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**MASH TL-4 Engineering Analyses and Detailing of 36-in. and 42-in. High Median Barriers for LADOTD**

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13. Abstract
Single-slope median barriers are currently planned for several bridges in Louisiana. For these bridges, both 36-in. and 42-in. designs were developed and considered as part of this project. Both barrier designs can be used near a longitudinal joint that is approximately 1 in. wide. The 36-in. high barrier is similar to the single-slope traffic rail (SSTR) used by the Texas Department of Transportation (TxDOT), which was successfully crash tested according to the *Manual for Assessing Safety Hardware* (MASH) Test Level 4 (TL-4) in July 2010. The Louisiana Department of Transportation and Development has incorporated the TxDOT SSTR bridge rail height and profile for the median barriers planned for this project. The 42-in. high barrier maintains the same slope as the 36-in. median barrier but has a smaller top thickness. This project aimed to evaluate the strength of the proposed median barrier designs according to the American Association of State Highways and

Transportation Officials *Load and Resistance Factor Design (LRFD) Bridge Design Specifications* for MASH TL-4 crash performance. The report presents the results of the strength analyses performed on these designs and offers recommendations for improving their strength and performance under MASH TL-4 impact conditions.

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# MASH TL-4 Engineering Analyses and Detailing of 36-in. and 42-in. High Median Barriers for DOTD

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conducted for

Louisiana Department of Transportation and Development
Louisiana Transportation Research Center

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July 2023

# Abstract

Single-slope median barriers are currently planned for several bridges in Louisiana. For these bridges, both 36-in. and 42-in. high single-slope median barriers were developed and considered as part of this project. Both barrier designs can be used near a longitudinal joint that is approximately 1 in. wide. The 36-in. high barrier is similar to the single-slope traffic rail (SSTR) used by the Texas Department of Transportation (TxDOT), which was successfully crash tested according to the *Manual for Assessing Safety Hardware* (MASH) Test Level 4 (TL-4) in July 2010 (Texas A&M Transportation Institute Project 420020-9). The Louisiana Department of Transportation and Development has incorporated the TxDOT SSTR bridge rail height and profile for the median barrier planned for this project. The 42-in. high barrier maintains the same slope as the 36-in. median barrier design. The top thickness of the 42-in. barrier is smaller. The purpose of this project was to analyze the strength of the proposed designs with respect to the American Association of State Highways and Transportation Officials *Load and Resistance Factor Design (LRFD) Bridge Design Specifications* [1] for MASH TL-4 crash performance requirements [2]. This report presents the results of the strength analyses performed on the 32-in. and 42-in. median barriers analyzed for this project and provides recommendations on improving the strength and performance of these designs with respect to MASH TL-4 impact conditions.

# Acknowledgments

The authors would like to thank Walid Alaywan, Ph.D., Senior Structures Research Engineer at the Louisiana Transportation Research Center; ZhengZheng Fu, Bridge Design Engineer Administrator at the Louisiana Department of Transportation and Development (DOTD); Chris Guidry, Assistant Bridge Design Administrator at DOTD; and Carl Gaudry, Bridge Design Manager at DOTD. These individuals contributed greatly to the success of this project. Their assistance and involvement in this project are highly appreciated.

# Implementation Statement

The bridge rail designs analyzed and presented herein meet the strength and performance requirements for the *Manual for Assessing Safety Hardware* Test Level 4 specifications [2]. These bridge rail designs are recommended for implementation on the Louisiana bridges that meet the deck requirements as presented herein. For additional information, refer to the information, drawings, and calculations provided in this report.

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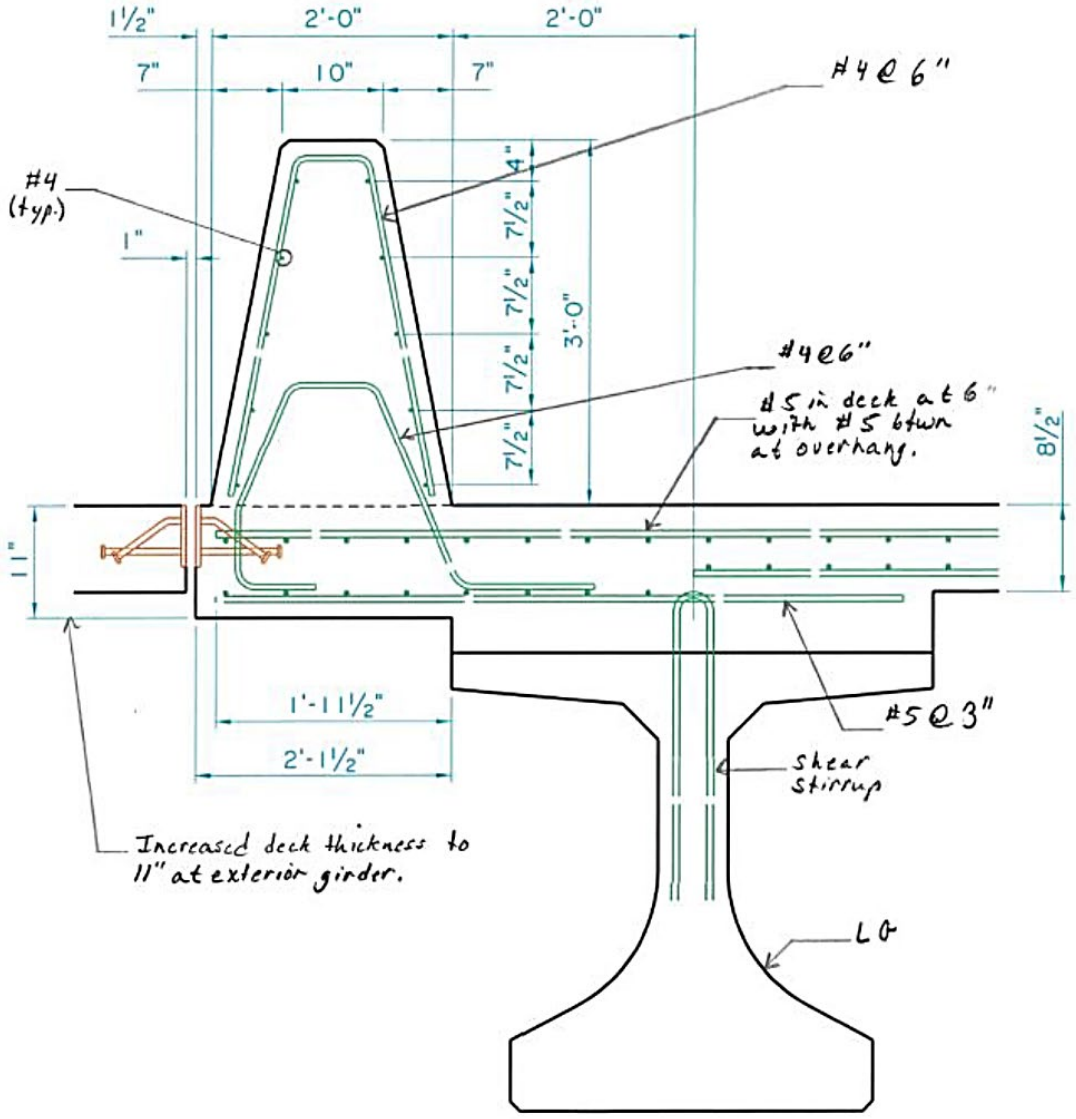
# Introduction

Single-slope median barriers are currently planned for several bridges in Louisiana. For these bridges, both 36-in. and 42-in. high single-slope median barrier designs were developed and considered as part of this project. The 36-in. high single-slope design initially received for this project is shown in Figure 1. The proposed design shown in Figure 1 is similar in profile and height to the Texas Department of Transportation (TxDOT) single-slope traffic rail (SSTR), which was successfully crash tested according to the *Manual for Assessing Safety Hardware* (MASH) [2] Test Level 4 (TL-4) in July 2010 (Texas A&M Transportation Institute [TTI] Project 420020-9). The Louisiana Department of Transportation and Development (DOTD) has incorporated the TxDOT SSTR bridge rail height and profile for the median barrier design shown in Figure 1. In addition to the 36-in. design, a similar 42-in. barrier with the same slope is needed for this project. The top width of the 42-in. barrier will be reduced to 7⅝ in. The profile, geometry, and reinforcing steel will also be similar for the 42-in. barrier—only taller.

**Figure 1. Proposed 36-in. median barrier design**




For this project, TTI proposed performing engineering strength calculations to determine if the proposed designs meet the strength and performance requirements of MASH TL-4. MASH TL-4 strength analyses were performed on four different barrier cases (six total sets of analyses). These four cases are as follows:

1. A 36-in. single-slope median barrier without the longitudinal open joint (as shown in Figure 1 except no longitudinal open joint) with an 8½-in. thick deck supported by girders spaced 8 ft. O/C.
2. A 36-in. single-slope median barrier with the longitudinal open joint (as shown in Figure 1) with possible impacts on both sides of the barrier (two analyses).
3. A 42-in. single-slope median barrier without the longitudinal open joint (same as Figure 1 except 42 in. tall and 7⅝ in. wide at top) with an 8½-in. thick deck supported by girders spaced 8 ft. O/C.
4. A 42-in. single-slope median barrier with the longitudinal open joint (same as Figure 1 except 42 in. tall and 7⅝ in. wide at top) with possible impacts on both sides of the barrier.

The strength analyses performed for this project followed the procedures in Section 13 of the American Association of State Highway and Transportation Officials (AASHTO) *Load and Resistance Factor Design (LRFD) Bridge Design Specifications* [1] for MASH TL-4 impact loading conditions [2]. Based on the analyses, review of the proposed details, and all available information, TTI made recommendations as necessary to improve the strength and performance of the barrier designs with respect to MASH TL-4 impact conditions. This technical report summarizes the engineering strength analyses and any recommended changes or details to improve the strength and performance of the barrier designs with respect to MASH TL-4 impact conditions. TTI will also provide a summary of its review of all available information for the barrier designs with respect to MASH TL-4 specifications in the report.

# Objective

The objective of this research was to analyze the strengths of the four proposed median barrier designs considered for this project in accordance with AASHTO LRFD Section 13 specifications for MASH TL-4 impact conditions. These designs are briefly described below and shown in Figure 1 (36-in. median barrier):

1. A 36-in. single-slope median barrier without the longitudinal open joint (as shown in Figure 1 except no longitudinal open joint).
2. A 36-in. single-slope median barrier with the longitudinal open joint (as shown in Figure 1).
3. A 42-in. single-slope median barrier without the longitudinal open joint (same as Figure 1 except 42 in. tall and 7⅝ in. wide at top).
4. A 42-in. single-slope median barrier with the longitudinal open joint (same as Figure 1 except 42 in. tall and 7⅝ in. wide at top).

Recommendations and improvements are provided in this technical report as necessary based on the analyses performed for this project to improve the strength and performance of the barrier designs for MASH TL-4 impact conditions.

# Scope

The scope of this project was to provide engineering analyses and details on the proposed median barrier designs and to prepare a technical report of the findings. A brief discussion of the tasks is presented in this section.

## Task 1 — Engineering Analysis and Details

For this task, engineering strength analyses were performed on the four proposed designs considered for this project in accordance with AASHTO LRFD Section 13 specifications for MASH TL-4 impact conditions. These designs are briefly described below and shown in the figures that follow.

1. An engineering strength analysis was performed using a 36-in. single-slope median barrier without a longitudinal open joint in the deck. This analysis considered an 8.5-in. thick deck supported between two concrete girders spaced 8 ft. O/C. The barrier was anchored to the deck in the center between the two concrete girders. Appendix A provides additional details.
2. Two engineering strength analyses were performed using a 36-in. single-slope median barrier with a longitudinal open joint in the deck. These analyses considered an 11.0-in. thick deck cantilever. The width of the deck cantilever was 4 ft. 1½ in. wide from the centerline of the exterior girder to the edge of the deck. The barrier was anchored to the deck 1½ in. from the edge of the deck cantilever. Strength analyses were performed considering crash impact loading on each side of the barrier with the longitudinal joint in the deck. Appendix A provides additional details.
3. An engineering strength analysis was performed using a 42-in. single-slope median barrier without a longitudinal open joint in the deck. This analysis considered an 8.5-in. thick deck supported between two concrete girders spaced 8 ft. O/C. The barrier was anchored to the deck in the center between the two concrete girders. Appendix A provides additional details.
4. Two engineering strength analyses were performed using a 42-in. single-slope median barrier with a longitudinal open joint in the deck. This analysis considered an 11.0-in. thick deck cantilever. The width of the deck cantilever was 4 ft. 1½ in. wide from the centerline of the exterior girder to the edge of the deck. The barrier

was anchored to the deck 1½ in. from the edge of the deck cantilever. Strength analyses were performed considering crash impact loading on each side of the barrier with the longitudinal joint in the deck. Appendix A provides additional details, and Appendix B presents the calculations.

Engineering details were developed for each design, as necessary, to improve the strength and performance of the proposed designs with respect to MASH TL-4 impact conditions. The principal investigator worked closely with the DOTD and Louisiana Transportation Research Center (LTRC) project team to develop the details used for this project. All analyses generated for the proposed designs developed for this project were submitted to the DOTD and LTRC project team for their review and approval. These analyses are included in Appendix B.

## Task 2 — Reporting

Generating a final report was part of the scope of this project. This report provides details and descriptions of the proposed median barrier designs developed for this project. This report contains all analyses done in Mathcad 8.0 format developed and generated for this project. All details developed to improve the strength and performance of the median barriers included in this project are provided in the drawings in Appendix A.

# Methodology

The procedures outlined in Section 13 of the AASHTO *Load and Resistance Factor Design (LRFD) Bridge Design Specifications* [1] were used to perform the analyses on the median barrier designs for this project. The commercial software RISA-3D was used to perform finite element modeling of the median barrier designs and the concrete decks to determine the reactions from the barrier to the supporting concrete decks. The reactions from the barrier models were then used on separate finite element models for the supporting concrete deck structures. The bending moments in the deck from the barrier reactions were recorded and used as the demand bending moments. For the different barrier cases, the demand bending moments in the deck from the MASH TL-4 impact conditions on the barrier were then compared to the actual design bending moments that were calculated based on the deck design parameters and conditions.

Since the development of the crash testing specifications in MASH in 2009, the crash loads for TL-4 barriers have increased from those currently listed in Section 13 of the LRFD specifications [1]. In 2017, a separate research project determined the magnitude and location of the resultant force from MASH crash vehicles [3]. The design loads from this study were used in place of the LRFD Section 13 design load specifications. Table 1 provides the design loads used in the analyses for MASH TL-4 impact conditions.

**Table 1. Design forces for traffic railings**

| Test Level | Rail Height (inch) | $F_t$ (kip) | $F_L$ (kip) | $F_V$ (kip) | $L_t/L_L$ (ft) | $L_V$ (ft) | $H_e$ (inch) | $H_{min}$ (inch) |
|---|---|---|---|---|---|---|---|---|
| TL-1 | 18 or above | 13.5 | 4.5 | 4.5 | 4.0 | 18.0 | 18.0 | 18.0 |
| TL-2 | 18 or above | 27.0 | 9.0 | 4.5 | 4.0 | 18.0 | 20.0 | 18.0 |
| TL-3 | 29 or above | 71.0 | 18.0 | 4.5 | 4.0 | 18.0 | 19.0 | 29.0 |
| TL-4 (a) | 36 | 68.0 | 22.0 | 38.0 | 4.0 | 18.0 | 25.0 | 36.0 |
| TL-4 (b) | 36–42 | 80.0 | 27.0 | 22.0 | 5.0 | 18.0 | 30.0 | 36.0 |
| TL-5 (a) | 42 | 160.0 | 41.0 | 80.0 | 10.0 | 40.0 | 35.0 | 42.0 |
| TL-5 (b) | Greater than 42 | 262.0 | 75.0 | 160.0 | 10.0 | 40.0 | 43.0 | 42.0 |

# Engineering Analyses and Design of 36-in. and 42-in. Median Barriers for MASH TL-4 Loading Specifications

## DOTD 36-in. Median Barrier with Longitudinal Joint

Details were developed for the proposed DOTD 36-in. median barrier with a 1.0-in. wide longitudinal joint. The proposed barrier will be anchored to a 4-ft. 1½-in. wide deck cantilever. The thickness of the deck cantilever immediately adjacent to the 1.0-in. wide longitudinal joint is 11 in. The concrete compressive strength of the deck and barrier is 4000 psi. Details of the design are shown in Figure 2 and Figure 3. For additional information, refer to the drawings and details in Appendix A.

**Figure 2. Dimensional details of 36-in. median barrier with longitudinal joint**

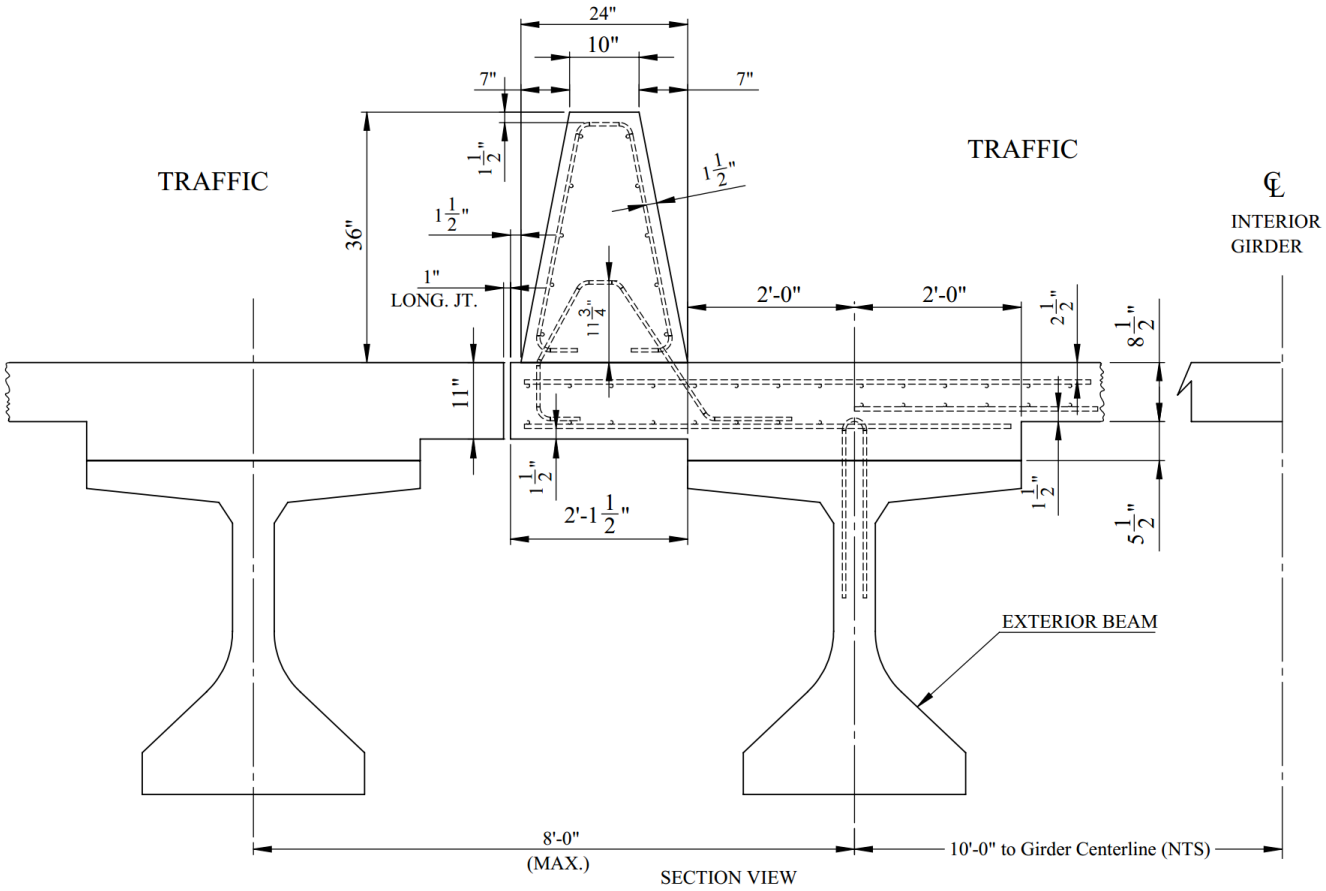
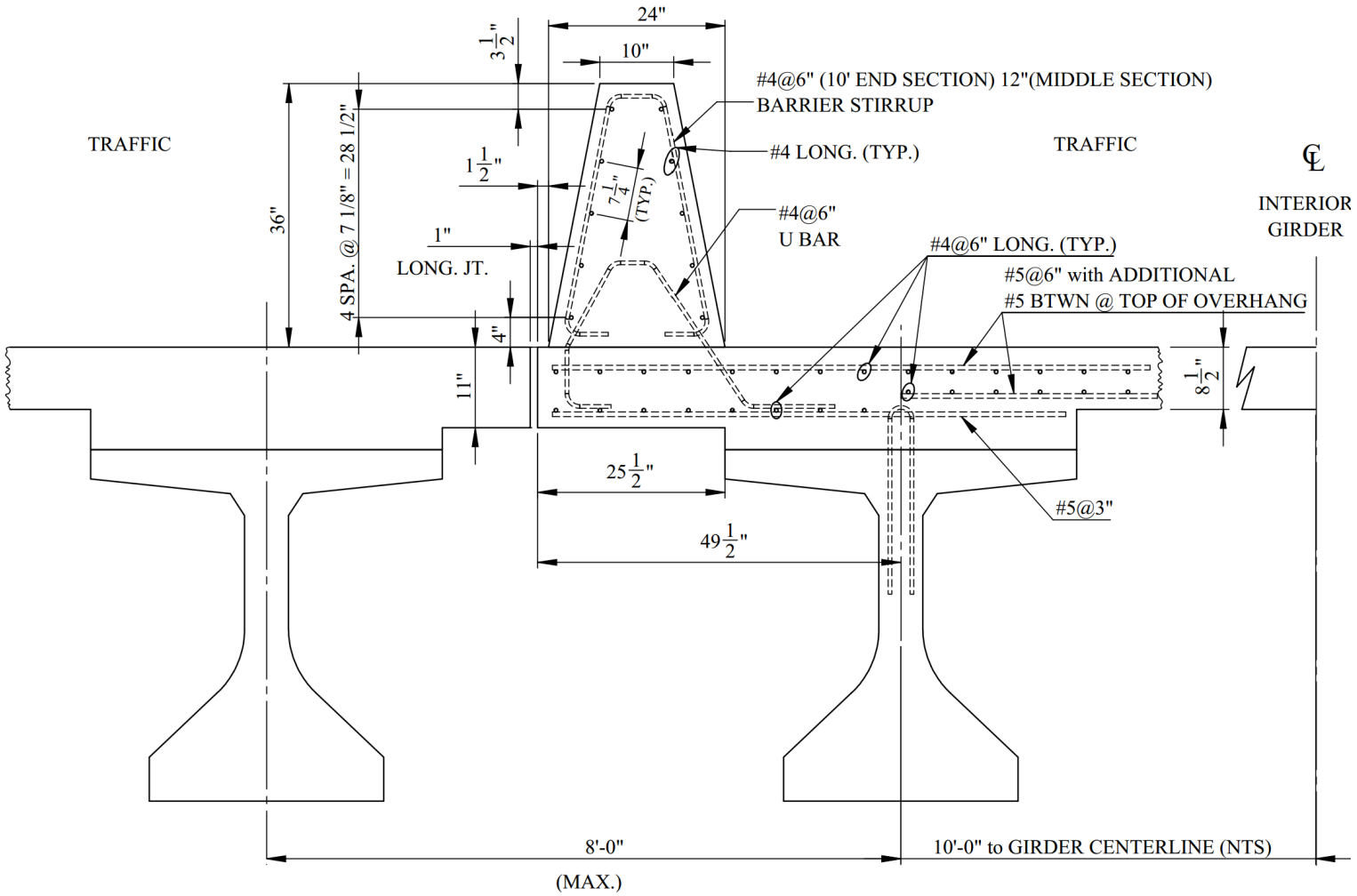


**Figure 3. Dimensional details of 36-in. median barrier with longitudinal joint**



### DOTD 36-in. Median Barrier without Longitudinal Joint

Details were developed for the proposed DOTD 36-in. median barrier without a 1.0-in. wide longitudinal joint adjacent to the barrier. For this case, the proposed barrier will be anchored between two girders spaced 8 ft. O/C. The thickness of the deck section between the two girders is 8.5 in. The concrete compressive strength of the deck and barrier is 4000 psi. Details of this design anchored between the girders are shown in Figure 4 and Figure 5. For additional information, refer to the drawings and details in Appendix A.

**Figure 4. Dimensional details of 36-in. median barrier without longitudinal joint**

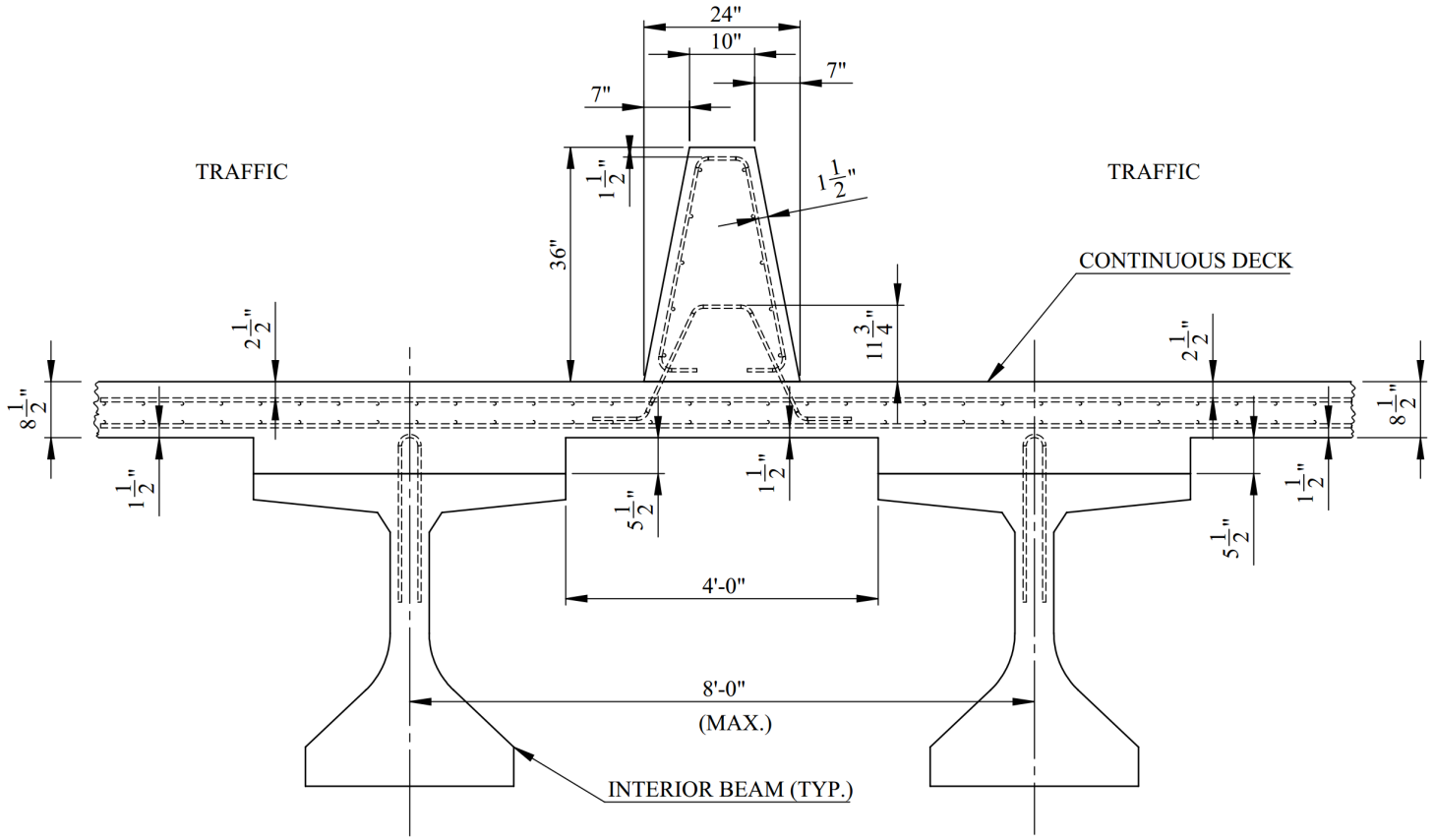
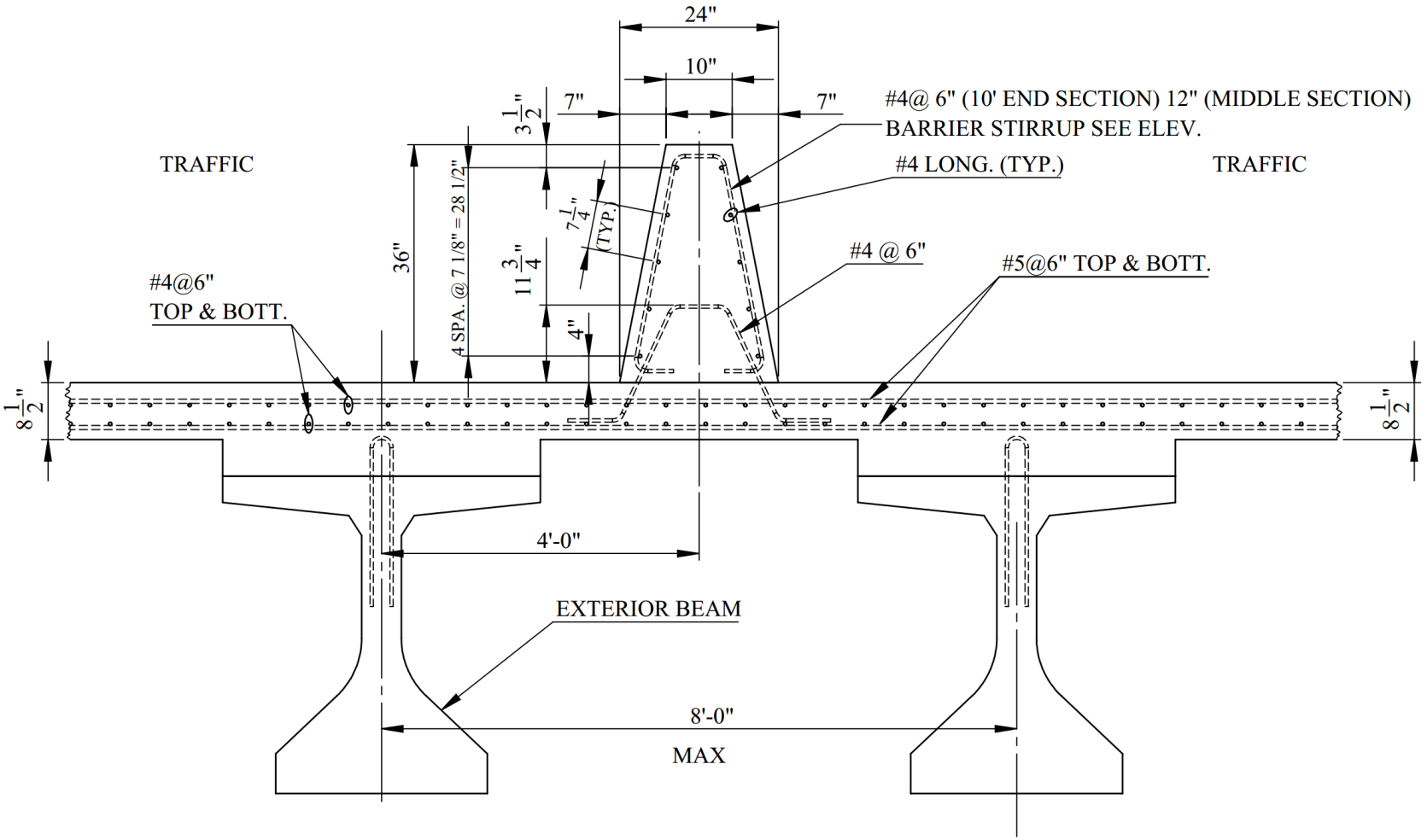


**Figure 5. Reinforcing details of 36-in. median barrier without longitudinal joint**



### DOTD 42-in. Median Barrier with Longitudinal Joint

Details were developed for the proposed DOTD 42-in. median barrier with a 1.0-in. wide longitudinal joint. The proposed barrier will be anchored to a 4-ft. 1½-in. wide deck cantilever. The thickness of the deck cantilever immediately adjacent to the 1.0-in. wide longitudinal joint is 11 in. The concrete compressive strength of the deck and barrier is 4000 psi. Details of the design are shown in Figure 6 and Figure 7. For additional information, refer to the drawings and details in Appendix A.

**Figure 6. Dimensional details of 42-in. median barrier with longitudinal joint**

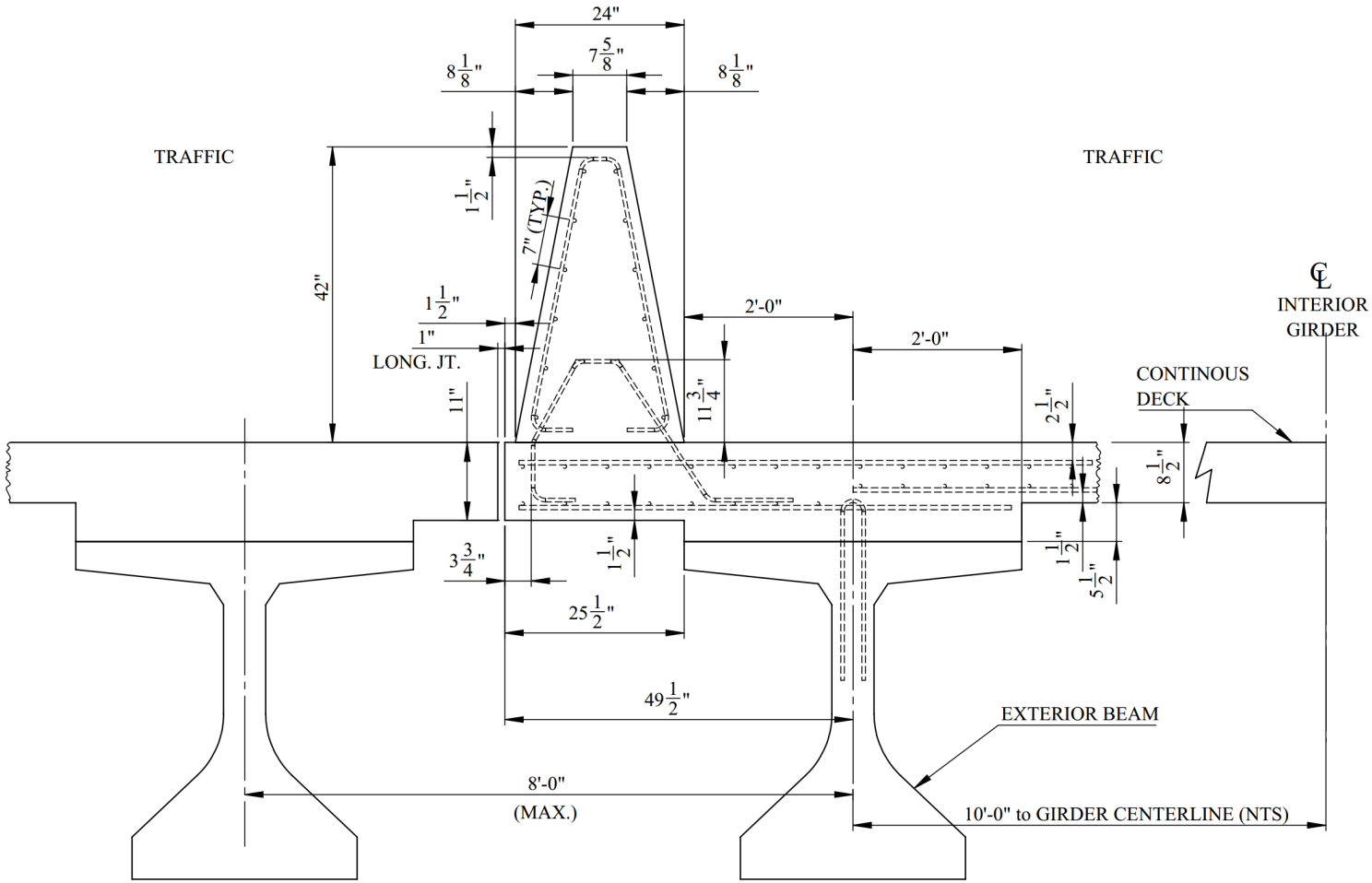
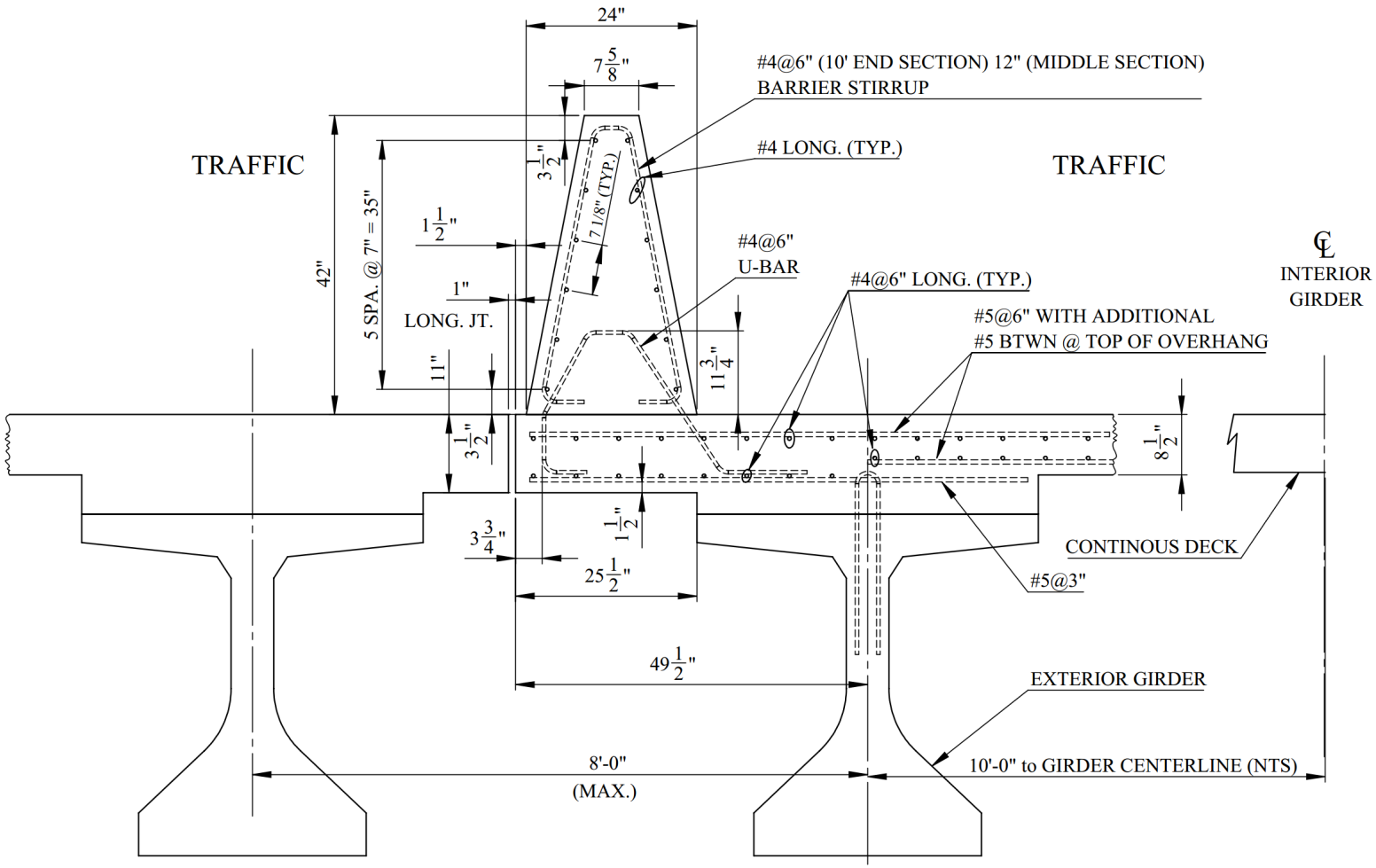


**Figure 7. Reinforcing details of 42-in. median barrier with longitudinal joint**



### DOTD 42-in. Median Barrier without Longitudinal Joint

Details were developed for the proposed DOTD 42-in. median barrier without a 1.0-in. wide longitudinal joint adjacent to the barrier. For this case, the proposed barrier will be anchored between two girders spaced 8 ft. O/C. The thickness of the deck section between the two girders is 8.5 in. The concrete compressive strength of the deck and barrier is 4000 psi. Details of this design anchored between the girders are shown in Figure 8 and Figure 9. For additional information, refer to the drawings and details in Appendix A.

**Figure 8. Dimensional details of 42-in. median barrier without longitudinal joint**

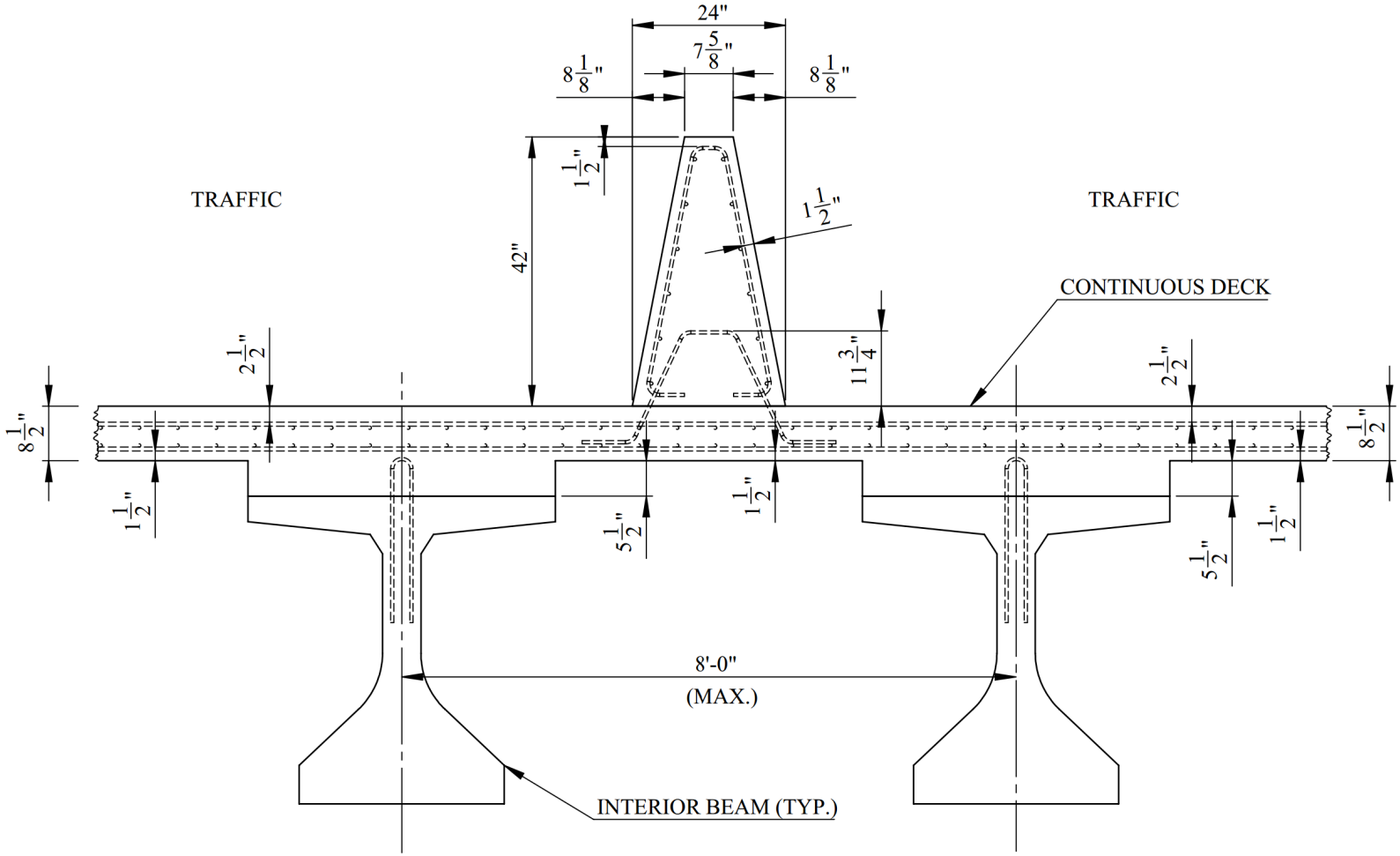
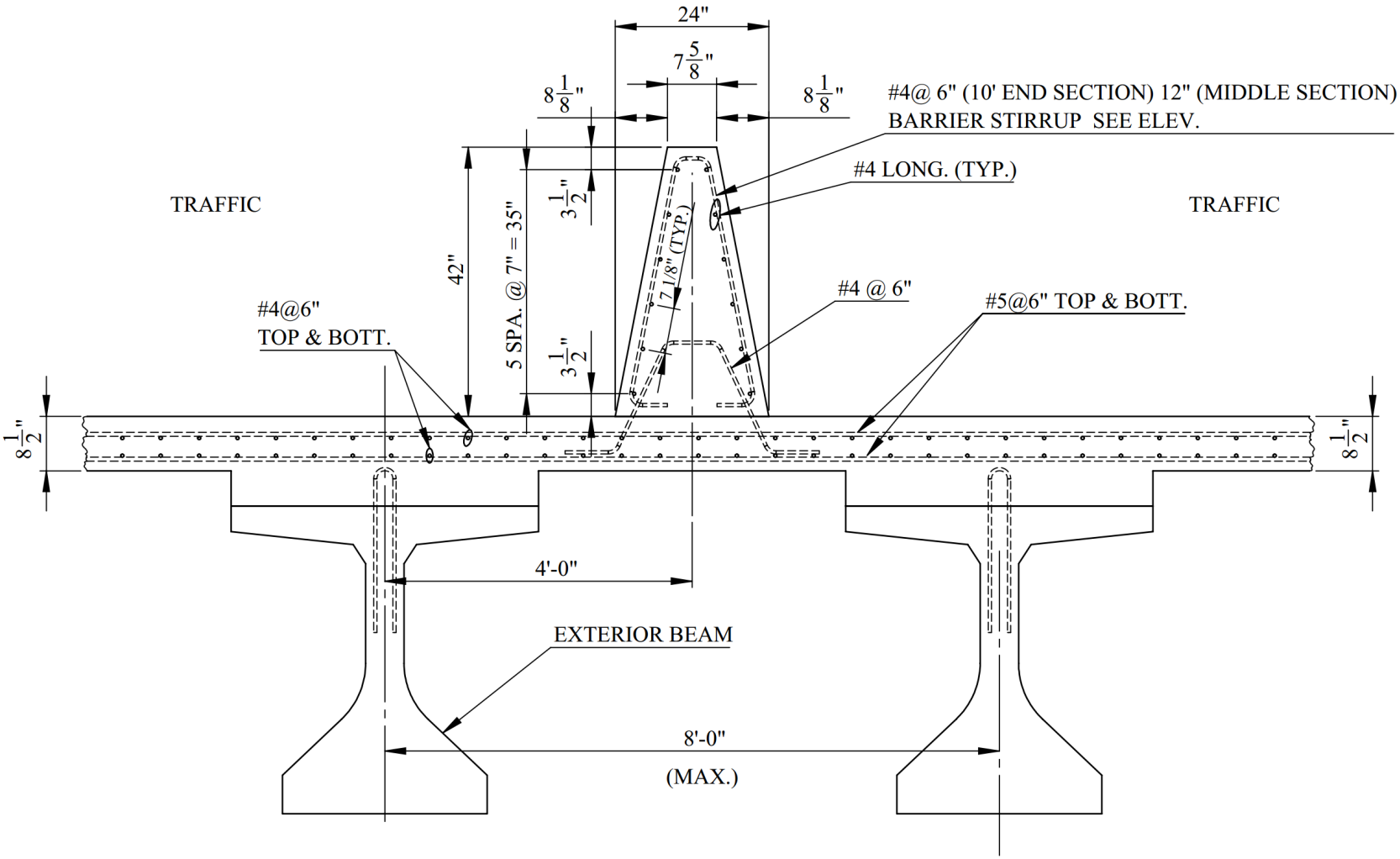


**Figure 9. Reinforcing details of 42-in. median barrier without longitudinal joint**



**Finite Element Modeling of Barriers Using RISA-3D**

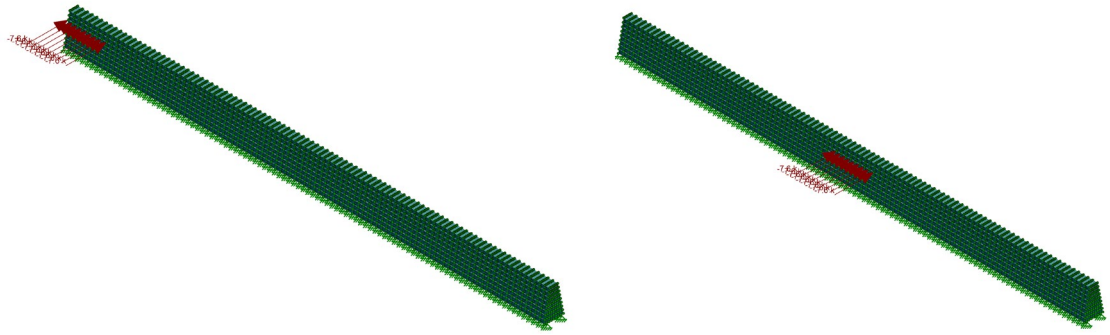
The barriers were separated from the deck and modeled independently using meshed solid elements with the commercial structural analysis program RISA-3D. Figure 10 shows the overview of the barrier finite element analysis (FEA) model of a typical barrier modeled with the loads applied at the end-section and mid-span areas of the barrier. The design loads provided in Table 1 for both the 36-in. and 42-in. barriers were used in the FEA models.

