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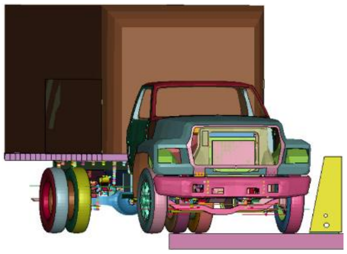
INVESTIGATION, CRASH TESTING, AND EVALUATION OF A MASH TL-4 PRECAST CONCRETE BRIDGE RAIL



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16. Abstract

Recently, a precast concrete bridge barrier with unique connection details for barrier-to-deck and barrier-to-barrier interfaces was developed at the Institute of Transportation (InTrans)-Iowa State University (ISU) for ABC applications. Successful laboratory quasi-static tests led to the current study, in which the primary objectives were to determine if the new bridge railing system complied with the AASHTO *Manual for Assessing Safety Hardware* (MASH) Test-Level 4 (TL-4) impact safety standards through a sequence of stages, including pre-crash simulations, one full-scale crash test with a 10000S single-unit truck (SUT), and subsequent post-crash numerical evaluations. Initial analyses incorporated LS-DYNA computer simulations emulating MASH TL-4 impacts on two prototype barrier configurations, i.e., a single-slope shape and a near-vertical shape. These simulations facilitated the discernment of the bridge rail length, reinforcement details, crashworthiness for passenger vehicles, selection of the single-slope shape for crash testing, and determination of a critical impact point for the 10000S SUT crash test. Subsequent modifications to the single-slope barrier system were predicated on these computational findings. A full-scale crash test (test no. ABCBRM-1) assessed the bridge railing and the loading to the inclined steel anchor bars under MASH test designation no. 4-12, focusing on its impact safety performance and potential damage to the barrier and bridge deck. In test no. ABCBRM-1, the 22,200-lb SUT impacted the precast concrete bridge railing at a speed of 55.4 mph and an angle of 14.7 degrees. The SUT was successfully contained and redirected, with the barrier and deck sustaining minimal damage, and all safety performance criteria were within acceptable limits as defined in MASH. Finally, after completing the full-scale crash test, an updated numerical model was developed based on the test data and the results obtained from the pre-crash test simulations. The close agreement between the numerical and experimental results from the post-crash test validated the effectiveness of the numerical modeling approach employed in this project. The study findings demonstrated that the modified single-slope, precast concrete bridge rail system met the MASH TL-4 impact safety criteria.

17. Key Words
Highway Safety, Crash Test, Compliance Test, AASHTO, MASH, Test Level 4, TL-4, Precast Concrete Bridge Rail, Bridge Deck, LS-DYNA, Computer Simulation, and Accelerated Bridge Construction

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INDEPENDENT APPROVING AUTHORITY

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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 yard	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 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short ton (2,000 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
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela per square meter	cd/m^2
		FORCE & 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 yard	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliter	0.034	fluid ounces	fl 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 ton (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela per square meter	0.2919	foot-Lamberts	fl
		FORCE & PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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1 INTRODUCTION

1.1 Problem Statement

At the Institute of Transportation (InTrans), housed within Iowa State University (ISU), an innovative precast concrete bridge barrier was developed for Accelerated Bridge Construction (ABC) applications, featuring special details for both barrier-to-deck and barrier-to-barrier connections [1]. In order to evaluate the barrier systems' connection performance and their individual force transfer and strength, as well as the corresponding stress distribution in the barrier and bridge overhang, a comprehensive series of full-scale component tests were conducted at the Structures Testing Laboratory of ISU. These examinations employed quasi-static loadings on a representative barrier prototype supported on a bridge deck overhang.

Figures 1 through 5 provide schematics and photographic illustrations of the prefabricated concrete barriers [2]. These barriers had undergone experimental evaluation using quasi-static testing methods. Additionally, the figures elucidate the specialized connections employed to ensure the structural integrity of the prefabricated concrete barriers.

As a subsequent phase in the investigation, the researchers were poised to undertake a crash test on modified barrier designs, i.e., single-slope shape or a near-vertical shape. Details of the modified precast concrete barriers and connections are provided in Figures 6 through 11. The overarching objective of this examination was to substantiate whether the bridge railing system, including its connection details, met or exceeded design Test Level 4 (TL-4) in accordance with the American Association of State Highway and Transportation Officials (AASHTO's) *Manual for Assessing Safety Hardware* (MASH) and Load and Resistance Factor Design (LRFD) Bridge Design Specifications [3-4].

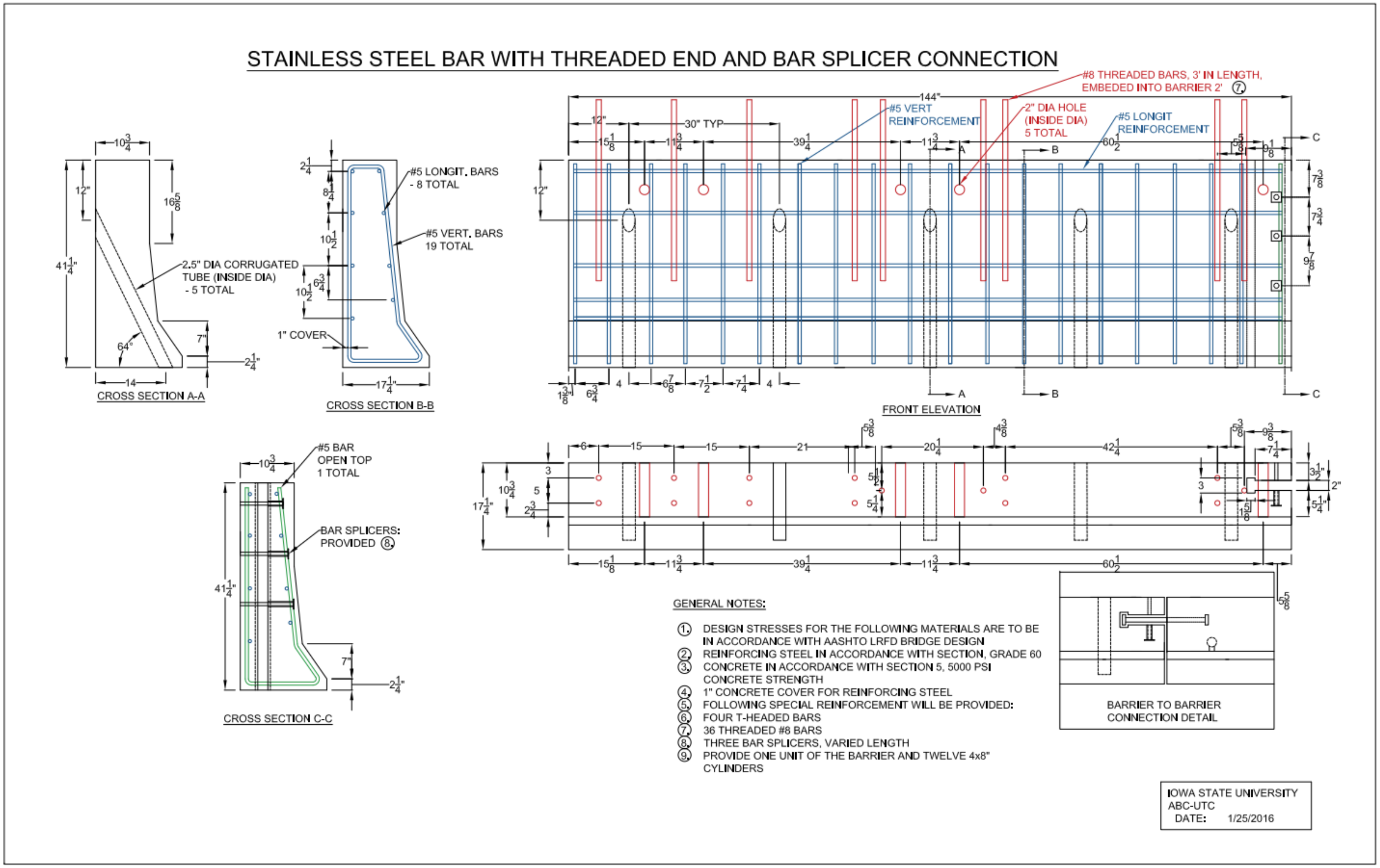


Figure 1. Detailed Prefabricated Barrier Drawings, Dimensions in Inches [2]

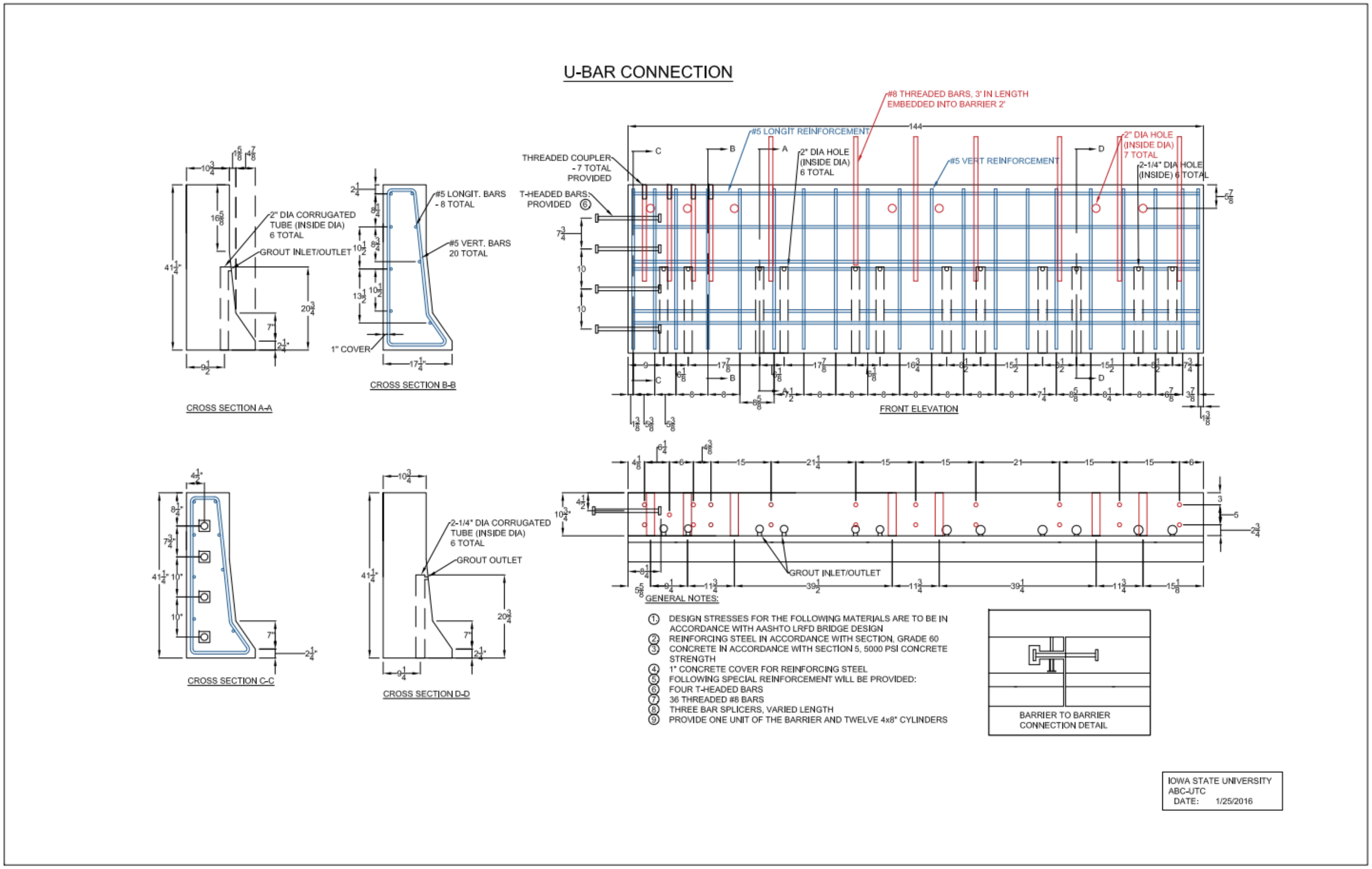
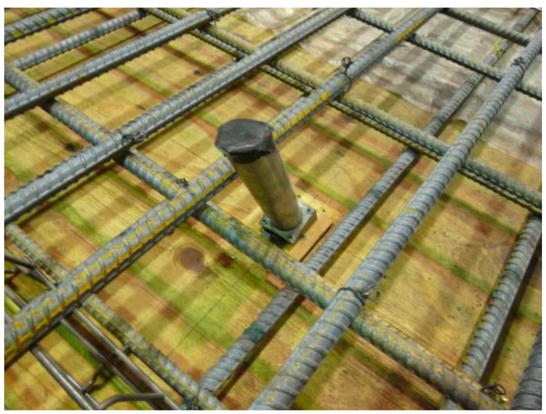


Figure 2. Detailed Prefabricated Barrier and Connection Drawings [2]

(a)

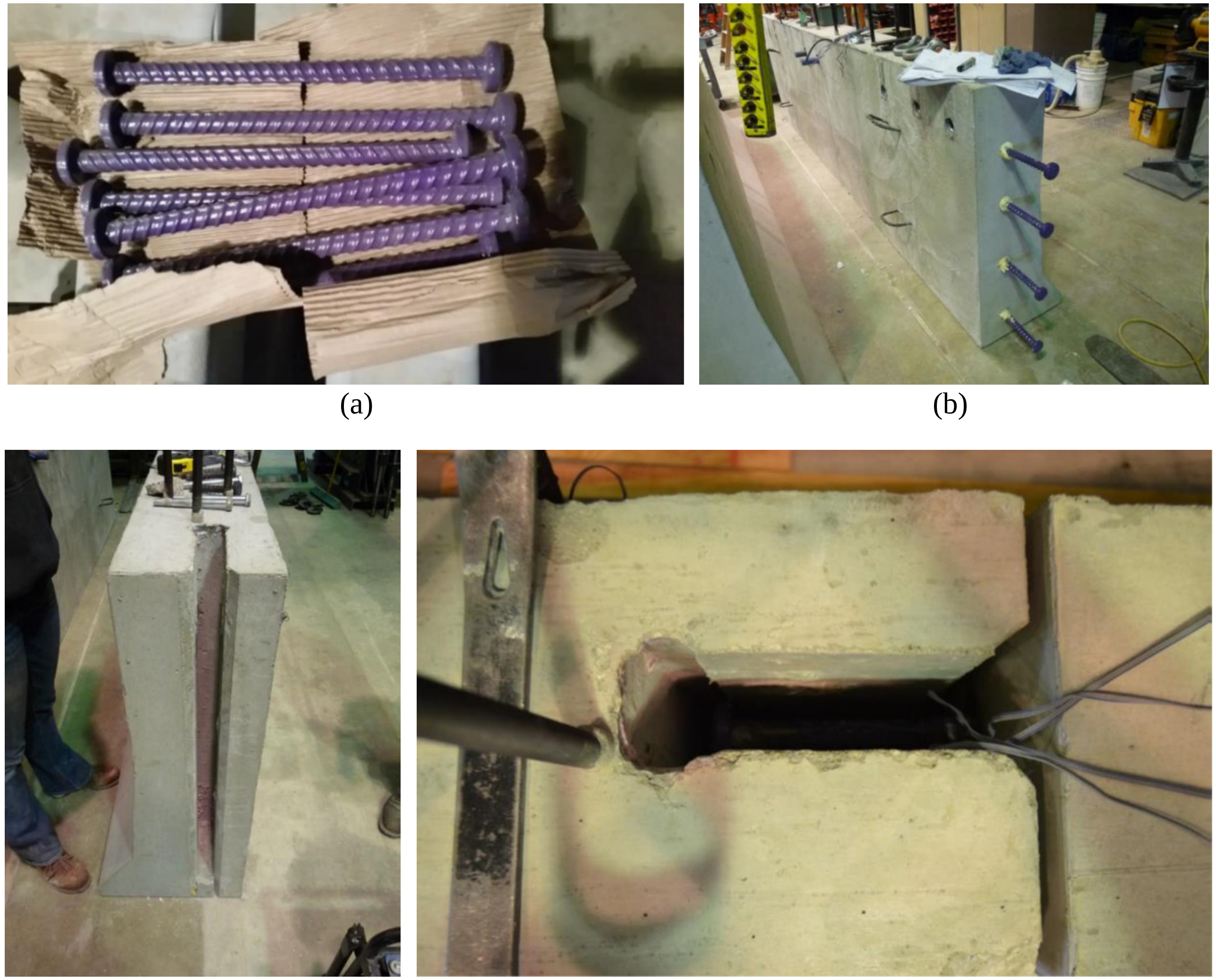
(b)



(c)

(d)

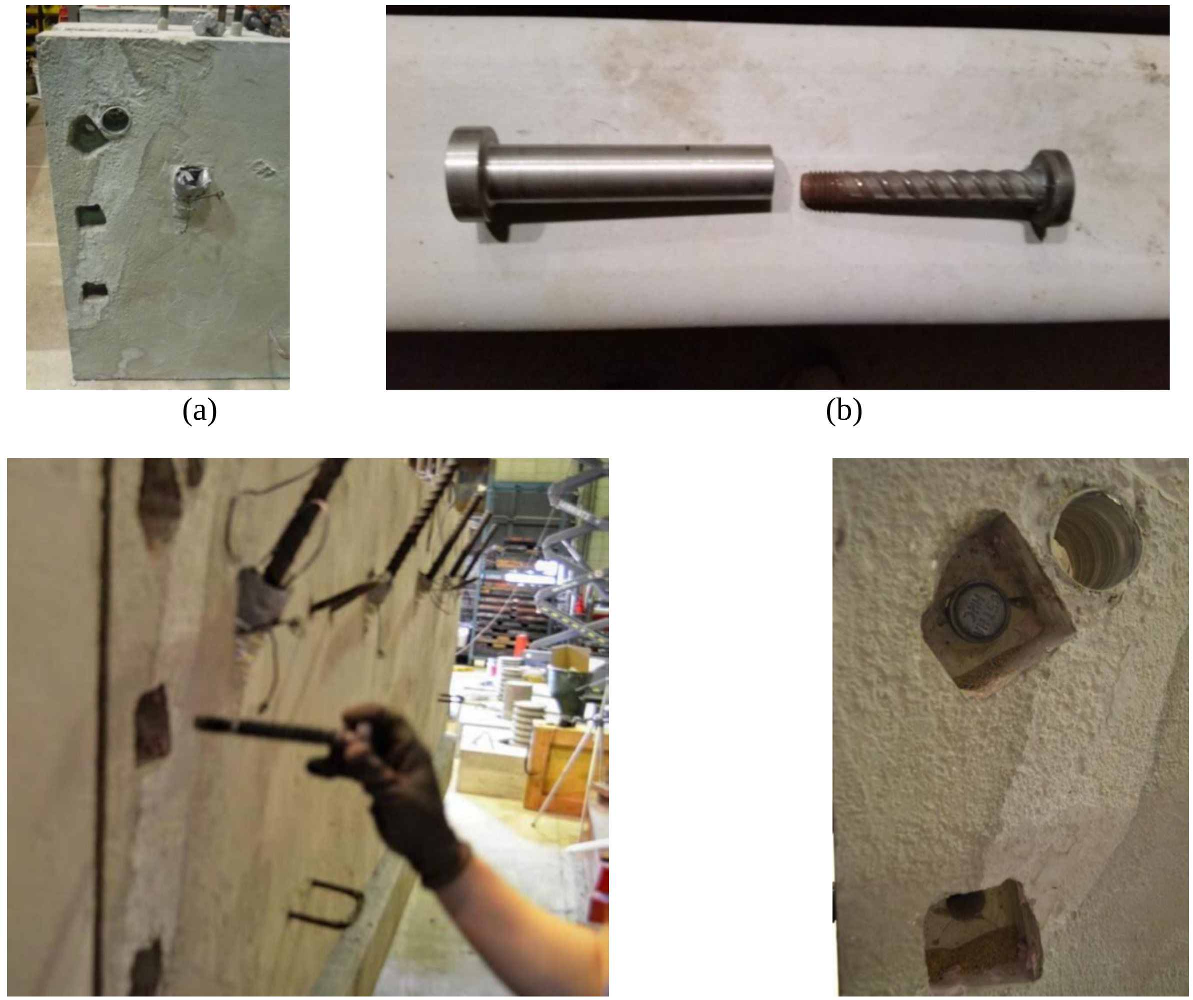
Figure 3. Iowa State University Component Testing Program: (a) Reinforcement Receiver; (b) Receiver Placed in Bridge Deck Formwork; (c) Receiver Placed with Reinforcement; and (d) #8 Reinforcement with Threaded Ends [2]



(a) (b)

(c) (d)

Figure 4. (a) Iowa State University Component Testing Program: Double Headed Ties; (b) Barrier End with Double Headed Ties; (c) Barrier End with Receiving Slot; and (d) Barriers End-to-End [2]



(a) (b) (c) (d)

Figure 5. Iowa State University Component Testing Program: (a) Receiving End of Barrier (Side View); (b) Transverse Ties Detail (receiving/female end placed when forming barrier); (c) Detail Showing Male Transverse Tie Above Actual Location; (c) Placing Male Transverse Ties Once Barriers are Placed; and (d) Placed Transverse Tie Detail [2]

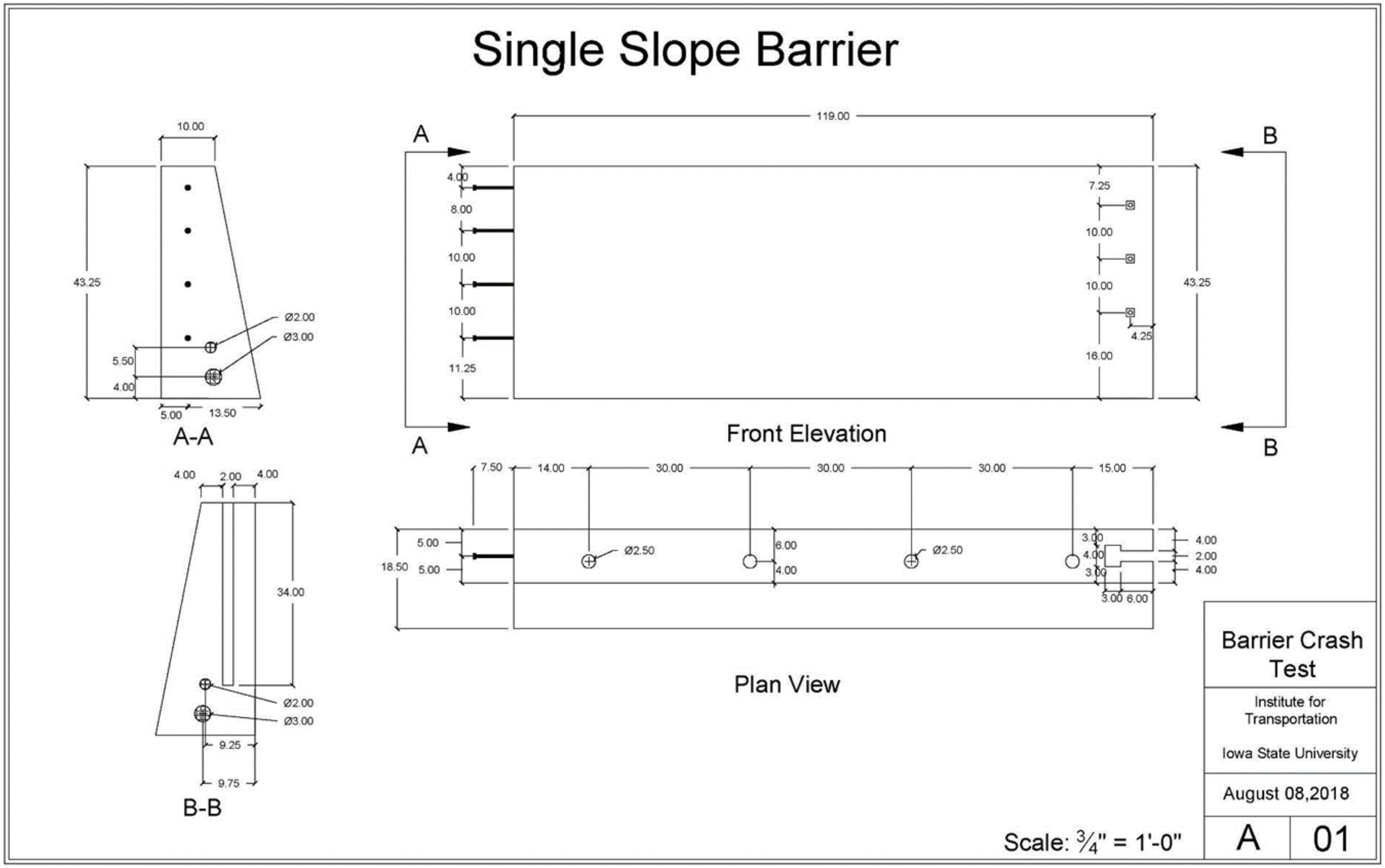


Figure 6. Single-Slope Barrier Segment, Dimensions in Inches [5]

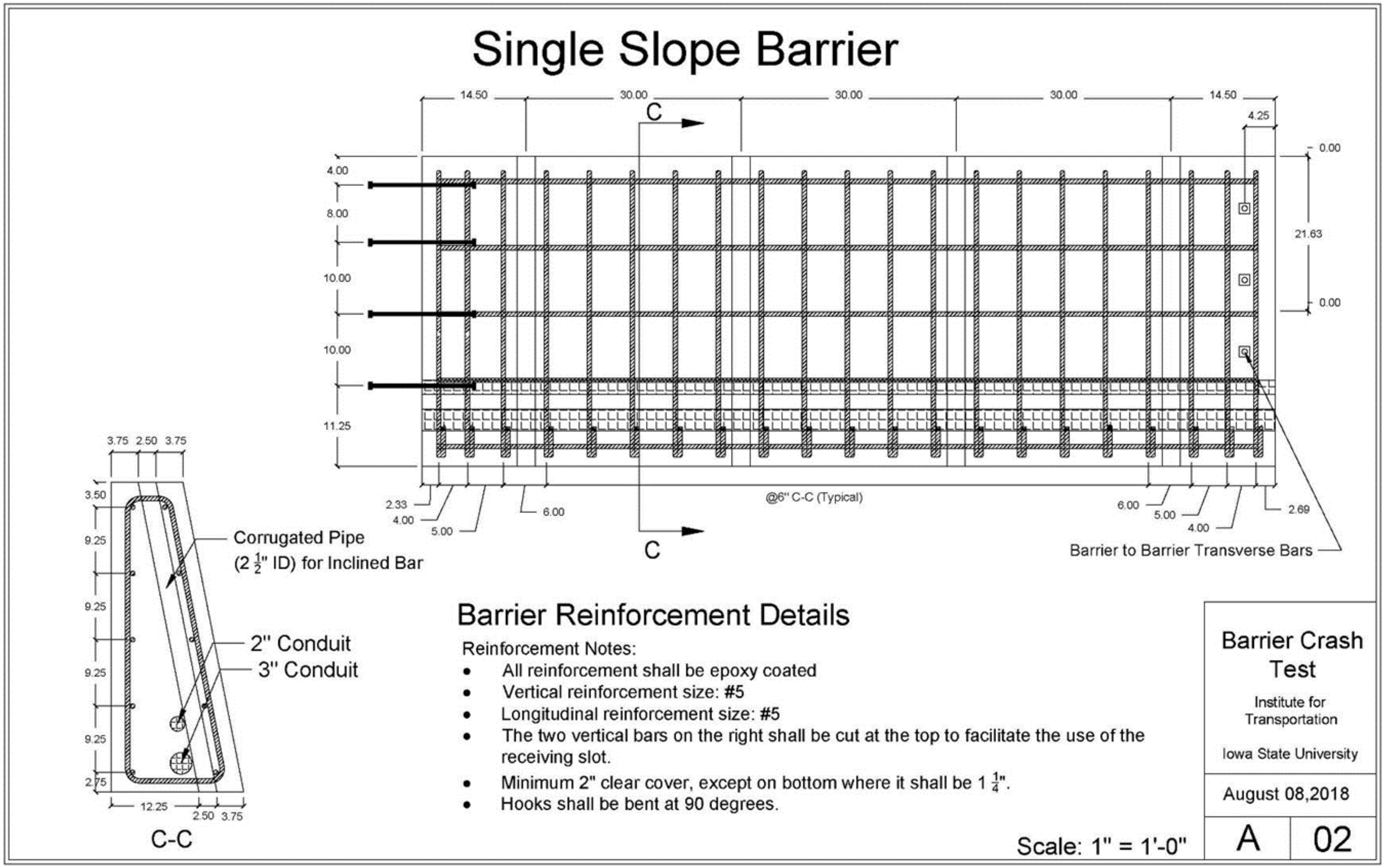


Figure 7. Single-Slope Barrier Segment, Reinforcement Details (Note: the spacing of the inclined tie-down bar was later reduced) [5]

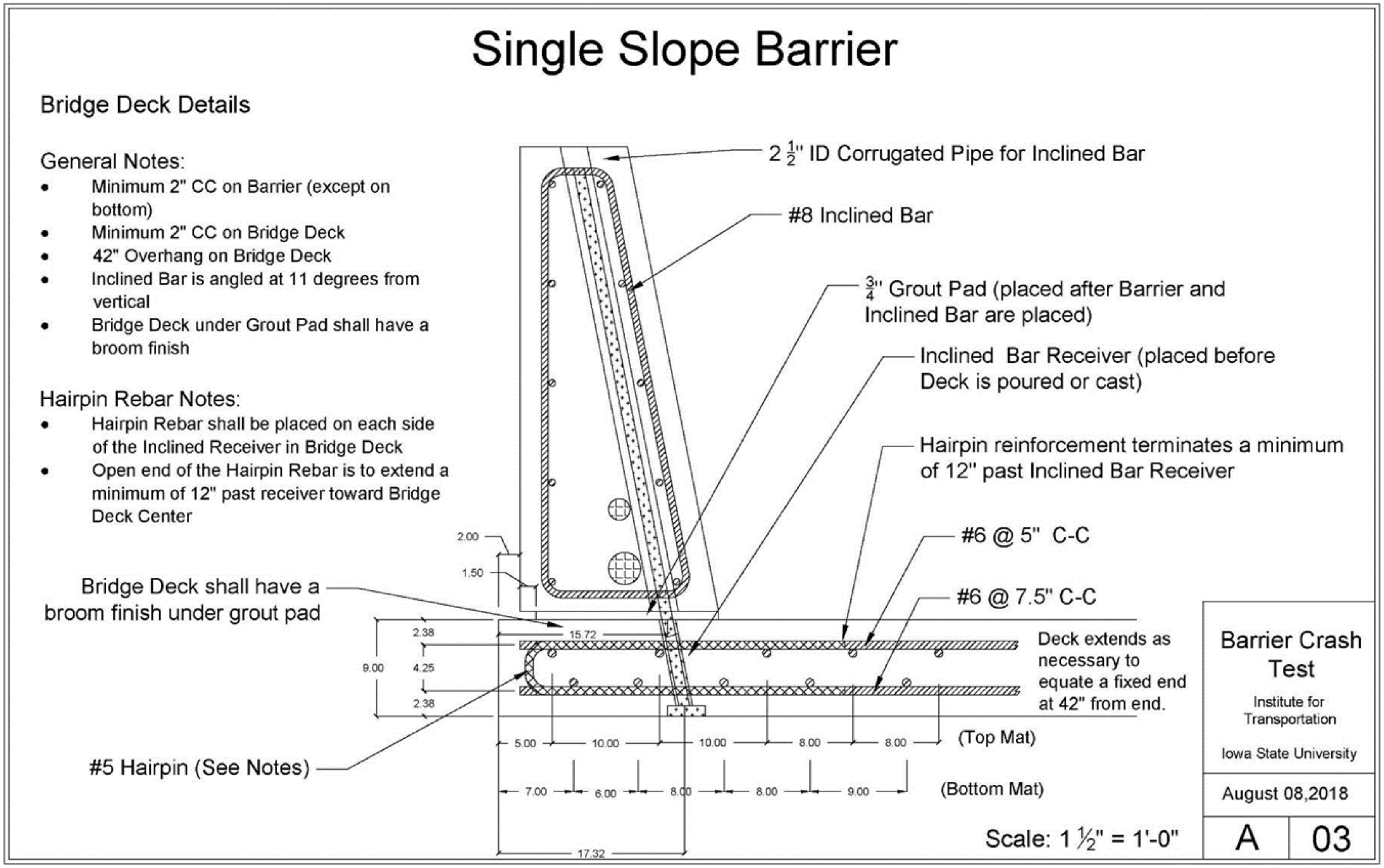


Figure 8. Single-Slope Barrier Segment, Deck and Barrier-to-Deck Attachment Details [5]

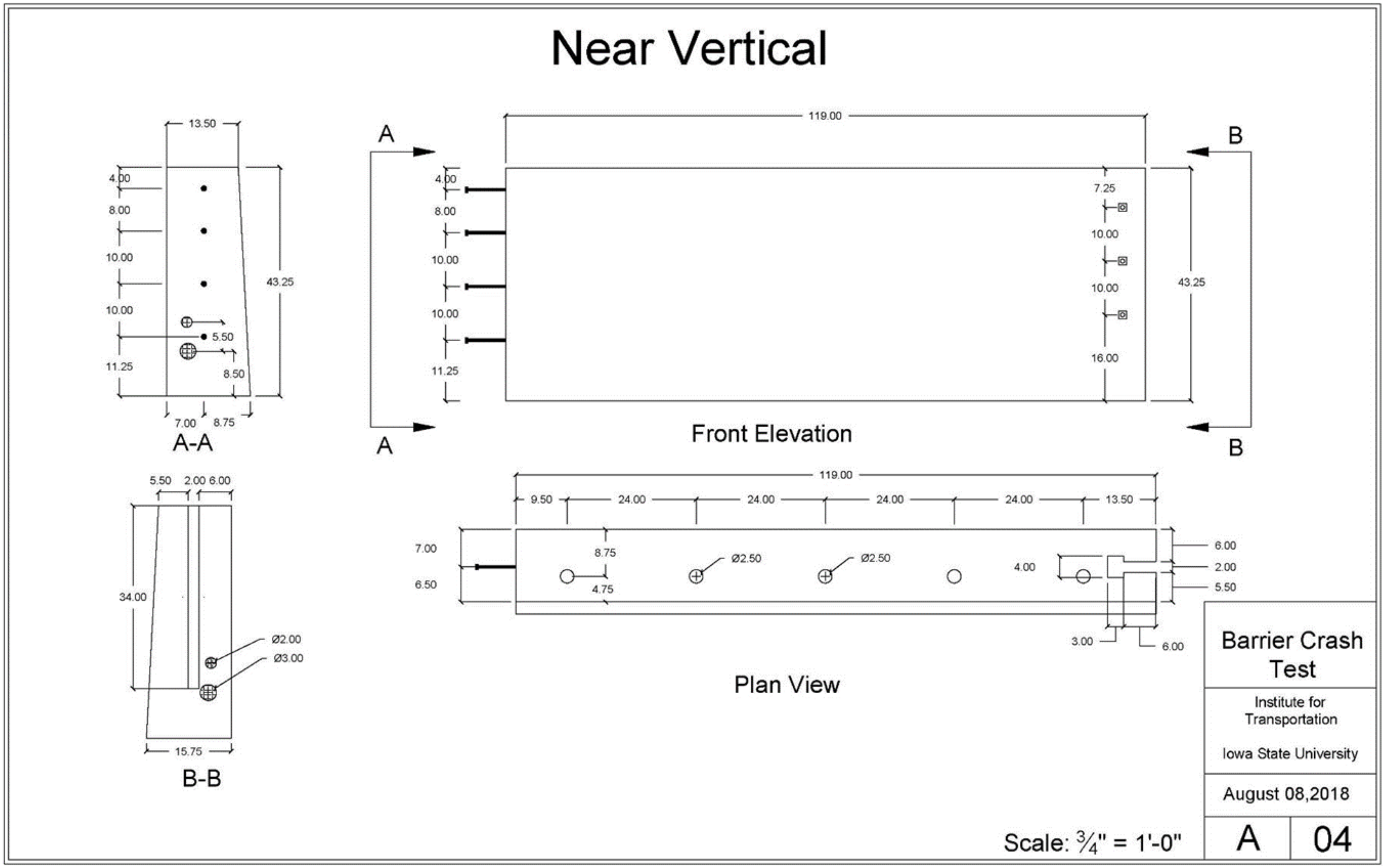


Figure 9. Near-Vertical Barrier Segment, Dimensions in Inches [5]

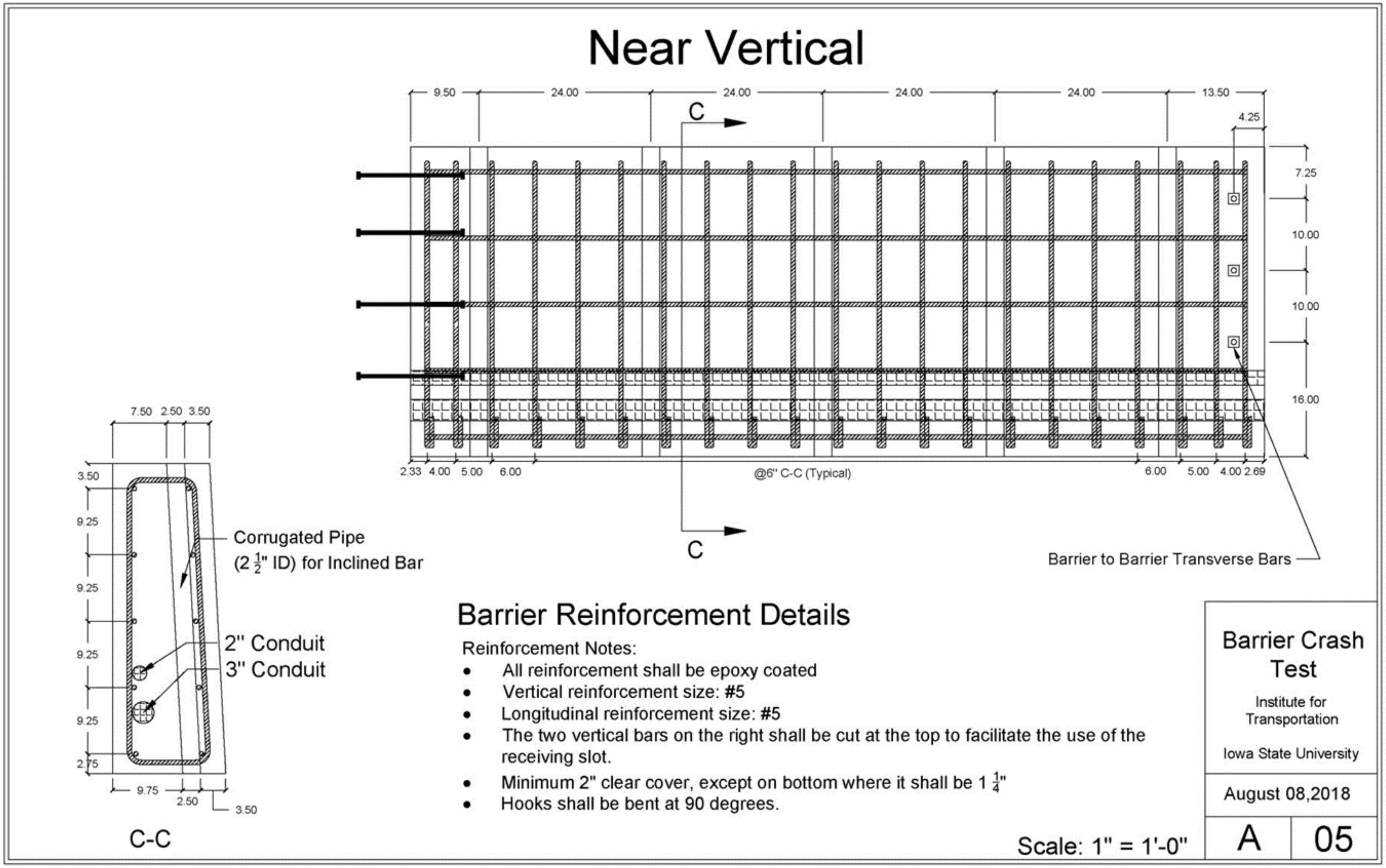


Figure 10. Near-Vertical Barrier Segment, Reinforcement Details [5]

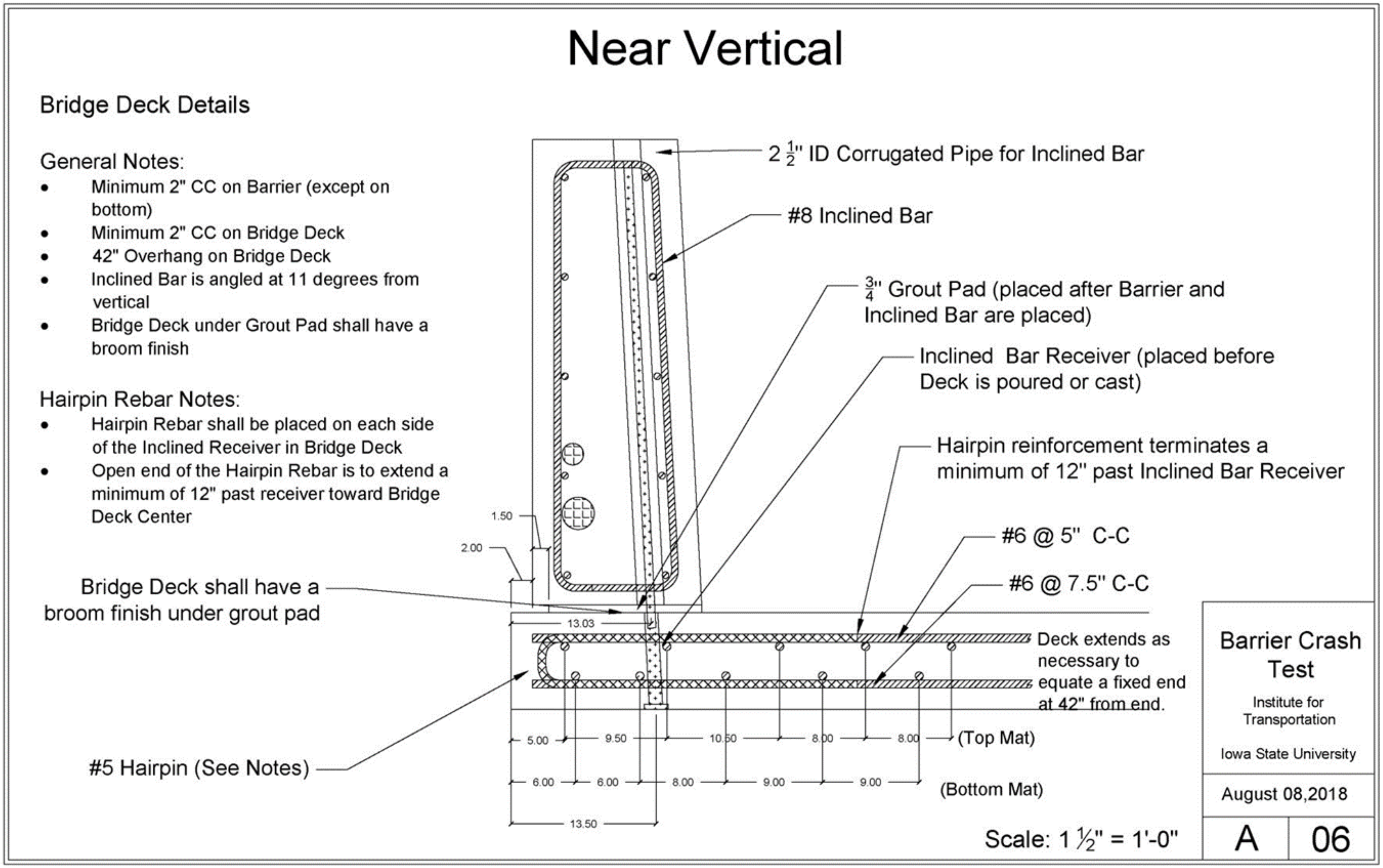


Figure 11. Near-Vertical Barrier Segment, Deck and Barrier-to-Deck Attachment Details [5]

1.2 Background

To mitigate time-intensive installations or replacements of bridge structures, many transportation agencies have started to implement Accelerated Bridge Construction (ABC) methodologies. A predominant technique in ABC entails the usage of Prefabricated Bridge Elements and Systems (PBES) instead of traditional cast-in-place construction methods. These prefabricated elements, applicable to the bridge superstructure, typically encompass elements such as girders and decks. In this approach, the interconnections between these elements often only require on-site assembly and fixation.

An area of ABC that has received comparatively less attention is the development of prefabricated elements specifically designed for concrete bridge rails. Most bridge rails, predominantly composed of concrete, are still created through cast-in-place methods. This process is intrinsically time-consuming, requiring significant durations for casting and curing to reach the desired capacity. In response to this limitation, InTrans devised a precast concrete bridge barrier with an integral attachment system, which features unique connection details for the barrier-to-deck and barrier-to-barrier couplings for utilization in ABC initiatives [1].

InTrans formulated two alternative methods of connections between the deck and the precast concrete barrier. A traditional precast concrete barrier was examined alongside these two connection alternatives, using full-scale precast barriers for evaluation. The first type of barrier-to-deck connection employed inclined reinforcing bars with threaded ends, joined to bar splicers embedded within the bridge deck, as depicted in Figure 12. The second type (shown in Figure 13) involved U-shaped bars inserted into the barrier from the underside of the bridge deck overhang. The design considerations for these connections included minimal damage to the deck, ease of barrier replacement, constructability, durability, and economic feasibility. The performance of the inclined reinforcement connection was found to be superior to the U-shaped bar connection, and suggestions were provided to further optimize the performance of the detail.

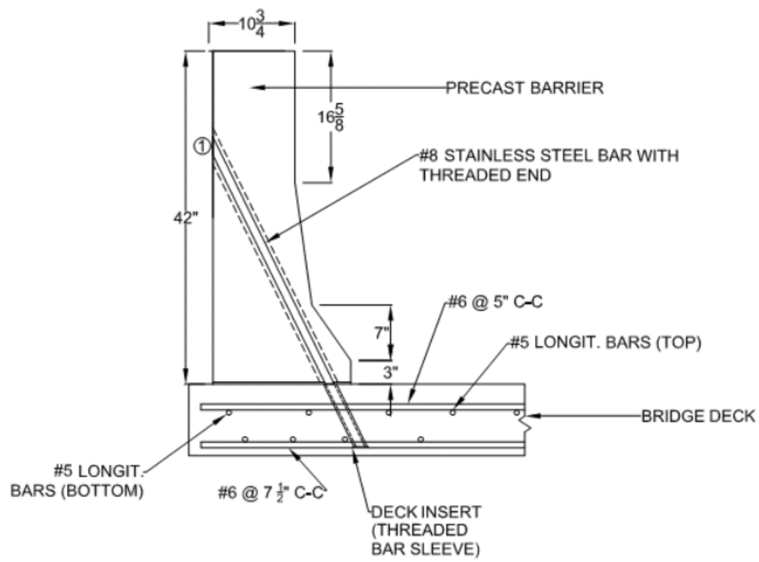


Figure 12. Iowa State University Inclined Bar Connection Between Precast Barrier and Deck (all dimensions are in inches) [1]

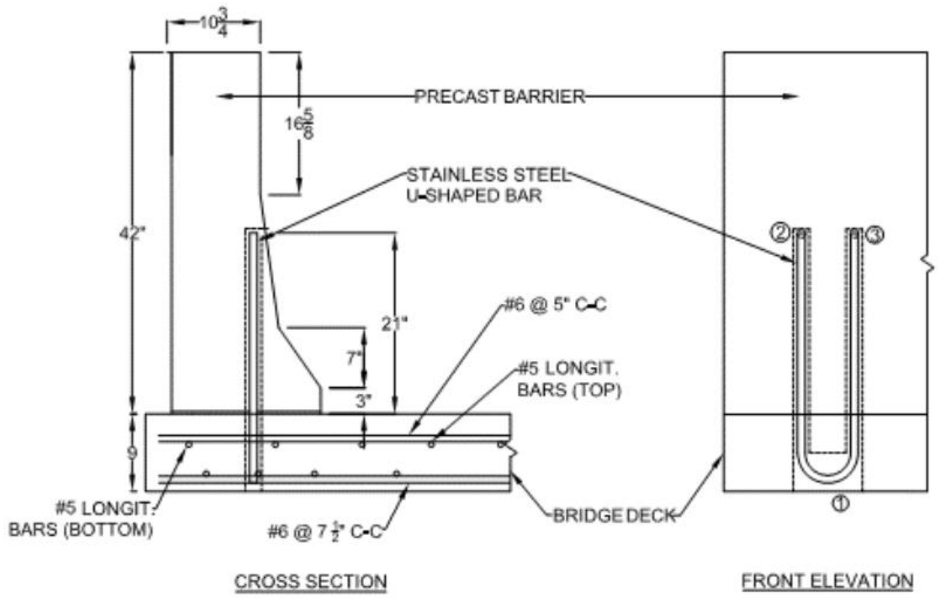


Figure 13. Iowa State University U-bar Connection Between Precast Barrier and Deck (all dimensions are in inches) [1]

Following the development and testing efforts for the precast concrete barrier, it was noted that results from NCHRP Project No. 22-20(2) [6] indicated that the MASH TL-4 impact loads were substantially greater than the previous TL-4 loads under NCHRP Report 350 [7]. The current guidance from NCHRP Project No. 22-20(2) recommended approximately an 80-kip lateral impact load for designing bridge rails and concrete parapets under MASH TL-4 test conditions with a 10000S single-unit truck (SUT) vehicle [6]. This lateral design load is distributed across a 5-ft length and applied at a height of 30 in. It should be noted that more detailed information is provided for use in determining the magnitude of design load and load application height as a function of barrier height.

1.3 Research Objectives and Methodology

The primary objectives of this research were to: (1) perform numerical simulations preceding the crash test; (2) conduct a crash test utilizing a 10000S SUT; and (3) undertake numerical evaluations subsequent to the full-scale crash test.

Within the numerical analysis parts of this project, the intent was to evaluate a crashworthy TL-4 precast bridge rail through various simulations. They complemented the physical evaluation of the precast concrete bridge barrier designed by InTrans at ISU to MASH TL-4 [1]. The investigations were separated into two phases: (1) pre-crash test predictions and design modifications and (2) post-crash test analysis. Extensive modeling was performed in the first phase, and the physically tested specimen was decided based on these numerical results.

The crash test, which aligned with MASH TL-4 test designation no. 4-12, entailed constructing a full-scale precast concrete bridge railing and deck system. The full-scale crash testing was conducted to evaluate the MASH safety performance of the precast concrete bridge rail, damage to the barrier and deck, and the working width for the precast concrete barrier.

1.4 Scope

The research objectives were achieved through the systematic execution of several tasks, each contributing to the understanding and evaluation of the crash performance of the prototype precast concrete bridge barrier.

The first task involved the research team conducting an initial evaluation. This evaluation was informed by their accumulated expertise, previous experiences, and the employment of LS-DYNA computer simulations. Pre-crash modeling and analysis were carried out prior to the crash test. The pre-crash investigation encompassed: (1) LS-DYNA computer simulations to predict the barrier and the vehicle performance for impacts into both the prototype single-slope barrier and prototype near-vertical barrier using all three MASH TL-4 test vehicles (1100C, 2270P, and 10000S); (2) determination of the required test length for the crash testing program; (3) selection of the critical barrier shape for the crash testing program based on the simulation analysis; (4) comparative study of the simulation results across all three test vehicles and both barrier shapes; (5) determination of the Critical Impact Point (CIP) for all three test vehicles on both barrier shapes; (6) investigation of impacts at various points including in the middle of a barrier segment, at the barrier-to-barrier connection, and upstream from the barrier-to-barrier connection; and (7) comparison of simulated CIPs to the CIPs established from MASH Section 2.3.2.2.

Following the pre-crash modeling and analysis, the information obtained was used to make informed decisions regarding the preliminary test layout, revisions to the preliminary 3-D CAD details, and the placement of sensor instrumentation on selected barrier and deck locations prior to the crash test. The barrier system's test length was determined in accordance with the findings of the pre-crash analysis and the MASH guidelines. The system's length was configured such that the barrier's ends were not expected to undergo any lateral displacement. If deemed necessary, the research was also to make suggestions to the ISU design team regarding modifications to the barrier system that would improve the potential for a successful test and crashworthy barrier system. During the pre-crash modeling and analysis effort, the research team raised concerns and conducted more LS-DYNA computer simulations that led to decisions to modify the barrier design using (1) a higher-grade steel (60 ksi vs. 80 ksi) for the inclined bars and (2) a greater quantity of inclined bars in the single-slope configuration than initially designed.

Subsequently, a MASH TL-4 10000S SUT crash test was conducted on the single-slope concrete precast bridge rail. The test was conducted in compliance with the Midwest Roadside Safety Facility's (MwRSF) accredited testing services, validated by the A2LA laboratory accreditation body (A2LA Cert. No. 2937.01). The test results were thoroughly analyzed, evaluated, and documented. From this effort, conclusions were drawn, and recommendations were proposed regarding the safety performance of the single-slope concrete bridge rail.

Finally, a post-crash analysis was performed upon the crash test's completion. This analysis included comparisons between the simulation results obtained from the pre-crash analysis and the actual physical test results obtained from the 10000S SUT crash event. This final step ensured a comprehensive understanding of the performance of the barrier system under realistic crash conditions, confirming or contesting the initial predictions established during the pre-crash analysis phase.

2 PRE-CRASH TEST ANALYSIS

2.1 Purpose

This chapter serves as a comprehensive summary of the numerical analyses conducted before crash testing to predict the crashworthiness of the two ISU barrier configurations. It outlines the key elements of the analyses, including a detailed description of the Finite Element (FE) models developed for crash test simulations. The geometry, general modeling techniques, and material properties used in these models are also explained in this section.

FE models were created in the LS-DYNA software package [8]. This powerful package is specifically designed to simulate nonlinear collision simulations and has been successfully used to predict the behavior of concrete barriers when subjected to vehicular impact events. LS-DYNA is an effective tool for researchers and engineers to assess the barrier's safety performance under various impact scenarios.

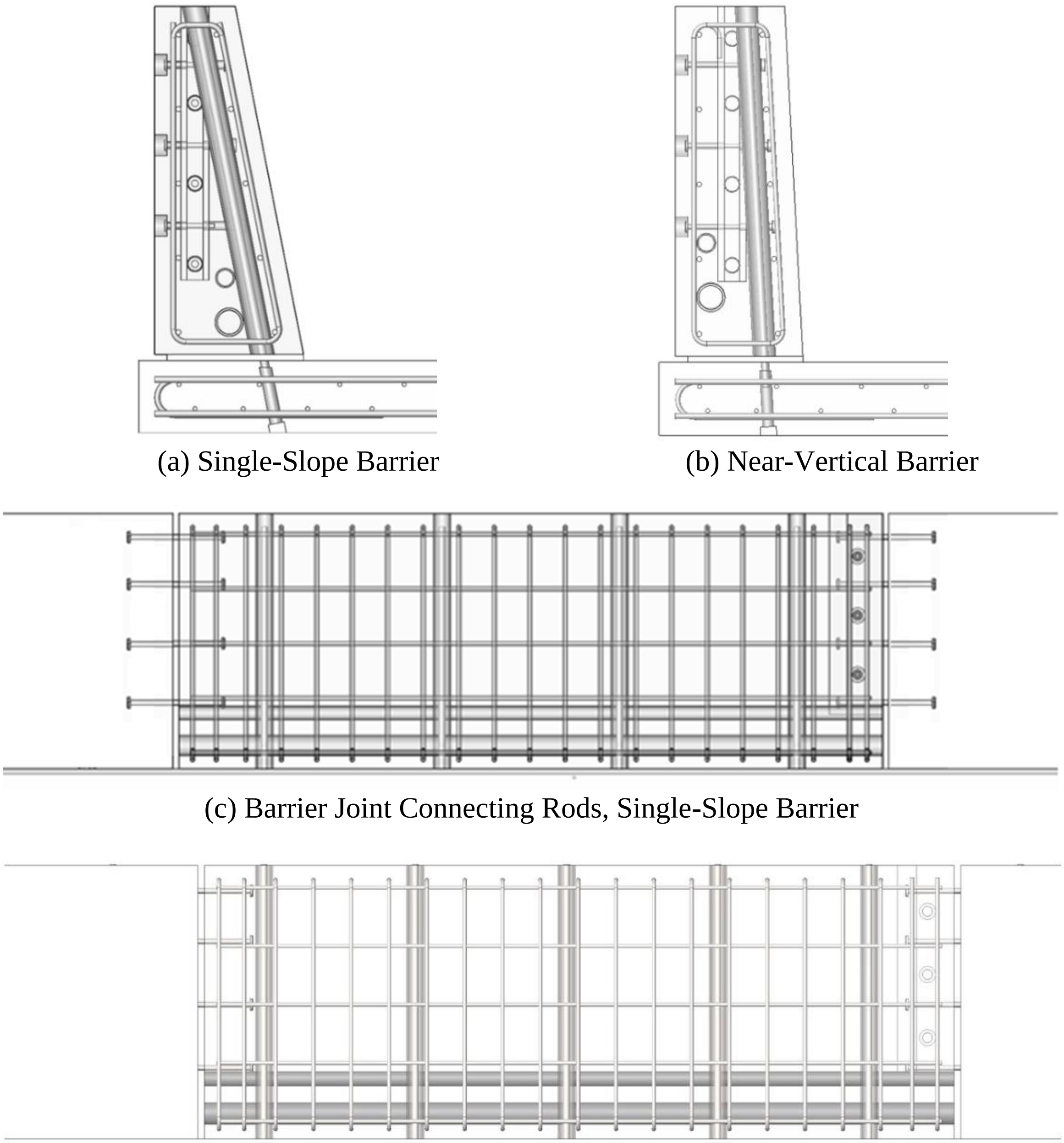
Several parameters define full-scale vehicle crash tests, including impact speed, impact angle, test vehicle mass and geometry, and impact location. For TL-4, the testing matrix includes 1100C and 2270P vehicle impacts at 62 mph and 25 degrees along with 10000S vehicle impacts at 56 mph and 15 degrees. These three test conditions were simulated in this project. It should be noted that the vehicle models used in this project were originally developed by the Center for Collision Safety and Analysis (CCSA) at George Mason University (GMU) [9], which later included updates that were provided by MwRSF researchers. The primary objective of the computer simulation effort was to shed light on the behavior and crashworthiness of the two ISU precast concrete barrier systems when subjected to MASH vehicle impact loading.

2.2 Geometry of Barriers and Impacting Objects

Two design alternatives (single-slope and near-vertical barrier shapes) were considered in this study. Schematics of the two barrier shapes are shown in Figure 14. The single-slope barrier design (10.9-degree slope) had four 1 in. diameter (Grade 60) inclined anchor rods per segment, while the near-vertical barrier design (3-degree slope) had five 1 in. diameter (Grade 60) inclined anchor rods. Both barrier shapes had four $^7/_8$ in. diameter barrier joint connecting rods, as depicted in Figure 14. The LS-DYNA model of the barrier and deck is shown in Figure 15. These two barrier types' geometry is shown in Figures 16 and 17. The total length of the modeled system for both barrier shapes was 80 ft and consisted of 8 segments, each with a length of 10 ft, as depicted in Figure 15. The grade beam beneath the deck was fixed. The maximum barrier height with the grout pad was 44 in.

The bridge deck was configured with a 42-in. lateral overhang extending away from the outer face of the grade beam. The lateral reinforcement embedded in the deck comprised two #6 bars spaced at 5 in. and 7½ in. on center on the top and bottom steel mats, respectively. A #5 rebar was placed on each side of the inclined receiver in the bridge deck. The deck was reinforced with #4 bars spaced longitudinally. The single-slope bridge rail segment was 10 in. wide at the top and 18½ in. wide at the base, while the near-vertical barrier was 13½ in. wide at the top and 15¾ in. wide at the base. In terms of reinforcement, each segment of the bridge rail was equipped with ten #5 longitudinal bars, divided between the front and back faces of the bridge rail.

Modeling all barrier components can be quite complex, which can yield data that may be difficult to interpret. This investigation prioritized resources and computational efforts toward aspects of the model that were deemed to have a greater impact on the study's overall objectives. Therefore, the investigation focused on the primary elements of interest – normal barrier reinforcement, inclined reinforcing bars, and double-headed ties across the barrier joints. As such, the transverse ties were not included in the simulation models. This decision was made to simplify the analysis at the ends of the reinforced concrete segments to manage the scope of research within practical bounds without compromising the integrity and relevance of the findings.



(a) Single-Slope Barrier

(b) Near-Vertical Barrier

(c) Barrier Joint Connecting Rods, Single-Slope Barrier

(d) Barrier Joint Connecting Rods, Near-Vertical Barrier

Figure 14. Schematics of Single-Slope and Near-Vertical Barrier Shapes: (a) Single-Slope Barrier; (b) Near-Vertical Barrier(c) Barrier Joint Connecting Rods, Single-Slope Barrier; and (d) Barrier Joint Connecting Rods, Near-Vertical Barrier

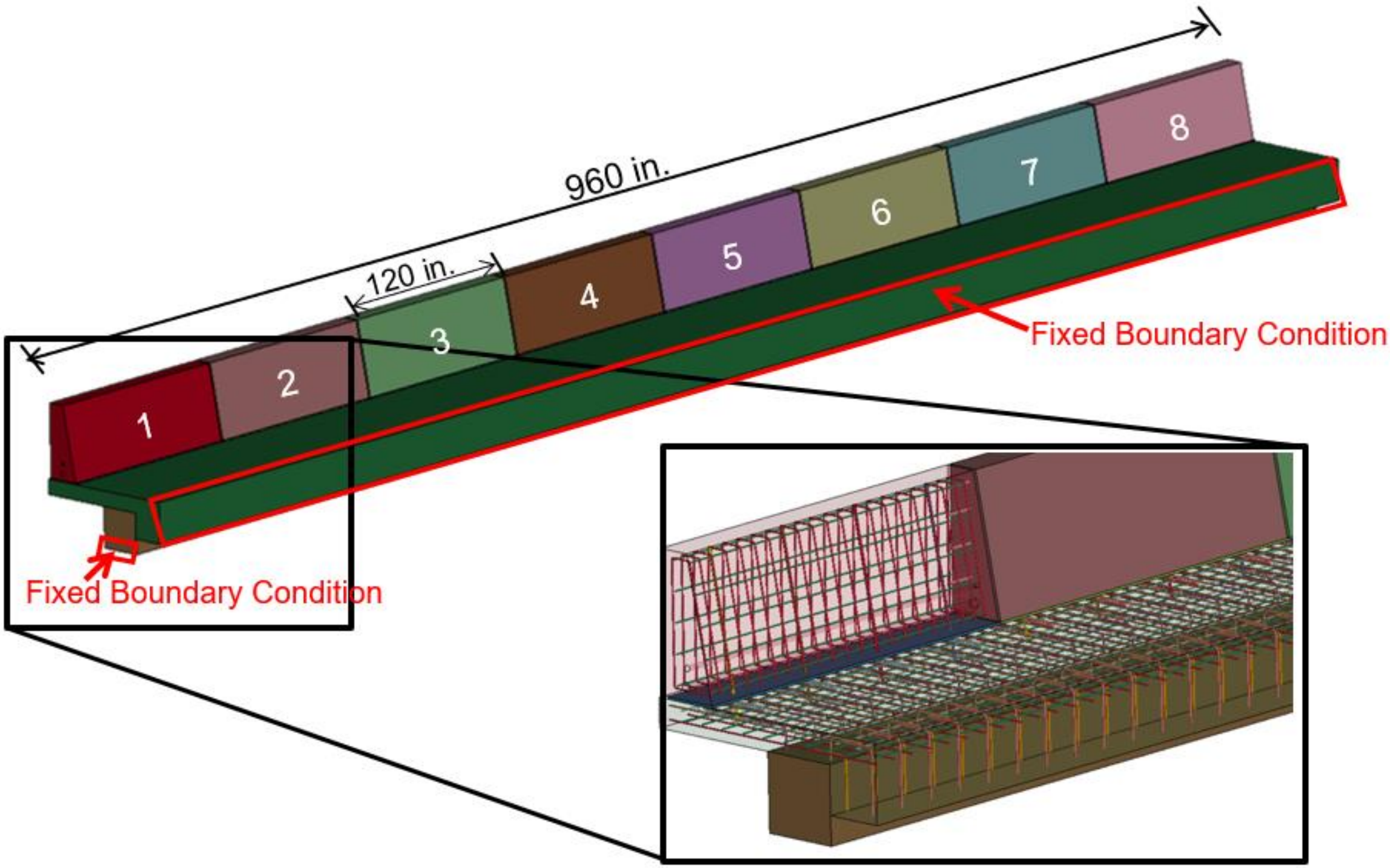


Figure 15. Overview of LS-DYNA Model of Precast Concrete Barrier System – Bridge Deck Region Only

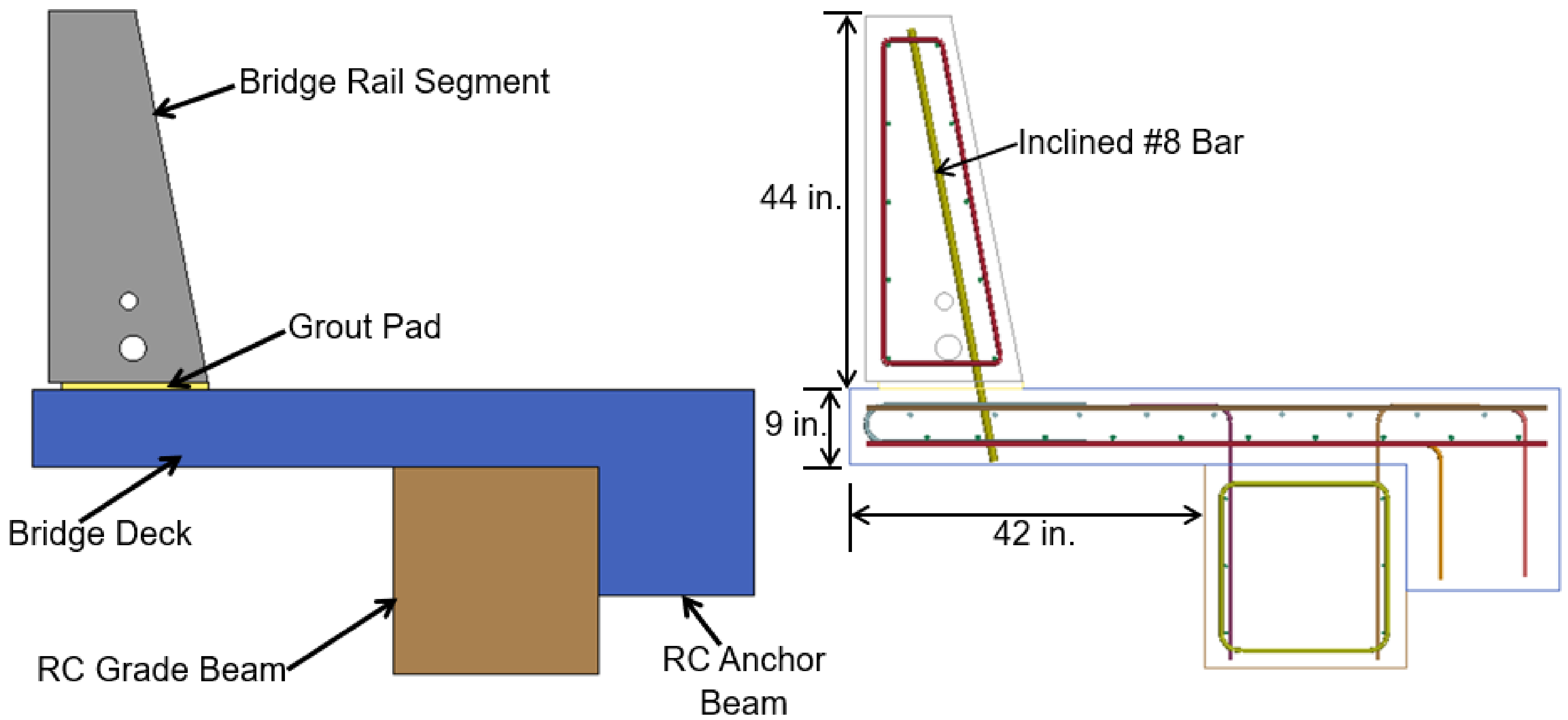


Figure 16. Overview of LS-DYNA Model of Bridge Deck, Grade Beam, Anchor Beam, and Barrier System for Single-Slope Barrier Shape

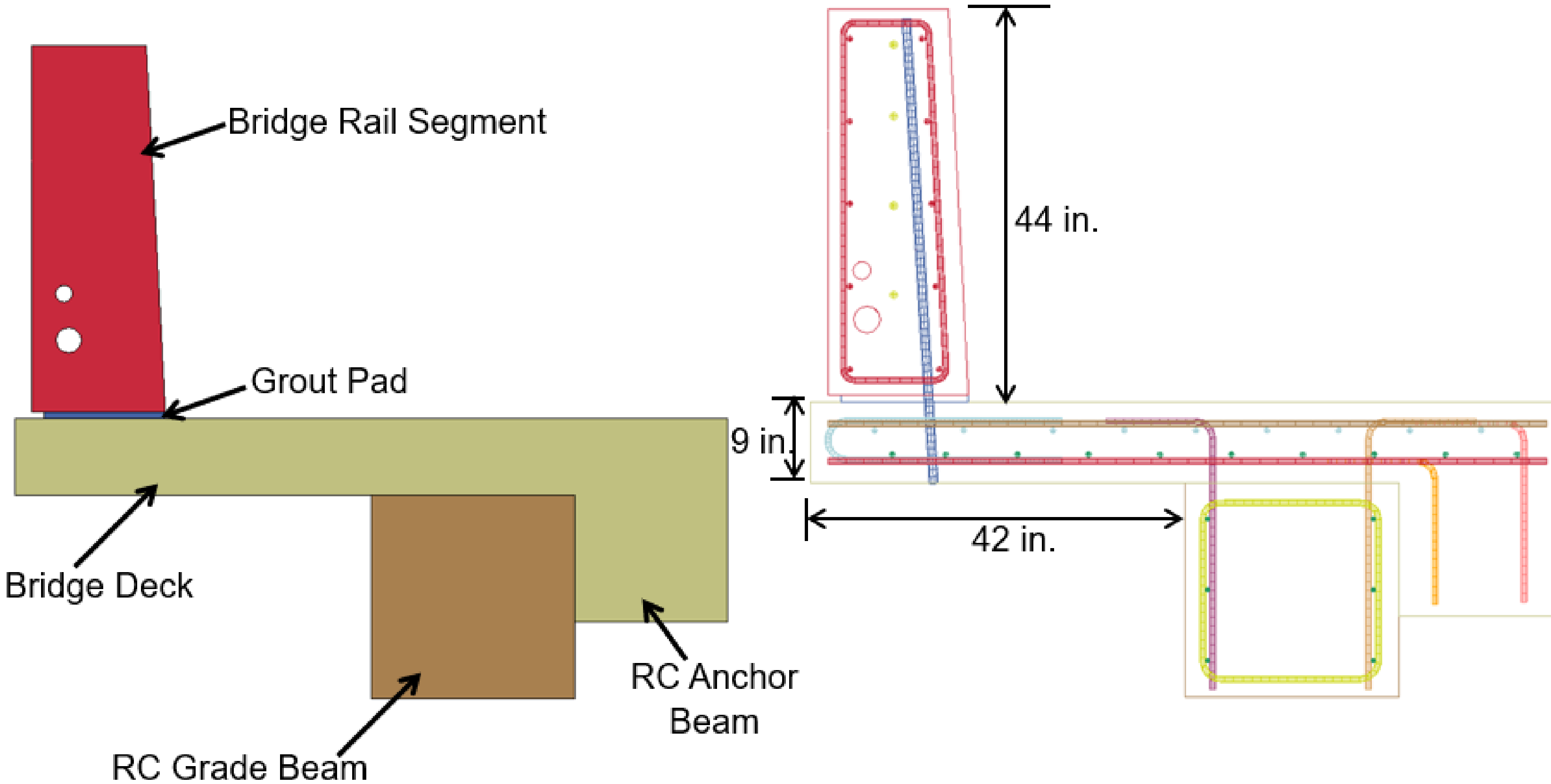


Figure 17. Overview of LS-DYNA Model of Bridge Deck, Grade Beam, Anchor Beam, and Barrier System for Near-Vertical Barrier Shape

The type, size, and weight of the test vehicles can significantly affect the impact safety associated with the MASH crash tests. Both small and large passenger vehicles can pose a significant and unique set of challenges for most types of roadside safety hardware. The specified MASH test vehicles considered for the current study were a small car weighing approximately 2,420 lb (designation 1100C), a four-door, two-wheel drive, half-ton pickup truck weighing 5,000 lb (designation 2270P), and a single-unit truck weighing 22,046 lb (designation 10000S). LS-DYNA models of these vehicles are shown in Figure 18. Note that the vehicle models were developed by the CCSA at GMU [9], which were later updated by MwRSF researchers.

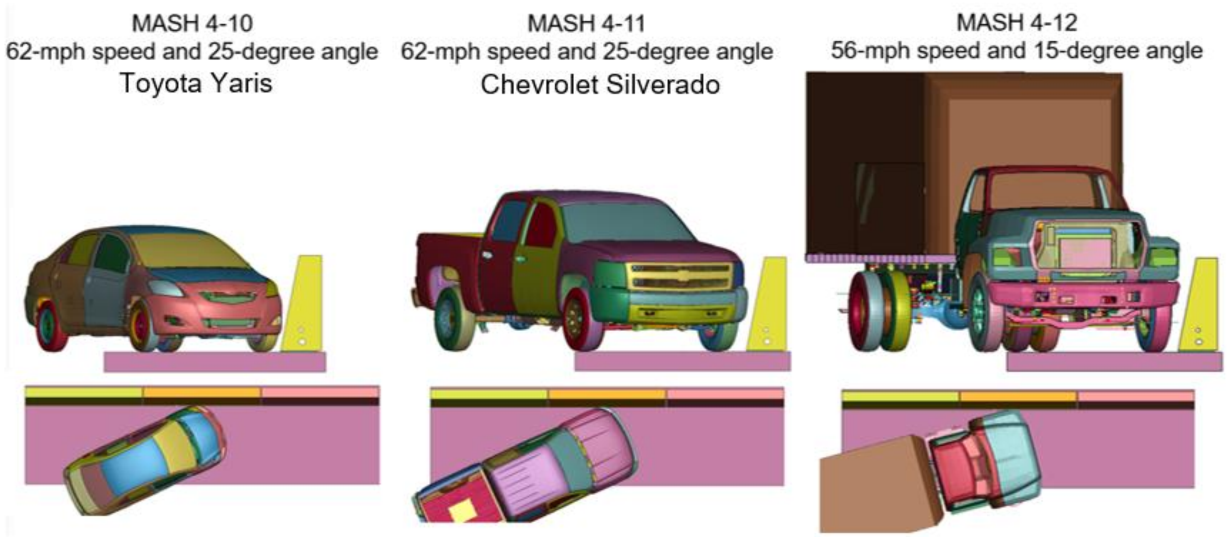


Figure 18. LS-DYNA Models of 1100C, 2270P, and 10000S Test Vehicles

2.3 Material Properties

All concrete parts used the Continuous Surface Cap Model (CSCM) in LS-DYNA [10]. The CSCM considers various characteristics of concrete, such as strength, stiffness, hardening/softening, damage, and the influence of strain rate. The model's formulation comprises three surfaces: triaxial compression; triaxial extension; and torsional shear. These surfaces technically make up the yield surface. There are also ultimate and residual surfaces.

Additionally, there is a hardening cap surface that determines the pressure at which the material starts exhibiting inelastic strains. The damage formulation within the CSCM involves strain softening in both compression and tension, as well as modulus reduction. The strain rate effect accounts for the increase in concrete strength as the strain rate rises.

This study utilized normal-weight concrete with a density of 150 pounds per cubic foot. The unconfined compressive strength of the concrete was estimated to be 4,000 psi. Previous research works have successfully applied the CSCM to accurately capture the impact response of various concrete structures subjected to impact loads [11-15].

Steel reinforcement was modeled using the piecewise linear plasticity model [15–17]. This material model enables the specification of parameters, such as steel reinforcement density, modulus of elasticity, yield strength, Poisson's ratio, effective stress–plastic strain relationship, and strain rate effect. The density of the steel reinforcement was assumed to be 490 pounds per cubic foot. The moduli of elasticity and yield strength of the steel were considered 29,000 ksi and 60 ksi, respectively. The Poisson's ratio was assumed to be 0.3. The strain rate effect in the steel reinforcement followed the equations proposed by Malvar and Crawford [18]. The parameter C and P were considered 0, and V_p was considered 1 in the simulations. A bilinear stress-strain curve was considered for the rebar steel material. Eight-node solid elements were used to model concrete components. Friction contact was used to model the contact between the barrier, grout, and pad. The embedded reinforcement within the concrete was represented using beam elements. The interaction between the concrete and rebar was simulated using the constrained beam in solid feature of LS-DYNA. As such, the bond between the reinforcement bars and the surrounding concrete was modeled as perfect.

2.4 Vehicle Models and Impact Locations

Full-scale crash testing is the primary method for evaluating the impact performance of roadside safety features. These tests are crucial in assessing how well these safety features can withstand vehicular collisions. One vital aspect of the impact performance evaluation process is carefully selecting the test vehicles. Choosing vehicles that represent a wide range of sizes and types commonly encountered on the roads is important. MASH designates three test vehicles for TL-4 to account for the various vehicle types that may collide with barriers on highways. These designations aim to encompass a diverse set of impacting vehicles. Table 1 provides an overview of the properties of these test vehicles. The test vehicle designations ensure that the safety feature's performance is evaluated comprehensively, as both light vehicles prone to rollover or severe ride down and heavy trucks prone to override are included.

The philosophy behind selecting these test vehicles is rooted in the idea that if a safety feature can demonstrate satisfactory performance for the smallest and largest passenger vehicles, it is expected to perform adequately well for all passenger vehicle sizes [3]. This approach allows for a holistic assessment of the safety feature's effectiveness, considering the entire spectrum of vehicles encountered in service.

Impact locations on a safety feature should be carefully chosen to represent a critical impact point, which is the point where the highest probability of test failure occurs [3]. In order to locate this point, simulations were conducted with multiple vehicles. For each vehicle type, three different impact locations were used. For the 1100C vehicle, the impact locations were at the mid-span of barrier no. 2, 3.6 ft upstream of the joint, and at the joint between barrier nos. 2 and 3. Similarly, for the 2270P vehicle, the impact locations were at the mid-span of barrier no. 2, 4.3 ft upstream of the joint, and at the joint between barrier nos. 2 and 3. Finally, for the 10000S vehicle, the impact locations were at the mid-span of barrier no. 2, 2.5 ft upstream of the joint (which corresponded to ¾-span location), and at the joint between barrier nos. 2 and 3. These impact locations were investigated and analyzed through numerical simulations, and details of the simulation matrix can be found in Table 2. In total, 18 different combinations of barrier types, impact vehicles, and impact locations were considered during the numerical analysis.

Table 1. MASH TL-4 Test Designations and Evaluation Criteria

MASH Test Designation No.	4-10	4-11	4-12
Description	2,420-lb car at 62 mph/25 degrees	5,000-lb pickup at 62 mph/25 degrees	22,000-lb single-unit truck at 56 mph/15 degrees
Structural Adequacy	A. Contain and redirect vehicle without override of barrier	A.Contain and redirect vehicle without override of barrier	B. Contain and redirect vehicle without override of barrier
Occupant Risk	D. No penetration and limited deformations of occupant compartment	D. No penetration and limited deformations of occupant compartment	D. No penetration and limited deformations of occupant compartment
	F. Remain upright; maximum roll and pitch angles of 75 degrees	F. Remain upright; maximum roll and pitch angles of 75 degrees	F. Preferable, but not essential, that the vehicle remain upright
	H. Lateral and longitudinal occupant impact velocity (OIV) ≤ 40 ft/s (12.2 m/s)	H. Lateral and longitudinal occupant impact velocity (OIV) ≤ 40 ft/s (12.2 m/s)	NA
	I. Lateral and longitudinal occupant ridedown acceleration (ORA) ≤ 20.49 g’s	I. Lateral and longitudinal occupant ridedown acceleration (ORA) ≤ 20.49 g’s	NA

Table 2. Final Numerical Simulation Matrix (for each Barrier Shape)

Test No.	Vehicle	Speed (mph)	Angle (deg)	Impact point
4-10	1100C	62	25	Mid-span of barrier
				3.6 ft upstream of joint
				Joint
4-11	2270P	62	25	Mid-span of barrier
				4.3 ft upstream of joint
				Joint
4-12	10000S	56	15	Mid-span of barrier
				¾-span
				Joint

2.5 Results and Discussion

The performance of the two barrier shapes under vehicle impact loading was investigated and analyzed using various model response measures, such as concrete damage pattern, axial and shear force in rebars, impact force, and velocity or acceleration-time history from the vehicle impact simulations.

2.5.1 General Behavior and Concrete Damage

The general effect of different vehicle impacts on the barriers were first assessed by analyzing the concrete damage contours, as depicted in Figure 19, for an impact at the mid-span of barrier no. 2. The damage value increased whenever the material was undergoing yielding, meaning it accumulated when the stress state was beyond the yield surface. This figure clearly illustrated that the damage predominantly occurred at the second and third barriers, which were the locations of the collisions. Among the impacting vehicles, the 10000S vehicle caused the most significant damage and displacement in the impact zone. This notable damage was primarily due to the vehicle 10000S's greater mass and impact severity. Further, the increased center of gravity (C.G.) height of the 10000S vehicle resulted in a higher lateral load and, consequently, a greater overall moment exerted on the barrier/bridge railing and the deck.

Additionally, it was observed that the barriers' traffic-side surface suffered more damage than the back-side face. Moreover, in the case of the near-vertical barriers, generally, more damage was seen on the barrier-to-barrier joint connections compared to what was observed in the single-slope barriers. These joint connections experienced higher stresses due to the specific geometry and configuration of the near-vertical barrier design. Greater impact force for the near-vertical barriers was likely due to decreased vehicle roll and climb, resulting in more energy dissipated through lateral load. It is worth noting that in all tested conditions, the impacting vehicles collided with the barriers twice. The initial collision involved the vehicle's front bumper, followed by a secondary collision involving the side of the vehicle near the quarter panel or the back of the cargo box (tail slap). Throughout the impact simulations, the barriers gradually returned to a lesser displacement from their peak displacement, indicating some degree of elastic rebound after the impact event.

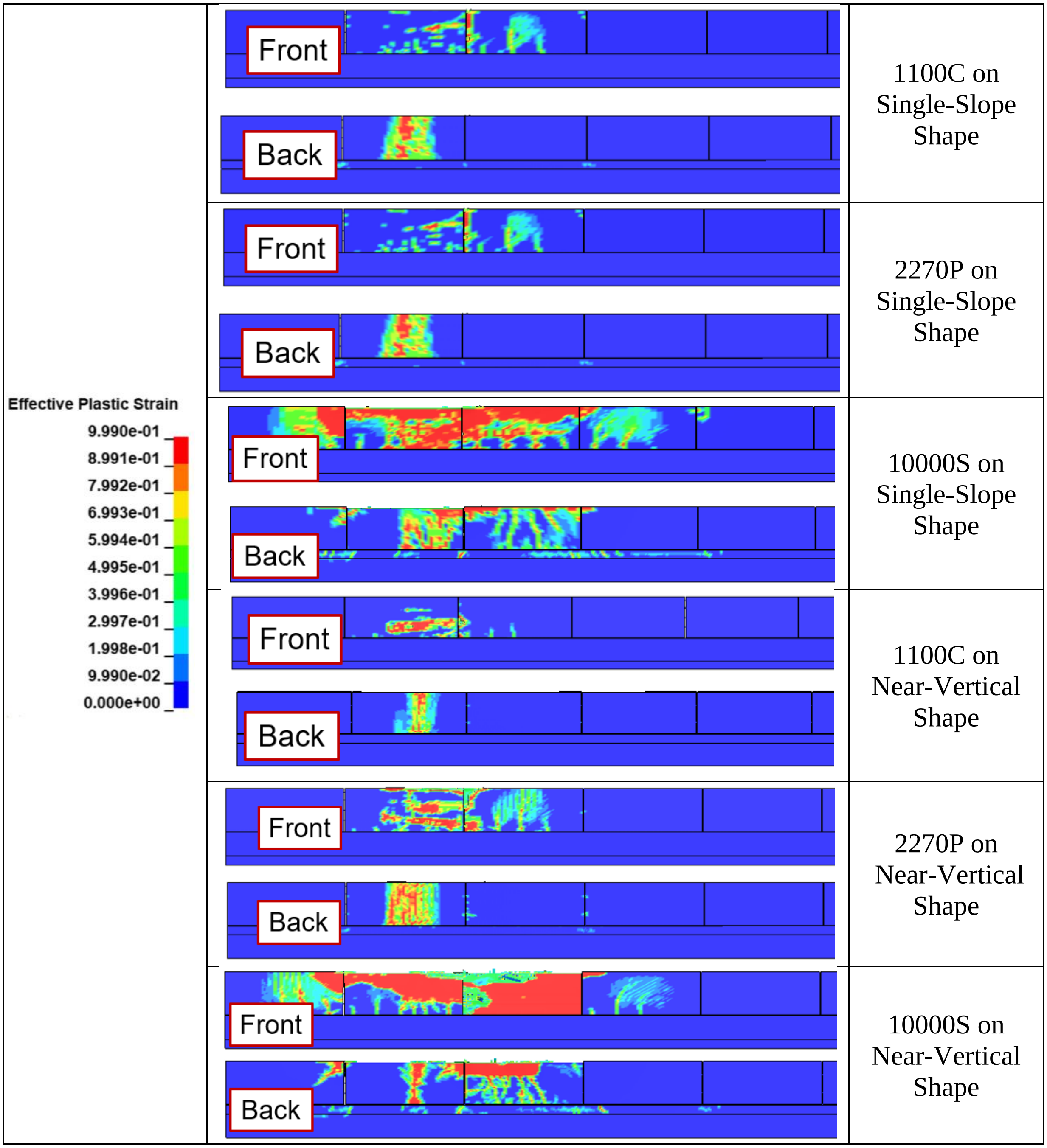


Figure 19. Concrete Damage Contours for Selected Simulations, Impact at Mid-Span of Barrier No. 2

2.5.2 Stresses in Inclined and Joint Rebars

Axial and von Mises stresses that were developed in the inclined and longitudinal joint rebars at critical locations are shown in Tables 3 through 5. The reinforcing steel rebars initially had a yield strength of 60 ksi. The numbers in parentheses indicated the count of rebars that yielded in a given simulation. Based on the number of yielded rebar for the three SUT (TL-4) impact scenarios, impact at mid-span appeared more critical than impact at ¾-span and joint for the single-slope barrier. Also, impact at ¾-span appeared more critical than that impact at mid-span and joint for the near-vertical barrier. As shown, it was found that inclined bars in both types of barriers reached stresses beyond their yield point in the case of impacts with the 2270P pickup truck and 10000S SUT.

Tables 3 through 5 demonstrated that as the impact severity and load height increased, the maximum stress experienced by the rebar also increased. Additionally, the number of yielded rebar increased with higher vehicle masses and impact severity. Note that the numbers in parentheses are the number of yielded bars. Moreover, it was observed that although the near-vertical barrier included one more inclined bar than the single slope barrier, bars in this design were still stressed beyond yield during impacts involving pickup trucks and SUTs. This highlights the load-reducing effect of the single slope barrier due to an allowance for increased vehicle roll and climb.

