Bridge Load Rating through Load Testing

(037B00074N – KY 676 road over Kentucky River in Franklin County, D05)

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Executive Summary

The Bridge over the Kentucky River on route KY 676 (East-West Connector) in Franklin County, KY (037B00074N) is an 840 ft long post-tensioned segmental box girder bridge. The bridge was constructed in 1979 and is made up of twin side-by-side three-span post-tensioned segmental box girders.

An initial Load and Resistance Factor Rating (LRFR) carried out by Stantec found the superstructure Inventory and Operating Rating Factor (RF) to be less than 1.0 for the HL-93 load, along with the Operating RF for several Kentucky legal trucks and FHWA Specialized Hauling Vehicles. Load testing was considered in order to validate and potentially increase the load rating results. This report presents the load test results for the Westbound bridge carried out on November 2, 2020. Three load cases, each using nine trucks, were placed to create load effects similar to the HL-93 vehicle at each of the four locations selected for load testing. The experimental strains are determined and compared with the analytical strains derived by Stantec using the CSiBridge analysis software. An adjustment factor is developed following AASHTO Manual for Bridge Evaluation (MBE) and used to update the theoretical load rating.

According to the MBE, all strength and inventory level service load ratings are performed on the three design lanes of the bridge. The experimental strains for the controlling criterion for Inventory Level Rating of the HL-93 vehicle are larger than the analytical ones, leading to lower RFs relative to the analytical ones.

According to the MBE, all operating level service load ratings are performed on the two striped lanes of the bridge. The experimental strains for the controlling condition for Operating

Level Rating are less than the analytical ones, leading to higher RFs relative to the analytical ones for most of the rating vehicles (Table E1).

Recommendations: 1- For the two striped lanes, the bridge should be posted according to the experimental load limits listed in column (7) in Table E1 for all Rating Vehicles other than the HL-93.

2- Based on the cracks observed in the webs of the box sections, it is recommended that the bridge be kept under periodic monitoring.

Table E1: Operating Level Rating of the KY 676 Bridge Over Kentucky River - 037B00074N *(same as Table 5 in this report)*

Rating Vehicle	Analytical Rating [1]			Experimental Rating [2]		
	Controlling Criterion[3]	Rating Factor	Load Limit (Tons)	Controlling Criterion[3,4]	Rating Factor	Load Limit (Tons)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
HL-93	Longitudinal Tensile Stress	0.51	-	Shear Strength	0.53	-
KY Type 1	Transverse Tensile Stress	1.05	21.0	Transverse Tensile Stress	1.05	21.0
KY Type 2	Transverse Tensile Stress	1.08	30.6	Transverse Tensile Stress	1.08	30.6
KY Type 3	Longitudinal Tensile Stress	0.89	31.4	Transverse Tensile Stress	1.02	37.5
KY Type 4	Longitudinal Tensile Stress	0.87	33.1	Shear Strength	1.03	41.2
SU4	Longitudinal Tensile Stress	1.11	31.3	Transverse Tensile Stress	1.37	37.0
SU5	Longitudinal Tensile Stress	1.01	31.6	Shear Strength	1.25	38.8
SU6	Longitudinal Tensile Stress	0.94	31.8	Shear Strength	1.15	40.0
SU7	Longitudinal Tensile Stress	0.87	32.3	Shear Strength	1.05	40.7
EV2	Transverse Tensile Stress	1.00	28.8	Transverse Tensile Stress	1.00	28.8
EV3	Longitudinal Tensile Stress	0.79	31.3	Transverse Tensile Stress	0.85	36.6

[1] The analytical rating factors are derived by Stantec using the CSiBridge analysis software.
[2] The experimental rating factors are derived from the load tests conducted on the Westbound bridge on November 2, 2020.
[3] Shear Strength is a Strength Limit State, while Longitudinal Flexural Stress (tension) and Transverse Tensile Stress are Service I and/or Service III limit states.
[4] Analytical ratings for Transverse Tensile Stress and Shear Strength are used herein as it was not determined experimentally.

Analytical Load Rating Carried out by Stantec

The analytical load rating was carried out by Stantec in accordance with the AASHTO LRFD Bridge Design Specifications (2014) and AASHTO Manual for Bridge Evaluation (MBE) (2018). Additional guidance regarding segmental box girder load rating was taken from Volume 10A – Load Rating Post-Tensioned Concrete Segmental Bridges from the Florida DOT New Directions for Florida Post-Tensioned Bridges Report (2004). The bridge was rated longitudinally for flexural strength, combined shear and torsional strength at the Strength limit state. Longitudinal stress due to flexure (tension and compression), principal stress at the neutral axis, and tendon service stresses were evaluated at the Service I and/or Service III limit states. The ratings are primarily based on a bridge model developed in CSiBridge analysis software. For all strength and inventory level service load ratings, the live load was applied to the number of design lanes (3 lanes as per AAHTO LRFD). The live loads also include a 33% dynamic load allowance on the axle loads, but not on the lane loading. A summary of the controlling longitudinal load ratings for the HL-93 load is provided in Table 1. As seen in the table, Flexural Strength and the Longitudinal Flexural Stress in Compression have Inventory Level RFs greater than 1.0 and do not limit the loading on the bridge.

Table 1: Summary of the HL-93 Analytical Load Rating [1]

Controlling Criterion[2]	Location [3]	HL-93 Rating Factor [4]	
		Inventory	Operating
Flexural Strength	Joint 12	**1.10**	**1.43**
Shear Strength	Joint 51	**0.37**	**0.53**
Longitudinal Flexural Stress (Compression)	Joint 25	**2.01**	**2.56**
Longitudinal Flexural Stress (Tension)	Joint 122	**0.40**	**0.51**
Principal Stress	Joint 76	**0.24**	**0.66**

[1] The analytical rating factors are derived by Stantec using the CSiBridge analysis software.
[2] Flexural and Shear Strength are Strength Limit States, while Longitudinal Flexural Stress (tension and compression) and Principal Stress are Service I and/or Service III limit states.
[3] Refer to Appendix A, Fig. A1, for Joint locations.
[4] Tendon stress ratings and transverse load ratings are not included in this table since they do not govern and are not specific to a single joint or location on the bridge [Stantec Consulting Services Inc. (2018)].

The bridge was also load rated transversely for flexural strength and service stresses. As seen in Table 2, Transverse Tensile Stress controlled the Operating Level RFs of the KY Type 1, KY Type 2, and the EV2 truck. The RFs were greater than or equal to 1.0 and do not limit the loading on the bridge.

For all longitudinal Operating Level service load ratings, only the striped two lanes were loaded. As the spans were over 200 ft in length, an additional lane load of 0.2 klf was placed in each striped lane in accordance with the AASHTO Manual for Bridge Evaluation (2018). Per MBE (2018), lane loads were not utilized for any of the transverse load rating. A summary of the Operating load rating is provided in Table 2 for KY Type trucks (Type 1 to Type 4), FHWA Specialized Hauling Vehicles (SU4 to SU7), and FHWA Emergency Vehicles EV2 and EV3. It is noted that the governing criterion for the operating rating is either Longitudinal Tensile Stress or the Transverse Tensile Stress.

