Calibration of AASHTO-LRFD Section 4.6.2.1.8 with Historical Performance of Filled, Partially Filled, Unfilled and Composite Grid Decks

Final Report

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Introduction

To evaluate the current AASHTO-LRFD design specification for partially-filled grid decks, design comparisons for 26 in-service decks were made. The deck designs pre-date the current AASHTO-LRFD design procedures and have been reported as having adequate service performance history of at least 10 years. Details of the deck and supporting bridge elements were provided by BGFMA. Deck design section calculations for the strong and weak directions were provided and spot checks were performed to indicate that these were reasonable. For many of the decks, additional details were provided including year of installation, field inspection data and/or evidence documenting adequate field performance from the owner, drawings of the deck, bridge superstructure drawings (span lengths, girder sizes, etc.), bridge ADT and ADTT. Key deck properties are shown in Table 1.

These deck designs were considered in the main, meaning specific unique details (such as joints and connections to the superstructure) were not considered in the analysis. The deck designs were compared with the current AASHTO-LRFD design moments (for strength and fatigue) as well as deflection criteria, the previous AASHTO-LRFD (1994) design moments, and with AASHTO-LRFD concrete slab deck design tables. Design demands, fatigue stress ranges, and deflection limits were compared for each of the decks considered. Three decks were identified for further detailed finite element analysis.

AASHTO-LRFD-2004 Live Load Deflection and Moments

Design checks were made with the current American Association of State Highway Officials Load and Resistance Design Specifications (2004) (AASHTO-LRFD-2004). The specified design moments (kip-in/in) and deflections (in) due to live load are:

Main bars perpendicular to traffic:

$$\Delta_{transverse} = \frac{0.0052 D^{0.19} L^3}{D_X} \qquad [1]$$

For $L \leq 120$ in

$$M_{transverse} = 1.28 D^{0.197} L^{0.459} C \qquad [2a]$$

For $L > 120$ in

$$M_{transverse} = \frac{D^{0.188}(3.7L^{1.35} - 956.3)}{L}C \quad [2b]$$

Main bars parallel to traffic:

$$\Delta_{parallel} = \frac{0.0072D^{0.11}L^3}{D_X} \quad [3]$$

For L≤120 in

$$M_{parallel} = 0.73D^{0.123}L^{0.64}C \quad [4a]$$

For L>120 in

$$M_{parallel} = \frac{D^{0.138}(3.1L^{1.429} - 1088.5)}{L}C \quad [4b]$$

where L=span length from center to center of supports (in), C=Continuity factor; 1.0 for simply supported and 0.8 for continuous spans, $D=D_x/D_y$. D_x is the flexural rigidity of deck in main bar direction (kip-in^2/in) and D_y is the flexural rigidity of deck perpendicular to main bar direction (kip-in^2/in). D_x and D_y were taken from the section properties of the different decks provided by BGFMA.

Deflection and moment values were calculated using the prescribed formulas and results are tabulated in Table 2. Although AASHTO-LRFD-2004 recommends use of cracked section properties, in order to quantify the effect of different section properties, uncracked section properties were also used to determine moment and deflection values. Comparisons of the design moments and deflections using cracked (considered cracked in both directions) and uncracked (considered uncracked in both directions) section properties are shown in Figs. 1 and 2, respectively. It is observed that the mean and the coefficient of variation of $Moment_{Cracked}/Moment_{Uncracked}$ and $Deflection_{Cracked}/ Deflection_{Uncracked}$ are 1.23, 0.092; 1.81, 0.226, respectively. Thus use of uncracked section properties would provide reduced design moments if justified.

AASHTO-LRFD (1994) Live Load Moments

The design moment demands obtained from the current AASHTO-LRFD-2004 were compared with the earlier American Association of State Highway Officials Load and Resistance Design Specifications (1994) (AASHTO-LRFD (1994)). Design moment (kip-ft/ft) values were determined as:

Main bars transverse to traffic:

$$M_{transverse} = ClpD^{0.25}[20\ln(12.0S) - 35] \quad [5]$$

Main bars parallel to direction of traffic:

$$M_{parallel} = Cp(150D^{0.29}\ln(12.0S) - 190D^{0.46})\frac{1}{8} \quad [6]$$

Where S=span length (ft), p=tire pressure taken as 0.125 ksi, L=tire length, along direction of traffic, as specified as:

$$l = \gamma(1 + IM/100)\frac{P}{2.5} \quad [7]$$

Where γ=1.75 (Strength-I), IM=33, P= 16.0 kip for design truck, P=12.5 kip for the design tandem. For the specified values, l_{tandem}=11.64 in. and $l_{design\text{-}truck}$=14.90 in.

Moment values were calculated for the decks using the above formulas with both cracked and uncracked sections and results are tabulated in Table 3. Since design truck moment values are always bigger than tandem values, design truck values were used to compare cracked and uncracked moment values. Moments using cracked and uncracked section properties are shown in Fig. 3. It is observed that the mean and the coefficient of variation of $Moment_{Cracked}/Moment_{Uncracked}$ for AASHTO-LRFD (1994) are 1.31 and 0.118, respectively. Comparison of AASHTO-LRFD (1994) (design truck) and AASHTO-LRFD (2004) design moment values are shown in Fig. 4. It is seen here that the current AASHTO produces larger design moments in the lower moment range and smaller moments in the upper moment range. The parallel to traffic cases are all higher in the current AASHTO-LRFD than the previous version. In order to compare AASHTO-LRFD (1994) (design truck) with AASHTO-LRFD (2004) design moments, both were plotted in Figs. 5 and 6 for D values ranging from 0 to 40 and L or S (span length) values ranging from 10 in. to 160 in. For main bars transverse to traffic, AASHTO-LRFD (2004) produced larger design moments except for D values bigger than 10 and L ranging from 30 to 120 in., where AASHTO-LRFD (1994) produced larger design moments. For main bars parallel to traffic AASHTO-LRFD (2004) produced larger design moments than AASHTO-LRFD (1994) except a very small region bounded by very short span lengths, L, ranging from 10 to 40 in., and D ranging from 2-14. AASHTO-LRFD (1994) and AASHTO-LRFD (2004) design moments for parallel and transverse were tabulated for D=2, 2.5, 8 and 10, as specified in AASHTO, and for a range of span length changing from 10 to 150 in. Table 4 and Table 5, respectively. The mean and the coefficient of variation of AASHTO-LRFD Moment (2004)/AASHTO-LRFD Moment (1994) over the range of spans and stiffness ratios described above were 1.20, 0.196 for main bars transverse and 1.23, 0.164 for parallel to traffic, respectively. As the span length increases, the 2004 moments tend to be larger than the 1994 moments. The parallel case produces larger differences than the transverse case. In the largest span for all the decks considered in Table 1, the differences are about 15% higher for the more common transverse to traffic orientation and 26% higher for the parallel to traffic orientation (averaging across different D values).

AASHTO-LRFD Live Load Moment for Conventional Deck Slabs

Both the current and previous versions of AASHTO-LRFD used orthotropic plate theory to develop the design moment equations. If the stiffnesses of the strong and weak directions are equal to one another, the stiffness ratio, D, becomes unity or isotropic and thus the design moments can be compared with conventional reinforced concrete decks. AASHTO-LRFD provides unfactored live load moment design tables for traditional design of concrete slab decks in Appendix A4. These values include multiple presence and impact factors and assume at least three parallel girder lines and maximum span of 14 ft. AASHTO-LRFD (2004) and AASHTO-LRFD (1994) design moments were computed by setting D=1 and considering C= 1.0 and 0.8 with the results shown along with the A4 slab design table values for both positive and negative moment in Figs. 7 to 9. As seen in these figures, where continuity is employed, the current AASHTO-LRFD design moments with D=1 correspond well with the factored design table values for conventional decks for the parallel to traffic case and are lower for the transverse to traffic case. By this measure, the orthotropic plate theory design moments appear reasonably consistent with conventional concrete bridge deck live load demands. Thus, it can be concluded that current AASHTO-LRFD moments for filled, partially filled, unfilled and composite grid decks are in line with current AASHTO-LRFD strength moments for conventional reinforced concrete decks and fatigue may more likely be the limiting issue in the current specification.

Comparison of AASHTO-LRFD Design Demands with Available Resistance

Strength Limit State

The available resistance of the deck designs was determined by using first yield of the main bars as the strength limit. Yield moment values were calculated using cracked and uncracked section properties for strong directions of the 26 decks considered. Section moduli with respect to the top and bottom of the main rail were calculated for positive bending using both cracked and uncracked section properties and for negative bending using cracked section properties in the strong direction. Modulus of elasticity and yield stress of the steel was assumed as 29,000 ksi and 50 ksi, respectively. The yield moment of the deck section was determined for the top and the bottom of the main rail (top for negative moments and bottom for positive moments). Positive bending yield moment values for cracked and uncracked sections and negative bending yielding moment for cracked section values are shown in Table 6. Considering ADTT data simultaneously, the yielding moments were divided by the design demand moment provided by AASHTO-LRFD (2004), as $M_{\text{Positive yielding}}/M_{\text{AASHTO-LRFD (2004)}}$, and $M_{\text{Negative yielding}}/M_{\text{AASHTO-LRFD (2004)}}$ and are shown in Fig. 10 and 11, respectively. Ranking of $M_{\text{Positive yielding}}/M_{\text{AASHTO-LRFD (2004)}}$, $M_{\text{Negative yielding}}/M_{\text{AASHTO-LRFD (2004)}}$ and $M_{\text{Positive yielding}}/M_{\text{AASHTO-LRFD (2004)}}$, $M_{\text{Negative yielding}}/M_{\text{AASHTO-LRFD (2004)}}$ with ADTT data are shown in Table 7, 8, and 9. In all cases the 26 decks were below yielding at the strength level. Values for $M_{\text{Positive yielding}}/M_{\text{AASHTO-LRFD (2004)}}$ ranged from 1.269 to 2.322 with a mean of 1.635 and values for $M_{\text{Negative yielding}}/M_{\text{AASHTO-LRFD (2004)}}$ ranged from 1.080 to 2.768 with a mean of 1.483. For the negative moment, 35% of the cases were above 1.5 times the yield moment and for positive moment, 58% of the cases were above 1.5 times the yield moment. Considering that first yield is not the actual strength condition (the plastic section could be used), thus, many of the decks can be considered as very conservative with respect to the AASHTO-LRFD specified strength moment demands. Further it is observed that the current AASHTO specification moment demands would not have limited these designs.

To consider the effects of realistic superstructure support conditions, three of the bridges were modeled in more detail using finite element methods with the software package ABAQUS 6.5-1. The three bridges selected for this detailed study were West Street over Chicopee River, Westbound GA route 53 over Lake Lanier, and WB-I70 over the Missouri River. These bridges have regular layout, no skew, and uniform girder stiffness distribution across the section. Details regarding the FE models of these bridges and deck systems as well as the analysis results are provided in the Appendix. In summary, the analysis results showed that superstructure flexibility slightly reduced negative moments and slightly increased positive moments for strength. These effects were not sufficient to significantly alter overall performance from those using idealized rigid supports. For systems that have nonuniform support or span conditions, finite element analyses may better reveal moment demands in the deck than the generalized orthotropic plate model with the rigid and regularly spaced supporting conditions considered in the Specification and in this study. It would be reasonable to assume that bridges that do not meet the criteria that would allow use of AASHTO-LRFD load distribution factors (those *not* meeting requirements of section 4.6.2.2.1), would benefit from such finite element modeling.

Deflection Criteria

Using positive bending cracked section properties in Eqn. 1, deflections were computed for the 26 deck systems and were rank ordered as shown in Table 10. Deflections were normalized with the span length and are shown in Figs. 12 and 13 with ADTT data including reference lines representing different specification recommended deflection criteria. All decks were below L/360.

Fatigue Limit State

For fatigue, AASHTO-LRFD (2004) strength design moments (with C=0.8) were divided by 3 to obtain the fatigue moment range. The fatigue stress range was determined by dividing the fatigue moment by the section modulus at the top of the crossbar in main rail for negative bending and section modulus of the bottom of the crossbar punch out in the main rail for positive bending. The computed fatigue stress ranges (SR) for negative and positive bending were ranked and are shown in Table 11 and12. These are also shown with reference to the infinite life stress threshold for fatigue Category C (5 ksi) in Figs. 14 and 15. As seen in these figures, the positive moment stress range for all decks is below the amplitude required for infinite life. However, for the negative moment stress range (over the supports) the computed stress range is sufficiently high as to limit the fatigue life of the decks. Additional analysis for fatigue was performed to clarify the limiting performance issues.

Finite element analysis for fatigue induced stresses was performed using ABAQUS 6.5-1. West Street over Chicopee River was used as the reference deck and superstructure system when considering the fatigue load effects. Detail regarding the FE model of the bridge and deck system is provided in the Appendix. The 16 kip patch loads from the HL93 fatigue truck (32 kip axle) were positioned on the deck surface as shown in Fig.16. The axle loads were modified with an impact factor of 1.15 and the fatigue load factor of 0.75. Negative moment over the interior support was calculated as Case 1, and positive moment was calculated as Case 2 and Case 3, representing different axle positions on the span to produce the worst load effect. Both flexible and rigid supports were considered and different D values were assigned to the negative and positive moment regions as was described in the finite element analysis section. Using the superposition principle, HL93 fatigue truck induced moments were monitored as the patches move over the deck surface and the induced moment histories at the deck locations are plotted in Fig. 17 and 18 for the rigid and flexible support cases, respectively. As seen in these figures, the flexible supports produced only slightly smaller negative moment ranges and slightly increased the positive moment ranges in the deck and also result in some small stress reversals for the negative moment.

Actual trucks in the traffic stream tend to be more closely related to the 3S2 truck configuration illustrated in Fig. 19 rather than the notional HL93 fatigue truck model. Based on weigh-in-motion (WIM) data collected in Oregon on Interstate 5 in Oregon (the major north-south freight corridor from Mexico to Canada via California, Oregon and Washington) and Interstate 84 (the major east-west Oregon freight corridor), the 3S2 truck configuration represents about 70% of the trucks operating on the system (Elkins and Higgins, 2006). The WIM measured tandem axle weight distributions are shown in Figs. 20a and 20b and 21a and 21b, for I5 (with 5000 ADTT) and I84 (with 1800 ADTT), respectively. These data include permit trucks and show the upper limit of the commonly occurring tandem weights is near 42 kips, with approximately 99.7% of tandems below 35 kips and 95% below 32 kips. There are 891,587 tandems in the I5 data set and 305,308 tandems in the I84 data set. There were no records above 42 kips in the I84 data and only 0.01% of records above 42 kips in the I5 data. Using Miner's Rule, to represent the variable weight amplitudes by an equivalent single amplitude tandem weight produces a tandem weight of 23.4 kips, which is below the AASHTO-LRFD factored fatigue truck axle when converted to tandems (32*1.15*0.75=27.6 kips).

To better represent more realistic fatigue induced stresses on the deck from the most common truck configuration shown in Fig. 19, the 3S2, the HL93 fatigue truck's 32 kip single axles were converted to 32 kip tandem axles (16 kip axles spaced 4 ft on-center). Thus, the fatigue truck is taken as a 5 axle truck (more representative of actual trucks) with the same GVW and steer axle weight. Analysis results for this fatigue truck conversion (still using the AASHTO-LRFD fatigue impact (1.15) and load factors (0.75)) are also shown in Fig. 17 and 18.

The fatigue truck induced moments were converted to stresses by dividing by the appropriate section modulus (top of the grid on the main bar for negative moment regions and bottom of the punch-out on the main bar for positive moment regions). The maximum stress range of 10.83 ksi was observed for Case 1 with the rigidly supported deck from the 32 kip axle loading. This value is within 5% of the value obtained by AASHTO-LRFD (2004) (11.21 ksi). For the situation where the single 32 kip HL93 fatigue truck axle was converted to a 32 kip tandem, the induced stress range was reduced by a factor of about 2 (2.03). Utilizing Miner's Rule, the fatigue truck induced stress histories were converted to an equivalent stress range with the corresponding number of cycles and are tabulated in Table 13 and 14. Since Case 2 and Case 3 provide almost the same stress history, Case 3 values were not used to calculate an equivalent stress range. According to AASHTO-LRFD (2004) C6.6.1.2.5 fatigue life of the structure is related with the cube of the stress range and decreasing the stress range by a factor of two increases the fatigue life of the element 8 times. However since the 32 kip single axle was converted to two 16 kip axles, the number of cycles per passage of the fatigue truck increased from 3 to 5. Stress range values and corresponding number of cycles for the conventional HL93 fatigue truck and the modified HL93 fatigue truck (32 kip single axle converted to 32 kip tandem) are shown in Fig. 22 with the AASHTO S-N curves. AASHTO-LRFD (2004) describes nominal fatigue resistance as:

$$(\Delta F)_n = \left(\frac{A}{N}\right)^{1/3} \qquad [8]$$

where

$$N = (365)(75)n(ADTT) \qquad [9]$$

A is the detail category constant (taken as 44.0×10^8 ksi for Category C detail) and n is the number of stress range cycles per truck passage (3 for the HL93 fatigue truck, 5 for the fatigue truck converted to tandem axles). For Category C details with the equivalent stress range in the negative moment region shown in Table 14, the tandem axle trailer fatigue truck model produced 3.02E7 cycles and the HL93 fatigue truck model produced 3.73E6 cycles. Using the 595 ADTT provided by BGFMA for this bridge deck and the number of cycles as 3 and 5 for the single and tandem axle fatigue trucks, respectively, the fatigue life was estimated at 5.7 and 27.8 years, respectively.

Utilizing the positive and negative equivalent SR values and Eq. 8 and 9, the fatigue lives of all 26 in-service decks were estimated and are shown in Table 15 and 16, respectively. It is observed that almost all decks were projected to have very short fatigue lives for negative moment over the supports. The projected fatigue lives appear to be reasonably long for the positive moment cases.

To adjust for stress reductions at the design section, considering the decks are supported on flanges of the superstructure, the adjustments from Table A4-1 in AASHTO-LRFD (2004) were considered. The normalized moment relative to the centerline of the girder versus distance to the critical section from the center line of girder was extracted from Table A4-1 and these are shown in Fig. 23. As seen in this figure, the negative SR values may be decreased at least 10% for all span lengths, if the design section is taken approximately 3 in. from the centerline of support (a reasonable distance for steel flange supports). Therefore, using the HL93 fatigue truck converted to tandems with the reduction in negative SR values at the design section, the fatigue life of the 26 in-service decks were estimated and tabulated in Table 17. These results provide a more reasonable projection of fatigue life for many of the decks considered.

In order to generalize the possible negative moment reductions due to the conversion of the AASHTO-LRFD factored fatigue truck with single 32 kip axles to a similar truck with tandem axles, further analyses were done with different span lengths (L=5ft, 10ft, and 15 ft) for main bars transverse and parallel to direction of the traffic. To conservatively represent continuity effects, a two-span continuous deck was used instead of a three-span continuous deck, which was used in the reference analysis (West Street over Chicopee River). The AASHTO-LRFD fatigue impact factor (1.15) and load factor (0.75) were used in these analyses. Patch load orientations are shown in Fig. 24 for the two deck span orientations relative to the direction of traffic. The current AASHTO-LRFD fatigue truck model with single 32 kip axles and an equivalent truck but with 32 kip tandem axles were modeled as patches moving over the deck surface and negative moment histories over the support were determined using superposition. For main bars transverse to traffic direction, the negative moments from the fatigue truck with single 32 kips axles and 32 kip tandem axles are shown in Fig. 25. Since analysis for main bars parallel to traffic requires many more incremental analysis steps to move the patches over the deck surface, in order to decrease the analysis time, peak points were determined using D=2.5 and moment curves were reconstructed using these peak points for span lengths of 10 and 15 ft. For main bars parallel to traffic direction, moments from the fatigue truck with single axles and with tandem axles are shown in Fig. 26. Utilizing Minor's Rule, equivalent negative moment ranges were determined from these results and are tabulated in Table 18 and 19 and shown in Fig. 27 and Fig. 28 for main bars transverse to traffic direction and main bars parallel to traffic direction, respectively. It is observed from Table 18 and 19 that negative moments caused by the fatigue truck with 32 kip single axles can be reduced by a factor of approximately 2.0 for main bars transverse to traffic direction and 2.5 for main bars parallel to traffic direction when tandems are used to more realistically represent the loads on the bridge that are responsible for fatigue of deck components. Using these reductions and number of cycles provided in Table 18 and 19, the fatigue lives of the 26 in service decks for this calibration were then estimated and are tabulated in Table 20. As seen in this table, using the proposed reductions many of the calibration decks have longer expected fatigue lives. Still however, for some decks, the projected lives are exceedingly short compared with the reported service history and others are still seen to have finite lives. The cause of this discrepancy may be related to several factors:

1) The AASHTO-LRFD fatigue thresholds are set at 95% confidence which should conservatively underestimate the actual fatigue life (although not necessarily to the levels observed with some of the decks in the current data set).

2) The ability to predict negative moment induced stresses over the supports is not adequately captured in the current methods. The reduction in transverse curvature near negative moment regions due to the stiffening action of the supporting superstructure may further reduce negative moment magnitudes by locally transforming the effective D

value for consideration of negative moment. Additional study is required to fully calibrate this effect. Additional deck tests that incorporate realistic superstructure interaction at the negative moment region (like those to be conducted at Purdue University (NCHRP-Project 10-72, Bridge Deck Design Criteria and testing Procedures)) may provide data needed to better predict these stresses.

3) The definition of fatigue failure, based principally on individual components, may not relate directly to highly internally redundant bridge decks. Fatigue failure would be recognized at the first member cracking, which undoubtedly would not cause deck failure. The redistribution of stresses in continuous span decks after first cracking is something that would require further study to quantify the fatigue effect of internal redundancy and establish a threshold for defining deck fatigue failure.

4) Cracking over the negative support may not cause significant system performance degradation. If, for example, all the main bars cracked over the continuous supports, the negative moment magnitudes would decrease and the deck system becomes simply supported. This would cause a corresponding increase in the positive moment as the continuity factor would go from 0.8 to 1.0. For the deck systems considered here, there is sufficient reserve to accommodate these higher fatigue stress range demands, as seen in the far right columns in Table 15 (even using the current AASHTO-LRFD fatigue provisions). Using even more realistic representations of a fatigue truck for deck elements, there is a lower likelihood of fatigue failure from positive moments.

In order to estimate limits on possible span lengths for the bridges in the calibration suite, theoretical spans were determined such that $M_{\text{Positive yielding}}$ is achieved, the stress range is achieved for fatigue Category (5 ksi), or the deflection limit of L/800 was achieved as tabulated in Tables 21-23. It is observed that L/800 produced the most conservative limit on possible span length. Utilizing the newly estimated limiting span lengths (controlled by the L/800 criteria), new live load moments (C=0.8 for negative moment and C=1.0 for positive moment) were calculated and divided by γ_p=1.75 (Strength I) and corresponding service level stresses were obtained. Results are tabulated in Table 24-25. The maximum stresses observed were 29.24 ksi and 26.35 ksi for positive and negative moments, respectively.

Conclusions and Recommendations for Additional Detailed Study

Based on comparisons of previous and current AASHTO-LRFD specifications and review of 26 in-service decks relative to the specification requirements, the following conclusions are presented:

1) The current AASHTO-LRFD moment provisions are not substantially higher than those specified for traditional design of concrete decks.

2) The 26 decks used in the calibration provided yielding moment resistance sufficient to resist the current AASHTO-LRFD strength design moment demands for both positive and negative moment locations. Thus, strength does not appear to limit designs of these decks.

3) The 26 decks used in the calibration met the current AASHTO-LRFD fatigue provisions for positive moment, even if the continuity factor is set to 1.0.

4) Almost all the decks used in the calibration were limited by the current AASHTO-LRFD fatigue provisions for negative moment. Predicted service lives for most decks in the calibration were unreasonably short relative to their field performance.

5) Fatigue design in the negative moment is the limiting design constraint for the decks in this calibration suite.

6) Design negative moments in fatigue could be reduced by changing the fatigue truck model into one with tandems instead of single axles, using an effective moment range, and including the critical design section which is located closer to the face of the support. These would reduce the current AASHTO-LRFD negative fatigue moment by a factor of 2.2 for decks transverse to traffic and 2.8 for decks parallel to traffic. This was still not sufficient to account for the performance of 9 of the 26 decks, and most of the rest were still seen to have finite fatigue lives.

7) Additional analysis and/or testing of decks around the negative moment region may help identify additional load distribution that further reduces stresses over the support for fatigue design.

8) Alternatively, conservative strength design and fatigue design for infinite life in the positive moment region could permit negative moment fatigue to be ignored if there is no history of performance issues in this region.

9) Superstructure flexibility was seen to slightly reduce negative moments and slightly increase positive moments when system performance was studied for three the bridges (West Street over Chicopee River, Westbound GA Route 53 over Lake Lanier, and WB I-70 over the Missouri River) in the calibration suite. For these regular bridges the observed effects were not sufficient to significantly alter overall performance from those using idealized rigid supports. Detailed FEA conducted for these bridges can be found in the Appendix A.

10) A possible design approach would be to use the current AASHTO-LRFD design provisions to design for Strength I with a continuity factor of 1.0, detail the deck to ensure infinite life for positive bending considering a continuity factor of 1.0 and further dividing the current AASHTO-LRFD fatigue moments by two to account for tandem rather than single axle loading, and finally limiting deflections to L/800 using the current AASHTO-LRFD approach to compute deflections. All the decks in the calibration suite would achieve the strength and fatigue requirements and by specifying a deflection limit would further regulate designs.

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Table 1. Design information.

	Bridge #	Name	Main Bar Dir.	Span (ft)	Dx/Dy (Cr.)	Dx/Dy (Uncr.)	ADT	ADTT
Fully Filled	1	Green Island Bridge Lift Span	Perpen. to t.	10.170	2.87	1.49	15000	890
	2	Quincy Memorial Bridge	Parallel to t.	4.830	1.74	1.42	8900	623
	3	Country Road 18 over Lake Milton	Perpen. to t.	8.170	1.89	1.14	NA	NA
	4	Meadowcroft Bridge over Cross Creek	Perpen. to t.	10.000	2.21	1.20	246	3
	5	Gold Star Bridge	Perpen. to t.	6.670	4.30	1.52	49700	6958
	6	Mackinac Bridge	Parallel to t.	5.000	5.30	1.62	11323	830
	7	Interstate 55 over Des Plaines River	Perpen. to t.	6.500	3.40	1.50	25050	7014
	8	Pennsylvania Turnpike over the Allegheny River	Perpen. to t.	6.420	3.40	1.50	39000	7020
	9	Tarentum Bridge	Perpen. to t.	6.500	3.40	1.50	26500	1855
	10	US Route 6 over CSX and Black River	Perpen. to t.	6.330	2.69	1.27	15000	220
	11	Jerome Street Bridge	Perpen. to t.	6.120	3.40	1.50	16786	1007
	12	Ohio State Route 611 over Blackriver Shipping Cen.	Perpen. to t.	6.330	2.71	1.28	15000	360
	13	Crown Point Bridge over Lake Champlain (Perpen.)	Perpen. to t.	6.370	2.69	1.35	3400	296
	14	North Main Street over Cuyahoga River	Perpen. to t.	6.380	2.91	1.34	20750	625
	15	Crown Point Bridge over Lake Champlain (Parallel)	Parallel to t.	8.000	3.95	1.63	3400	296
	16	Tobin Bridge, US 1 over Mystic River	Parallel to t.	6.460	34.20	1.71	30000(SB)-45000(NB)	4500-6000(SB)-6750-9000(NB)
Partially Filled	17	WB I-70 over the Missouri River	Perpen. to t.	7.125	31.91	6.73	70000	77009
	18	Cairo Bridge (WV 31 over North Fork Hughes River	Perpen. to t.	4.500	34.20	7.26	1000	40
	19	Gypsy Bridge (US 19 over West Fork River)	Perpen. to t.	6.170	34.20	7.26	7900	NA
	20	US 219 over Tygart Valley River	Parallel to t.	4.250	33.39	6.77	1850	204
	21	Daybrook Bridge (WV State Route 218 over Days Run)	Perpen. to t.	5.250	33.39	6.77	1550	NA
	22	State Route 601 over Pennsylvania Turnpike	Perpen. to t.	4.670	27.67	5.67	16852	1348
	23	West Street over Chicopee River	Perpen. to t.	5.500	30.42	6.21	9910	595
	24	Westbound GA Route 53 over Lake Lanier	Perpen. to t.	4.330	26.71	5.45	25290	1265
	25	Upper Buckeye Bridge	Perpen. to t.	8.250	17.04	5.36	NA	NA
	26	Smithfield Bridge	Perpen. to t.	6.000	31.85	6.43	12666	1140

Table 2. Moment and deflection values using AASHTO-LRFD (2004) (C=1.0) (Using cracked and uncracked section properties).

