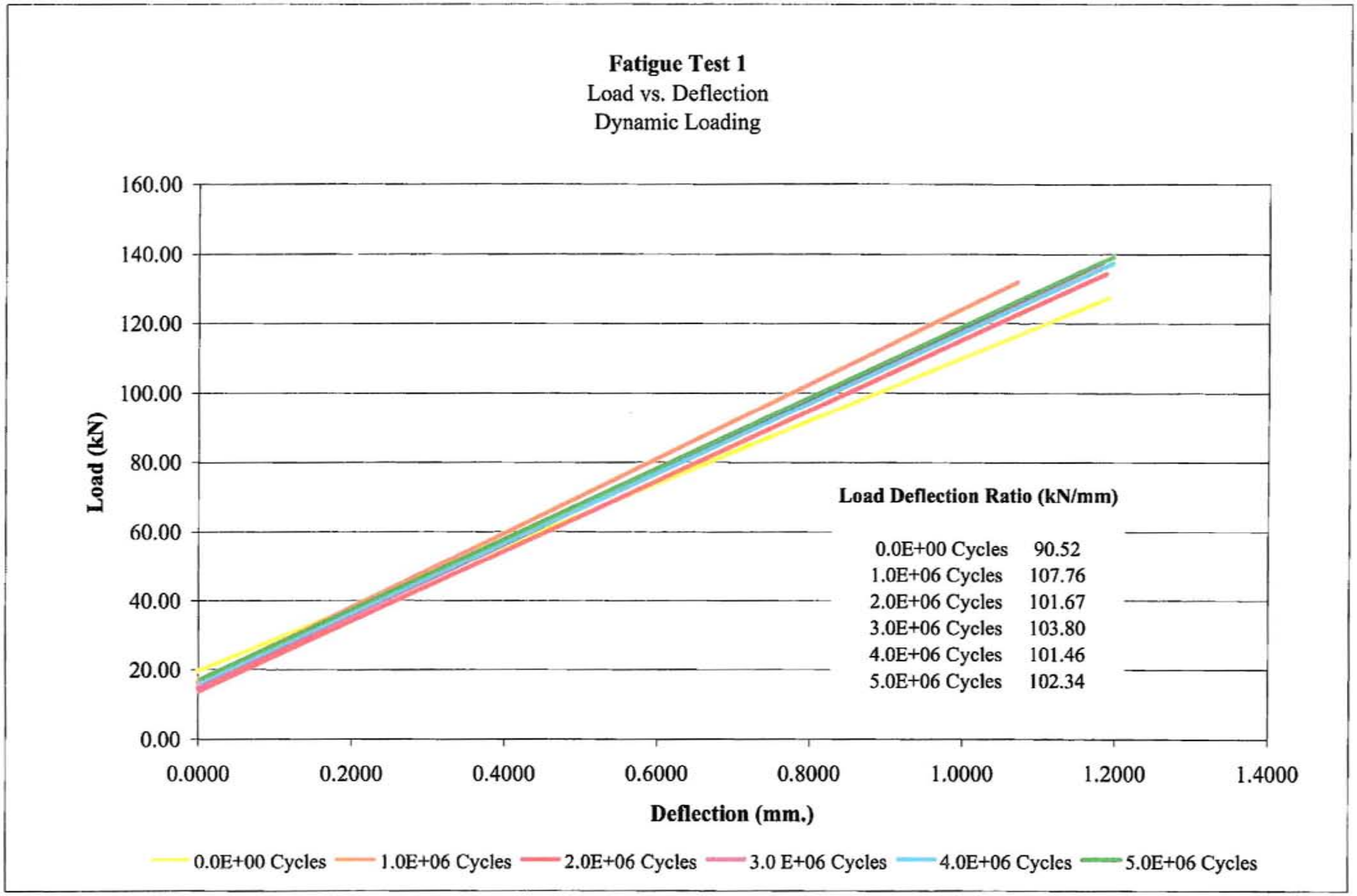

FIGURE 20. Fatigue Test 1 - Dynamic Loading - Load vs. Deflection, Midspan Side A