Table 2: Summary of the Analytical Operating Level Load Rating [1]

Rating Vehicle	Controlling Criterion	Analytical Operating Rating	
		Rating Factor	tons
HL-93	Longitudinal Tensile Stress	**0.51**	-
KY Type 1	Transverse Tensile Stress	**1.05**	21.0
KY Type 2	Transverse Tensile Stress	**1.08**	30.6
KY Type 3	Longitudinal Tensile Stress	**0.89**	31.4
KY Type 4	Longitudinal Tensile Stress	**0.87**	33.1
SU4	Longitudinal Tensile Stress	**1.11**	31.3
SU5	Longitudinal Tensile Stress	**1.01**	31.6
SU6	Longitudinal Tensile Stress	**0.94**	31.8
SU7	Longitudinal Tensile Stress	**0.87**	32.3
EV2	Transverse Tensile Stress	**1.00**	28.8
EV3	Longitudinal Tensile Stress	**0.79**	31.3

[1] Analytical load rating carried out by Stantec (2018).

Load Testing

Instrumentation

The East and West bound bridges are identical, and the Westbound bridge is selected for load testing. The testing focused on evaluating the longitudinal rating as the transverse rating did not limit truck loads on the bridge. It should be noted that out of the controlling criterion listed in Table 1, only the Principal Stresses and Longitudinal Flexural Stresses (both tension and compression) can be directly calculated using surface mounted strain gauges. Evaluation of Flexural and Shear Strengths requires the knowledge of the prestressing force at that location, and therefore is not attempted. Four locations/joints along the bridge are selected for instrumentation based on the analytical inventory load ratings in Table 1. Two of the selected joints have the lowest analytical rating for Principal Stress and Flexural Tensile Stress. The other two locations had low Principal Stress and Flexural Tensile Stress ratings and allowed for additional confirmation of test results. The selected locations on the bridge are shown in Fig. A1 in Appendix A.

- **Joint 76** has the lowest inventory rating factor of 0.24 for the Principal Stress.
- **Joint 122** has the lowest inventory rating factor of 0.40 for the Flexural Tensile Stress.
- **Joint 51** (Fig. 1) has a low inventory rating for Principal Stress (RF = 0.38).
- **Joint 109** has a low inventory rating factor of 0.66 for the Flexural Tensile Stress.

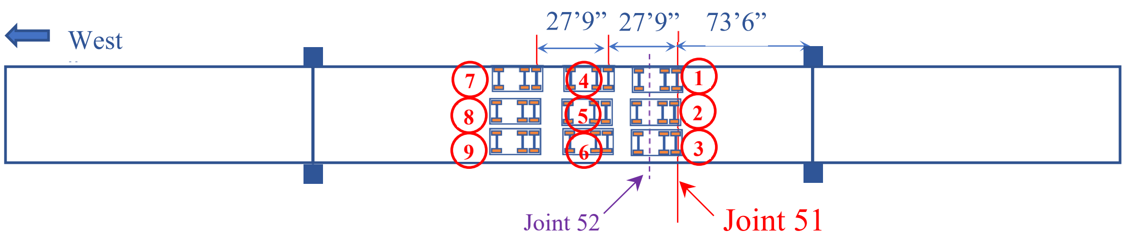
For the Inventory Load Rating, and in order to replicate the HL-93 loading on the 3-design lanes of the bridge, 9 tandem axle dump trucks were placed on the bridge, 3 trucks per lane in 3 lanes (Fig. 1). The positioning of the trucks for the different load cases in Figs. A2 to A5 is based on analysis carried out on the bridge model using CSiBridge to identify axle placement for maximum stresses.

Joints 51, 76, 109, and 122 were instrumented using strain gages. Adjacent joints, 52, 77, 110, and 121 were lightly instrumented for additional information. The gage layout is dependent on the stress evaluation criteria, e.g., principal stress, flexural stress (Figures 1, A2 to A4). Figure 1 presents the strain gage layout on segments 48, 49, and 50 adjacent to joints 51 and 52. The instrumentation used at Joint 51 and 52 is shown in Figure 2.

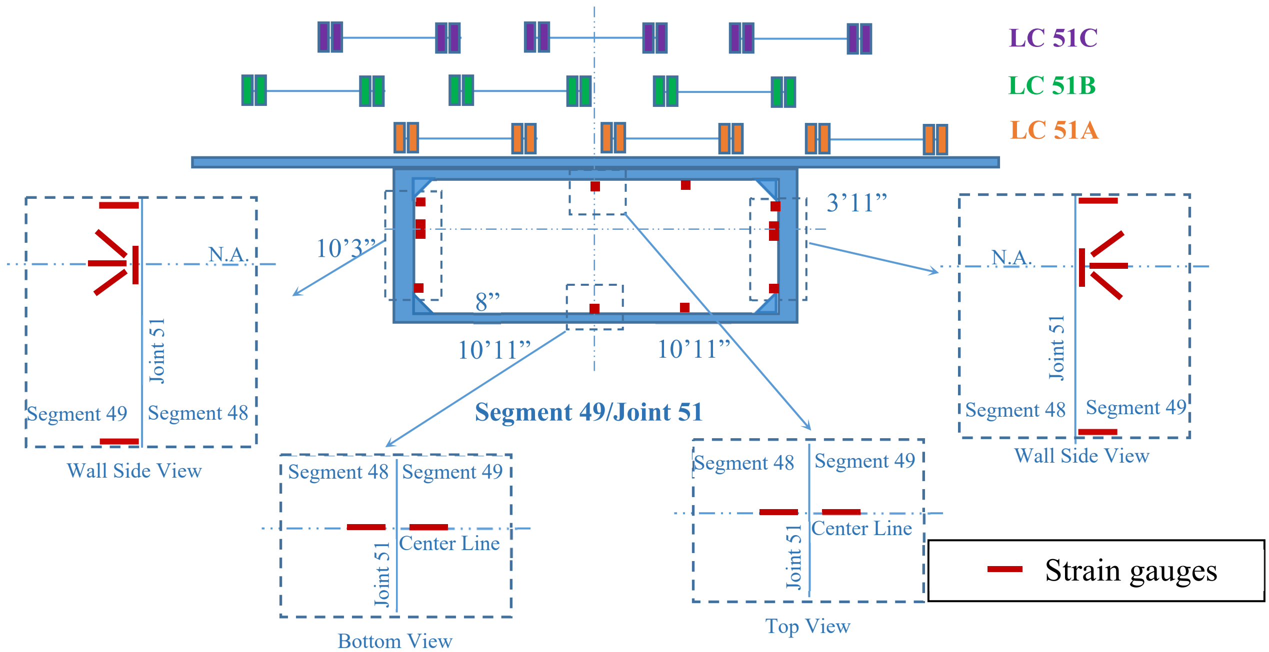
Load Cases

Three load cases (LC) were carried out at each of the 4-joints under consideration (Joints 51, 76, 109, and 122). Each load case consisted of placing the truck axles on the roadway to the right, left, and middle relative to the center line of the bridge (LC51A, LC51B, and LC51C, respectively in Figure 1). Figure 3 presents an aerial view of the 9 trucks positioned over joint 51 on the Westbound bridge.