The length of the model was set as 50 ft. to ensure the barriers have sufficient length to distribute the transverse impact load at the end-section and the mid-span, and the engaged areas do not interfere with each other. After the project meeting on November 22, 2022, 40 ft. long minimum median barrier sections were analyzed for both the end and mid-span loading cases for the 42-in. barrier design. The reaction loads from the FEA analyses using the shorter 40-ft. long sections were the same as the 50-ft. long sections that were analyzed for this project. In summary, 40-ft. long minimum sections can be used for this project.

The width of the solid elements was 6 in. in the longitudinal direction to represent the spacing of the deck anchorage vertical reinforcement. The barrier models were supported at two locations to represent the vertical deck anchorage into the barriers. As depicted in Figure 11, the two legs of the anchorage reinforcement were set as the supporting points at the base of the barrier to achieve the transfer of the loadings from the barriers to the deck. Pinned supports were used to represent these anchoring locations.

Figure 12 shows the schematic of the barrier FEA models for both 36-in. and 42-in. barriers. In the transverse direction shown in Figure 12, the width of the element at the base layer was set as 3 in. and gradually decreased over the height of the barrier. The transverse MASH TL-4 impact loads were applied at the side of the barrier at the corresponding $H_e$ heights provided in Table 1.

**Figure 10. Overview of barrier FEA model**



(a) Load at end-section (b) Load at mid-section

**Figure 11. Schematic of barrier cross section**

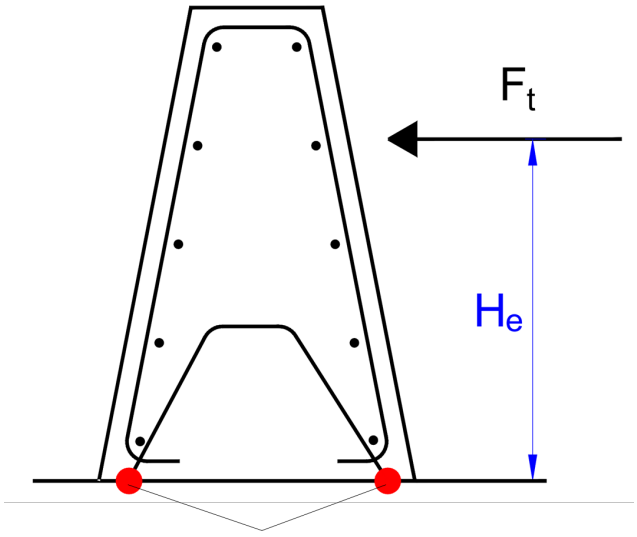
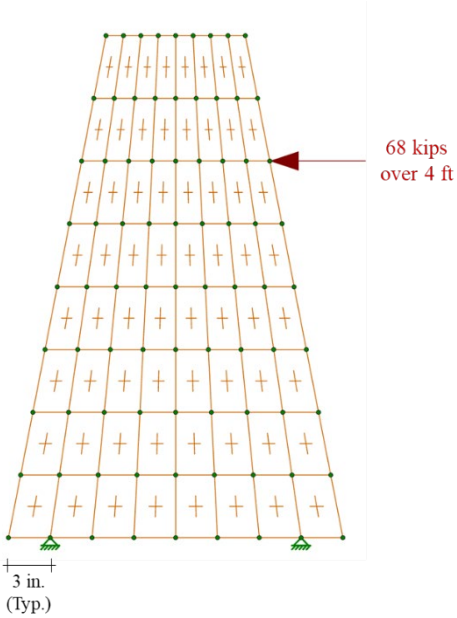
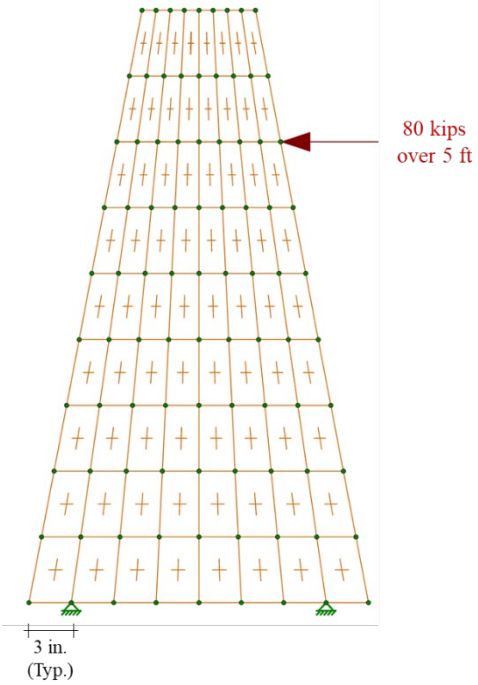


**Figure 12. Schematic of barrier FEA model**




(a) 36-in. barrier

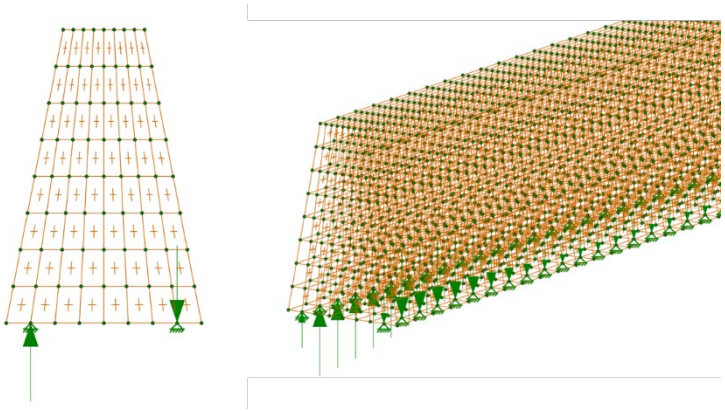



(b) 42-in. barrier

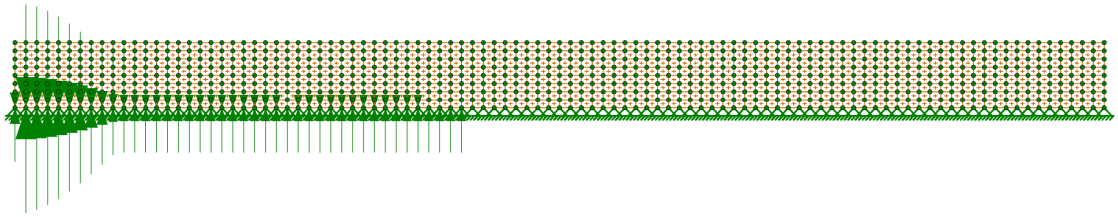
Figure 13 presents the reactions from the barrier FEA model from the applied MASH TL-4 impact loads. The reactions at the two supporting points at every transverse plane

typically had identical magnitudes with opposite directions. The figure also presents how the transverse impact loads at the end-section and the mid-span disturbed over the length of the barrier. It was apparent from the modeling efforts that the engaged areas for the distribution of the reactions to the deck for both the end-section and the mid-span loading cases did not interfere with each other.

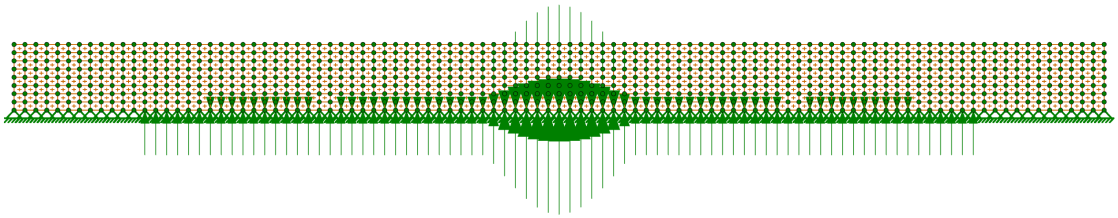
**Figure 13. Reaction of barrier FEA model (Typical)**



(a) Closer view of reactions



(b) Reactions of end-section model



(c) Reactions of mid-span model

Figure 14 and Figure 15 plot the reactions from the barrier FEA models loaded at the end-section and the mid-span sections, respectively. The reactions were plotted over the

length of the barrier. The plots present the absolute magnitude of the reactions at a single supporting point.

**Figure 14. Reaction of barrier FEA model — Load at end-section**

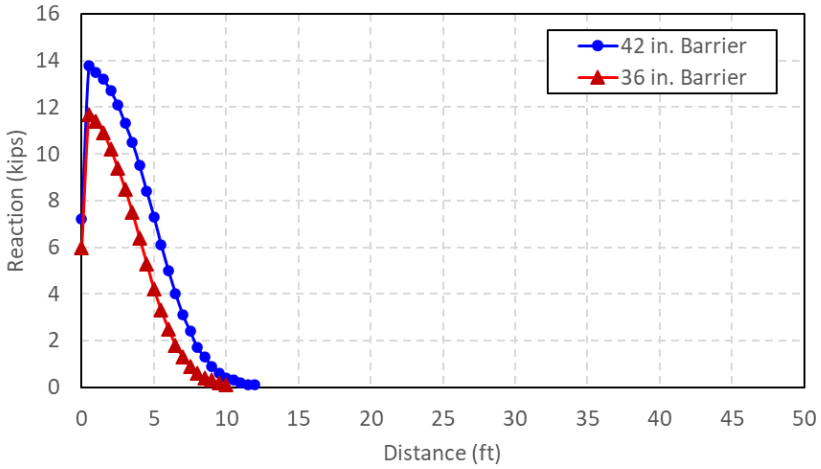
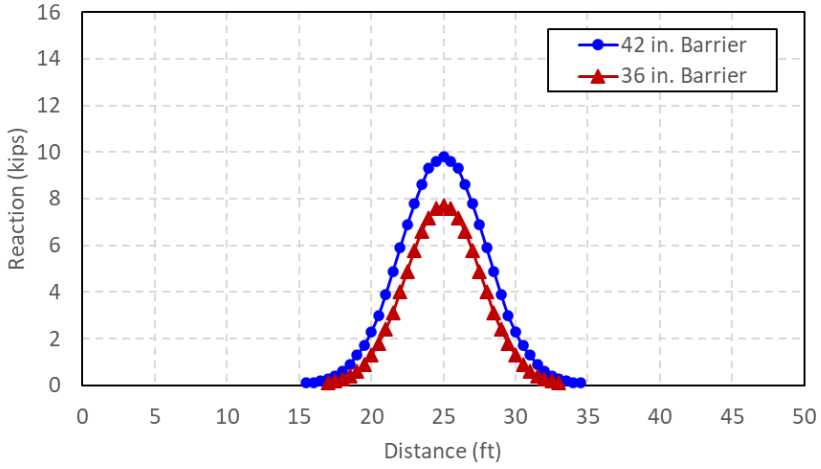



**Figure 15. Reaction of barrier FEA model — Load at mid-span**




## Finite Element Modeling of 36-in. and 42-in. Median Barriers on Deck Sections Using RISA-3D

The deck was modeled using meshed plate elements with RISA-3D. The reactions from the barrier solid models were applied to the deck plate models at the corresponding locations to achieve the deck bending moment demand.

Figure 16 shows an overview of the exterior deck plate model. The length of the plate models were set to 50 ft., the same as the length of the barrier solid models. The width of the exterior plate models (designs incorporating the open longitudinal joints) was set as 4 ft. to represent the distance from the free end of the deck to the center of the adjacent girder. The joint sides of the deck, both longitudinal and transverse, were set as free (no supports). A 6-in. × 6-in. element size was used for the plate model, while the plate elements at the barrier location were set as 6-in. × 3-in. elements to align with the barrier solid models.

**Figure 16. Exterior plate FEA model**

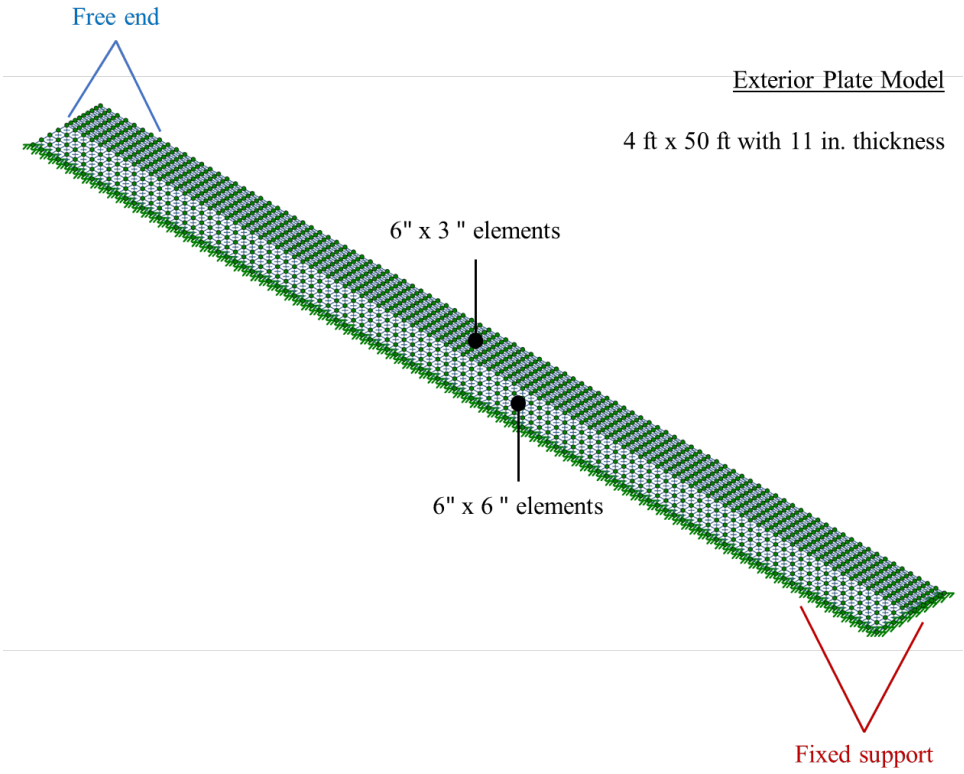



Figure 17 shows the overview of the interior plate model. The interior model is similar to the exterior model except the interior model uses fixed supports at three sides, as shown in Figure 17. The long sides were fixed to simulate the rigid connection to stiff concrete girders. The width of the interior plate model was set as 8 ft. to represent the center-to-center spacing of the girders.

The reactions from the barrier solid models were then applied to the deck plate models, as shown in Figure 18. Three analysis cases were generated for each barrier model:

(a) exterior plate with impact load from right side, (b) exterior plate with impact load from left side, and (c) interior plate.

**Figure 17. Interior plate FEA model**

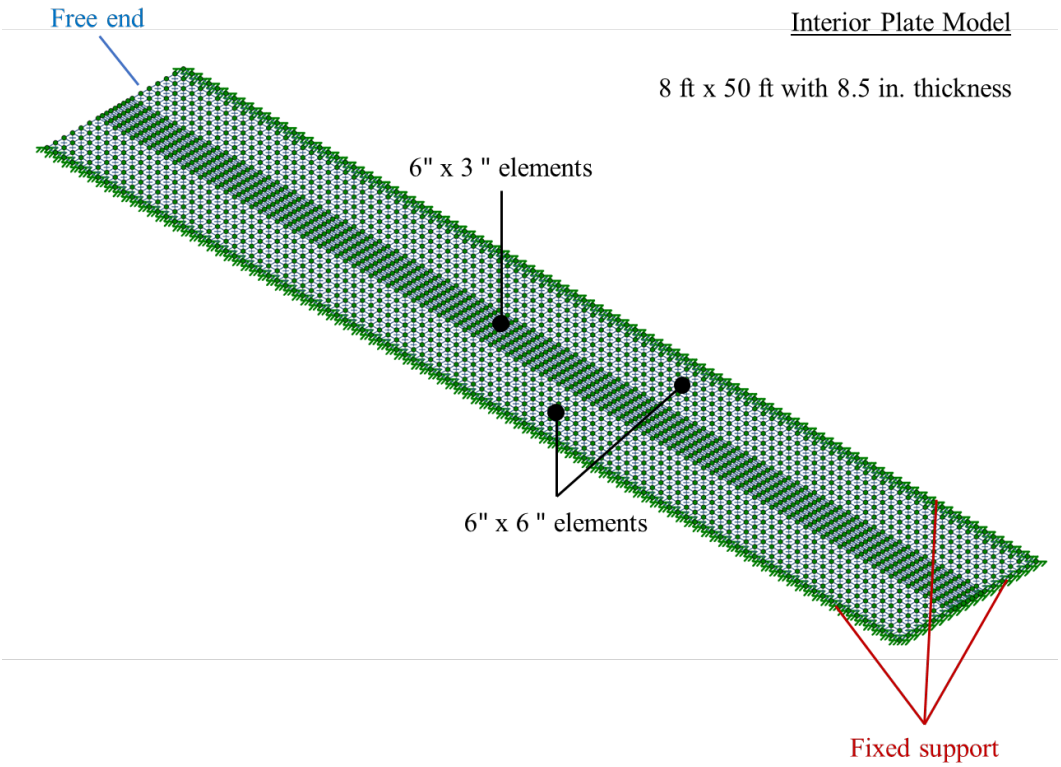
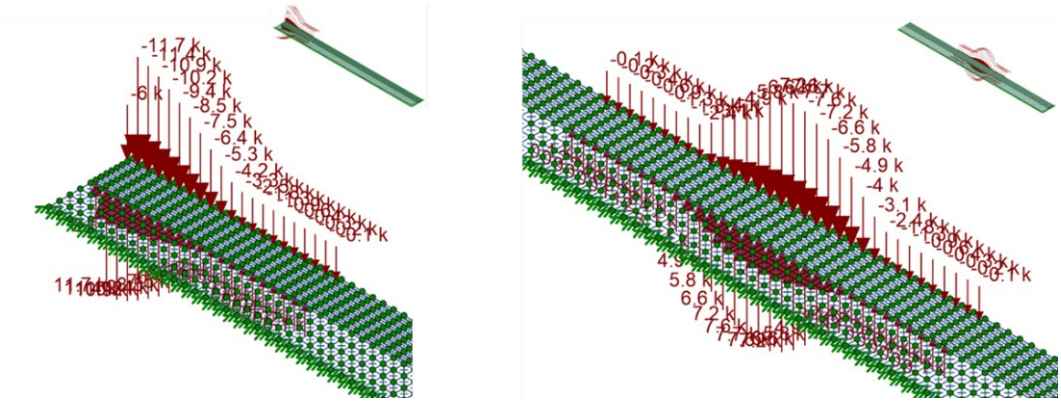
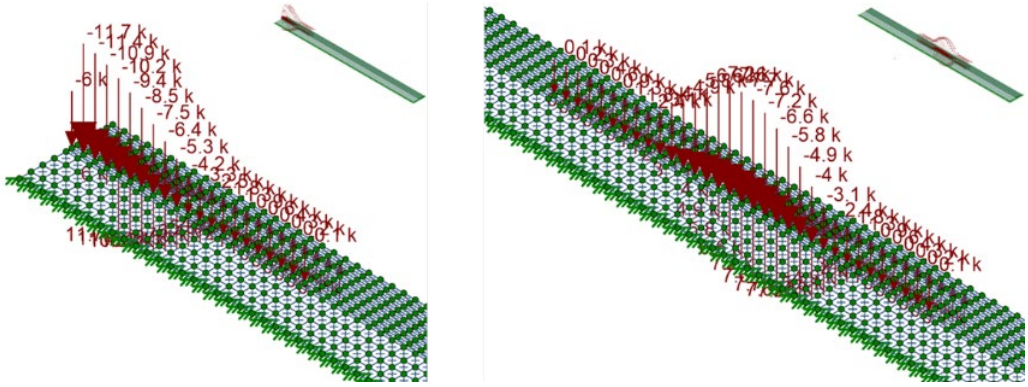


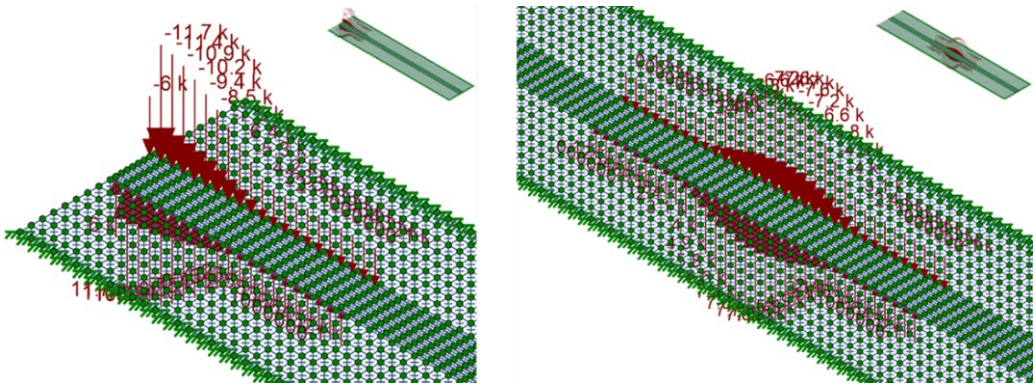
**Figure 18. Loadings on plate FEA models (Typical)**




(a) Exterior plate model load from inside barrier




(b) Exterior plate model load from outside barrier



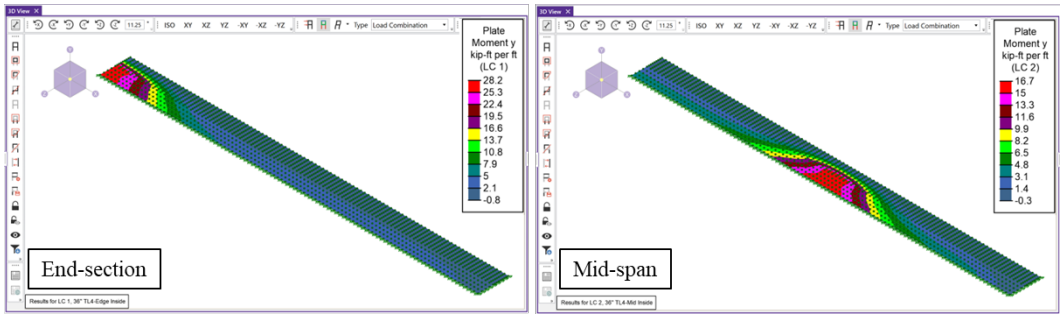

(c) Interior plate model

Figure 19 and Figure 20 present the moment analysis results from the deck plate models for the 36-in. and 42-in. median barriers, respectively. Table 2 summarizes the maximum

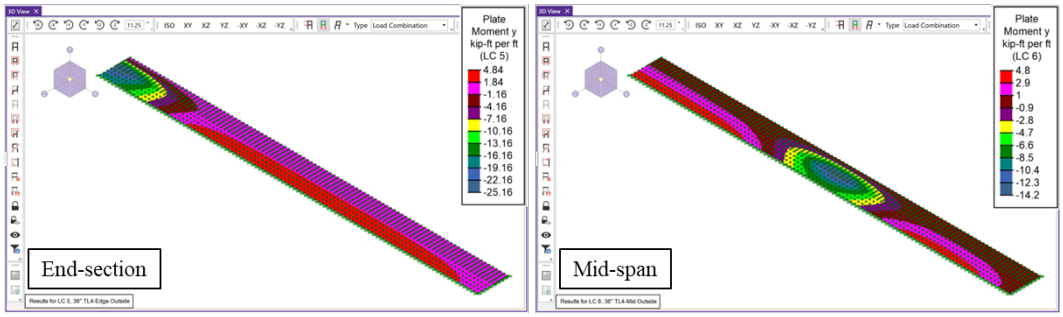
plate moment demand for each analysis case. For all the analysis cases, the exterior barrier loaded from the right side was the critical case.

The moment demands achieved from the plate analyses were used to evaluate the sufficiency of the deck reinforcement designs.

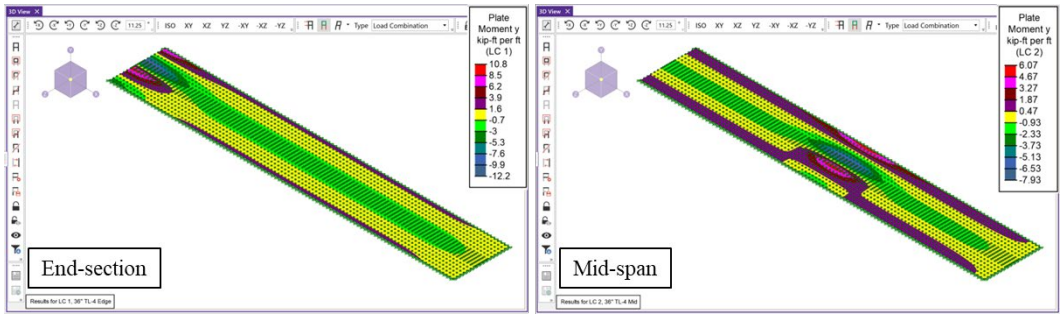
**Figure 19. Plate model analysis results for 36-in. median barrier**




(a) Exterior plate moment load from inside barrier

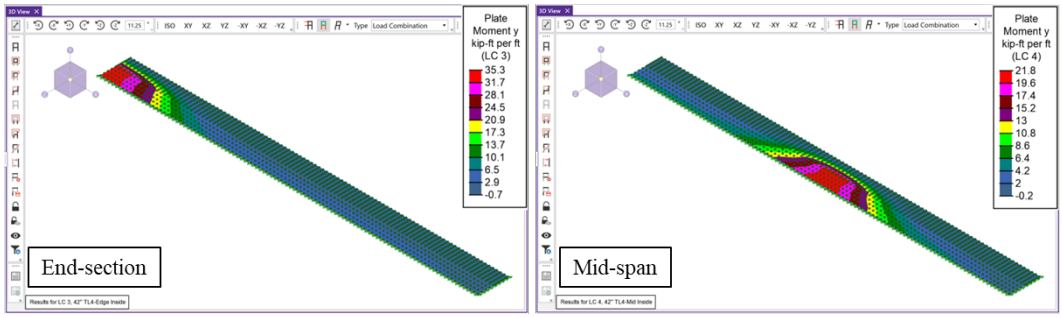



(b) Exterior plate moment load from outside barrier

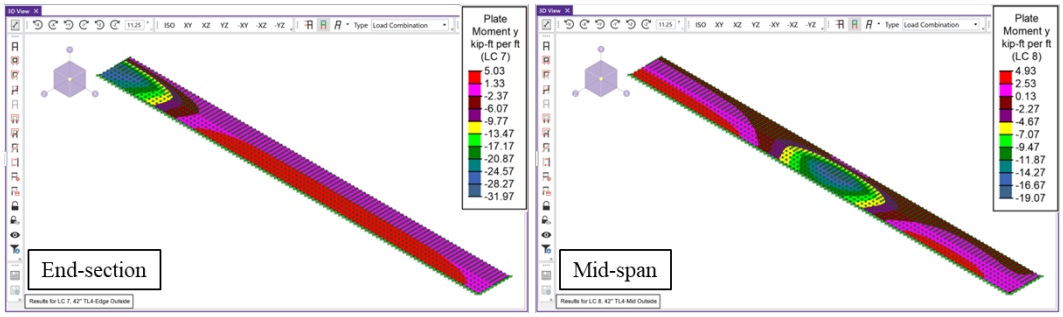



(c) Interior plate moment

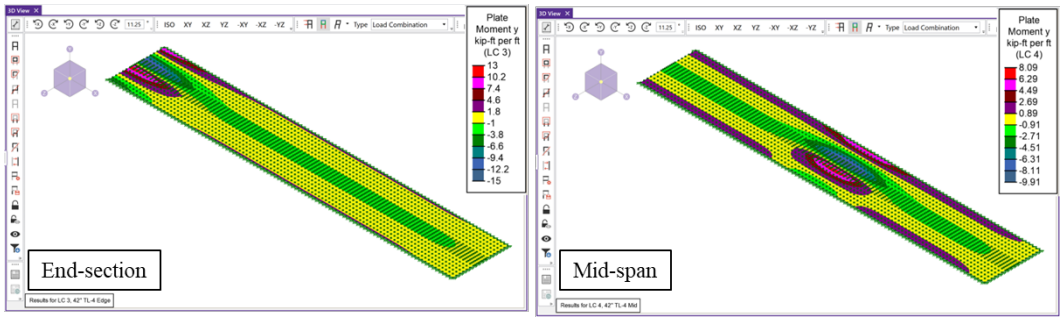
**Figure 20. Plate model analysis results for 42-in. median barrier**




(a) Exterior plate moment load from inside barrier




(b) Exterior plate moment load from outside barrier




(c) Interior plate moment

**Table 2. Plate model analysis results**

| Analysis No. | Description | Loading Location | Max. Plate Moment (kip-ft./ft.) |
|---|---|---|---|
| 1 | Exterior 36-in. barrier Load from right side | End-Section | 28.2 |
| | | Mid-Span | 16.7 |
| 2 | Exterior 36-in. barrier Load from left side | End-Section | 25.2 |
| | | Mid-Span | 14.2 |
| 3 | Interior 36-in. barrier | End-Section | 12.2 |
| | | Mid-Span | 7.9 |
| 4 | Exterior 42-in. barrier Load from right side | End-Section | 35.3 |
| | | Mid-Span | 21.8 |
| 5 | Exterior 42-in. barrier Load from left side | End-Section | 31.2 |
| | | Mid-Span | 19.1 |
| 6 | Interior 42-in. barrier | End-Section | 15.0 |
| | | Mid-Span | 9.9 |

**Summary of Analyses for the 36-in. and 42-in. Median Barriers (Six Analyses)**

Engineering strength analyses were performed on the 36-in. and 42-in. median barriers for this project. The procedures outlined in Section 13 of the AASHTO *Load and Resistance Factor Design (LRFD) Bridge Design Specifications* [1] were used to perform the analyses on the median barrier designs for this project. The commercial software RISA-3D was used to perform finite element modeling of the median barrier designs and the concrete decks for this project. Finite element modeling was performed on the median barrier designs to determine the reactions from the barriers to the supporting concrete decks. The reactions from the median barrier models were then used on separate finite element models for the supporting concrete deck structures. The bending moments in the deck from the barrier reactions were recorded and used as the demand bending moments. For the different median barrier cases, these demand bending moments in the deck from the MASH TL-4 impact conditions on the barrier were then compared to the actual design bending moments that were calculated based on the concrete deck design parameters and conditions provided for this project.

Since the development of the crash testing specifications in MASH in 2009, the crash loads for TL-4 barriers have increased from those currently listed in the LRFD Section 13 specifications. In 2017, a separate research project determined the magnitude and location of the resultant force from the MASH crash vehicles [3]. The design loads from this study were used in place of the current design loads listed in the LRFD Section 13 specifications. The design loads used in the analyses for MASH TL-4 impact conditions

are provided in Table 1. The strength of the median barriers for this project were calculated at the effective load heights $H_e$ listed in Table 1. These calculated strengths were then compared to the required strengths at $H_e$ listed in Table 1. In all six cases, the calculated strengths of the barrier designs exceeded the required strengths listed in Table 1. The calculations presented in Appendix B provide more information.

The overall analysis results for both 36-in. and 42-in. median barriers are presented in this section. For each analysis case, barrier ultimate resistance, punching shear capacity, and deck moment capacity were evaluated at end-section and mid-span based on AASHTO LRFD Section 13 and Section 5. Table 3 through Table 5 present the analysis results for 36-in. median barriers, and Table 6 through Table 8 present the analysis results for 42-in. median barriers. The detailed calculations for these barriers are provided in Appendix B.

**Table 3. DOTD 36-in. median barrier with longitudinal joint right side (Opposite Joint Impact)**

| Component Strength | End-Section | | | Mid-Span | | |
|---|---|---|---|---|---|---|
| | Capacity (C) | Demand (D) | C/D | Capacity (C) | Demand (D) | C/D |
| Barrier Ultimate Resistance (kip) | 154 | 68 | 2.26 | 187 | 68 | 2.75 |
| Barrier Punching Shear Capacity (kip) | 201 | 68 | 2.96 | 268 | 68 | 3.94 |
| Deck Moment Capacity (kip-ft/ft) | 49 | 25 | 1.96 | 49 | 14 | 3.50 |

**Table 4. DOTD 36-in. median barrier with longitudinal joint left side (Longitudinal Joint Side Impact)**

| Component Strength | End-Section | | | Mid-Span | | |
|---|---|---|---|---|---|---|
| | Capacity (C) | Demand (D) | C/D | Capacity (C) | Demand (D) | C/D |
| Barrier Ultimate Resistance (kip) | 154 | 68 | 2.26 | 187 | 68 | 2.75 |
| Barrier Punching Shear Capacity (kip) | 201 | 68 | 2.96 | 268 | 68 | 3.94 |
| Deck Moment Capacity (kip-ft/ft) | 43 | 28 | 1.54 | 43 | 17 | 2.53 |

**Table 5. DOTD 36-in. median barrier without longitudinal joint**

| Component Strength | End-Section | | | Mid-Span | | |
|---|---|---|---|---|---|---|
| | Capacity (C) | Demand (D) | C/D | Capacity (C) | Demand (D) | C/D |
| Barrier Ultimate Resistance (kip) | 154 | 68 | 2.26 | 187 | 68 | 2.75 |
| Barrier Punching Shear Capacity (kip) | 201 | 68 | 2.96 | 268 | 68 | 3.94 |
| Deck Moment Capacity (kip-ft/ft) | 17 | 12 | 1.42 | 17 | 8 | 2.13 |

**Table 6. DOTD 42-in. median barrier with longitudinal joint right side (Opposite Joint Impact)**

| Component Strength | End-Section | | | Mid-Span | | |
|---|---|---|---|---|---|---|
| | Capacity (C) | Demand (D) | C/D | Capacity (C) | Demand (D) | C/D |
| Barrier Ultimate Resistance (kip) | 144 | 80 | 1.80 | 172 | 80 | 2.15 |
| Barrier Punching Shear Capacity (kip) | 185 | 80 | 2.31 | 234 | 80 | 2.93 |
| Deck Moment Capacity (kip-ft/ft) | 49 | 32 | 1.53 | 49 | 19 | 2.58 |

**Table 7. DOTD 42-in. median barrier with longitudinal joint left side (Longitudinal Joint Side Impact)**

| Component Strength | End-Section | | | Mid-Span | | |
|---|---|---|---|---|---|---|
| | Capacity (C) | Demand (D) | C/D | Capacity (C) | Demand (D) | C/D |
| Barrier Ultimate Resistance (kip) | 144 | 80 | 1.80 | 172 | 80 | 2.15 |
| Barrier Punching Shear Capacity (kip) | 185 | 80 | 2.31 | 234 | 80 | 2.93 |
| Deck Moment Capacity (kip-ft/ft) | 43 | 35 | 1.23 | 43 | 22 | 1.95 |

**Table 8. DOTD 42-in. median barrier without longitudinal joint**

| Component Strength | End-Section | | | Mid-Span | | |
|---|---|---|---|---|---|---|
| | Capacity (C) | Demand (D) | C/D | Capacity (C) | Demand (D) | C/D |
| Barrier Ultimate Resistance (kip) | 144 | 80 | 1.80 | 172 | 80 | 2.15 |
| Barrier Punching Shear Capacity (kip) | 185 | 80 | 2.31 | 234 | 80 | 2.93 |
| Deck Moment Capacity (kip-ft/ft) | 18 | 15 | 1.20 | 18 | 10 | 1.80 |

# Discussion of Results

Based on the results of the analyses performed for this project, the details shown for the 36-in. and 42-in. high median barriers presented herein are acceptable for MASH TL-4 impact conditions. The reinforcing steel shown on the drawings in this report for the decks are also acceptable for MASH TL-4 impact conditions. For both the 36-in. and 42-in. median barrier designs:

1. Vertical No. 4 stirrup should be spaced 6 in. O/C from the end of the barrier sections for a minimum distance of 10 ft. After 10 ft. from the ends, these No. 4 stirrups should be spaced on 12 in. O/C.
2. For the 42-in. median barriers, six equally spaced longitudinal No. 4 bars should be provided on each face and located within the No. 4 stirrups. A total of 12 longitudinal bars should be provided for the 42-in. high median barriers for this project.
3. For the 36-in. median barriers, five equally spaced longitudinal No. 4 bars should be provided on each face and located within the No. 4 stirrups. Ten longitudinal bars should be provided for the 36-in. high median barriers for this project.
4. For this project, a minimum section length of 40 ft. is recommended for all designs.
5. The drawings and details in Appendix A provide additional information.
6. The designs of the barriers and decks, as shown in the drawings in Appendix A, are acceptable for MASH TL-4 impact conditions.
7. The calculations for the median barrier designs in Appendix B provide additional information.

The designs provided herein for the 36-in. and 42-in. median barriers meet the strength and performance criteria for MASH TL-4. In all cases provided in the previous tables, the capacities of the barriers and decks exceed the demand strengths for MASH TL-4 impact conditions.

# Conclusions

Based on the results of the analyses performed for this project, the details shown for the 36-in. and 42-in. high median barriers presented herein are acceptable for MASH TL-4 impact conditions. The reinforcing steel shown on the drawings in this report for the concrete decks associated with the median barrier designs are also acceptable for MASH TL-4 impact conditions. The drawings and details in Appendix A and the calculations in Appendix B provide additional information.

# Recommendations

Based on the results of the analyses performed for this project, the details shown for the 36-in. and 42-in. high median barriers presented herein are acceptable for MASH TL-4 impact conditions. It is therefore recommended that these barriers, as detailed herein, be used for MASH TL-4 impact conditions. The reinforcing steel shown on the drawings in this report for the concrete decks are also acceptable for MASH TL-4 impact conditions. For both the 36-in. and the 42-in. barriers planned for this project, the drawings and details in Appendix A provide additional information. A minimum barrier length of 40 ft. is recommended for the barriers analyzed for this project.

# Acronyms, Abbreviations, and Symbols

| Term | Description |
|---|---|
| AASHTO | American Association of State Highway and Transportation Officials |
| FEA | Finite Element Analysis |
| ft. | foot (feet) |
| in. | inch(es) |
| DOTD | Louisiana Department of Transportation and Development |
| LRFD | Load and Resistance Factor Design |
| LTRC | Louisiana Transportation Research Center |
| lb. | Pound(s) |
| MASH | Manual for Assessing Safety Hardware |
| psi | Pound per square inch |
| SSTR | Single-Slope Traffic Rail |
| TL-4 | Test Level 4 |
| TTI | Texas A&M Transportation Institute |
| TxDOT | Texas Department of Transportation |

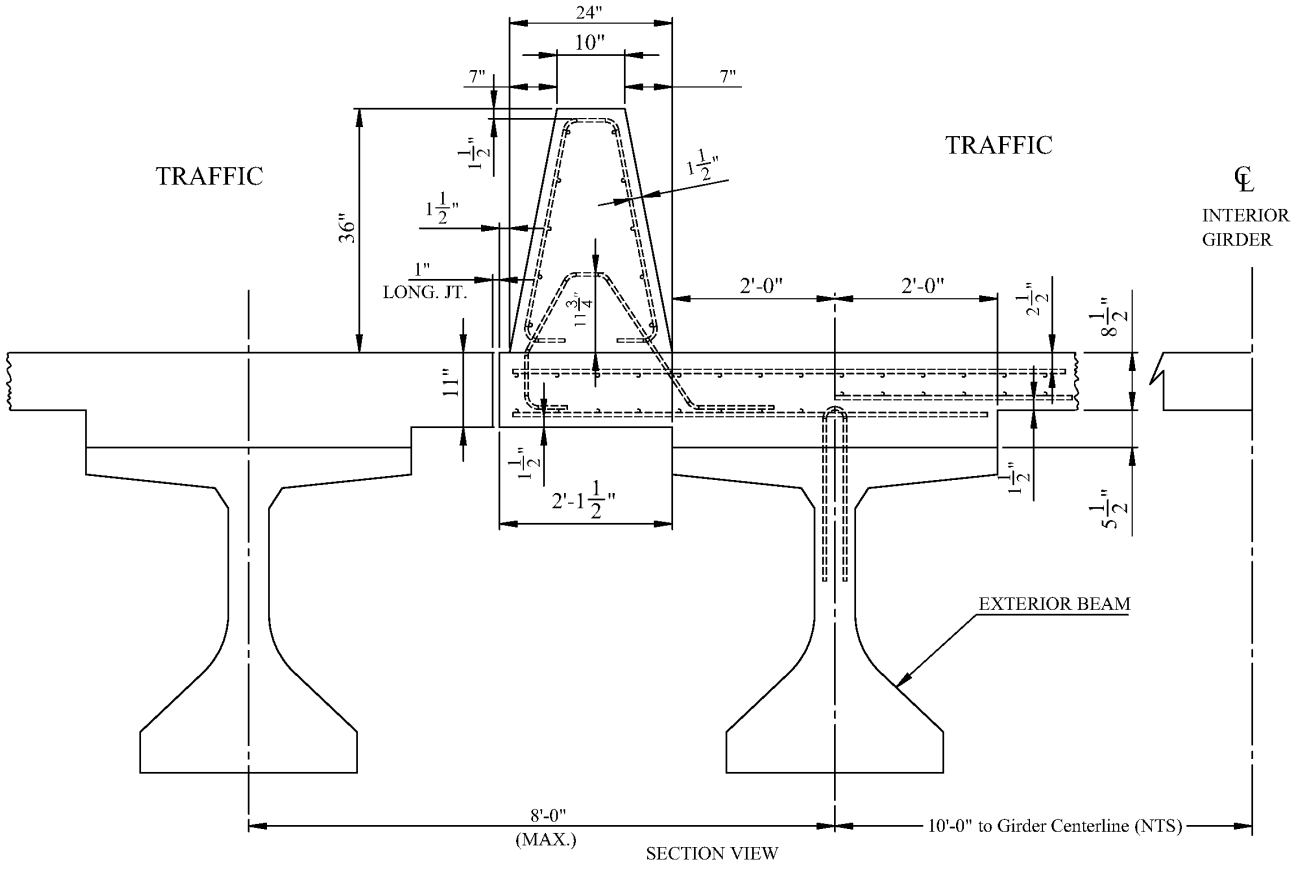
# References

[1] AASHTO, Load and Resistance Factor Design (LRFD) Bridge Design Specifications, Washington, DC: AASHTO, 2020.