Bridge #	Name	Main Bar Direction	Span (ft)	Cracked		Uncracked	
				M. (kip-in/in)	Δ (in)	M. (kip-in/in)	Δ (in)
1	Green Island Bridge	Perpen. to traffic	10.170	14.69	0.308	12.98	0.140
2	Quincy Memorial Bridge	Parallel to traffic	4.830	10.50	0.043	10.24	0.021
3	Country Road 18 over Lake Milton	Perpen. to traffic	8.170	11.90	0.115	10.77	0.045
4	Meadowcroft Bridge over Cross Creek	Perpen. to traffic	10.000	13.47	0.198	11.94	0.087
5	Gold Star Bridge	Perpen. to traffic	6.670	12.75	0.173	10.39	0.079
6	Mackinac Bridge	Parallel to traffic	5.000	12.31	0.077	10.64	0.040
7	Interstate 55 over Des Plaines River	Perpen. to traffic	6.500	12.04	0.131	10.25	0.067
8	Pennsylvania Turnpike over the Allegheny River	Perpen. to traffic	6.420	11.97	0.126	10.19	0.065
9	Tarentum Bridge	Perpen. to traffic	6.500	12.04	0.131	10.25	0.067
10	US Route 6 over CSX and Black River	Perpen. to traffic	6.330	11.35	0.070	9.79	0.034
11	Jerome Street Bridge	Perpen. to traffic	6.120	11.71	0.109	9.97	0.056
12	Ohio State Route 611 over Blackriver Shipping Cen.	Perpen. to traffic	6.330	11.37	0.070	9.80	0.035
13	Crown Point Bridge over Lake Champlain (Perpen.)	Perpen. to traffic	6.370	11.39	0.149	9.94	0.069
14	North Main Street over Cuyahoga River	Perpen. to traffic	6.380	11.57	0.089	9.93	0.045
15	Crown Point Bridge over Lake Champlain (Parallel)	Parallel to traffic	8.000	16.05	0.269	14.39	0.157
16	Tobin Bridge, US 1 over Mystic River	Parallel to traffic	6.460	18.25	0.121	12.63	0.047
17	WB I-70 over the Missouri River	Perpen. to traffic	7.125	19.51	0.164	14.36	0.121
18	Cairo Bridge (WV 31 over North Fork Hughes River	Perpen. to traffic	4.500	16.02	0.039	11.80	0.029
19	Gypsy Bridge (US 19 over West Fork River)	Perpen. to traffic	6.170	18.51	0.101	13.64	0.074
20	US 219 over Tygart Valley River	Parallel to traffic	4.250	13.92	0.037	11.44	0.030
21	Daybrook Bridge (WV State Route 218 over Days Run)	Perpen. to traffic	5.250	17.11	0.067	12.50	0.048
22	State Route 601 over Pennsylvania Turnpike	Perpen. to traffic	4.670	15.63	0.055	11.43	0.039
23	West Street over Chicopee River	Perpen. to traffic	5.500	17.16	0.083	12.55	0.059
24	Westbound GA Route 53 over Lake Lanier	Perpen. to traffic	4.330	14.99	0.045	10.96	0.032
25	Upper Buckeye Bridge	Perpen. to traffic	8.250	18.44	0.166	14.68	0.131
26	Smithfield Bridge	Perpen. to traffic	6.000	18.02	0.103	13.15	0.075

Table 3. Moment values using AASHTO-LRFD (1994) (C=1.0) (Using cracked and uncracked section properties).

Br. #	Name	Cracked		Uncracked	
		M. (kip-ft/ft) (D. Truck)	M.(kip-ft/ft) (Tan.)	M. (kip-ft/ft) (D. Truck)	M.(kip-ft/ft) (Tan.)
1	Green Island Bridge	12.33	9.64	10.47	8.18
2	Quincy Memorial Bridge	9.11	7.12	8.74	6.83
3	Country Road 18 over Lake Milton	10.31	8.06	9.09	7.10
4	Meadowcroft Bridge over Cross Creek	11.50	8.98	9.86	7.70
5	Gold Star Bridge	11.76	9.19	9.07	7.08
6	Mackinac Bridge	11.39	8.89	9.10	7.11
7	Interstate 55 over Des Plaines River	10.99	8.58	8.96	7.00
8	Pennsylvania Turnpike over the Allegheny River	10.94	8.54	8.91	6.96
9	Tarentum Bridge	10.99	8.58	8.96	7.00
10	US Route 6 over CSX and Black River	10.25	8.01	8.50	6.64
11	Jerome Street Bridge	10.73	8.39	8.75	6.84
12	Ohio State Route 611 over Blackriver Shipping Cen.	10.28	8.03	8.51	6.65
13	Crown Point Bridge over Lake Champlain (Perpen.)	10.28	8.03	8.65	6.76
14	North Main Street over Cuyahoga River	10.49	8.19	8.64	6.75
15	Crown Point Bridge over Lake Champlain (Parallel)	12.85	10.04	10.68	8.35
16	Tobin Bridge, US 1 over Mystic River	16.54	12.92	10.07	7.87
17	WB I-70 over the Missouri River	19.90	15.55	13.49	10.54
18	Cairo Bridge (WV 31 over North Fork Hughes River	16.80	13.13	11.41	8.91
19	Gypsy Bridge (US 19 over West Fork River)	19.17	14.98	13.01	10.17
20	US 219 over Tygart Valley River	13.13	10.26	11.04	8.62
21	Daybrook Bridge (WV State Route 218 over Days Run)	17.85	13.95	11.98	9.36
22	State Route 601 over Pennsylvania Turnpike	16.20	12.66	10.90	8.52
23	West Street over Chicopee River	17.78	13.89	11.95	9.34
24	Westbound GA Route 53 over Lake Lanier	15.52	12.13	10.44	8.15
25	Upper Buckeye Bridge	17.94	14.01	13.43	10.50
26	Smithfield Bridge	18.63	14.55	12.49	9.76

Table 4. AASHTO-LRFD (1994) and AASHTO-LRFD (2004) design moments for transverse to traffic (C=1)

		Transverse to Traffic (AASHTO-LRFD Moment kip-in/in)											
		D=2			D=2.5			D=8			D=10		
		2004	1994	2004/1994	2004	1994	2004/1994	2004	1994	2004/1994	2004	1994	2004/1994
L (in)	10	4.222	2.039	2.07	4.412	2.156	2.05	5.548	2.884	1.92	5.797	3.049	1.90
	20	5.803	4.597	1.26	6.064	4.861	1.25	7.626	6.502	1.17	7.969	6.875	1.16
	30	6.991	6.094	1.15	7.305	6.443	1.13	9.186	8.618	1.07	9.599	9.112	1.05
	40	7.977	7.155	1.11	8.336	7.566	1.10	10.483	10.119	1.04	10.954	10.700	1.02
	50	8.838	7.979	1.11	9.235	8.437	1.09	11.613	11.284	1.03	12.135	11.931	1.02
	60	9.609	8.652	1.11	10.041	9.148	1.10	12.627	12.236	1.03	13.194	12.938	1.02
	70	10.314	9.221	1.12	10.777	9.750	1.11	13.553	13.040	1.04	14.162	13.788	1.03
	80	10.966	9.714	1.13	11.458	10.271	1.12	14.409	13.737	1.05	15.057	14.525	1.04
	90	11.575	10.148	1.14	12.095	10.730	1.13	15.210	14.352	1.06	15.893	15.175	1.05
	100	12.148	10.537	1.15	12.694	11.142	1.14	15.963	14.902	1.07	16.681	15.757	1.06
	110	12.692	10.889	1.17	13.262	11.514	1.15	16.677	15.399	1.08	17.427	16.283	1.07
	120	13.209	11.210	1.18	13.802	11.853	1.16	17.357	15.853	1.09	18.137	16.763	1.08
	130	14.777	11.505	1.28	15.410	12.165	1.27	19.176	16.271	1.18	19.998	17.204	1.16
	140	15.984	11.779	1.36	16.669	12.455	1.34	20.743	16.658	1.25	21.631	17.613	1.23
	150	17.083	12.033	1.42	17.815	12.724	1.40	22.170	17.018	1.30	23.120	17.994	1.28

Table 5. AASHTO-LRFD (1994) and AASHTO-LRFD (2004) design moments for parallel to traffic (C=1)

	Parallel to Traffic (AASHTO-LRFD Moment kip-in/in)											
	D=2			D=2.5			D=8			D=10		
L (in)	2004	1994	2004/1994	2004	1994	2004/1994	2004	1994	2004/1994	2004	1994	2004/1994
10	3.470	3.121	1.11	3.567	3.121	1.14	4.115	2.652	1.55	4.230	2.434	1.74
20	5.408	5.587	0.97	5.558	5.751	0.97	6.413	6.338	1.01	6.591	6.366	1.04
30	7.010	7.029	1.00	7.205	7.290	0.99	8.313	8.494	0.98	8.544	8.666	0.99
40	8.427	8.053	1.05	8.661	8.382	1.03	9.994	10.024	1.00	10.272	10.298	1.00
50	9.721	8.846	1.10	9.991	9.229	1.08	11.528	11.210	1.03	11.849	11.564	1.02
60	10.924	9.495	1.15	11.228	9.921	1.13	12.955	12.180	1.06	13.315	12.598	1.06
70	12.056	10.043	1.20	12.392	10.506	1.18	14.298	12.999	1.10	14.696	13.473	1.09
80	13.132	10.518	1.25	13.497	11.012	1.23	15.573	13.709	1.14	16.007	14.230	1.12
90	14.160	10.937	1.29	14.554	11.459	1.27	16.793	14.336	1.17	17.260	14.898	1.16
100	15.148	11.312	1.34	15.569	11.859	1.31	17.964	14.896	1.21	18.464	15.496	1.19
110	16.101	11.651	1.38	16.549	12.221	1.35	19.094	15.403	1.24	19.625	16.037	1.22
120	17.023	11.961	1.42	17.496	12.551	1.39	20.187	15.865	1.27	20.749	16.530	1.26
130	18.315	12.245	1.50	18.888	12.855	1.47	22.177	16.291	1.36	22.870	16.984	1.35
140	19.863	12.509	1.59	20.484	13.136	1.56	24.050	16.685	1.44	24.802	17.405	1.43
150	21.287	12.754	1.67	21.952	13.398	1.64	25.775	17.052	1.51	26.581	17.796	1.49

Table 6. Positive and negative bending yielding moment values for cracked and uncracked sections.

Bridge #	Cracked Pos. Yielding M. (kip-in/in)		Uncracked Pos. and Neg. Yielding M. (kip-in/in)		Cracked Neg. Yielding M. (kip-in/in)	
	Top	Bottom	Top	Bottom	Top	Bottom
1	-42.27	18.79	-82.38	36.61	27.40	-41.80
2	-38.92	17.55	-77.37	34.89	23.26	-39.03
3	-119.70	19.41	-274.89	44.58	13.57	-30.69
4	-95.74	22.64	-194.94	46.09	16.75	-34.75
5	-25.10	13.07	-45.34	23.61	11.02	-25.01
6	-29.97	15.74	-51.05	26.80	16.96	-29.81
7	-27.75	15.81	-46.14	26.28	13.74	-27.85
8	-27.75	15.81	-46.14	26.28	13.74	-27.85
9	-27.75	15.81	-46.14	26.28	13.74	-27.85
10	-79.95	21.08	-140.43	37.02	13.74	-27.85
11	-27.75	15.81	-46.14	26.28	13.74	-27.85
12	-79.95	21.08	-140.43	37.02	13.74	-27.85
13	-23.63	12.03	-44.51	22.66	10.43	-23.43
14	-49.53	18.61	-85.58	32.16	13.74	-27.85
15	-30.87	18.80	-47.89	29.17	16.37	-31.24
16	-44.16	20.96	-81.60	38.74	29.89	-43.45
17	-37.99	20.38	-38.50	20.65	18.42	-18.30
18	-44.16	20.96	-45.05	21.39	26.58	-19.71
19	-44.16	20.96	-45.05	21.39	26.58	-19.71
20	-40.39	19.61	-41.18	19.99	21.99	-18.24
21	-40.39	19.61	-41.18	19.99	21.99	-18.24
22	-35.22	15.86	-36.28	16.34	17.59	-14.59
23	-38.48	17.49	-39.52	17.96	21.31	-16.22
24	-32.84	15.56	-33.71	15.97	15.11	-13.77
25	-76.70	23.66	-77.73	23.98	21.99	-18.24
26	-36.60	19.19	-37.16	19.48	17.26	-17.15

Table 7. Ranking of the positive bending yielding moment divided by live load moments obtained by AASHTO-LRFD (2004) (C=0.8).

Bridge #	Name	Main Bar Direction	$M_{\text{Positive yielding}}/M_{\text{AASHTO-LRFD (2004)}}$
22	State Route 601 over Pennsylvania Turnpike	Perpen. to traffic	1.269
23	West Street over Chicopee River	Parallel to traffic	1.274
5	Gold Star Bridge	Perpen. to traffic	1.281
24	Westbound GA Route 53 over Lake Lanier	Perpen. to traffic	1.297
17	WB I-70 over the Missouri River	Perpen. to traffic	1.306
13	Crown Point Bridge over Lake Champlain (Perpen.)	Parallel to traffic	1.321
26	Smithfield Bridge	Perpen. to traffic	1.331
19	Gypsy Bridge (US 19 over West Fork River)	Perpen. to traffic	1.415
21	Daybrook Bridge (WV State Route 218 over Days Run)	Perpen. to traffic	1.432
16	Tobin Bridge, US 1 over Mystic River	Perpen. to traffic	1.436
15	Crown Point Bridge over Lake Champlain (Parallel)	Perpen. to traffic	1.465
6	Mackinac Bridge	Perpen. to traffic	1.598
1	Green Island Bridge	Perpen. to traffic	1.599
25	Upper Buckeye Bridge	Perpen. to traffic	1.604
18	Cairo Bridge (WV 31 over North Fork Hughes River	Parallel to traffic	1.636
7	Interstate 55 over Des Plaines River	Parallel to traffic	1.641
9	Tarentum Bridge	Perpen. to traffic	1.641
8	Pennsylvania Turnpike over the Allegheny River	Perpen. to traffic	1.651
11	Jerome Street Bridge	Perpen. to traffic	1.687
20	US 219 over Tygart Valley River	Parallel to traffic	1.761
14	North Main Street over Cuyahoga River	Perpen. to traffic	2.011
3	Country Road 18 over Lake Milton	Perpen. to traffic	2.039
2	Quincy Memorial Bridge	Perpen. to traffic	2.089
4	Meadowcroft Bridge over Cross Creek	Perpen. to traffic	2.100
12	Ohio State Route 611 over Blackriver Shipping Cen.	Perpen. to traffic	2.317
10	US Route 6 over CSX and Black River	Perpen. to traffic	2.322

Table 8. Ranking of the negative bending yielding moment divided by live load moments obtained by AASHTO-LRFD (2004) (C=0.8).

Bridge #	Name	Main Bar Direction	$M_{Negative\ yielding}/M_{AASHTO\text{-}LRFD\ (2004)}$
5	Gold Star Bridge	Perpen. to traffic	1.080
13	Crown Point Bridge over Lake Champlain (Perpen.)	Parallel to traffic	1.145
24	Westbound GA Route 53 over Lake Lanier	Perpen. to traffic	1.148
22	State Route 601 over Pennsylvania Turnpike	Perpen. to traffic	1.167
17	WB I-70 over the Missouri River	Perpen. to traffic	1.172
23	West Street over Chicopee River	Parallel to traffic	1.182
26	Smithfield Bridge	Perpen. to traffic	1.190
25	Upper Buckeye Bridge	Perpen. to traffic	1.236
15	Crown Point Bridge over Lake Champlain (Parallel)	Perpen. to traffic	1.275
19	Gypsy Bridge (US 19 over West Fork River)	Perpen. to traffic	1.331
21	Daybrook Bridge (WV State Route 218 over Days Run)	Perpen. to traffic	1.332
3	Country Road 18 over Lake Milton	Perpen. to traffic	1.425
7	Interstate 55 over Des Plaines River	Parallel to traffic	1.427
9	Tarentum Bridge	Perpen. to traffic	1.427
8	Pennsylvania Turnpike over the Allegheny River	Perpen. to traffic	1.435
11	Jerome Street Bridge	Perpen. to traffic	1.467
14	North Main Street over Cuyahoga River	Perpen. to traffic	1.484
12	Ohio State Route 611 over Blackriver Shipping Cen.	Perpen. to traffic	1.510
10	US Route 6 over CSX and Black River	Perpen. to traffic	1.513
18	Cairo Bridge (WV 31 over North Fork Hughes River	Parallel to traffic	1.538
4	Meadowcroft Bridge over Cross Creek	Perpen. to traffic	1.554
20	US 219 over Tygart Valley River	Parallel to traffic	1.638
6	Mackinac Bridge	Perpen. to traffic	1.722
16	Tobin Bridge, US 1 over Mystic River	Perpen. to traffic	2.048
1	Green Island Bridge	Perpen. to traffic	2.332
2	Quincy Memorial Bridge	Perpen. to traffic	2.768

Table 9. Ranking of the ADTT values with corresponding $M_{AASHTO\text{-}LRFD\ (2004)}/M_{Positive\ yielding}$ and $M_{AASHTO\text{-}LRFD\ (2004)}/M_{Negative\ yielding}$ (C=0.8).

Bridge #	Name	$M_{Positive\ yielding}/M_{AASHTO\text{-}LRFD\ (2004)}$	$M_{Negative\ yielding}/M_{AASHTO\text{-}LRFD\ (2004)}$	ADTT
16	Tobin Bridge, US 1 over Mystic River	1.436	2.048	9000
17	WB I-70 over the Missouri River	1.306	1.172	7700
8	Pennsylvania Turnpike over the Allegheny River	1.651	1.435	7020
7	Interstate 55 over Des Plaines River	1.641	1.427	7014
5	Gold Star Bridge	1.281	1.080	6958
9	Tarentum Bridge	1.641	1.427	1855
22	State Route 601 over Pennsylvania Turnpike	1.269	1.167	1348
24	Westbound GA Route 53 over Lake Lanier	1.297	1.148	1265
26	Smithfield Bridge	1.331	1.190	1140
11	Jerome Street Bridge	1.687	1.467	1007
1	Green Island Bridge	1.599	2.332	890
6	Mackinac Bridge	1.598	1.722	830
14	North Main Street over Cuyahoga River	2.011	1.484	625
2	Quincy Memorial Bridge	2.089	2.768	623
23	West Street over Chicopee River	1.274	1.182	595
12	Ohio State Route 611 over Blackriver Shipping Cen.	2.317	1.510	360
13	Crown Point Bridge over Lake Champlain (Perpen.)	1.321	1.145	296
15	Crown Point Bridge over Lake Champlain (Parallel)	1.465	1.275	296
10	US Route 6 over CSX and Black River	2.322	1.513	220
20	US 219 over Tygart Valley River	1.761	1.638	204
18	Cairo Bridge (WV 31 over North Fork Hughes River	1.636	1.538	40
4	Meadowcroft Bridge over Cross Creek	2.100	1.554	3
3	Country Road 18 over Lake Milton	2.039	1.425	NA
19	Gypsy Bridge (US 19 over West Fork River)	1.415	1.331	NA
21	Daybrook Bridge (WV State Route 218 over Days Run)	1.432	1.332	NA
25	Upper Buckeye Bridge	1.604	1.236	NA

Table 10. Ranking of the deflections due to live load.

Bridge #	Name	Main Bar Direction	Deflection (in)
1	Green Island Bridge	Perpen. to traffic	0.308
15	Crown Point Bridge over Lake Champlain (Parallel)	Parallel to traffic	0.269
4	Meadowcroft Bridge over Cross Creek	Perpen. to traffic	0.198
5	Gold Star Bridge	Perpen. to traffic	0.173
25	Upper Buckeye Bridge	Perpen. to traffic	0.166
17	WB I-70 over the Missouri River	Perpen. to traffic	0.164
13	Crown Point Bridge over Lake Champlain (Perpen.)	Perpen. to traffic	0.149
7	Interstate 55 over Des Plaines River	Perpen. to traffic	0.131
9	Tarentum Bridge	Perpen. to traffic	0.131
8	Pennsylvania Turnpike over the Allegheny River	Perpen. to traffic	0.126
16	Tobin Bridge, US 1 over Mystic River	Parallel to traffic	0.121
3	Country Road 18 over Lake Milton	Perpen. to traffic	0.115
11	Jerome Street Bridge	Perpen. to traffic	0.109
26	Smithfield Bridge	Perpen. to traffic	0.103
19	Gypsy Bridge (US 19 over West Fork River)	Perpen. to traffic	0.101
14	North Main Street over Cuyahoga River	Perpen. to traffic	0.089
23	West Street over Chicopee River	Perpen. to traffic	0.083
6	Mackinac Bridge	Parallel to traffic	0.077
12	Ohio State Route 611 over Blackriver Shipping Cen.	Perpen. to traffic	0.070
10	US Route 6 over CSX and Black River	Perpen. to traffic	0.070
21	Daybrook Bridge (WV State Route 218 over Days Run)	Perpen. to traffic	0.067
22	State Route 601 over Pennsylvania Turnpike	Perpen. to traffic	0.055
24	Westbound GA Route 53 over Lake Lanier	Perpen. to traffic	0.045
2	Quincy Memorial Bridge	Parallel to traffic	0.043
18	Cairo Bridge (WV 31 over North Fork Hughes River	Perpen. to traffic	0.039
20	US 219 over Tygart Valley River	Parallel to traffic	0.037

Table 11. Fatigue stress range (positive bending) ranking using AASHTO-LRFD (2004).

Bridge #	Name	Main Bar Direction	SR Positive bending	ADTT
3	Country Road 18 over Lake Milton	Perpen. to traffic	2.201	NA
25	Upper Buckeye Bridge	Perpen. to traffic	1.785	NA
4	Meadowcroft Bridge over Cross Creek	Perpen. to traffic	1.744	3
15	Crown Point Bridge over Lake Champlain (Parallel)	Parallel to traffic	1.614	296
23	West Street over Chicopee River	Perpen. to traffic	1.511	595
7	Interstate 55 over Des Plaines River	Perpen. to traffic	1.144	7014
9	Tarentum Bridge	Perpen. to traffic	1.144	1855
8	Pennsylvania Turnpike over the Allegheny River	Perpen. to traffic	1.138	7020
11	Jerome Street Bridge	Perpen. to traffic	1.113	1007
22	State Route 601 over Pennsylvania Turnpike	Perpen. to traffic	1.013	1348
5	Gold Star Bridge	Perpen. to traffic	0.998	6958
13	Crown Point Bridge over Lake Champlain (Perpen.)	Perpen. to traffic	0.859	296
1	Green Island Bridge	Perpen. to traffic	0.846	890
12	Ohio State Route 611 over Blackriver Shipping Cen.	Perpen. to traffic	0.811	360
10	US Route 6 over CSX and Black River	Perpen. to traffic	0.810	220
24	Westbound GA Route 53 over Lake Lanier	Perpen. to traffic	0.791	1265
19	Gypsy Bridge (US 19 over West Fork River)	Perpen. to traffic	0.717	NA
16	Tobin Bridge, US 1 over Mystic River	Parallel to traffic	0.707	9000
21	Daybrook Bridge (WV State Route 218 over Days Run)	Perpen. to traffic	0.626	NA
18	Cairo Bridge (WV 31 over North Fork Hughes River	Perpen. to traffic	0.621	40
2	Quincy Memorial Bridge	Parallel to traffic	0.613	623
6	Mackinac Bridge	Parallel to traffic	0.590	830
20	US 219 over Tygart Valley River	Parallel to traffic	0.509	204
26	Smithfield Bridge	Perpen. to traffic	0.349	1140
17	WB I-70 over the Missouri River	Perpen. to traffic	0.252	7700
14	North Main Street over Cuyahoga River	Perpen. to traffic	0.250	625

Table 12. Fatigue stress range (negative bending) ranking using AASHTO-LRFD (2004).

Bridge #	Name	Main Bar Direction	SR Negative Bending	ADTT
13	Crown Point Bridge over Lake Champlain (Perpen.)	Perpen. to traffic	15.194	296
17	WB I-70 over the Missouri River	Perpen. to traffic	14.747	7700
26	Smithfield Bridge	Perpen. to traffic	14.532	1140
24	Westbound GA Route 53 over Lake Lanier	Perpen. to traffic	13.804	1265
15	Crown Point Bridge over Lake Champlain (Parallel)	Parallel to traffic	13.645	296
5	Gold Star Bridge	Perpen. to traffic	12.366	6958
22	State Route 601 over Pennsylvania Turnpike	Perpen. to traffic	12.364	1348
3	Country Road 18 over Lake Milton	Perpen. to traffic	12.212	NA
7	Interstate 55 over Des Plaines River	Perpen. to traffic	12.194	7014
9	Tarentum Bridge	Perpen. to traffic	12.194	1855
8	Pennsylvania Turnpike over the Allegheny River	Perpen. to traffic	12.125	7020
11	Jerome Street Bridge	Perpen. to traffic	11.861	1007
14	North Main Street over Cuyahoga River	Perpen. to traffic	11.722	625
25	Upper Buckeye Bridge	Perpen. to traffic	11.674	NA
12	Ohio State Route 611 over Blackriver Shipping Cen.	Perpen. to traffic	11.520	360
10	US Route 6 over CSX and Black River	Perpen. to traffic	11.497	220
23	West Street over Chicopee River	Perpen. to traffic	11.208	595
4	Meadowcroft Bridge over Cross Creek	Perpen. to traffic	11.199	3
21	Daybrook Bridge (WV State Route 218 over Days Run)	Perpen. to traffic	10.831	NA
6	Mackinac Bridge	Parallel to traffic	10.104	830
19	Gypsy Bridge (US 19 over West Fork River)	Perpen. to traffic	9.696	NA
20	US 219 over Tygart Valley River	Parallel to traffic	8.810	204
16	Tobin Bridge, US 1 over Mystic River	Parallel to traffic	8.498	9000
18	Cairo Bridge (WV 31 over North Fork Hughes River	Perpen. to traffic	8.388	40
1	Green Island Bridge	Perpen. to traffic	7.460	890
2	Quincy Memorial Bridge	Parallel to traffic	6.285	623

Table 13. Equivalent stress range considering different fatigue truck axle configurations for rigid support cases.

32 kip Axle	Case 1		Equivalent Range	
	Cycle	Range	Moment (kip-in/in)	Stress (ksi)
	2	-5.07	-4.44	-10.83
	1	-1.27		
Total Cycles	3			

32 kip Tandem	Case 1		Equivalent Range	
	Cycle	Range	Moment (kip-in/in)	Stress (ksi)
	2	-2.54	-2.18	-5.33
	2	-2.06		
	1	-1.27		
Total Cycles	5			

32 kip Axle	Case 2		Equivalent Range	
	Cycle	Range	Moment (kip-in/in)	Stress (ksi)
	2	4.77	4.18	5.88
	1	1.19		
Total Cycles	3			

32 kip Tandem	Case 2		Equivalent Range	
	Cycle	Range	Moment (kip-in/in)	Stress (ksi)
	2	2.40	2.00	2.82
	2	1.76		
	1	1.19		
Total Cycles	5			

Table 14. Equivalent stress range considering different fatigue truck axle configurations for flexible supports.

32 kip Axle	Case 1		Equivalent Range	
	Cycle	Range	Moment (kip-in/in)	Stress (ksi)
	2	-4.95	-4.33	-10.57
	1	-1.24		
Total Cycles	3			

32 kip Tandem	Case 1		Equivalent Range	
	Cycle	Range	Moment (kip-in/in)	Stress (ksi)
	2	-2.40	-2.16	-5.26
	2	-2.09		
	1	-1.61		
Total Cycles	5			

32 kip Axle	Case 2		Equivalent Range	
	Cycle	Range	Moment (kip-in/in)	Stress (ksi)
	1	5.04	4.47	6.30
	1	5.18		
	1	1.26		
Total Cycles	3			

32 kip Tandem	Case 2		Equivalent Range	
	Cycle	Range	Moment (kip-in/in)	Stress (ksi)
	1	2.66	2.12	2.98
	1	2.53		
	2	1.74		
	1	1.26		
Total Cycles	5			

Table 15.Current AASHTO-LRFD (2004) fatigue stress and projected life for positive moment.