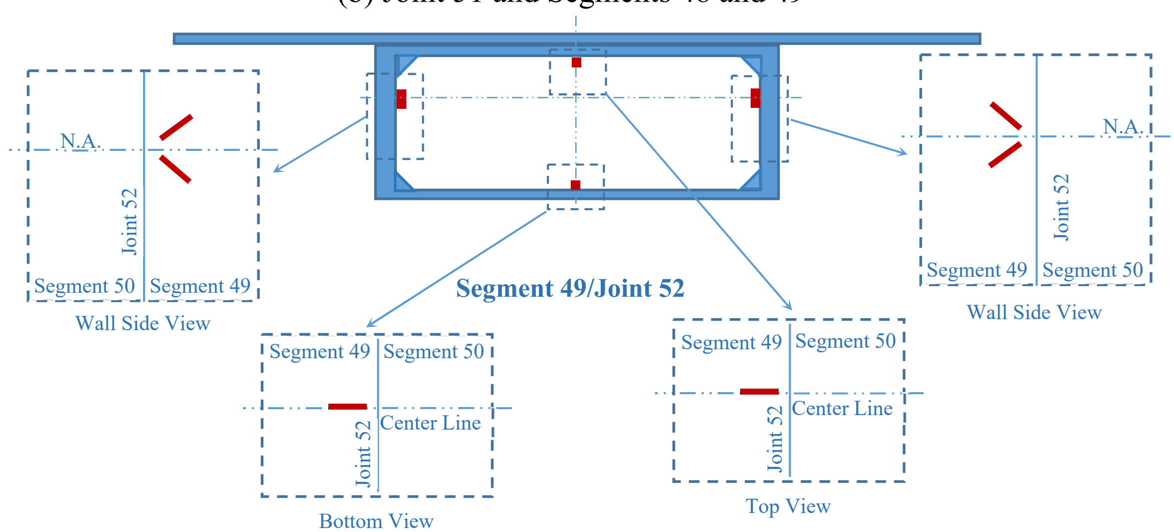
The weight of each truck's front axle, combined rear axles, and the truck itself were determined separately using a truck scale. The scale measured truck weight for truck #3 varied slightly from the combined weight of the front and rear axles. Table 3 presents the scale measured weights of the front and rear axles, and the combined axle weight is used for the truck weight. The 9 trucks were sorted based on total truck weight and identified as Truck 1 to 9, with Truck 1 being the heaviest. The weight difference between Truck 1 and Truck 9 is 2.43 tons (8.3%), and the heavier trucks were placed near the joint location to maximize load effects. Following the load tests, the CSiBridge model was updated with the actual truck axle weights to determine the model predicted strains. The dimensions of each truck were measured and incorporated in the CSiBridge model.



(a) Truck positions at Joint 51

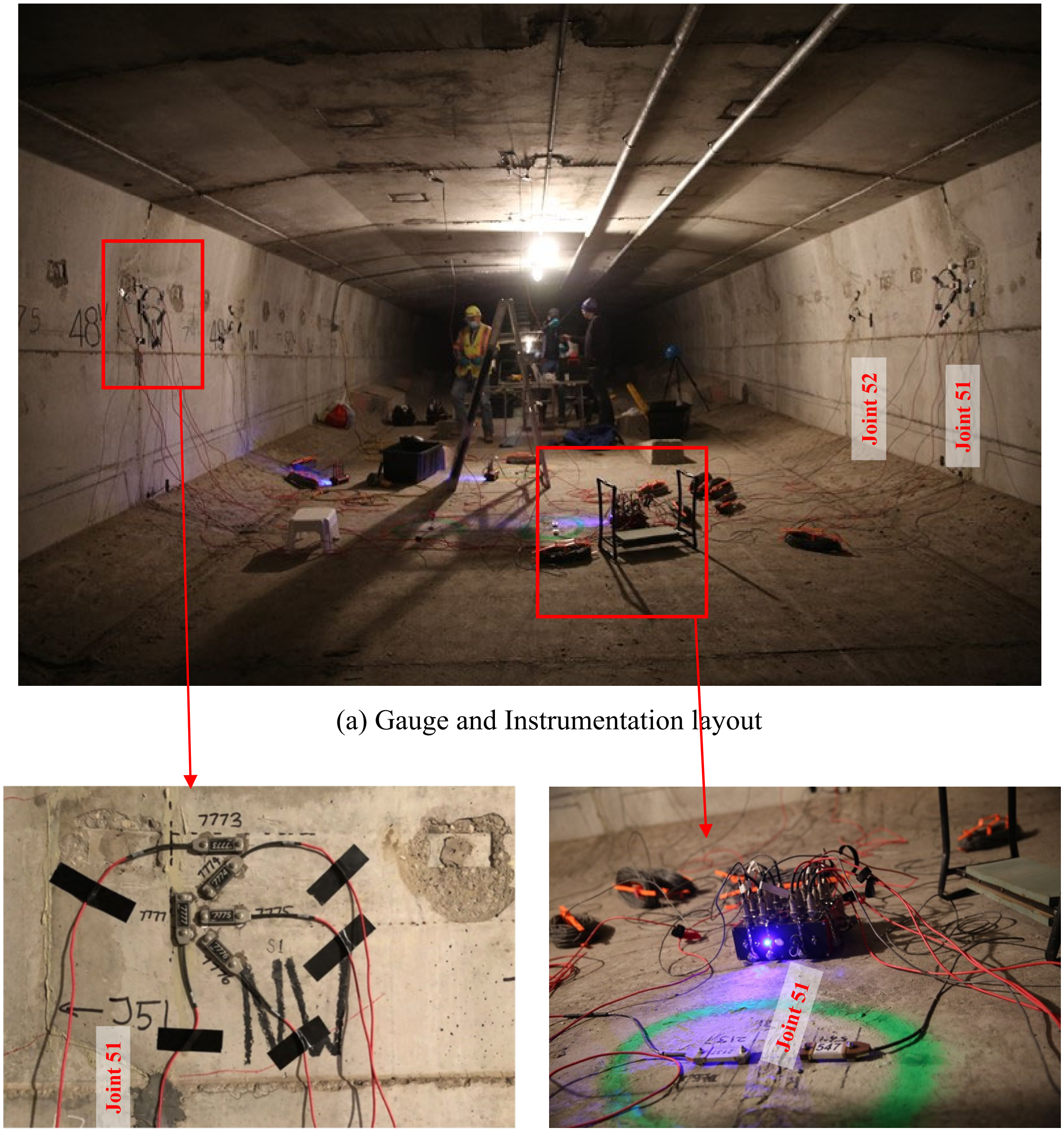


(b) Joint 51 and Segments 48 and 49



(c) Joint 52 and Segments 49 and 50

Figure 1: Load Cases when the 9-Trucks are Positioned Over Joint 51 and Gauge Layout on Segments Adjacent to Joints 51 and 52