[2] AASHTO, Manual for Assessing Safety Hardware, Second Edition, Washington, DC: AASHTO, 2016.

[3] S. Silvestri-Dobrovolny, N. Schulz, S. Moran, T. Skinner, R. Bligh and W. Willliams, NCHRP Report 20-07, Task 395: MASH Equivalency of NCHRP Report 350 Approved Bridge Railings, College Station, TX: Texas A&M Transportation Institute, 2017.

# Appendix A — Drawings and Details




SECTION VIEW

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| Approved:<br>WILLIAM WILLIAMS: | William Williams | Date:<br>2022-11-18 |

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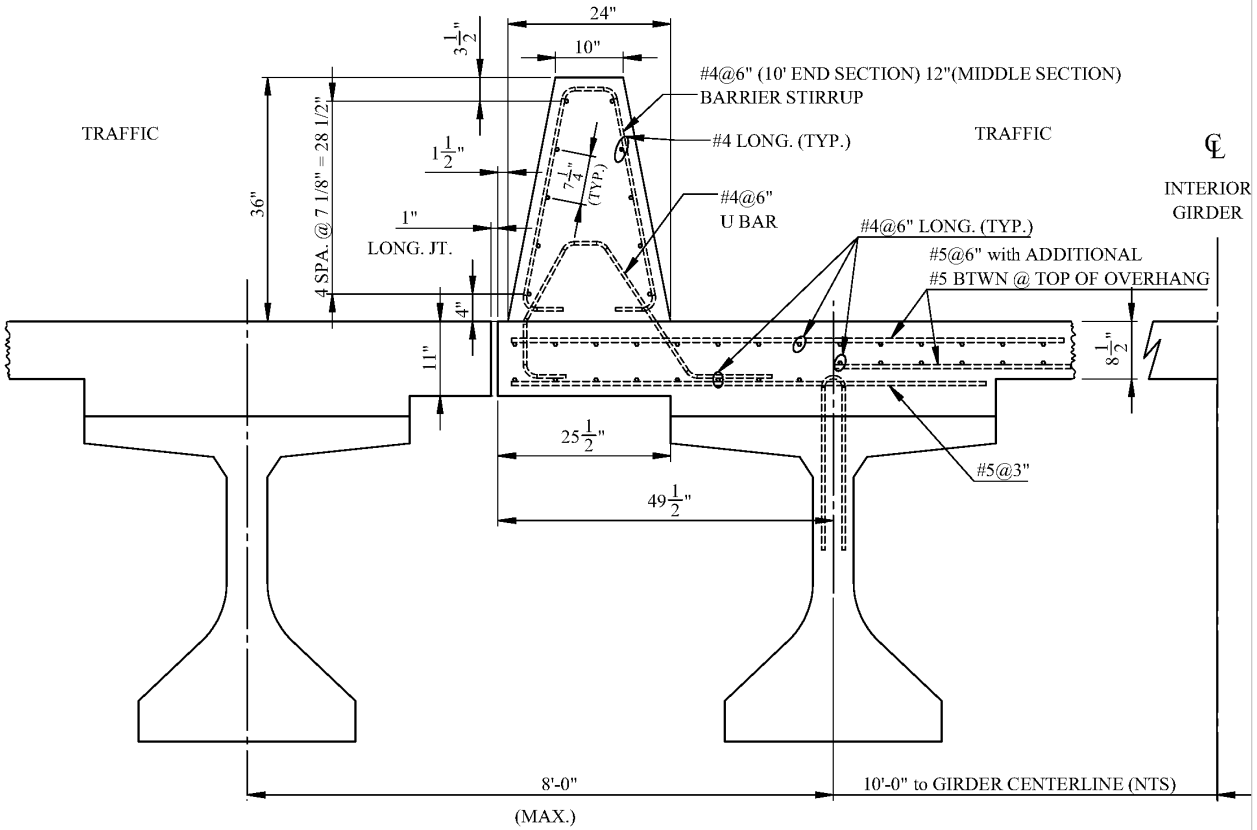


SECTION A-A
SCALE 1 : 20

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| Drawn By WILLIAMS Scale 1:20 | Sheet 2 of 5 SECTION A-A |
| Approved: WILLIAM WILLIAMS: | William Williams Date: 2022-11-18 |

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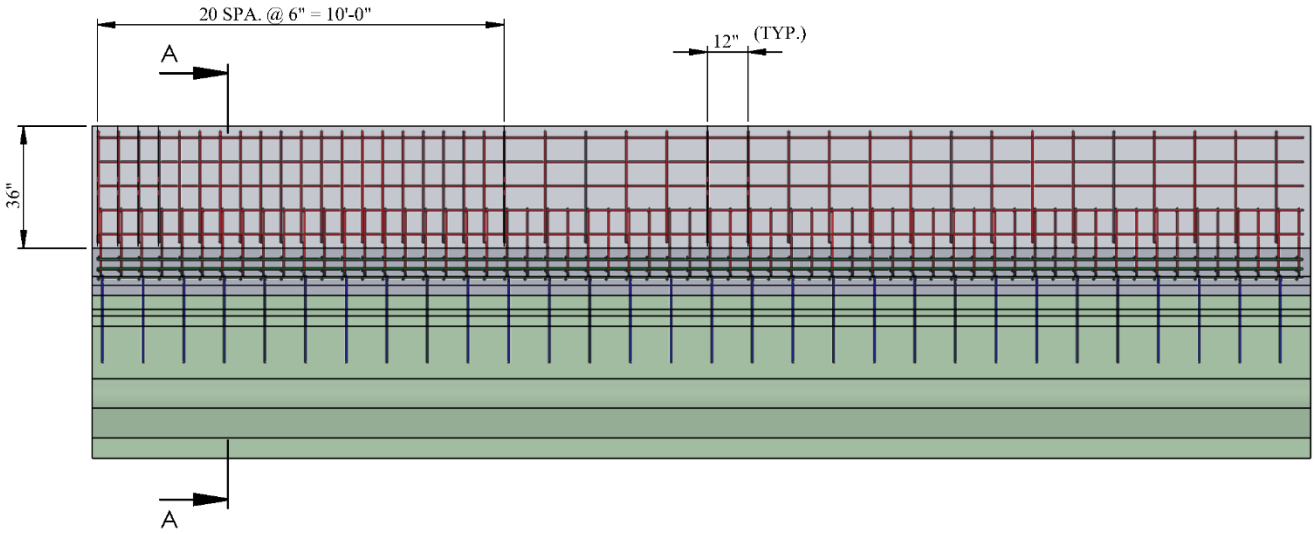


ELEVATION

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| Approved: | | Date: |
| WILLIAM WILLIAMS: | William Williams | 2022-11-18 |

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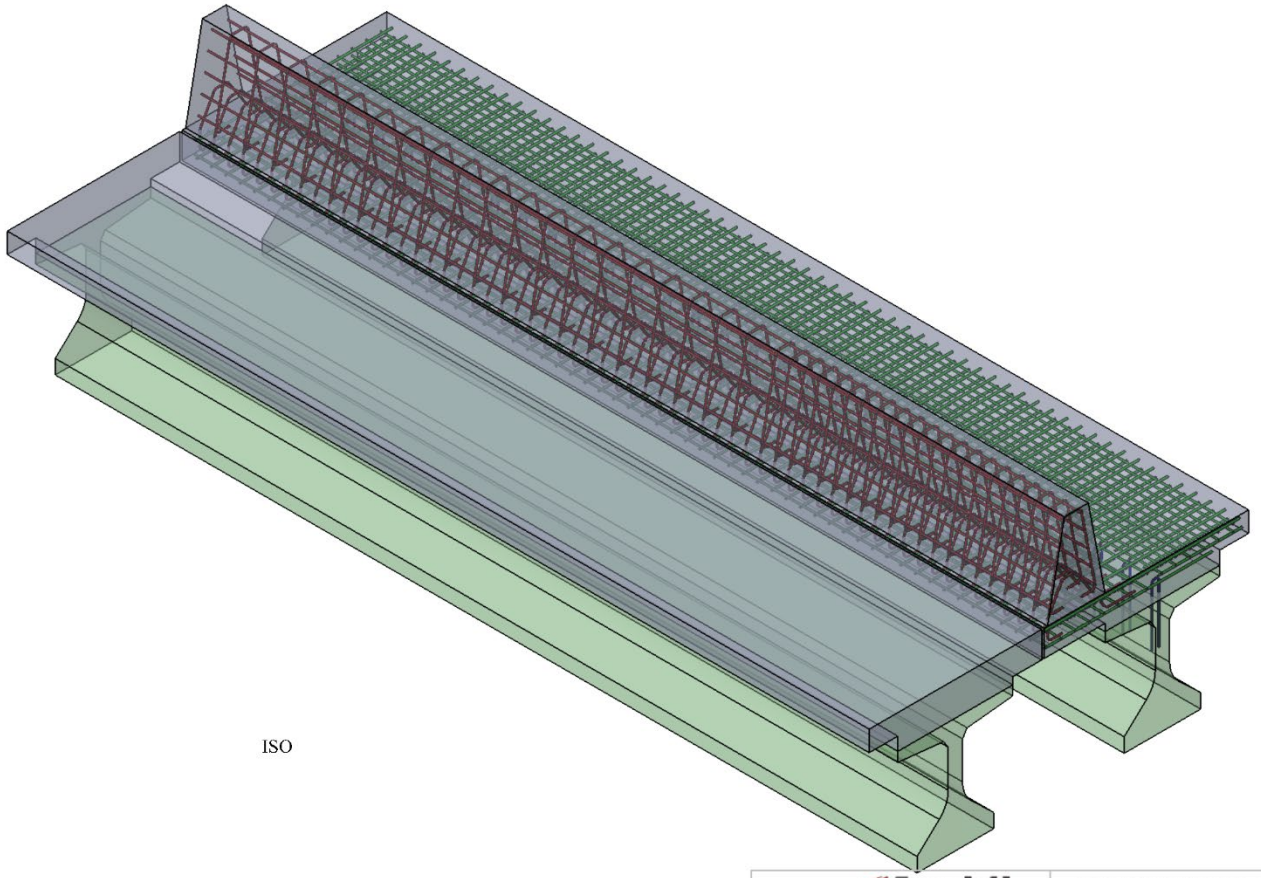

ISO

Texas A&M Transportation Institute

Roadside Safety and Physical Security Division
Proving Ground -

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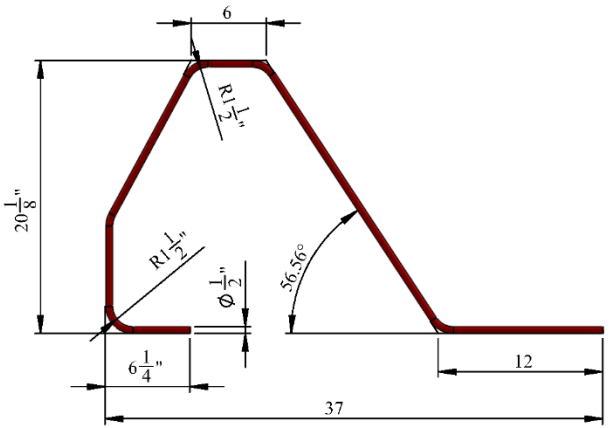
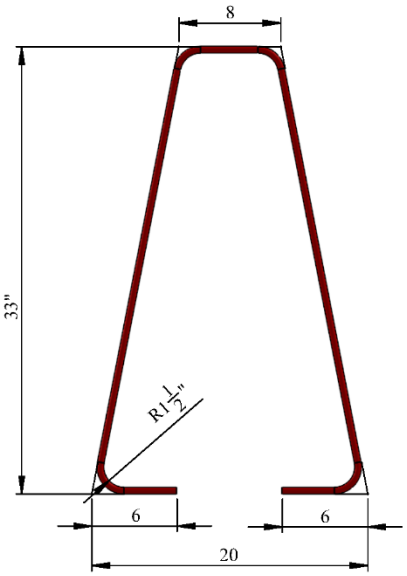



#4 U-BAR DETAILS




#4 BARRIER STIRRUP

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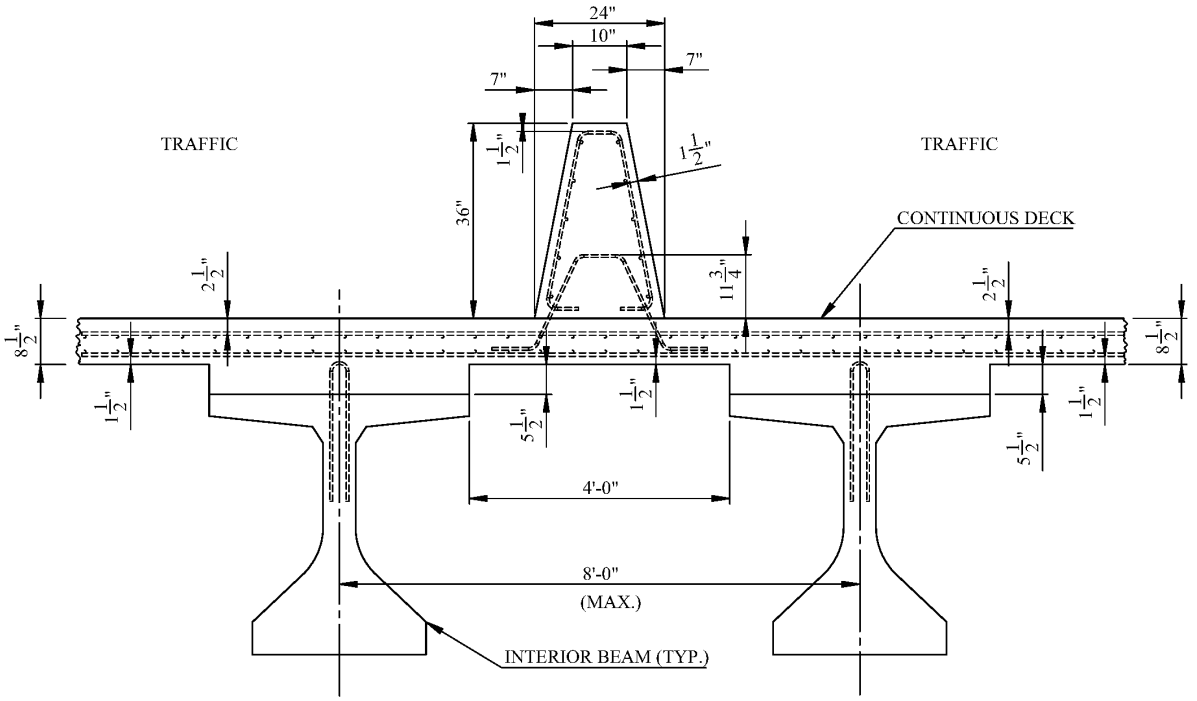


SECTION DETAILS

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| Approved: WILLIAM WILLIAMS: William Williams | Date: 2022-11-18 |

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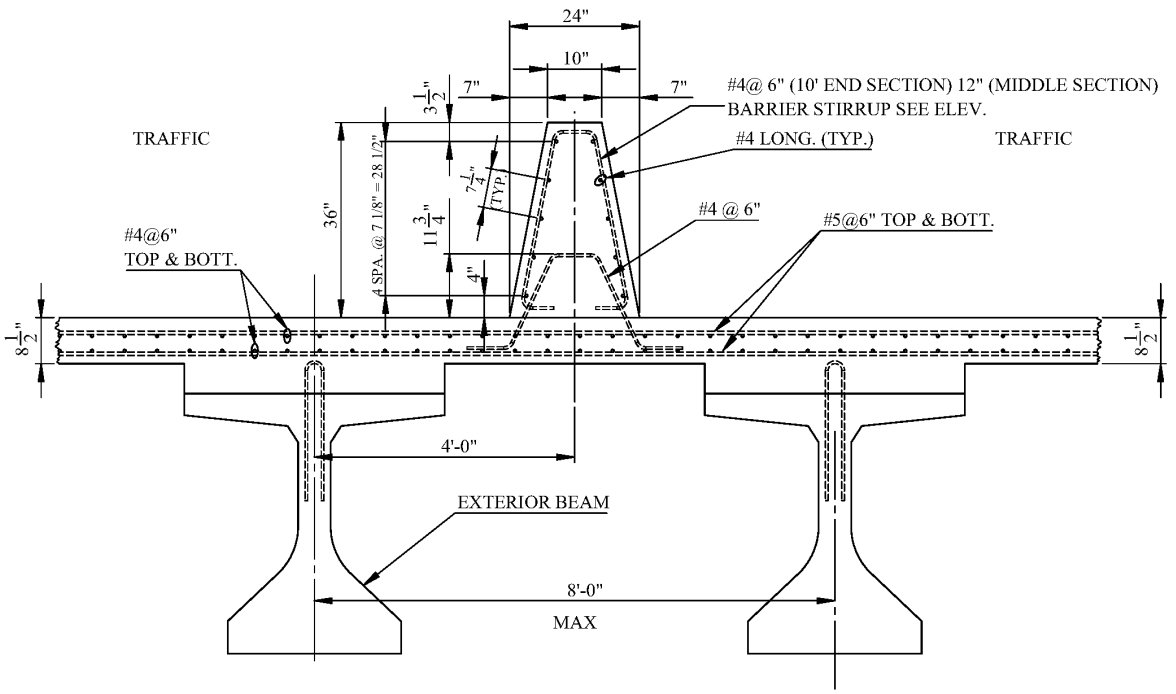


SECTION DETAILS CONT'D.

SECTION A-A
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| Project 617971 | LADOTD TL-4 36" MEDIAN BARRIER | |
| Drawn By WILLIAMS | Scale 1:25 | Sheet 2 of 5 SECTION A-A |
| Approved: WILLIAM WILLIAMS: | William Williams | Date: 2022-11-18 |

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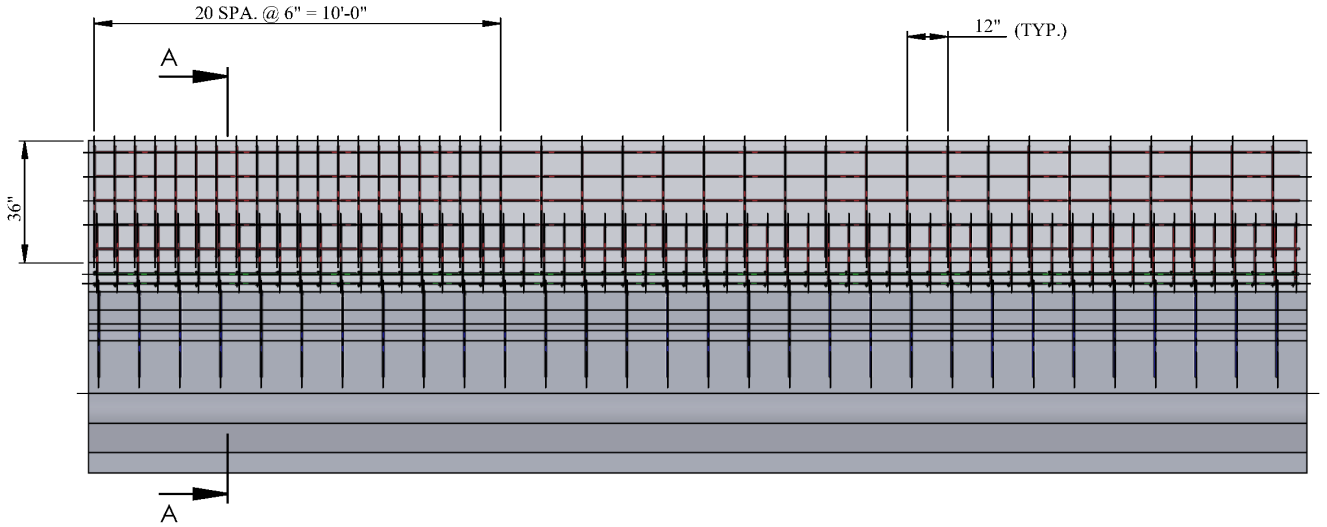


ELEVATION

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| Texas A&M Transportation Institute | Roadside Safety and Physical Security Division<br>Proving Ground - | |
| Project 617971 | LADOTD TL-4 36" MEDIAN BARRIER | |
| Drawn By WILLIAMS | Scale 1:40 | Sheet 3 of 5 ELEV. |
| Approved: | | Date: |
| WILLIAM WILLIAMS: | William Williams | 2022-11-18 |

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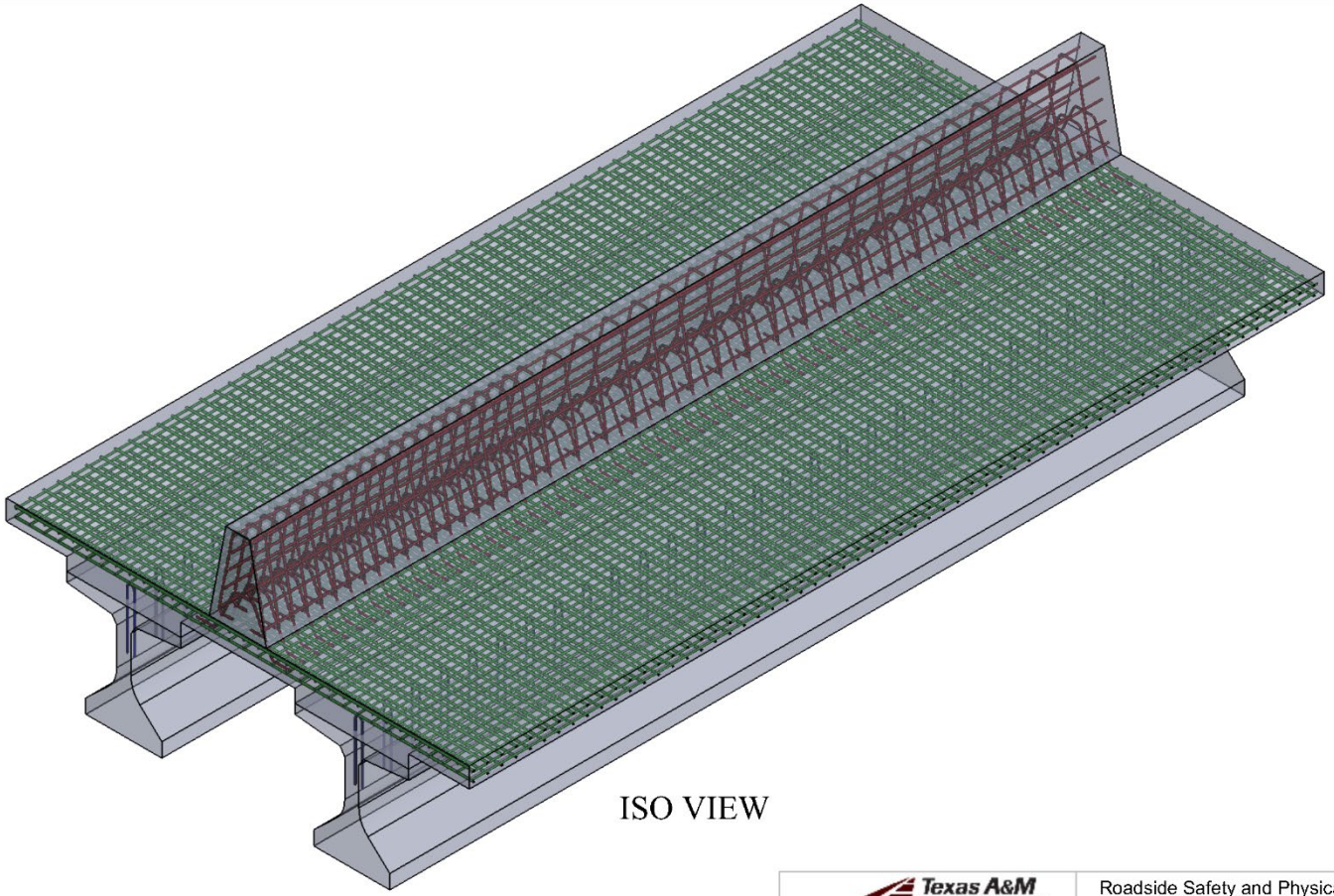

ISO VIEW

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|---|---|---|
| Texas A&M Transportation Institute | Roadside Safety and Physical Security Division<br>Proving Ground - | |
| Project 617971 | LADOTD TL-4 36" MEDIAN BARRIER | |
| Drawn By WILLIAMS | Scale 1:40 | Sheet 4 of 5 ISO |
| Approved: | | Date: |
| WILLIAM WILLIAMS: | William Williams | 2022-11-18 |

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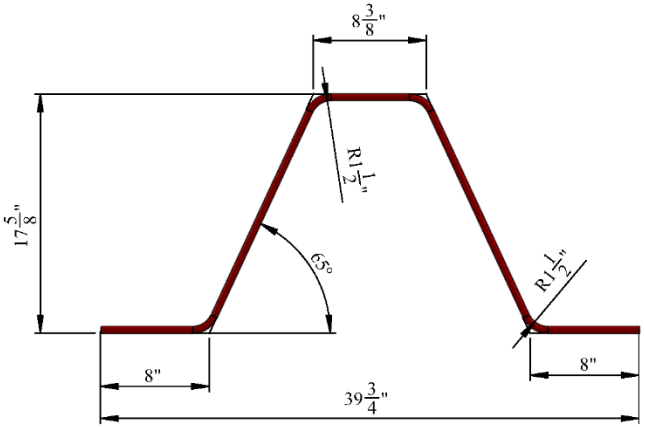
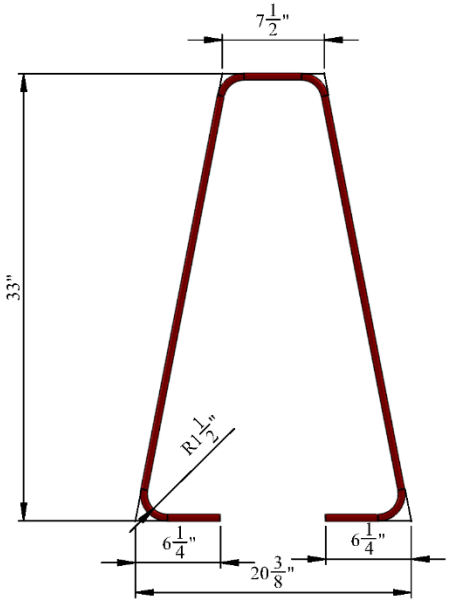



#4 U-BAR DETAILS




#4 BARRIER STIRRUP

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|---|---|
| Texas A&M Transportation Institute | Roadside Safety and Physical Security Division<br>Proving Ground - |
| Project 617971 | LADOTD TL-4 36" MEDIAN BARRIER |
| Drawn By WILLIAMS Scale 1:10 | Sheet 5 of 5 REBAR |
| Approved: WILLIAM WILLIAMS: William Williams | Date: 2022-11-18 |

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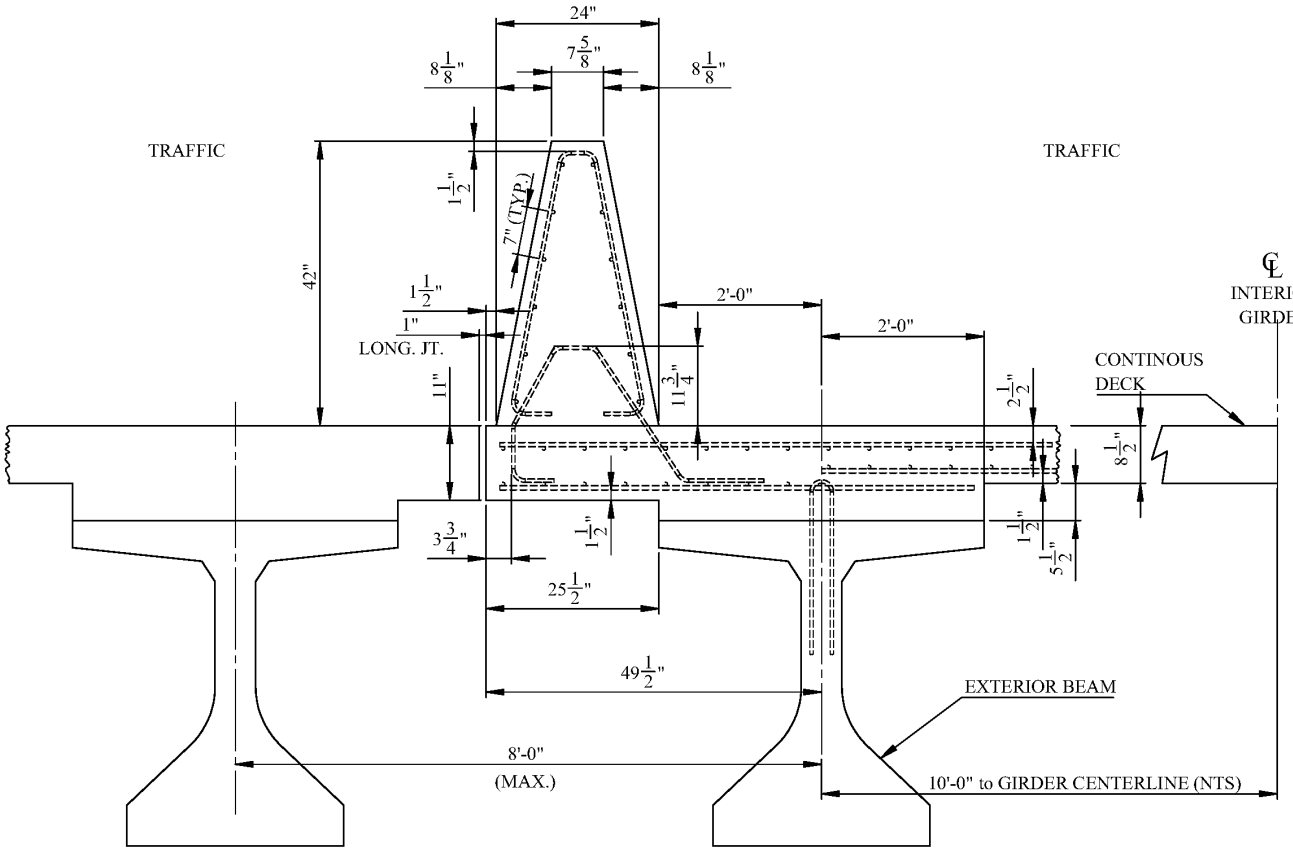


SECTION DETAILS

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|---|---|
| Texas A&M Transportation Institute | Roadside Safety and Physical Security Division<br>Proving Ground - |
| Project 617971 | LADOTD TL-4 42" MED. BARRIER with LONG. JOINT |
| Drawn By WILLIAMS Scale 1:20 | Sheet 1 of 5 SECTION |
| Approved: | Date: |
| WILLIAM WILLIAMS: *William Williams* | *2022-11-18* |

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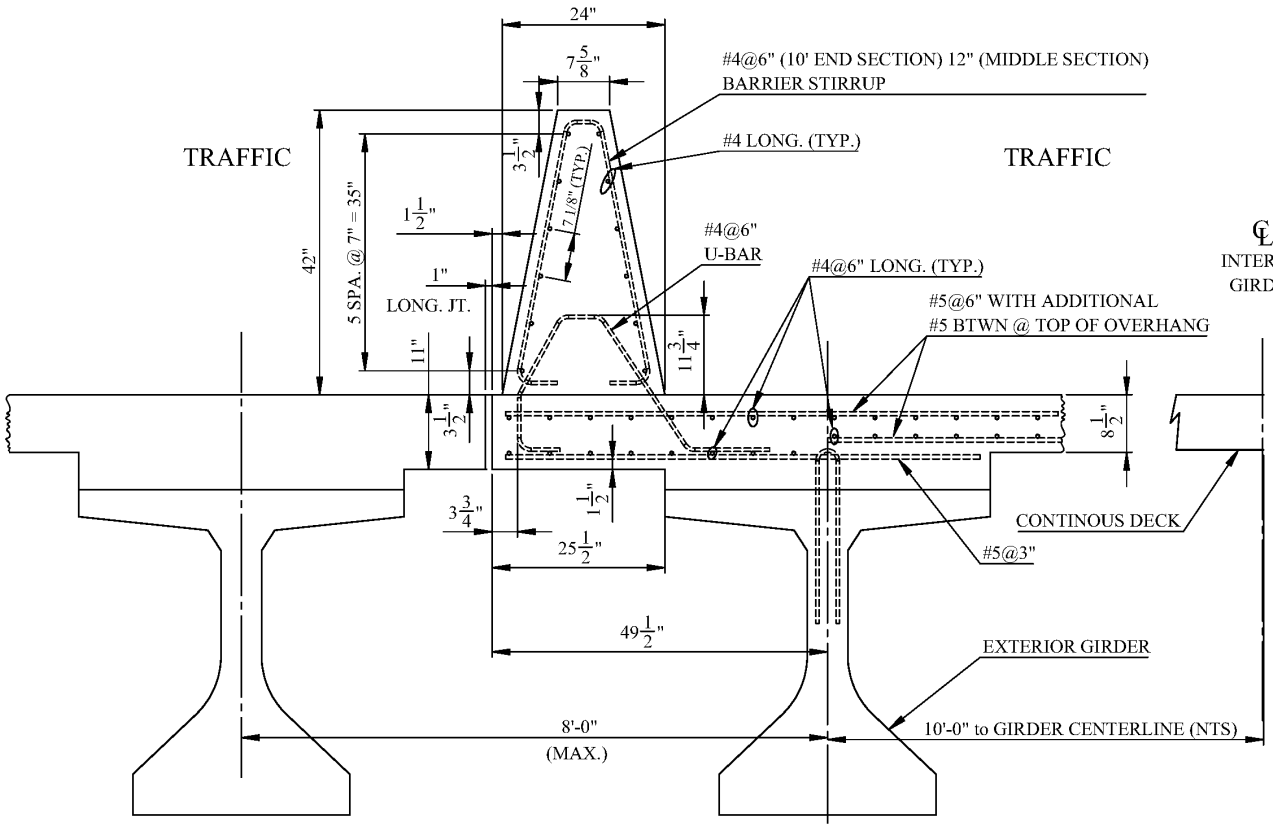


SECTION A-A
SCALE 1 : 20

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|---|---|
| Texas A&M Transportation Institute | Roadside Safety and Physical Security Division<br>Proving Ground - |
| Project 617971 | LADOTD TL-4 42" MED. BARRIER with LONG. JOINT |
| Drawn By WILLIAMS Scale 1:20 | Sheet 2 of 5 SECTION A-A |
| Approved: | Date: |
| WILLIAM WILLIAMS: William Williams | 2022-11-18 |

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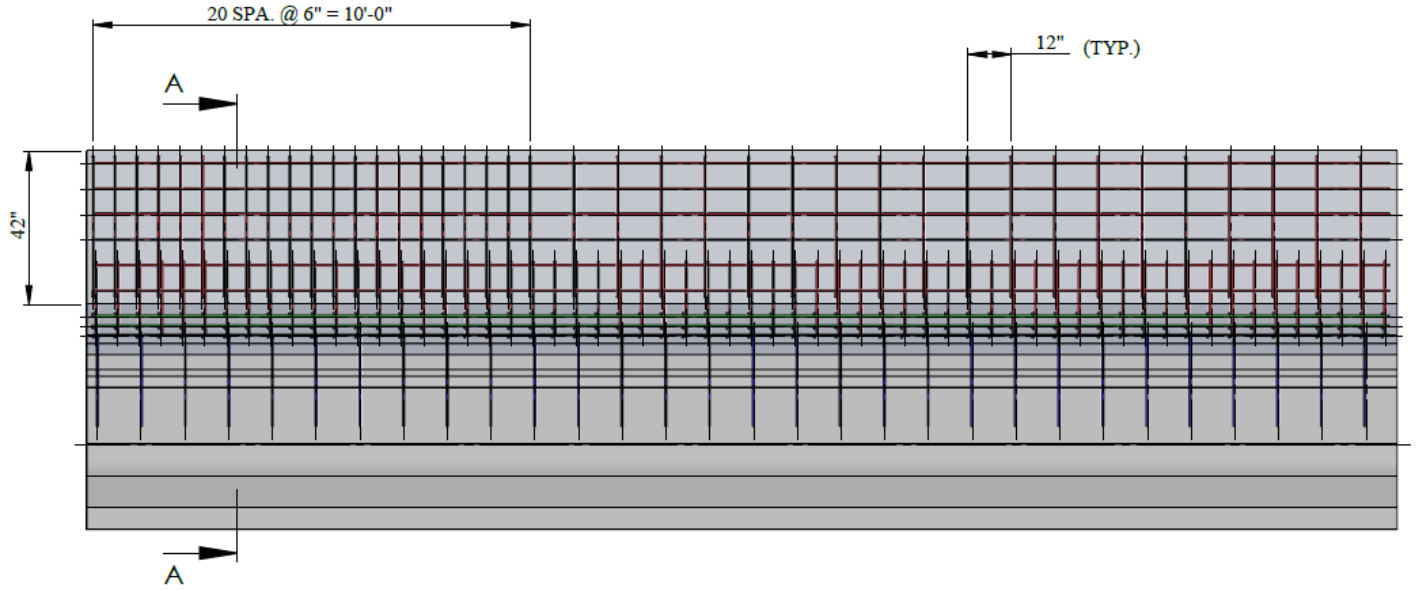


ELEVATION

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|---|---|---|
| Texas A&M Transportation Institute | Roadside Safety and Physical Security Division<br>Proving Ground - | |
| Project 617971 | LADOTD TL-4 42" MED. BARRIER with LONG. JOINT | |
| Drawn By WILLIAMS | Scale 1:40 | Sheet 3 of 5 ELEV. |
| Approved:<br>WILLIAM WILLIAMS: | William Williams | Date:<br>2022-11-18 |

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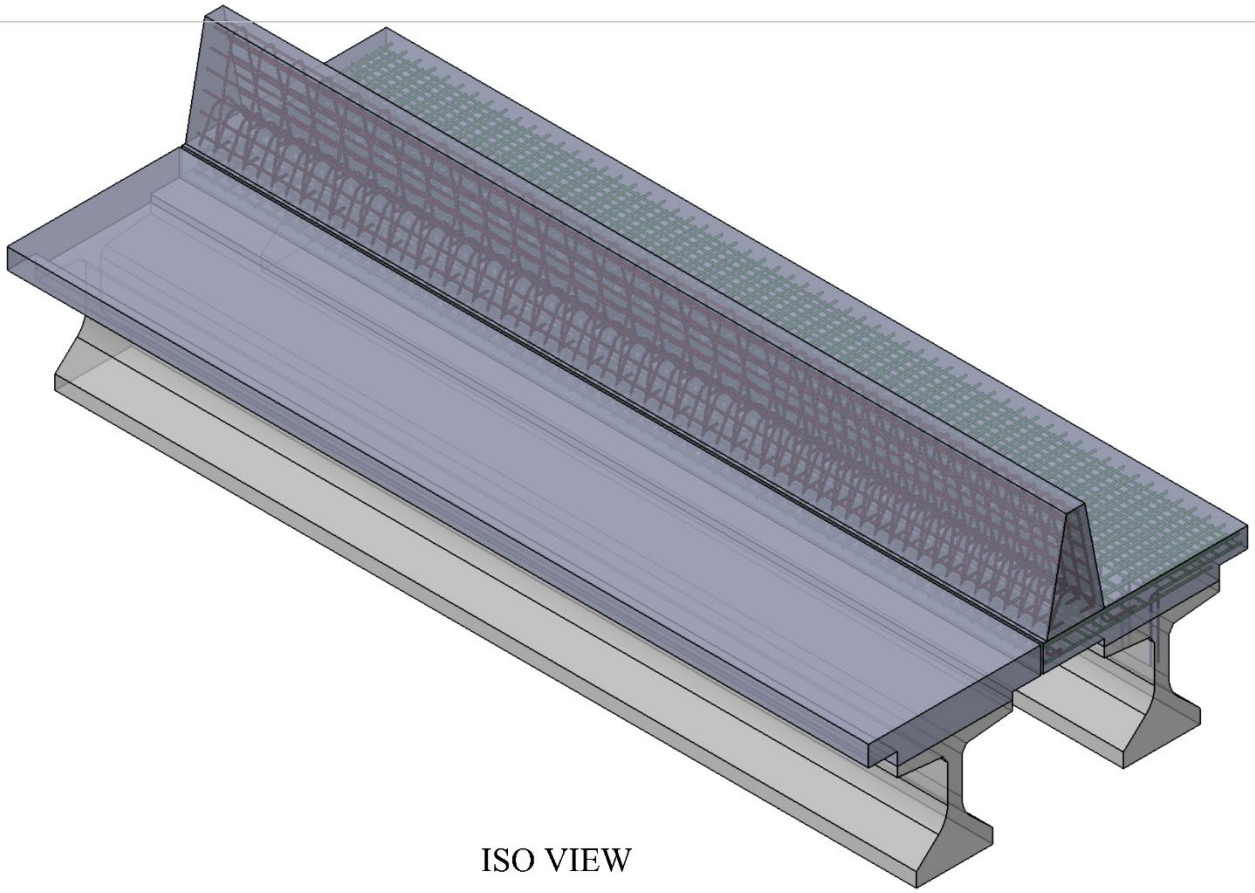

ISO VIEW

Texas A&M Transportation Institute

Roadside Safety and Physical Security Division
Proving Ground -

| | | |
|---|---|---|
| Project 617971 | LADOTD TL-4 42" MED. BARRIER with LONG. JOINT | |
| Drawn By WILLIAMS | Scale 1:40 | Sheet 4 of 5 ISO |
| Approved: WILLIAM WILLIAMS: | William Williams | Date: 2022-11-18 |

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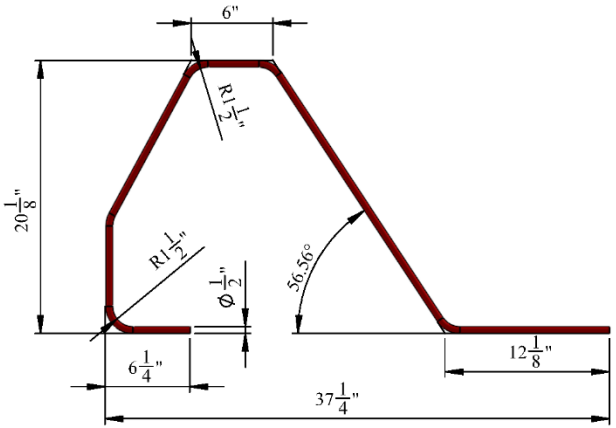
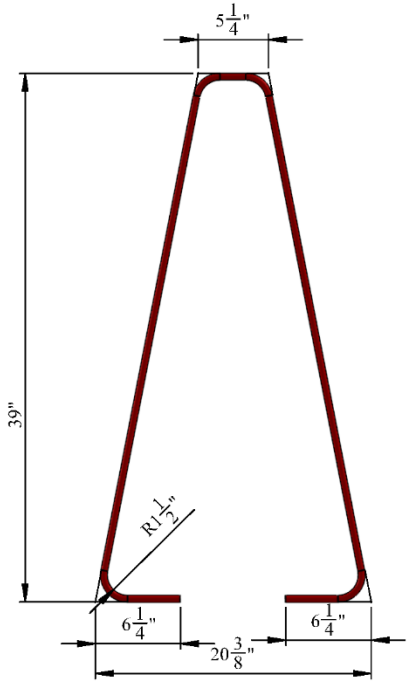



#4 U-BAR DETAILS




#4 BARRIER STIRRUP

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|---|---|
| Texas A&M Transportation Institute | Roadside Safety and Physical Security Division<br>Proving Ground - |
| Project 617971 | LADOTD TL-4 42" MED. BARRIER with LONG. JOINT |
| Drawn By WILLIAMS Scale 1:10 | Sheet 5 of 5 REBAR |
| Approved: WILLIAM WILLIAMS: William Williams | Date: 2022-11-18 |