Table 3. Axial and von Mises (VM) Stresses in Inclined and Joint Rebars (1100C vehicle)

Simulation results	**Single-slope barrier (four inclined bars)**			**Near-vertical barrier (five inclined bars)**		
	Mid-span	**3.6 ft u/s**	**Joint**	**Mid-span**	**3.6 ft u/s**	**Joint**
Max. impact force (kips)	53.50	51.70	58.45	58.00	54.40	49.45
Max. axial stress in No. 8 inclined bar (ksi)	32.60	55.11	43.61	36.25	46.41	57.74
Max. VM stress in No. 8 inclined bar (ksi)	38.44	60.91 (2)	50.76	49.31	57.28	60.91 (1)
Max. axial stress in No. 7 joint rebar (ksi)	15.23	26.83	20.30	24.65	26.10	25.38
Max. VM stress in No. 7 joint rebar (ksi)	21.03	28.28	27.55	29.00	31.90	33.35

Table 4. Axial and von Mises (VM) Stresses in Inclined and Joint Rebars (2270P vehicle)

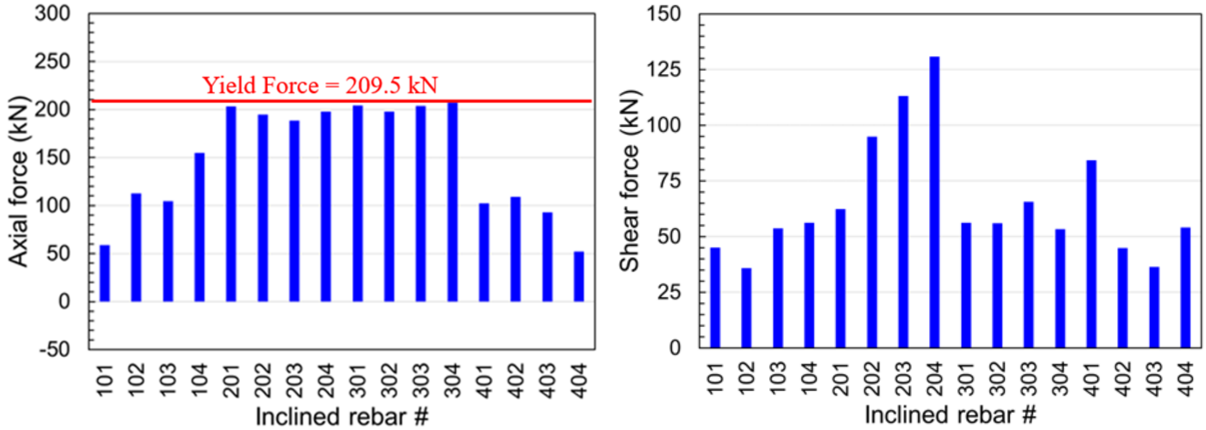
Simulation results	**Single-slope barrier (four inclined bars)**			**Near-vertical barrier (five inclined bars)**		
	Mid-span	**4.3 ft u/s**	**Joint**	**Mid-span**	**4.3 ft u/s**	**Joint**
Max. impact force (kips)	64.07	63.17	68.57	71.94	69.92	74.19
Max. axial stress in No. 8 inclined bar (ksi)	66.71	66.43	63.81	60.19	63.6	58.01
Max. VM stress in No. 8 inclined bar (ksi)	67.41 (3)	68.17 (2)	65.27 (5)	63.81 (2)	64.00 (2)	60.91 (1)
Max. axial stress in No. 7 joint rebar (ksi)	34.80	49.31	44.96	55.11	43.51	55.31
Max. VM stress in No. 7 joint rebar (ksi)	43.51	58.01	53.66	60.91 (2)	55.11	64.10 (2)

Table 5. Axial and von Mises (VM) Stresses in Inclined and Joint Rebars (10000S vehicle)

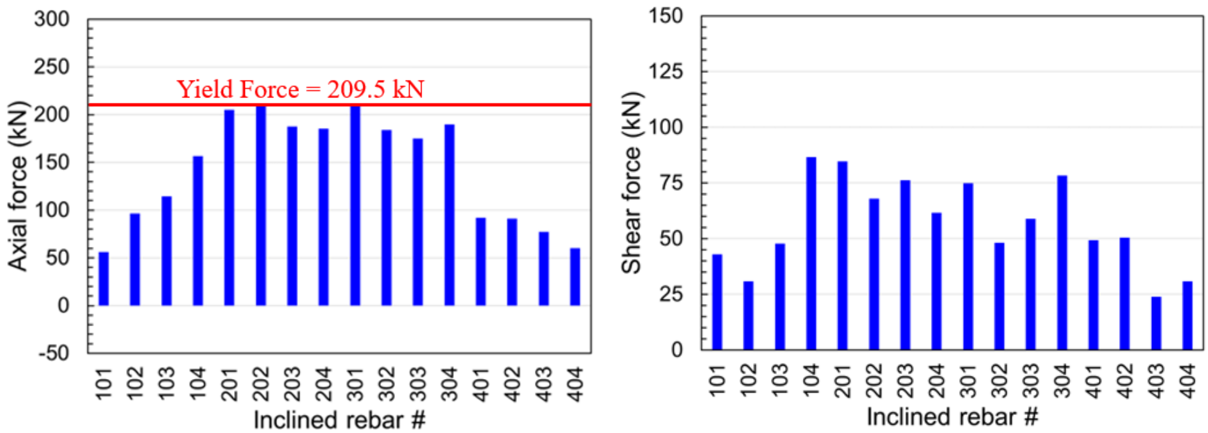
Simulation results	Single-slope barrier (four inclined bars)			Near-vertical barrier (five inclined bars)		
	Mid-span	3/4-span	Joint	Mid-span	3/4-span	Joint
Max. impact force (kips)	116.90	109.03	105.66	57.78	76.88	50.36
Max. axial stress in No. 8 inclined bar (ksi)	89.62	87.02	72.52	78.32	75.51	61.64
Max. VM stress in No. 8 inclined bar (ksi)	94.27 (8)	88.47 (7)	76.87 (6)	79.77 (9+6)	77.59 (10)	66.42 (10+5)
Max. axial stress in No. 7 joint rebar (ksi)	60.91	60.50	61.64	63.09	63.81	63.51
Max. VM stress in No. 7 joint rebar (ksi)	66.71 (6)	61.20 (3)	62.05 (4)	63.52 (6)	69.61 (11)	63.81 (7)

Figure 20 illustrates the maximum axial and shear forces observed in inclined rebars within the single-slope barriers during impacts involving the 10000S vehicle. It is important to note that the diagrams showcasing the forces acting on the rebars can be found in Appendix A. As shown, the location of the maximum forces experienced by the rebars varies based on the impact location. For instance, when the impact occurs at the joint between barrier nos. 2 and 3, the rebar in barrier no. 4 reaches a maximum axial force of approximately 182.08 kN (40.93 kip). However, in other impact locations, the maximum axial force in the same rebar was approximately 100.00 kN (22.48 kip). This observation highlights the influence of different impact points on the distribution of forces within the single-slope barrier system. The impact location determines which rebars bear the highest axial forces. This information was considered when determining the critical impact point for physical testing. Note the plot in Figure 19 depicts the maximum observed axial and shear forces regardless of time. These forces were plotted at a time when axial forces are maximum in a rebar and shown in Appendix A.

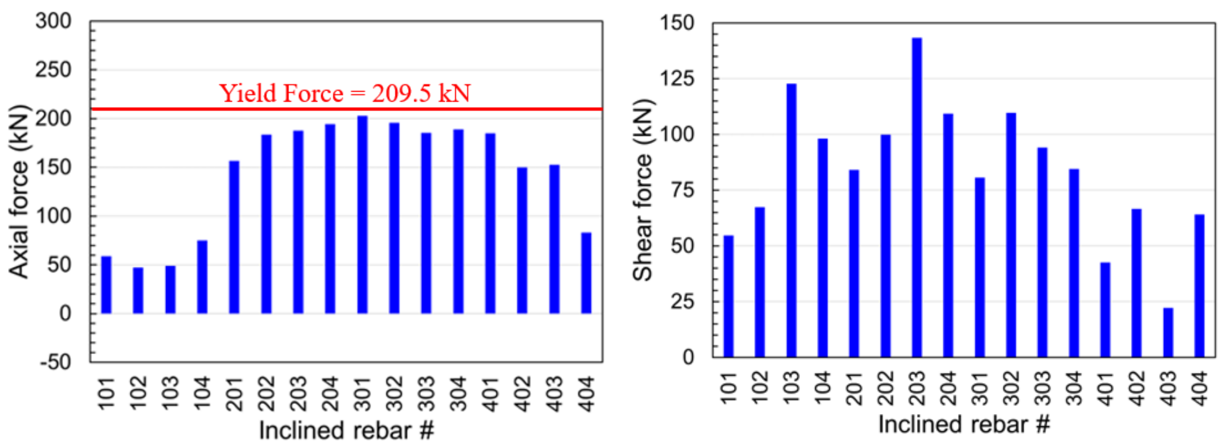
Figure 21 shows the maximum axial and shear forces observed in inclined rebars within the near-vertical barrier shape during impact from 10000S vehicle. This figure similarly established that the location of the maximum forces on the reinforcement bars were influenced by the impact location. For instance, an impact at ¾-span location yielded a peak axial force of approximately 236.5 kN (53.17 kip). in the rebar of barrier no.2. Conversely, alternative impact points resulted in a peak axial force of approximately 212.2 kN (47.70 kip) in the same rebar. This pattern reiterates the substantial influence of varying impact locations on the force distribution within the near-vertical bridge railing system.



(a) Mid-span

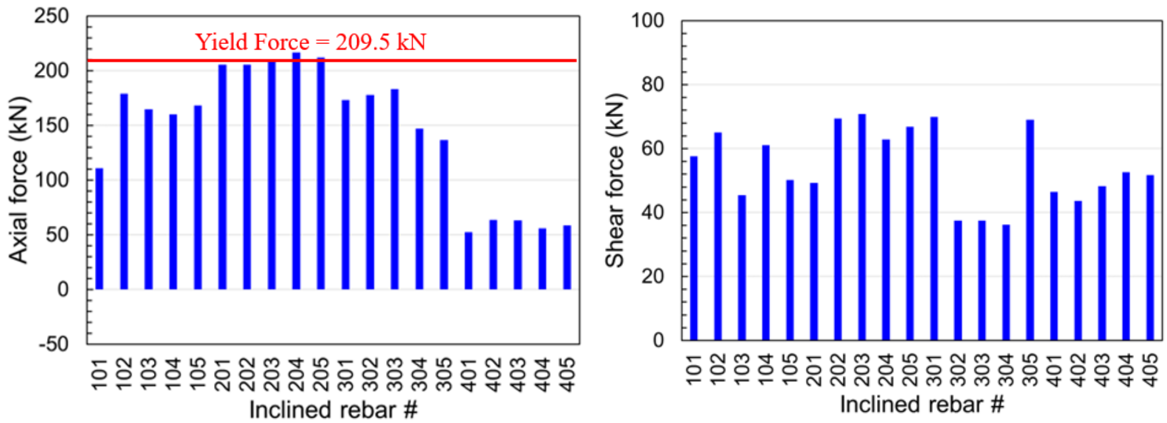


(b) ¾-span

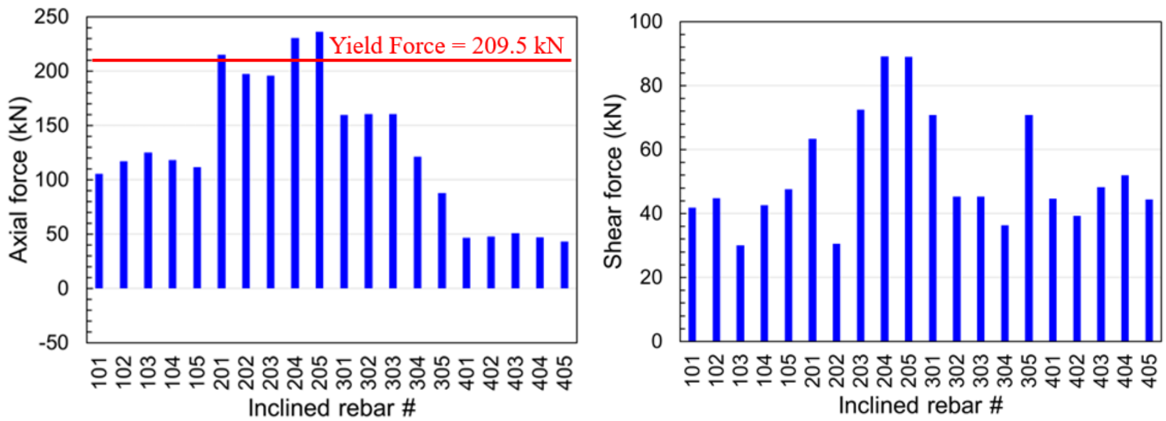


(c) Joint

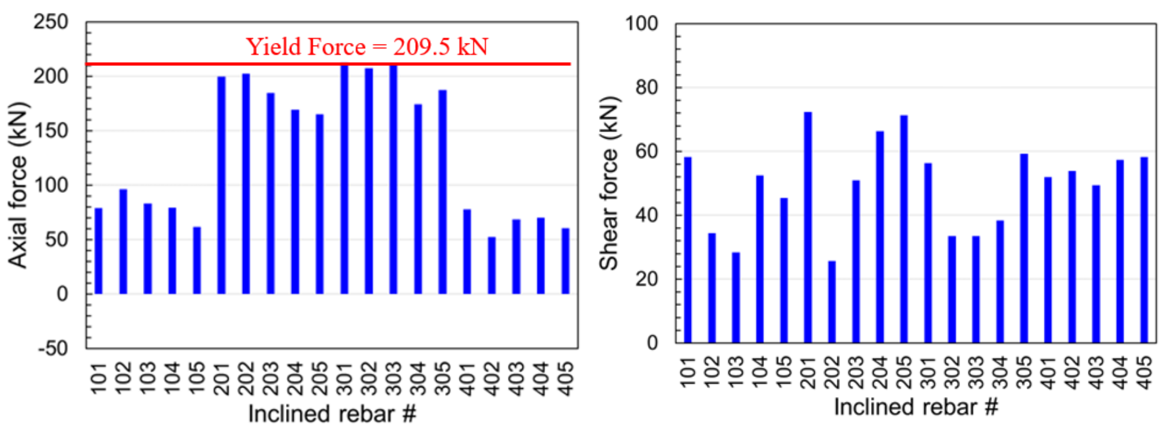
Figure 20. Maximum Observed Axial and Shear Forces in Single-Slope Barrier Shape – 10000S Vehicle Impact: (a) Impact at Mid-Span; (b) Impact at ¾-span; and (c) Impact at a Joint. Note that the plot depicts maximum observed forces regardless of time and the inclined bars are named using the generalized name 101 through 404.



(a) Mid-span



(b) ¾-Span



(c) Joint

Figure 21. Maximum Observed Axial and Shear Forces in Near-Vertical Barrier Shape – 10000S Vehicle Impact: (a) Impact at Mid-Span; (b) Impact at ¾-span; and (c) Impact at a Joint. Note that the plot depicts maximum observed forces regardless of time and the inclined bars are named using the generalized name 101 through 405.

2.5.3 Occupant Risk

The calculated occupant impact velocities (OIVs) and maximum 0.010-sec occupant ride down accelerations (ORAs) in both the longitudinal and lateral directions are shown in Tables 6 through 8. It should be noted that for the 1100C model, roll angles did not exceed the MASH limits (the maximum recorded angle was 66 degrees, which would have been higher if the termination time had been extended). Existing full-scale crash testing of single-slope barriers has not indicated vehicle roll as high as the roll angles observed in the simulation models. As such, it was believed that the recorded roll angles were due to issues with the Yaris (1100C) model and its interaction with the barrier model and did not represent an actual concern for high vehicle roll. A recent full-scale crash test conducted by the California Department of Transportation (Caltrans) on a single-slope concrete barrier with a small car (Test 3-10) had only 12 degrees of roll [20]. The ORA limits for 2270P were exceeded, which is a known simulation issue (i.e., overestimation of tail-slap loads with the Silverado pickup truck model).

Table 6. OIV, ORA, and Maximum Angular Displacement Value (1100C vehicle)

Evaluation Criteria		**Single Slope**			**Near Vertical**			**MASH Limits**
		Mid-span	**3.6 ft u/s**	**Joint**	**Mid-span**	**3.6 ft u/s**	**Joint**	
OIV (ft/s)	Longitudinal	-4.47	-4.61	-4.58	-5.52	-5.57	-5.77	±12.2
	Lateral	-9.14	-9.01	-9.00	-9.52	-9.46	-9.43	±12.2
ORA (g's)	Longitudinal	-6.07	-5.56	-5.18	-9.32	-10.12	-9.30	±20.49
	Lateral	-15.95	-15.63	-16.17	-14.91	-14.97	-13.11	±20.49
Maximum Angular Displacement (deg.)	Roll*	-66.49°	-66.31°	-54.44°	8.09°	8.17°	7.68°	±*75*
	Pitch	-7.64°	-7.54°	-7.95°	-4.75°	-4.41°	-4.68°	±75
	Yaw	-51.02°	-57.32°	-47.23°	-38.09°	-36.96°	-36.15°	not required

Table 7. OIV, ORA, and Maximum Angular Displacement Value (2270P vehicle)

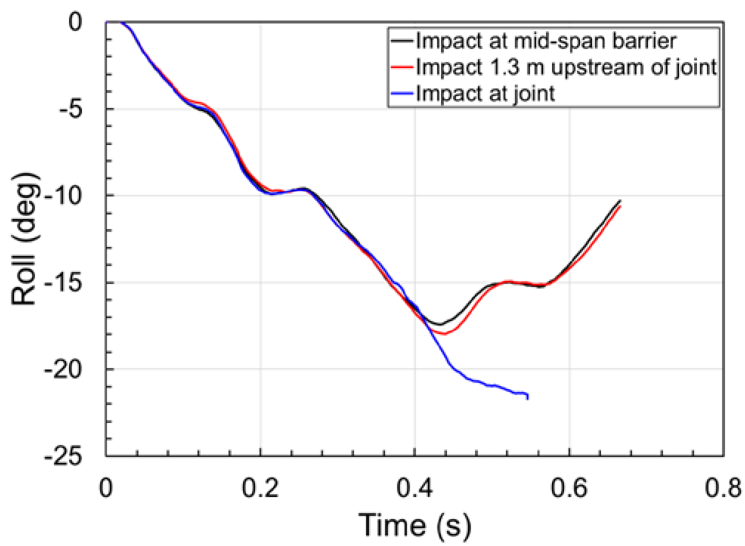
Evaluation Criteria		**Single Slope**			**Near Vertical**			**MASH Limits**
		Mid-span	**4.3ft u/s**	**Joint**	**Mid-span**	**4.3 ft u/s**	**Joint**	
OIV (ft/s)	Longitudinal	-4.31	-4.44	-4.20	-5.51	-5.62	-5.82	±12.2
	Lateral	-7.79	-7.78	-7.95	-7.88	-7.73	-8.31	±12.2
ORA (g's)	Longitudinal	-8.75	-13.72	-11.13	-7.66	-6.45	-6.78	±20.49
	Lateral	-20.14	-21.03	-22.49	-13.66	-13.65	-16.11	±20.49
Maximum Angular Displacement (deg.)	Roll	-33.18°	-38.56°	-43.08°	-21.94°	-23.42°	-22.59°	±75
	Pitch	-5.27°	12.48°	11.39°	9.42°	10.2°	7.83°	±75
	Yaw	-28.74°	-29.17°	-30.16°	-31.75°	-31.47°	-32.30°	not required

Table 8. OIV, ORA, and Maximum Angular Displacement Value (10000S vehicle)

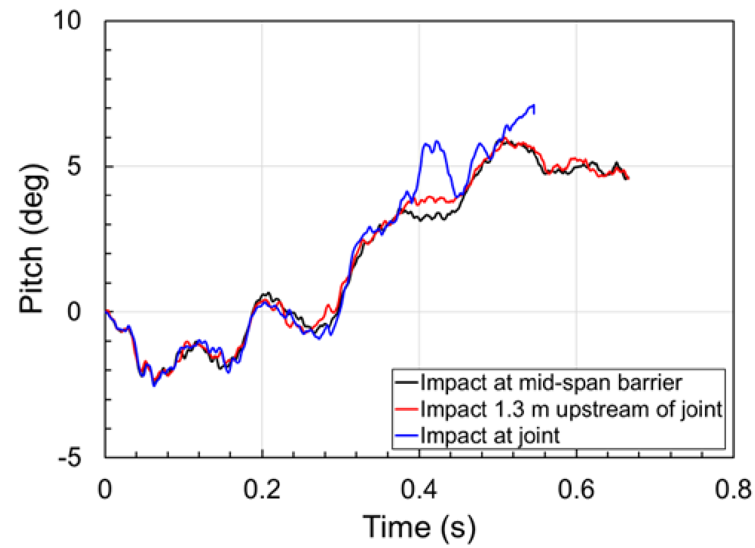
Evaluation Criteria		Single Slope			Near Vertical			MASH Limits
		Mid-span	¾-span	Joint	Mid-span	¾-span	Joint	
OIV (m/s)	Longitudinal	-0.99	-0.72	-0.86	-0.99	-1.35	-2.01	not required
	Lateral	-5.31	-5.19	-5.33	-5.31	-5.61	-5.02	not required
ORA (g's)	Longitudinal	-6.27	-6.92	-4.68	-6.27	-6.02	-10.19	not required
	Lateral	-7.10	-8.55	-6.41	-7.10	-8.82	-6.13	not required
Maximum Angular Displacement (deg.)	Roll	-17.40°	-17.96°	-21.70°	-8.87°	-15.17°	-9.42°	not required
	Pitch	5.87°	6.00°	7.11°	2.88°	4.36°	4.13°	not required
	Yaw	-20.96°	-21.08°	-18.16°	-17.07°	-20.86°	-15.27°	not required

Figure 22 shows the angular displacement-time histories of the 10000S vehicle collision model with the single-slope barrier. An analysis of the roll, yaw, and pitch dynamics revealed a general insensitivity to the point of impact for the majority of simulated collision events. Notably, the angular displacement metrics exhibit pronounced deviations at later time intervals when the point of impact aligns with the barrier joint, in contrast to mid-span and 1.3 meters (4.3 feet) upstream of a joint locations. Interestingly, the angular displacement-time histories for impacts at the mid-span and 1.3 meters upstream of a joint were nearly congruent, as corroborated by Figure 22. Maximal roll behavior was observed for impact at the joint. A comprehensive set of angular displacement-time histories for 1100C and 2270P vehicle models in collisions with a single-slope barrier is documented in Appendix B.

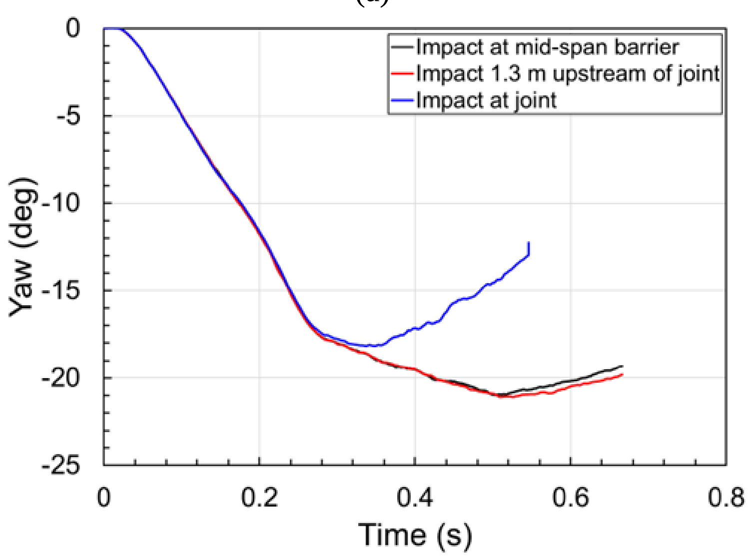
Figure 23 elucidates the angular displacement-time histories for the 10000S vehicle upon collision with a near-vertical barrier. While yaw and pitch dynamics remained largely invariant across varying impact locations, roll behavior exhibited marked disparities between points of impact. Specifically, the most accentuated roll response was observed for impacts situated 1.1 m (3.6 ft) upstream of the barrier joint. The complete datasets for angular displacement-time histories for 1100C and 2270P vehicle models with near-vertical barriers are also encompassed in Appendix B.



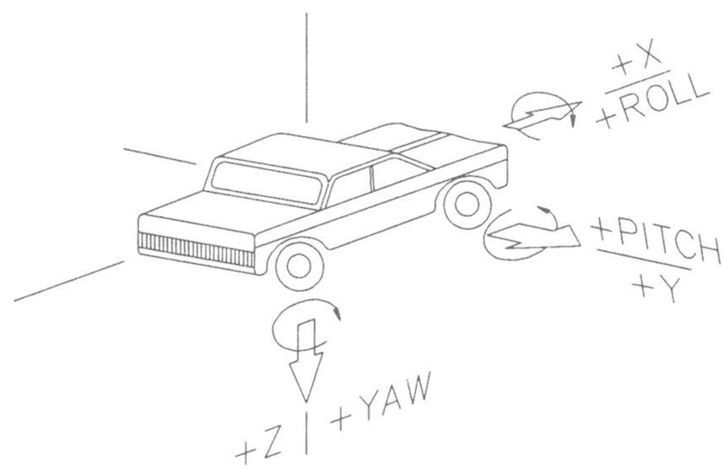
(a)



(b)



(c)



(d)

Figure 22. Angular Displacement-Time History and Vehicle Coordination System – 10000S Vehicle Impact with Single-Slope Barrier

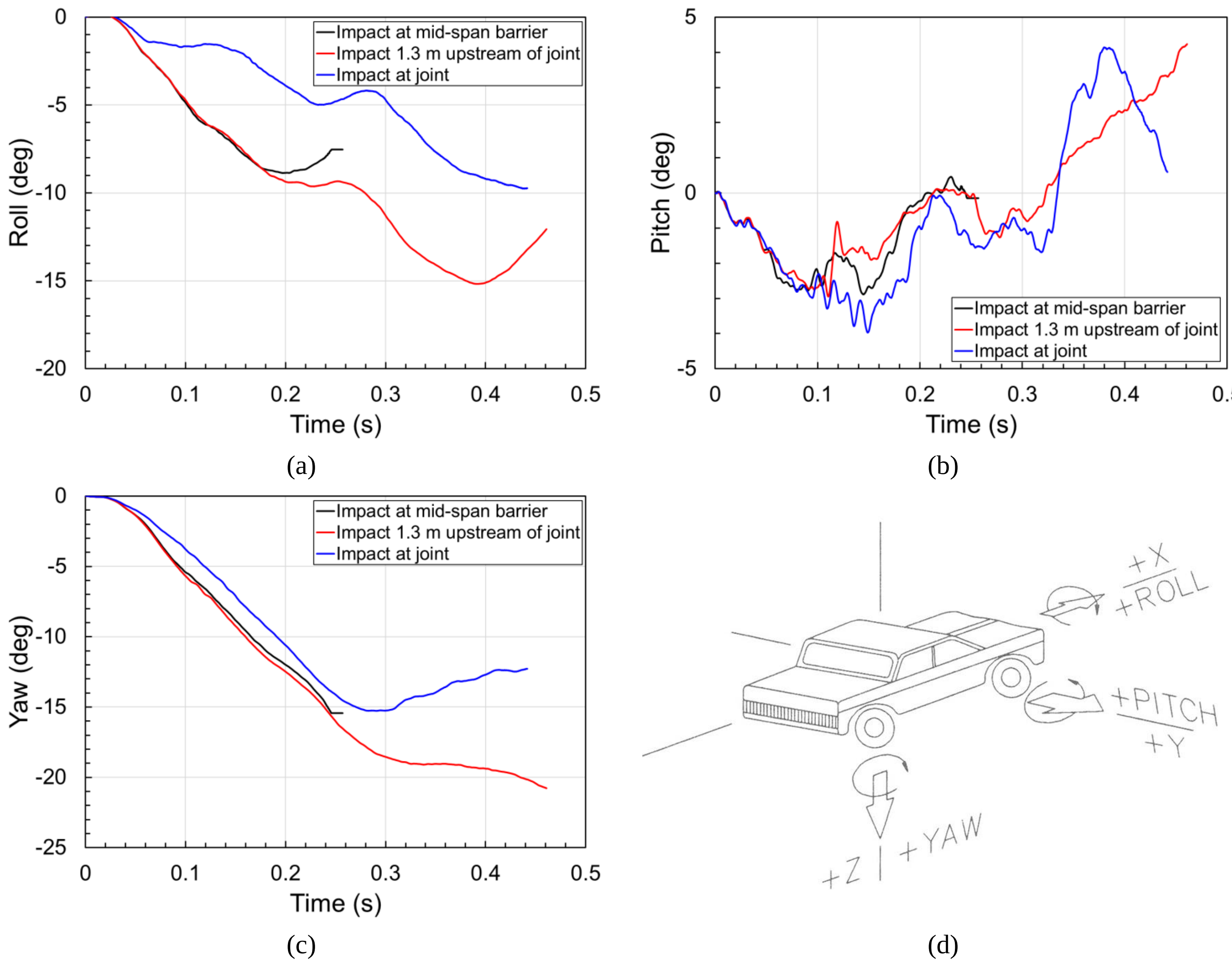


Figure 23. Angular Displacement-Time History and Vehicle Coordination System – 10000S Vehicle Impact with Near-Vertical Barrier

2.5.4 Impact Forces

The impact force-time history of the 10000S vehicle collision models with the single-slope barrier is depicted in Figure 24. The contact force data was filtered using a CFC 60 filter to obtain impact forces on the barrier and averaged over a moving 50-millisecond interval. As shown in Figure 24, the location of impact significantly influenced the forces experienced by the barriers. When the impact occurred at the mid-span of barrier no.2, the impact forces on barrier no.4 were approximately zero. However, when the impact location is oriented at the joint between barrier nos. 2 and 3, barrier no. 4 started to experience forces. The complete impact force-time histories for 1100C and 2270P vehicle collisions with single-slope barriers can be found in Appendix C.

Figure 25 further elucidates the force-time histories of the 10000S vehicle model during a collision with the near-vertical barrier. The location of the impact point exerted a conspicuous influence on the force dissipation across different barrier segments. Impacts at the mid-span and ¾-span locations primarily funnel to barrier no. 2, which experienced the highest impact loads, while barrier no. 4 registered the smallest. Conversely, impacts localized at the joint between barrier nos. 2 and 3 resulted in peak force to barrier no. 3. The complete datasets of the impact force-time histories for the 1100C and 2270P vehicle models collisions with near-vertical barrier are archived in Appendix C.

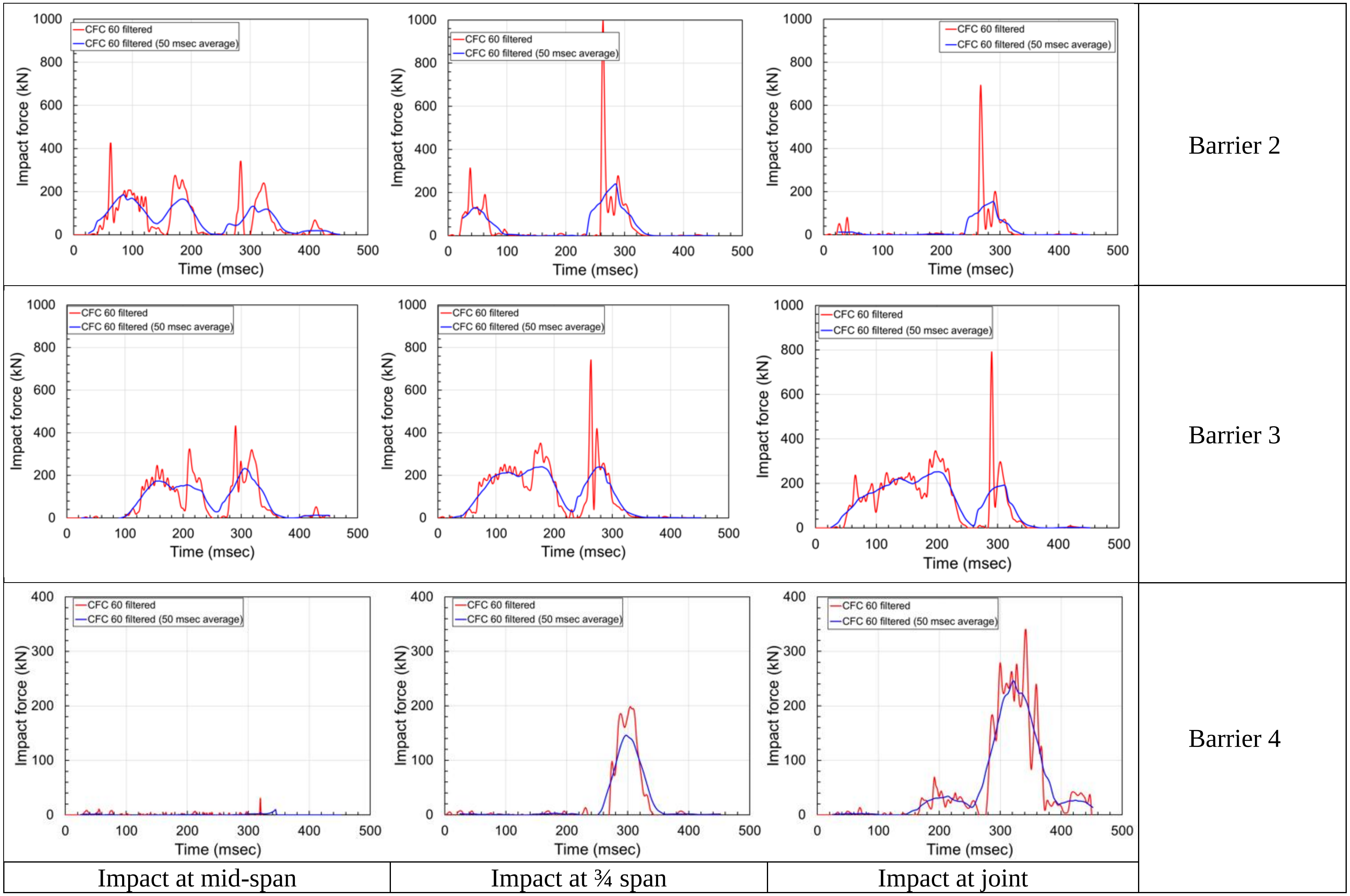


Figure 24. Impact Force-Time History – 10000S Vehicle Impact with Single-Slope Barrier

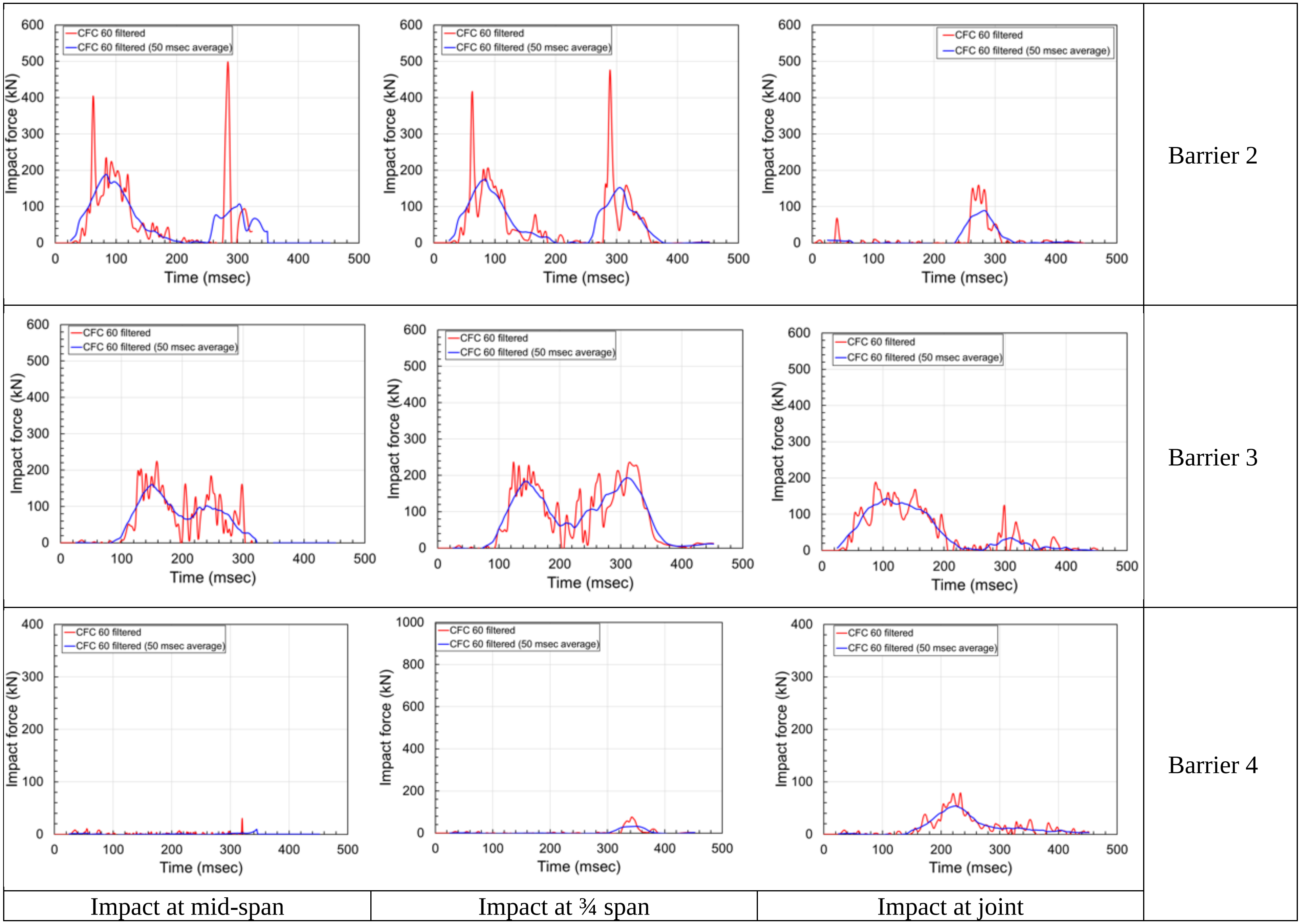


Figure 25. Impact Force-Time History – 10000S Vehicle Impact with Near-Vertical Barrier

2.5.5 Forces in Barrier Connections

To analyze the joint between the barrier ends, data recording cross sections were placed at each joint location. These cross sections served the purpose of measuring the shear and tensile forces developed at the joints. The locations of these cross sections and the corresponding numbers assigned to the joint connection rebar can be found in Figure 26. Figures 27 through 29 present the axial stress-time histories on the joint rebars for different barriers numbered 1 to 4, indicating no yielding of the rebars. Data shown corresponds to the 10000S vehicle impacting the single-slope barrier at the mid-span, ¾-span, and joint. The complete axial force-time and von-Mises-time histories for 1100C, 2270P, 10000S vehicle collisions with single-slope and near-vertical barriers can be found in Appendix D.

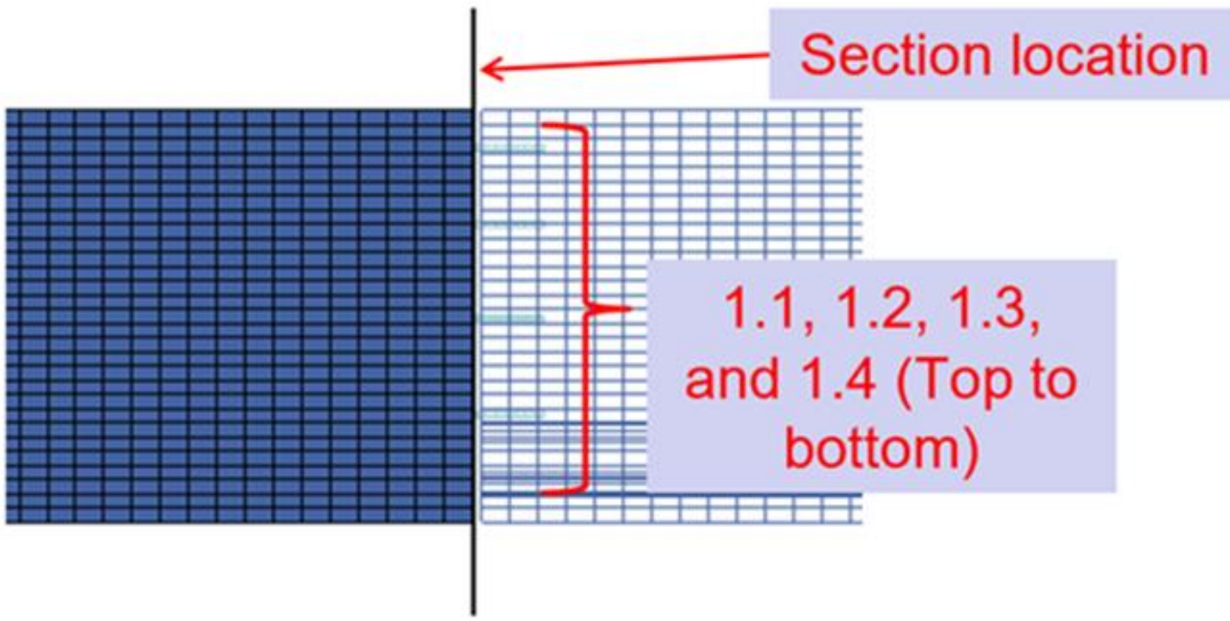


Figure 26. Section Location and Number of the Joint-Spanning Rebar

2.5.6 Velocity and Acceleration

The longitudinal and lateral vehicle velocity and acceleration histories were measured at the center of gravity and processed using a moving average with a 10-millisecond interval. Figures 30 and 31 display the velocity and acceleration time history of the 10000S vehicle collision with the mid-span of the single-slope and near-vertical barriers, respectively. The complete longitudinal and lateral vehicle acceleration and velocity time histories can be found in Appendix E.

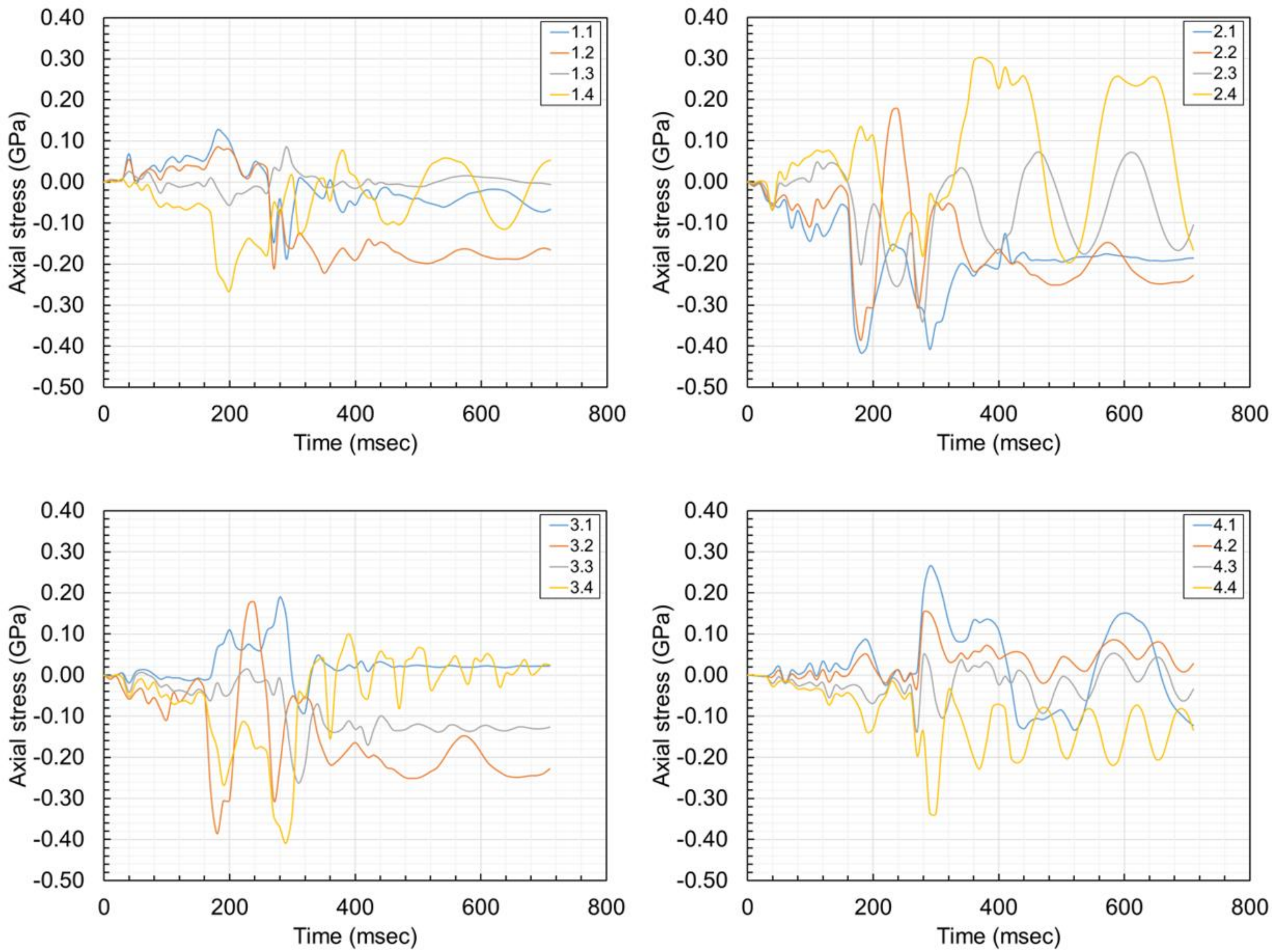


Figure 27. Axial Stress Developed in Joint-Spanning Rebar – 10000S Vehicle Impact at Mid-Span – Single-Slope Barrier

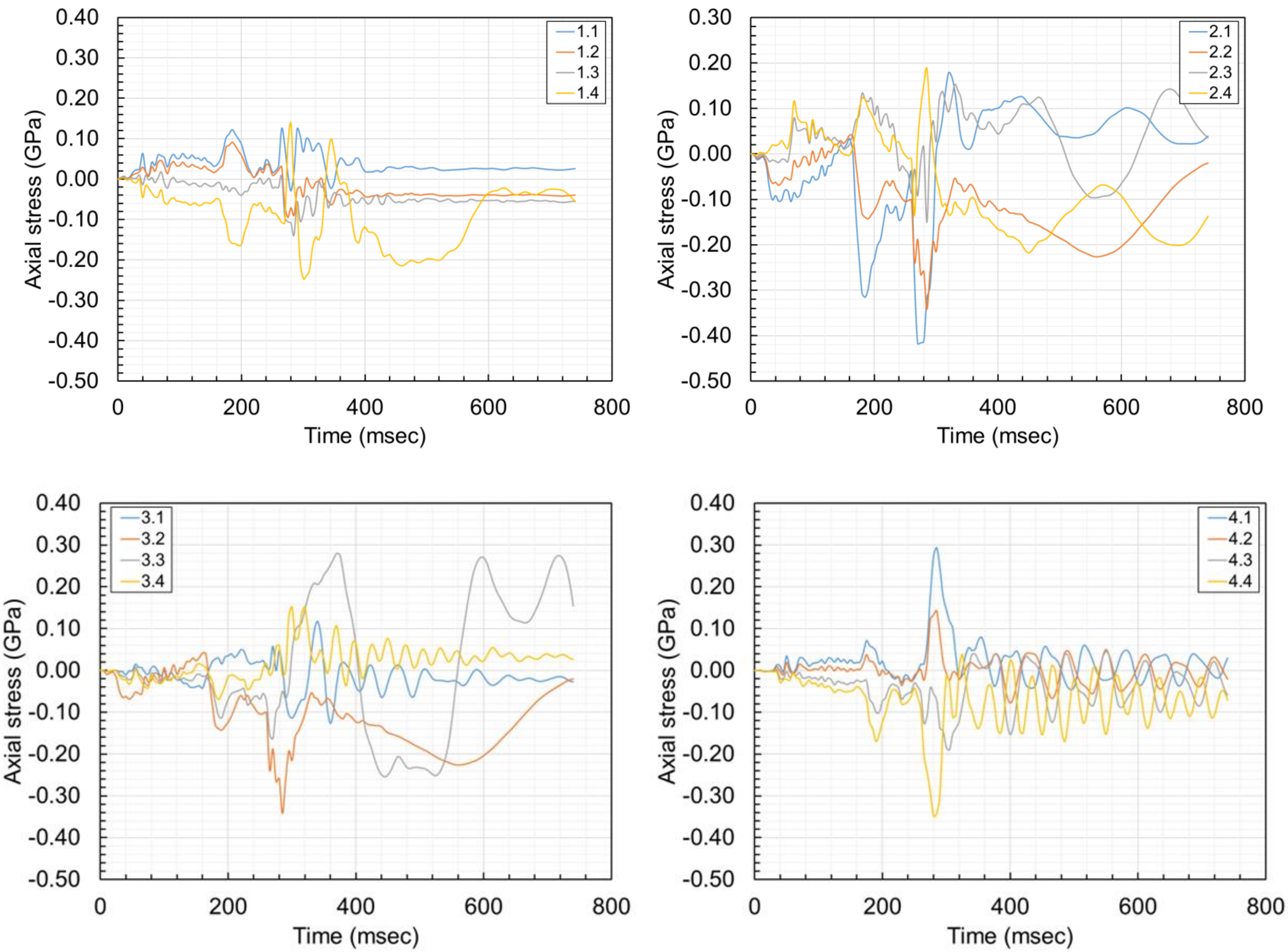


Figure 28. Axial Stress Developed in Joint-Spanning Rebar – 10000S Vehicle Impact at ¾ -Span – Single-Slope Barrier

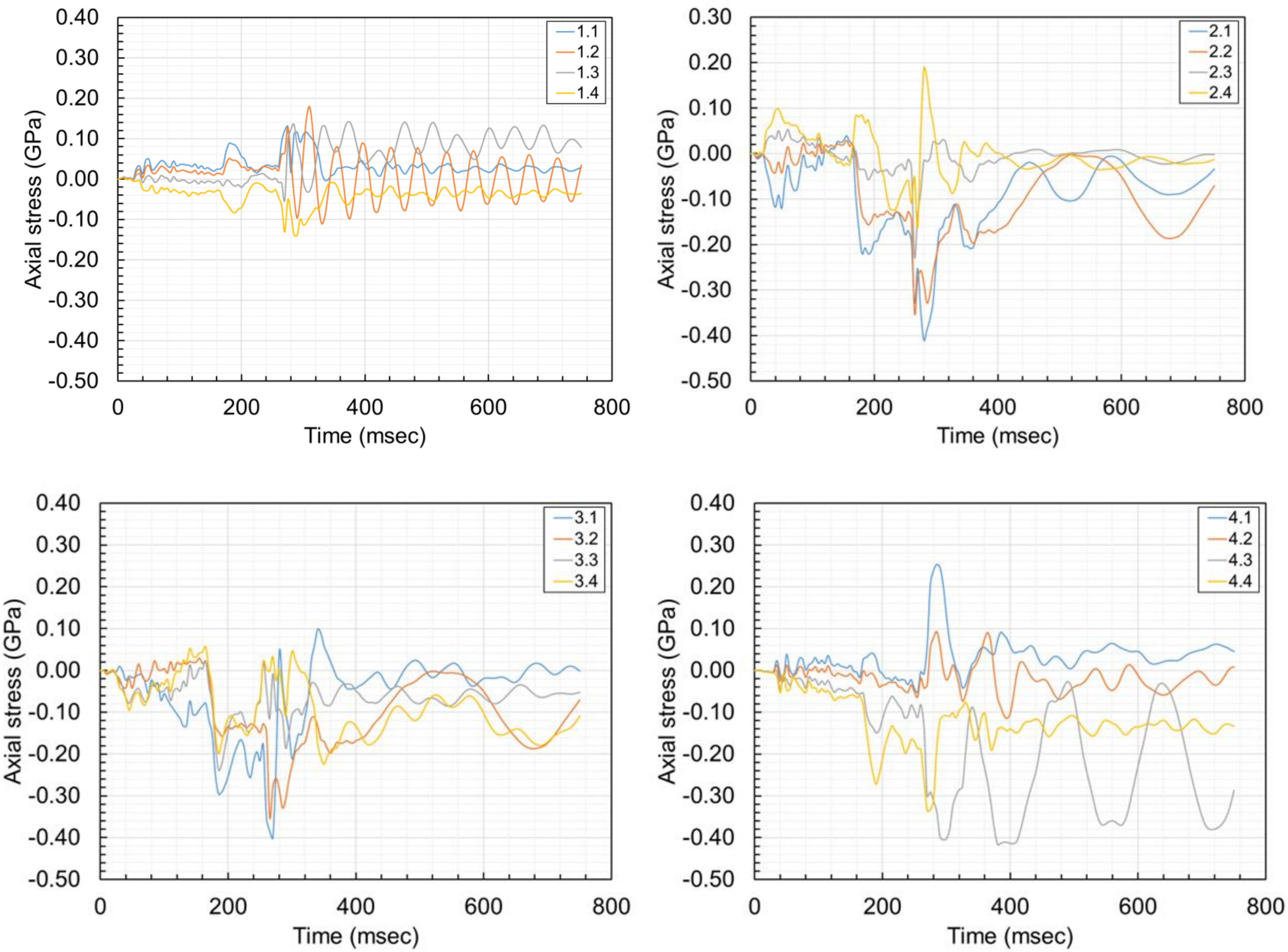


Figure 29. Axial Stress Developed in Joint-Spanning Rebar – 10000S Vehicle Impact at Joint – Single-Slope Barrier

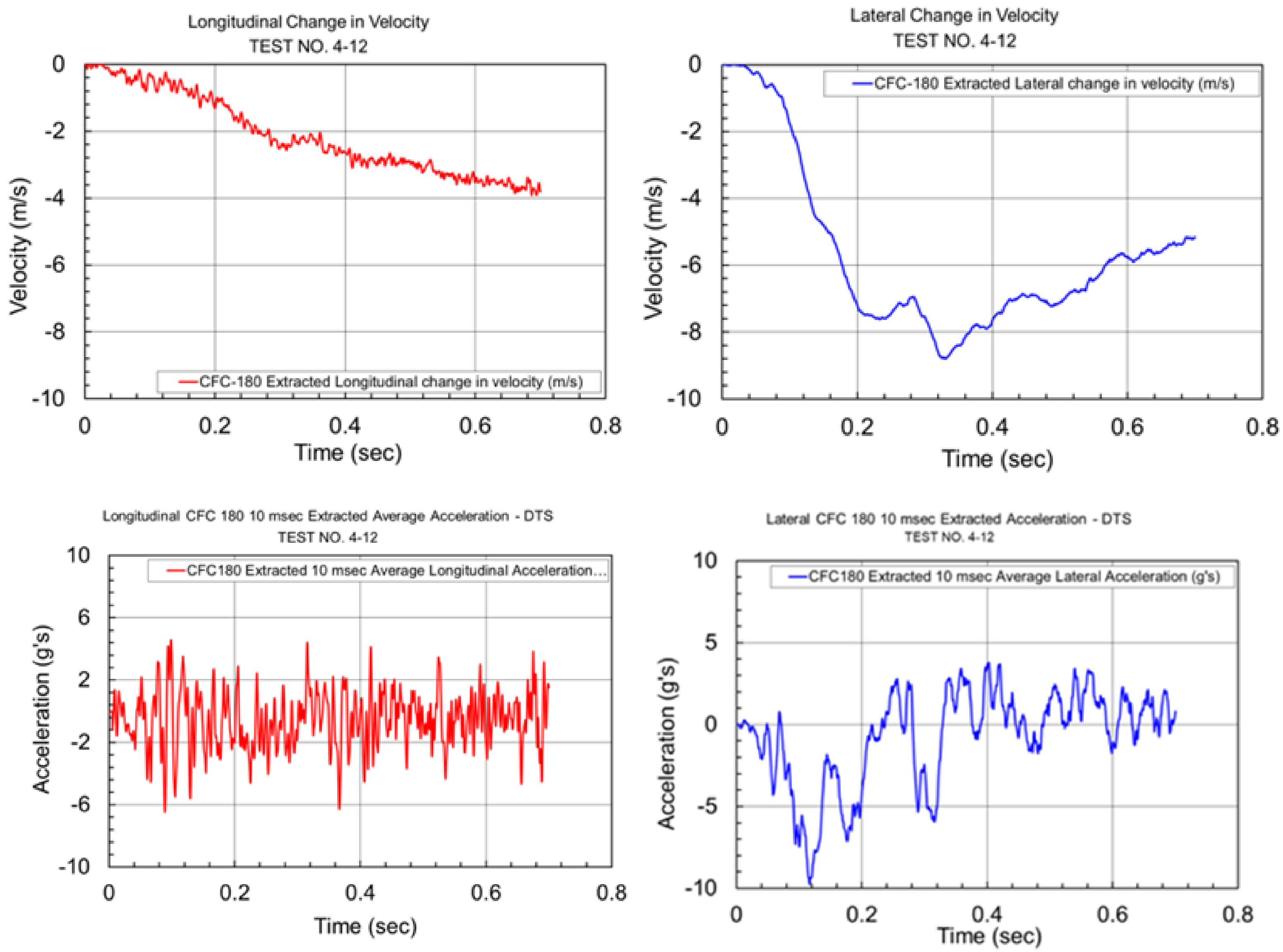


Figure 30. Velocity and Acceleration Time History – 10000S Vehicle Impact at Mid-Span – Single-Slope Barrier

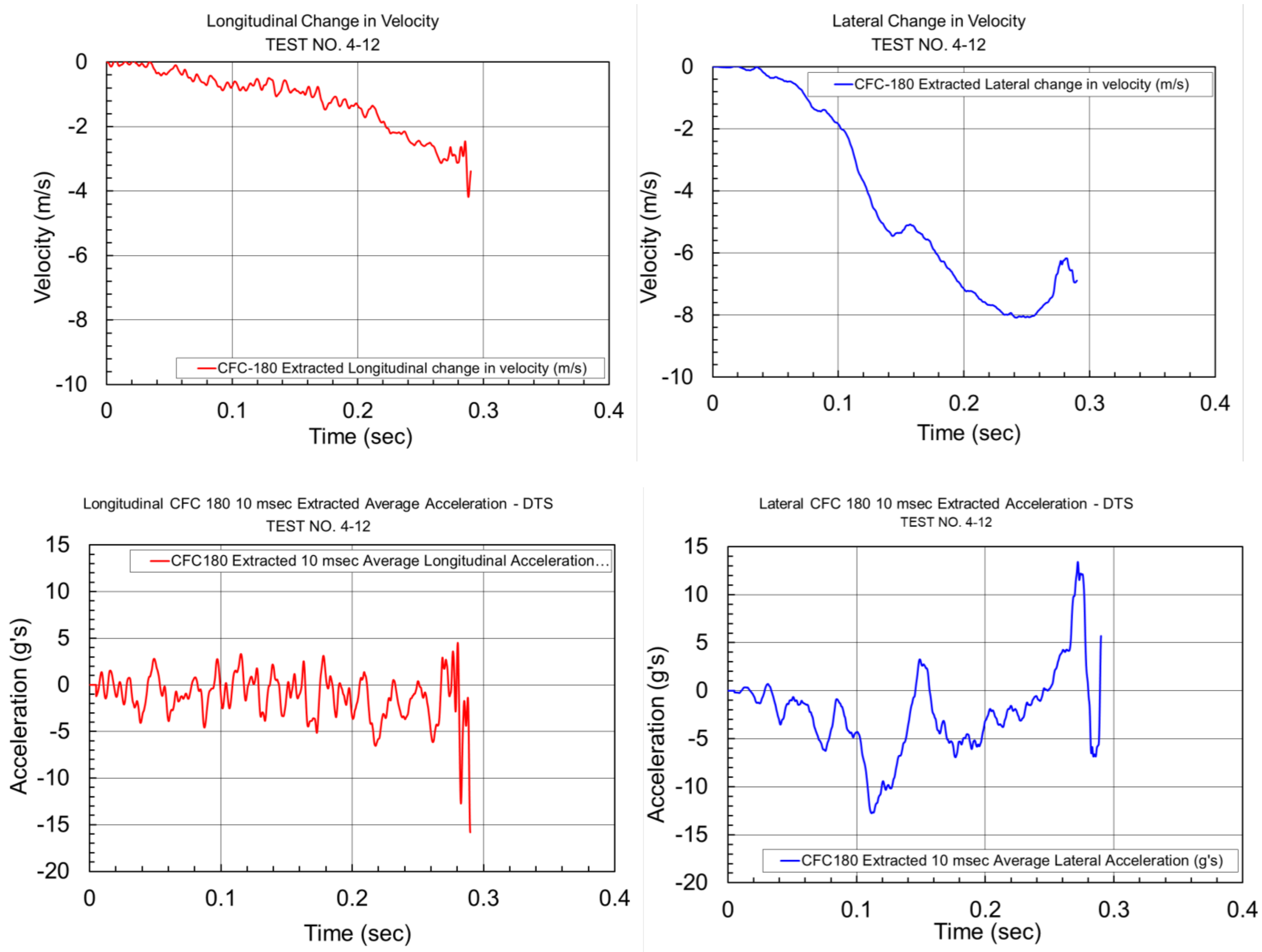


Figure 31. Velocity and Acceleration Time History – 10000S Vehicle Impact at Mid-Span – Near-Vertical Barrier

2.5.7 Deck Load Distribution Lengths

The load distribution length was investigated by observing stresses in transverse deck bars at the time of peak stress for two cross sections, which are shown in Table 9. The evaluation focal points are the mid-span, ¾-span, and joint locations, and the load distribution length was studied in the context of a 10000S vehicle impact. The data shows that both barrier configurations exhibited an increasing trend in load distribution length as the impact location moved from the mid-span toward the joint. It is noteworthy that the near-vertical barrier system, despite its additional inclined bar, does not manifest a substantially different load distribution profile compared to its single-slope counterpart. The slight divergence between the two systems at the barrier base level for impact at the joint location warrants further computational and experimental studies to elucidate the underlying mechanics.

Table 9. Load Distribution Length (10000S vehicle)

Section Location	Single-slope barrier (four inclined bars)			Near-vertical barrier (five inclined bars)		
	Mid-span	**¾-span**	**Joint**	**Mid-span**	**¾-span**	**Joint**
Deck at barrier base	6.61 m	7.24 m	9.53 m	6.73 m	7.24 m	7.49 m
Deck at girder	11.31 m	12.32 m	13.21 m	11.19 m	12.19 m	13.46 m

2.5.8 Investigation on Dynamic Response of Inclined Bars

To determine the mechanical response of inclined reinforcing bars, comprehensive stress analyses were conducted on Grades 60 and 75 reinforcement bars, as depicted in Figure 32. For inclined bars of Grade 60, the anticipated yield strength was quantified as 415 MPa (60 ksi), while the ultimate tensile strength was expected to be 620 MPa (90 ksi). In contrast, Grade 75 bars manifested superior mechanical characteristics, with an estimated yield strength and ultimate tensile strength of 520 MPa (75 ksi) and 720 MPa (105 ksi), respectively.

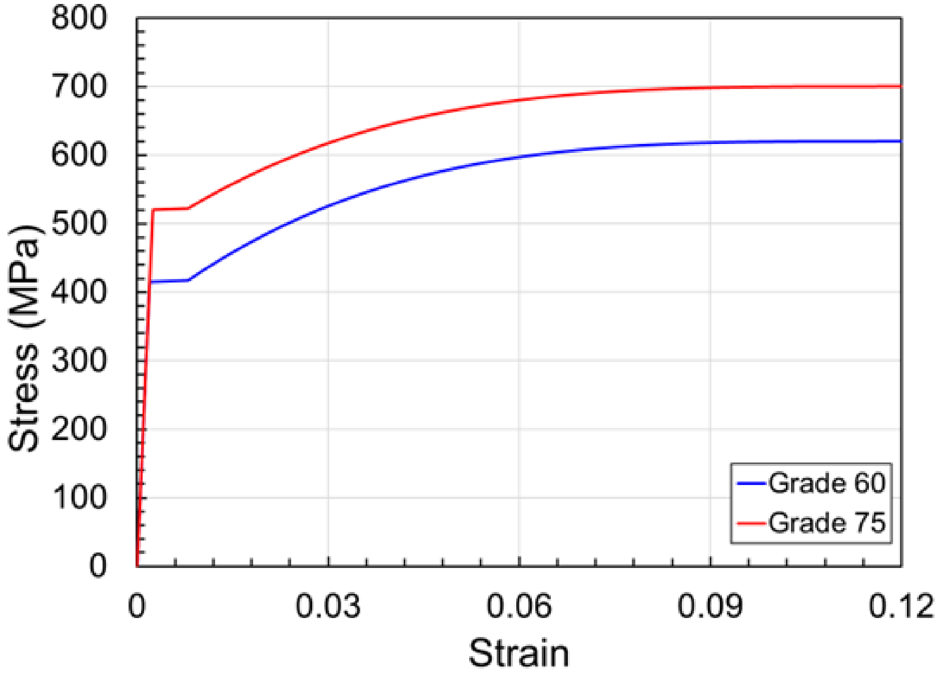


Figure 32. Stress vs. Strain Curves of Grade 60 and Grade 75 Bars [21]

Stress distribution profiles were assessed along the longitudinal axis of the inclined bars in proximity to the deck interface. Two specific constraint conditions were employed to evaluate the interaction between the inclined bars and the overlying barrier in the presence of grout: (1) a fully constrained condition in all spatial dimensions (Case 1) and (2) an axially unconstrained condition over a length of 4 in. (Case 2), as illustrated in Figure 33.

A selection of three distinct elements (Element 1, Element 2, and Element 3) was chosen to determine the stress magnitudes localized within the inclined bars. This multi-element approach enabled an understanding of the mechanical behavior of these specialized reinforcing elements under varied constraint conditions.

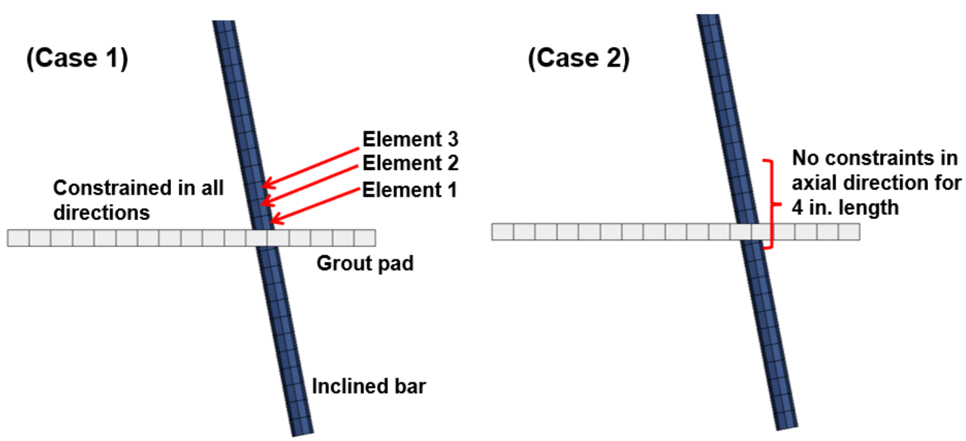


Figure 33. Constraint Conditions Between Inclined Bars and Barrier Above Grout Pad

Figures 34 through 37 present the von Mises stress distribution within selected elements – specifically Element 1, Element 2, and Element 3 as identified in Figure 33– subjected to the impact of a 10000S vehicle at a ¾-span of barrier segment no. 2 of the single-slope barrier. A comparison between two distinct constraint conditions, Case 1 and Case 2, is presented for Grades 60 and 75 steel inclined bars.

For Grade 60 inclined bars under Case 1 constraint condition, peak (von Mises) stress values were observed at 680 MPa (98.6 ksi), 600 MPa (87.0 ksi), and 460 MPa (66.7 ksi). In contrast, under the Case 2 constraint condition, the maximum stress levels were quantified as 640 MPa (92.2 ksi), 670 MPa (97.2 ksi), and 530 MPa (76.9 ksi). For Grade 75 inclined bars, Case 1 constraint yielded stresses at 660 MPa (95.7 ksi), 660 MPa (95.7 ksi), and 530 MPa (76.9 ksi); while Case 2 constraint condition led to stress levels of 690 MPa (100.1 ksi), 760 MPa (110.2 ksi), and 580 MPa (84.1 ksi).

A summary of these stress magnitudes within barrier segments nos. 1, 2, 3, and 4 is tabulated in Table 10. The overarching conclusion is that the inclined bars exceeded the yield stress threshold when subjected to the impact of a 10000S vehicle. Based on these computational simulations, it was recommended to elevate the yield strength specification of the inclined rebars from 60 ksi to 75 ksi. Additionally, an increment in the number of inclined rebars per barrier, from 4 to 5, was recommended to mitigate the probability of rebar yielding during vehicular impact events for single-slope barrier.

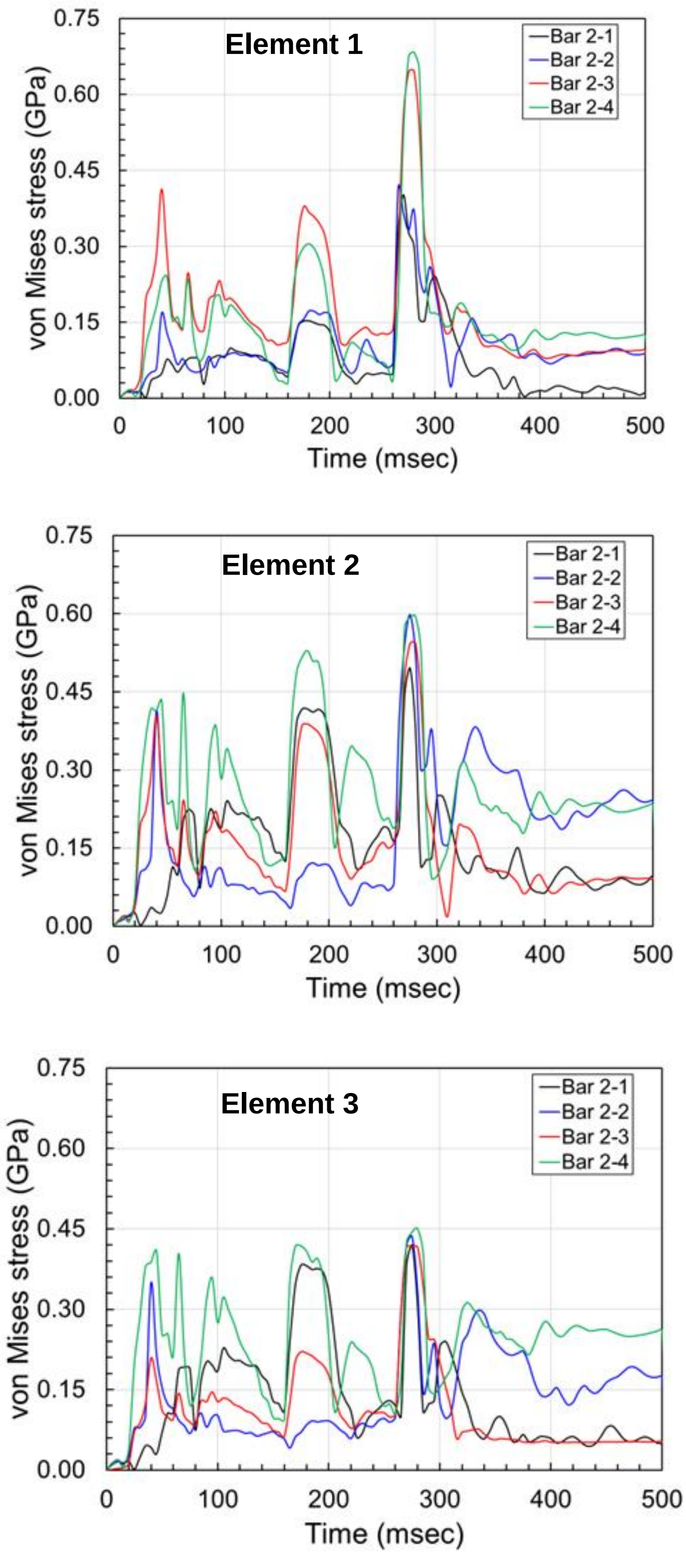


Figure 34. Von Mises Stress Time Histories in Grade 60 Inclined Bars – 10000S Vehicle Impact at ¾-Span (Case 1) – Single-Slope Barrier

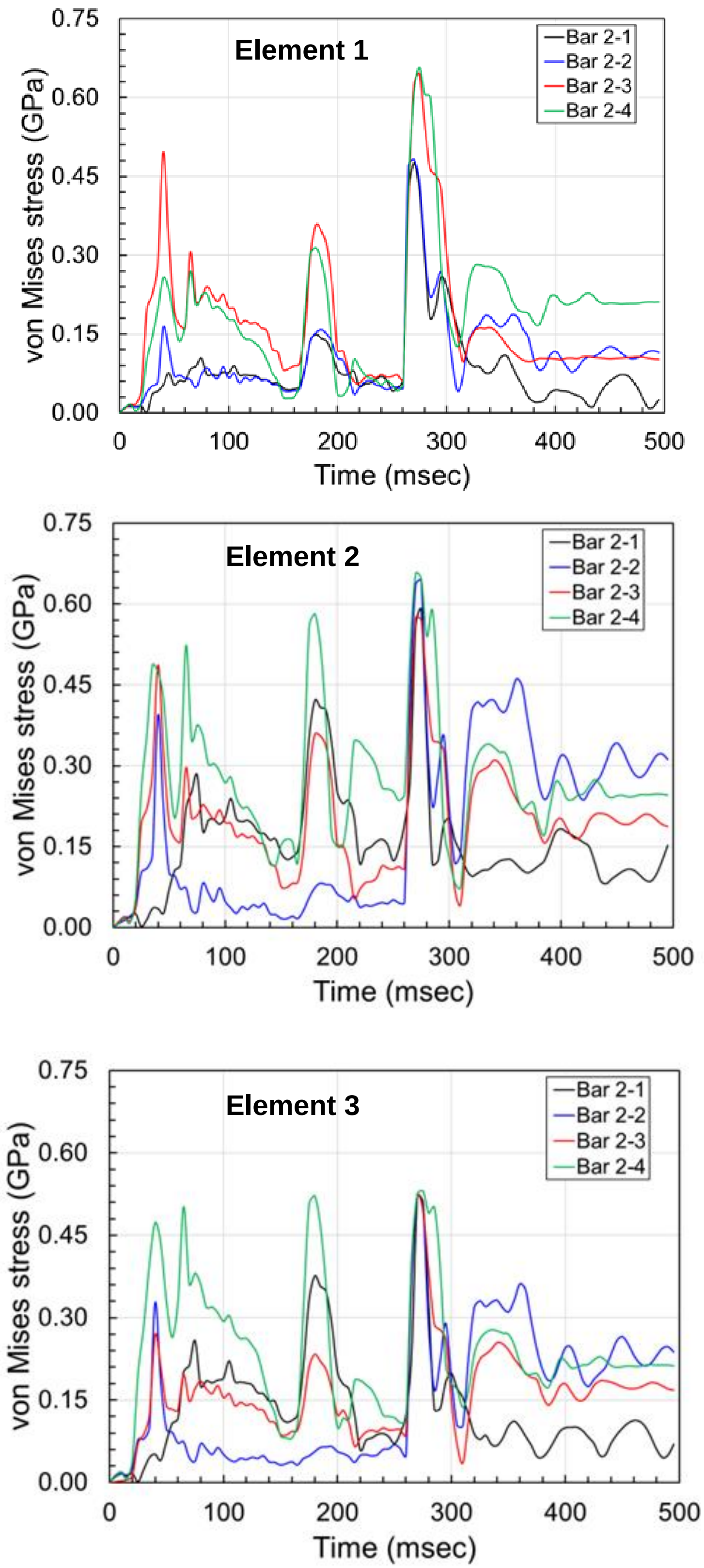


Figure 35. Von Mises Stress Time Histories in Grade 75 Inclined Bars – 10000S Vehicle Impact at ¾-Span (Case 1) – Single-Slope Barrier

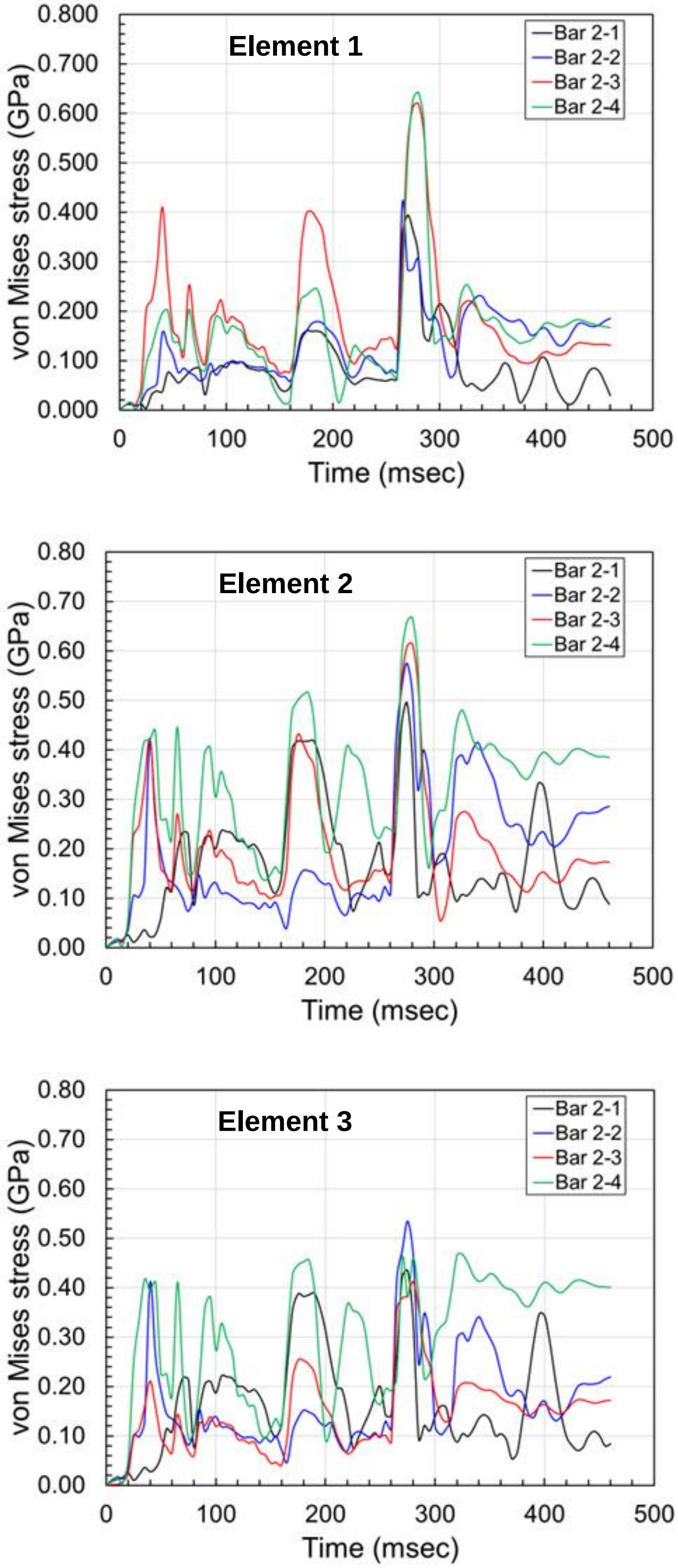


Figure 36. Von Mises Stress Time Histories in Grade 60 Inclined Bars – 10000S Vehicle Impact at ¾-Span (Case 2) - Single-Slope Barrier

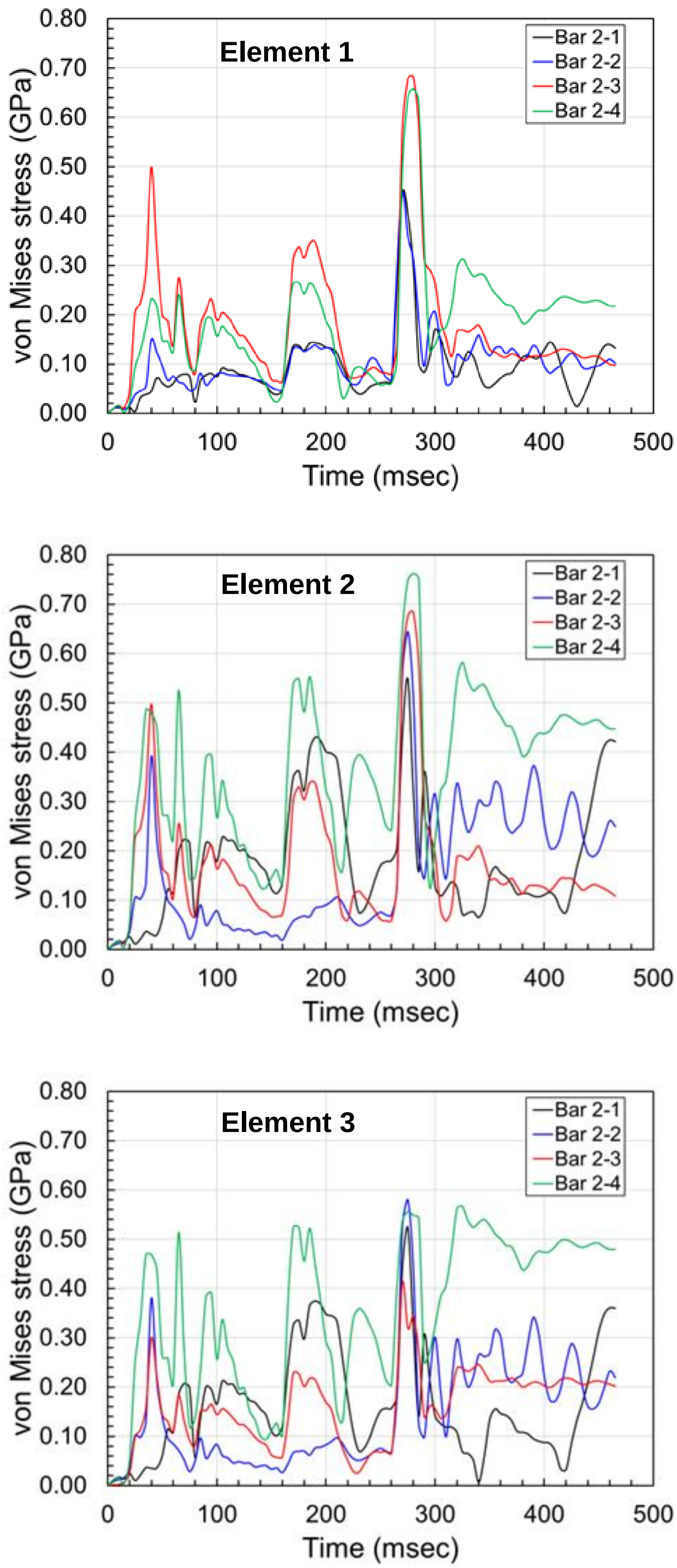


Figure 37. Von Mises Stress Time Histories in Grade 75 Inclined Bars – 10000S Vehicle Impact at ¾-Span (Case 2) – Single-Slope Barrier

Table 10. Summary of Stress Levels in Grades 60 and 75 Inclined Bars – 10000S Vehicle Impact at ¾ -Span – Single-Slope Barrier

Barrier Segment	Distance Above Grout Pad (in.)	Max. Stress (MPa (ksi)) (Case 1)		Max. Stress (MPa (ksi)) (Case 2)	
		Grade 60	Grade 75	Grade 60	Grade 75
Barrier 1	0.4	290 (42.1)	350 (50.7)	290 (42.1)	330 (47.8)
	1.2	510 (73.9)	620 (89.9)	500 (72.5)	570 (82.7)
	2	460 (66.7)	550 (79.8)	450 (65.3)	530 (76.9)
Barrier 2	0.4	680 (98.6)	660 (95.7)	640 (92.2)	690 (100.1)
	1.2	600 (87.0)	660 (95.7)	670 (97.2)	760 (110.2)
	2	460 (66.7)	530 (76.9)	530 (76.9)	580 (84.1)
Barrier 3	0.4	510 (73.9)	560 (81.2)	500 (72.5)	530 (76.9)
	1.2	**710 (102.9)**	**750 (108.7)**	610 (88.5)	690 (100.1)
	2	530 (76.9)	610 (88.5)	**690 (100.1)**	**790 (114.6)**
Barrier 4	0.4	470 (68.2)	530 (76.9)	450 (65.2)	520 (75.4)
	1.2	430 (62.4)	520 (75.4)	480 (69.6)	550 (79.8)
	2	420 (60.9)	520 (75.4)	420 (60.9)	520 (75.4)

Overall, the computational simulations executed in this study yielded an evaluation of load demand and salient response characteristics within the two barrier systems under examination i.e., single-slope and near-vertical barrier shapes. These simulations served as a seminal precursor, revealing critical parameters, and thereby facilitating the optimization of experimental setups for forthcoming full-scale vehicle crash test investigations.

2.6 Recommendations for Full-Scale Crash Test with Single-Slope Barrier

The aim of this investigation was the development of a crashworthy MASH TL-4 compliant, precast concrete bridge rail system. In pursuit of this objective, vehicles of three distinct classifications, as per MASH TL-4 criteria, were employed to scrutinize the structural integrity of the single-slope and near-vertical varieties of the precast concrete barrier systems. An exhaustive suite of pre-crash computational simulations was conducted, serving as an empirical foundation for delineating the parameters of the ensuing full-scale crash tests. Drawing on these investigative results, the following recommendations were put forward:

- A barrier and deck length of 80 ft was deemed sufficient for the purposes of full-scale crash testing to examine peak lateral loading to the structure. A 130-ft barrier length was deemed necessary to evaluate vehicle stability and barrier override.

- As confirmed by simulation data, enhancing the minimum yield strength of the inclined rebars is recommended from an initial value of 60 ksi to 75 ksi. Concurrently, an increment in the number of inclined rebars per barrier segment, from 4 to 5, is advised as a risk-mitigation measure to curtail the potential for rebar yielding during vehicular impacts. These modifications were deemed appropriate since ISU's original test unit design was conducted, assuming an impact load of 54 kips. It is further noted that ISU recommended using 80 ksi yield strength inclined bars for the full-scale crash test instead of 75 ksi primarily due to availability considerations.

- The near-vertical barrier with five inclined bars had CIP at 2.5 ft upstream of the joint (which corresponded to a ¾-span location), and this CIP was adapted to a single-slope barrier when inclined bars increased from four to five.

- Similar barrier shapes with the necessary structural capacity and adequacy have contained and redirected MASH TL-4 SUT vehicles with a 36 in. height. Testing the bridge railing with 44 in. height was expected to impart the peak demand to the barrier and deck system by reducing vehicle roll motion and lateral extent over the top of the barrier.

It should be noted that based on FE investigations into both barrier shapes and configurations, the research team from MwRSF and ISU recommended testing the near-vertical shape as it would impose a higher impact load on the structure and place greater demand on the barrier, connections, and deck. If successful, the researchers would recommend using both shapes. However, the project advisory panel preferred a single-slope barrier design due to application considerations. As such, the single-slope barrier configuration was evaluated through full-scale vehicle crash testing.