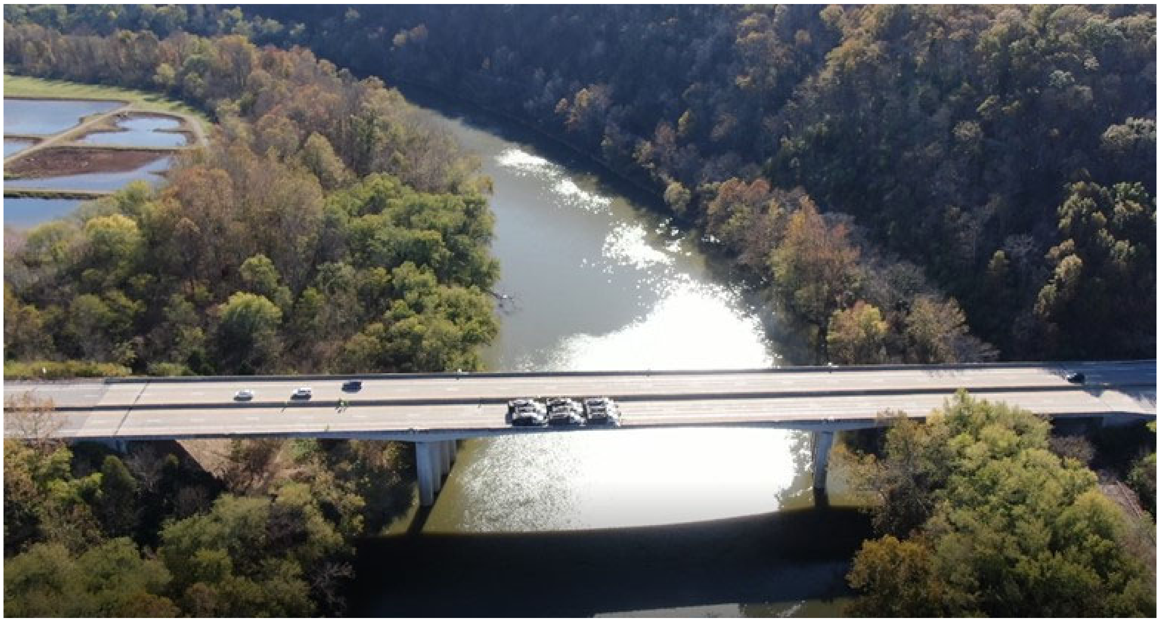


(a) Gauge and Instrumentation layout

(b) Gauges mounted on wall

(c) Gauges on floor and data acquisition node

Figure 2: Gauge and Data Acquisition Instrumentation layout at Joint 51 and 52



(a) Aerial view of the 9-loaded trucks

(b) Three truck lanes with 3 trucks per lane at Joint 51 (Fig. 1a)

Figure 3: Trucks placed on the Westbound bridge over Joint 51

Table 3: Truck IDs and Axle Weights

Truck ID	Front Axle	Total Rear Axles	Total Truck Weight[1]
	ton	ton	ton
1	10.17	21.45	31.62
2	10.52	20.85	31.37
3	9.80	21.28	31.08[2]
4	9.34	21.76	31.10
5	9.01	21.93	30.94
6	10.16	20.06	30.22
7	10.34	19.85	30.19
8	9.72	19.79	29.51
9	9.29	19.90	29.19

[1] Combined weight of the front and rear axles are used for the total weight in place of the scale measured total truck weight.
[2] The scale measured total truck weight was used in sorting the trucks based on weight for placement on the bridge (Fig. 1a). The scale measured total truck weight for Truck #3 was 31.33 tons, and Truck #4 was 31.10 tons.

Seven (7) of the 9 trucks had the axle spacing presented in Figure 4. Two trucks had rear axle spacing of 4’8”, or 2” longer than the other 7, and the front to rear first axle spacing of 13’6”, or 3” shorter. The dimensions presented in Figure 4 were used for all 9 trucks.

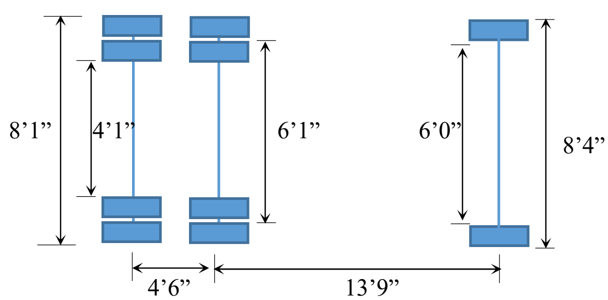


Figure 4: Load Test Truck Dimensions

Field Test Data

For each load case, the strains were recorded as the trucks approached the location of interest (e.g., Joint 51). Figure 5 presents the strains recorded for load case LC51B for a period of 800 seconds by the 18 strain gauges placed on the segments adjacent to Joint 51. The 9 trucks, in 3-lanes and 3-trucks per lane, was positioned for load case LC51B and kept stationary for approximately 150 seconds. For each strain gauge, the strains were observed during the stationary period. The process was repeated for each of three load cases (A, B, and C) and each location of interest (Joints 51, 76, 109, 122).

The recorded strains for each load case (A, B, C) at the 4 locations of interest (Joints 51, 76, 109, 122) are summarized in Table 4. The theoretical strains in Table 4, derived using CSiBridge software, are used for comparison with the experimental strains.

It should be noted that at Joints 109 and 122, the theoretical neutral axis location was within the section with a varying wall thickness, and above the strain gauge application location. Therefore, comparison is made with the theoretical strains expected at the gauge application location. While the strain gauges for measuring principal stress were applied at 45° to the longitudinal axis, the theoretical angle of principle stress at Joint 109 and 122 are 39.3° and 39.1° respectively. This difference is ignored in the calculations in Table 4.

