TECHNICAL MEMORANDUM: THRIE-BEAM RETROFIT PHASE 2 - APPLICATION OF A NEW DESIGN WITHOUT A CURB FOR *MASH* TL-3 AND PERFORMANCE AND IMPROVEMENTS FOR *MASH* TL-4 (TTI PROJECT 619601)

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Roadside Safety Pooled Fund

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	Square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lb/in^2

*SI is the symbol for the International System of Units

CHAPTER 1.

INTRODUCTION & BACKGROUND

1.1. PROBLEM STATEMENT AND BACKGROUND

Many bridge rails in the United States are outdated with respect to the Manual for Assessing Safety Hardware (*MASH* [1]). It is not economically feasible to completely replace the obsolete bridge rails with newer *MASH*-compliant designs. Oftentimes, state transportation agencies may need to utilize a crash-worthy bridge rail that is retrofit to the existing bridge deck when an obsolete bridge railing needs to be replaced for a *MASH*-compliant bridge rail system.

In the preceding research (referred to as 'Phase 1' herein), TTI has designed and successfully crash-tested a new Thrie-beam retrofit bridge rail design to be used on obsolete bridges [2]. Details of Phase 1 crash-tested design are shown in Figure 1.1.

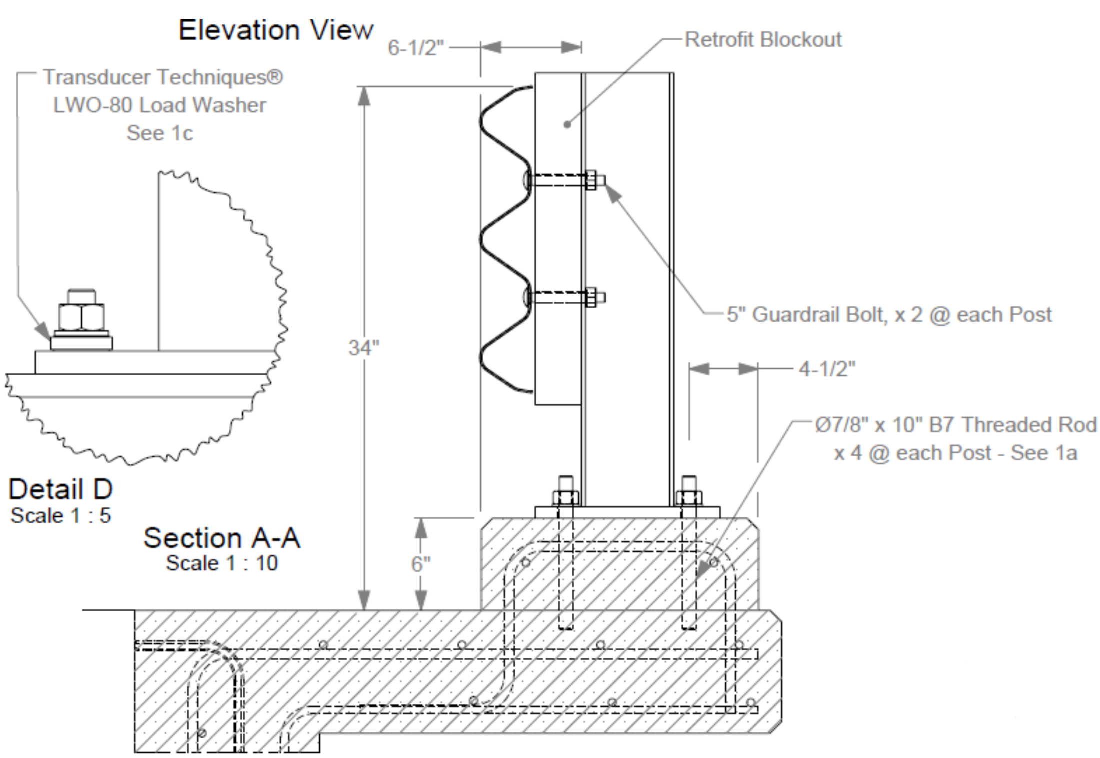


Figure 1.1. Details of Thrie-beam Bridge Rail Retrofit [2]

Actual conditions on bridges may vary from this as-tested design. Several conditions such as no curb, taller curb, wider curb, changes in deck thickness and reinforcing steel, and the location of existing obsolete bridge rails left in place will differ from the as-tested design. Thus, following questions arose to apply this Thrie-beam bridge rail retrofit for more bridge conditions:

- Can the as-tested design be used for bridge rails without a curb at TL-3?
- How does the as-tested design perform for *MASH* TL-4?
- What changes are needed to the as-tested design to meet *MASH* TL-4?

In the present project (Phase 2), TTI researchers conducted a study to answer these questions using LS-DYNA simulations.

1.2. OBJECTIVE

The main objective of this project will be to perform LS-DYNA simulations on the as-tested design using no curb for *MASH* TL-3. If necessary, modification(s) will be made to the design to improve performance to meet *MASH* TL-3 specifications. In addition, LS-DYNA simulations will be performed on the as-tested design for *MASH* Test 4-12. If necessary, modification(s) will be made to the design to improve performance for *MASH* Test 4-12.

1.3. BENEFITS

The main benefit of this project will be to expand the use of a new Thrie-beam retrofit system to bridge rails without a curb to meet the crash requirements of *MASH* TL-3. Also, this project will investigate if a new Thrie-beam retrofit system can be used for *MASH* TL-4 and explore what changes are needed (if any) to the as-tested design to improve performance for satisfying *MASH* TL-4. This will provide broader retrofit options using a new Thrie-beam for more existing bridge rails.

1.4. PRODUCTS

Brief letter report summarizing the simulation efforts, design, and details for both the no curb *MASH* TL-3 design and the *MASH* TL-4 design (2 designs). Professional opinions (separate tasks outside the scope and funding for this project, for each) can be provided for the following conditions:

- Taller curb (approx. 9 inches)
- Wider curb (approximately 24 inches)

- Substandard bridge deck conditions (thinner deck, less reinforcing, lower compressive strength (1 case here for further review after the results are reviewed from this project).
- Existing obsolete bridge rails that are left in place, i.e., reviewing the working width from the TL-3 crash test to determine if existing rails left in place will influence performance.

1.5. WORK PLAN

For this project, TTI investigates whether the as-tested Thrie-beam retrofit design bridge rail without a curb meets *MASH* TL-3 requirements. The as tested Thrie-beam retrofit design will be modified accordingly to meet the *MASH* specifications if necessary. Also, the application of the as-tested Thrie-beam for *MASH* TL-4 specification will be explored. TTI plans to develop engineering drawings of the proposed details using SolidWorks. The crashworthiness of proposed designs will be evaluated using LS-DYNA simulation to examine that required *MASH* test level requirements are met for each design. This project focuses on developing engineering design details and evaluating crashworthiness using computer simulation; no testing is planned for this project. The work plan is as follows:

1.) Task 1: Engineering Analyses & Detailing of Retrofit Designs for *MASH* TL-4 - TTI will develop details of the new Thrie-beam retrofit system without a curb. Particularly, TTI proposes connection details between existing deck and Thrie-beam bridge rail retrofit. The proposed design will be analyzed as per the strength analysis of the current AASHTO LRFD, Section 13 Design Specifications [3] and modified accordingly to meet *MASH* TL-3 requirements. The strength analysis using *MASH* TL-4 loading conditions will be also performed on the as-tested design, and modifications will be proposed if necessary for *MASH* TL-4.

2.) Task 2: TTI will prepare engineering drawings of the proposed details for both designs from Task 1 using SolidWorks.

3.) Task 3 – Simulations of As-Tested Design without a Curb for *MASH* TL-3 - TTI will perform crashworthiness evaluation on the as-tested Thrie-beam bridge rail retrofit with no curb at *MASH* TL-3. TTI will generate simulation models using LS-DYNA and assess evaluation criteria including structural adequacy and occupant risk. Design modification will be proposed if necessary.

4.) Task 4 – Simulations of AS-Tested Design with a Curb for *MASH* TL-4 - Same as Task 3, TTI will perform crashworthiness evaluation on the as-tested Thrie-beam bridge rail retrofit at *MASH* TL-4. TTI will generate simulation models using LS-DYNA and assess evaluation criteria including structural adequacy and occupant risk. Design modification will be proposed if necessary.

5.) Task 5 – Brief Letter Report Summarizing the from Tasks 1 to 4 – TTI will prepare a brief letter report summarizing the results from Task 1 1 to 4.

CHAPTER 2.

FINITE ELEMENT MODEL DEVELOPMENT

For this project LS-DYNA computer simulations were performed to determine the predictive behavior of the designs evaluated for this study. The FE models developed for this project were developed using the same conditions as a full-scale crash testing to compare the results. Representative vehicle models for the small car (*MASH* Tests 3-10 and 4-10) and the pickup truck (*MASH* Test 3-11 and 4-11), and single unit truck (*MASH* Test 4-12) were used for this project. A discussion of the simulations performed on the various systems investigated for this project are discussed as follows in Chapter 3.

3D finite element models of two bridge rail systems were developed. LS-PrePost was used as the primary tool to develop the models. The first model represented the full-scale system that was tested and evaluated with full-scale crash testing (*2*). Another variation of the crash tested system was developed that did not include a curb. Figure 2.1 through Figure 2.4 shows the finite element model of the Thrie-beam Retrofit system. Figure 2.5 and Figure 2.6 shows the finite element model of the Thrie-beam Retrofit system without a curb.

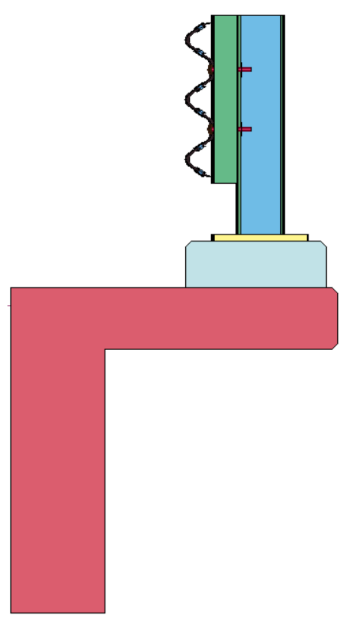


Figure 2.1. End View of Thrie-beam Retrofit Finite Element Model.

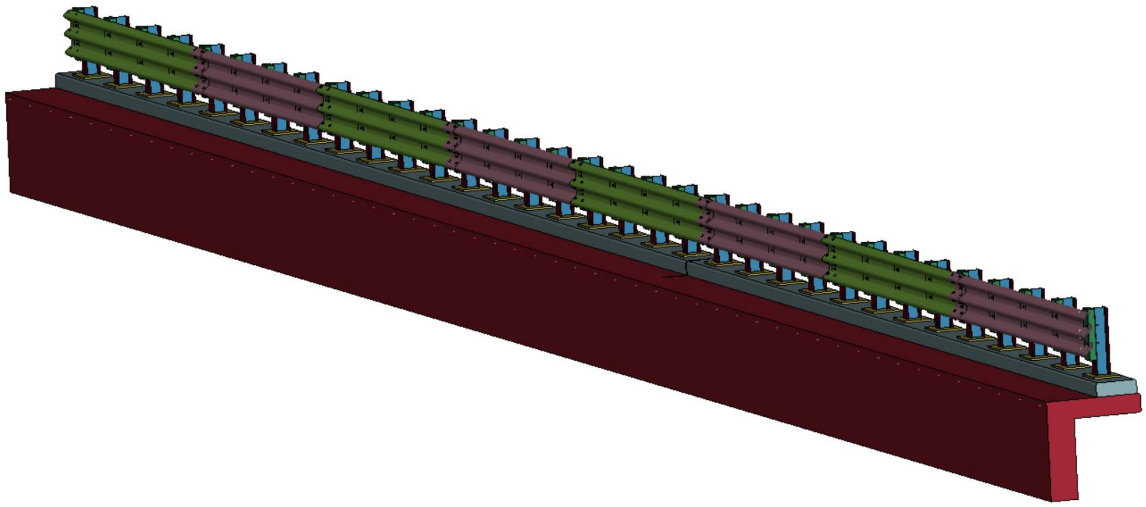


Figure 2.2. Overall View of Thrie-beam Retrofit Finite Element Model.

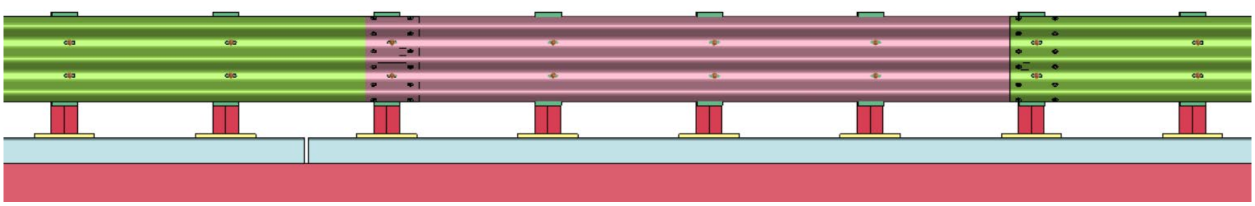


Figure 2.3. Side View of Thrie-beam Retrofit Finite Element Model.

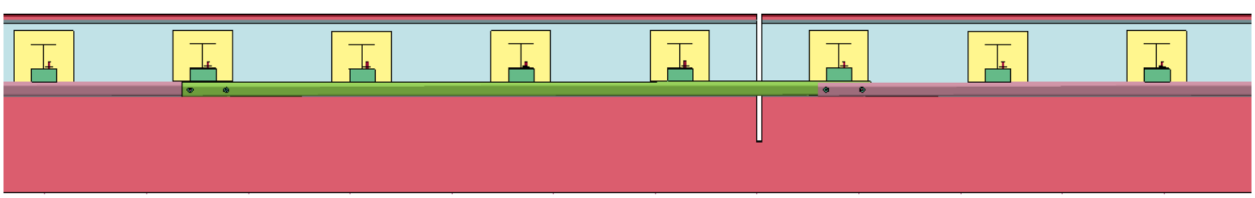


Figure 2.4. Top View of Thrie-beam Retrofit Finite Element Model.