3 TEST REQUIREMENTS AND EVALUATION CRITERIA

3.1 Test Requirements

Longitudinal barriers, such as concrete bridge rails, must satisfy impact safety standards in order to be declared eligible for federal reimbursement by the Federal Highway Administration for use on the National Highway System. According to MASH, TL-4 longitudinal barrier systems must be subjected to three full-scale vehicle crash tests, as summarized in Table 11.

Table 11. MASH [3] TL-4 Crash Test Conditions for Concrete Barriers

Test Article	Test Designation No.	Test Vehicle	Vehicle Weight, lb	Impact Conditions		Evaluation Criteria [1]
				Speed, mph	Angle, deg.	
Concrete Barrier	4-10	1100C	2,420	62	25	A,D,F,H,I
	4-11	2270P	5,000	62	25	A,D,F,H,I
	4-12	10000S	22,000	56	15	A,D,G

[1] Evaluation criteria explained in Table 12.

Following a review of previous crash testing into concrete barrier systems, only MASH test designation no. 4-12 was determined to be critical for evaluating the TL-4 single-slope, precast concrete bridge rail. Due to the mass of the 10000S vehicle being more than four times that of the 2270P pickup truck, MASH test designation no. 4-12 has an impact severity 34 percent higher than MASH test designation no. 4-11 and 278 percent higher than MASH test designation no. 4-10. NCHRP Project 22-20(2) found that the increased impact severity translated to increased impact loads for the 10000S impacts as compared to the 2270P, as observed in the recommended impact loads for TL-3 and TL-4 MASH impacts [6]. Subsequently, the 10000S test would impart the highest impact loads to the barrier and be the critical test for evaluating the strength of both the bridge rail and bridge deck overhang.

Vehicle stability was not considered to be critical for the small car or pickup truck tests. Previous crash testing of the 2270P pickup into an 11-degree single-slope concrete bridge rail and vertical-faced concrete bridge rails resulted in successful MASH tests with minimal vehicle roll and pitch displacements [23-25]. Similarly, previous 1100C crash tests have been successfully conducted on both single-slope and vertical-face concrete bridge rails [20, 26]. Thus, vehicle performance had been effectively bracketed by previous crash tests, and there were no concerns for vehicle instability or excessive occupant risk measures. Therefore, MASH test designation nos. 4-10 and 4-11 were not deemed critical and were not conducted as part of this study.

It should be noted that the test matrix detailed herein represents the researchers' best engineering judgement with respect to the MASH safety requirements and their internal evaluation of critical tests necessary to evaluate the crashworthiness of the barrier system. However, any tests within the evaluation matrix deemed non-critical may potentially need to be evaluated based on additional knowledge gained over time or revisions to the MASH criteria.

3.2 Evaluation Criteria

Evaluation criteria for full-scale vehicle crash testing are based on three factors: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after collision. Criteria for structural adequacy are intended to evaluate the ability of the concrete bridge rail to contain and redirect impacting vehicles. Additionally, controlled lateral deflection of the test article is acceptable. Occupant risk evaluates the degree of hazard to occupants in the impacting vehicle. Post-impact vehicle trajectory is a measure of the potential of the vehicle to result in a secondary collision with other vehicles and/or fixed objects, thereby increasing the risk of injury to the occupants of the impacting vehicle and/or other vehicles. These evaluation criteria are summarized in Table 12 and discussed in greater detail in MASH. The full-scale vehicle crash test documented herein was conducted and reported in accordance with the procedures provided in MASH.

In addition to the standard occupant risk measures, the Post-Impact Head Deceleration (PHD), the Theoretical Head Impact Velocity (THIV), and the Acceleration Severity Index (ASI) were determined and reported. Additional discussion on PHD, THIV and ASI is provided in MASH.

Table 12. MASH Evaluation Criteria for Longitudinal Barriers

<table>
<tr><td>Structural Adequacy</td><td>A. Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td></tr>
<tr><td rowspan="5">Occupant Risk</td><td>D. Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of MASH.</td></tr>
<tr><td>F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.</td></tr>
<tr><td>G. It is preferable, although not essential, that the vehicle remain upright during and after collision.</td></tr>
<tr><td>H. Occupant Impact Velocity (OIV) (see Appendix A, Section A5.2.2 of MASH for calculation procedure) should satisfy the following limits:<table><tr><td colspan="3">Occupant Impact Velocity Limits</td></tr><tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr><tr><td>Longitudinal and Lateral</td><td>30 ft/s</td><td>40 ft/s</td></tr></table></td></tr>
<tr><td>I. The Occupant Ridedown Acceleration (ORA) (see Appendix A, Section A5.2.2 of MASH for calculation procedure) should satisfy the following limits:<table><tr><td colspan="3">Occupant Ridedown Acceleration Limits</td></tr><tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr><tr><td>Longitudinal and Lateral</td><td>15.0 g's</td><td>20.49 g's</td></tr></table></td></tr>
</table>

4 DESIGN DETAILS – SINGLE-SLOPE BRIDGE RAIL

The test installation constituted a single-slope, precast concrete bridge rail, extending a total length of 130 ft. The single-slope precast concrete bridge rail had a 44-in. height from the top surface of the bridge deck. Each bridge rail segment was 10 in. wide at the top and 18½ in. wide at the base. The design incorporated a 2-in. offset between the bridge rail's backside and the deck's edge. The design details for the TL-4 precast concrete bridge rail and deck systems are shown in Figures 38 through 58. Further, Figures 59 and 60 provide photographs of the test installation.

The barrier was attached to a simulated bridge deck in the upstream portion of the system. A 9-in. thick reinforced concrete bridge deck was cast atop a 24 in. by 24 in. grade beam. In terms of reinforcement, each barrier segment of the bridge rail had ten #5 longitudinal bars, divided between the front and back faces of the bridge rail. A total of 19 transverse U-bars were embedded within the bridge rail with a concrete clear cover of 2½ in. The minimum compressive strength of concrete in the bridge deck and rail was 4,000 psi, and all transverse and longitudinal reinforcing steel rebars had a yield strength of 60 ksi. The interior edge of the deck was connecting the bridge deck to the existing concrete tarmac. All barrier-to-barrier and barrier-to-deck connections used a non-shrink, high-flow grout with a strength of 4,000 psi within an 8-hour curing period and increasing to an 8,000-psi strength at 28 days.

Per the data on February 2, 2023, as presented in Table 13, an evaluation of the compressive strength of the grout at various stages and barrier segments was conducted. All specimens exceed the targeted minimum strength of 8,000 psi at the 28-day mark, with the 28-day compressive strength reaching a value of 15,280 psi.

Table 13. Grout Compressive Strength Data

Item	Casting Date	Testing Date	Compressive Strength (psi)	Remark
Inside Barrier Nos. 1 and 2	01/04/2023	01/09/2023	13,180	5-day Strength
Outside Barrier Nos. 1 and 2	01/04/2023	01/09/2023	13,300	5-day Strength
Barriers Nos. 3, 4, 5, and 6 – 1st Stage	01/11/2023	01/13/2023	7,820	2-day Strength
Barrier Nos. 3, 4, 5, and 6 – 2nd Stage, Barriers Nos. 7 and 8 – 1st Stage	01/17/2023	02/02/2023	11,210	16-day Strength
Barrier Nos. 7, 8, 9, 10,11 2nd Stage 12, &13 – 1st Stage	01/27/2023	02/02/2023	11,480	6-day Strength
Barrier Nos. 3, 4, 5, 6 – 1st Stage	01/11/2023	02/08/2023	15,280	28-day Strength
Barrier Nos. 7, 8, 9, 10,11 – 2nd Stage	01/27/2023	02/08/2023	14,350	12-day Strength

The tabulated results show that the compressive strength during the initial stages – 2-day and 5-day testing periods – substantially increased over time, ultimately surpassing the 8,000-psi baseline. It is particularly noteworthy that the compressive strength values recorded at 5-day and 28-day testing periods were remarkably higher for both the inside and outside barrier nos. 1 and 2 and the subsequent stages of barriers nos. 3 to 11. These findings represent the effectiveness of the grouting materials, meeting the compressive strength specifications. Detailed specifications, mill certifications, and certificates of conformity for the materials used in the system are presented in Appendix F.

The simulated bridge deck was configured with a 42-in. lateral overhang extending away from the outer face of the grade beam. The lateral reinforcement in the deck consisted of two #6 bars spaced at 5 in. within the top steel mat and 7½ in. on-center in the bottom steel mat. The longitudinal steel in the deck consisted of #4 bars at 8 in. and 9 in. on-center in the top and bottom steel mats, respectively.

The connection of the barrier to the deck was primarily facilitated through the use of an inclined #8 steel bars, acting as a primary structural connector, as illustrated in Figure 42. Five #8 Grade 80 steel bars with bottom-end fittings were used, with the spacing of 24 in. and two #5 U-bars placed around each socket/receiver to anchor socket receiver in the deck. After the bars were threaded into the socket embedded in the deck, the sleeves were filled with grout.

The interface between two adjacent barriers incorporated four $^{7}/_{8}$ in. diameter, 16½ in. long, double-headed ties to facilitate secure binding. Additionally, transverse reinforcement was introduced to offer confinement in the orthogonal direction to the double-headed ties, as demonstrated in Figure 43.

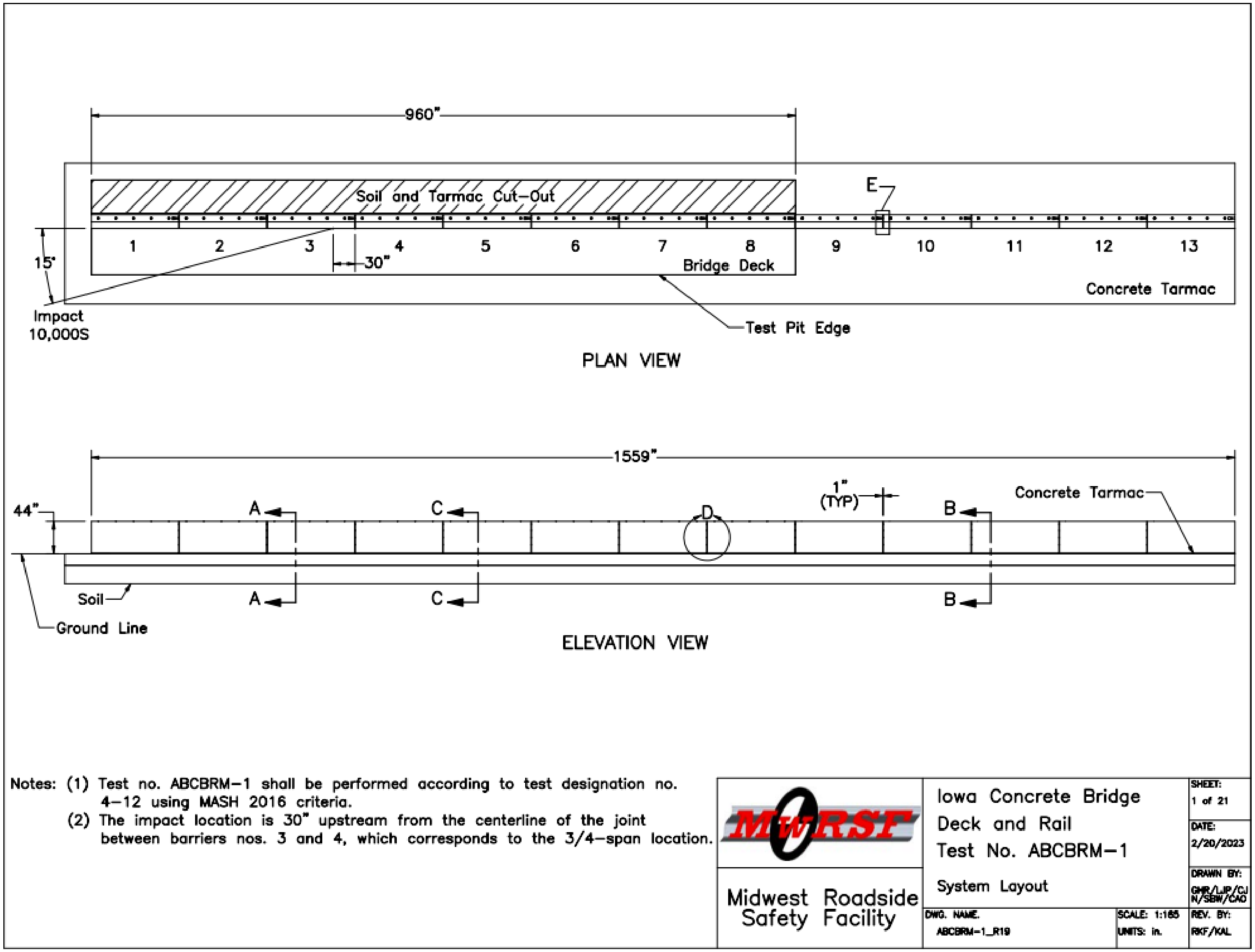


Figure 38. Iowa Concrete Bridge Deck and Rail System Layout, Test No. ABCBRM-1

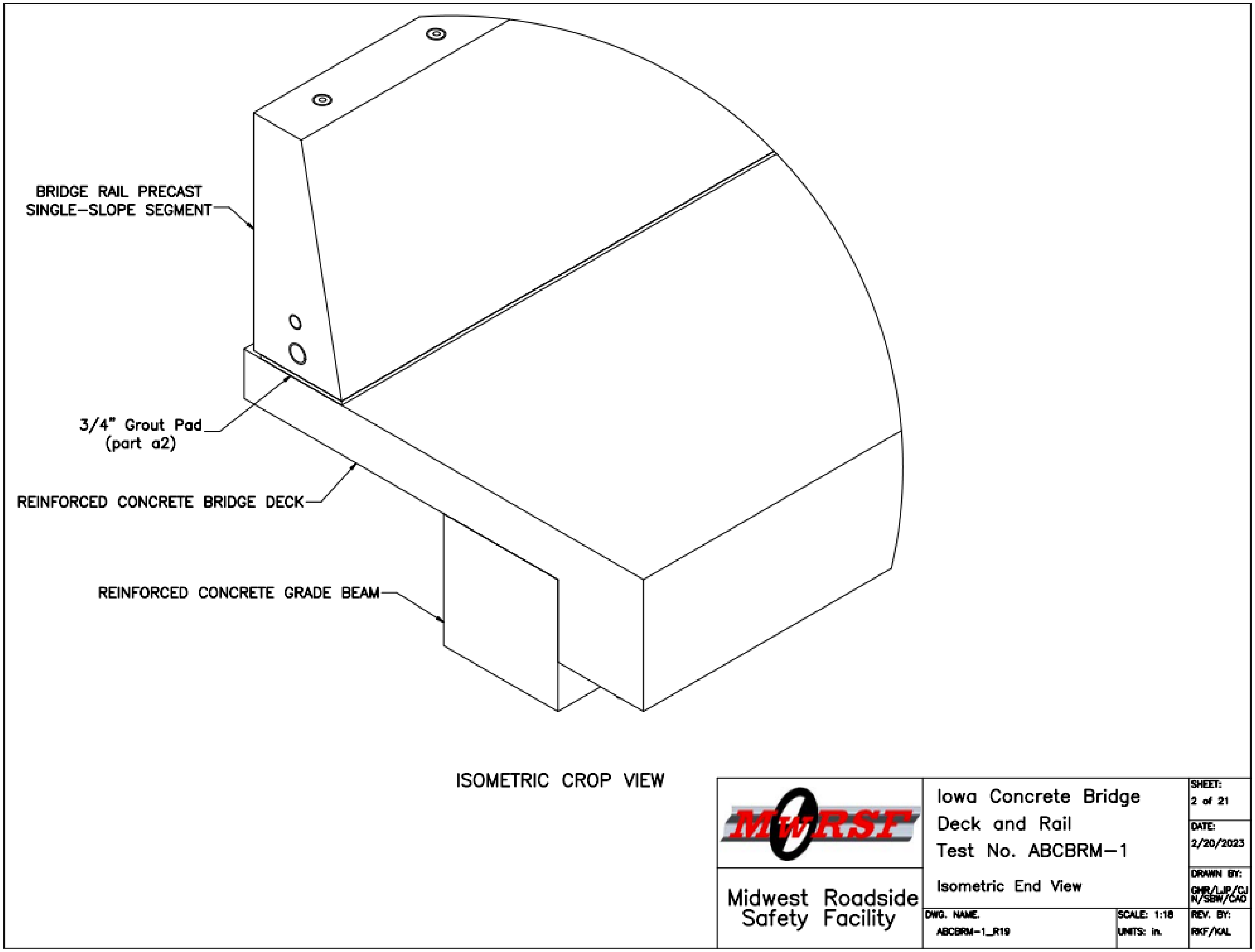


Figure 39. Isometric End View, Test No. ABCBRM-1

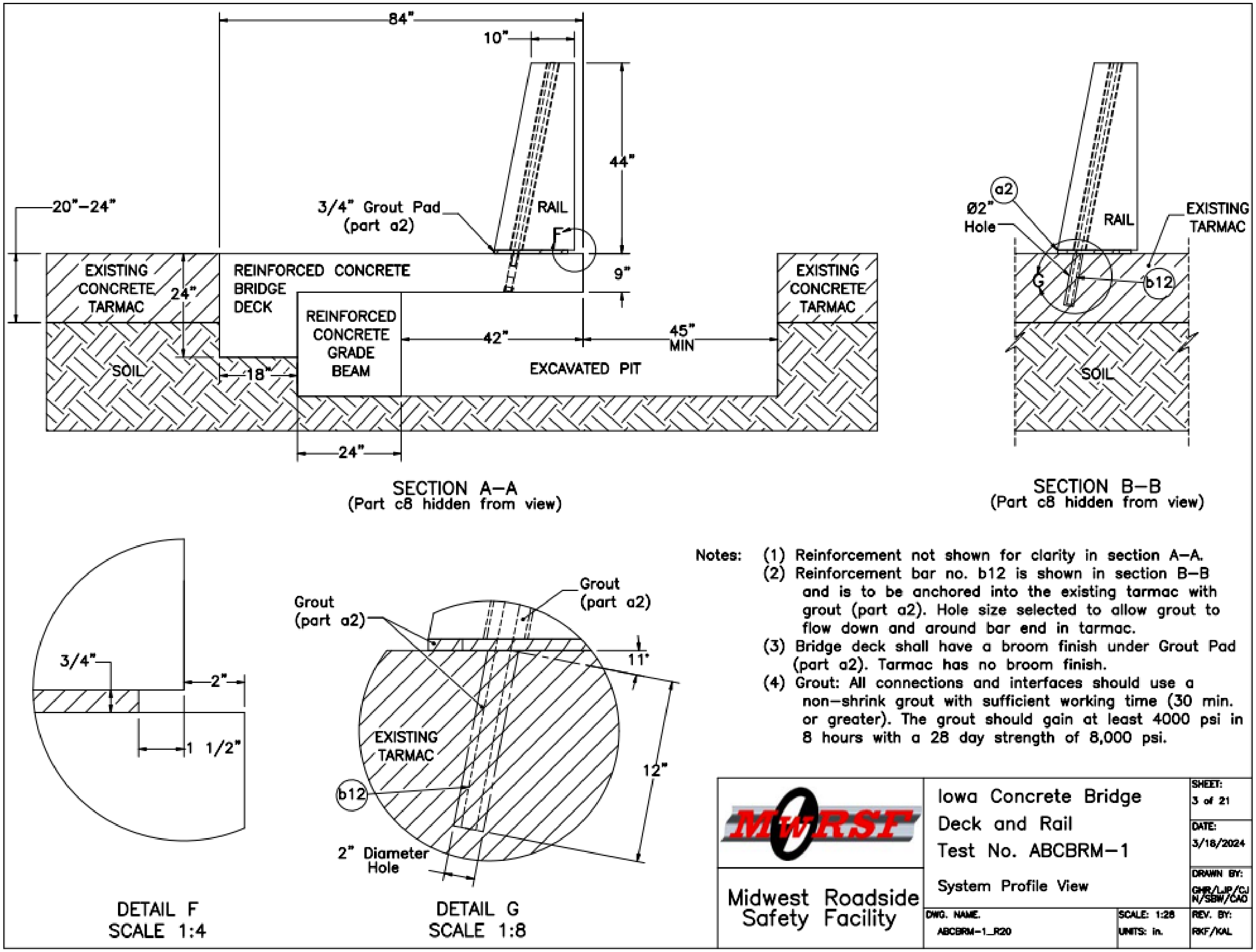


Figure 40. System Cross Sections, Test No. ABCBRM-1

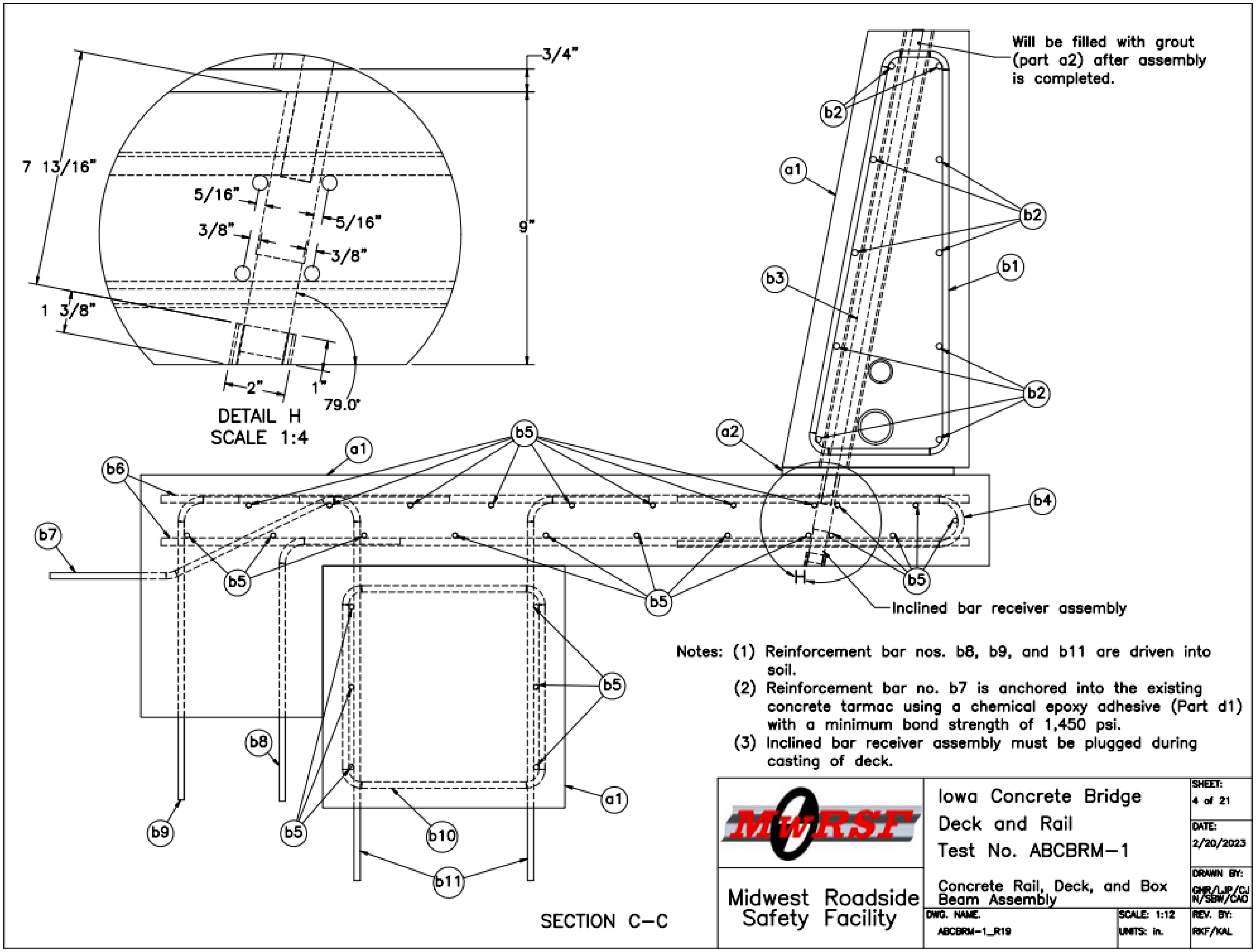


Figure 41. Concrete Rail, Deck, and Box Beam Assembly, Test No. ABCBRM-1

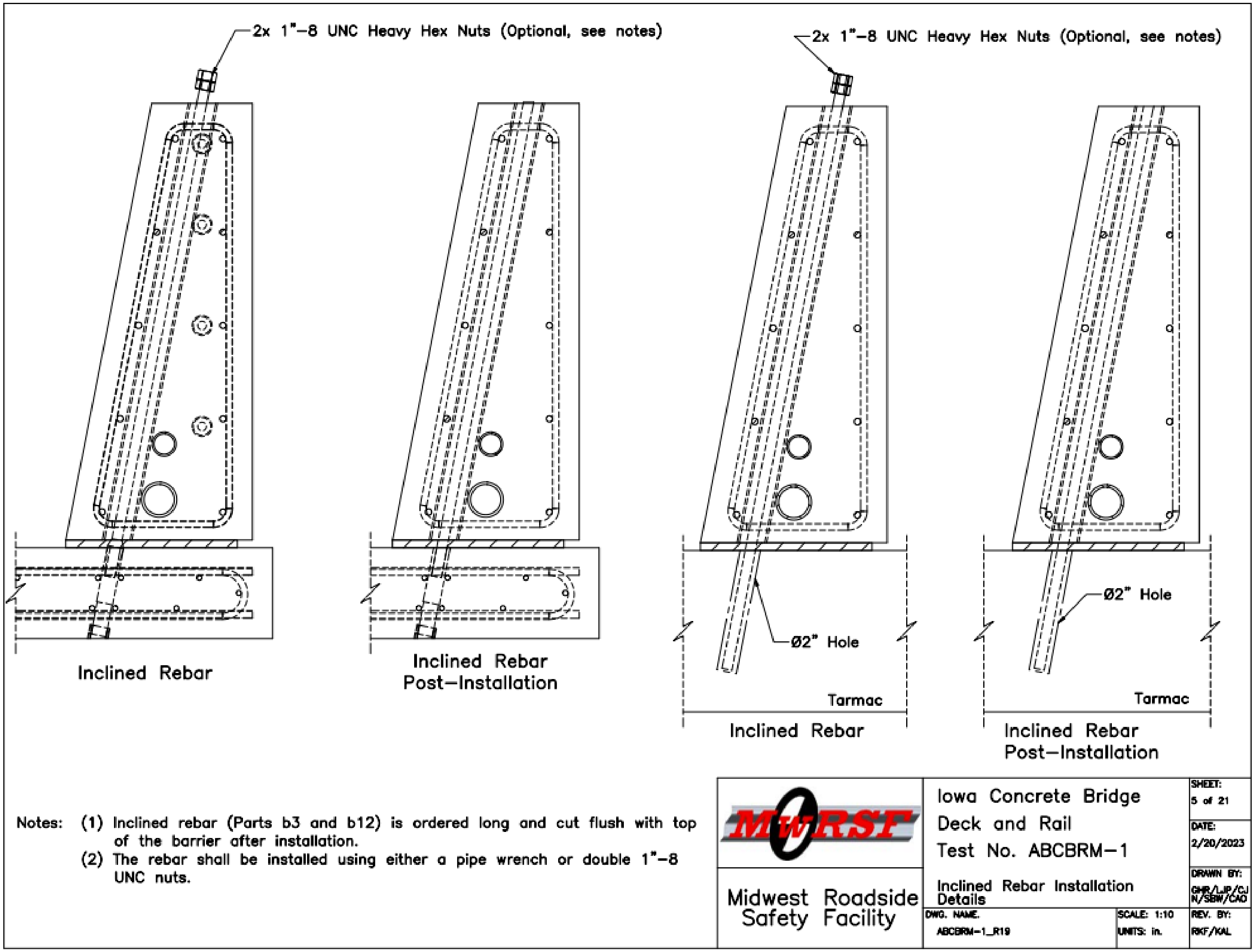


Figure 42. Inclined Rebar Installation Details, Test No. ABCBRM-1

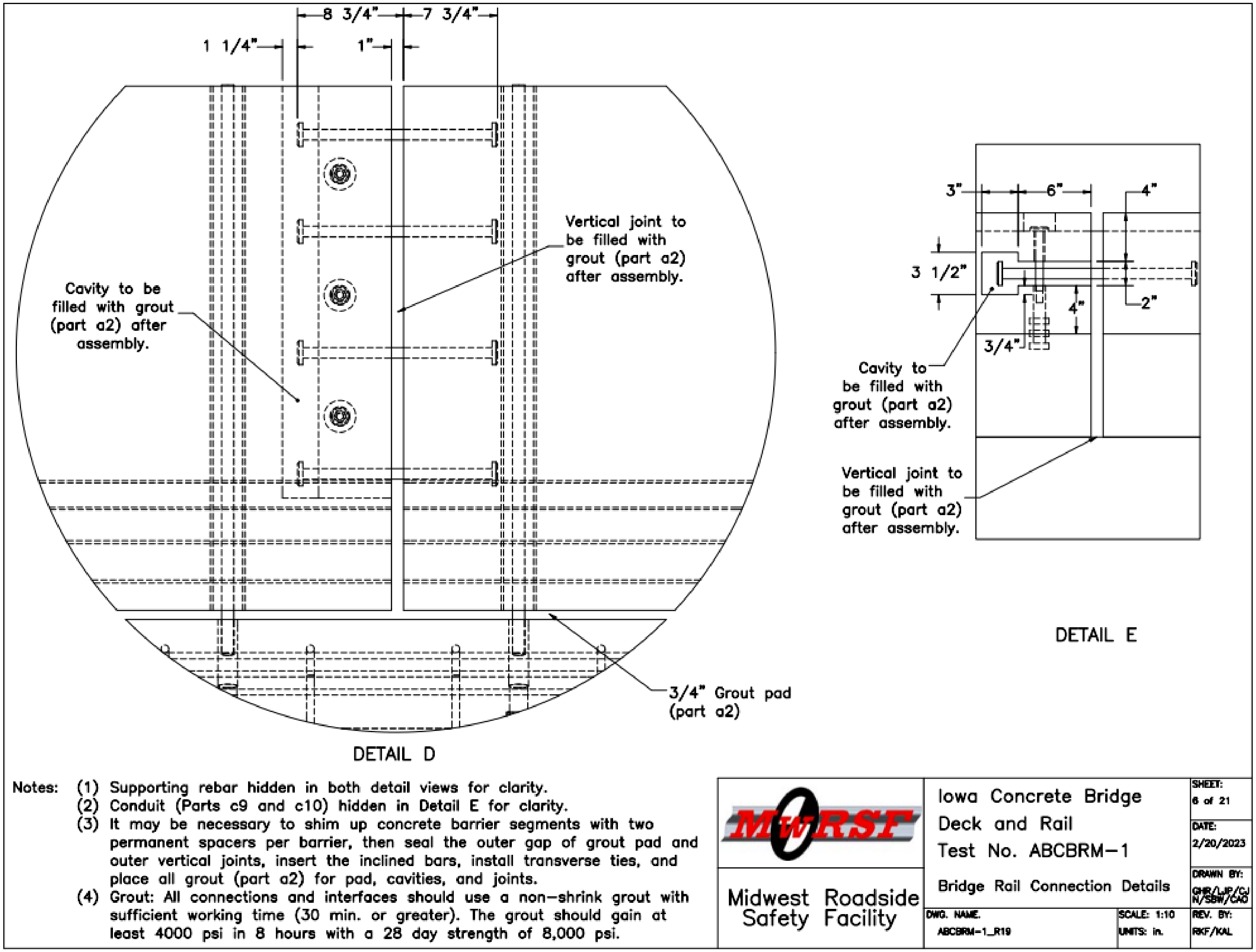


Figure 43. Bridge Rail Connection Details, Test No. ABCBRM-1

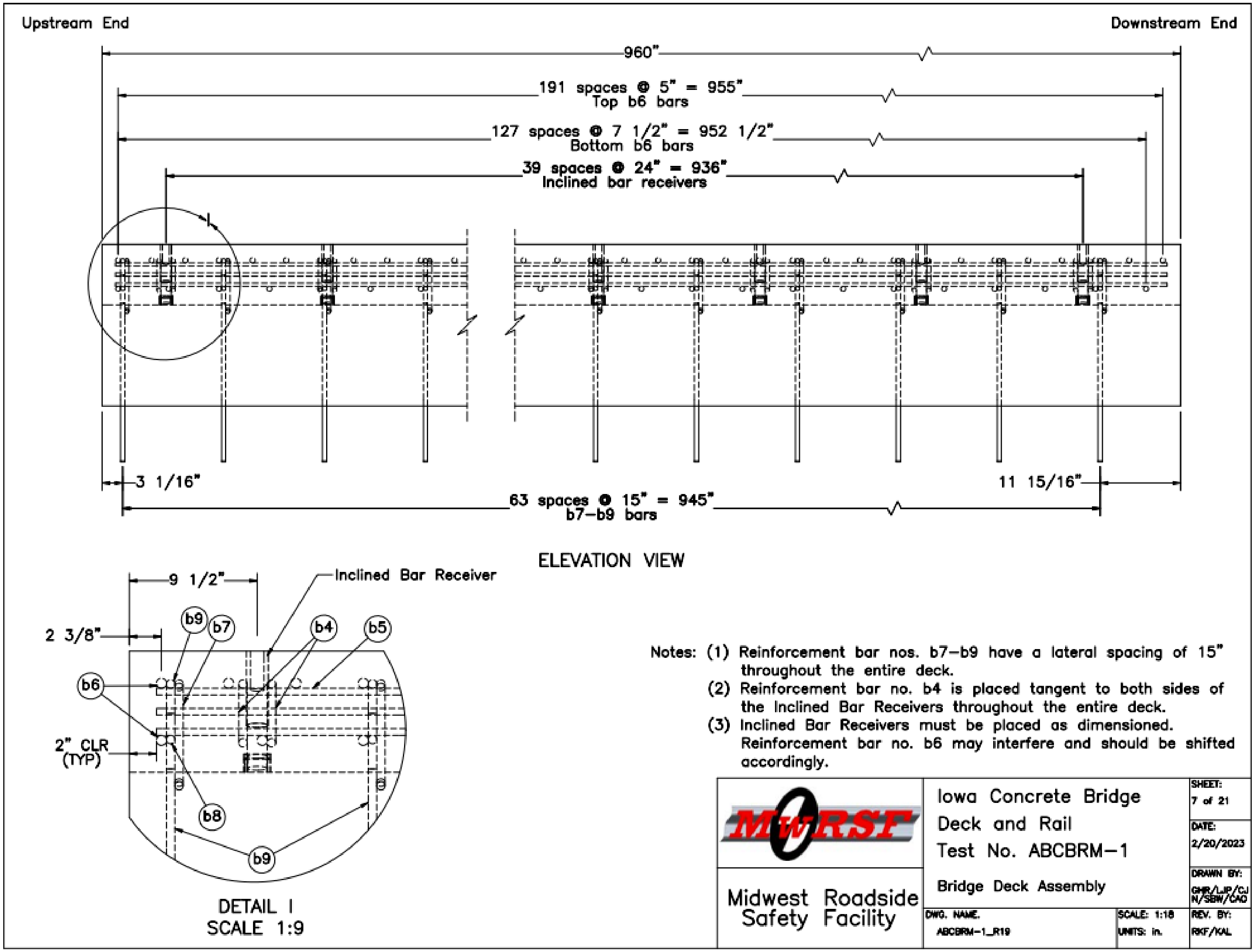
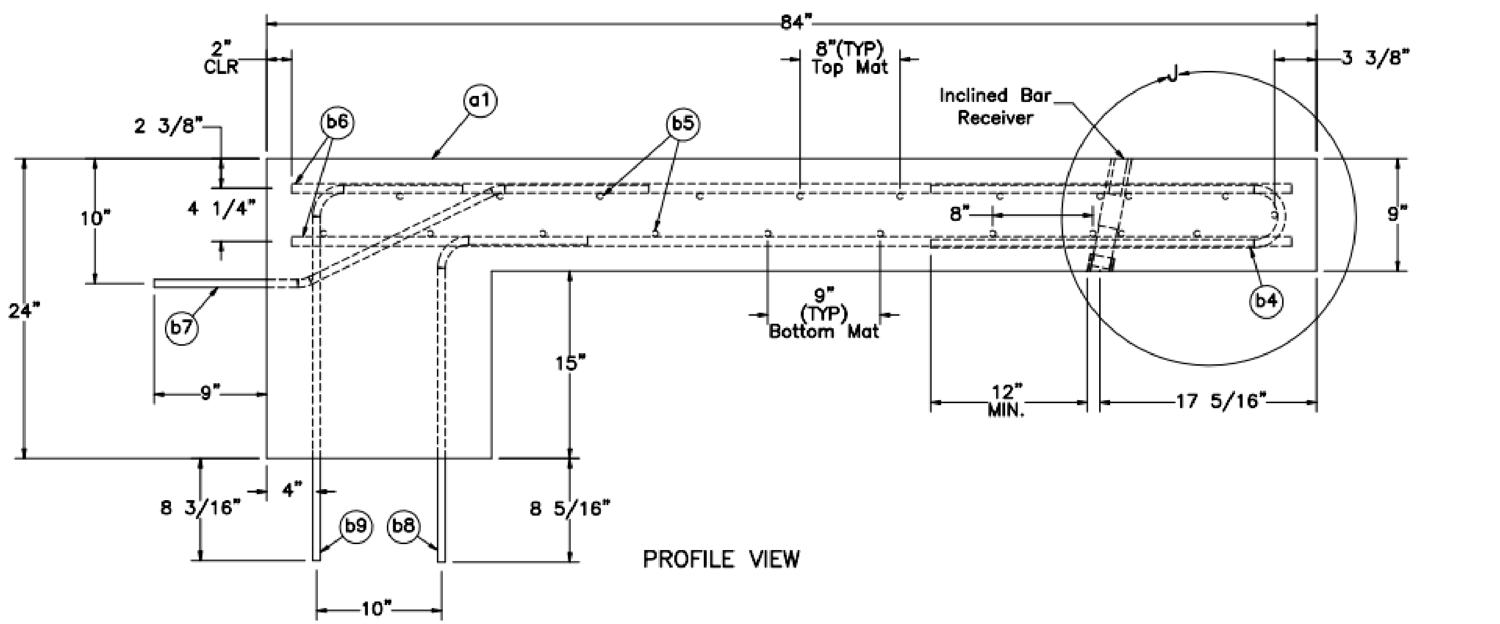


Figure 44. Bridge Deck Assembly, Test No. ABCBRM-1

Item No.	QTY.	Description	Material Specification	Treatment Specification	Hardware Guide
–	1	Concrete Bridge Deck Assembly	–	–	
a1	–	Concrete	Min. f'c = 4,000 psi	–	–
b4	80	#5 Bent Rebar, 58 5/8" Total Unbent Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b5	21	#4 Rebar, 956" Total Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b6	320	#6 Rebar, 80" Total Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b7	64	#5 Bent Rebar, 41 5/16" Total Unbent Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b8	64	#5 Bent Rebar, 36 1/2" Total Unbent Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b9	64	#5 Bent Rebar, 40 1/2" Total Unbent Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
–	40	Inclined Bar Receiver Assembly	–	–	–



Notes: (1) Reinforcement bar no. b7 is anchored into the existing concrete tarmac using a chemical epoxy adhesive with a minimum bond strength of 1,450 psi (Part d1).
(2) Open end of hairpin rebar (Part b4) must extend a minimum of 12" past inclined bar receivers.
(3) Plug top of Inclined Bar Receivers when casting concrete deck. Remove plugs to later install threaded inclined bars.

MwRSF Midwest Roadside Safety Facility	Iowa Concrete Bridge Deck and Rail Test No. ABCBRM-1		SHEET: 8 of 21 DATE: 2/20/2023
	Bridge Deck Assembly		DRAWN BY: GHR/LJP/CJ N/SBW/CAO
	DWG. NAME. ABCBRM-1_R19	SCALE: 1:12 UNITS: in.	REV. BY: RKF/KAL

Figure 45. Bridge Deck Assembly, Cont., Test No. ABCBRM-1

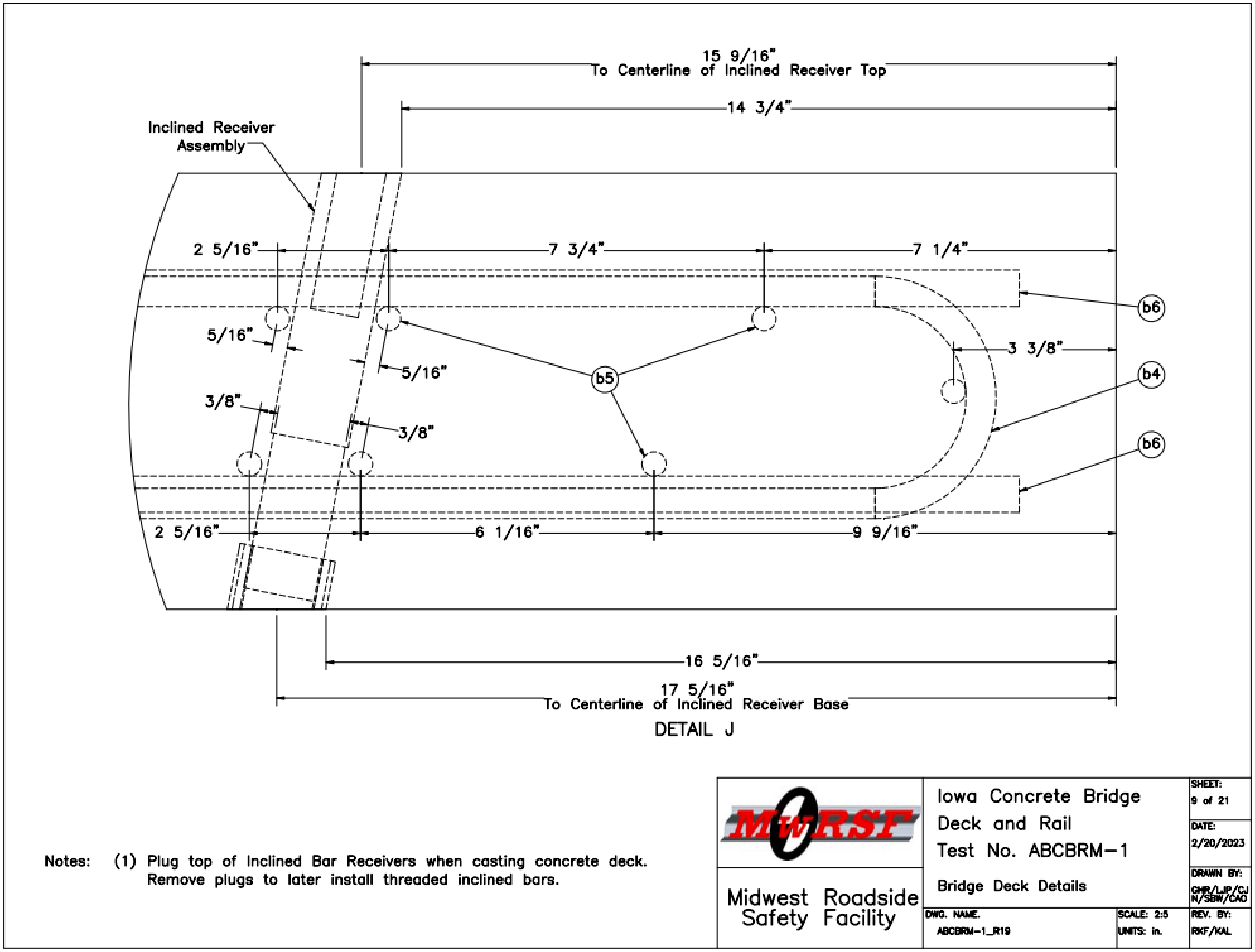
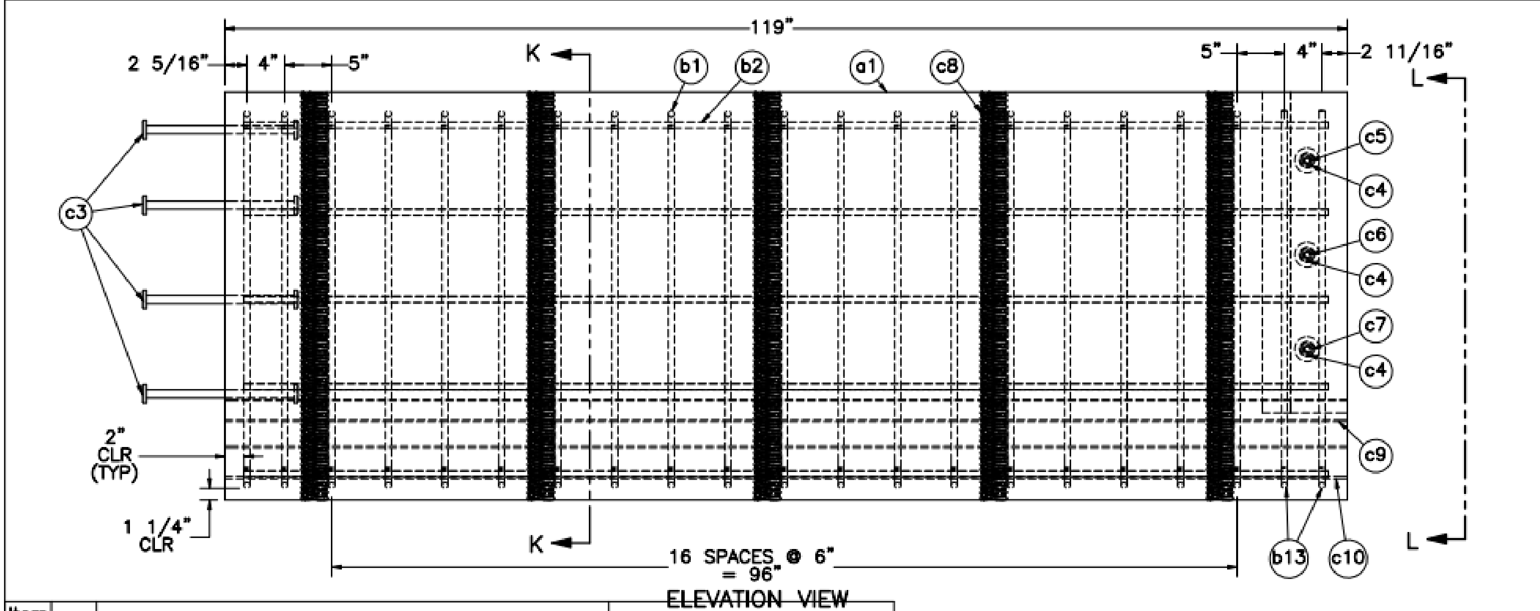


Figure 46. Bridge Deck Details, Test No. ABCBRM-1



Item No.	QTY.	Description	Material Specification
–	13	Bridge Rail Assembly	–
a1	–	Concrete	Min. f'c = 4,000 psi (SEE NOTE 1)
b1	19	#5 Bent Rebar, 108" Total Unbent Length	ASTM A615 Gr. 60
b2	10	#5 Rebar, 115" Total Length	ASTM A615 Gr. 60
b13	2	#5 Bent Rebar, 92" Total Unbent Length	ASTM A615 Gr. 60
c3	4	7/8" Dia., 16 1/2" Long, Double–Headed Shear Tie, HRC 555 T–Head Both Ends	ASTM A970 & ASTM A706 Grade X
c4	3	5/8" Dia., 5 1/4" Long, 5/8"–11 UNC Male Transverse Tie, HRC 555 Series T–Head – One End, HRC 300M – One End	ASTM A970 & ASTM A706 Grade X
c5	1	5/8"–11 UNC Internally Threaded Transverse Receiving Tie, 1" Dia., 3 3/16" Long, Special #5 Head – One End, HRC 320 – One End	ASTM A706 and ASTM A615 Grade X
c6	1	5/8"–11 UNC Internally Threaded Transverse Receiving Tie, 1" Dia., 4 3/16" Long, Special #5 Head – One End, HRC 320 – One End	ASTM A706 and ASTM A615 Grade X
c7	1	5/8"–11 UNC Internally Threaded Transverse Receiving Tie, 1" Dia., 5 1/4" Long, Special #5 Headed – One End, HRC 320 – One End	ASTM A706 and ASTM A615 Grade X
c8	5	2 1/2" I.D., 2 5/8" O.D., 26–gauge 44 5/8" Long Corrugated Inclined Pipe or Post–Tensioning Pipe	ASTM A53 Corr. Pipe
c9	1	2" Dia. Conduit, 119" Long (4)	ASTM D3350, Min. SDR 13.5
c10	1	3" Dia. Conduit, 119" Long (5)	ASTM D3350, Min. SDR 13.5

Notes:
(1) The two stirrups (part b13) on the downstream end shall be cut at the top to facilitate the use of the receiving slot.
(2) The farthest upstream bridge rail does not require Double–Headed Shear Ties (part c3).
(3) Clear cover shall be 2" minimum, except on the bottom of the barrier, where it shall be 1 1/4".
(4) I.D. = 2.002", O.D. = 2.375", Minimum Wall = 0.176".
(5) I.D. = 2.951", O.D. = 3.5", Minimum Wall = 0.259".
(6) When casting concrete barriers, a dowel shall be inserted into part no. c8 to prevent bending of material.

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Iowa Concrete Bridge Deck and Rail Test No. ABCBRM–1

Bridge Rail Segment Assembly

SHEET: 10 of 21
DATE: 2/20/2023
DRAWN BY: GHR/LJP/CJN/SBW/CAO
DWG. NAME. ABCBRM–1_R19
SCALE: 1:16
UNITS: in.
REV. BY: RKF/KAL

Figure 47. Bridge Rail Segment Assembly, Test No. ABCBRM-1

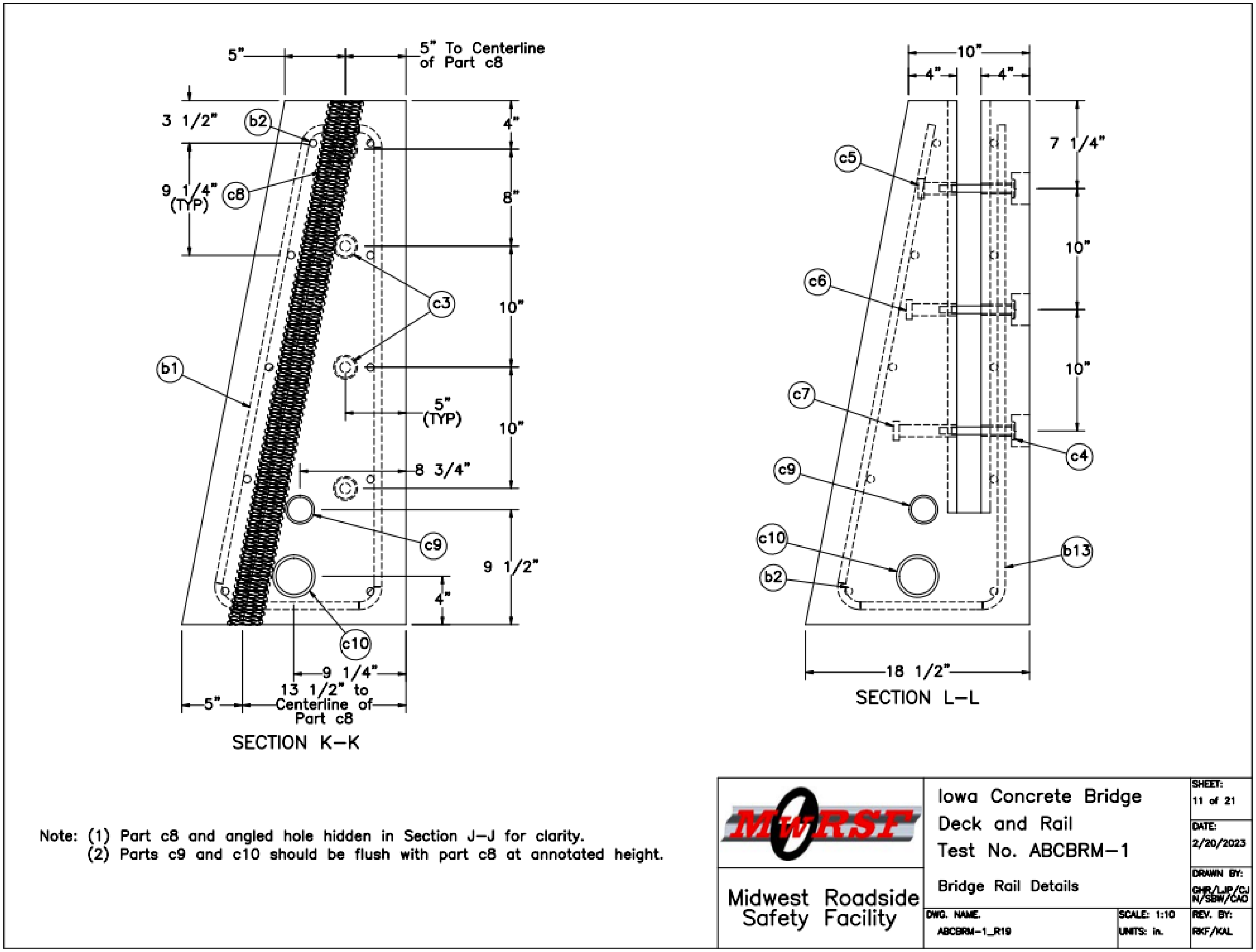


Figure 48. Bridge Rail Details, Test No. ABCBRM-1

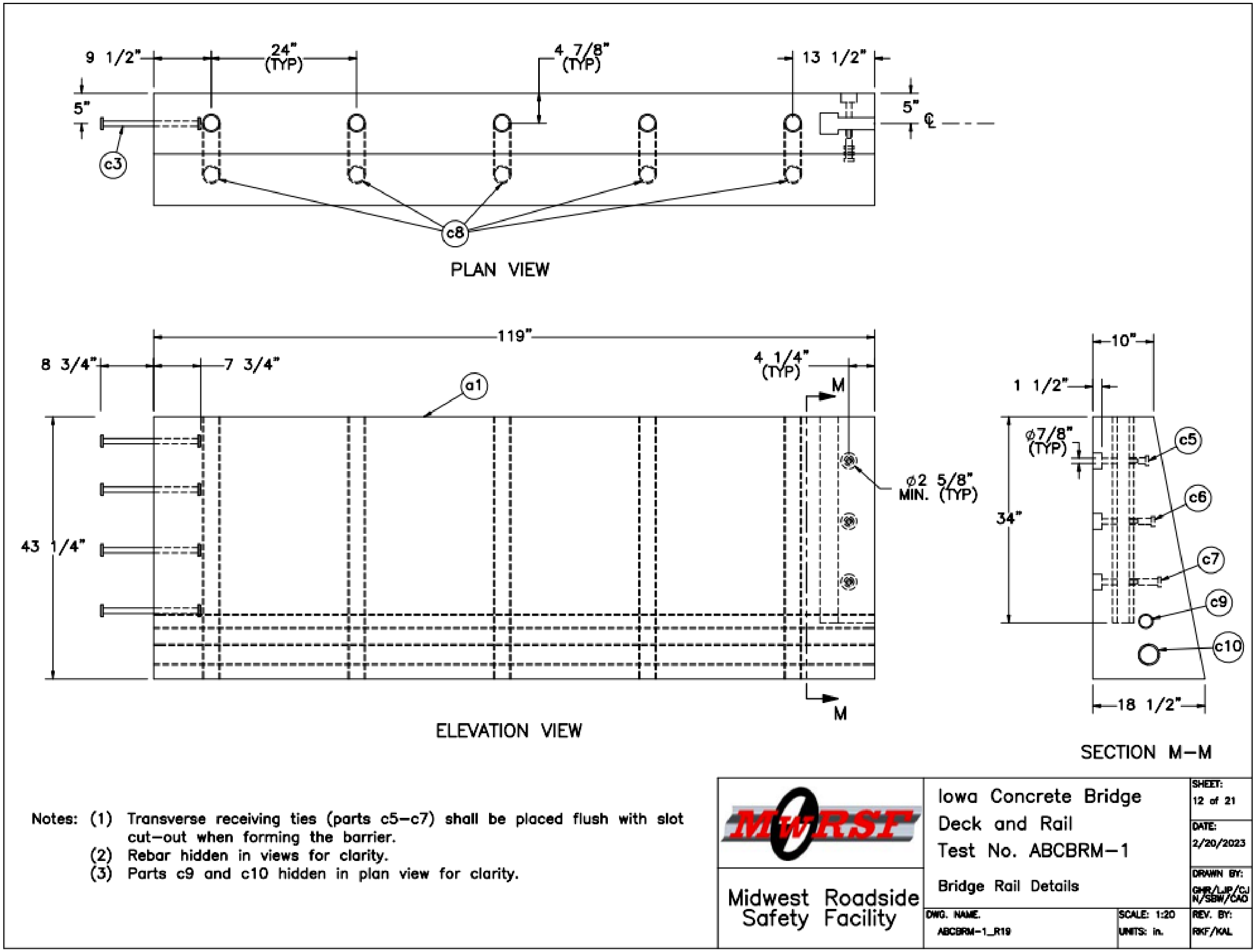
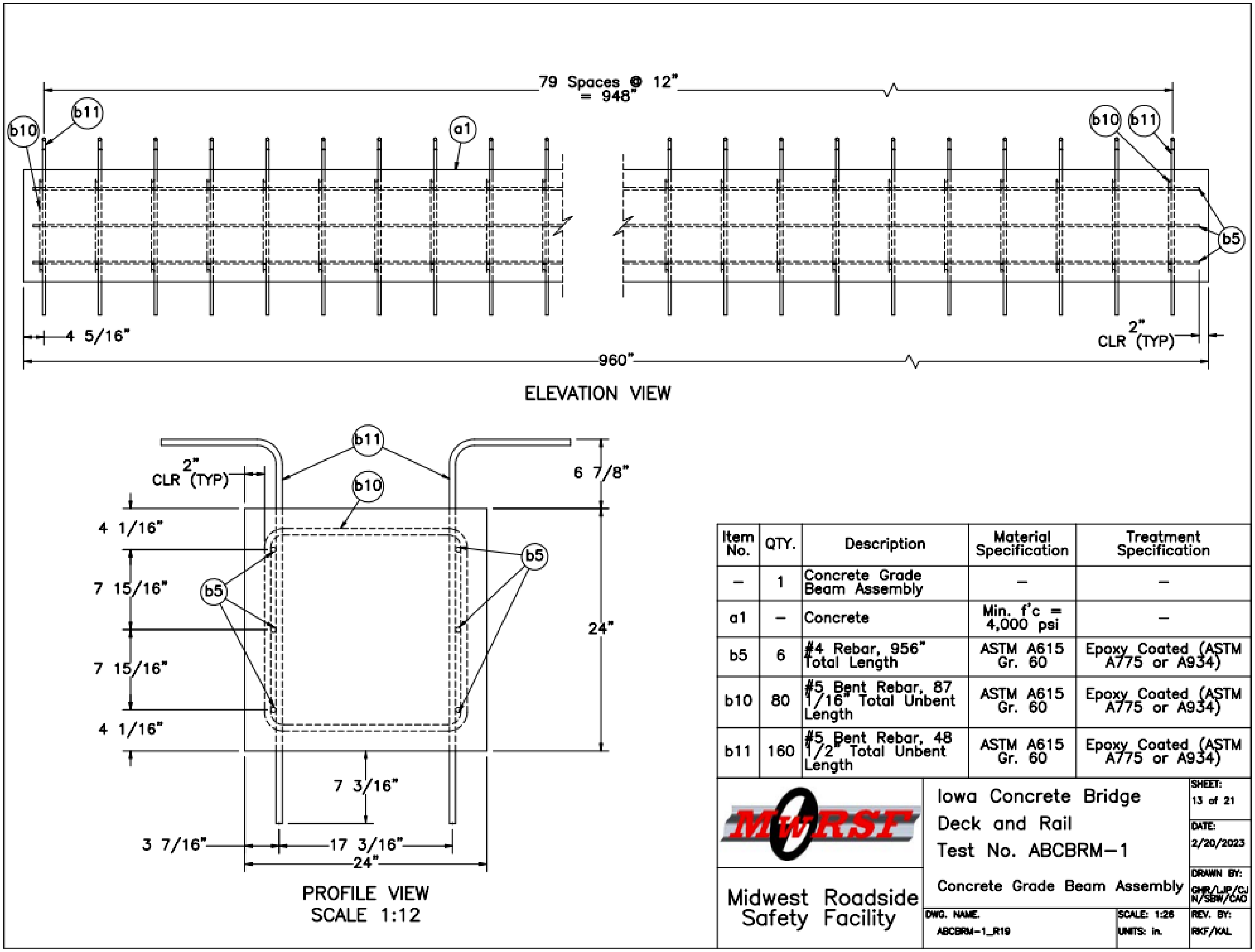
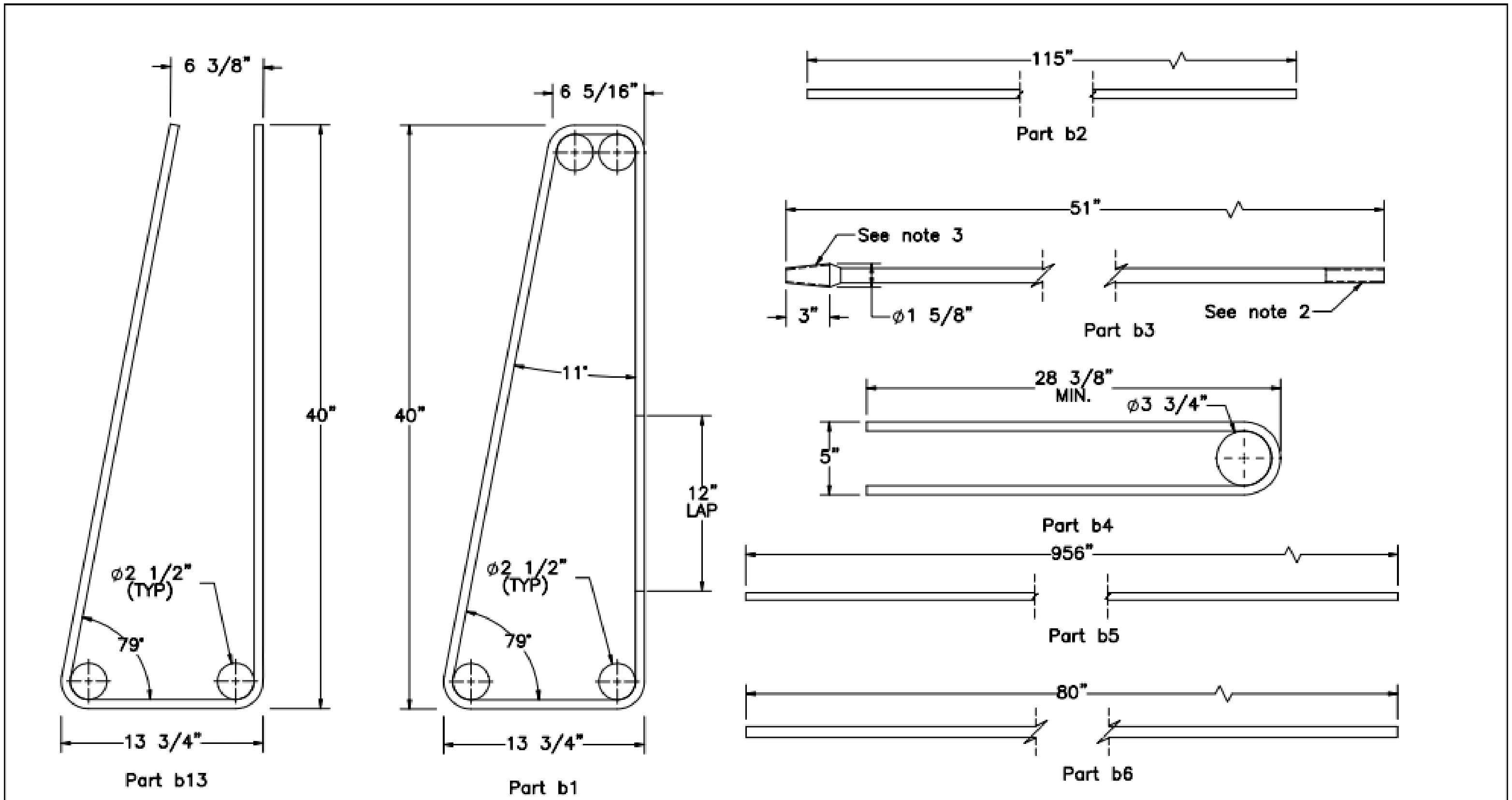


Figure 49. Bridge Rail Details, Cont., Test No. ABCBRM-1



Item No.	QTY.	Description	Material Specification	Treatment Specification
–	1	Concrete Grade Beam Assembly	–	–
a1	–	Concrete	Min. f'c = 4,000 psi	–
b5	6	#4 Rebar, 956" Total Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)
b10	80	#5 Bent Rebar, 87 1/16" Total Unbent Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)
b11	160	#5 Bent Rebar, 48 1/2" Total Unbent Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)

Figure 50. Concrete Grade Beam Assembly, Test No. ABCBRM-1



Notes: (1) Part b3 is cut at the barrier top after installation.
(2) If double nuts are used to help install and turn Part b3, top end shall be threaded with 1"–8 UNC x3".
(3) Part 3 shall have a threaded end that conforms to HRC 410 end splice specifications.

Bill of Bars

Bar	QTY	Size	Total Length	Min. Lap Length	Material
b1	273	#5	108"	12"	ASTM A615 Gr. 60
b2	130	#5	115"	24"	ASTM A615 Gr. 60
b3	65	#8	51"	–	ASTM A615 Gr. 80
b4	80	#5	58 5/8"	–	ASTM A615 Gr. 60
b5	27	#4	956"	24"	ASTM A615 Gr. 60
b6	320	#6	80"	29"	ASTM A615 Gr. 60
b13	26	#5	92"	–	ASTM A615 Gr. 60

Midwest Roadside Safety Facility

Iowa Concrete Bridge Deck and Rail Test No. ABCBRM-1

System Rebar

SHEET: 14 of 21

DATE: 2/20/2023

DRAWN BY: GHR/LJP/CJN/SBW/CAO

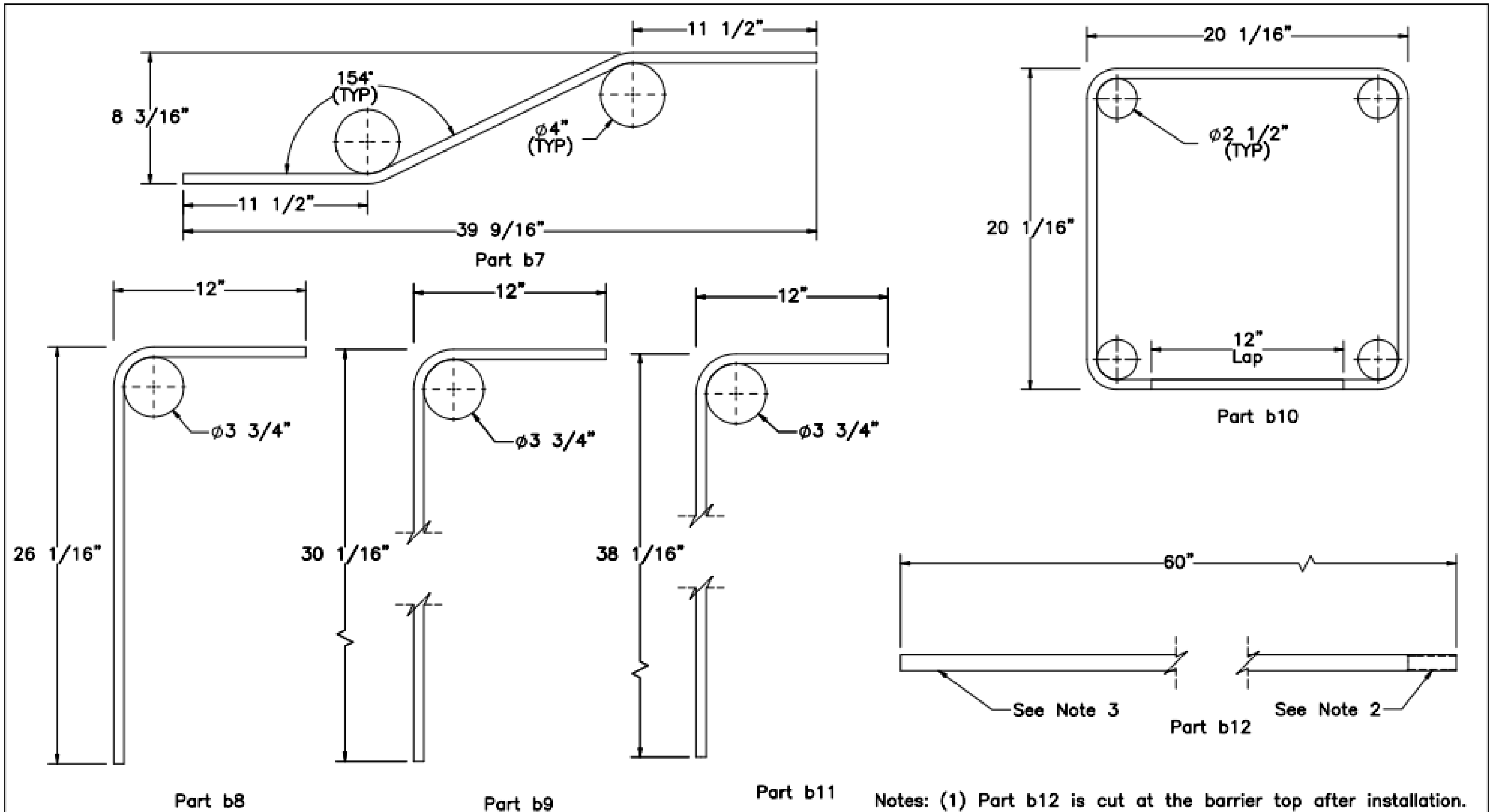
DWG. NAME. ABCBRM-1_R19

SCALE: 1:10

UNITS: in.

REV. BY: RKF/KAL

Figure 51. System Rebar, Test No. ABCBRM-1



Notes:
(1) Part b12 is cut at the barrier top after installation.
(2) If double nuts are used to help install and turn Part b12, one end shall be threaded with 1-8" UNC threads.
(3) End installed into drilled/cored hole placed within concrete tarmac.

Bill of Bars

Bar	QTY	Size	Total Length	Min. Lap Length	Material
b7	64	#5	41 5/16"	–	ASTM A615 Gr. 60
b8	64	#5	36 1/2"	–	ASTM A615 Gr. 60
b9	64	#5	40 1/2"	–	ASTM A615 Gr. 60
b10	80	#5	87 1/16"	12"	ASTM A615 Gr. 60
b11	160	#5	48 1/2"	–	ASTM A615 Gr. 60
b12	20	#8	60"	–	ASTM A615 Gr. 80

MwRSF
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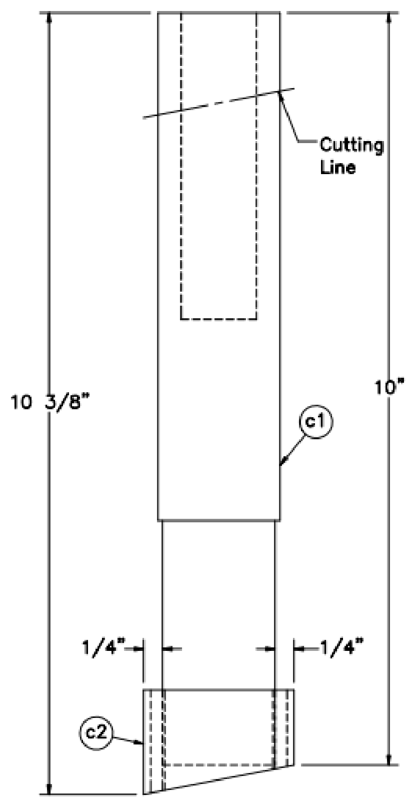
Iowa Concrete Bridge Deck and Rail
Test No. ABCBRM-1

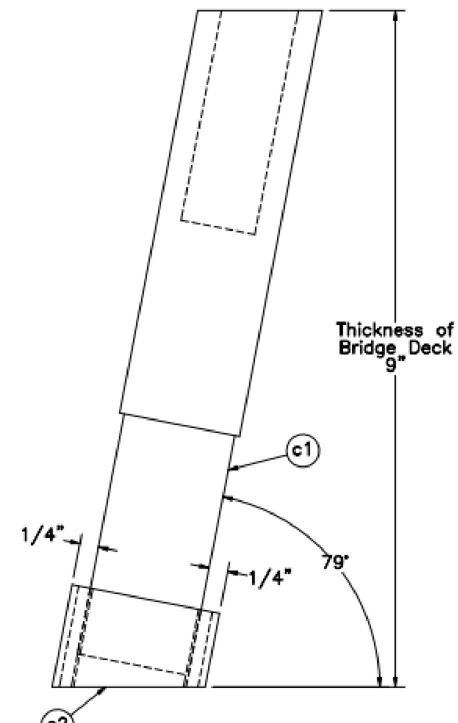
System Rebar

SHEET: 15 of 21
DATE: 2/20/2023
DRAWN BY: GHR/LJP/CJN/SBW/CAO
DWG. NAME. ABCBRM-1_R19
SCALE: 1:9
UNITS: in.
REV. BY: RKF/KAL

Figure 52. System Rebar, Cont., Test No. ABCBRM-1



PROFILE VIEW
(Pre–Installation)



PROFILE VIEW
(Post–Installation)

Notes: (1) Plans are preliminary and subject to change.
(2) Fabrication details to connect c1 to c2 are to be determined by the manufacturer of the specialty hardware.
(3) Assembly will be cut after installation to be flush with the top of the bridge deck.

Item No.	QTY.	Description	Material Specification	Treatment Specification
–	40	Inclined Bar Receiver Assembly	–	–
c1	1	1 5/8" Dia., 9 1/16" Long, 1"–8 UNC x 2" Internally Threaded Tube	Stainless Steel – (TBD)	–
c2	1	Inclined Bar Receiver Assembly	Stainless Steel – (TBD)	–

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Iowa Concrete Bridge Deck and Rail
Test No. ABCBRM–1

Inclined Bar Receiver Assembly and Components

SHEET: 16 of 21
DATE: 2/20/2023
DRAWN BY: GHR/LJP/CJN/SBW/CAO
DWG. NAME. ABCBRM–1_R19
SCALE: 1:2
UNITS: in.
REV. BY: RKF/KAL

Figure 53. Inclined Bar Receiver Assembly and Components, Test No. ABCBRM-1

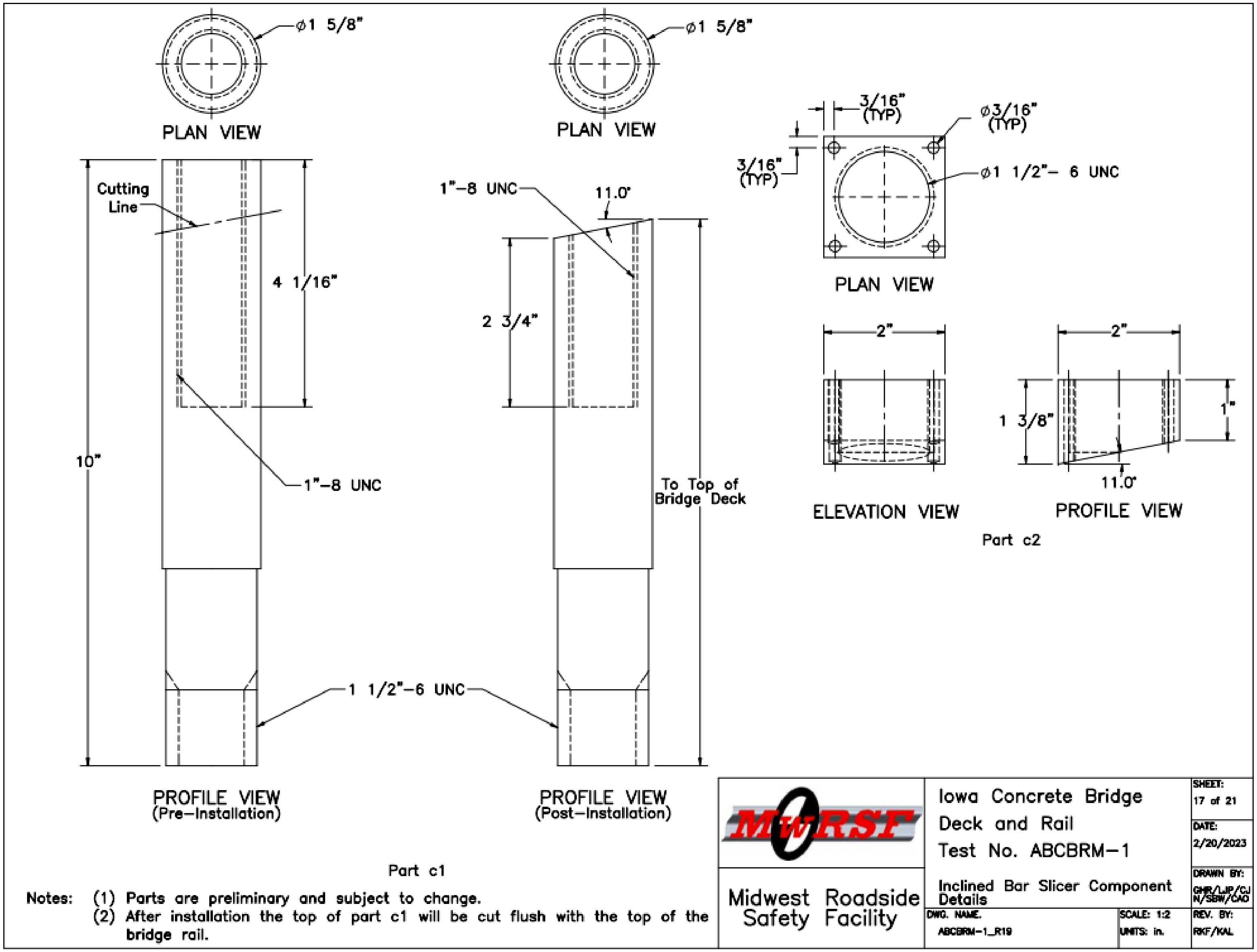


Figure 54. Inclined Bar Slicer Component Details, Test No. ABCBRM-1

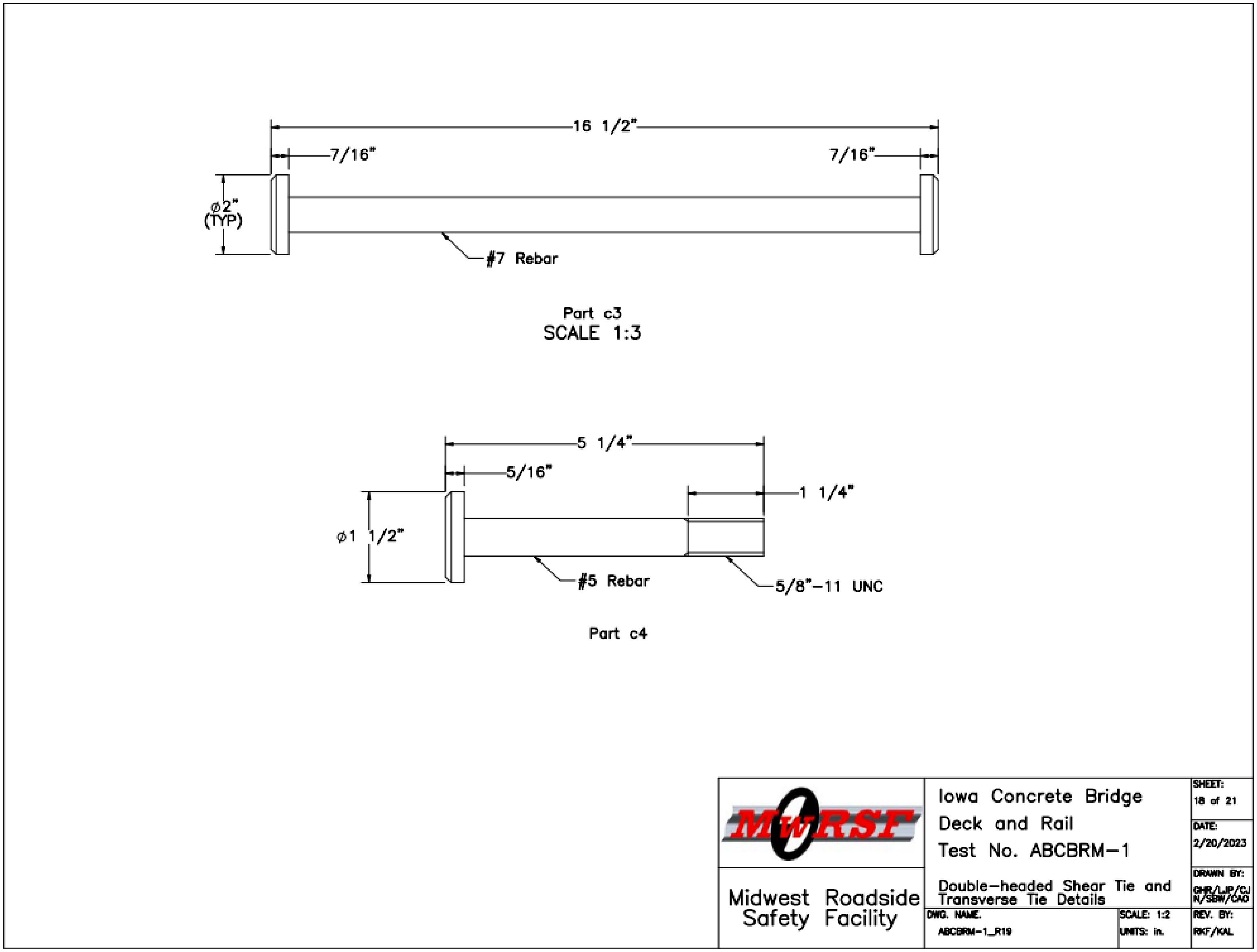


Figure 55. Double-Headed Shear Tie and Transverse Tie Details, Test No. ABCBRM-1

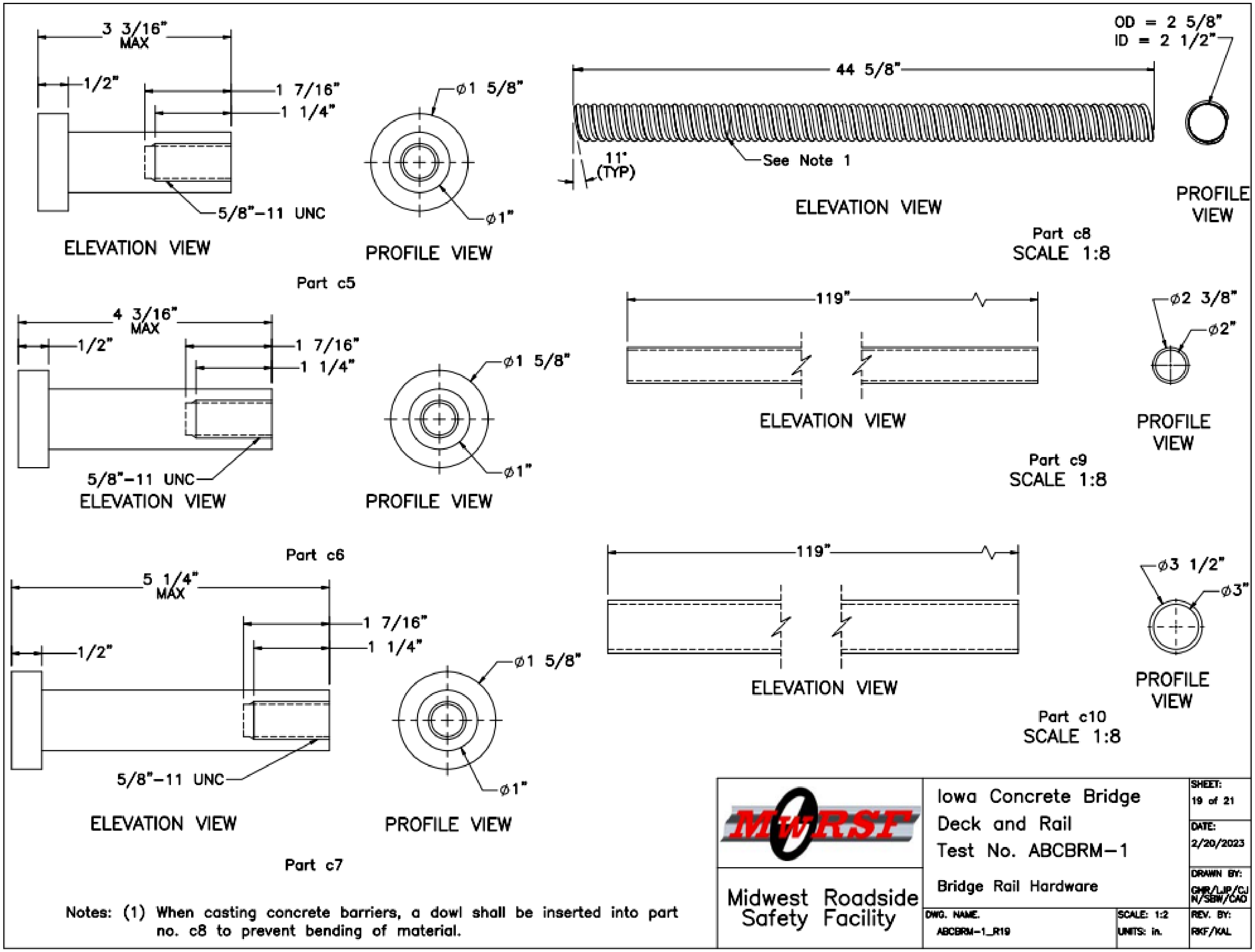


Figure 56. Bridge Rail Hardware, Test No. ABCBRM-1

Item No.	QTY.	Description	Material Specification	Treatment Specification	Hardware Guide
a1	–	Concrete	Min. f'c = 4,000 psi (SEE NOTE 1)	–	–
a2	–	Grout	Min. 8–hour f'c = 4,000 psi; Min. 28–day f'c = 8,000 psi (SEE NOTE 2)	–	–
b1	247	#5 Bent Rebar, 108" Total Unbent Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b2	130	#5 Rebar, 115" Total Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b3	40	#8 Rebar with 1"–8 UNC x 3" section, 51" Long, HRC – one end, threaded – one end (SEE NOTE 3)	ASTM A615 Gr. 80	–	–
b4	80	#5 Bent Rebar, 58 5/8" Total Unbent Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b5	27	#4 Rebar, 956" Total Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b6	320	#6 Rebar, 80" Total Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b7	64	#5 Bent Rebar, 41 5/16" Total Unbent Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b8	64	#5 Bent Rebar, 36 1/2" Total Unbent Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b9	64	#5 Bent Rebar, 40 1/2" Total Unbent Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b10	80	#5 Bent Rebar, 87 1/16" Total Unbent Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b11	160	#5 Bent Rebar, 48 1/2" Total Unbent Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–
b12	25	#8 Rebar with 1"–8 UNC x 12" section, 60" Long, threaded – one end (SEE NOTE 3)	ASTM A615 Gr. 80	–	–
b13	26	#5 Bent Rebar, 92" Total Unbent Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)	–

Notes: (1) NE 47BD/1PF4000 concrete mix was used for testing purposes, but any concrete mix that meets the f'c can be used.
(2) Grout: All connections and interfaces should use a non–shrink grout with sufficient working time (30 min. or greater). The grout should gain at least 4000 psi in 8 hours with a 28 day strength of 8,000 psi.
(3) If double nuts are used to install parts b3 and b12 the top end of both shall be threaded with 1–8" UNC threads.