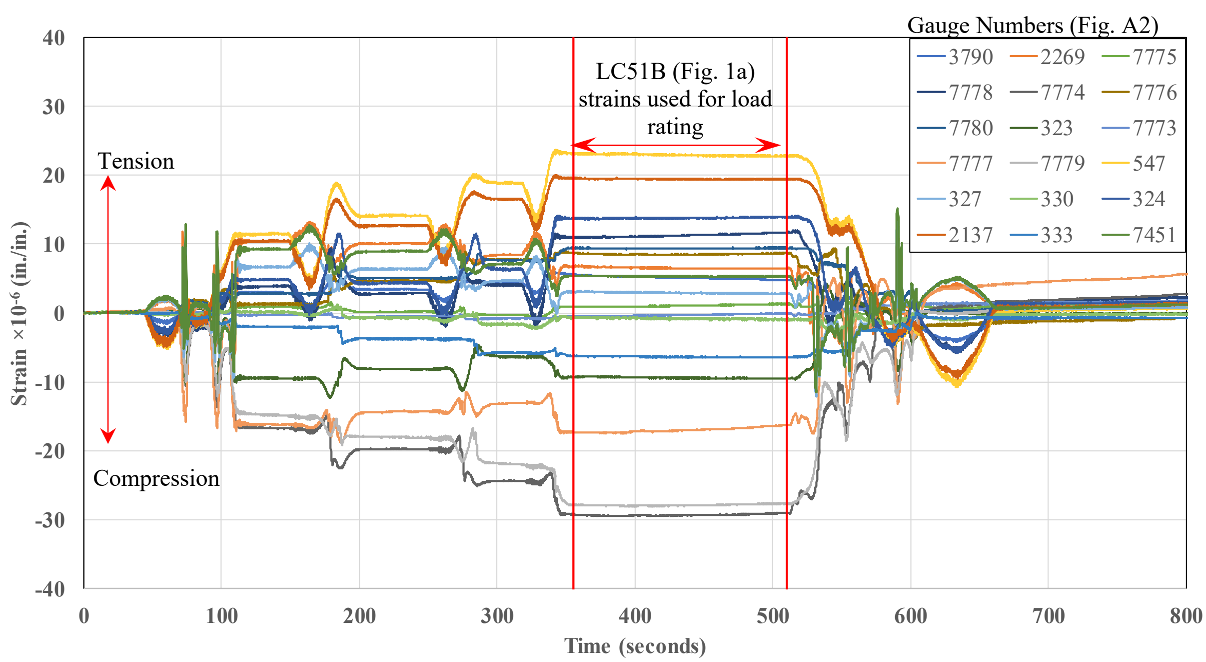


Figure 5: Strains for load case LC51B

Table 4: Analytical Strains Compared with Experimental Strains

Location	Controlling Criterion	Experimental[1,2] Strains × 10^{-6} (in./in.) Load Case A	B	C	Maximum[2] Experimental Strain × 10^{-6} ε_e (in./in.)	Theoretical[2] Strain × 10^{-6} ε_t (in./in.)	ε_e relative to ε_t ($\varepsilon_e = \alpha\, \varepsilon_t$) α
Joint 51	Principal Stress	-26.7	-29.3	-26.8	-29.3	-24.1	1.216
	Flexural Stress (Compression)[3]	-4.9	-0.3	-0.6	-4.9	-23.6	0.208
	Flexural Stress (Tension)	20.1	19.5	17.8	20.1	43.0	0.467
Joint 76	Principal Stress	-31.3	-32.6	-30.6	-32.6	-23.7	1.376
	Flexural Stress (Compression)[3]	-0.9	-3.2	-7.5	-7.5	-25.5	0.294
	Flexural Stress (Tension)	10.5	12.4	12.2	12.4	46.4	0.267
Joint 109	Principal Stress	-6.1	-7.6	-7.8	-7.8	-6.4	1.219
	Flexural Stress (Compression)	-11.9	-13.5	-14.9	-14.8	-69.9	0.212
	Flexural Stress (Tension)	84.9	90.7	89.1	90.7	132.0	0.687
Joint 122	Principal Stress	-5.1	-7.7	Not Tested	-7.7	-19.7	0.391
	Flexural Stress (Compression)	-6.6	-7.3		-7.3	-54.0	0.135
	Flexural Stress (Tension)	34.5	35.6		35.6	104.0	0.342

[1] The reported strains are the maximum recorded strains for each load case at each tested location once all the trucks have been placed as shown in Figure 5.
[2] Compressive strains are negative (-) and tensile strains are positive (+).
[3] Certain gauges on the bottom surface of the top slab recorded tensile strains, possibly as a result of localized bending due to truck tire positions. For these cases, the wall strain at the top has been substituted at it provides a larger compressive strain.

Load Rating based on Load Testing

The following conclusions can be made based on the results in Table 4.

1. Any load rating, for which the controlling criterion is Principal Stress cannot be improved.

2. The Inventory Rating of the HL-93 truck is based on Principal Stress, consequently the rating cannot be improved.

3. Any load rating, for which the controlling criterion is Flexural Stress (longitudinal tension or compression), can be improved. The improvement will be limited to the adjustment factor resulting from comparing the measured and analytical strains as specified in the MBE (2018) without exceeding the limit of another controlling criterion (e.g. Principal Stress).

4. The majority of the Operating Rating of the legal trucks listed in Table 2 are controlled by Flexural Stress (longitudinal tensile stress), consequently the Operating Rating of the legal trucks in Table 2 can be improved.

Conclusions and Recommendations

The Inventory Rating, performed on the design lanes of the bridge (3) and governed by Principle Stresses, could not be improved due to the observed principle strains during the load test. The Operating Rating at the Service I and/or Service III limit states, performed on the striped lanes of the bridge (2), could be improved for the rating trucks for which Longitudinal Stress was the governing criterion. The load test results were able to increase the Operating Rating of the bridge and prevent it from being substandard for the legal trucks KYTC 1-4, FHWA Specialized Hauling Vehicles SU4-SU7 and the Emergency Vehicle EV2. The bridge is still substandard for the Emergency Vehicle EV3. The controlling criterion for none of the rated vehicles is Longitudinal Tensile Stress (Table 5). The increase in load rating for Longitudinal Tensile Stress provided by the load testing allowed the rating to be increased to the next controlling criterion, that was either Shear Strength or Transverse Tensile Stress.

While the bridge is not substandard for all legal trucks except EV3, the rating in tons for all the trucks is less than 44 tons. This is the maximum allowable gross vehicle weight according to Kentucky Revised Statutes (KRS 189.222). Based on the cracks observed in the webs of the box sections, it is recommended that the bridge be kept under periodic monitoring and be posted according to the rating provided in Table 5.

Table 5: Operating Level Rating of the KY 676 Bridge Over Kentucky River - 037B00074N

Rating Vehicle	Analytical Rating [1]			Experimental Rating [2]		
	Controlling Criterion[3]	Rating Factor	Load Limit (Tons)	Controlling Criterion[3,4]	Rating Factor	Load Limit (Tons)
HL-93	Longitudinal Tensile Stress	**0.51**	-	Shear Strength	**0.53**	-
KY Type 1	Transverse Tensile Stress	**1.05**	21.0	Transverse Tensile Stress	**1.05**	21.0
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SU4	Longitudinal Tensile Stress	**1.11**	31.3	Transverse Tensile Stress	**1.37**	37.0
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[1] The analytical rating factors are derived by Stantec using the CSiBridge analysis software

[2] The experimental rating factors are derived from the load tests conducted on the Westbound bridge on November 2, 2020

[3] Shear Strength is a Strength Limit State, while Longitudinal Flexural Stress (tension) and Transverse Tensile Stress are Service I and/or Service III limit states.

[4] Analytical ratings for Transverse Tensile Stress and Shear Strength are used herein as it was not determined experimentally.

References

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American Association of State Highway and Transportation Officials. (2014). *AASHTO LRFD bridge design specification,* 7th Edition, Washington, DC.

American Association of State Highway and Transportation Officials. (2011). *AASHTO Manual for bridge evaluation,* 3rd Edition, Washington, DC.