Bridge #	Name	ADTT	Inst. Y.	Y. in ser.	N	N occurred	C=0.8		C=1	
							SR pos. (ksi)	Fat L. (Y.)	SR pos. (ksi)	Fat. L. (Y.)
1	Green Island Bridge Lift Span	890	1981	27	3	26,312,850	0.85	Inf.	1.06	Inf. life
2	Quincy Memorial Bridge	623	1983	25	3	17,054,625	0.61	Inf.	0.77	Inf. life
3	Country Road 18 over Lake Milton	NA	1992	16	3	NA	2.20	Inf.	2.75	Inf. life
4	Meadowcroft Bridge over Cross Creek	3	2002	6	3	19,710	1.74	Inf.	2.18	Inf. life
5	Gold Star Bridge	6958	1974	34	3	259,046,340	1.00	Inf.	1.25	Inf. life
6	Mackinac Bridge	830	1957	51	3	46,351,350	0.59	Inf.	0.74	Inf. life
7	Interstate 55 over Des Plaines River	7014	1980	28	3	215,049,240	1.14	Inf.	1.43	Inf. life
8	Pennsylvania Turnpike over the Allegheny River	7020	1986	22	3	169,111,800	1.14	Inf.	1.42	Inf. life
9	Tarentum Bridge	1855	1987	21	3	42,655,725	1.14	Inf.	1.43	Inf. life
10	US Route 6 over CSX and Black River	220	1988	20	3	4,818,000	0.81	Inf.	1.01	Inf. life
11	Jerome Street Bridge	1007	1989	19	3	20,950,635	1.11	Inf.	1.39	Inf. life
12	Ohio State Route 611 over Blackriver Shipping Cen.	360	1991	17	3	6,701,400	0.81	Inf.	1.01	Inf. life
13	Crown Point Bridge over Lake Champlain (Perpen.)	296	1991	17	3	5,510,040	0.86	Inf.	1.07	Inf. life
14	North Main Street over Cuyahoga River	625	1993	15	3	10,265,625	0.25	Inf.	0.31	Inf. life
15	Crown Point Bridge over Lake Champlain (Parallel)	296	1991	17	3	5,510,040	1.61	Inf.	2.02	Inf. life
16	Tobin Bridge, US 1 over Mystic River	9000	1980	28	3	275,940,000	0.71	Inf.	0.88	Inf. life
17	WB I-70 over the Missouri River	7700	1979	29	3	244,513,500	0.25	Inf.	0.32	Inf. life
18	Cairo Bridge (WV 31 over North Fork Hughes River	40	1979	29	3	1,270,200	0.62	Inf.	0.78	Inf. life
19	Gypsy Bridge (US 19 over West Fork River)	NA	1980	28	3	NA	0.72	Inf.	0.90	Inf. life
20	US 219 over Tygart Valley River	204	1983	25	3	5,584,500	0.51	Inf.	0.64	Inf. life
21	Daybrook Bridge (WV State Route 218 over Days Run)	NA	1985	23	3	NA	0.63	Inf.	0.78	Inf. life
22	State Route 601 over Pennsylvania Turnpike	1348	1992	16	3	23,616,960	1.01	Inf.	1.27	Inf. life
23	West Street over Chicopee River	595	1993	15	3	9,772,875	1.51	Inf.	1.89	Inf. life
24	Westbound GA Route 53 over Lake Lanier	1265	1993	15	3	20,777,625	0.79	Inf.	0.99	Inf. life
25	Upper Buckeye Bridge	NA	1994	14	3	NA	1.78	Inf.	2.23	Inf. life
26	Smithfield Bridge	1140	1995	13	3	16,227,900	0.35	Inf.	0.44	Inf. life

Table 16.Current AASHTO-LRFD (2004) fatigue stress and projected life for negative moment induced fatigue.

Bridge #	Name	ADTT	Inst. Y.	Y. in ser.	n	N occurred	C=0.8	
							SR neg. (ksi)	Fat. L. (Years)
1	Green Island Bridge Lift Span	890	1981	27	3	26,312,850	7.5	10.9
2	Quincy Memorial Bridge	623	1983	25	3	17,054,625	6.3	26.0
3	Country Road 18 over Lake Milton	NA	1992	16	3	NA	12.2	NA
4	Meadowcroft Bridge over Cross Creek	3	2002	6	3	19,710	11.2	>75 years
5	Gold Star Bridge	6958	1974	34	3	259,046,340	12.4	0.3
6	Mackinac Bridge	830	1957	51	3	46,351,350	10.1	4.7
7	Interstate 55 over Des Plaines River	7014	1980	28	3	215,049,240	12.2	0.3
8	Pennsylvania Turnpike over the Allegheny River	7020	1986	22	3	169,111,800	12.1	0.3
9	Tarentum Bridge	1855	1987	21	3	42,655,725	12.2	1.2
10	US Route 6 over CSX and Black River	220	1988	20	3	4,818,000	11.5	12.0
11	Jerome Street Bridge	1007	1989	19	3	20,950,635	11.9	2.4
12	Ohio State Route 611 over Blackriver Shipping Cen.	360	1991	17	3	6,701,400	11.5	7.3
13	Crown Point Bridge over Lake Champlain (Perpen.)	296	1991	17	3	5,510,040	15.2	3.9
14	North Main Street over Cuyahoga River	625	1993	15	3	10,265,625	11.7	4.0
15	Crown Point Bridge over Lake Champlain (Parallel)	296	1991	17	3	5,510,040	13.6	5.3
16	Tobin Bridge, US 1 over Mystic River	9000	1980	28	3	275,940,000	8.5	0.7
17	WB I-70 over the Missouri River	7700	1979	29	3	244,513,500	14.7	0.2
18	Cairo Bridge (WV 31 over North Fork Hughes River	40	1979	29	3	1,270,200	8.4	>75 years
19	Gypsy Bridge (US 19 over West Fork River)	NA	1980	28	3	NA	9.7	NA
20	US 219 over Tygart Valley River	204	1983	25	3	5,584,500	8.8	28.8
21	Daybrook Bridge (WV State Route 218 over Days Run)	NA	1985	23	3	NA	10.8	NA
22	State Route 601 over Pennsylvania Turnpike	1348	1992	16	3	23,616,960	12.4	1.6
23	West Street over Chicopee River	595	1993	15	3	9,772,875	11.2	4.8
24	Westbound GA Route 53 over Lake Lanier	1265	1993	15	3	20,777,625	13.8	1.2
25	Upper Buckeye Bridge	NA	1994	14	3	NA	11.7	NA
26	Smithfield Bridge	1140	1995	13	3	16,227,900	14.5	1.1

Table 17.Negative moment with modified fatigue tandem (1/2) and support section (0.9) (**BOLD=Stress below 5 ksi for Category C detail**).

Bridge #	Name	ADTT	Inst. Y.	Y. in ser.	n	N occurred	C=0.8	
							SR neg. (ksi)	Fat. L. (Years)
1	Green Island Bridge Lift Span	890	1981	27	5	43,854,750	3.4	**Inf. life**
2	Quincy Memorial Bridge	623	1983	25	5	28,424,375	2.8	**Inf. life**
3	Country Road 18 over Lake Milton	NA	1992	16	5	NA	5.5	NA
4	Meadowcroft Bridge over Cross Creek	3	2002	6	5	32,850	5.0	**Inf. life**
5	Gold Star Bridge	6958	1974	34	5	431,743,900	5.6	2.0
6	Mackinac Bridge	830	1957	51	5	77,252,250	4.5	**Inf. life**
7	Interstate 55 over Des Plaines River	7014	1980	28	5	358,415,400	5.5	2.1
8	Pennsylvania Turnpike over the Allegheny River	7020	1986	22	5	281,853,000	5.5	2.1
9	Tarentum Bridge	1855	1987	21	5	71,092,875	5.5	7.9
10	US Route 6 over CSX and Black River	220	1988	20	5	8,030,000	5.2	>75 years
11	Jerome Street Bridge	1007	1989	19	5	34,917,725	5.3	15.7
12	Ohio State Route 611 over Blackriver Shipping Cen.	360	1991	17	5	11,169,000	5.2	48.1
13	Crown Point Bridge over Lake Champlain (Perpen.)	296	1991	17	5	9,183,400	6.8	25.5
14	North Main Street over Cuyahoga River	625	1993	15	5	17,109,375	5.3	26.3
15	Crown Point Bridge over Lake Champlain (Parallel)	296	1991	17	5	9,183,400	6.1	35.2
16	Tobin Bridge, US 1 over Mystic River	9000	1980	28	5	459,900,000	3.8	**Inf. life**
17	WB I-70 over the Missouri River	7700	1979	29	5	407,522,500	6.6	1.1
18	Cairo Bridge (WV 31 over North Fork Hughes River	40	1979	29	5	2,117,000	3.8	**Inf. life**
19	Gypsy Bridge (US 19 over West Fork River)	NA	1980	28	5	NA	4.4	**Inf. life**
20	US 219 over Tygart Valley River	204	1983	25	5	9,307,500	4.0	**Inf. life**
21	Daybrook Bridge (WV State Route 218 over Days Run)	NA	1985	23	5	NA	4.9	**Inf. life**
22	State Route 601 over Pennsylvania Turnpike	1348	1992	16	5	39,361,600	5.6	10.4
23	West Street over Chicopee River	595	1993	15	5	16,288,125	5.0	**Inf. life**
24	Westbound GA Route 53 over Lake Lanier	1265	1993	15	5	34,629,375	6.2	8.0
25	Upper Buckeye Bridge	NA	1994	14	5	NA	5.3	NA
26	Smithfield Bridge	1140	1995	13	5	27,046,500	6.5	7.6

Table 18. Moment ranges determined from FEA and AASHTO Fatigue Moment for main bars transverse to traffic.

L=5 D	AASHTO Fatigue Moment (1)	FEA Truck (2)	n	FEA Tan. Equiv. (3)	n	1/2	1/3	2/3
1	-2.24	-2.01	3	-0.98	5	1.11	2.28	2.05
2	-2.56	-2.38	3	-1.10	5	1.08	2.33	2.16
2.5	-2.68	-2.51	3	-1.14	5	1.07	2.35	2.20
8	-3.37	-3.31	3	-1.51	5	1.02	2.23	2.19
10	-3.52	-3.49	3	-1.61	5	1.01	2.19	2.17

L=10 D	AASHTO Fatigue Moment (1)	FEA Truck (2)	n	FEA Tan. Equiv. (3)	n	1/2	1/3	2/3
1	-3.07	-3.09	3	-1.69	5	0.99	1.82	1.83
2	-3.52	-3.73	3	-1.9	5	0.94	1.85	1.96
2.5	-3.68	-3.95	3	-1.98	5	0.93	1.86	1.99
8	-4.63	-5.3	3	-2.47	5	0.87	1.87	2.15
10	-4.84	-5.59	3	-2.59	5	0.87	1.87	2.16

L=15 D	AASHTO Fatigue Moment (1)	FEA Truck (2)	n	FEA Tan. Equiv. (3)	n	1/2	1/3	2/3
1	-4.66	-3.26	3	-1.83	5	1.43	2.55	1.78
2	-5.31	-3.96	3	-2.08	5	1.34	2.55	1.90
2.5	-5.53	-4.21	3	-2.17	5	1.31	2.55	1.94
8	-6.89	-5.7	3	-2.73	5	1.21	2.52	2.09
10	-7.18	-6.02	3	-2.86	5	1.19	2.51	2.10

Table 19. Moment ranges determined from FEA and AASHTO Fatigue Moment for main bars parallel to traffic.

L=5 D	AASHTO Fatigue Moment (1)	FEA Truck (2)	n	FEA Tan. Equiv. (3)	n	1/2	1/3	2/3
1	-2.67	-1.42	6	-0.98	8	1.88	2.73	1.45
2	-2.91	-1.62	6	-1.12	8	1.80	2.60	1.45
2.5	-2.99	-1.69	6	-1.17	8	1.77	2.56	1.44
8	-3.45	-2.06	6	-1.43	8	1.68	2.42	1.44
10	-3.55	-2.14	6	-1.48	8	1.66	2.40	1.45

L=10 D	AASHTO Fatigue Moment (1)	FEA Truck (2)	n	FEA Tan. Equiv. (3)	n	1/2	1/3	2/3
1	-4.17	-1.91	5	-1.36	7	2.18	3.06	1.40
2	-4.54	-2.09	5	-1.54	7	2.17	2.95	1.36
2.5	-4.67	-2.18	5	-1.62	7	2.14	2.88	1.35
8	-5.38	-2.74	5	-1.96	7	1.96	2.75	1.40
10	-5.53	-2.83	5	-2.08	7	1.96	2.66	1.36

L=15 D	AASHTO Fatigue Moment (1)	FEA Truck (2)	n	FEA Tan. Equiv. (3)	n	1/2	1/3	2/3
1	-6.06	-2.30	5	-1.59	7	2.63	3.81	1.45
2	-6.67	-2.57	5	-1.77	7	2.59	3.77	1.45
2.5	-6.87	-2.66	5	-1.84	7	2.58	3.74	1.45
8	-8.07	-3.20	5	-2.2	7	2.52	3.67	1.45
10	-8.32	-3.34	5	-2.28	7	2.49	3.65	1.46

Table 20.Negative moment with modified fatigue tandem (1/2 and 1/2.5) and support section (0.9) (**BOLD=Stress below 5 ksi for Category C detail**).

Bridge #	Name	ADTT	Inst. Y.	Y. in ser.	n	N occurred	C=0.8	
							SR neg. (ksi)	Fat. L. (Years)
1	Green Island Bridge Lift Span	890	1981	27	5	43,854,750	3.4	**Inf. life**
2	Quincy Memorial Bridge	623	1983	25	8	45479000	2.2	**Inf. life**
3	Country Road 18 over Lake Milton	NA	1992	16	5	NA	5.5	NA
4	Meadowcroft Bridge over Cross Creek	3	2002	6	5	32,850	5.0	**Inf. life**
5	Gold Star Bridge	6958	1974	34	5	431,743,900	5.6	2.0
6	Mackinac Bridge	830	1957	51	8	123,603,600	3.6	**Inf. life**
7	Interstate 55 over Des Plaines River	7014	1980	28	5	358,415,400	5.5	2.1
8	Pennsylvania Turnpike over the Allegheny River	7020	1986	22	5	281,853,000	5.5	2.1
9	Tarentum Bridge	1855	1987	21	5	71,092,875	5.5	7.9
10	US Route 6 over CSX and Black River	220	1988	20	5	8,030,000	5.2	>75 years
11	Jerome Street Bridge	1007	1989	19	5	34,917,725	5.3	15.7
12	Ohio State Route 611 over Blackriver Shipping Cen.	360	1991	17	5	11,169,000	5.2	48.1
13	Crown Point Bridge over Lake Champlain (Perpen.)	296	1991	17	5	9,183,400	6.8	25.5
14	North Main Street over Cuyahoga River	625	1993	15	5	17,109,375	5.3	26.3
15	Crown Point Bridge over Lake Champlain (Parallel)	296	1991	17	7	12,856,760	4.88	**Inf. life**
16	Tobin Bridge, US 1 over Mystic River	9000	1980	28	8	735,840,000	3.1	**Inf. life**
17	WB I-70 over the Missouri River	7700	1979	29	5	407,522,500	6.6	1.1
18	Cairo Bridge (WV 31 over North Fork Hughes River	40	1979	29	5	2,117,000	3.8	**Inf. life**
19	Gypsy Bridge (US 19 over West Fork River)	NA	1980	28	5	NA	4.4	**Inf. life**
20	US 219 over Tygart Valley River	204	1983	25	8	14,892,000	3.2	**Inf. life**
21	Daybrook Bridge (WV State Route 218 over Days Run)	NA	1985	23	5	NA	4.9	**Inf. life**
22	State Route 601 over Pennsylvania Turnpike	1348	1992	16	5	39,361,600	5.6	10.4
23	West Street over Chicopee River	595	1993	15	5	16,288,125	5.0	**Inf. life**
24	Westbound GA Route 53 over Lake Lanier	1265	1993	15	5	34,629,375	6.2	8.0
25	Upper Buckeye Bridge	NA	1994	14	5	NA	5.3	NA
26	Smithfield Bridge	1140	1995	13	5	27,046,500	6.5	7.6

Table 21. Span lengths calculated from limiting positive moment to first yield $M_{Positive\ yielding}$.

Bridge #	Name	Main Bar D.	Span (ft)	Strength			
				Mpos (kip-in/in)	M yield (kip-in/in)	L_str. (ft)	L_str./L.
1	Green Island Bridge	Per.	10.17	14.69	18.79	12.88	1.27
2	Quincy Memorial Bridge	Par.	4.83	10.50	17.55	10.78	2.23
3	Country Road 18 over Lake Milton	Per.	8.17	11.90	19.41	23.72	2.90
4	Meadowcroft Bridge over Cross Creek	Per.	10.00	13.47	22.64	30.97	3.10
5	Gold Star Bridge	Per.	6.67	12.75	13.07	7.03	1.05
6	Mackinac Bridge	Par.	5.00	12.31	15.74	7.33	1.47
7	Interstate 55 over Des Plaines River	Per.	6.50	12.04	15.81	11.77	1.81
8	Pennsylvania Turnpike over the Allegheny River	Per.	6.42	11.97	15.81	11.77	1.83
9	Tarentum Bridge	Per.	6.50	12.04	15.81	11.77	1.81
10	US Route 6 over CSX and Black River	Per.	6.33	11.35	21.08	24.39	3.85
11	Jerome Street Bridge	Per.	6.12	11.71	15.81	11.77	1.92
12	Ohio State Route 611 over Blackriver Shipping Cen.	Per.	6.33	11.37	21.08	24.28	3.84
13	Crown Point Bridge over Lake Champlain (Perpen.)	Per.	6.37	11.39	12.03	7.18	1.13
14	North Main Street over Cuyahoga River	Per.	6.38	11.57	18.61	17.97	2.82
15	Crown Point Bridge over Lake Champlain (Parallel)	Par.	8.00	16.05	18.80	10.25	1.28
16	Tobin Bridge, US 1 over Mystic River	Par.	6.46	18.25	20.96	8.02	1.24
17	WB I-70 over the Missouri River	Per.	7.13	19.51	20.38	7.84	1.10
18	Cairo Bridge (WV 31 over North Fork Hughes River	Per.	4.50	16.02	20.96	8.09	1.80
19	Gypsy Bridge (US 19 over West Fork River)	Per.	6.17	18.51	20.96	8.09	1.31
20	US 219 over Tygart Valley River	Par.	4.25	13.92	19.61	7.26	1.71
21	Daybrook Bridge (WV State Route 218 over Days Run)	Per.	5.25	17.11	19.61	7.06	1.35
22	State Route 601 over Pennsylvania Turnpike	Per.	4.67	15.63	15.86	4.83	1.03
23	West Street over Chicopee River	Per.	5.50	17.16	17.49	5.73	1.04
24	Westbound GA Route 53 over Lake Lanier	Per.	4.33	14.99	15.56	4.70	1.08
25	Upper Buckeye Bridge	Per.	8.25	18.44	23.66	14.20	1.72
26	Smithfield Bridge	Per.	6.00	18.02	19.19	6.88	1.15
Average			**6.40**	**14.33**	**18.32**	**11.79**	**1.80**

Table 22. Span length calculated from limiting stress range to Category C (5 ksi).

Bridge #	Name	Main Bar D.	Span (ft)	Fatigue Positive			
				SR (ksi)	Cat. C (5 ksi)	L_fat_pos (ft)	L_fat_pos/L
1	Green Island Bridge	Per.	10.17	1.057	5.000	209.81	20.63
2	Quincy Memorial Bridge	Par.	4.83	0.766	5.000	90.63	18.76
3	Country Road 18 over Lake Milton	Per.	8.17	2.752	5.000	30.01	3.67
4	Meadowcroft Bridge over Cross Creek	Per.	10.00	2.180	5.000	61.02	6.10
5	Gold Star Bridge	Per.	6.67	1.247	5.000	137.39	20.60
6	Mackinac Bridge	Par.	5.00	0.737	5.000	99.56	19.91
7	Interstate 55 over Des Plaines River	Per.	6.50	1.430	5.000	99.37	15.29
8	Pennsylvania Turnpike over the Allegheny River	Per.	6.42	1.422	5.000	99.37	15.48
9	Tarentum Bridge	Per.	6.50	1.430	5.000	99.37	15.29
10	US Route 6 over CSX and Black River	Per.	6.33	1.012	5.000	205.52	32.47
11	Jerome Street Bridge	Per.	6.12	1.391	5.000	99.32	16.23
12	Ohio State Route 611 over Blackriver Shipping Cen.	Per.	6.33	1.014	5.000	204.66	32.33
13	Crown Point Bridge over Lake Champlain (Perpen.)	Per.	6.37	1.074	5.000	181.62	28.51
14	North Main Street over Cuyahoga River	Per.	6.38	0.312	5.000	2681.26	420.26
15	Crown Point Bridge over Lake Champlain (Parallel)	Par.	8.00	2.017	5.000	33.05	4.13
16	Tobin Bridge, US 1 over Mystic River	Par.	6.46	0.884	5.000	96.84	14.99
17	WB I-70 over the Missouri River	Per.	7.13	0.315	5.000	2941.20	412.80
18	Cairo Bridge (WV 31 over North Fork Hughes River	Per.	4.50	0.776	5.000	260.69	57.93
19	Gypsy Bridge (US 19 over West Fork River)	Per.	6.17	0.897	5.000	260.69	42.25
20	US 219 over Tygart Valley River	Par.	4.25	0.636	5.000	106.54	25.07
21	Daybrook Bridge (WV State Route 218 over Days Run)	Per.	5.25	0.782	5.000	298.96	56.94
22	State Route 601 over Pennsylvania Turnpike	Per.	4.67	1.266	5.000	93.03	19.92
23	West Street over Chicopee River	Per.	5.50	1.888	5.000	45.89	8.34
24	Westbound GA Route 53 over Lake Lanier	Per.	4.33	0.989	5.000	147.92	34.16
25	Upper Buckeye Bridge	Per.	8.25	2.231	5.000	47.87	5.80
26	Smithfield Bridge	Per.	6.00	0.437	5.000	1215.49	202.58
Average			**6.40**	**1.190**	**5.000**	**378.73**	**59.63**

Table 23. Span length calculated at limit of L/800.

Bridge #	Name	Main Bar D.	Span (ft)	Deflection			
				Δ (in)	L/800	L_def (ft)	L_deflection/L
1	Green Island Bridge	Per.	10.17	0.308	0.153	8.05	0.79
2	Quincy Memorial Bridge	Par.	4.83	0.043	0.072	5.76	1.19
3	Country Road 18 over Lake Milton	Per.	8.17	0.115	0.123	8.35	1.02
4	Meadowcroft Bridge over Cross Creek	Per.	10.00	0.198	0.150	9.12	0.91
5	Gold Star Bridge	Per.	6.67	0.173	0.100	5.55	0.83
6	Mackinac Bridge	Par.	5.00	0.077	0.075	4.96	0.99
7	Interstate 55 over Des Plaines River	Per.	6.50	0.131	0.098	5.89	0.91
8	Pennsylvania Turnpike over the Allegheny River	Per.	6.42	0.126	0.096	5.87	0.91
9	Tarentum Bridge	Per.	6.50	0.131	0.098	5.89	0.91
10	US Route 6 over CSX and Black River	Per.	6.33	0.070	0.095	7.01	1.11
11	Jerome Street Bridge	Per.	6.12	0.109	0.092	5.77	0.94
12	Ohio State Route 611 over Blackriver Shipping Cen.	Per.	6.33	0.070	0.095	7.01	1.11
13	Crown Point Bridge over Lake Champlain (Perpen.)	Per.	6.37	0.149	0.096	5.49	0.86
14	North Main Street over Cuyahoga River	Per.	6.38	0.089	0.096	6.52	1.02
15	Crown Point Bridge over Lake Champlain (Parallel)	Par.	8.00	0.269	0.120	6.12	0.76
16	Tobin Bridge, US 1 over Mystic River	Par.	6.46	0.121	0.097	6.00	0.93
17	WB I-70 over the Missouri River	Per.	7.13	0.164	0.107	6.18	0.87
18	Cairo Bridge (WV 31 over North Fork Hughes River	Per.	4.50	0.039	0.068	5.40	1.20
19	Gypsy Bridge (US 19 over West Fork River)	Per.	6.17	0.101	0.093	6.00	0.97
20	US 219 over Tygart Valley River	Par.	4.25	0.037	0.064	5.10	1.20
21	Daybrook Bridge (WV State Route 218 over Days Run)	Per.	5.25	0.067	0.079	5.55	1.06
22	State Route 601 over Pennsylvania Turnpike	Per.	4.67	0.055	0.070	5.08	1.09
23	West Street over Chicopee River	Per.	5.50	0.083	0.083	5.50	1.00
24	Westbound GA Route 53 over Lake Lanier	Per.	4.33	0.045	0.065	4.90	1.13
25	Upper Buckeye Bridge	Per.	8.25	0.166	0.124	7.48	0.91
26	Smithfield Bridge	Per.	6.00	0.103	0.090	5.73	0.96
Average			**6.40**	**0.117**	**0.096**	**6.16**	**0.98**

Table 24. Stresses calculated from spans limited to L/800 for positive moment.

Bridge #	Name	Main Bar Direction	L (L/800) (ft)	Dx/Dy	M. (kip-in/in)	Stress (ksi) (Pos.)
1	Green Island Bridge	Perpen. to traffic	8.05	2.87	5.86	15.60
2	Quincy Memorial Bridge	Parallel to traffic	5.76	1.74	6.72	19.13
3	Country Road 18 over Lake Milton	Perpen. to traffic	8.35	1.89	5.80	14.94
4	Meadowcroft Bridge over Cross Creek	Perpen. to traffic	9.12	2.21	6.89	15.23
5	Gold Star Bridge	Perpen. to traffic	5.55	4.30	6.70	25.63
6	Mackinac Bridge	Parallel to traffic	4.96	5.30	7.00	22.26
7	Interstate 55 over Des Plaines River	Perpen. to traffic	5.89	3.40	6.57	20.80
8	Pennsylvania Turnpike over the Allegheny River	Perpen. to traffic	5.87	3.40	6.56	20.76
9	Tarentum Bridge	Perpen. to traffic	5.89	3.40	6.57	20.80
10	US Route 6 over CSX and Black River	Perpen. to traffic	7.01	2.69	6.80	16.12
11	Jerome Street Bridge	Perpen. to traffic	5.77	3.40	6.51	20.61
12	Ohio State Route 611 over Blackriver Shipping Cen.	Perpen. to traffic	7.01	2.71	6.81	16.15
13	Crown Point Bridge over Lake Champlain (Perpen.)	Perpen. to traffic	5.49	2.69	6.08	25.27
14	North Main Street over Cuyahoga River	Perpen. to traffic	6.52	2.91	6.68	17.95
15	Crown Point Bridge over Lake Champlain (Parallel)	Parallel to traffic	6.12	3.95	7.72	20.53
16	Tobin Bridge, US 1 over Mystic River	Parallel to traffic	6.00	34.20	9.95	23.73
17	WB I-70 over the Missouri River	Perpen. to traffic	6.18	31.91	10.44	25.61
18	Cairo Bridge (WV 31 over North Fork Hughes River	Perpen. to traffic	5.40	34.20	9.95	23.73
19	Gypsy Bridge (US 19 over West Fork River)	Perpen. to traffic	6.00	34.20	10.44	24.90
20	US 219 over Tygart Valley River	Parallel to traffic	5.10	33.39	8.94	22.79
21	Daybrook Bridge (WV State Route 218 over Days Run)	Perpen. to traffic	5.55	33.39	10.03	25.58
22	State Route 601 over Pennsylvania Turnpike	Perpen. to traffic	5.08	27.67	9.28	29.24
23	West Street over Chicopee River	Perpen. to traffic	5.50	30.42	9.81	28.04
24	Westbound GA Route 53 over Lake Lanier	Perpen. to traffic	4.90	26.71	9.07	29.14
25	Upper Buckeye Bridge	Perpen. to traffic	7.48	17.04	10.08	21.29
26	Smithfield Bridge	Perpen. to traffic	5.73	31.85	10.08	26.28

Table 25. Stresses calculated from spans limited to L/800 for negative moment.

Bridge #	Name	Main Bar Direction	L (L/800) (ft)	Dx/Dy	M. (kip-in/in)	Stress (ksi) (Neg)
1	Green Island Bridge	Perpen. to traffic	8.05	2.87	4.69	8.55
2	Quincy Memorial Bridge	Parallel to traffic	5.76	1.74	5.37	11.55
3	Country Road 18 over Lake Milton	Perpen. to traffic	8.35	1.89	4.64	17.10
4	Meadowcroft Bridge over Cross Creek	Perpen. to traffic	9.12	2.21	5.52	16.47
5	Gold Star Bridge	Perpen. to traffic	5.55	4.30	5.36	24.31
6	Mackinac Bridge	Parallel to traffic	4.96	5.30	5.60	16.52
7	Interstate 55 over Des Plaines River	Perpen. to traffic	5.89	3.40	5.26	19.14
8	Pennsylvania Turnpike over the Allegheny River	Perpen. to traffic	5.87	3.40	5.25	19.10
9	Tarentum Bridge	Perpen. to traffic	5.89	3.40	5.26	19.14
10	US Route 6 over CSX and Black River	Perpen. to traffic	7.01	2.69	5.44	19.79
11	Jerome Street Bridge	Perpen. to traffic	5.77	3.40	5.21	18.96
12	Ohio State Route 611 over Blackriver Shipping Cen.	Perpen. to traffic	7.01	2.71	5.45	19.82
13	Crown Point Bridge over Lake Champlain (Perpen.)	Perpen. to traffic	5.49	2.69	4.86	23.31
14	North Main Street over Cuyahoga River	Perpen. to traffic	6.52	2.91	5.34	19.45
15	Crown Point Bridge over Lake Champlain (Parallel)	Parallel to traffic	6.12	3.95	6.18	18.87
16	Tobin Bridge, US 1 over Mystic River	Parallel to traffic	6.00	34.20	7.96	13.31
17	WB I-70 over the Missouri River	Perpen. to traffic	6.18	31.91	8.35	22.83
18	Cairo Bridge (WV 31 over North Fork Hughes River	Perpen. to traffic	5.40	34.20	7.96	20.19
19	Gypsy Bridge (US 19 over West Fork River)	Perpen. to traffic	6.00	34.20	8.35	21.19
20	US 219 over Tygart Valley River	Parallel to traffic	5.10	33.39	7.15	19.60
21	Daybrook Bridge (WV State Route 218 over Days Run)	Perpen. to traffic	5.55	33.39	8.03	22.00
22	State Route 601 over Pennsylvania Turnpike	Perpen. to traffic	5.08	27.67	7.42	25.43
23	West Street over Chicopee River	Perpen. to traffic	5.50	30.42	7.84	24.18
24	Westbound GA Route 53 over Lake Lanier	Perpen. to traffic	4.90	26.71	7.25	26.35
25	Upper Buckeye Bridge	Perpen. to traffic	7.48	17.04	8.06	22.10
26	Smithfield Bridge	Perpen. to traffic	5.73	31.85	8.07	23.52

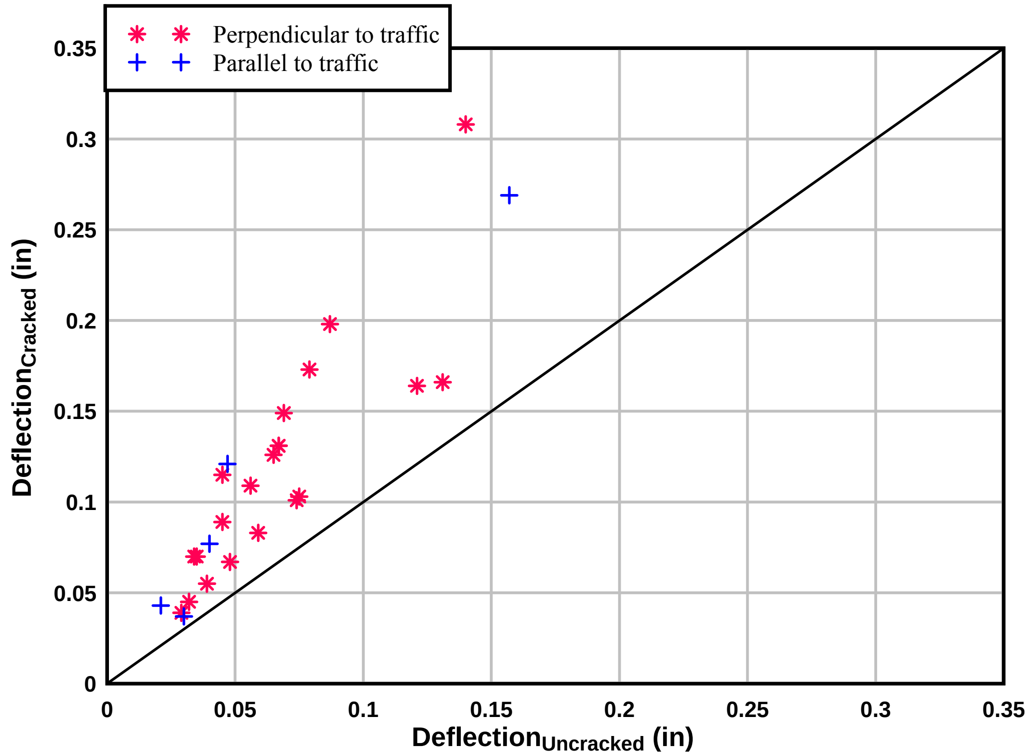


Figure 1. Deflection$_{\text{Cracked}}$ versus Deflection$_{\text{Uncracked}}$ values using AASHTO-LRFD (2004).