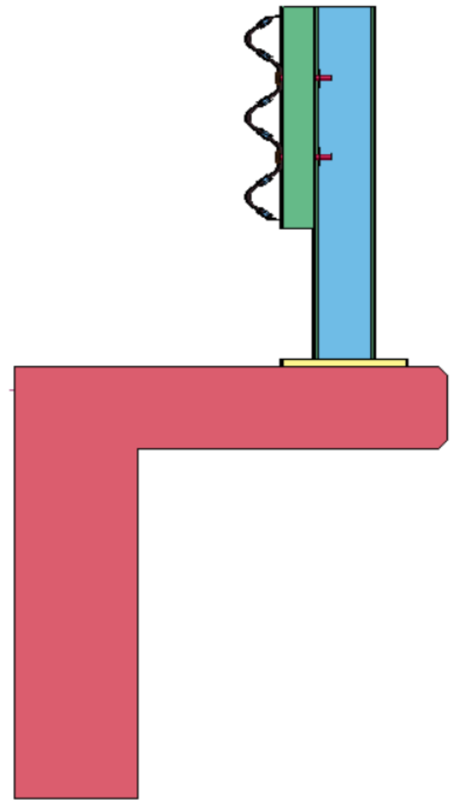


Figure 2.5. End View of Thrie-beam Retrofit (without Curb) Finite Element Model.

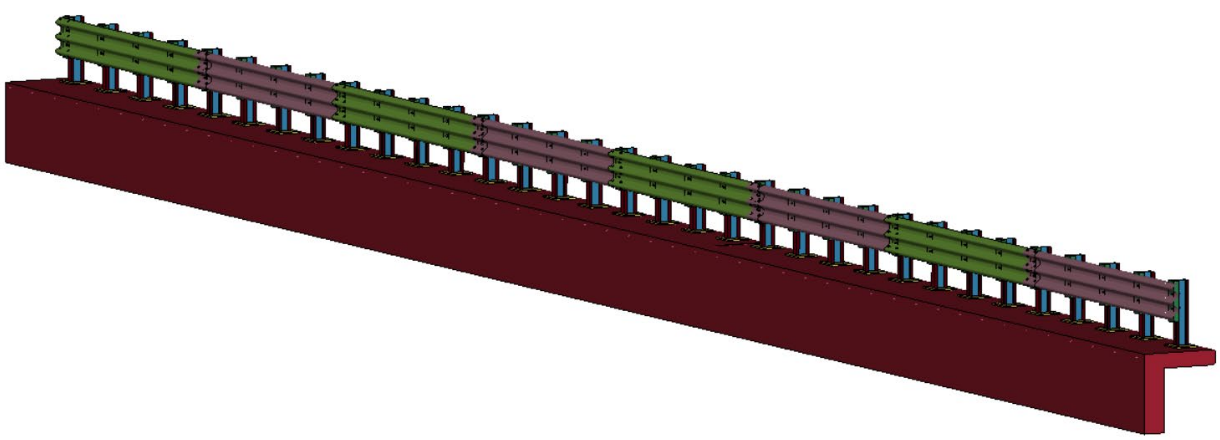


Figure 2.6. Overall View of Thrie-beam Retrofit (without Curb) Finite Element Model.

The concrete deck and curb were modeled with Solid elements and MAT_CSCM_Concrete. A concrete strength of 3300 psi was used in the model. A damage-based failure criterion was incorporated into the material model to allow for the prediction of concrete damage. The reinforcement was modeled with Beam elements and MAT_PIECEWISE_LINEAR_PLASTICITY. A 40 ksi yield strength was used for the reinforcement. The steel posts and Thrie-beam rail were modeled with shell elements and MAT_PIECEWISE_LINEAR_PLASTICITY. The wood blockouts were modeled with solid elements and MAT_ELASTIC. A boundary condition was applied on the end of the deck to simulate attachment to a bridge deck superstructure.

CHAPTER 3.

COMPUTER SIMULATIONS

Finite element analysis of the models was performed using impact computer simulations. The simulations were conducted using LS-DYNA, a commercial general purpose nonlinear finite element analysis code capable of simulating complex engineering systems with impact-contact phenomena.

Two systems were evaluated with finite element computer simulations. First, the Thrie-beam Retrofit finite element was evaluated according to *MASH* TL-4. This consisted of conducting a *MASH* Test 4-12 impact with the computer simulations. Second, the Thrie-beam Retrofit without a curb finite element model was evaluated according to *MASH* TL-3. The finite element computer simulation evaluation of the systems is presented in the below sections.

3.1. FINITE ELEMENT MODEL VALIDATION

To validate the behavior of the finite element developed and discussed in Chapter 2, computer simulations were performed replicating the previous full-scale crash test *MASH* Test 3-11 impact conditions (*2*). The impact speed was 62.0 mi/h and the impact angle was 25.1 degrees. The impact location was 8.2 ft upstream of the centerline of post 16.

Figure 3.1 and Figure 3.2 show a comparison of the computer simulation and full-scale crash impact. The computer simulation indicated similar performance to the full-scale crash test. The computer simulation vehicle was redirected and showed similar vehicle kinematics to the full-scale crash test. The occupant risk factors were comparable (Table 3.1) between the computer simulation and full-scale crash test.

Overall, the finite element indicated similar behavior and characteristics when compared to the full-scale crash test. Thus, this finite element model was used in the predictive computer simulations presented in the later sections in this chapter.

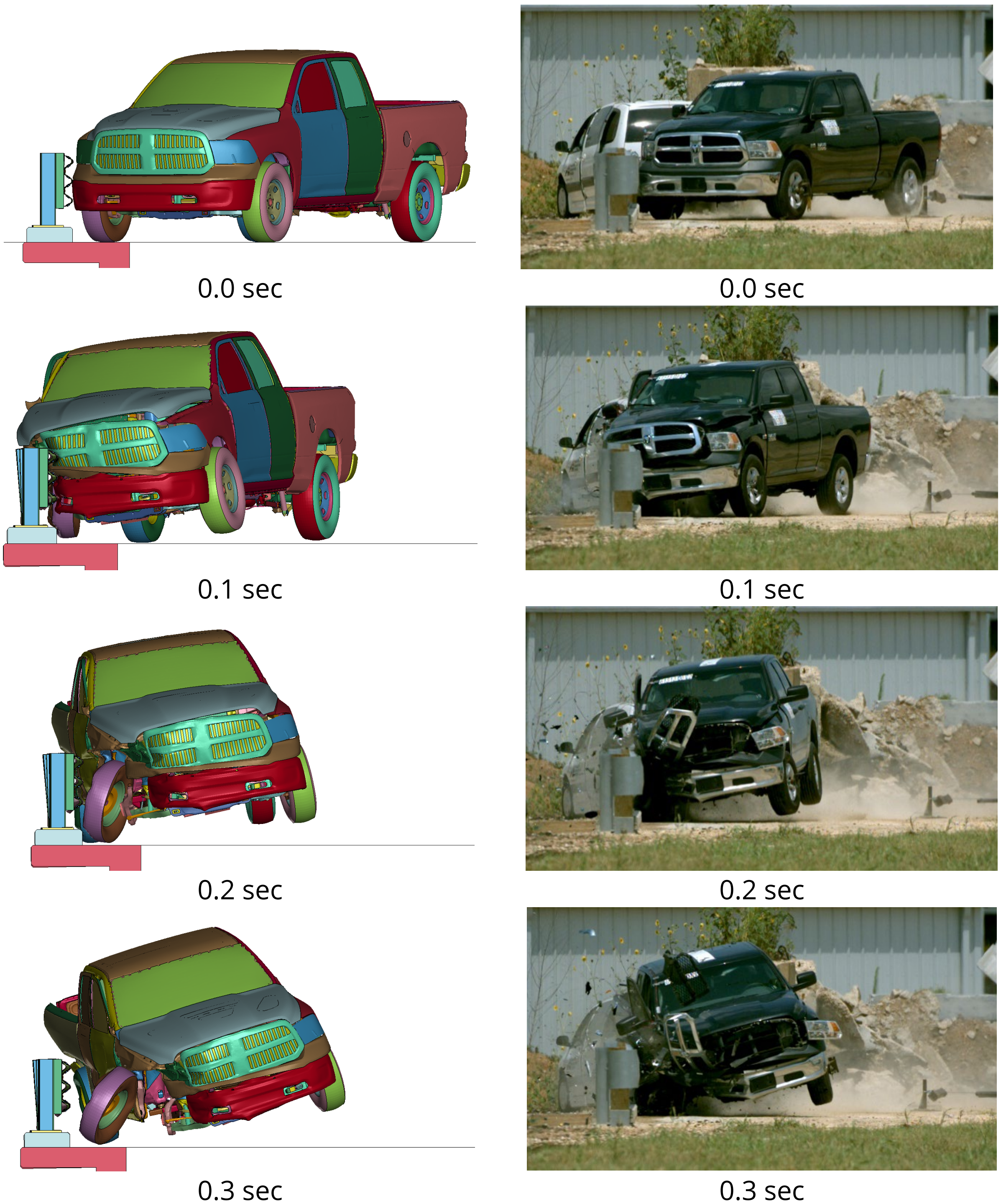


Figure 3.1. Comparison of FE Computer Simulation and Full-Scale Crash Test (Gut View).

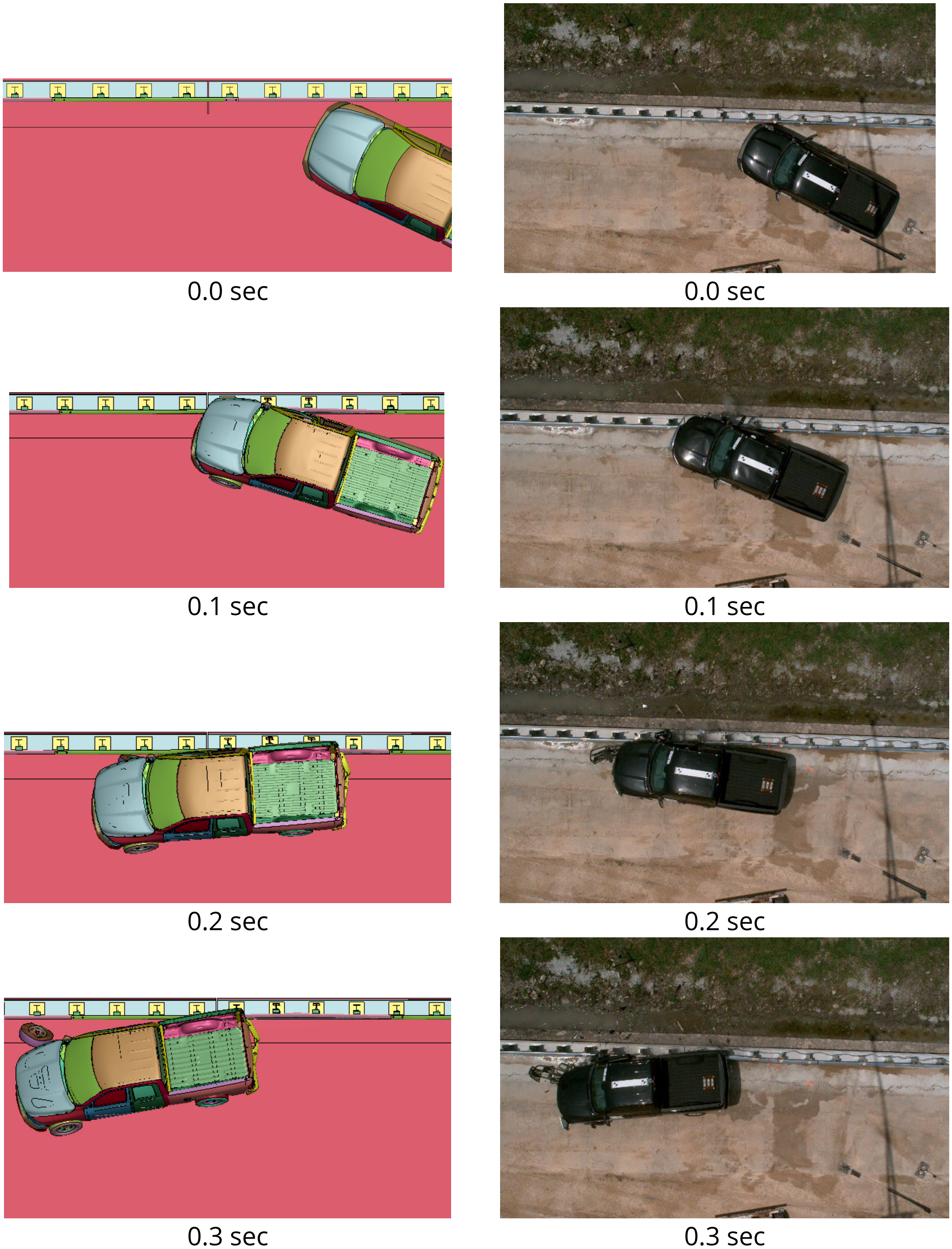


Figure 3.2. Comparison of FE Computer Simulation and Full-Scale Crash Test (Overhead View).

Table 3.1. Comparison of Occupant Risk Factors for Full-Scale Crash Test and FE Computer Simulation.