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Appendix A

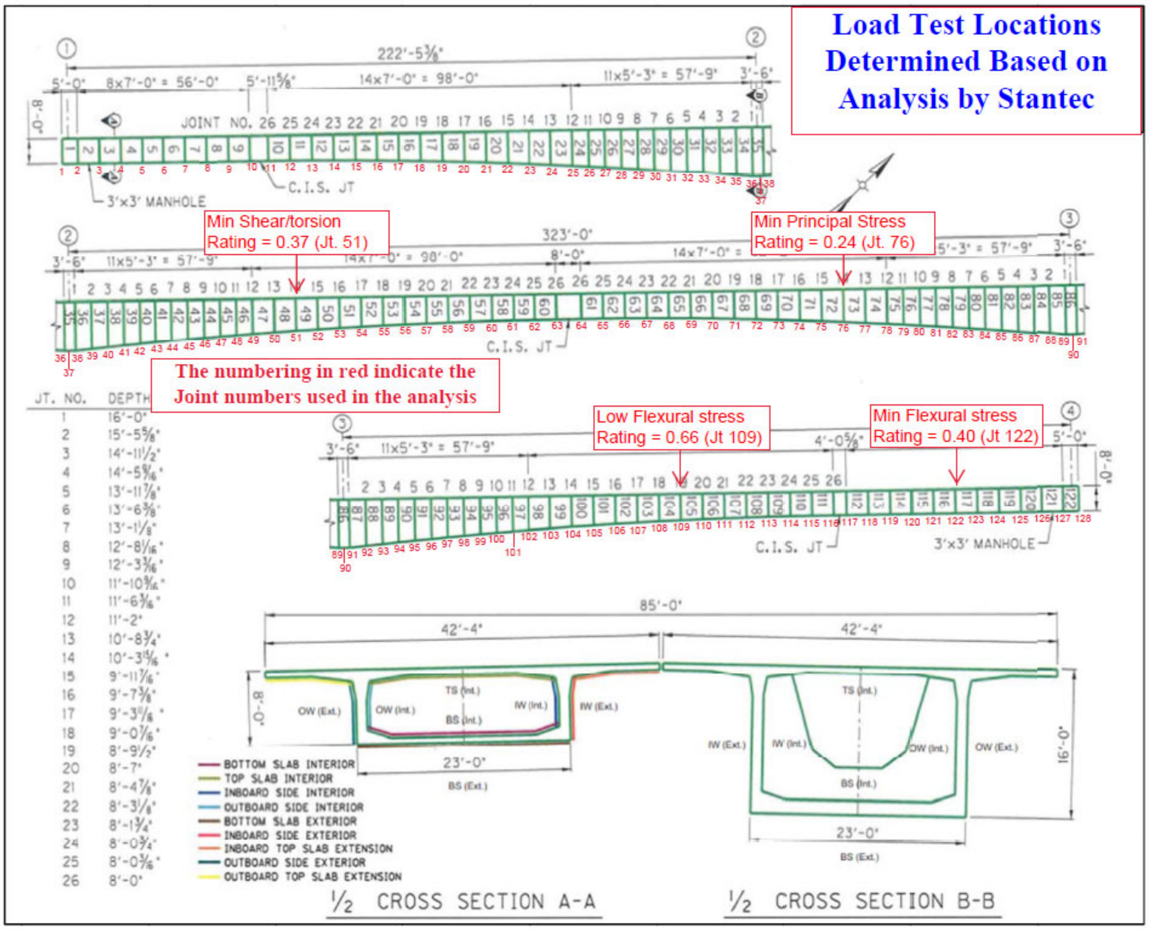
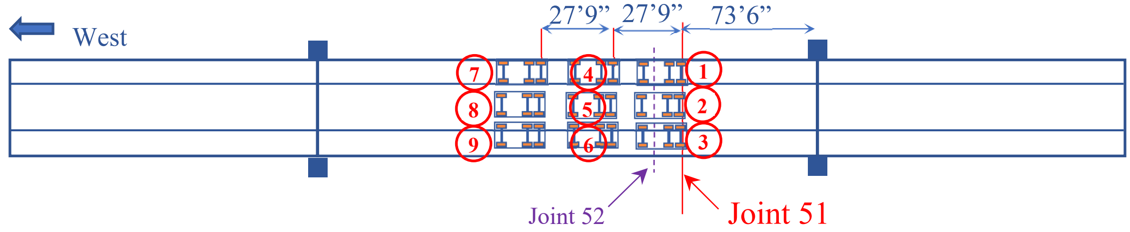
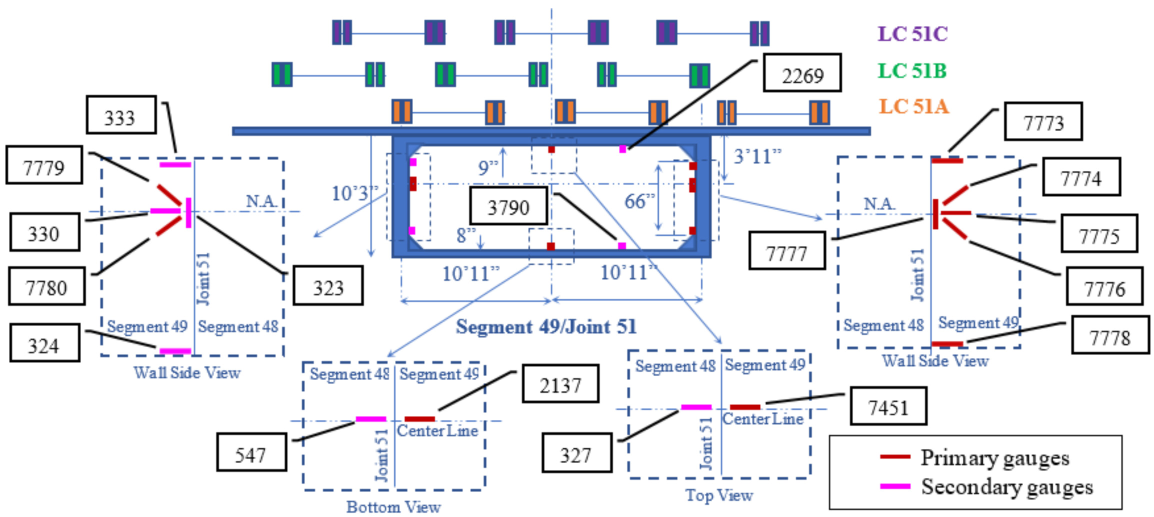


Figure A1: Load test locations and Bridge joint numbers

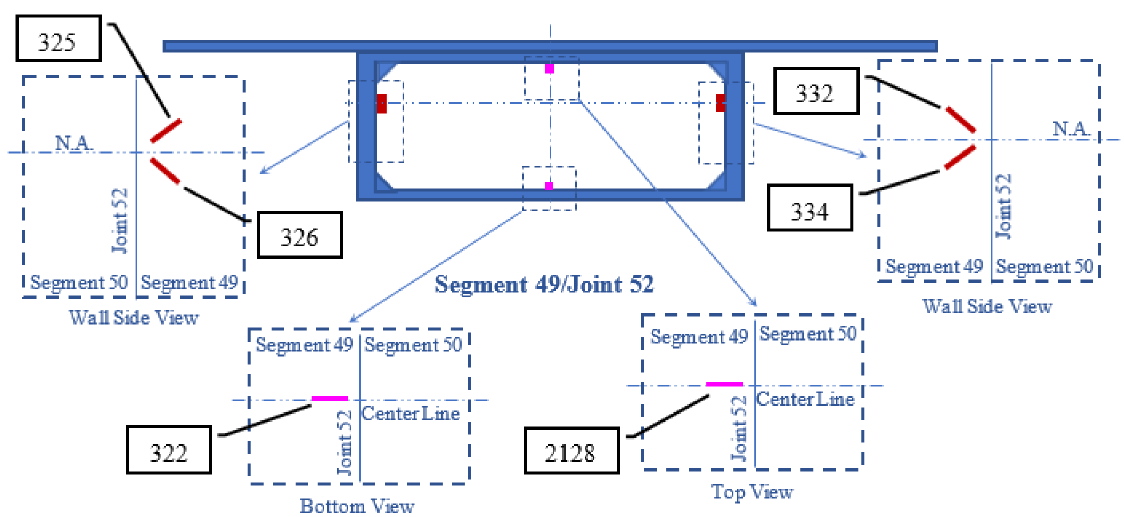
Joint 51: Flexure RF = 1.88, Principle Stress RF = 0.38