Midwest Roadside Safety Facility

Iowa Concrete Bridge Deck and Rail Test No. ABCBRM–1

Bill of Materials

SHEET: 20 of 21

DATE: 2/20/2023

DRAWN BY: GMR/LJP/CJN/SBW/CAO

DWG. NAME. ABCBRM–1_R19

SCALE: None UNITS: in.

REV. BY: RKF/KAL

Figure 57. Bill of Materials, Test No. ABCBRM-1

Item No.	QTY.	Description	Material Specification	Treatment Specification	Hardware Guide
c1	40	1 5/8" Dia., 9 1/16" Long, 1"-8 UNC x 2" Internally Threaded Tube	Stainless Steel – (TBD)	–	–
c2	40	2"x2"x1 3/8" Base Plate	Stainless Steel – (TBD)	–	–
c3	48	7/8" Dia., 16 1/2" Long, Double-Headed Shear Tie, HRC 555 T-Head Both Ends	ASTM A970 & ASTM A706 Grade X	(TBD)	–
c4	39	5/8" Dia., 5 1/4" Long, 5/8"-11 UNC Male Transverse Tie, HRC 555 Series T-Head – One End, HRC 300M – One End	ASTM A970 & ASTM A706 Grade X	(TBD)	–
c5	13	5/8"-11 UNC Internally Threaded Transverse Receiving Tie, 1" Dia., 3 3/16" Long, Special #5 Head – One End, HRC 320 – One End	ASTM A706 and ASTM A615 Grade X	–	–
c6	13	5/8"-11 UNC Internally Threaded Transverse Receiving Tie, 1" Dia., 4 3/16" Long, Special #5 Head – One End, HRC 320 – One End	ASTM A706 and ASTM A615 Grade X	–	–
c7	13	5/8"-11 UNC Internally Threaded Transverse Receiving Tie, 1" Dia., 5 1/4" Long, Special #5 Headed – One End, HRC 320 – One End	ASTM A706 and ASTM A615 Grade X	–	–
c8	65	2 1/2" ID, 44 5/8" Long Corrugated Inclined Pipe	ASTM A53 Corr. Pipe	–	–
c9	13	2" Dia. Conduit, 119" Long	ASTM D3350, Min. SDR 13.5	–	–
c10	13	3" Dia. Conduit, 119" Long	ASTM D3350, Min. SDR 13.5	–	–
–	2**	1"-8 UNC Heavy Hex Nut	ASTM A563A or equivalent	ASTM A153	FNX24b

Note: ** Hex nuts not required if inclined rebar is tightened using a pipe wrench.

Midwest Roadside Safety Facility

Iowa Concrete Bridge Deck and Rail Test No. ABCBRM-1

Bill of Materials, Cont.

SHEET: 21 of 21
DATE: 2/20/2023
DRAWN BY: GHR/LJP/CJN/SBW/CAO
DWG. NAME. ABCBRM-1_R19
SCALE: None UNITS: in.
REV. BY: RKF/KAL

Figure 58. Bill of Materials, Cont., Test No. ABCBRM-1

Figure 59. Test Installation Photographs, Test No. ABCBRM-1

Figure 60. Test Installation Photographs, Test No. ABCBRM-1, Cont.

Figure 61. Test Installation Photographs, Test No. ABCBRM-1, Cont.

5 TEST INSTALLATION SEQUENCE

5.1 Overview

The process of test installation comprised a series of organized steps to ensure the structural configuration aligned with the study's objectives. These construction sequences were executed precisely, owing to their influence on the full-scale crash test results. The full-scale crash test barrier assembly was completed with multiple materials, including special structural fittings, reinforcement, and grout. In the following sections, test installation sequences are briefly described.

5.2 Fabrication of Precast Concrete Barriers

Fabrication of the precast concrete barriers was completed at MwRSF's Outdoor Proving Grounds, situated at the Lincoln Air Park adjacent to the Lincoln Municipal Airport. The construction stages before and during concrete casting are depicted in Figure 62.

5.3 Bridge Deck Construction

5.3.1 Grade Beam/Girder and Anchor Beam Installation

The bridge deck construction began with installing a supporting grade beam/girder and anchor beam. Figure 63 illustrates the formwork and rebar for the grade beam/girder and anchor beam, a pivotal load-bearing component, highlighting the necessity of accurate positioning for the overall structural stability and integrity of the assembly.

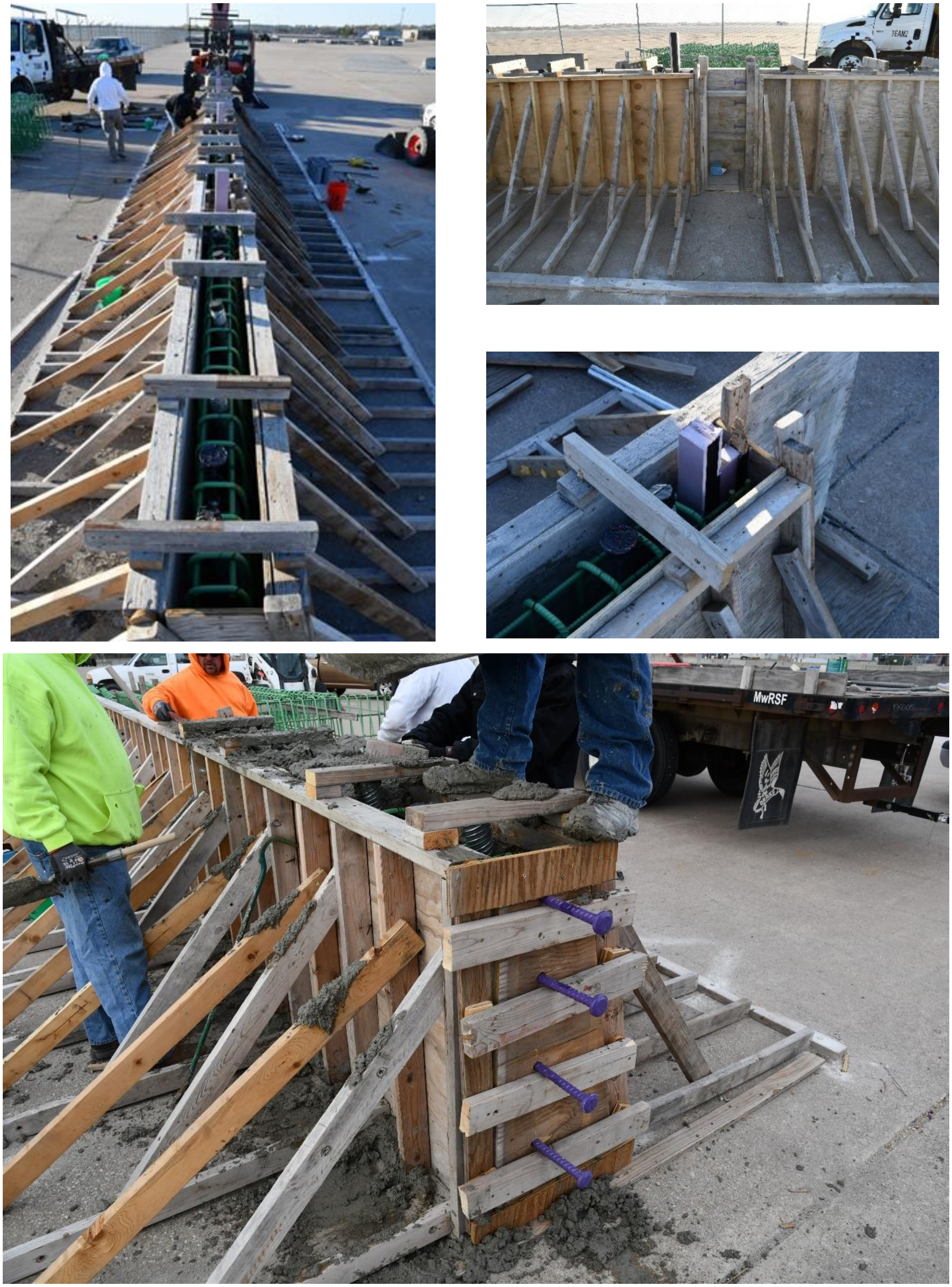


Figure 62. Precast Concrete Barrier Construction Prior to and During Concrete Casting

Figure 63. Grade Beam and Anchor Beam Installation

5.3.2 Rebar Cage, Formwork, and Receiver Installation

Upon completion of the grade beam/girder formwork with steel rebar and subsequent placement and concrete placement, deck slab and anchor beam formwork commenced, and the receivers for the barrier-to-deck connection were integrated. After the materials needed for the barrier-to-deck connection were installed, the reinforcement bars for the anchor beam, bridge deck, and cantilevered overhang were placed on top of the grade beam/girder. Concurrently, the formwork, designed to maintain the concrete's shape during curing, was integrated into the structure, as shown in Figure 64.

5.3.3 Bridge Deck and Anchor Beam Concrete Placement and Inclined Bar Receivers

The concrete for the bridge deck and anchor beam was placed into the assembled formwork following the reinforcing steel bar installation. A texturized broom finish was applied to the concrete near the barrier region. This technique was used to increase the adhesive potential between the concrete surface, the future grout pad, and the precast concrete barriers. A pivotal stage of the construction sequence was the installation of the inclined bar receivers, which were covered to prevent concrete from flowing into the sockets. The coverings were later removed after the concrete was cured. Photographs of bridge deck concrete pouring, cured bridge deck concrete, and inclined bar hole are shown in Figure 65.

Figure 64. Installation of Bridge Deck Reinforcement, Rebar Cage, Formwork, and Receiver

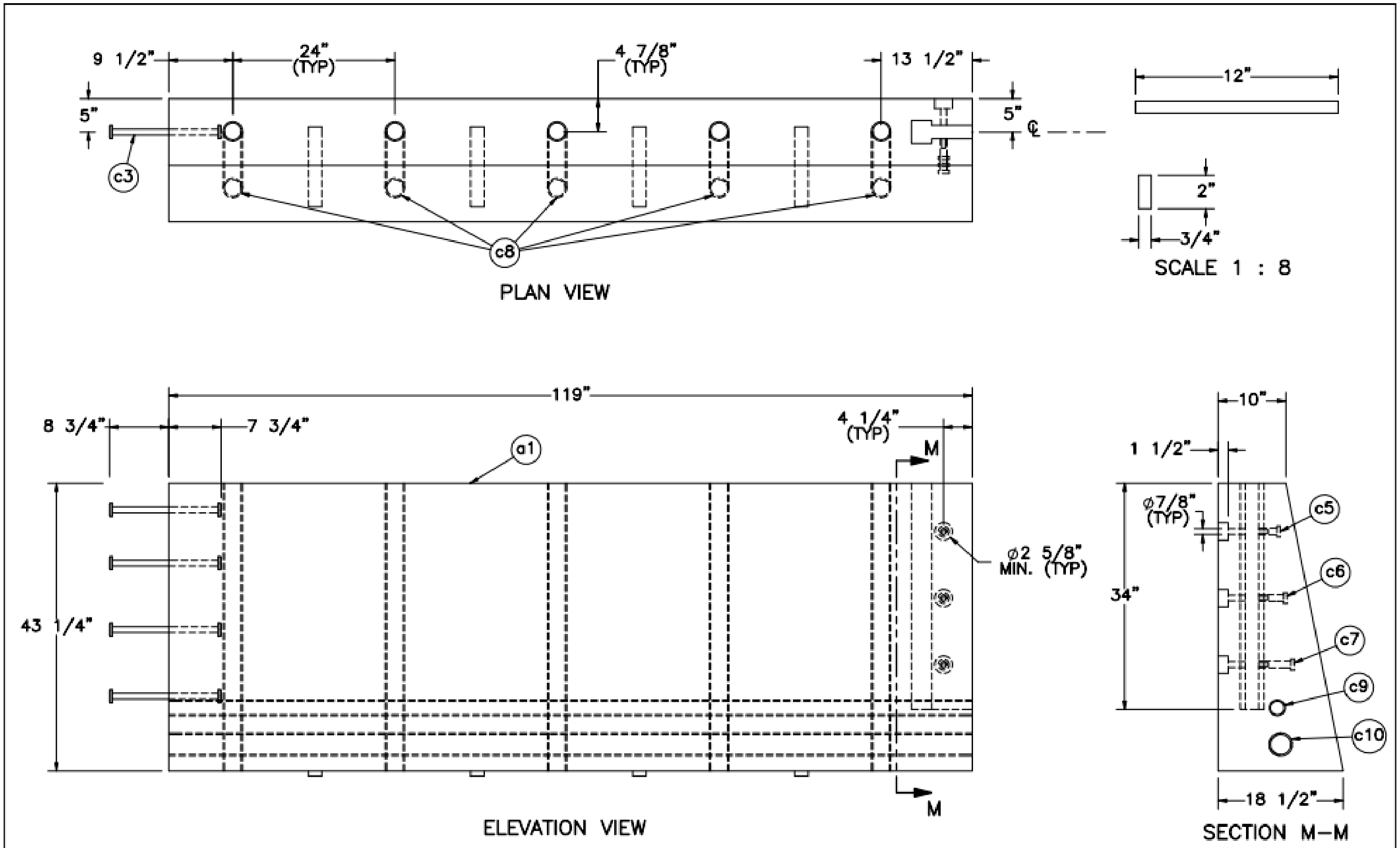
Figure 65. Bridge Deck Concrete Placement, Cured Concrete Bridge Deck, and Inclined Bar Receiver Holes

5.4 Assembly and Grouting

5.4.1 Steel Shim or Grout Pad Placement and Inclined Reinforcing Bars Installation

Once the bridge deck concrete was placed, the next step in the installation was connecting the barriers and inclined bars to the bridge deck. To facilitate this process, ASTM A36 steel shim plates were employed to provide a stable base for the precast concrete barriers during their lowering on to the deck. Specifically, four ¾-in. thick by 20-in. long by 2-in. wide steel spacer shims per barrier segment were positioned on the deck to support the precast concrete barriers. Then, inclined bars were inserted into holes with barrier elevated and screwed into place and tightened with each barrier set down. A photograph of the spacer shim and the inclined reinforcement bars connected to the bridge deck before the installation of the precast barrier is shown in Figure 66. The construction detail for the steel spacer shims is exhibited in Figure 67.

Figure 66. Spacer Shim and Inclined Reinforcing Bars Installation



Item No.	QTY.	Description	Material Specification	Treatment Specification	Hardware Guide
d1	4	Steel Shim	–	–	–

Midwest Roadside Safety Facility

Iowa Concrete Bridge Deck and Rail Test No. ABCBRM-1

Construction Detail

SHEET: 1 of 1
DATE: 9/6/2023
DRAWN BY: GHR/LJP/CJN/SBW/CAC/ZMM
DWG. NAME. ABCBRM-1_Shim
SCALE: 1:20
UNITS: in.
REV. BY: RKF/KAL

Figure 67. Steel Shim Construction Detail, Test No. ABCBRM-1

5.4.2 Precast Concrete Barrier Placement

The precast concrete barriers were vertically positioned on the steel spacer shims or plates. An alignment operation was executed to connect the barriers with the inclined bar receivers in the deck and align the double-headed joint shear ties with the open cavities in the adjacent barrier end. Following, inclined reinforcement bars were inserted and aligned with receivers using a special tool to turn the inclined rebar's top into the deck socket's open end. Finally, three transverse ties were introduced at the joints, followed by an alignment procedure with the receivers installed within the barriers. These transverse ties significantly contributed to the overall structural integrity of the joint. Photographs of the precast concrete barriers on the bridge deck are shown in Figure 68.

Figure 68. Precast Concrete Barriers on Bridge Deck

5.4.3 Grout Application

After the precast concrete barriers were placed on the bridge deck, the flowable grout was placed between the bridge deck and the precast barriers, within the barrier-barrier joint pockets and within the inclined corrugated ducts surrounding the inclined reinforcing bars, as shown in Figure 69. This grouting process solidified the structural assembly, filled all voids, and enhanced the load-bearing attributes of the precast concrete barrier on the bridge deck. The use of specialized formwork, shims, foam filler and other materials prevented the grout from exiting the forms. Additional precast concrete barrier placement images are shown in Figure 70. Upon completion of the grout application and subsequent curing, all protruding inclined reinforcing bars were trimmed to align flush with the top surface of the barrier segments, as shown in Figure 71.

This organized and systematic construction sequence contributed to the valid representation of a precast concrete bridge barrier and bridge deck system, thus making the full-scale crash test results derived from the setup both meaningful and applicable.

Figure 69. Grout Placement Under Barriers, in Barrier-Barrier Joint Pocket, and Around Inclined Rebar

Figure 70. Precast Concrete Barrier Placement Process

Figure 71. Inclined Bars After Grout Application

6 TEST CONDITIONS

6.1 Test Facility

The Outdoor Test Site is located at the Lincoln Air Park on the northwest side of the Lincoln Municipal Airport and is approximately 5 miles northwest of the University of Nebraska-Lincoln.

6.2 Vehicle Tow and Guidance System

A reverse-cable tow system with a 1:2 mechanical advantage was used to propel the test vehicle. The distance traveled and the speed of the tow vehicle were one-half that of the test vehicle. The test vehicle was released from the tow cable before impact with the barrier system. A digital speedometer on the tow vehicle increased the accuracy of the test vehicle impact speed.

A vehicle guidance system developed by Hinch [27] was used to steer the test vehicle. A guide flag, attached to the left-front wheel and the guide cable, was sheared off before impact with the barrier system. The ⅜-in. diameter guide cable was tensioned to approximately 3,500 lb and supported both laterally and vertically every 100 ft by hinged stanchions. The hinged stanchions stood upright while holding up the guide cable, but as the vehicle was towed down the line, the guide flag struck and knocked each stanchion to the ground.

6.3 Test Vehicle

For test no. ABCBRM-1, a 2013 Freightliner M2 single-unit truck was used as the test vehicle. The curb, test inertial, and gross static vehicle weights were 14,686 lb, 22,200 lb, and 22,220 lb, respectively. The test vehicle is shown in Figures 72 through 74, and vehicle dimensions are shown in Figure 75. The authors acknowledge that the single unit height measurement of 51 $^{3}/_{8}$ in., measurement L in Figure 75, was $^{3}/_{8}$ in. outside of the MASH recommended limits of 49±2 in. This measurement was deemed acceptable as $^{3}/_{8}$ in. beyond the limit would not affect the safety performance of the system or vehicle behavior. MASH states that these recommendations should be adhered to when practical.

The longitudinal component of the center of gravity (c.g.) was determined using the measured axle weights. The location of the c.g. is shown in Figures 75 and 76. Data used to calculate the location of the c.g. and ballast information are shown in Appendix G.

Square, black- and white-checkered targets were placed on the vehicle for reference to be viewed from the high-speed digital video cameras and aid in the video analysis, as shown in Figure 76.

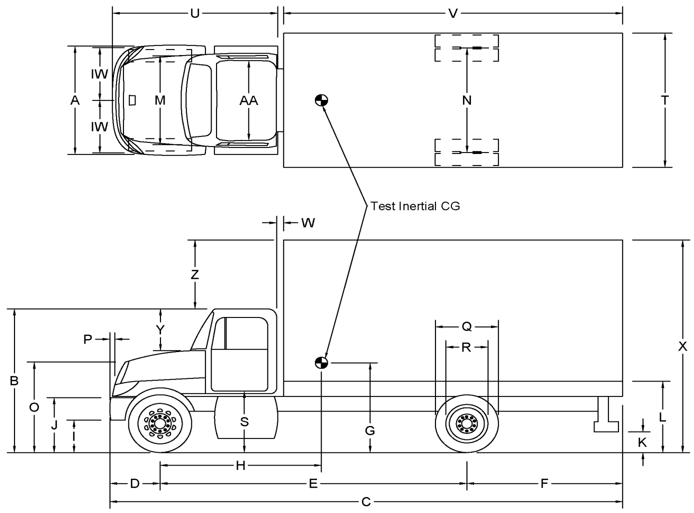
The front wheels of the test vehicle were aligned to vehicle standards except the toe-in value was adjusted to zero such that the vehicle would track properly along the guide cable. A 5B flash bulb was mounted under the vehicle's left-side windshield wiper and was fired by a pressure tape switch mounted at the impact corner of the bumper. The flash bulb was fired upon initial impact with the test article to create a visual indicator of the precise time of impact on the high-speed digital videos. A radio-controlled brake system was installed in the test vehicle so the vehicle could be brought safely to a stop after the test.

Figure 72. Test Vehicle, Test No. ABCBRM-1

Figure 73. Test Vehicle Ballast, Test No. ABCBRM-1

Figure 74. Test Vehicle’s Interior Floorboards and Undercarriage, Test No. ABCBRM-1

		Test Name:	ABCBR-1	**VIN No:**	3ALACXDT6EDFX0132
Model Year:	2013	**Make:**	Freightliner	**Model:**	M2
Tire Size:	11R22.5 S	**Tire Inflation Pressure:**	105 psi	**Odometer:**	446899



Vehicle Geometry - in. (mm)
Target Ranges listed below

	in.	(mm)		in.	(mm)
A:	93	2362 1/5	**B:**	99 3/8	2524 1/8
C:	390 3/4	9925 1/20	**D:**	29 13/16	757 19/80
	Max: 394 (10000)				
E:	240	6096	**F:**	120 15/16	3071 13/16
	Max: 240 (6100)				
G:	46 1/2	1181 1/10	**H:**	157 3/8	3997 13/40
I:	18 3/8	466 29/40	**J:**	32	812 4/5
K:	19	482 3/5	**L:**	51 3/8	1304 37/40
				49±2 (1245±50)	
M:	82 1/4	2089 3/20	**N:**	72 3/4	1847 17/20
O:	55 1/2	1409 7/10	**P:**	0	0
Q:	40 1/2	1028 7/10	**R:**	23 1/4	590 11/20
S:	35 1/2	901 7/10	**T:**	95 1/2	2425 7/10
U:	105 1/2	2679 7/10	**V:**	27 5/8	701 27/40
W:	3 1/2	88 9/10	**X:**	158	4013 1/5
Y:	34 3/4	882 13/20	**Z:**	56 3/8	1431 37/40
IW (Impact Width):	46 1/8	1171 23/40	**AA:**	70 1/2	1790 7/10

Ballast

Weight lb (kg):	7741 (3511)
CG height in. (mm):	63 1/2 (1612)
	63±2 (1600±50)

Mass Distribution - lb (kg)

Gross Static	**LF**	3770 (1710)	**RF**	3870 (1755)
	LR	7310 (3316)	**RR**	7250 (3289)

Wheel Center Height (Front):	19 1/2	495 3/10
Wheel Center Height (Rear):	20	508
Wheel Well Clearance (Front):	47 3/4	1212 17/20
Wheel Well Clearance (Rear):	44 1/2	1130 3/10
Bottom Frame Height (Front):	26 1/2	673 1/10
Bottom Frame Height (Rear):	28 3/4	730 1/4

Weights lb (kg)	**Curb**	**Test Inertial**	**Gross Static**
W-front	6696 (3037)	7640 (3465)	7640 (3465)
W-rear	7990 (3624)	14560 (6604)	14560 (6604)
W-total	14686 (6661)	22200 (10070)	22200 (10070)
	13200±2200 (6000±1000)	22046±660 (10000±300)	

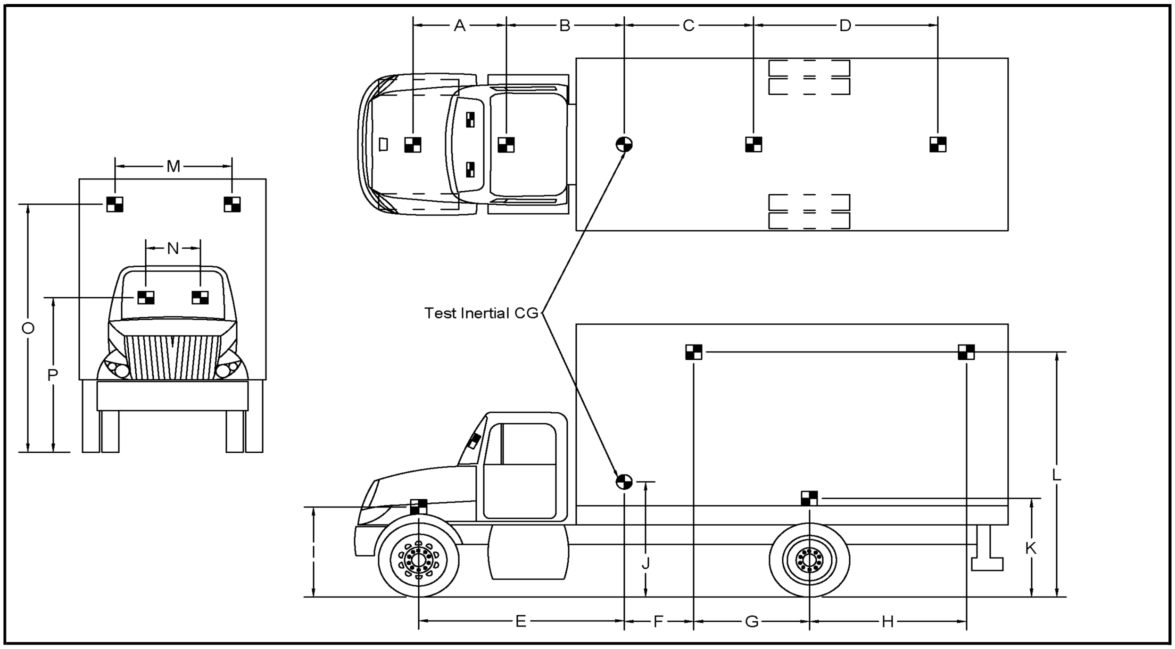
GVWR Ratings - lb		**Surrogate Occupant Data**			
Front	12000	**Type:**	Hybrid II	**Engine Type:**	Diesel
Rear	21000	**Mass:**	161 lb	**Engine Size:**	6.7L I6
Total	33000	**Seat Position:**	N/A	**Transmission Type:**	Automatic
				Drive Type:	RWD

Note any damage prior to test: None

Figure 75. Vehicle Dimensions, Test No. ABCBRM-1

Test Name: ABCBR-1 **VIN:** 3ALACXDT6EDFX0132

Model Year: 2013 **Make:** Freightliner **Model:** M2



TARGET GEOMETRY-- in. (mm)

A:	56	(1422)	**F:**	1/4	(6)	**L:**	147 1/8	(3737)
B:	124 7/8	(3172)	**G:**	81 1/4	(2064)	**M:**	37 1/8	(943)
C:	36 7/8	(937)	**H:**	34 3/4	(883)	**N:**	51 7/8	(1318)
D:	94	(2388)	**I:**	51 1/4	(1302)	**O:**	145 1/4	(3689)
E:	157 1/4	(3994)	**J:**	54 3/4	(1391)	**P:**	86 1/8	(2188)
			K:	54 15/16	(1395)			

Figure 76. Target Geometry, Test No. ABCBRM-1

6.4 Simulated Occupant

For test no. ABCBRM-1, a Hybrid II 50th-Percentile, Adult Male Dummy equipped with footwear was placed in the right-front seat of the test vehicle with the seat belt fastened. The simulated occupant had a final weight of 161 lb. As recommended by MASH, the simulated occupant weight was not included in calculating the c.g. location.

6.5 Data Acquisition Systems

6.5.1 Accelerometers

Accelerometer systems used in the full-scale crash testing were the SLICE-1, SLICE-2, and TDAS systems described below. The electronic accelerometer data obtained in dynamic testing was filtered using the SAE Class 60 and the SAE Class 180 Butterworth filters conforming to the SAE J211/1 specifications [28].

The SLICE-1 and SLICE-2 units were environmental shock and vibration sensor/recorder systems used to measure the accelerations in the longitudinal, lateral, and vertical directions. The units were modular data acquisition systems manufactured by Diversified Technical Systems, Inc. of Seal Beach, California. The acceleration sensors were mounted inside the body of custom-built, SLICE 6DX event data recorders and recorded data at 10,000 Hz to the onboard microprocessor. Each SLICE 6DX was configured with 7 GB of non-volatile flash memory, a range of ±500 g's, a sample rate of 10,000 Hz, and a 1,650 Hz (CFC 1000) anti-aliasing filter. The "SLICEWare" computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

The TDAS unit was a two-arm piezoresistive accelerometer system manufactured by Endevco of San Juan Capistrano, California. The unit was configured to record two sets of triaxial data along with roll and yaw data. Two sets of accelerometers were used to measure each of the longitudinal, lateral, and vertical accelerations independently at a sample rate of 10,000 Hz. The accelerometers were configured and controlled using a system developed and manufactured by Diversified Technical Systems, Inc. of Seal Beach, California. More specifically, data was collected using a DTS Sensor Input Module (SIM), Model TDAS3-SIM-16M. The SIM was configured with 16 MB SRAM and eight sensor input channels with 250 kB SRAM/channel. The SIM was mounted on a TDAS3-R4 module rack. The module rack was configured with isolated power/event/communications, 10BaseT Ethernet and RS232 communication, and an internal backup battery. Both the SIM and module rack were crashworthy. The "DTS TDAS Control" computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

The SLICE-1 unit was mounted on the rear axle, SLICE-2 unit was mounted near the c.g., and the TDAS unit was mounted on the cab of the single-unit truck. The SLICE-2 unit was designated as the primary unit.

6.5.2 Rate Transducers

Two identical angular rate sensor systems mounted inside the body of the SLICE-1 and SLICE-2 event data recorders were used to measure the rates of rotation of the test vehicles. The units were positioned as described in Section 6.5.1. Each SLICE MICRO Triax ARS had a range of 1,500 degrees/sec in each of the three directions (roll, pitch, and yaw) and recorded data at 10,000 Hz to the onboard microprocessors. The raw data measurements were then downloaded, converted to the proper Euler angles for analysis, and plotted. The “SLICEWare” computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the angular rate sensor data.

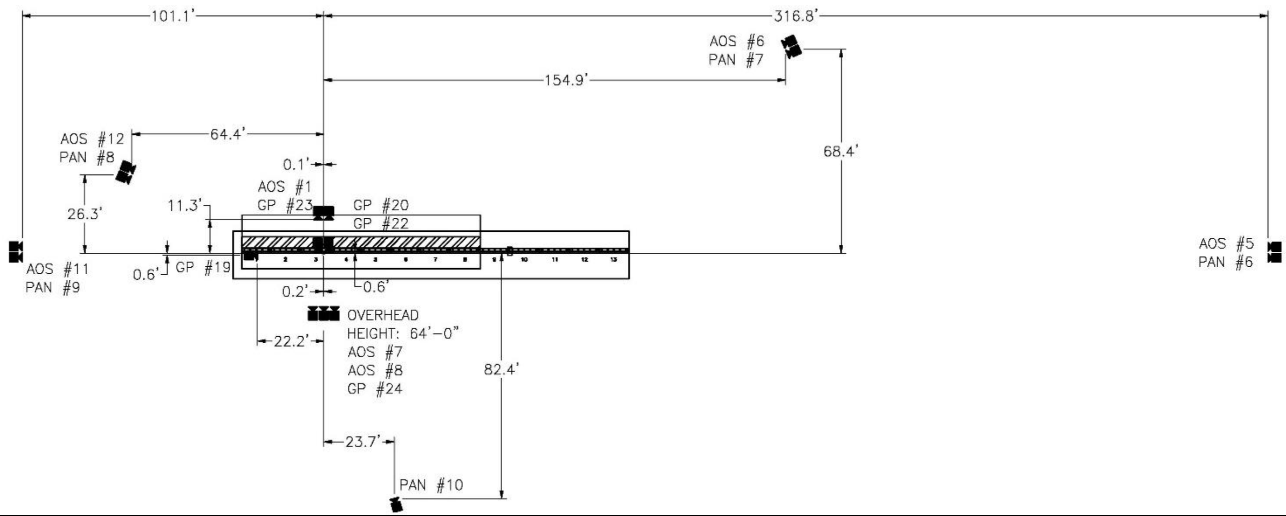
A third angular rate sensor, the ARS-1500, with a range of 1,500 degrees/sec was configured to measure the rates of rotation of the test vehicle in two directions (roll and yaw). The angular rate sensor was mounted on an aluminum block at the rear axle of the single-unit truck and recorded data at 10,000 Hz to the DTS SIM. The raw data measurements were then downloaded, converted to the proper Euler angles for analysis, and plotted. The “DTS TDAS Control” computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the angular rate sensor data. Normally, triaxial rate transducer data is required to determine Euler angles in all three directions (roll, pitch, and yaw). The pitch rate and angle of the vehicle were assumed to be low at the time of peak lateral loading to the bridge railing. Therefore, when determining Euler angles, a pitch rate equal to zero was assumed for the third rotational axis at the rear-axle rate sensor location. Then, the modified Euler angles for all three axes were combined with the accelerations from the two TDAS sets of triaxial accelerometers at the rear axle to determine barrier loading.

6.5.3 Retroreflective Optic Speed Trap

The retroreflective optic speed trap system, designated for determining the pre-impact velocity of the test article, encountered technical malfunctions and failed to capture relevant data. Consequently, high-speed digital video analysis was utilized as an alternative methodology. Frame-by-frame strobe analysis was conducted to accurately determine the initial velocity of the test vehicle before the impact event.

6.5.4 Digital Photography

Seven AOS high-speed digital video cameras, five GoPro digital video cameras, and five Panasonic digital video cameras were utilized to film test no. ABCBRM-1. Camera details, camera operating speeds, lens information, and a schematic of the camera locations relative to the system are shown in Figure 77. Note that cameras AOS-5 and GP-24 experienced technical difficulties and did not record the impact event. The high-speed videos were analyzed using TEMA Motion and Redlake MotionScope software programs. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed videos. A digital still camera was also used to document pre- and post-test conditions for test no. ABCBRM-1.



No.	Type	Operating Speed (frames/sec)	Lens	Lens Setting
AOS-1	AOS X-PRI Gigabit	500	KOWA 8 mm Fixed	-
AOS-5*	AOS X-PRI Gigabit	500	100 mm Fixed	-
AOS-6	AOS X-PRI Gigabit	500	Fuji 50 mm Fixed	-
AOS-7	AOS X-PRI Gigabit	500	Kowa 12 mm Fixed	-
AOS-8	AOS S-VIT 1531	500	Kowa 16 mm Fixed	-
AOS-11	AOS J-PRI	500	Nikon 50 mm Fixed	Midpoint 35-50
AOS-12	AOS J-PRI	500	Nikon 50 mm Fixed	-
GP-19	GoPro Hero 6	120		
GP-20	GoPro Hero 6	120		
GP-22	GoPro Hero 7	120		
GP-23	GoPro Hero 7	120		
GP-24*	GoPro Hero 7	120		
PAN-6	Panasonic HC-VX981	120		
PAN-7	Panasonic HC-VX981	120		
PAN-8	Panasonic HC-VX981	120		
PAN-9	Panasonic HC-VX981	120		
PAN-10	Panasonic HC-VX981	120		

*Camera did not record impact event due to technical difficulties.

Figure 77. Camera Locations, Speeds, and Lens Settings, Test No. ABCBRM-1

6.5.5 Strain Gauges

During the full-scale crash test, axial strains in the inclined anchor bars were measured using linear foil strain gauges. Specifically, Texas Measurements Laboratories (TML) FLAB-5-11-3LJC-F strain gauges were employed, characterized by a gauge length of 0.2 in. and designed for application to steel surfaces. The original installation included 14 strain gauges. However, due to technical complications and/or mechanical damage sustained during the installation phase, only 11 of these gauges remained functional on the day of the experimental evaluation.

Strain gauges were applied to inclined bars in barrier segments 3 and 4, as shown in Figure 78. Eight strain gauges were installed near the deck surface, just above the tapered receiver welded to the bottom edge of the inclined bars. Three additional strain gauges were installed 4 in. above the lower strain gauges.

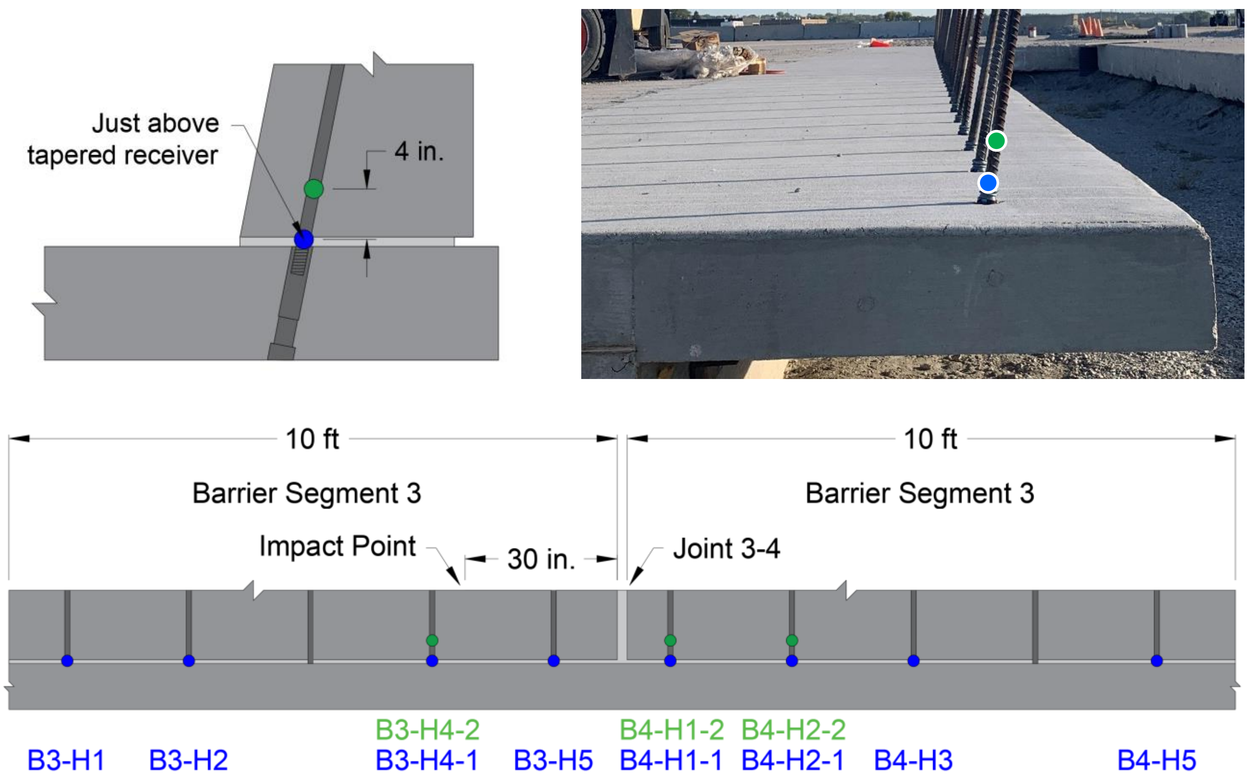


Figure 78. Inclined Bar Strain Gauge Locations

Strain gauges were installed using the methodology and products recommended by Micro-Measurements for application to steel rebar. First, bar ribs were removed, and the resulting flat surfaces were smoothed using a die grinder. Then, 36-grit pads were used to remove bar ribs, 100-grit pads were used to flatten the resulting surface, and 3M 7480 and 7515 pads were used to further smooth the surfaces. The surfaces were then prepared using CSM-5 degreaser, MCA acid conditioner, and MN5A neutralizer. Gauges were applied using Micro-Measurements M-Bond 200 adhesive and catalyst.

Basic moisture protection was provided by applying M-Coat A polyurethane over the adhered strain gauges. A generic system was used to provide mechanical and further moisture protection. First, 3M adhesive pads were placed over the strain gauge and exposed lead wires. Then, the adhesive pads and surrounding areas were wrapped in electrical tape, and the entire regions are sealed with FlexSeal sprayable rubber coating. Application steps for this generic protection system are shown in Figure 79. It should be noted that the photograph in Figure 79 were taken from a different system. However, the procedure used for the system tested herein was identical. A generic protection system was used in lieu of proprietary systems sold by TML and Micro-Measurements due to material unavailability.

(a) 3M adhesive pads (b) Electrical tape (c) Spray-on rubber

Figure 79. Strain Gauge Protection System

Strain gauges were applied to inclined bars before installing the inclined bars into the deck sockets. Gauges were applied and protected using the abovementioned procedure, and their lead wires were coiled around the bar, extending to the top edge. During the barrier installation procedure, lead wires were held to the bar during rotation to mitigate wire damage. After inclined bars were installed, lead wires were passed through sawcut slits at the top of the barrier for protection against the potential sliding of the cargo box along the barrier. These slits were filled with grout prior to testing. Strain data was recorded at 10,000 Hz using a National Instruments Data Acquisition System (DAQ). Results shown herein were passed through a CFC-60 filter.

It should be noted that the research team was unable to allocate resources toward the extensive instrumenting of the bridge rail components for the full-scale crash testing program due to budgetary constraints. Consequently, the instrumentation of the single-slope, precast concrete bridge railing system was limited overall, focusing strain gauge instrumentation toward the 1-in. diameter inclined anchor bars.

7 FULL-SCALE CRASH TEST NO. ABCBRM-1

7.1 Weather Conditions

Test no. ABCBRM-1 was conducted on February 07, 2023 at approximately 02:45 p.m. The weather conditions as reported by the National Oceanic and Atmospheric Administration (station 14939/KLNK) are shown in Table 14.

Table 14. Weather Conditions, Test No. ABCBRM-1

Temperature	51°F
Humidity	35%
Wind Speed	6 mph
Wind Direction	28° from True North
Sky Conditions	Clear
Visibility	10 Statute Miles
Pavement Surface	Dry
Previous 3-Day Precipitation	0 in.
Previous 7-Day Precipitation	0 in.

7.2 Test Description

The full-scale crash test was completed with impact point located 30 in. upstream from the midpoint of the joint between barrier segments 3 and 4, corresponding to the ¾-span location as depicted in Figure 80. The impact location was determined based on the pre-crash test numerical simulation effort discussed in Chapter 2 of this report.

During test no. ABCBRM-1, a SUT weighing 22,200-lb impacted the single-slope. precast bridge railing system. The SUT approached the barrier at a speed of 55.4 mph and at an angle of 14.7 degrees. The barrier effectively contained and redirected the SUT with minimal system deflection and damage.

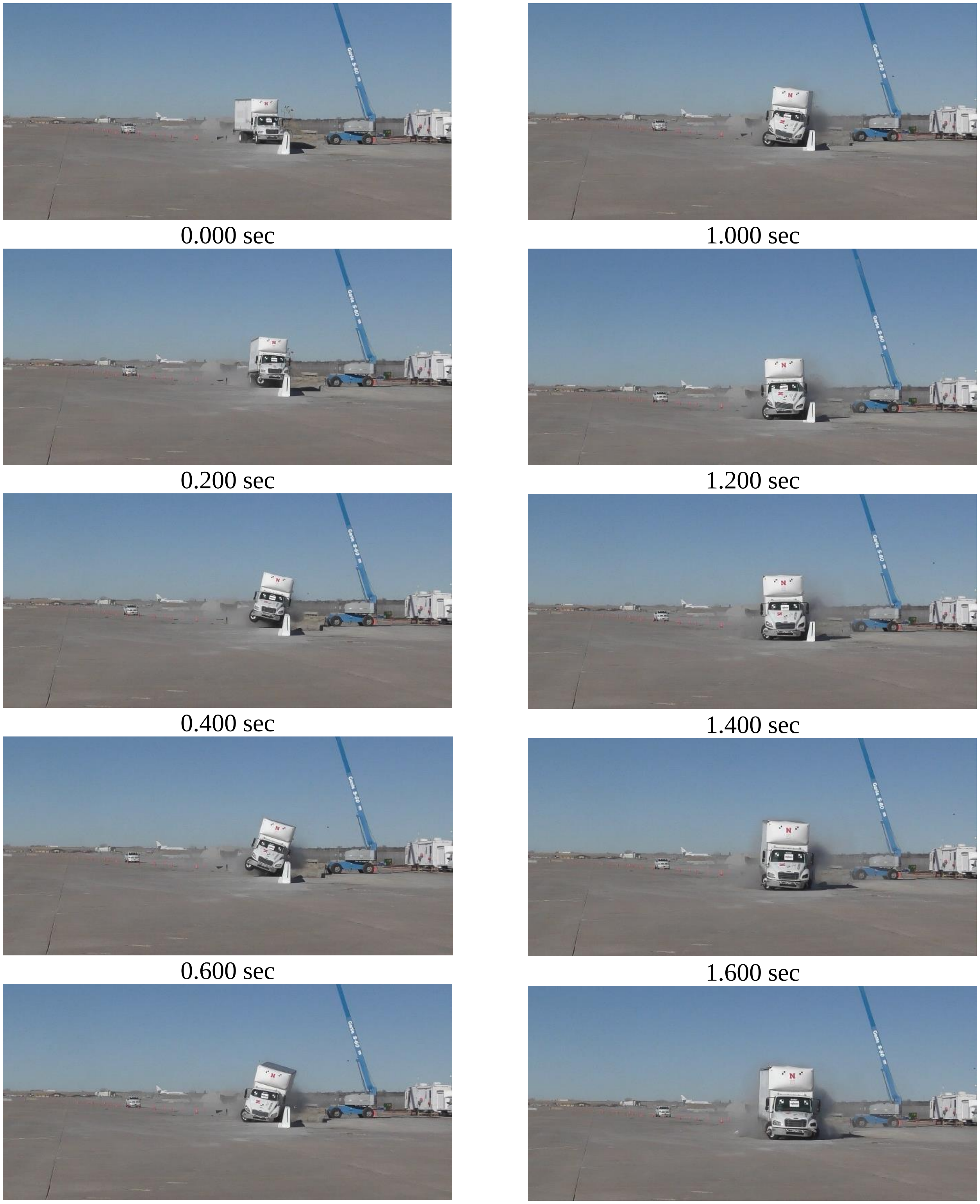
The SUT achieved a maximum roll angle of 18.9 degrees throughout the redirection phase. The SUT's final exit speed was 45.4 mph. Following the vehicle’s exit from the bridge rail, the SUT continued downstream, colliding with a line of portable concrete barriers that were used to protect property and people located behind, rupturing several barrier segments The SUT eventually stopped atop one of the barrier segments, approximately 279 ft downstream from the initial point of impact.

A sequential description of the impact events is provided in Table 15. Sequential photographs capturing the progressive stages of the impact event can be viewed in Figures 81 through 85. Documentary photographs offering supplementary perspectives of the crash test are presented in Figures 86 and 87. Additionally, photographs illustrating the vehicle's trajectory and its final post-impact position are available in Figure 88.

Figure 80. Target Impact Location, Test No. ABCBRM-1

Table 15. Sequential Description of Impact Events, Test No. ABCBRM-1

Time (sec)	Event
0.000	Vehicle's front bumper and left-front tire contacted barrier and deformed.
0.016	Vehicle's hood contacted barrier and deformed.
0.026	Vehicle's left headlight contacted barrier and detached. Vehicle's left fender deformed.
0.038	Vehicle's grille contacted barrier and detached.
0.048	Vehicle's left-front tire deformed rearward into the fuel tank, steps, and left door causing them to deform. Vehicle yawed away from barrier.
0.058	Vehicle's left-front fender contacted barrier. Vehicle's left door deformed.
0.106	Vehicle's left-front tire deflated.
0.134	Vehicle rolled toward the barrier.
0.150	Vehicle's right-front tire became airborne.
0.233	Vehicle's right-rear tire became airborne.
0.304	Vehicle's left-rear tire contacted barrier.
0.328	Vehicle's left-rear corner of box contacted barrier.
0.344	Vehicle became parallel to system at a speed of 53.5 mph.
0.678	Vehicle rolled away from the barrier.
0.733	Vehicle's right-front tire contacted the ground.
0.822	Vehicle exited system at a speed of 45.4 mph.
0.988	Vehicle's right-rear tire contacted the ground.
1.242	Vehicle came to rest.



0.000 sec

0.200 sec

0.400 sec

0.600 sec

0.800 sec

1.000 sec

1.200 sec

1.400 sec

1.600 sec

1.800 sec

Figure 81. Sequential Photographs, Test No. ABCBRM-1

0.000 sec | 1.000 sec
0.200 sec | 1.200 sec
0.400 sec | 1.400 sec
0.600 sec | 1.600 sec
0.800 sec | 1.800 sec

Figure 82. Sequential Photographs, Test No. ABCBRM-1, Cont.


0.000 sec


0.200 sec


0.400 sec


0.600 sec


0.800 sec


1.000 sec


1.200 sec


1.400 sec


1.600 sec

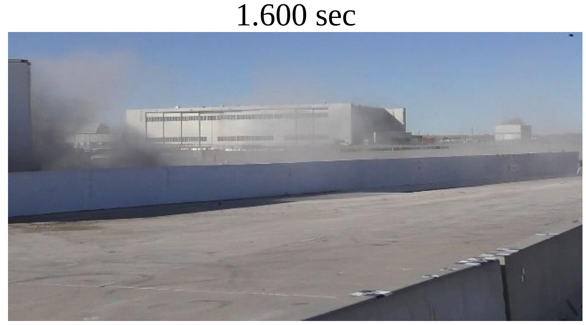

1.800 sec

Figure 83. Sequential Photographs, Test No. ABCBRM-1, Cont.

0.000 sec 0.000 sec

0.200 sec 0.020 sec

0.400 sec 0.040 sec

0.600 sec 0.060 sec

0.800 sec 0.080 sec

Figure 84. Sequential Photographs, Test No. ABCBRM-1, Cont.

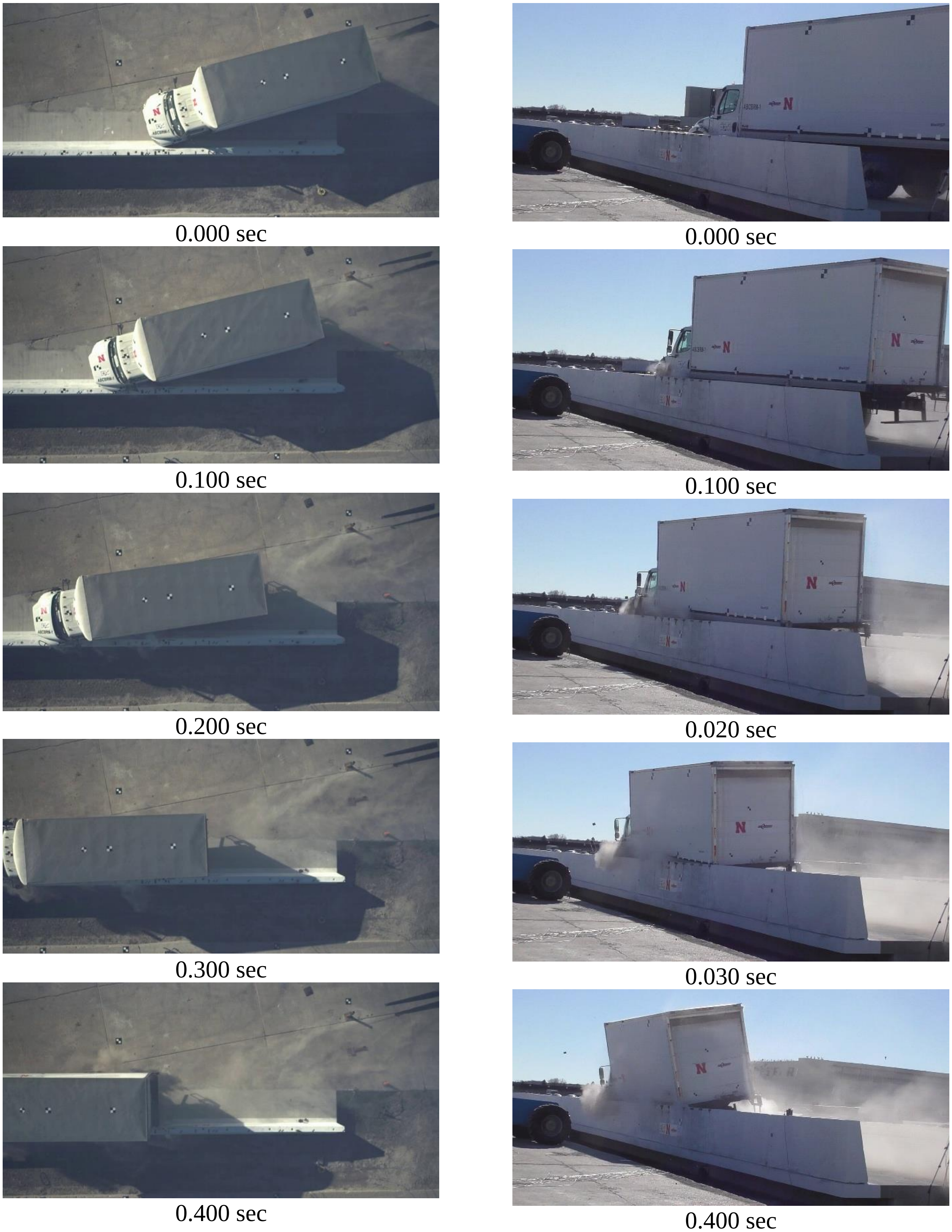


Figure 85. Sequential Photographs, Test No. ABCBRM-1, Cont.

Figure 86. Documentary Photographs, Test No. ABCBRM-1

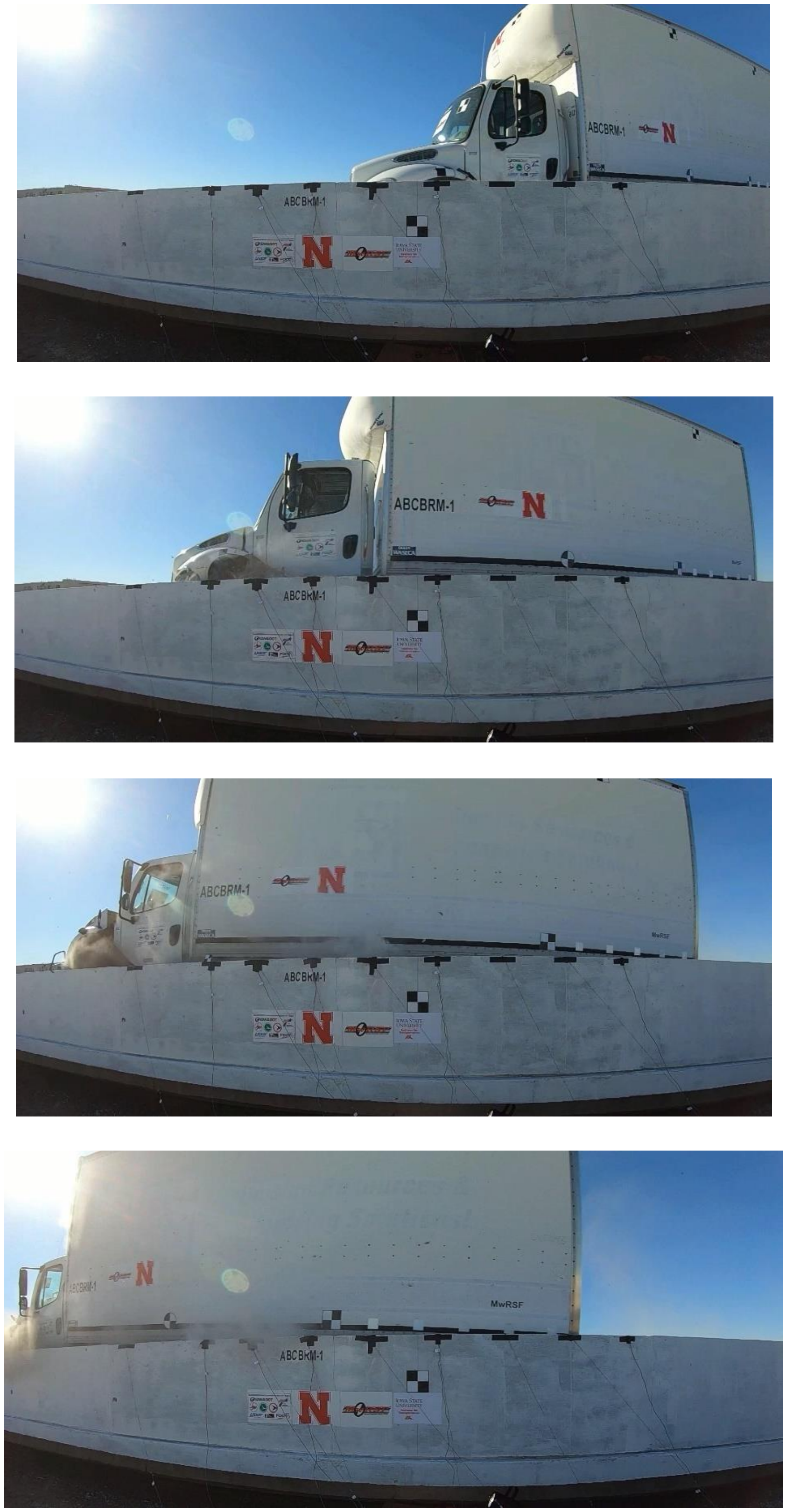


Figure 87. Documentary Photographs, Test No. ABCBRM-1, Cont.

Figure 88. Vehicle Final Position and Trajectory Marks, Test No. ABCBRM-1

7.3 Barrier Damage

Damage to the barrier was minimal, as documented in Figures 89 through 93. The extent of damage encompassed contact marks, minor gouges in the concrete, and superficial cracking. Hairline cracks were identified on the backside of the bridge railing. These cracks are depicted in Figure 92, where they have been accentuated with a marker to enhance visibility. Accordingly, such hairline cracks should not be construed as indicative of substantial barrier damage. The vehicle made contact with the barrier over a length of approximately 102 ft.

7.3.1 Contact Marks

The primary contact mark, visible on the bridge rail's front face, initiated at the point of impact and extended 43 ft downstream. Another substantial contact mark was observed on the top face of the barrier, commencing 46 ft – ¼ in. downstream from the centerline of the joint between barrier segments 4 and 5, and spanned a length of 10 ft. This contact coincided with the cargo box leaning on the barrier. Further significant contact was found on the traffic face of the barrier, starting 18 in. downstream from the centerline of the joint between barrier segments 11 and 12, spanning a length of 18 ft – 7 in. Additional contact marks of less severity were noted on the front face of the barrier (6 in. above ground), starting 16 in. downstream from the centerline of the joint between barrier segments 9 and 10 and extending over a span of 2 ft.

7.3.2 Concrete Gouges

Incidents of concrete gouging were predominantly found on the front face of the bridge rail and the top front edge of the railing, with a series of specific occurrences recorded at various distances from the centerline of the joint between barrier nos. 2 and 3, 3 and 4, and 4 and 5. The bridge deck remained intact throughout the impact event.

7.3.3 Lateral Dynamic Barrier Deflection

The maximum lateral dynamic barrier deflection, including deck flexure, was measured to be 2.3 in. This deformation occurred 7 ft – 6 in. (i.e., mid-span of barrier no. 3) downstream from the point of impact, as determined via high-speed digital video analysis. Post-impact, both the deck overhang and the barrier reverted back to their original positions, indicating a permanent set of 0.6 in. The working width of the system ascertained through high-speed digital video analysis, was determined to be 40.5 in. A schematic detailing the permanent set, dynamic deflection, and working width can be referred to in Figure 94.

Figure 89. Overall System Damage, Test No. ABCBRM-1

Figure 90. System Damage, Downstream Gouge Details, Test No. ABCBRM-1

Figure 91. System Damage, Barrier Segment Nos. 2 and 3, Test No. ABCBRM-1

Figure 92. System Damage, Backside of Bridge Rail, Test No. ABCBRM-1

Figure 93. Deck Damage, Test No. ABCBRM-1

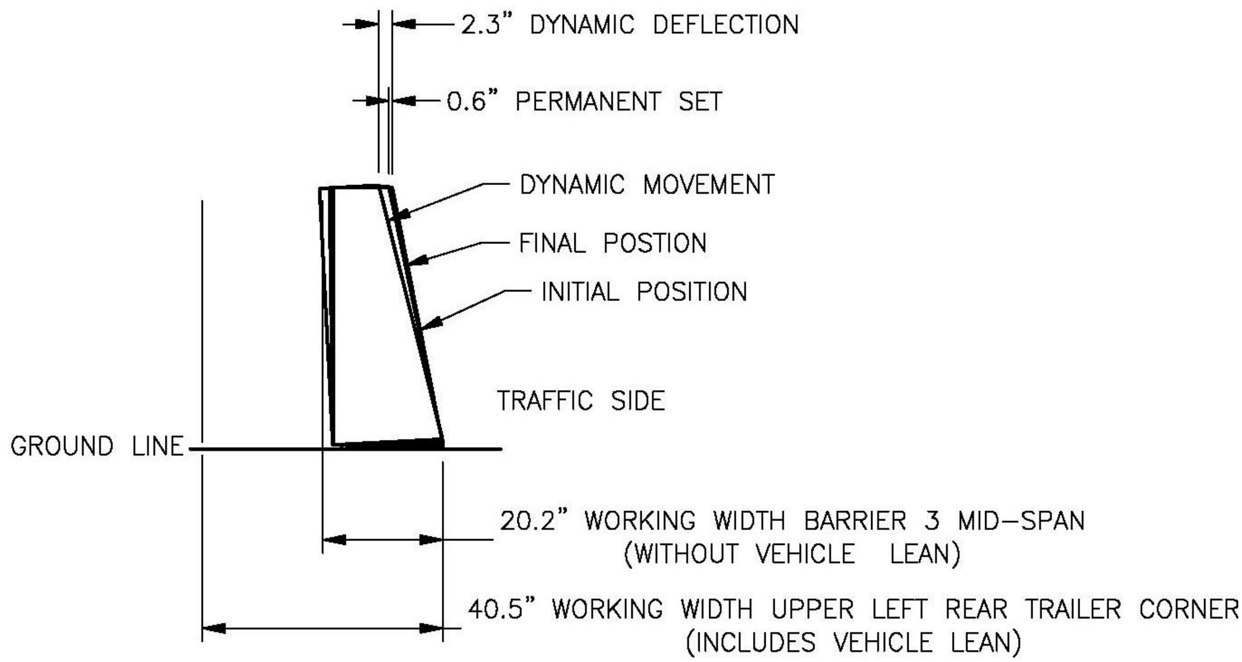


Figure 94. Permanent Set, Dynamic Deflection, and Working Width, Test No. ABCBRM-1

7.4 Vehicle Damage

7.4.1 Overview

Test no. ABCBRM-1 presented the test vehicle with two distinct impact sequences: (1) a primary impact with the precast concrete bridge railing and (2) a subsequent, more severe impact event with portable concrete barriers (PCBs) arranged to contain the vehicle after its exit from the primary system. The majority of the vehicle damage was a result of this secondary impact sequence. It is crucial to distinguish the damages sustained during each impact sequence, as the secondary impact damage does not contribute to the safety performance evaluation of the precast concrete bridge railing system.

7.4.2 Primary Impact Damage

The primary collision with the precast concrete bridge railing system caused relatively minor damage to the vehicle, predominantly localized to the left-front corner. Deformation and inward indentation characterized the left side of the front bumper. The left fender experienced an upward push and an inward dent. Deformations and gouging were evident on the left-front and left-rear wheel assemblies, including each wheel's steel rim. The rear bumper on the left side showed dents and scuffing. Further, the right-side box door dislodged from its hinges. Figure 95 depicts the damages inflicted on the vehicle during the primary impact with the bridge rail system, showing that the vehicle was able to continue rolling downstream on all wheels.

Figure 95. Vehicle Damage after Primary Impact

7.4.3 Secondary Impact Damage

A subsequent, severe collision with a PCB installation resulted in extensive damages, which included but not limited to dislodged and cracked components at the front of the vehicle and on the left side of the cab, a backward-crushed bottom leading edge of the door, rearward crashed fuel tank, and a tire forced rearward into the fuel tank and door. A comprehensive breakdown of damage, including the suspension, chassis, and undercarriage, is presented in Figures 96 through 98.

However, despite the extent of the secondary impact damage, it is important to note that the damage inflicted during the primary impact with the precast concrete bridge rail system was relatively minimal.

7.4.4 Occupant Compartment Intrusion

Table 16 lists the maximum occupant compartment intrusions alongside the intrusion limits defined by MASH [3] for various areas within the occupant compartment. The complete set of occupant compartment and vehicle deformations and their respective locations are provided in Appendix H. According to MASH, intrusion or deformation is described as a reduction in size and deformation of the occupant compartment with no observed penetration.

The floor pan deformation and seam opening near the left-front corner of the floor pan, illustrated in Figure 99, were sustained during the secondary impact as the front axle and wheel were driven backward and under the occupant compartment. As such, this deformation was not included in the safety evaluation of the precast bridge railing system. Thus, in test no. ABCBRM-1, none of the deformation limits set by MASH were exceeded. Outward deformations, represented by negative values in Table 16, do not account for crush toward the occupant and are thus not evaluated by MASH criteria.

Figure 96. Vehicle Damage, Test No. ABCBRM-1

Figure 97. Vehicle Damage – Front End, Test No. ABCBRM-1

Figure 98. Vehicle Damage – Rear, Test No. ABCBRM-1

Figure 99. Post-Test Floor Pan Photos, Test No. ABCBRM-1

Table 16. Maximum Occupant Compartment Intrusion by Location, Test No. ABCBRM-1

Location	Maximum Intrusion in.	MASH 2016 Allowable Intrusion in.
Wheel Well & Toe Pan	5.8	≤ 9
Floor Pan & Transmission Tunnel	2.1	≤ 12
A-Pillar	0.8	≤ 5
A-Pillar (Lateral)	0.0*	≤ 3
B-Pillar	0.7	≤ 5
B-Pillar (Lateral)	0.0*	≤ 3
Side Front Panel (in Front of A-Pillar)	0.0*	≤ 12
Side Door (Above Seat)	0.0*	≤ 9
Side Door (Below Seat)	0.0*	≤ 12
Roof	0.0*	≤ 4
Windshield	0.0	≤ 3
Side Window	Intact	No shattering resulting from contact with structural member of test article
Dash	1.0	N/A

N/A – No MASH criteria exist for this location.
*Negative value reported as 0.0. See Appendix H for further information.

7.5 Occupant Risk

Table 17 displays the computed occupant impact velocities (OIVs), the peak 0.010-second average occupant ridedown accelerations (ORAs) in both the longitudinal and lateral directions, and the maximum Euler angles. Although MASH does not set precise limits for OIVs, ORAs, or angular displacements, they were included herein for benchmarking and future historical reference. Furthermore, additional calculated parameters, such as Total Human Impact Velocity (THIV), Post-Impact Head Deceleration (PHD), and Acceleration Severity Index (ASI) values were determined and presented in Table 17. For detailed time-series data from the accelerometers and rate transducers, refer to Appendix I.

Table 17. Summary of OIV, ORA, THIV, PHD, and ASI Values, Test No. ABCBRM-1

Evaluation Criteria		Transducer			MASH Limits
		SLICE-1 (at rear axle)	SLICE-2 (at c.g.,) primary	TDAS (at cab)	
OIV ft/s	Longitudinal	-4.82	-10.73	-3.31	not required
	Lateral	21.19	10.04	13.45	not required
ORA g's	Longitudinal	-3.85	-6.69	-6.42	not required
	Lateral	31.38	20.83	6.20	not required
Maximum Angular Displacement deg.	Roll	-18.94	-11.46	-14.10	not required
	Pitch	5.10	-6.57	4.65	not required
	Yaw	20.07	13.36*	18.93	not required
THIV – ft/s		29.07	11.32	14.24	not required
PHD – g's		39.79	24.90	6.69	not required
ASI		2.13	0.86	0.96	not required

*The accuracy of the maximum yaw angle might be compromised. Researchers are exploring alternative methods to ascertain this value.

7.6 Barrier Impact Loads

The vehicle's longitudinal and lateral accelerations, recorded at the vehicle's center of gravity (c.g.), were processed via an SAE CFC-60 filter, in conjunction with a 50-millisecond moving average. These processed accelerations, combined with the isolated yaw angle versus time data, were utilized to estimate the vehicular loading exerted on the barrier system. From this data processing, the perpendicular impact forces acting upon the precast concrete bridge railing were determined and are graphically represented in Figure 100.

The SLICE-2 (primary) unit measured a maximum perpendicular (or lateral) impact load of 160.3 kips, applied to the barrier at 0.341 seconds post-impact. A peak frictional load of 55.4 kips was noted at 0.304 seconds after impact. Notably, these recorded impact loads were higher than those typically observed in previous MASH TL-4 crash tests into deformable bridge rails, which often ranged from 95 to 110 kips [29-34]. However, MwRSF researchers recently developed a 36-in. tall, MASH TL-4 optimized near-vertical, concrete bridge rail for the Midwest Pooled Fund Program, suited for an 8-in. thick reinforced concrete deck. That test demonstrated a maximum lateral impact load of 153 kips on the barrier, 0.275 seconds post-impact, as recorded by the SLICE-2 unit [33].

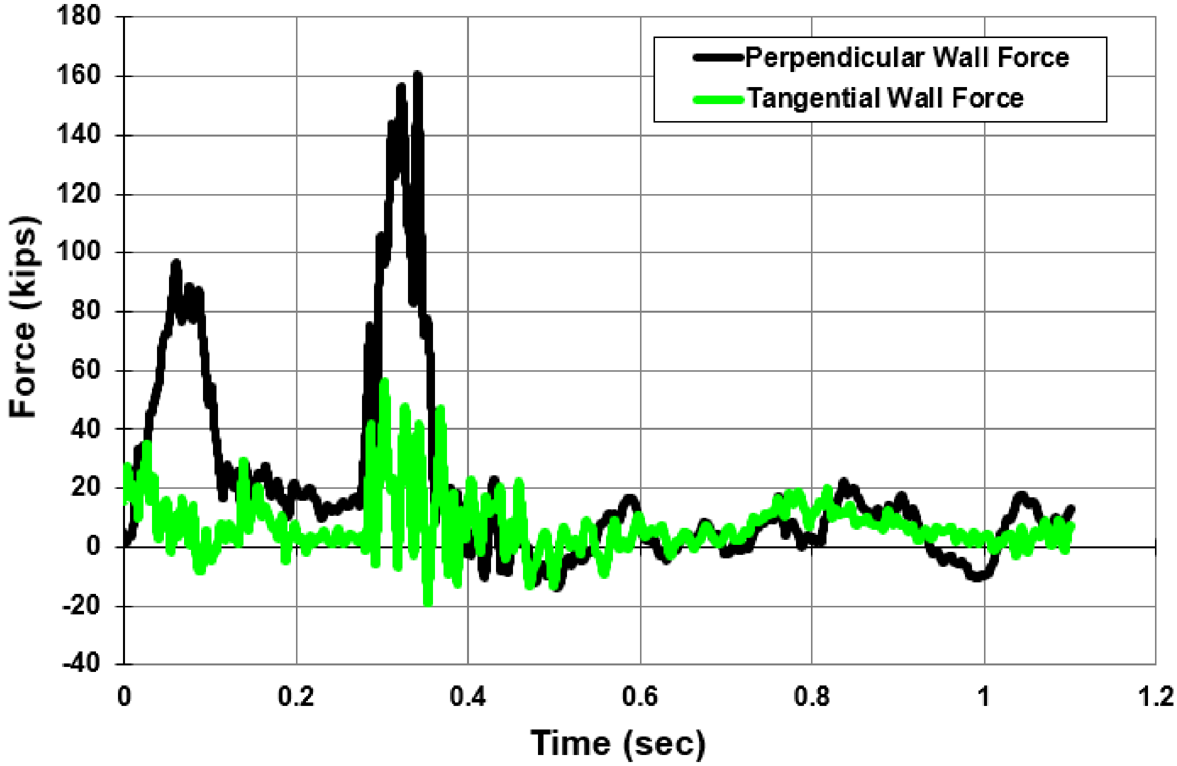


Figure 100. Perpendicular and Tangential Impact Forces, Test No. ABCBRM-1

7.7 Strain Gauge Data

Inclined bar strains were recorded during the crash test and are shown in Figure 101. Strain gauge identifiers correspond to the barrier and bar number on which the gauge was installed – the first number indicates the barrier segment (BX), and the second number indicates the bar hole number (HX). Bar numbers begin at 1 on the US side of each barrier segment. The third number indicates the vertical position of the strain gauge – gauges with no third label, or labeled with a 1, were near the deck surface, just above tapered bar receivers, and gauges labeled with a 2 were 4 in. above the deck surface. Detailed strain gauge locations are shown in Figure 78.

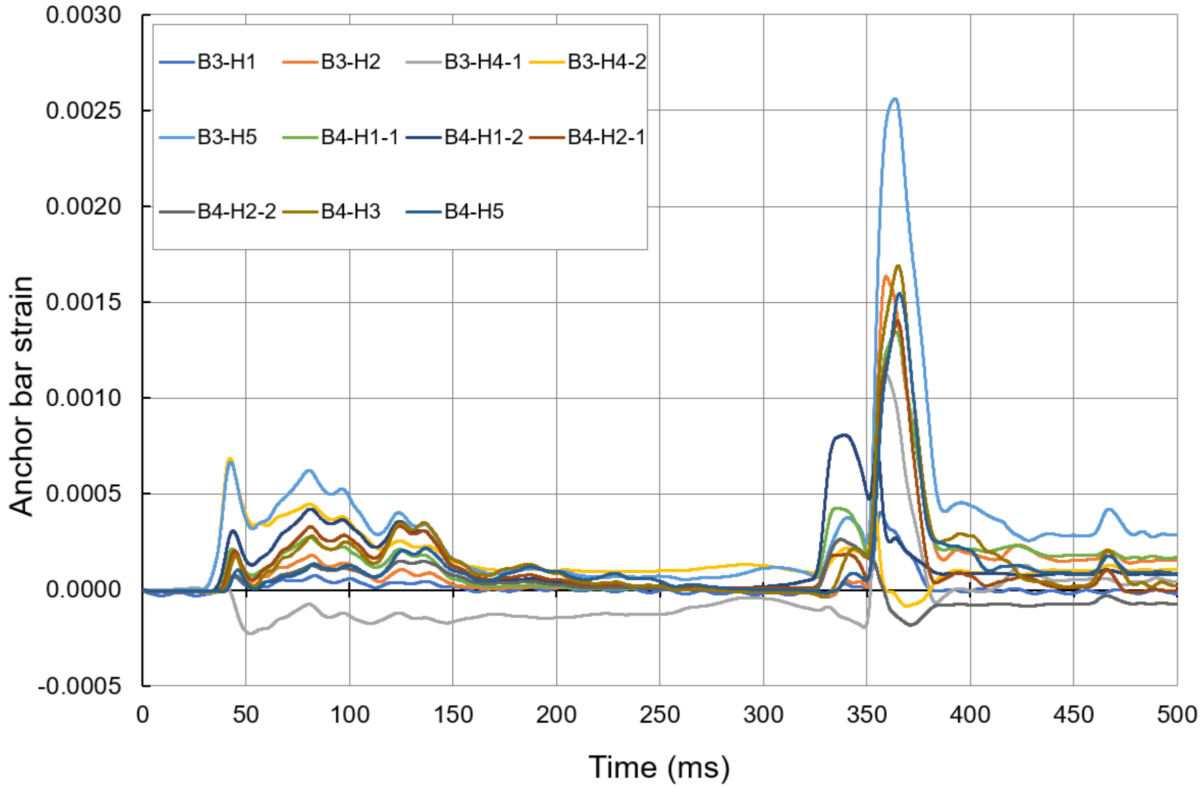


Figure 101. Inclined anchor bar strain gauge measurement history

Strains measured during the initial portion of the impact event, in which the cab impacted the barrier, were minor. The peak strain measured during this phase was 665 με. Strains developed during the tail slap portion of the impact event were significantly more severe, with a peak strain of 2,561 με measured during this phase. Longitudinal distributions of inclined bar strains at the times of peak cab impact and tail slap loading, which occurred 43 ms and 364 ms after first contact, are shown in Figures 102 and 103, respectively. As shown, the peak strain of 2,561 με was measured at the deck surface in the anchor bar just upstream of expansion joints 3-4.

The as-tested inclined bar yield stress, as indicated by mill certifications, was 87.3 ksi. Assuming an elastic modulus of 29,000 ksi, the as-tested yield strain was 3,010 με. Therefore, the strain gauge data collected during the crash test suggests that none of the inclined bars were strained beyond their yield point. This result is consistent with the minimal lateral deflection measured during the test, as well as the minor concrete damage observed after the test, which was superficial and limited to hairline cracking.

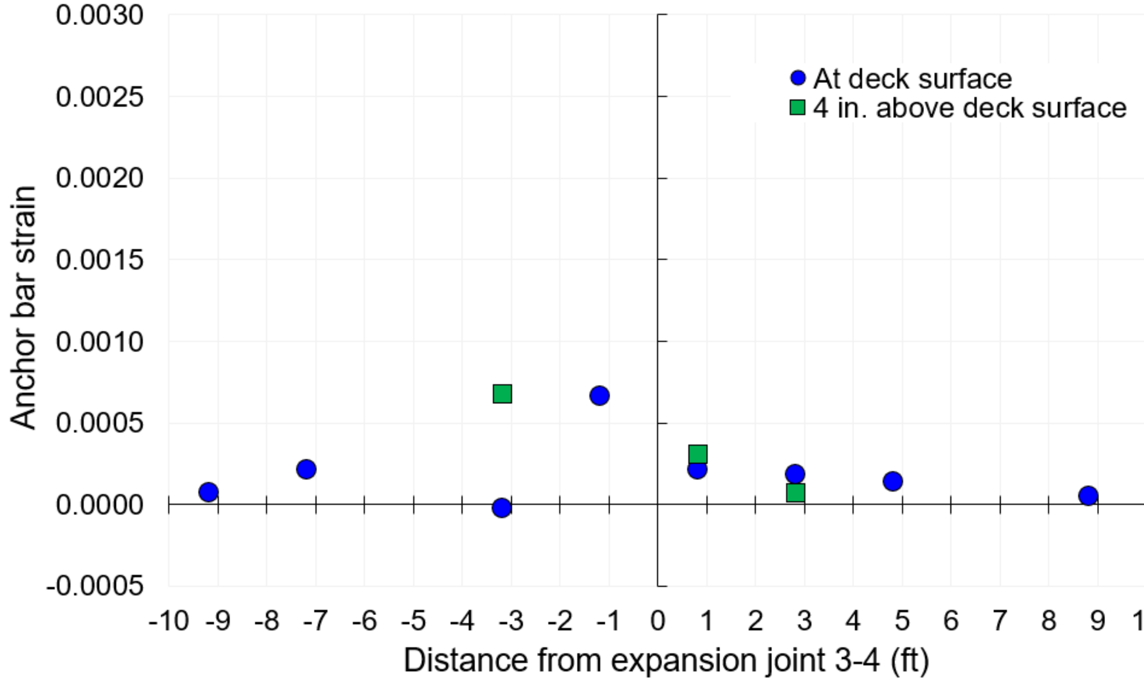


Figure 102. Inclined Anchor Bar Strains at Peak Cab Impact Load (43 ms)

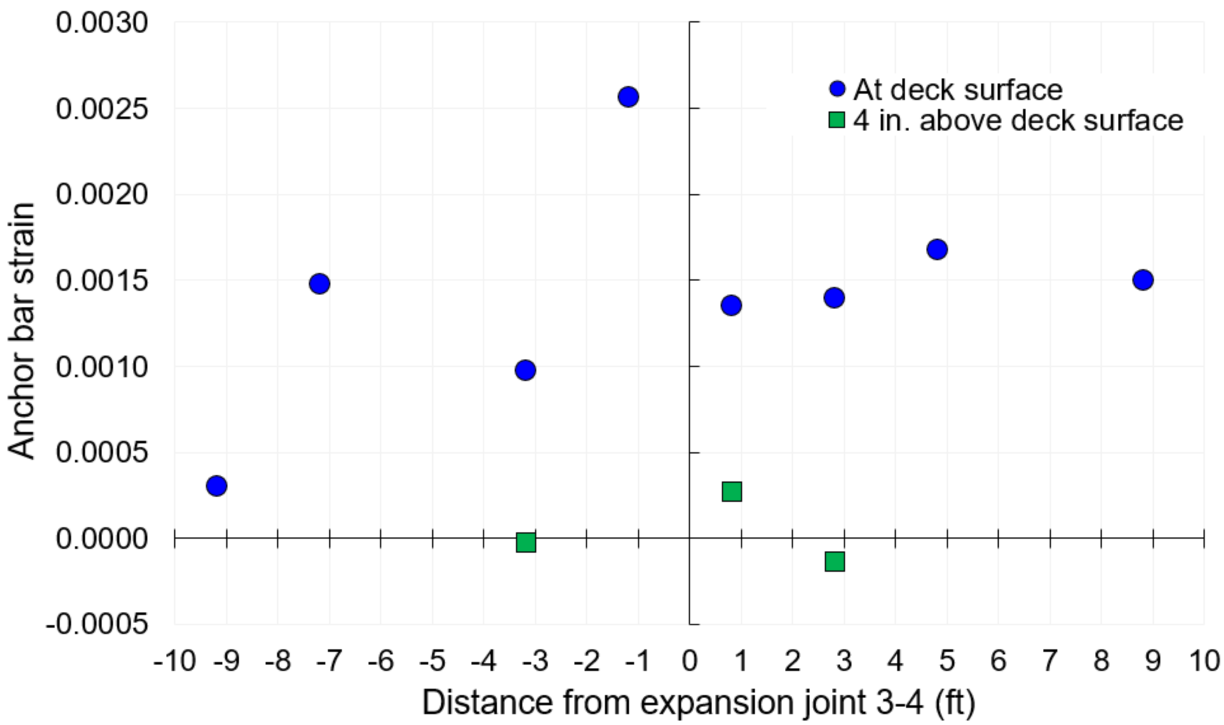


Figure 103. Inclined Anchor Bar Strains at Peak Tail Slap Load (364 ms)

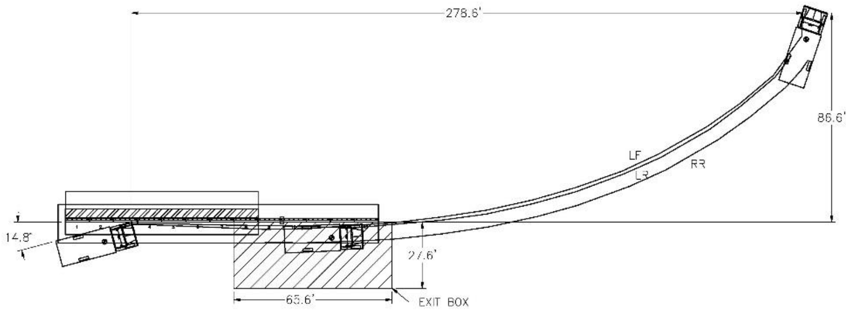
7.8 Discussion

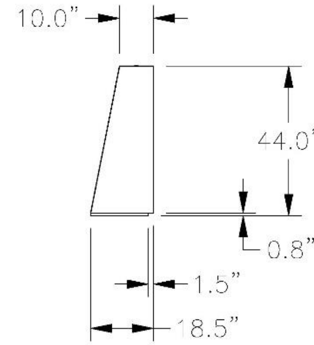
Figure 104 provides a comprehensive summary of the test results along with sequential photographs of the impact event. Test no. ABCBRM-1 demonstrated that the bridge railing system effectively contained and redirected the 10000S vehicle, with only minimal lateral displacement of the barrier, minor surface cracking damage and minimal concrete gouges. The vehicle neither penetrated nor overrode the barrier and maintained its upright orientation throughout.

Debris or detached fragments from the test did not penetrate the occupant compartment or pose potential hazards to other traffic, pedestrians, or work-zone personnel. As indicated in Appendix D, the vehicle's roll, pitch, and yaw angular displacements were deemed acceptable as they did not substantially increase occupant risk or induce vehicle rollover. Following the impact event, the vehicle exited the barrier approximately at an angle of 0 degrees, ensuring its trajectory remained within the designated exit box limits.

The vehicle did not exhibit any significant deformation or intrusion into the occupant compartment that could have resulted in severe injuries during the primary crash test within the bridge railing. Therefore, based on the safety performance criteria outlined in MASH for test designation no. 4-12, test no. ABCBRM-1 was determined to be satisfactory.

0.000 sec | 0.100 sec | 0.200 sec | 0.300 sec | 0.400 sec





- Test Agency .... MwRSF
- Test Number ABCBRM-1
- Date 02/07/23
- MASH Test Designation No. 4-12
- Test Article .... MASH TL-4 ABC Precast Concrete Bridge Railing
- Total Length .... 130 ft
- Key Component – Concrete Bridge Rail
  - Length .... 130 ft
  - Height .... 44 in. from top of existing tarmac
  - Shape .... Single slope
  - Width .... 10 in. wide at top and 18½ in. wide at base
  - Deck Thickness .... 9 in.
- Vehicle Make /Model .... 2013 Freightliner M2 single unit truck
  - Curb .... 14,686 lb
  - Test Inertial .... 22,200 lb
  - Gross Static .... 22,200 lb
- Impact Conditions
  - Speed 55.4mph
  - Angle .... 14.7 deg.
  - Impact Location .... 30 in. upstream from centerline of joint b/n barriers nos. 3 and 4
- Impact Severity .... 146.7 kip-ft > 142.1 kip-ft limit from MASH
- Exit Conditions
  - Speed .... 45.4 mph
  - Angle .... 0 deg.
- Exit Box Criterion .... Pass
- Vehicle Stability .... Satisfactory
- Vehicle Stopping Distance .... 278 ft – 7 in.
- Vehicle Damage .... Minimal
  - VDS [35] 11-FL-6
  - CDC [36] 11-FLEW-3
  - Maximum Interior Deformation .... 5.8 in.
- Test Article Damage .... Minimal
- Maximum Test Article Deflections
  - Permanent Set .... 0.6 in.
  - Dynamic .... 2.3 in.
  - Working Width .... 40.5 in.
- Transducer Data

Evaluation Criteria		Transducer			MASH Limit
		SLICE-1 (at rear axle)	SLICE-2 (at c.g.) primary	TDAS (at cab)	
OIV ft/s	Longitudinal	-4.82	-10.73	-3.31	Not required
	Lateral	21.19	10.04	13.45	Not required
ORA g's	Longitudinal	-3.85	-6.69	-6.42	not required
	Lateral	31.38	20.83	6.20	Not required
Maximum Angular Displacement deg.	Roll	-18.94	-11.46	-14.10	Not required
	Pitch	5.10	-6.57	4.65	Not required
	Yaw	20.07	13.36	18.93	Not required
THIV – ft/s		29.07	11.32	14.24	Not required
PHD – g's		39.79	24.90	6.69	Not required
ASI		2.31	0.86	0.96	Not required

Figure 104. Summary of Test Results and Sequential Photographs, Test No. ABCBRM-1

8 POST-CRASH TEST ANALYSIS

8.1 Purpose

In this chapter, experimental results were compared with pre-test computer simulation results. This comparison evaluated the numerical model in predicting the behavior of the crash test. Any similarities or differences between the two were identified and analyzed by comparing the experimental test data with the corresponding simulation results.

8.2 Changed Model Properties

Following the crash test, model parameters were modified to reflect as-tested conditions. These modification included updating the number of inclined reinforcing bars from four to five and the impact conditions (i.e., mass, speed, and angle) as well as the impact location to match the full-scale crash test. In particular, material properties were updated to match the as-tested mechanical properties of the flowable grout, Grade 80 inclined bars, as well as other materials used in the physical test specimen. Following these modifications, the accuracy of the developed FE models was assessed by comparing the simulation results with the corresponding experimental crash test results. Various metrics, such as deformation patterns, load-displacement curves, and other relevant parameters, were analyzed to evaluate the level of agreement between the model and the experimental results, as well as allowed for a thorough understanding of the model's capabilities in replicating the behavior of the barrier under impact. Specifically, the strength of the grout was revised from 4 ksi to 8 ksi. The as-tested properties of the grout were incorporated into the model such that it accurately reflected the behavior and strength of the material as reported during the experimental testing phase. The steel for the inclined bars was increased to 80 ksi but using actual mill certification data.