Test Parameter	Crash Test	Computer Simulation
OIV, Longitudinal (ft/s)	26.3	18.7
OIV, Lateral (ft/s)	25.3	28.6
Ridedown, Longitudinal (g)	8.2	3.4
Ridedown, Lateral (g)	7.6	14.7
Roll (deg.)	20.0	22.1
Pitch (deg.)	9.0	4.1
Yaw (deg.)	41.0	37.5

3.2. THRIE-BEAM RETROFIT - *MASH* TL-4 EVALUATION

To evaluate the performance of the Thrie-beam Retrofit bridge rail system under *MASH* TL-4 conditions, a series of computer simulations for *MASH* Test 4-12 with the SUT vehicle model was performed. This system was previously evaluated with full-scale crash testing according to *MASH* Test 3-11 (*2*). Thus, there was no need to perform computer simulations with the small car (*MASH* Test 4-10) or pickup truck (*MASH* Test 4-11) vehicle impacts.

The SUT vehicle impacted the bridge rail at an impact speed and angle of 56 mi/h and 15 degrees. The impact point was 5 ft upstream of middle of the bridge deck where the concrete joint exists. This impact point maximized the damage on bridge deck and was considered the critical impact point for testing.

Based on the results of the simulations, several design changes were made to improve the performance of the bridge rail system. These changes were then also modeled and new impact simulations were performed to arrive at the final retrofit design to make a recommendation for full-scale crash testing.

3.2.1. As-Tested Design with a Curb

First, the researchers performed *MASH* Test 4-12 simulation on the *MASH* TL-3 compliant bridge railing system which was tested in the previous project [2].

Based on the computer simulation, the bridge rail deflection was minor: the maximum dynamic and permanent deflection of the guardrail system was 4 inches and 3.26 inches, respectively. However, the box of SUT excessively leaned over the rail with the maximum intrusion width of 10.73 ft. When the front bottom corner of the box was torn and tended to go over the rail, the cab also engaged with the rail and tended to go over the rail. Figure 3.3 shows the vehicle behavior at impact and maximum box lean. Since the as-tested system could not contain the vehicle and could not meet *MASH* TL-4 evaluation criteria, the researchers decided to increase the rail height to improve the vehicle stability during impact.

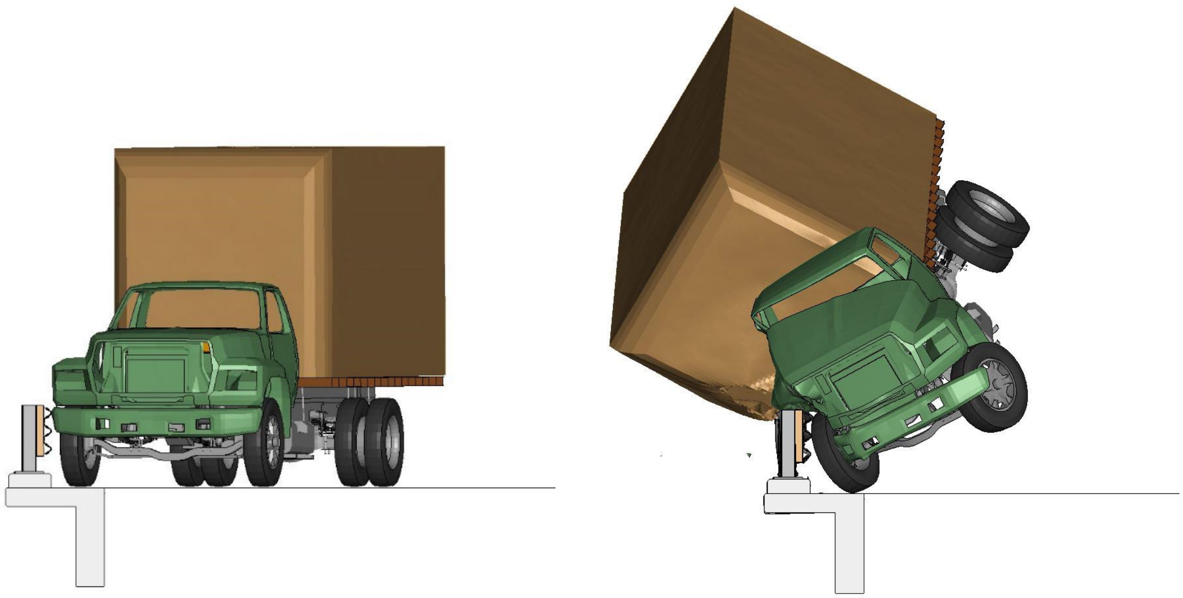


Figure 3.3. Test 4-12 Simulation Images for 34-inch Tall Thrie-beam System.

3.2.2. Different Heights

To investigate the performance of the Thrie-beam rail with a taller rail height, the height of the Thrie-beam rail was increased to 38 inches. The 38-inch tall system was evaluated with the same impact conditions.

Figure 3.4 shows the simulation images showing when impacting the rail and when the maximum intrusion was observed. Similar to the as-tested system, when the front bottom corner of the box hit the rail, the box overrode the rail, and the system likely failed to contain the vehicle. The maximum intrusion width was 10.7 ft, which was not different from that for the as-tested system. The 38-inch tall system did not indicate satisfactory performance in redirecting and containing the SUT vehicle. Thus, the researchers increased the rail height by an additional 4 inches to improve vehicle stability.

(a) initial impact (b) maximum vehicle lean

Figure 3.4. Test 4-12 Simulation Images for 38-inch Tall Thrie-beam System.

As shown in Figure 3.5, the SUT vehicle was successfully contained and redirected in the simulation with the 42-inch tall system. The maximum dynamic and permanent deflection of the guardrail system was 5.3 inches and 3.8 inches, respectively. The maximum intrusion width was 9.5 ft, which is 1.2 ft (approximately 15 inches) less than that for both the as-tested system and the 34-high system. Based on the simulation results, the Thrie-beam system with a 42-inch height could be expected to pass *MASH* Test 4-12 evaluation criteria in a full-scale crash test.

(a) initial impact (b) maximum lean (c) vehicle exit

Figure 3.5. Test 4-12 Simulation Images for 42-inch Tall Thrie-beam System.

As the height of the barrier increases, there is less vehicle roll and more floor box is engaged in the impact, thereby increasing the impact load (shown in Figure

3.4). At a 36-inch and 38-inch rail height, the box overrides and over-engaged to the rail, while the box floor contact the rail in early stage and contained and redirected vehicle at 42-inch high rail.

(a) 34-inch rail height (b) 38-inch rail height (c) 42-inch rail height

Figure 3.6. Contact Area Comparison Depending on Rail Height.

After evaluating the performance of the Thrie-beam retrofit system according to *MASH* Test 4-12, it was necessary to evaluate the performance according to *MASH* Test 4-11 to determine the effect of the increased rail height.

A *MASH* Test 4-11 computer simulation was performed with pickup truck vehicle model impacting the 42-inch tall Thrie-beam system. Due to the large opening between the Thrie-beam and curb, the impact side front tire was snagged, and the vehicle could not be redirected as shown in Figure 3.7. Thus, it was recommended to modify the system to improve the performance for the *MASH* Test 4-11 impact conditions.

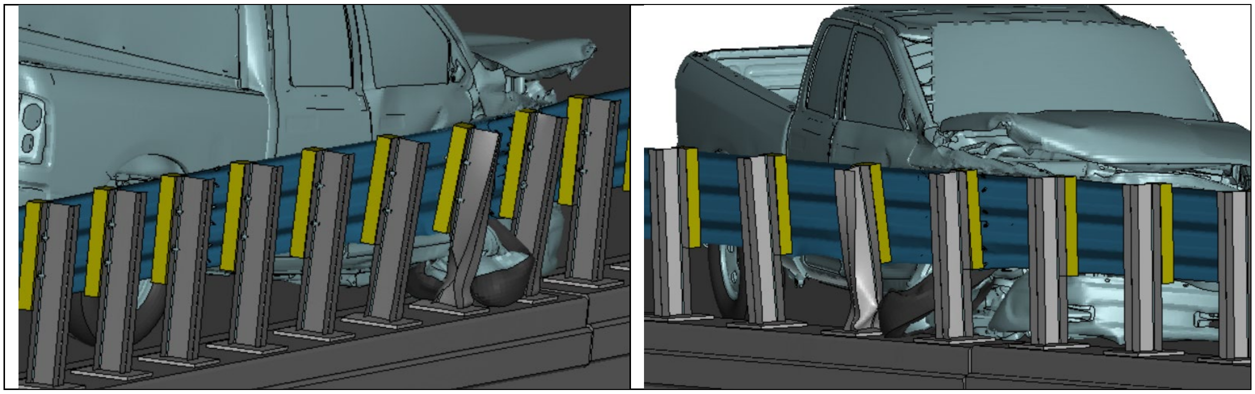
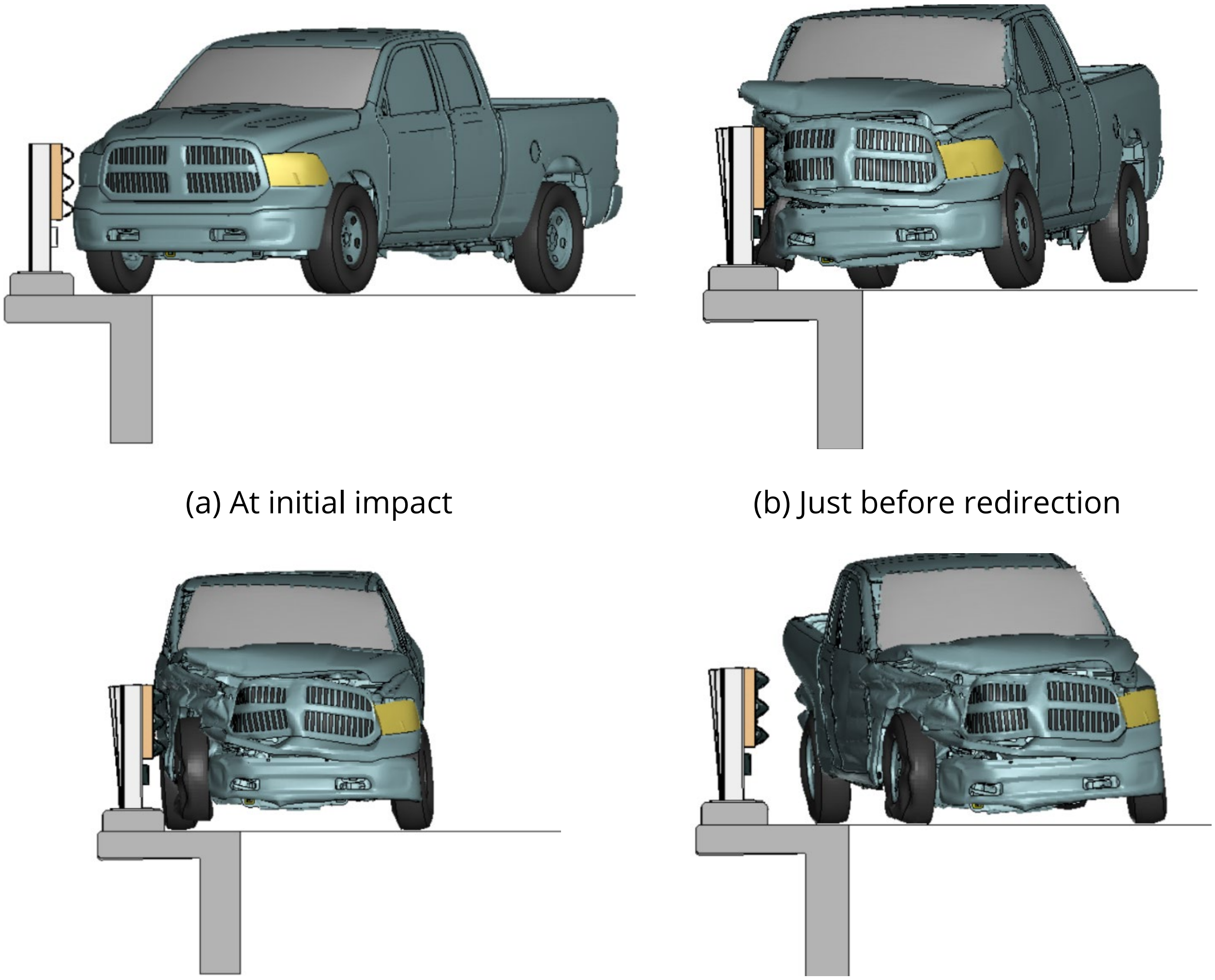


Figure 3.7. *MASH* Test 4-11 Computer Simulation with 42-inch Tall Thrie-beam System.

3.2.3. 42-inch Tall Thire Beam Retrofit System with Rubrail

While the 42-inch tall Thrie-beam retrofit system performed adequately for *MASH* Test 4-12, the performance was unsatisfactory for *MASH* Test 4-11 due to the large opening between the curb and the bottom of the rail. This large opening allowed severe wheel snag and high vehicle accelerations. Therefore, the researchers decided to retrofit the 42-inch tall Thrie-beam system.

The first modification option was to add a rubrail to the 42-inch Thrie-beam system. *MASH* Test 4-11 was performed for the 42-inch Thrie-beam system with a rubrail. Figure 3.8 shows the sequential images for the simulation performed on the 42-inch Thrie-beam system with a rubrail.



(a) At initial impact

(b) Just before redirection

(c) Vehicle parallel to the system

(d) vehicle exiting the system

Figure 3.8. Test 4-11 Simulation on 42-inch Thrie-beam System with Rubrail.