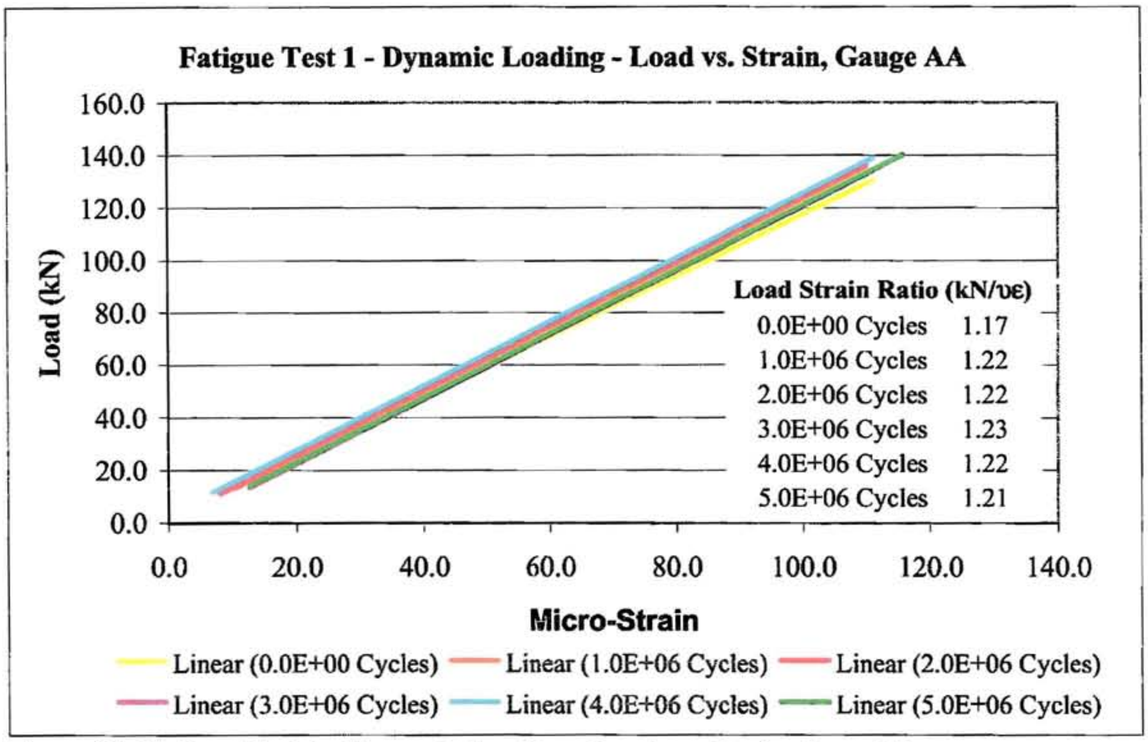

Figure 21. Fatigue Test 1 - Dynamic Loading - Load vs. Strain, Gage AA

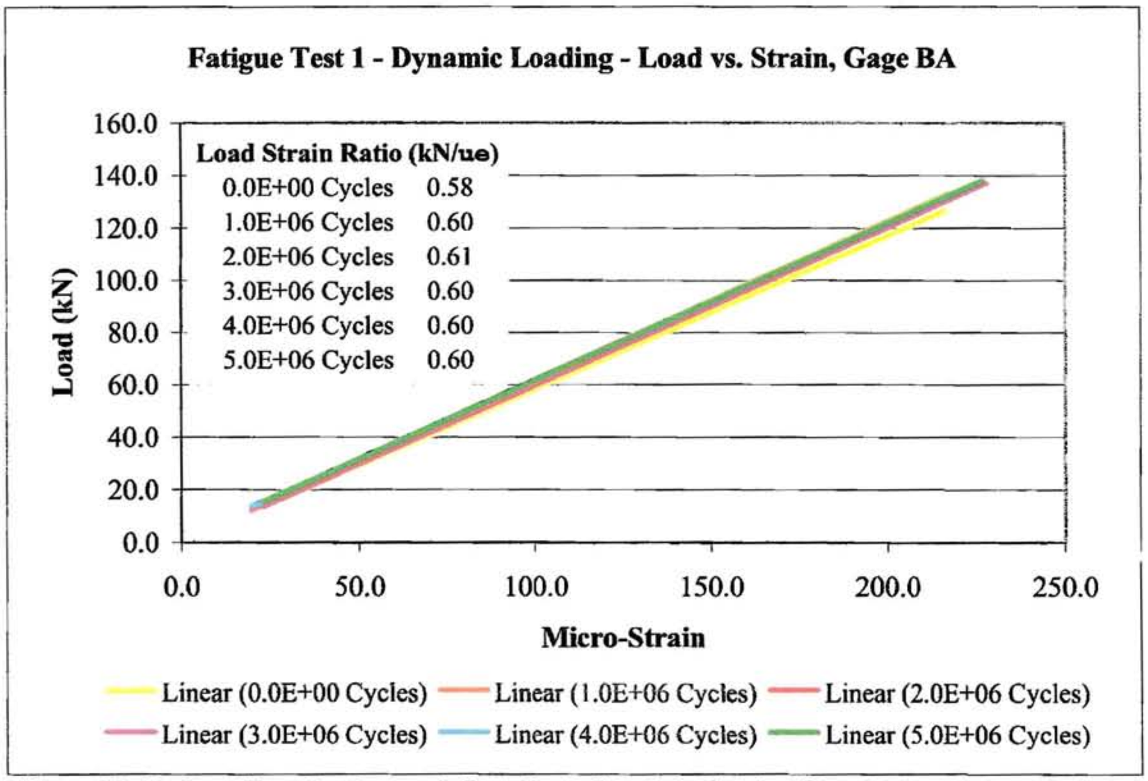

Figure 22. Fatigue Test 1 - Dynamic Loading - Load vs. Strain, Gage BA

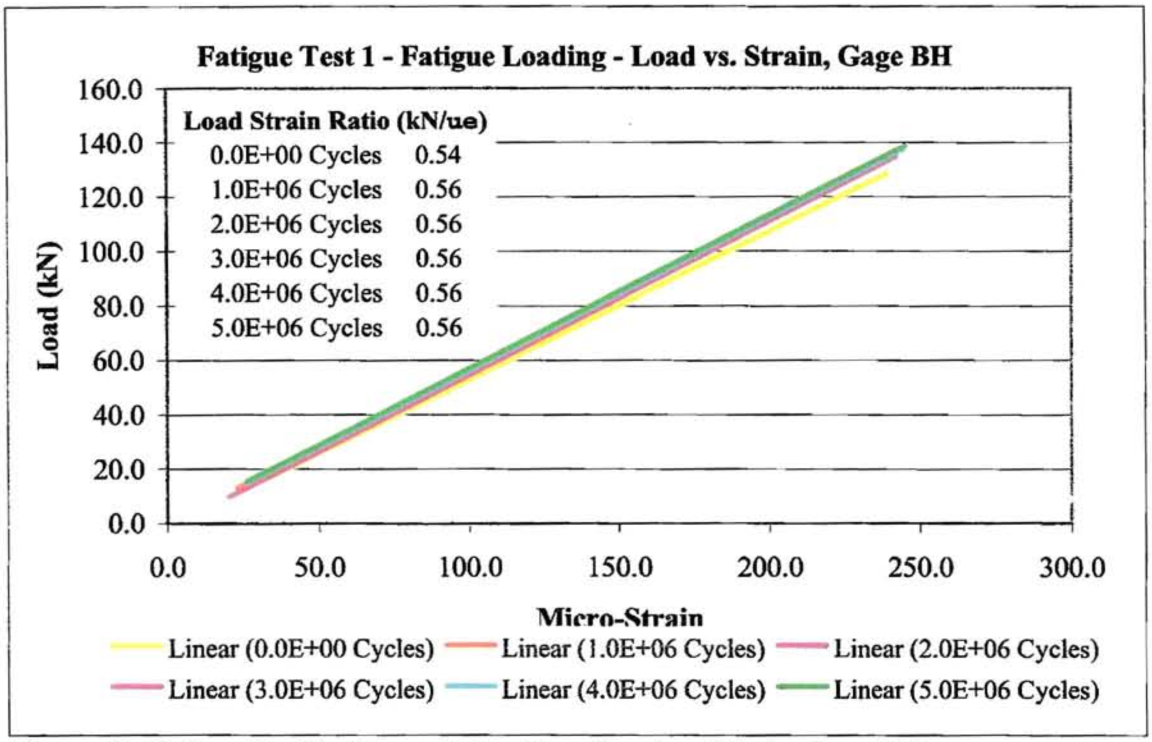

Figure 23. Fatigue Test 1 - Dynamic Loading - Load vs. Strain, Gage BH

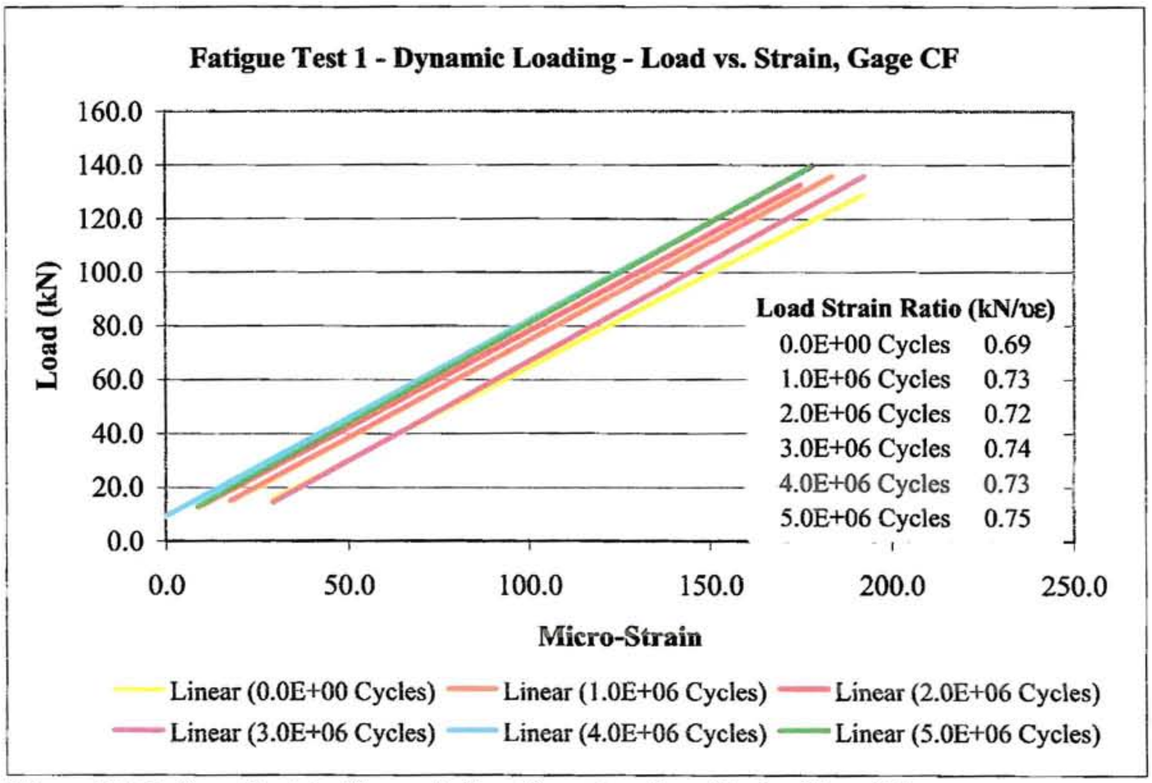

Figure 24. Fatigue Test 1 - Dynamic Loading - Load vs. Strain, Gage CF

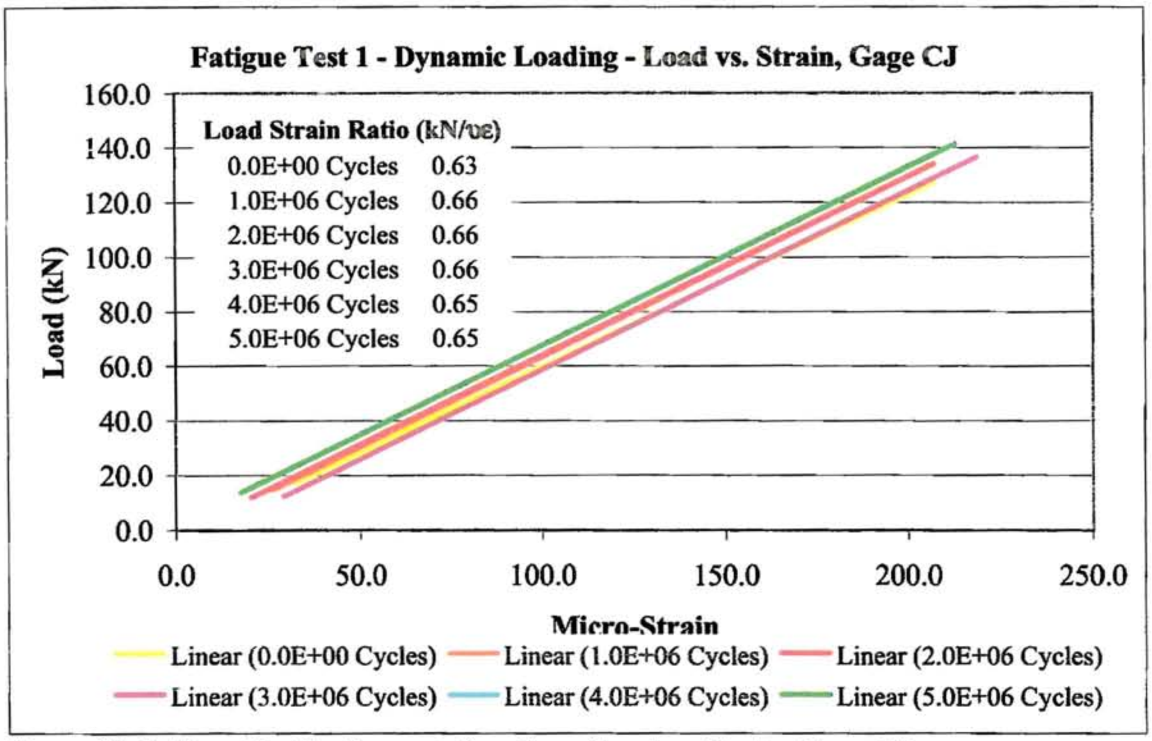

Figure 25. Fatigue Test 1 - Dynamic Loading - Load vs. Strain, Gage CJ

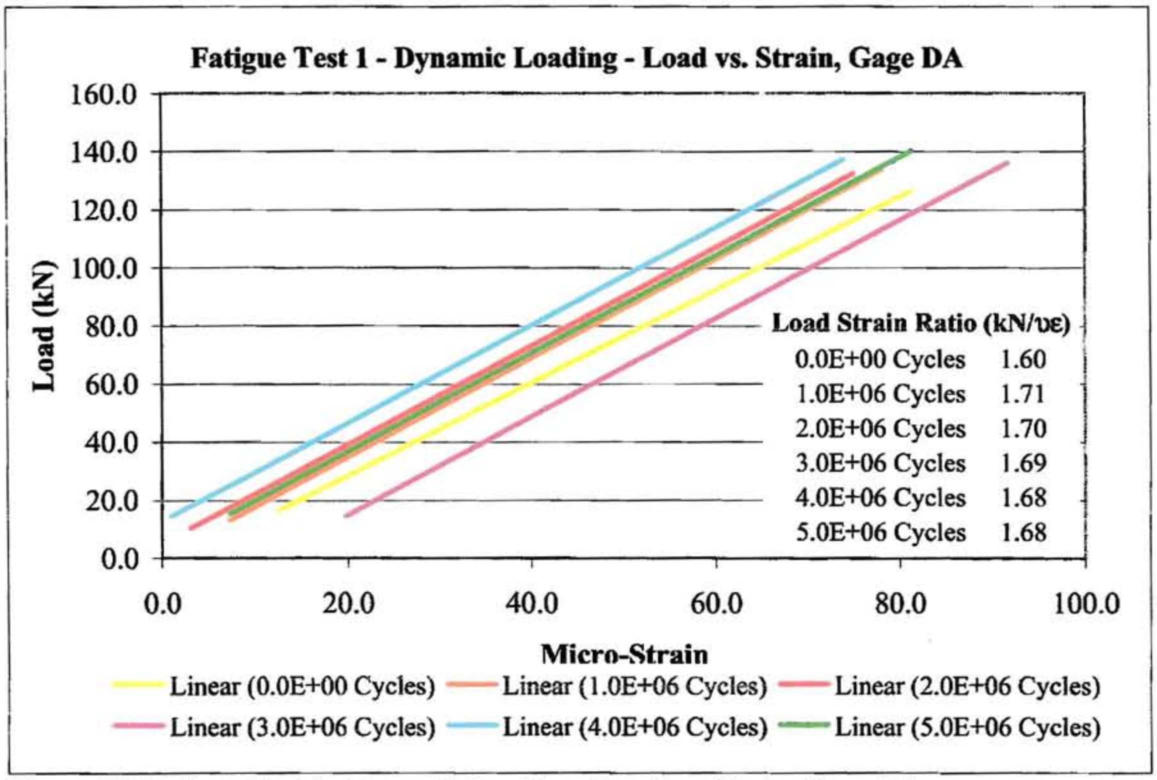

Figure 26. Fatigue Test 1 - Dynamic Loading - Load vs. Strain, Gage DA

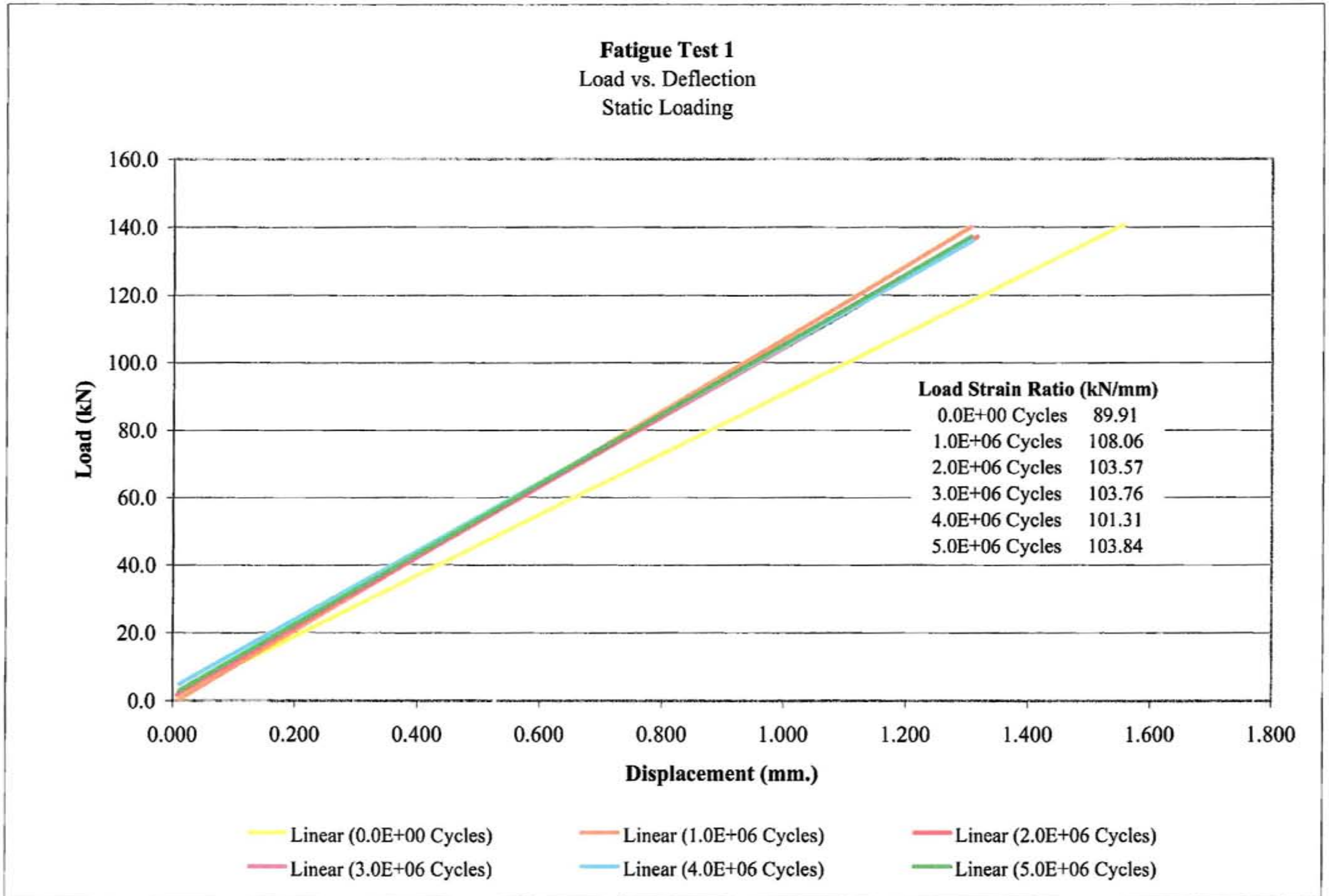

FIGURE 27. Fatigue Test 1 - Stiffness Loading - Load vs. Deflection, Midspan Side A