(a) Truck positions at Joint 51



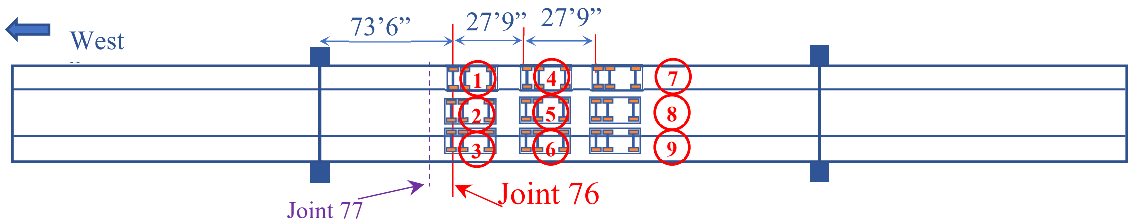
(b) Joint 51 and Segments 48 and 49



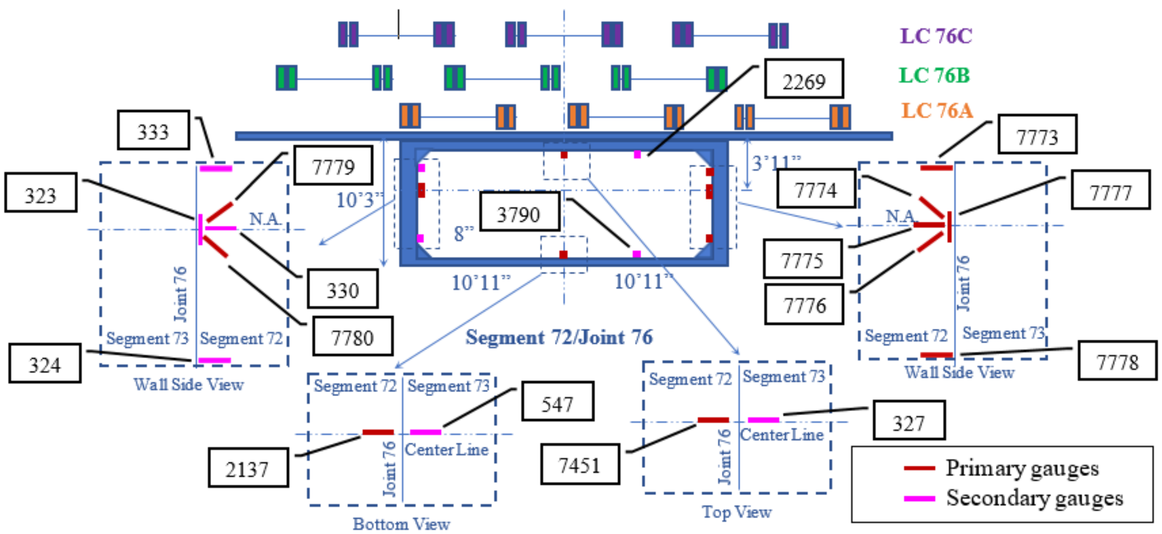
(c) Joint 52 and Segments 49 and 50

Figure A2: Load Cases When the 9-Trucks are Positioned Over Joint 51 and Gauge Layout on Segments Adjacent to Joints 51 and 52

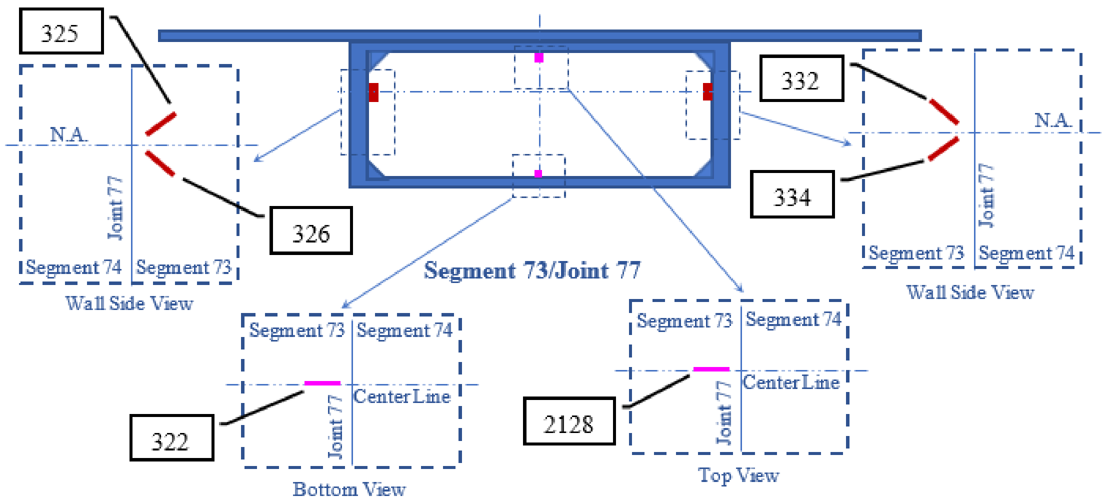
Joint 76: Flexure RF = 1.59, Principle Stress RF = 0.24



(a) Truck positions at Joint 76



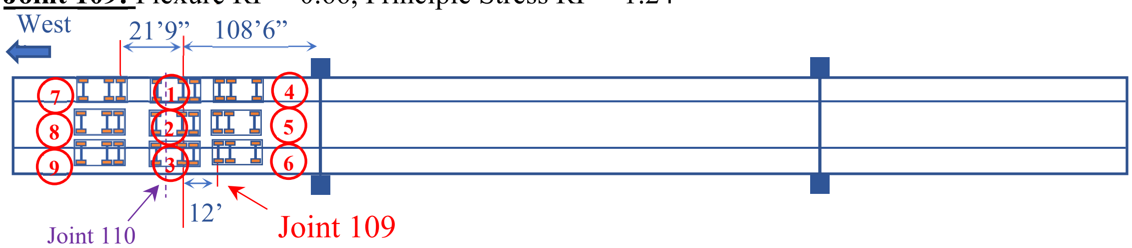
(b) Joint 76 and Segments 72 and 73



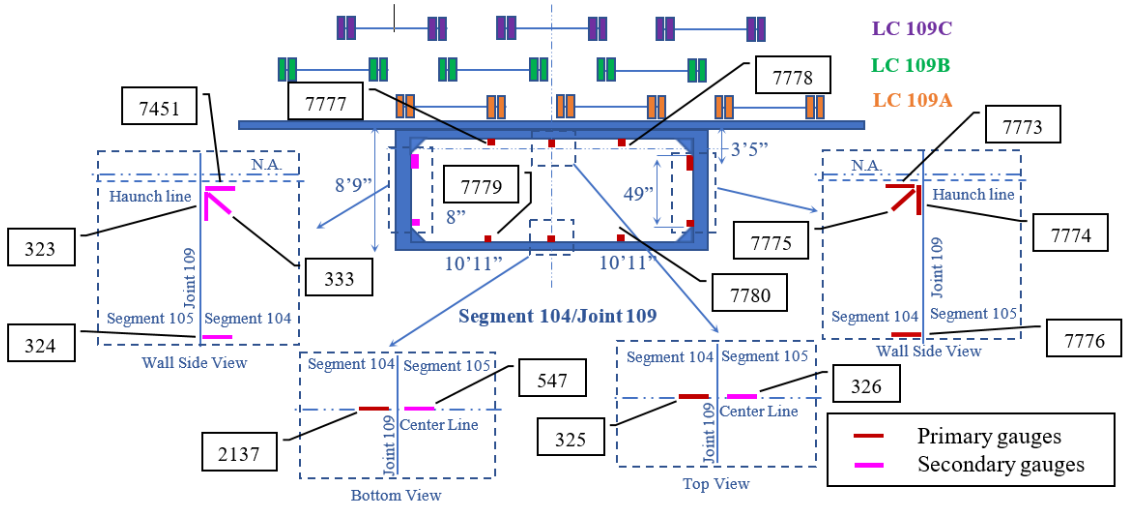
(c) Joint 77 and Segments 73 and 74

Figure A3: Load Cases When the 9-Trucks are Positioned Over Joint 76 and Gauge Layout on Segments Adjacent to Joints 76 and 77