The vehicle was successfully contained and redirected without tire snagging. However, no *MASH* compliant transition system can be used to connect the Thrie-beam system higher than 36 inches to a *MASH* compliant W-beam system and terminal. Therefore, the research team and technical representatives decided to add a hollow structural section (HSS) tube to the top of the as-tested Thrie-beam rail system. This would allow the top of the Thrie-beam rail to stay at 34 inches. This modified system was evaluated as discussed in the next section.

3.2.4. 42-inch Tall Thire Beam Retrofit System with Top HSS Tube

A previous research study was performed that developed a *MASH* TL-4 compliant guardrail system. The system included a HSS tube attached to the top of a standard W-beam guardrail system to increase the rail height. The system successfully met the *MASH* TL-4 evaluation criteria [3]. A transition system for the upper tube was also successfully tested and evaluated for *MASH*. This *MASH* TL-4 design concept will be referred as TxDOT *MASH* TL-4 guardrail system herein.

To increase the height of the Thrie-beam retrofit system and maintain the 34-inch Thrie-beam rail height, a design concept of TxDOT *MASH* TL-4 guardrail system was adapted. An HSS (10-inch x 4-inch x ¼-inch) rail was added to the top of the as-tested Thrie-beam system (34 inches tall). This resulted in an increased overall system height of 43 inches. Figure 3.9 shows a detailed drawing layout of the modified system. This modified design keeps Thrie-beam at 34 inches high from the deck and enables use of the existing *MASH* compliant transition system to connect a Thrie-beam rail to a standard W-beam guardrail and terminal system.

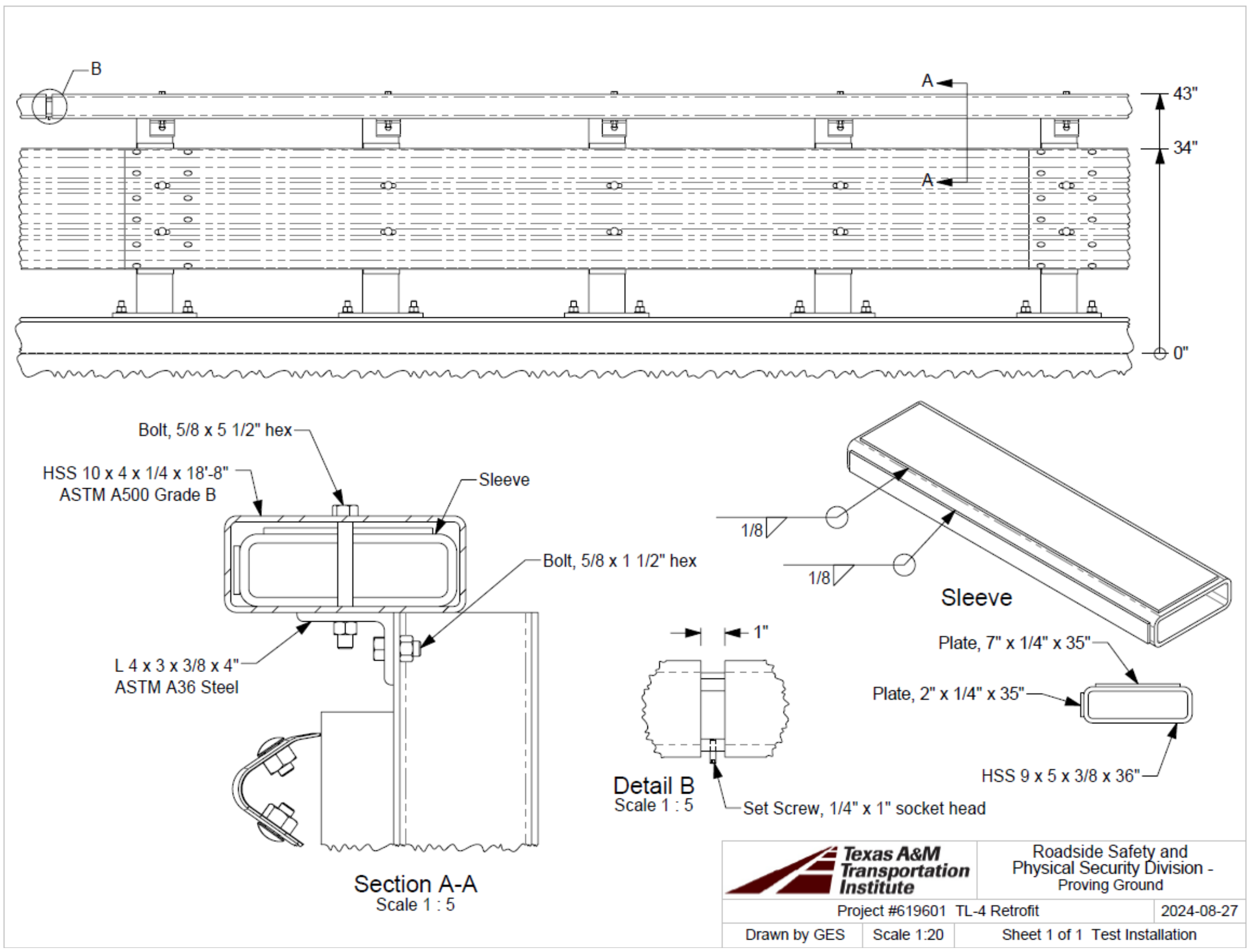
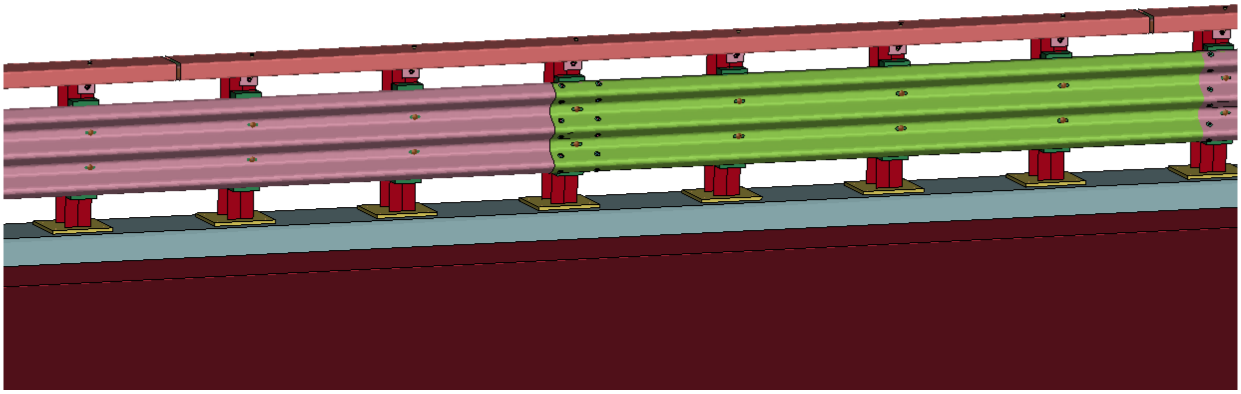


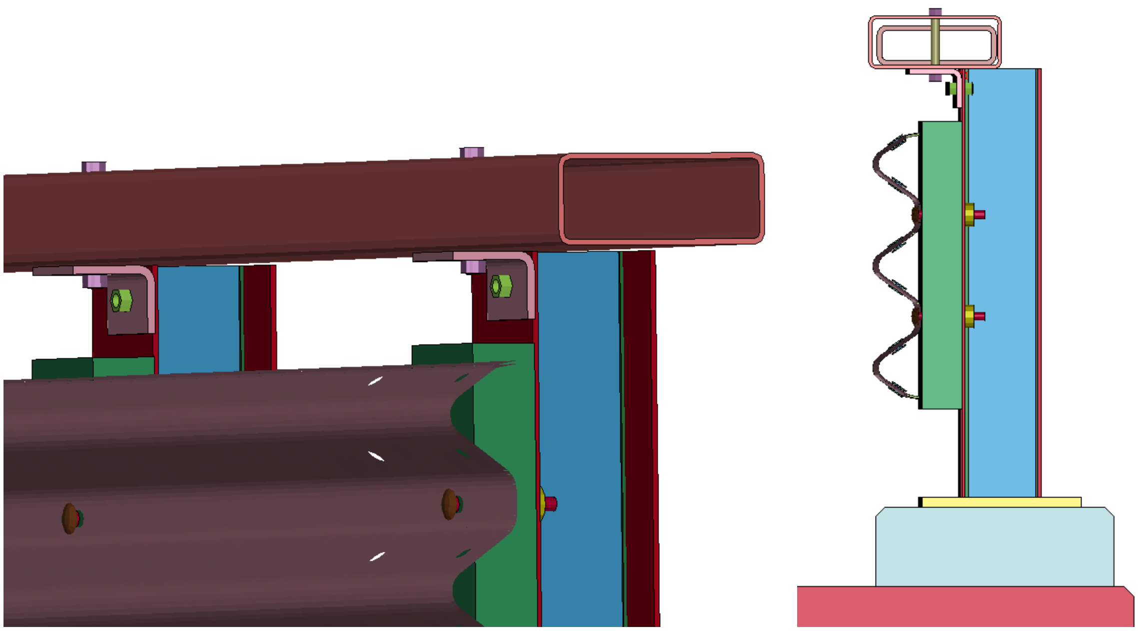
Figure 3.9. *MASH* TL-4 Thrie-beam Bridge Rail Design Retrofitted by HSS Tube.

To evaluate the crashworthiness of the retrofitted system, a finite element model was developed, and a *MASH* Test 4-12 simulation was performed on the retrofitted system.

The HSS tubular rail and HSS rail attachment brackets were represented with elastic-plastic material models. The HSS beam in the model was unrestrained at each end of the model because the HSS rail tube primarily works by providing lateral bending stiffness to the system and does not require anchoring at the ends. Figure 3.10 presents images of the overall guardrail system model, as well as closer details of the various key components of the model.



(a) Overall System



(b) Detailed Retrofit Components: HSS rails, L-bracket

Figure 3.10. *MASH* TL-4 Thrie-beam Retrofitted Design.

MASH Test 4-12 impact simulation with the SUT model was performed on the developed FE model. The vehicle impacted the bridge rail at an impact speed and angle of 56 mi/h and 15 degrees. The previously determined impact point of 5 ft upstream of a post was used.

Results of the simulation are presented in Figure 3.11. The SUT vehicle was successfully contained and redirected in the simulation. The maximum dynamic deflection of the guardrail system was 17.7 inches. The permanent deflection was 15.3 inches. Results of the simulation showed that the modified Thrie-beam retrofit design should be considered satisfactory for *MASH* Test 4-12 evaluation criteria.

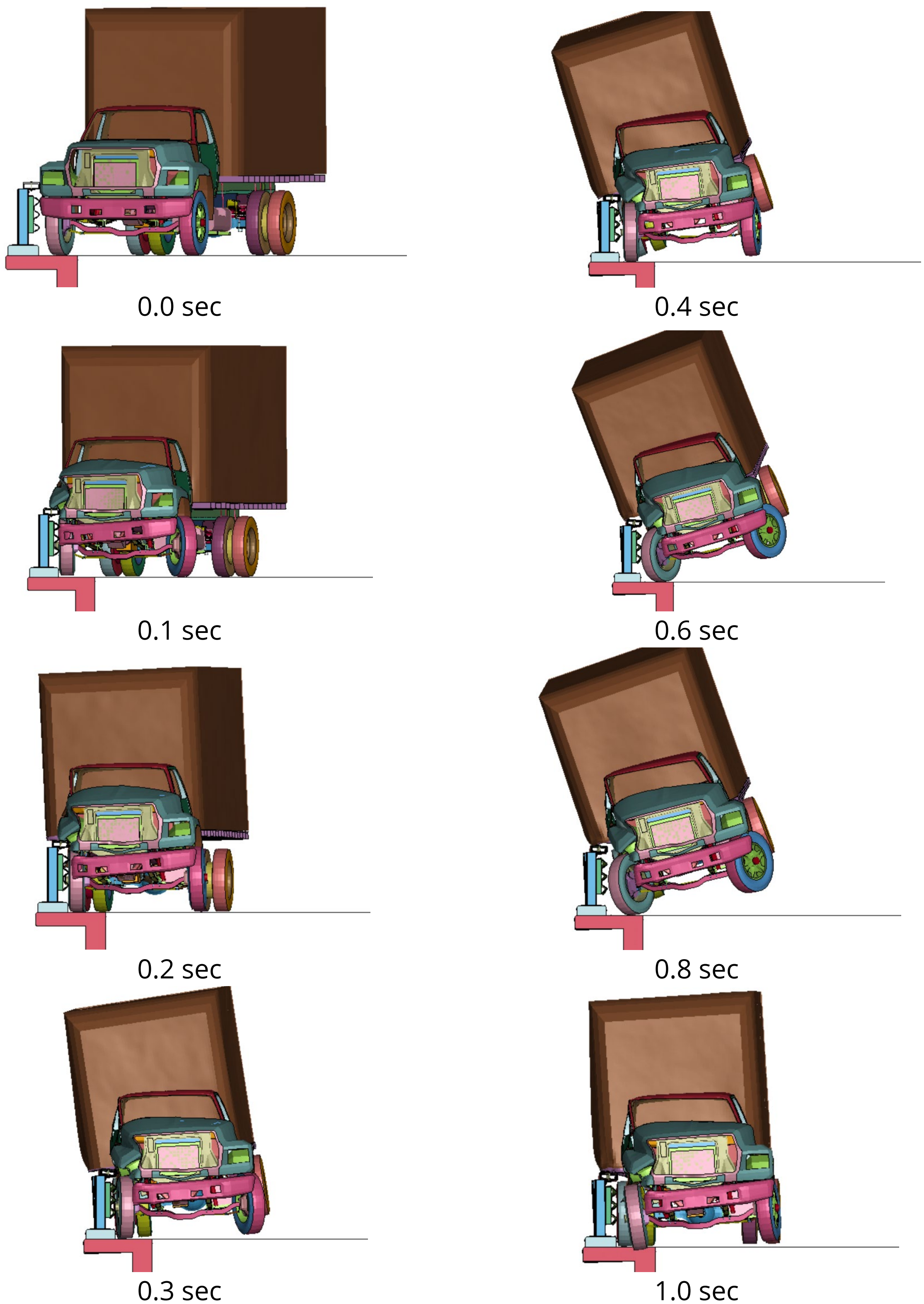


Figure 3.11. FE Simulation Sequential Images for Retrofitted Thrie-beam System.