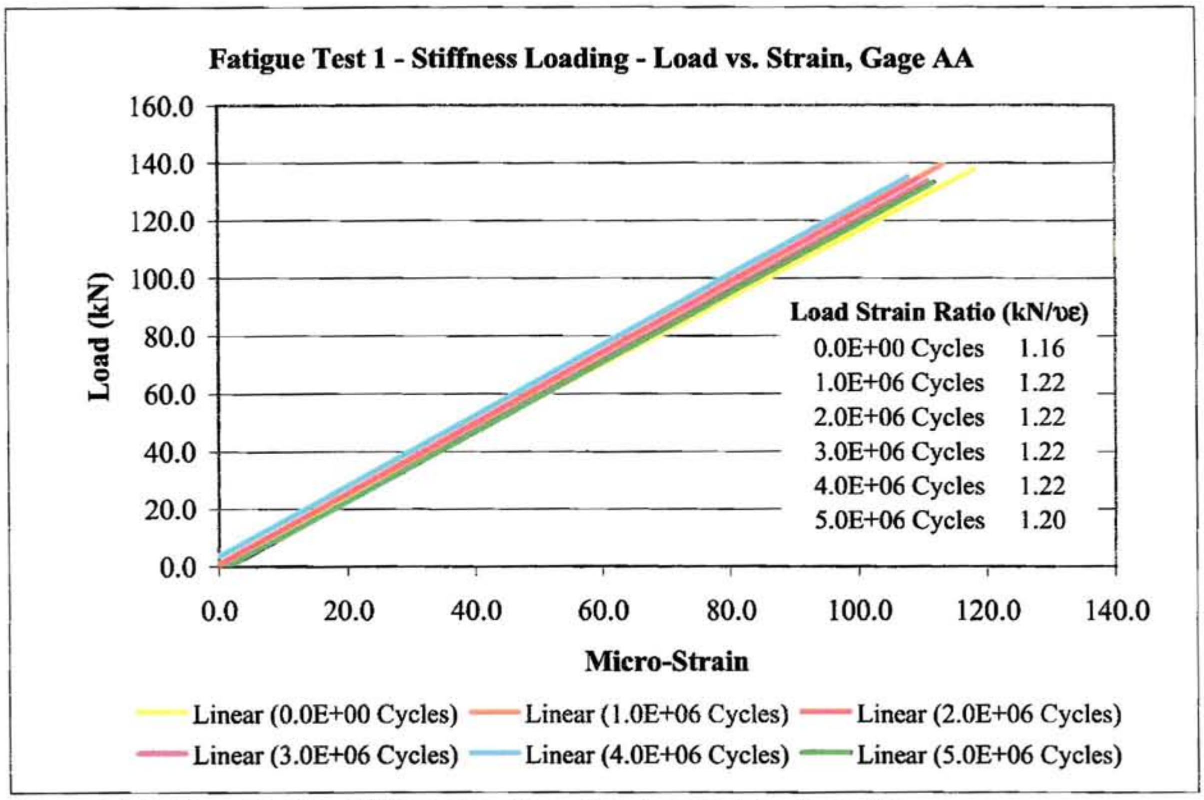

Figure 28. Fatigue Test 1 - Stiffness Loading - Load vs. Strain, Gage AA

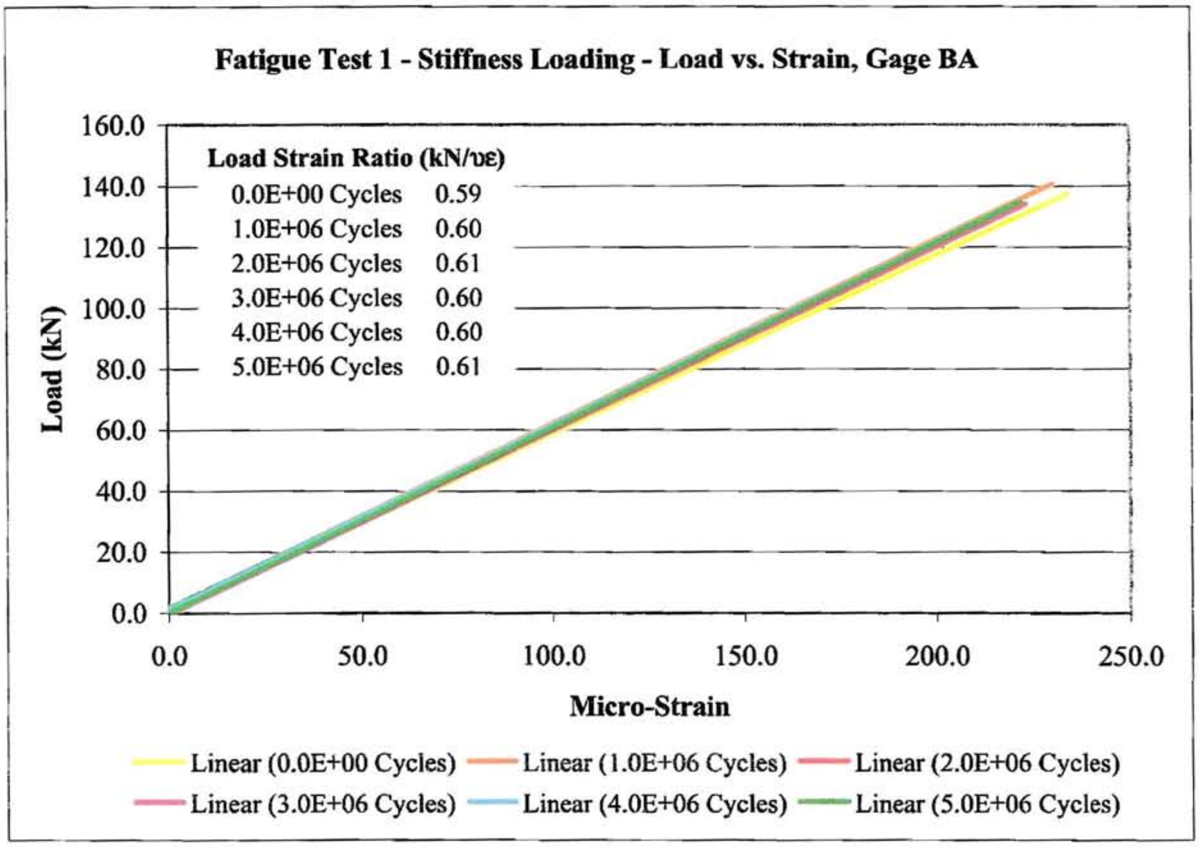

Figure 29. Fatigue Test 1 - Stiffness Loading - Load vs. Strain, Gage BA

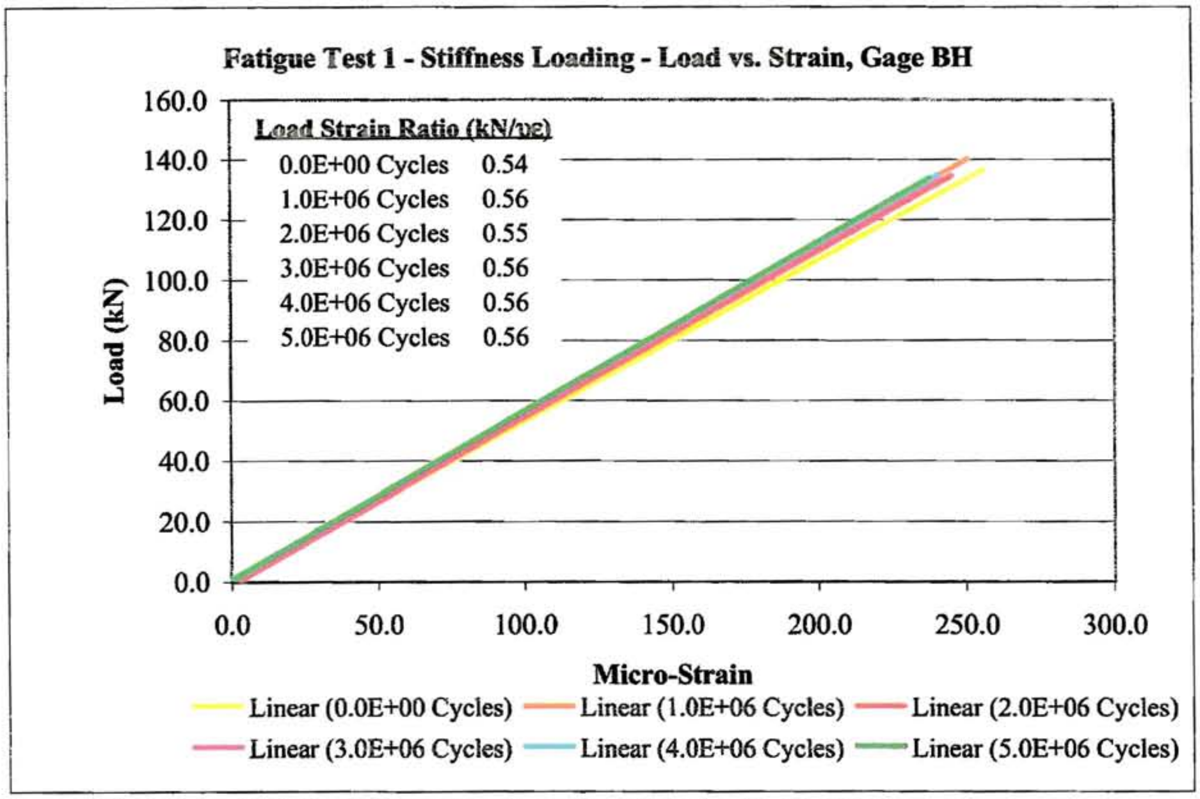

Figure 30. Fatigue Test 1 - Stiffness Loading - Load vs. Strain, Gage BH

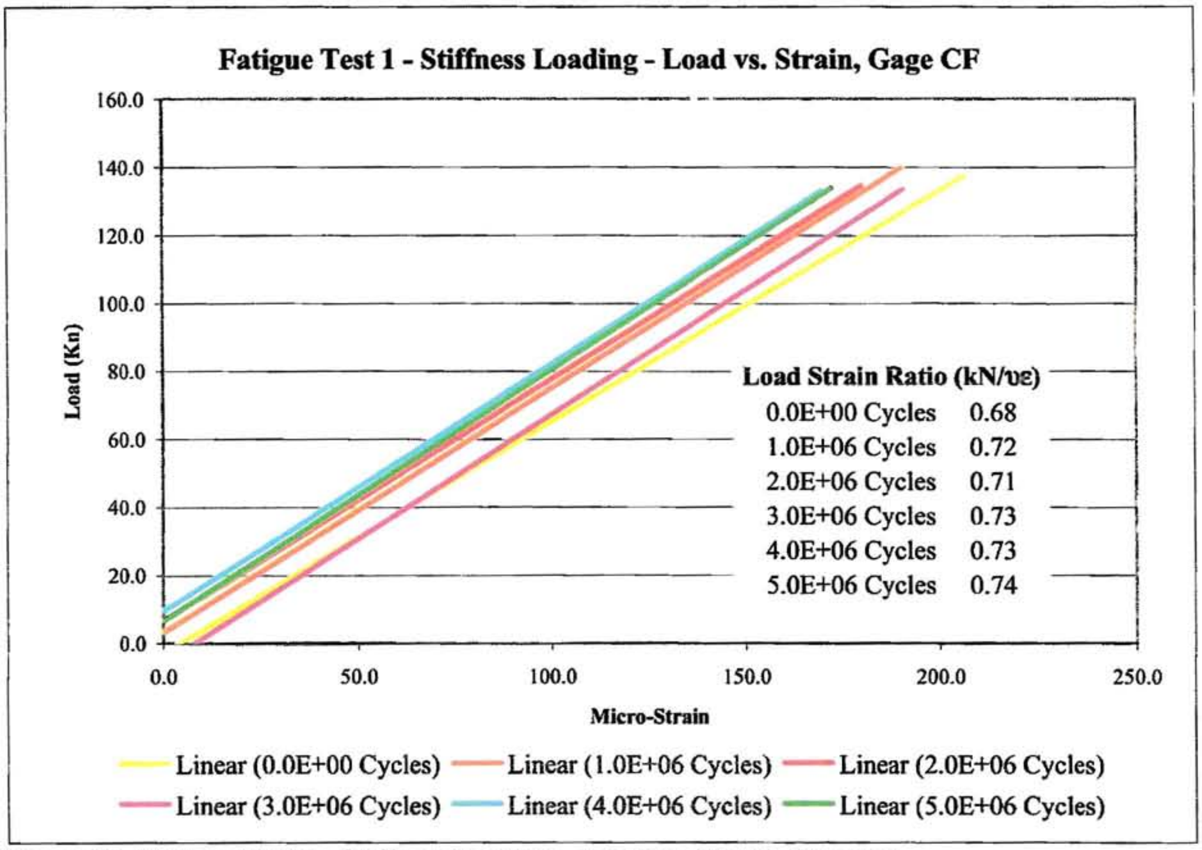

Figure 31. Fatigue Test 1 - Stiffness Loading - Load vs. Strain, Gage CF

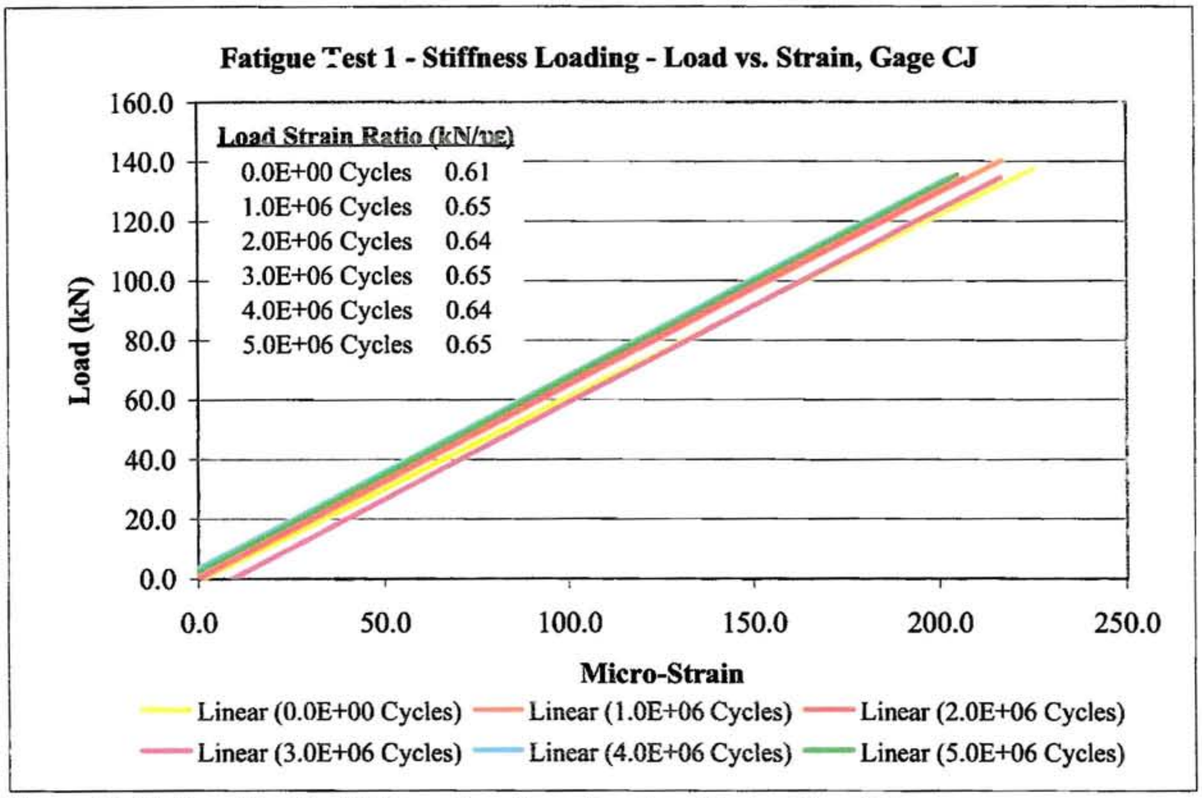

Figure 32. Fatigue Test 1 - Stiffness Loading - Load vs. Strain, Gage CJ