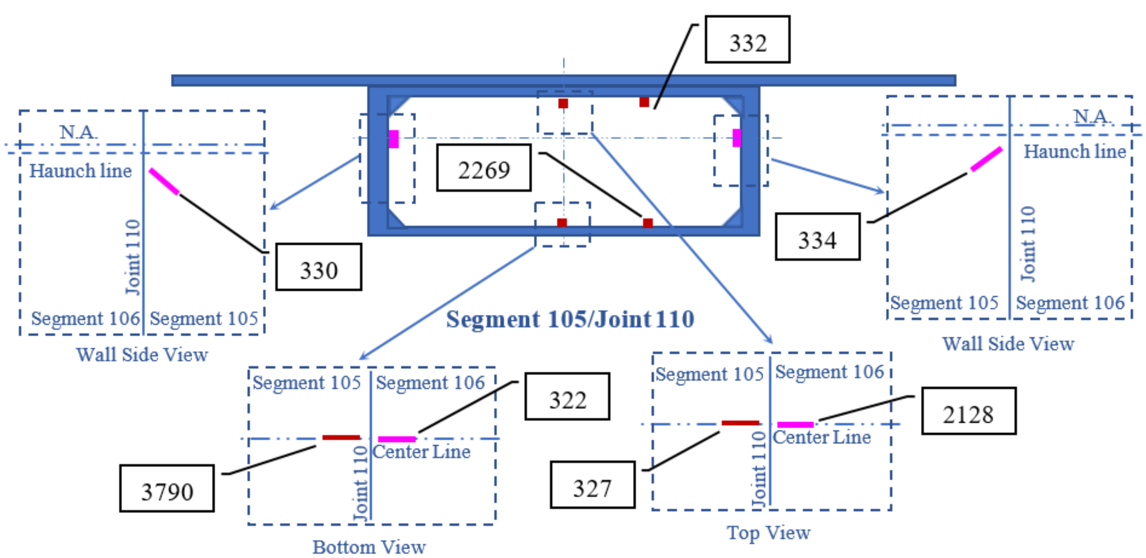
Joint 109: Flexure RF = 0.66, Principle Stress RF = 1.24



(a) Truck positions at Joint 109



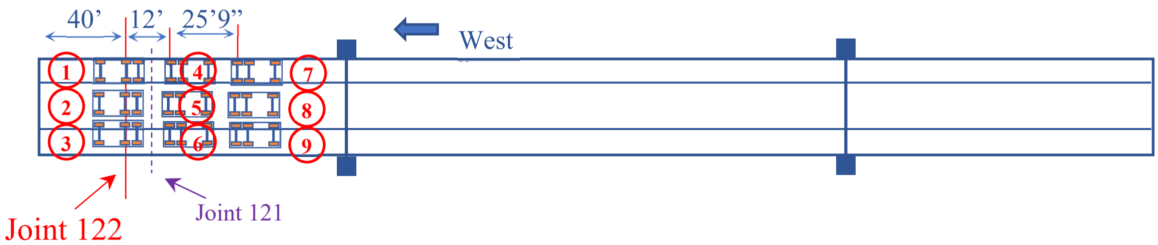
(b) Joint 109 and Segments 104 and 105



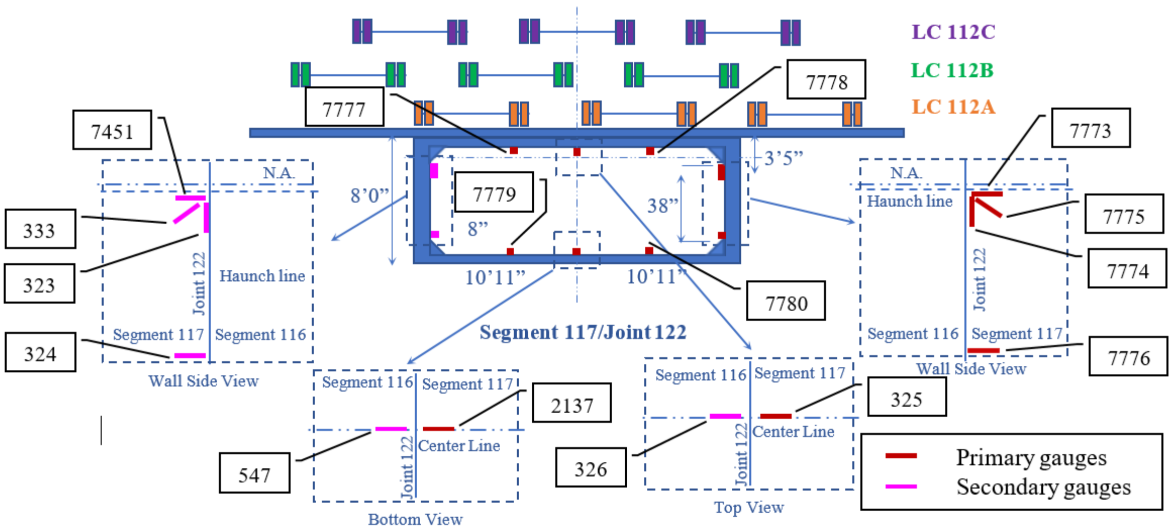
(c) Joint 110 and Segments 105 and 106

Figure A4: Load Cases When the 9-Trucks are Positioned Over Joint 109 and Gauge Layout on Segments Adjacent to Joints 109 and 110

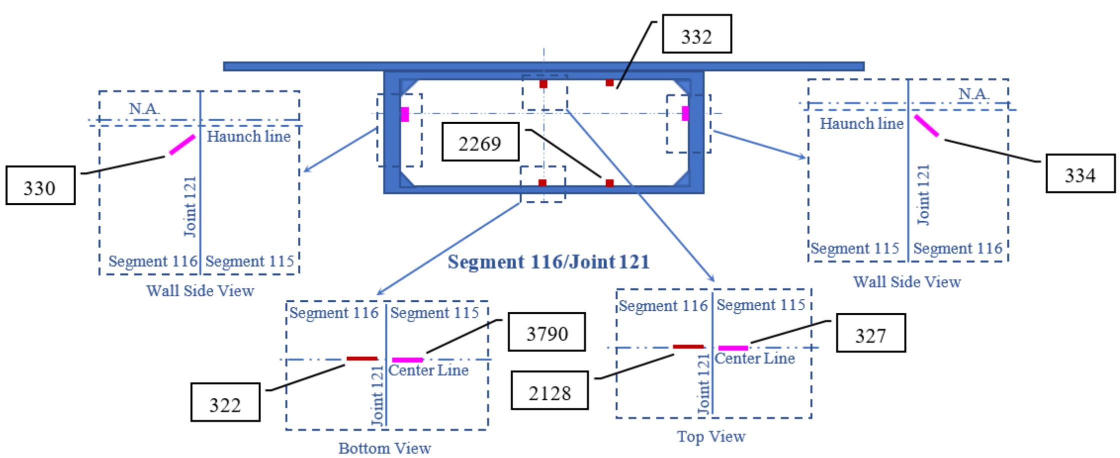
<u>Joint 122:</u> Flexure RF = 0.40, Principle Stress RF = 1.79



(a) Truck positions at Joint 122



(b) Joint 122 and Segments 116 and 117



(c) Joint 121 and Segments 115 and 116

Figure A5: Load Cases When the 9-Trucks are Positioned Over Joint 122 and Gauge Layout on Segments Adjacent to Joints 122 and 121