The impact simulations for *MASH* Tests 4-10 and 11 with the small car and the pickup truck model were not performed. Since the Thrie-beam system with a 34-inch tall rail height has already met *MASH* TL-3 evaluation criteria (*2*), the retrofitted system is expected to provide satisfactory performance when the small car and the pickup truck impact the system.

Based on the impact simulation results presented herein, the research team recommends performing full-scale *MASH* TL-4 testing with the retrofitted Thrie-beam system as a next step.

3.3. THRIE-BEAM RETROFIT WITHOUT CURB - *MASH* TL-3 EVALUATION

To evaluate the performance of the Thrie-beam Retrofit bridge rail system without a curb under *MASH* TL-3 conditions, a series of computer simulations for *MASH* Test 3-10 with the small car model and *MASH* Test 3-11 with the pickup truck model were performed. The vehicles impacted the bridge rail at an impact speed and angle of 62 mi/h and 25 degrees. The impact point was 3.6 ft upstream of the concrete joint for the Test 3-10 computer simulation. The impact point was 4.3 ft upstream of the concrete joint for the Test 3-11 computer simulation.

Figure 3.10 present sequential images from the Test 3-10 simulation impact event. The bridge rail system successfully contained and redirected the small car vehicle. The vehicle remained stable throughout the impact event. Table 3.1 shows the occupant risk parameters. The occupant risk values were within the *MASH* limits. The Thrie-beam Retrofit system without a curb indicated satisfactory performance for *MASH* Test 3-10.

Figure 3.11 present sequential images from the Test 3-11 simulation impact event. The bridge rail system successfully contained and redirected the pickup truck vehicle. The vehicle remained stable throughout the impact event. Table 3.2 shows the occupant risk parameters. The occupant risk values were within the *MASH* limits. The Thrie-beam Retrofit system without a curb indicated satisfactory performance for *MASH* Test 3-11.

Based on the results of the simulations, the small car and the pickup truck performed acceptably with respect to the *MASH* criteria for *MASH* Tests 3-10 and 3-11. Thus, the Thrie-beam Retrofit system without a curb should be considered acceptable as a *MASH* TL-3 compliant bridge rail system.

Figure 3.12. FE Simulation Sequential Images for Thrie-beam System without Curb – *MASH* Test 3-10.

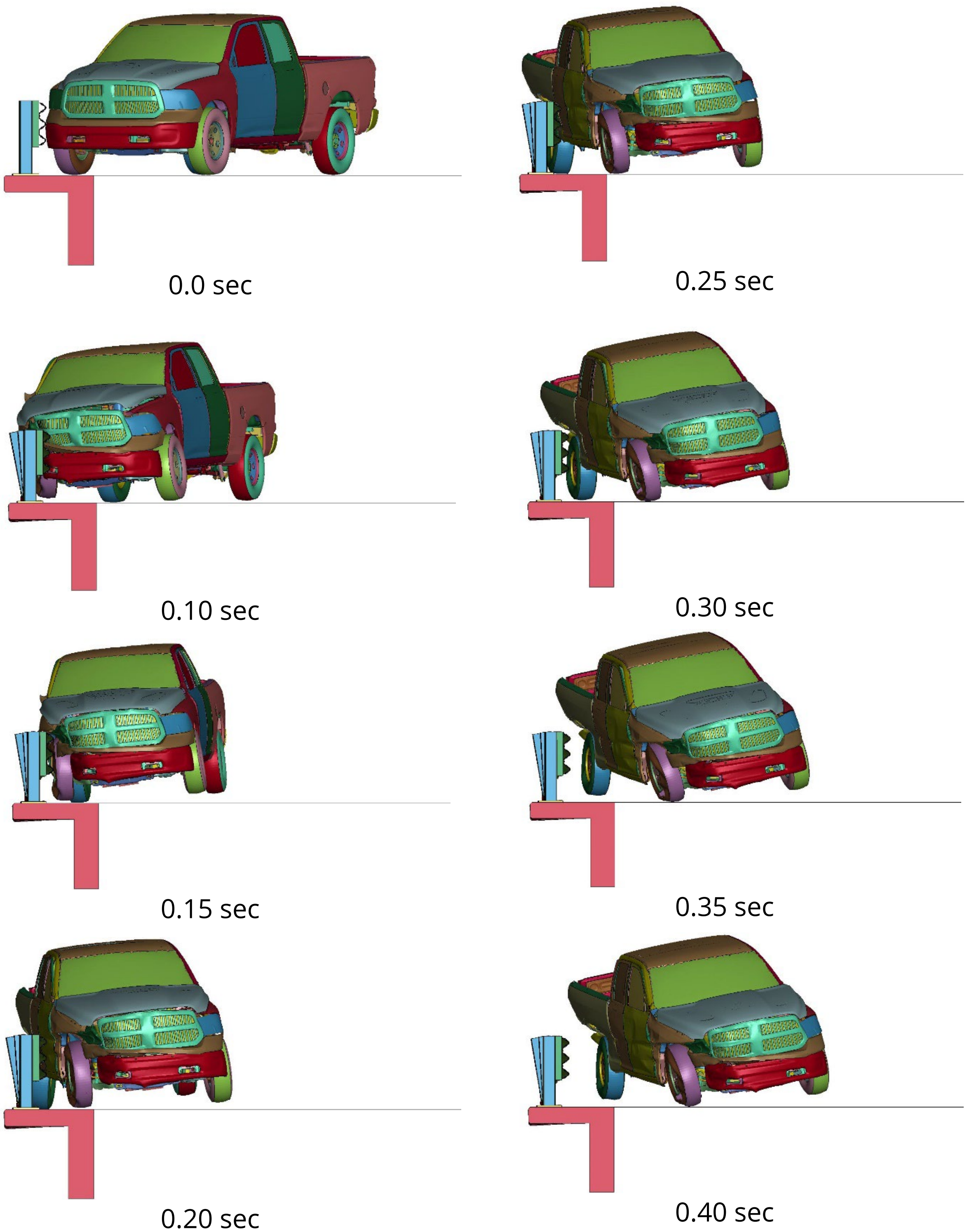


Figure 3.13. FE Simulation Sequential Images for Thrie-beam System without Curb – *MASH* Test 3-11.

Table 3.2. Occupant Risk Results for *MASH* Test 3-10 Simulation.

Test Parameter	***MASH* Limit**	**Measured**
OIV, Longitudinal (ft/s)	≤40.0	23.1
OIV, Lateral (ft/s)	≤40.0	30.0
Ridedown, Longitudinal (g)	≤20.49	3.6
Ridedown, Lateral (g)	≤20.49	10.0
Roll (deg.)	≤75	6.5
Pitch (deg.)	≤75	4.0
Yaw (deg.)	N/A	36.8

Table 3.3. Occupant Risk Results for *MASH* Test 3-11 Simulation.

Test Parameter	***MASH* Limit**	**Measured**
OIV, Longitudinal (ft/s)	≤40.0	17.9
OIV, Lateral (ft/s)	≤40.0	27.4
Ridedown, Longitudinal (g)	≤20.49	3.4
Ridedown, Lateral (g)	≤20.49	13.7
Roll (deg.)	≤75	12.8
Pitch (deg.)	≤75	3.0
Yaw (deg.)	N/A	40.7

CHAPTER 4.

STRUCTURAL ANALYSIS

An engineering strength analysis was performed on the new *MASH* TL-4 design as shown in Figure 3.9 in Chapter 3. The strength analysis was performed in accordance with the American Association of State Highways and Transportation Officials (AASHTO) Load and Resistance Factor Design, Section 13 Specifications (4). The calculated strength of the 43 inches high bridge rail was 113 kips @ 30 inches height. Based on this calculated strength, the design shown in Figure 3.9 satisfies the strength requirements for *MASH* TL-4 with post spacing a at 3'-1 ½" inches on centers. For additional information, please refer to the calculations shown in Appendix A.

CHAPTER 5.

SUMMARY & CONCLUSIONS

1.) Task 1: Engineering Analyses & Detailing of a new retrofit designs for *MASH* TL-4 was developed for this project. This new design utilized a HSS 10x4x3/8 tube mounted to the top of the Thrie-beam Retrofit Design previously tested to *MASH* TL-3 using post spacing of 3'-1 1 /2" on centers. The total height of this design was 43 inches. LS-DYNA simulations using the *MASH* TL-4 Vehicle (SUT) were successful. Engineering strength analyses were performed on the new retrofit design. The calculated strength was 100 kips at 30 inches height. This new design meets the strength requirements of *MASH* TL-4 (80 kips at 30 inches height). The new design shown herein is recommended for *MASH* TL-4 applications.

2.) Task 2: TTI has prepared engineering details of this recommended design retrofit. These details are shown in Figure 3.9 and in the calculations in Appendix A. This design is recommended for *MASH* TL-4.

3.) Task 3 – Simulations of As-Tested Design without a Curb for *MASH* TL-3 were performed. The As-Tested design without a curb is recommended for *MASH* TL-3. No design modifications were needed for *MASH*-TL-3.

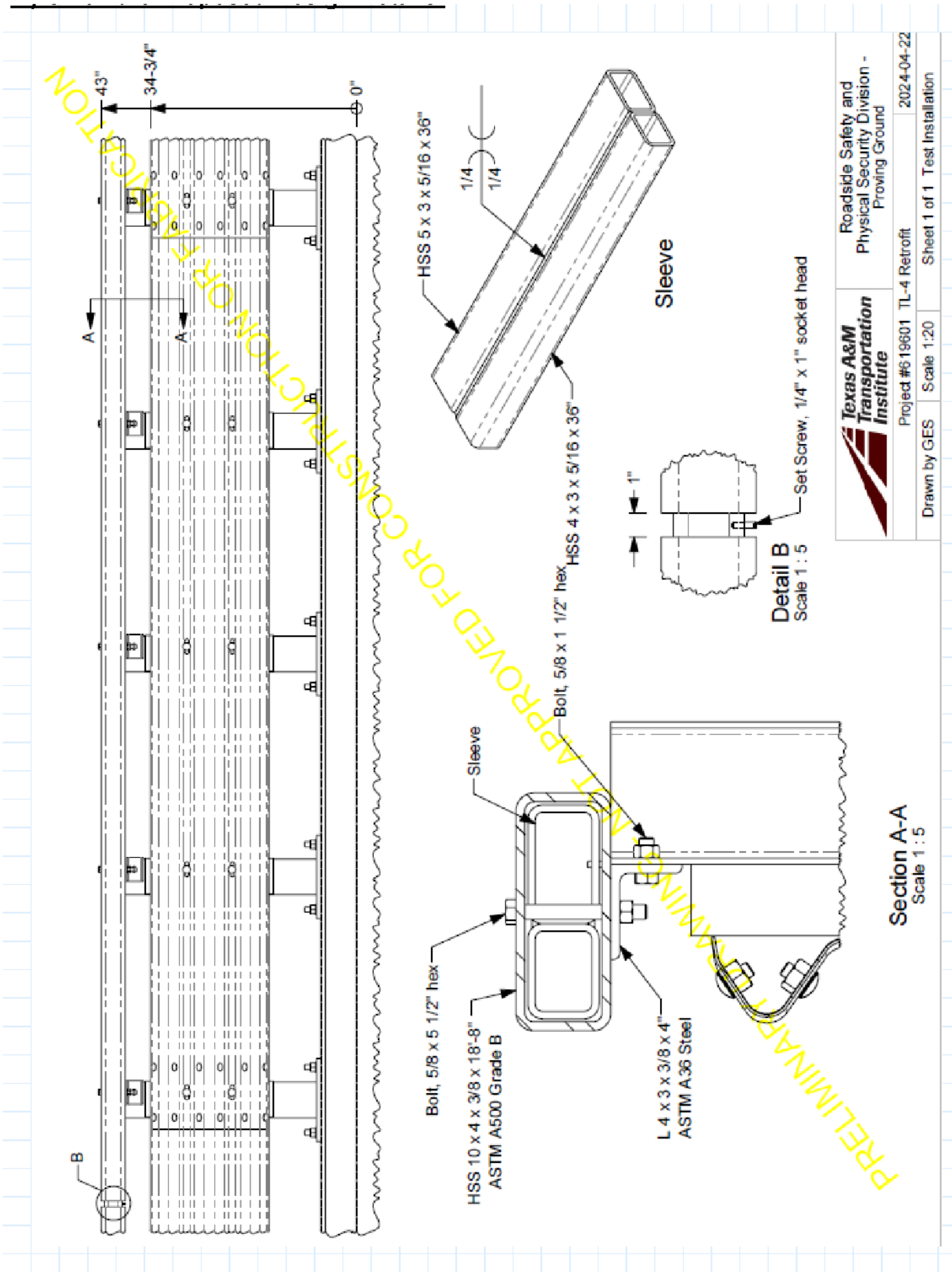
4.) Task 4 – Simulations were performed on the as-tested Design with a Curb for *MASH* TL-4. Due to strength and instability of the SUT, this design (As-Tested for *MASH* TL-3 under TTI Project 615131) is not recommended for *MASH* TL-4.