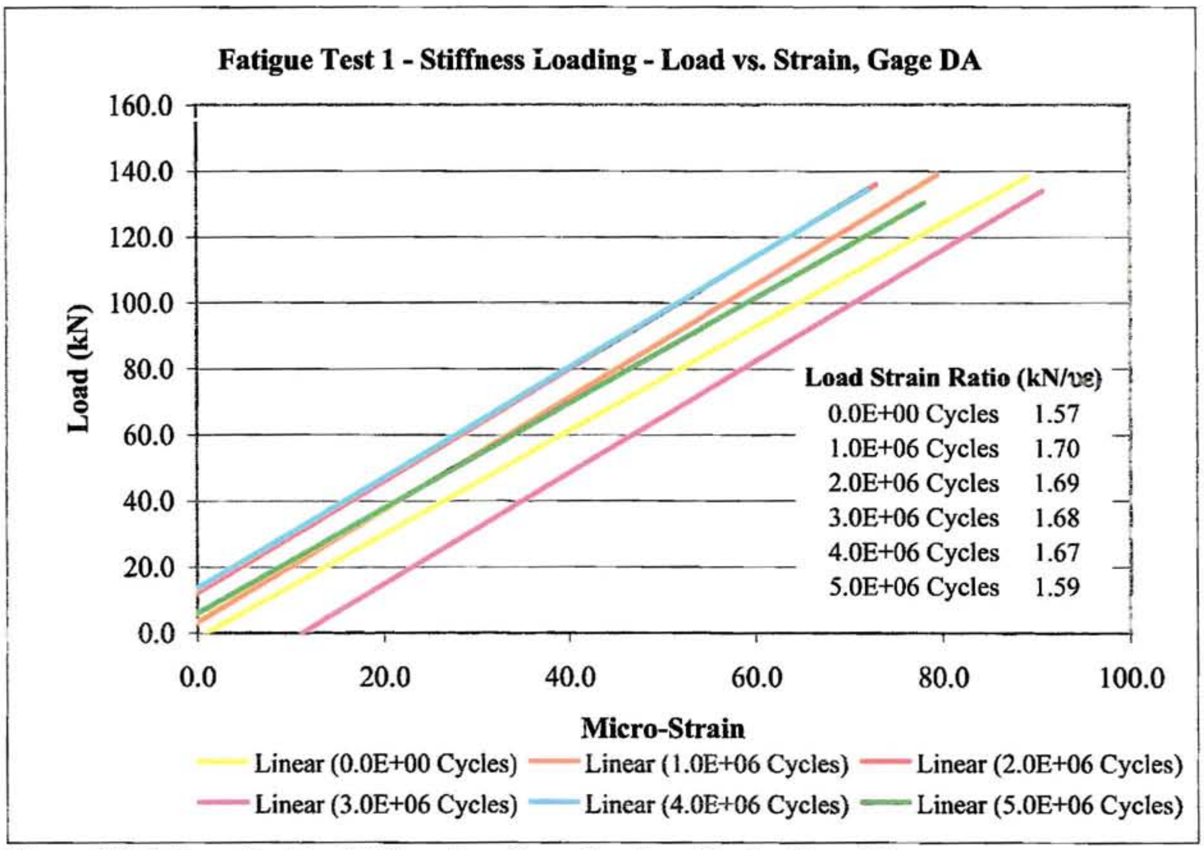

Figure 33. Fatigue Test 1 - Stiffness Loading - Load vs. Strain, Gage DA

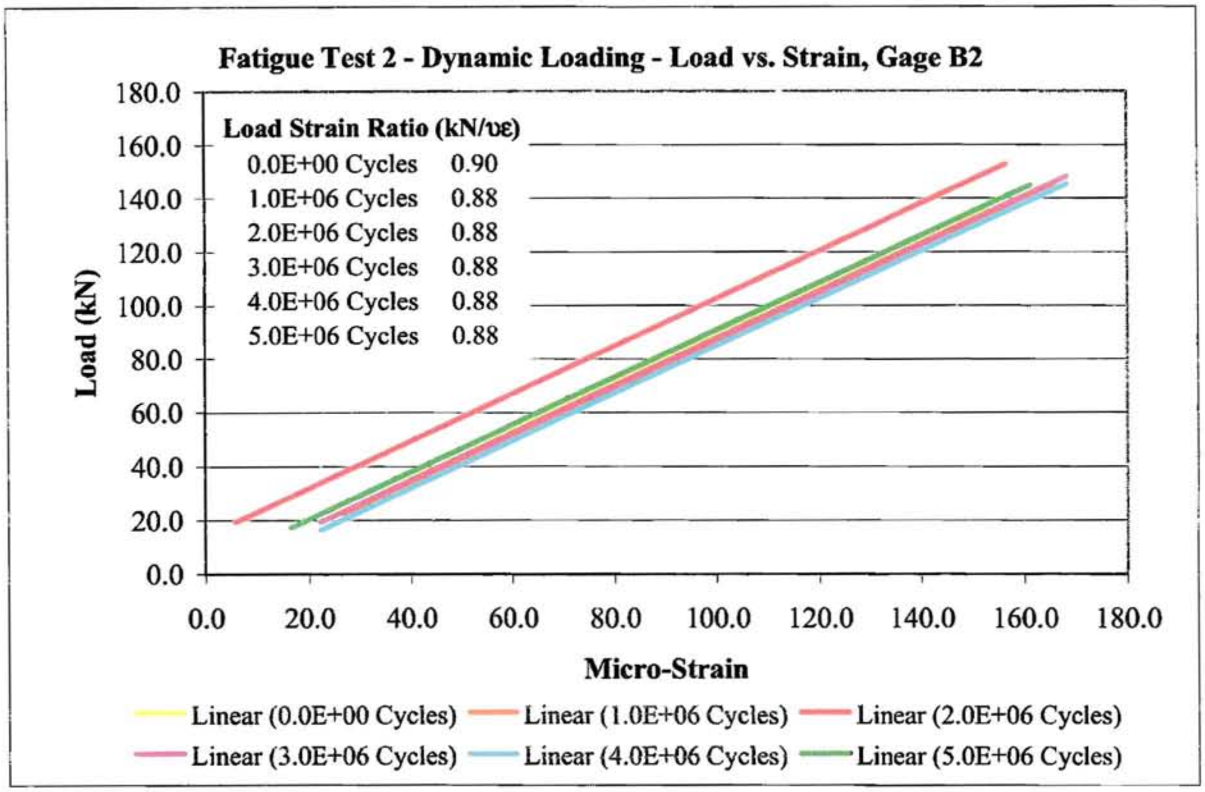

FIGURE 34. Fatigue Test 2 - Dynamic Loading - Load vs. Strain, Gage B2

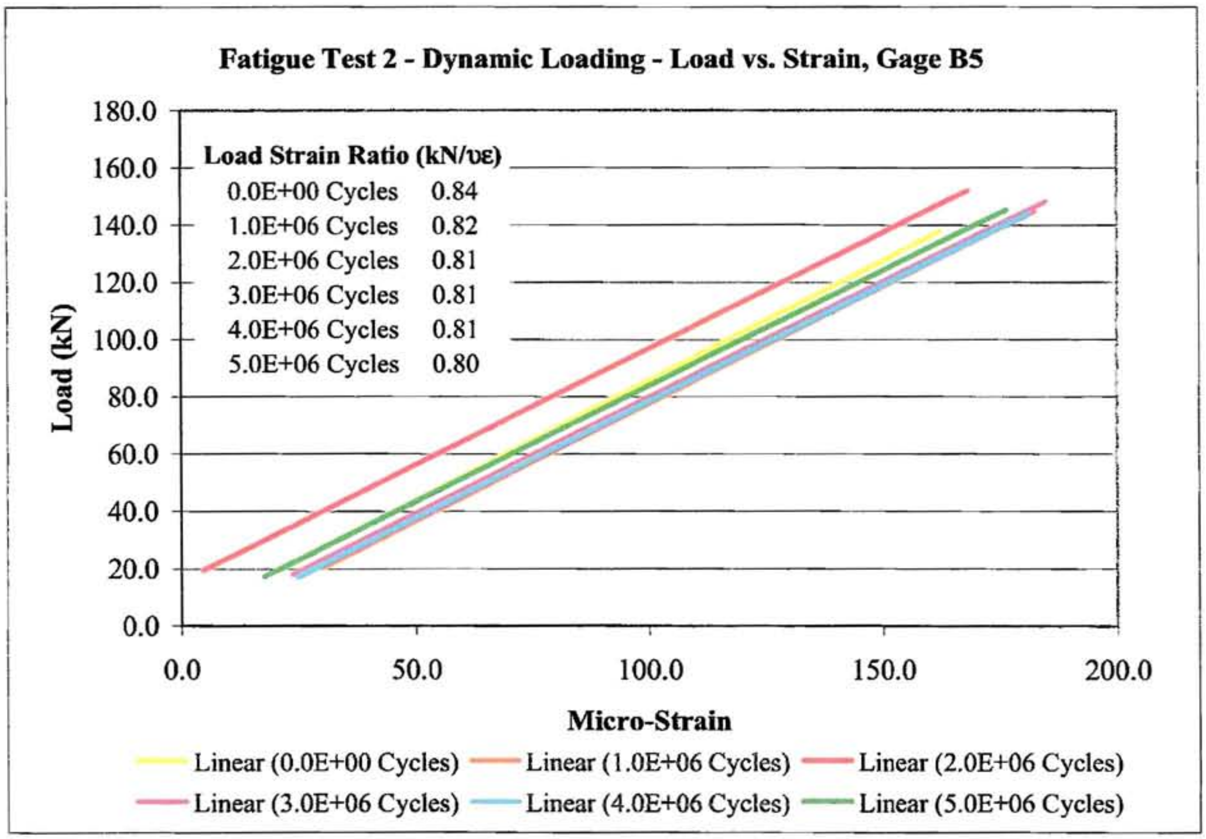

FIGURE 35. Fatigue Test 2 - Dynamic Loading - Load vs. Strain, Gage B5

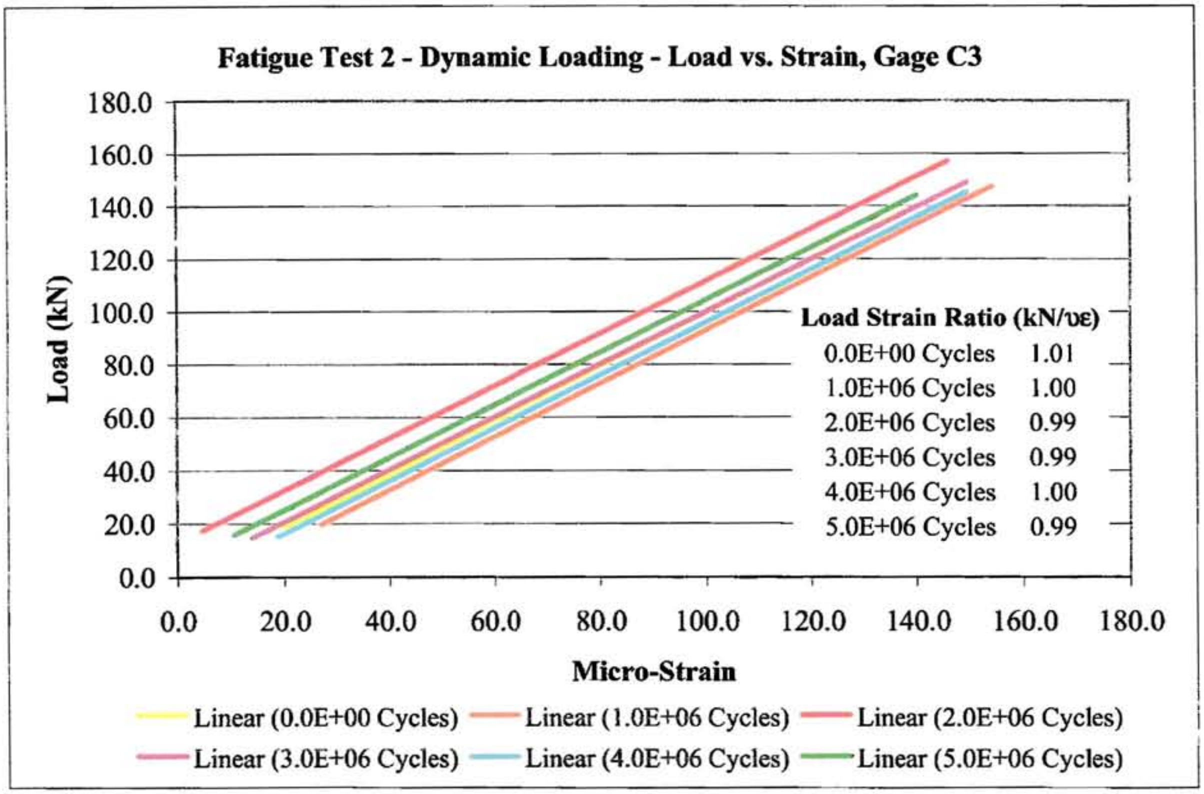

FIGURE 36. Fatigue Test 2 - Dynamic Loading - Load vs. Strain, Gage C3

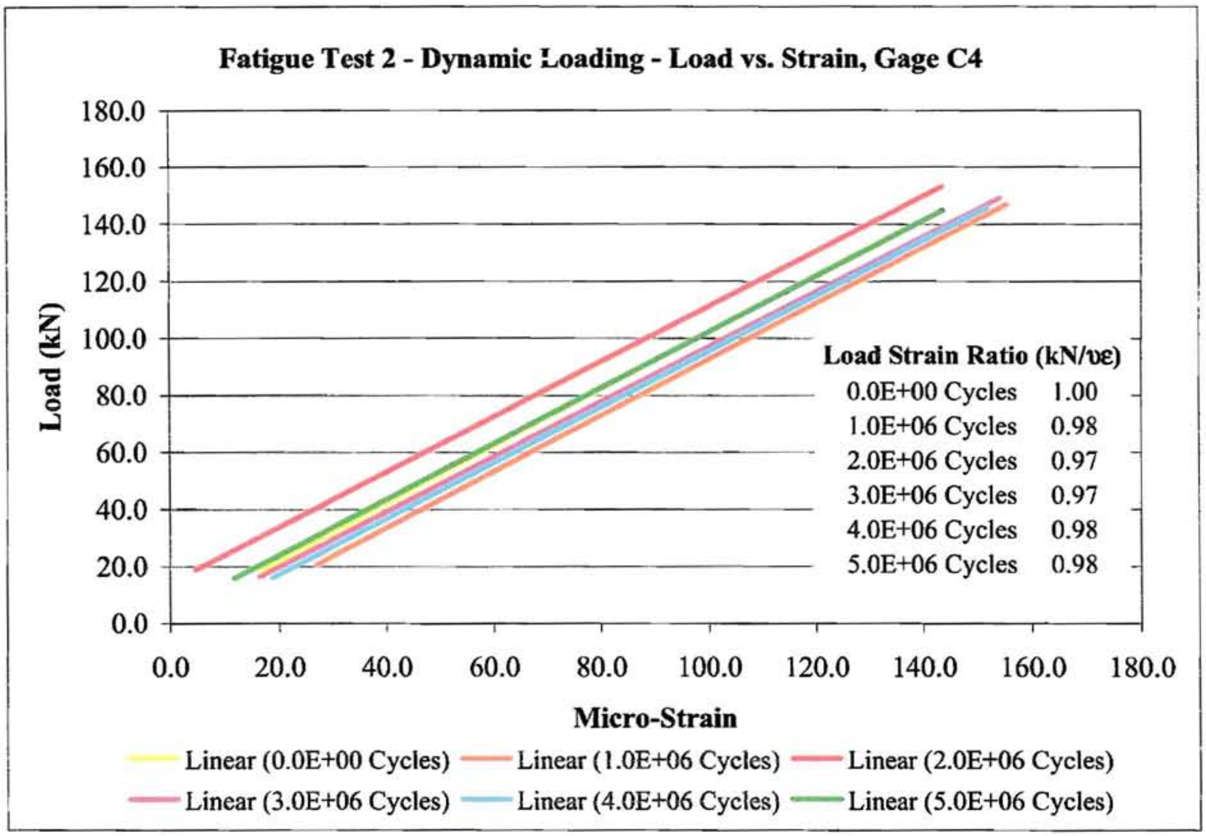

FIGURE 37. Fatigue Test 2 - Dynamic Loading - Load vs. Strain, Gage C4