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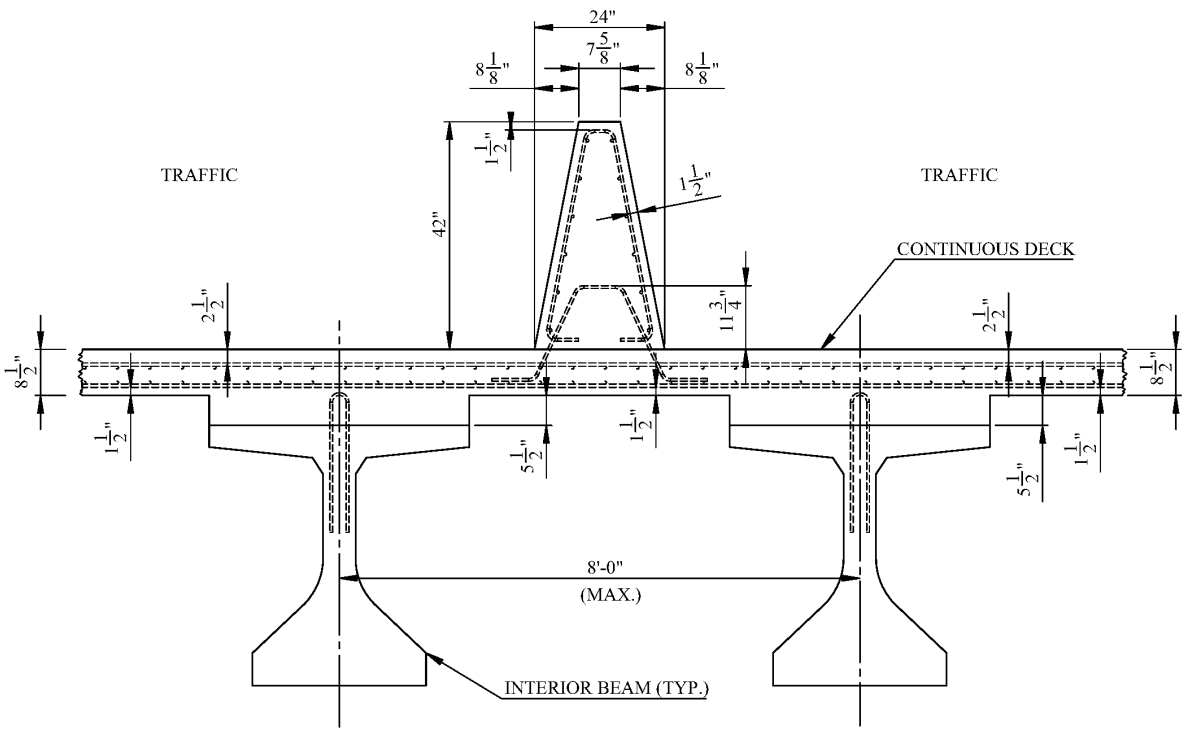


SECTION DETAILS

| | | |
|---|---|---|
| Texas A&M Transportation Institute | Roadside Safety and Physical Security Division<br>Proving Ground - | |
| Project 617971 | LADOTD TL-4 42" MEDIAN BARRIER | |
| Drawn By WILLIAMS | Scale 1:25 | Sheet 1 of 5 SECTION |
| Approved:<br>WILLIAM WILLIAMS: | William Williams | Date:<br>2022-11-18 |

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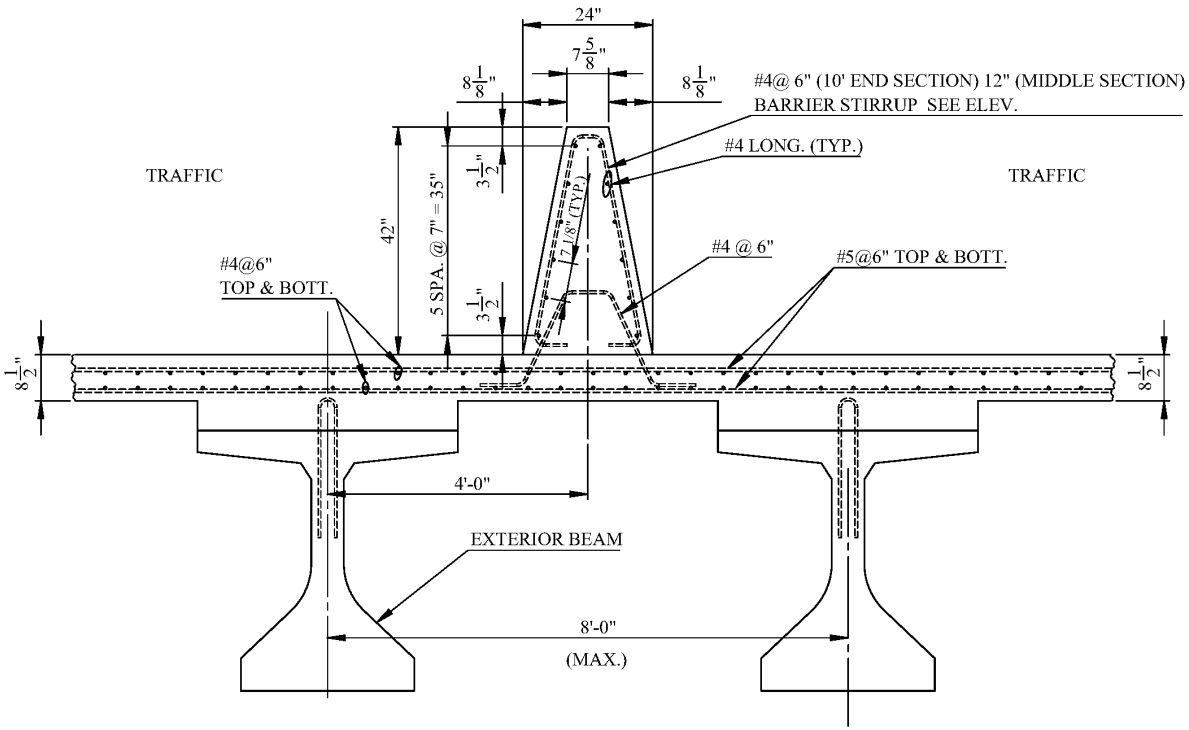


SECTION A-A
SCALE 1 : 25

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|---|---|
| Texas A&M Transportation Institute | Roadside Safety and Physical Security Division<br>Proving Ground - |
| Project 617971 | LADOTD TL-4 42" MEDIAN BARRIER |
| Drawn By WILLIAMS Scale 1:100 | Sheet 2 of 5 SECTION A-A |
| Approved: | Date: |
| WILLIAM WILLIAMS: | |

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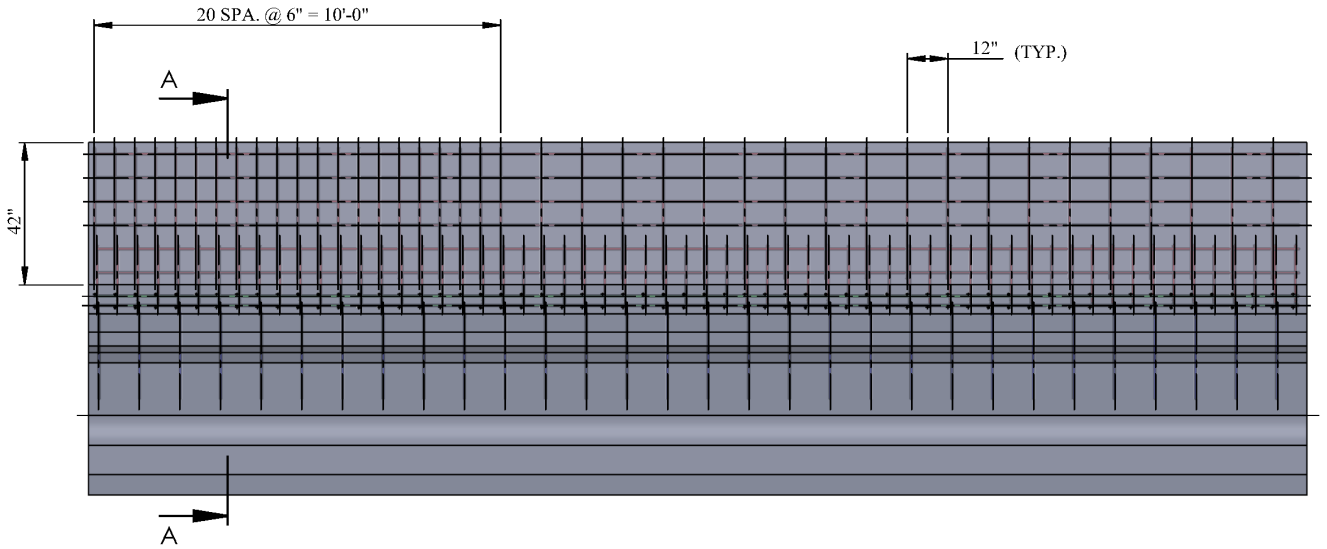


ELEVATION

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|---|---|---|
| Texas A&M Transportation Institute | Roadside Safety and Physical Security Division<br>Proving Ground - | |
| Project 617971 | LADOTD TL-4 42" MEDIAN BARRIER | |
| Drawn By WILLIAMS | Scale 1:40 | Sheet 3 of 5 ELEV. |
| Approved:<br>WILLIAM WILLIAMS: William Williams | | Date:<br>2022-11-18 |

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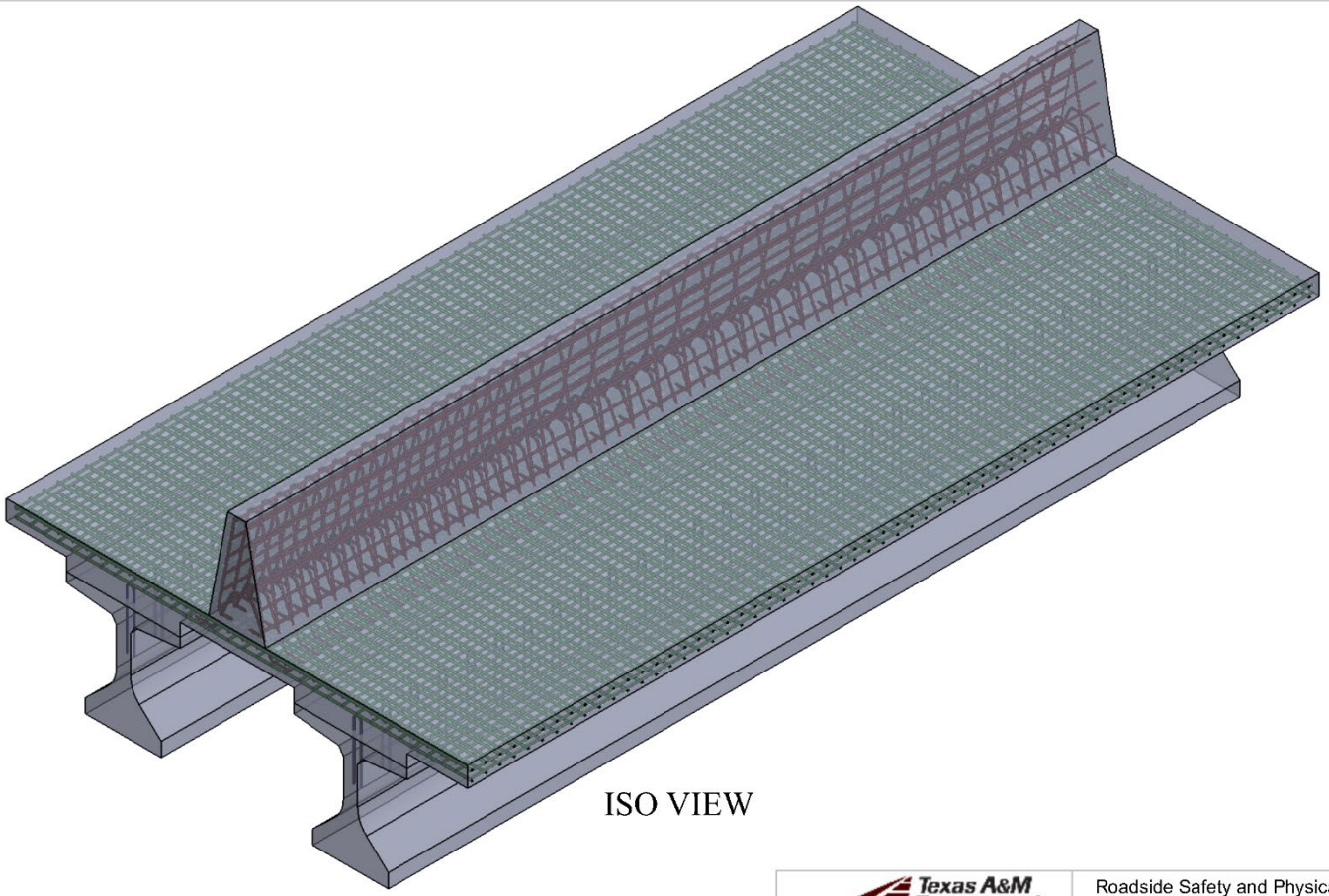

ISO VIEW

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|---|---|---|
| Texas A&M Transportation Institute | Roadside Safety and Physical Security Division<br>Proving Ground - | |
| Project 617971 | LADOTD TL-4 42" MEDIAN BARRIER | |
| Drawn By WILLIAMS | Scale 1:40 | Sheet 4 of 5 ISO |
| Approved:<br>WILLIAM WILLIAMS: | William Williams | Date:<br>2022-11-18 |

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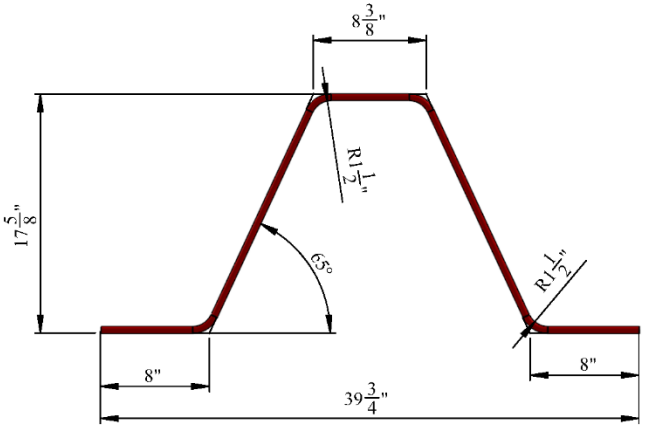
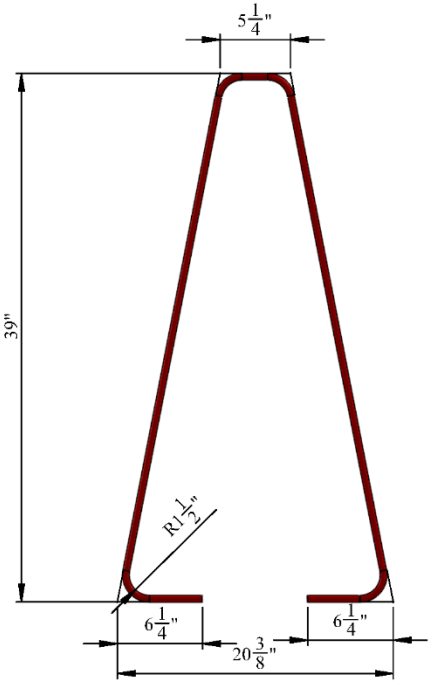



#4 U-BAR DETAILS




#4 BARRIER STIRRUP

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|---|---|
| Texas A&M Transportation Institute | Roadside Safety and Physical Security Division<br>Proving Ground - |
| Project 617971 | LADOTD TL-4 42" MEDIAN BARRIER |
| Drawn By WILLIAMS Scale 1:10 | Sheet 5 of 5 REBAR |
| Approved: | Date: |
| WILLIAM WILLIAMS: William Williams | 2022-11-18 |

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# Appendix B — Calculation Worksheets

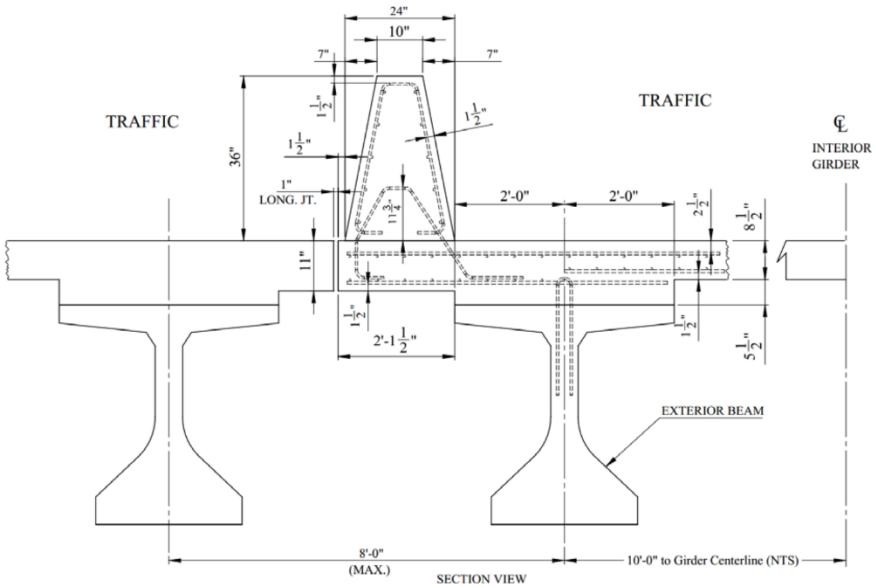
**SUBJECT:** 36" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Outside Barrier (left side)

**Overview:**

These calcualtions evaluate the strength of the given barrier design for MASH TL-4 impact load condtions.

- 36" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from the Barrier Left Side in the Section View below.

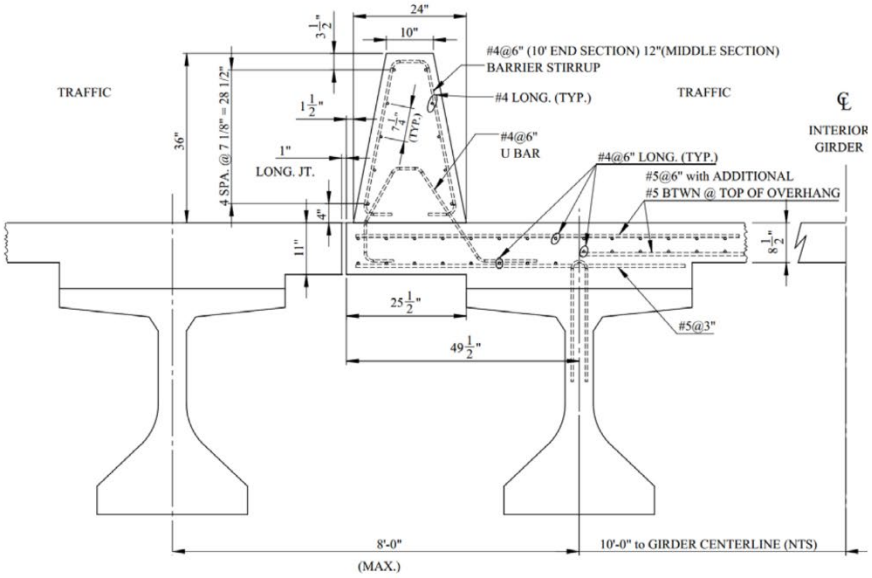
**Design Details:**



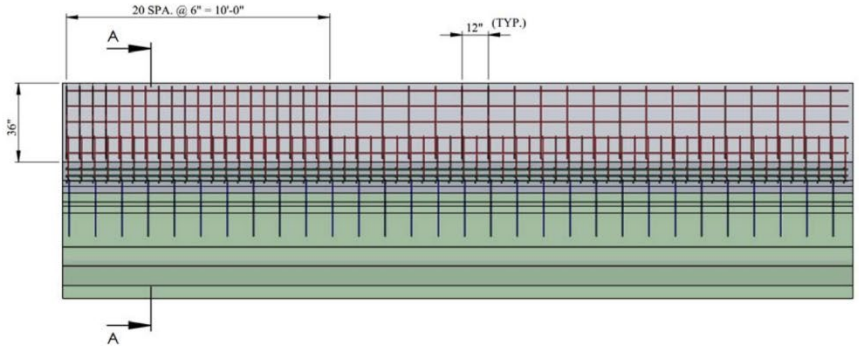

**Section View (a)**

Texas A&M Transportation Institute

**SUBJECT:** 36" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Outside Barrier (left side)



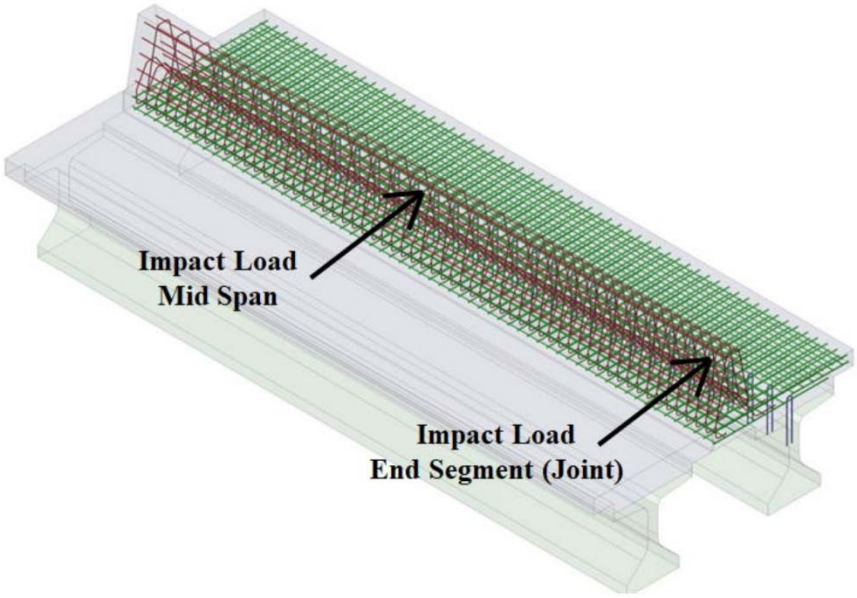

**Section View (b)**




**Elevation**

Texas A&M Transportation Institute

**SUBJECT:** 36" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Outside Barrier (left side)




**Iso View**

**SUBJECT:** 36" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Outside Barrier (left side)

**(1) Define Inputs:**

**(1a) General Inputs:**

$f'_c := 4000\ psi$ — *Compressive strength of concrete*

$f_y := 60\ ksi$ — *Yield strength reinforcing steel*

$E_s := 29000\ ksi$ — *Modulus of elasticity of steel*

$H_w := 36\ in$ — *Height of barrier*

$T_{w.top} := 10\ in$ — *Top width of barrier*

$T_{w.bot} := 24\ in$ — *Bottom width of barrier*

$t_s := 11\ in$ — *Depth of deck*

$d_{\#4} := 0.5\ in$ ; $A_{\#4} := 0.2\ in^2$ — *Diameter and section area of #4 bar*

$d_{\#5} := 0.625\ in$ ; $A_{\#5} := 0.31\ in^2$ — *Diameter and section area of #5 bar*

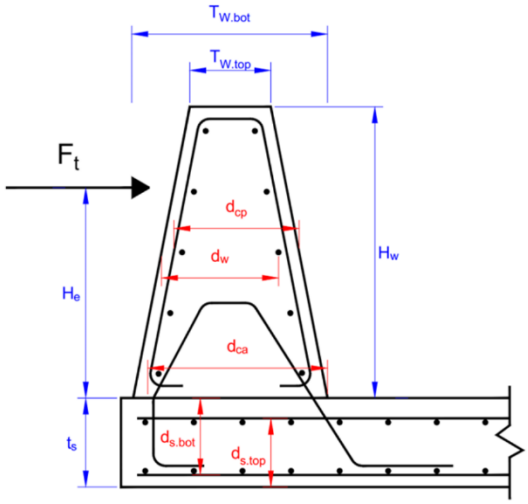



*Figure 1. Sketch of Concrete Wall/Parapet Showing Input Variable*

**(1b) Concrete Barrier Inputs:**

$t_{b.cov} := 1.5\ in$ *Concrete clear cover of barrier*

Barrier vertical reinforcement inputs (#4 bars):

$A_{vpl.mid} := 0.2\ in^2$ *Area of one barrier vertical reinforcement leg at midspan*

$S_{vp.mid} := 12\ in$ *Spacing of barrier vertical reinforcement at midspan*

$d_{cp.mid} := 15.25\ in$ *Average extreme distance of barrier vertical reinforcement at midspan*

$A_{vpl.end} := 0.2\ in^2$ *Area of one barrier vertical reinforcement leg at joints/ends*

$S_{vp.end} := 6\ in$ *Spacing of barrier vertical reinforcement at joints/ends*

$d_{cp.end} := 15.25\ in$ *Average extreme distance of barrier vertical reinforcement at joints/ends*

Deck anchorage reinforcement inputs (#4 bars):

$A_{val.mid} := 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} := 6\ in$ *Spacing of deck anchorage vertical reinforcement at midspan*

$d_{ca.mid} := 22.25\ in$ *Extreme distance of tension deck anchorage reinforcement at midspan*

$A_{val.end} := 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at joints/ends*

$S_{va.end} := 6\ in$ *Spacing of deck anchorage vertical reinforcement at joints/ends*

$d_{ca.end} := 22.25\ in$ *Extreme distance of tension deck anchorage reinforcement at joints/ends*

Barrier Longitudinal reinforcement inputs (#4 bars):

$A_w := 0.2 \cdot 5\ in^2 = 1\ in^2$ *Area of longitudinal reinforcement bars in tension*

$d_w := 14.75\ in$ *Average extreme distance of tension longitudinal reinforcement*

**(1c) Concrete Deck Inputs:**

$t_{s.cov.bot} := 1.5\ in$ *Concrete clear cover of deck at bottom*

$d_{s.bot} := 9.1875\ in$ *Extreme distance of deck flexural reinforcement at bottom*

$A_{s.bot} := 0.31\ in^2$ *Section area of deck flexural reinforcement at bottom (single bar)*

$S_{s.bot} := 3\ in$ *Spacing of deck flexural reinforcement at bottom*

$t_{s.cov.top} := 2.5\ in$ *Concrete clear cover of deck at top*

$d_{s.top} := 8.1875\ in$ *Extreme distance of deck flexural reinforcement at top*

$A_{s.top} := 0.31\ in^2$ *Section area of deck flexural reinforcement at top (single bar)*

$S_{s.top} := 3\ in$ *Spacing of deck flexural reinforcement at top*

**(1d) Design Force Inputs:**

**Design Forces for Traffic Railings**

| Test Level | Rail Height (in.) | $F_t$ (kip) | $F_L$ (kip) | $F_T$ (kip) | $L_t/L_L$ (ft) | $L_T$ (ft) | $H_e$ (in) | $H_{min}$ (in) |
|---|---|---|---|---|---|---|---|---|
| TL-1 | 18 or above | 13.5 | 4.5 | 4.5 | 4.0 | 18.0 | 18.0 | 18.0 |
| TL-2 | 18 or above | 27.0 | 9.0 | 4.5 | 4.0 | 18.0 | 20.0 | 18.0 |
| TL-3 | 29 or above | 71.0 | 18.0 | 4.5 | 4.0 | 18.0 | 19.0 | 29.0 |
| TL-4 (a) | 36 | 68.0 | 22.0 | 38.0 | 4.0 | 18.0 | 25.0 | 36.0 |
| TL-4 (b) | between 36 and 42 | 80.0 | 27.0 | 22.0 | 5.0 | 18.0 | 30.0 | 36.0 |
| TL-5 (a) | 42 | 160.0 | 41.0 | 80.0 | 10.0 | 40.0 | 35.0 | 42.0 |
| TL-5 (b) | greater than 42 | 262.0 | 75.0 | 160.0 | 10.0 | 40.0 | 43.0 | 42.0 |
| TL 6 | | 175.0 | 58.0 | 80.0 | 8.0 | 40.0 | 56.0 | 90.0 |

References:
- TL-1 and TL-2 Design Forces are from AASHTO LRFD Section 13 Table A13.2-1
- TL-3 Design Forces are from research conducted under NCHRP Project 20-07 Task 395
- TL-4 (a), TL-4 (b), TL-5 (a), and TL-5 (b) Design Forces are from research conducted under NCHRP Project 22-20(2)

$TL := 4$ *Test level*

$F_t := 68\ kip$ *Transverse impact force*

$L_t := 4\ ft$ *Longitudinal length of distribution of impact force*

$H_e := 25\ in$ *Height of equivalent transverses load*

$H_{min} := 36\ in$ *Minimum height of a MASH TL-4 barrier*

$H_w = 36\ in$ *Height of concrete barrier*

**(2) Stability Criteria:**

$H_{min} = 36\ in$ *Minimum height of a MASH TL-4 barrier*

$H_w = 36\ in$ *Height of concrete barrier measured from the top of the roadway surface/asphalt overlay*

$$Minimum_Height_of_Barrier_Check := \begin{cases} \text{if } H_w \geq H_{min} \\ \quad \text{“OK”} \\ \text{else} \\ \quad \text{“Not OK”} \end{cases}$$

$Minimum_Height_of_Barrier_Check = \text{“OK”}$

**(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification:**

**(3a) Bending Capacity of the Barrier about the Longitudinal Axis at Midspan: $M_{cmid}$ (k-ft/ft)**

For parapet vertical reinforcement:

$b_c := 12\ in$ *Unit width of wall (take as 1 ft per AASHTO Section 13 procedure)*

$A_{vpl.mid} = 0.2\ in^2$ *Area of one parapet vertical reinforcement leg at midspan*

$S_{vp.mid} = 12\ in$ *Spacing of parapet vertical reinforcement at midspan*

$$A_{vp.mid} := \left(\frac{b_c}{S_{vp.mid}}\right) \cdot A_{vpl.mid} = 0.2\ in^2$$

*Total area of parapet vertical reinforcement per unit length at midspan*

$d_{cp.mid} = 15.25\ in$ *Average extreme distance of parapet vertical reinforcement at midspan*

$$a_{cp.mid} := \frac{A_{vp.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.294\ in$$ *Depth of Whitney stress block*

$$M_{cp.mid} := \frac{\left(A_{vp.mid} \cdot f_y \cdot \left(d_{cp.mid} - \frac{a_{cp.mid}}{2}\right)\right)}{b_c} = 15.103 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the parapet vertical reinforcement specified in Article A 13.3.1 (k-ft/ft)*

For deck anchorage reinforcement:

$b_c = 12 \ in$ *Unit width of wall (take as 1 ft per AASHTO Section 13 procedure)*

$A_{val.mid} = 0.2 \ in^2$ *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} = 6 \ in$ *Spacing of deck anchorage vertical reinforcement at midspan*

$$A_{va.mid} := \left(\frac{b_c}{S_{va.mid}}\right) \cdot A_{val.mid} = 0.4 \ in^2$$

*Total area of deck anchorage vertical reinforcement per unit length at midspan*

$d_{ca.mid} = 22.25 \ in$ *Extreme distance of tension deck anchorage vertical reinforcement at midspan*

$$a_{ca.mid} := \frac{A_{va.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588 \ in$$ *Depth of Whitney stress block*

$$M_{ca.mid} := \frac{\left(A_{va.mid} \cdot f_y \cdot \left(d_{ca.mid} - \frac{a_{ca.mid}}{2}\right)\right)}{b_c} = 43.912 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

$$M_{c.mid} := min\left(M_{cp.mid}, M_{ca.mid}\right) = 15.103 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering the critical reinforcement*

**(3b) Bending Capacity of the Barrier about the Longitudinal Axis at Joints/Ends:** $M_{ccnd}$ **(k-ft/ft)**

For parapet vertical reinforcement:

$A_{vpl.end} = 0.2\ in^2$ *Area of one parapet vertical reinforcement leg at joints/ends*

$S_{vp.end} = 6\ in$ *Spacing of parapet vertical reinforcement at joints/ends*

$A_{vp.end} := \left(\frac{b_c}{S_{vp.end}}\right) \cdot A_{vpl.end} = 0.4\ in^2$ *Total area of deck anchorage vertical reinforcement per unit length at midspan*

$d_{cp.end} = 15.25\ in$ *Average extreme distance of parapet vertical reinforcement at joints/ends (at barrier mid-height)*

$a_{cp.end} := \frac{A_{vp.end} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588\ in$ *Depth of Whitney stress block*

$$M_{cp.end} := \frac{\left(A_{vp.end} \cdot f_y \cdot \left(d_{cp.end} - \frac{a_{cp.end}}{2}\right)\right)}{b_c} = 29.912\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at Joints/ Ends when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

For deck anchorage reinforcement:

$A_{val.end} = 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at joints/ends*

$S_{va.end} = 6\ in$ *Spacing of deck anchorage vertical reinforcement at joints/ends*

$A_{va.end} := \left(\frac{b_c}{S_{va.end}}\right) \cdot A_{val.end} = 0.4\ in^2$ *Total area of deck anchorage vertical reinforcement per unit length at joints/ends*

$d_{ca.end} = 22.25\ in$ *Extreme distance of tension deck anchorage vertical reinforcement at joints/ends*

$$a_{ca.end} := \frac{A_{va.end} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588\ in$$

*Depth of Whitney stress block*

$$M_{ca.end} := \frac{\left(A_{va.end} \cdot f_y \cdot \left(d_{ca.end} - \frac{a_{ca.end}}{2}\right)\right)}{b_c} = 43.912\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at Joints/ Ends when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

$$M_{c.end} := min\left(M_{cp.end}, M_{ca.end}\right) = 29.912\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at joints/ends when considering the critical reinforcement*

**(3c) Bending Capacity of the Barrier about the Vertical Axis:** $M_w$

$d_w = 14.75\ in$ *Effective depth of longitudinal reinforcement bars*

$A_w = 1\ in^2$ *Area of longitudinal reinforcement bars in tension*

$H_w = 36\ in$ *Extreme distance of tension longitudinal reinforcement of barrier*

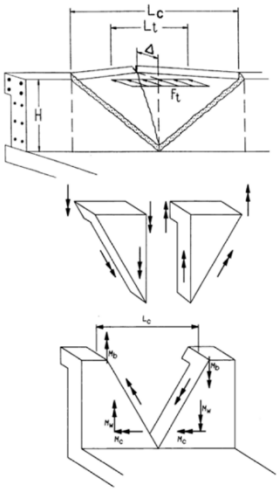
$$a_w := \frac{A_w \cdot f_y}{0.85 \cdot f'_c \cdot H_w} = 0.49\ in$$

*Depth of Whitney stress block*

$$M_w := A_w \cdot f_y \cdot \left(d_w - \frac{a_w}{2}\right) = 72.525\ kip \cdot ft$$

*Flexural resistance of the barrier about the vertical axis specified in Article A 13.3.1*

**(3d) Ultimate Resistance of the Wall at Midspan: $R_{w.mid}$**




$H_w = 36\ in$ — *Height of barrier*

$M_B := 0\ kip \cdot ft$ — *No additional beam strength*

$M_{c.mid} = 15.103\ \frac{kip \cdot ft}{ft}$ — *Flexural resistance about the long. axis at midspan*

$M_w = 72.525\ kip \cdot ft$ — *Flexural resistance about the vert. axis*

$L_t = 4\ ft$ — *Long. length of distribution of impact force*

*Figure 2. Yield Line Analysis of Concrete Parapet Walls for Impact within Wall Segment (figure taken from AASHTO).*

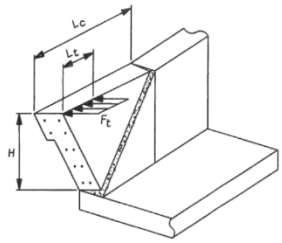
$$L_{c.mid} := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{8 \cdot H_w \cdot (M_B + M_w)}{M_{c.mid}}} = 12.92\ ft$$

*AASHTO Equation A13.3.1-2*

$$R_{w.mid} := \left(\frac{2}{2 \cdot L_{c.mid} - L_t}\right) \cdot \left(8 \cdot M_B + 8 \cdot M_w + \frac{M_{c.mid} \cdot (L_{c.mid})^2}{H_w}\right) \cdot \frac{H_w}{H_e} = 187.326\ kip$$

*AASHTO Equation A13.3.1-1*

**(3e) Ultimate Resistance of the Wall at Joints/Ends: $R_{w.end}$**




$H_w = 36\ in$ — *Height of barrier*

$M_B := 0\ kip \cdot ft$ — *No additional beam strength*

$M_{c.end} = 29.912\ \frac{kip \cdot ft}{ft}$ — *Flexural resistance about the long. axis at joints/ends*

$M_w = 72.525\ kip \cdot ft$ — *Flexural resistance about the vert. axis*

$L_t = 4\ ft$ — *Long. length of distribution of impact force*

*Figure 3. Yield Line Analysis of Concrete Parapet Walls for Impact near End of Wall Segment (figure taken from AASHTO)*

$$L_{c.end} := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{H_w \cdot (M_B + M_w)}{M_{c.end}}} = 5.358\ ft$$ *AASHTO Equation A13.3.1-4*

$$R_{w.end} := \left(\frac{2}{2 \cdot L_{c.end} - L_t}\right) \cdot \left(M_B + M_w + \frac{M_{c.end} \cdot (L_{c.end})^2}{H_w}\right) \cdot \frac{H_w}{H_e} = 153.847\ kip$$

*AASHTO Equation A13.3.1-3*

**(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification - Summary of Results:**

$H_w = 36\ in$ *Height of the concrete barrier measured from the top of the roadway surface*

$H_e = 25\ in$ *Height of the transverse impact force, Ft*

$F_t = 68\ kip$ *Transverses impact force located at He*

$R_{w.mid} = 187.326\ kip$ *Ultimate resistance of the wall at midspan*

$R_{w.end} = 153.847\ kip$ *Ultimate resistance of the wall at joints/ends*

$$\text{Structural_Capacity_of_Barrier_at_Midspan_Check} := \begin{cases} \text{“OK”} & \text{if } R_{w.mid} > F_t \\ \text{“Not OK”} & \text{else} \end{cases}$$

Structural_Capacity_of_Barrier_at_Midspan_Check = “OK”

$$\text{Structural_Capacity_of_Barrier_at_Ends_Check} := \begin{cases} \text{“OK”} & \text{if } R_{w.end} > F_t \\ \text{“Not OK”} & \text{else} \end{cases}$$

Structural_Capacity_of_Barrier_at_Ends_Check = “OK”

**(4) Punching Shear Capacity of the Barrier:**

$\lambda := 1.0$ *Concrete weight modification factor*

$d_c := 12.53\ in$ *Depth of shear zone at height of equivalent transverse load*

$T_{w.top} := 10\ in$ *Top width of barrier*

$h_c := 11\ in$ *Width of shear zone*

$L_t = 4\ ft$ *Distribution width of transverse impact force*

$f'_c = 4\ ksi$ *Concrete barrier compressive strength*

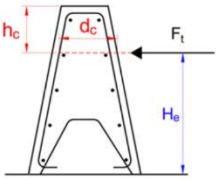



*Figure 4. Punching Shear Variables*

$$d_f := \frac{T_{w.top} + d_c}{2} = 11.265\ in$$ *Median depth of shear zone*

$$b_{o.int} := (L_t + d_c) + 2 \cdot \left(h_c + \frac{d_c}{2}\right) = 95.06\ in$$

*Median perimeter of interior critical section (AASHTO 5.8.4.3.4)*

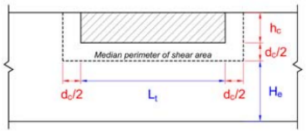



*Figure 5. Punching Shear at Interior Segment*

$$V_{c.int} := 0.125 \cdot \lambda \cdot \left(\sqrt{\frac{f'_c}{1000\ psi}} \cdot ksi\right) \cdot b_{o.int} \cdot d_f = 267.713\ kip$$

*Interior punching shear capacity (AASHTO Eq.5.8.4.3.4-3)*

$$b_{o.end} := \left(L_t + \frac{d_c}{2}\right) + \left(h_c + \frac{d_c}{2}\right) = 71.53\ in$$

*Median perimeter of exterior critical section (AASHTO 5.8.4.3.4)*

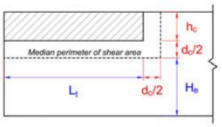



*Figure 6. Punching Shear at Exterior Segment*

$$V_{c.end} := 0.125 \cdot \lambda \cdot \left(\sqrt{\frac{f'_c}{1000\ psi}} \cdot ksi\right) \cdot b_{o.end} \cdot d_f = 201.446\ kip$$

*Exterior punching shear capacity (AASHTO Eq.5.8.4.3.4-3)*

$V_c := min\left(V_{c.int}, V_{c.end}\right) = 201.446\ kip$ *Critical punching shear capacity*

$F_t = 68\ kip$ *Transverse impact force*

Punching_Shear_Capacity_of_Barrier_Check := if $V_c > F_t$
"OK"
else
"Not OK"

Punching_Shear_Capacity_of_Barrier_Check = "OK"

**(5) Deck Moment Capacity:**

**(5a) Deck Moment Demand:**

- The moment demand on the deck due to the TL-4 impact loading was determined using RISA-3D structral analysis.

- A solid model of the 36" barrier, as shown in Figure 5, was developed to determine the barrier loads to the deck. This model was generated with 6" wide elements in the longitudinal direction to represent the spacing of the barrier vertical reinforcements.

- The deck was modeled using meshed plate elements (4' x 50' with 6" x 6" plate elements). The reactions from the barrier to the deck were applied at the corresponding locations as shown in Figure 6.

* Detailed discussion will be provided in the final report.