8.3 Comparison of Model and Physical Test Results

The results obtained from the numerical (i.e., computer simulation) models were compared with the corresponding physical test results across various parameters, including angular displacement, impact forces, and rebar strain measurements. The LS-DYNA models were found to be reasonably accurate as they predicted the angular displacements of the vehicle. Further, the models provided valuable insights into the impact forces experienced by the barrier. In the subsequent sections, the results derived from the numerical analysis are discussed and analyzed. The comparison between the numerical predictions and the actual physical test results yielded additional information regarding the overall performance of the developed barrier system.

8.3.1 Angular Displacements

Figure 105 compared angular displacements of vehicle roll, pitch, and yaw, as obtained from the LS-DYNA numerical simulations and experimental measurements. This comparative analysis aimed to evaluate the degree of similarity between the angular displacement values predicted by the numerical model and those observed in the physical crash test. The numerical results closely resembled the experimental data for the yaw, pitch, and roll behavior, suggesting good agreement between the FE model and the physical test.

8.3.2 Inclined Rebar Strains

Figure 106 compared the processed axial strains observed in the inclined rebars obtained from strain gauge data and numerical simulations. The purpose of this analysis was to evaluate the agreement between the axial strains predicted by the numerical model and those measured in the physical experiment. Figure 106 shows some agreement in the trends, although the numerical model tended to overestimate axial strains during tail slap of the SUT vehicle. This overestimation was primarily due to conservative assumptions made in the model. Despite this overestimation, strain values during tail slap, the model was still able to capture the general behavior and deformations of the barrier system and inclined rebars. However, some caution should be exercised in interpreting the absolute values of the modeled strain results.

8.3.3 Impact Force -Time History

Figure 107 compares the filtered 50-millisecond moving average force values obtained from the physical test and the corresponding simulation. This figure shows the overall agreement between the impact force-time histories predicted by the numerical model and those observed in the experiment. As shown, the impact force versus time history trend remained similar between the numerical and experimental results.

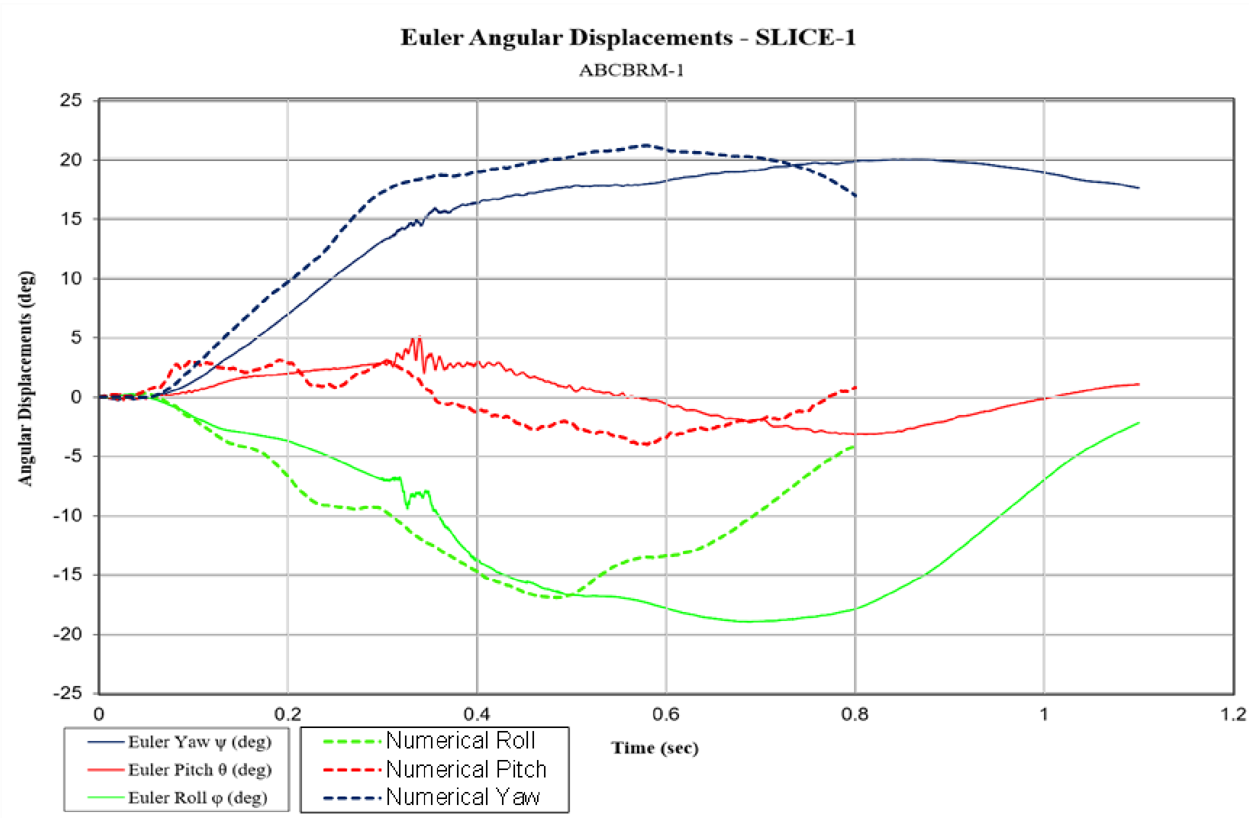
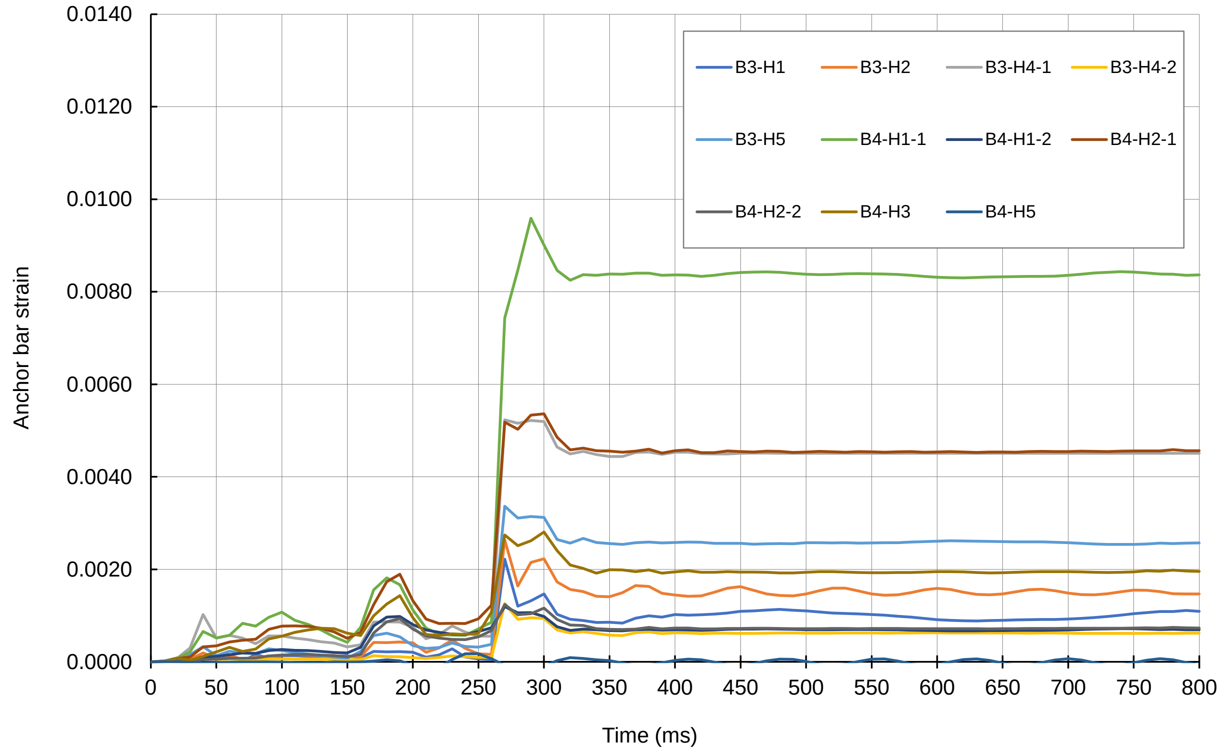
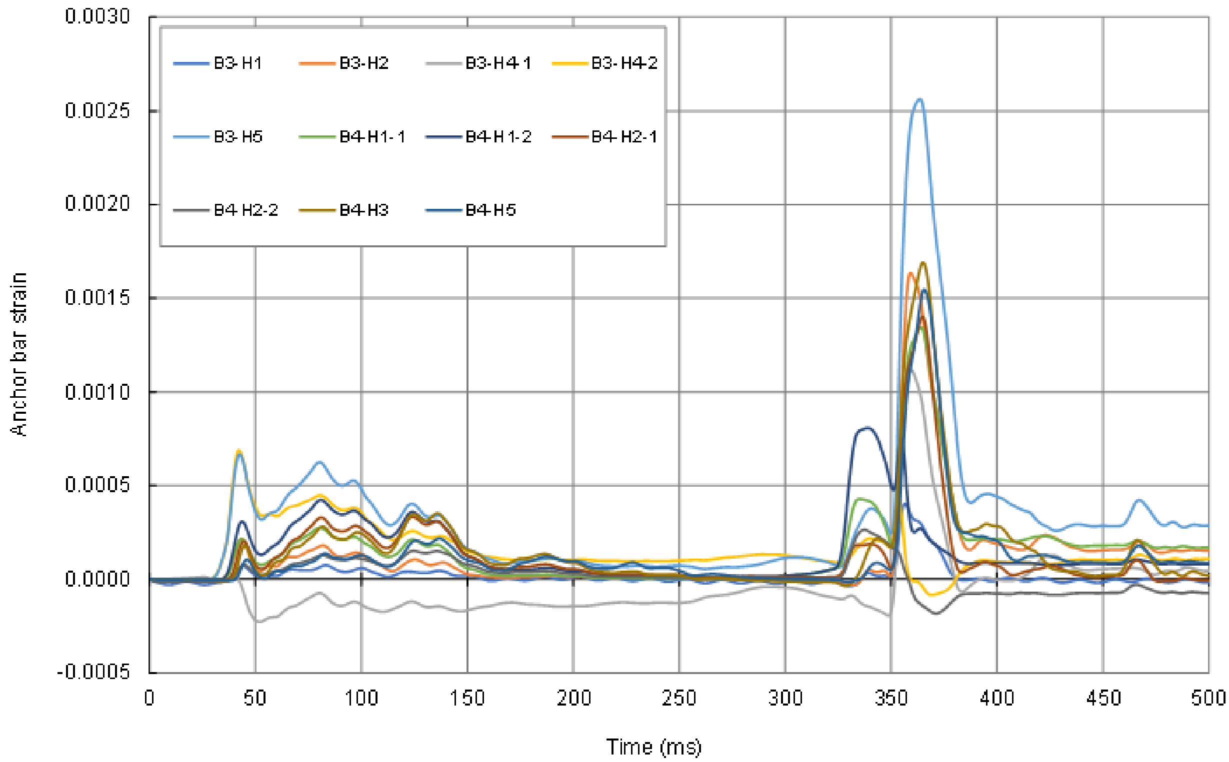


Figure 105. Angular Displacements of the Vehicle from LS-DYNA Simulation and Physical Testing



(a)



(b)

Figure 106. Axial Strains in Inclined Rebars: (a) Numerical Simulation and (b) Full-Scale Crash Test

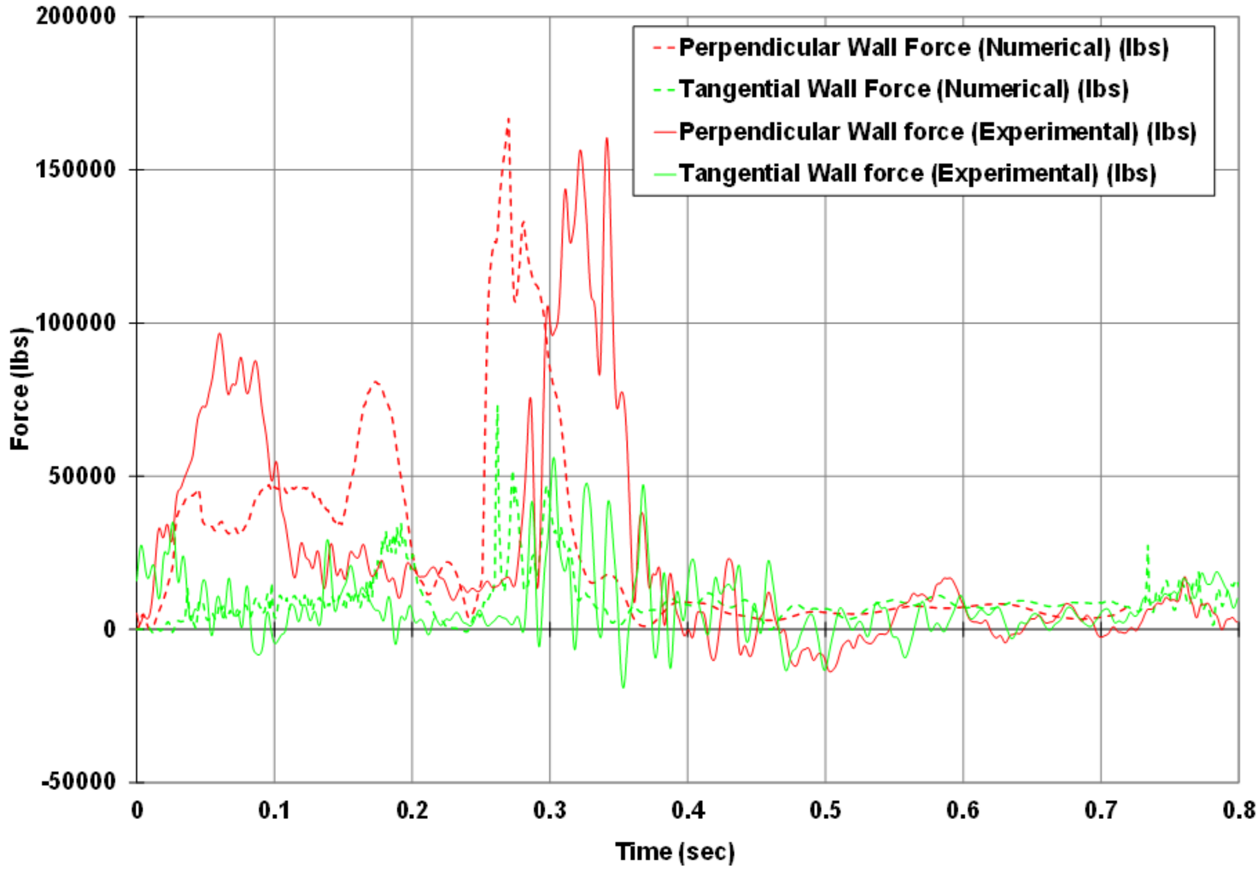


Figure 107. Impact Force-Time Histories

9 SUMMARY AND CONCLUSIONS

Researchers at InTrans-ISU developed a precast concrete bridge railing for ABC applications utilizing special connection details for the barrier-to-deck and barrier-to-barrier connections [1]. A series of quasi-static tests were completed on these new connections at ISU's Structures Testing Laboratory using quasi-static loadings on a prototype barrier supported on a bridge deck overhang. Based on this successful work, researchers later desired to conduct sufficient crash testing in order to verify that the design and connection details would meet or exceed current impact safety requirements. Based on the existing barrier shapes and heights, the primary objectives of this research project were to: (1) conduct pre-crash test analyses; (2) construct a bridge railing and deck system; (3) perform a crash test and evaluation of the selected bridge railing utilizing a 10000S (SUT) at the MASH TL-4 impact conditions; and (4) conduct post-crash test analyses with conclusions and recommendations.

The pre-crash test analyses comprised several activities. First, computer simulations were carried out using the LS-DYNA software to mimic MASH TL-4 impacts into both the single-slope and near-vertical barrier configurations with all three test vehicles, i.e., passenger car (1100C), pickup truck (2270P), and single-unit truck (10000S). These simulations aimed to identify the most critical barrier shape appropriate for the 10000S SUT crash test. Second, the total barrier length that was required for testing and evaluating the new bridge railing system was established, and the CIP was determined for all three vehicle types on both barrier configurations. Next, the barrier system was modified based on insights derived from the simulation results. The near-vertical barrier with five inclined bars had CIP at 2.5 ft upstream of the joint (which corresponded to a ¾-span location), and this CIP was adapted to a single-slope barrier when inclined bars increased from four to five since the crash test would be performed using a 10000S SUT.

One full-scale vehicle crash test, test no. ABCBRM-1, was conducted on the precast bridge rail in accordance with MASH test designation no. 4-12. During the crash test, the 22,200-lb single-unit truck impacted the precast concrete bridge railing system at a speed of 55.4 mph and an angle of 14.7 degrees, thus resulting in an impact severity of 146.7 kip-ft, which is greater than the minimum impact severity of 142.1 kip-ft. The single-unit truck was successfully contained and redirected, and the vehicle exited the system approximately at an angle of 0 degrees. The truck box leaned over the top of the bridge rail to establish a 40.5-in. working width, but the vehicle did not show any propensity for rollover during or after the test. After the crash test, minimal damage in the form of limited concrete gouges and hairline cracks was observed in the bridge rail near the impact region and along the top of the barrier. No damage related to the impact event was found on the top or bottom surfaces of the deck. A summary of the MASH evaluation of the bridge rail is shown in Table 18.

Table 18. Summary of Safety Performance Evaluation

Evaluation Factors	Evaluation Criteria		Test No. ABCBRM-1
Structural Adequacy	A.	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	S
Occupant Risk	D.	1. Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone.	S
		2. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of MASH.	S
	G.	It is preferable, although not essential, that the vehicle remain upright during and after collision.	S
MASH Test Designation No.			4-12
Final Evaluation (Pass or Fail)			Pass

S – Satisfactory U – Unsatisfactory N/A – Not Applicable

In this study, an absence of strain gauges on the transverse steel reinforcement bars within the bridge deck precluded the direct quantification and analysis of strain responses. This omission effectively limited our capacity to elucidate the degree of deck engagement or the specific strain demands imparted by the single-slope, precast concrete bridge railing system. Understanding the deck engagement and reinforcement requirements in bridge railing design is important, especially given the prevalent design standards that often require considerable deck reinforcement over limited lengths.

In response to these identified gaps, considerable scholarly endeavor has been mobilized, exemplified by the initiatives encapsulated in NCHRP Projects 12-119 and 22-41 [37-38]. These projects have focused on synthesizing recent crash testing and analytical studies to inform revisions to the AASHTO LRFD BDS Section 13. An extensive revision of this segment is currently underway, targeting a heightened refinement of design procedures pertaining to deck engagement and reinforcement requisites. Although direct measurements of deck strain were beyond the scope of this study, the anticipated modifications to the LRFD BDS, informed by the collective insights of recent research, are expected to provide crucial guidelines for improving deck engagement and reinforcement strategies in bridge design.

After completing the full-scale vehicle crash test, an updated numerical model was developed based on the test data, and the results obtained from the pre-crash test simulations were verified and validated. The comparison of the performance extracted from pre-crash and post-crash simulations involved the assessment of various parameters, including impact force, element stresses at critical locations, angular displacements, and occupant risk values.

The reasonable agreement between the numerical and experimental results from the post-crash test validated the effectiveness of the numerical modeling approach employed in this project. This agreement confirmed the findings contributing to an understanding of the near-vertical and single-slope barriers' safety performance and structural behavior. Overall, a range of modeling assumptions contributed to the numerical simulation results. While the overall patterns were successfully captured in this project, future research can be conducted to further calibrate the simulation models, improve model accuracy, and expand the numerical investigations.

10 FURTHER CONSIDERATIONS

10.1 Evaluation of Near-Vertical Versus Single-Slope Bridge Railing

In assessing the impact safety performance of precast concrete bridge railings, an analytical comparison was made between a railing system featuring a near-vertical front face and one with a 10.9-degree single-slope front face. The analysis suggested that the near-vertical configuration might be subjected to higher lateral impact forces attributed to its geometry, which limits vehicular climb, thereby applying increased stress on the barrier, connections to the deck and adjacent barriers, and the supporting bridge structure. Despite these concerns, the project's advisory panel elected to prioritize full-scale crash testing of the single-slope barrier configuration, driven by its prevalent adoption among state DOTs.

A full-scale vehicle crash test was conducted on a single-slope bridge railing distinguished by a broader base and extended distance between the rear face and inclined reinforcement bars. The study explored both barriers: a near-vertical barrier with an 18½-in. base width and a single-slope barrier with a 15¾-in. base width, each reinforced with five inclined bars.

The full-scale crash test results for the single-slope barrier with newly developed connections were noteworthy. The system effectively contained and redirected the test vehicle, ensuring its stable exit with all wheels maintaining forward motion. Minimal damage was observed, limited to superficial concrete gouging, hairline cracks, and cosmetic contact marks, while the top and bottom surfaces of the deck remained undamaged. This outcome confirmed the single-slope precast barrier's compliance with the AASHTO MASH test designation no. 4-12, surpassing both anticipated performance and computational predictions.

These results implicitly suggest that the near-vertical design could potentially meet the AASHTO MASH TL-4 impact safety standards in real-world conditions and full-scale crash testing. However, a definitive evaluation of its performance and safety metrics requires direct, full-scale crash testing.

Absent empirical data from such critical full-scale crash testing, the narrower, near-vertical configuration is hypothesized to face increased impact forces, potentially leading to more pronounced damage and marginally compromised safety efficacy. The precise assessment of its crashworthiness and the extent of barrier damage remain speculative until substantiated by targeted full-scale crash tests. Despite these uncertainties, there is optimism that the near-vertical design could satisfy the AASHTO MASH TL-4 impact safety standards.

Given these considerations, the preference leans towards bridge railing systems validated by full-scale crash testing or those that demonstrably offer comparable or superior impact performance. Further research is imperative to conclusively determine the crashworthiness of the near-vertical barrier and its performance under MASH TL-4 impact conditions.

10.2 Constructability Improvements in Single-Slope Bridge Railing System

In enhancing precast concrete bridge railing systems, particularly the single-slope barrier, empirical findings have notably surpassed initial predictions established through LS-DYNA computational modeling. Despite this advancement, the research team adopts a prudential approach regarding modifying structural elements, such as double-headed bars and transverse ties. This cautious perspective will be informed by the ongoing investigations of the NCHRP Project 22-56, titled *Development of Non-proprietary Prefabricated Solutions for Concrete Barrier Systems for Accelerated Bridge Construction* [39], which is expected to yield critical insights into the ramifications of such adjustments on the system's overall impact behavior and performance under vehicular impacts.

The research team has identified several design improvements aimed at refining the constructability of the single-slope, precast concrete bridge railing system without compromising its structural integrity or impacting safety performance. One simple suggestion is to replace the current vertical end-joint with an inclined end-joint. In other words, the end cavity and end double-headed joint would follow the front face inclined vs. the back vertical face. Thus, the precast barrier segments could be installed by lowering the segments onto pre-set inclined reinforcing bars, and the double-headed bars could follow the same path into the inclined cavities, facilitating a more streamlined and efficient installation process by enabling the concurrent placement of barriers and joint components.

Further explorations consider the potential for reducing or altogether omitting transverse tie bars. This approach considers the post-installation of double-headed tie bars, with barrier segments designed to accommodate identical grout-filled cavities at each end. This ensures joint strength and structural continuity through exposed closed rebar ties at the top and end regions. Such a modification presupposes an equivalent or enhanced barrier performance relative to current standards, necessitating rigorous empirical validation of the additional vertical and horizontal steel reinforcement required.

Although minimizing reinforcement elements appears advantageous from a construction standpoint, advocating for a reduction in reinforcement requires a foundation built upon exhaustive empirical evidence and analytical rigor. The anticipated outcomes of the NCHRP 22-56 project stand to significantly inform and guide future recommendations, ensuring that any proposed constructability enhancements do not detract from the safety, performance, and durability of precast concrete bridge railing systems.

11 MASH EVALUATION

The precast concrete bridge rail with newly developed connections was subjected to one full-scale crash test in accordance with MASH test designation no. 4-12. The single-unit truck (SUT) was successfully contained and redirected, and the vehicle exited the system while stable with all four wheels rolling forward. Damage to the system consisted only of limited, easily repairable concrete gouging, hairline cracks, and cosmetic contact marks. The deck remained undamaged during the crash test. Thus, the new ABC, precast, single-slope concrete bridge railing and deck systems satisfied all safety performance criteria for MASH test designation no. 4-12.

A review of previous crash testing into concrete barrier and bridge railing systems along with the computer simulation investigation led to the conclusion that only MASH test designation no. 4-12 was critical for evaluating the TL-4 single-slope, precast concrete bridge railing system. The impact severity of the 10000S SUT test was 34 percent higher than the 2700P pickup test and 278 percent higher than the 1100C small car test. NCHRP Project 22-20(2) found that the increased impact severity translated to increased impact loads for the 10000S SUT compared to the passenger vehicles, as observed in the recommended impact loads for TL-3 and TL-4 MASH impacts [6]. Further, the 10000S SUT crash test imparted the highest lateral impact load to the ABC, single-slope, concrete bridge railing and deck systems and served as the critical test for evaluation for strength, containment, and damage to the components and joint hardware.

Previously, both 11-degree single-slope and vertical-faced concrete bridge railings have been successfully crash tested to both 1100C and 2270P vehicles [20, 23-26]. The 10.9-degree slope of the ABC precast concrete bridge rail ranged between typical single-slope barriers and vertical-face parapets, so vehicle performance had been effectively bracketed by previous crash tests, and there were no concerns for vehicle instability or excessive occupant risk values. Therefore, MASH test designation nos. 4-10 and 4-11 were deemed non-critical. As a result, the single-slope, precast concrete bridge railing with the recommended connections was determined to be crashworthy to MASH TL-4 impact safety standards.

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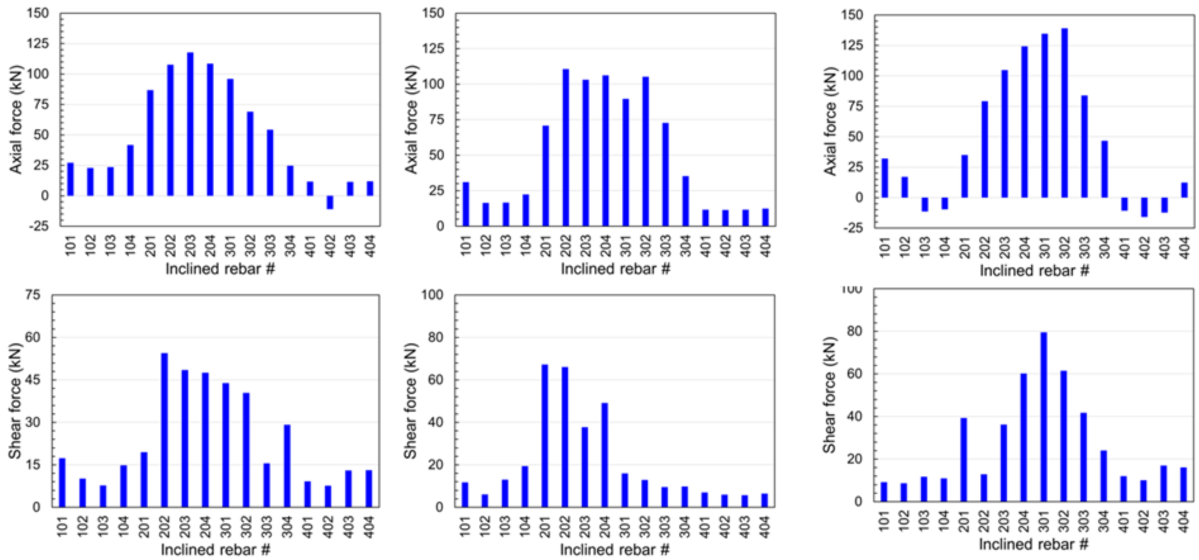
13 APPENDICES

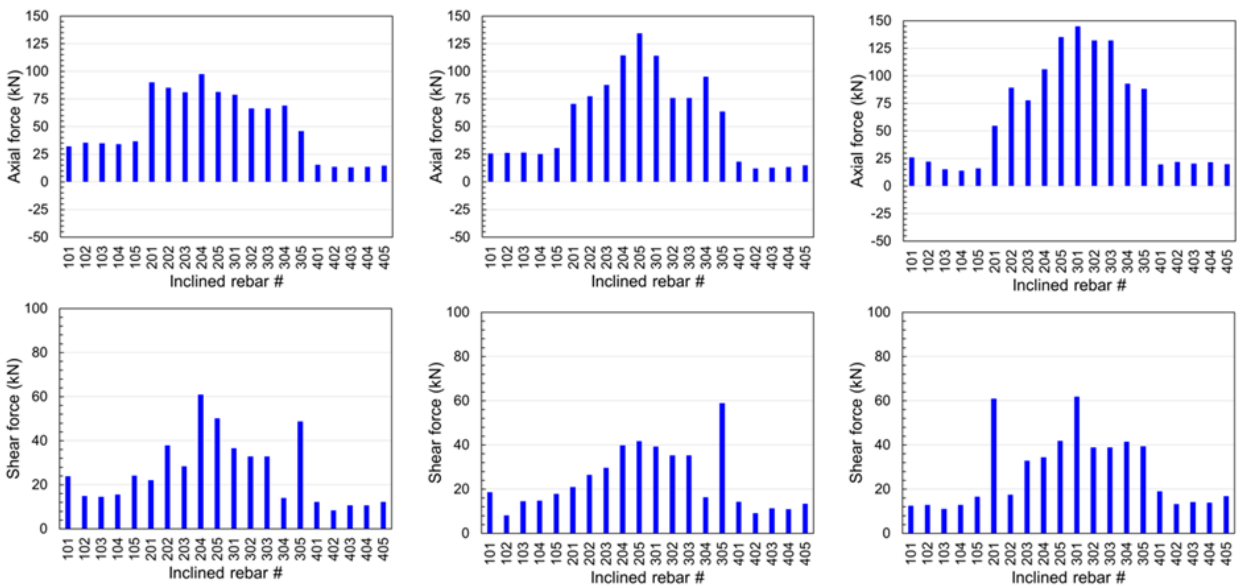
Appendix A. Axial and Shear Forces in Inclined Rebars

The recorded maximum axial and shear forces observed in inclined bars within the single-slope and near-vertical barriers are provided in this appendix. The plots depict the maximum observed forces regardless of time.



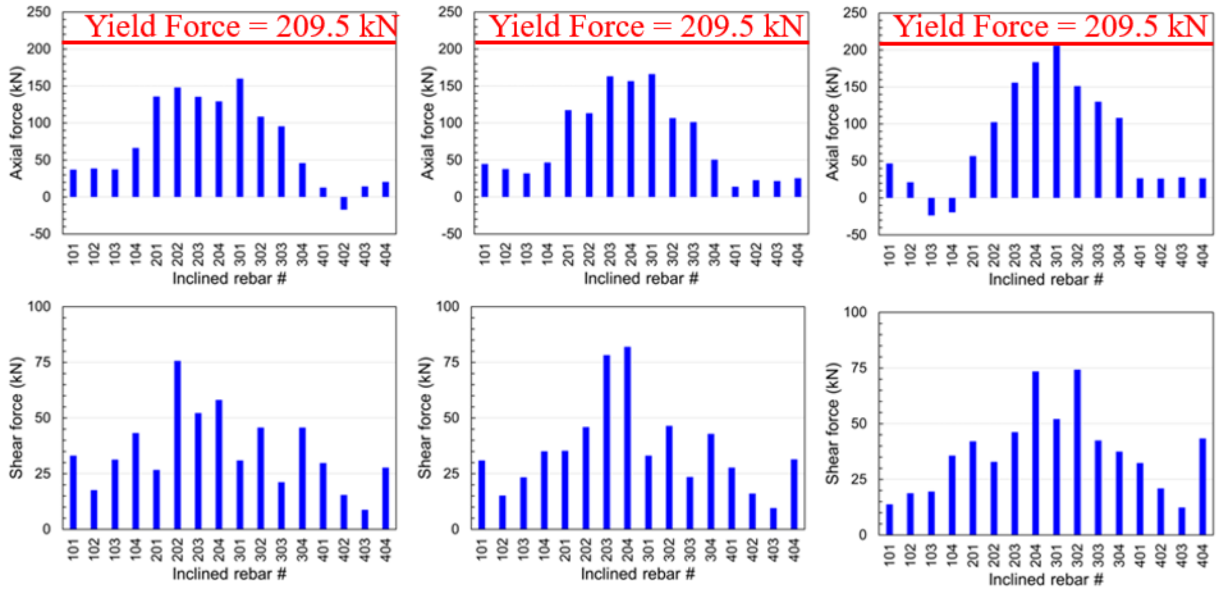
(a) (b) (c)

Figure A-1. Maximum Axial and Shear Forces in Inclined Rebars, 1000C Vehicle Impact with Single-Slope Barrier (SSB): (a) Impact at Mid-Span; (b) Impact at 3.6 ft Upstream of Joint; and (c) Impact at Joint



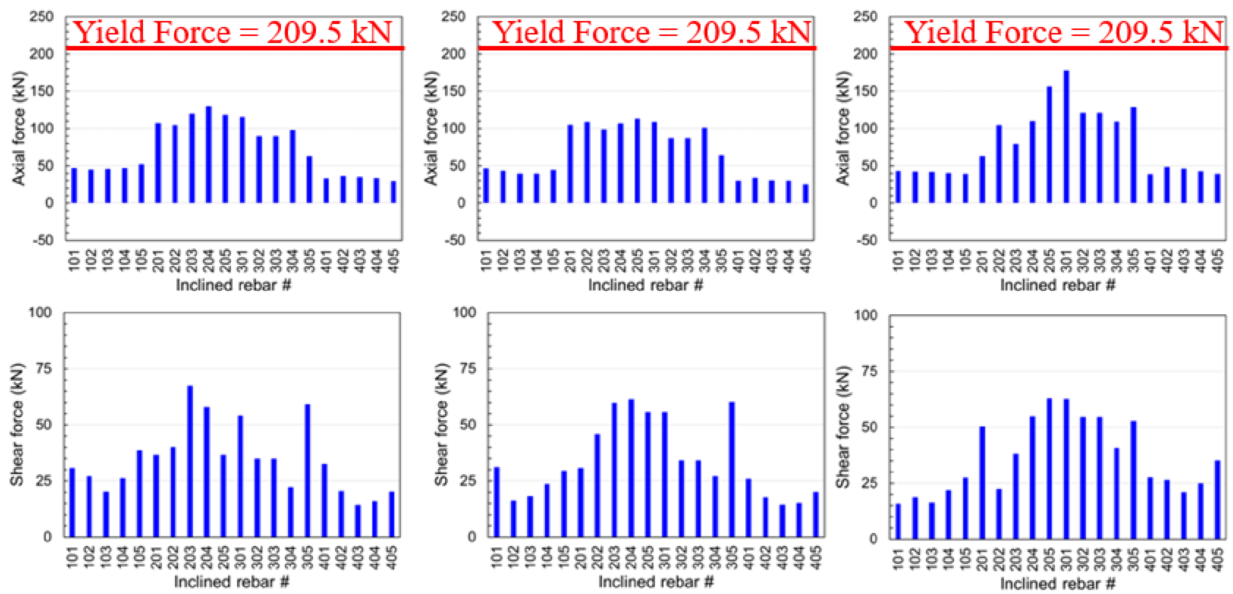
(a) (b) (c)

Figure A-2. Maximum Axial and Shear Forces in Inclined Rebars, 1000C Vehicle Impact with Near-Vertical Barrier (NVB): (a) Impact at Mid-Span; (b) Impact at 3.6 ft Upstream of Joint; and (c) Impact at Joint



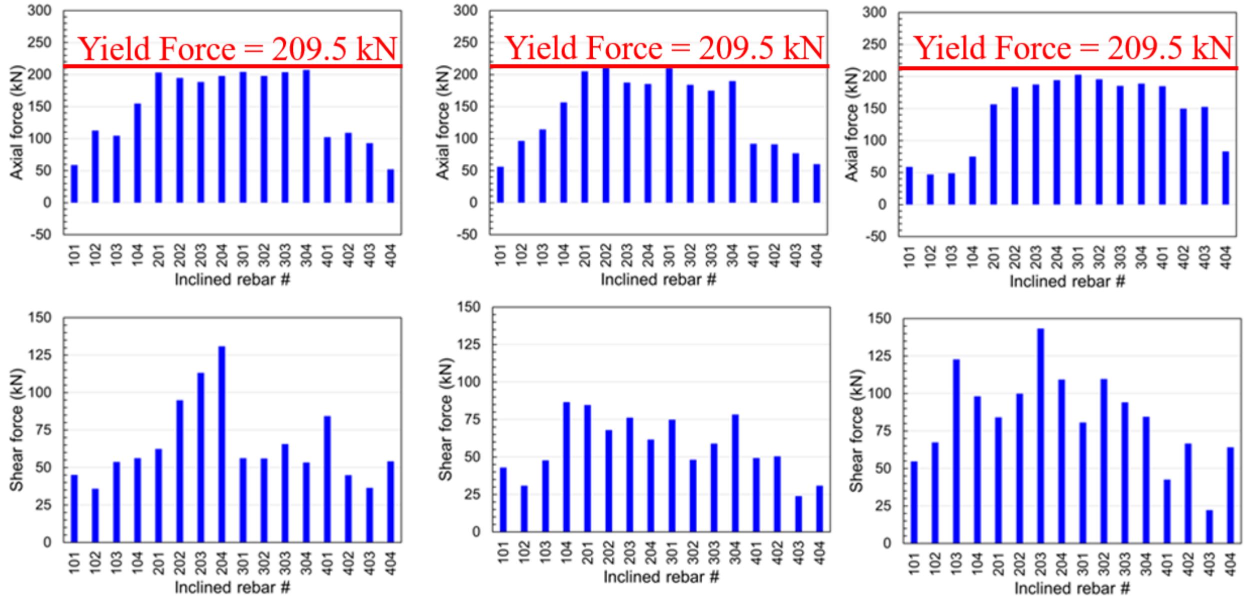
(a) (b) (c)

Figure A-3. Maximum Axial and Shear Forces in Inclined Rebars, 2270P Vehicle Impact with Single-Slope Barrier (SSB): (a) Impact at Mid-Span; (b) Impact at 4.3 ft Upstream of Joint; and (c) Impact at Joint



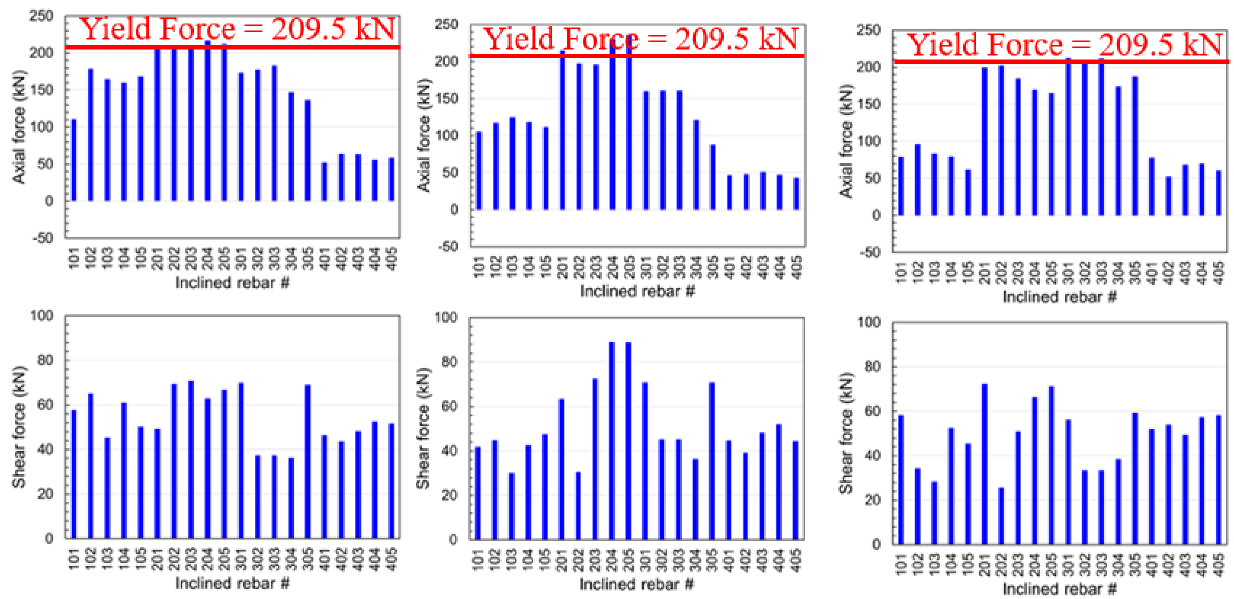
(a) (b) (c)

Figure A-4. Maximum Axial and Shear Forces in Inclined Rebars, 2270P Vehicle Impact with Near-Vertical Barrier (NVB): (a) Impact at Mid-Span; (b) Impact at 4.3 ft Upstream of Joint; and (c) Impact at Joint



(a) (b) (c)

Figure A-5. Maximum Axial and Shear Forces in Inclined Rebars, 10000S Vehicle Impact with Single-Slope Barrier (SSB): (a) Impact at Mid-Span; (b) Impact at ¾-Span; and (c) Impact at Joint



(a) (b) (c)

Figure A-6. Maximum Axial and Shear Forces in Inclined Rebars, 10000S Vehicle Impact with Near-Vertical Barrier (NVB): (a) Impact at Mid-Span; (b) Impact at ¾-Span; and (c) Impact at Joint

Appendix B. Angular Displacement Time Histories

The angular displacement time histories for 1100C and 2270P vehicle models with single-slope and near-vertical barrier shapes are provided in this appendix.

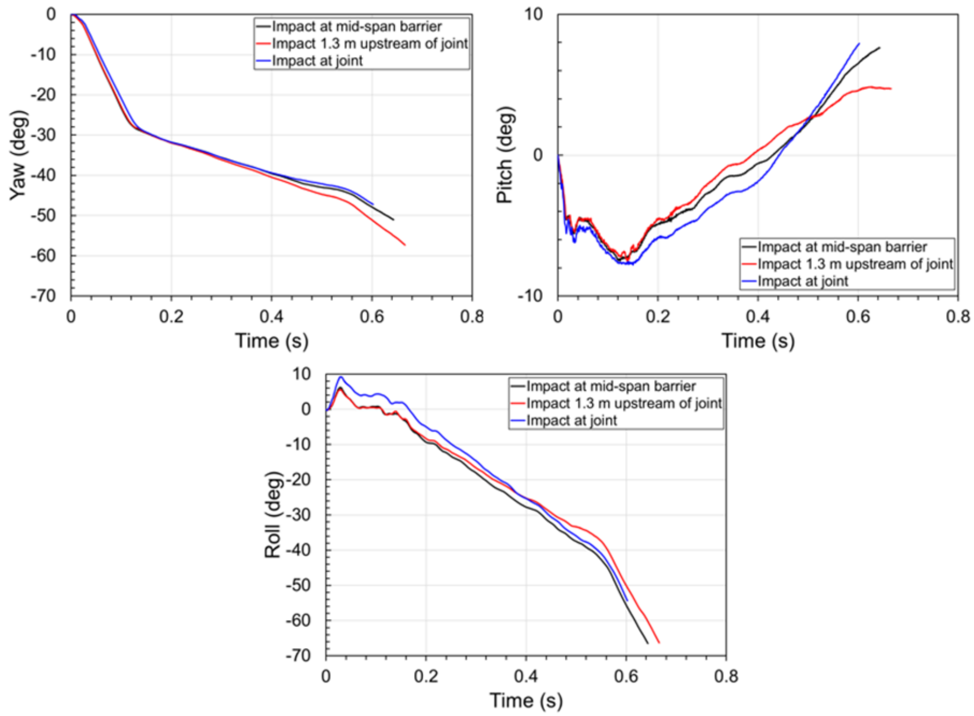


Figure B-1. Angular Displacement-Time History and Recommended Vehicle Coordination System (SSB: 1100C)

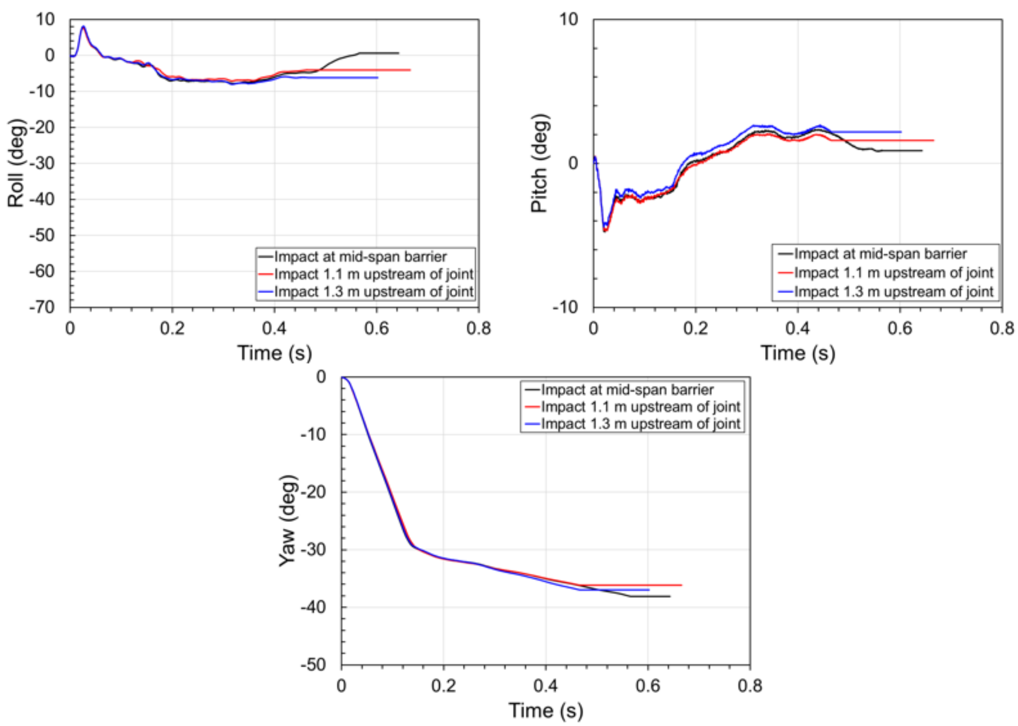


Figure B-2. Angular Displacement-Time History and Recommended Vehicle Coordination System (NVB: 1100C)

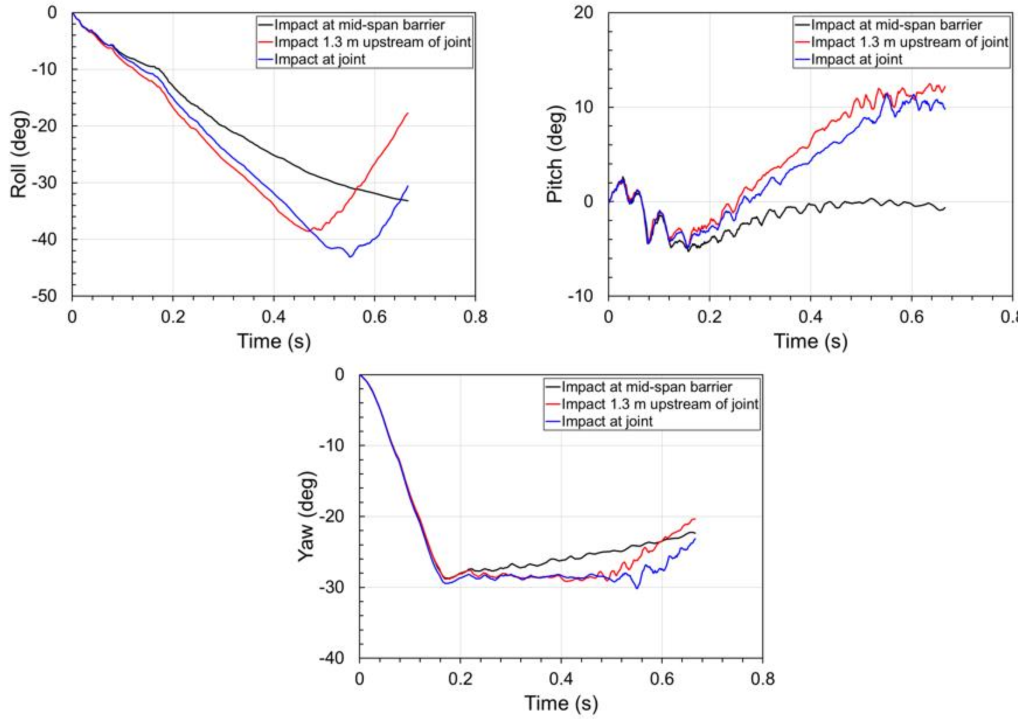


Figure B-3. Angular Displacement-Time History and Recommended Vehicle Coordination System (SSB: 2270P)

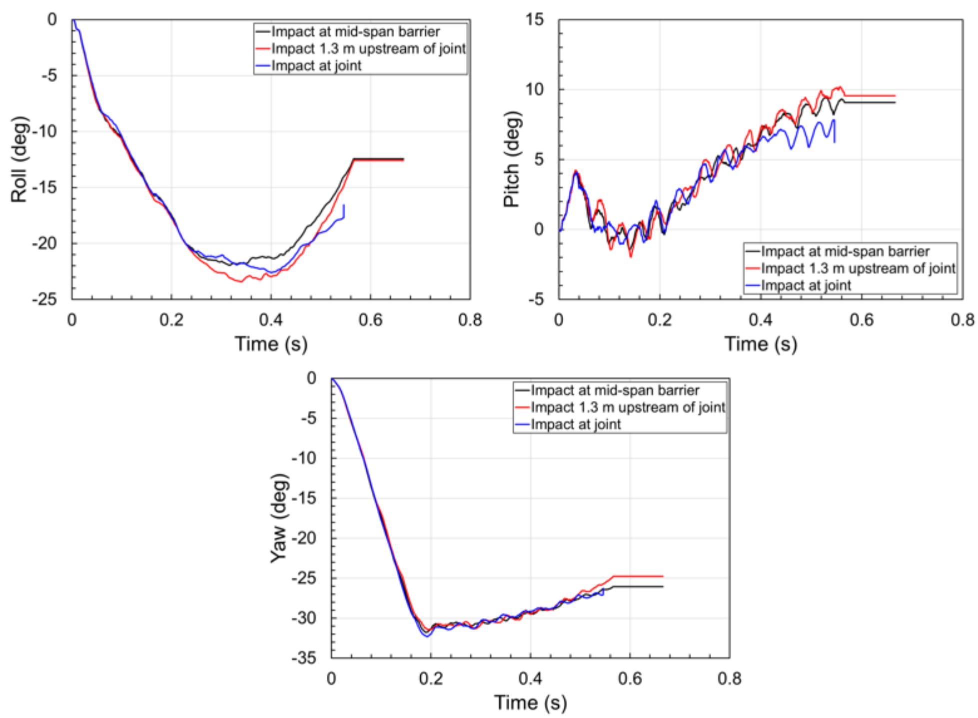
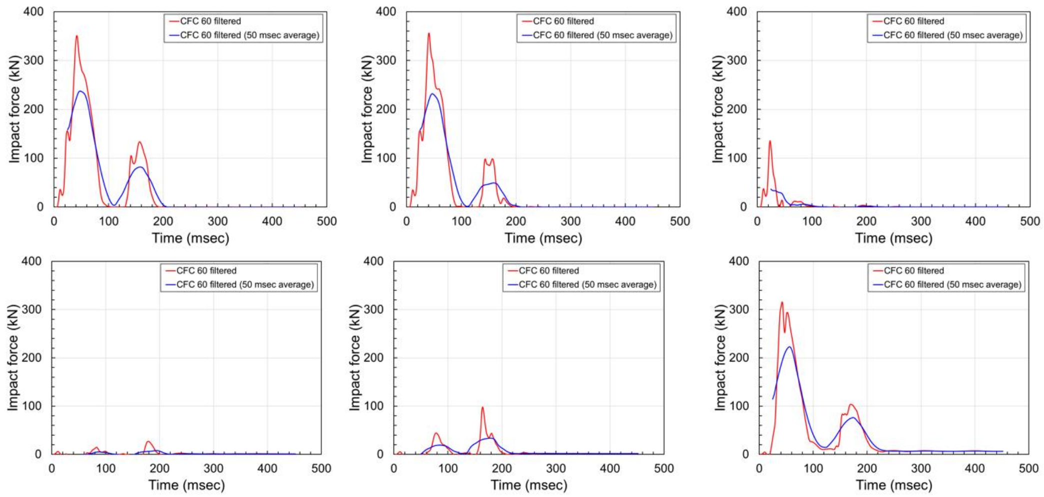


Figure B-4. Angular Displacement-Time History and Recommended Vehicle Coordination System (NVB: 2270P)

Appendix C. Impact Force Results

The impact force-time histories for 1100C and 2270P vehicle collision with single-slope and near-vertical barriers are provided in this appendix.

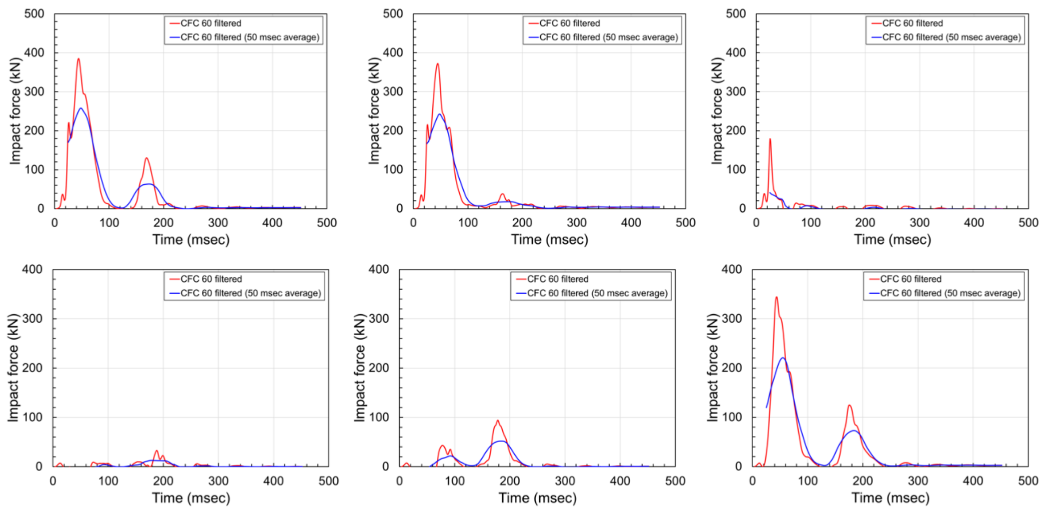


Barrier 2

Barrier 3

Impact at mid-span | Impact 1.1 m (3.6 ft) upstream | Impact at joint

Figure C-1. Impact Force-Time History (SSB: 1100C)

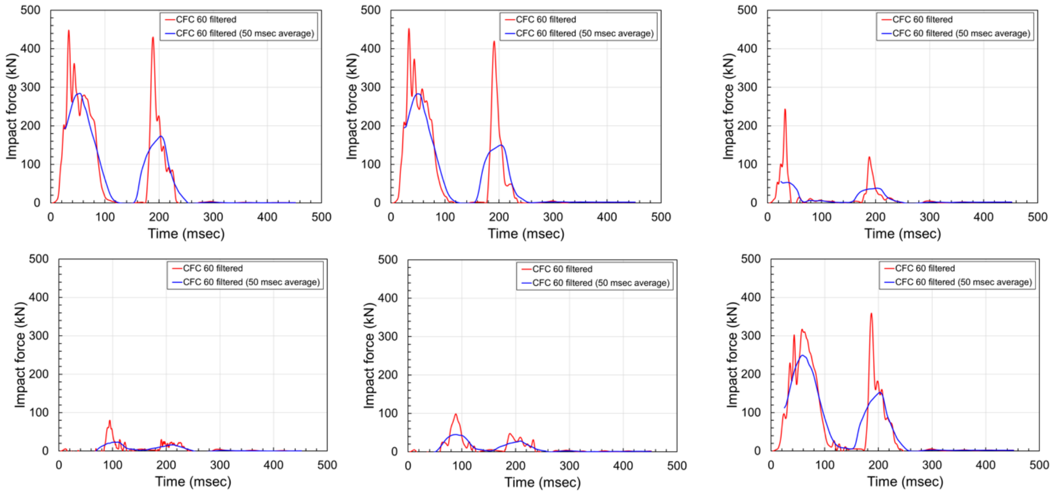


Barrier 2

Barrier 3

Impact at mid-span | Impact 1.1 m (3.6 ft) upstream | Impact at joint

Figure C-2. Impact Force-Time History (NVB: 1100C)



Barrier 2

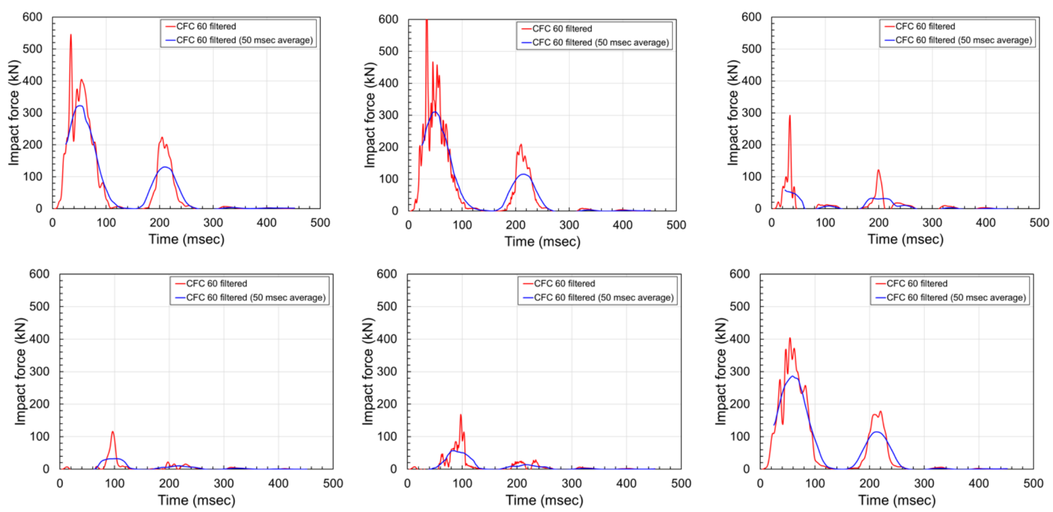
Barrier 3

Impact at mid-span

Impact 1.3 m (4.3 ft) upstream

Impact at joint

Figure C-3. Impact Force-Time History (SSB: 2270P)



Barrier 2

Barrier 3

Impact at mid-span

Impact 1.3 m (4.3 ft) upstream

Impact at joint

Figure C-4. Impact Force-Time History (NVB: 2270P)

Appendix D. Forces in Barrier Connections

The results axial force-time and von-Mises-time histories for 1100C, 2270P, 10000S vehicle collisions with single-slope and near-vertical barriers are provided in this appendix.

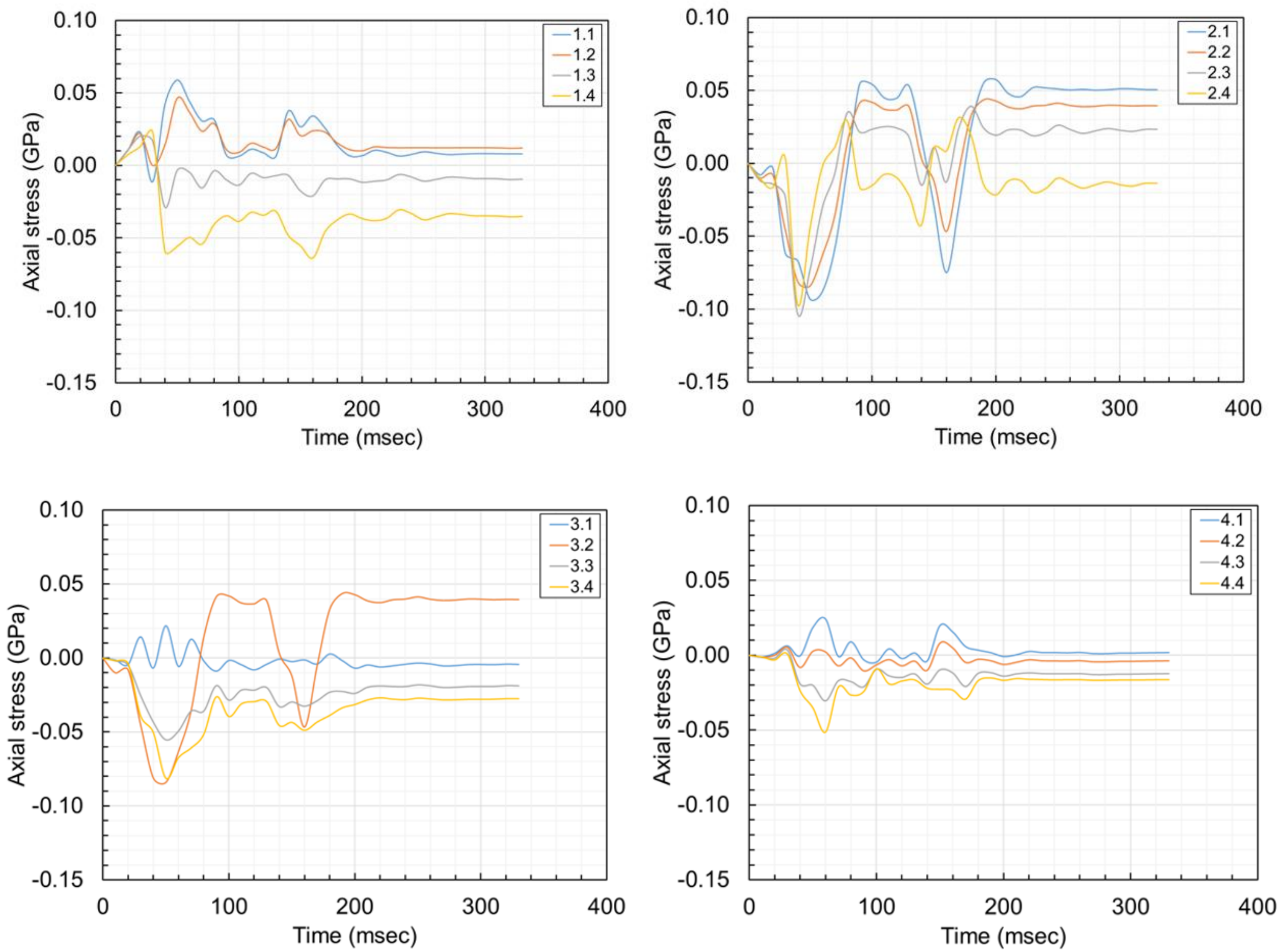


Figure D-1. Axial Stress Developed in Joint-Spanning Rebar – 1000C Vehicle Impact at Mid-Span – Single-Slope Barrier

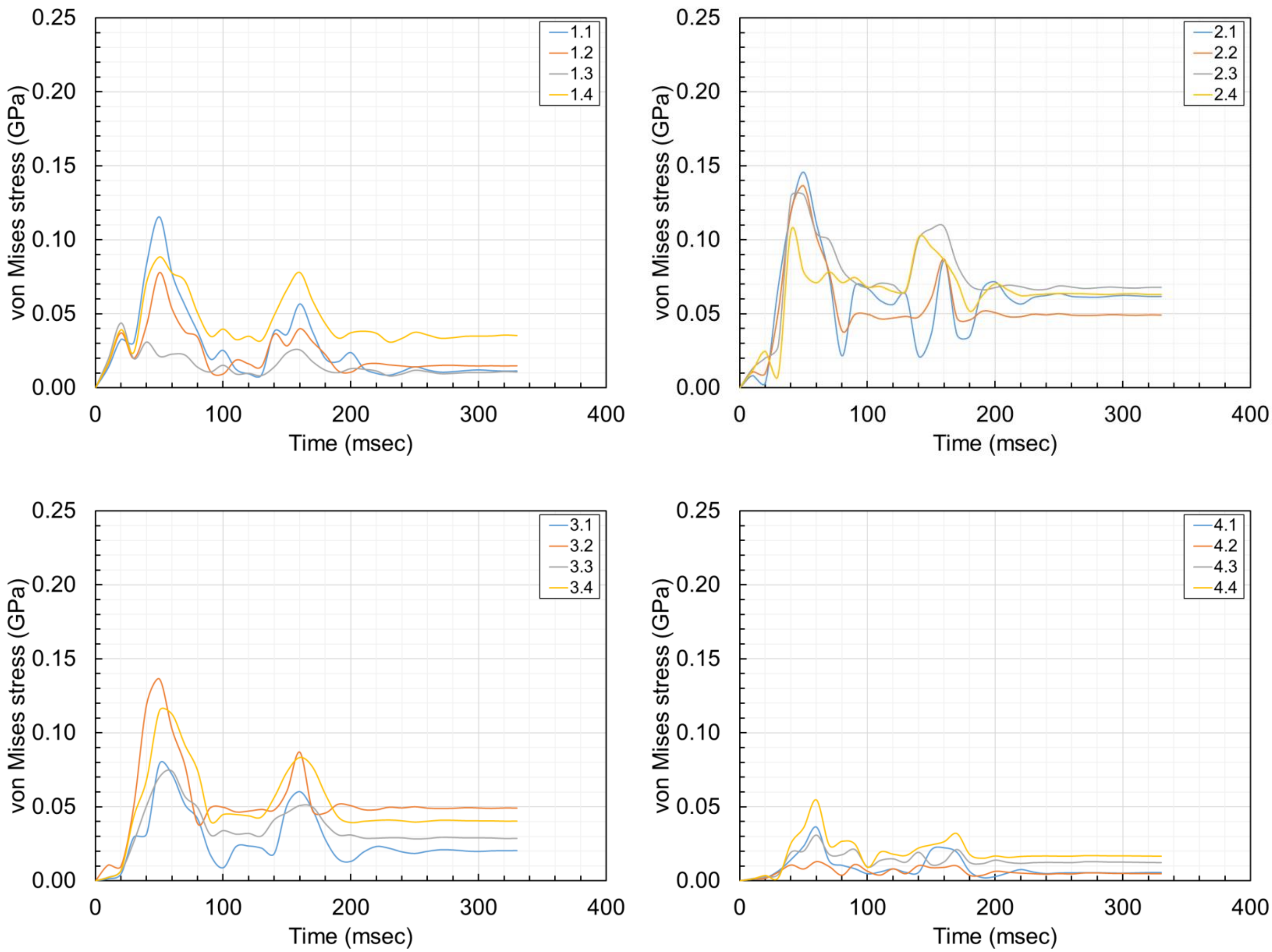


Figure D-2. Von-Mises Stress Developed in Joint-Spanning Rebar – 1000C Vehicle Impact at Mid-Span – Single-Slope Barrier

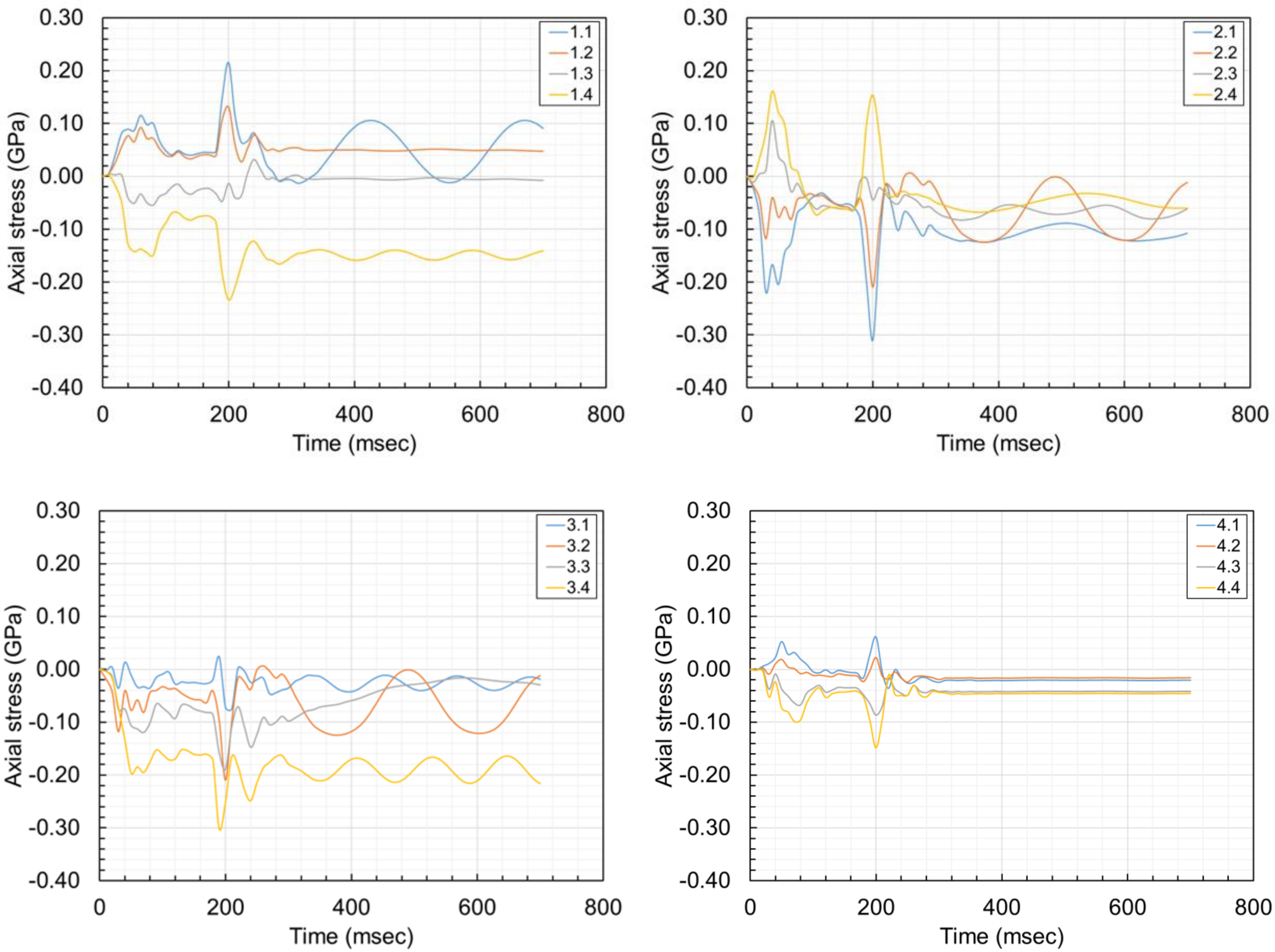


Figure D-3. Axial Stress Developed in Joint-Spanning Rebar – 2270P Vehicle Impact at Mid-Span – Single-Slope Barrier

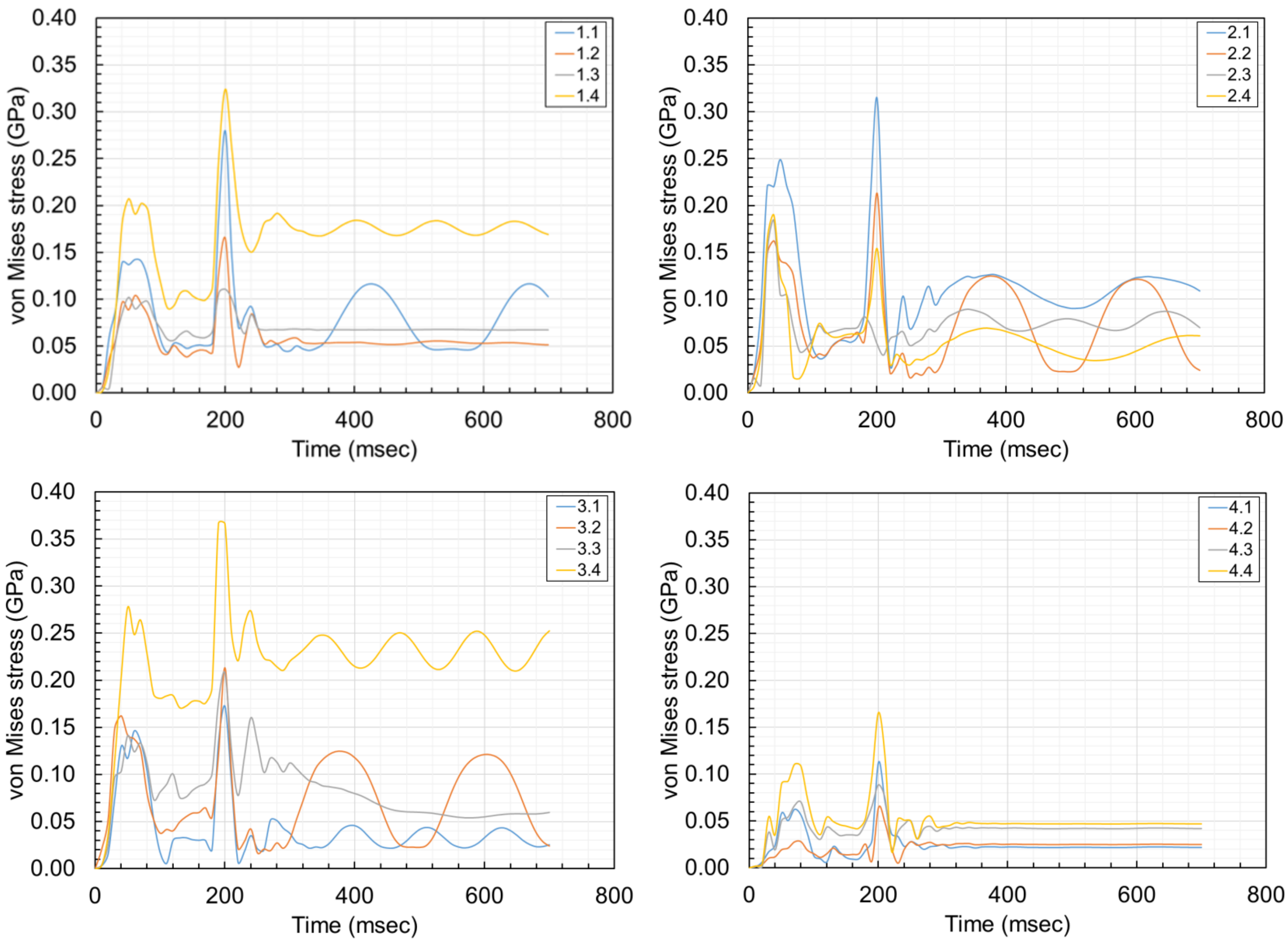


Figure D-4. Von-Mises Stress Developed in Joint-Spanning Rebar – 2270P Vehicle Impact at Mid-Span – Single-Slope Barrier

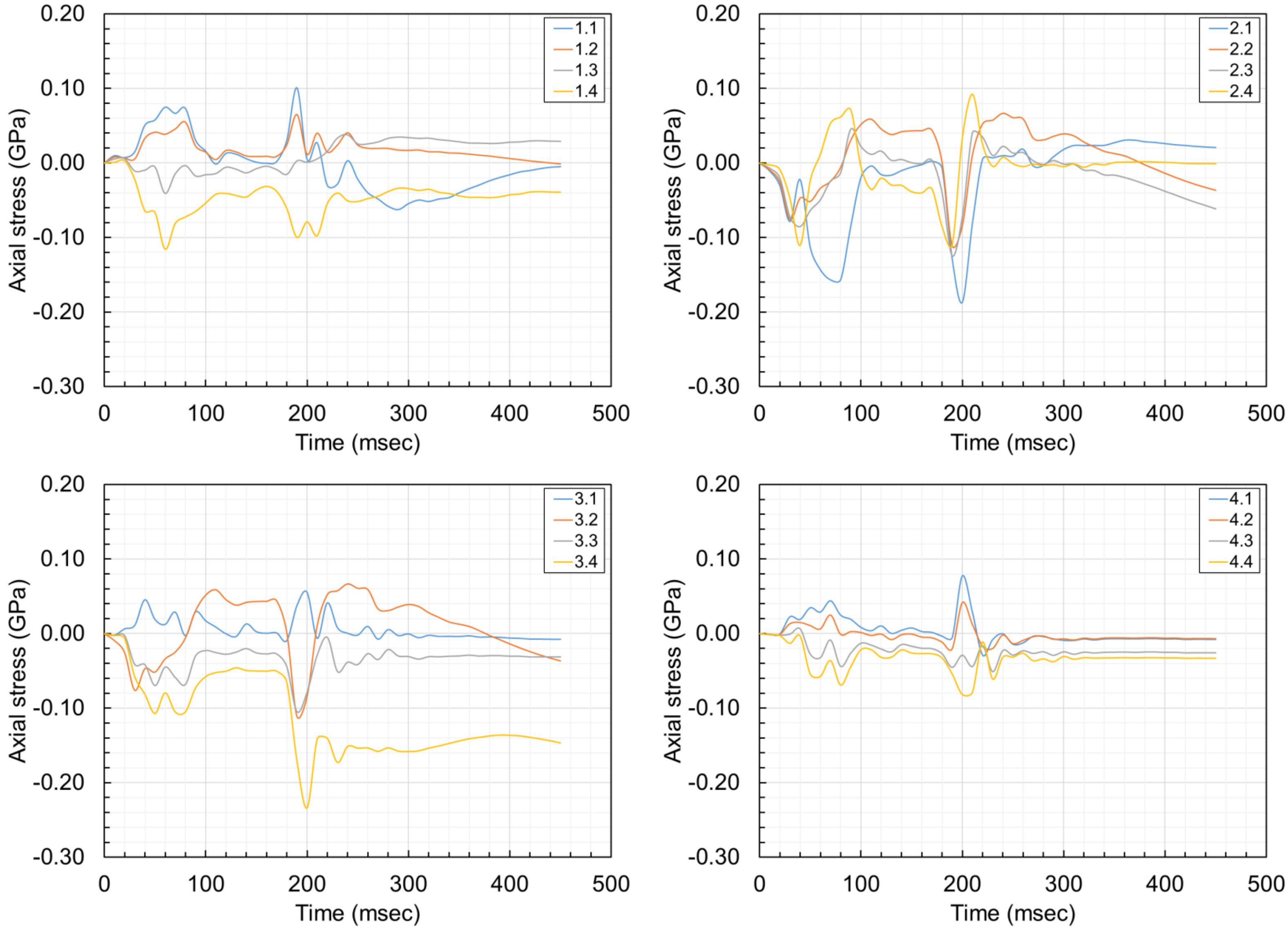


Figure D-5. Axial Stress Developed in Joint-Spanning Rebar – 2270P Vehicle Impact at 4.3 ft Upstream from a Joint – Single-Slope Barrier

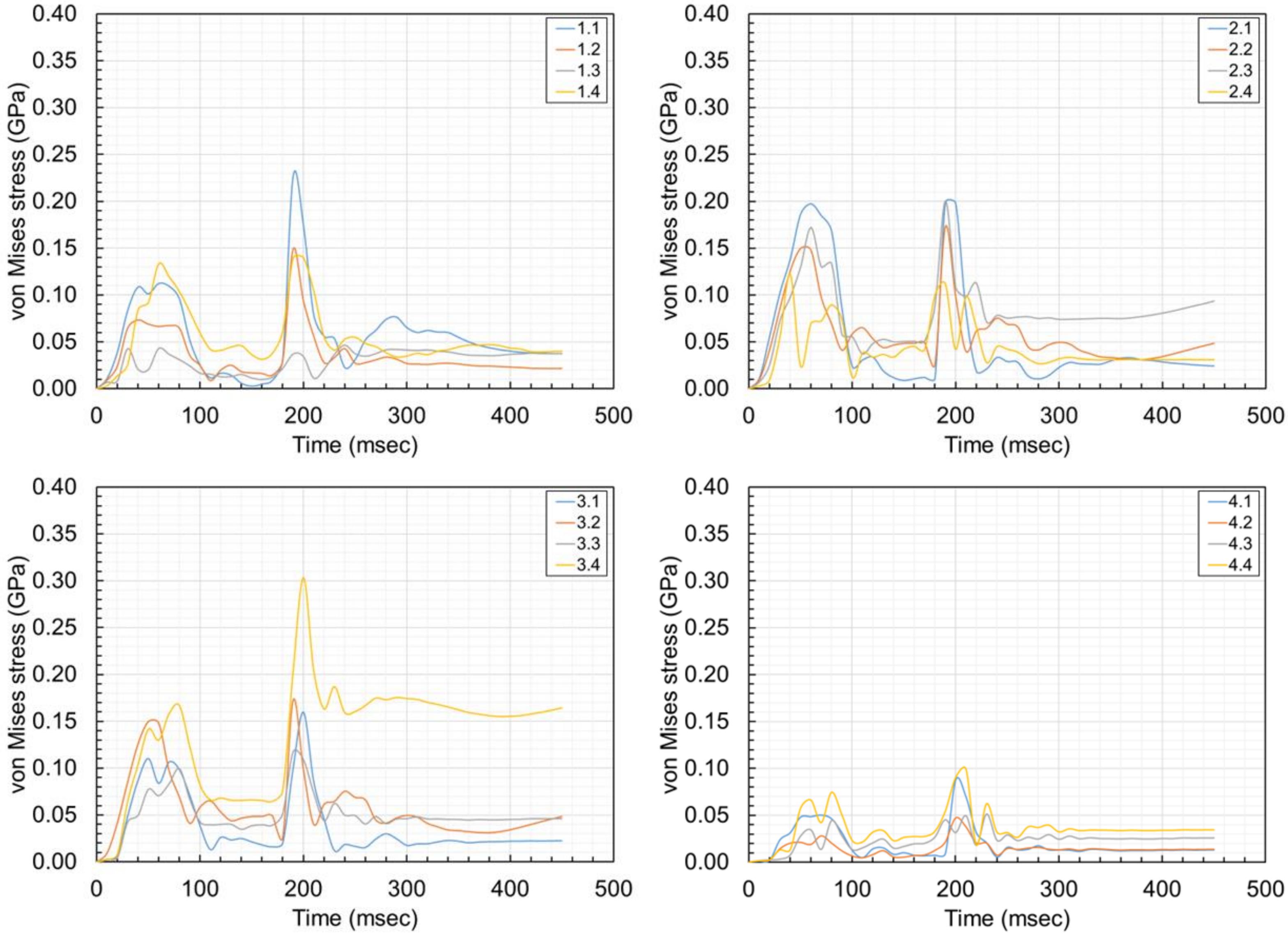


Figure D-6. Von-Mises Stress Developed in Joint-Spanning Rebar – 2270P Vehicle Impact at 4.3 ft Upstream from a Joint – Single-Slope Barrier

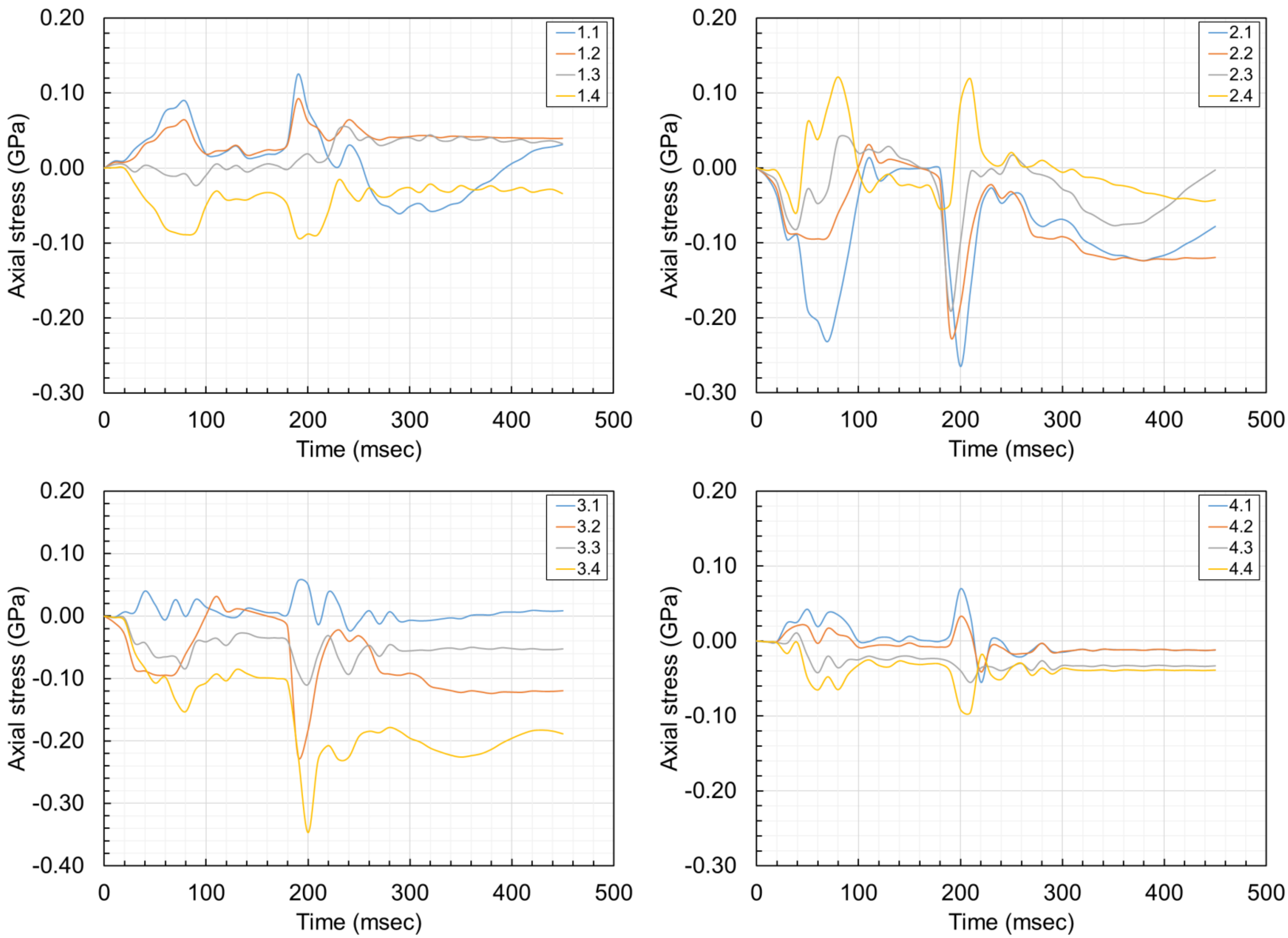


Figure D-7. Axial Stress Developed in Joint-Spanning Rebar – 2270P Vehicle Impact at a Joint – Single-Slope Barrier