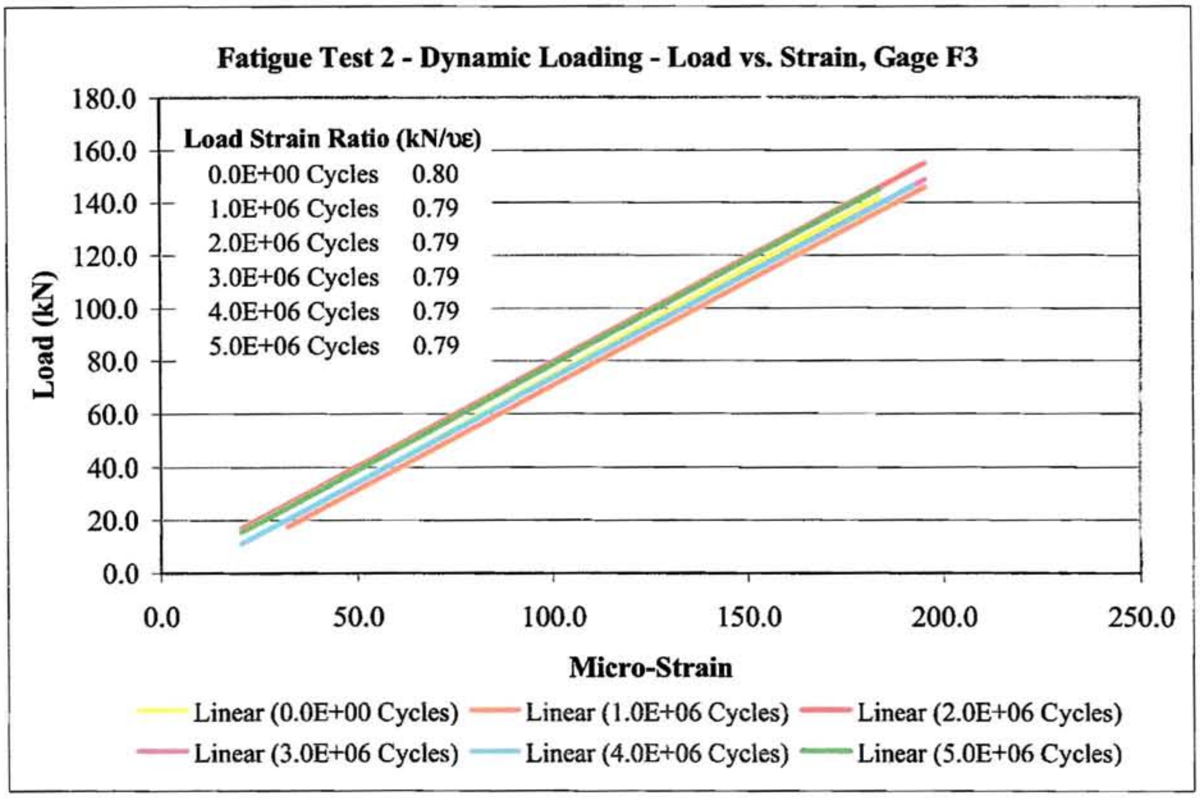

FIGURE 38. Fatigue Test 2 - Dynamic Loading - Load vs. Strain, Gage F3

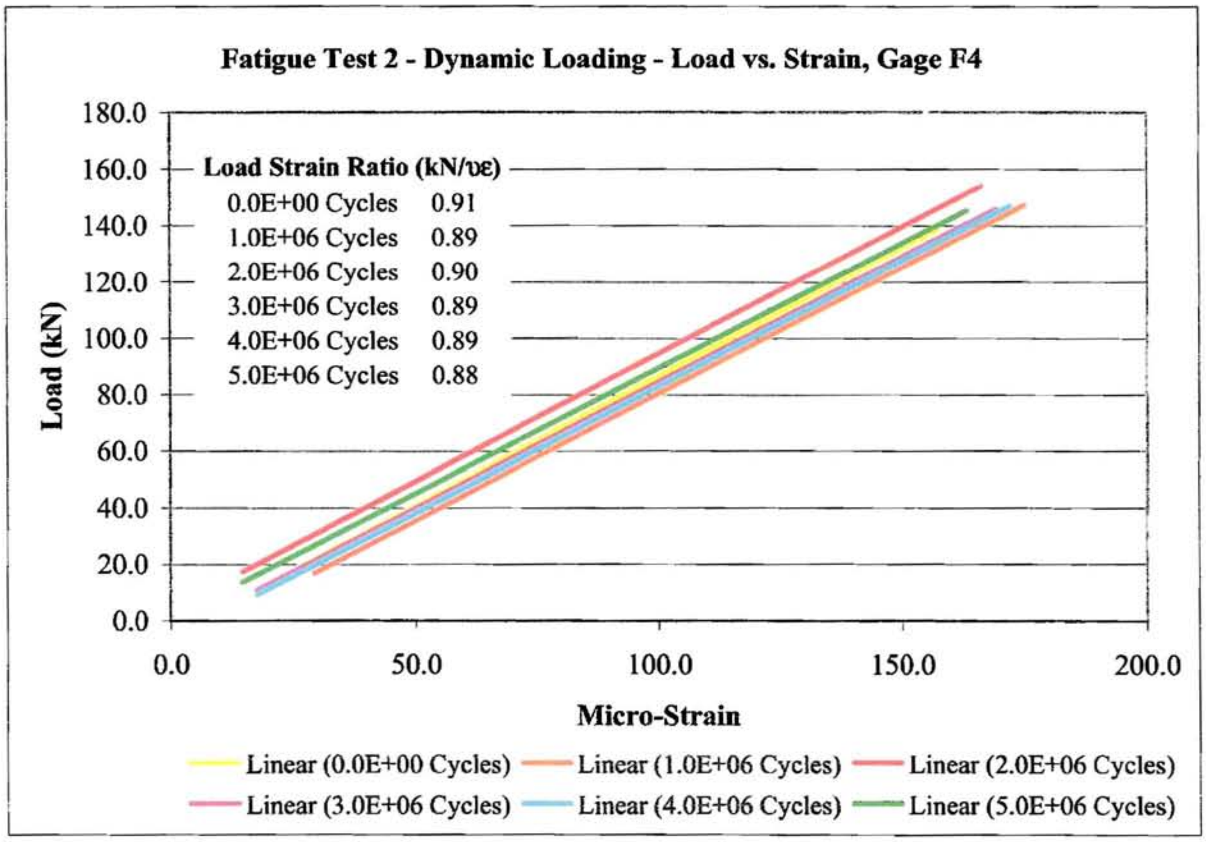

FIGURE 39. Fatigue Test 2 - Dynamic Loading - Load vs. Strain, Gage F4

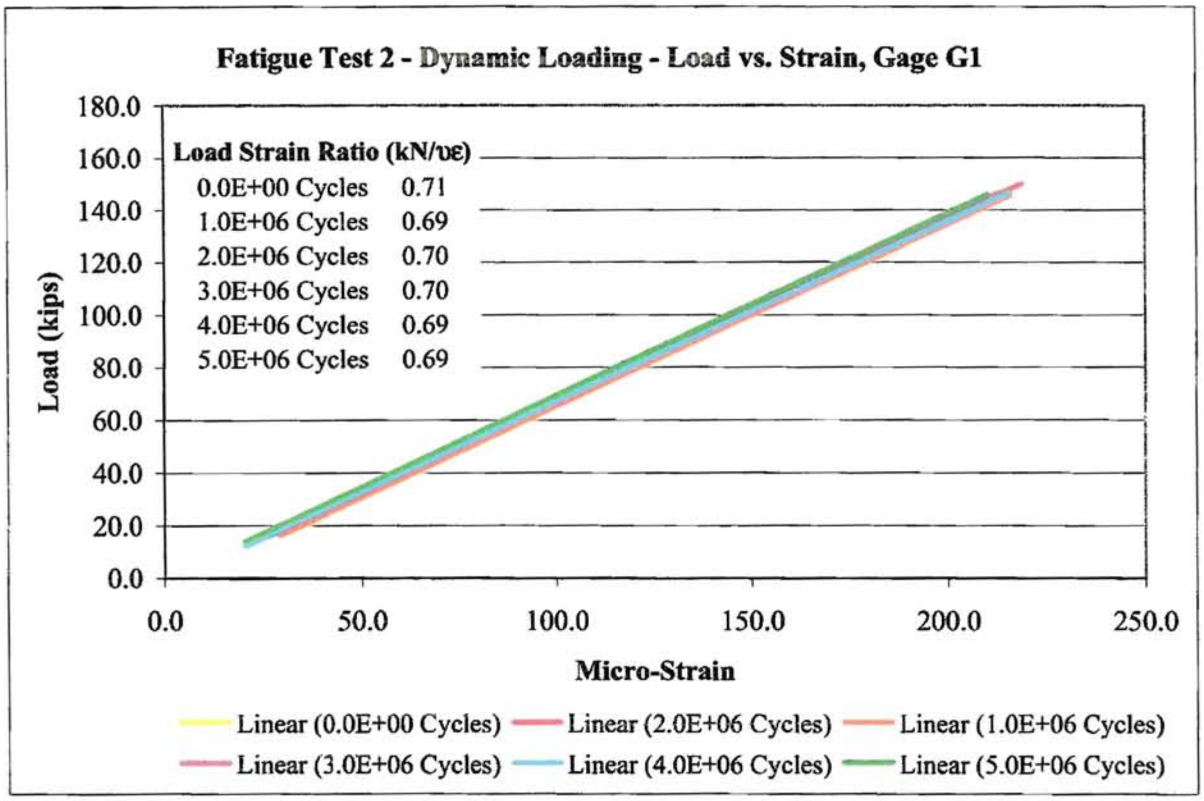

FIGURE 40. Fatigue Test 2 - Dynamic Loading - Load vs. Strain, Gage G1

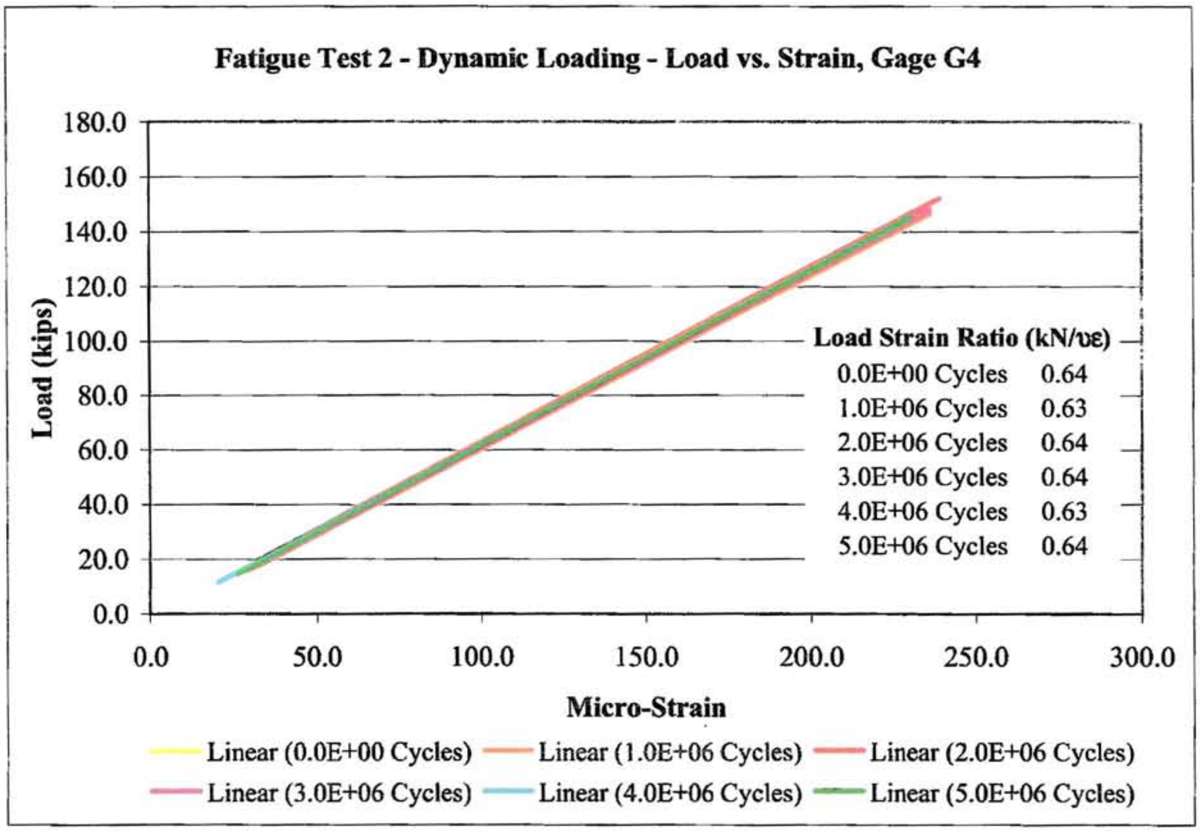

FIGURE 41. Fatigue Test 2 - Dynamic Loading - Load vs. Strain, Gage G4

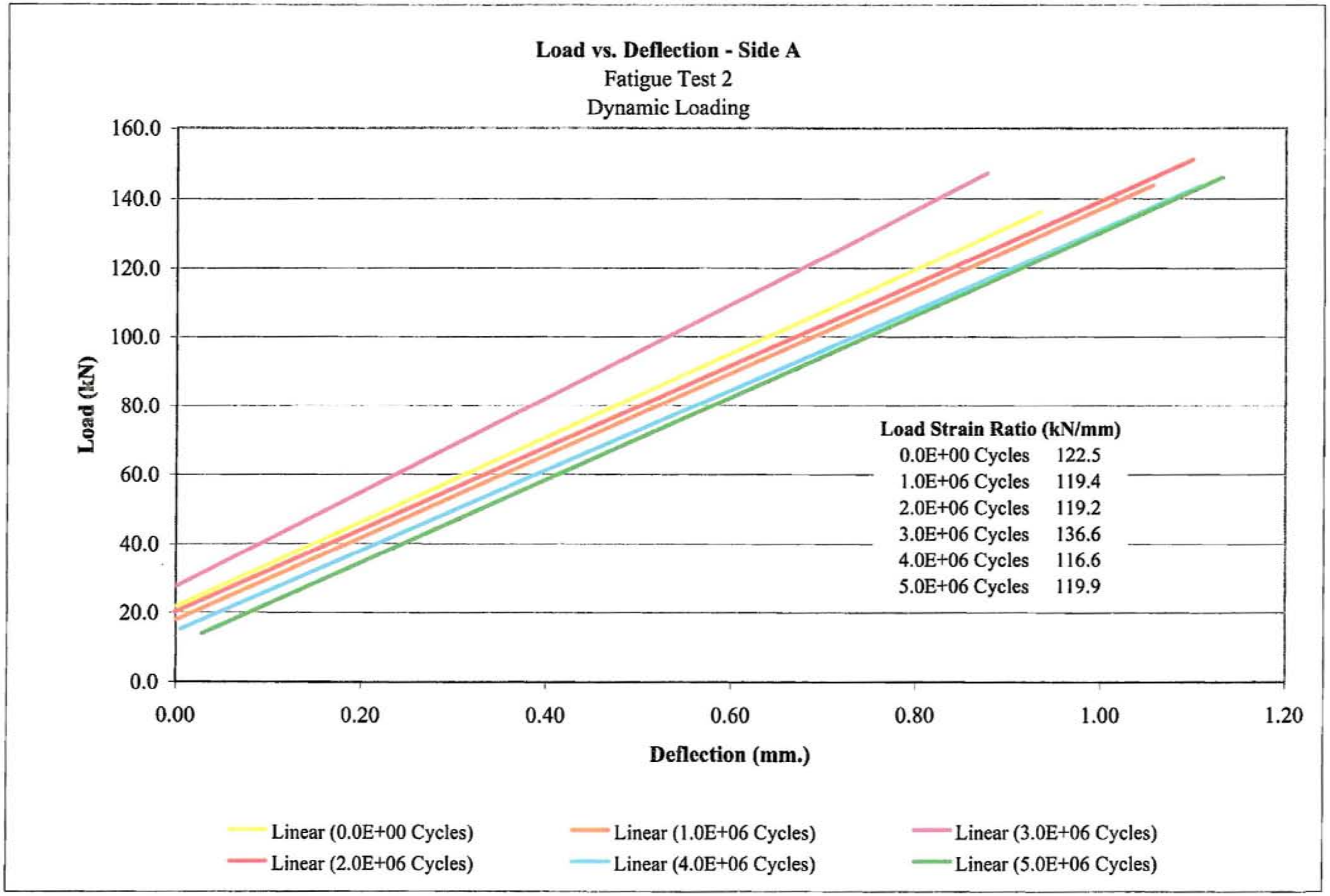

FIGURE 42. Fatigue Test 2 - Fatigue Loading - Load vs. Deflection, Midspan Side A