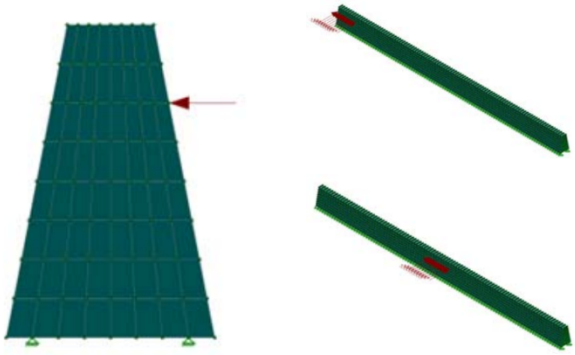


*Figure 7. Barrier Solid Model*

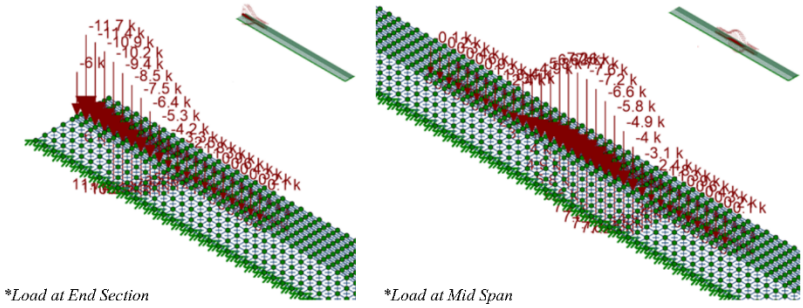
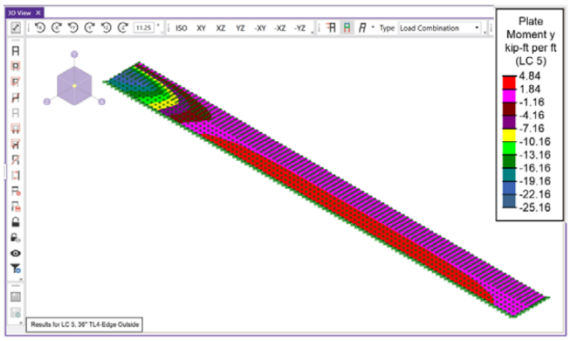


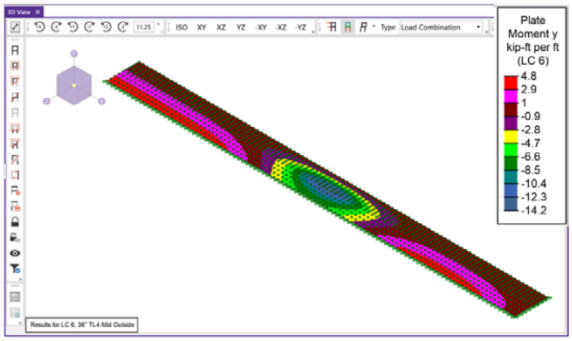

*Figure 8. Deck Plate Model with Barrier Reactions*

Deck moment demand from RISA 3-D analysis:

Max. moment demand at end-section: $M_{u.end} := 25.16\ kip \cdot ft$




Max. moment demand at mid-span: $M_{u.mid} := 14.2\ kip \cdot ft$




**(5b) Deck Nominal Moment Capacity:**

$b_{c.unit} := 12\ in$ *Unit width of deck*

$t_s = 11\ in$ *Depth of deck*

$d_{s.bot} = 9.188\ in$ *Extreme distance of deck flexural reinforcement at top*

$A_{s.bot} = 0.31\ in^2$ *Section area of deck flexural reinforcement at top*

$S_{s.bot} = 3\ in$ *Spacing of deck flexural reinforcement at top*

$A_{s.unit} := \frac{A_{s.bot}}{S_{s.bot}} \cdot b_{c.unit} = 1.24\ in^2$ *Unit area of deck flexural reinforcement at end section*

$a_s := \frac{A_{s.unit} \cdot f_y}{0.85 \cdot f'_c \cdot b_{c.unit}} = 1.824\ in$ *Depth of Whitney stress block at end section*

$M_{n.s} := A_{s.unit} \cdot f_y \cdot \left(d_{s.bot} - 0.5 \cdot a_s\right) = 51.31\ kip \cdot ft$ *Nominal moment capacity of deck*

**(5c) Deck Moment Capacity with Coincident Tensile Forces (AASHTO A 13.4.2):**

- Check at critical location: end-section

$L_{c.end} = 5.358\ ft$ *Distribution length of yield line mechanism*

$R_{w.end} = 153.847\ kip$ *Nominal resistance of barrier to transverse load*

$H_w = 36\ in$ *Height of barrier*

$T := \frac{R_{w.end}}{L_{c.end} + 2 \cdot H_w} = 13.546\ \frac{kip}{ft}$ *Coincident tensile force from vehicle impact (AASHTO Eq. A 13.4.2.-1)*

$T_a := A_{s.unit} \cdot f_y = 74.4\ kip$ *Tensile load provided by deck flexural reinforcement*

$C := T_a - T \cdot ft = 60.854\ kip$ *Resultant compression force in deck section*

$a_c := \frac{C}{0.85 \cdot f'_c \cdot b_c} = 1.492\ in$ *Depth of Whitney stress block for compression force*

$M_{n.t} := T_a \cdot \left(d_{s.bot} - \frac{a_c}{2}\right) - T \cdot ft \cdot \left(\frac{d_{s.bot}}{2} - \frac{a_c}{2}\right) = 47.995\ kip \cdot ft$

*Moment capacity of deck with coincident tensile force*

$M_{u.deck} := \max\left(M_{u.end}, M_{u.mid}\right) = 25.16\ kip \cdot ft$ *Maximum moment demand*

$$\text{Moment_Capacity_of_Deck_Check} := \begin{cases} \text{if } M_{n.t} > M_{u.deck} \\ \quad \text{“OK”} \\ \text{else} \\ \quad \text{“Not OK”} \end{cases}$$

$$\text{Moment_Capacity_of_Deck_Check} = \text{“OK”}$$

**(6) Reinforcement Development Length:**

$d_{b.\#4} := 0.5\ in$ ; $d_{b.\#5} := 0.625\ in$ *Bar diameter*

$$l_{db.\#4} := 2.4 \cdot d_{b.\#4} \cdot \frac{f_y}{\sqrt{f'_c \cdot \frac{1}{1000\ psi}} \cdot ksi} = 3\ ft$$

$$l_{db.\#5} := 2.4 \cdot d_{b.\#5} \cdot \frac{f_y}{\sqrt{f'_c \cdot \frac{1}{1000\ psi}} \cdot ksi} = 3.75\ ft$$

*Basic development length (AASHTO Eq. 5.10.8.2.1a-2)*

$\lambda := 1.0$ *Concrete weight modification factor*

$\lambda_{rl} := 1.0$ *Reinforcement location factor (AASHTO 5.10.8.2.1b)*

$\lambda_{cf} := 1.0$ *Coating factor (AASHTO 5.10.8.2.1b)*

$\lambda_{er} := 1.0$ *Excess reinforcement factor (AASHTO 5.10.8.2.1c)*

$k_{tr} := 0$ *Transverse reinforcement index (conservatively taken as 0 as per AASHTO C5.10.8.2.1c)*

$c_{b.\#4} := 1.75\ in$ ; $c_{b.\#5} := 1.8125\ in$ *Smaller of reinforcement edge distance and one-half of spacing*

$$\lambda_{rc.\#4} := \max\left(\frac{d_{b.\#4}}{c_{b.\#4} + k_{tr}}, 0.4\right) = 0.4 \quad ; \quad \lambda_{rc.\#5} := \max\left(\frac{d_{b.\#5}}{c_{b.\#5} + k_{tr}}, 0.4\right) = 0.4$$

*Reinforcement confinement factor , $0.4 < \lambda_{rc} < 1.0$ (AASHTO 5.10.8.2.1c)*

$$l_{d.\#4} := l_{db.\#4} \cdot \left( \frac{\lambda_{rl} \cdot \lambda_{cf} \cdot \lambda_{rc.\#4} \cdot \lambda_{er}}{\lambda} \right) = 14.4 \ in$$

$$l_{d.\#5} := l_{db.\#5} \cdot \left( \frac{\lambda_{rl} \cdot \lambda_{cf} \cdot \lambda_{rc.\#5} \cdot \lambda_{er}}{\lambda} \right) = 18 \ in$$

*Development lengths needed (modified tension development length, AASHTO Eq. 5.10.8.2.1a-1)*

$l_{anc} := 18.375 \ in$ *Anchorage reinforcement development lengths provided (#4 bar, green)*

$l_{s.top} := 48 \ in$ *Deck flexural reinforcement development lengths provided (#5 bar, purple)*

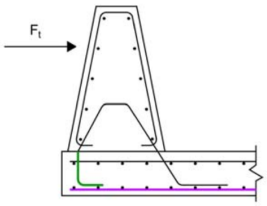



*Figure 9. Reinforcement Development Length*

$$\text{Deck_Reinforcement_Development_Length_Check} := \begin{cases} \text{if } l_{anc} > l_{d.\#4} \ \| \ l_{s.top} > l_{d.\#5} \\ \quad \| \ \text{“OK”} \\ \text{else} \\ \quad \| \ \text{“Not OK”} \end{cases}$$

Deck_Reinforcement_Development_Length_Check = “OK”

**(7) Analysis Results Overview:**

Minimum_Height_of_Barrier_Check = “OK”

Structural_Capacity_of_Barrier_at_Midspan_Check = “OK”

Structural_Capacity_of_Barrier_at_Ends_Check = “OK”

Punching_Shear_Capacity_of_Barrier_Check = “OK”

Moment_Capacity_of_Deck_Check = “OK”

Deck_Reinforcement_Development_Length_Check = “OK”

**(8) Summary of Barrier Design:**

1. Use Vertical Barrier Stirrup #4 @ 6" O.C. for 10'-0" at Barrier End Section

2. Use Vertical Barrier Stirrup #4 @ 12" O.C. out at Mid-Section (greater than 10'-0" from End Sections)

3. All other details as shown on Section and Elevation Views as provided herein for the 36" Barrier as analyzed herein are acceptable for MASH TL-4 Impact conditions.

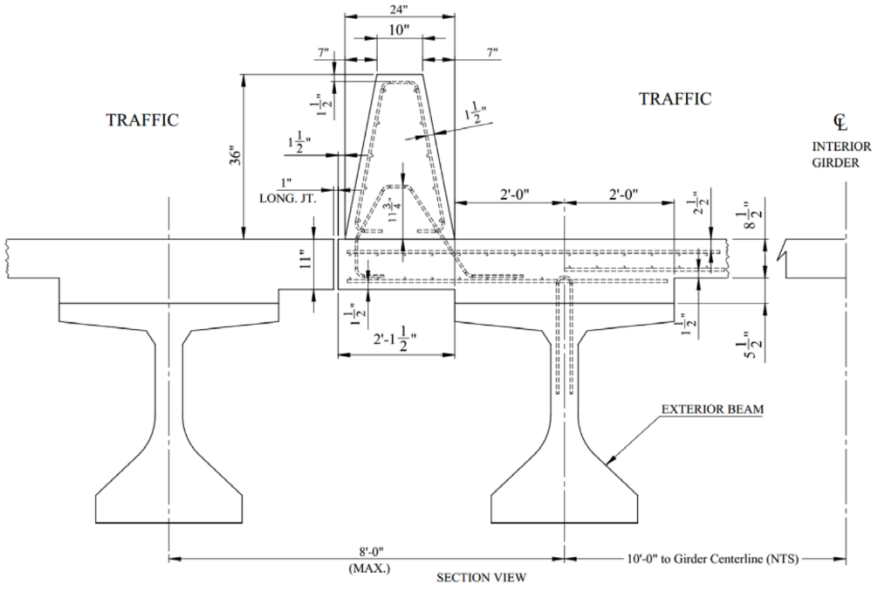
**SUBJECT:** 36" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Inside Barrier (right side)

**Overview:**

These calcualtions evaluate the strength of the given barrier design for MASH TL-4 impact load condtions.

- 36" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from the Barrier Right Side in the Section View below.

**Design Details:**




**Section View (a)**

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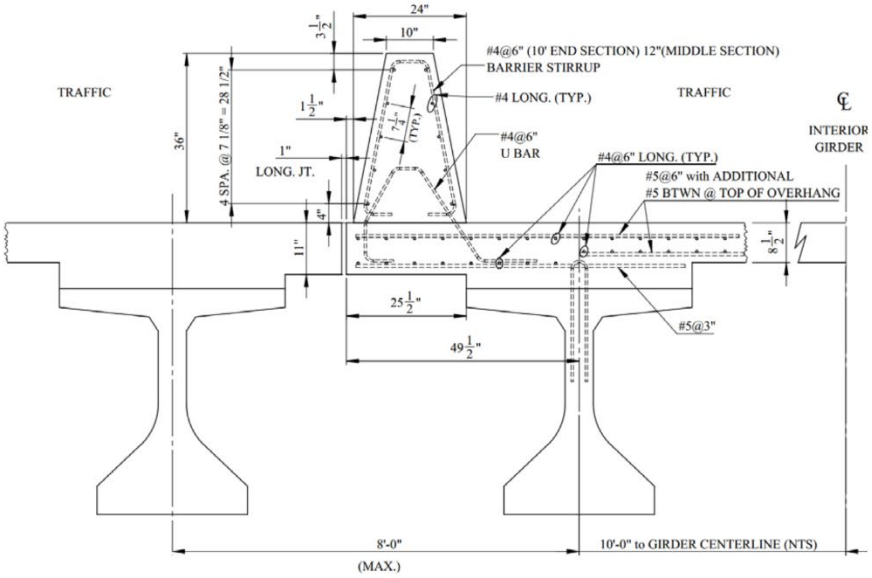
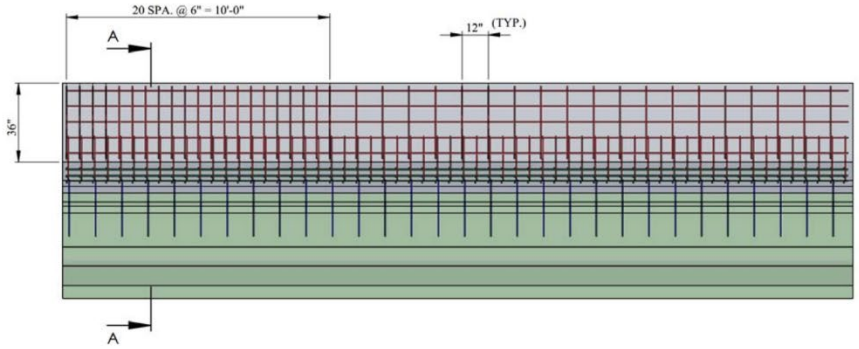
**SUBJECT:** 36" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Inside Barrier (right side)

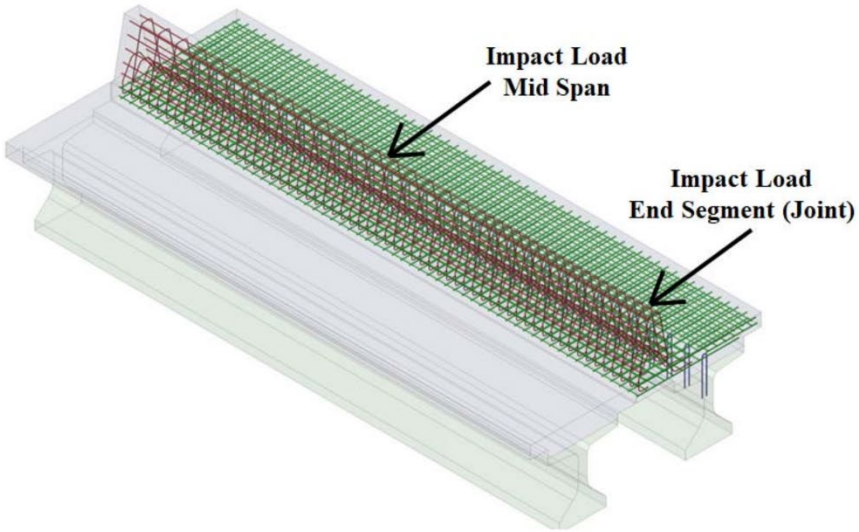



**Section View (b)**




**Elevation**

**SUBJECT:** 36" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Inside Barrier (right side)




**Iso View**

**SUBJECT:** 36" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Inside Barrier (right side)

**(1) Define Inputs:**

**(1a) General Inputs:**

$f'_c := 4000\ psi$ — *Compressive strength of concrete*

$f_y := 60\ ksi$ — *Yield strength reinforcing steel*

$E_s := 29000\ ksi$ — *Modulus of elasticity of steel*

$H_w := 36\ in$ — *Height of barrier*

$T_{w.top} := 10\ in$ — *Top width of barrier*

$T_{w.bot} := 24\ in$ — *Bottom width of barrier*

$t_s := 11\ in$ — *Depth of deck*

$d_{\#4} := 0.5\ in$ ; $A_{\#4} := 0.2\ in^2$ — *Diameter and section area of #4 bar*

$d_{\#5} := 0.625\ in$ ; $A_{\#5} := 0.31\ in^2$ — *Diameter and section area of #5 bar*

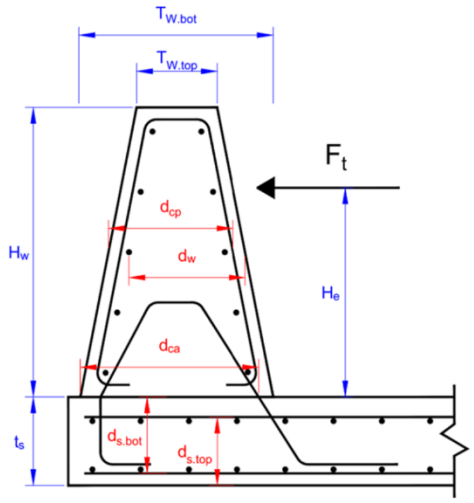



*Figure 1. Sketch of Concrete Wall/Parapet Showing Input Variable*

**(1b) Concrete Barrier Inputs:**

$t_{b.cov} := 1.5\ in$ *Concrete clear cover of barrier*

Barrier vertical reinforcement inputs (#4 bars):

$A_{vpl.mid} := 0.2\ in^2$ *Area of one barrier vertical reinforcement leg at midspan*

$S_{vp.mid} := 12\ in$ *Spacing of barrier vertical reinforcement at midspan*

$d_{cp.mid} := 15.25\ in$ *Average extreme distance of barrier vertical reinforcement at midspan*

$A_{vpl.end} := 0.2\ in^2$ *Area of one barrier vertical reinforcement leg at joints/ends*

$S_{vp.end} := 6\ in$ *Spacing of barrier vertical reinforcement at joints/ends*

$d_{cp.end} := 15.25\ in$ *Average extreme distance of barrier vertical reinforcement at joints/ends*

Deck anchorage reinforcement inputs (#4 bars):

$A_{val.mid} := 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} := 6\ in$ *Spacing of deck anchorage vertical reinforcement at midspan*

$d_{ca.mid} := 22.25\ in$ *Extreme distance of tension deck anchorage reinforcement at midspan*

$A_{val.end} := 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at joints/ends*

$S_{va.end} := 6\ in$ *Spacing of deck anchorage vertical reinforcement at joints/ends*

$d_{ca.end} := 22.25\ in$ *Extreme distance of tension deck anchorage reinforcement at joints/ends*

Barrier Longitudinal reinforcement inputs (#4 bars):

$A_w := 0.2 \cdot 5\ in^2 = 1\ in^2$ *Area of longitudinal reinforcement bars in tension*

$d_w := 14.75\ in$ *Average extreme distance of tension longitudinal reinforcement*

**(1c) Concrete Deck Inputs:**

$t_{s.cov.bot} := 1.5\ in$ *Concrete clear cover of deck at bottom*

$d_{s.bot} := 9.1875\ in$ *Extreme distance of deck flexural reinforcement at bottom*

$A_{s.bot} := 0.31\ in^2$ *Section area of deck flexural reinforcement at bottom (single bar)*

$S_{s.bot} := 3\ in$ *Spacing of deck flexural reinforcement at bottom*

$t_{s.cov.top} := 2.5\ in$ *Concrete clear cover of deck at top*

$d_{s.top} := 8.1875\ in$ *Extreme distance of deck flexural reinforcement at top*

$A_{s.top} := 0.31\ in^2$ *Section area of deck flexural reinforcement at top (single bar)*

$S_{s.top} := 3\ in$ *Spacing of deck flexural reinforcement at top*

**(1d) Design Force Inputs:**

**Design Forces for Traffic Railings**

| Test Level | Rail Height (in.) | $F_t$ (kip) | $F_L$ (kip) | $F_T$ (kip) | $L_t/L_L$ (ft) | $L_T$ (ft) | $H_e$ (in) | $H_{min}$ (in) |
|---|---|---|---|---|---|---|---|---|
| TL-1 | 18 or above | 13.5 | 4.5 | 4.5 | 4.0 | 18.0 | 18.0 | 18.0 |
| TL-2 | 18 or above | 27.0 | 9.0 | 4.5 | 4.0 | 18.0 | 20.0 | 18.0 |
| TL-3 | 29 or above | 71.0 | 18.0 | 4.5 | 4.0 | 18.0 | 19.0 | 29.0 |
| TL-4 (a) | 36 | 68.0 | 22.0 | 38.0 | 4.0 | 18.0 | 25.0 | 36.0 |
| TL-4 (b) | between 36 and 42 | 80.0 | 27.0 | 22.0 | 5.0 | 18.0 | 30.0 | 36.0 |
| TL-5 (a) | 42 | 160.0 | 41.0 | 80.0 | 10.0 | 40.0 | 35.0 | 42.0 |
| TL-5 (b) | greater than 42 | 262.0 | 75.0 | 160.0 | 10.0 | 40.0 | 43.0 | 42.0 |
| TL 6 | | 175.0 | 58.0 | 80.0 | 8.0 | 40.0 | 56.0 | 90.0 |

References:
- TL-1 and TL-2 Design Forces are from AASHTO LRFD Section 13 Table A13.2-1
- TL-3 Design Forces are from research conducted under NCHRP Project 20-07 Task 395
- TL-4 (a), TL-4 (b), TL-5 (a), and TL-5 (b) Design Forces are from research conducted under NCHRP Project 22-20(2)

$TL := 4$ *Test level*

$F_t := 68\ kip$ *Transverse impact force*

$L_t := 4\ ft$ *Longitudinal length of distribution of impact force*

$H_e := 25\ in$ *Height of equivalent transverses load*

$H_{min} := 36\ in$ *Minimum height of a MASH TL-4 barrier*

$H_w = 36\ in$ *Height of concrete barrier*

**(2) Stability Criteria:**

$H_{min} = 36\ in$ *Minimum height of a MASH TL-4 barrier*

$H_w = 36\ in$ *Height of concrete barrier measured from the top of the roadway surface/asphalt overlay*

$$\text{Minimum_Height_of_Barrier_Check} := \begin{cases} \text{if } H_w \geq H_{min} \\ \quad \text{“OK”} \\ \text{else} \\ \quad \text{“Not OK”} \end{cases}$$

$\text{Minimum_Height_of_Barrier_Check} = \text{“OK”}$

**(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification:**

**(3a) Bending Capacity of the Barrier about the Longitudinal Axis at Midspan:** $M_{cmid}$ **(k-ft/ft)**

For parapet vertical reinforcement:

$b_c := 12\ in$ *Unit width of wall (take as 1 ft per AASHTO Section 13 procedure)*

$A_{vpl.mid} = 0.2\ in^2$ *Area of one parapet vertical reinforcement leg at midspan*

$S_{vp.mid} = 12\ in$ *Spacing of parapet vertical reinforcement at midspan*

$$A_{vp.mid} := \left(\frac{b_c}{S_{vp.mid}}\right) \cdot A_{vpl.mid} = 0.2\ in^2$$

*Total area of parapet vertical reinforcement per unit length at midspan*

$d_{cp.mid} = 15.25\ in$ *Average extreme distance of parapet vertical reinforcement at midspan*

$$a_{cp.mid} := \frac{A_{vp.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.294\ in$$ *Depth of Whitney stress block*

$$M_{cp.mid} := \frac{\left(A_{vp.mid} \cdot f_y \cdot \left(d_{cp.mid} - \frac{a_{cp.mid}}{2}\right)\right)}{b_c} = 15.103 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the parapet vertical reinforcement specified in Article A 13.3.1 (k-ft/ft)*

For deck anchorage reinforcement:

$b_c = 12 \ in$ *Unit width of wall (take as 1 ft per AASHTO Section 13 procedure)*

$A_{val.mid} = 0.2 \ in^2$ *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} = 6 \ in$ *Spacing of deck anchorage vertical reinforcement at midspan*

$$A_{va.mid} := \left(\frac{b_c}{S_{va.mid}}\right) \cdot A_{val.mid} = 0.4 \ in^2$$

*Total area of deck anchorage vertical reinforcement per unit length at midspan*

$d_{ca.mid} = 22.25 \ in$ *Extreme distance of tension deck anchorage vertical reinforcement at midspan*

$$a_{ca.mid} := \frac{A_{va.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588 \ in$$ *Depth of Whitney stress block*

$$M_{ca.mid} := \frac{\left(A_{va.mid} \cdot f_y \cdot \left(d_{ca.mid} - \frac{a_{ca.mid}}{2}\right)\right)}{b_c} = 43.912 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

$$M_{c.mid} := min\left(M_{cp.mid}, M_{ca.mid}\right) = 15.103 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering the critical reinforcement*

**(3b) Bending Capacity of the Barrier about the Longitudinal Axis at Joints/Ends:** $M_{ccnd}$ **(k-ft/ft)**

For parapet vertical reinforcement:

$A_{vpl.end} = 0.2\ in^2$ *Area of one parapet vertical reinforcement leg at joints/ends*

$S_{vp.end} = 6\ in$ *Spacing of parapet vertical reinforcement at joints/ends*

$A_{vp.end} := \left(\frac{b_c}{S_{vp.end}}\right) \cdot A_{vpl.end} = 0.4\ in^2$ *Total area of deck anchorage vertical reinforcement per unit length at midspan*

$d_{cp.end} = 15.25\ in$ *Average extreme distance of parapet vertical reinforcement at joints/ends (at barrier mid-height)*

$a_{cp.end} := \frac{A_{vp.end} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588\ in$ *Depth of Whitney stress block*

$$M_{cp.end} := \frac{\left(A_{vp.end} \cdot f_y \cdot \left(d_{cp.end} - \frac{a_{cp.end}}{2}\right)\right)}{b_c} = 29.912\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at Joints/ Ends when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

For deck anchorage reinforcement:

$A_{val.end} = 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at joints/ends*

$S_{va.end} = 6\ in$ *Spacing of deck anchorage vertical reinforcement at joints/ends*

$A_{va.end} := \left(\frac{b_c}{S_{va.end}}\right) \cdot A_{val.end} = 0.4\ in^2$ *Total area of deck anchorage vertical reinforcement per unit length at joints/ends*

$d_{ca.end} = 22.25\ in$ *Extreme distance of tension deck anchorage vertical reinforcement at joints/ends*

$$a_{ca.end} := \frac{A_{va.end} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588\ in$$ *Depth of Whitney stress block*

$$M_{ca.end} := \frac{\left(A_{va.end} \cdot f_y \cdot \left(d_{ca.end} - \frac{a_{ca.end}}{2}\right)\right)}{b_c} = 43.912\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at Joints/ Ends when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

$$M_{c.end} := min\left(M_{cp.end}, M_{ca.end}\right) = 29.912\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at joints/ends when considering the critical reinforcement*

**(3c) Bending Capacity of the Barrier about the Vertical Axis:** $M_w$

$d_w = 14.75\ in$ *Effective depth of longitudinal reinforcement bars*

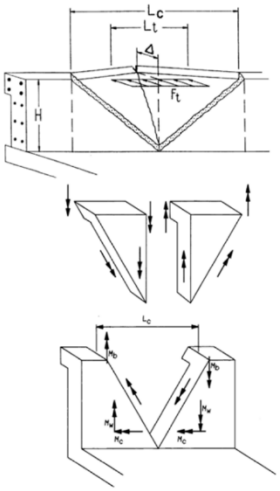
$A_w = 1\ in^2$ *Area of longitudinal reinforcement bars in tension*

$H_w = 36\ in$ *Extreme distance of tension longitudinal reinforcement of barrier*

$$a_w := \frac{A_w \cdot f_y}{0.85 \cdot f'_c \cdot H_w} = 0.49\ in$$ *Depth of Whitney stress block*

$$M_w := A_w \cdot f_y \cdot \left(d_w - \frac{a_w}{2}\right) = 72.525\ kip \cdot ft$$ *Flexural resistance of the barrier about the vertical axis specified in Article A 13.3.1*

**(3d) Ultimate Resistance of the Wall at Midspan: $R_{w.mid}$**




$H_w = 36\ in$ — *Height of barrier*

$M_B := 0\ kip \cdot ft$ — *No additional beam strength*

$M_{c.mid} = 15.103\ \frac{kip \cdot ft}{ft}$ — *Flexural resistance about the long. axis at midspan*

$M_w = 72.525\ kip \cdot ft$ — *Flexural resistance about the vert. axis*

$L_t = 4\ ft$ — *Long. length of distribution of impact force*

*Figure 2. Yield Line Analysis of Concrete Parapet Walls for Impact within Wall Segment (figure taken from AASHTO).*

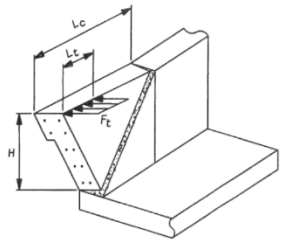
$$L_{c.mid} := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{8 \cdot H_w \cdot (M_B + M_w)}{M_{c.mid}}} = 12.92\ ft$$

*AASHTO Equation A13.3.1-2*

$$R_{w.mid} := \left(\frac{2}{2 \cdot L_{c.mid} - L_t}\right) \cdot \left(8 \cdot M_B + 8 \cdot M_w + \frac{M_{c.mid} \cdot (L_{c.mid})^2}{H_w}\right) \cdot \frac{H_w}{H_e} = 187.326\ kip$$

*AASHTO Equation A13.3.1-1*

**(3e) Ultimate Resistance of the Wall at Joints/Ends: $R_{w.end}$**




$H_w = 36\ in$ — *Height of barrier*

$M_B := 0\ kip \cdot ft$ — *No additional beam strength*

$M_{c.end} = 29.912\ \frac{kip \cdot ft}{ft}$ — *Flexural resistance about the long. axis at joints/ends*

$M_w = 72.525\ kip \cdot ft$ — *Flexural resistance about the vert. axis*

$L_t = 4\ ft$ — *Long. length of distribution of impact force*

*Figure 3. Yield Line Analysis of Concrete Parapet Walls for Impact near End of Wall Segment (figure taken from AASHTO)*

$$L_{c.end} := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{H_w \cdot (M_B + M_w)}{M_{c.end}}} = 5.358\ ft$$ *AASHTO Equation A13.3.1-4*

$$R_{w.end} := \left(\frac{2}{2 \cdot L_{c.end} - L_t}\right) \cdot \left(M_B + M_w + \frac{M_{c.end} \cdot (L_{c.end})^2}{H_w}\right) \cdot \frac{H_w}{H_e} = 153.847\ kip$$

*AASHTO Equation A13.3.1-3*

**(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification - Summary of Results:**

$H_w = 36\ in$ — *Height of the concrete barrier measured from the top of the roadway surface*

$H_e = 25\ in$ — *Height of the transverse impact force, Ft*

$F_t = 68\ kip$ — *Transverses impact force located at He*

$R_{w.mid} = 187.326\ kip$ — *Ultimate resistance of the wall at midspan*

$R_{w.end} = 153.847\ kip$ — *Ultimate resistance of the wall at joints/ends*

Structural_Capacity_of_Barrier_at_Midspan_Check := if $R_{w.mid} > F_t$ "OK" else "Not OK"

Structural_Capacity_of_Barrier_at_Midspan_Check = "OK"

Structural_Capacity_of_Barrier_at_Ends_Check := if $R_{w.end} > F_t$ "OK" else "Not OK"

Structural_Capacity_of_Barrier_at_Ends_Check = "OK"

**(4) Punching Shear Capacity of the Barrier:**

$\lambda := 1.0$ *Concrete weight modification factor*

$d_c := 12.53\ in$ *Depth of shear zone at height of equivalent transverse load*

$T_{w.top} := 10\ in$ *Top width of barrier*

$h_c := 11\ in$ *Width of shear zone*

$L_t = 4\ ft$ *Distribution width of transverse impact force*

$f'_c = 4\ ksi$ *Concrete barrier compressive strength*

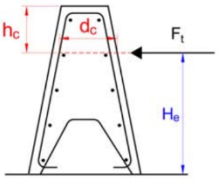



*Figure 4. Punching Shear Variables*

$$d_f := \frac{T_{w.top} + d_c}{2} = 11.265\ in$$ *Median depth of shear zone*

$$b_{o.int} := (L_t + d_c) + 2 \cdot \left(h_c + \frac{d_c}{2}\right) = 95.06\ in$$

*Median perimeter of interior critical section (AASHTO 5.8.4.3.4)*

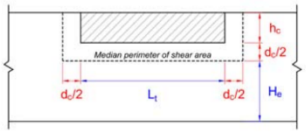



*Figure 5. Punching Shear at Interior Segment*

$$V_{c.int} := 0.125 \cdot \lambda \cdot \left(\sqrt{\frac{f'_c}{1000\ psi}} \cdot ksi\right) \cdot b_{o.int} \cdot d_f = 267.713\ kip$$

*Interior punching shear capacity (AASHTO Eq.5.8.4.3.4-3)*

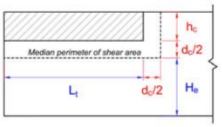



*Figure 6. Punching Shear at Exterior Segment*

$$b_{o.end} := \left(L_t + \frac{d_c}{2}\right) + \left(h_c + \frac{d_c}{2}\right) = 71.53\ in$$

*Median perimeter of exterior critical section (AASHTO 5.8.4.3.4)*

$$V_{c.end} := 0.125 \cdot \lambda \cdot \left(\sqrt{\frac{f'_c}{1000\ psi}} \cdot ksi\right) \cdot b_{o.end} \cdot d_f = 201.446\ kip$$

*Exterior punching shear capacity (AASHTO Eq.5.8.4.3.4-3)*

$V_c := min\left(V_{c.int}, V_{c.end}\right) = 201.446\ kip$ *Critical punching shear capacity*

$F_t = 68\ kip$ *Transverse impact force*

Punching_Shear_Capacity_of_Barrier_Check := if $V_c > F_t$
"OK"
else
"Not OK"

Punching_Shear_Capacity_of_Barrier_Check = "OK"

**(5) Deck Moment Capacity:**

**(5a) Deck Moment Demand:**

- The moment demand on the deck due to the TL-4 impact loading was determined using RISA-3D structral analysis.

- A solid model of the 36" barrier, as shown in Figure 5, was developed to determine the barrier loads to the deck. This model was generated with 6" wide elements in the longitudinal direction to represent the spacing of the barrier vertical reinforcements.

- The deck was modeled using meshed plate elements (4' x 50' with 6" x 6" plate elements). The reactions from the barrier to the deck were applied at the corresponding locations as shown in Figure 6.

* Detailed discussion will be provided in the final report.

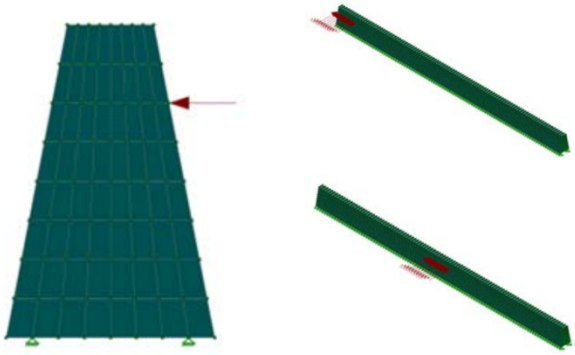


*Figure 7. Barrier Solid Model*

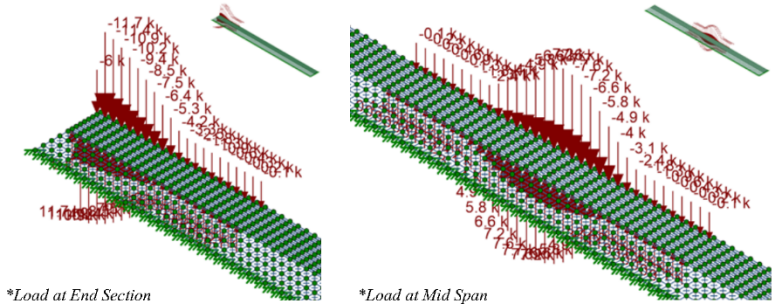
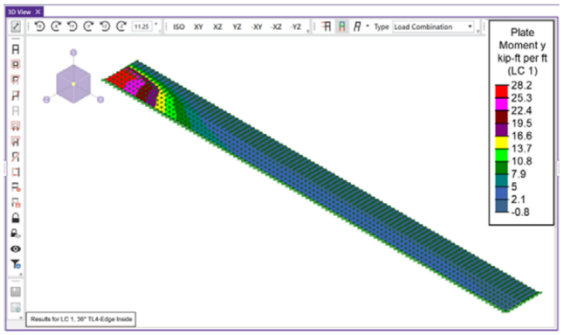


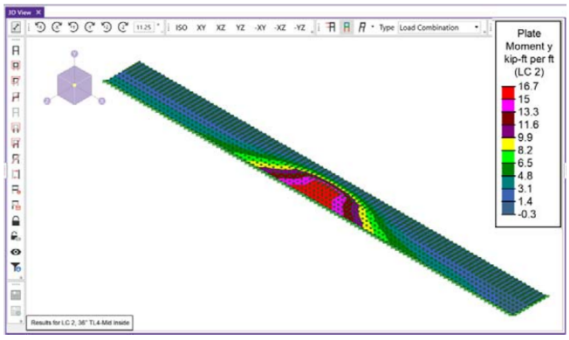

*Figure 8. Deck Plate Model with Barrier Reactions*

Deck moment demand from RISA 3-D analysis:

Max. moment demand at end-section: $M_{u.end} := 28.2\ kip \cdot ft$




Max. moment demand at mid-span: $M_{u.mid} := 16.7\ kip \cdot ft$




**(5b) Deck Nominal Moment Capacity:**

$b_{c.unit} := 12\ in$ *Unit width of deck*

$t_s = 11\ in$ *Depth of deck*

$d_{s.top} = 8.188\ in$ *Extreme distance of deck flexural reinforcement at top*

$A_{s.top} = 0.31\ in^2$ *Section area of deck flexural reinforcement at top*

$S_{s.top} = 3\ in$ *Spacing of deck flexural reinforcement at top*

$A_{s.unit} := \frac{A_{s.top}}{S_{s.top}} \cdot b_{c.unit} = 1.24\ in^2$ *Unit area of deck flexural reinforcement at end section*

$a_s := \frac{A_{s.unit} \cdot f_y}{0.85 \cdot f'_c \cdot b_{c.unit}} = 1.824\ in$ *Depth of Whitney stress block at end section*

$M_{n.s} := A_{s.unit} \cdot f_y \cdot \left(d_{s.top} - 0.5 \cdot a_s\right) = 45.11\ kip \cdot ft$ *Nominal moment capacity of deck*

**(5c) Deck Moment Capacity with Coincident Tensile Forces (AASHTO A 13.4.2):**

- Check at critical location: end-section

$L_{c.end} = 5.358\ ft$ *Distribution length of yield line mechanism*

$R_{w.end} = 153.847\ kip$ *Nominal resistance of barrier to transverse load*

$H_w = 36\ in$ *Height of barrier*

$T := \frac{R_{w.end}}{L_{c.end} + 2 \cdot H_w} = 13.546\ \frac{kip}{ft}$ *Coincident tensile force from vehicle impact (AASHTO Eq. A 13.4.2.-1)*

$T_a := A_{s.unit} \cdot f_y = 74.4\ kip$ *Tensile load provided by deck flexural reinforcement*

$C := T_a - T \cdot ft = 60.854\ kip$ *Resultant compression force in deck section*

$a_c := \frac{C}{0.85 \cdot f'_c \cdot b_c} = 1.492\ in$ *Depth of Whitney stress block for compression force*

$M_{n.t} := T_a \cdot \left(d_{s.top} - \frac{a_c}{2}\right) - T \cdot ft \cdot \left(\frac{d_{s.top}}{2} - \frac{a_c}{2}\right) = 42.36\ kip \cdot ft$

*Moment capacity of deck with coincident tensile force*

$M_{u.deck} := \max\left(M_{u.end}, M_{u.mid}\right) = 28.2\ kip \cdot ft$ *Maximum moment demand*

$$\text{Moment_Capacity_of_Deck_Check} := \begin{cases} \text{“OK”} & \text{if } M_{n.t} > M_{u.deck} \\ \text{“Not OK”} & \text{else} \end{cases}$$

$$\text{Moment_Capacity_of_Deck_Check} = \text{“OK”}$$

**(6) Reinforcement Development Length:**

$d_{b.\#4} := 0.5\ in$ ; $d_{b.\#5} := 0.625\ in$ *Bar diameter*

$$l_{db.\#4} := 2.4 \cdot d_{b.\#4} \cdot \frac{f_y}{\sqrt{f'_c \cdot \frac{1}{1000\ psi}} \cdot ksi} = 3\ ft$$

$$l_{db.\#5} := 2.4 \cdot d_{b.\#5} \cdot \frac{f_y}{\sqrt{f'_c \cdot \frac{1}{1000\ psi}} \cdot ksi} = 3.75\ ft$$

*Basic development length (AASHTO Eq. 5.10.8.2.1a-2)*

$\lambda := 1.0$ *Concrete weight modification factor*

$\lambda_{rl} := 1.0$ *Reinforcement location factor (AASHTO 5.10.8.2.1b)*

$\lambda_{cf} := 1.0$ *Coating factor (AASHTO 5.10.8.2.1b)*

$\lambda_{er} := 1.0$ *Excess reinforcement factor (AASHTO 5.10.8.2.1c)*

$k_{tr} := 0$ *Transverse reinforcement index (conservatively taken as 0 as per AASHTO C5.10.8.2.1c)*

$c_{b.\#4} := 1.75\ in$ ; $c_{b.\#5} := 1.8125\ in$ *Smaller of reinforcement edge distance and one-half of spacing*

$$\lambda_{rc.\#4} := \max\left(\frac{d_{b.\#4}}{c_{b.\#4} + k_{tr}}, 0.4\right) = 0.4 \quad ; \quad \lambda_{rc.\#5} := \max\left(\frac{d_{b.\#5}}{c_{b.\#5} + k_{tr}}, 0.4\right) = 0.4$$

*Reinforcement confinement factor , $0.4 < \lambda_{rc} < 1.0$ (AASHTO 5.10.8.2.1c)*

$$l_{d.\#4} := l_{db.\#4} \cdot \left( \frac{\lambda_{rl} \cdot \lambda_{cf} \cdot \lambda_{rc.\#4} \cdot \lambda_{er}}{\lambda} \right) = 14.4\ in$$

$$l_{d.\#5} := l_{db.\#5} \cdot \left( \frac{\lambda_{rl} \cdot \lambda_{cf} \cdot \lambda_{rc.\#5} \cdot \lambda_{er}}{\lambda} \right) = 18\ in$$

*Development lengths needed (modified tension development length, AASHTO Eq. 5.10.8.2.1a-1)*

$l_{anc} := 22\ in$ *Anchorage reinforcement development lengths provided (#4 bar, green)*

$l_{s.top} := 48\ in$ *Deck flexural reinforcement development lengths provided (#5 bar, purple)*

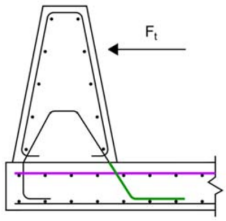



*Figure 9. Reinforcement Development Length*

Deck_Reinforcement_Development_Length_Check := if $l_{anc} > l_{d.\#4}$ || $l_{s.top} > l_{d.\#5}$
|| "OK"
else
|| "Not OK"

Deck_Reinforcement_Development_Length_Check = "OK"

**(7) Analysis Results Overview:**

Minimum_Height_of_Barrier_Check = "OK"

Structural_Capacity_of_Barrier_at_Midspan_Check = "OK"

Structural_Capacity_of_Barrier_at_Ends_Check = "OK"

Punching_Shear_Capacity_of_Barrier_Check = "OK"

Moment_Capacity_of_Deck_Check = "OK"

Deck_Reinforcement_Development_Length_Check = "OK"

**(8) Summary of Barrier Design:**

1. Use Vertical Barrier Stirrup #4 @ 6" O.C. for 10'-0" at Barrier End Section

2. Use Vertical Barrier Stirrup #4 @ 12" O.C. out at Mid-Section (greater than 10'-0" from End Sections)

3. All other details as shown on Section and Elevation Views as provided herein for the 36" Barrier as analyzed herein are acceptable for MASH TL-4 Impact conditions.

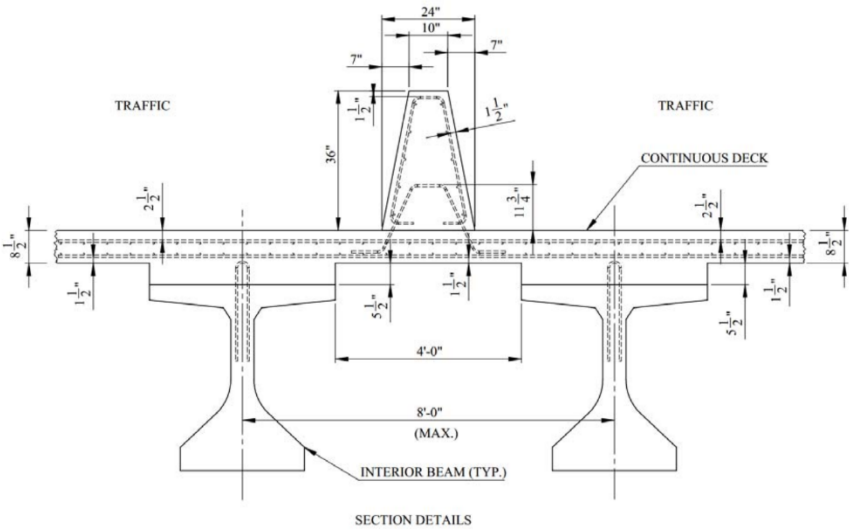
**SUBJECT:** 36" LADOTD Median Barrier

**Overview:**

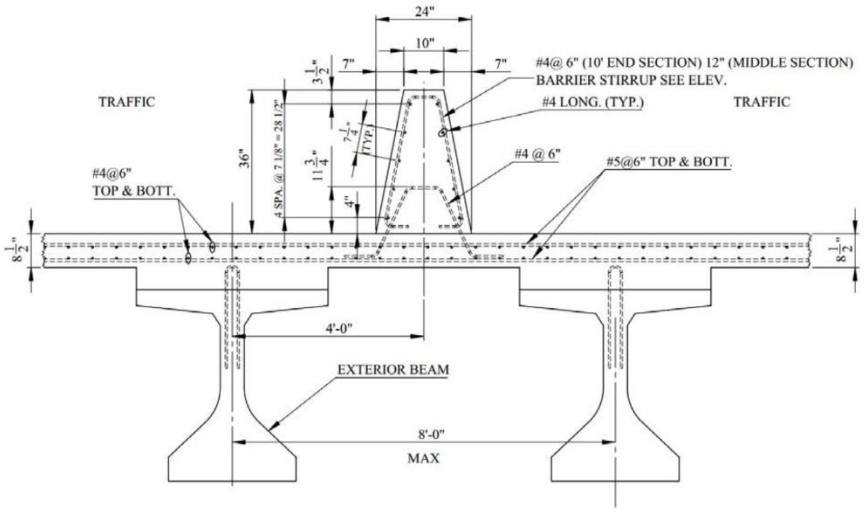
These calcualtions evaluate the strength of the given barrier design for MASH TL-4 impact load condtions.