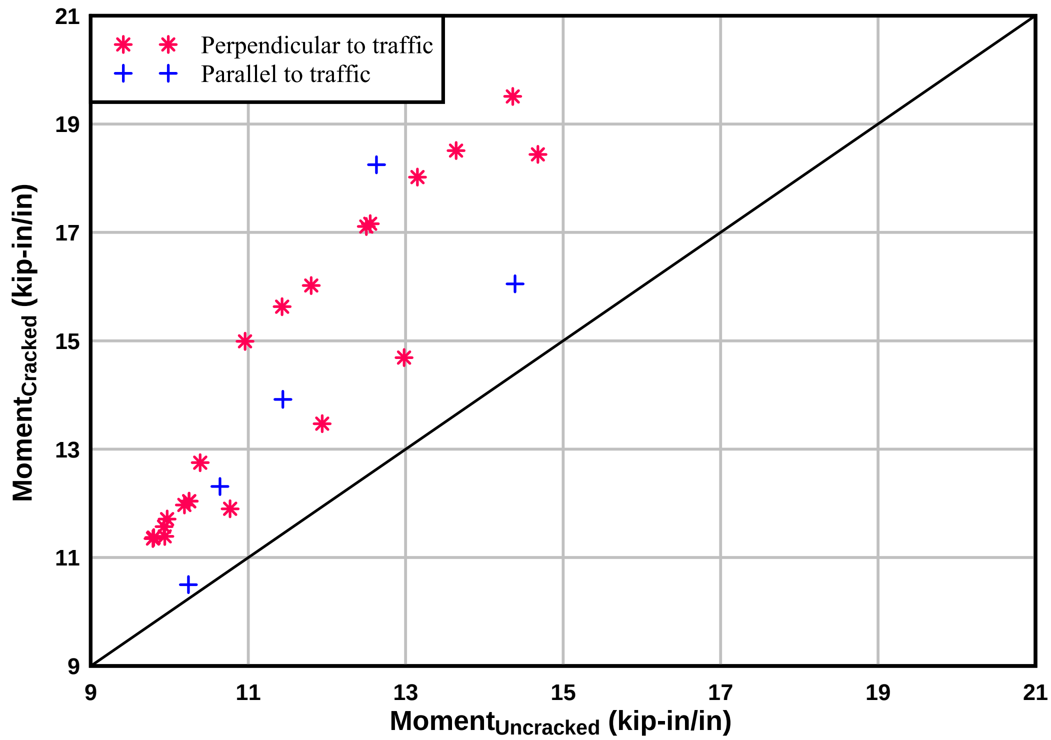


Figure 2. Moment$_{\text{Cracked}}$ versus Moment$_{\text{Uncracked}}$ values usingAASHTO-LRFD (2004).

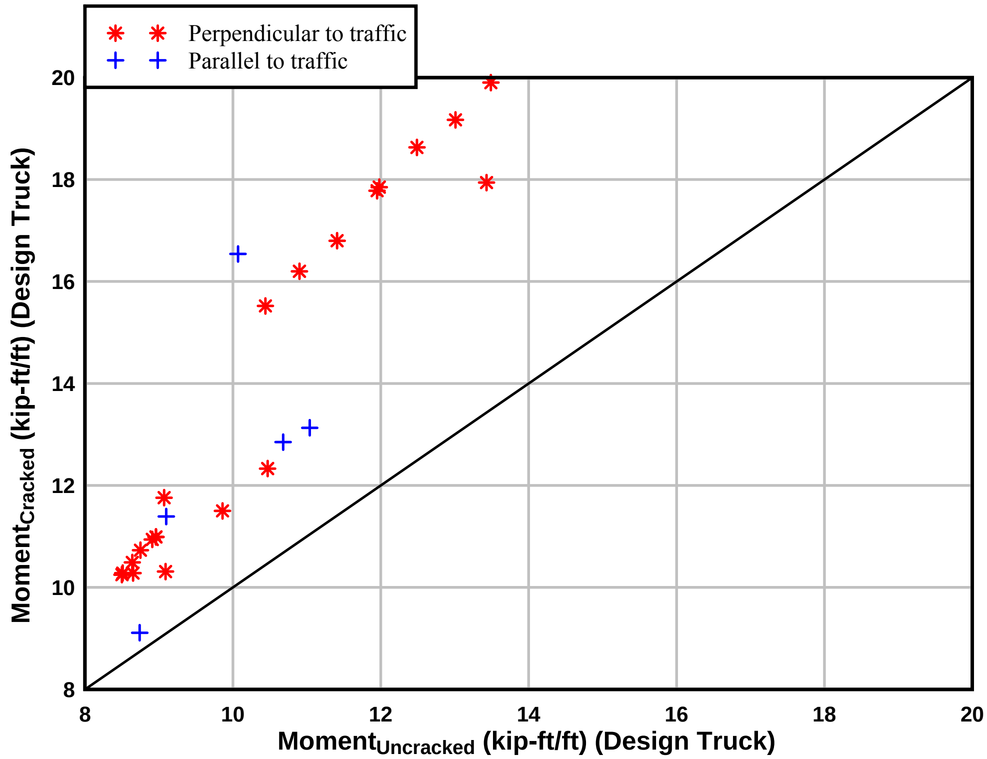


Figure 3 - Moment$_{Cracked}$ versus Moment$_{Uncracked}$ values using AASHTO-LRFD (1994).

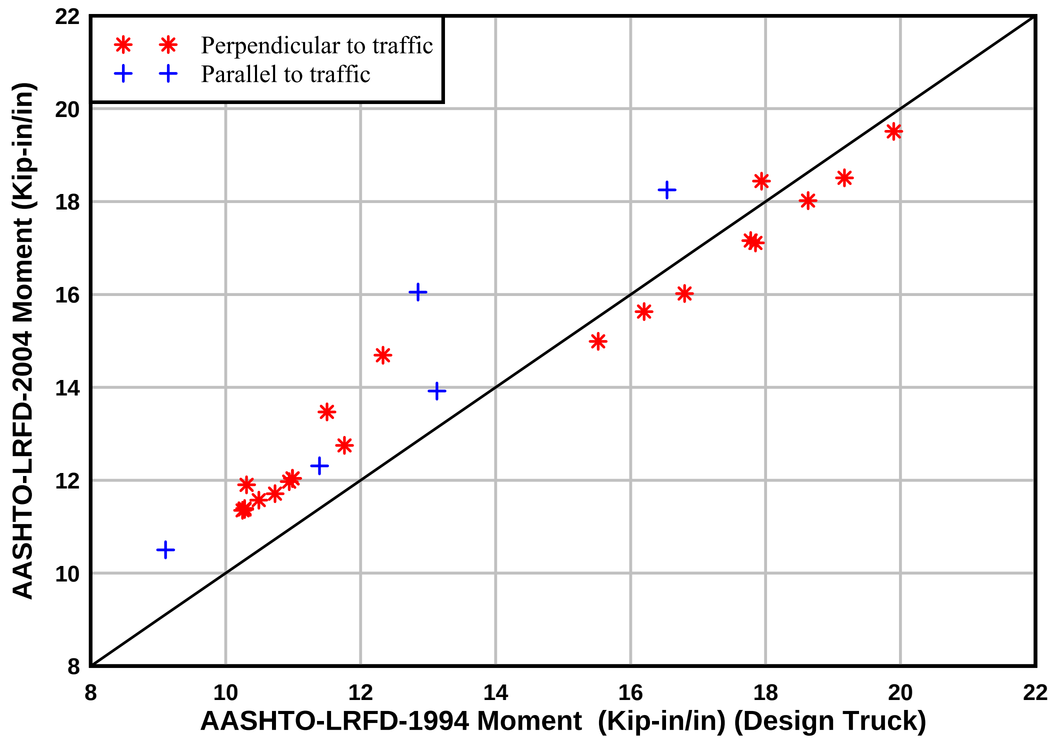


Figure 4 - Moment values for AASHTO-LRFD (1994) and AASHTO-LRFD (2004).

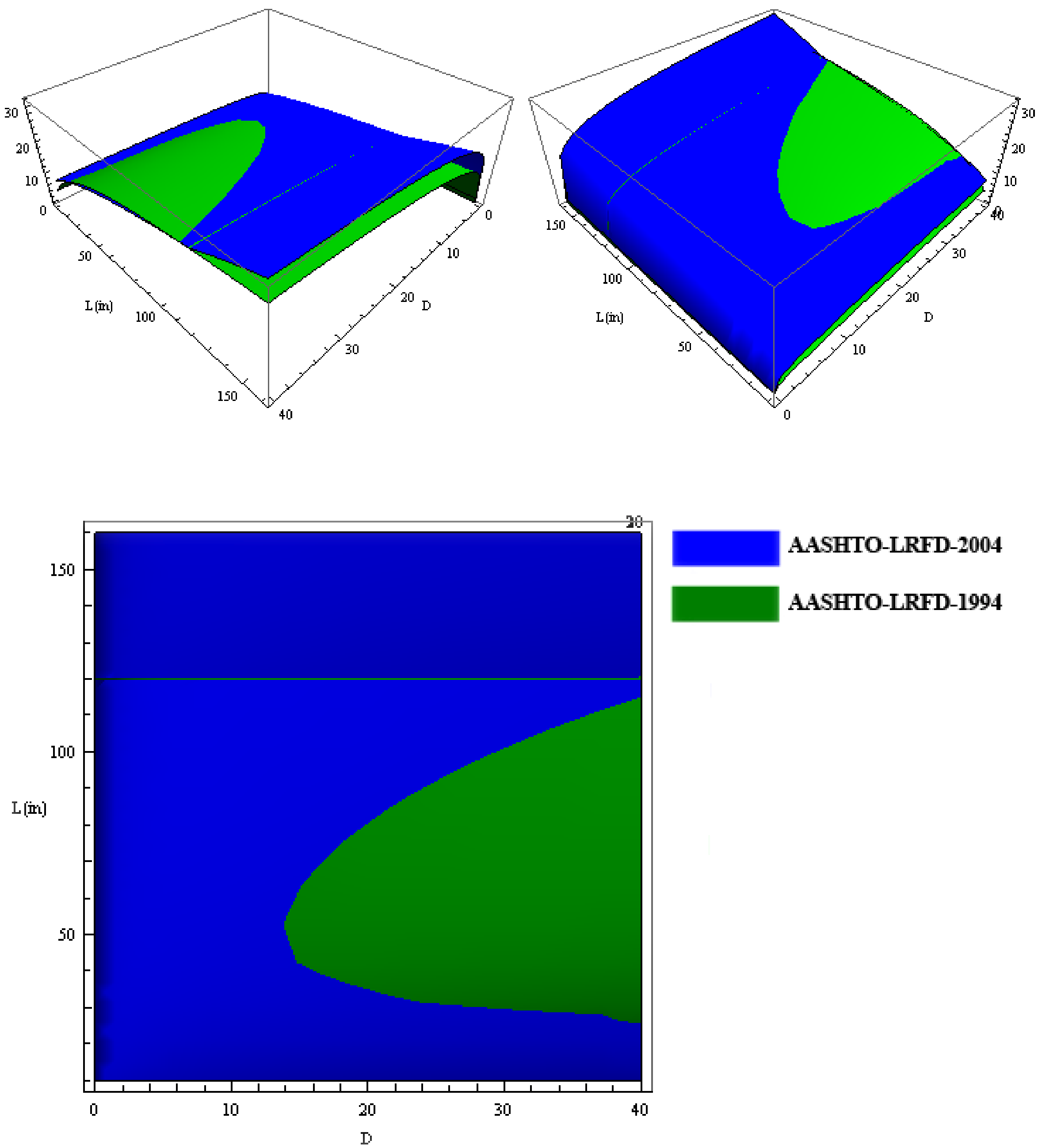


Figure 5 - Different views of AASHTO-LRFD (2004) (design truck) versus AASHTO-LRFD (1994) (design truck) for main bars transverse to traffic and C=1.

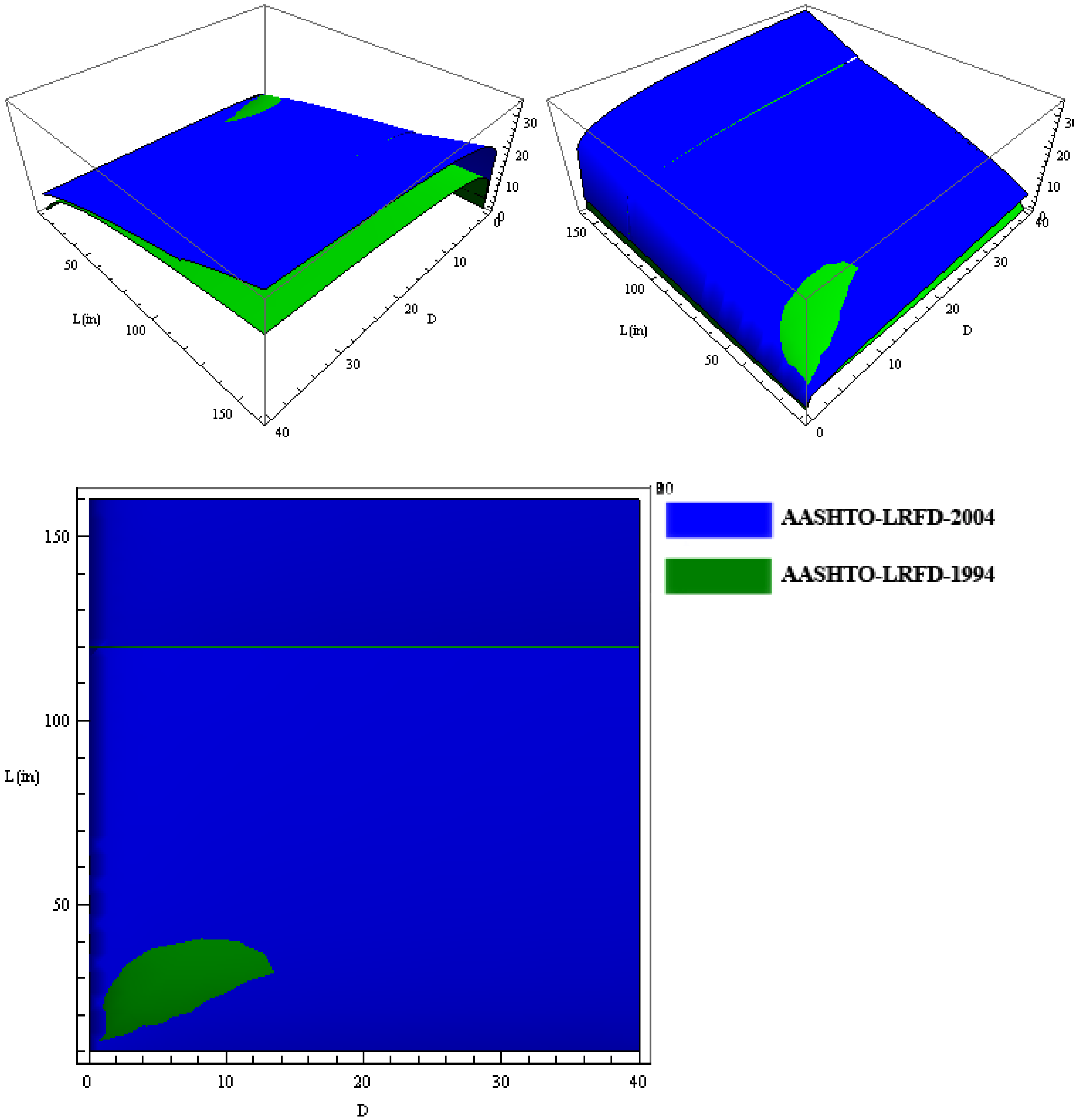


Figure 6 - Different views of AASHTO-LRFD (2004) (design truck) versus AASHTO-LRFD (1994) (design truck) for main bars parallel to traffic and C=1

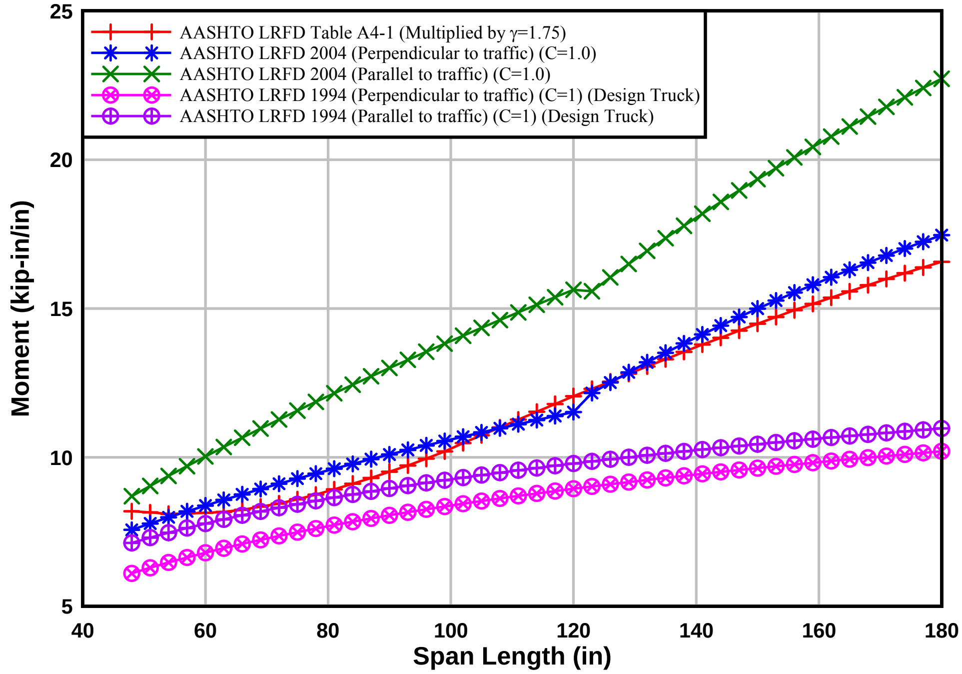


Figure 7 - AASHTO-LRFD (2004), AASHTO-LRFD (1994) moment values for D=1.0 and C=1.0, and AASHTO-LRFD (2004) deck slab design table positive moment values.

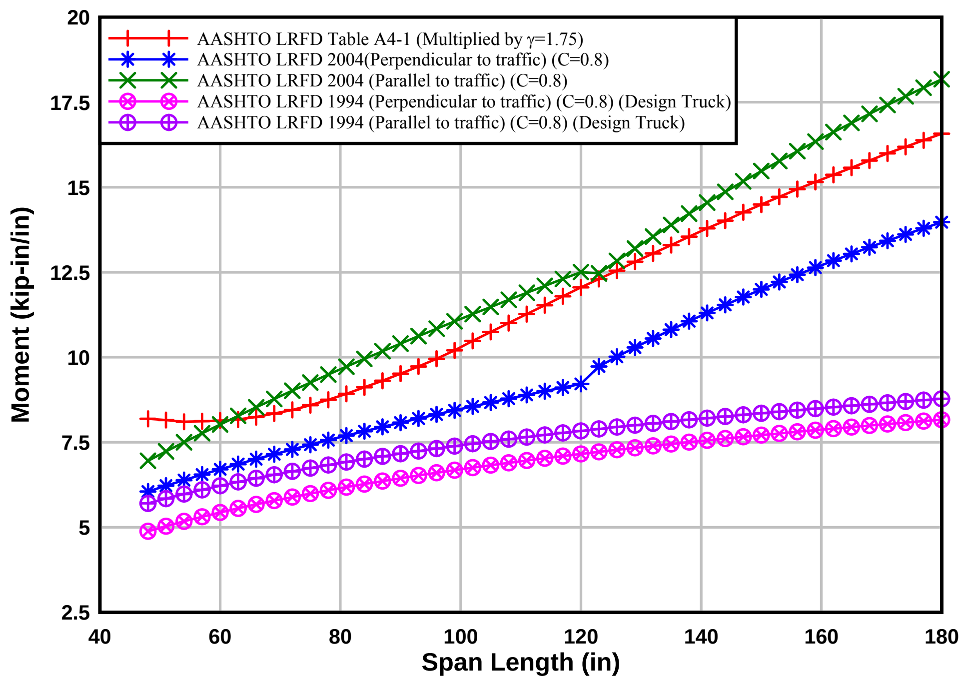


Figure 8 - AASHTO-LRFD (2004), AASHTO-LRFD (1994) moment values for D=1.0 and C=0.8, and AASHTO-LRFD (2004) deck slab design table positive moment values (A4).

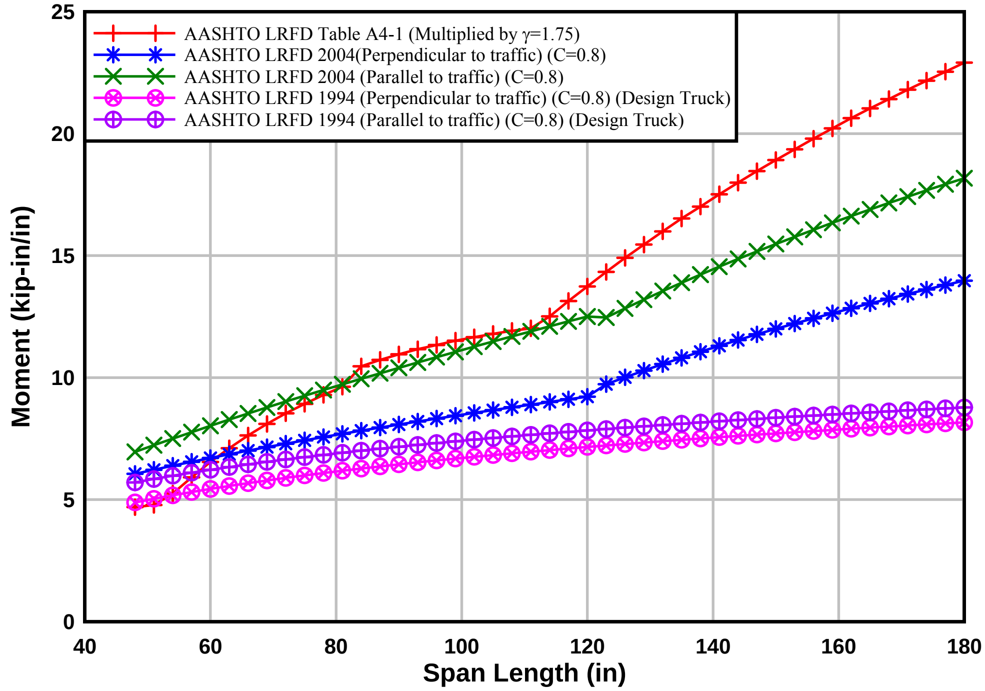


Figure 9 - AASHTO-LRFD (2004), AASHTO-LRFD (1994) moment values for D=1.0 and C=0.8, and AASHTO-LRFD (2004) deck slab design table negative moment values (A4).

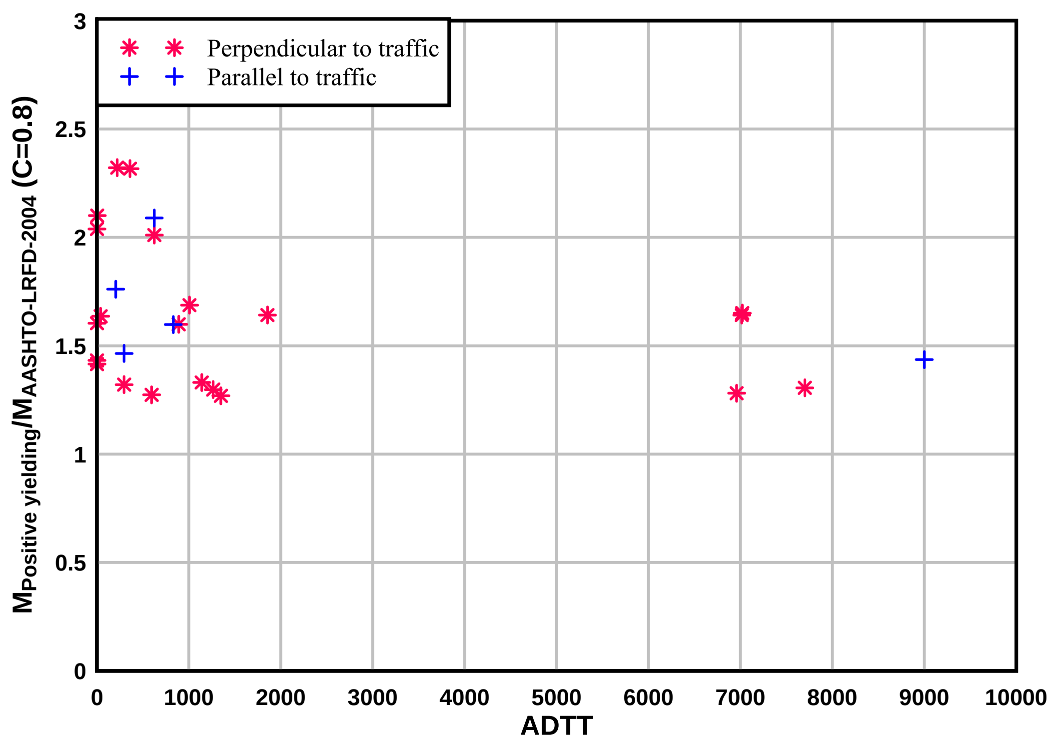


Figure 10 - ADTT versus strength $M_{\text{Positive yielding}}/M_{\text{AASHTO-LRFD (2004)}}$.

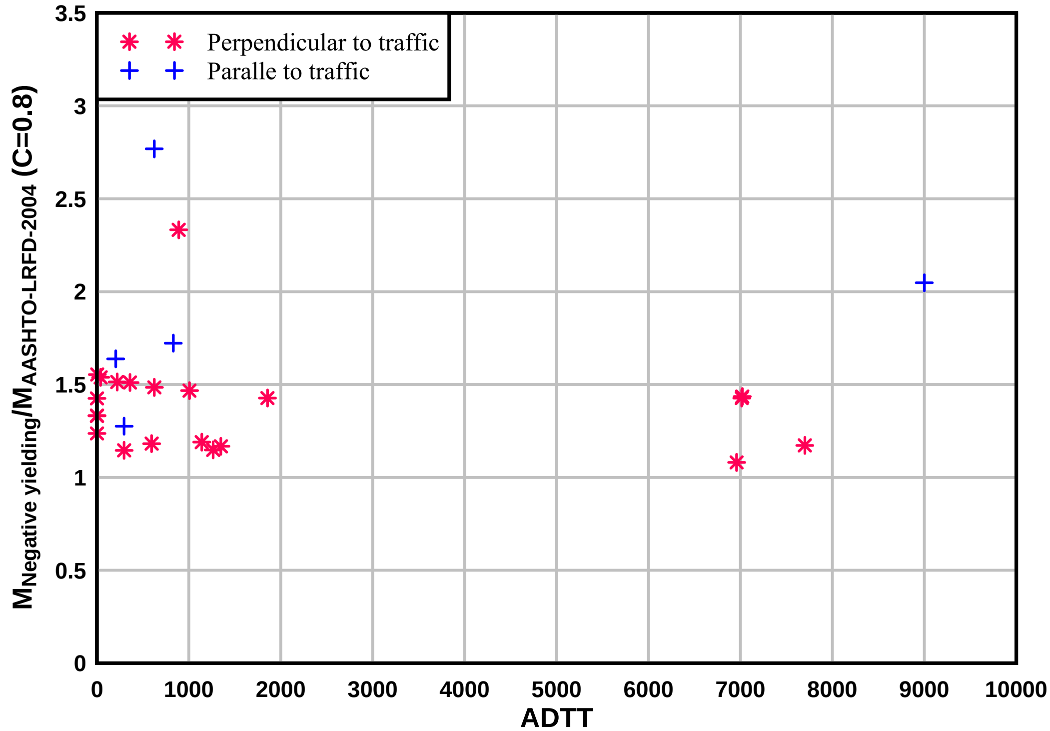


Figure 11 - ADTT versus strength $M_{\text{Negative yielding}}/M_{\text{AASHTO-LRFD (2004)}}$.