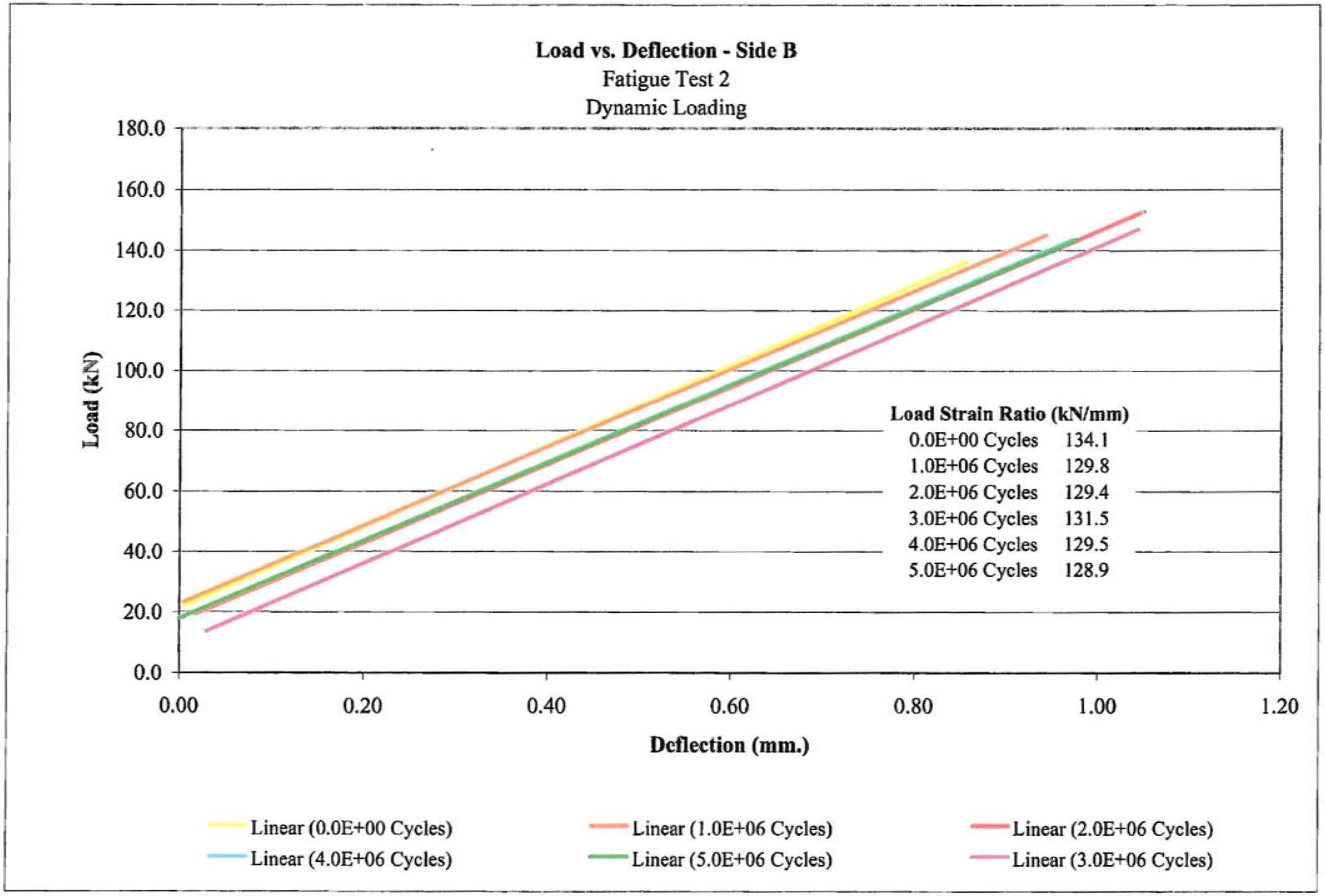

FIGURE 43. Fatigue Test 2 - Fatigue Loading - Load vs. Deflection, Midspan Side B