REFERENCES

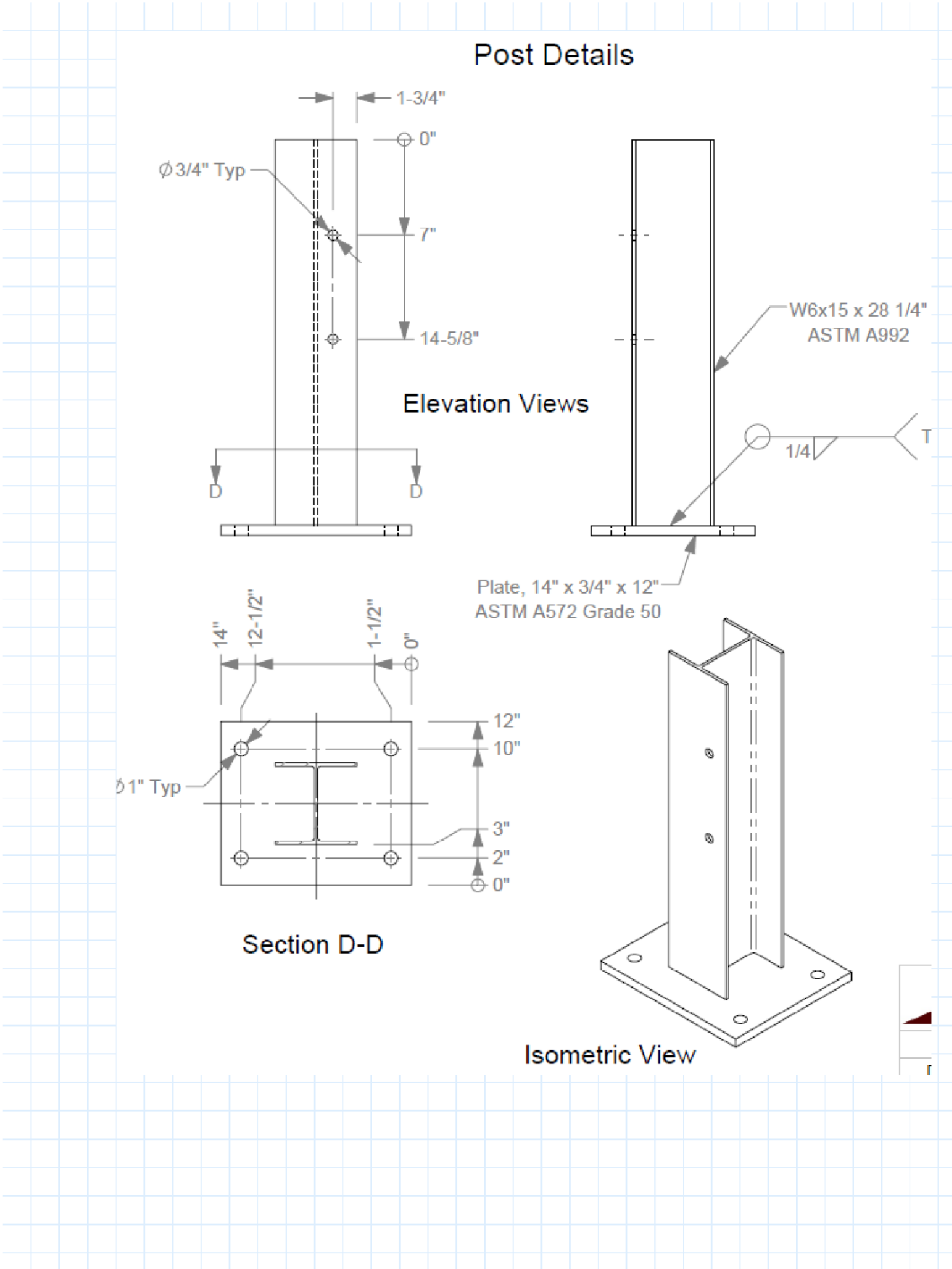
1. AASHTO. *Manual for Assessing Safety Hardware*, Second Edition. American Association of State Highway and Transportation Officials, Washington, DC, 2016.
2. Williams, W.F., Moran, S., Menges, W.L., Schroeder, W.J.L., Giffith, B.L., Wegenast, S.W., and Kuhn, D.L. *Development of Thrie-beam Retrofit for Upgrading Obsolete Bridge Rails.* Texas A&M Transportation Institute, TX. 2021.
3. Sheikh, N.M., Bligh, R.P., Menges, W.L., Schroeder, W., Griffith, B.L., and Kuhn, D.L. *Development of a MASH Test-Level 4 Compliant Guardrail.* Report No. FHWA/TX-21/0-7091-R1. Texas A&M Transportation Institute, TX, 2021.
4. American Association of State Highways and Transportation Officials (AASHTO) LRFD Bridge Design Specifications, Section 13: Railings, 9^{th} Edition, 2020

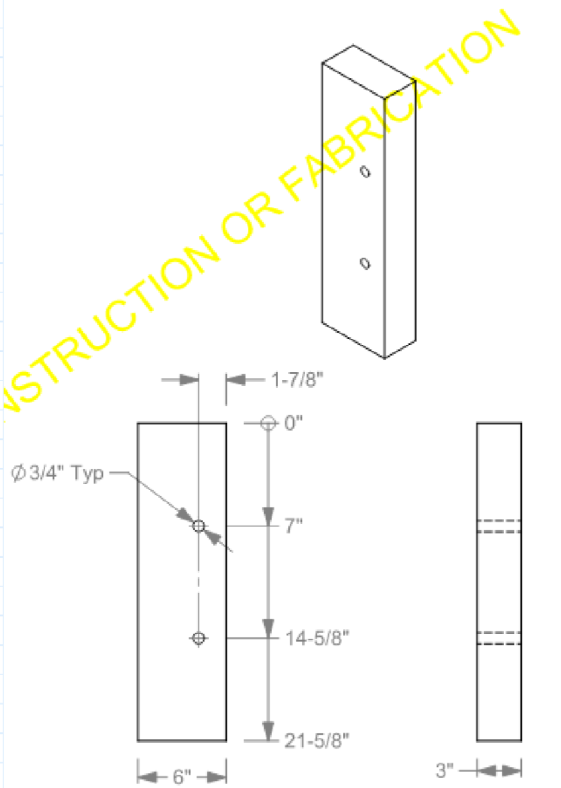
APPENDIX A.

CALCULATIONS


43"
34-3/4"
0"
A
A
B
HSS 5 x 3 x 5/16 x 36"
1/4
1/4
HSS 4 x 3 x 5/16 x 36"
Sleeve
Set Screw, 1/4" x 1" socket head
1"
Detail B
Scale 1 : 5
Bolt, 5/8 x 1 1/2" hex
Sleeve
Bolt, 5/8 x 5 1/2" hex
HSS 10 x 4 x 3/8 x 18'-8"
ASTM A500 Grade B
L 4 x 3 x 3/8 x 4"
ASTM A36 Steel
Section A-A
Scale 1 : 5
PRELIMINARY DRAWING - NOT APPROVED FOR CONSTRUCTION OR FABRICATION
Roadside Safety and Physical Security Division - Proving Ground
2024-04-22
Texas A&M Transportation Institute
Project #619601
TL-4 Retrofit
Sheet 1 of 1
Test Installation
Drawn by GES
Scale 1:20

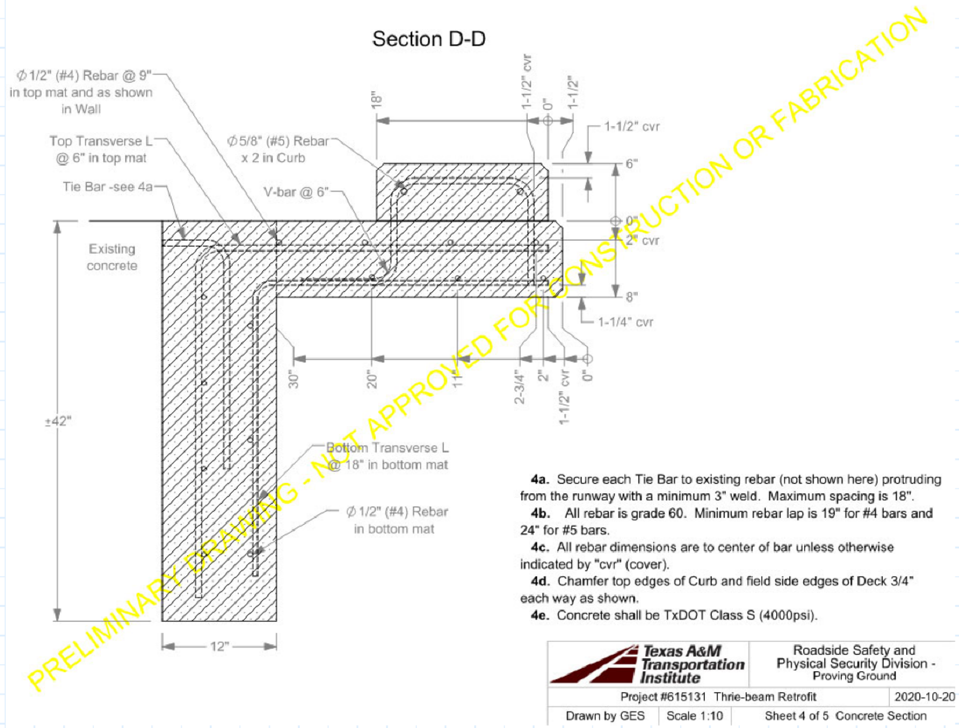
1 of 21


Post Details
1-3/4"
Ø3/4" Typ
0"
7"
14-5/8"
D
D
Elevation Views
W6x15 x 28 1/4"
ASTM A992
1/4
T
Plate, 14" x 3/4" x 12"
ASTM A572 Grade 50
14"
12-1/2"
1-1/2"
0"
Ø1" Typ
12"
10"
3"
2"
0"
Section D-D
Isometric View



Retrofit Blockout

Timber blockout treated with a preservative in accordance with AASHTO M 133 after all cutting and drilling.


Section D-D
PRELIMINARY DRAWING - NOT APPROVED FOR CONSTRUCTION OR FABRICATION
∅ 1/2" (#4) Rebar @ 9" in top mat and as shown in Wall
Top Transverse L @ 6" in top mat
Tie Bar -see 4a
∅ 5/8" (#5) Rebar x 2 in Curb
V-bar @ 6"
Existing concrete
Bottom Transverse L @ 18" in bottom mat
∅ 1/2" (#4) Rebar in bottom mat
18"
1-1/2" cvr
0"
1-1/2"
1-1/2" cvr
6"
0"
2" cvr
8"
1-1/4" cvr
30"
20"
11"
2-3/4"
2"
1-1/2" cvr
0"
±42"
12"
4a. Secure each Tie Bar to existing rebar (not shown here) protruding from the runway with a minimum 3" weld. Maximum spacing is 18".
4b. All rebar is grade 60. Minimum rebar lap is 19" for #4 bars and 24" for #5 bars.
4c. All rebar dimensions are to center of bar unless otherwise indicated by "cvr" (cover).
4d. Chamfer top edges of Curb and field side edges of Deck 3/4" each way as shown.
4e. Concrete shall be TxDOT Class S (4000psi).
Texas A&M Transportation Institute
Roadside Safety and Physical Security Division - Proving Ground
Project #615131 Thrie-beam Retrofit
2020-10-20
Drawn by GES
Scale 1:10
Sheet 4 of 5 Concrete Section

4 of 21

(1) General Information and Inputs:

1) Reference: AASHTO MASH Condictions
2) Assess the adequacy of the barrier based on AASHTO LRFD Section 13 criteria

(1a) General Inputs:

$f'_c := 4.000\ ksi$ Compressive strength of concrete (ksi)

$f_y := 60\ ksi$ Yield strength of concrete reinforcing steel (ksi)

$H_r := 43.0\ in$ Total height of bridge rail system measured from the top of the roadway surface/overlay to the top of highest rail (in.)

$H_R := 24.00\ in$ Height of the bridge rail system measured from the top of the roadway surface/overlay to the centroid of the steel rail elements (in.)

$curb_{ht} := 6\ in$ "Height of curb (inches)"

$t_0 := 0.0\ in$ Thickness of overlay (in.)

(1b) Concrete deck and curb inputs:

$H_{curb} := 6.0\ in$ Height of Curb (in.)

$t_{deck} := 8.0\ in$ Thickness of Deck (inches)

(1b) Steel Rail, Post, and Anchor Rod Inputs:

Steel Rail Inputs:

a) Use 10 gage Thrie Beam (50 ksi)
b) Use W6x15 Posts Fy = 50 ksi

$F_{yR} := 50\ ksi$ Yield strength of steel rail (ksi)

$h_R := 20\ in$ Height of a single steel rail (in)

$N_R := 1$ Number of steel rail elements

$Z_R := 47000\ mm^3 \cdot 1.15 = 3.298\ in^3$ Plastice Section Modulus of Rail (in^3)

Steel Post Inputs:

a) Steel Post is W6x15
b) A992 Fy = 50 ksi

$F_{yP} := 50\ ksi$ Yield strength of steel post (ksi)

$w_p := 6\ in$ Width of steel post about the bending axis (in.)

$t_w := 0.23\ in$ Thickness of steel post web (in.)

$t_f := 0.26\ in$ Thickness of flange (in)

$Z_P := 10.8\ in^3$ Plastice Section Modulus of Post (in^3)

$L_p := 3\ ft + 1.5\ in$ Steel post spacing (ft)

Anchor Rod Inputs:

a) Anchor Rods are Hilti HAS-E Rods, Fu = 120 ksi
b) Anchor Rods are 7/8" ϕ x 10" embedded 7 inches

$F_{u.rod} := 120\ ksi$ Tensile strength of anchor rods (ksi)

$N_{rod} := 4$ Number of anchor rods

$N_{rod.tension} := 2$ Number of anchor rods in tension

$d_{rod} := 10\ in$ Distance from the anchor rods acting in tension to the back of the steel plate (in.)