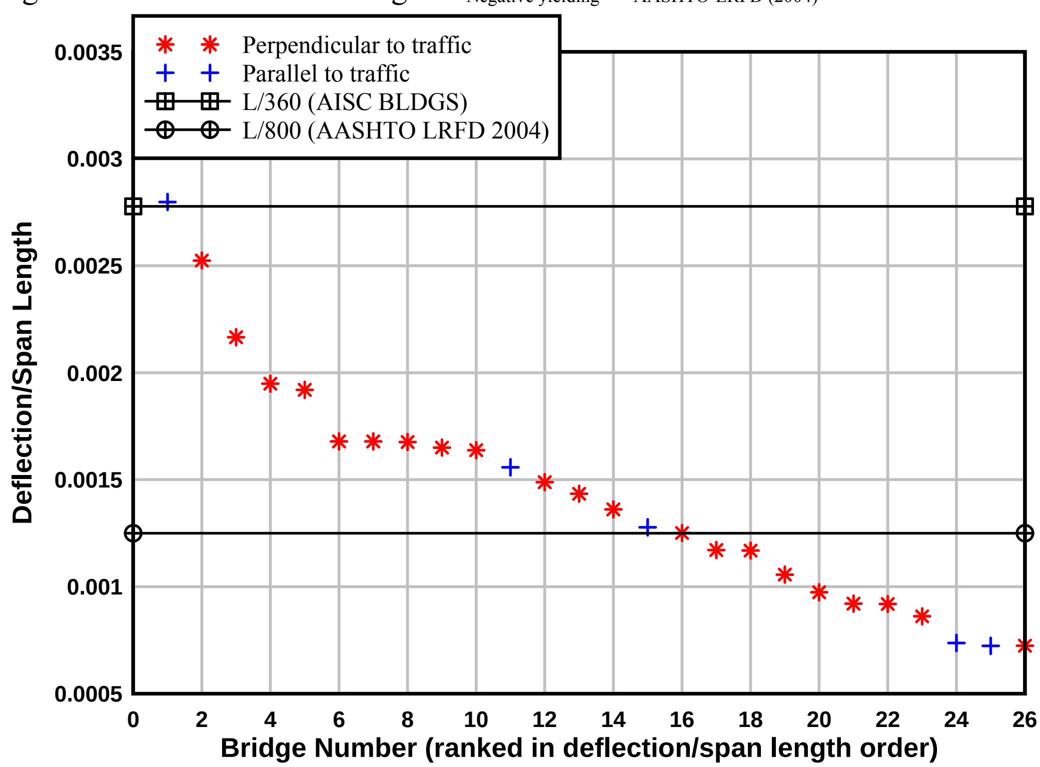


Figure 12 - Rank order of deflection/span length with specification reference deflection limits.

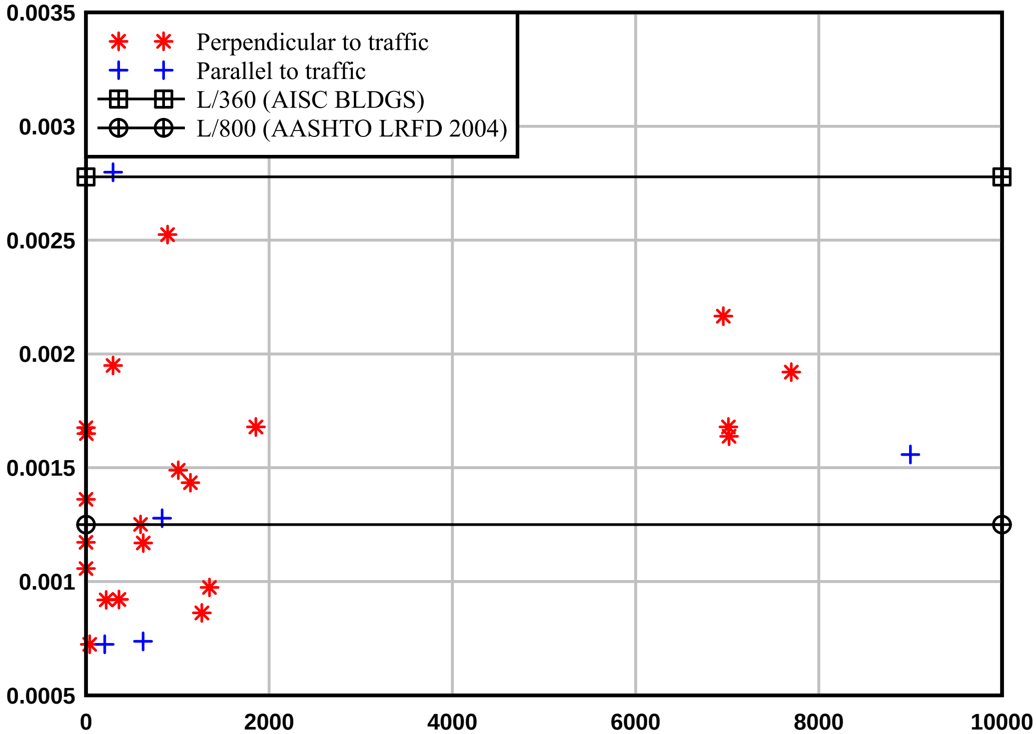


Figure 13 - Deflection/span length versus ADTT with specification reference deflection limits.

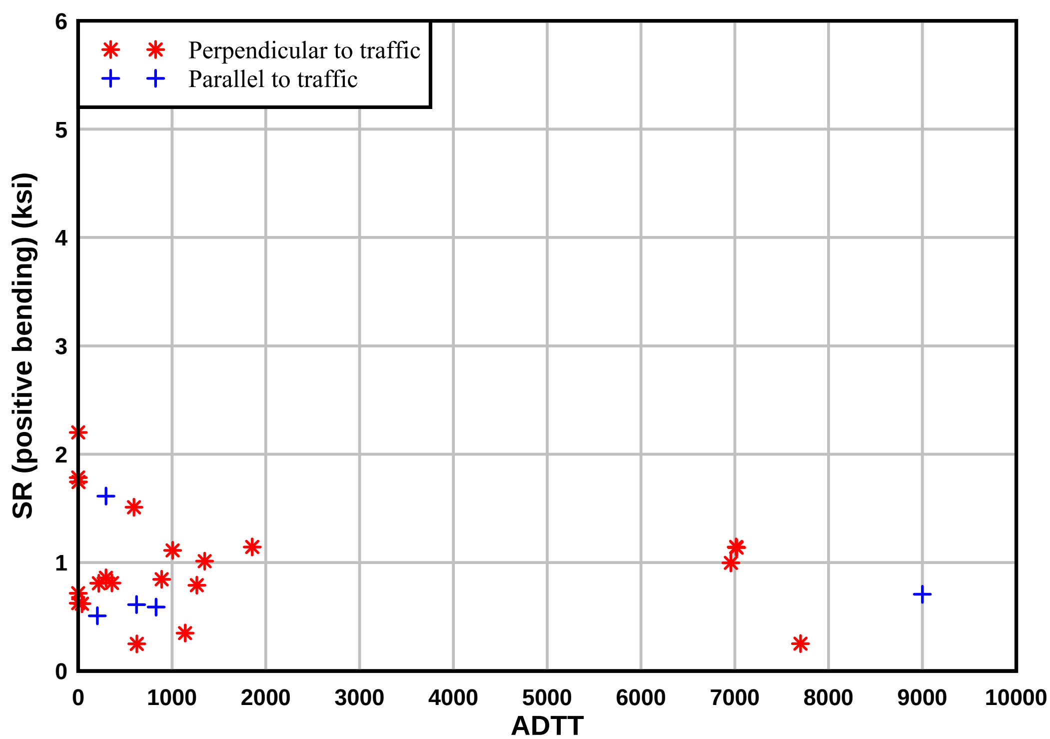


Figure 14 - Fatigue stress range (positive bending) versus ADTT.

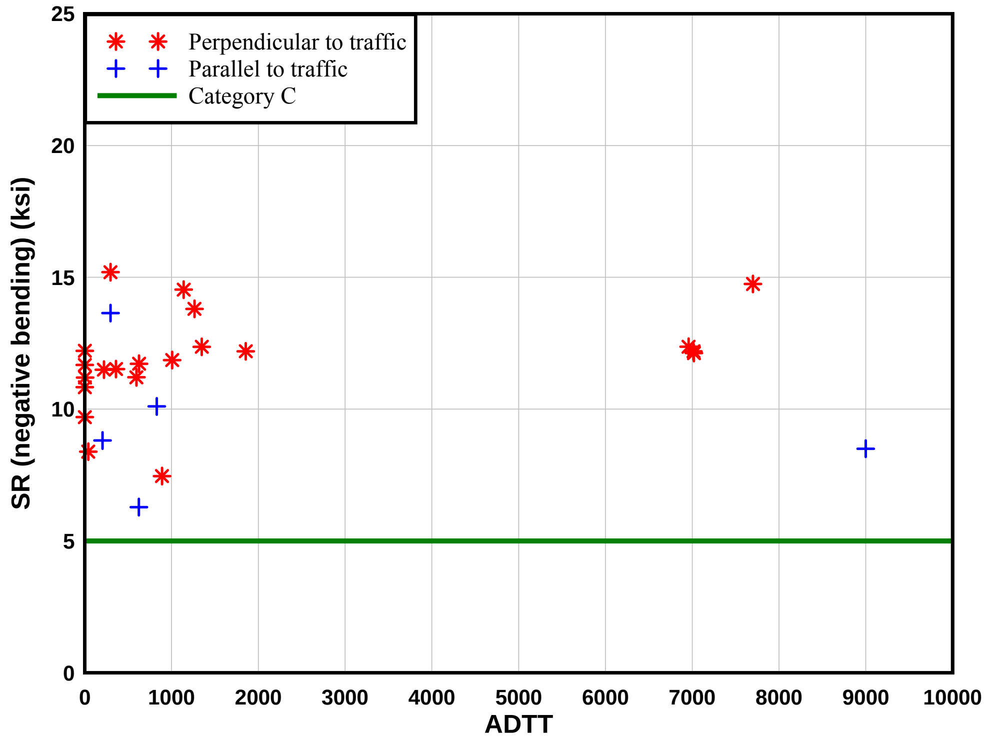
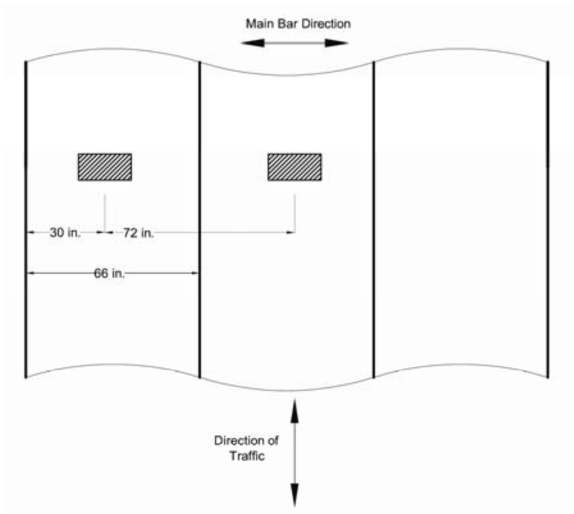
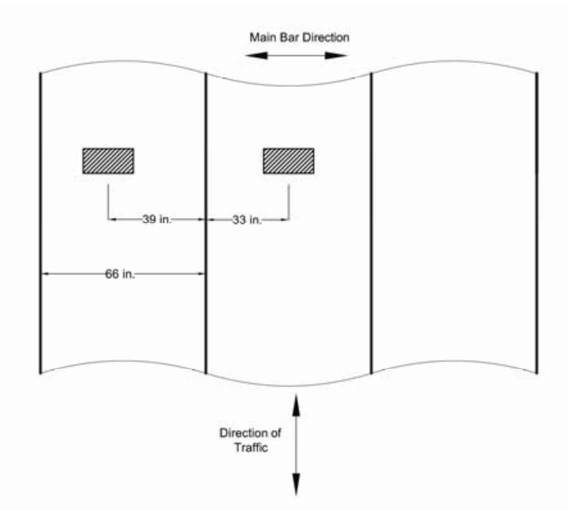


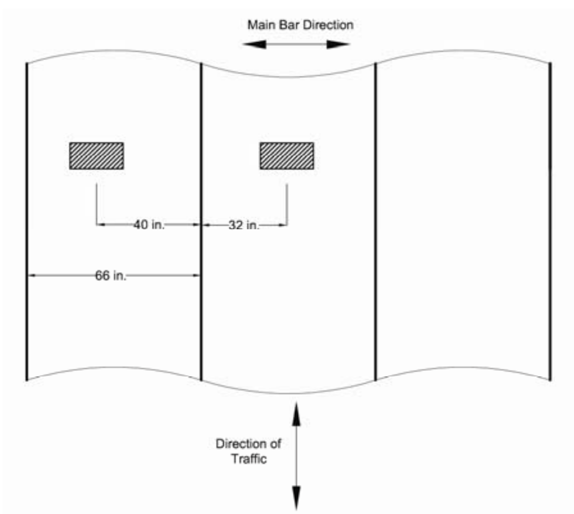
Figure 15 - Fatigue stress range (negative bending) versus ADTT using current AASHTO-LRFD specification.



Case 1



Case 2



Case 3

Figure 16 - Patch locations for fatigue Case 1-2-3.

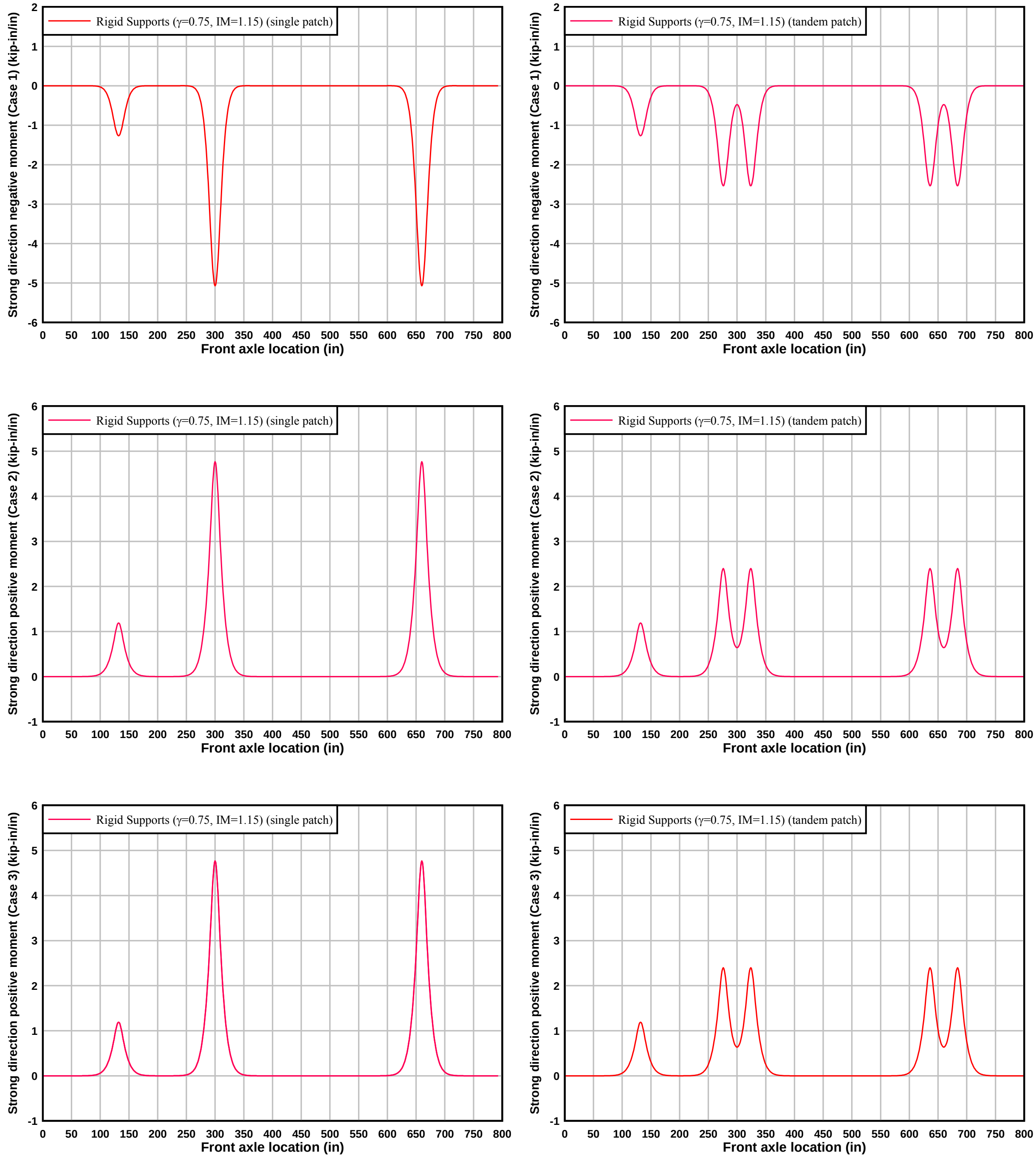


Figure 17 - Maximum fatigue moments for Case 1, Case 2, Case 3 (rigid supports).

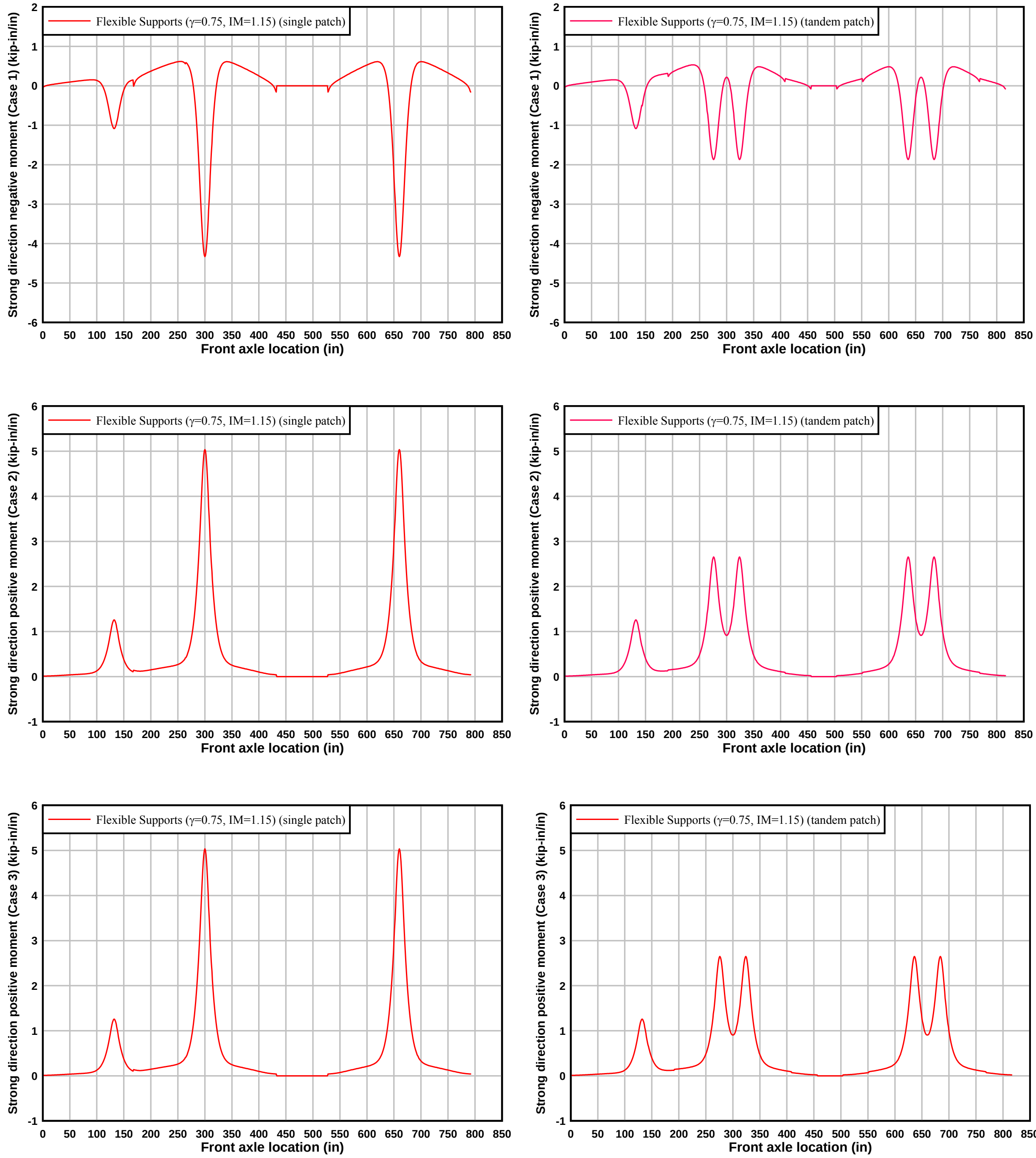


Figure 18 - Maximum fatigue moments for Case 1, Case 2, Case 3 (flexible supports).

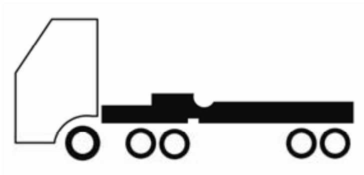


Figure 19 - 3S2 truck configuration.

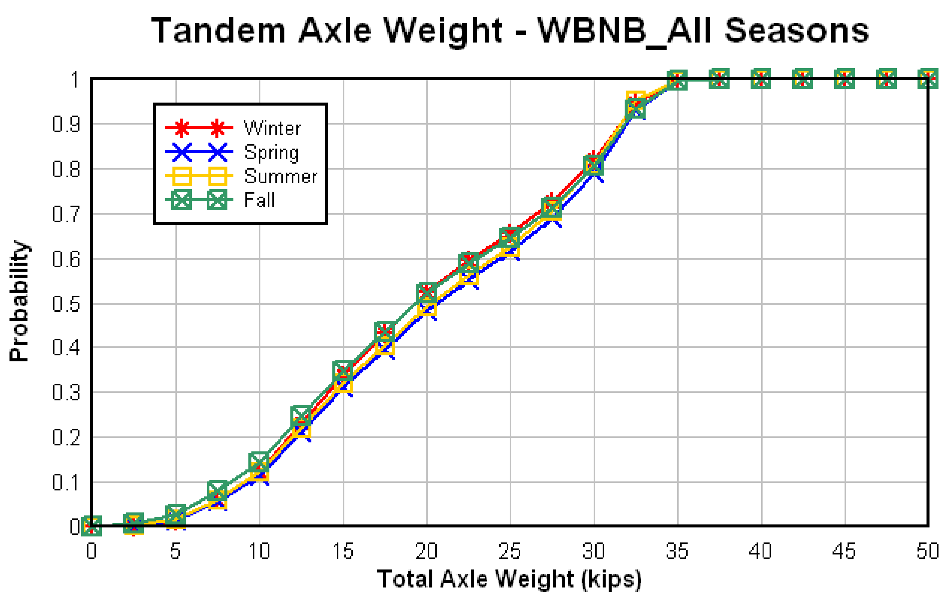


Figure 20a - Tandem axle weight distributions from WIM data for I5 in Oregon (Woodburn).

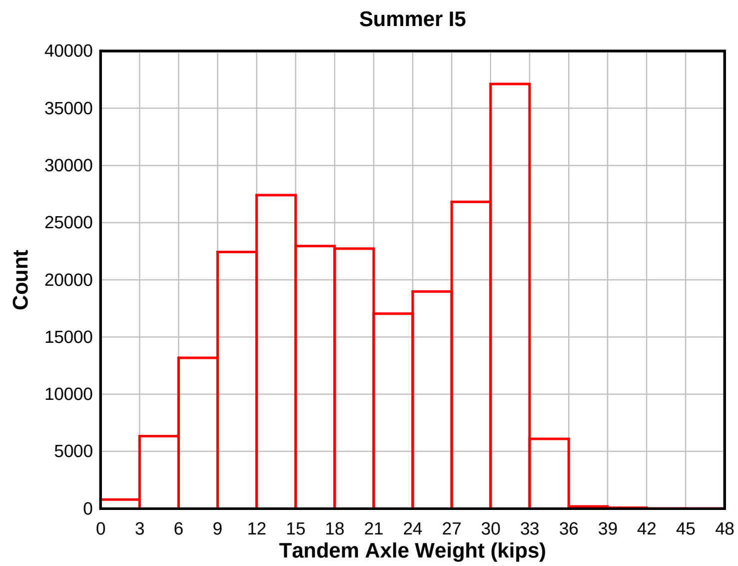


Figure 20b - Tandem axle weight histogram from summer WIM data for I5 in Oregon (Woodburn).

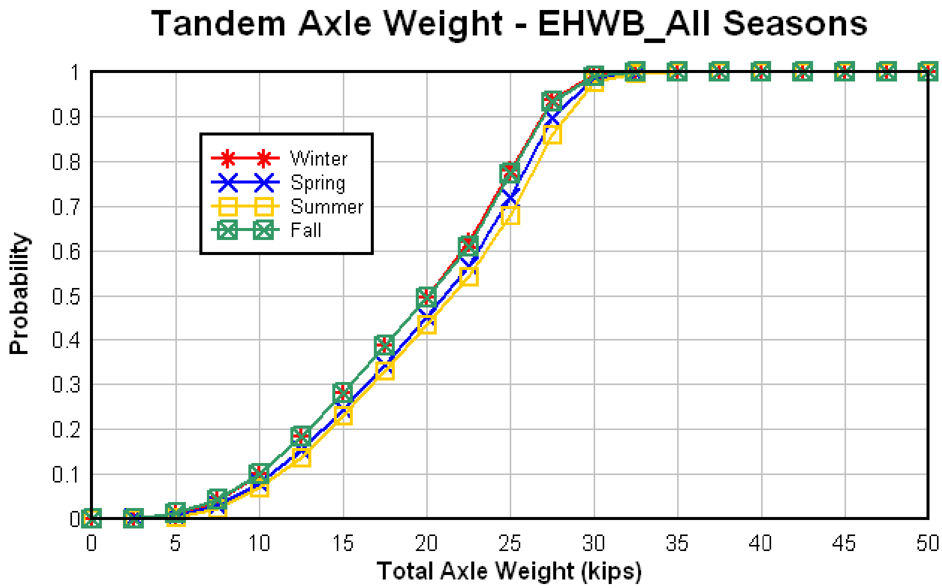


Figure 21a - Tandem axle weight distributions from WIM data for I84 in Oregon (Emigrant Hill).

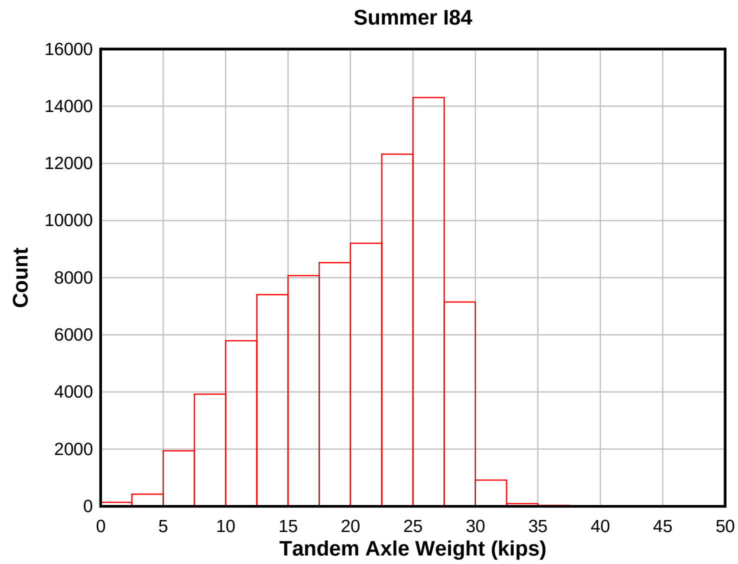


Figure 21b - Tandem axle weight histogram from summer WIM data for I84 in Oregon (Emigrant Hill).