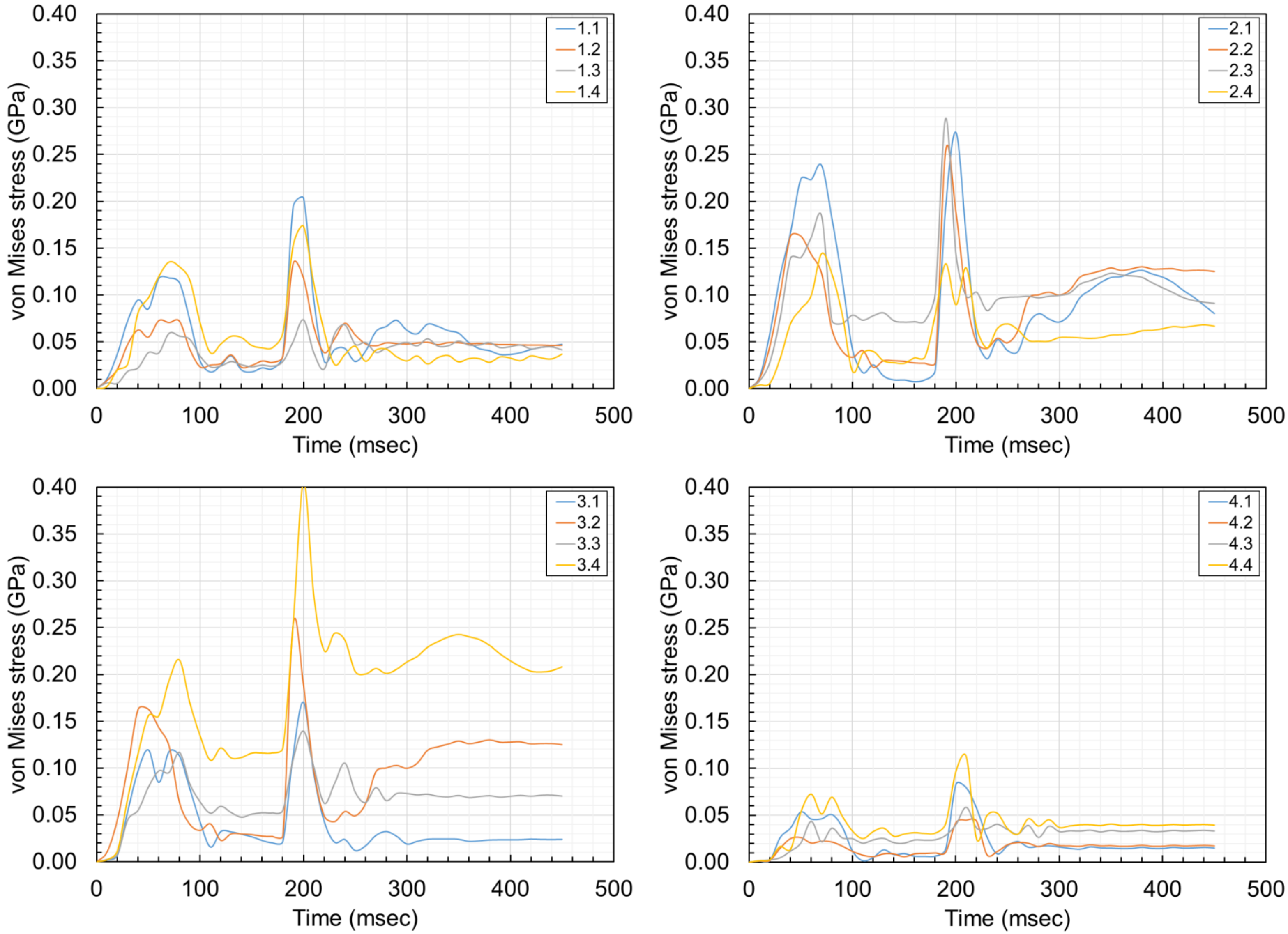


Figure D-8. Von-Mises Stress Developed in Joint-Spanning Rebar – 2270P Vehicle Impact at a Joint – Single-Slope Barrier

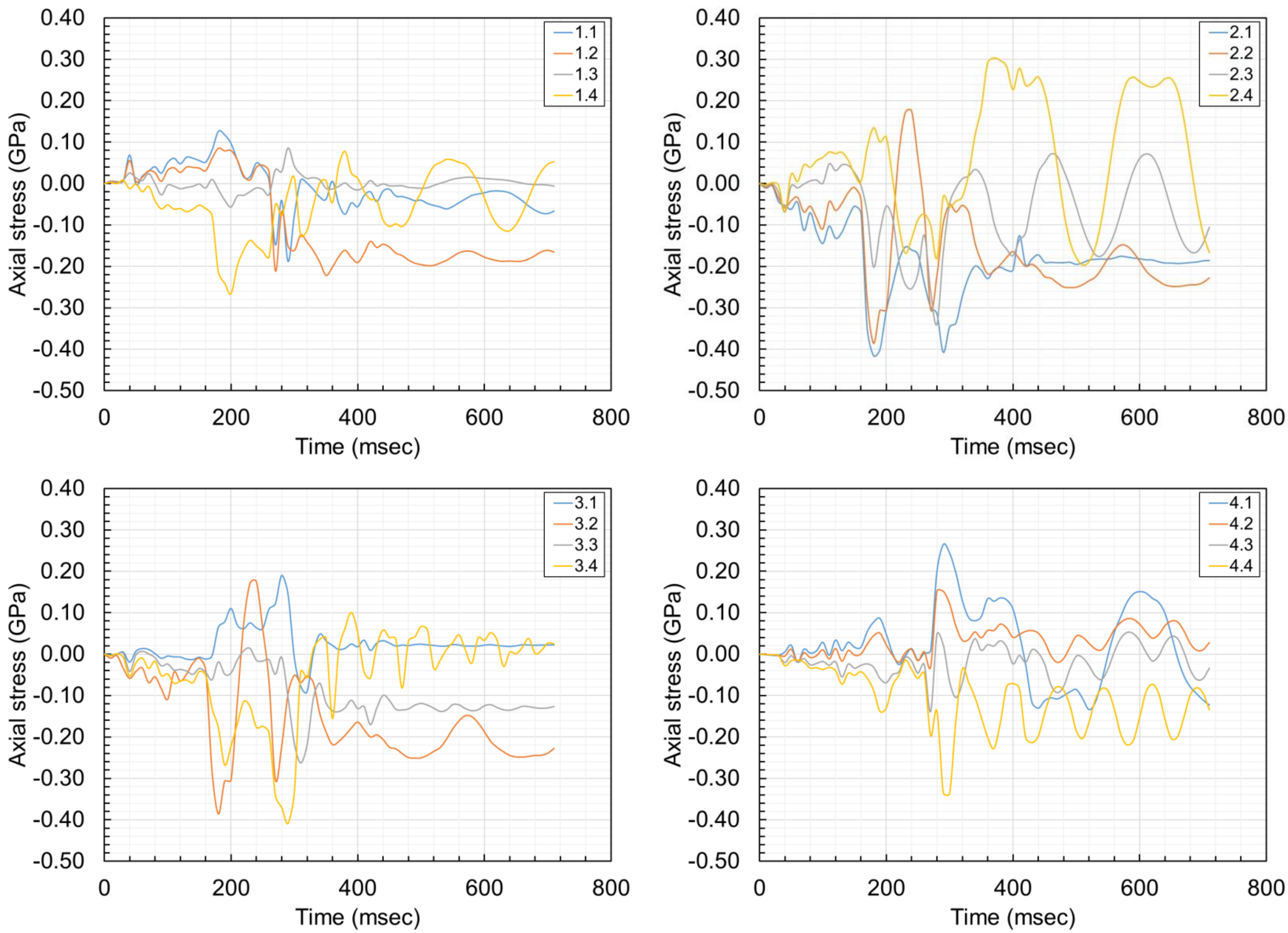


Figure D-9. Axial Stress Developed in Joint-Spanning Rebar – 10000S Vehicle Impact at Mid-Span – Single-Slope Barrier

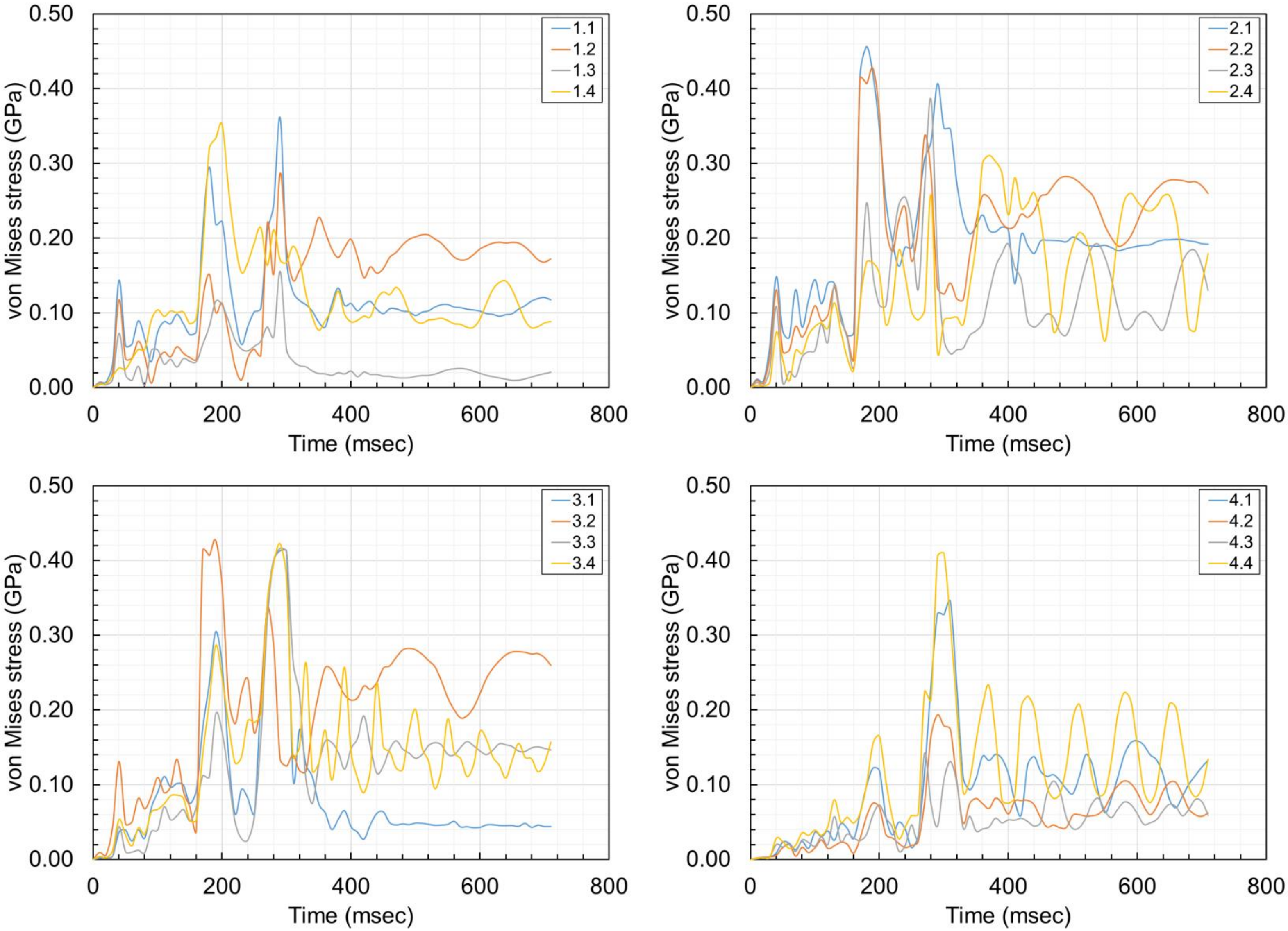


Figure D-10. Von-Mises Stress Developed in Joint-Spanning Rebar – 10000S Vehicle Impact at Mid-Span – Single-Slope Barrier

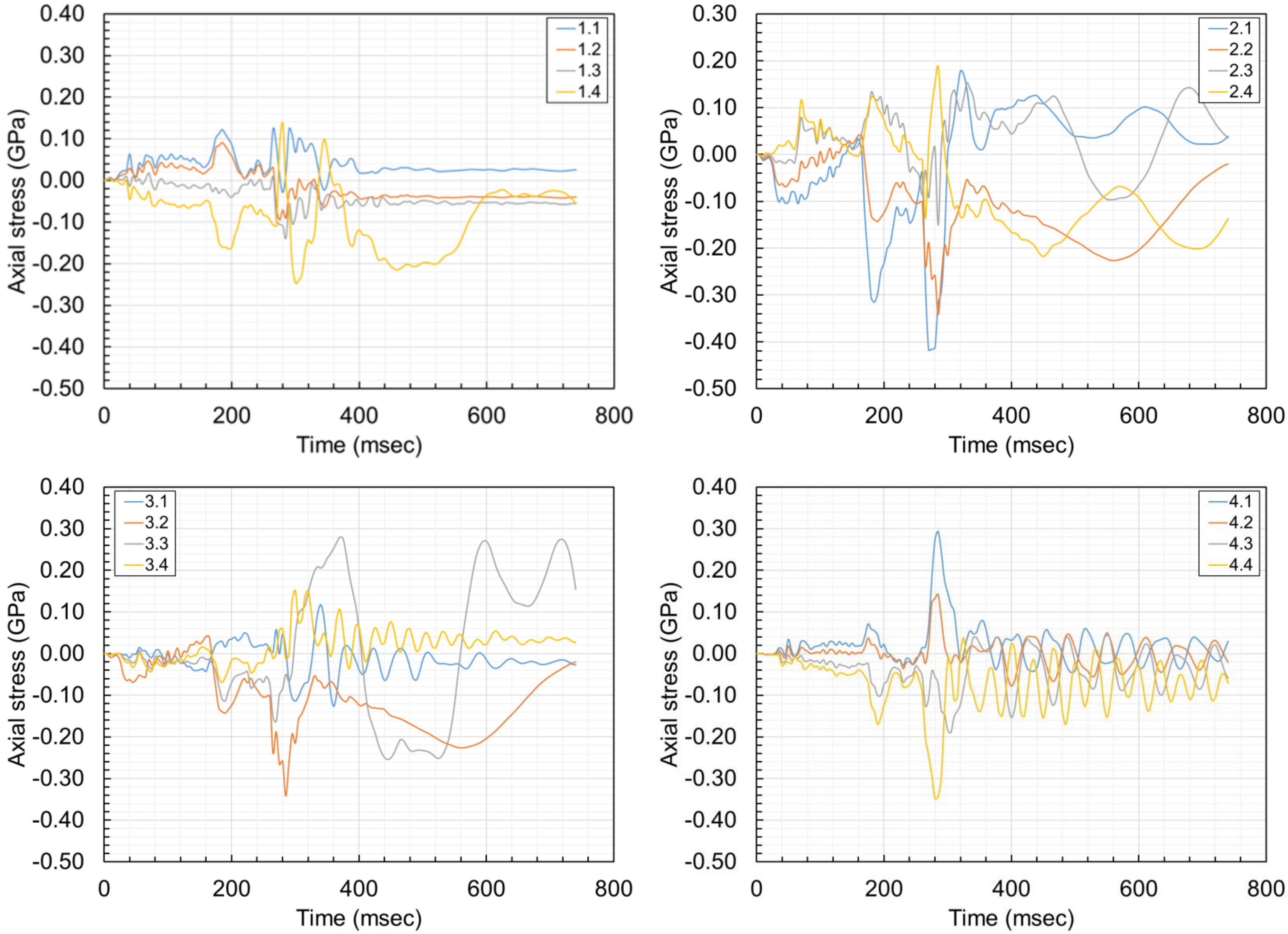


Figure D-11. Axial Stress Developed in Joint-Spanning Rebar – 10000S Vehicle Impact at ¾ -Span – Single-Slope Barrier

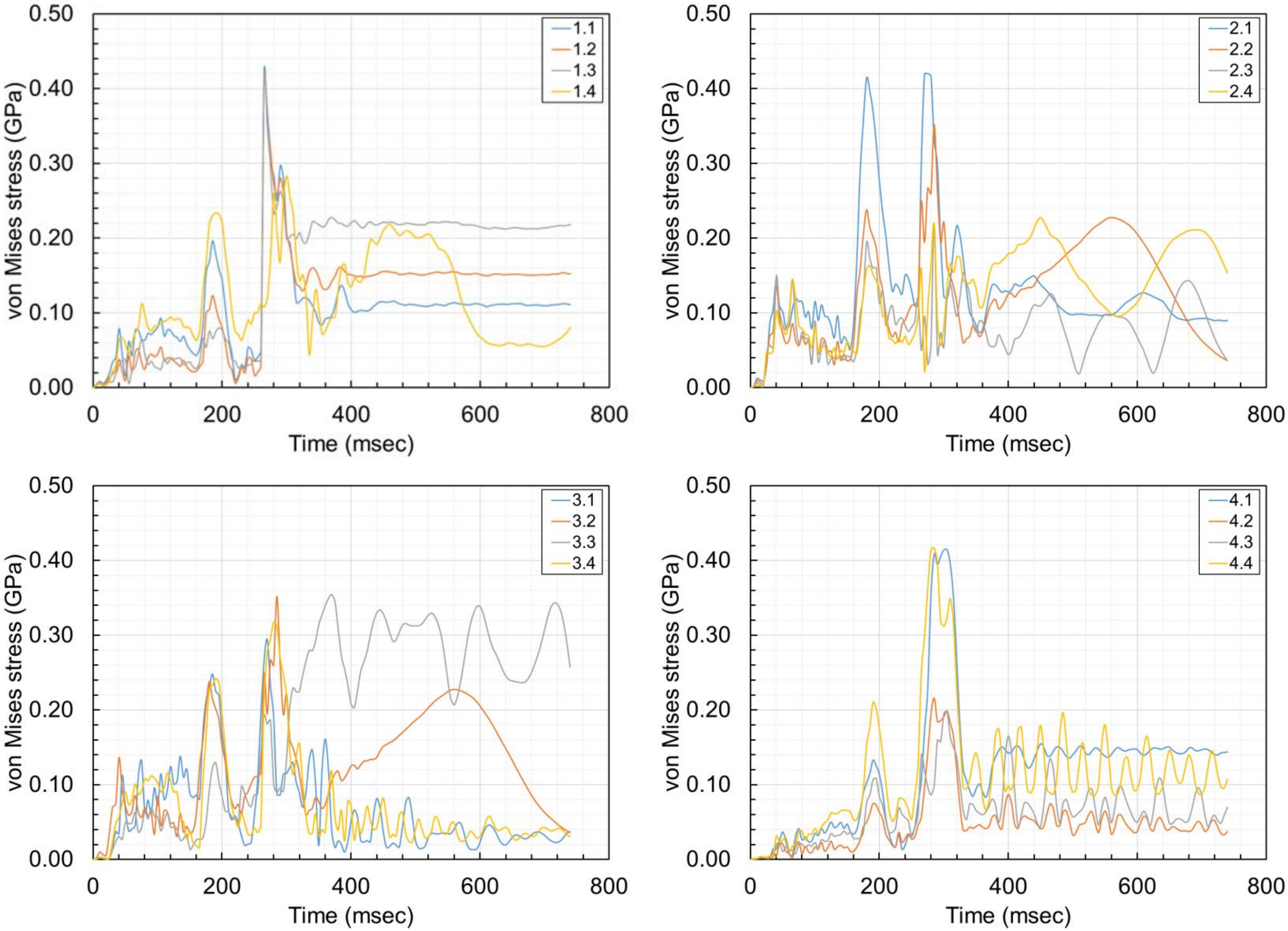


Figure D-12. Von-Mises Stress Developed in Joint-Spanning Rebar – 10000S Vehicle Impact at ¾ -Span – Single-Slope Barrier

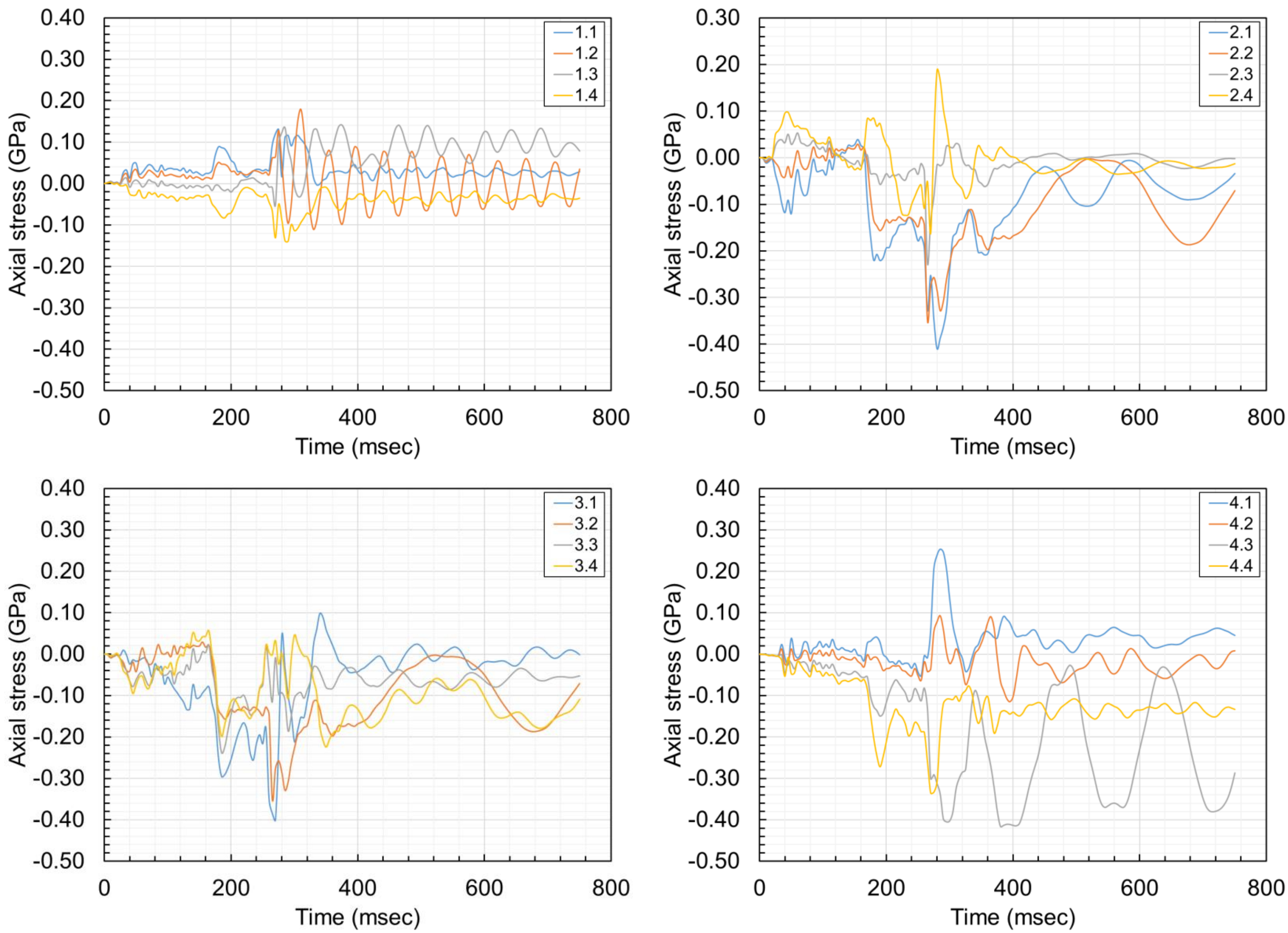


Figure D-13. Axial Stress Developed in Joint-Spanning Rebar – 10000S Vehicle Impact at Joint – Single-Slope Barrier

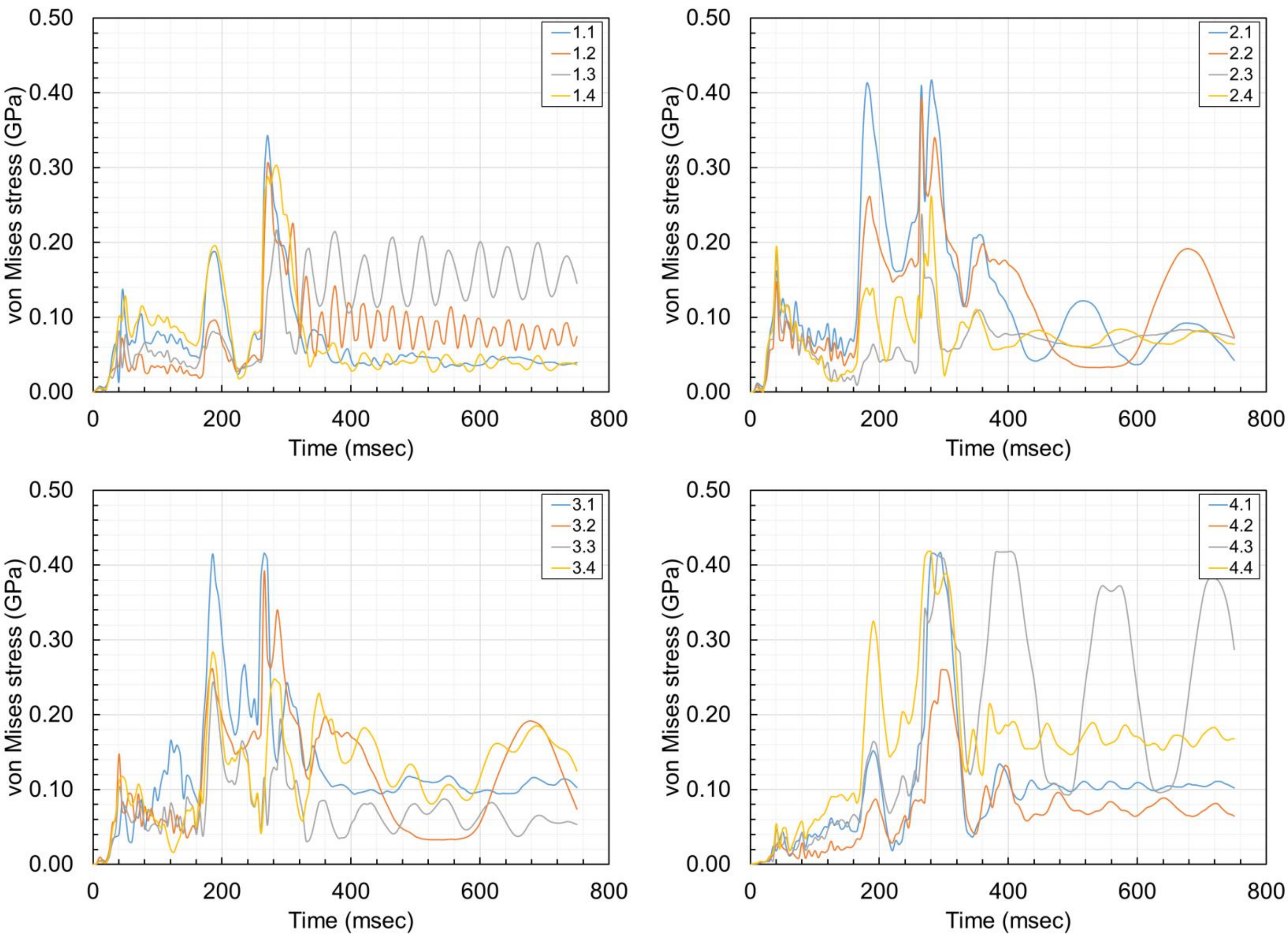


Figure D-14. Von-Mises Stress Developed in Joint-Spanning Rebar – 10000S Vehicle Impact at Joint – Single-Slope Barrier

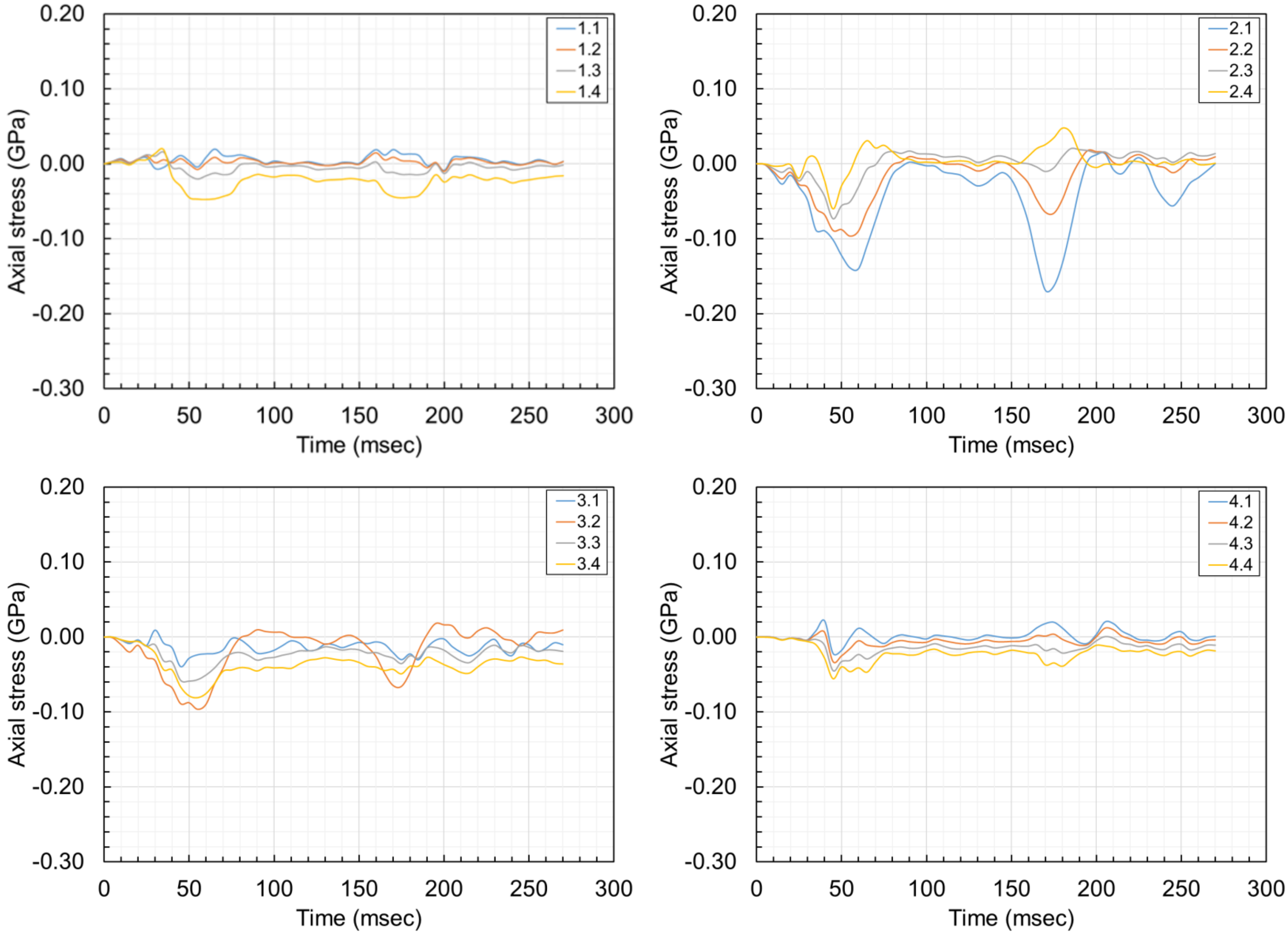


Figure D-15. Axial Stress Developed in Joint-Spanning Rebar – 1000C Vehicle Impact at Mid-Span – Near-Vertical Barrier

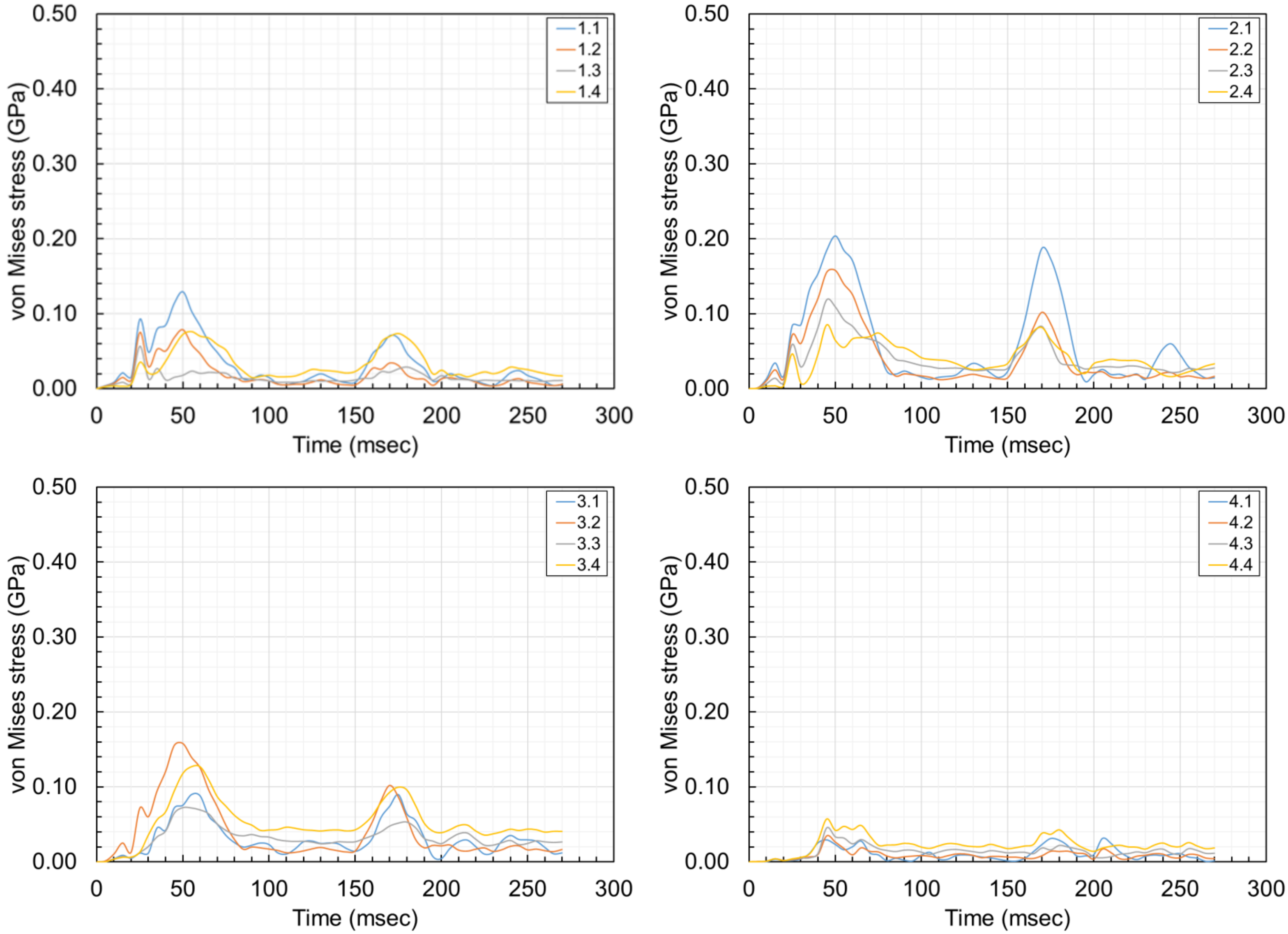


Figure D-16. Von-Mises Stress Developed in Joint-Spanning Rebar – 1000C Vehicle Impact at Mid-Span – Near-Vertical Barrier

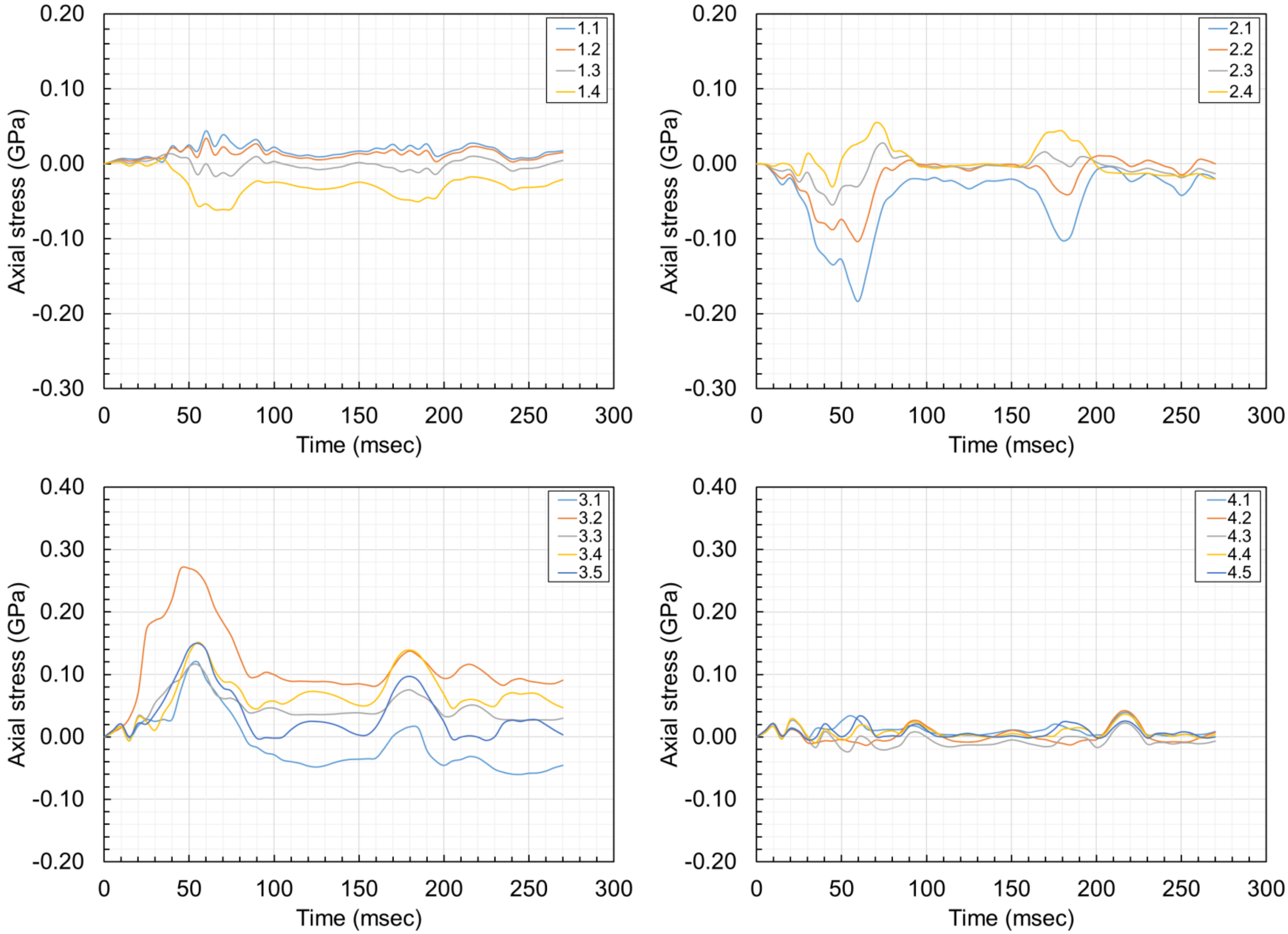


Figure D-17. Axial Stress Developed in Joint-Spanning Rebar – 1000C Vehicle Impact at 3.6 ft Upstream of a Joint – Near-Vertical Barrier

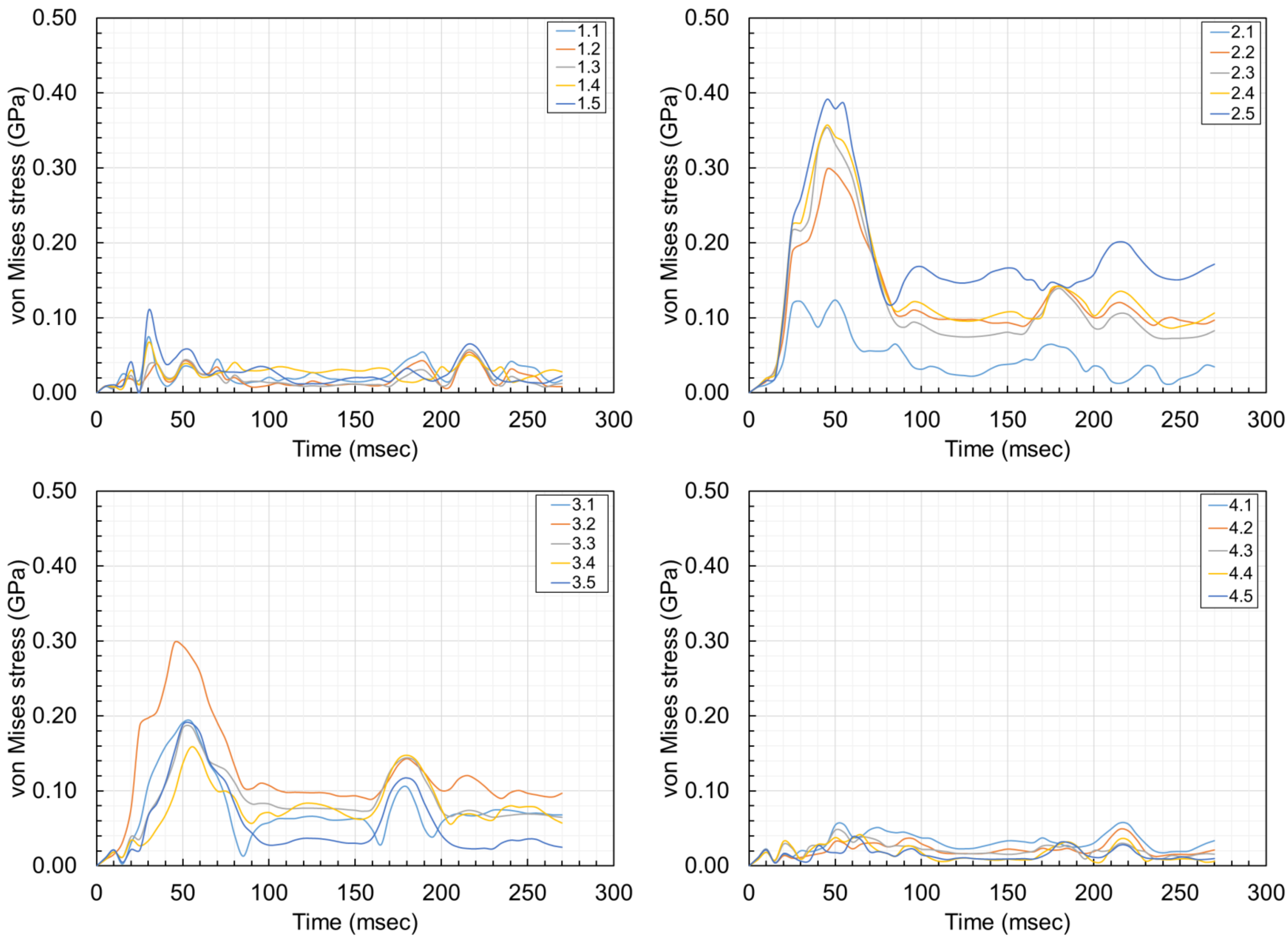


Figure D-18. Von-Mises Developed in Joint-Spanning Rebar – 1000C Vehicle Impact at 3.6 ft Upstream of a Joint – Near-Vertical Barrier

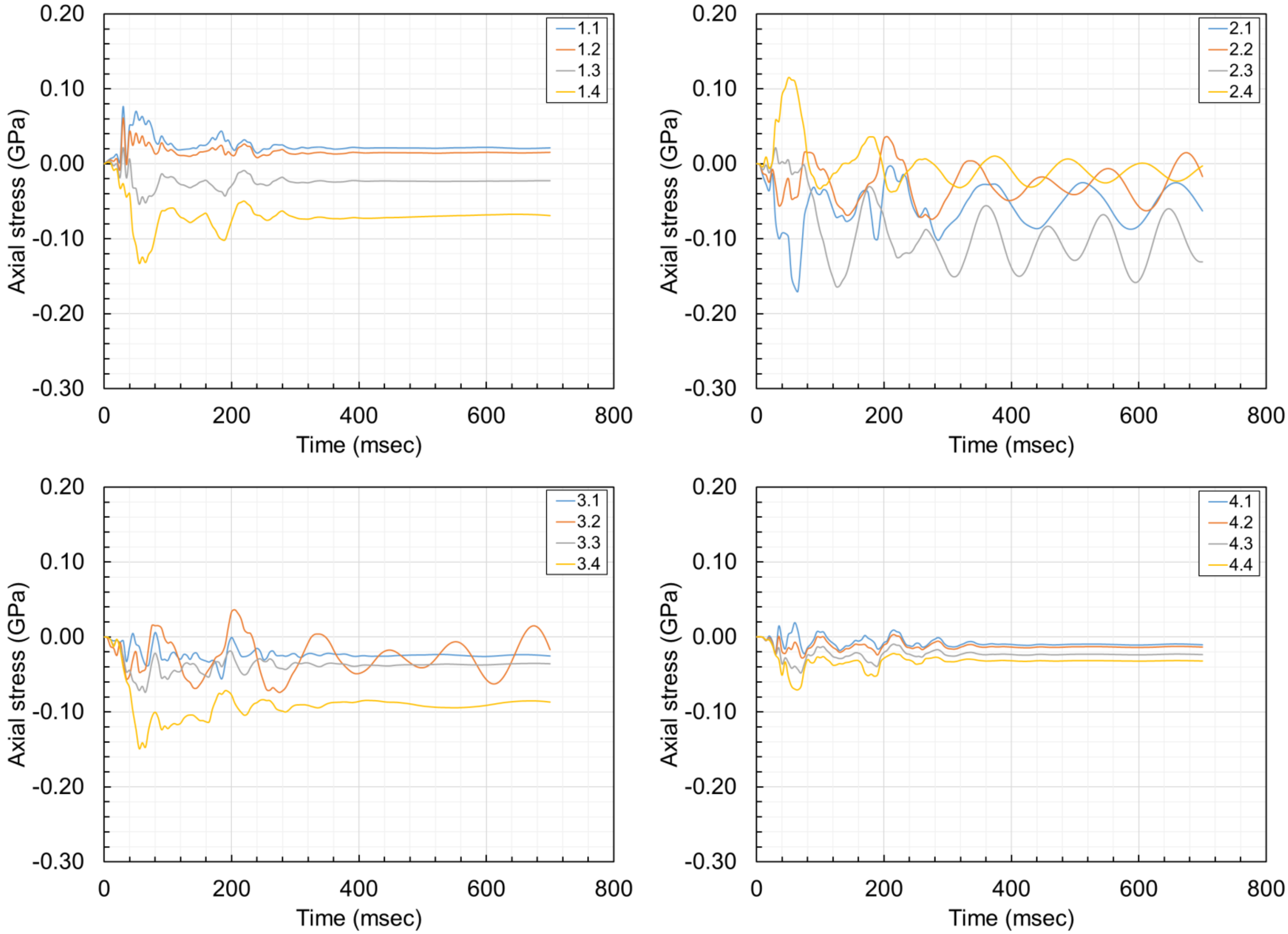


Figure D-19. Axial Stress Developed in Joint-Spanning Rebar – 1000C Vehicle Impact at a Joint – Near-Vertical Barrier

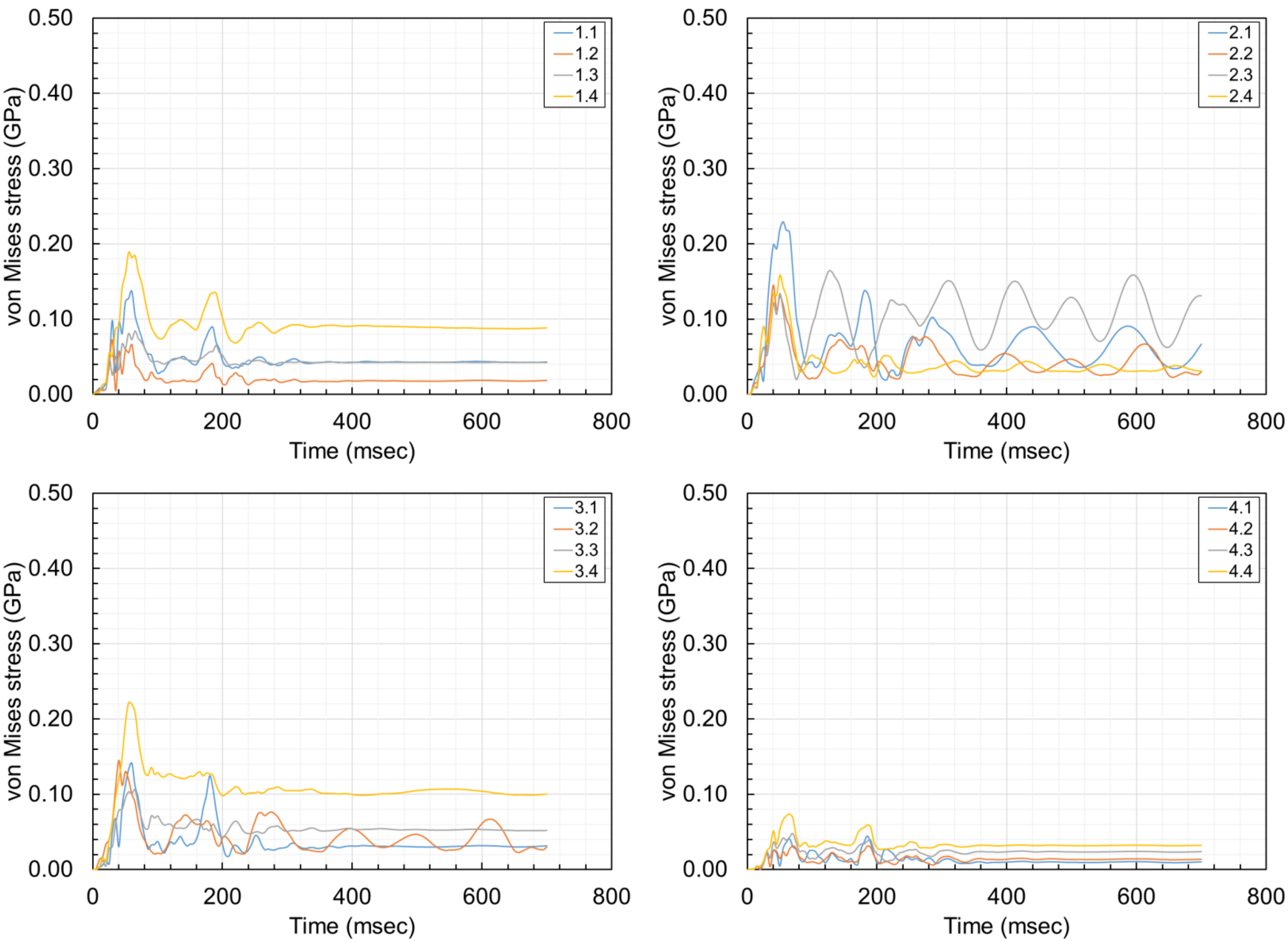


Figure D-20. Von-Mises Stress Developed in Joint-Spanning Rebar – 1000C Vehicle Impact at a Joint – Near-Vertical Barrier

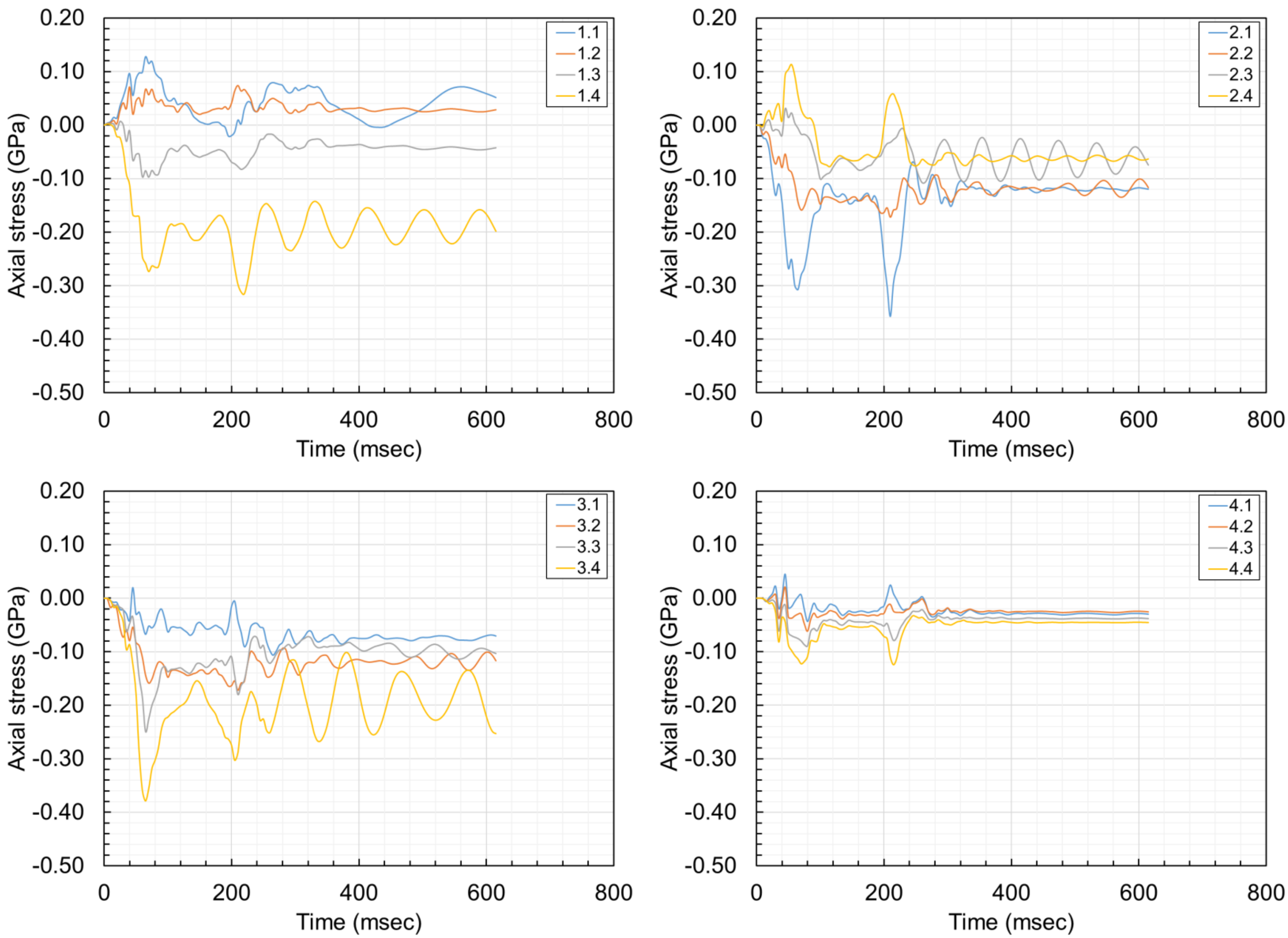


Figure D-21. Axial Stress Developed in Joint-Spanning Rebar – 2270P Vehicle Impact at Mid-Span – Near-Vertical Barrier

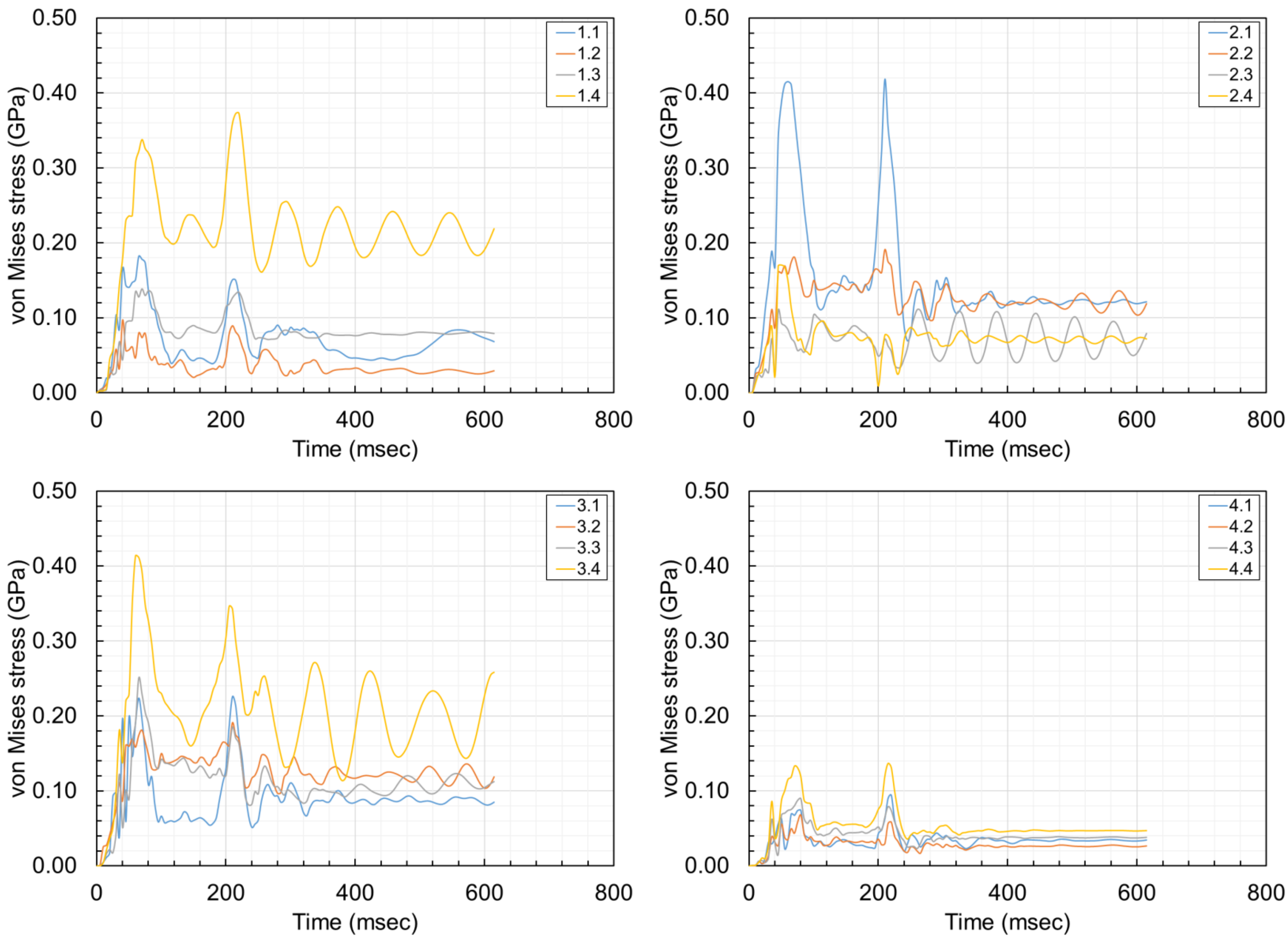


Figure D-22. Von-Mises Stress Developed in Joint-Spanning Rebar – 2270P Vehicle Impact at Mid-Span – Near-Vertical Barrier

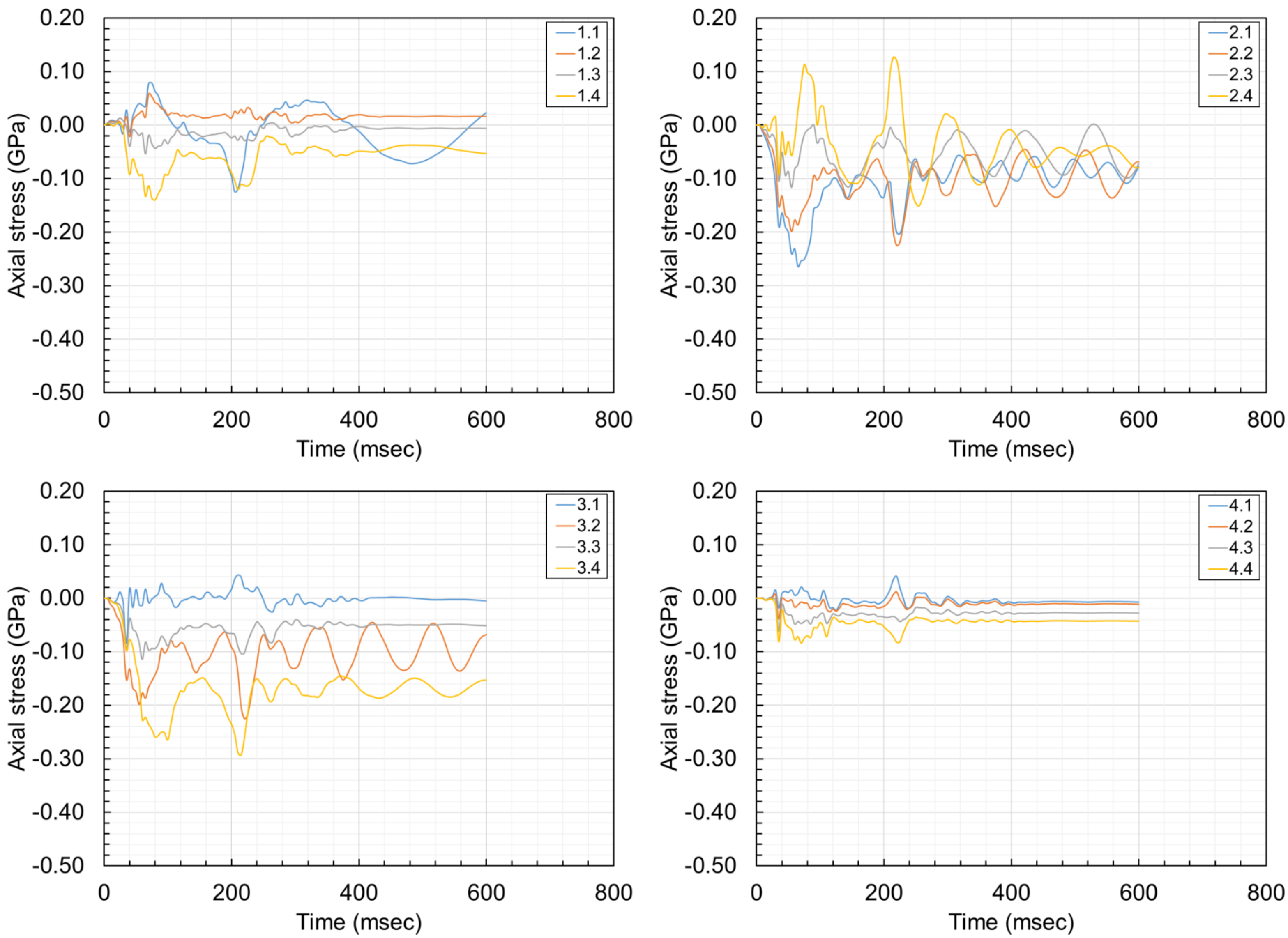


Figure D-23. Axial Stress Developed in Joint-Spanning Rebar – 2270P Vehicle Impact at 4.3 ft Upstream of a Joint – Near-Vertical Barrier

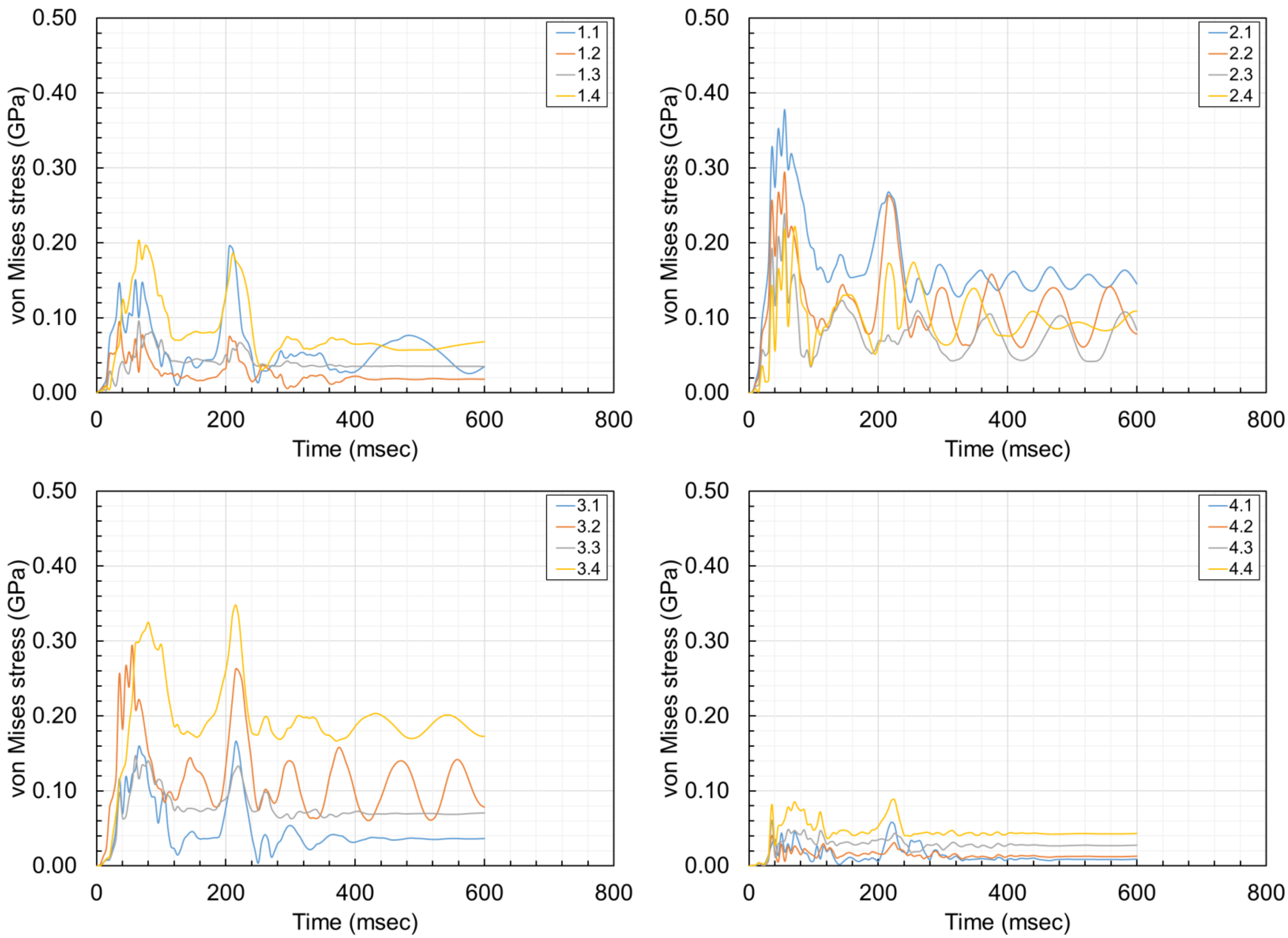


Figure D-24. Von-Mises Stress Developed in Joint-Spanning Rebar – 2270P Vehicle Impact at 4.3 ft Upstream of a Joint – Near-Vertical Barrier

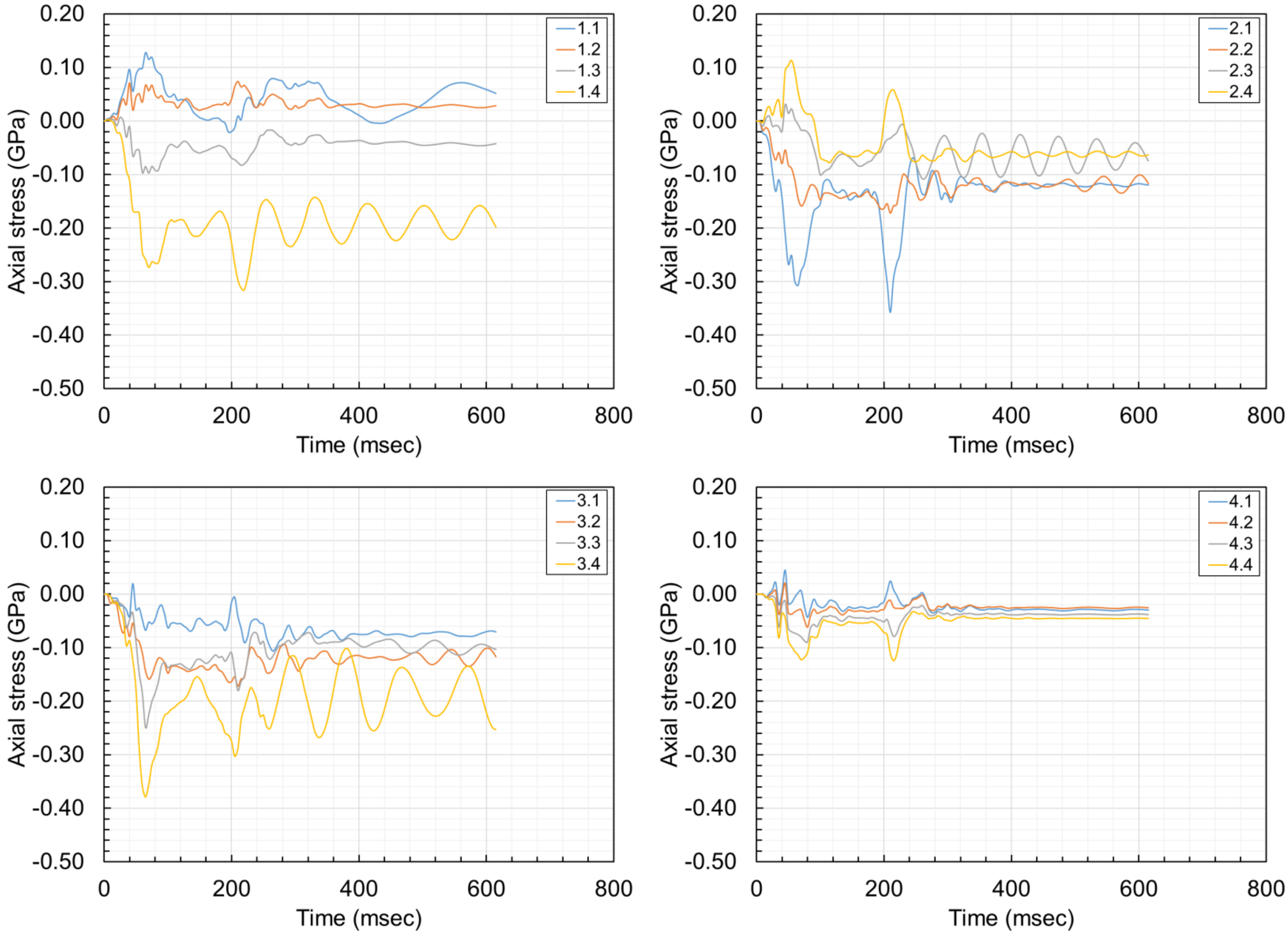


Figure D-25. Axial Stress Developed in Joint-Spanning Rebar – 2270P Vehicle Impact a Joint – Near-Vertical Barrier

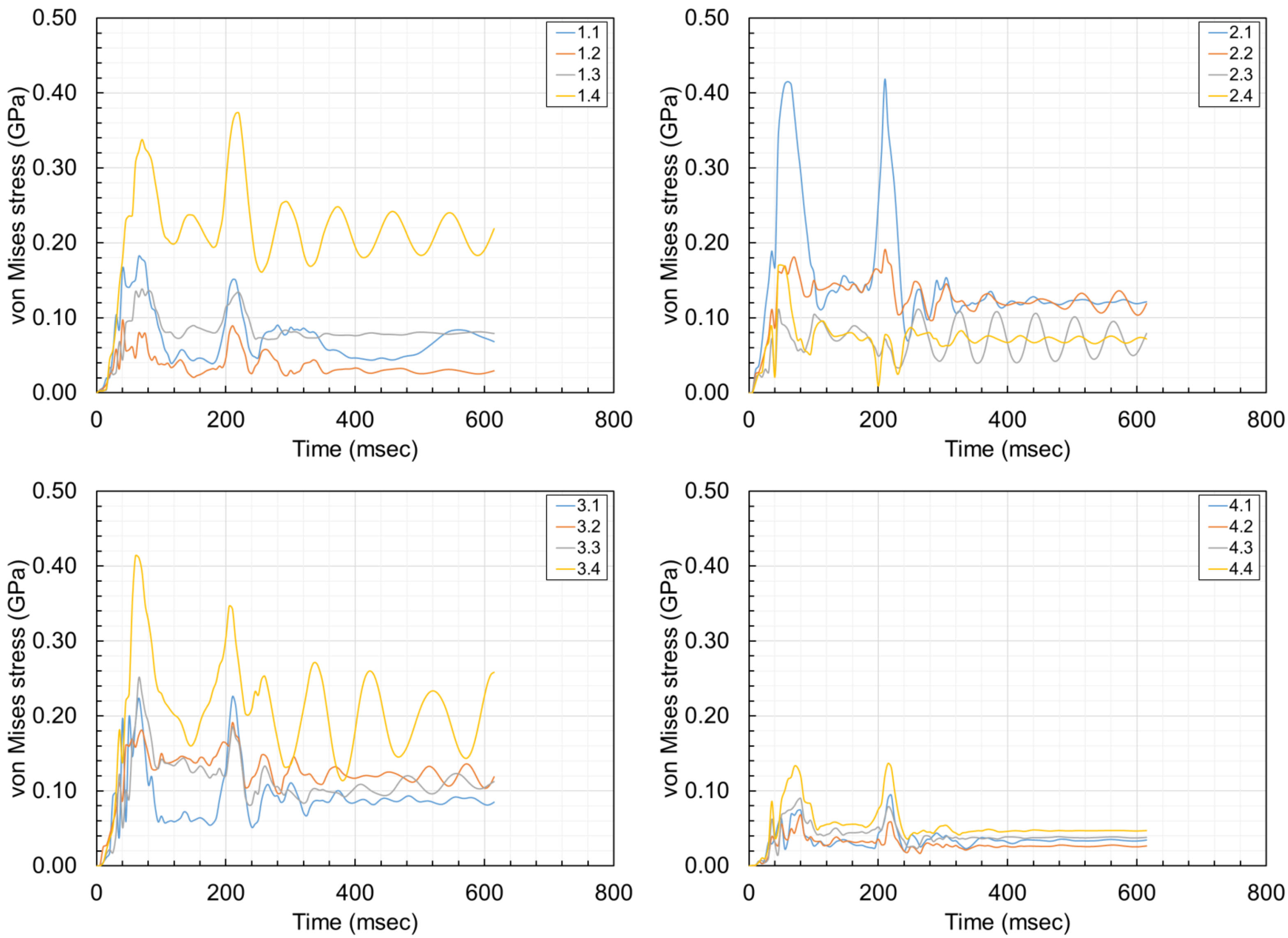


Figure D-26. Von-Mises Stress Developed in Joint-Spanning Rebar – 2270P Vehicle Impact a Joint – Near-Vertical Barrier

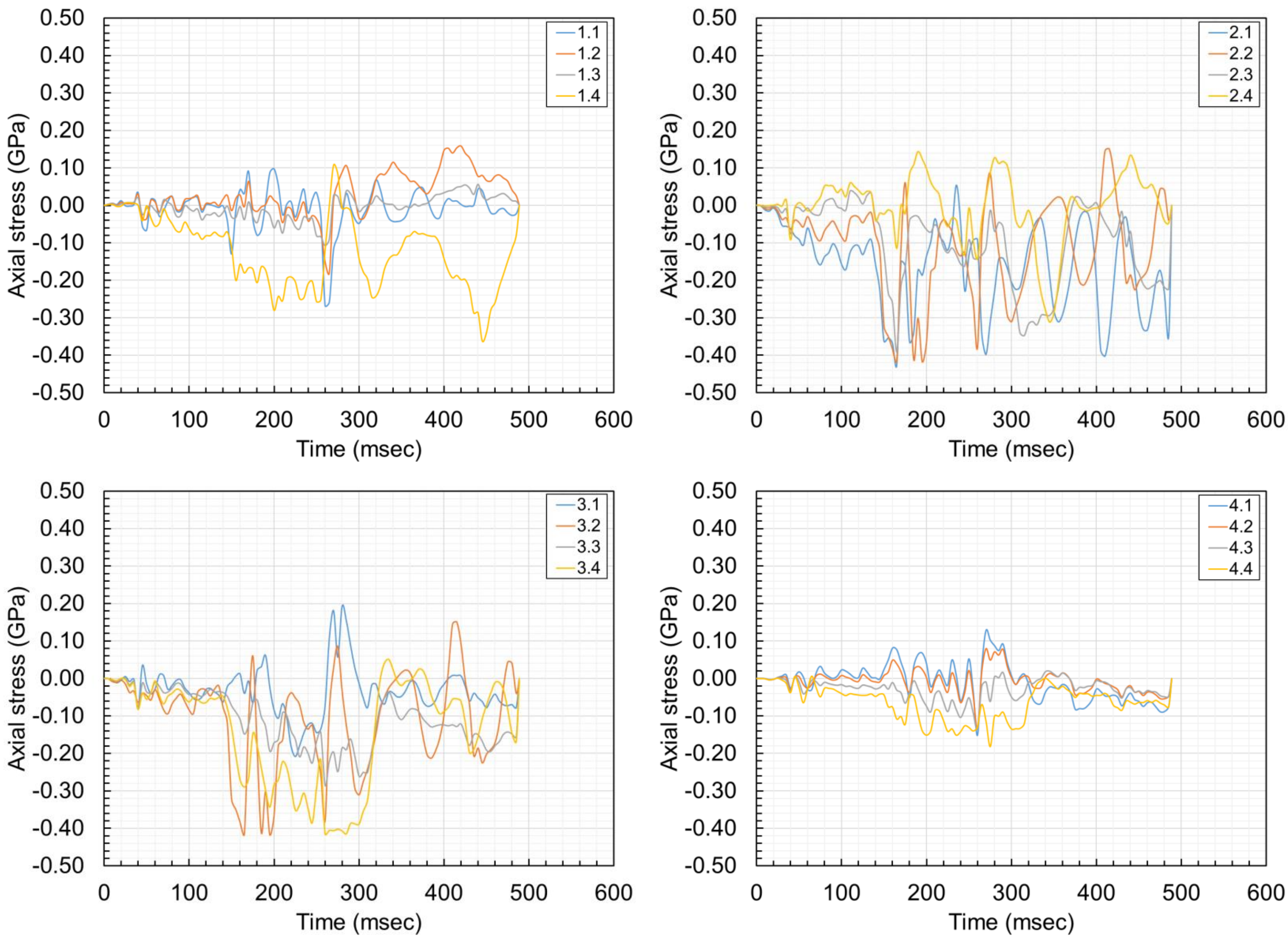


Figure D-27. Axial Stress Developed in Joint-Spanning Rebar – 10000S Vehicle Impact a Mid-Span – Near-Vertical Barrier

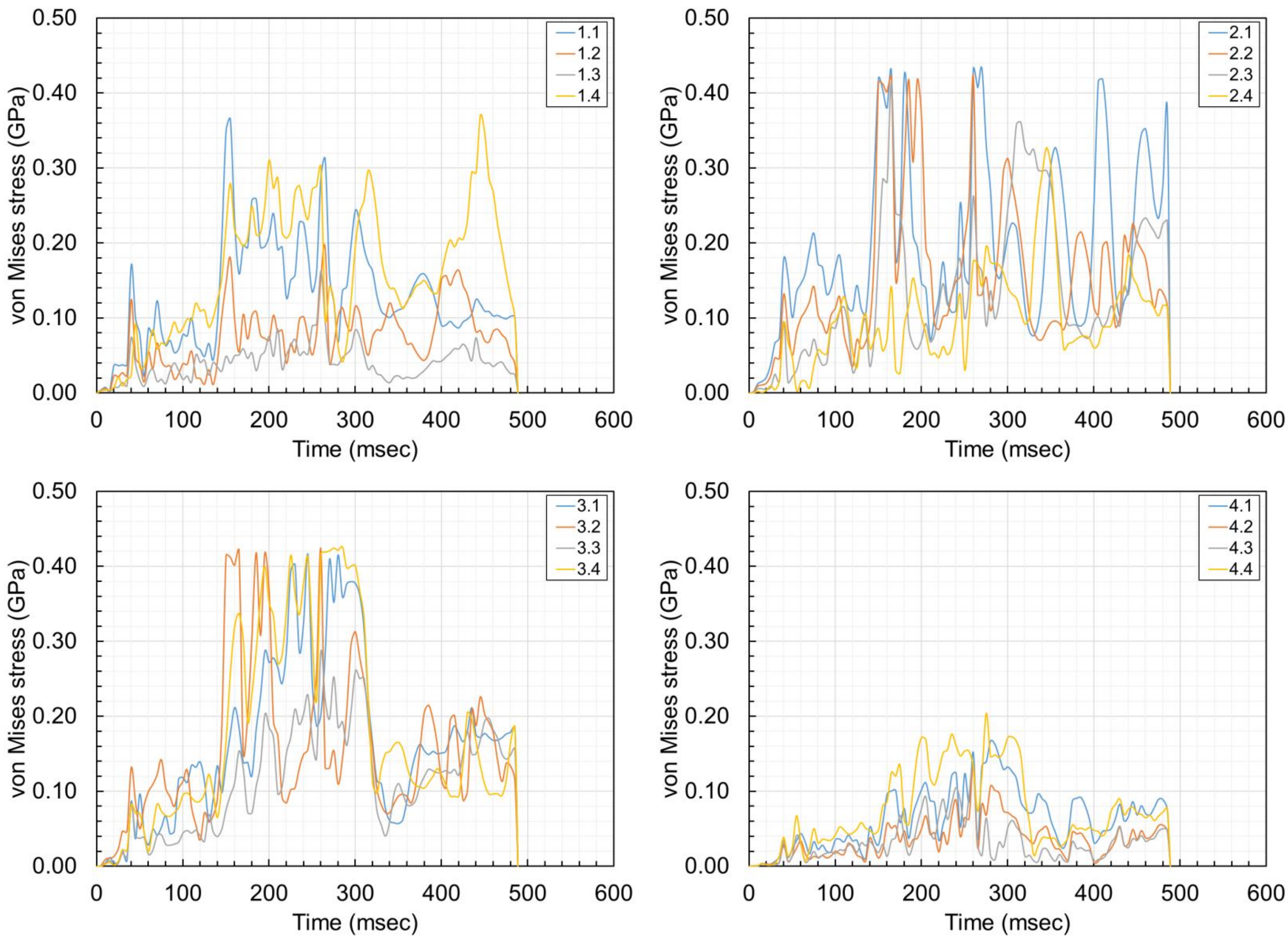


Figure D-28. Von-Mises Stress Developed in Joint-Spanning Rebar – 10000S Vehicle Impact a Mid-Span – Near-Vertical Barrier

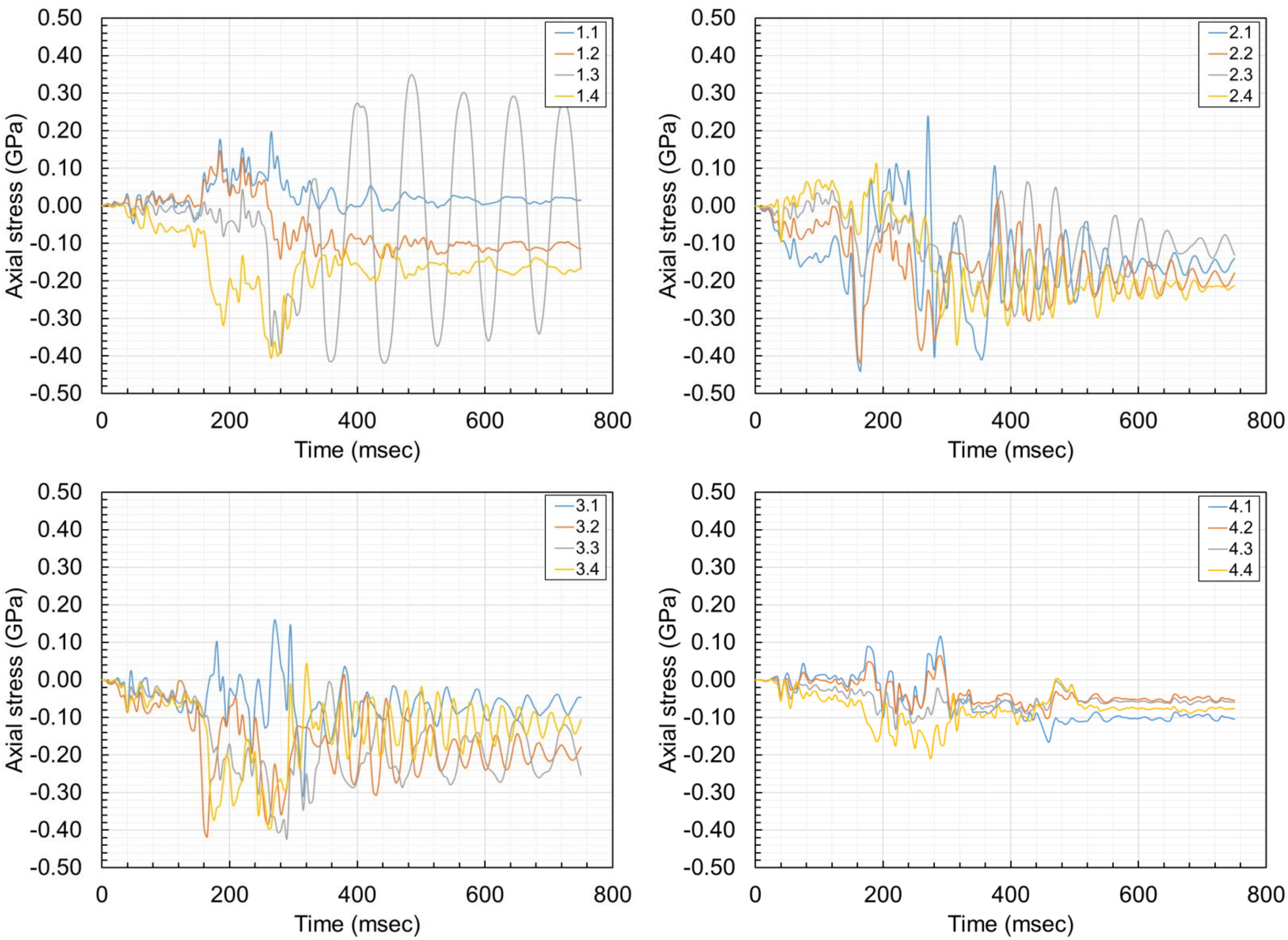


Figure D-29. Axial Stress Developed in Joint-Spanning Rebar – 10000S Vehicle Impact at ¾ -Span – Near-Vertical Barrier

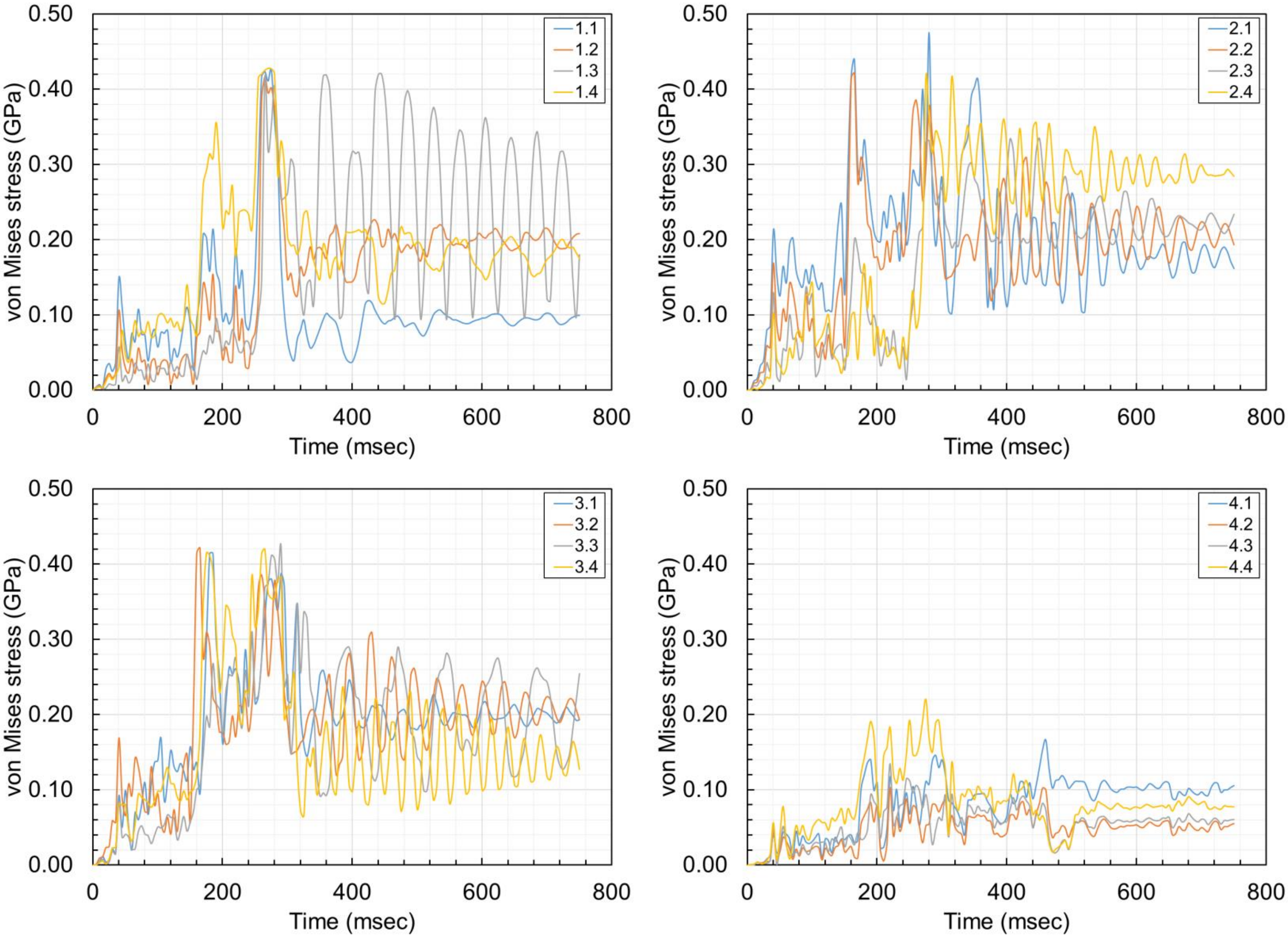


Figure D-30. Von-Mises Stress Developed in Joint-Spanning Rebar – 10000S Vehicle Impact at ¾ -Span – Near-Vertical Barrier

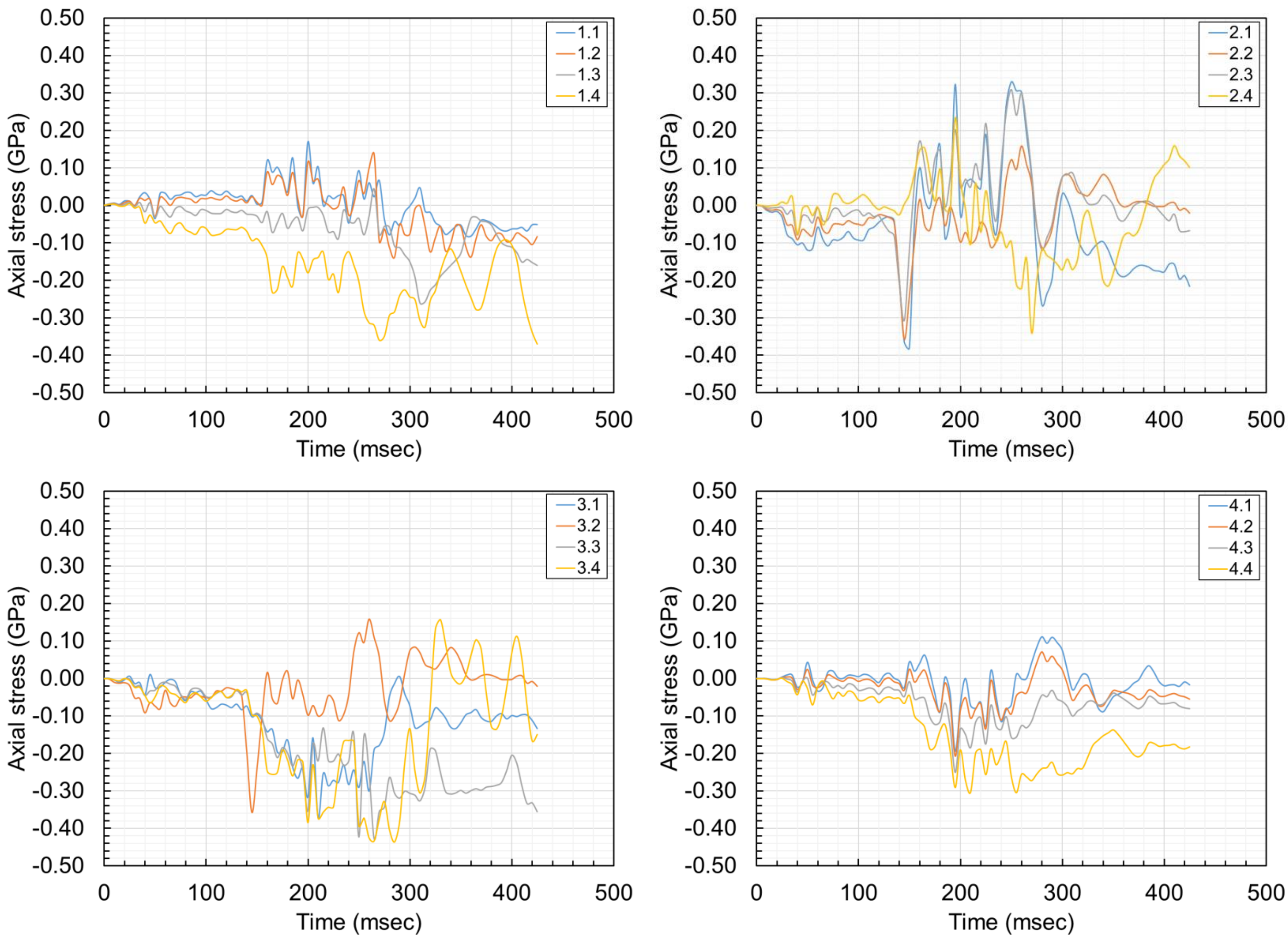


Figure D-31. Axial Stress Developed in Joint-Spanning Rebar – 10000S Vehicle Impact at a Joint – Near-Vertical Barrier

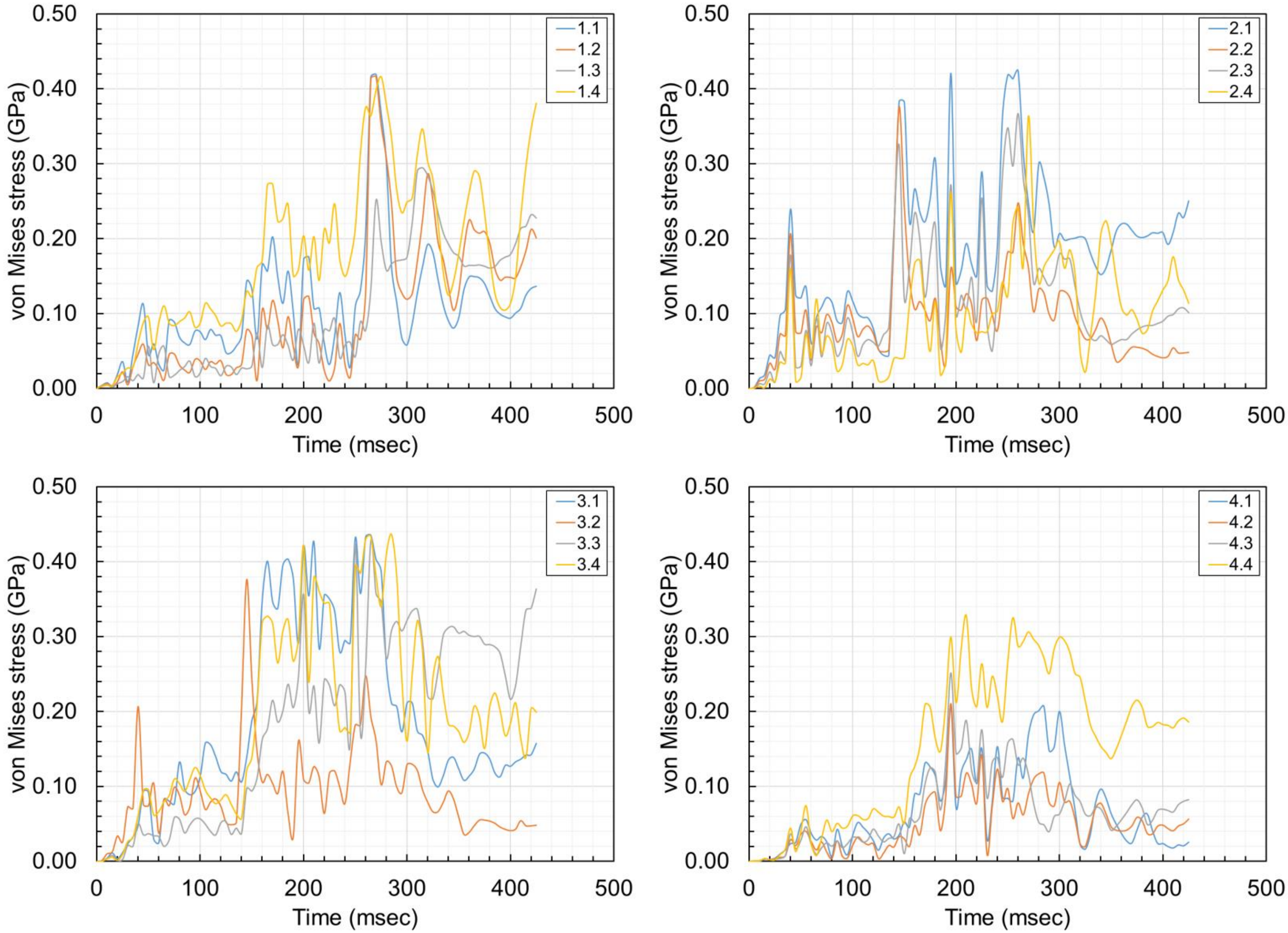


Figure D-32. Axial Stress Developed in Joint-Spanning Rebar – 10000S Vehicle Impact at a Joint – Near-Vertical Barrier

Appendix E. Longitudinal and Lateral Vehicle Accelerations and Velocity

The results of the longitudinal and lateral vehicle accelerations-time histories for 1100C, 2270P; and 10000S vehicle collisions with single-slope and near-vertical barriers are provided in this appendix.