$\phi_{rod} := \frac{7}{8}\ in$ Diameter of anchor rods (in.)

(1c) Design Force Inputs:

Design Forces for Traffic Railings:

Test Level	Rail Height (in.)	F_t (kip)	F_L (kip)	F_v (kip)	L_t/L_L (ft)	L_v (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 (kips)

$L_t := 5.0\ ft$ Longitudinal length of distribution of impact force (ft)

$H_e := 30\ in$ Height of equivalent transverse load from top of overlay (in.)

$H_{min} := 36.0\ in$ Minimum height of a MASH TL-3 barrier (in.)

$h_e := H_e + t_0 = 30\ in$ Total equivalent transverse impact height (in.)

$H_r = 43\ in$ Total height of bridge rail system measured from the top of the roadway surface/overlay to the top of highest rail (in.)

(2) Stability Criteria:

$h_{min} := 29\ in$ Minimum height of a MASH TL-3 barrier (in.)

$H_r = 43\ in$ Total height of bridge rail system measured from the top of the roadway surface/overlay to the top of highest rail (in.)

$$Check\_Barrier\_Minimum\_Height := \begin{array}{l} \text{if } H_r \geq H_{min} \\ \quad \text{“OK”} \\ \text{else} \\ \quad \text{“NOT OK”} \end{array}$$

$$Check\_Barrier\_Minimum\_Height = \text{“OK”}$$

(3) Geometric Criteria:

$s_{post} := 6\ in$ Post setback (in.)

$c_b := 6.375\ in$ Vertical clear opening (in.)

$\Sigma A := H_{curb} + h_R = 26\ in$ Total rail contact width (in.)

$H_r = 43\ in$ Total height of the bridge rail measured from the top of the roadway surface/overlay (in.)

Note: Denoted as "H" in figure below

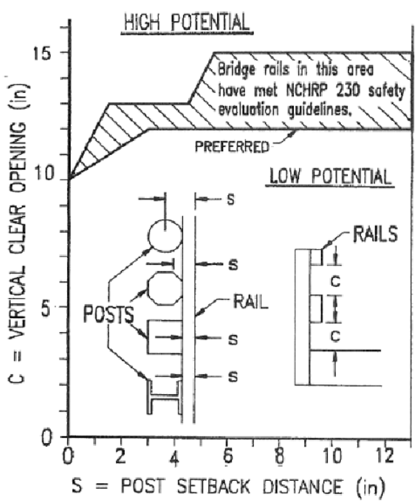
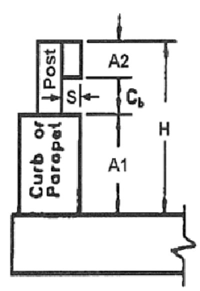


Figure A13.1.1-2—Potential for Wheel, Bumper, or Hood Impact with Post



CONCRETE AND METAL RAIL

(3-conti.) Geometric Criteria:

$s_{post} = 6\ in$ $\qquad H_r = 43\ in$

$\Sigma A = 26\ in$

$ratio_{\Sigma AH} := \frac{\Sigma A}{H_r} = 0.605$

$Set_{low.x} := [0\ 1\ 2\ 3\ 4\ 5\ 6\ 7\ 8\ 9\ 10]$

Lower boundary for post setback criteria x and y coordinates

$Set_{low.y} := [0.75\ 0.63\ 0.52\ 0.4\ 0.315\ 0.28\ 0.27\ 0.26\ 0.25\ 0.245\ 0.245]$

$Set_{up.x} := [2.5\ 3\ 4\ 5\ 6\ 7\ 8\ 9\ 10]$

Upper boundary for post setback criteria x and y coordinates

$Set_{up.y} := [0.8\ 0.725\ 0.6\ 0.5\ 0.46\ 0.44\ 0.43\ 0.425\ 0.42]$

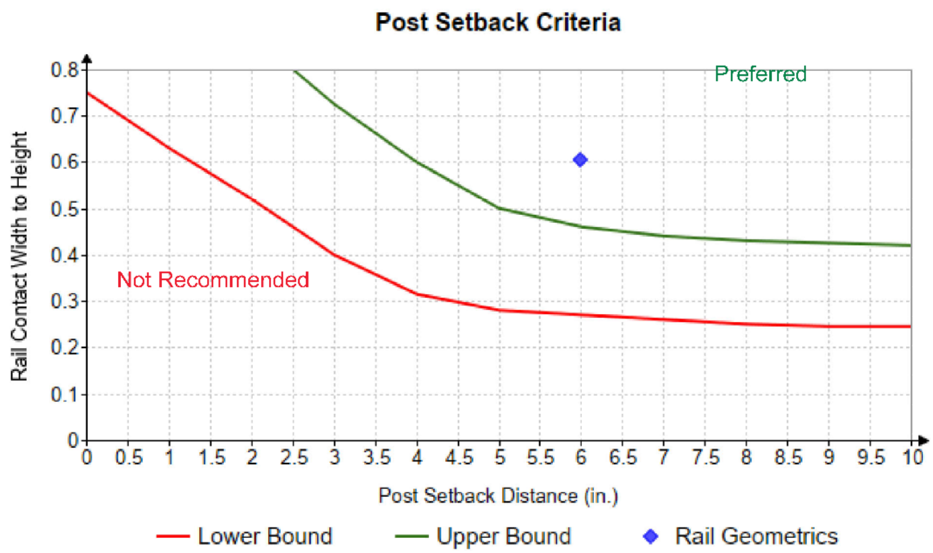
$Set_{sys.x} := \frac{s_{post}}{in} = 6$ Post setback rail geometric point

$Set_{sys.y} := ratio_{\Sigma AH} = 0.605$ Ratio of contact width to total height rail geometric point

$Set_{low.x}$	$Set_{low.y}$	$Set_{up.x}$	$Set_{up.y}$
0	0.75	2.5	0.8
1	0.63	3	0.725
2	0.52	4	0.6
3	0.4	5	0.5
4	0.315	6	0.46
5	0.28	7	0.44
6	0.27	8	0.43
7	0.26	9	0.425
8	0.25	10	0.42
9	0.245		
10	0.245		

Inputs

$\mathbf{X}_1 := Set_{low.x}$ $\mathbf{Y}_1 := Set_{low.y}$ $\mathbf{X}_2 := Set_{up.x}$ $\mathbf{Y}_2 := Set_{up.y}$ $\mathbf{X}_3 := Set_{sys.x}$ $\mathbf{Y}_3 := Set_{sys.y}$



$NotRecommended := 1$ $Marginal := 2$ $Preferred := 3$

Region Designation
Note: Marginal region is between Lower and Upper Bounds

$Post\_Setback\_Criteria\_Rail\_Geometric\_Point := Marginal$

(3-conti.) Geometric Criteria:

$snag_{low.x} := [0 \;\; 3 \;\; 13]$

$snag_{low.y} := [10 \;\; 12 \;\; 12]$

Lower boundary for snag potential criteria x and y coordinates

$snag_{up.x} := [0 \;\; 1.25 \;\; 4.25 \;\; 5.25 \;\; 13]$

$snag_{up.y} := [10 \;\; 13 \;\; 13 \;\; 15 \;\; 15]$

Upper boundary for snag potential criteria x and y coordinates

$snag_{sys.x} := \frac{s_{post}}{in} = 6$

Post setback geometric point

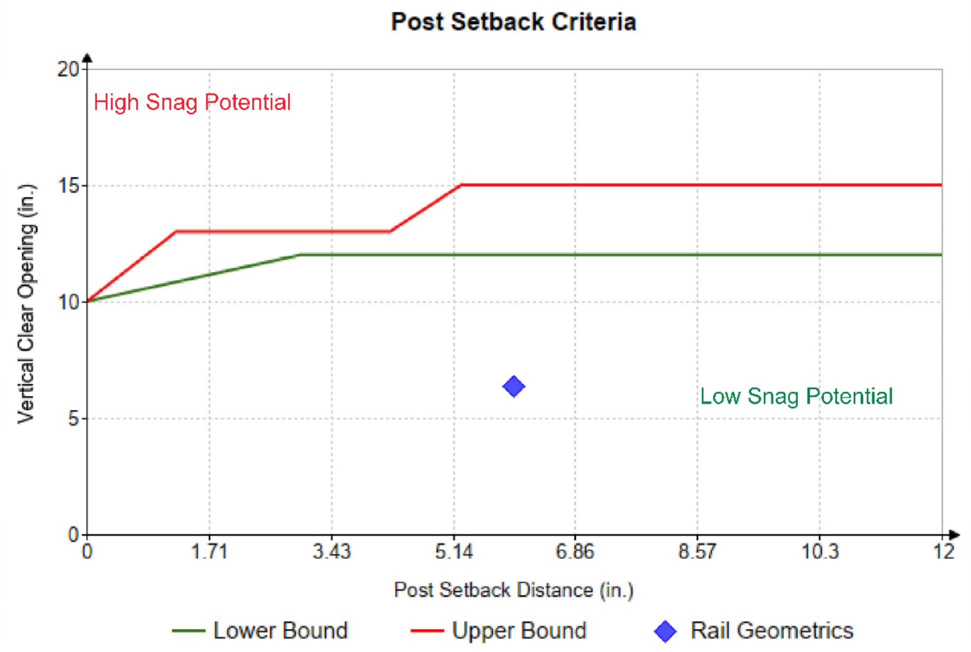
$snag_{sys.y} := \frac{c_b}{in} = 6.375$

Vertical clear opening rail geometric point

$snag_{low.x}$	$snag_{low.y}$
0	10
3	12
13	12

$snag_{up.x}$	$snag_{up.y}$
0	10
1.25	13
4.25	13
5.25	15
13	15

$X_1 := snag_{low.x}$ $Y_1 := snag_{low.y}$ $X_2 := snag_{up.x}$ $Y_2 := snag_{up.y}$ $X_3 := snag_{sys.x}$ $Y_3 := snag_{sys.y}$



$HighSnagPotential := 1$ $Marginal := 2$ $LowSnagPotential := 3$

Region Designation
Note: Marginal region is between Lower and Upper Bounds

$$Snag\_Potential\_Criteria\_Rail\_Geometric\_Point := LowSnagPotential$$

(3) Geometric Criteria - Summary of Results:

$$Check\_Post\_Setback\_Criteria := \left\| \begin{array}{l} \text{if } Post\_Setback\_Criteria\_Rail\_Geometric\_Point \ge 2 \\ \quad \left\| \text{“OK”} \right. \\ \text{else} \\ \quad \left\| \text{“NOT OK”} \right. \end{array} \right.$$

$$Check\_Post\_Setback\_Criteria = \text{“OK”}$$

$$Check\_Snag\_Potential\_Criteria := \left\| \begin{array}{l} \text{if } Snag\_Potential\_Criteria\_Rail\_Geometric\_Point \ge 2 \\ \quad \left\| \text{“OK”} \right. \\ \text{else} \\ \quad \left\| \text{“NOT OK”} \right. \end{array} \right.$$

$$Check\_Snag\_Potential\_Criteria = \text{“OK”}$$

(4) Steel Rail & Post Strength Analysis:

$F_{yR} = 50\ ksi$ Yield Strength of all steel rail elementsl (ksi)

$Z_R = 3.298\ in^3$ Plastic Sectional Modulus of the Steel Thrie Beam (in.3)

$n_R := 1$ Number of Tube Rail

$H_{thrie} := 34.75\ in - \left(\frac{506\ mm}{2}\right) = 24.789\ in$

$M_{pthrie} := n_R \cdot F_{yR} \cdot Z_R = 13.743\ kip \cdot ft$ Plastic Moment Capacity of the Steel Tube Rail (kip-ft)

$Z_{HSS} := 19.0\ in^3$ $H_{HSS} := 41\ in$ HSS10x4x1/4 Top Tube

$M_{pHSS} := Z_{HSS} \cdot F_{yR} = 79.167\ kip \cdot ft$

$M_p := M_{pHSS} + M_{pthrie} = 92.91\ kip \cdot ft$

$Y_{rails} := \frac{M_{pthrie} \cdot H_{thrie} + M_{pHSS} \cdot H_{HSS}}{M_p} = 38.602\ in$

$h_p := Y_{rails} - curb_{ht}$ Height from the bottom of the post to the centroid of the steel rail (in.)

$h_p = 32.602\ in$

$H_p := h_p + curb_{ht} = 38.602\ in$

Calculate the Plastic Strength of the Post: P_{P1}

$Z_P = 10.8\ in^3$ Plastic Sectional Modulus of the Steel Post about the Bending axis (in.)

$F_{yP} = 50\ ksi$ Yield strength of steel post (ksi)

$M_{post} := F_{yP} \cdot Z_P = 45\ kip \cdot ft$ Plastic strength of the Steel Post (kip-ft)

$h_p = 32.602\ in$ Height from the bottom of the post to the centroid of the rail elements (in.)

$P_{P1} := \frac{M_{post}}{h_p} = 16.563\ kip$ Post strength based on the plastic failure of a steel post @ Ybar of rails (kip)

Calculate the Post Strength based on the Ultimate Strength of the Anchor Rods: P_{P2}

$F_{u.rod} = 120\ ksi$ Tensile strength of the anchor rods (ksi)

$\phi_{rod} = 0.875\ in$ Diameter of anchor (in.)