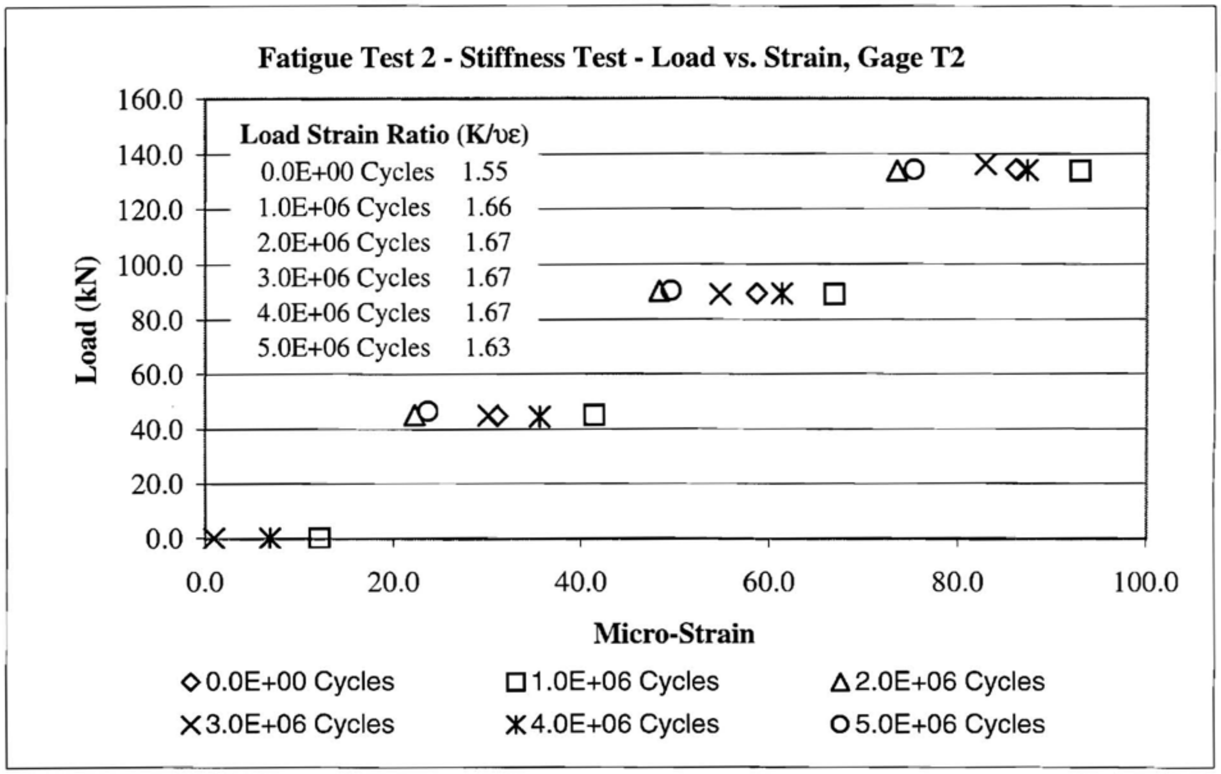

FIGURE 44. Fatigue Test 2 - Stiffness Test - Load vs. Strain, Gage T2

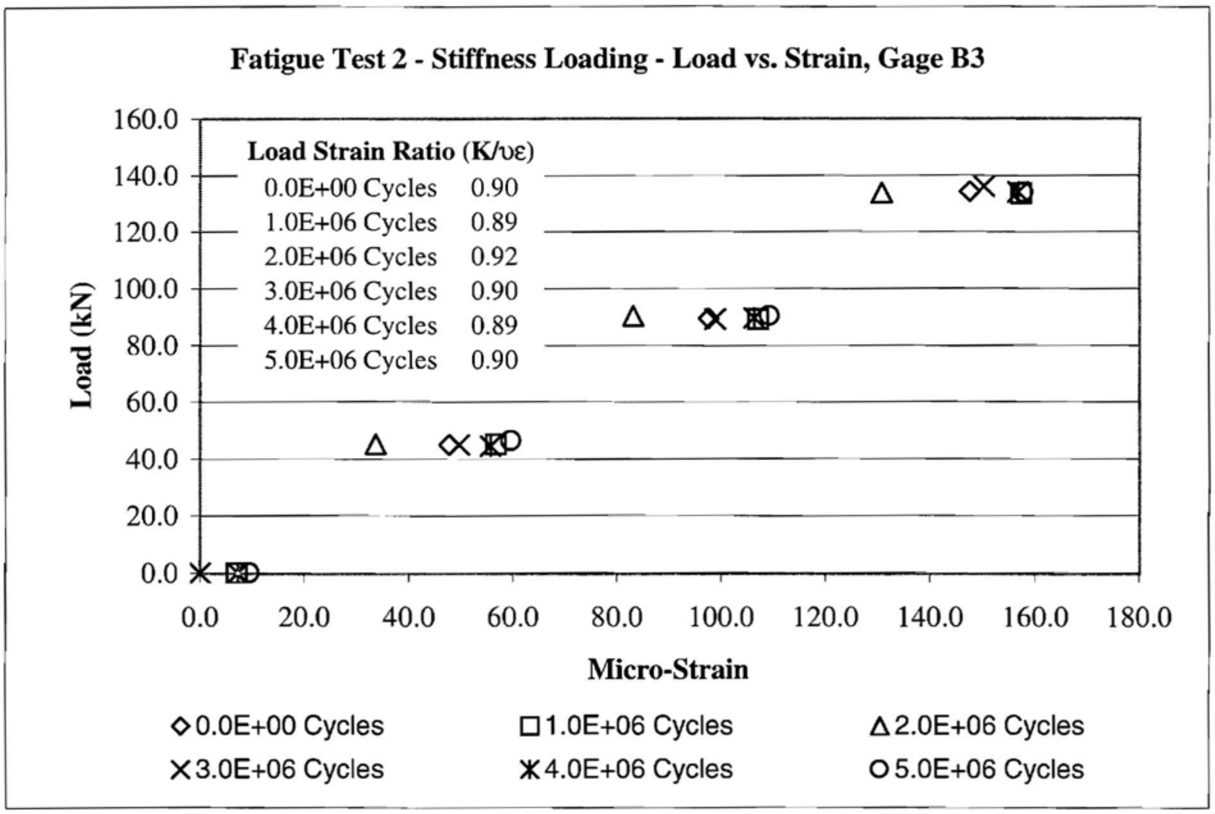

FIGURE 45. Fatigue Test 2 - Stiffness Test - Load vs. Strain, Gage B3

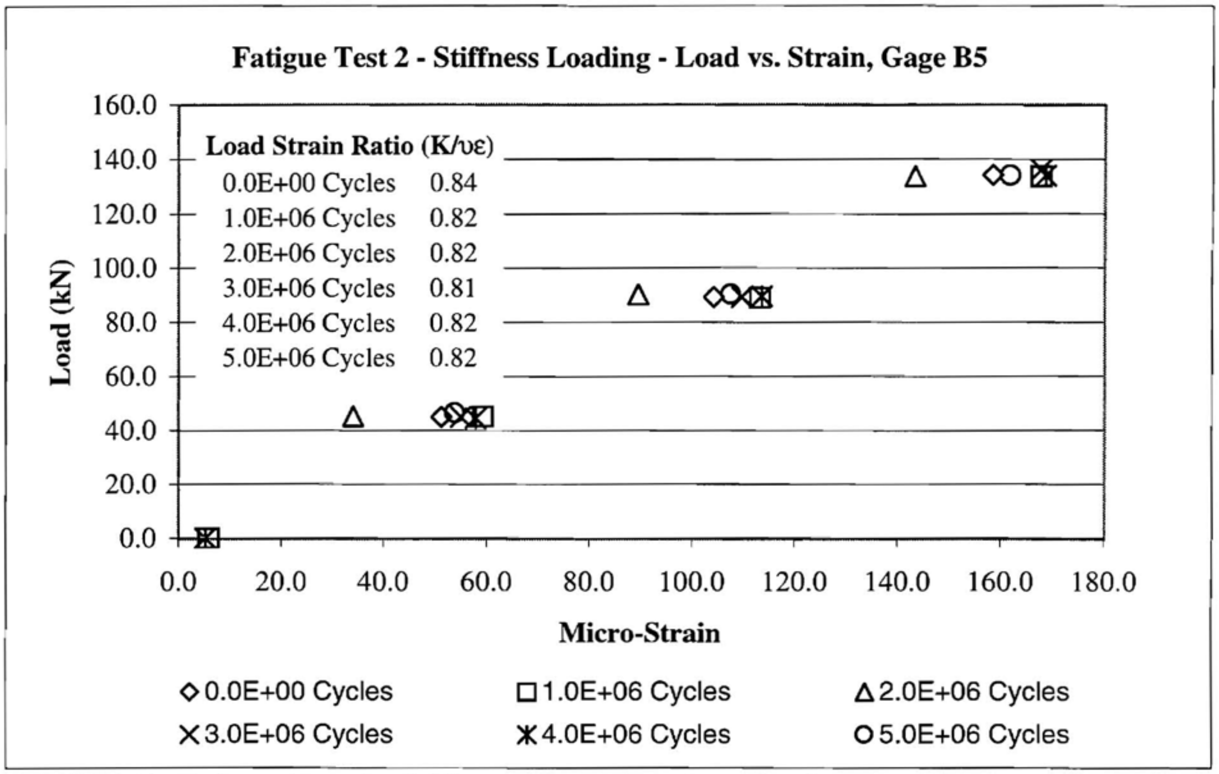

FIGURE 46. Fatigue Test 2 - Stiffness Test - Load vs. Strain, Gage B5

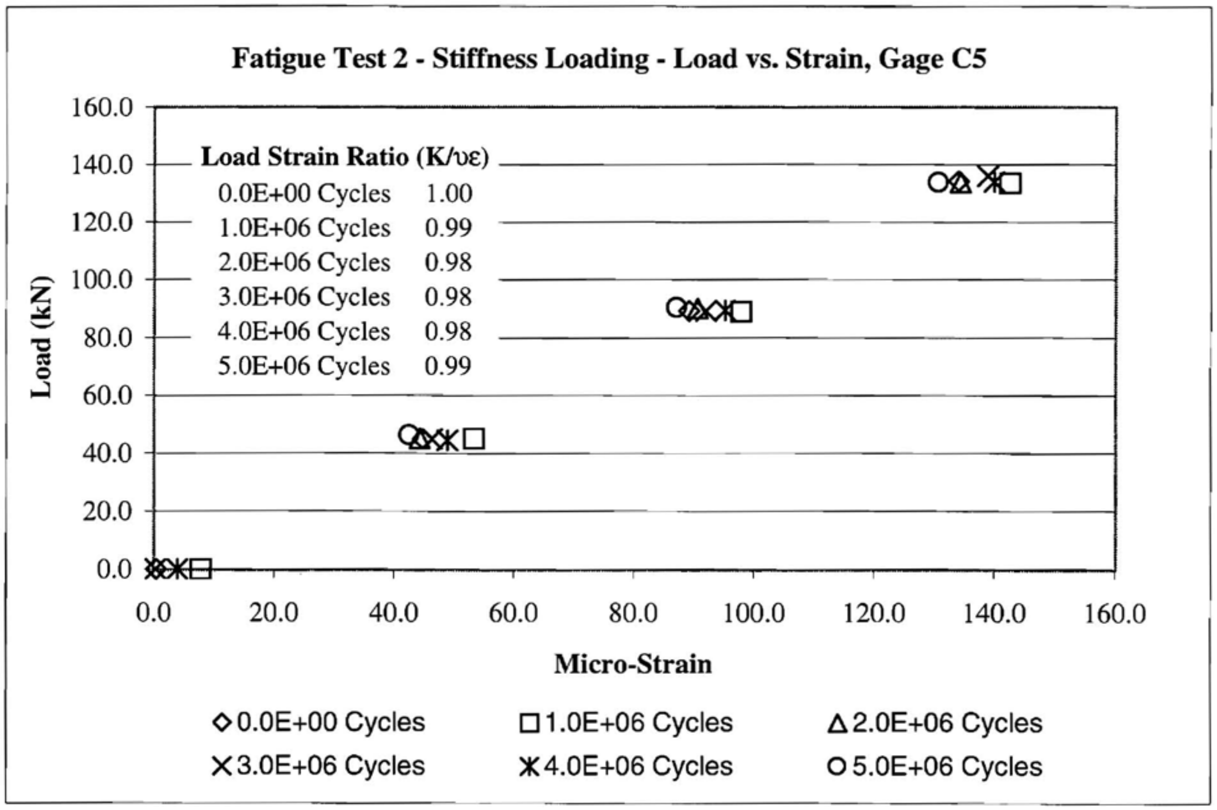

FIGURE 47. Fatigue Test 2 - Stiffness Test - Load vs. Strain, Gage C5

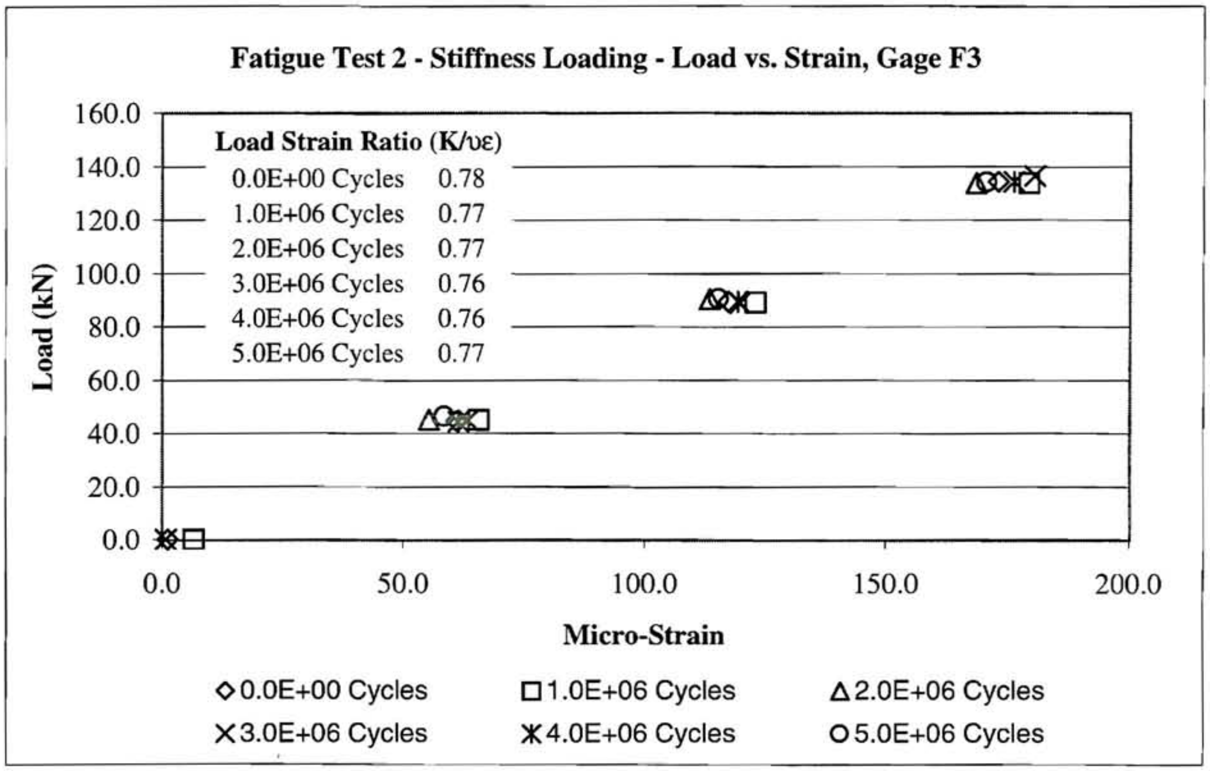

FIGURE 48. Fatigue Test 2 - Stiffness Test - Load vs. Strain, Gage F3

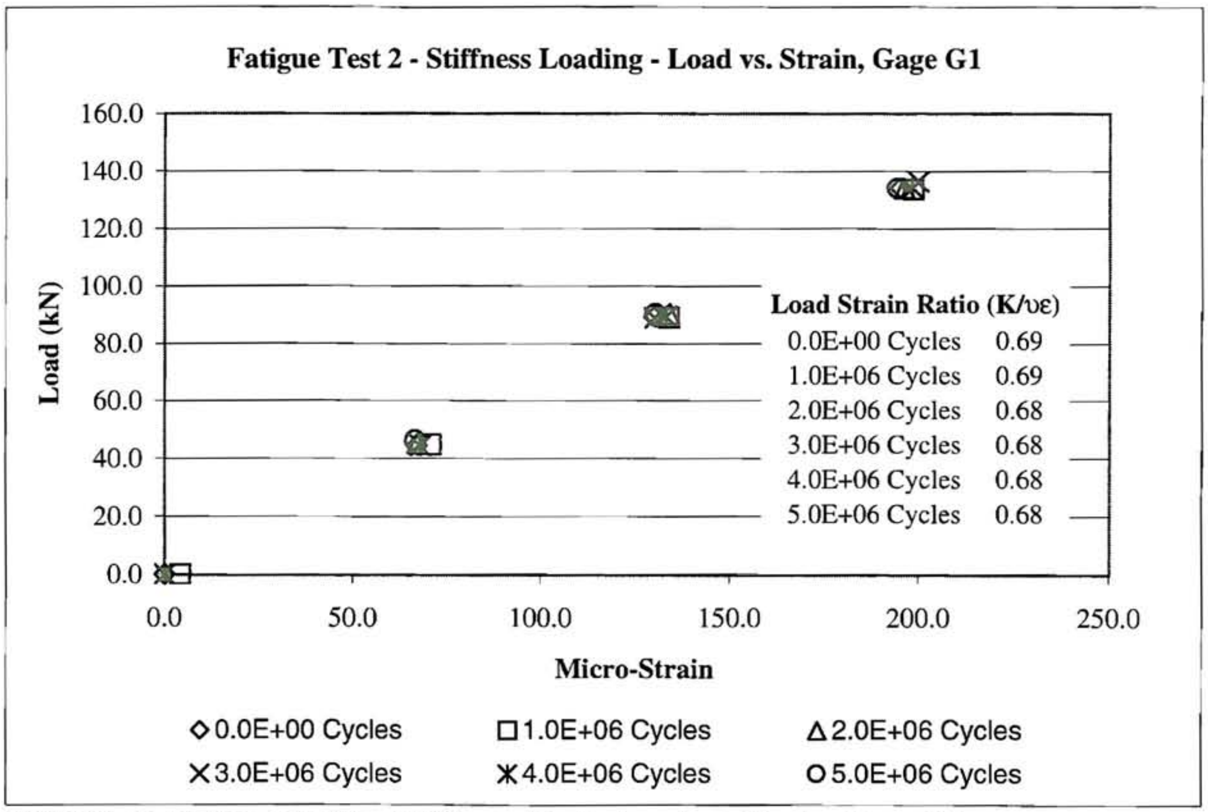

FIGURE 49. Fatigue Test 2 - Stiffness Test - Load vs. Strain, Gage G1

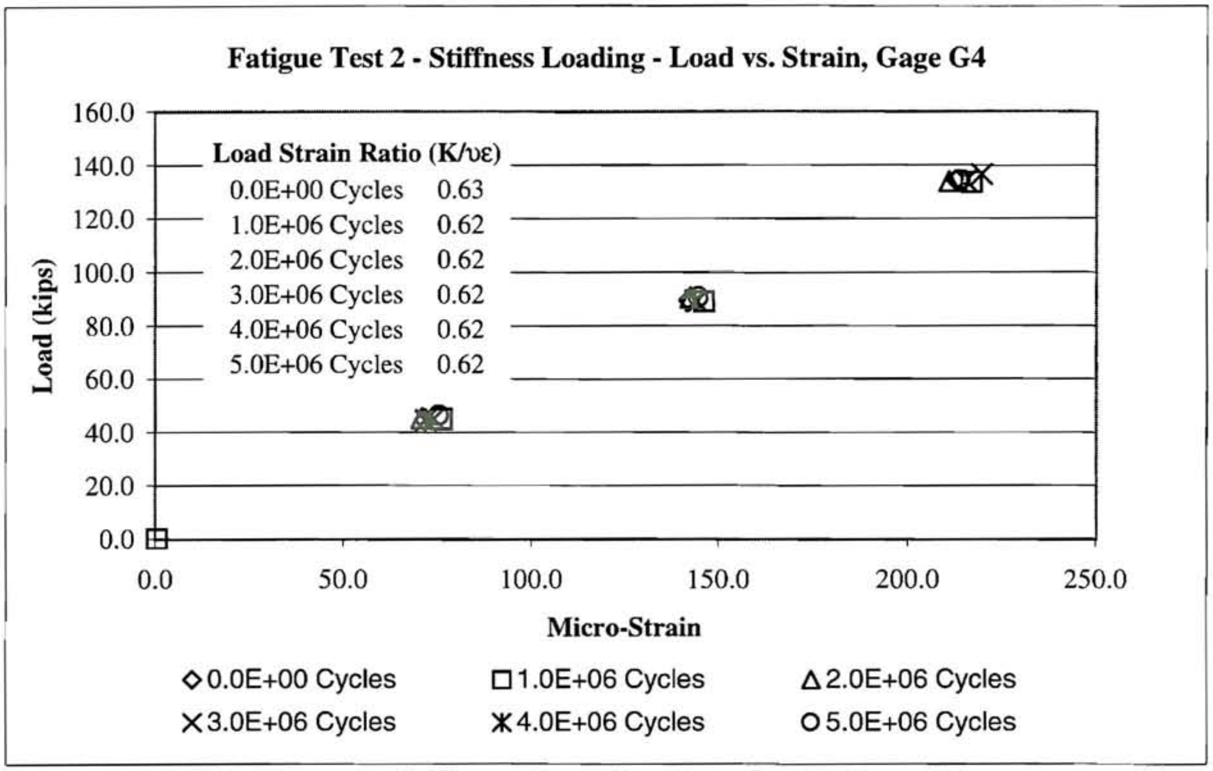

FIGURE 50. Fatigue Test 2 - Stiffness Test - Load vs. Strain, Gage G4

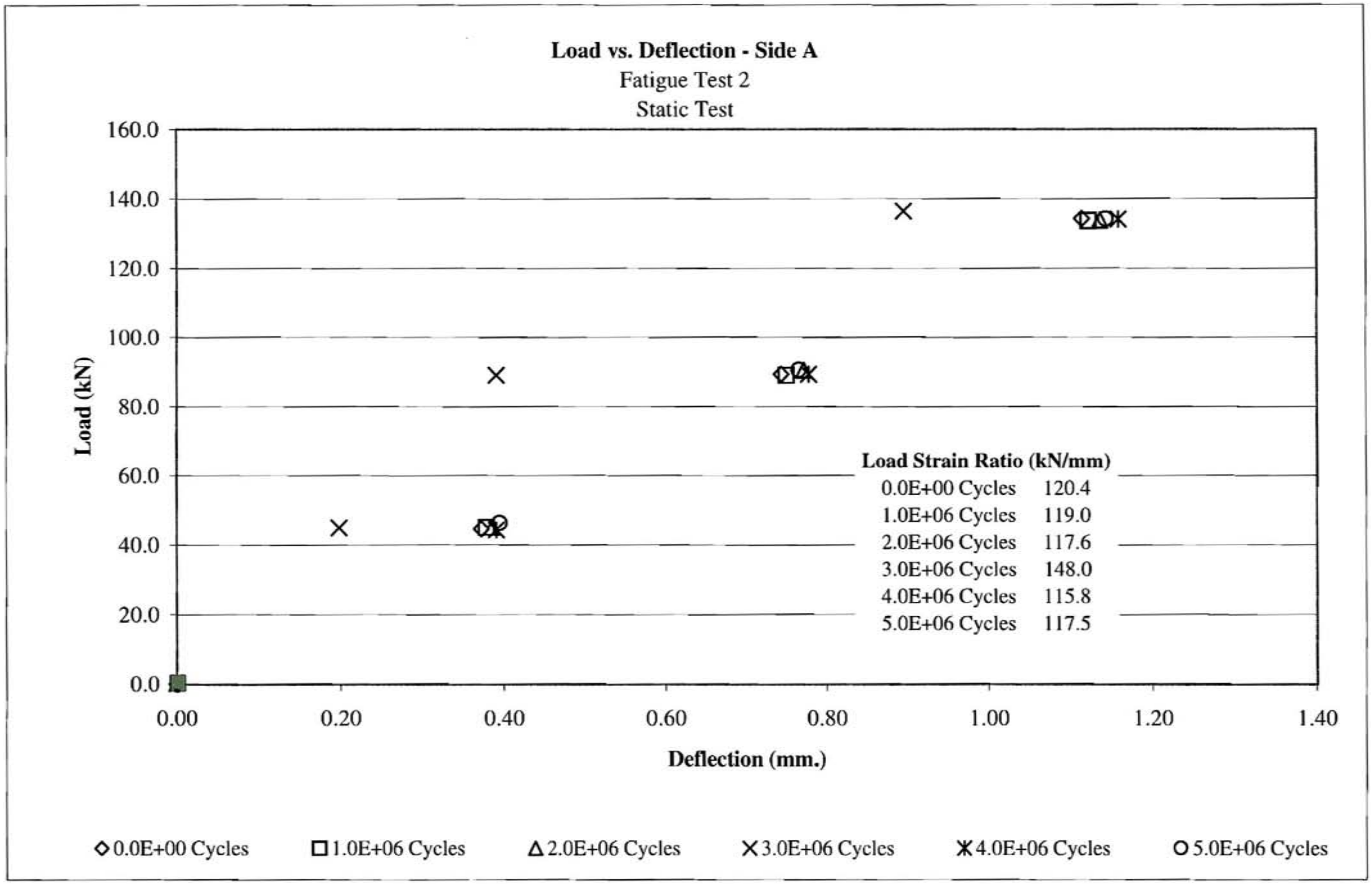

FIGURE 51. Fatigue Test 2 - Stiffness Loading - Load vs. Deflection, Midspan Side A