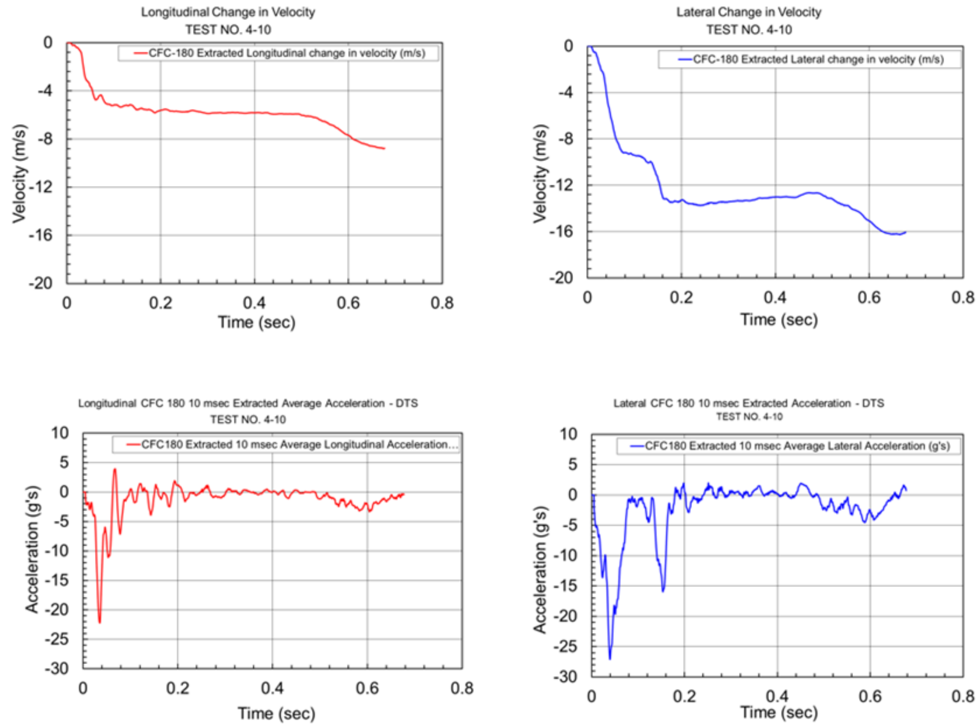


Figure E-1. Longitudinal and Lateral Vehicle Accelerations and Velocity – 1100C Vehicle Collison with Single-Slope Barrier – Impact at Mid-Span

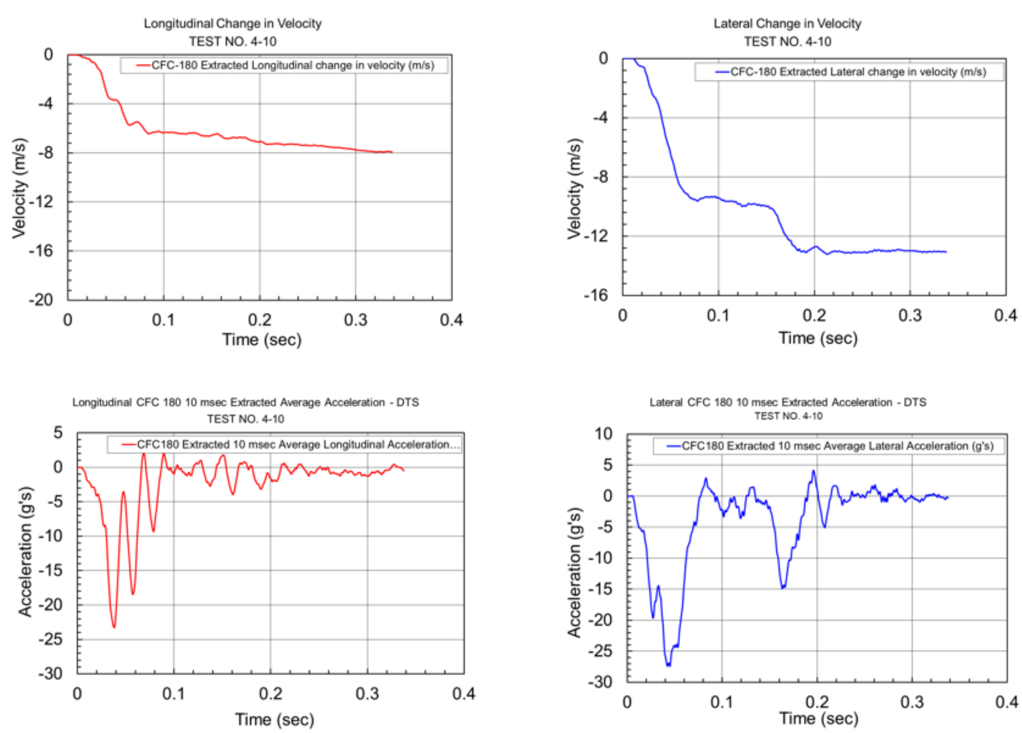


Figure E-2. Longitudinal and Lateral Vehicle Accelerations and Velocity – 1100C Vehicle Collison with Near-Vertical Barrier – Impact at Mid-Span

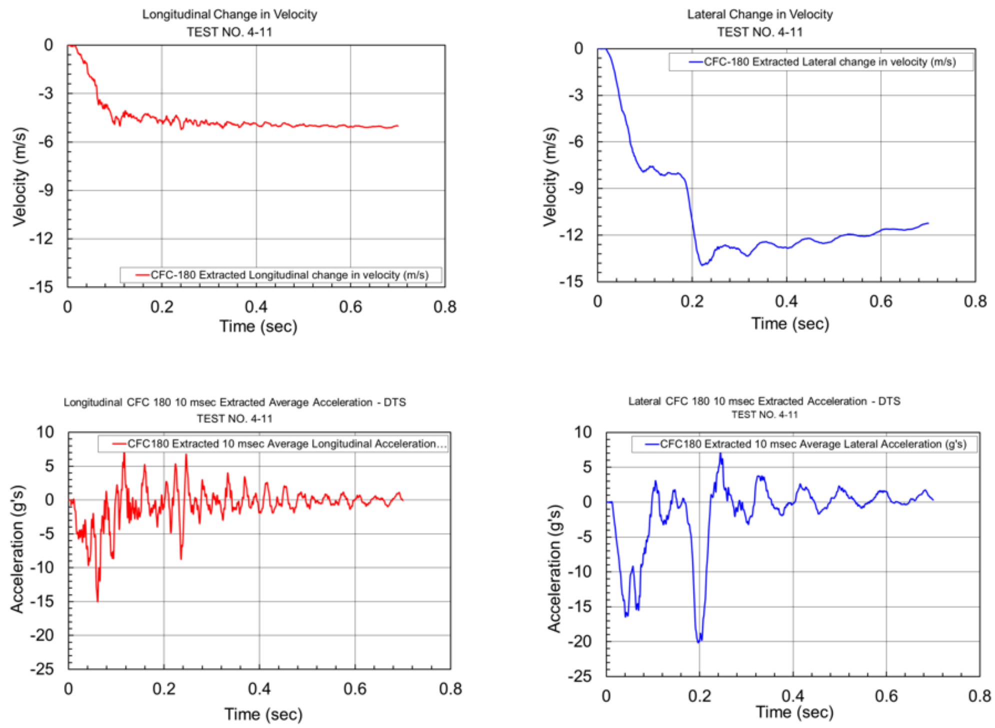


Figure E-3. Longitudinal and Lateral Vehicle Accelerations and Velocity – 2270P Vehicle Collision with Single-Slope Barrier – Impact at Mid-Span

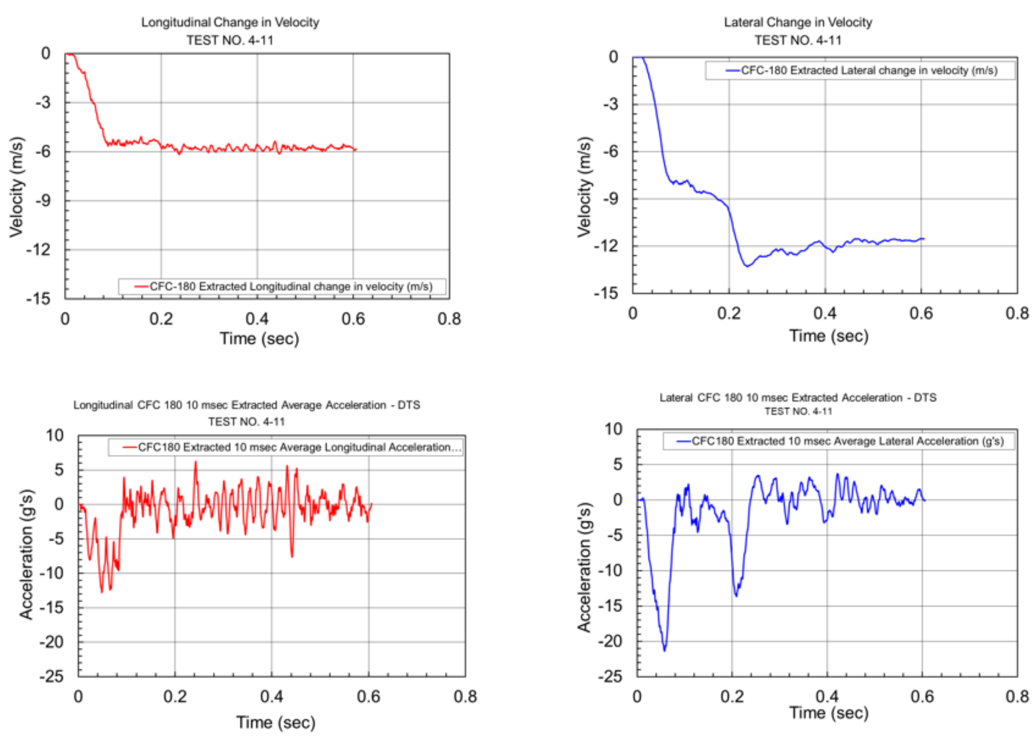


Figure E-4. Longitudinal and Lateral Vehicle Accelerations and Velocity 2270P Vehicle Collision with Near-Vertical Barrier – Impact at Mid-Span

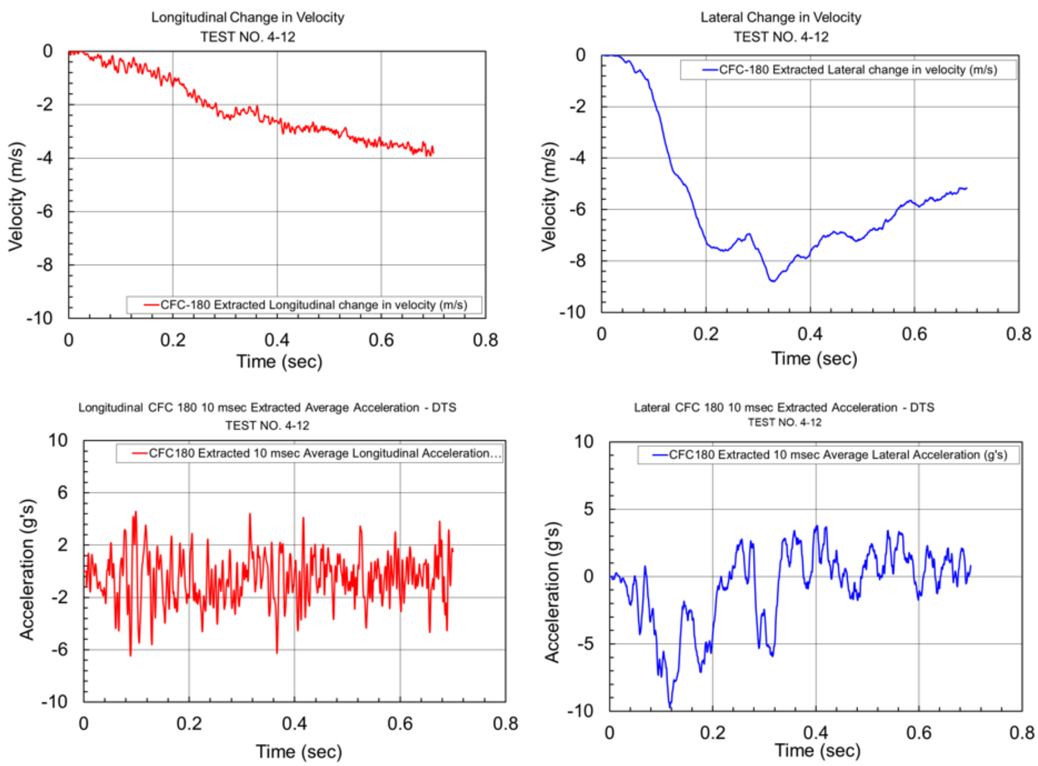


Figure E-5. Longitudinal and Lateral Vehicle Accelerations and Velocity – 10000S Vehicle Collision with Single-Slope Barrier – Impact at Mid-Span

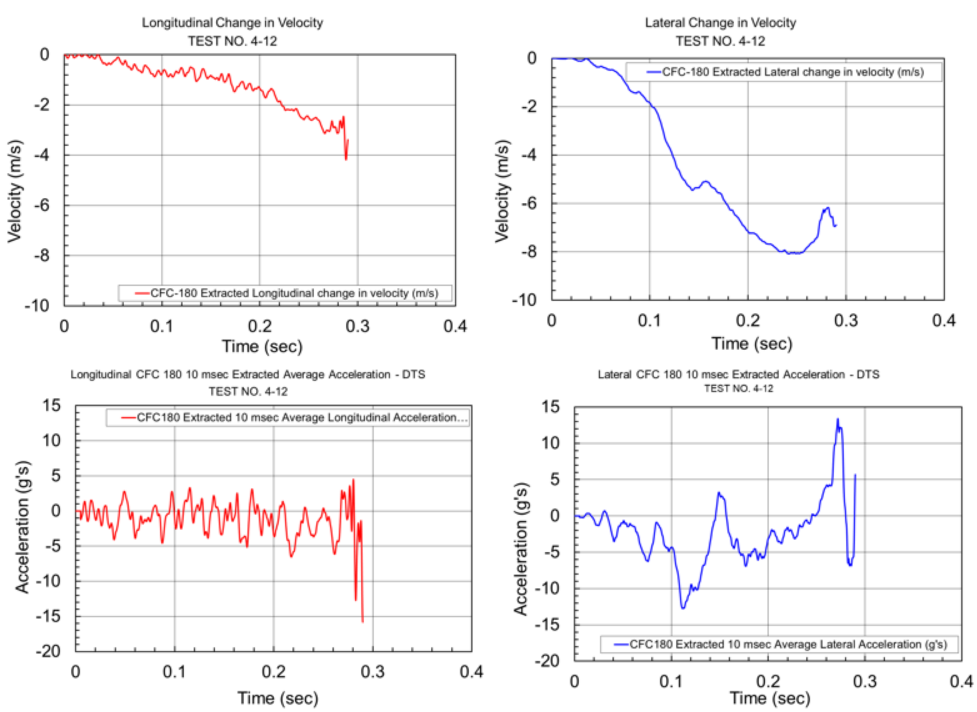


Figure E-6. Longitudinal and Lateral Vehicle Accelerations and Velocity – 10000S Vehicle Collision with Near-Vertical Barrier – Impact at Mid-Span

Appendix F. Material Specifications

Table F-1. Bill of Materials, Test No. ABCBRM-1

Item No.	Description	Material Specification	Reference
a1	Concrete	Min. *f'c* = 4,000 psi	Test Reports Enclosed
a2	Grout	Min. *f'c* = 8,000 psi (28-day) UltraFlow Grout	Rapid Set UltraFlow 4000/8
b1	#5 Bent Rebar, 108" Total Unbent Length	ASTM A615 Gr. 60	H#9700015322
b2	#5 Rebar, 115" Total Length	ASTM A615 Gr. 60	H#3600013409 H#3600018787
b3	#8 Rebar with 1"-8 UNC x 3" section, 51" Long, HRC	ASTM A615 Gr. 80 or ASTM A706-80 or ASTM A970 80	H#4119617
b3a	Rebar Component Head Fitting from 2⅛" Cold Finish Round Bar	CF Grade: 1018 ASTM A108	H#100101456 L#B1130464
b4	#5 Bent Rebar, 58⅝" Total Unbent Length	ASTM A615 Gr. 60	H#9700003155
b5	#4 Rebar, 956" Total Length (Grade Beam)	ASTM A615 Gr. 60	H#970007616 R#22-189
b5a	#4 Rebar, 956" Total Length (Bridge Deck)	ASTM A615 Gr. 60	H#3600021414 H#36000121966
b6	#6 Rebar, 80" Total Length	ASTM A615 Gr. 60	H#58044785 H#58043752 H#58045414 H#58045945 H#58044201
b7	#5 Bent Rebar, 41 5/16" Total Unbent Length	ASTM A615 Gr. 60	H#9700003155
b8	#5 Bent Rebar, 36½" Total Unbent Length	ASTM A615 Gr. 60	H#9700003155
b9	#5 Bent Rebar, 40½" Total Unbent Length	ASTM A615 Gr. 60	H#9700003155
b10	#5 Bent Rebar, 87 1/16" Total Unbent Length	ASTM A615 Gr. 60	H#7019522 R#22-189
b11	#5 Bent Rebar, 48½" Total Unbent Length	ASTM A615 Gr. 60	H#7019522 R#22-189
b12	#8 Rebar with 1"-8 UNC x 12" section, 60" Long, threaded - one end	ASTM A615 Gr. 80 or ASTM A706-80 or ASTM A970 80	H#4119617
b13	#5 Bent Rebar, 92" Total Unbent Length	ASTM A615 Gr. 60	H#3600013409 H#3600018787
c1	1 1/2" Dia., 8 1/16" Long, 1"-8 UNC x 2" Internally Threaded Tube	MTR says: ASTM A108-18 Grade 1018	H#10021154521

Table F-2. Bill of Materials, Test No. ABCBRM-1, Cont.

Item No.	Description	Material Specification	Reference
c2	2"x2"x1 3/8" Base Plate	Stainless Steel - (TBD)	H#10020925820
c3	7/8" Dia., 16 1/2" Long, Double-Headed Shear Tie, HRC 555 T-Head Both Ends	Mil Certs says this: ASTM A615 & A706 GR60	H#6031854 Order#21-1397-2
c4	5/8" Dia., 5 1/4" Long, 5/8"-11 UNC Male Transverse Tie, HRC 555 Series T-Head - One End, HRC 300M - One End	ASTM A970 & ASTM A706	H#4111735
c4a	Rebar Component Head Fitting from 1-5/8" Round Bar	MTR says: ASTM A108-18 Grade 1018 Cold Drawn	H#58047404
c5	5/8"-11 UNC Internally Threaded Transverse Receiving Tie, 1" Dia., 3 3/16" Long, Special #5 Head - One End, HRC 320 -One End	MTR says: ASTM A108-18 Grade 1018	H#10021154521
c6	5/8"-11 UNC Internally Threaded Transverse Receiving Tie, 1" Dia., 4 3/16" Long, Special #5 Head - One End, HRC 320- One End	MTR says: ASTM A108-18 Grade 1018	H#10021154521
c7	5/8"-11 UNC Internally Threaded Transverse Receiving Tie, 1" Dia., 5 1/4" Long, Special #5 Headed - One End, HRC 320 - One End	MTR says: ASTM A108-18 Grade 1018	H#10021154521
c8	2 1/2" ID, 44 5/8" Long Corrugated Inclined Pipe	ASTM A53 Gr. B Schedule 40	H#1350207 H#1441631
c9	2" Dia. Conduit, 119" Long	ASTM D3350, Min. SDR 13.5	Menards Receipt
c10	3" Dia. Conduit, 119" Long	ASTM D3350, Min. SDR 13.5	COC
d1	Epoxy Adhesive	Min. Bond Strength = 1,450 psi	COC
-	1"-8 UNC Heavy Hex Nut	ASTM A563A or equivalent	n/a

Table F-3. Concrete Compressive Strength Data

Item	Casting Date	Testing Date	Compressive Strength (psi)	Remark
Barrier No.1	10/07/2022	02/08/2023	4,450	124-day
Barrier Nos. 2, 3, 4, and 5	10/20/2022	02/08/2023	4,360	111-day
Barrier Nos. 6, 7, 8, and 9	10/27/2022	02/08/2023	4,640	104-day
Barrier Nos. 10, 11, 12, and 13	11/03/2022	02/08/2023	4,590	97-day
Deck, Truck #1	08/12/2022	10/07/2022	5,290	56-day
Deck, Truck #2	08/12/2022	10/07/2022	4,420	56-day
Deck, Truck #2	08/12/2022	10/07/2022	4,370	56-day
Barrier Pour #1A	10/07/2022	10/22/2022	3,450	13-day
1st Barrier Pour	10/07/2022	11/14/2022	4,150	38-day
2nd Barrier Pour	10/07/2022	11/14/2022	4,030	25-day
4th Barrier Pour	11/03/2022	11/14/2022	3,650	11-day
3A	10/27/2022	12/19/2022	4,590	53-day
3B	10/27/2022	12/19/2022	4,640	53-day
4B	11/03/2022	12/19/2022	4,280	46-day
4C	11/03/2022	12/19/2022	4,340	46-day

Table F-4. Grout Compressive Strength Data

Item	Casting Date	Testing Date	Compressive Strength (psi)	Remark
Inside Barrier Nos. 1 and 2	01/04/2023	01/09/2023	13,180	5-day
Outside Barrier Nos. 1 and 2	01/04/2023	01/09/2023	13,300	5-day
Barriers Nos. 3, 4, 5, and 6 1st Stage	01/11/2023	01/13/2023	7,820	2-day
Barrier Nos. 3, 4, 5, and 6 – 2nd Stage, Barriers Nos. 7 and 8 – 1st Stage	01/17/2023	02/02/2023	11,210	16-day
Barrier Nos. 7, 8, 9, 10,11 2nd Stage 12, &13 – 1st Stage	01/27/2023	02/02/2023	11,480	6-day
Barrier Nos. 3, 4, 5, 6 – 1st Stage	01/11/2023	02/08/2023	15,280	28-day
Barrier Nos. 7, 8, 9, 10,11 – 2nd Stage	01/27/2023	02/08/2023	14,350	12-day

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	ABCBR: Deck
Sample:	08122022.1
Description:	Truck #1

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:		Slump (in):	
Mix Name:		Air Content (%):	
Ticket Number:		Unit Weight (lb/ft³):	
Truck Number:		Air Temp (°F):	
Load Volume (yd³):		Mix Temp (°F):	
Mold Date:	08/12/2022	Min Temp (°F):	
Molded By:		Max Temp (°F):	
Initial Cure Method:			

Laboratory Test Data (ASTM C39)

Sample Number:	08122022.1					
Set Number:	Truck #1					
Specimen Number:	1					
Age:	56					
Length (in):	12					
Diameter (in):	5.98					
Area (in²):	28.09					
Density (lb/ft³):	140					
Test Date:	10/07/2022					
Break Type:	6					
Max Load (lbf):	148,685					
Strength (psi):	5,290					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set Truck #1, Specimen 1, 56-day Compressive Strength (psi): **5,290**

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Sample Receive Date: 10/07/2022

Approved by:

Matt Roessler

Matt Roessler Manager

Date: 10/18/2022

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Figure F-1. Concrete Material Specification, Test No. ABCBRM-1 (Item No. a1)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	ABCBR: Deck
Sample:	08122022.2
Description:	Truck #2

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:			
Mix Name:		Slump (in):	
Ticket Number:		Air Content (%):	
Truck Number:		Unit Weight (lb/ft³):	
Load Volume (yd³):		Air Temp (°F):	
Mold Date:	08/12/2022	Mix Temp (°F):	
Molded By:		Min Temp (°F):	
Initial Cure Method:		Max Temp (°F):	

Laboratory Test Data (ASTM C39)

Sample Number:	08122022.2					
Set Number:	Truck #2					
Specimen Number:	1					
Age:	56					
Length (in):	12					
Diameter (in):	5.99					
Area (in²):	28.18					
Density (lb/ft³):	139					
Test Date:	10/07/2022					
Break Type:	6					
Max Load (lbf):	124,493					
Strength (psi):	4,420					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set Truck #2, Specimen 1, 56-day Compressive Strength (psi): **4,420**

Sample Receive Date: 10/07/2022

Approved by:

Matt Roessler Manager

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Date: 10/18/2022

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Figure F-2. Concrete Material Specification, Test No. ABCBRM-1 (Item No. a1)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	ABCBR: Deck
Sample:	08122022.3
Description:	Truck #3

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

Supplier:		Property	Test Result
Mix Name:		Slump (in):	
Ticket Number:		Air Content (%):	
Truck Number:		Unit Weight (lb/ft^3):	
Load Volume (yd^3):		Air Temp (°F):	
Mold Date:	08/12/2022	Mix Temp (°F):	
Molded By:		Min Temp (°F):	
Initial Cure Method:		Max Temp (°F):	

Laboratory Test Data (ASTM C39)

Sample Number:	08122022.3					
Set Number:	Truck #3					
Specimen Number:	1					
Age:	56					
Length (in):	12					
Diameter (in):	5.99					
Area (in^2):	28.18					
Density (lb/ft^3):	139					
Test Date:	10/07/2022					
Break Type:	5					
Max Load (lbf):	123,250					
Strength (psi):	4,370					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set Truck #3, Specimen 1, 56-day Compressive Strength (psi): **4,370**

Sample Receive Date: 10/07/2022

Approved by:

Matt Roessler Manager

Date: 10/18/2022

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Figure F-3. Concrete Material Specification, Test No. ABCBRM-1 (Item No. a1)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	10072022.1
Description:	ABCBR Barrier - Barrier Pour #1A

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:			
Mix Name:		Slump (in):	
Ticket Number:		Air Content (%):	
Truck Number:		Unit Weight (lb/ft³):	
Load Volume (yd³):		Air Temp (°F):	
Mold Date:	10/07/2022	Mix Temp (°F):	
Molded By:		Min Temp (°F):	
Initial Cure Method:		MaxTemp (°F):	

Laboratory Test Data (ASTM C39)

Sample Number:	10072022.1					
Set Number:	1					
Specimen Number:	1					
Age:	13					
Length (in):	12					
Diameter (in):	5.95					
Area (in²):	27.81					
Density (lb/ft³):	140					
Test Date:	10/20/2022					
Break Type:	2					
Max Load (lbf):	95,963					
Strength (psi):	3,450					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set 1, Specimen 1, 13-day Compressive Strength (psi): **3,450**

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Date received:
Curing: ☒ Standard ☐ Field
ASTM C511
Submitted by:

Distribution:

Report Date:

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Figure F-4. Concrete Material Specification, Test No. ABCBRM-1 (Item No. a1)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	1C
Description:	ABCBR: 1rst BARRIER POUR

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:		Slump (in):	
Mix Name:		Air Content (%):	
Ticket Number:		Unit Weight (lb/ft³):	
Truck Number:		Air Temp (°F):	
Load Volume (yd³):		Mix Temp (°F):	
Mold Date:	10/07/2022	Min Temp (°F):	
Molded By:		MaxTemp (°F):	
Initial Cure Method:			

Laboratory Test Data (ASTM C39)

Sample Number:	1C					
Set Number:	38					
Specimen Number:	1					
Age:	38					
Length (in):	12					
Diameter (in):	5.98					
Area (in²):	28.09					
Density (lb/ft³):	140					
Test Date:	11/14/2022					
Break Type:	2					
Max Load (lbf):	116,500					
Strength (psi):	4,150					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set 38, Specimen 1, 38-day Compressive Strength (psi): **4,150**

Date received: 11/14/2022
Curing: ☒ Standard ☐ Field
ASTM C511
Submitted by:

Distribution:

Report Date:

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Figure F-5. Concrete Material Specification, Test No. ABCBRM-1 (Item No. a1)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	2A
Description:	ABCBR: 2nd BARRIER POUR

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:		Slump (in):	
Mix Name:		Air Content (%):	
Ticket Number:		Unit Weight (lb/ft³):	
Truck Number:		Air Temp (°F):	
Load Volume (yd³):		Mix Temp (°F):	
Mold Date:	10/20/2022	Min Temp (°F):	
Molded By:		MaxTemp (°F):	
Initial Cure Method:			

Laboratory Test Data (ASTM C39)

Sample Number:	2A					
Set Number:	25					
Specimen Number:	1					
Age:	25					
Length (in):	12					
Diameter (in):	5.95					
Area (in²):	27.81					
Density (lb/ft³):	140					
Test Date:	11/14/2022					
Break Type:	2					
Max Load (lbf):	112,178					
Strength (psi):	4,030					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set 25, Specimen 1, 25-day Compressive Strength (psi): **4,030**

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Date received: 11/14/2022
Curing: ☒ Standard ☐ Field
ASTM C511
Submitted by:

Distribution:

Report Date:

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Figure F-6. Concrete Material Specification, Test No. ABCBRM-1 (Item No. a1)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	10202022.1
Description:	ABCBR Barrier 2,3,4 & 5

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:			
Mix Name:		Slump (in):	
Ticket Number:		Air Content (%):	
Truck Number:		Unit Weight (lb/ft³):	
Load Volume (yd³):		Air Temp (°F):	
Mold Date:	10/20/2022	Mix Temp (°F):	
Molded By:	MwRSF	Min Temp (°F):	
Initial Cure Method:		Max Temp (°F):	

Laboratory Test Data (ASTM C39)

Sample Number:	10202022.1					
Set Number:	1					
Specimen Number:	1					
Age:	111					
Length (in):	12					
Diameter (in):	5.95					
Area (in²):	27.81					
Density (lb/ft³):	141					
Test Date:	02/08/2023					
Break Type:	3					
Max Load (lbf):	121,345					
Strength (psi):	4,360					
Spec Strength (psi):	7,000					
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set 1, Specimen 1, 111-day Compressive Strength (psi): **4,360**

Sample Receive Date: 02/08/2023

Approved by:

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Date:

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Figure F-7. Concrete Material Specification, Test No. ABCBRM-1 (Item No. a1)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	3B
Description:	ABCBR: 3B

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:		Slump (in):	
Mix Name:		Air Content (%):	
Ticket Number:		Unit Weight (lb/ft³):	
Truck Number:		Air Temp (°F):	
Load Volume (yd³):		Mix Temp (°F):	
Mold Date:	10/27/2022	Min Temp (°F):	
Molded By:		MaxTemp (°F):	
Initial Cure Method:			

Laboratory Test Data (ASTM C39)

Sample Number:	3B					
Set Number:	3B					
Specimen Number:	1					
Age:	53					
Length (in):	12					
Diameter (in):	5.96					
Area (in²):	27.90					
Density (lb/ft³):	140					
Test Date:	12/19/2022					
Break Type:	2					
Max Load (lbf):	129,318					
Strength (psi):	4,640					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set 3B, Specimen 1, 53-day Compressive Strength (psi): **4,640**

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Date received: 12/19/2022
Curing: ☒ Standard ☐ Field
ASTM C511
Submitted by:

Distribution:

Report Date:

This report shall not be reproduced, except in full, without prior approval of Alfred Benesch & Company. Results relate only to items tested.

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Figure F-8. Concrete Material Specification, Test No. ABCBRM-1 (Item No. a1)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	10272022.1
Description:	ABCBR Barrier 6,7,8, & 9

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:			
Mix Name:		Slump (in):	
Ticket Number:		Air Content (%):	
Truck Number:		Unit Weight (lb/ft³):	
Load Volume (yd³):		Air Temp (°F):	
Mold Date:	10/27/2022	Mix Temp (°F):	
Molded By:	MwRSF	Min Temp (°F):	
Initial Cure Method:		Max Temp (°F):	

Laboratory Test Data (ASTM C39)

Sample Number:	10272022.1					
Set Number:	1					
Specimen Number:	1					
Age:	104					
Length (in):	12					
Diameter (in):	5.97					
Area (in²):	27.99					
Density (lb/ft³):	138					
Test Date:	02/08/2023					
Break Type:	3					
Max Load (lbf):	129,897					
Strength (psi):	4,640					
Spec Strength (psi):	7,000					
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set 1, Specimen 1, 104-day Compressive Strength (psi): **4,640**

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Sample Receive Date: 02/08/2023

Approved by:

Matt Roessler Manager

Date: 02/08/2023

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Figure F-9. Concrete Material Specification, Test No. ABCBRM-1 (Item No. a1)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	3A
Description:	ABCBR: 3A

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

Supplier:		Property	Test Result
Mix Name:		Slump (in):	
Ticket Number:		Air Content (%):	
Truck Number:		Unit Weight (lb/ft³):	
Load Volume (yd³):		Air Temp (°F):	
Mold Date:	10/27/2022	Mix Temp (°F):	
Molded By:		Min Temp (°F):	
Initial Cure Method:		Max Temp (°F):	

Laboratory Test Data (ASTM C39)

Sample Number:	3A					
Set Number:	3A					
Specimen Number:	1					
Age:	53					
Length (in):	12					
Diameter (in):	5.97					
Area (in²):	27.99					
Density (lb/ft³):	139					
Test Date:	12/19/2022					
Break Type:	2					
Max Load (lbf):	128,579					
Strength (psi):	4,590					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set 3A, Specimen 1, 53-day Compressive Strength (psi): **4,590**

Sample Receive Date: 12/19/2022

Approved by:

Matt Roessler

Matt Roessler Manager

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Date: 12/19/2022

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Figure F-10. Concrete Material Specification, Test No. ABCBRM-1 (Item No. a1)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	4A
Description:	ABCBR: 4th BARRIER POUR

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:			
Mix Name:		Slump (in):	
Ticket Number:		Air Content (%):	
Truck Number:		Unit Weight (lb/ft³):	
Load Volume (yd³):		Air Temp (°F):	
Mold Date:	11/03/2022	Mix Temp (°F):	
Molded By:		Min Temp (°F):	
Initial Cure Method:		Max Temp (°F):	

Laboratory Test Data (ASTM C39)

Sample Number:	4A					
Set Number:	11					
Specimen Number:	1					
Age:	11					
Length (in):	12					
Diameter (in):	5.96					
Area (in²):	27.90					
Density (lb/ft³):	138					
Test Date:	11/14/2022					
Break Type:	2					
Max Load (lbf):	101,701					
Strength (psi):	3,650					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set 11, Specimen 1, 11-day Compressive Strength (psi): **3,650**

Sample Receive Date: 11/14/2022

Approved by:

Matt Roessler Manager

Date: 11/14/2022

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Figure F-11. Concrete Material Specification, Test No. ABCBRM-1 (Item No. a1)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	4C
Description:	ABCBR: 4C

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:		Slump (in):	
Mix Name:		Air Content (%):	
Ticket Number:		Unit Weight (lb/ft³):	
Truck Number:		Air Temp (°F):	
Load Volume (yd³):		Mix Temp (°F):	
Mold Date:	11/03/2022	Min Temp (°F):	
Molded By:		MaxTemp (°F):	
Initial Cure Method:			

Laboratory Test Data (ASTM C39)

Sample Number:	4C					
Set Number:	4C					
Specimen Number:	1					
Age:	46					
Length (in):	12					
Diameter (in):	5.99					
Area (in²):	28.18					
Density (lb/ft³):	138					
Test Date:	12/19/2022					
Break Type:	2					
Max Load (lbf):	122,267					
Strength (psi):	4,340					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set 4C, Specimen 1, 46-day Compressive Strength (psi): **4,340**

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Date received: 12/19/2022
Curing: ☒ Standard ☐ Field
ASTM C511
Submitted by:

Distribution:

Report Date:

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Figure F-12. Concrete Material Specification, Test No. ABCBRM-1 (Item No. a1)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	4B
Description:	ABCBR: 4B

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:		Slump (in):	
Mix Name:		Air Content (%):	
Ticket Number:		Unit Weight (lb/ft³):	
Truck Number:		Air Temp (°F):	
Load Volume (yd³):		Mix Temp (°F):	
Mold Date:	11/03/2022	Min Temp (°F):	
Molded By:		MaxTemp (°F):	
Initial Cure Method:			

Laboratory Test Data (ASTM C39)

Sample Number:	4B					
Set Number:	4B					
Specimen Number:	1					
Age:	46					
Length (in):	12					
Diameter (in):	6					
Area (in²):	28.27					
Density (lb/ft³):	139					
Test Date:	12/19/2022					
Break Type:	2					
Max Load (lbf):	121,039					
Strength (psi):	4,280					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set 4B, Specimen 1, 46-day Compressive Strength (psi): **4,280**

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Date received: 12/19/2022
Curing: ☒ Standard ☐ Field
ASTM C511
Submitted by:

Distribution:

Report Date:

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Figure F-13. Concrete Material Specification, Test No. ABCBRM-1 (Item No. a1)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	4A
Description:	ABCBR: 4th BARRIER POUR

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:		Slump (in):	
Mix Name:		Air Content (%):	
Ticket Number:		Unit Weight (lb/ft³):	
Truck Number:		Air Temp (°F):	
Load Volume (yd³):		Mix Temp (°F):	
Mold Date:	11/03/2022	Min Temp (°F):	
Molded By:		MaxTemp (°F):	
Initial Cure Method:			

Laboratory Test Data (ASTM C39)

Sample Number:	4A					
Set Number:	11					
Specimen Number:	1					
Age:	11					
Length (in):	12					
Diameter (in):	5.96					
Area (in²):	27.90					
Density (lb/ft³):	138					
Test Date:	11/14/2022					
Break Type:	2					
Max Load (lbf):	101,701					
Strength (psi):	3,650					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set 11, Specimen 1, 11-day Compressive Strength (psi): **3,650**

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Date received: 11/14/2022
Curing: ☒ Standard ☐ Field
ASTM C511
Submitted by:

Distribution:

Report Date:

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Figure F-14. Concrete Material Specification, Test No. ABCBRM-1 (Item No. a1)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	11032022.1
Description:	ABCBR Barrier 10,11,12 & 13

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:			
Mix Name:		Slump (in):	
Ticket Number:		Air Content (%):	
Truck Number:		Unit Weight (lb/ft³):	
Load Volume (yd³):		Air Temp (°F):	
Mold Date:	11/03/2022	Mix Temp (°F):	
Molded By:	MwRSF	Min Temp (°F):	
Initial Cure Method:		Max Temp (°F):	

Laboratory Test Data (ASTM C39)

Sample Number:	11032022.1					
Set Number:	1					
Specimen Number:	1					
Age:	97					
Length (in):	12					
Diameter (in):	5.99					
Area (in²):	28.18					
Density (lb/ft³):	139					
Test Date:	02/08/2023					
Break Type:	2					
Max Load (lbf):	129,373					
Strength (psi):	4,590					
Spec Strength (psi):	7,000					
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set 1, Specimen 1, 97-day Compressive Strength (psi): **4,590**

Sample Receive Date: 02/08/2023

Approved by:

Matt Roessler Manager

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Date: 02/08/2023

Figure F-15. Concrete Material Specification, Test No. ABCBRM-1 (Item No. a1)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	Inside Sample Barriers 1&2 Wet Mix
Description:	ABCBR (Grout)

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:		Slump (in):	
Mix Name:		Air Content (%):	
Ticket Number:		Unit Weight (lb/ft³):	
Truck Number:		Air Temp (°F):	
Load Volume (yd³):		Mix Temp (°F):	
Mold Date:	01/04/2023	Min Temp (°F):	
Molded By:		Max Temp (°F):	
Initial Cure Method:			

Laboratory Test Data (ASTM C39)

Sample Number:	Inside Sample Barri					
Set Number:	ABCBR(Grout)					
Specimen Number:	1					
Age:	5					
Length (in):	8					
Diameter (in):	3.98					
Area (in²):	12.44					
Density (lb/ft³):	134					
Test Date:	01/09/2023					
Break Type:	6					
Max Load (lbf):	163,997					
Strength (psi):	13,180					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set ABCBR(Grout), Specimen 1, 5-day Compressive Strength (ps **13,180**

Sample Receive Date: 01/09/2023

Approved by:

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Date:

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Figure F-16. Grout Material Specification, Test No. ABCBRM-1 (Item No. a2)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	Outside Sample Barriers 1&2 (Next To System)
Description:	ABCBR (Grout)

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

Supplier:		Property	Test Result
Mix Name:		Slump (in):	
Ticket Number:		Air Content (%):	
Truck Number:		Unit Weight (lb/ft³):	
Load Volume (yd³):		Air Temp (°F):	
Mold Date:	01/04/2023	Mix Temp (°F):	
Molded By:		Min Temp (°F):	
Initial Cure Method:		Max Temp (°F):	

Laboratory Test Data (ASTM C39)

Sample Number:	Outside Sample Ba					
Set Number:	ABCBR (Grout)					
Specimen Number:	1					
Age:	5					
Length (in):	8					
Diameter (in):	3.99					
Area (in²):	12.50					
Density (lb/ft³):	129					
Test Date:	01/09/2023					
Break Type:	2					
Max Load (lbf):	166,310					
Strength (psi):	13,300					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set ABCBR (Grout), Specimen 1, 5-day Compressive Strength (p **13,300**

Sample Receive Date: 01/09/2023

Approved by:

Matt Roessler

Matt Roessler Manager

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Date: 01/09/2023

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Figure F-17. Grout Material Specification, Test No. ABCBRM-1 (Item No. a2)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	01172023.1
Description:	ABCBR Grout Barriers 3,4,5,&6 2nd Stage 7&8 1st Stage. Cyl. 4

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:			
Mix Name:		Slump (in):	
Ticket Number:		Air Content (%):	
Truck Number:		Unit Weight (lb/ft³):	
Load Volume (yd³):		Air Temp (°F):	
Mold Date:	01/17/2023	Mix Temp (°F):	
Molded By:		Min Temp (°F):	
Initial Cure Method:		Max Temp (°F):	

Laboratory Test Data (ASTM C39)

Sample Number:	01172023.1					
Set Number:	4					
Specimen Number:	1					
Age:	16					
Length (in):	8					
Diameter (in):	3.99					
Area (in²):	12.50					
Density (lb/ft³):	126					
Test Date:	02/02/2023					
Break Type:	2					
Max Load (lbf):	140,209					
Strength (psi):	11,210					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set 4, Specimen 1, 16-day Compressive Strength (psi): **11,210**

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Sample Receive Date: 02/02/2023

Approved by:

Matt Roessler Manager

Date: 02/02/2023

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Figure F-18. Grout Material Specification, Test No. ABCBRM-1 (Item No. a2)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	01272023.1
Description:	ABCBR Grout Barriers 7,8,9,10,11 2nd Stage 12,13 1st Stage, Cyl 5

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:		Slump (in):	
Mix Name:		Air Content (%):	
Ticket Number:		Unit Weight (lb/ft³):	
Truck Number:		Air Temp (°F):	
Load Volume (yd³):		Mix Temp (°F):	
Mold Date:	01/27/2023	Min Temp (°F):	
Molded By:		Max Temp (°F):	
Initial Cure Method:			

Laboratory Test Data (ASTM C39)

Sample Number:	01272023.1					
Set Number:	5					
Specimen Number:	1					
Age:	6					
Length (in):	8					
Diameter (in):	4					
Area (in²):	12.57					
Density (lb/ft³):	133					
Test Date:	02/02/2023					
Break Type:	2					
Max Load (lbf):	144,259					
Strength (psi):	11,480					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set 5, Specimen 1, 6-day Compressive Strength (psi): **11,480**

Sample Receive Date: 02/02/2023

Approved by:

Matt Roessler Manager

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Date: 02/02/2023

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Figure F-19. Grout Material Specification, Test No. ABCBRM-1 (Item No. a2)

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Concrete Sample Test Report
Cylinder Compressive Strength

Project Name:	Midwest Roadside Safety - Misc Testing
Project Number:	00110546.00
Client:	Midwest Roadside Safety Facility
Location:	Midwest Roadside Safety
Sample:	01132023.1
Description:	ABCBR Grout Barriers 3,4,5,&6 1st Stage

Field Data (ASTM C172, C143, C173/C231, C138, C1064)

		Property	Test Result
Supplier:			
Mix Name:		Slump (in):	
Ticket Number:		Air Content (%):	
Truck Number:		Unit Weight (lb/ft³):	
Load Volume (yd³):		Air Temp (°F):	
Mold Date:	01/11/2023	Mix Temp (°F):	
Molded By:		Min Temp (°F):	
Initial Cure Method:		MaxTemp (°F):	

Laboratory Test Data (ASTM C39)

Sample Number:	01132023.1					
Set Number:	Cylinder Name 3					
Specimen Number:	1					
Age:	2					
Length (in):	8					
Diameter (in):	4					
Area (in²):	12.57					
Density (lb/ft³):	129					
Test Date:	01/13/2023					
Break Type:	3					
Max Load (lbf):	98,247					
Strength (psi):	7,820					
Spec Strength (psi):						
Excl in Avg Strength:	☐	☐	☐	☐	☐	☐

Remarks:
Set Cylinder Name 3, Specimen 1, 2-day Compressive Strength (**7,820**

Date received: 01/13/2023
Curing: ☒ Standard ☐ Field
ASTM C511
Submitted by:

Type 1 Type 2 Type 3 Type 4 Type 5 Type 6

Distribution:

Report Date:

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Figure F-20. Grout Material Specification, Test No. ABCBRM-1 (Item No. a2)

NUCOR

Mill Certification
05/06/2022

MTR#:1024037-2
Lot #:970001532220
500 REBAR RD
SEDALIA, MO 65301 US
660 951-1679
Fax: 660 951-1698

Sold To: ABC COATING CO INC
PO BOX 9693
TULSA, OK 74157 US

Ship To: ABC COATING CO - MN
2500 W CR B
DOOR 16A
ROSEVILLE, MN 55113 US

Customer PO	22-0331 NCMO	Sales Order #	97006272 - 5.8
Product Group	Rebar	Product #	3019447
Grade	A615 Gr 60/AASHTO M31	Lot #	970001532220
Size	#5	Heat #	9700015322
BOL #	BOL-1122295	Load #	1024037
Description	Rebar #5/16mm A615 Gr 60/AASHTO M31 60' 0" [720"] 6001-10000 lbs	Customer Part #	
Production Date	04/28/2022	Qty Shipped LBS	32040
Product Country Of Origin	United States	Qty Shipped EA	512
Original Item Description		Original Item Number	

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed above and that it satisfies those requirements.

Melt Country of Origin : United States   Melting Date: 04/28/2022

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Ni (%)	Cr (%)	Mo (%)	V (%)	Nb (%)
0.24	0.78	0.008	0.023	0.221	0.08	0.10	0.02	0.004	0.000

Tensile testing

	Yield (PSI)	Tensile (PSI)	Elongation in 8" (%)
(1)	75600	89400	15.2

Mechanical

	Average Deformation Height (IN)	Bend Test
(1)	0.040	Pass

Comments:
1. All manufacturing processes of the steel materials in this product, including melting, casting and rolling were performed in the USA.
2. Mercury, Radium, Hexavalent Chrome or Alpha source materials in any form have not been used in the production and testing of this material.
3. Weld repair was not performed on this material.

Figure F-21. #5 Bent Rebar Material Specification, Test No. ABCBRM-1 (Item No. b1)

NUCOR

Mill Certification
09/18/2020

MTR#:486159-2
Lot #:360001340921
ONE NUCOR WAY
BOURBONNAIS, IL 60914 US
815 937-3131
Fax: 815 939-5599

Sold To: AMBASSADOR STEEL FAB LLC
PO BOX 627
AUBURN, IN 46706 US

Ship To: AMBASSADOR STEEL CORP
1050 ST GEORGE RD
BOURBONNAIS, IL 60914 US

Customer PO	PO116607A	Sales Order #	36014877 - 7.5
Product Group	Rebar	Product #	2110230
Grade	A615 Gr 60/AASHTO M31	Lot #	360001340921
Size	#5	Heat #	3600013409
BOL #	BOL-579306	Load #	486159
Description	Rebar #5/16mm A615 Gr 60/AASHTO M31 40' 0" [480"] 4001-8000 lbs	Customer Part #	
Production Date	06/12/2020	Qty ShippedLBS	22530
Product Country Of Origin	United States	Qty ShippedEA	540
Original Item Description		Original Item Number	

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed above and that it satisfies those requirements.

Melt Country of Origin : United States — Melting Date: 06/08/2020

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Ni (%)	Cr (%)	Mo (%)	Cu (%)	V (%)	Nb (%)
0.39	0.86	0.012	0.055	0.180	0.24	0.12	0.09	0.34	0.010	0.002

Other Test Results

Yield (PSI) : 65100 — Tensile (PSI) : 101100 — Average Deformation Height (IN) : 0.047

Elongation in 8" (%) : 15.5 — Bend Test : Pass — Weight Percent Variance (%) : -2.70

Comments:

All manufacturing processes of the steel materials in this product, including melting, have occurred within the United States. Products produced are weld free. Mercury, in any form, has not been used in the production or testing of this material.

Figure F-22. #5 Rebar Material Specification, Test No. ABCBRM-1 (Item No. b2)

NUCOR

Mill Certification
03/01/2021

MTR#:625286-2
Lot #:360001878720
ONE NUCOR WAY
BOURBONNAIS, IL 60914 US
815 937-3131
Fax: 815 939-5599

Sold To: AMBASSADOR STEEL FAB LLC
PO BOX 627
AUBURN, IN 46706 US

Ship To: AMBASSADOR STEEL CORP
1050 ST GEORGE RD
BOURBONNAIS, IL 60914 US

Customer PO	PO118082A	Sales Order #	36019060 - 3.9
Product Group	Rebar	Product #	2110230
Grade	A615 Gr 60/AASHTO M31	Lot #	360001878720
Size	#5	Heat #	3600018787
BOL #	BOL-706126	Load #	625286
Description	Rebar #5/16mm A615 Gr 60/AASHTO M31 40' 0" [480"] 4001-8000 lbs	Customer Part #	
Production Date	02/20/2021	Qty ShippedLBS	22530
Product Country Of Origin	United States	Qty ShippedEA	540
Original Item Description		Original Item Number	

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed above and that it satisfies those requirements.

Melt Country of Origin : United States | Melting Date: 02/14/2021

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Ni (%)	Cr (%)	Mo (%)	Cu (%)	V (%)	Nb (%)
0.40	1.00	0.014	0.031	0.158	0.22	0.14	0.07	0.38	0.011	0.002

Mechanical

	Average Deformation Height (IN)	Bend Test
(1)	0.041	Pass

Tensile testing

	Yield (PSI)	Tensile (PSI)	Elongation in 8" (%)
(1)	73200	112100	13.6

Other Test Results
Weight Percent Variance (%) : -3.40

Comments:

All manufacturing processes of the steel materials in this product, including melting, have occurred within the United States. Products produced are weld free. Mercury, in any form, has not been used in the production or testing of this material.

Figure F-23. #5 Rebar Material Specification, Test No. ABCBRM-1 (Item No. b2)

CMC

CMC STEEL ARIZONA
11444 E. GERMANN RD.
MESA AZ 85212-9700

CERTIFIED MILL TEST REPORT
For additional copies call
830-372-8771

We hereby certify that the test results presented here are accurate and conform to the reported grade specification

Jacob Selzer – CMC Steel
Quality Assurance Manager

#8

EAT NO.:4119617 ECTION: REBAR 25MM (#8) 60'0" .615/A706-80 RADE: ASTM A615 & A706 GR80 Dual Gr OLL DATE: 06/10/2022 IELT DATE: 06/10/2022 ert. No.: 85086503 / 119617F660	SOLD TO	HRC Headed Reinforcement Corp 11200 Condor Ave Fountain Valley CA US 92708-6106 7145571455 7145574460	SHIP TO	HRC Headed Reinforcement Corp 11200 Condor Ave Fountain Valley CA US 92708-6106 7145571455 7145574460	Delivery#: 85086503 BOL#: 74855744 CUST PO#: 28830 CUST P/N: DLVRY LBS / HEAT: 24352.000 LB DLVRY PCS / HEAT: 152 EA

Characteristic	Value	Characteristic	Value	Characteristic	Value
C	0.29%	Elongation test 1	14%		
Mn	1.23%	Elongation Gage Lgth test 1	8IN		
P	0.018%	Tensile to Yield ratio test1	1.27		
S	0.031%	Bend Test 1	Passed		
Si	0.19%	Rebar Deformation Avg. Spaci	0.672IN		
Cu	0.32%	Rebar Deformation Avg. Heigh	0.062IN		
Cr	0.19%	Rebar Deformation Max. Gap	0.163IN		
Ni	0.12%	Bend Test Diameter	5.000IN		
Mo	0.069%	Strain at Peak Stress test 1	11.0%		
V	0.018%				
Cb	0.004%				
Sn	0.012%				
Al	0.002%				
N	0.0100%				
Carbon Eq A706	0.52%				
Yield Strength test 1	87.3ksi				
Yield Strength test 1 (metri	602MPa				
Tensile Strength test 1	110.9ksi				
Tensile Strength 1 (metric)	765MPa				

The Following is true of the material represented by this MTR:
*Material is fully killed and is Hot Rolled Steel
*100% melted and rolled in the USA
*EN10204:2004 3.1 compliant
*Contains no weld repair
*Contains no Mercury contamination
*Manufactured in accordance with the latest version of the plant quality manual
*Meets the "Buy America" requirements of 23 CFR635.410, 49 CFR 661
*Warning: This product can expose you to chemicals which are known to the State of California to cause cancer, birth defects or other reproductive harm. For more information go to www.P65Warnings.ca.gov

MARKS :

Figure F-24. #8 Rebar Material Specification, Test No. ABCBRM-1 (Item No. b3)

NUCOR
NUCOR CORPORATION
NUCOR COLD FINISH UTAH

Mill Certification
3/4/2020

MTR #: B1-119676
1875 West Highway 13 South
BRIGHAM CITY, UT 84302
(435) 734-9334
Fax: (435) 734-4581

Sold To: HEADED REINFORCEMENT CORP
11200 CONDOR AVE
FOUNTAIN VALLEY, CA 92708-6106
(714) 557-1455

Ship To: HEADED REINFORCEMENT CORP
11165 CONDOR AVE
FOUNTAIN VALLEY, CA 92708

Customer P.O.	26049	Sales Order	554432.5
Product Group	Cold Finish Bar	Part Number	320037
Grade	1018 ASTM A108	Lot #	B1130464
Size	Round 2.1250 (.0030)	Heat #	100101456
Product	RD 2.1250" 1018 12-R CD	B.L. Number	B1-421435
Description	CF Grade 1018	Load Number	B1-119676
Customer Spec		Customer Part #	

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed above and that it satisfies those requirements.

Part Detail: RD 2.1250" 1018 12-R Cold Drawn
Process: Cold Drawn

C	Mn	P	S	Si	Cu	Cr	Ni	Mo	Sn	V	Cb
0.17%	0.85%	0.008%	0.031%	0.28%	0.20%	0.08%	0.08%	0.020%	0.008%	0.0030%	0.002%

Al	As	Pb	B
0.001%	0.004%	0.000%	0.0000%

Melting Mill: NSNE   Country of Melting: USA

Reduction Ratio 11.7 :1   Country of Rolling: USA   Rolling Mill: NSNE

ASTM E381
Surface: 1   Mid Radius: 1   Center: 2

Country of Cold Finishing: USA

Specification Comments:

Comments: ISO 9001 certified quality system

1. Material certifies to ASTM A 108 - 18 (unless otherwise noted) for Standard Cold Finished Bars.
2. This material has not been welded nor weld repaired.
3. Mercury has not been used in the production of this material.

Figure F-25. Rebar Component Head Fitting Room Material Specification, Test No. ABCBRM-1 (Item No. b3a)

NUCOR

Mill Certification
10/07/2020

MTR#:511826-1
Lot #:970000315520
500 REBAR RD
SEDALIA, MO 65301 US
660 951-1676
Fax: 660 951-1698

Sold To: HARRIS SUPPLY - STONEY CREEK
318 ARVIN AVE
STONEY CREEK, ON L8E 2M2 CA

Ship To: HARRIS SUPPLY SOLUTIONS INC
6801 N. 9TH STREET
KINDER MORGAN OMAHA
OMAHA, NE 68112 US

Customer PO	163445	Sales Order #	97001860 - 1.1
Product Group	Rebar	Product #	2110230
Grade	A615 Gr 60/AASHTO M31	Lot #	970000315520
Size	#5	Heat #	9700003155
BOL #	BOL-592697	Load #	511826
Description	Rebar #5/16mm A615 Gr 60/AASHTO M31 40' 0" [480"] 4001-8000 lbs	Customer Part #	
Production Date	09/28/2020	Qty Shipped LBS	47563.2
Product Country Of Origin	United States	Qty Shipped EA	1140
Original Item Description		Original Item Number	

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed above and that it satisfies those requirements.

Melt Country of Origin : United States — Melting Date: 09/28/2020

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Ni (%)	Cr (%)	Mo (%)	V (%)	Nb (%)
0.25	0.81	0.006	0.016	0.231	0.12	0.14	0.03	0.006	0.002

Other Test Results

Yield (PSI) : 84600 — Tensile (PSI) : 99300 — Average Deformation Height (IN) : 0.052

Elongation in 8" (%) : 10.2 — Bend Test : Pass

Comments:

1. All manufacturing processes of the steel materials in this product, including melting, casting and rolling were performed in the USA.
2. Mercury, Radium, Hexavalent Chrome or Alpha source materials in any form have not been used in the production and testing of this material.
3. Weld repair was not performed on this material.

Figure F-26. #5 Rebar Material Specification, Test No. ABCBRM-1 (Item No. b4, b7, b8, and b9)

NUCOR

Mill Certification
05/24/2021

MTR#:708712-1
Lot #:970000761620
500 REBAR RD
SEDALIA, MO 65301 US
660 951-1679
Fax: 660 951-1698

Sold To: SIMCOTE INC
1645 RED ROCK RD
ST PAUL, MN 55119 US

Ship To: SIMCOTE INC
1645 RED ROCK RD
ST PAUL, MN 55119 US

Customer PO	MN-3766	Sales Order #	97003933 - 1.24
Product Group	Rebar	Product #	2110206
Grade	A615 Gr 60/AASHTO M31	Lot #	970000761620
Size	#4	Heat #	9700007616
BOL #	BOL-784431	Load #	708712
Description	Rebar #4/13mm A615 Gr 60/AASHTO M31 60' 0" [720"] 6001-10000 lbs	Customer Part #	
Production Date	05/24/2021	Qty Shipped LBS	48335.88
Product Country Of Origin	United States	Qty Shipped EA	1206
Original Item Description		Original Item Number	

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed above and that it satisfies those requirements.

Melt Country of Origin : United States — Melting Date: 05/24/2021

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Ni (%)	Cr (%)	Mo (%)	V (%)	Nb (%)
0.24	0.78	0.011	0.020	0.211	0.12	0.22	0.05	0.006	0.002

Tensile testing

	Yield (PSI)	Tensile (PSI)	Elongation in 8" (%)
(1)	83200	99000	12.8

Mechanical

	Average Deformation Height (IN)	Bend Test
(1)	0.033	Pass

Comments:

1. All manufacturing processes of the steel materials in this product, including melting, casting and rolling were performed in the USA.
2. Mercury, Radium, Hexavalent Chrome or Alpha source materials in any form have not been used in the production and testing of this material.
3. Weld repair was not performed on this material.

Figure F-27. #4 Rebar Material Specification, Test No. ABCBRM-1 (Item No. b5)

NUCOR

Mill Certification
08/09/2021

MTR#:782747-2
Lot #:360002196620
ONE NUCOR WAY
BOURBONNAIS, IL 60914 US
815 937-3131
Fax: 815 939-5599

Sold To: HARRIS SUPPLY SOLUTIONS INC
318 ARVIN AVE
STONEY CREEK, ON L8E 2M2 CA

Ship To: HARRIS SUPPLY SOLUTIONS INC
1201 W ALTO RD STE 5
KOKOMO, IN 46904 US

Customer PO	P168117	Sales Order #	36023699 - 4.4
Product Group	Rebar	Product #	2110199
Grade	A615 Gr 60/AASHTO M31	Lot #	360002196620
Size	#4	Heat #	3600021966
BOL #	BOL-887166	Load #	782747
Description	Rebar #4/13mm A615 Gr 60/AASHTO M31 40' 0" [480"] 4001-8000 lbs	Customer Part #	
Production Date	07/26/2021	Qty Shipped LBS	31744
Product Country Of Origin	United States	Qty Shipped EA	1188
Original Item Description		Original Item Number	

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed above and that it satisfies those requirements.

Melt Country of Origin : United States   Melting Date: 07/10/2021

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Ni (%)	Cr (%)	Mo (%)	Cu (%)	V (%)	Nb (%)
0.34	0.84	0.016	0.037	0.196	0.28	0.25	0.08	0.39	0.010	0.002

Tensile testing

	Yield (PSI)	Tensile (PSI)	Elongation in 8" (%)
(1)	65600	100100	13.7

Mechanical

	Average Deformation Height (IN)	Bend Test
(1)	0.035	Pass

Other Test Results
Weight Percent Variance (%) : -4.20

Comments:
All manufacturing processes of the steel materials in this product, including melting, have occurred within the United States. Products produced are weld free. Mercury, in any form, has not been used in the production or testing of this material.

Figure F-28. #4 Rebar Material Specification, Test No. ABCBRM-1 (Item No. b5)

NUCOR

Mill Certification
08/09/2021

MTR#:782747-2
Lot #:360002141420
ONE NUCOR WAY
BOURBONNAIS, IL 60914 US
815 937-3131
Fax: 815 939-5599

Sold To: HARRIS SUPPLY SOLUTIONS INC
318 ARVIN AVE
STONEY CREEK, ON L8E 2M2 CA

Ship To: HARRIS SUPPLY SOLUTIONS INC
1201 W ALTO RD STE 5
KOKOMO, IN 46904 US

Customer PO	P168117	Sales Order #	36023699 - 4.4
Product Group	Rebar	Product #	2110199
Grade	A615 Gr 60/AASHTO M31	Lot #	360002141420
Size	#4	Heat #	3600021414
BOL #	BOL-887166	Load #	782747
Description	Rebar #4/13mm A615 Gr 60/AASHTO M31 40' 0" [480"] 4001-8000 lbs	Customer Part #	
Production Date	07/25/2021	Qty Shipped LBS	15872
Product Country Of Origin	United States	Qty Shipped EA	594
Original Item Description		Original Item Number	

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed above and that it satisfies those requirements.

Melt Country of Origin : United States — Melting Date: 07/07/2021

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Ni (%)	Cr (%)	Mo (%)	Cu (%)	V (%)	Nb (%)
0.40	0.94	0.013	0.032	0.204	0.23	0.14	0.08	0.28	0.015	0.002

Tensile testing

	Yield (PSI)	Tensile (PSI)	Elongation in 8" (%)
(1)	70700	103900	10.8

Mechanical

	Average Deformation Height (IN)	Bend Test
(1)	0.034	Pass

Other Test Results

Weight Percent Variance (%) : -4.20

Comments:
All manufacturing processes of the steel materials in this product, including melting, have occurred within the United States. Products produced are weld free. Mercury, in any form, has not been used in the production or testing of this material.

Figure F-29. #4 Rebar Material Specification, Test No. ABCBRM-1 (Item No. b5, b10, and b11)

CERTIFIED MATERIAL TEST REPORT Page 1 / 1

GERDAU

US-ML-MIDLOTHIAN
300 WARD ROAD
MIDLOTHIAN, TX 76065
USA

CUSTOMER SHIP TO	CUSTOMER BILL TO	GRADE	SHAPE / SIZE	DOCUMENT ID:
ADELPHIA 2101 7TH ST SIOUX CITY,IA 51101-2004 USA	ADELPHIA METALS LLC 411 MAIN ST E NEW PRAGUE,MN 56071-2237 USA	60 (420)	Rebar / #6 (19MM)	0000546486

LENGTH	WEIGHT	HEAT / BATCH
40'00"	23,251 LB	58044785/02

SALES ORDER	CUSTOMER MATERIAL Nº	SPECIFICATION / DATE or REVISION
10108152/000100		ASTM A615/A615M-16

CUSTOMER PURCHASE ORDER NUMBER	BILL OF LADING	DATE
833606	1327-0000397903	12/03/2020

CHEMICAL COMPOSITION

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Cu (%)	Ni (%)	Cr (%)	Mo(%)	Sn (%)	V (%)	Nb (%)	Al (%)	CEqyA706 (%)
0.42	0.83	0.010	0.017	0.21	0.21	0.10	0.11	0.027	0.036	0.023	0.000	0.003	0.58

MECHANICAL PROPERTIES

YS (PSI)	YS (MPa)	UTS (PSI)	UTS (MPa)	G/L (Inches)	G/L (mm)	Elong. (%)	BendTest
73508	507	106430	734	8.000	200.0	14.70	OK

COMMENTS / NOTES

The above figures are certified chemical and physical test records as contained in the permanent records of the company. We certify that these data are correct and in compliance with specified requirements. No weld repair was performed on this material. The material has not been in contact with mercury while in Gerdau possession. This material, including the billets, was produced (Electric Arc Furnace melted, Continuously cast, and/or Hot rolled) in the USA. CMTR complies with EN 10204 3.1.

Bhaskar
BHASKAR YALAMANCHILI
QUALITY DIRECTOR
Phone: (409) 267-1071 Email: Bhaskar.Yalamanchili@gerdau.com

Wade L. Lumpkins
WADE LUMPKINS
QUALITY ASSURANCE MGR.
Phone: 972-779-3118 Email: Wade.Lumpkins@gerdau.com

Figure F-30. #6 Rebar Material Specification, Test No. ABCBRM-1 (Item No. b6)

GERDAU

US-ML-MIDLOTHIAN
300 WARD ROAD
MIDLOTHIAN, TX 76065
USA

CUSTOMER SHIP TO	CUSTOMER BILL TO	GRADE	SHAPE / SIZE	DOCUMENT ID:
ADELPHIA 2101 7TH ST SIOUX CITY,IA 51101-2004 USA	ADELPHIA METALS LLC 411 MAIN ST E NEW PRAGUE,MN 56071-2237 USA	60 (420)	Rebar / #6 (19MM)	0000500516

LENGTH	WEIGHT	HEAT / BATCH
40'00"	11,776 LB	58043752/02

SALES ORDER	CUSTOMER MATERIAL Nº	SPECIFICATION / DATE or REVISION
9260166/000090		ASTM A615/A615M-16

CUSTOMER PURCHASE ORDER NUMBER	BILL OF LADING	DATE
832032	1327-0000383646	09/02/2020

CHEMICAL COMPOSITION

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Cu (%)	Ni (%)	Cr (%)	Mo(%)	Sn (%)	V (%)	Nb (%)	Al (%)	CEqyA706 (%)
0.42	0.90	0.014	0.021	0.35	0.25	0.09	0.18	0.033	0.016	0.031	0.000	0.003	0.60

MECHANICAL PROPERTIES

YS (PSI)	YS (MPa)	UTS (PSI)	UTS (MPa)	G/L (Inches)	G/L (mm)	Elong. (%)	BendTest
79330	547	113339	781	8.000	200.0	12.90	OK

COMMENTS / NOTES

The above figures are certified chemical and physical test records as contained in the permanent records of company. We certify that these data are correct and in compliance with specified requirements. Weld repair has not been performed on this material. This material, including the billets, was melted and manufactured in the USA. CMTR complies with EN 10204 3.1.

Bhaskar
BHASKAR YALAMANCHILI
QUALITY DIRECTOR
Phone: (409) 267-1071 Email: Bhaskar.Yalamanchili@gerdau.com

Wade L. Lumpkins
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QUALITY ASSURANCE MGR.
Phone: 972-779-3118 Email: Wade.Lumpkins@gerdau.com

Figure F-31. #6 Rebar Material Specification, Test No. ABCBRM-1 (Item No. b6)

GERDAU

US-ML-MIDLOTHIAN
300 WARD ROAD
MIDLOTHIAN, TX 76065
USA

CERTIFIED MATERIAL TEST REPORT

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CUSTOMER SHIP TO	CUSTOMER BILL TO	GRADE	SHAPE / SIZE	DOCUMENT ID:
ADELPHIA METALS LLC 801 DIVISION ST SIOUX CITY,IA 51105-2644 USA	ADELPHIA METALS LLC 411 MAIN ST E NEW PRAGUE,MN 56071-2237 USA	60 (420)	Rebar / #6 (19MM)	0000552998
		LENGTH 40'00"	WEIGHT 58,880 LB	HEAT / BATCH 58045414/02

SALES ORDER	CUSTOMER MATERIAL N°	SPECIFICATION / DATE or REVISION
10144115/000050		ASTM A615/A615M-16

CUSTOMER PURCHASE ORDER NUMBER	BILL OF LADING	DATE
833770	1327-0000400189	12/17/2020

CHEMICAL COMPOSITION

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Cu (%)	Ni (%)	Cr (%)	Mo(%)	Sn (%)	V (%)	Nb (%)	Al (%)	CEqyA706 (%)
0.41	0.92	0.011	0.025	0.25	0.16	0.08	0.11	0.020	0.021	0.025	0.000	0.004	0.58

MECHANICAL PROPERTIES

YS (PSI)	YS (MPa)	UTS (PSI)	UTS (MPa)	G/L (Inches)	G/L (mm)	Elong. (%)	BendTest
72385	499	102739	708	8.000	200.0	14.10	OK

COMMENTS / NOTES

The above figures are certified chemical and physical test records as contained in the permanent records of the company. We certify that these data are correct and in compliance with specified requirements. No weld repair was performed on this material. The material has not been in contact with mercury while in Gerdau possession. This material, including the billets, was produced (Electric Arc Furnace melted, Continuously cast, and/or Hot rolled) in the USA. CMTR complies with EN 10204 3.1.

Bhaskar
BHASKAR YALAMANCHILI
QUALITY DIRECTOR
Phone: (409) 267-1071 Email: Bhaskar.Yalamanchili@gerdau.com

Wade A. Lumpkins
WADE LUMPKINS
QUALITY ASSURANCE MGR.
Phone: 972-779-3118 Email: Wade.Lumpkins@gerdau.com

Figure F-32. #6 Rebar Material Specification, Test No. ABCBRM-1 (Item No. b6)

GERDAU

US-ML-MIDLOTHIAN
300 WARD ROAD
MIDLOTHIAN, TX 76065
USA

CERTIFIED MATERIAL TEST REPORT

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CUSTOMER SHIP TO	CUSTOMER BILL TO	GRADE	SHAPE / SIZE	DOCUMENT ID:
ADELPHIA METALS LLC 801 DIVISION ST SIOUX CITY,IA 51105-2644 USA	ADELPHIA METALS LLC 411 MAIN ST E NEW PRAGUE,MN 56071-2237 USA	60 (420)	Rebar / #6 (19MM)	0000579785
		LENGTH 40'00"	WEIGHT 35,208 LB	HEAT / BATCH 58045945/02

SALES ORDER	CUSTOMER MATERIAL N°	SPECIFICATION / DATE or REVISION
10237157/000060		ASTM A615/A615M-16

CUSTOMER PURCHASE ORDER NUMBER	BILL OF LADING	DATE
834359	1327-0000409297	02/22/2021

CHEMICAL COMPOSITION

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Cu (%)	Ni (%)	Cr (%)	Mo(%)	Sn (%)	V (%)	Nb (%)	Al (%)	CEqyA706 (%)
0.41	0.88	0.009	0.027	0.27	0.21	0.08	0.14	0.029	0.003	0.021	0.000	0.003	0.58

MECHANICAL PROPERTIES

YS (PSI)	YS (MPa)	UTS (PSI)	UTS (MPa)	G/L (Inches)	G/L (mm)	Elong. (%)	BendTest
71894	496	105589	728	8.000	200.0	14.40	OK

COMMENTS / NOTES

The above figures are certified chemical and physical test records as contained in the permanent records of the company. We certify that these data are correct and in compliance with specified requirements. No weld repair was performed on this material. The material has not been in contact with mercury while in Gerdau possession. This material, including the billets, was produced (Electric Arc Furnace melted, Continuously cast, and/or Hot rolled) in the USA. CMTR complies with EN 10204 3.1.

Bhaskar
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QUALITY DIRECTOR
Phone: (409) 267-1071 Email: Bhaskar.Yalamanchili@gerdau.com

Wade A. Lumpkins
WADE LUMPKINS
QUALITY ASSURANCE MGR.
Phone: 972-779-3118 Email: Wade.Lumpkins@gerdau.com

Figure F-33. #6 Rebar Material Specification, Test No. ABCBRM-1 (Item No. b6)

Cert ID 13095

GERDAU

US-ML-MIDLOTHIAN
300 WARD ROAD
MIDLOTHIAN, TX 76065
USA

CERTIFIED MATERIAL TEST REPORT

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CUSTOMER SHIP TO	CUSTOMER BILL TO	GRADE	SHAPE / SIZE	DOCUMENT ID:
ADELPHIA 2101 7TH ST SIOUX CITY,IA 51101-2004 USA	ADELPHIA METALS LLC 411 MAIN ST E NEW PRAGUE,MN 56071-2237 USA	60 (420)	Rebar / #6 (19MM)	0000526521

LENGTH	WEIGHT	HEAT / BATCH
40'00"	11,596 LB	58044201/03

SALES ORDER	CUSTOMER MATERIAL N°	SPECIFICATION / DATE or REVISION
9499737/000020		ASTM A615/A615M-16

CUSTOMER PURCHASE ORDER NUMBER	BILL OF LADING	DATE
833020	1327-0000391827	10/26/2020

CHEMICAL COMPOSITION

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Cu (%)	Ni (%)	Cr (%)	Mo(%)	Sn (%)	V (%)	Nb (%)	Al (%)	CEqyA706 (%)
0.40	0.83	0.007	0.029	0.23	0.20	0.07	0.09	0.024	0.010	0.046	0.000	0.003	0.55

MECHANICAL PROPERTIES

YS (PSI)	YS (MPa)	UTS (PSI)	UTS (MPa)	G/L (Inches)	G/L (mm)	Elong. (%)	BendTest
76003	524	105300	726	8.000	200.0	15.60	OK

COMMENTS / NOTES

The above figures are certified chemical and physical test records as contained in the permanent records of the company. We certify that these data are correct and in compliance with specified requirements. No weld repair was performed on this material. The material has not been in contact with mercury while in Gerdau possession. This material, including the billets, was produced (Electric Arc Furnace melted, Continuously cast, and/or Hot rolled) in the USA. CMTR complies with EN 10204 3.1.

Bhaskar
BHASKAR YALAMANCHILI
QUALITY DIRECTOR
Phone: (409) 267-1071 Email: Bhaskar.Yalamanchili@gerdau.com

Wade A. L.
WADE LUMPKINS
QUALITY ASSURANCE MGR.
Phone: 972-779-3118 Email: Wade.Lumpkins@gerdau.com

Heat 58044201

Figure F-34. #6 Rebar Material Specification, Test No. ABCBRM-1 (Item No. b6)

CMC

CMC STEEL ARIZONA
11444 E. GERMANN RD.
MESA AZ 85212-9700

CERTIFIED MILL TEST REPORT
For additional copies call
830-372-8771

We hereby certify that the test results presented here are accurate and conform to the reported grade specification

Jacob Selzer – CMC Steel
Quality Assurance Manager

EAT NO.:4119617
ECTION: REBAR 25MM (#8) 60'0"
615/A706-80
RADE: ASTM A615 & A706 GR80 Dual Gr
OLL DATE: 06/10/2022
IELT DATE: 06/10/2022
ert. No.: 85086503 / 119617F660

SOLD TO: HRC Headed Reinforcement Corp
11200 Condor Ave
Fountain Valley CA
US 92708-6106
7145571455
7145574460

SHIP TO: HRC Headed Reinforcement Corp
11200 Condor Ave
Fountain Valley CA
US 92708-6106
7145571455
7145574460

Delivery#: 85086503
BOL#: 74855744
CUST PO#: 28830
CUST P/N:
DLVRY LBS / HEAT: 24352.000 LB
DLVRY PCS / HEAT: 152 EA

Characteristic	Value	Characteristic	Value	Characteristic	Value
C	0.29%	Elongation test 1	14%		
Mn	1.23%	Elongation Gage Lgth test 1	8IN		
P	0.018%	Tensile to Yield ratio test1	1.27		
S	0.031%	Bend Test 1	Passed		
Si	0.19%	Rebar Deformation Avg. Spaci	0.672IN		
Cu	0.32%	Rebar Deformation Avg. Heigh	0.062IN		
Cr	0.19%	Rebar Deformation Max. Gap	0.163IN		
Ni	0.12%	Bend Test Diameter	5.000IN		
Mo	0.069%	Strain at Peak Stress test 1	11.0%		
V	0.018%				
Cb	0.004%				
Sn	0.012%				
Al	0.002%				
N	0.0100%				
Carbon Eq A706	0.52%				
Yield Strength test 1	87.3ksi				
Yield Strength test 1 (metri	602MPa				
Tensile Strength test 1	110.9ksi				
Tensile Strength 1 (metric)	765MPa				

The Following is true of the material represented by this MTR:
*Material is fully killed and is Hot Rolled Steel
*100% melted and rolled in the USA
*EN10204:2004 3.1 compliant
*Contains no weld repair
*Contains no Mercury contamination
*Manufactured in accordance with the latest version of the plant quality manual
*Meets the "Buy America" requirements of 23 CFR635.410, 49 CFR 661
*Warning: This product can expose you to chemicals which are known to the State of California to cause cancer, birth defects or other reproductive harm. For more information go to www.P65Warnings.ca.gov

MARKS :

Figure F-35. #8 Rebar Material Specification, Test No. ABCBRM-1 (Item No. b12)

NUCOR

Mill Certification
09/18/2020

MTR#:486159-2
Lot #:360001340921
ONE NUCOR WAY
BOURBONNAIS, IL 60914 US
815 937-3131
Fax: 815 939-5599

Sold To: AMBASSADOR STEEL FAB LLC
PO BOX 627
AUBURN, IN 46706 US

Ship To: AMBASSADOR STEEL CORP
1050 ST GEORGE RD
BOURBONNAIS, IL 60914 US

Customer PO	PO116607A	Sales Order #	36014877 - 7.5
Product Group	Rebar	Product #	2110230
Grade	A615 Gr 60/AASHTO M31	Lot #	360001340921
Size	#5	Heat #	3600013409
BOL #	BOL-579306	Load #	486159
Description	Rebar #5/16mm A615 Gr 60/AASHTO M31 40' 0" [480"] 4001-8000 lbs	Customer Part #	
Production Date	06/12/2020	Qty ShippedLBS	22530
Product Country Of Origin	United States	Qty ShippedEA	540
Original Item Description		Original Item Number	

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed above and that it satisfies those requirements.