- 36" LADOTD Median Barrier

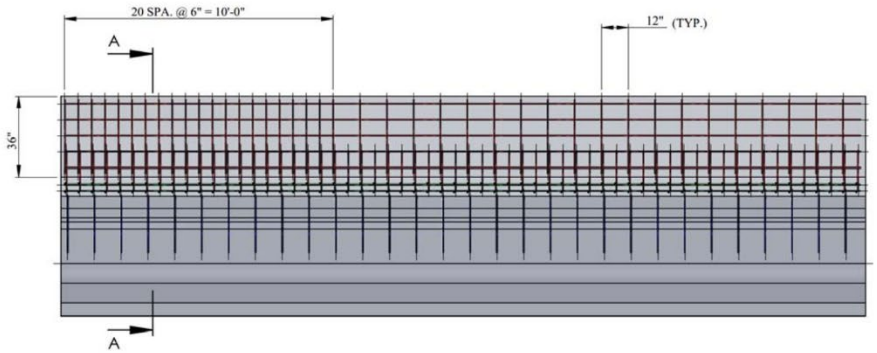
**Design Details:**



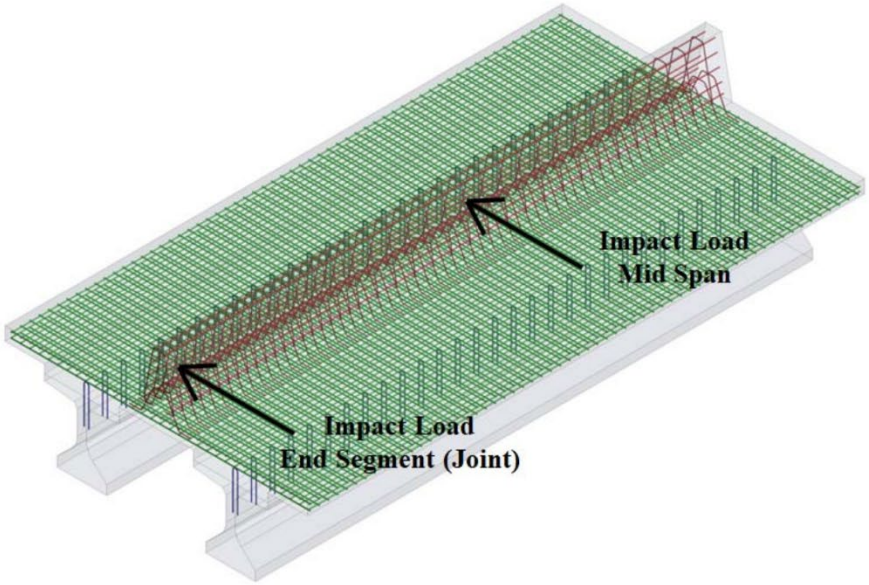

**Section View (a)**




**Section View (b)**




**Elevation**




**Iso View**

**(1) Define Inputs:**

**(1a) General Inputs:**

$f'_c := 4000\ psi$ — *Compressive strength of concrete*

$f_y := 60\ ksi$ — *Yield strength reinforcing steel*

$E_s := 29000\ ksi$ — *Modulus of elasticity of steel*

$H_w := 36\ in$ — *Height of barrier*

$T_{w.top} := 10\ in$ — *Top width of barrier*

$T_{w.bot} := 24\ in$ — *Bottom width of barrier*

$t_s := 8.5\ in$ — *Depth of deck*

$d_{\#4} := 0.5\ in$ ; $A_{\#4} := 0.2\ in^2$ — *Diameter and section area of #4 bar*

$d_{\#5} := 0.625\ in$ ; $A_{\#5} := 0.31\ in^2$ — *Diameter and section area of #5 bar*

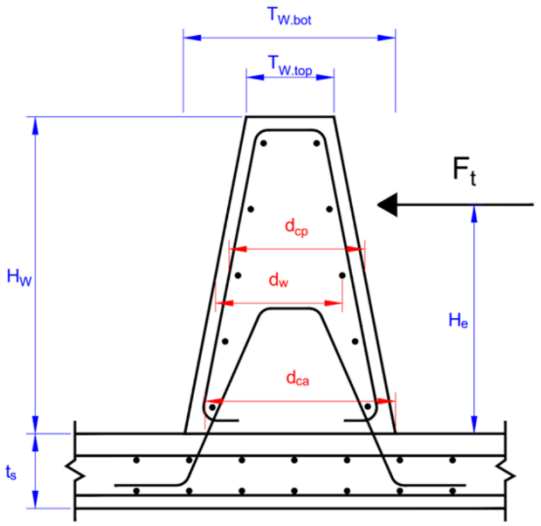



*Figure 1. Sketch of Concrete Wall/Parapet Showing Input Variable*

**(1b) Concrete Barrier Inputs:**

$t_{b.cov} := 1.5\ in$ *Concrete clear cover of barrier*

Barrier vertical reinforcement inputs (#4 bars):

$A_{vpl.mid} := 0.2\ in^2$ *Area of one barrier vertical reinforcement leg at midspan*

$S_{vp.mid} := 12\ in$ *Spacing of barrier vertical reinforcement at midspan*

$d_{cp.mid} := 15.25\ in$ *Average extreme distance of barrier vertical reinforcement at midspan*

$A_{vpl.end} := 0.2\ in^2$ *Area of one barrier vertical reinforcement leg at joints/ends*

$S_{vp.end} := 6\ in$ *Spacing of barrier vertical reinforcement at joints/ends*

$d_{cp.end} := 15.25\ in$ *Average extreme distance of barrier vertical reinforcement at joints/ends*

Deck anchorage reinforcement inputs (#4 bars):

$A_{val.mid} := 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} := 6\ in$ *Spacing of deck anchorage vertical reinforcement at midspan*

$d_{ca.mid} := 22.25\ in$ *Extreme distance of tension deck anchorage reinforcement at midspan*

$A_{val.end} := 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at joints/ends*

$S_{va.end} := 6\ in$ *Spacing of deck anchorage vertical reinforcement at joints/ends*

$d_{ca.end} := 22.25\ in$ *Extreme distance of tension deck anchorage reinforcement at joints/ends*

Barrier Longitudinal reinforcement inputs (#4 bars):

$A_w := 0.2 \cdot 5\ in^2 = 1\ in^2$ *Area of longitudinal reinforcement bars in tension*

$d_w := 14.75\ in$ *Average extreme distance of tension longitudinal reinforcement*

**(1c) Concrete Deck Inputs:**

| | |
|---|---|
| $t_{s.cov.bot} := 1.5\ in$ | *Concrete clear cover of deck at bottom* |
| $d_{s.bot} := 6.6875\ in$ | *Extreme distance of deck flexural reinforcement at bottom* |
| $A_{s.bot} := 0.31\ in^2$ | *Section area of deck flexural reinforcement at bottom (single bar)* |
| $S_{s.bot} := 6\ in$ | *Spacing of deck flexural reinforcement at bottom* |
| $t_{s.cov.top} := 2.5\ in$ | *Concrete clear cover of deck at top* |
| $d_{s.top} := 5.875\ in$ | *Extreme distance of deck flexural reinforcement at top* |
| $A_{s.top} := 0.31\ in^2$ | *Section area of deck flexural reinforcement at top (single bar)* |
| $S_{s.top} := 6\ in$ | *Spacing of deck flexural reinforcement at top* |

**(1d) Design Force Inputs:**

**Design Forces for Traffic Railings**

| Test Level | Rail Height (in.) | $F_t$ (kip) | $F_L$ (kip) | $F_T$ (kip) | $L_t/L_L$ (ft) | $L_T$ (ft) | $H_e$ (in) | $H_{min}$ (in) |
|---|---|---|---|---|---|---|---|---|
| TL-1 | 18 or above | 13.5 | 4.5 | 4.5 | 4.0 | 18.0 | 18.0 | 18.0 |
| TL-2 | 18 or above | 27.0 | 9.0 | 4.5 | 4.0 | 18.0 | 20.0 | 18.0 |
| TL-3 | 29 or above | 71.0 | 18.0 | 4.5 | 4.0 | 18.0 | 19.0 | 29.0 |
| TL-4 (a) | 36 | 68.0 | 22.0 | 38.0 | 4.0 | 18.0 | 25.0 | 36.0 |
| TL-4 (b) | between 36 and 42 | 80.0 | 27.0 | 22.0 | 5.0 | 18.0 | 30.0 | 36.0 |
| TL-5 (a) | 42 | 160.0 | 41.0 | 80.0 | 10.0 | 40.0 | 35.0 | 42.0 |
| TL-5 (b) | greater than 42 | 262.0 | 75.0 | 160.0 | 10.0 | 40.0 | 43.0 | 42.0 |
| TL 6 | | 175.0 | 58.0 | 80.0 | 8.0 | 40.0 | 56.0 | 90.0 |

References:
- TL-1 and TL-2 Design Forces are from AASHTO LRFD Section 13 Table A13.2-1
- TL-3 Design Forces are from research conducted under NCHRP Project 20-07 Task 395
- TL-4 (a), TL-4 (b), TL-5 (a), and TL-5 (b) Design Forces are from research conducted under NCHRP Project 22-20(2)

| | |
|---|---|
| $TL := 4$ | *Test level* |
| $F_t := 68\ kip$ | *Transverse impact force* |
| $L_t := 4\ ft$ | *Longitudinal length of distribution of impact force* |
| $H_e := 25\ in$ | *Height of equivalent transverses load* |

$H_{min} := 36\ in$ *Minimum height of a MASH TL-4 barrier*

$H_w = 36\ in$ *Height of concrete barrier*

**(2) Stability Criteria:**

$H_{min} = 36\ in$ *Minimum height of a MASH TL-4 barrier*

$H_w = 36\ in$ *Height of concrete barrier measured from the top of the roadway surface/asphalt overlay*

$$Minimum_Height_of_Barrier_Check := \begin{cases} \text{if } H_w \geq H_{min} \\ \quad \text{“OK”} \\ \text{else} \\ \quad \text{“Not OK”} \end{cases}$$

$Minimum_Height_of_Barrier_Check = \text{“OK”}$

**(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification:**

**(3a) Bending Capacity of the Barrier about the Longitudinal Axis at Midspan:** $M_{cmid}$ **(k-ft/ft)**

For parapet vertical reinforcement:

$b_c := 12\ in$ *Unit width of wall (take as 1 ft per AASHTO Section 13 procedure)*

$A_{vpl.mid} = 0.2\ in^2$ *Area of one parapet vertical reinforcement leg at midspan*

$S_{vp.mid} = 12\ in$ *Spacing of parapet vertical reinforcement at midspan*

$$A_{vp.mid} := \left(\frac{b_c}{S_{vp.mid}}\right) \cdot A_{vpl.mid} = 0.2\ in^2$$

*Total area of parapet vertical reinforcement per unit length at midspan*

$d_{cp.mid} = 15.25\ in$ *Average extreme distance of parapet vertical reinforcement at midspan*

$$a_{cp.mid} := \frac{A_{vp.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.294\ in$$ *Depth of Whitney stress block*

$$M_{cp.mid} := \frac{\left(A_{vp.mid} \cdot f_y \cdot \left(d_{cp.mid} - \frac{a_{cp.mid}}{2}\right)\right)}{b_c} = 15.103 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the parapet vertical reinforcement specified in Article A 13.3.1 (k-ft/ft)*

For deck anchorage reinforcement:

$b_c = 12 \ in$ *Unit width of wall (take as 1 ft per AASHTO Section 13 procedure)*

$A_{val.mid} = 0.2 \ in^2$ *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} = 6 \ in$ *Spacing of deck anchorage vertical reinforcement at midspan*

$$A_{va.mid} := \left(\frac{b_c}{S_{va.mid}}\right) \cdot A_{val.mid} = 0.4 \ in^2$$

*Total area of deck anchorage vertical reinforcement per unit length at midspan*

$d_{ca.mid} = 22.25 \ in$ *Extreme distance of tension deck anchorage vertical reinforcement at midspan*

$$a_{ca.mid} := \frac{A_{va.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588 \ in$$ *Depth of Whitney stress block*

$$M_{ca.mid} := \frac{\left(A_{va.mid} \cdot f_y \cdot \left(d_{ca.mid} - \frac{a_{ca.mid}}{2}\right)\right)}{b_c} = 43.912 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

$$M_{c.mid} := min\left(M_{cp.mid}, M_{ca.mid}\right) = 15.103 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering the critical reinforcement*

**(3b) Bending Capacity of the Barrier about the Longitudinal Axis at Joints/Ends:** $M_{ccnd}$ **(k-ft/ft)**

For parapet vertical reinforcement:

$A_{vpl.end} = 0.2\ in^2$ *Area of one parapet vertical reinforcement leg at joints/ends*

$S_{vp.end} = 6\ in$ *Spacing of parapet vertical reinforcement at joints/ends*

$A_{vp.end} := \left(\frac{b_c}{S_{vp.end}}\right) \cdot A_{vpl.end} = 0.4\ in^2$ *Total area of deck anchorage vertical reinforcement per unit length at midspan*

$d_{cp.end} = 15.25\ in$ *Average extreme distance of parapet vertical reinforcement at joints/ends (at barrier mid-height)*

$a_{cp.end} := \frac{A_{vp.end} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588\ in$ *Depth of Whitney stress block*

$$M_{cp.end} := \frac{\left(A_{vp.end} \cdot f_y \cdot \left(d_{cp.end} - \frac{a_{cp.end}}{2}\right)\right)}{b_c} = 29.912\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at Joints/ Ends when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

For deck anchorage reinforcement:

$A_{val.end} = 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at joints/ends*

$S_{va.end} = 6\ in$ *Spacing of deck anchorage vertical reinforcement at joints/ends*

$A_{va.end} := \left(\frac{b_c}{S_{va.end}}\right) \cdot A_{val.end} = 0.4\ in^2$ *Total area of deck anchorage vertical reinforcement per unit length at joints/ends*

$d_{ca.end} = 22.25\ in$ *Extreme distance of tension deck anchorage vertical reinforcement at joints/ends*

$$a_{ca.end} := \frac{A_{va.end} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588\ in$$

*Depth of Whitney stress block*

$$M_{ca.end} := \frac{\left(A_{va.end} \cdot f_y \cdot \left(d_{ca.end} - \frac{a_{ca.end}}{2}\right)\right)}{b_c} = 43.912\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at Joints/ Ends when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

$$M_{c.end} := min\left(M_{cp.end}, M_{ca.end}\right) = 29.912\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at joints/ends when considering the critical reinforcement*

**(3c) Bending Capacity of the Barrier about the Vertical Axis:** $M_w$

$d_w = 14.75\ in$ *Effective depth of longitudinal reinforcement bars*

$A_w = 1\ in^2$ *Area of longitudinal reinforcement bars in tension*

$H_w = 36\ in$ *Extreme distance of tension longitudinal reinforcement of barrier*

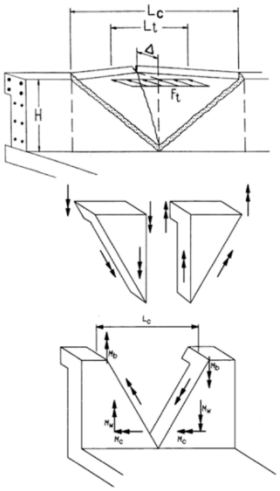
$$a_w := \frac{A_w \cdot f_y}{0.85 \cdot f'_c \cdot H_w} = 0.49\ in$$

*Depth of Whitney stress block*

$$M_w := A_w \cdot f_y \cdot \left(d_w - \frac{a_w}{2}\right) = 72.525\ kip \cdot ft$$

*Flexural resistance of the barrier about the vertical axis specified in Article A 13.3.1*

**(3d) Ultimate Resistance of the Wall at Midspan: $R_{w.mid}$**




$H_w = 36\ in$ — *Height of barrier*

$M_B := 0\ kip \cdot ft$ — *No additional beam strength*

$M_{c.mid} = 15.103\ \frac{kip \cdot ft}{ft}$ — *Flexural resistance about the long. axis at midspan*

$M_w = 72.525\ kip \cdot ft$ — *Flexural resistance about the vert. axis*

$L_t = 4\ ft$ — *Long. length of distribution of impact force*

*Figure 2. Yield Line Analysis of Concrete Parapet Walls for Impact within Wall Segment (figure taken from AASHTO).*

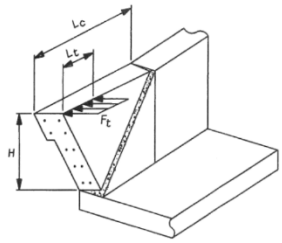
$$L_{c.mid} := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{8 \cdot H_w \cdot (M_B + M_w)}{M_{c.mid}}} = 12.92\ ft$$

*AASHTO Equation A13.3.1-2*

$$R_{w.mid} := \left(\frac{2}{2 \cdot L_{c.mid} - L_t}\right) \cdot \left(8 \cdot M_B + 8 \cdot M_w + \frac{M_{c.mid} \cdot (L_{c.mid})^2}{H_w}\right) \cdot \frac{H_w}{H_e} = 187.326\ kip$$

*AASHTO Equation A13.3.1-1*

**(3e) Ultimate Resistance of the Wall at Joints/Ends: $R_{w.end}$**




$H_w = 36\ in$ — *Height of barrier*

$M_B := 0\ kip \cdot ft$ — *No additional beam strength*

$M_{c.end} = 29.912\ \frac{kip \cdot ft}{ft}$ — *Flexural resistance about the long. axis at joints/ends*

$M_w = 72.525\ kip \cdot ft$ — *Flexural resistance about the vert. axis*

$L_t = 4\ ft$ — *Long. length of distribution of impact force*

*Figure 3. Yield Line Analysis of Concrete Parapet Walls for Impact near End of Wall Segment (figure taken from AASHTO)*

$$L_{c.end} := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{H_w \cdot (M_B + M_w)}{M_{c.end}}} = 5.358\ ft$$ *AASHTO Equation A13.3.1-4*

$$R_{w.end} := \left(\frac{2}{2 \cdot L_{c.end} - L_t}\right) \cdot \left(M_B + M_w + \frac{M_{c.end} \cdot (L_{c.end})^2}{H_w}\right) \cdot \frac{H_w}{H_e} = 153.847\ kip$$

*AASHTO Equation A13.3.1-3*

**(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification - Summary of Results:**

$H_w = 36\ in$ *Height of the concrete barrier measured from the top of the roadway surface*

$H_e = 25\ in$ *Height of the transverse impact force, Ft*

$F_t = 68\ kip$ *Transverses impact force located at He*

$R_{w.mid} = 187.326\ kip$ *Ultimate resistance of the wall at midspan*

$R_{w.end} = 153.847\ kip$ *Ultimate resistance of the wall at joints/ends*

Structural_Capacity_of_Barrier_at_Midspan_Check := if $R_{w.mid} > F_t$ "OK" else "Not OK"

Structural_Capacity_of_Barrier_at_Midspan_Check = "OK"

Structural_Capacity_of_Barrier_at_Ends_Check := if $R_{w.end} > F_t$ "OK" else "Not OK"

Structural_Capacity_of_Barrier_at_Ends_Check = "OK"

**(4) Punching Shear Capacity of the Barrier:**

$\lambda := 1.0$ *Concrete weight modification factor*

$d_c := 12.53\ in$ *Depth of shear zone at height of equivalent transverse load*

$T_{w.top} := 10\ in$ *Top width of barrier*

$h_c := 11\ in$ *Width of shear zone*

$L_t = 4\ ft$ *Distribution width of transverse impact force*

$f'_c = 4\ ksi$ *Concrete barrier compressive strength*

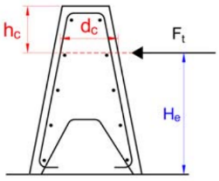



*Figure 4. Punching Shear Variables*

$$d_f := \frac{T_{w.top} + d_c}{2} = 11.265\ in$$ *Median depth of shear zone*

$$b_{o.int} := (L_t + d_c) + 2 \cdot \left(h_c + \frac{d_c}{2}\right) = 95.06\ in$$

*Median perimeter of interior critical section (AASHTO 5.8.4.3.4)*

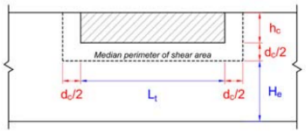



*Figure 5. Punching Shear at Interior Segment*

$$V_{c.int} := 0.125 \cdot \lambda \cdot \left(\sqrt{\frac{f'_c}{1000\ psi}} \cdot ksi\right) \cdot b_{o.int} \cdot d_f = 267.713\ kip$$

*Interior punching shear capacity (AASHTO Eq.5.8.4.3.4-3)*

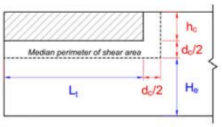



*Figure 6. Punching Shear at Exterior Segment*

$$b_{o.end} := \left(L_t + \frac{d_c}{2}\right) + \left(h_c + \frac{d_c}{2}\right) = 71.53\ in$$

*Median perimeter of exterior critical section (AASHTO 5.8.4.3.4)*

$$V_{c.end} := 0.125 \cdot \lambda \cdot \left(\sqrt{\frac{f'_c}{1000\ psi}} \cdot ksi\right) \cdot b_{o.end} \cdot d_f = 201.446\ kip$$

*Exterior punching shear capacity (AASHTO Eq.5.8.4.3.4-3)*

$V_c := min\left(V_{c.int}, V_{c.end}\right) = 201.446\ kip$ *Critical punching shear capacity*

$F_t = 68\ kip$ *Transverse impact force*

Punching_Shear_Capacity_of_Barrier_Check := if $V_c > F_t$
"OK"
else
"Not OK"

Punching_Shear_Capacity_of_Barrier_Check = "OK"

**(5) Deck Moment Capacity:**

**(5a) Deck Moment Demand:**

- The moment demand on the deck due to the TL-4 impact loading was determined using RISA-3D structral analysis.

- A solid model of the 36" barrier, as shown in Figure 5, was developed to determine the barrier loads to the deck. This model was generated with 6" wide elements in the longitudinal direction to represent the spacing of the barrier vertical reinforcements.

- The deck was modeled using meshed plate elements (8' x 50' with 6" x 6" plate elements). The reactions from the barrier to the deck were applied at the corresponding locations as shown in Figure 6.

* Detailed discussion will be provided in the final report.

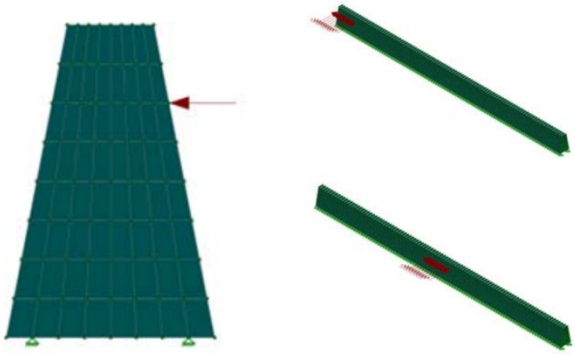


*Figure 7. Barrier Solid Model*

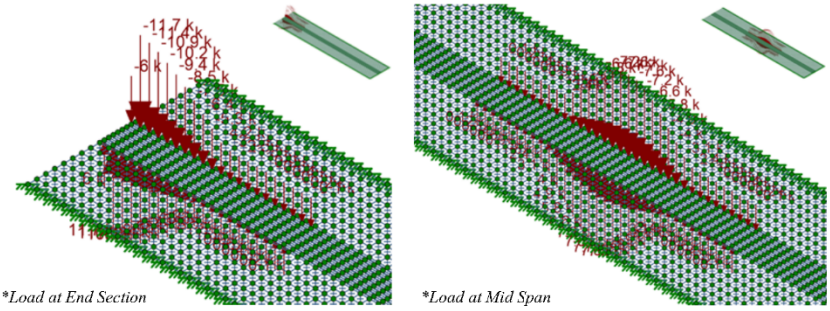
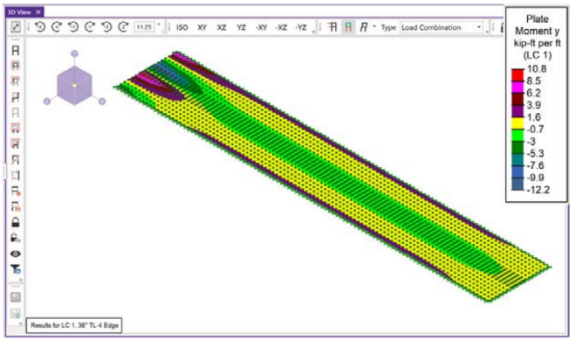


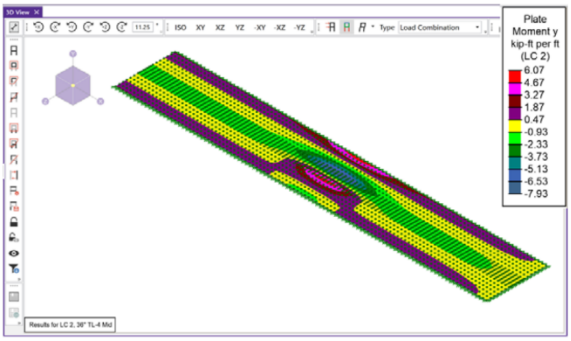

*Figure 8. Deck Plate Model with Barrier Reactions*

Deck moment demand from RISA 3-D analysis:

Max. moment demand at end-section: $M_{u.end} := 12.2\ kip \cdot ft$




Max. moment demand at mid-span: $M_{u.mid} := 7.93\ kip \cdot ft$




**(5b) Deck Nominal Moment Capacity:**

$b_{c.unit} := 12\ in$ — *Unit width of deck*

$t_s = 8.5\ in$ — *Depth of deck*

$d_{s.bot} = 6.688\ in$ — *Extreme distance of deck flexural reinforcement at top*

$A_{s.bot} = 0.31\ in^2$ — *Section area of deck flexural reinforcement at top*

$S_{s.bot} = 6\ in$ — *Spacing of deck flexural reinforcement at top*

$A_{s.unit} := \frac{A_{s.bot}}{S_{s.bot}} \cdot b_{c.unit} = 0.62\ in^2$ *Unit area of deck flexural reinforcement at end section*

$a_s := \frac{A_{s.unit} \cdot f_y}{0.85 \cdot f'_c \cdot b_{c.unit}} = 0.912\ in$ *Depth of Whitney stress block at end section*

$M_{n.s} := A_{s.unit} \cdot f_y \cdot \left(d_{s.bot} - 0.5 \cdot a_s\right) = 19.318\ kip \cdot ft$ *Nominal moment capacity of deck*

**(5c) Deck Moment Capacity with Coincident Tensile Forces (AASHTO A 13.4.2):**

- Check at critical location: end-section

$L_{c.end} = 5.358\ ft$ *Distribution length of yield line mechanism*

$R_{w.end} = 153.847\ kip$ *Nominal resistance of barrier to transverse load*

$H_w = 36\ in$ *Height of barrier*

$T := \frac{R_{w.end}}{L_{c.end} + 2 \cdot H_w} = 13.546\ \frac{kip}{ft}$ *Coincident tensile force from vehicle impact (AASHTO Eq. A 13.4.2.-1)*

$T_a := A_{s.unit} \cdot f_y = 37.2\ kip$ *Tensile load provided by deck flexural reinforcement*

$C := T_a - T \cdot ft = 23.654\ kip$ *Resultant compression force in deck section*

$a_c := \frac{C}{0.85 \cdot f'_c \cdot b_c} = 0.58\ in$ *Depth of Whitney stress block for compression force*

$M_{n.t} := T_a \cdot \left(d_{s.bot} - \frac{a_c}{2}\right) - T \cdot ft \cdot \left(\frac{d_{s.bot}}{2} - \frac{a_c}{2}\right) = 16.385\ kip \cdot ft$

*Moment capacity of deck with coincident tensile force*

$M_{u.deck} := \max\left(M_{u.end}, M_{u.mid}\right) = 12.2\ kip \cdot ft$ *Maximum moment demand*

$$\text{Moment_Capacity_of_Deck_Check} := \begin{cases} \text{if } M_{n.t} > M_{u.deck} \\ \quad \text{“OK”} \\ \text{else} \\ \quad \text{“Not OK”} \end{cases}$$

$$\text{Moment_Capacity_of_Deck_Check} = \text{“OK”}$$

**(6) Reinforcement Development Length:**

$d_{b.\#4} := 0.5\ in$ ; $d_{b.\#5} := 0.625\ in$ *Bar diameter*

$$l_{db.\#4} := 2.4 \cdot d_{b.\#4} \cdot \frac{f_y}{\sqrt{f'_c \cdot \frac{1}{1000\ psi}} \cdot ksi} = 3\ ft$$

$$l_{db.\#5} := 2.4 \cdot d_{b.\#5} \cdot \frac{f_y}{\sqrt{f'_c \cdot \frac{1}{1000\ psi}} \cdot ksi} = 3.75\ ft$$

*Basic development length (AASHTO Eq. 5.10.8.2.1a-2)*

$\lambda := 1.0$ *Concrete weight modification factor*

$\lambda_{rl} := 1.0$ *Reinforcement location factor (AASHTO 5.10.8.2.1b)*

$\lambda_{cf} := 1.0$ *Coating factor (AASHTO 5.10.8.2.1b)*

$\lambda_{er} := 1.0$ *Excess reinforcement factor (AASHTO 5.10.8.2.1c)*

$k_{tr} := 0$ *Transverse reinforcement index (conservatively taken as 0 as per AASHTO C5.10.8.2.1c)*

$c_{b.\#4} := 1.75\ in$ ; $c_{b.\#5} := 1.8125\ in$ *Smaller of reinforcement edge distance and one-half of spacing*

$$\lambda_{rc.\#4} := \max\left(\frac{d_{b.\#4}}{c_{b.\#4} + k_{tr}}, 0.4\right) = 0.4 \quad ; \quad \lambda_{rc.\#5} := \max\left(\frac{d_{b.\#5}}{c_{b.\#5} + k_{tr}}, 0.4\right) = 0.4$$

*Reinforcement confinement factor , $0.4 < \lambda_{rc} < 1.0$ (AASHTO 5.10.8.2.1c)*

$$l_{d.\#4} := l_{db.\#4} \cdot \left( \frac{\lambda_{rl} \cdot \lambda_{cf} \cdot \lambda_{rc.\#4} \cdot \lambda_{er}}{\lambda} \right) = 14.4 \ in$$

$$l_{d.\#5} := l_{db.\#5} \cdot \left( \frac{\lambda_{rl} \cdot \lambda_{cf} \cdot \lambda_{rc.\#5} \cdot \lambda_{er}}{\lambda} \right) = 18 \ in$$

*Development lengths needed (mod.fied tension development length, AASHTO Eq. 5.10.8.2.1a-1)*

$l_{anc} := 16.4 \ in$ *Anchorage reinforcement development lengths provided (#4 bar, green)*

$l_{s.top} := 60 \ in$ *Deck flexural reinforcement development lengths provided (#5 bar)*

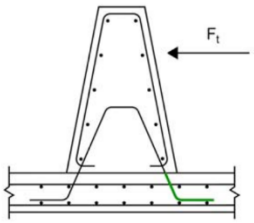



*Figure 9. Reinforcement Development Length*

$$\text{Deck_Reinforcement_Development_Length_Check} := \begin{cases} \text{if } l_{anc} > l_{d.\#4} \ \| \ l_{s.top} > l_{d.\#5} \\ \quad \| \ \text{“OK”} \\ \text{else} \\ \quad \| \ \text{“Not OK”} \end{cases}$$

Deck_Reinforcement_Development_Length_Check = “OK”

**(7) Analysis Results Overview:**

Minimum_Height_of_Barrier_Check = “OK”

Structural_Capacity_of_Barrier_at_Midspan_Check = “OK”

Structural_Capacity_of_Barrier_at_Ends_Check = “OK”

Punching_Shear_Capacity_of_Barrier_Check = “OK”

Moment_Capacity_of_Deck_Check = “OK”

Deck_Reinforcement_Development_Length_Check = “OK”

**(8) Summary of Barrier Design:**

1. Use Vertical Barrier Stirrup #4 @ 6" O.C. for 10'-0" at Barrier End Section

2. Use Vertical Barrier Stirrup #4 @ 12" O.C. out at Mid-Section (greater than 10'-0" from End Sections)

3. All other details as shown on Section and Elevation Views as provided herein for the 36" Barrier as analyzed herein are acceptable for MASH TL-4 Impact conditions.

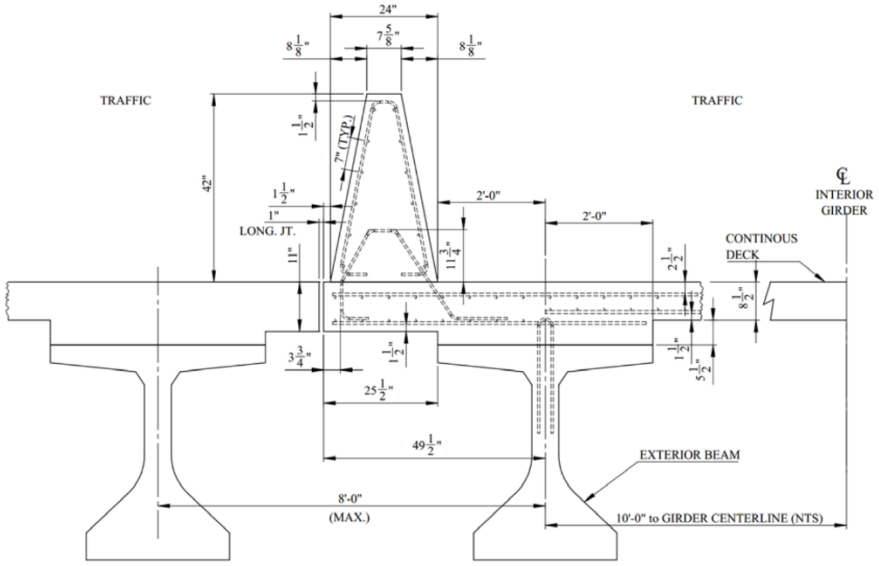
**SUBJECT:** 42" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Outside Barrier (left side)

**Overview:**

These calcualtions evaluate the strength of the given barrier design for MASH TL-4 impact load condtions.

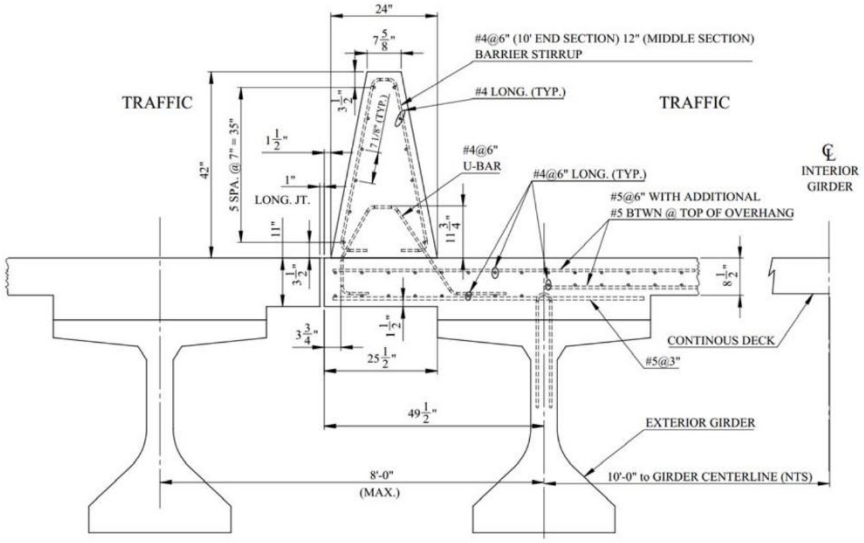
- 42" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from the Barrier Left Side in the Section View below.

**Design Details:**

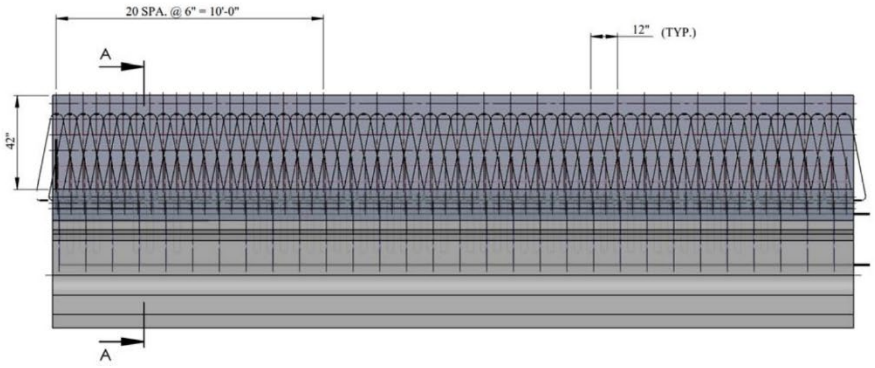



**Section View (a)**

**SUBJECT:** 42" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Outside Barrier (left side)



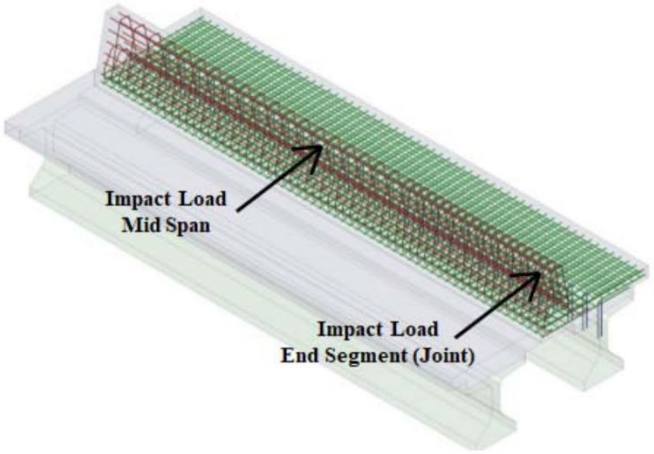

**Section View (b)**




**Elevation**

Texas A&M Transportation Institute

**SUBJECT:** 42" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Outside Barrier (left side)




**Iso View**

Texas A&M Transportation Institute

**SUBJECT:** 42" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Outside Barrier (left side)

**(1) Define Inputs:**

**(1a) General Inputs:**

$f'_c := 4000\ psi$ — *Compressive strength of concrete*

$f_y := 60\ ksi$ — *Yield strength reinforcing steel*

$E_s := 29000\ ksi$ — *Modulus of elasticity of steel*

$H_w := 42\ in$ — *Height of barrier*

$T_{w.top} := 7.625\ in$ — *Top width of barrier*

$T_{w.bot} := 24\ in$ — *Bottom width of barrier*

$t_s := 11\ in$ — *Depth of deck*

$d_{\#4} := 0.5\ in$ ; $A_{\#4} := 0.2\ in^2$ — *Diameter and section area of #4 bar*

$d_{\#5} := 0.625\ in$ ; $A_{\#5} := 0.31\ in^2$ — *Diameter and section area of #5 bar*

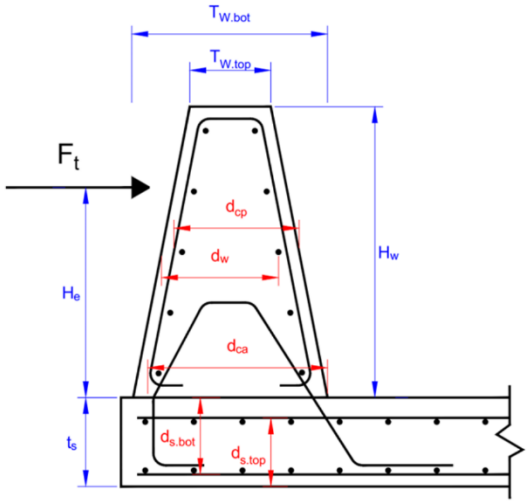



*Figure 1. Sketch of Concrete Wall/Parapet Showing Input Variable*

**(1b) Concrete Barrier Inputs:**

$t_{b.cov} := 1.5\ in$ *Concrete clear cover of barrier*

Barrier vertical reinforcement inputs (#4 bars):

$A_{vpl.mid} := 0.2\ in^2$ *Area of one barrier vertical reinforcement leg at midspan*

$S_{vp.mid} := 12\ in$ *Spacing of barrier vertical reinforcement at midspan*

$d_{cp.mid} := 14.0625\ in$ *Average extreme distance of barrier vertical reinforcement at midspan*

$A_{vpl.end} := 0.2\ in^2$ *Area of one barrier vertical reinforcement leg at joints/ends*

$S_{vp.end} := 6\ in$ *Spacing of barrier vertical reinforcement at joints/ends*

$d_{cp.end} := 14.0625\ in$ *Average extreme distance of barrier vertical reinforcement at joints/ends*

Deck anchorage reinforcement inputs (#4 bars):

$A_{val.mid} := 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} := 6\ in$ *Spacing of deck anchorage vertical reinforcement at midspan*

$d_{ca.mid} := 22.25\ in$ *Extreme distance of tension deck anchorage reinforcement at midspan*

$A_{val.end} := 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at joints/ends*

$S_{va.end} := 6\ in$ *Spacing of deck anchorage vertical reinforcement at joints/ends*

$d_{ca.end} := 22.25\ in$ *Extreme distance of tension deck anchorage reinforcement at joints/ends*

Barrier Longitudinal reinforcement inputs (#4 bars):

$A_w := 0.2 \cdot 6\ in^2 = 1.2\ in^2$ *Area of longitudinal reinforcement bars in tension*

$d_w := 13.5625\ in$ *Average extreme distance of tension longitudinal reinforcement*

**(1c) Concrete Deck Inputs:**

$t_{s.cov.bot} := 1.5\ in$ *Concrete clear cover of deck at bottom*

$d_{s.bot} := 9.1875\ in$ *Extreme distance of deck flexural reinforcement at bottom*

$A_{s.bot} := 0.31\ in^2$ *Section area of deck flexural reinforcement at bottom (single bar)*

$S_{s.bot} := 3\ in$ *Spacing of deck flexural reinforcement at bottom*

$t_{s.cov.top} := 2.5\ in$ *Concrete clear cover of deck at top*

$d_{s.top} := 8.1875\ in$ *Extreme distance of deck flexural reinforcement at top*

$A_{s.top} := 0.31\ in^2$ *Section area of deck flexural reinforcement at top (single bar)*

$S_{s.top} := 3\ in$ *Spacing of deck flexural reinforcement at top*

**(1d) Design Force Inputs:**

**Design Forces for Traffic Railings**

| Test Level | Rail Height (in.) | $F_t$ (kip) | $F_L$ (kip) | $F_T$ (kip) | $L_t/L_L$ (ft) | $L_T$ (ft) | $H_e$ (in) | $H_{min}$ (in) |
|---|---|---|---|---|---|---|---|---|
| TL-1 | 18 or above | 13.5 | 4.5 | 4.5 | 4.0 | 18.0 | 18.0 | 18.0 |
| TL-2 | 18 or above | 27.0 | 9.0 | 4.5 | 4.0 | 18.0 | 20.0 | 18.0 |
| TL-3 | 29 or above | 71.0 | 18.0 | 4.5 | 4.0 | 18.0 | 19.0 | 29.0 |
| TL-4 (a) | 36 | 68.0 | 22.0 | 38.0 | 4.0 | 18.0 | 25.0 | 36.0 |
| TL-4 (b) | between 36 and 42 | 80.0 | 27.0 | 22.0 | 5.0 | 18.0 | 30.0 | 36.0 |
| TL-5 (a) | 42 | 160.0 | 41.0 | 80.0 | 10.0 | 40.0 | 35.0 | 42.0 |
| TL-5 (b) | greater than 42 | 262.0 | 75.0 | 160.0 | 10.0 | 40.0 | 43.0 | 42.0 |
| TL 6 | | 175.0 | 58.0 | 80.0 | 8.0 | 40.0 | 56.0 | 90.0 |

References:
- TL-1 and TL-2 Design Forces are from AASHTO LRFD Section 13 Table A13.2-1
- TL-3 Design Forces are from research conducted under NCHRP Project 20-07 Task 395
- TL-4 (a), TL-4 (b), TL-5 (a), and TL-5 (b) Design Forces are from research conducted under NCHRP Project 22-20(2)

$TL := 4$ *Test level*

$F_t := 80\ kip$ *Transverse impact force*

$L_t := 5\ ft$ *Longitudinal length of distribution of impact force*

$H_e := 30\ in$ *Height of equivalent transverses load*

$H_{min} := 36\ in$ *Minimum height of a MASH TL-4 barrier*

$H_w = 42\ in$ *Height of concrete barrier*

**(2) Stability Criteria:**

$H_{min} = 36\ in$ *Minimum height of a MASH TL-4 barrier*

$H_w = 42\ in$ *Height of concrete barrier measured from the top of the roadway surface/asphalt overlay*

$$Minimum_Height_of_Barrier_Check := \begin{cases} \text{if } H_w \geq H_{min} \\ \quad \text{“OK”} \\ \text{else} \\ \quad \text{“Not OK”} \end{cases}$$

$Minimum_Height_of_Barrier_Check = \text{“OK”}$

**(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification:**

**(3a) Bending Capacity of the Barrier about the Longitudinal Axis at Midspan: $M_{cmid}$ (k-ft/ft)**

For parapet vertical reinforcement:

$b_c := 12\ in$ *Unit width of wall (take as 1 ft per AASHTO Section 13 procedure)*

$A_{vpl.mid} = 0.2\ in^2$ *Area of one parapet vertical reinforcement leg at midspan*

$S_{vp.mid} = 12\ in$ *Spacing of parapet vertical reinforcement at midspan*

$$A_{vp.mid} := \left(\frac{b_c}{S_{vp.mid}}\right) \cdot A_{vpl.mid} = 0.2\ in^2$$

*Total area of parapet vertical reinforcement per unit length at midspan*

$d_{cp.mid} = 14.063\ in$ *Average extreme distance of parapet vertical reinforcement at midspan*

$a_{cp.mid} := \frac{A_{vp.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.294\ in$ *Depth of Whitney stress block*

$$M_{cp.mid} := \frac{\left(A_{vp.mid} \cdot f_y \cdot \left(d_{cp.mid} - \frac{a_{cp.mid}}{2}\right)\right)}{b_c} = 13.915 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the parapet vertical reinforcement specified in Article A 13.3.1 (k-ft/ft)*

For deck anchorage reinforcement:

$b_c = 12 \ in$ *Unit width of wall (take as 1 ft per AASHTO Section 13 procedure)*

$A_{val.mid} = 0.2 \ in^2$ *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} = 6 \ in$ *Spacing of deck anchorage vertical reinforcement at midspan*

$$A_{va.mid} := \left(\frac{b_c}{S_{va.mid}}\right) \cdot A_{val.mid} = 0.4 \ in^2$$

*Total area of deck anchorage vertical reinforcement per unit length at midspan*

$d_{ca.mid} = 22.25 \ in$ *Extreme distance of tension deck anchorage vertical reinforcement at midspan*

$$a_{ca.mid} := \frac{A_{va.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588 \ in$$ *Depth of Whitney stress block*

$$M_{ca.mid} := \frac{\left(A_{va.mid} \cdot f_y \cdot \left(d_{ca.mid} - \frac{a_{ca.mid}}{2}\right)\right)}{b_c} = 43.912 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

$$M_{c.mid} := min\left(M_{cp.mid}, M_{ca.mid}\right) = 13.915 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering the critical reinforcement*

**(3b) Bending Capacity of the Barrier about the Longitudinal Axis at Joints/Ends:** $M_{ccnd}$ **(k-ft/ft)**

For parapet vertical reinforcement:

$A_{vpl.end} = 0.2\ in^2$ *Area of one parapet vertical reinforcement leg at joints/ends*