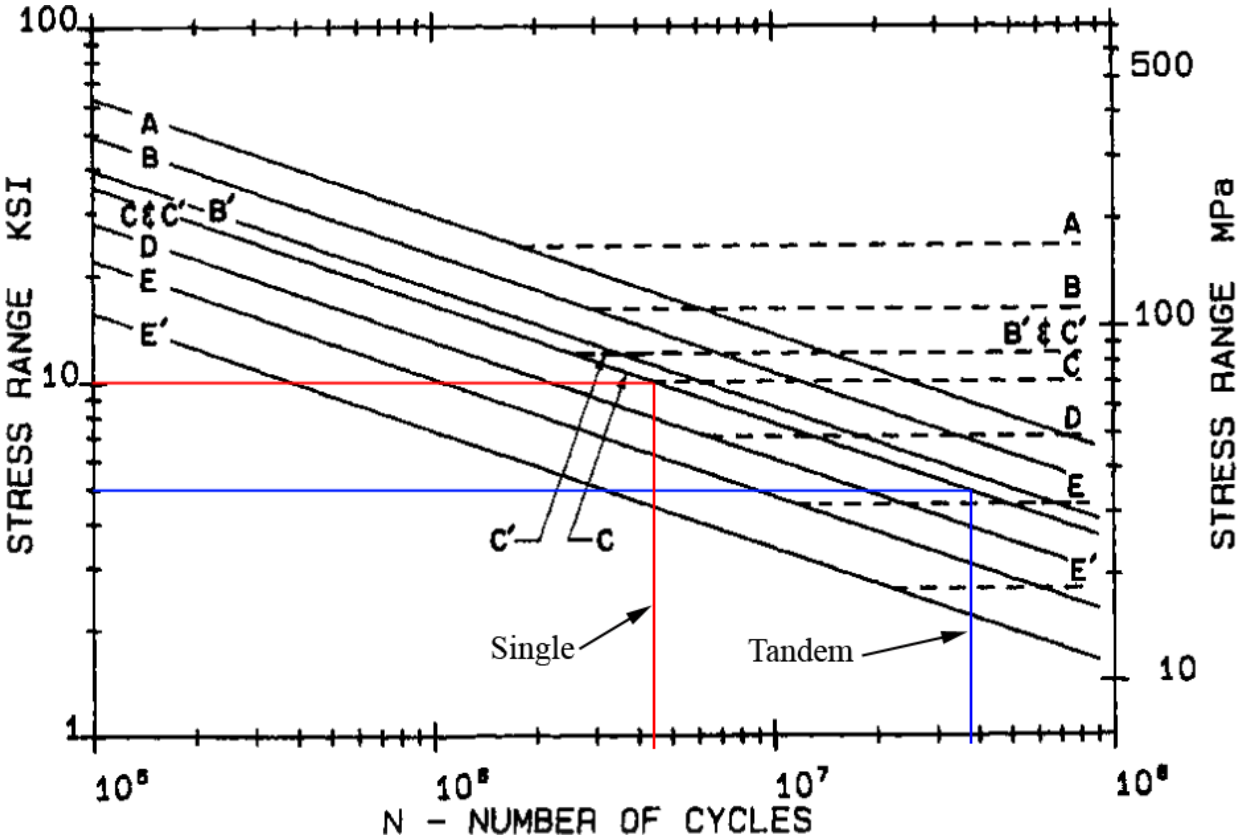


Figure 22 - Stress Range versus number of cycles for Single and Tandem patches.

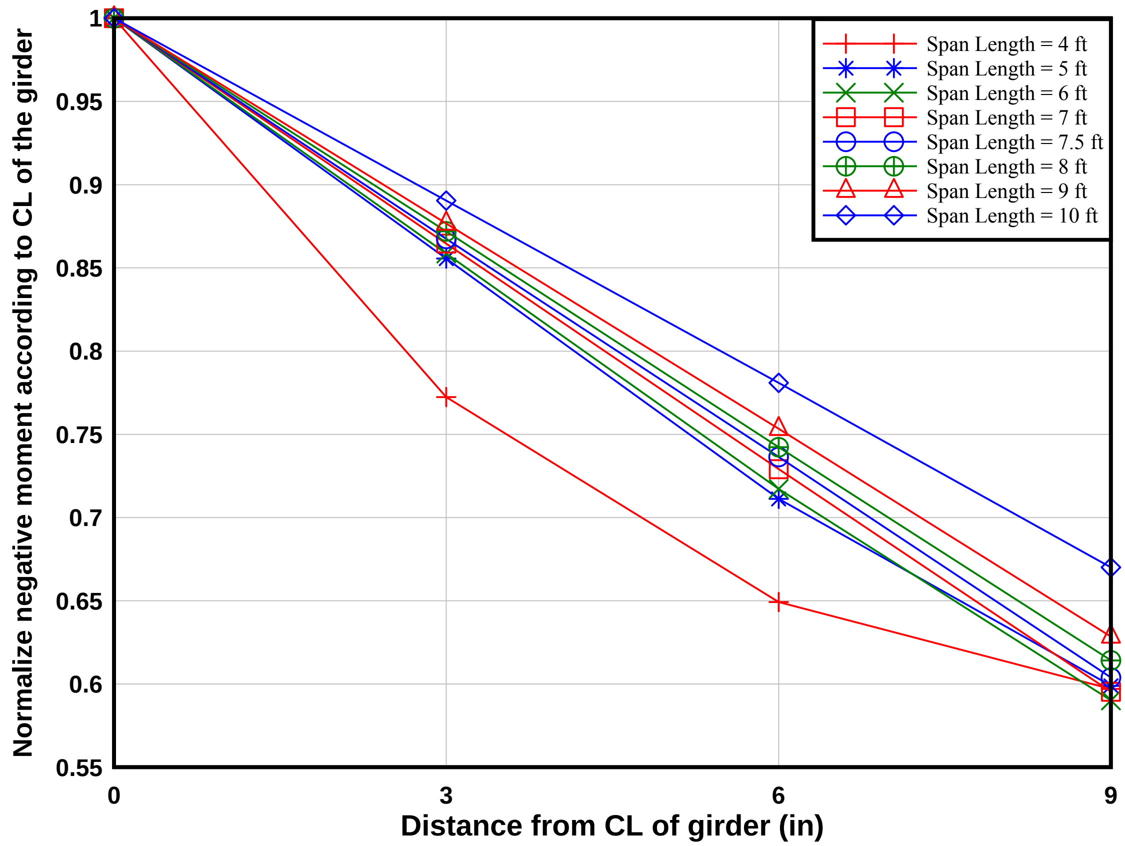


Figure 23 - Normalized negative moment as design section moves from the center line of the girder (from Table A4-1 AASHTO-LRFD).

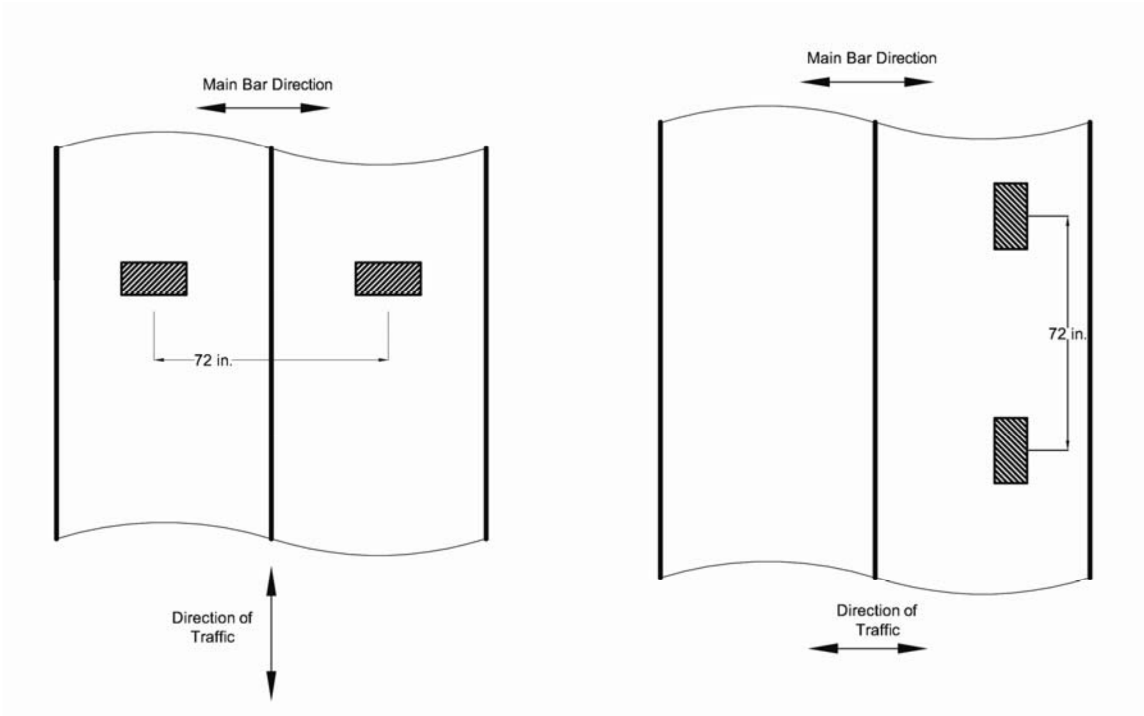


Figure 24. Patch orientations for fatigue truck used for determining negative moments with FEA.

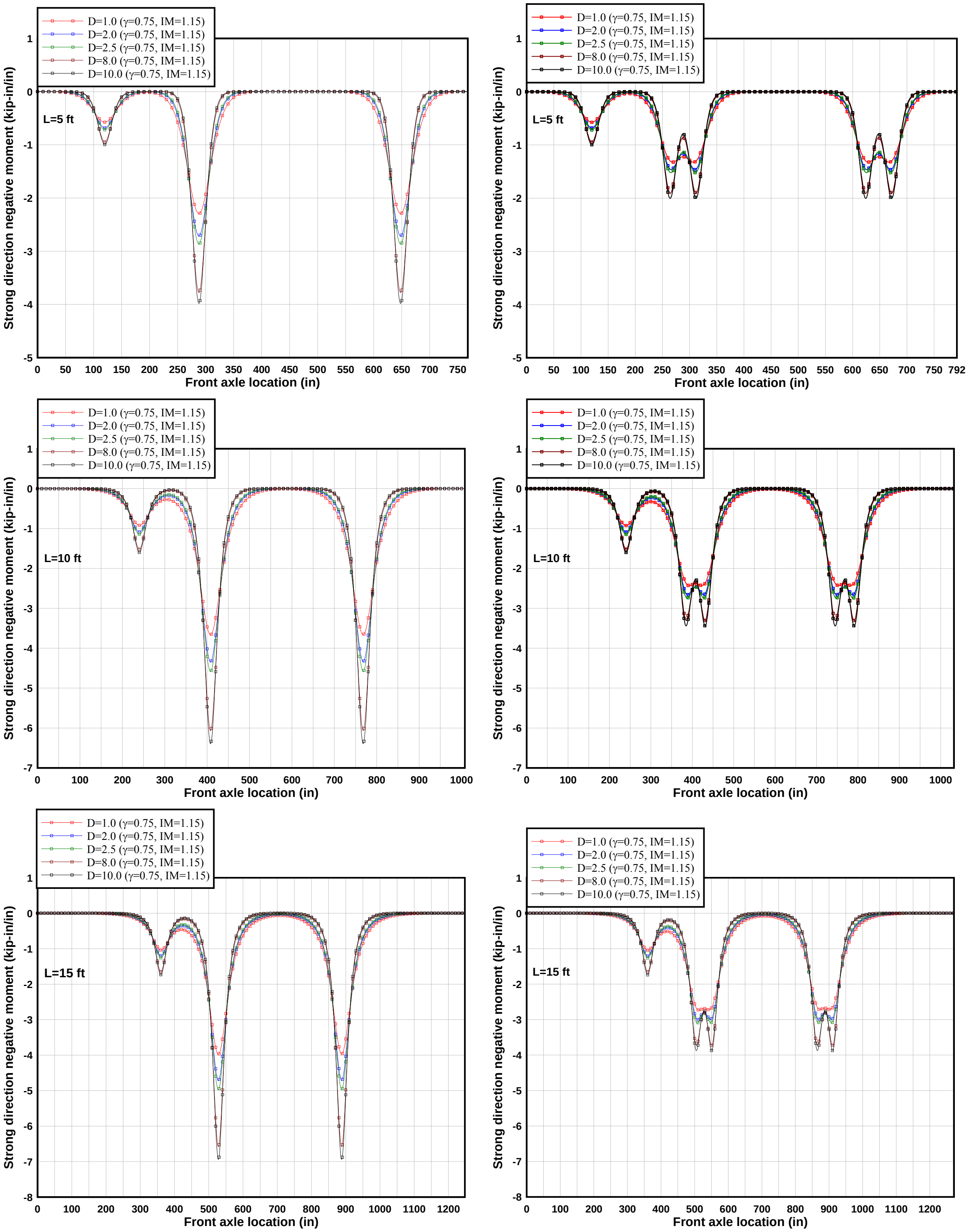


Figure 25.Strong direction negative moment for main bars transverse to traffic (L=5 ft, L=10 ft, and L=15ft).

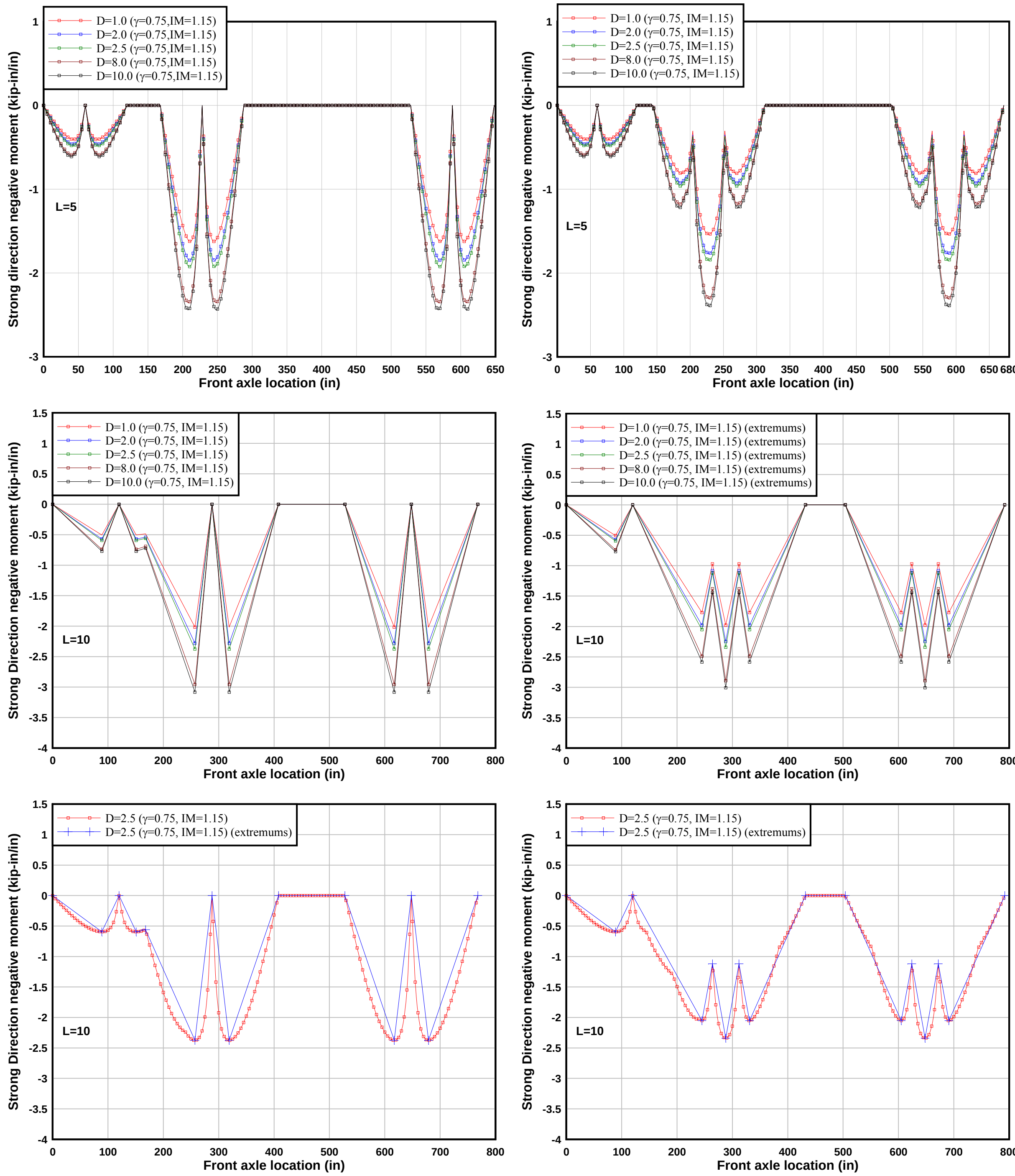


Figure 26a.Strong direction negative moment for main bars parallel to traffic (L=5 ft, L=10 ft)

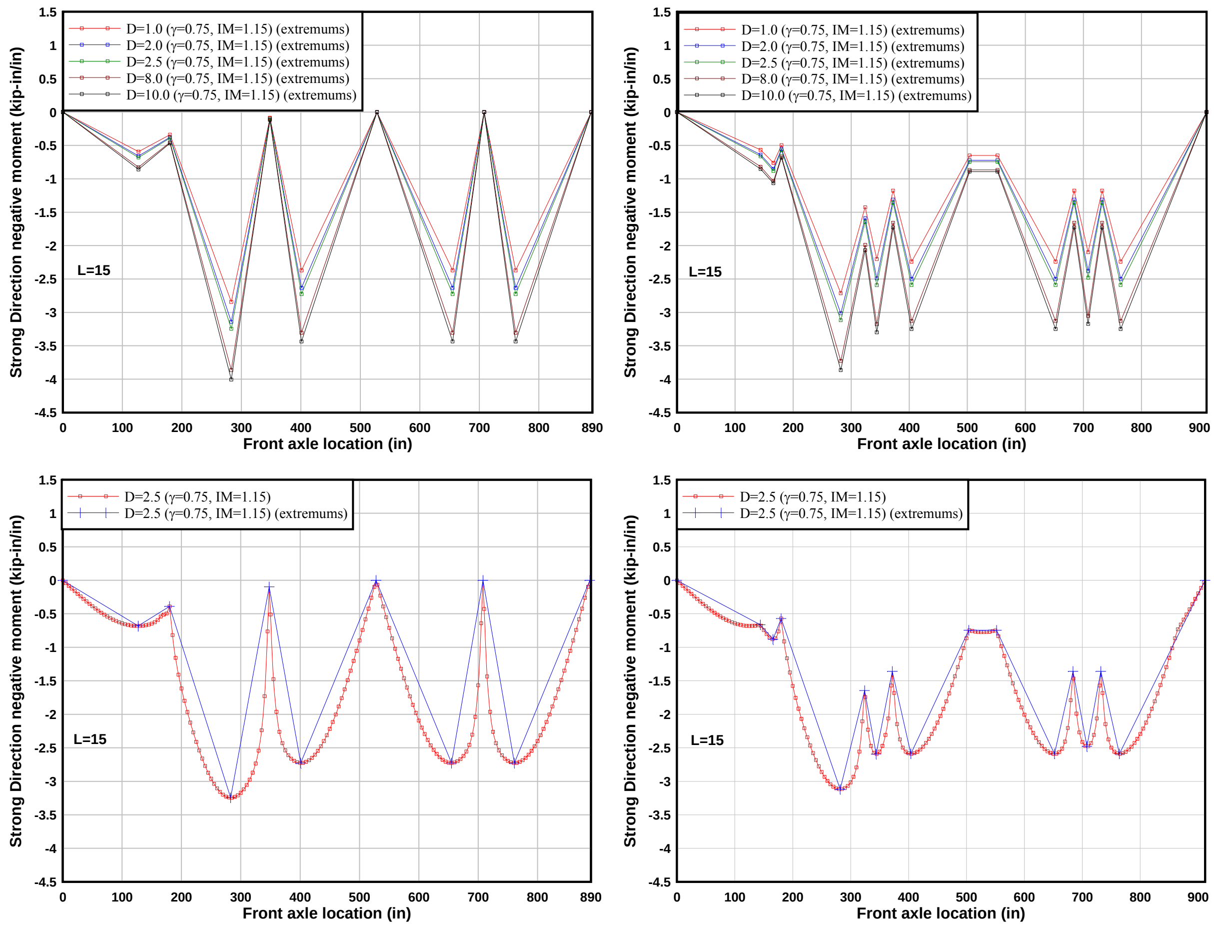


Figure 26b.Strong direction negative moment for main bars parallel to traffic (L=15 ft)

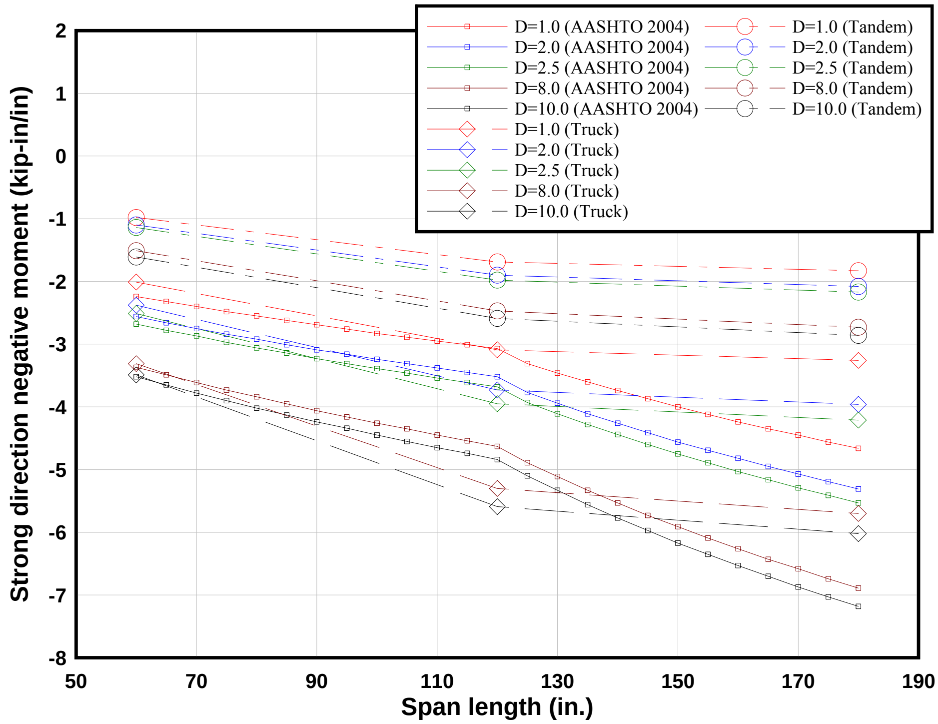


Figure 27. Equivalent negative moment ranges determined from FEA and the AASHTO-LRFD fatigue provisions for main bars transverse to traffic.

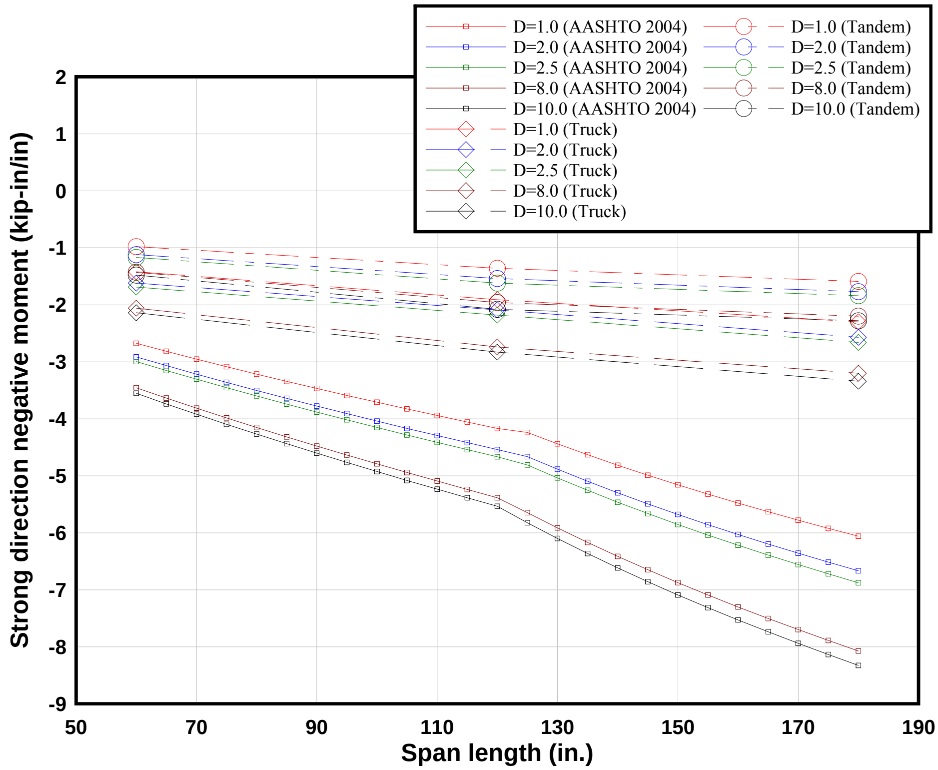


Figure 28. Negative moment ranges determined from FEA and AASHTO-LRFD fatigue provisions for main bars parallel to traffic.

Appendix A

Detailed Finite Element Analysis of Selected Deck Systems

West Street over Chicopee River, Westbound GA Route 53 over Lake Lanier, and WB I-70 over the Missouri River

Finite element analysis was performed using ABAQUS 6.5-1. Twelve different analysis cases were investigated by changing section properties (cracked, uncracked), continuity (single span, three span continuous), and supports (flexible, rigid) for West Street over Chicopee River, Westbound GA Route 53 over Lake Lanier and WB I-70 over the Missouri River. Every case is loaded by the 32 kip truck axle or the 25 kip tandem axles, separately. The analysis span width was chosen as 4 times the span length because when the span width is more than four times the span length, the deflections and moments are negligible at the boundaries (Higgins 2003).

Critical patch locations orthogonal to the traffic direction for maximum moment effect were determined by running single and tandem axles over a simply supported single span beam model. Maximum moment was observed 2.75 , 2.17 and 3.56 ft away from the support for West Street over Chicopee River, Westbound GA Route 53 over Lake Lanier and WB I-70 over the Missouri River, respectively. The first patch was located at these points, however since the total width of the deck is 5.5, 4.33, 7.13 ft respectively, the second patch was not applied for single span cases. For the 3 span continuous cases a second patch was located 6 ft away from the first patch (representing the adjacent truck tire patch on the axle), however since the total width of Westbound GA Route 53 over Lake Lanier is 4.33 ft, second patch was not applied for this bridge. As an example, patch locations for the 25 and 32 kips axle loads for West Street over Chicopee River are shown in Fig. 1A. Negative and positive D regions were obtained by analyzing a 3 span continuous beam loaded uniformly to identify positive and negative moment regions.

Using orthotropic thin plate theory, decks were assumed as plate elements, and S4R, 4 node, reduced integration, conventional stress, thin or thick shell elements were used. In order to get the stress equal to moment per unit length, 2.449 in. thickness was assigned to the thickness of the deck. For flexible cases B31, 2 node, shear flexible beam elements were used as supports. Mesh refinement for simply supported and single span cases was done until the error compared to the formula provided by Higgins (2003) was less than 0.5%. This same mesh was used for all subsequent analysis cases.

For cases 7 through 12 (flexible support), beams were tied using multi point constrains to the center node of the shell element. Eccentricity was ignored and the center of the beam is tied to the center of the deck without eccentricity. Beam elements with flexural and torsional stiffnesses to that of W24x76, W 36x150 and W 12x58 were used as flexible supporting elements for West Street over Chicopee River, Westbound GA Route 53 over Lake Lanier and WB I-70 over the Missouri River, respectively.

Maximum deflection, maximum and minimum moments in the strong direction and maximum and minimum moments in weak direction are tabulated for all three bridges in Table 1A-9A. Stress contours were similar for the three bridge and therefore only contour plots of deflection and moments for all analysis cases of West Street over Chicopee River are provided in Fig. 1A through Fig. 12A to illustrate the results.

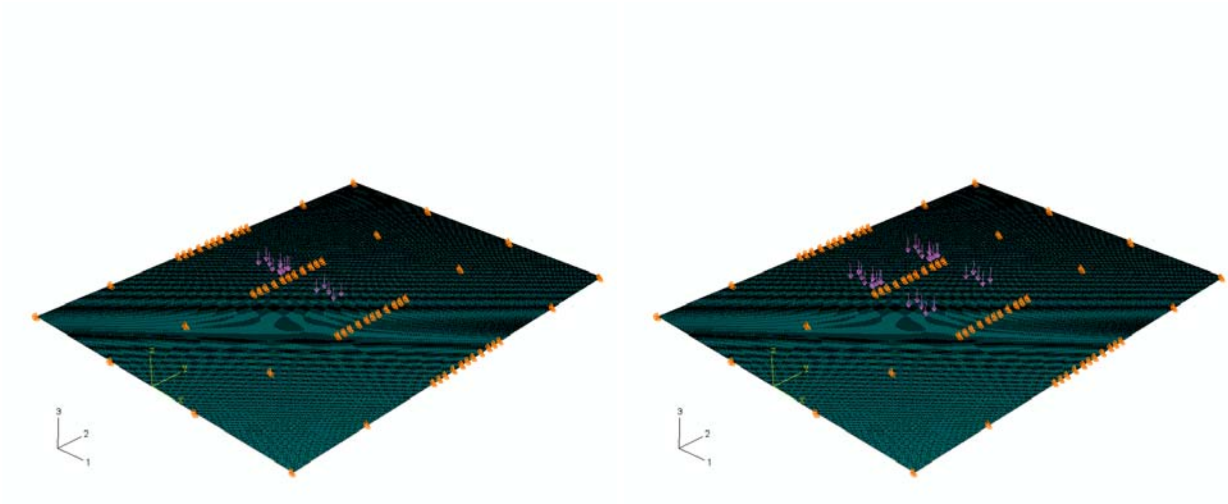


Figure 1A - Patch locations for 25 and 32 kips axle loads.