$A_{rod} := \frac{\pi}{4} \cdot \phi_{rod}^{\ 2} = 0.601\ in^2$ Area of a single anchor rod (in.)

$R_{nt} := F_{u.rod} \cdot (0.75 \cdot A_{rod}) = 54.119\ kip$ Nominal strength of one anchor rod in tension (kip)

$N_{rod.tension} = 2$ Number of anchor rods acting in tension

$d_{rod} = 10\ in$ Distance from the anchor rods acting in tension to the back of the steel plate (in.)

$d_b := 1.5\ in$ Length of the steel plate bearing pressure acting on the concrete parapet (in.)

$w_{rod} := d_{rod} - \frac{d_b}{3} = 9.5\ in$ Distance from anchor rods acting in tension to the centroid of the bearing pressure acting on the concrete parapet (in.)

$M_{t.rod} := w_{rod} \cdot R_{nt} \cdot N_{rod.tension} = 85.688\ kip \cdot ft$ Moment strength of post based on tensile capacity of anchor rods (kip-ft)

$h_p = 32.602\ in$ Height from the bottom of the post to the centroid of the steel tube (in.)

$P_{t.rod} := \frac{M_{t.rod}}{h_p} = 31.54\ kip$ Post strength based on the tensile capacity of anchor rods (kip)

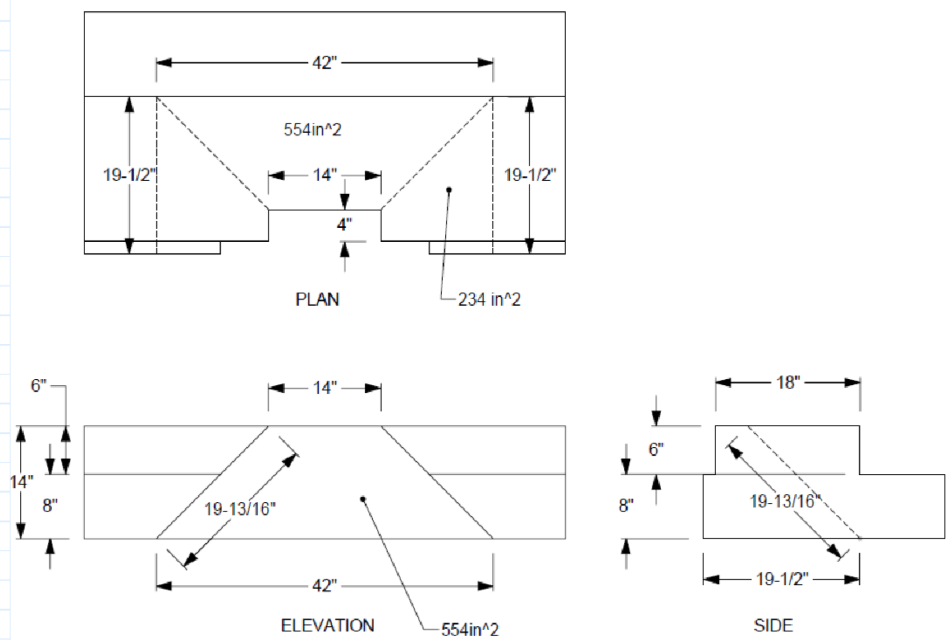
$R_{nv} := F_{u.rod} \cdot (0.45 \cdot A_{rod}) = 32.471\ kip$ Nominal strength of one anchor rod in shear w/ treads in shear plane (kip)

$P_{v.rod} := N_{rod} \cdot R_{nv} = 129.885\ kip$ Post strength base on the shear capacity of anchor rods (kip)

$P_{P2} := min(P_{t.rod}, P_{v.rod}) = 31.54\ kip$ Post strength base on the ultimate strength of the anchor rods (kip)

Calculate the Post Strength based on the Vertical Punching Shear Resistance of Concrete from Traffic Side Baseplate edge:

Note: This failure mechanism was modeled in SolidWorks P_{P3}



(-cont.) Calculate the Post Strength based on the Vertical Punching Shear Resistance of Concrete

from Traffic Side Baseplate: P_{P3}

$A_{sides} := 234\ in^2$ $A_{back} := 554\ in^2$ $\phi_v := 0.7$ Shear strength reduction factor

$A_{VPS} := A_{sides} + A_{back} = 788\ in^2$ $f'_c = 4\ ksi$ Concrete compressive strength (ksi)

$V_{c.vert} := \phi_v \cdot 2 \cdot \sqrt{\dfrac{f'_c}{psi}} \cdot psi = 88.544\ psi$ Concrete stress from block shear of baseplate punching shear based on ACI 318-19 Table 22.5.5.1

$P_{P3} := \dfrac{V_{c.vert} \cdot A_{VPS} \cdot 9\ in}{h_p} = 19.261\ kip$ Post strength based on the lateral punching shear resistance of concrete from centroid of rails (kip)

$h_p = 32.602\ in$

$P_{P3} = 19.261\ kip$

Calculate the Post Strength based on the Tension Bond Strength of the Anchor Bolt Epoxy

P_{P4}

Use Hilti RE500 V3 Epoxy for 3/4" DIA. Anchors Embedded 7 inches min.

Reference: Table 25 - Hilti RE-500 V3 Epoxy Adhesive Design Strength with concrete bond failure for threaded rod in uncracked Concrete, 2016 Design Guide, page 151

45000 = 7" depth

$F_{T\_\phi N} := 45000\ \mathbf{lbf}$ Extrapolated ultimate Strength for embedded depth = 7 inches from TTI Testing of anchor with RE500V3

From Table 38 - Load Adjustment factors for 7/8" Diameter threaded rods in uncracked concrete, Hilti Design Guide, page 158

$h_p = 32.602\ \mathbf{in}$

$f_{AN} := 0.71$ Spacing Factor in tension (11 inches anchor spacing)

$f_{temp} := 0.9$ 140 deg. temp. reduction

$f_{RN} := 0.49$ Edge Distance reduction factor for tension (5 inches edge distance)

0.4 = 7" depth

$F_{TRE500} := F_{T\_\phi N} \cdot f_{AN} \cdot f_{RN} \cdot f_{temp} \cdot 1.5 = 21.135\ \mathbf{kip}$

$$P_{P4} := \frac{F_{TRE500} \cdot 10\ \mathbf{in} \cdot 2}{h_p} = 12.965\ \mathbf{kip}$$

Edge distance and spacing values from Hilti are conservative for reinforced concrete use 1.5 factor for reinforced and dynamic loading

Calculate the Weld Strength of Post Joint: P_{P4}

$$\frac{(.4 \cdot 6) + (1.0 \cdot 1)}{7} = 0.486$$

$b_{weld.joint} := 6.0\ \mathbf{in}$ Width of welded joint (in.)

$d_{weld.joint} := 6.0\ \mathbf{in}$ Depth of welded joint (in.)

$t_{weld.joint} := 0.707 \cdot 0.25\ \mathbf{in}$ Thickness of welding (in.)

$\phi_{weld.joint} := 1.00$ Strength reduction factor for welded joint

Section modulus about hrizontal axis x-x (in.2)

$$S_w := 2 \cdot b_{weld.joint} \cdot d_{weld.joint} + \frac{d_{weld.joint}^{\ 2}}{3} = 84\ \mathbf{in}^2$$

Weld Treated as a line for a W-Shape welded all around on a baseplate

$E70XX := 70\ \mathbf{ksi}$ Electrodes (ksi)

$$P_{P5} := \frac{\phi_{weld.joint} \cdot S_w \cdot t_{weld.joint} \cdot E70XX}{h_p} = 31.878\ \mathbf{kip}$$

Weld strength of rail joint (kip)

Determine the Limiting Post Strength (kips):

$P_{P1}=16.563$ ***kip*** Post strength based on the plastic failure of a steel post (kip)

$P_{P2}=31.54$ ***kip*** Post strength base on the ultimate strength of the anchor rods (kip)

$P_{P3}=19.261$ ***kip*** Post strength based on the vertical punching shear resistance of concrete from traffic side anchor rods (kip)

$P_{P4}=12.965$ ***kip*** Post Strength based on adhesive bond strength of anchors (kip) ... 7" anchor embedment

$P_{P5}=31.878$ ***kip*** Post strength based on strength of Welds (kips)

$P_P := min\left(P_{P1}, P_{P2}, P_{P3}, P_{P4}, P_{P5}\right)=12.965$ ***kip*** Post strength found by using the limiting ("Worst case") post strength (kips)

$P_P=12.965$ ***kip*** Limiting Post Strength Based on Bond Failure ... close to post yeilding strength!

5.) Determine Ultimate Capacity of Steel Rail for 1, 2, 3, 4, & 5, Span Failure Mode:

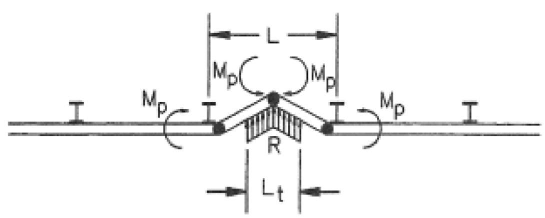
$L_t = 5\ ft$ Length of the distribution of the transverse impact force (ft)

$L_p = 3.125\ ft$ Steel post spacing (ft)

$M_p = 92.91\ kip \cdot ft$ Flexural capacity of the steel tube (kip-ft)

$P_P = 12.965\ kip$ Post strength found by using the limiting ("Worst case") post strength (kips)

Single-Span



Single−Span Failure Mode

$N_1 := 1$ Number of spans $M_p = 92.91\ kip \cdot ft$ Flexural capacity of the steel rail (kip-ft)

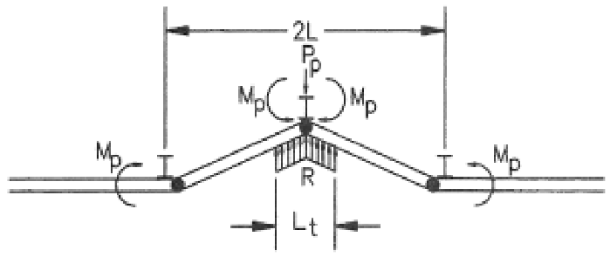
$P_P = 12.965\ kip$ Post strength found by using the limiting (worst case) post strength (kips) $L_p = 3.125\ ft$ $H_e = 30\ in$

$$R_{R1} := \frac{16 \cdot M_p + (N_1 - 1) \cdot (N_1 + 1) \cdot P_P \cdot L_p}{(2 \cdot N_1 \cdot L_p) - L_t} \cdot \left(\frac{H_p}{H_e}\right) = (1.53 \cdot 10^3)\ kip$$

Ultimate capacity of rail over one span (kip)

(-cont.) Determine Ultimate Capacity of Steel Rail for a Single and Double Span Failure Mode:

Two-Span



Two–Span Failure Mode

$N_2 := 2$ Number of spans

$$R_{R2'} := \frac{(16 \cdot M_p) + N_2^{\,2} \cdot P_P \cdot L_p}{(2 \cdot N_2 \cdot L_p) - L_t} \cdot \left(\frac{H_p}{H_e}\right) = 282.846\ \textit{kip}$$

Ultimate capacity of rail over one span (kip)

$H_R = 24\ \textit{in}$ $\quad H_e = 30\ \textit{in}$

$N_3 := 3$

$$R_{R3} := \frac{16 \cdot M_p + (N_3 - 1) \cdot (N_3 + 1) \cdot P_P \cdot L_p}{(2 \cdot N_3 \cdot L_p) - L_t} \cdot \left(\frac{H_p}{H_e}\right) = 169.446\ \textit{kip}$$

Ultimate capacity of rail over three spans (kip)

$N_4 := 4$

$$R_{R4'} := \frac{(16 \cdot M_p) + N_4^{\,2} \cdot P_P \cdot L_p}{(2 \cdot N_4 \cdot L_p) - L_t} \cdot \left(\frac{H_p}{H_e}\right) = 137.348\ \textit{kip}$$

Ultimate capacity of rail over four spans (kip)

$N_5 := 5$

$$R_{R5} := \frac{16 \cdot M_p + (N_5 - 1) \cdot (N_5 + 1) \cdot P_P \cdot L_p}{(2 \cdot N_5 \cdot L_p) - L_t} \cdot \left(\frac{H_p}{H_e}\right) = 120.535\ \textit{kip}$$

Ultimate capacity of rail over five spans (kip)

$N_6 := 6$

$$R_{R6} := \frac{(16 \cdot M_p) + N_6^{\,2} \cdot P_P \cdot L_p}{(2 \cdot N_6 \cdot L_p) - L_t} \cdot \left(\frac{H_p}{H_e}\right) = 116.605\ \textit{kip}$$

$N_7 := 7$

$$R_{R7} := \frac{16 \cdot M_p + (N_7 - 1) \cdot (N_7 + 1) \cdot P_P \cdot L_p}{(2 \cdot N_7 \cdot L_p) - L_t} \cdot \left(\frac{H_p}{H_e}\right) = 113.942 \; kip$$

$N_8 := 8$

$$R_{R8} := \frac{(16 \cdot M_p) + N_8^{\,2} \cdot P_P \cdot L_p}{(2 \cdot N_8 \cdot L_p) - L_t} \cdot \left(\frac{H_p}{H_e}\right) = 116.654 \; kip$$

(6) Conclusions:

Check_Barrier_Minimum_Height = "OK"

Check_Post_Setback_Criteria = "OK"

Check_Snag_Potential_Criteria = "OK"

The Thrie Beam Retrofit Barrier as shown herein satisfies the geometric requirements for MASH TL-4. The barrier calculated minimum strength over 7 Spans = 113 kips @ 30" (> 100 kips). Barrier strength satisfies the strength requirements for MASH TL-4 with post spacings at 3'-1 1/2" inches on centers