$S_{vp.end} = 6\ in$ *Spacing of parapet vertical reinforcement at joints/ends*

$A_{vp.end} := \left(\frac{b_c}{S_{vp.end}}\right) \cdot A_{vpl.end} = 0.4\ in^2$ *Total area of deck anchorage vertical reinforcement per unit length at midspan*

$d_{cp.end} = 14.063\ in$ *Average extreme distance of parapet vertical reinforcement at joints/ends (at barrier mid-height)*

$a_{cp.end} := \frac{A_{vp.end} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588\ in$ *Depth of Whitney stress block*

$$M_{cp.end} := \frac{\left(A_{vp.end} \cdot f_y \cdot \left(d_{cp.end} - \frac{a_{cp.end}}{2}\right)\right)}{b_c} = 27.537\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at Joints/ Ends when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

For deck anchorage reinforcement:

$A_{val.end} = 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at joints/ends*

$S_{va.end} = 6\ in$ *Spacing of deck anchorage vertical reinforcement at joints/ends*

$A_{va.end} := \left(\frac{b_c}{S_{va.end}}\right) \cdot A_{val.end} = 0.4\ in^2$ *Total area of deck anchorage vertical reinforcement per unit length at joints/ends*

$d_{ca.end} = 22.25\ in$ *Extreme distance of tension deck anchorage vertical reinforcement at joints/ends*

$$a_{ca.end} := \frac{A_{va.end} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588\ in$$

*Depth of Whitney stress block*

$$M_{ca.end} := \frac{\left(A_{va.end} \cdot f_y \cdot \left(d_{ca.end} - \frac{a_{ca.end}}{2}\right)\right)}{b_c} = 43.912\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at Joints/ Ends when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

$$M_{c.end} := min\left(M_{cp.end}, M_{ca.end}\right) = 27.537\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at joints/ends when considering the critical reinforcement*

**(3c) Bending Capacity of the Barrier about the Vertical Axis:** $M_w$

$d_w = 13.563\ in$ *Effective depth of longitudinal reinforcement bars*

$A_w = 1.2\ in^2$ *Area of longitudinal reinforcement bars in tension*

$H_w = 42\ in$ *Extreme distance of tension longitudinal reinforcement of barrier*

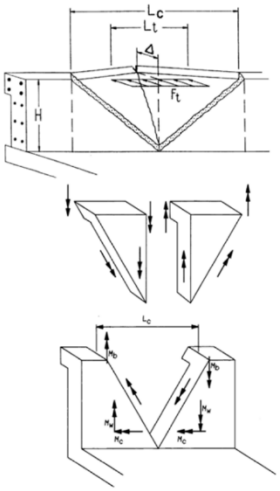
$$a_w := \frac{A_w \cdot f_y}{0.85 \cdot f'_c \cdot H_w} = 0.504\ in$$

*Depth of Whitney stress block*

$$M_w := A_w \cdot f_y \cdot \left(d_w - \frac{a_w}{2}\right) = 79.862\ kip \cdot ft$$

*Flexural resistance of the barrier about the vertical axis specified in Article A 13.3.1*

**(3d) Ultimate Resistance of the Wall at Midspan: $R_{w.mid}$**




$H_w = 42\ in$ — *Height of barrier*

$M_B := 0\ kip \cdot ft$ — *No additional beam strength*

$M_{c.mid} = 13.915\ \frac{kip \cdot ft}{ft}$ — *Flexural resistance about the long. axis at midspan*

$M_w = 79.862\ kip \cdot ft$ — *Flexural resistance about the vert. axis*

$L_t = 5\ ft$ — *Long. length of distribution of impact force*

*Figure 2. Yield Line Analysis of Concrete Parapet Walls for Impact within Wall Segment (figure taken from AASHTO).*

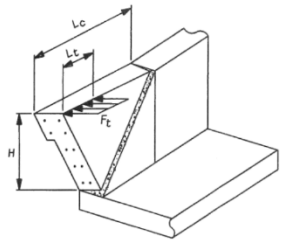
$$L_{c.mid} := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{8 \cdot H_w \cdot (M_B + M_w)}{M_{c.mid}}} = 15.421\ ft$$

*AASHTO Equation A13.3.1-2*

$$R_{w.mid} := \left(\frac{2}{2 \cdot L_{c.mid} - L_t}\right) \cdot \left(8 \cdot M_B + 8 \cdot M_w + \frac{M_{c.mid} \cdot (L_{c.mid})^2}{H_w}\right) \cdot \frac{H_w}{H_e} = 171.669\ kip$$

*AASHTO Equation A13.3.1-1*

**(3e) Ultimate Resistance of the Wall at Joints/Ends: $R_{w.end}$**




$H_w = 42\ in$ — *Height of barrier*

$M_B := 0\ kip \cdot ft$ — *No additional beam strength*

$M_{c.end} = 27.537\ \frac{kip \cdot ft}{ft}$ — *Flexural resistance about the long. axis at joints/ends*

$M_w = 79.862\ kip \cdot ft$ — *Flexural resistance about the vert. axis*

$L_t = 5\ ft$ — *Long. length of distribution of impact force*

*Figure 3. Yield Line Analysis of Concrete Parapet Walls for Impact near End of Wall Segment (figure taken from AASHTO)*

$$L_{c.end} := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{H_w \cdot (M_B + M_w)}{M_{c.end}}} = 6.55\ ft$$ *AASHTO Equation A13.3.1-4*

$$R_{w.end} := \left(\frac{2}{2 \cdot L_{c.end} - L_t}\right) \cdot \left(M_B + M_w + \frac{M_{c.end} \cdot (L_{c.end})^2}{H_w}\right) \cdot \frac{H_w}{H_e} = 144.288\ kip$$

*AASHTO Equation A13.3.1-3*

**(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification - Summary of Results:**

$H_w = 42\ in$ *Height of the concrete barrier measured from the top of the roadway surface*

$H_e = 30\ in$ *Height of the transverse impact force, Ft*

$F_t = 80\ kip$ *Transverses impact force located at He*

$R_{w.mid} = 171.669\ kip$ *Ultimate resistance of the wall at midspan*

$R_{w.end} = 144.288\ kip$ *Ultimate resistance of the wall at joints/ends*

$$\text{Structural_Capacity_of_Barrier_at_Midspan_Check} := \begin{cases} \text{if } R_{w.mid} > F_t \\ \quad \text{“OK”} \\ \text{else} \\ \quad \text{“Not OK”} \end{cases}$$

Structural_Capacity_of_Barrier_at_Midspan_Check = “OK”

$$\text{Structural_Capacity_of_Barrier_at_Ends_Check} := \begin{cases} \text{if } R_{w.end} > F_t \\ \quad \text{“OK”} \\ \text{else} \\ \quad \text{“Not OK”} \end{cases}$$

Structural_Capacity_of_Barrier_at_Ends_Check = “OK”

**(4) Punching Shear Capacity of the Barrier:**

$\lambda := 1.0$ *Concrete weight modification factor*

$d_c := 10.55\ in$ *Depth of shear zone at height of equivalent transverse load*

$T_{w.top} := 7.625\ in$ *Top width of barrier*

$h_c := 11\ in$ *Width of shear zone*

$L_t = 5\ ft$ *Distribution width of transverse impact force*

$f'_c = 4\ ksi$ *Concrete barrier compressive strength*

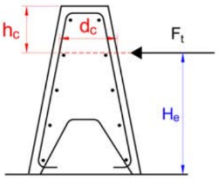



*Figure 4. Punching Shear Variables*

$$d_f := \frac{T_{w.top} + d_c}{2} = 9.088\ in$$ *Median depth of shear zone*

$$b_{o.int} := (L_t + d_c) + 2 \cdot \left(h_c + \frac{d_c}{2}\right) = 103.1\ in$$

*Median perimeter of interior critical section (AASHTO 5.8.4.3.4)*

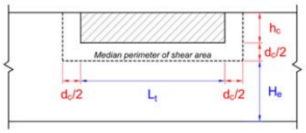



*Figure 5. Punching Shear at Interior Segment*

$$V_{c.int} := 0.125 \cdot \lambda \cdot \left(\sqrt{\frac{f'_c}{1000\ psi}} \cdot ksi\right) \cdot b_{o.int} \cdot d_f = 234.23\ kip$$

*Interior punching shear capacity (AASHTO Eq.5.8.4.3.4-3)*

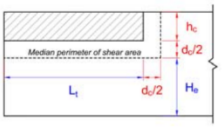



*Figure 6. Punching Shear at Exterior Segment*

$$b_{o.end} := \left(L_t + \frac{d_c}{2}\right) + \left(h_c + \frac{d_c}{2}\right) = 81.55\ in$$

*Median perimeter of exterior critical section (AASHTO 5.8.4.3.4)*

$$V_{c.end} := 0.125 \cdot \lambda \cdot \left(\sqrt{\frac{f'_c}{1000\ psi}} \cdot ksi\right) \cdot b_{o.end} \cdot d_f = 185.271\ kip$$ *Exterior punching shear capacity (AASHTO Eq.5.8.4.3.4-3)*

$V_c := min\left(V_{c.int}, V_{c.end}\right) = 185.271\ kip$ *Critical punching shear capacity*

$F_t = 80\ kip$ *Transverse impact force*

Punching_Shear_Capacity_of_Barrier_Check := if $V_c > F_t$
"OK"
else
"Not OK"

Punching_Shear_Capacity_of_Barrier_Check = "OK"

**(5) Deck Moment Capacity:**

**(5a) Deck Moment Demand:**

- The moment demand on the deck due to the TL-4 impact loading was determined using RISA-3D structral analysis.

- A solid model of the 42" barrier, as shown in Figure 5, was developed to determine the barrier loads to the deck. This model was generated with 6" wide elements in the longitudinal direction to represent the spacing of the barrier vertical reinforcements.

- The deck was modeled using meshed plate elements (4' x 50' with 6" x 6" plate elements). The reactions from the barrier to the deck were applied at the corresponding locations as shown in Figure 6.

* Detailed discussion will be provided in the final report.

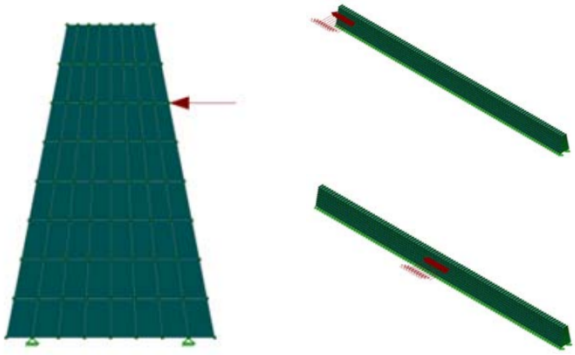
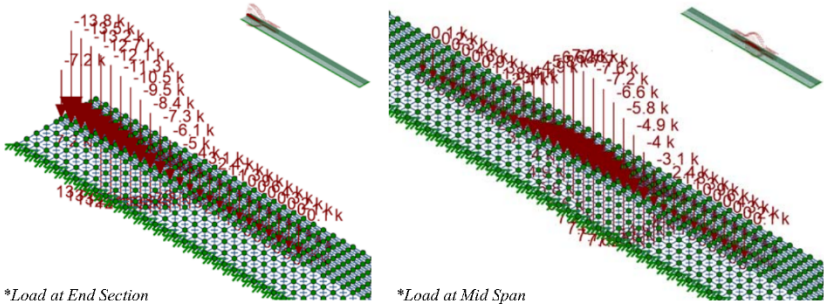


*Figure 7. Barrier Solid Model*

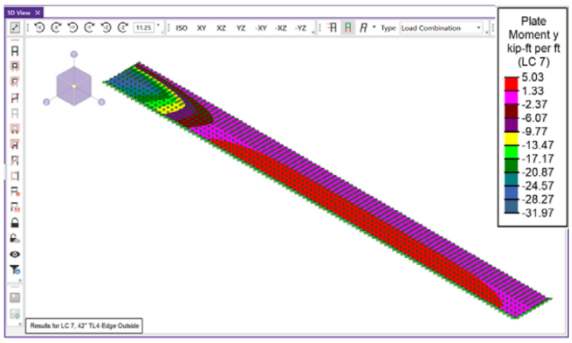



**Load at End Section* **Load at Mid Span*

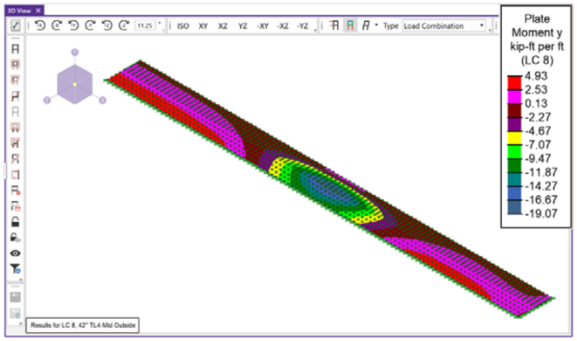
*Figure 8. Deck Plate Model with Barrier Reactions*

Deck moment demand from RISA 3-D analysis:

Max. moment demand at end-section: $M_{u.end} := 31.97\ kip \cdot ft$




Max. moment demand at mid-span: $M_{u.mid} := 19.07\ kip \cdot ft$




**(5b) Deck Nominal Moment Capacity:**

$b_{c.unit} := 12\ in$ *Unit width of deck*

$t_s = 11\ in$ *Depth of deck*

$d_{s.bot} = 9.188\ in$ *Extreme distance of deck flexural reinforcement at top*

$A_{s.bot} = 0.31\ in^2$ *Section area of deck flexural reinforcement at top*

$S_{s.bot} = 3\ in$ *Spacing of deck flexural reinforcement at top*

$A_{s.unit} := \frac{A_{s.bot}}{S_{s.bot}} \cdot b_{c.unit} = 1.24\ in^2$ *Unit area of deck flexural reinforcement at end section*

$a_s := \frac{A_{s.unit} \cdot f_y}{0.85 \cdot f'_c \cdot b_{c.unit}} = 1.824\ in$ *Depth of Whitney stress block at end section*

$M_{n.s} := A_{s.unit} \cdot f_y \cdot \left(d_{s.bot} - 0.5 \cdot a_s\right) = 51.31\ kip \cdot ft$ *Nominal moment capacity of deck*

**(5c) Deck Moment Capacity with Coincident Tensile Forces (AASHTO A 13.4.2):**

- Check at critical location: end-section

$L_{c.end} = 6.55\ ft$ *Distribution length of yield line mechanism*

$R_{w.end} = 144.288\ kip$ *Nominal resistance of barrier to transverse load*

$H_w = 42\ in$ *Height of barrier*

$T := \frac{R_{w.end}}{L_{c.end} + 2 \cdot H_w} = 10.649\ \frac{kip}{ft}$ *Coincident tensile force from vehicle impact (AASHTO Eq. A 13.4.2.-1)*

$T_a := A_{s.unit} \cdot f_y = 74.4\ kip$ *Tensile load provided by deck flexural reinforcement*

$C := T_a - T \cdot ft = 63.751\ kip$ *Resultant compression force in deck section*

$a_c := \frac{C}{0.85 \cdot f'_c \cdot b_c} = 1.563\ in$ *Depth of Whitney stress block for compression force*

$M_{n.t} := T_a \cdot \left(d_{s.bot} - \frac{a_c}{2}\right) - T \cdot ft \cdot \left(\frac{d_{s.bot}}{2} - \frac{a_c}{2}\right) = 48.735\ kip \cdot ft$

*Moment capacity of deck with coincident tensile force*

$M_{u.deck} := \max\left(M_{u.end}, M_{u.mid}\right) = 31.97\ kip \cdot ft$ *Maximum moment demand*

$$\text{Moment_Capacity_of_Deck_Check} := \begin{cases} \text{“OK”} & \text{if } M_{n.t} > M_{u.deck} \\ \text{“Not OK”} & \text{else} \end{cases}$$

$$\text{Moment_Capacity_of_Deck_Check} = \text{“OK”}$$

**(6) Reinforcement Development Length:**

$d_{b.\#4} := 0.5\ in$ ; $d_{b.\#5} := 0.625\ in$ *Bar diameter*

$$l_{db.\#4} := 2.4 \cdot d_{b.\#4} \cdot \frac{f_y}{\sqrt{f'_c \cdot \frac{1}{1000\ psi}} \cdot ksi} = 3\ ft$$

$$l_{db.\#5} := 2.4 \cdot d_{b.\#5} \cdot \frac{f_y}{\sqrt{f'_c \cdot \frac{1}{1000\ psi}} \cdot ksi} = 3.75\ ft$$

*Basic development length (AASHTO Eq. 5.10.8.2.1a-2)*

$\lambda := 1.0$ *Concrete weight modification factor*

$\lambda_{rl} := 1.0$ *Reinforcement location factor (AASHTO 5.10.8.2.1b)*

$\lambda_{cf} := 1.0$ *Coating factor (AASHTO 5.10.8.2.1b)*

$\lambda_{er} := 1.0$ *Excess reinforcement factor (AASHTO 5.10.8.2.1c)*

$k_{tr} := 0$ *Transverse reinforcement index (conservatively taken as 0 as per AASHTO C5.10.8.2.1c)*

$c_{b.\#4} := 1.75\ in$ ; $c_{b.\#5} := 1.8125\ in$ *Smaller of reinforcement edge distance and one-half of spacing*

$$\lambda_{rc.\#4} := \max\left(\frac{d_{b.\#4}}{c_{b.\#4} + k_{tr}}, 0.4\right) = 0.4 \quad ; \quad \lambda_{rc.\#5} := \max\left(\frac{d_{b.\#5}}{c_{b.\#5} + k_{tr}}, 0.4\right) = 0.4$$

*Reinforcement confinement factor , $0.4 < \lambda_{rc} < 1.0$ (AASHTO 5.10.8.2.1c)*

$$l_{d.\#4} := l_{db.\#4} \cdot \left( \frac{\lambda_{rl} \cdot \lambda_{cf} \cdot \lambda_{rc.\#4} \cdot \lambda_{er}}{\lambda} \right) = 14.4 \ in$$

$$l_{d.\#5} := l_{db.\#5} \cdot \left( \frac{\lambda_{rl} \cdot \lambda_{cf} \cdot \lambda_{rc.\#5} \cdot \lambda_{er}}{\lambda} \right) = 18 \ in$$

*Development lengths needed (modified tension development length, AASHTO Eq. 5.10.8.2.1a-1)*

$l_{anc} := 18.375 \ in$ *Anchorage reinforcement development lengths provided (#4 bar, green)*

$l_{s.top} := 48 \ in$ *Deck flexural reinforcement development lengths provided (#5 bar, purple)*

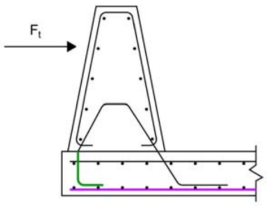



*Figure 9. Reinforcement Development Length*

Deck_Reinforcement_Development_Length_Check := if $l_{anc} > l_{d.\#4}$ ‖ $l_{s.top} > l_{d.\#5}$ ‖ "OK" else ‖ "Not OK"

Deck_Reinforcement_Development_Length_Check = "OK"

**(7) Analysis Results Overview:**

Minimum_Height_of_Barrier_Check = "OK"

Structural_Capacity_of_Barrier_at_Midspan_Check = "OK"

Structural_Capacity_of_Barrier_at_Ends_Check = "OK"

Punching_Shear_Capacity_of_Barrier_Check = "OK"

Moment_Capacity_of_Deck_Check = "OK"

Deck_Reinforcement_Development_Length_Check = "OK"

**(8) Summary of Barrier Design:**

1. Use Vertical Barrier Stirrup #4 @ 6" O.C. for 10'-0" at Barrier End Section

2. Use Vertical Barrier Stirrup #4 @ 12" O.C. out at Mid-Section (greater than 10'-0" from End Sections)

3. All other details as shown on Section and Elevation Views as provided herein for the 42" Barrier as analyzed herein are acceptable for MASH TL-4 Impact conditions.

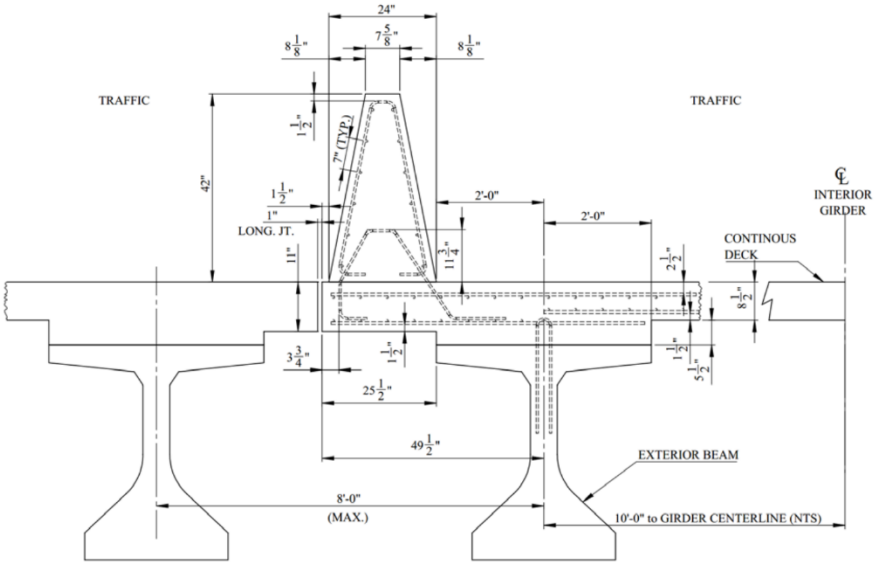
**SUBJECT:** 42" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Inside Barrier (right side)

**Overview:**

These calcualtions evaluate the strength of the given barrier design for MASH TL-4 impact load condtions.

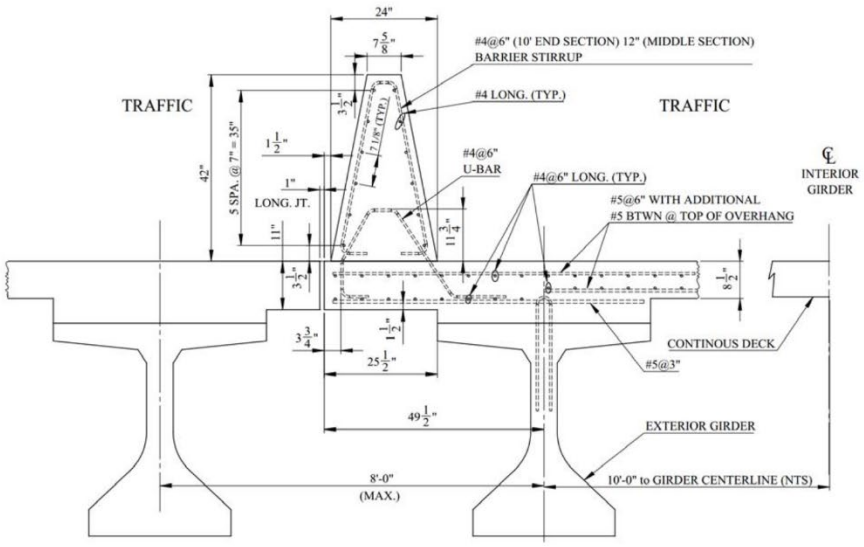
- 42" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from the Barrier Right Side in the Section View below.

**Design Details:**

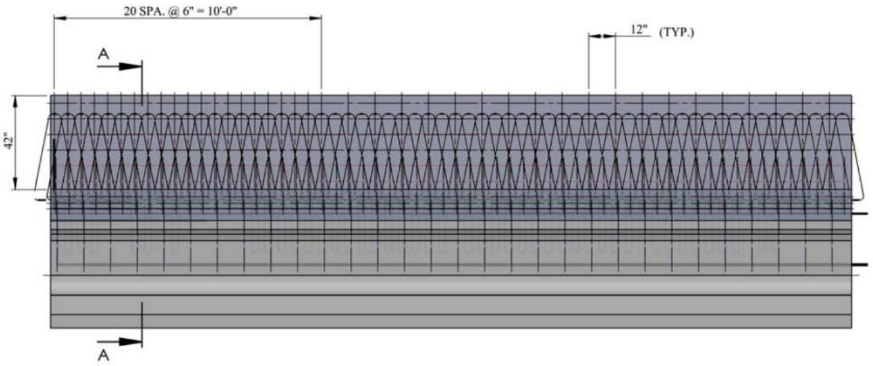



**Section View (a)**

**SUBJECT:** 42" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Inside Barrier (right side)



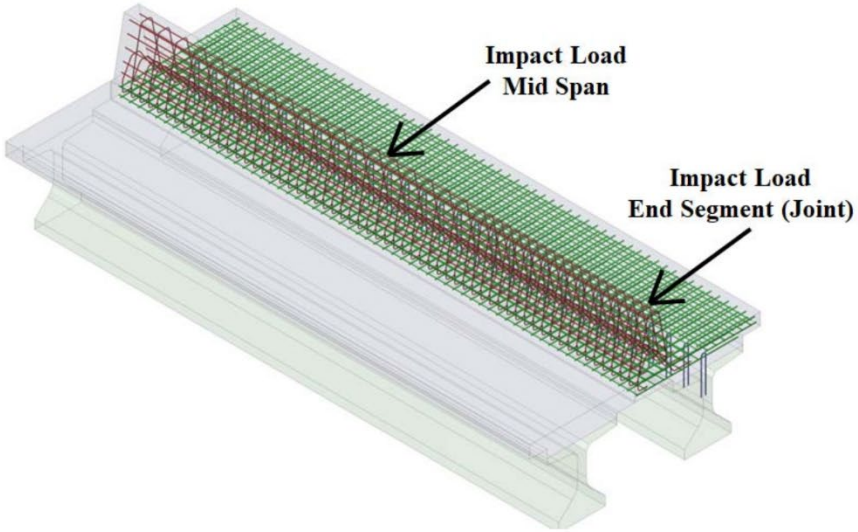

**Section View (b)**




**Elevation**

Texas A&M Transportation Institute

**SUBJECT:** 42" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Inside Barrier (right side)




**Iso View**

**SUBJECT:** 42" LADOTD Barrier with a Longitudinal Open Joint on Cantilever Deck with Impact Load from Inside Barrier (right side)

**(1) Define Inputs:**

**(1a) General Inputs:**

$f'_c := 4000\ psi$ — *Compressive strength of concrete*

$f_y := 60\ ksi$ — *Yield strength reinforcing steel*

$E_s := 29000\ ksi$ — *Modulus of elasticity of steel*

$H_w := 42\ in$ — *Height of barrier*

$T_{w.top} := 7.625\ in$ — *Top width of barrier*

$T_{w.bot} := 24\ in$ — *Bottom width of barrier*

$t_s := 11\ in$ — *Depth of deck*

$d_{\#4} := 0.5\ in$ ; $A_{\#4} := 0.2\ in^2$ — *Diameter and section area of #4 bar*

$d_{\#5} := 0.625\ in$ ; $A_{\#5} := 0.31\ in^2$ — *Diameter and section area of #5 bar*

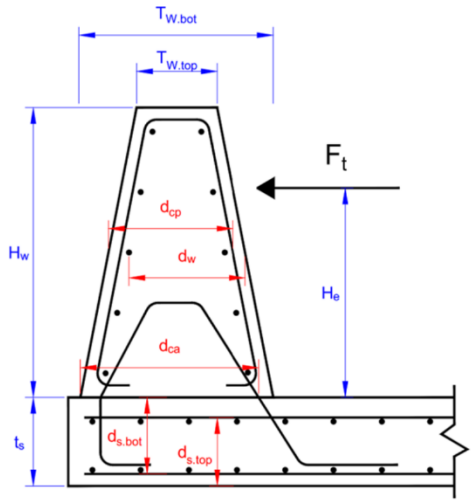



*Figure 1. Sketch of Concrete Wall/Parapet Showing Input Variable*

**(1b) Concrete Barrier Inputs:**

$t_{b.cov} := 1.5\ in$ *Concrete clear cover of barrier*

Barrier vertical reinforcement inputs (#4 bars):

$A_{vpl.mid} := 0.2\ in^2$ *Area of one barrier vertical reinforcement leg at midspan*

$S_{vp.mid} := 12\ in$ *Spacing of barrier vertical reinforcement at midspan*

$d_{cp.mid} := 14.0625\ in$ *Average extreme distance of barrier vertical reinforcement at midspan*

$A_{vpl.end} := 0.2\ in^2$ *Area of one barrier vertical reinforcement leg at joints/ends*

$S_{vp.end} := 6\ in$ *Spacing of barrier vertical reinforcement at joints/ends*

$d_{cp.end} := 14.0625\ in$ *Average extreme distance of barrier vertical reinforcement at joints/ends*

Deck anchorage reinforcement inputs (#4 bars):

$A_{val.mid} := 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} := 6\ in$ *Spacing of deck anchorage vertical reinforcement at midspan*

$d_{ca.mid} := 22.25\ in$ *Extreme distance of tension deck anchorage reinforcement at midspan*

$A_{val.end} := 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at joints/ends*

$S_{va.end} := 6\ in$ *Spacing of deck anchorage vertical reinforcement at joints/ends*

$d_{ca.end} := 22.25\ in$ *Extreme distance of tension deck anchorage reinforcement at joints/ends*

Barrier Longitudinal reinforcement inputs (#4 bars):

$A_w := 0.2 \cdot 6\ in^2 = 1.2\ in^2$ *Area of longitudinal reinforcement bars in tension*

$d_w := 13.5625\ in$ *Average extreme distance of tension longitudinal reinforcement*

**(1c) Concrete Deck Inputs:**

| | |
|---|---|
| $t_{s.cov.bot} := 1.5\ in$ | *Concrete clear cover of deck at bottom* |
| $d_{s.bot} := 9.1875\ in$ | *Extreme distance of deck flexural reinforcement at bottom* |
| $A_{s.bot} := 0.31\ in^2$ | *Section area of deck flexural reinforcement at bottom (single bar)* |
| $S_{s.bot} := 3\ in$ | *Spacing of deck flexural reinforcement at bottom* |
| $t_{s.cov.top} := 2.5\ in$ | *Concrete clear cover of deck at top* |
| $d_{s.top} := 8.1875\ in$ | *Extreme distance of deck flexural reinforcement at top* |
| $A_{s.top} := 0.31\ in^2$ | *Section area of deck flexural reinforcement at top (single bar)* |
| $S_{s.top} := 3\ in$ | *Spacing of deck flexural reinforcement at top* |

**(1d) Design Force Inputs:**

**Design Forces for Traffic Railings**

| Test Level | Rail Height (in.) | $F_t$ (kip) | $F_L$ (kip) | $F_T$ (kip) | $L_t/L_L$ (ft) | $L_T$ (ft) | $H_e$ (in) | $H_{min}$ (in) |
|---|---|---|---|---|---|---|---|---|
| TL-1 | 18 or above | 13.5 | 4.5 | 4.5 | 4.0 | 18.0 | 18.0 | 18.0 |
| TL-2 | 18 or above | 27.0 | 9.0 | 4.5 | 4.0 | 18.0 | 20.0 | 18.0 |
| TL-3 | 29 or above | 71.0 | 18.0 | 4.5 | 4.0 | 18.0 | 19.0 | 29.0 |
| TL-4 (a) | 36 | 68.0 | 22.0 | 38.0 | 4.0 | 18.0 | 25.0 | 36.0 |
| TL-4 (b) | between 36 and 42 | 80.0 | 27.0 | 22.0 | 5.0 | 18.0 | 30.0 | 36.0 |
| TL-5 (a) | 42 | 160.0 | 41.0 | 80.0 | 10.0 | 40.0 | 35.0 | 42.0 |
| TL-5 (b) | greater than 42 | 262.0 | 75.0 | 160.0 | 10.0 | 40.0 | 43.0 | 42.0 |
| TL 6 | | 175.0 | 58.0 | 80.0 | 8.0 | 40.0 | 56.0 | 90.0 |

References:
- TL-1 and TL-2 Design Forces are from AASHTO LRFD Section 13 Table A13.2-1
- TL-3 Design Forces are from research conducted under NCHRP Project 20-07 Task 395
- TL-4 (a), TL-4 (b), TL-5 (a), and TL-5 (b) Design Forces are from research conducted under NCHRP Project 22-20(2)

| | |
|---|---|
| $TL := 4$ | *Test level* |
| $F_t := 80\ kip$ | *Transverse impact force* |
| $L_t := 5\ ft$ | *Longitudinal length of distribution of impact force* |
| $H_e := 30\ in$ | *Height of equivalent transverses load* |

$H_{min} := 36\ in$ *Minimum height of a MASH TL-4 barrier*

$H_w = 42\ in$ *Height of concrete barrier*

**(2) Stability Criteria:**

$H_{min} = 36\ in$ *Minimum height of a MASH TL-4 barrier*

$H_w = 42\ in$ *Height of concrete barrier measured from the top of the roadway surface/asphalt overlay*

$$Minimum_Height_of_Barrier_Check := \begin{cases} \text{if } H_w \geq H_{min} \\ \quad \text{“OK”} \\ \text{else} \\ \quad \text{“Not OK”} \end{cases}$$

$Minimum_Height_of_Barrier_Check = \text{“OK”}$

**(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification:**

**(3a) Bending Capacity of the Barrier about the Longitudinal Axis at Midspan:** $M_{cmid}$ **(k-ft/ft)**

For parapet vertical reinforcement:

$b_c := 12\ in$ *Unit width of wall (take as 1 ft per AASHTO Section 13 procedure)*

$A_{vpl.mid} = 0.2\ in^2$ *Area of one parapet vertical reinforcement leg at midspan*

$S_{vp.mid} = 12\ in$ *Spacing of parapet vertical reinforcement at midspan*

$$A_{vp.mid} := \left(\frac{b_c}{S_{vp.mid}}\right) \cdot A_{vpl.mid} = 0.2\ in^2$$

*Total area of parapet vertical reinforcement per unit length at midspan*

$d_{cp.mid} = 14.063\ in$ *Average extreme distance of parapet vertical reinforcement at midspan*

$$a_{cp.mid} := \frac{A_{vp.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.294\ in$$ *Depth of Whitney stress block*

$$M_{cp.mid} := \frac{\left(A_{vp.mid} \cdot f_y \cdot \left(d_{cp.mid} - \frac{a_{cp.mid}}{2}\right)\right)}{b_c} = 13.915 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the parapet vertical reinforcement specified in Article A 13.3.1 (k-ft/ft)*

For deck anchorage reinforcement:

$b_c = 12 \ in$ *Unit width of wall (take as 1 ft per AASHTO Section 13 procedure)*

$A_{val.mid} = 0.2 \ in^2$ *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} = 6 \ in$ *Spacing of deck anchorage vertical reinforcement at midspan*

$$A_{va.mid} := \left(\frac{b_c}{S_{va.mid}}\right) \cdot A_{val.mid} = 0.4 \ in^2$$

*Total area of deck anchorage vertical reinforcement per unit length at midspan*

$d_{ca.mid} = 22.25 \ in$ *Extreme distance of tension deck anchorage vertical reinforcement at midspan*

$$a_{ca.mid} := \frac{A_{va.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588 \ in$$ *Depth of Whitney stress block*

$$M_{ca.mid} := \frac{\left(A_{va.mid} \cdot f_y \cdot \left(d_{ca.mid} - \frac{a_{ca.mid}}{2}\right)\right)}{b_c} = 43.912 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

$$M_{c.mid} := min\left(M_{cp.mid}, M_{ca.mid}\right) = 13.915 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering the critical reinforcement*

**(3b) Bending Capacity of the Barrier about the Longitudinal Axis at Joints/Ends:** $M_{ccnd}$ **(k-ft/ft)**

For parapet vertical reinforcement:

$A_{vpl.end} = 0.2\ in^2$ *Area of one parapet vertical reinforcement leg at joints/ends*

$S_{vp.end} = 6\ in$ *Spacing of parapet vertical reinforcement at joints/ends*

$A_{vp.end} := \left(\frac{b_c}{S_{vp.end}}\right) \cdot A_{vpl.end} = 0.4\ in^2$ *Total area of deck anchorage vertical reinforcement per unit length at midspan*

$d_{cp.end} = 14.063\ in$ *Average extreme distance of parapet vertical reinforcement at joints/ends (at barrier mid-height)*

$a_{cp.end} := \frac{A_{vp.end} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588\ in$ *Depth of Whitney stress block*

$$M_{cp.end} := \frac{\left(A_{vp.end} \cdot f_y \cdot \left(d_{cp.end} - \frac{a_{cp.end}}{2}\right)\right)}{b_c} = 27.537\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at Joints/ Ends when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

For deck anchorage reinforcement:

$A_{val.end} = 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at joints/ends*

$S_{va.end} = 6\ in$ *Spacing of deck anchorage vertical reinforcement at joints/ends*

$A_{va.end} := \left(\frac{b_c}{S_{va.end}}\right) \cdot A_{val.end} = 0.4\ in^2$ *Total area of deck anchorage vertical reinforcement per unit length at joints/ends*

$d_{ca.end} = 22.25\ in$ *Extreme distance of tension deck anchorage vertical reinforcement at joints/ends*

$$a_{ca.end} := \frac{A_{va.end} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588\ in$$

*Depth of Whitney stress block*

$$M_{ca.end} := \frac{\left(A_{va.end} \cdot f_y \cdot \left(d_{ca.end} - \frac{a_{ca.end}}{2}\right)\right)}{b_c} = 43.912\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at Joints/ Ends when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

$$M_{c.end} := min\left(M_{cp.end}, M_{ca.end}\right) = 27.537\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at joints/ends when considering the critical reinforcement*

**(3c) Bending Capacity of the Barrier about the Vertical Axis:** $M_w$

$d_w = 13.563\ in$ *Effective depth of longitudinal reinforcement bars*

$A_w = 1.2\ in^2$ *Area of longitudinal reinforcement bars in tension*

$H_w = 42\ in$ *Extreme distance of tension longitudinal reinforcement of barrier*

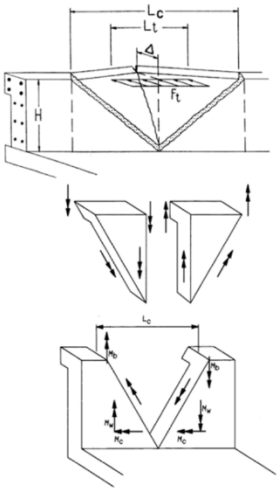
$$a_w := \frac{A_w \cdot f_y}{0.85 \cdot f'_c \cdot H_w} = 0.504\ in$$

*Depth of Whitney stress block*

$$M_w := A_w \cdot f_y \cdot \left(d_w - \frac{a_w}{2}\right) = 79.862\ kip \cdot ft$$

*Flexural resistance of the barrier about the vertical axis specified in Article A 13.3.1*

**(3d) Ultimate Resistance of the Wall at Midspan: $R_{w.mid}$**




$H_w = 42\ in$ — *Height of barrier*

$M_B := 0\ kip \cdot ft$ — *No additional beam strength*

$M_{c.mid} = 13.915\ \frac{kip \cdot ft}{ft}$ — *Flexural resistance about the long. axis at midspan*

$M_w = 79.862\ kip \cdot ft$ — *Flexural resistance about the vert. axis*

$L_t = 5\ ft$ — *Long. length of distribution of impact force*

*Figure 2. Yield Line Analysis of Concrete Parapet Walls for Impact within Wall Segment (figure taken from AASHTO).*

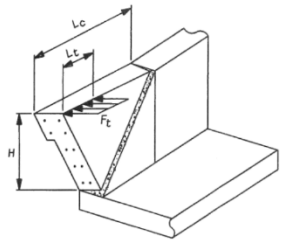
$$L_{c.mid} := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{8 \cdot H_w \cdot (M_B + M_w)}{M_{c.mid}}} = 15.421\ ft$$

*AASHTO Equation A13.3.1-2*

$$R_{w.mid} := \left(\frac{2}{2 \cdot L_{c.mid} - L_t}\right) \cdot \left(8 \cdot M_B + 8 \cdot M_w + \frac{M_{c.mid} \cdot (L_{c.mid})^2}{H_w}\right) \cdot \frac{H_w}{H_e} = 171.669\ kip$$

*AASHTO Equation A13.3.1-1*

**(3e) Ultimate Resistance of the Wall at Joints/Ends: $R_{w.end}$**




$H_w = 42\ in$ — *Height of barrier*

$M_B := 0\ kip \cdot ft$ — *No additional beam strength*

$M_{c.end} = 27.537\ \frac{kip \cdot ft}{ft}$ — *Flexural resistance about the long. axis at joints/ends*

$M_w = 79.862\ kip \cdot ft$ — *Flexural resistance about the vert. axis*

$L_t = 5\ ft$ — *Long. length of distribution of impact force*

*Figure 3. Yield Line Analysis of Concrete Parapet Walls for Impact near End of Wall Segment (figure taken from AASHTO)*

$$L_{c.end} := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{H_w \cdot (M_B + M_w)}{M_{c.end}}} = 6.55\ ft$$ *AASHTO Equation A13.3.1-4*

$$R_{w.end} := \left(\frac{2}{2 \cdot L_{c.end} - L_t}\right) \cdot \left(M_B + M_w + \frac{M_{c.end} \cdot (L_{c.end})^2}{H_w}\right) \cdot \frac{H_w}{H_e} = 144.288\ kip$$

*AASHTO Equation A13.3.1-3*

**(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification - Summary of Results:**

$H_w = 42\ in$ — *Height of the concrete barrier measured from the top of the roadway surface*

$H_e = 30\ in$ — *Height of the transverse impact force, Ft*

$F_t = 80\ kip$ — *Transverses impact force located at He*

$R_{w.mid} = 171.669\ kip$ — *Ultimate resistance of the wall at midspan*

$R_{w.end} = 144.288\ kip$ — *Ultimate resistance of the wall at joints/ends*

Structural_Capacity_of_Barrier_at_Midspan_Check := if $R_{w.mid} > F_t$ "OK" else "Not OK"

Structural_Capacity_of_Barrier_at_Midspan_Check = "OK"

Structural_Capacity_of_Barrier_at_Ends_Check := if $R_{w.end} > F_t$ "OK" else "Not OK"

Structural_Capacity_of_Barrier_at_Ends_Check = "OK"

**(4) Punching Shear Capacity of the Barrier:**

$\lambda := 1.0$ *Concrete weight modification factor*

$d_c := 10.55\ in$ *Depth of shear zone at height of equivalent transverse load*

$T_{w.top} := 7.625\ in$ *Top width of barrier*

$h_c := 11\ in$ *Width of shear zone*

$L_t = 5\ ft$ *Distribution width of transverse impact force*

$f'_c = 4\ ksi$ *Concrete barrier compressive strength*

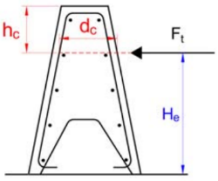



*Figure 4. Punching Shear Variables*

$$d_f := \frac{T_{w.top} + d_c}{2} = 9.088\ in$$ *Median depth of shear zone*

$$b_{o.int} := (L_t + d_c) + 2 \cdot \left(h_c + \frac{d_c}{2}\right) = 103.1\ in$$

*Median perimeter of interior critical section (AASHTO 5.8.4.3.4)*

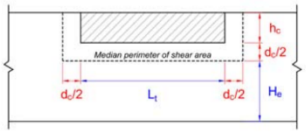



*Figure 5. Punching Shear at Interior Segment*

$$V_{c.int} := 0.125 \cdot \lambda \cdot \left(\sqrt{\frac{f'_c}{1000\ psi}} \cdot ksi\right) \cdot b_{o.int} \cdot d_f = 234.23\ kip$$

*Interior punching shear capacity (AASHTO Eq.5.8.4.3.4-3)*

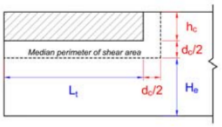



*Figure 6. Punching Shear at Exterior Segment*

$$b_{o.end} := \left(L_t + \frac{d_c}{2}\right) + \left(h_c + \frac{d_c}{2}\right) = 81.55\ in$$

*Median perimeter of exterior critical section (AASHTO 5.8.4.3.4)*

$$V_{c.end} := 0.125 \cdot \lambda \cdot \left(\sqrt{\frac{f'_c}{1000\ psi}} \cdot ksi\right) \cdot b_{o.end} \cdot d_f = 185.271\ kip$$ *Exterior punching shear capacity (AASHTO Eq.5.8.4.3.4-3)*

$V_c := min\left(V_{c.int}, V_{c.end}\right) = 185.271\ kip$ *Critical punching shear capacity*

$F_t = 80\ kip$ *Transverse impact force*

Punching_Shear_Capacity_of_Barrier_Check := if $V_c > F_t$
"OK"
else
"Not OK"

Punching_Shear_Capacity_of_Barrier_Check = "OK"

**(5) Deck Moment Capacity:**

**(5a) Deck Moment Demand:**

- The moment demand on the deck due to the TL-4 impact loading was determined using RISA-3D structral analysis.

- A solid model of the 42" barrier, as shown in Figure 5, was developed to determine the barrier loads to the deck. This model was generated with 6" wide elements in the longitudinal direction to represent the spacing of the barrier vertical reinforcements.

- The deck was modeled using meshed plate elements (4' x 50' with 6" x 6" plate elements). The reactions from the barrier to the deck were applied at the corresponding locations as shown in Figure 6.

* Detailed discussion will be provided in the final report.