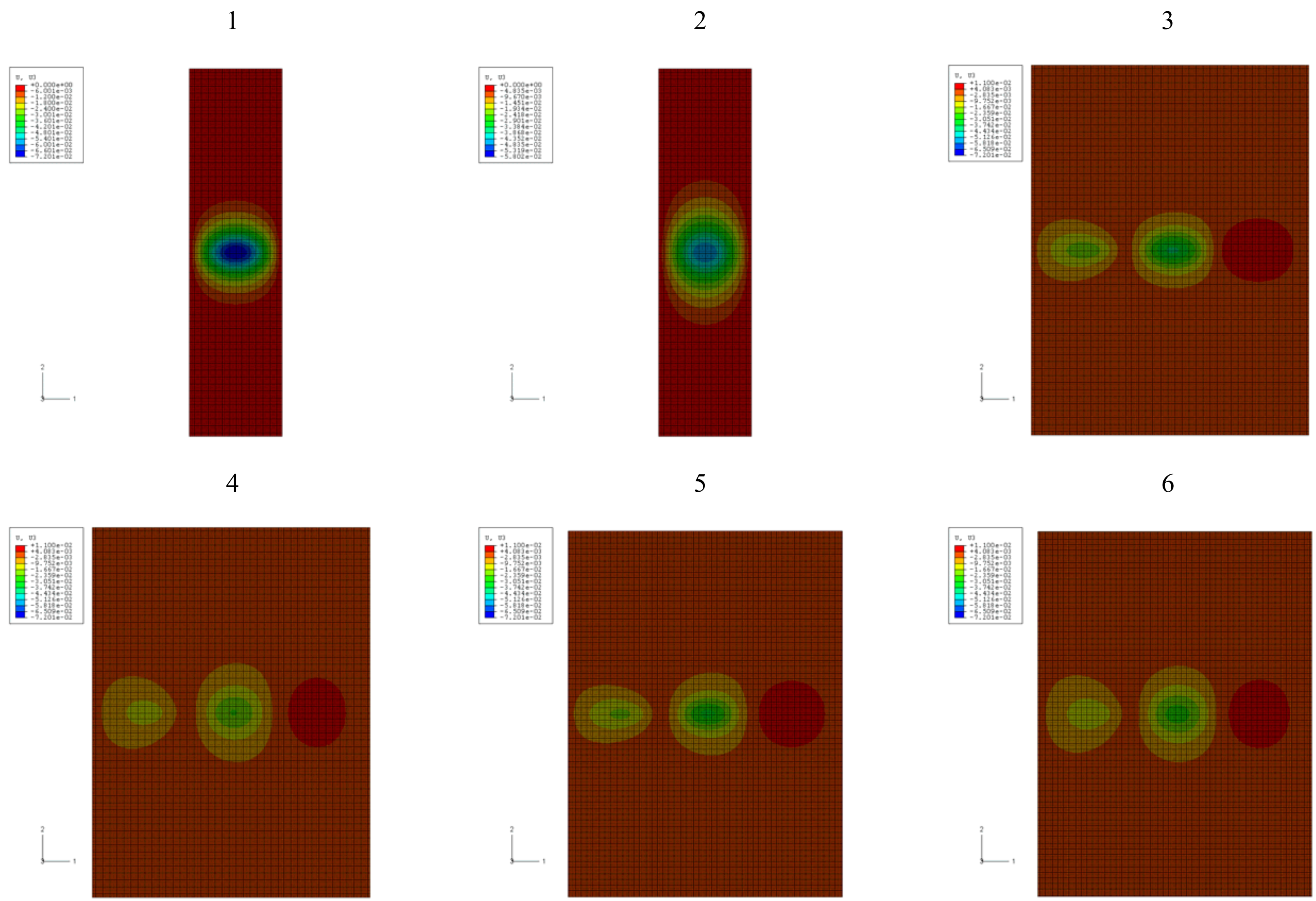


Figure 2A. Deflection plots for 32 kips axle loading for Case1 through Case 6.

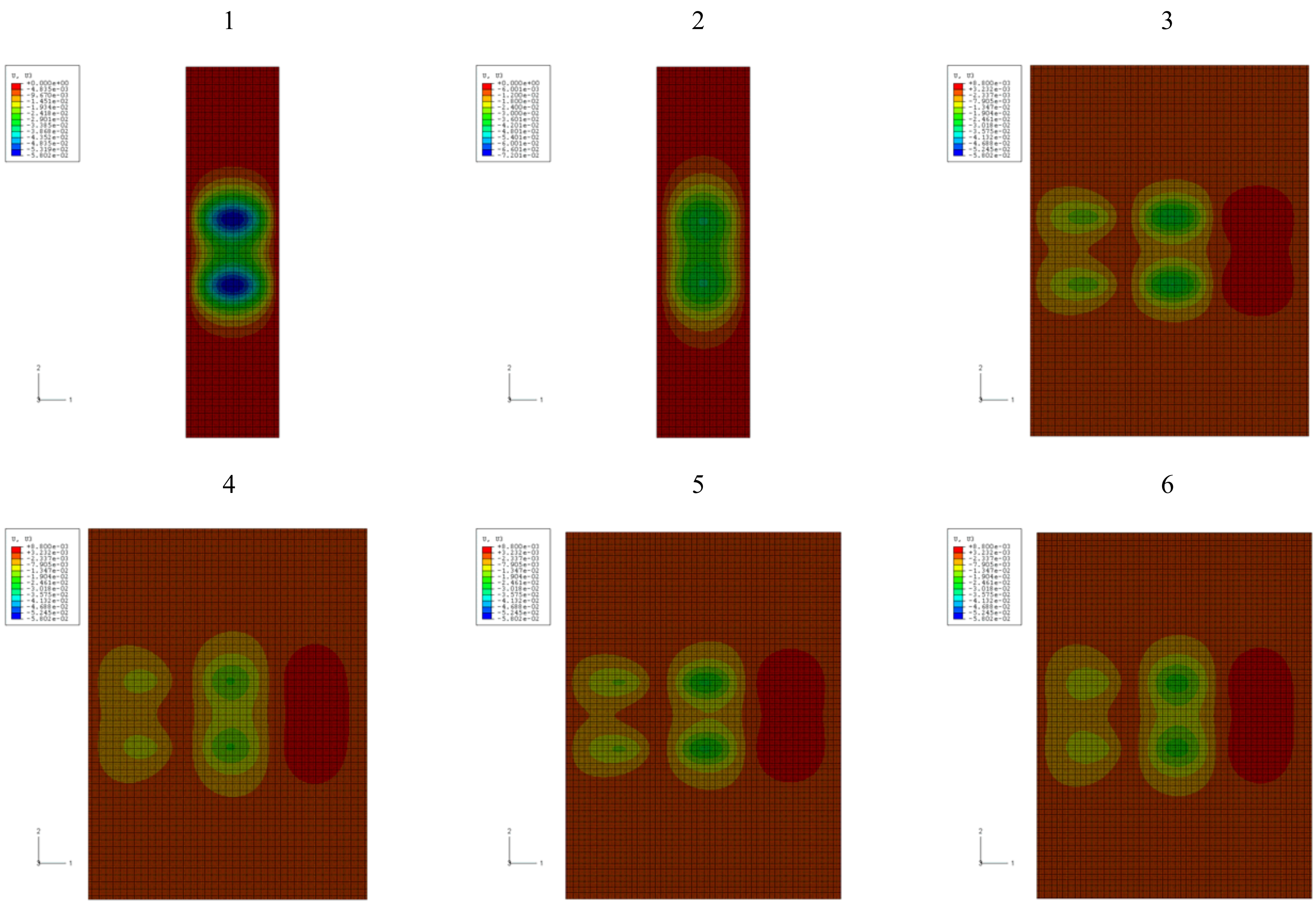


Figure 3A. Deflection plots for 25 kips axle loading for Case1 through Case 6.

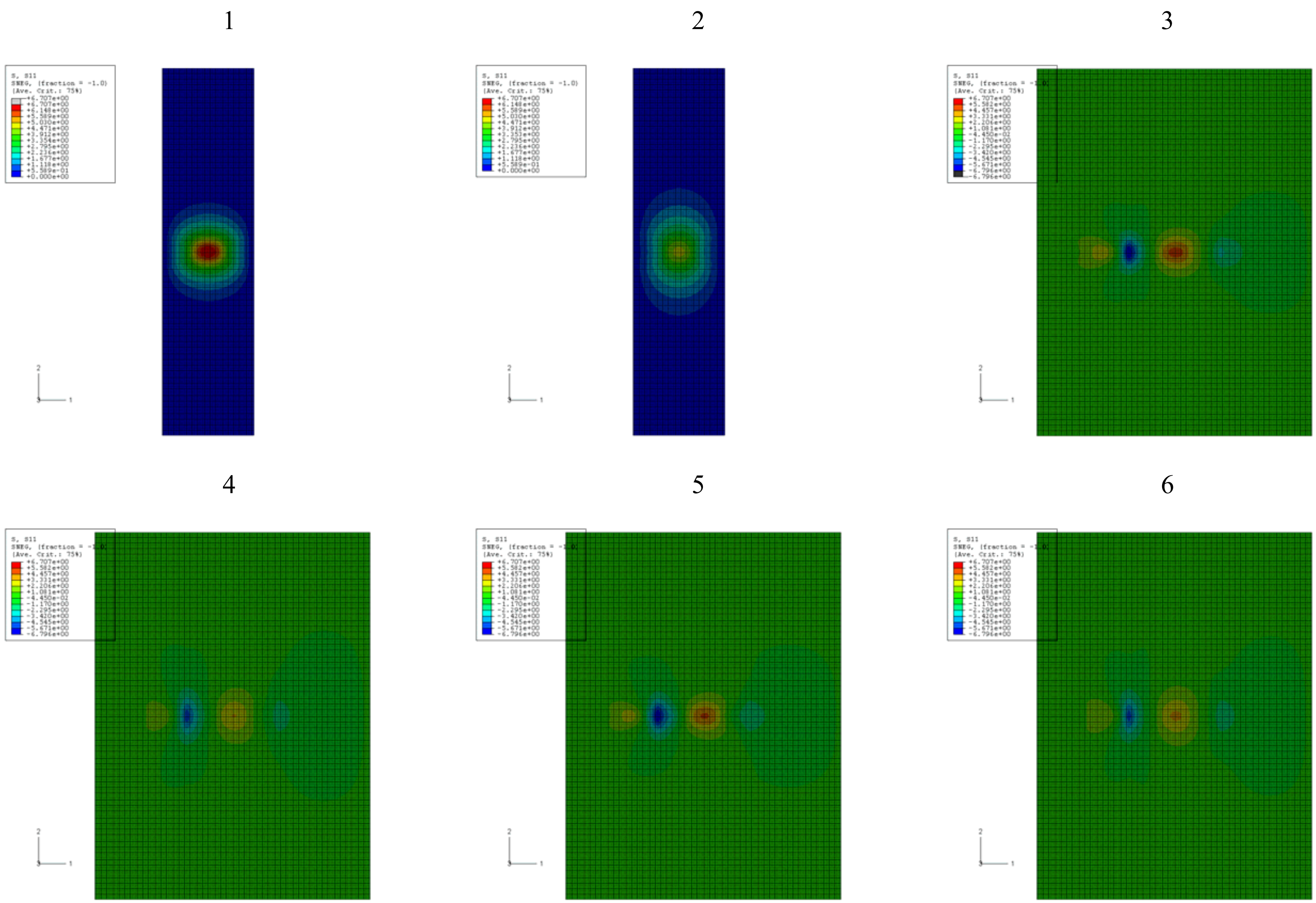


Figure 4A. Strong Direction Moment for 32 kips axle loading for Case1 through Case 6.

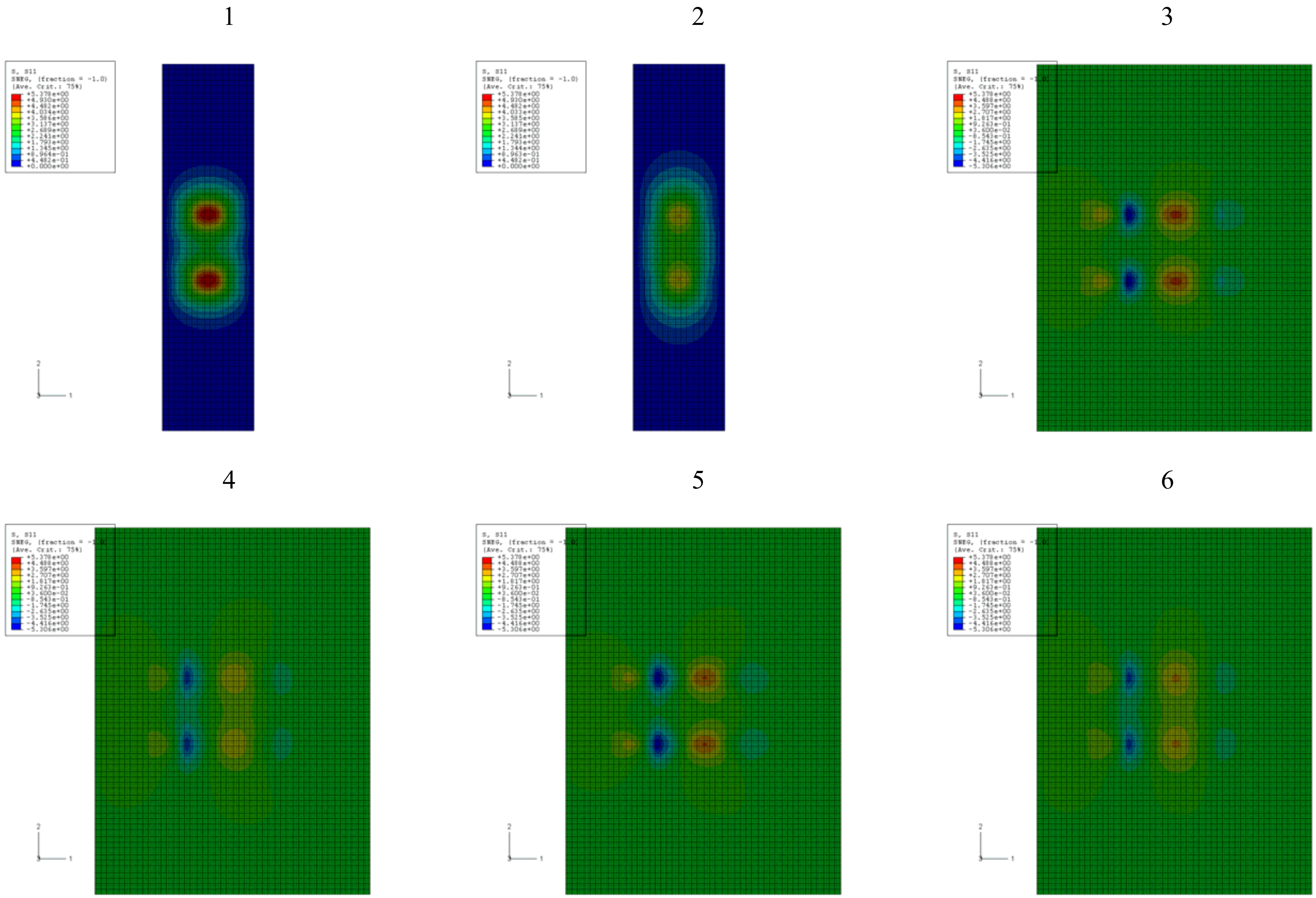


Figure 5A. Strong Direction Moment for 25 kips axle loading for Case1 through Case 6.

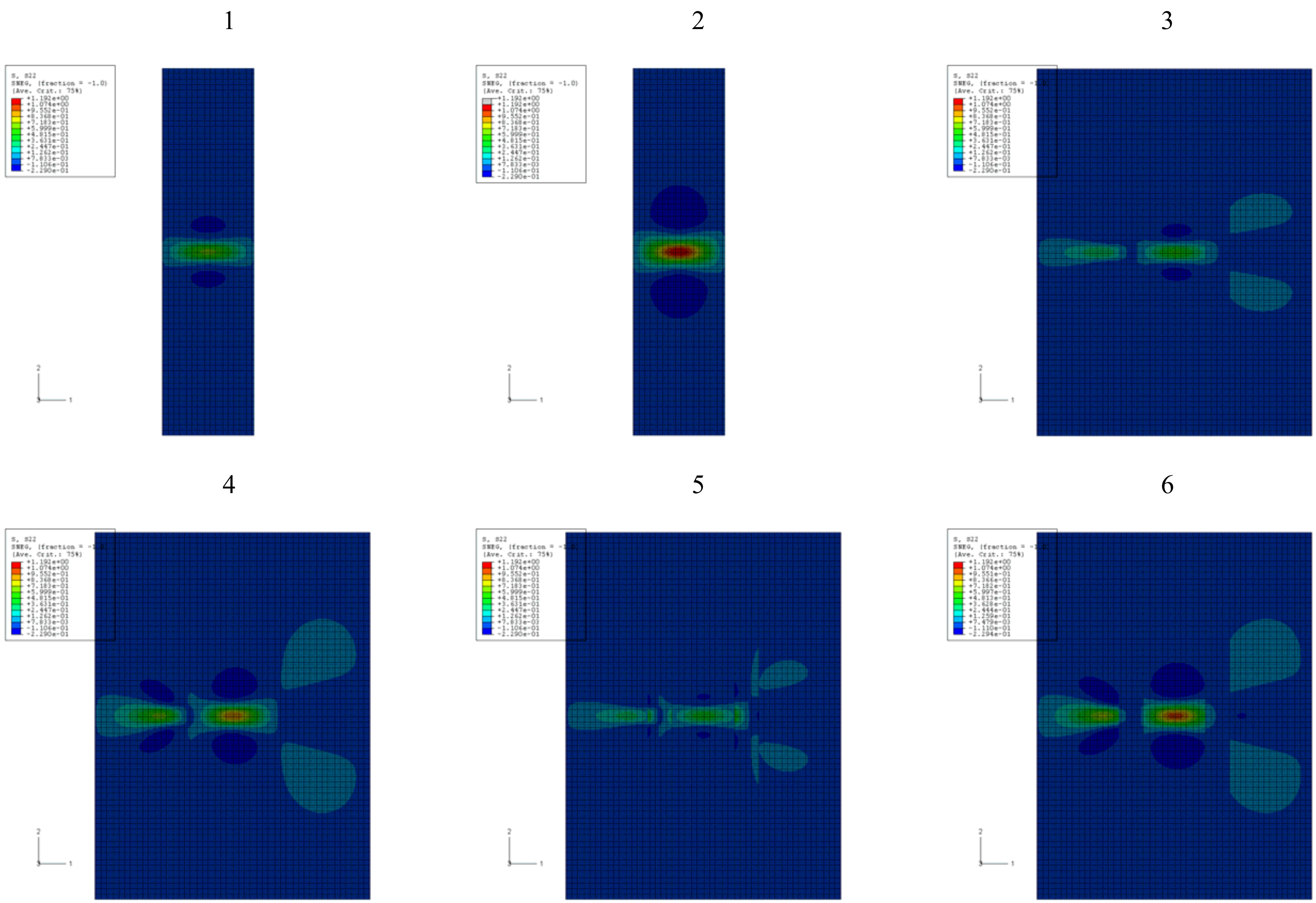


Figure 6A. Weak Direction Moment for 32 kips axle loading for Case1 through Case 6.

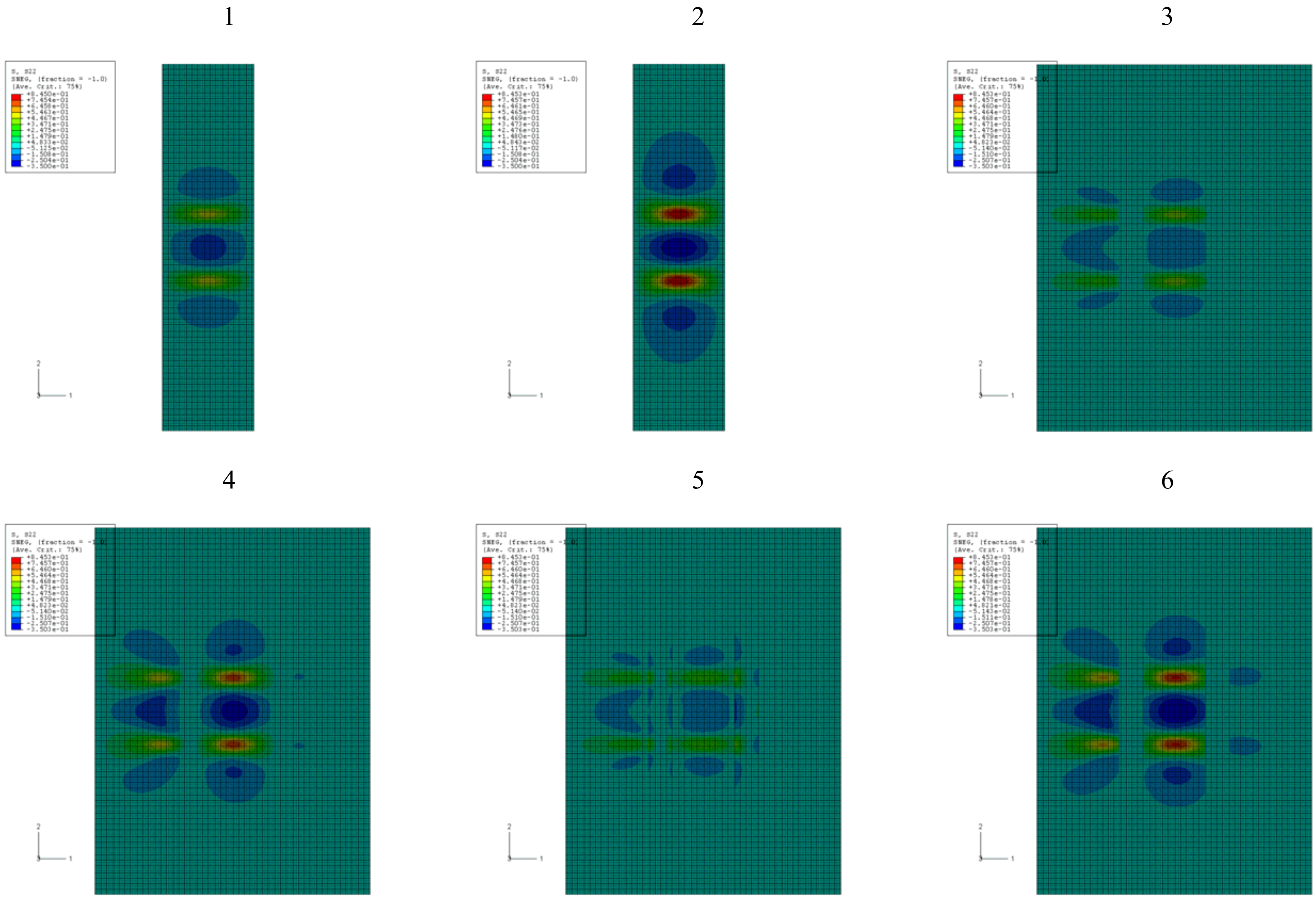


Figure 7A. Weak Direction Moment for 25 kips axle loading for Case1 through Case 6.

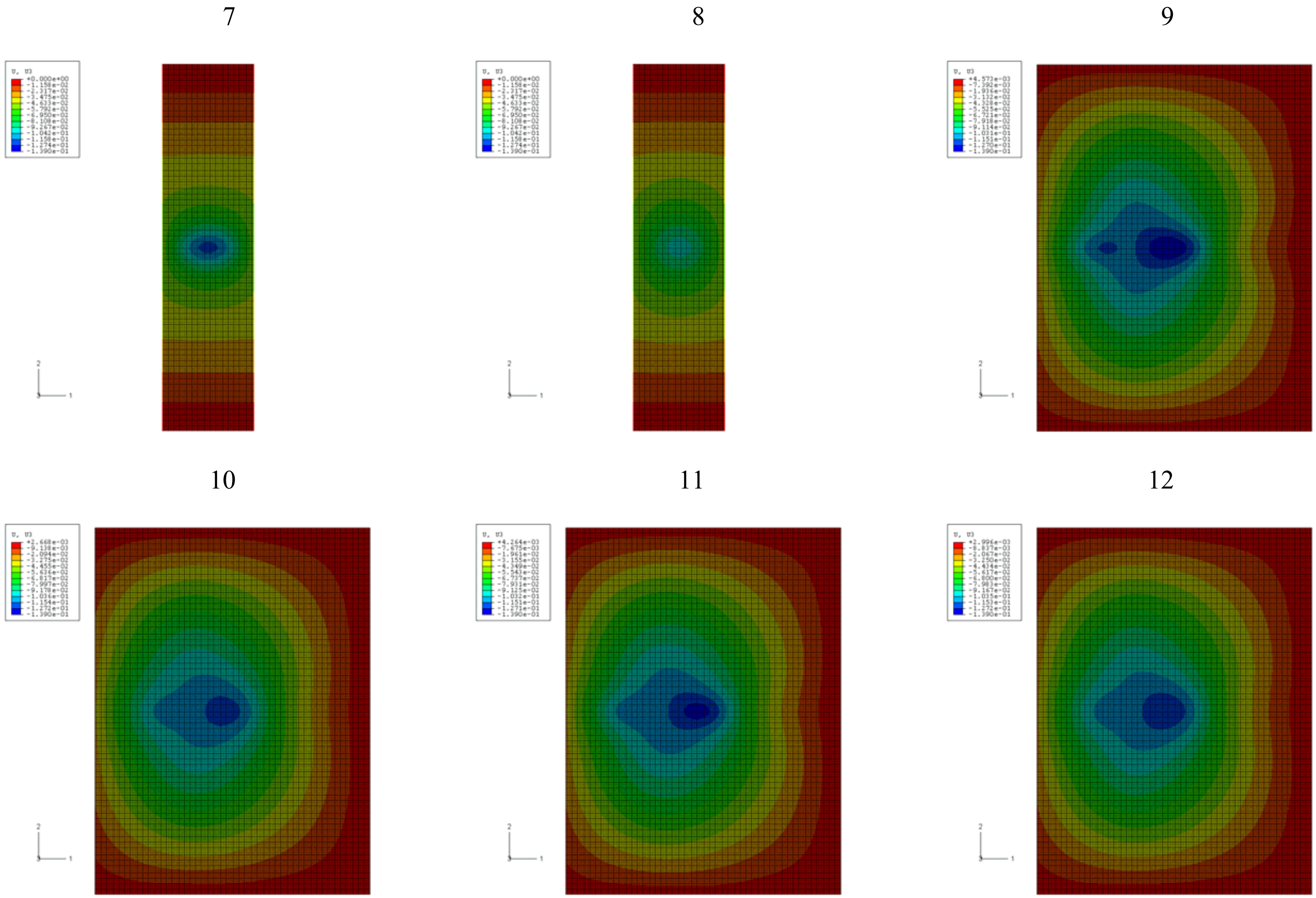


Figure 8A. Deflection plots for 32 kips axle loading for Case7 through Case 12.

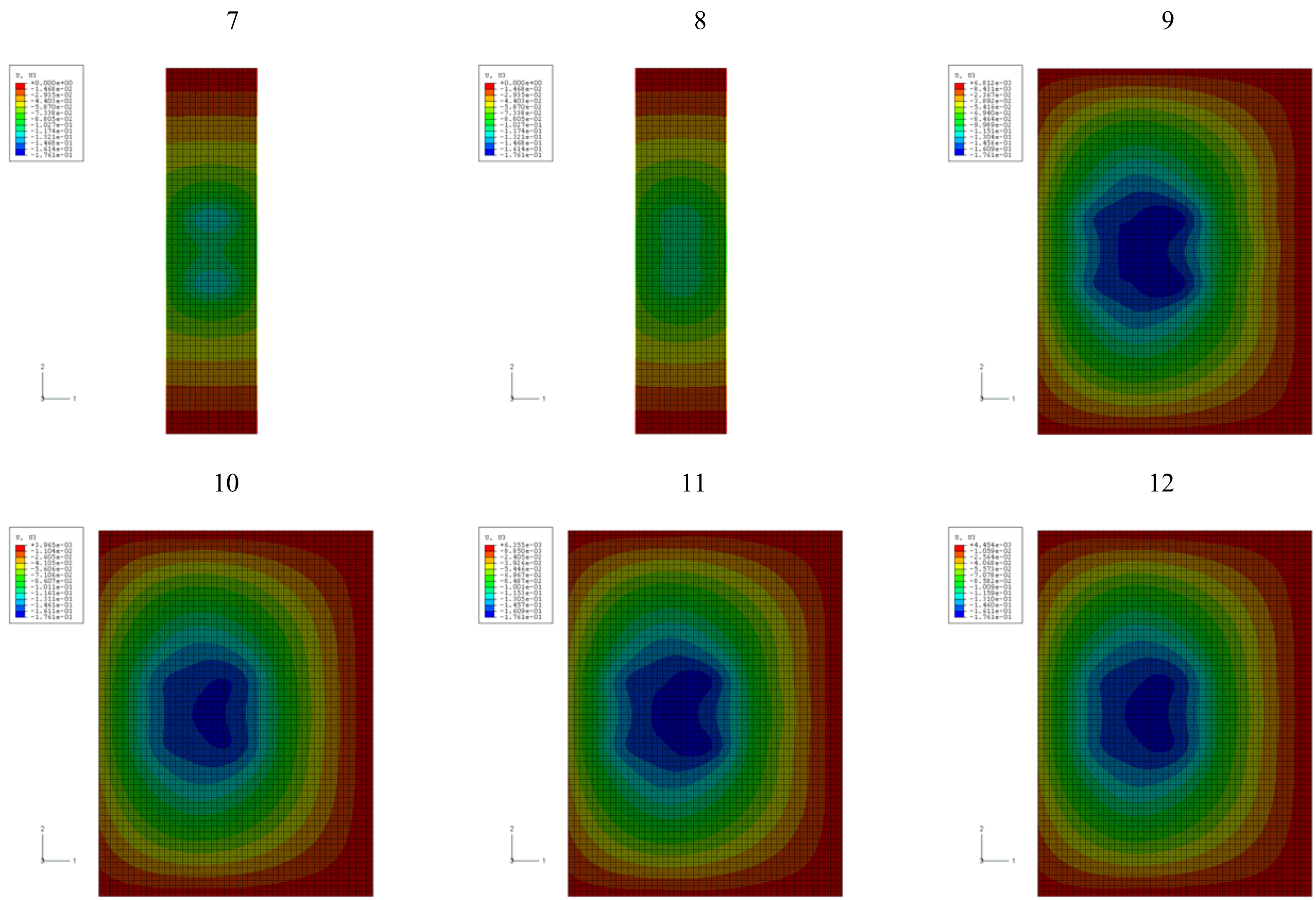


Figure 9A. Deflection plots for 25 kips axle loading for Case7 through Case 12.