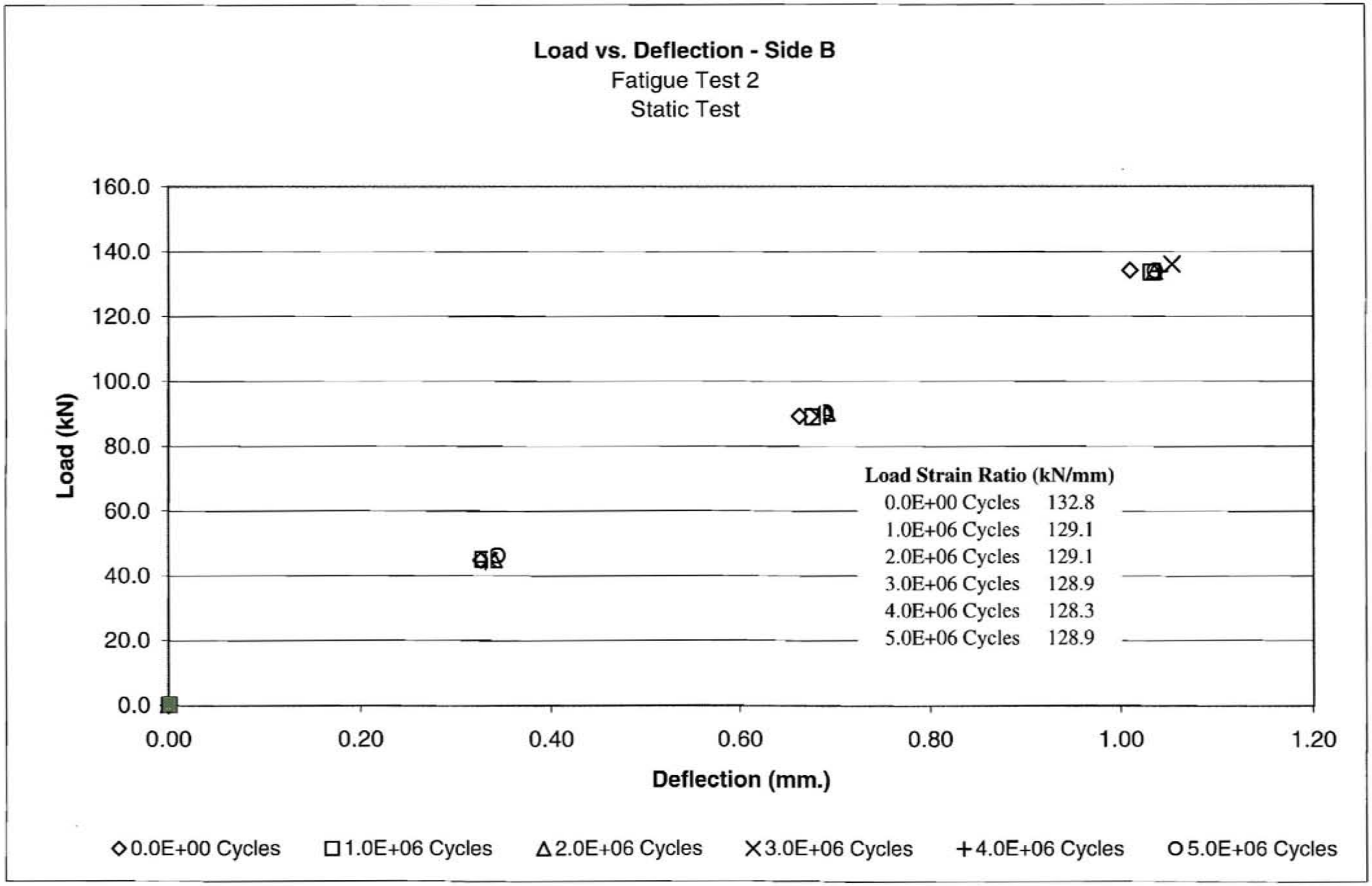

FIGURE 52. Fatigue Test 2 - Stiffness Loading - Load vs. Deflection, Midspan Side B

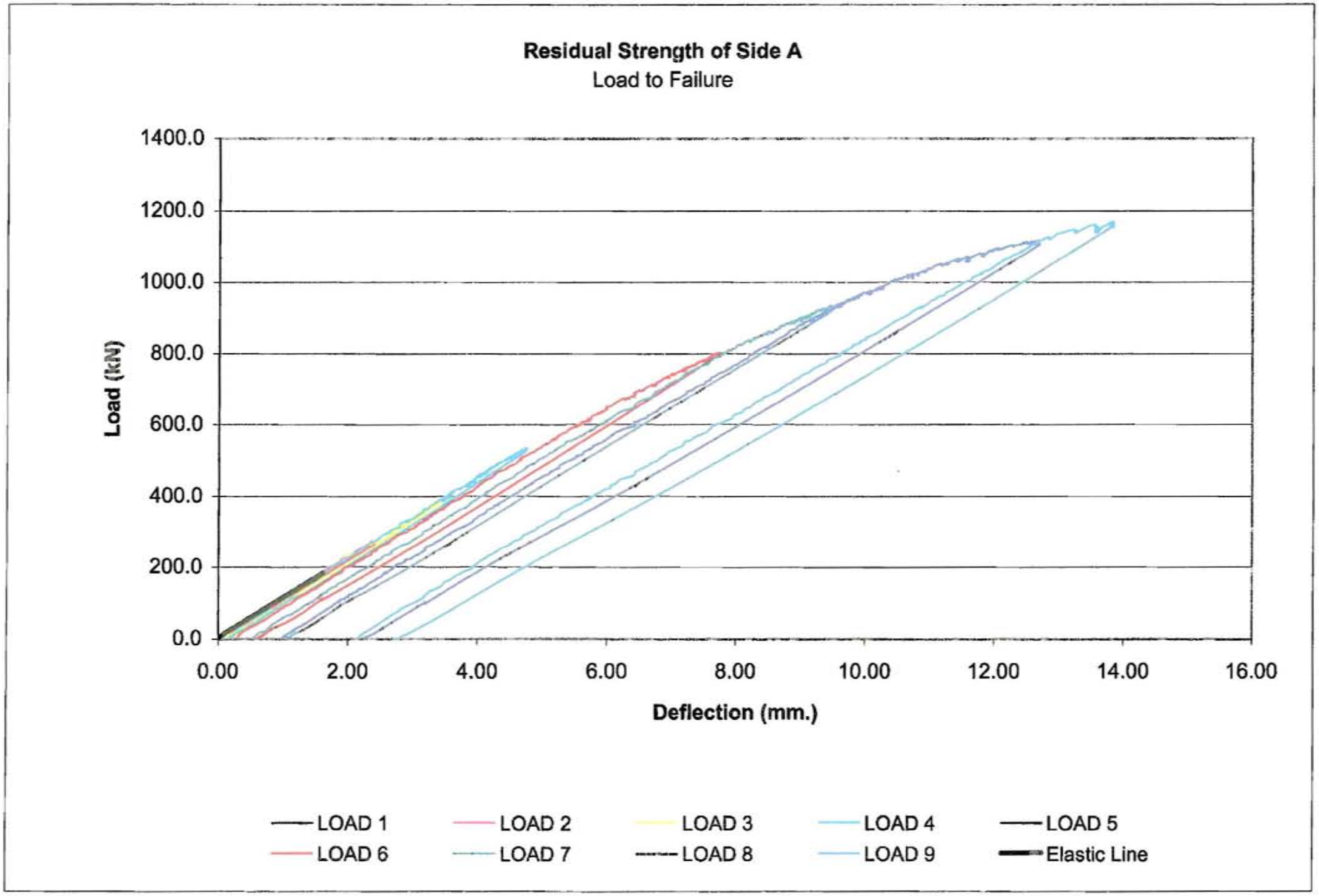

FIGURE 53. Residual Strength Test - Load vs. Deflection, Load to Failure

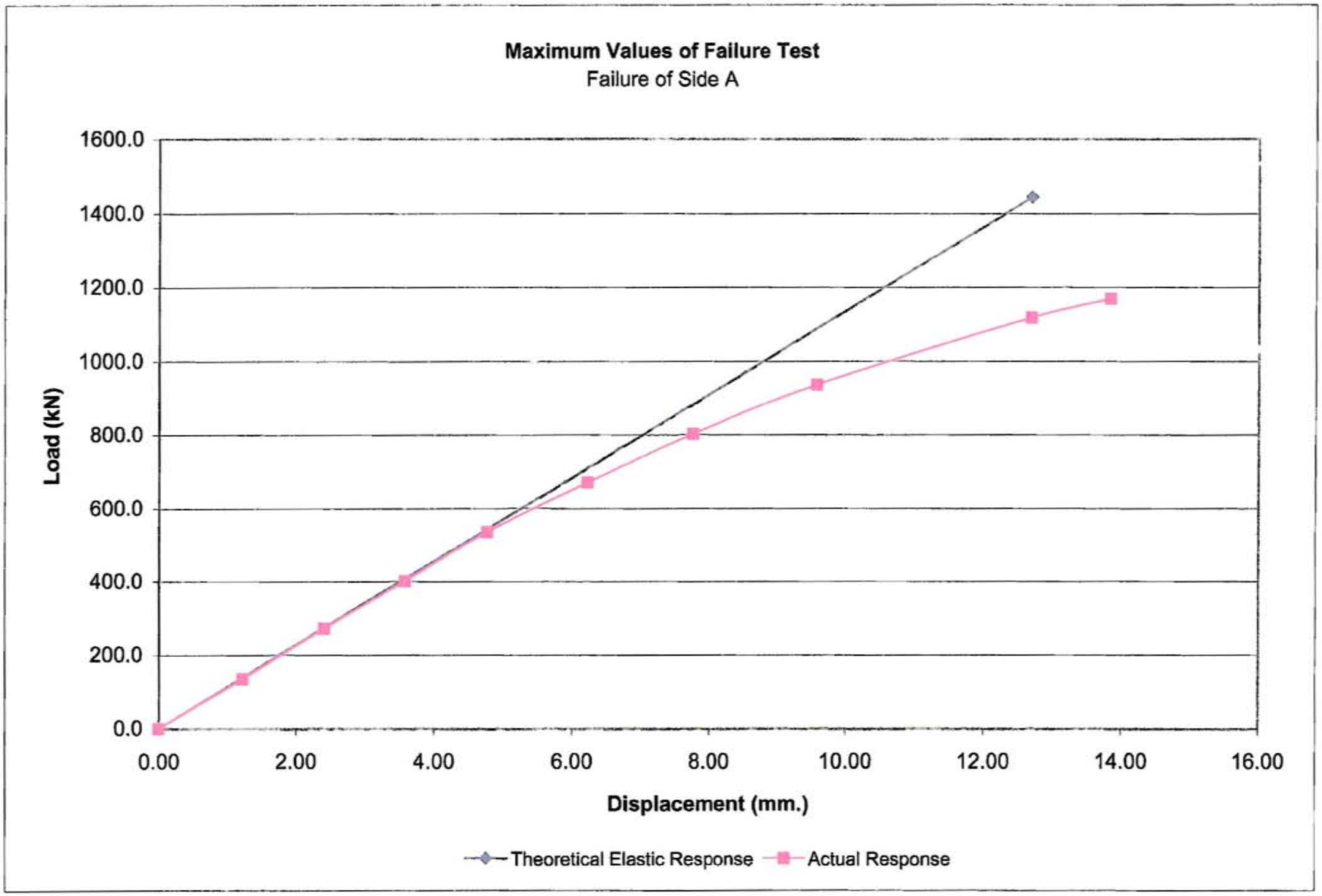

FIGURE 54. Residual Strength Test - Load vs. Deflection, Maximum Values

FIGURE 55. Buckled Web After Failure of Side A Occurred.

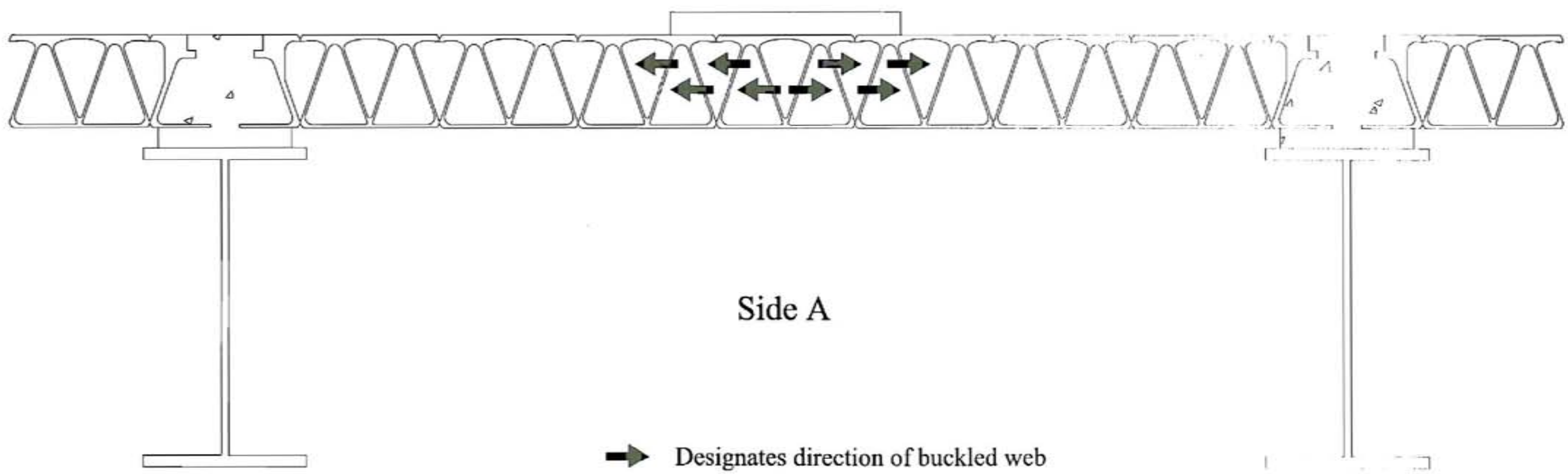

FIGURE 56. Diagram of Buckled Web Location