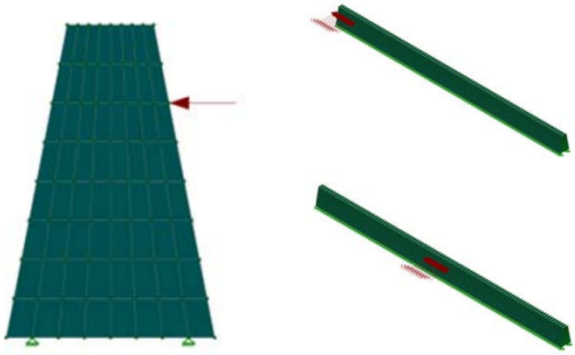


*Figure 7. Barrier Solid Model*

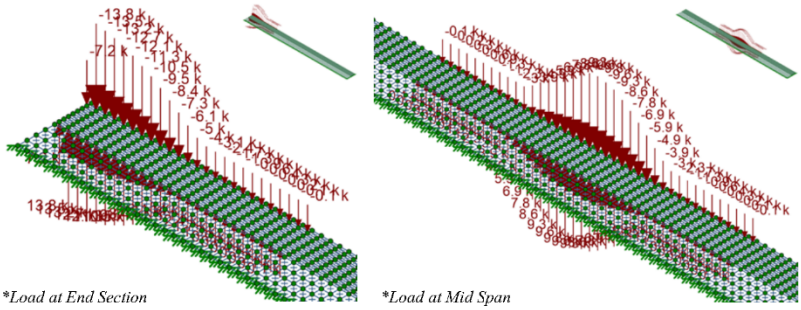
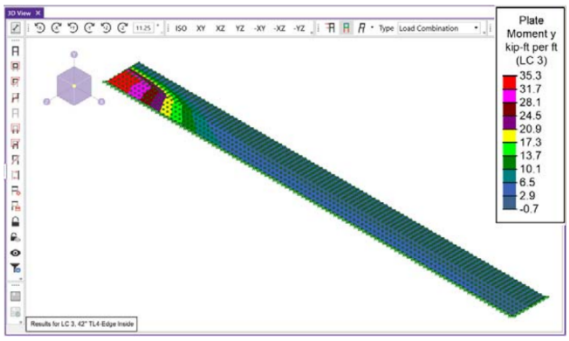


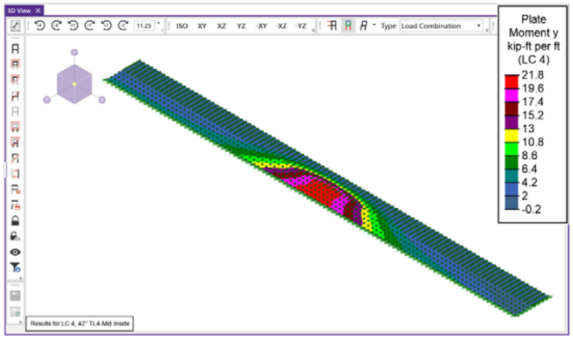

*Figure 8. Deck Plate Model with Barrier Reactions*

Deck moment demand from RISA 3-D analysis:

Max. moment demand at end-section: $M_{u.end} := 35.3\ kip \cdot ft$




Max. moment demand at mid-span: $M_{u.mid} := 21.8\ kip \cdot ft$




**(5b) Deck Nominal Moment Capacity:**

| | |
|---|---|
| $b_{c.unit} := 12\ in$ | *Unit width of deck* |
| $t_s = 11\ in$ | *Depth of deck* |
| $d_{s.top} = 8.188\ in$ | *Extreme distance of deck flexural reinforcement at top* |
| $A_{s.top} = 0.31\ in^2$ | *Section area of deck flexural reinforcement at top* |
| $S_{s.top} = 3\ in$ | *Spacing of deck flexural reinforcement at top* |

$A_{s.unit} := \frac{A_{s.top}}{S_{s.top}} \cdot b_{c.unit} = 1.24\ in^2$ *Unit area of deck flexural reinforcement at end section*

$a_s := \frac{A_{s.unit} \cdot f_y}{0.85 \cdot f'_c \cdot b_{c.unit}} = 1.824\ in$ *Depth of Whitney stress block at end section*

$M_{n.s} := A_{s.unit} \cdot f_y \cdot (d_{s.top} - 0.5 \cdot a_s) = 45.11\ kip \cdot ft$ *Nominal moment capacity of deck*

**(5c) Deck Moment Capacity with Coincident Tensile Forces (AASHTO A 13.4.2):**

- Check at critical location: end-section

$L_{c.end} = 6.55\ ft$ *Distribution length of yield line mechanism*

$R_{w.end} = 144.288\ kip$ *Nominal resistance of barrier to transverse load*

$H_w = 42\ in$ *Height of barrier*

$T := \frac{R_{w.end}}{L_{c.end} + 2 \cdot H_w} = 10.649\ \frac{kip}{ft}$ *Coincident tensile force from vehicle impact (AASHTO Eq. A 13.4.2.-1)*

$T_a := A_{s.unit} \cdot f_y = 74.4\ kip$ *Tensile load provided by deck flexural reinforcement*

$C := T_a - T \cdot ft = 63.751\ kip$ *Resultant compression force in deck section*

$a_c := \frac{C}{0.85 \cdot f'_c \cdot b_c} = 1.563\ in$ *Depth of Whitney stress block for compression force*

$M_{n.t} := T_a \cdot \left(d_{s.top} - \frac{a_c}{2}\right) - T \cdot ft \cdot \left(\frac{d_{s.top}}{2} - \frac{a_c}{2}\right) = 42.979\ kip \cdot ft$

*Moment capacity of deck with coincident tensile force*

$M_{u.deck} := \max(M_{u.end}, M_{u.mid}) = 35.3\ kip \cdot ft$ *Maximum moment demand*

$$\text{Moment_Capacity_of_Deck_Check} := \begin{cases} \text{if } M_{n.t} > M_{u.deck} \\ \quad \text{“OK”} \\ \text{else} \\ \quad \text{“Not OK”} \end{cases}$$

$$\text{Moment_Capacity_of_Deck_Check} = \text{“OK”}$$

**(6) Reinforcement Development Length:**

$d_{b.\#4} := 0.5\ in$ ; $d_{b.\#5} := 0.625\ in$ *Bar diameter*

$$l_{db.\#4} := 2.4 \cdot d_{b.\#4} \cdot \frac{f_y}{\sqrt{f'_c \cdot \frac{1}{1000\ psi}} \cdot ksi} = 3\ ft$$

$$l_{db.\#5} := 2.4 \cdot d_{b.\#5} \cdot \frac{f_y}{\sqrt{f'_c \cdot \frac{1}{1000\ psi}} \cdot ksi} = 3.75\ ft$$

*Basic development length (AASHTO Eq. 5.10.8.2.1a-2)*

$\lambda := 1.0$ *Concrete weight modification factor*

$\lambda_{rl} := 1.0$ *Reinforcement location factor (AASHTO 5.10.8.2.1b)*

$\lambda_{cf} := 1.0$ *Coating factor (AASHTO 5.10.8.2.1b)*

$\lambda_{er} := 1.0$ *Excess reinforcement factor (AASHTO 5.10.8.2.1c)*

$k_{tr} := 0$ *Transverse reinforcement index (conservatively taken as 0 as per AASHTO C5.10.8.2.1c)*

$c_{b.\#4} := 1.75\ in$ ; $c_{b.\#5} := 1.8125\ in$ *Smaller of reinforcement edge distance and one-half of spacing*

$$\lambda_{rc.\#4} := \max\left(\frac{d_{b.\#4}}{c_{b.\#4} + k_{tr}}, 0.4\right) = 0.4 \quad ; \quad \lambda_{rc.\#5} := \max\left(\frac{d_{b.\#5}}{c_{b.\#5} + k_{tr}}, 0.4\right) = 0.4$$

*Reinforcement confinement factor , $0.4 < \lambda_{rc} < 1.0$ (AASHTO 5.10.8.2.1c)*

$$l_{d.\#4} := l_{db.\#4} \cdot \left( \frac{\lambda_{rl} \cdot \lambda_{cf} \cdot \lambda_{rc.\#4} \cdot \lambda_{er}}{\lambda} \right) = 14.4\ in$$

$$l_{d.\#5} := l_{db.\#5} \cdot \left( \frac{\lambda_{rl} \cdot \lambda_{cf} \cdot \lambda_{rc.\#5} \cdot \lambda_{er}}{\lambda} \right) = 18\ in$$

*Development lengths needed (modified tension development length, AASHTO Eq. 5.10.8.2.1a-1)*

$l_{anc} := 22\ in$ *Anchorage reinforcement development lengths provided (#4 bar, green)*

$l_{s.top} := 48\ in$ *Deck flexural reinforcement development lengths provided (#5 bar, purple)*

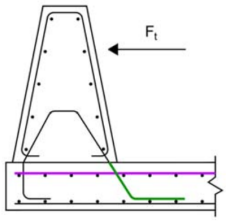



*Figure 9. Reinforcement Development Length*

Deck_Reinforcement_Development_Length_Check := if $l_{anc} > l_{d.\#4}$ || $l_{s.top} > l_{d.\#5}$
|| "OK"
else
|| "Not OK"

Deck_Reinforcement_Development_Length_Check = "OK"

**(7) Analysis Results Overview:**

Minimum_Height_of_Barrier_Check = "OK"

Structural_Capacity_of_Barrier_at_Midspan_Check = "OK"

Structural_Capacity_of_Barrier_at_Ends_Check = "OK"

Punching_Shear_Capacity_of_Barrier_Check = "OK"

Moment_Capacity_of_Deck_Check = "OK"

Deck_Reinforcement_Development_Length_Check = "OK"

**(8) Summary of Barrier Design:**

1. Use Vertical Barrier Stirrup #4 @ 6" O.C. for 10'-0" at Barrier End Section
2. Use Vertical Barrier Stirrup #4 @ 12" O.C. out at Mid-Section (greater than 10'-0" from End Sections)
3. All other details as shown on Section and Elevation Views as provided herein for the 42" Barrier as analyzed herein are acceptable for MASH TL-4 Impact conditions.

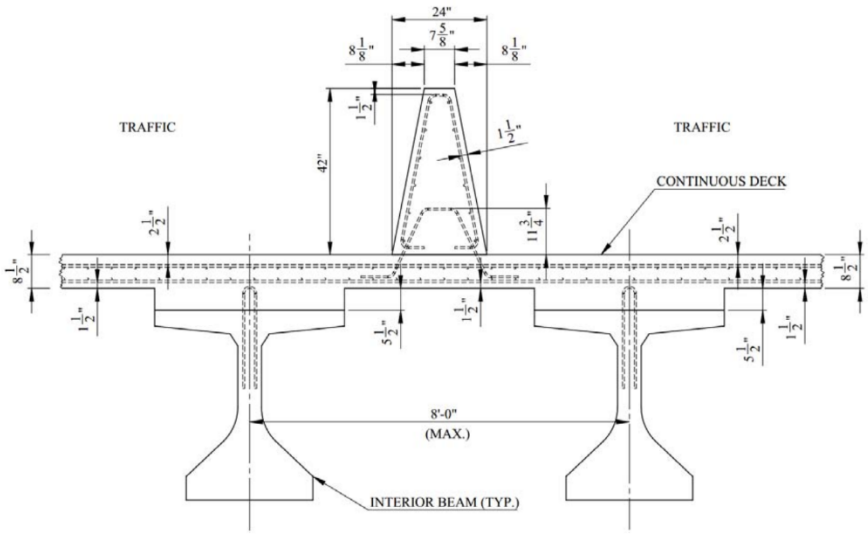
**SUBJECT:** 42" LADOTD Median Barrier

**Overview:**

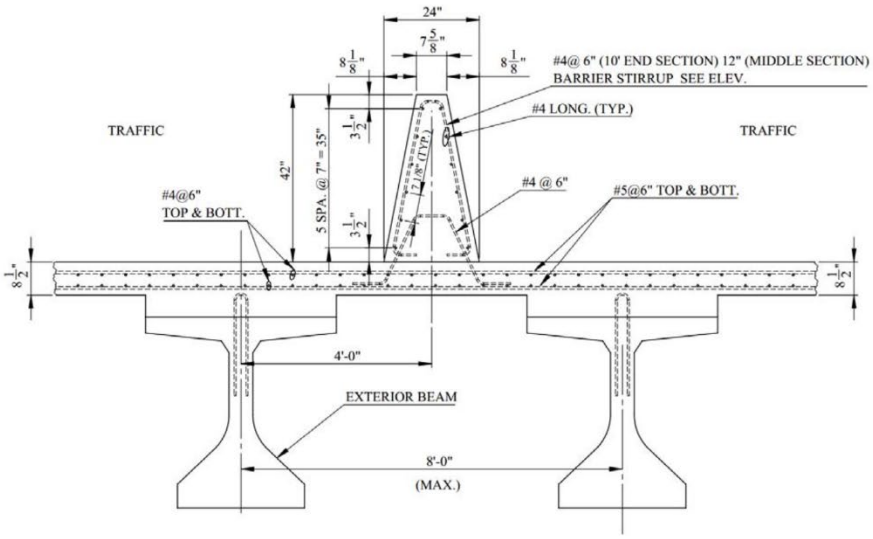
These calcualtions evaluate the strength of the given barrier design for MASH TL-4 impact load condtions.

- 42" LADOTD Median Barrier

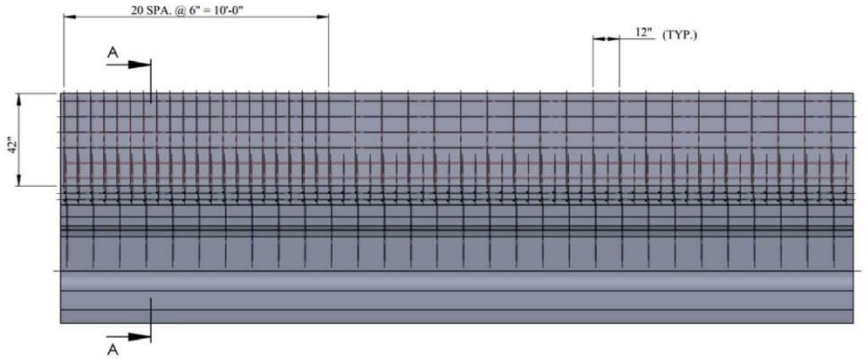
**Design Details:**



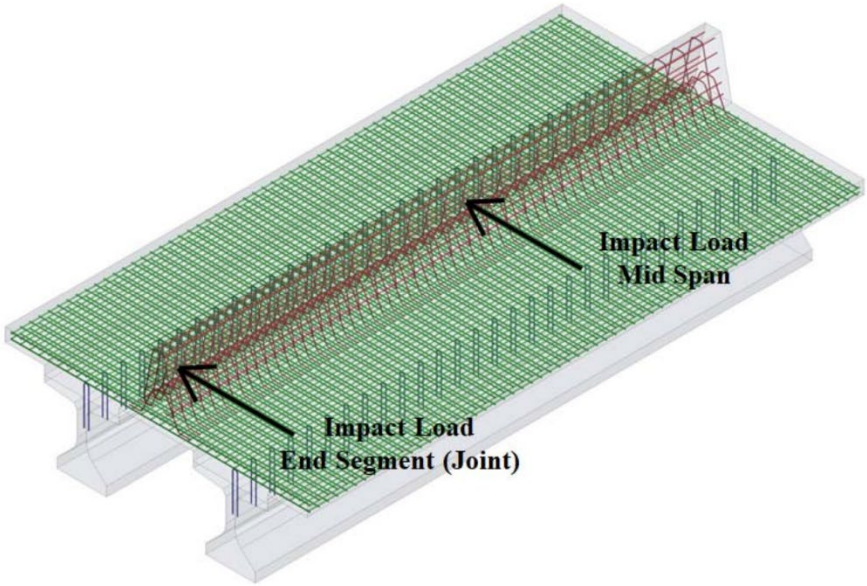

**Section View (a)**




**Section View (b)**




**Elevation**




**Iso View**

**(1) Define Inputs:**

**(1a) General Inputs:**

$f'_c := 4000\ psi$ — *Compressive strength of concrete*

$f_y := 60\ ksi$ — *Yield strength reinforcing steel*

$E_s := 29000\ ksi$ — *Modulus of elasticity of steel*

$H_w := 42\ in$ — *Height of barrier*

$T_{w.top} := 7.625\ in$ — *Top width of barrier*

$T_{w.bot} := 24\ in$ — *Bottom width of barrier*

$t_s := 8.5\ in$ — *Depth of deck*

$d_{\#4} := 0.5\ in$ ; $A_{\#4} := 0.2\ in^2$ — *Diameter and section area of #4 bar*

$d_{\#5} := 0.625\ in$ ; $A_{\#5} := 0.31\ in^2$ — *Diameter and section area of #5 bar*

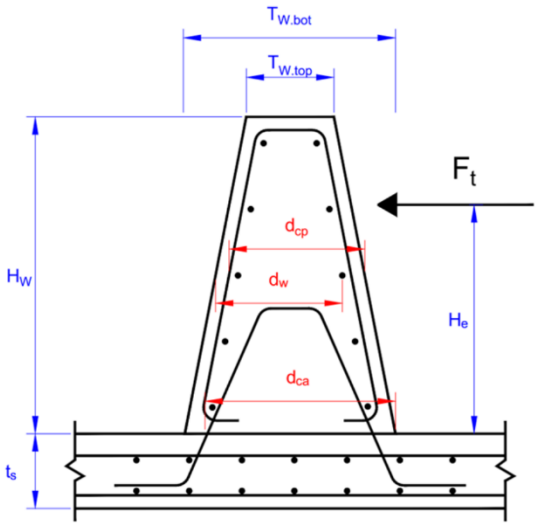



*Figure 1. Sketch of Concrete Wall/Parapet Showing Input Variable*

**(1b) Concrete Barrier Inputs:**

$t_{b.cov} := 1.5\ in$ *Concrete clear cover of barrier*

Barrier vertical reinforcement inputs (#4 bars):

$A_{vpl.mid} := 0.2\ in^2$ *Area of one barrier vertical reinforcement leg at midspan*

$S_{vp.mid} := 12\ in$ *Spacing of barrier vertical reinforcement at midspan*

$d_{cp.mid} := 14.0625\ in$ *Average extreme distance of barrier vertical reinforcement at midspan*

$A_{vpl.end} := 0.2\ in^2$ *Area of one barrier vertical reinforcement leg at joints/ends*

$S_{vp.end} := 6\ in$ *Spacing of barrier vertical reinforcement at joints/ends*

$d_{cp.end} := 14.0625\ in$ *Average extreme distance of barrier vertical reinforcement at joints/ends*

Deck anchorage reinforcement inputs (#4 bars):

$A_{val.mid} := 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} := 6\ in$ *Spacing of deck anchorage vertical reinforcement at midspan*

$d_{ca.mid} := 22.25\ in$ *Extreme distance of tension deck anchorage reinforcement at midspan*

$A_{val.end} := 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at joints/ends*

$S_{va.end} := 6\ in$ *Spacing of deck anchorage vertical reinforcement at joints/ends*

$d_{ca.end} := 22.25\ in$ *Extreme distance of tension deck anchorage reinforcement at joints/ends*

Barrier Longitudinal reinforcement inputs (#4 bars):

$A_w := 0.2 \cdot 6\ in^2 = 1.2\ in^2$ *Area of longitudinal reinforcement bars in tension*

$d_w := 13.5625\ in$ *Average extreme distance of tension longitudinal reinforcement*

**(1c) Concrete Deck Inputs:**

$t_{s.cov.bot} := 1.5\ in$ *Concrete clear cover of deck at bottom*

$d_{s.bot} := 6.6875\ in$ *Extreme distance of deck flexural reinforcement at bottom*

$A_{s.bot} := 0.31\ in^2$ *Section area of deck flexural reinforcement at bottom (single bar)*

$S_{s.bot} := 6\ in$ *Spacing of deck flexural reinforcement at bottom*

$t_{s.cov.top} := 2.5\ in$ *Concrete clear cover of deck at top*

$d_{s.top} := 5.875\ in$ *Extreme distance of deck flexural reinforcement at top*

$A_{s.top} := 0.31\ in^2$ *Section area of deck flexural reinforcement at top (single bar)*

$S_{s.top} := 6\ in$ *Spacing of deck flexural reinforcement at top*

**(1d) Design Force Inputs:**

**Design Forces for Traffic Railings**

| Test Level | Rail Height (in.) | $F_t$ (kip) | $F_L$ (kip) | $F_T$ (kip) | $L_t/L_L$ (ft) | $L_T$ (ft) | $H_e$ (in) | $H_{min}$ (in) |
|---|---|---|---|---|---|---|---|---|
| TL-1 | 18 or above | 13.5 | 4.5 | 4.5 | 4.0 | 18.0 | 18.0 | 18.0 |
| TL-2 | 18 or above | 27.0 | 9.0 | 4.5 | 4.0 | 18.0 | 20.0 | 18.0 |
| TL-3 | 29 or above | 71.0 | 18.0 | 4.5 | 4.0 | 18.0 | 19.0 | 29.0 |
| TL-4 (a) | 36 | 68.0 | 22.0 | 38.0 | 4.0 | 18.0 | 25.0 | 36.0 |
| TL-4 (b) | between 36 and 42 | 80.0 | 27.0 | 22.0 | 5.0 | 18.0 | 30.0 | 36.0 |
| TL-5 (a) | 42 | 160.0 | 41.0 | 80.0 | 10.0 | 40.0 | 35.0 | 42.0 |
| TL-5 (b) | greater than 42 | 262.0 | 75.0 | 160.0 | 10.0 | 40.0 | 43.0 | 42.0 |
| TL 6 | | 175.0 | 58.0 | 80.0 | 8.0 | 40.0 | 56.0 | 90.0 |

References:
- TL-1 and TL-2 Design Forces are from AASHTO LRFD Section 13 Table A13.2-1
- TL-3 Design Forces are from research conducted under NCHRP Project 20-07 Task 395
- TL-4 (a), TL-4 (b), TL-5 (a), and TL-5 (b) Design Forces are from research conducted under NCHRP Project 22-20(2)

$TL := 4$ *Test level*

$F_t := 80\ kip$ *Transverse impact force*

$L_t := 5\ ft$ *Longitudinal length of distribution of impact force*

$H_e := 30\ in$ *Height of equivalent transverses load*

$H_{min} := 36\ in$ *Minimum height of a MASH TL-4 barrier*

$H_w = 42\ in$ *Height of concrete barrier*

**(2) Stability Criteria:**

$H_{min} = 36\ in$ *Minimum height of a MASH TL-4 barrier*

$H_w = 42\ in$ *Height of concrete barrier measured from the top of the roadway surface/asphalt overlay*

$$Minimum_Height_of_Barrier_Check := \begin{cases} \text{if } H_w \geq H_{min} \\ \quad \text{“OK”} \\ \text{else} \\ \quad \text{“Not OK”} \end{cases}$$

$Minimum_Height_of_Barrier_Check = \text{“OK”}$

**(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification:**

**(3a) Bending Capacity of the Barrier about the Longitudinal Axis at Midspan: $M_{cmid}$ (k-ft/ft)**

For parapet vertical reinforcement:

$b_c := 12\ in$ *Unit width of wall (take as 1 ft per AASHTO Section 13 procedure)*

$A_{vpl.mid} = 0.2\ in^2$ *Area of one parapet vertical reinforcement leg at midspan*

$S_{vp.mid} = 12\ in$ *Spacing of parapet vertical reinforcement at midspan*

$$A_{vp.mid} := \left(\frac{b_c}{S_{vp.mid}}\right) \cdot A_{vpl.mid} = 0.2\ in^2$$

*Total area of parapet vertical reinforcement per unit length at midspan*

$d_{cp.mid} = 14.063\ in$ *Average extreme distance of parapet vertical reinforcement at midspan*

$$a_{cp.mid} := \frac{A_{vp.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.294\ in$$ *Depth of Whitney stress block*

$$M_{cp.mid} := \frac{\left(A_{vp.mid} \cdot f_y \cdot \left(d_{cp.mid} - \frac{a_{cp.mid}}{2}\right)\right)}{b_c} = 13.915 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the parapet vertical reinforcement specified in Article A 13.3.1 (k-ft/ft)*

For deck anchorage reinforcement:

$b_c = 12 \ in$ *Unit width of wall (take as 1 ft per AASHTO Section 13 procedure)*

$A_{val.mid} = 0.2 \ in^2$ *Area of one deck anchorage vertical reinforcement leg at midspan*

$S_{va.mid} = 6 \ in$ *Spacing of deck anchorage vertical reinforcement at midspan*

$$A_{va.mid} := \left(\frac{b_c}{S_{va.mid}}\right) \cdot A_{val.mid} = 0.4 \ in^2$$

*Total area of deck anchorage vertical reinforcement per unit length at midspan*

$d_{ca.mid} = 22.25 \ in$ *Extreme distance of tension deck anchorage vertical reinforcement at midspan*

$$a_{ca.mid} := \frac{A_{va.mid} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588 \ in$$ *Depth of Whitney stress block*

$$M_{ca.mid} := \frac{\left(A_{va.mid} \cdot f_y \cdot \left(d_{ca.mid} - \frac{a_{ca.mid}}{2}\right)\right)}{b_c} = 43.912 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

$$M_{c.mid} := min\left(M_{cp.mid}, M_{ca.mid}\right) = 13.915 \ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at midspan when considering the critical reinforcement*

**(3b) Bending Capacity of the Barrier about the Longitudinal Axis at Joints/Ends:** $M_{ccnd}$ **(k-ft/ft)**

For parapet vertical reinforcement:

$A_{vpl.end} = 0.2\ in^2$ *Area of one parapet vertical reinforcement leg at joints/ends*

$S_{vp.end} = 6\ in$ *Spacing of parapet vertical reinforcement at joints/ends*

$A_{vp.end} := \left(\frac{b_c}{S_{vp.end}}\right) \cdot A_{vpl.end} = 0.4\ in^2$ *Total area of deck anchorage vertical reinforcement per unit length at midspan*

$d_{cp.end} = 14.063\ in$ *Average extreme distance of parapet vertical reinforcement at joints/ends (at barrier mid-height)*

$a_{cp.end} := \frac{A_{vp.end} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588\ in$ *Depth of Whitney stress block*

$$M_{cp.end} := \frac{\left(A_{vp.end} \cdot f_y \cdot \left(d_{cp.end} - \frac{a_{cp.end}}{2}\right)\right)}{b_c} = 27.537\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at Joints/ Ends when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

For deck anchorage reinforcement:

$A_{val.end} = 0.2\ in^2$ *Area of one deck anchorage vertical reinforcement leg at joints/ends*

$S_{va.end} = 6\ in$ *Spacing of deck anchorage vertical reinforcement at joints/ends*

$A_{va.end} := \left(\frac{b_c}{S_{va.end}}\right) \cdot A_{val.end} = 0.4\ in^2$ *Total area of deck anchorage vertical reinforcement per unit length at joints/ends*

$d_{ca.end} = 22.25\ in$ *Extreme distance of tension deck anchorage vertical reinforcement at joints/ends*

$$a_{ca.end} := \frac{A_{va.end} \cdot f_y}{0.85 \cdot f'_c \cdot b_c} = 0.588\ in$$ *Depth of Whitney stress block*

$$M_{ca.end} := \frac{\left(A_{va.end} \cdot f_y \cdot \left(d_{ca.end} - \frac{a_{ca.end}}{2}\right)\right)}{b_c} = 43.912\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at Joints/ Ends when considering only the deck anchorage reinforcement specified in Article A 13.3.1 (k-ft/ft)*

$$M_{c.end} := min\left(M_{cp.end}, M_{ca.end}\right) = 27.537\ \frac{kip \cdot ft}{ft}$$

*Flexural resistance of the barrier about the longitudinal axis at joints/ends when considering the critical reinforcement*

**(3c) Bending Capacity of the Barrier about the Vertical Axis: $M_w$**

$d_w = 13.563\ in$ *Effective depth of longitudinal reinforcement bars*

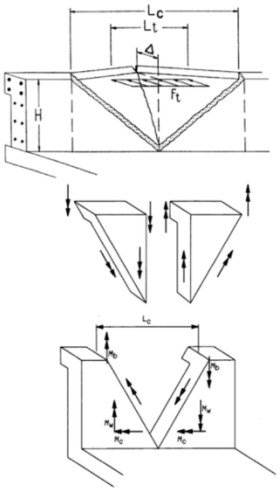
$A_w = 1.2\ in^2$ *Area of longitudinal reinforcement bars in tension*

$H_w = 42\ in$ *Extreme distance of tension longitudinal reinforcement of barrier*

$$a_w := \frac{A_w \cdot f_y}{0.85 \cdot f'_c \cdot H_w} = 0.504\ in$$ *Depth of Whitney stress block*

$$M_w := A_w \cdot f_y \cdot \left(d_w - \frac{a_w}{2}\right) = 79.862\ kip \cdot ft$$ *Flexural resistance of the barrier about the vertical axis specified in Article A 13.3.1*

**(3d) Ultimate Resistance of the Wall at Midspan: $R_{w.mid}$**




$H_w = 42\ in$ — *Height of barrier*

$M_B := 0\ kip \cdot ft$ — *No additional beam strength*

$M_{c.mid} = 13.915\ \frac{kip \cdot ft}{ft}$ — *Flexural resistance about the long. axis at midspan*

$M_w = 79.862\ kip \cdot ft$ — *Flexural resistance about the vert. axis*

$L_t = 5\ ft$ — *Long. length of distribution of impact force*

*Figure 2. Yield Line Analysis of Concrete Parapet Walls for Impact within Wall Segment (figure taken from AASHTO).*

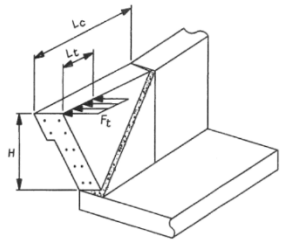
$$L_{c.mid} := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{8 \cdot H_w \cdot (M_B + M_w)}{M_{c.mid}}} = 15.421\ ft$$

*AASHTO Equation A13.3.1-2*

$$R_{w.mid} := \left(\frac{2}{2 \cdot L_{c.mid} - L_t}\right) \cdot \left(8 \cdot M_B + 8 \cdot M_w + \frac{M_{c.mid} \cdot (L_{c.mid})^2}{H_w}\right) \cdot \frac{H_w}{H_e} = 171.669\ kip$$

*AASHTO Equation A13.3.1-1*

**(3e) Ultimate Resistance of the Wall at Joints/Ends: $R_{w.end}$**




$H_w = 42\ in$ — *Height of barrier*

$M_B := 0\ kip \cdot ft$ — *No additional beam strength*

$M_{c.end} = 27.537\ \frac{kip \cdot ft}{ft}$ — *Flexural resistance about the long. axis at joints/ends*

$M_w = 79.862\ kip \cdot ft$ — *Flexural resistance about the vert. axis*

$L_t = 5\ ft$ — *Long. length of distribution of impact force*

*Figure 3. Yield Line Analysis of Concrete Parapet Walls for Impact near End of Wall Segment (figure taken from AASHTO)*

$$L_{c.end} := \frac{L_t}{2} + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{H_w \cdot (M_B + M_w)}{M_{c.end}}} = 6.55\ ft$$ *AASHTO Equation A13.3.1-4*

$$R_{w.end} := \left(\frac{2}{2 \cdot L_{c.end} - L_t}\right) \cdot \left(M_B + M_w + \frac{M_{c.end} \cdot (L_{c.end})^2}{H_w}\right) \cdot \frac{H_w}{H_e} = 144.288\ kip$$

*AASHTO Equation A13.3.1-3*

**(3) LRFD Strength Analysis of the Barrier per AASHTO Section 13 Specification - Summary of Results:**

$H_w = 42\ in$ *Height of the concrete barrier measured from the top of the roadway surface*

$H_e = 30\ in$ *Height of the transverse impact force, Ft*

$F_t = 80\ kip$ *Transverses impact force located at He*

$R_{w.mid} = 171.669\ kip$ *Ultimate resistance of the wall at midspan*

$R_{w.end} = 144.288\ kip$ *Ultimate resistance of the wall at joints/ends*

Structural_Capacity_of_Barrier_at_Midspan_Check := if $R_{w.mid} > F_t$ "OK" else "Not OK"

Structural_Capacity_of_Barrier_at_Midspan_Check = "OK"

Structural_Capacity_of_Barrier_at_Ends_Check := if $R_{w.end} > F_t$ "OK" else "Not OK"

Structural_Capacity_of_Barrier_at_Ends_Check = "OK"

**(4) Punching Shear Capacity of the Barrier:**

$\lambda := 1.0$ *Concrete weight modification factor*

$d_c := 10.55\ in$ *Depth of shear zone at height of equivalent transverse load*

$T_{w.top} := 7.625\ in$ *Top width of barrier*

$h_c := 11\ in$ *Width of shear zone*

$L_t = 5\ ft$ *Distribution width of transverse impact force*

$f'_c = 4\ ksi$ *Concrete barrier compressive strength*

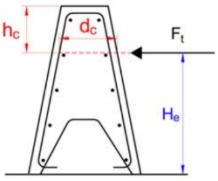



*Figure 4. Punching Shear Variables*

$$d_f := \frac{T_{w.top} + d_c}{2} = 9.088\ in$$ *Median depth of shear zone*

$$b_{o.int} := (L_t + d_c) + 2 \cdot \left(h_c + \frac{d_c}{2}\right) = 103.1\ in$$

*Median perimeter of interior critical section (AASHTO 5.8.4.3.4)*

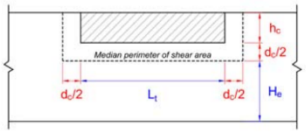



*Figure 5. Punching Shear at Interior Segment*

$$V_{c.int} := 0.125 \cdot \lambda \cdot \left(\sqrt{\frac{f'_c}{1000\ psi}} \cdot ksi\right) \cdot b_{o.int} \cdot d_f = 234.23\ kip$$

*Interior punching shear capacity (AASHTO Eq.5.8.4.3.4-3)*

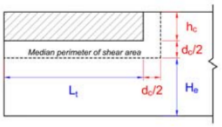



*Figure 6. Punching Shear at Exterior Segment*

$$b_{o.end} := \left(L_t + \frac{d_c}{2}\right) + \left(h_c + \frac{d_c}{2}\right) = 81.55\ in$$

*Median perimeter of exterior critical section (AASHTO 5.8.4.3.4)*

$$V_{c.end} := 0.125 \cdot \lambda \cdot \left(\sqrt{\frac{f'_c}{1000\ psi}} \cdot ksi\right) \cdot b_{o.end} \cdot d_f = 185.271\ kip$$ *Exterior punching shear capacity (AASHTO Eq.5.8.4.3.4-3)*

$V_c := min\left(V_{c.int}, V_{c.end}\right) = 185.271\ kip$ *Critical punching shear capacity*

$F_t = 80\ kip$ *Transverse impact force*

Punching_Shear_Capacity_of_Barrier_Check := if $V_c > F_t$
"OK"
else
"Not OK"

Punching_Shear_Capacity_of_Barrier_Check = "OK"

**(5) Deck Moment Capacity:**

**(5a) Deck Moment Demand:**

- The moment demand on the deck due to the TL-4 impact loading was determined using RISA-3D structral analysis.

- A solid model of the 42" barrier, as shown in Figure 5, was developed to determine the barrier loads to the deck. This model was generated with 6" wide elements in the longitudinal direction to represent the spacing of the barrier vertical reinforcements.

- The deck was modeled using meshed plate elements (8' x 50' with 6" x 6" plate elements). The reactions from the barrier to the deck were applied at the corresponding locations as shown in Figure 6.

* Detailed discussion will be provided in the final report.

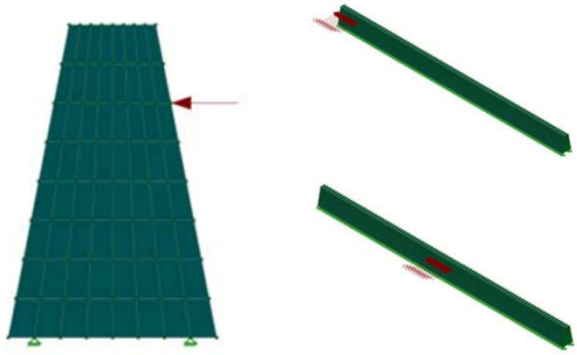


*Figure 7. Barrier Solid Model*

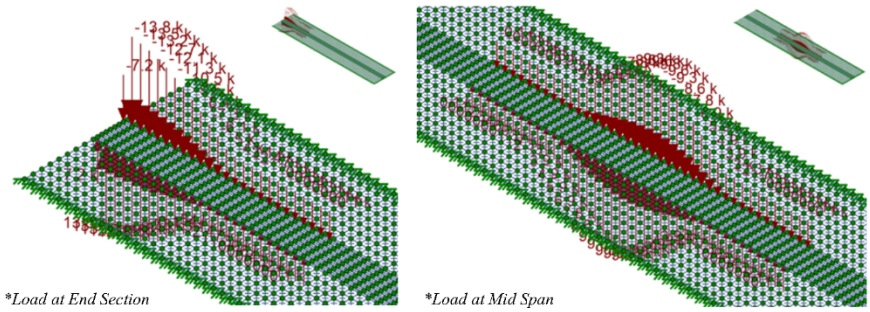
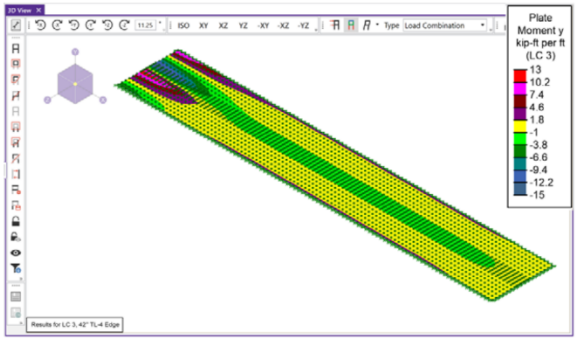


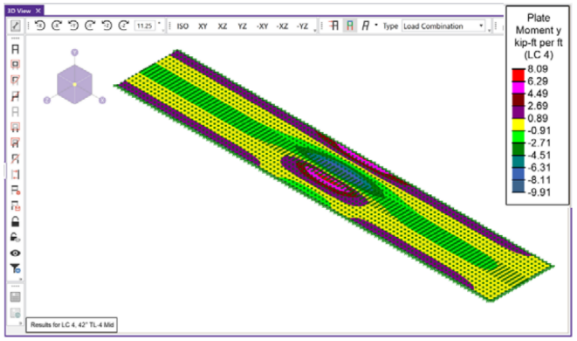

*Figure 8. Deck Plate Model with Barrier Reactions*

Deck moment demand from RISA 3-D analysis:

Max. moment demand at end-section: $M_{u.end} := 15\ kip \cdot ft$




Max. moment demand at mid-span: $M_{u.mid} := 9.91\ kip \cdot ft$




**(5b) Deck Nominal Moment Capacity:**

$b_{c.unit} := 12\ in$ *Unit width of deck*

$t_s = 8.5\ in$ *Depth of deck*

$d_{s.bot} = 6.688\ in$ *Extreme distance of deck flexural reinforcement at top*

$A_{s.bot} = 0.31\ in^2$ *Section area of deck flexural reinforcement at top*

$S_{s.bot} = 6\ in$ *Spacing of deck flexural reinforcement at top*

$A_{s.unit} := \frac{A_{s.bot}}{S_{s.bot}} \cdot b_{c.unit} = 0.62\ in^2$ *Unit area of deck flexural reinforcement at end section*

$a_s := \frac{A_{s.unit} \cdot f_y}{0.85 \cdot f'_c \cdot b_{c.unit}} = 0.912\ in$ *Depth of Whitney stress block at end section*

$M_{n.s} := A_{s.unit} \cdot f_y \cdot \left(d_{s.bot} - 0.5 \cdot a_s\right) = 19.318\ kip \cdot ft$ *Nominal moment capacity of deck*

**(5c) Deck Moment Capacity with Coincident Tensile Forces (AASHTO A 13.4.2):**

- Check at critical location: end-section

$L_{c.end} = 6.55\ ft$ *Distribution length of yield line mechanism*

$R_{w.end} = 144.288\ kip$ *Nominal resistance of barrier to transverse load*

$H_w = 42\ in$ *Height of barrier*

$T := \frac{R_{w.end}}{L_{c.end} + 2 \cdot H_w} = 10.649\ \frac{kip}{ft}$ *Coincident tensile force from vehicle impact (AASHTO Eq. A 13.4.2.-1)*

$T_a := A_{s.unit} \cdot f_y = 37.2\ kip$ *Tensile load provided by deck flexural reinforcement*

$C := T_a - T \cdot ft = 26.551\ kip$ *Resultant compression force in deck section*

$a_c := \frac{C}{0.85 \cdot f'_c \cdot b_c} = 0.651\ in$ *Depth of Whitney stress block for compression force*

$M_{n.t} := T_a \cdot \left(d_{s.bot} - \frac{a_c}{2}\right) - T \cdot ft \cdot \left(\frac{d_{s.bot}}{2} - \frac{a_c}{2}\right) = 17.044\ kip \cdot ft$

*Moment capacity of deck with coincident tensile force*

$M_{u.deck} := \max\left(M_{u.end}, M_{u.mid}\right) = 15\ kip \cdot ft$ *Maximum moment demand*

$$\text{Moment_Capacity_of_Deck_Check} := \begin{cases} \text{if } M_{n.t} > M_{u.deck} \\ \quad \text{“OK”} \\ \text{else} \\ \quad \text{“Not OK”} \end{cases}$$

$$\text{Moment_Capacity_of_Deck_Check} = \text{“OK”}$$

**(6) Reinforcement Development Length:**

$d_{b.\#4} := 0.5\ in$ ; $d_{b.\#5} := 0.625\ in$ *Bar diameter*

$$l_{db.\#4} := 2.4 \cdot d_{b.\#4} \cdot \frac{f_y}{\sqrt{f'_c \cdot \frac{1}{1000\ psi}} \cdot ksi} = 3\ ft$$

$$l_{db.\#5} := 2.4 \cdot d_{b.\#5} \cdot \frac{f_y}{\sqrt{f'_c \cdot \frac{1}{1000\ psi}} \cdot ksi} = 3.75\ ft$$

*Basic development length (AASHTO Eq. 5.10.8.2.1a-2)*

$\lambda := 1.0$ *Concrete weight modification factor*

$\lambda_{rl} := 1.0$ *Reinforcement location factor (AASHTO 5.10.8.2.1b)*

$\lambda_{cf} := 1.0$ *Coating factor (AASHTO 5.10.8.2.1b)*

$\lambda_{er} := 1.0$ *Excess reinforcement factor (AASHTO 5.10.8.2.1c)*

$k_{tr} := 0$ *Transverse reinforcement index (conservatively taken as 0 as per AASHTO C5.10.8.2.1c)*

$c_{b.\#4} := 1.75\ in$ ; $c_{b.\#5} := 1.8125\ in$ *Smaller of reinforcement edge distance and one-half of spacing*

$$\lambda_{rc.\#4} := \max\left(\frac{d_{b.\#4}}{c_{b.\#4} + k_{tr}}, 0.4\right) = 0.4 \quad ; \quad \lambda_{rc.\#5} := \max\left(\frac{d_{b.\#5}}{c_{b.\#5} + k_{tr}}, 0.4\right) = 0.4$$

*Reinforcement confinement factor , $0.4 < \lambda_{rc} < 1.0$ (AASHTO 5.10.8.2.1c)*

$$l_{d.\#4} := l_{db.\#4} \cdot \left( \frac{\lambda_{rl} \cdot \lambda_{cf} \cdot \lambda_{rc.\#4} \cdot \lambda_{er}}{\lambda} \right) = 14.4\ in$$

$$l_{d.\#5} := l_{db.\#5} \cdot \left( \frac{\lambda_{rl} \cdot \lambda_{cf} \cdot \lambda_{rc.\#5} \cdot \lambda_{er}}{\lambda} \right) = 18\ in$$

*Development lengths needed (mod.fied tension development length, AASHTO Eq. 5.10.8.2.1a-1)*

$l_{anc} := 16.4\ in$ *Anchorage reinforcement development lengths provided (#4 bar, green)*

$l_{s.top} := 60\ in$ *Deck flexural reinforcement development lengths provided (#5 bar)*

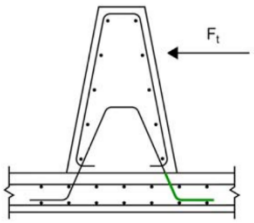



*Figure 9. Reinforcement Development Length*

$$\text{Deck_Reinforcement_Development_Length_Check} := \begin{cases} \text{if } l_{anc} > l_{d.\#4} \left\| l_{s.top} > l_{d.\#5} \right. \\ \quad \left\| \text{“OK”} \right. \\ \text{else} \\ \quad \left\| \text{“Not OK”} \right. \end{cases}$$

Deck_Reinforcement_Development_Length_Check = “OK”

**(7) Analysis Results Overview:**

Minimum_Height_of_Barrier_Check = “OK”

Structural_Capacity_of_Barrier_at_Midspan_Check = “OK”

Structural_Capacity_of_Barrier_at_Ends_Check = “OK”

Punching_Shear_Capacity_of_Barrier_Check = “OK”

Moment_Capacity_of_Deck_Check = “OK”

Deck_Reinforcement_Development_Length_Check = “OK”

**(8) Summary of Barrier Design:**

1. Use Vertical Barrier Stirrup #4 @ 6" O.C. for 10'-0" at Barrier End Section

2. Use Vertical Barrier Stirrup #4 @ 12" O.C. out at Mid-Section (greater than 10'-0" from End Sections)

3. All other details as shown on Section and Elevation Views as provided herein for the 42" Barrier as analyzed herein are acceptable for MASH TL-4 Impact conditions.