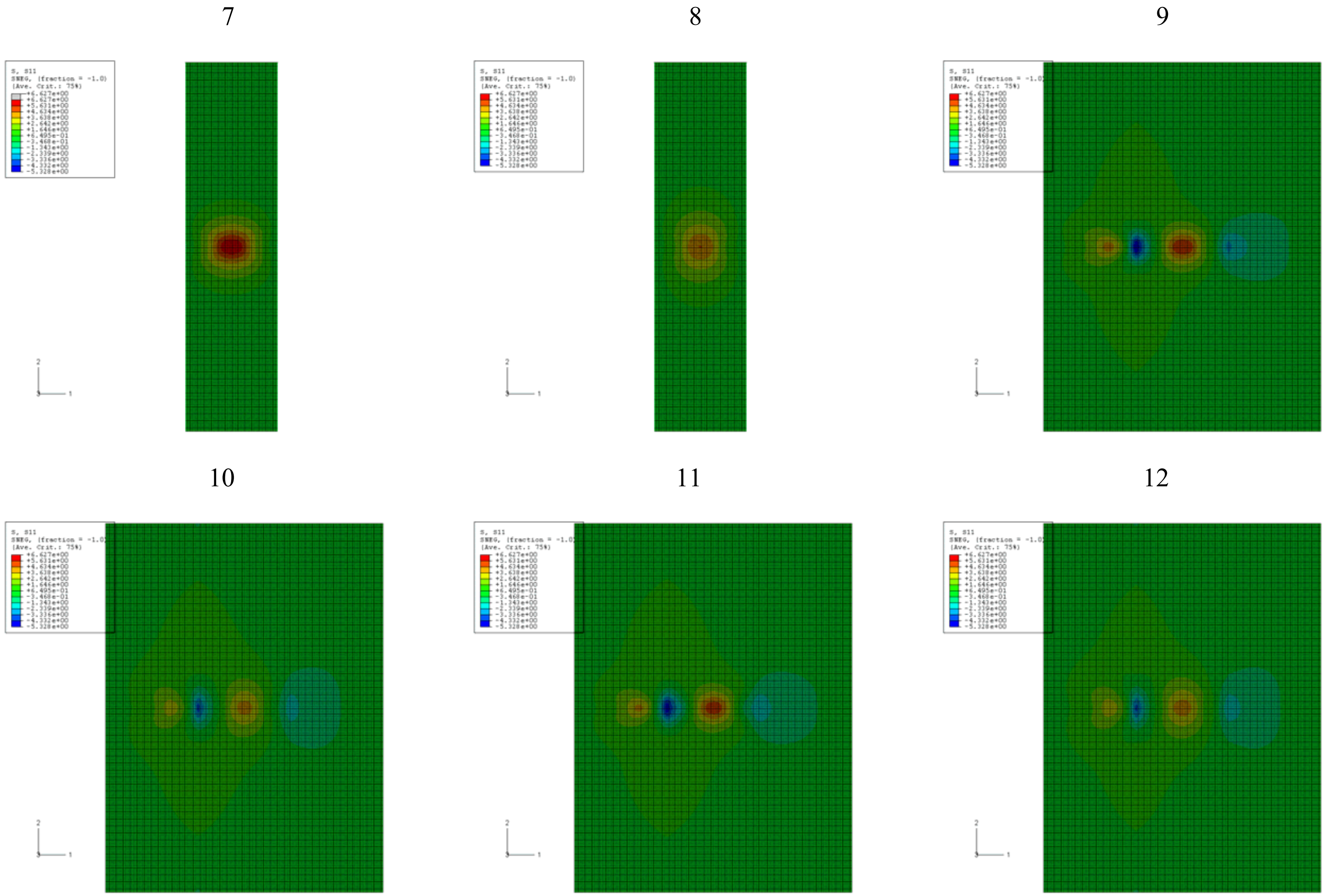


Figure 10A. Strong Direction Moment for 32 kips axle loading for Case7 through Case 12.

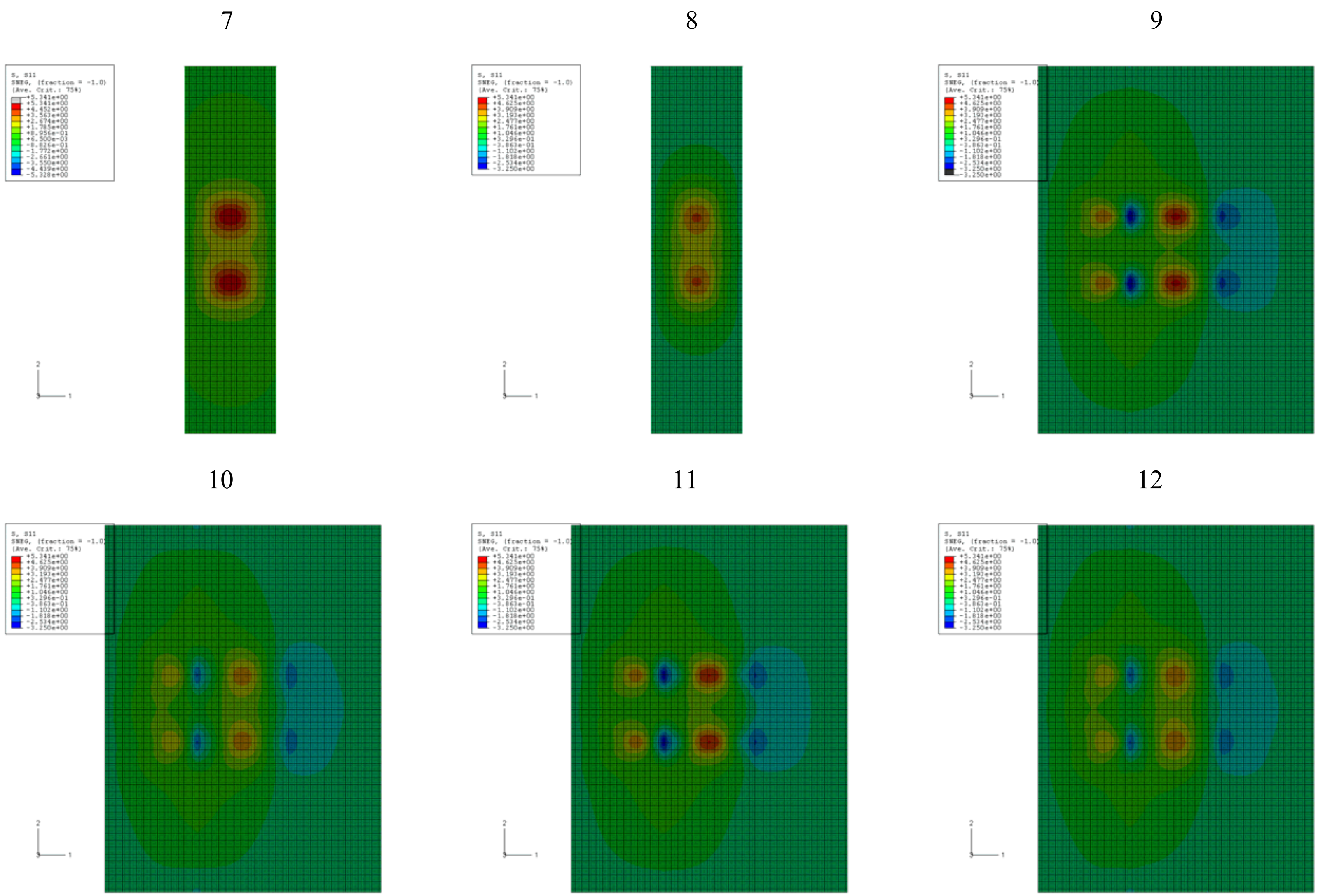


Figure 11A. Strong Direction Moment for 25 kips axle loading for Case7 through Case 12.

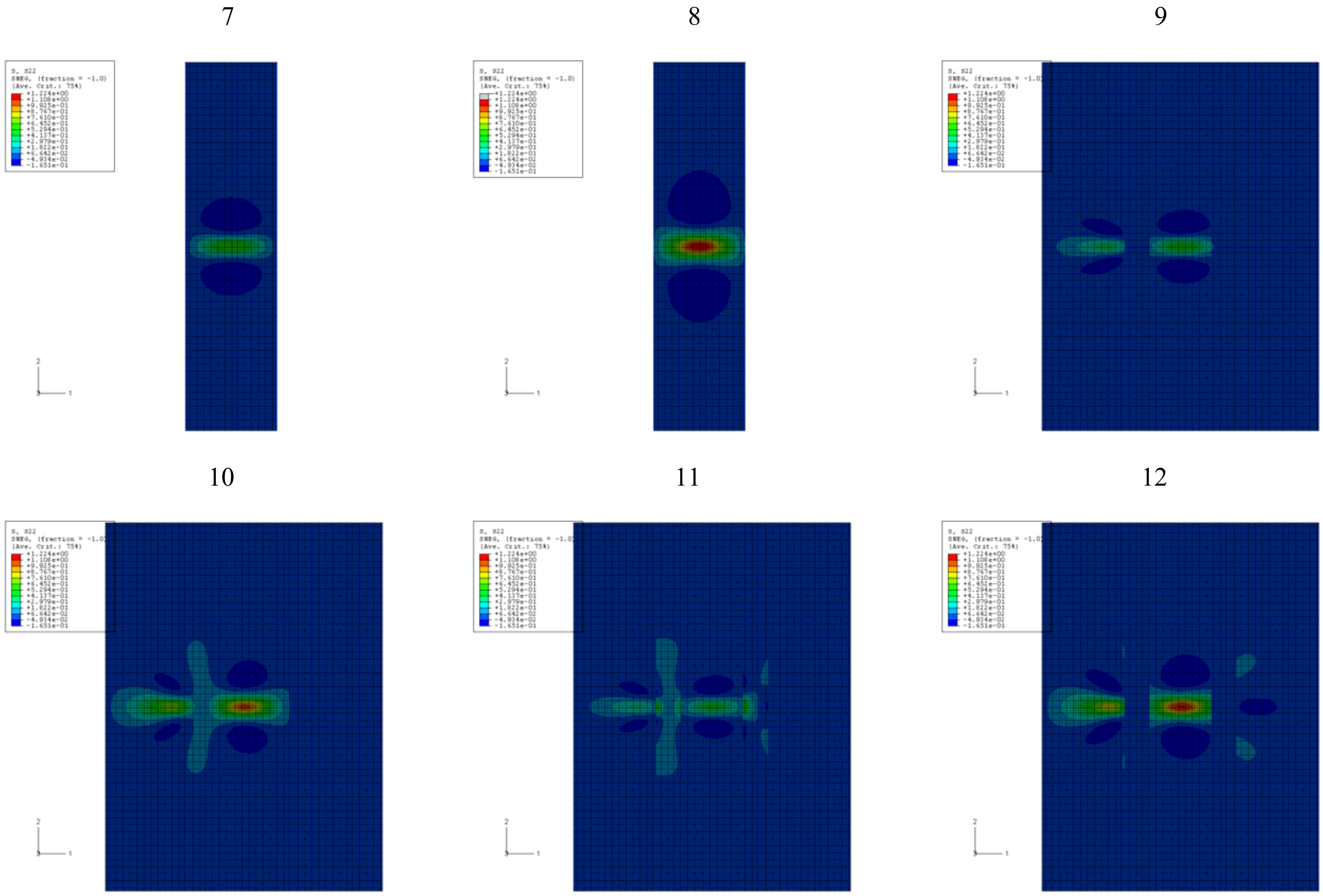


Figure 12A. Weak Direction Moment for 32 kips axle loading for Case7 through Case 12.

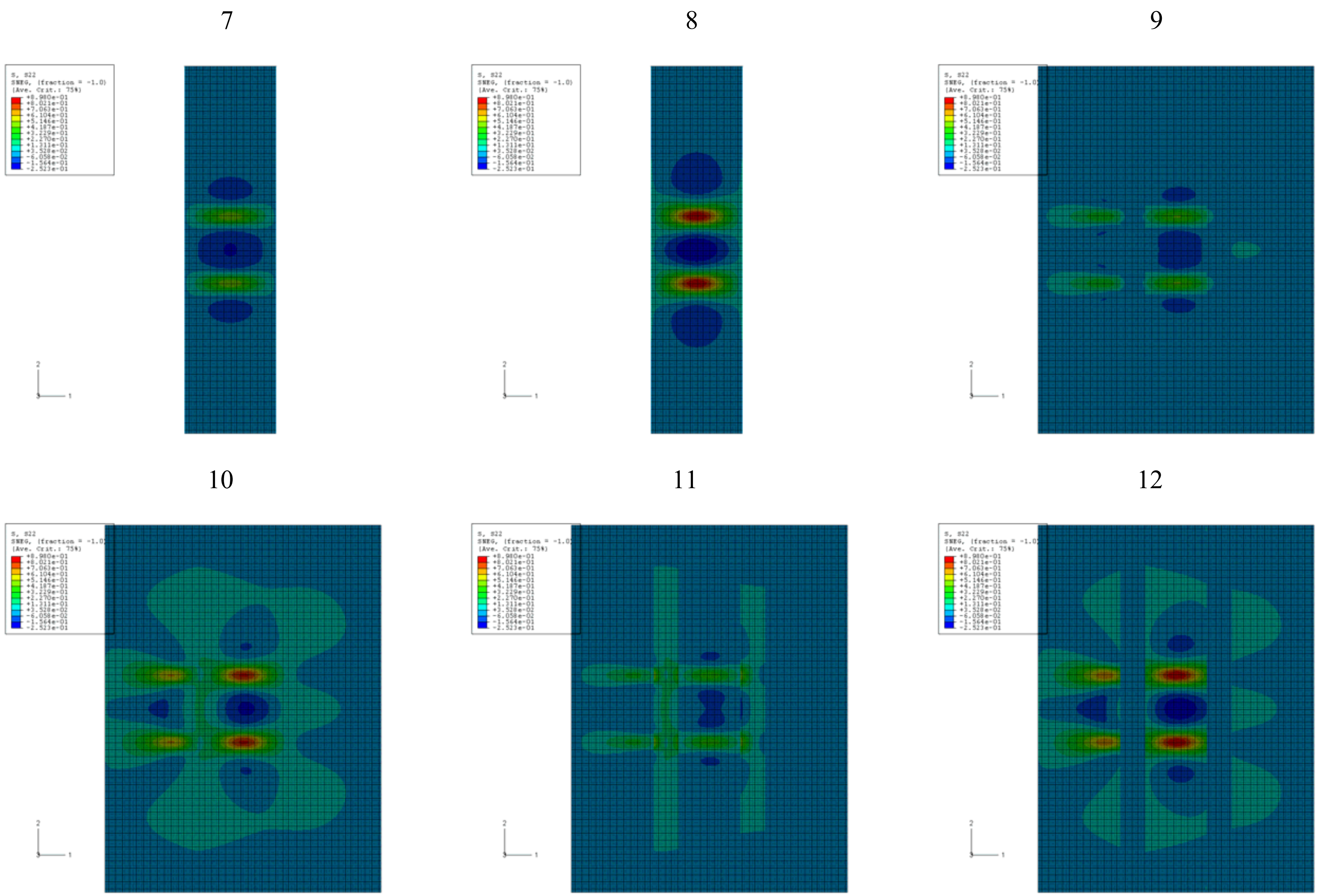


Figure 13A. Weak Direction Moment for 25 kips axle loading for Case7 through Case 12.

Table 1A. Deflection values of West Street over Chicopee River for the cases that were analyzed.

Deflection	D (postive region)	D (negative region)	Number of Spans	Supports	32 kips Axle	25 kips Axle
Case 1	Cracked	NA	Single	Rigid	0.072	0.058
Case 2	Uncracked	NA	Single	Rigid	0.048	0.043
Case 3	Cracked	Cracked	3 Span	Rigid	0.039	0.030
Case 4	Uncracked	Uncracked	3 Span	Rigid	0.024	0.019
Case 5	Cracked	Uncracked	3 Span	Rigid	0.032	0.026
Case 6	Uncracked	Cracked	3 Span	Rigid	0.022	0.027
Case 7	Cracked	NA	Single	Flexible	0.120	0.129
Case 8	Uncracked	NA	Single	Flexible	0.114	0.098
Case 9	Cracked	Cracked	3 Span	Flexible	0.139	0.176
Case 10	Uncracked	Uncracked	3 Span	Flexible	0.122	0.164
Case 11	Cracked	Uncracked	3 Span	Flexible	0.133	0.172
Case 12	Uncracked	Cracked	3 Span	Flexible	0.126	0.167

Table 2A. Strong direction moments of West Street over Chicopee River for the cases that were analyzed.

M strong (kip-in/in)	D (postive region)	D (negative region)	Number of Spans	Supports	Max.		Min.	
					32 kips Axle	25 kips Axle	32 kips Axle	25 kips Axle
Case 1	Cracked	NA	Single	Rigid	6.707	5.378	0.000	0.000
Case 2	Uncracked	NA	Single	Rigid	4.686	4.055	0.000	0.000
Case 3	Cracked	Cracked	3 Span	Rigid	4.940	3.863	-6.796	-5.306
Case 4	Uncracked	Uncracked	3 Span	Rigid	3.362	2.699	-5.239	-4.134
Case 5	Cracked	Uncracked	3 Span	Rigid	4.629	3.654	-6.653	-5.201
Case 6	Uncracked	Cracked	3 Span	Rigid	3.530	2.813	-5.034	-3.948
Case 7	Cracked	NA	Single	Flexible	6.627	5.341	-0.409	-0.294
Case 8	Uncracked	NA	Single	Flexible	4.656	4.037	-0.118	-0.063
Case 9	Cracked	Cracked	3 Span	Flexible	5.576	4.790	-5.328	-3.250
Case 10	Uncracked	Uncracked	3 Span	Flexible	4.029	3.664	-3.663	-1.934
Case 11	Cracked	Uncracked	3 Span	Flexible	5.317	4.650	-5.037	-2.965
Case 12	Uncracked	Cracked	3 Span	Flexible	4.150	3.712	-3.592	-1.932

Table 3A. Weak direction moments of West Street over Chicopee River for the cases that were analyzed.

M strong (kip-in/in)	D (postive region)	D (negative region)	Number of Spans	Supports	Max.		Min.	
					32 kips Axle	25 kips Axle	32 kips Axle	25 kips Axle
Case 1	Cracked	NA	Single	Rigid	0.644	0.486	-0.138	-0.187
Case 2	Uncracked	NA	Single	Rigid	1.192	0.845	-0.210	-0.322
Case 3	Cracked	Cracked	3 Span	Rigid	0.522	0.405	-0.140	-0.136
Case 4	Uncracked	Uncracked	3 Span	Rigid	0.949	0.710	-0.205	-0.299
Case 5	Cracked	Uncracked	3 Span	Rigid	0.547	0.417	-0.168	-0.182
Case 6	Uncracked	Cracked	3 Span	Rigid	1.036	0.769	-0.229	-0.350
Case 7	Cracked	NA	Single	Flexible	0.634	0.484	-0.122	-0.161
Case 8	Uncracked	NA	Single	Flexible	1.224	0.898	-0.165	-0.252
Case 9	Cracked	Cracked	3 Span	Flexible	0.539	0.428	-0.123	-0.110
Case 10	Uncracked	Uncracked	3 Span	Flexible	1.039	0.828	-0.123	-0.176
Case 11	Cracked	Uncracked	3 Span	Flexible	0.612	0.506	-0.101	-0.082
Case 12	Uncracked	Cracked	3 Span	Flexible	1.126	0.887	-0.149	-0.227

Table 4A. Deflection values of Westbound GA Route 53 over Lake Lanier for the cases that were analyzed.

Deflection	D (positive region)	D (negative region)	Number of Spans	Supports	32 kips Axle	25 kips Axle
Case 1	Cracked	NA	Single	Rigid	0.047	0.037
Case 2	Uncracked	NA	Single	Rigid	0.032	0.027
Case 3	Cracked	Cracked	3 Span	Rigid	0.036	0.028
Case 4	Uncracked	Uncracked	3 Span	Rigid	0.020	0.016
Case 5	Cracked	Uncracked	3 Span	Rigid	0.024	0.020
Case 6	Uncracked	Cracked	3 Span	Rigid	0.027	0.021
Case 7	Cracked	NA	Single	Flexible	0.154	0.184
Case 8	Uncracked	NA	Single	Flexible	0.139	0.175
Case 9	Cracked	Cracked	3 Span	Flexible	0.141	0.170
Case 10	Uncracked	Uncracked	3 Span	Flexible	0.116	0.148
Case 11	Cracked	Uncracked	3 Span	Flexible	0.125	0.156
Case 12	Uncracked	Cracked	3 Span	Flexible	0.127	0.158

Table 5A. Strong direction moments of Westbound GA Route 53 over Lake Lanier for the cases that were analyzed.

M Strong (kip-in/in)	D (positive region)	D (negative region)	Number of Spans	Supports	Max.		Min.	
					32 kips Axle	25 kips Axle	32 kips Axle	25 kips Axle
Case 1	Cracked	NA	Single	Rigid	5.802	4.579	0.000	0.000
Case 2	Uncracked	NA	Single	Rigid	4.069	3.370	0.000	0.000
Case 3	Cracked	Cracked	3 Span	Rigid	4.786	3.739	-2.771	-2.162
Case 4	Uncracked	Uncracked	3 Span	Rigid	3.172	2.544	-2.049	-1.599
Case 5	Cracked	Uncracked	3 Span	Rigid	4.098	3.255	-2.317	-1.818
Case 6	Uncracked	Cracked	3 Span	Rigid	3.472	2.710	-2.147	-1.652
Case 7	Cracked	NA	Single	Flexible	5.718	4.530	-0.359	-0.270
Case 8	Uncracked	NA	Single	Flexible	4.024	3.343	-0.102	-0.062
Case 9	Cracked	Cracked	3 Span	Flexible	5.621	4.878	-1.876	-0.973
Case 10	Uncracked	Uncracked	3 Span	Flexible	4.044	3.731	-1.066	-0.600
Case 11	Cracked	Uncracked	3 Span	Flexible	5.030	4.522	-1.292	-0.457
Case 12	Uncracked	Cracked	3 Span	Flexible	4.256	3.779	-1.294	-0.696

Table 6A. Weak direction moments of Westbound GA Route 53 over Lake Lanier for the cases that were analyzed.

M weak (kip-in/in)	D (positive region)	D (negative region)	Number of Spans	Supports	Max.		Min.	
					32 kips Axle	25 kips Axle	32 kips Axle	25 kips Axle
Case 1	Cracked	NA	Single	Rigid	0.553	0.425	-0.135	-0.143
Case 2	Uncracked	NA	Single	Rigid	1.055	0.774	-0.209	-0.321
Case 3	Cracked	Cracked	3 Span	Rigid	0.558	0.435	-0.166	-0.144
Case 4	Uncracked	Uncracked	3 Span	Rigid	0.899	0.679	-0.202	-0.272
Case 5	Cracked	Uncracked	3 Span	Rigid	0.883	0.676	-0.220	-0.227
Case 6	Uncracked	Cracked	3 Span	Rigid	1.229	0.936	-0.321	-0.452
Case 7	Cracked	NA	Single	Flexible	0.565	0.449	-0.098	-0.092
Case 8	Uncracked	NA	Single	Flexible	1.197	0.959	-0.067	-0.102
Case 9	Cracked	Cracked	3 Span	Flexible	0.582	0.467	-0.133	-0.100
Case 10	Uncracked	Uncracked	3 Span	Flexible	1.045	0.855	-0.071	-0.082
Case 11	Cracked	Uncracked	3 Span	Flexible	1.031	0.855	-0.080	-0.034
Case 12	Uncracked	Cracked	3 Span	Flexible	1.374	1.113	-1.832	-0.248

Table 7A. Deflection values of WB I-70 over the Missouri River for the cases that were analyzed.

Deflection	D (positive region)	D (negative region)	Number of Spans	Supports	32 kips Axle	25 kips Axle
Case 1	Cracked	NA	Single	Rigid	0.115	0.097
Case 2	Uncracked	NA	Single	Rigid	0.078	0.076
Case 3	Cracked	Cracked	3 Span	Rigid	0.066	0.051
Case 4	Uncracked	Uncracked	3 Span	Rigid	0.037	0.032
Case 5	Cracked	Uncracked	3 Span	Rigid	0.051	0.041
Case 6	Uncracked	Cracked	3 Span	Rigid	0.048	0.039
Case 7	Cracked	NA	Single	Flexible	0.133	0.131
Case 8	Uncracked	NA	Single	Flexible	0.101	0.112
Case 9	Cracked	Cracked	3 Span	Flexible	0.116	0.127
Case 10	Uncracked	Uncracked	3 Span	Flexible	0.088	0.108
Case 11	Cracked	Uncracked	3 Span	Flexible	0.100	0.116
Case 12	Uncracked	Cracked	3 Span	Flexible	0.098	0.115

Table 8A. Strong direction moments of WB I-70 over the Missouri River for the cases that were analyzed.

M Strong (kip-in/in)	D (positive region)	D (negative region)	Number of Spans	Supports	Max.		Min.	
					32 kips Axle	25 kips Axle	32 kips Axle	25 kips Axle
Case 1	Cracked	NA	Single	Rigid	7.580	6.292	0.000	0.000
Case 2	Uncracked	NA	Single	Rigid	5.313	4.879	0.000	0.000
Case 3	Cracked	Cracked	3 Span	Rigid	5.813	4.543	-7.211	-5.637
Case 4	Uncracked	Uncracked	3 Span	Rigid	3.855	3.167	-5.518	-4.517
Case 5	Cracked	Uncracked	3 Span	Rigid	5.201	4.156	-6.713	-5.354
Case 6	Uncracked	Cracked	3 Span	Rigid	4.176	3.389	-5.320	-4.247
Case 7	Cracked	NA	Single	Flexible	7.383	6.204	-1.098	-0.731
Case 8	Uncracked	NA	Single	Flexible	5.246	4.828	-0.403	-0.224
Case 9	Cracked	Cracked	3 Span	Flexible	5.994	4.827	-6.567	-4.761
Case 10	Uncracked	Uncracked	3 Span	Flexible	4.084	3.512	-4.777	-3.451
Case 11	Cracked	Uncracked	3 Span	Flexible	5.431	4.502	-5.942	-4.274
Case 12	Uncracked	Cracked	3 Span	Flexible	4.363	3.674	-4.722	-3.396

Table 9A. Weak direction moments of WB I-70 over the Missouri River for the cases that were analyzed.

M weak (kip-in/in)	D (positive region)	D (negative region)	Number of Spans	Supports	Max.		Min.	
					32 kips Axle	25 kips Axle	32 kips Axle	25 kips Axle
Case 1	Cracked	NA	Single	Rigid	0.765	0.558	-0.141	-0.220
Case 2	Uncracked	NA	Single	Rigid	1.361	0.933	-0.212	-0.265
Case 3	Cracked	Cracked	3 Span	Rigid	0.697	0.533	-0.172	-0.230
Case 4	Uncracked	Uncracked	3 Span	Rigid	1.114	0.803	-0.218	-0.340
Case 5	Cracked	Uncracked	3 Span	Rigid	1.063	0.806	-0.259	-0.356
Case 6	Uncracked	Cracked	3 Span	Rigid	1.365	0.961	-0.303	-0.458
Case 7	Cracked	NA	Single	Flexible	0.725	0.534	-0.126	-0.191
Case 8	Uncracked	NA	Single	Flexible	1.339	0.936	-0.189	-0.244
Case 9	Cracked	Cracked	3 Span	Flexible	0.698	0.538	-0.165	-0.217
Case 10	Uncracked	Uncracked	3 Span	Flexible	1.141	0.842	-0.192	-0.299
Case 11	Cracked	Uncracked	3 Span	Flexible	1.078	0.840	-0.224	-0.318
Case 12	Uncracked	Cracked	3 Span	Flexible	1.386	0.997	-0.275	-0.416