Melt Country of Origin : United States — Melting Date: 06/08/2020

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Ni (%)	Cr (%)	Mo (%)	Cu (%)	V (%)	Nb (%)
0.39	0.86	0.012	0.055	0.180	0.24	0.12	0.09	0.34	0.010	0.002

Other Test Results
Yield (PSI) : 65100
Tensile (PSI) : 101100
Average Deformation Height (IN) : 0.047
Elongation in 8" (%) : 15.5
Bend Test : Pass
Weight Percent Variance (%) : -2.70

Comments:

All manufacturing processes of the steel materials in this product, including melting, have occurred within the United States. Products produced are weld free. Mercury, in any form, has not been used in the production or testing of this material.

Zach Sprintz

Zachary Sprintz, Chief Metallurgist

Page 1 of 1

Figure F-36. #5 Rebar Material Specification, Test No. ABCBRM-1 (Item No. b13)

NUCOR

Mill Certification

03/01/2021

MTR#:625286-2
Lot #:360001878720
ONE NUCOR WAY
BOURBONNAIS, IL 60914 US
815 937-3131
Fax: 815 939-5599

Sold To: AMBASSADOR STEEL FAB LLC
PO BOX 627
AUBURN, IN 46706 US

Ship To: AMBASSADOR STEEL CORP
1050 ST GEORGE RD
BOURBONNAIS, IL 60914 US

Customer PO	PO118082A	Sales Order #	36019060 - 3.9
Product Group	Rebar	Product #	2110230
Grade	A615 Gr 60/AASHTO M31	Lot #	360001878720
Size	#5	Heat #	3600018787
BOL #	BOL-706126	Load #	625286
Description	Rebar #5/16mm A615 Gr 60/AASHTO M31 40' 0" [480"] 4001-8000 lbs	Customer Part #	
Production Date	02/20/2021	Qty ShippedLBS	22530
Product Country Of Origin	United States	Qty ShippedEA	540
Original Item Description		Original Item Number	

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed above and that it satisfies those requirements.

Melt Country of Origin : United States

Melting Date: 02/14/2021

C (%)	Mn (%)	P (%)	S (%)	Si (%)	Ni (%)	Cr (%)	Mo (%)	Cu (%)	V (%)	Nb (%)
0.40	1.00	0.014	0.031	0.158	0.22	0.14	0.07	0.38	0.011	0.002

Mechanical

	Average Deformation Height (IN)	Bend Test
(1)	0.041	Pass

Tensile testing

	Yield (PSI)	Tensile (PSI)	Elongation in 8" (%)
(1)	73200	112100	13.6

Other Test Results

Weight Percent Variance (%) : -3.40

Comments:

All manufacturing processes of the steel materials in this product, including melting, have occurred within the United States. Products produced are weld free. Mercury, in any form, has not been used in the production or testing of this material.

Zachary Sprintz, Chief Metallurgist

Page 1 of 1

Figure F-37. #5 Rebar Material Specification, Test No. ABCBRM-1 (Item No. b13)

Headed Reinforcement Corp. West
11200 Condor Avenue
Fountain Valley, CA 92708
Tel: (714) 557-1455
Fax: (714) 557-4460

Certificate of Compliance

Page 1 of 1

21-1397-1

Customer: Sri S. Sritharan
Iowa State University
406 Town Engineering Building
Ames, IA 50011-3232
Phone: (515) 294-5238
Fax: (515) 294-8216

Ship To: Jim Holloway
Iowa State University
4630 NW 36TH Street
Lincoln, NE 68524
Contact: Jim Holloway
Phone: (402) 450-6250
Fax: (515) 294-8216

Ship Date:
Order Date: 6/8/2022
Project: ABC Barrier
P.O. # :
Release: #5 & #7 HRC 555

SBM	Release	Bar Size	Item	Description	Qty	Heat / Mark
				(c5) Special #5 headed HRC 320	13	10021154521
				(c6) Special #5 headed HRC 320	13	10021154521
				(c7) Special #5 headed HRC 320	13	10021154521
				(c1/c2) Insert for #8 threaded bar	40	10021154521 / 10020925820

Headed Reinforcement Corp

Certificate issued and digitally signed by: Joe

Notification of shortage, or discrepancy must be made within 48 hours of delivery.

Certificate of Compliance

Headed Reinforcement Corp. (HRC) hereby certifies, that the items listed above meet all the specification requirements of the contract. Further note, that these items were fabricated in the United States.

Returned 11/10/22

Figure F-38. 1 1/2" Dia., 8 1/16" Long, 1"-8 UNC x 2" Internally Threaded Tube, Test No. ABCBRM-1 (Item No. c1)

Headed Reinforcement Corp. West
11200 Condor Avenue
Fountain Valley, CA 92708
Tel: (714) 557-1455
Fax: (714) 557-4460

Certificate of Compliance

Page 1 of 1

21-1397-1

Customer: Sri S. Sritharan
Iowa State University
406 Town Engineering Building
Ames, IA 50011-3232
Phone: (515) 294-5238
Fax: (515) 294-8216

Ship To: Jim Holloway
Iowa State University
4630 NW 36TH Street
Lincoln, NE 68524
Contact: Jim Holloway
Phone: (402) 450-6250
Fax: (515) 294-8216

Ship Date:
Order Date: 6/8/2022
Project: ABC Barrier
P.O. # :
Release: #5 & #7 HRC 555

SBM	Release	Bar Size	Item	Description	Qty	Heat / Mark
				(c5) Special #5 headed HRC 320	13	10021154521
				(c6) Special #5 headed HRC 320	13	10021154521
				(c7) Special #5 headed HRC 320	13	10021154521
				(c1/c2) Insert for #8 threaded bar	40	10021154521 / 10020925820

Headed Reinforcement Corp

Certificate issued and digitally signed by: Joe

Notification of shortage, or discrepancy must be made within 48 hours of delivery.

Certificate of Compliance

Headed Reinforcement Corp. (HRC) hereby certifies, that the items listed above meet all the specification requirements of the contract. Further note, that these items were fabricated in the United States.

Returned 11/10/22

Figure F-39. 2"x2"x1 3/8" Base Plate, Test No. ABCBRM-1 (Item No. c2)

CMC MHX WAREHOUSE
13600 Napa Street
Fontana CA 92335-2944

CERTIFIED MILL TEST REPORT
For additional copies call

We hereby certify that the test results presented here are accurate and conform to the reported grade specification

HEAT NO.:6031854 SECTION: REBAR 22MM (#7) 60'0" A615/A706-60 GRADE: ASTM A615 & A706 GR60 Dual Gr ROLL DATE: 04/15/2022 MELT DATE: Cert. No.: 85057934 / 031854J577	SOLD TO	HRC Headed Reinforcement Corp 11200 Condor Ave Fountain Valley CA US 92708-6106 7145571455 7145574460	SHIP TO	HRC Headed Reinforcement Corp 11200 Condor Ave Fountain Valley CA US 92708-6106 7145571455 7145574460	Delivery#: 85057934 BOL#: 74806557 CUST PO#: 28747 CUST P/N: DLVRY LBS / HEAT: 12264.000 LB DLVRY PCS / HEAT: 100 EA

Characteristic	Value	Characteristic	Value	Characteristic	Value
C	0.25%	Elongation Gage Lgth test 1	8IN		
Mn	1.24%	Tensile to Yield ratio test1	1.42		
P	0.010%	Bend Test 1	Passed		
S	0.022%	Rebar Deformation Avg. Spaci	0.535IN		
Si	0.22%	Rebar Deformation Avg. Heigh	0.045IN		
Cu	0.30%	Rebar Deformation Max. Gap	0.161IN		
Cr	0.17%	Bend Test Diameter	3.500IN		
Ni	0.15%	Strain at Peak Stress test 1	6.8%		
Mo	0.031%				
V	0.006%				
Sn	0.011%				
Al	0.001%				
N	0.0088%				
Carbon Eq A706	0.49%				
Yield Strength test 1	70.6ksi				
Yield Strength test 1 (metri	487MPa				
Tensile Strength test 1	100.0ksi				
Tensile Strength 1 (metric)	690MPa				
Elongation test 1	14%				

The Following is true of the material represented by this MTR:
*Material is fully killed
*100% melted and rolled in the USA
*EN10204:2004 3.1 compliant
*Contains no weld repair
*Contains no Mercury contamination
*Manufactured in accordance with the latest version of the plant quality manual
*Meets the "Buy America" requirements of 23 CFR635.410, 49 CFR 661
*Warning: This product can expose you to chemicals which are known to the State of California to cause cancer, birth defects or other reproductive harm. For more information go to www.P65Warnings.ca.gov

REMARKS : ALSO MEETS AASHTO M31

Figure F-40. 7/8" Dia., 16 1/2" Long, Double-Headed Shear Tie, HRC 555 T-Head Both Ends, Test No. ABCBRM-1 (Item No. c3)

CMC STEEL ARIZONA
11444 E. GERMANN RD.
MESA AZ 85212-9700

CERTIFIED MILL TEST REPORT
For additional copies call
830-372-8771

We hereby certify that the test results presented here are accurate and conform to the reported grade specification

Jacob Selzer – CMC Steel
Quality Assurance Manager

EAT NO.:4111735 ECTION: REBAR 16MM (#5) 60'0" 615/A706-60 RADE: ASTM A615 & A706 GR60 Dual Gr OLL DATE: 09/13/2021 IELT DATE: 09/13/2021 ert. No.: 83630500 / 111735F013	SOLD TO	HRC Headed Reinforcement Corp 11200 Condor Ave Fountain Valley CA US 92708-6106 7145571455 7145574460	SHIP TO	HRC Headed Reinforcement Corp 11200 Condor Ave Fountain Valley CA US 92708-6106 7145571455 7145574460	Delivery#: 83630500 BOL#: 74433911 CUST PO#: 27978 CUST P/N: DLVRY LBS / HEAT: 12266.000 LB DLVRY PCS / HEAT: 196 EA

Characteristic	Value	Characteristic	Value	Characteristic	Value
C	0.26%	Elongation test 1	15%		
Mn	1.20%	Elongation Gage Lgth test 1	8IN		
P	0.016%	Tensile to Yield ratio test1	1.35		
S	0.041%	Bend Test 1	Passed		
Si	0.20%	Rebar Deformation Avg. Spaci	0.426IN		
Cu	0.36%	Rebar Deformation Avg. Heigh	0.038IN		
Cr	0.18%	Rebar Deformation Max. Gap	0.157IN		
Ni	0.12%	Bend Test Diameter	1.875IN		
Mo	0.025%	Strain at Peak Stress test 1	10.6%		
V	0.001%				
Cb	0.000%				
Sn	0.011%				
Al	0.002%				
N	0.0064%				
Carbon Eq A706	0.49%				
Yield Strength test 1	71.0ksi				
Yield Strength test 1 (metri	490MPa				
Tensile Strength test 1	96.0ksi				
Tensile Strength 1 (metric)	662MPa				

The Following is true of the material represented by this MTR:
*Material is fully killed
*100% melted and rolled in the USA
*EN10204:2004 3.1 compliant
*Contains no weld repair
*Contains no Mercury contamination
*Manufactured in accordance with the latest version of the plant quality manual
*Meets the "Buy America" requirements of 23 CFR635.410, 49 CFR 661
*Warning: This product can expose you to chemicals which are known to the State of California to cause cancer, birth defects or other reproductive harm. For more information go to www.P65Warnings.ca.gov

MARKS : ALSO MEETS AASHTO M31

Figure F-41. 5/8" Dia., 5 1/4" Long, 5/8"-11 UNC Male Transverse Tie, HRC 555 Series T-Head, Test No. ABCBRM-1 (Item No. c4)

Customer Name	Customer PO#	Shipper No	Heat Number
HEADED REINFORCEMENT CORI	28774	200398	58047404

NIAGARA LASALLE CORPORATION 1412 150th Street Hammond IN 46327-1799

CERTIFICATION

CERTIFICATE H211340 Rev 2
DATE 09/22/21
PAGE 6

SHIP TO:
BERGSEN- SANTE FE SPRINGS
C/O CMI WAREHOUSE
3751 CEDAR CREEK DRIVE
JOLIET IL 60436
USA

PURCHASE ORDER 25895
ORDER 1188128-4
CUSTOMER ITEM
ITEM 111625240184A
GRADE 1018
SHAPE Round
SIZE 1.6250
SIZE MM 41.2750 MM
LENGTH 20' 0"
LENGTH MM 6096

1018 COLD DRAWN Spec/Rev: Spec/Rev: ASTM A108-18 Spec/Rev: ASTM A29/A29M-20 Spec/Rev: ASTM A576-17 Spec/Rev: JDM AO-QL-2

HEAT	GRAIN PRACTICE	SOURCE / MELTED	CAST	REDUCTION RATIO	DI
58047404	FINE(5-8)	Gerdau Ameristl-TX-Mdlthn (USA)	STRAND	18.9:1	

CHEMISTRY

C	MN	P	S	SI	NI	CR	MO	CU	AL	V
0.170	0.720	.010	.014	0.280	0.080	0.140	.025	.240	.025	.001

N	TE	AS	PB	SN	BI	B	NB
N/A	N/A	N/A	N/A	N/A	N/A	.0001	N/A

LOT

LOT	JOB	WEIGHT (LBS)	PIECES	LOT	JOB	WEIGHT (LBS)	PIECES
6373402	MS08927	1,985	14	6373403	MS08927	1,985	14

WE, hereby certify that these goods were produced in compliance with all applicable requirements of sections 6, 7, and 12 of the Fair Labor Standards Act, as amended, and all regulations and orders of the United States Department of Labor issued under section 14 thereof. Material was not exposed to mercury or any metal alloy that is liquid at ambient temperature during processing or while in our possession. No weld repairs performed on the above material.

CERTIFICATE OF TEST By: Walter P. Kretzler Walter P. Kretzler - Director of Q.A./Chief Metallurgist

Figure F-42. Rebar Component Head Fitting from 1-5/8" Round Bar, Test No. ABCBRM-1 (Item No. c4a)

HRC

Headed Reinforcement Corp. West
11200 Condor Avenue
Fountain Valley, CA 92708
Tel: (714) 557-1455
Fax: (714) 557-4460

Certificate of Compliance

Page 1 of 1

21-1397-1

Customer: Sri S. Sritharan
Iowa State University
406 Town Engineering Building
Ames, IA 50011-3232
Phone: (515) 294-5238
Fax: (515) 294-8216

Ship To: Jim Holloway
Iowa State University
4630 NW 36TH Street
Lincoln, NE 68524
Contact: Jim Holloway
Phone: (402) 450-6250
Fax: (515) 294-8216

Ship Date:
Order Date: 6/8/2022
Project: ABC Barrier
P.O. # :
Release: #5 & #7 HRC 555

SBM	Release	Bar Size	Item	Description	Qty	Heat / Mark
				(c5) Special #5 headed HRC 320	13	10021154521
				(c6) Special #5 headed HRC 320	13	10021154521
				(c7) Special #5 headed HRC 320	13	10021154521
				(c1/c2) Insert for #8 threaded bar	40	10021154521 / 10020925820

Headed Reinforcement Corp

Certificate issued and digitally signed by: Joe

Notification of shortage, or discrepancy must be made within 48 hours of delivery.

Certificate of Compliance

Headed Reinforcement Corp. (HRC) hereby certifies, that the items listed above meet all the specification requirements of the contract. Further note, that these items were fabricated in the United States.

Returned 11/10/22

Figure F-43. 5/8"-11 UNC Internally Threaded Transverse Receiving Tie, Test No. ABCBRM-1 (Item No. c5, c6, and c7)

MILL TEST CERTIFICATE steelscape **MTC NO. 81493845-10-20210621-113950**

ORDNO. 3158111-3000	CUST PO. 4037-03	SHIP DATE 06/15/2021	Page: 1
OTHER SPECIFICATIONS TruZinc® ASTM A653-15e1 0.0184 " M x 48.0000 " BMT min: 0.0174 " GRADE CSA G60 RoHS Passivation	SOLD TO MERIT USA 620 CLARK AVENUE PITTSBURG CA 94565 USA	SHIP TO Merit Fontana 11093 Beech Avenue Fontana CA 92337	

MECHANICAL PROPERTIES

COIL ID		HEAT NO.	TEST NO.	YIELD STR. KSI	TENSILE STR. KSI	ELONG (in 2") %	BEND	HARDNESS
1005573878	TruZinc®	1350207						
1005573884	TruZinc®							

CHEMICAL PROPERTIES

HEAT NO.	C (%)	Mn (%)	P (%)	S (%)	Si (%)	Cu (%)	Ni (%)	Cr (%)	Mo (%)	V (%)	Cb (%)	Ti (%)	Al (%)	N (%)	B (%)
1350207	0.050	0.300	0.019	0.013	0.010	0.030	0.010	0.030	0.010	0.000	0.000	0.000	0.043	0.002	***

*** Data not available

This report certifies that the material described herein has been manufactured, sampled and tested in accordance with the stated specification. The published results are certified to be factual and are identical to the results contained within the records of Steelscape, LLC.

Steelscape, LLC - Quality Systems Manager
Michelle Vondran

Steelscape, LLC 222 West Kalama River Road, Kalama, WA 98625,USA Call 360 673-8200 Fax 360 673-8250
11200 Arrow Route, Rancho Cucamonga, CA 91730, USA Call 909 987-4711 Fax 909 989-4470

Figure F-44. 2 1/2" ID, 44 5/8" Long Corrugated Inclined Pipe, Test No. ABCBRM-1 (Item No. c8)

MILL TEST CERTIFICATE steelscape **MTC NO. 81496789-10-20210706-084356**

ORDNO. 3158971-2000	CUST PO. 4072-02	SHIP DATE 06/22/2021	Page: 1
OTHER SPECIFICATIONS TruZinc® ASTM A653-15e1 0.0184 " M x 48.0000 " BMT min: 0.0174 " GRADE CSA G60 RoHS Passivation	SOLD TO MERIT USA 620 CLARK AVENUE PITTSBURG CA 94565 USA	SHIP TO Merit Fontana 11093 Beech Avenue Fontana CA 92337	

MECHANICAL PROPERTIES

COIL ID		HEAT NO.	TEST NO.	YIELD STR. KSI	TENSILE STR. KSI	ELONG (in 2") %	BEND	HARDNESS
1005595754	TruZinc®	1441631						
1005595758	TruZinc®							
1005595762	TruZinc®							

CHEMICAL PROPERTIES

HEAT NO.	C (%)	Mn (%)	P (%)	S (%)	Si (%)	Cu (%)	Ni (%)	Cr (%)	Mo (%)	V (%)	Cb (%)	Ti (%)	Al (%)	N (%)	B (%)
1441631	0.050	0.320	0.016	0.016	0.010	0.030	0.020	0.040	0.010	0.000	0.000	0.000	0.052	0.003	***

*** Data not available

This report certifies that the material described herein has been manufactured, sampled and tested in accordance with the stated specification. The published results are certified to be factual and are identical to the results contained within the records of Steelscape, LLC.

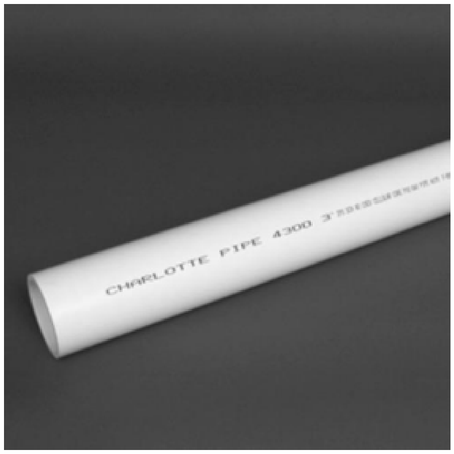
Steelscape, LLC - Quality Systems Manager
Michelle Vondran

Steelscape, LLC 222 West Kalama River Road, Kalama, WA 98625,USA Call 360 673-8200 Fax 360 673-8250
11200 Arrow Route, Rancho Cucamonga, CA 91730, USA Call 909 987-4711 Fax 909 989-4470

Figure F-45. 2 1/2" ID, 44 5/8" Long Corrugated Inclined Pipe, Test No. ABCBRM-1 (Item No. c8)

2"x10' PVC Sch 40 DWV Plain End Cellular Core Pipe

Model Number: PVC042000600 | Menards ® SKU: 6898287



EVERYDAY LOW PRICE $17.46
11% MAIL-IN REBATE Good Through 8/28/22 $1.92
FINAL PRICE **$15.54 each**

You Save $1.92 with Mail-In Rebate

382 People have purchased this product in the past 30 days

* Mail-in Rebate is in the form of merchandise credit check, valid in-store only. Merchandise credit check is not valid towards purchases made on MENARDS.COM®.

Pick Up At Store
236 In-Stock at **LINCOLN NORTH**
Check Another Store for Availability

Delivery
Available

Description & Documents

PVC Schedule 40 Foam Core Pipe is for drain, waste and vent purposes only. It is used in gravity fed waste elimination systems. It is for Non-Pressure systems where temperatures will not exceed 140 degrees F. PVC Schedule 40 Foam Core is lightweight, non-toxic and easy to install. It is coextruded and has a cellular core. Installation requires primer and solvent cement. PVC Schedule 40 Foam Core is used in DWV Applications. It is highly durable and with no rusting it offers years of trouble-free service.

MADE IN U.S.A.

Brand Name: **Charlotte Pipe and Foundry**

Features

- White pipe used in sanitary drain, waste, and vent (DWV), sewer and storm drainage applications
- Not intended for pressure use
- For use where systems will not exceed 140Â° F
- PVC Foam Core is highly durable and with no rusting it offers years of trouble-free service
- Require no special tools for cutting and to be installed with solvent cement
- Conforms to Standards: ASTM D 4396, ASTM F 891 and NSF Standard 14

Specifications

Actual Length	10 foot	Actual Inner Diameter	2.067 inch
Actual Outer Diameter	2-3/8 inch	Maximum Working Temperature	140 degrees Fahrenheit
Minimum Working Temperature	32 degrees Fahrenheit	End Type	Plain
Material	PVC	Wall Thickness	0.154 inch
Schedule	Schedule 40	Nominal Size	2 inch
For Use With	Drain, Waste and Vent applications, Gravity fed waste elimination systems	Listing Agency Standards	ASTM D4396, NSF 14, ASTM F891
Product Type	PVC Cellular Core Pipe	Weight	4.39 pound
Shipping Dimensions	120.00 H x 2.50 W x 2.40 D	Shipping Weight	5.0 lbs
Return Policy	Regular Return (view Return Policy)		

Please Note: Prices, promotions, styles and availability may vary by store and online. Inventory is sold and received continuously throughout the day; therefore, the quantity shown may not be available when you get to the store. This inventory may include a store display unit. Online orders and products purchased in-store qualify for rebate redemption. Mail-in Rebate is in the form of merchandise credit check, valid in-store only. Merchandise credit check is not valid towards purchases made on MENARDS.COM®. By submitting this rebate form, you agree to resolve any disputes related to rebate redemption by binding arbitration and you waive any right to file or participate in a class action. Terms and conditions available at www.rebateinternational.com

Figure F-46. 2" Dia. Conduit, 119" Long, Test No. ABCBRM-1 (Item No. c9)

GRAINGER
FOR THE ONES WHO GET IT DONE

July 18 2022

Certificate of Conformance

W.W. Grainger, Inc.
100 Grainger Parkway
Lake Forest, IL. 60045-5201

Attn: SHAUN M TIGHE
SHAUN M TIGHE
CANFIELD ADMINISTRATION
BLDG
LINCOLN, NE, 68588-0439

Fax #

Grainger Sales Order #: 1453068737
Customer PO #: E001001155

Dear SHAUN M TIGHE
The products sold by Grainger and that are identified in this document conform to the respective product description(s) and standard(s) as set forth on www.grainger.com.

Thank you.

Item #	Description	Vendor Part #	Catalog Page #	Order Quantity
1VEV4	Pipe,PVC,3 In,Schedule 80,10 Feet L	H0800300PG1000		13.000

Mikal McLendon

Mikal McLendon | Manager, Supplier Contracts and Lifecycle Management | W.W. Grainger, Inc.

Figure F-47. 3" Dia. Conduit, 119" Long, Test No. ABCBRM-1 (Item No. c10)

HILTI

P.O. Box 21148
Tulsa, OK 74121
P: 800-879-8000
F: 800-879-7000

Date: 7/28/2022

Customer: NEBRASKA-LINCOLN * UNIV OF

Customer PO: AGTRB-1-6

Subject: Certificate of Conformance - HIT RE-500 V3 Adhesive

Quantity: 20 PCS / 2123404 / Injectable mortar HIT-RE 500 V3/500/1

To Whom it May Concern:

This is to certify that the HIT-RE 500 V3 provided on the above referenced order is a high-strength, slow cure two-part epoxy adhesive contained in two cartridges separating the resin from the hardener.

Additionally, this certifies that the product has been seismically qualified per ICC-ES Acceptance Criteria AC308 and ACI 355.4 and meets the requirements of **ASTM** C881-90, **Type** I, II, IV and V, Grade 3, **Class** A, B and C.

The items are supplied under Hilti's **ISO 9001** quality program.

Sincerely,

B. Mitchell

B. Mitchell, Certification Specialist

HILTI, Inc.
RE500 V3

Figure F-48. Epoxy Adhesive, Test No. ABCBRM-1 (Item No. d1)

Appendix G. Vehicle Center of Gravity Determination

Model Year: 2013	Test Name: ABCBRM-1	VIN:	3ALACXDT6EDFX0132
	Make: Freightliner	Model:	M2

Vehicle CG Determination

		Vehicle Equipment	Weight (lb)	Vertical CG (in.)	Vertical M (lb-in.)
	+	Unballasted Truck (Curb)	14686	37.587	#########
	+	Hub	43	19.5	838.5
	+	Brake activation cylinder & frame	7	45.0	315.0
	+	Pneumatic tank (Nitrogen)	23	47.0	1081.0
	+	Strobe/Brake Battery	5	43.5	217.5
	+	Tow Pin Plate	9	12.5	112.5
	+	Brake Receiver/Wires	5	101.5	507.5
	+	Cab DAQ Unit & Mouting Plate	11	48.125	529.375
	+	CG DAQ Units & Enclosure	21	38.0	798.0
	-	Battery	-113	36.0	-4068.0
	-	Oil	-23	27.0	-621.0
	-	Interior	-94	71.0	-6674.0
	-	Fuel	0	21.5	0
	-	Coolant	-46	42.0	-1932.0
	-	Washer fluid	-4	29.5	-118.0
	-	DEF fluid	-76	27.0	-2052.0
	+	Rear DAQ Unit & Encolsure	17	30.5	518.5
BALLAST	+	Barrier+4" Foam	4990	67.625	337448.75
	+	Small Concrete blocks	1286	57.625	74105.75
	+	Metal tubes	810	54.625	44246.25
	+	Rectangle bogie head	473	55.125	26074.125
	+	Hardware	182	51.375	9350.25
					0
		Note: (+) is added equipment to vehicle, (-) is removed equipment from vehicle			1032676

Estimated Total Weight (lb)	22212	Total Ballast Weight (lb)	7741
Vertical CG Location (in.)	46.492	Ballast Vertical CG Location (in.)	63.458

Vehicle Dimensions for C.G. Calculations

Wheel Base:	240.0 in.	Front Track Width:	82.25 in.
		Rear Track Width:	72.75 in.

Center of Gravity	10000S MASH Targets	Test Inertial	Difference
Test Inertial Weight (lb)	22046 ± 660	22200	154.0
Longitudinal CG (in.)	NA	157.405	NA
Lateral CG (in.)	NA	0.07	NA
Vertical CG (in.)	NA	46.492	NA
Ballast Vertical CG (in.)	63 ± 2	63.458	0.45758

Note: Long. CG is measured from front axle of test vehicle
Note: Lateral CG measured from centerline - positive to vehicle right (passenger) side

CURB WEIGHT (lb)

	Left	Right
Front	3392	3304
Rear	4070	3920
FRONT	6696	lb
REAR	7990	lb
TOTAL	14686	lb

TEST INERTIAL WEIGHT (lb)

	Left	Right
Front	3770	3870
Rear	7310	7250
FRONT	7640	lb
REAR	14560	lb
TOTAL	22200	lb

Figure G-1. Vehicle Mass Distribution, Test No. ABCBRM-1

Appendix H. Vehicle Deformation Records

The following figures and tables describe all occupant compartment measurements taken on the test vehicle used in full-scale crash testing herein. MASH defines intrusion as the occupant compartment being deformed and reduced in size with no penetration. Outward deformations, which are denoted as negative numbers within this Appendix, are not considered as crush toward the occupant, and are not subject to evaluation by MASH criteria

Model Year: 2013 | Test Name: ABCBR-1 | VIN: 3ALACXDT6EDFX0132
Make: Freightliner | Model: M2

VEHICLE DEFORMATION
FLOOR PAN - SET 1

	POINT	Pretest X (in.)	Pretest Y (in.)	Pretest Z (in.)	Posttest X (in.)	Posttest Y (in.)	Posttest Z (in.)	ΔX[A] (in.)	ΔY[A] (in.)	ΔZ[A] (in.)	Total Δ (in.)	Crush[B] (in.)	Directions for Crush[C]
TOE PAN - WHEEL WELL (X, Z)	1	40.7767	-43.5060	0.8657	39.6756	-42.9903	-0.8973	1.1011	0.5157	1.7630	2.1416	2.0786	X, Z
	2	41.1295	-39.6980	3.0877	39.5782	-38.8463	1.1027	1.5513	0.8517	1.9850	2.6594	2.5193	X, Z
	3	41.6274	-34.0496	3.8462	40.6883	-33.5395	2.2030	0.9391	0.5101	1.6432	1.9602	1.8926	X, Z
	4	36.0271	-28.8246	4.5578	35.7186	-28.6735	4.7371	0.3085	0.1511	-0.1793	0.3875	0.3085	X
	5	35.5089	-21.5324	3.0094	35.4322	-21.5459	3.4787	0.0767	-0.0135	-0.4693	0.4757	0.0767	X
	6	32.4602	-42.9441	5.9015	30.3496	-40.9001	0.4957	2.1106	2.0440	5.4058	6.1527	5.8032	X, Z
	7	33.2712	-38.1170	4.8838	31.8252	-36.3466	0.5878	1.4460	1.7704	4.2960	4.8663	4.5328	X, Z
	8	33.8815	-33.4911	4.6223	33.3217	-32.6317	3.4143	0.5598	0.8594	1.2080	1.5847	1.3314	X, Z
	9	32.7439	-27.7910	4.7555	32.4660	-27.5539	5.1490	0.2779	0.2371	-0.3935	0.5369	0.2779	X
	10	31.2761	-20.2157	2.9844	31.2211	-20.2466	3.2732	0.0550	-0.0309	-0.2888	0.2956	0.0550	X
FLOOR PAN (Z)	11	25.8462	-45.0618	7.2249	25.2152	-42.4134	5.1621	0.6310	2.6484	2.0628	3.4157	2.0628	Z
	12	26.8982	-37.6636	5.3704	26.3332	-36.9809	3.6378	0.5650	0.6827	1.7326	1.9461	1.7326	Z
	13	27.8106	-29.9812	5.2126	27.5189	-29.5927	5.0813	0.2917	0.3885	0.1313	0.5033	0.1313	Z
	14	27.5392	-24.9094	5.0433	27.4002	-24.5862	5.5007	0.1390	0.3232	-0.4574	0.5771	-0.4574	Z
	15	27.7359	-19.4927	3.1966	27.6570	-19.5284	3.2970	0.0789	-0.0357	-0.1004	0.1326	-0.1004	Z
	16	21.5141	-45.4075	7.7056	21.4312	-43.4450	6.5616	0.0829	1.9625	1.1440	2.2731	1.1440	Z
	17	22.8407	-37.5867	5.6915	22.3698	-36.9647	4.2904	0.4709	0.6220	1.4011	1.6037	1.4011	Z
	18	23.4747	-30.0530	5.4522	23.2711	-29.6318	5.6814	0.2036	0.4212	-0.2292	0.5210	-0.2292	Z
	19	23.5734	-24.6397	5.2829	23.3902	-24.2631	5.7434	0.1832	0.3766	-0.4605	0.6225	-0.4605	Z
	20	23.3864	-19.5503	3.4585	23.3143	-19.5511	3.4266	0.0721	-0.0008	0.0319	0.0788	0.0319	Z
	21	14.3423	-44.8570	7.5862	14.6212	-44.5279	7.4032	-0.2789	0.3291	0.1830	0.4686	0.1830	Z
	22	16.5522	-37.7657	6.0134	16.5155	-37.3015	6.5827	0.0367	0.4642	-0.5693	0.7355	-0.5693	Z
	23	17.0965	-29.6362	5.6119	16.9527	-29.2885	6.2490	0.1438	0.3477	-0.6371	0.7399	-0.6371	Z
	24	16.8774	-24.1118	5.2264	16.8131	-23.7720	5.5558	0.0643	0.3398	-0.3294	0.4776	-0.3294	Z
	25	17.8361	-18.3644	4.1194	17.7267	-18.2923	3.9830	0.1094	0.0721	0.1364	0.1891	0.1364	Z
	26	11.3577	-44.3771	5.7308	11.5826	-44.0889	5.9656	-0.2249	0.2882	-0.2348	0.4345	-0.2348	Z
	27	11.9939	-37.6129	4.9635	12.1643	-37.2479	5.1218	-0.1704	0.3650	-0.1583	0.4328	-0.1583	Z
	28	12.6692	-29.2934	5.0289	12.5582	-29.0007	5.4050	0.1110	0.2927	-0.3761	0.4893	-0.3761	Z
	29	12.6693	-23.3639	4.6017	12.5129	-23.2173	4.6721	0.1564	0.1466	-0.0704	0.2256	-0.0704	Z
	30	13.0676	-18.4260	4.0909	13.0303	-18.4471	4.0571	0.0373	-0.0211	0.0338	0.0546	0.0338	Z

[A] Positive values denote deformation as inward toward the occupant compartment, negative values denote deformations outward away from the occupant compartment.

[B] Crush calculations that use multiple directional components will disregard components that are negative and only include positive values where the component is deforming inward toward the occupant compartment.

[C] Direction for Crush column denotes which directions are included in the crush calculations. If "NA" then no intrusion is recorded, and Crush will be 0.

Pretest Floor Pan	Posttest Floor Pan
	

Figure H-1. Floor Pan Deformation Data – Set 1, Test No. ABCBRM-1

Model Year: 2013	Test Name: ABCBR-1	VIN: 3ALACXDT6EDFX0132
	Make: Freightliner	Model: M2

VEHICLE DEFORMATION
FLOOR PAN - SET 2

	POINT	Pretest X (in.)	Pretest Y (in.)	Pretest Z (in.)	Posttest X (in.)	Posttest Y (in.)	Posttest Z (in.)	ΔX[A] (in.)	ΔY[A] (in.)	ΔZ[A] (in.)	Total Δ (in.)	Crush[B] (in.)	Directions for Crush[C]
TOE PAN - WHEEL WELL (X, Z)	1	44.3516	23.7881	-0.4422	43.2838	-23.3618	-0.5165	1.0678	47.1499	0.0743	47.1620	1.0704	X, Z
	2	44.3971	19.9195	-2.5858	42.8114	-19.2235	1.4450	1.5857	39.1430	-4.0308	39.3819	1.5857	X
	3	44.3822	14.2351	-3.2296	43.4136	-13.8707	2.4533	0.9686	28.1058	-5.6829	28.6909	0.9686	X
	4	38.3358	9.5399	-3.9824	37.9966	-9.4400	4.9514	0.3392	18.9799	-8.9338	20.9801	0.3392	X
	5	37.1040	2.3604	-2.3154	37.0529	-2.3582	3.5941	0.0511	4.7186	-5.9095	7.5624	0.0511	X
	6	36.1344	23.8997	-5.6676	33.7845	-22.1747	0.8814	2.3499	46.0744	-6.5490	46.5968	2.3499	X
	7	36.4678	19.0397	-4.5434	34.7978	-17.4978	0.9069	1.6700	36.5375	-5.4503	36.9795	1.6700	X
	8	36.6374	14.3834	-4.1834	35.9916	-13.6384	3.6692	0.6458	28.0218	-7.8526	29.1084	0.6458	X
	9	34.9757	8.8122	-4.2411	34.6778	-8.6403	5.3517	0.2979	17.4525	-9.5928	19.9173	0.2979	X
	10	32.7672	1.4436	-2.3693	32.7145	-1.4775	3.3888	0.0527	2.9211	-5.7581	6.4569	0.0527	X
FLOOR PAN (Z)	11	29.7786	26.5958	-7.1895	28.8802	-24.1133	5.6078	0.8984	50.7091	-12.7973	52.3067	-12.7973	Z
	12	30.0930	19.1709	-5.1764	29.4271	-18.5895	3.9898	0.6659	37.7604	-9.1662	38.8627	-9.1662	Z
	13	30.2800	11.4417	-4.8575	29.9857	-11.0988	5.3292	0.2943	22.5405	-10.1867	24.7372	-10.1867	Z
	14	29.5323	6.4216	-4.6031	29.3226	-6.0997	5.6946	0.2097	12.5213	-10.2977	16.2133	-10.2977	Z
	15	29.1806	1.0487	-2.6544	29.1017	-1.0710	3.4233	0.0789	2.1197	-6.0777	6.4372	-6.0777	Z
	16	25.5097	27.3328	-7.7814	25.2088	-25.4393	6.9979	0.3009	52.7721	-14.7793	54.8034	-14.7793	Z
	17	26.0543	19.4650	-5.5945	25.5094	-18.9197	4.6276	0.5449	38.3847	-10.2221	39.7262	-10.2221	Z
	18	25.9763	11.9114	-5.2036	25.6923	-11.5190	5.9601	0.2840	23.4304	-11.1637	25.9556	-11.1637	Z
	19	25.5651	6.5169	-4.9340	25.3313	-6.1367	5.9465	0.2338	12.6536	-10.8805	16.6899	-10.8805	Z
	20	24.8625	1.5050	-3.0229	24.7736	-1.5005	3.5792	0.0889	3.0055	-6.6021	7.2546	-6.6021	Z
	21	18.3168	27.4538	-7.8263	18.4866	-27.1530	7.8643	-0.1698	54.6068	-15.6906	56.8166	-15.6906	Z
	22	19.8188	20.2212	-6.0723	19.7321	-19.7757	6.9262	0.0867	39.9969	-12.9985	42.0562	-12.9985	Z
	23	19.5922	12.0861	-5.5106	19.3537	-11.7790	6.4950	0.2385	23.8651	-12.0056	26.7158	-12.0056	Z
	24	18.8495	6.6150	-5.0306	18.6735	-6.3406	5.7622	0.1760	12.9556	-10.7928	16.8631	-10.7928	Z
	25	19.2420	0.8270	-3.7968	19.1417	-0.8611	4.1315	0.1003	1.6881	-7.9283	8.1066	-7.9283	Z
	26	15.2595	27.2912	-6.0356	15.4156	-26.9872	6.4438	-0.1561	54.2784	-12.4794	55.6947	-12.4794	Z
	27	15.2437	20.5141	-5.1308	15.3939	-20.1464	5.5366	-0.1502	40.6605	-10.6674	42.0368	-10.6674	Z
	28	15.1403	12.1682	-5.0292	14.9867	-11.8901	5.6946	0.1536	24.0583	-10.7238	26.3406	-10.7238	Z
	29	14.5770	6.2743	-4.4949	14.3978	-6.1727	4.8878	0.1792	12.4470	-9.3827	15.5883	-9.3827	Z
	30	14.5007	1.3322	-3.8853	14.3956	-1.3592	4.1996	0.1051	2.6914	-8.0849	8.5218	-8.0849	Z

[A] Positive values denote deformation as inward toward the occupant compartment, negative values denote deformations outward away from the occupant compartment.

[B] Crush calculations that use multiple directional components will disregard components that are negative and only include positive values where the component is deforming inward toward the occupant compartment.

[C] Direction for Crush column denotes which directions are included in the crush calculations. If "NA" then no intrusion is recorded, and Crush will be 0.

Pretest Floor Pan	Posttest Floor Pan
	

Figure H-2. Floor Pan Deformation Data – Set 2, Test No. ABCBRM-1

Model Year: 2013 | Test Name: ABCBR-1 | VIN: 3ALACXDT6EDFX0132
Make: Freightliner | Model: M2

VEHICLE DEFORMATION
INTERIOR CRUSH - SET 1

	POINT	Pretest X (in.)	Pretest Y (in.)	Pretest Z (in.)	Posttest X (in.)	Posttest Y (in.)	Posttest Z (in.)	ΔX[A] (in.)	ΔY[A] (in.)	ΔZ[A] (in.)	Total Δ (in.)	Crush[B] (in.)	Directions for Crush[C]
DASH (X, Y, Z)	1	33.6045	-42.3193	-22.3297	32.9285	-42.6349	-21.7325	0.6760	-0.3156	0.5972	0.9556	0.9556	X, Y, Z
	2	36.2560	-25.1378	-24.6533	35.7412	-25.5474	-24.1795	0.5148	-0.4096	0.4738	0.8107	0.8107	X, Y, Z
	3	36.9027	-10.8415	-24.5949	36.5045	-11.3143	-24.2907	0.3982	-0.4728	0.3042	0.6889	0.6889	X, Y, Z
	4	29.3728	-41.6559	-15.4755	28.8010	-41.8677	-14.7843	0.5718	-0.2118	0.6912	0.9217	0.9217	X, Y, Z
	5	30.9767	-24.7337	-15.2707	30.5918	-25.0061	-14.7782	0.3849	-0.2724	0.4925	0.6818	0.6818	X, Y, Z
	6	31.3059	-11.7446	-15.0983	31.0005	-12.0927	-14.7103	0.3054	-0.3481	0.3880	0.6041	0.6041	X, Y, Z
SIDE PANEL (Y)	7	36.0399	-45.9195	-5.9331	35.3160	-47.5477	-5.3080	0.7239	-1.6282	0.6251	1.8883	-1.6282	Y
	8	36.7488	-45.6768	-0.5519	35.7756	-47.1149	-1.2988	0.9732	-1.4381	-0.7469	1.8903	-1.4381	Y
	9	40.0998	-46.2440	-2.9099	39.4001	-47.5652	-2.3258	0.6997	-1.3212	0.5841	1.6051	-1.3212	Y
IMPACT SIDE DOOR (Y)	10	5.1875	-44.9365	-21.5710	4.6683	-45.7939	-21.1366	0.5192	-0.8574	0.4344	1.0924	-0.8574	Y
	11	14.0926	-46.6475	-19.7807	13.5270	-47.5928	-19.3023	0.5656	-0.9453	0.4784	1.2010	-0.9453	Y
	12	26.3360	-47.6272	-19.3700	25.7785	-48.6647	-18.8670	0.5575	-1.0375	0.5030	1.2807	-1.0375	Y
	13	3.6753	-46.0318	-4.0001	3.0755	-46.9441	-3.5758	0.5998	-0.9123	0.4243	1.1714	-0.9123	Y
	14	14.3748	-47.5695	-3.3160	13.7550	-48.4644	-2.8475	0.6198	-0.8949	0.4685	1.1851	-0.8949	Y
	15	25.1678	-48.5317	2.5513	24.4805	-49.2150	3.0697	0.6873	-0.6833	0.5184	1.0991	-0.6833	Y
ROOF - (Z)	16	30.9984	-38.7794	-47.2231	30.6258	-39.5632	-46.7522	0.3726	-0.7838	0.4709	0.9874	0.4709	Z
	17	34.2300	-23.6360	-47.2477	33.9499	-24.4500	-46.9426	0.2801	-0.8140	0.3051	0.9133	0.3051	Z
	18	36.7939	-10.0160	-47.5863	36.5935	-10.8069	-47.4456	0.2004	-0.7909	0.1407	0.8279	0.1407	Z
	19	22.8090	-38.1075	-51.4361	22.4938	-38.9168	-50.9592	0.3152	-0.8093	0.4769	0.9908	0.4769	Z
	20	25.2741	-26.9397	-50.7253	24.9815	-27.7259	-50.3885	0.2926	-0.7862	0.3368	0.9040	0.3368	Z
	21	27.5243	-9.1430	-47.2806	27.3694	-9.9304	-47.1231	0.1549	-0.7874	0.1575	0.8178	0.1575	Z
	22	16.5624	-37.6563	-52.2323	16.2359	-38.4379	-51.7606	0.3265	-0.7816	0.4717	0.9695	0.4717	Z
	23	17.1014	-26.8983	-51.3466	16.8062	-27.6390	-50.9938	0.2952	-0.7407	0.3528	0.8719	0.3528	Z
	24	20.5741	-8.3829	-52.1439	20.4387	-9.1296	-51.9626	0.1354	-0.7467	0.1813	0.7802	0.1813	Z
	25	7.6216	-37.2406	-52.7295	7.2678	-37.9607	-52.2267	0.3538	-0.7201	0.5028	0.9469	0.5028	Z
	26	7.3984	-25.8825	-51.8590	7.1353	-26.5547	-51.4986	0.2631	-0.6722	0.3604	0.8068	0.3604	Z
	27	8.3535	-7.7961	-53.0765	8.1867	-8.5715	-52.8847	0.1668	-0.7754	0.1918	0.8160	0.1918	Z
	28	-1.1677	-36.3497	-53.1871	-1.4616	-36.9992	-52.6636	0.2939	-0.6495	0.5235	0.8845	0.5235	Z
	29	-0.8708	-25.2838	-52.1367	-1.1257	-25.9171	-51.7641	0.2549	-0.6333	0.3726	0.7777	0.3726	Z
	30	-1.9626	-6.8567	-53.2826	-2.1051	-7.5624	-53.1183	0.1425	-0.7057	0.1643	0.7385	0.1643	Z
A-PILLAR Maximum (X, Y, Z)	31	35.3969	-45.7790	-24.1416	34.8558	-46.5324	-23.5834	0.5411	-0.7534	0.5582	1.0826	0.7774	X, Z
	32	34.4586	-45.4450	-28.3192	33.9090	-46.1803	-27.7648	0.5496	-0.7353	0.5544	1.0724	0.7807	X, Z
	33	33.4966	-45.1950	-31.4077	32.9872	-45.9289	-30.8788	0.5094	-0.7339	0.5289	1.0382	0.7343	X, Z
	34	32.1654	-44.9955	-34.9932	31.7130	-45.7396	-34.4356	0.4524	-0.7441	0.5576	1.0341	0.7180	X, Z
	35	30.1499	-43.9878	-39.4846	29.7257	-44.7390	-38.9558	0.4242	-0.7512	0.5288	1.0119	0.6779	X, Z
	36	28.4542	-42.2636	-44.5553	28.1191	-43.0386	-44.0164	0.3351	-0.7750	0.5389	1.0017	0.6346	X, Z
A-PILLAR Lateral (Y)	31	35.3969	-45.7790	-24.1416	34.8558	-46.5324	-23.5834	0.5411	-0.7534	0.5582	1.0826	-0.7534	Y
	32	34.4586	-45.4450	-28.3192	33.9090	-46.1803	-27.7648	0.5496	-0.7353	0.5544	1.0724	-0.7353	Y
	33	33.4966	-45.1950	-31.4077	32.9872	-45.9289	-30.8788	0.5094	-0.7339	0.5289	1.0382	-0.7339	Y
	34	32.1654	-44.9955	-34.9932	31.7130	-45.7396	-34.4356	0.4524	-0.7441	0.5576	1.0341	-0.7441	Y
	35	30.1499	-43.9878	-39.4846	29.7257	-44.7390	-38.9558	0.4242	-0.7512	0.5288	1.0119	-0.7512	Y
	36	28.4542	-42.2636	-44.5553	28.1191	-43.0386	-44.0164	0.3351	-0.7750	0.5389	1.0017	-0.7750	Y
B-PILLAR Maximum (X, Y, Z)	37	-6.3224	-41.1244	-45.0573	-6.5943	-41.7119	-44.4524	0.2719	-0.5875	0.6049	0.8860	0.6632	X, Z
	38	-3.2450	-42.2635	-40.6325	-3.4838	-42.8411	-40.0239	0.2388	-0.5776	0.6086	0.8724	0.6538	X, Z
	39	-7.6378	-42.4150	-36.8254	-7.8249	-42.8984	-36.2186	0.1871	-0.4834	0.6068	0.7981	0.6350	X, Z
	40	-3.6881	-43.0428	-34.6560	-3.8503	-43.5580	-34.0203	0.1622	-0.5152	0.6357	0.8342	0.6561	X, Z
B-PILLAR Lateral (Y)	37	-6.3224	-41.1244	-45.0573	-6.5943	-41.7119	-44.4524	0.2719	-0.5875	0.6049	0.8860	-0.5875	Y
	38	-3.2450	-42.2635	-40.6325	-3.4838	-42.8411	-40.0239	0.2388	-0.5776	0.6086	0.8724	-0.5776	Y
	39	-7.6378	-42.4150	-36.8254	-7.8249	-42.8984	-36.2186	0.1871	-0.4834	0.6068	0.7981	-0.4834	Y
	40	-3.6881	-43.0428	-34.6560	-3.8503	-43.5580	-34.0203	0.1622	-0.5152	0.6357	0.8342	-0.5152	Y

[A] Positive values denote deformation as inward toward the occupant compartment, negative values denote deformations outward away from the occupant compartment.

[B] Crush calculations that use multiple directional components will disregard components that are negative and only include positive values where the component is deforming inward toward the occupant compartment.

[C] Direction for Crush column denotes which directions are included in the crush calculations. If "NA" then no intrusion is recorded, and Crush will be 0.

Figure H-3. Occupant Compartment Deformation Data – Set 1, Test No. ABCBRM-1

Model Year: 2013 | Test Name: ABCBR-1 | VIN: 3ALACXDT6EDFX0132
Make: Freightliner | Model: M2

VEHICLE DEFORMATION
INTERIOR CRUSH - SET 2

	POINT	Pretest X (in.)	Pretest Y (in.)	Pretest Z (in.)	Posttest X (in.)	Posttest Y (in.)	Posttest Z (in.)	ΔX[A] (in.)	ΔY[A] (in.)	ΔZ[A] (in.)	Total Δ (in.)	Crush[B] (in.)	Directions for Crush[C]
DASH (X, Y, Z)	1	36.5721	-23.5018	-22.3757	36.5247	-23.8155	-21.3916	0.0474	-0.3137	0.9841	1.0340	1.0340	X, Y, Z
	2	37.5578	-6.1975	-25.0630	37.6819	-6.5655	-24.0338	-0.1241	-0.3680	1.0292	1.1000	1.1000	X, Y, Z
	3	36.8705	8.0955	-25.2703	37.0776	7.6732	-24.3025	-0.2071	0.4223	0.9678	1.0760	1.0760	X, Y, Z
	4	32.4530	-23.0991	-15.4332	32.3576	-23.3697	-14.4390	0.0954	-0.2706	0.9942	1.0348	1.0348	X, Y, Z
	5	32.4772	-6.1003	-15.5632	32.5245	-6.4151	-14.6225	-0.0473	-0.3148	0.9407	0.9931	0.9931	X, Y, Z
	6	31.5984	6.8642	-15.6260	31.6940	6.4781	-14.6967	-0.0956	0.3861	0.9293	1.0108	1.0108	X, Y, Z
SIDE PANEL (Y)	7	39.7024	-26.5375	-5.9828	39.4072	-28.2934	-4.9223	0.2952	-1.7559	1.0605	2.0724	-1.7559	Y
	8	40.5070	-26.1243	-0.6256	39.8318	-27.7739	-0.9196	0.6752	-1.6496	-0.2940	1.8065	-1.6496	Y
	9	43.8422	-26.4245	-3.0541	43.4806	-27.8863	-1.9532	0.3616	-1.4618	1.1009	1.8654	-1.4618	Y
IMPACT SIDE DOOR (Y)	10	8.5470	-28.7280	-20.8801	8.6986	-29.6602	-20.6708	-0.1516	-0.9322	0.2093	0.9674	-0.9322	Y
	11	17.6110	-29.5702	-19.2774	17.6928	-30.5817	-18.8454	-0.0818	-1.0115	0.4320	1.1029	-1.0115	Y
	12	29.8986	-29.4017	-19.1477	29.9916	-30.4701	-18.4377	-0.0930	-1.0684	0.7100	1.2862	-1.0684	Y
	13	7.5411	-29.6131	-3.2611	7.2610	-30.7616	-3.0935	0.2801	-1.1485	0.1676	1.1940	-1.1485	Y
	14	18.3500	-30.1381	-2.8108	18.0386	-31.2438	-2.3829	0.3114	-1.1057	0.4279	1.2258	-1.1057	Y
	15	29.3156	-29.9794	2.8080	28.7993	-30.8974	3.5077	0.5163	-0.9180	0.6997	1.2645	-0.9180	Y
ROOF - (Z)	16	33.0854	-20.7090	-47.2563	33.8846	-21.2578	-46.4358	-0.7992	-0.5488	0.8205	1.2701	0.8205	Z
	17	34.8903	-5.3346	-47.6242	35.7448	-5.8987	-46.8016	-0.8545	-0.5641	0.8226	1.3134	0.8226	Z
	18	36.1656	8.4552	-48.2631	37.0679	7.9284	-47.4618	-0.9023	0.5268	0.8013	1.3167	0.8013	Z
	19	24.7759	-20.8826	-51.2799	25.7191	-21.4404	-50.6236	-0.9432	-0.5578	0.6563	1.2773	0.6563	Z
	20	26.2050	-9.5225	-50.8246	27.1242	-10.0570	-50.1829	-0.9192	-0.5345	0.6417	1.2419	0.6417	Z
	21	26.8643	8.4705	-47.7473	27.8029	7.9208	-47.1193	-0.9386	0.5497	0.6280	1.2560	0.6280	Z
	22	18.4980	-21.0285	-51.9316	19.4423	-21.5721	-51.4101	-0.9443	-0.5436	0.5215	1.2080	0.5215	Z
	23	18.0520	-10.2515	-51.2475	18.9769	-10.7603	-50.7629	-0.9249	-0.5088	0.4846	1.1615	0.4846	Z
	24	19.7653	8.4869	-52.4524	20.8171	7.9999	-51.9450	-1.0518	0.4870	0.5074	1.2653	0.5074	Z
	25	9.5485	-21.4537	-52.2183	10.4689	-21.9614	-51.8527	-0.9204	-0.5077	0.3656	1.1129	0.3656	Z
	26	8.2875	-10.1503	-51.5412	9.2455	-10.6130	-51.2485	-0.9580	-0.4627	0.2927	1.1034	0.2927	Z
	27	7.5253	7.9192	-53.0975	8.5660	7.3715	-52.8339	-1.0407	0.5477	0.2636	1.2052	0.2636	Z
	28	0.7063	-21.3910	-52.4774	1.6866	-21.8454	-52.2720	-0.9803	-0.4544	0.2054	1.0998	0.2054	Z
	29	-0.0057	-10.3267	-51.6280	0.9610	-10.7727	-51.4944	-0.9667	-0.4460	0.1336	1.0730	0.1336	Z
	30	-2.8354	7.8936	-53.0689	-1.7756	7.3875	-53.0455	-1.0598	0.5061	0.0234	1.1747	0.0234	Z
A-PILLAR Maximum (X, Y, Z)	31	38.6377	-26.8153	-24.1700	38.8127	-27.5308	-23.2061	-0.1750	-0.7155	0.9639	1.2131	0.9639	Z
	32	37.5781	-26.6520	-28.3286	37.8274	-27.3178	-27.3881	-0.2493	-0.6658	0.9405	1.1790	0.9405	Z
	33	36.5274	-26.5531	-31.3968	36.8792	-27.1905	-30.5016	-0.3518	-0.6374	0.8952	1.1539	0.8952	Z
	34	35.1027	-26.5484	-34.9517	35.5851	-27.1639	-34.0562	-0.4824	-0.6155	0.8955	1.1889	0.8955	Z
	35	32.9011	-25.8205	-39.4097	33.5013	-26.4087	-38.5806	-0.6002	-0.5882	0.8291	1.1805	0.8291	Z
	36	30.9380	-24.3611	-44.4670	31.7283	-24.9266	-43.6543	-0.7903	-0.5655	0.8127	1.2668	0.8127	Z
A-PILLAR Lateral (Y)	31	38.6377	-26.8153	-24.1700	38.8127	-27.5308	-23.2061	-0.1750	-0.7155	0.9639	1.2131	-0.7155	Y
	32	37.5781	-26.6520	-28.3286	37.8274	-27.3178	-27.3881	-0.2493	-0.6658	0.9405	1.1790	-0.6658	Y
	33	36.5274	-26.5531	-31.3968	36.8792	-27.1905	-30.5016	-0.3518	-0.6374	0.8952	1.1539	-0.6374	Y
	34	35.1027	-26.5484	-34.9517	35.5851	-27.1639	-34.0562	-0.4824	-0.6155	0.8955	1.1889	-0.6155	Y
	35	32.9011	-25.8205	-39.4097	33.5013	-26.4087	-38.5806	-0.6002	-0.5882	0.8291	1.1805	-0.5882	Y
	36	30.9380	-24.3611	-44.4670	31.7283	-24.9266	-43.6543	-0.7903	-0.5655	0.8127	1.2668	-0.5655	Y
B-PILLAR Maximum (X, Y, Z)	37	-3.7960	-26.4625	-44.1423	-2.9534	-26.9362	-43.9935	-0.8426	-0.4737	0.1488	0.9780	0.1488	Z
	38	-0.5265	-27.2240	-39.7745	0.2606	-27.7128	-39.5630	-0.7871	-0.4888	0.2115	0.9504	0.2115	Z
	39	-4.7989	-27.7074	-35.8596	-4.0469	-28.1432	-35.7434	-0.7520	-0.4358	0.1162	0.8769	0.1162	Z
	40	-0.7599	-27.9233	-33.7763	-0.0227	-28.3945	-33.5508	-0.7372	-0.4712	0.2255	0.9035	0.2255	Z
B-PILLAR Lateral (Y)	37	-3.7960	-26.4625	-44.1423	-2.9534	-26.9362	-43.9935	-0.8426	-0.4737	0.1488	0.9780	-0.4737	Y
	38	-0.5265	-27.2240	-39.7745	0.2606	-27.7128	-39.5630	-0.7871	-0.4888	0.2115	0.9504	-0.4888	Y
	39	-4.7989	-27.7074	-35.8596	-4.0469	-28.1432	-35.7434	-0.7520	-0.4358	0.1162	0.8769	-0.4358	Y
	40	-0.7599	-27.9233	-33.7763	-0.0227	-28.3945	-33.5508	-0.7372	-0.4712	0.2255	0.9035	-0.4712	Y

[A] Positive values denote deformation as inward toward the occupant compartment, negative values denote deformations outward away from the occupant compartment.

[B] Crush calculations that use multiple directional components will disregard components that are negative and only include positive values where the component is deforming inward toward the occupant compartment.

[C] Direction for Crush column denotes which directions are included in the crush calculations. If "NA" then no intrusion is recorded, and Crush will be 0.

Figure H-4. Occupant Compartment Deformation Data – Set 2, Test No. ABCBRM-1

Test Name:	ABCBR-1	VIN:	3ALACXDT6EDFX0132
Model Year: 2013	Make: Freightliner	Model:	M2

Reference Set 1			
Location	Maximum Deformation[A,B] (in.)	MASH Allowable Deformation (in.)	Directions of Deformation[C]
Roof	0.5	≤ 4	Z
Windshield[D]	0.0	≤ 3	X, Z
A-Pillar Maximum	0.8	≤ 5	X, Z
A-Pillar Lateral	-0.7	≤ 3	Y
B-Pillar Maximum	0.7	≤ 5	X, Z
B-Pillar Lateral	-0.5	≤ 3	Y
Toe Pan - Wheel Well	5.8	≤ 9	X, Z
Side Front Panel	-1.3	≤ 12	Y
Side Door (above seat)	-0.9	≤ 9	Y
Side Door (below seat)	-0.7	≤ 12	Y
Floor Pan	2.1	≤ 12	Z
Dash - no MASH requirement	1.0	NA	X, Y, Z

Reference Set 2			
Location	Maximum Deformation[A,B] (in.)	MASH Allowable Deformation (in.)	Directions of Deformation[C]
Roof	0.8	≤ 4	Z
Windshield[D]	NA	≤ 3	X, Z
A-Pillar Maximum	1.0	≤ 5	Z
A-Pillar Lateral	-0.6	≤ 3	Y
B-Pillar Maximum	0.2	≤ 5	Z
B-Pillar Lateral	-0.4	≤ 3	Y
Toe Pan - Wheel Well	2.3	≤ 9	X
Side Front Panel	-1.5	≤ 12	Y
Side Door (above seat)	-0.9	≤ 9	Y
Side Door (below seat)	-0.9	≤ 12	Y
Floor Pan	-6.1	≤ 12	Z
Dash - no MASH requirement	1.0	NA	X, Y, Z

[A] Items highlighted in red do not meet MASH allowable deformations.

[B] Positive values denote deformation as inward toward the occupant compartment, negative values denote deformations outward away from the occupant compartment.

[C] For Toe Pan - Wheel Well the direction of defromation may include X and Z direction. For A-Pillar Maximum and B-Pillar Maximum the direction of deformation may include X, Y, and Z directions. The direction of deformation for Toe Pan -Wheel Well, A-Pillar Maximum, and B-Pillar Maximum only include components where the deformation is positive and intruding into the occupant compartment. If direction of deformation is "NA" then no intrusion is recorded and deformation will be 0.

[D] If deformation is observered for the windshield then the windshield deformation is measured posttest with an examplar vehicle, therefore only one set of reference is measured and recorded.

Notes on vehicle interior crush:

Figure H-5. Maximum Occupant Compartment Deformation, Test No. ABCBRM-1

Appendix I. Accelerometer and Rate Transducer Data Plots, Test No. ABCBRM-1

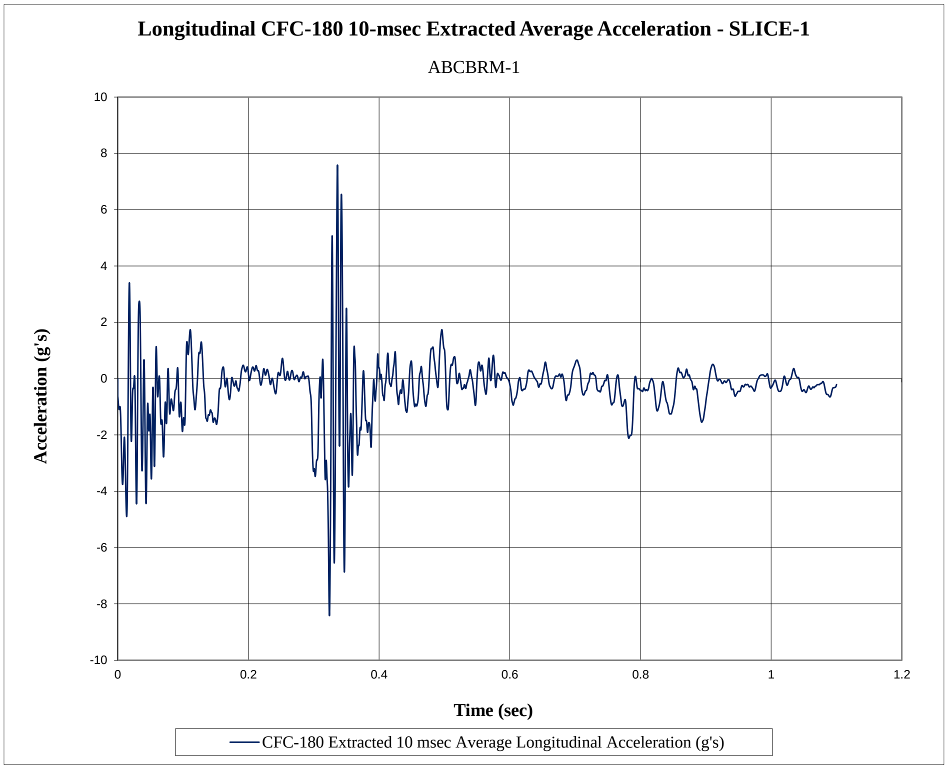


Figure I-1. 10-ms Average Longitudinal Acceleration (SLICE-1, Rear Axle), Test No. ABCBRM-1

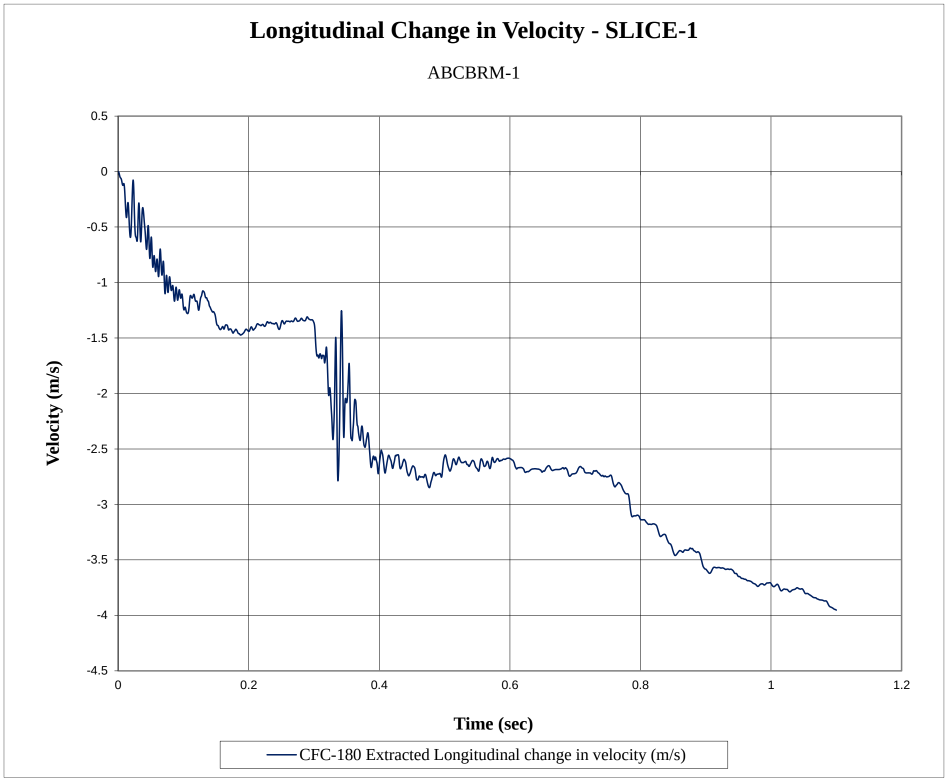


Figure I-2. Longitudinal Change in Velocity (SLICE-1, Rear Axle), Test No. ABCBRM-1

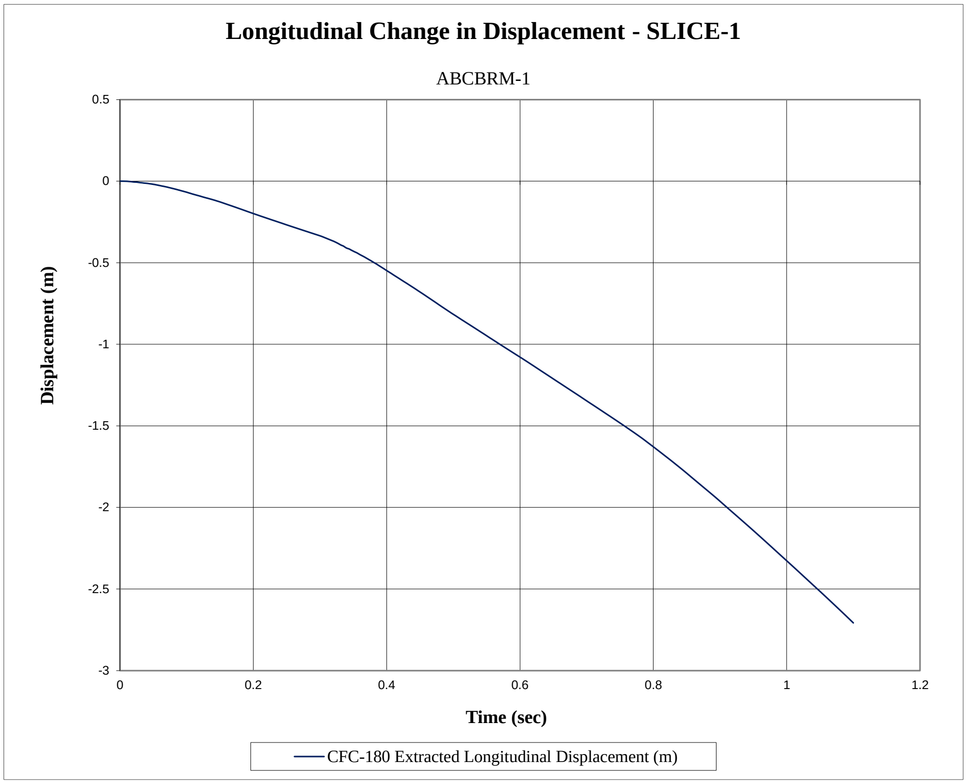


Figure I-3. Longitudinal Occupant Displacement (SLICE-1, Rear Axle), Test No. ABCBRM-1

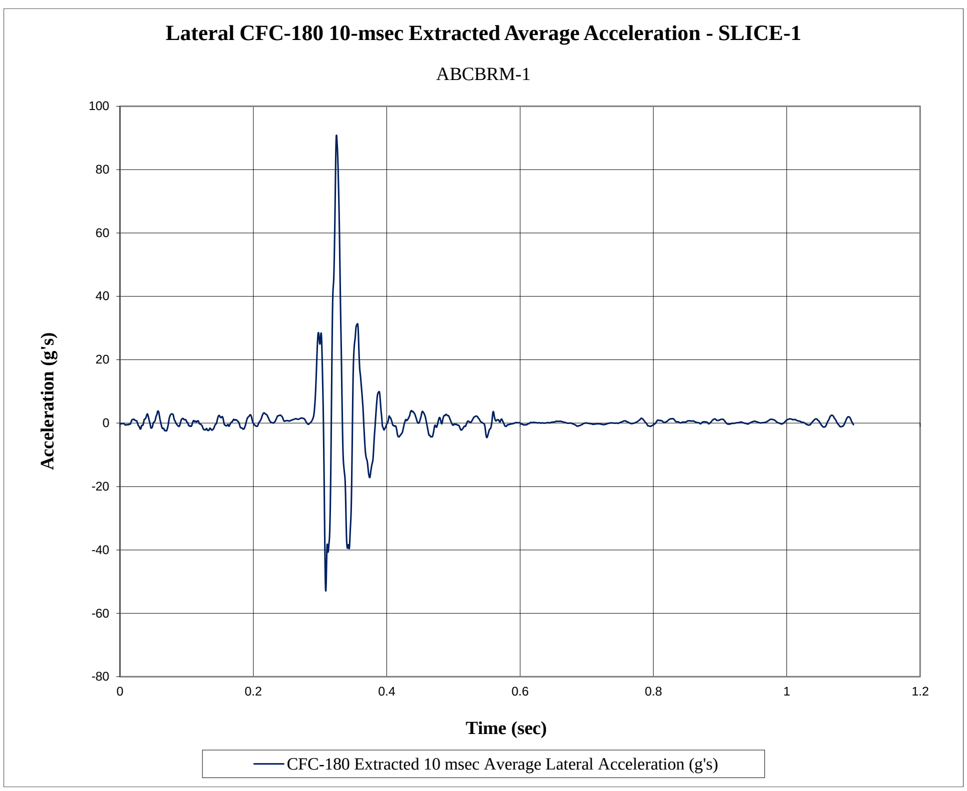


Figure I-4. 10-ms Average Lateral Acceleration (SLICE-1, Rear Axle), Test No. ABCBRM-1

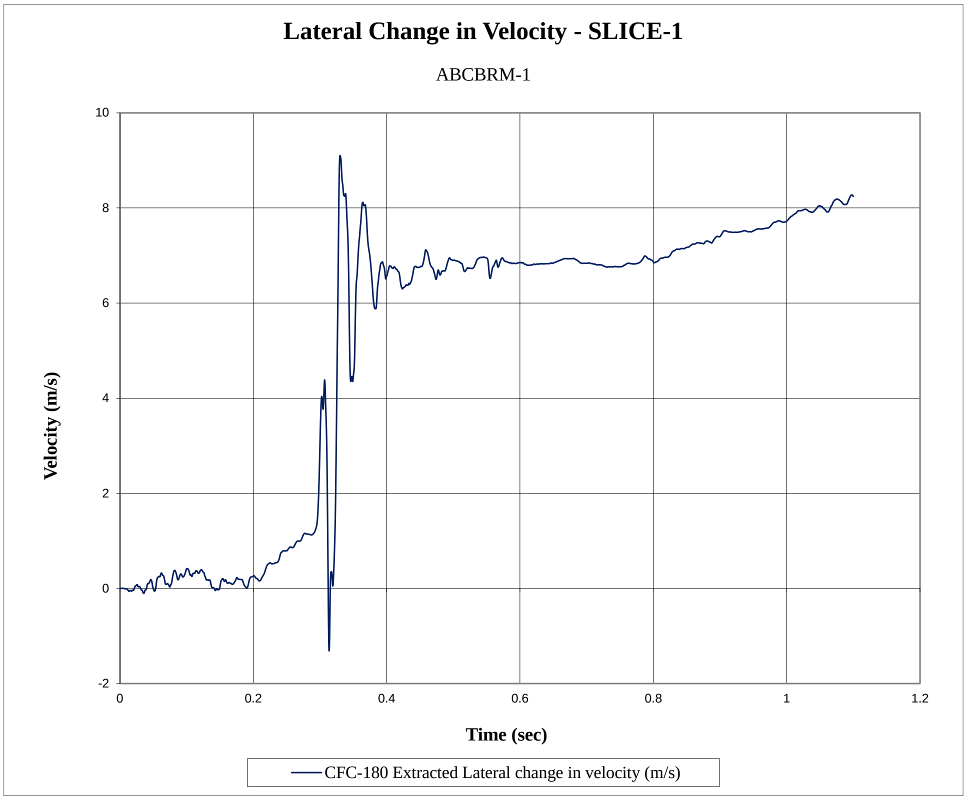


Figure I-5. Lateral Change in Velocity (SLICE-1, Rear Axle), Test No. ABCBRM-1

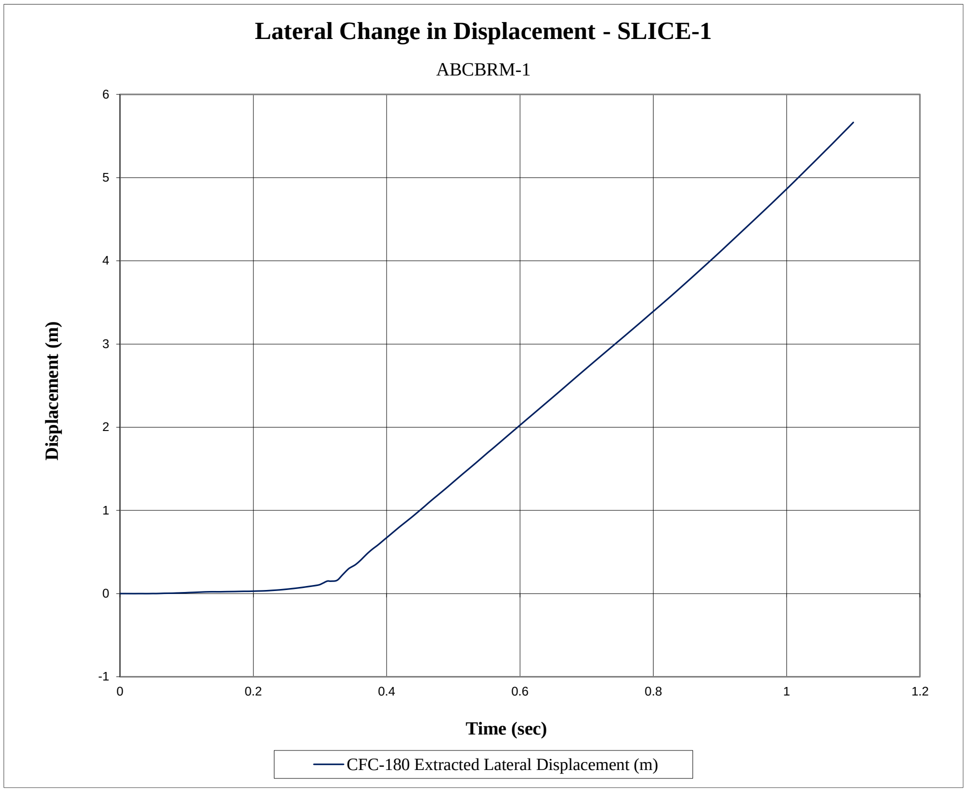


Figure I-6. Lateral Occupant Displacement (SLICE-1, Rear Axle), Test No. ABCBRM-1

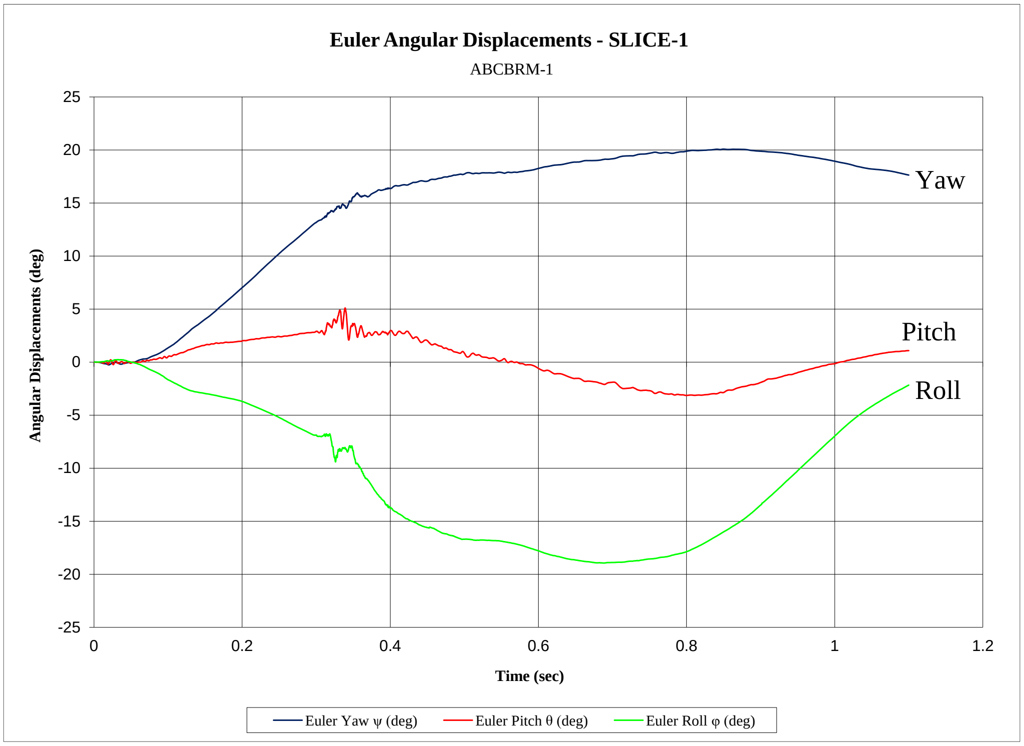


Figure I-7. Vehicle Angular Displacements (SLICE-1, Rear Axle), Test No. ABCBRM-1

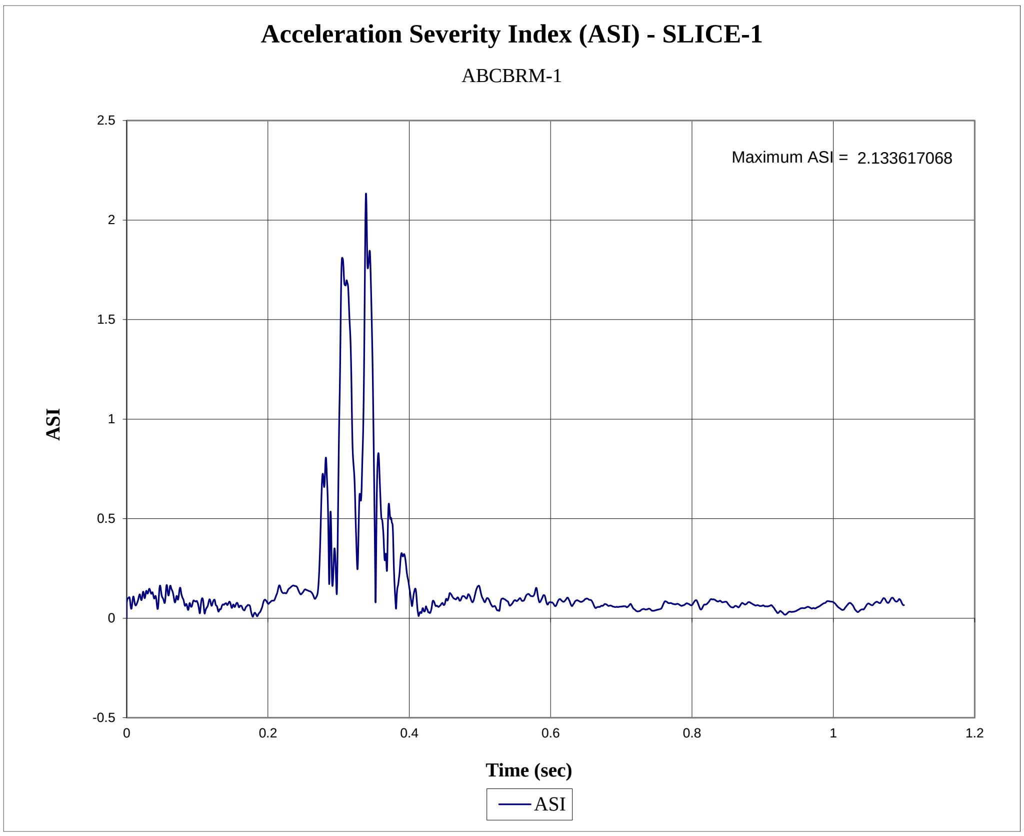


Figure I-8. Acceleration Severity Index (SLICE-1, Rear Axle), Test No. ABCBRM-1

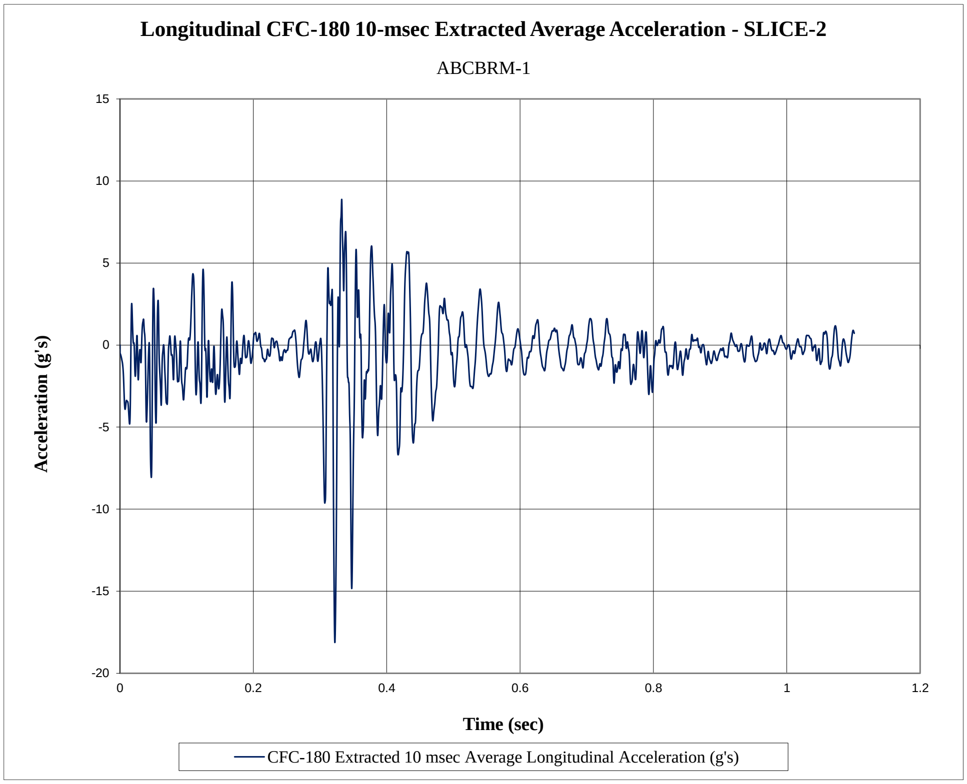


Figure I-9. 10-ms Average Longitudinal Acceleration (SLICE-2, C.G.), Test No. ABCBRM-1

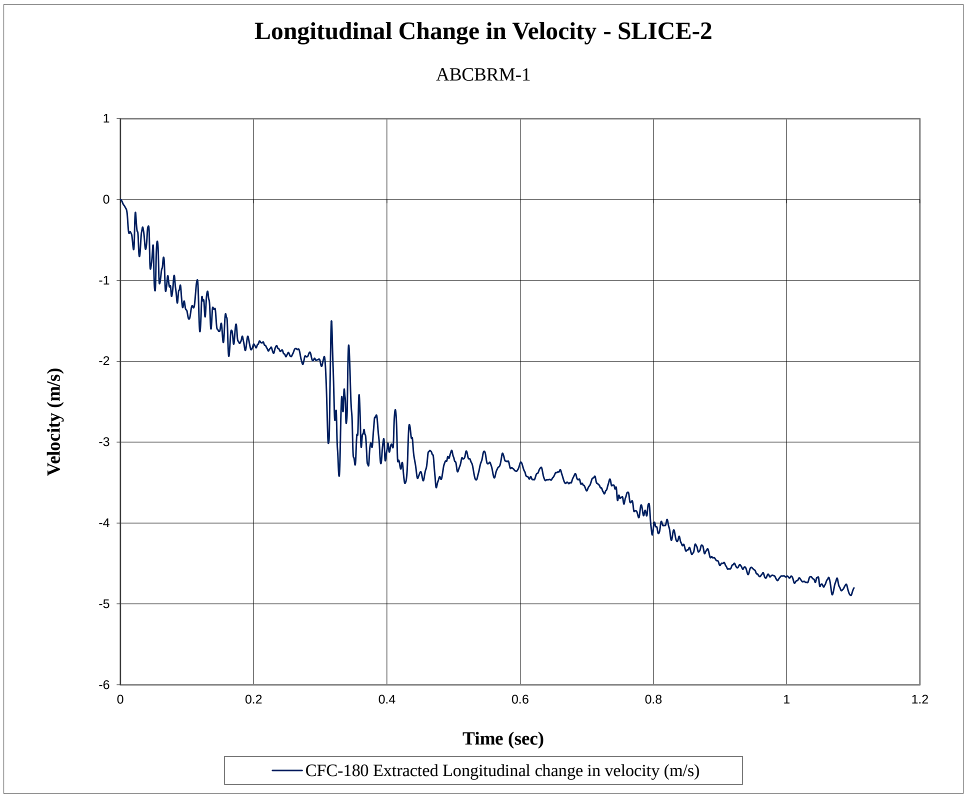


Figure I-10. Longitudinal Change in Velocity (SLICE-2, C.G.), Test No. ABCBRM-1

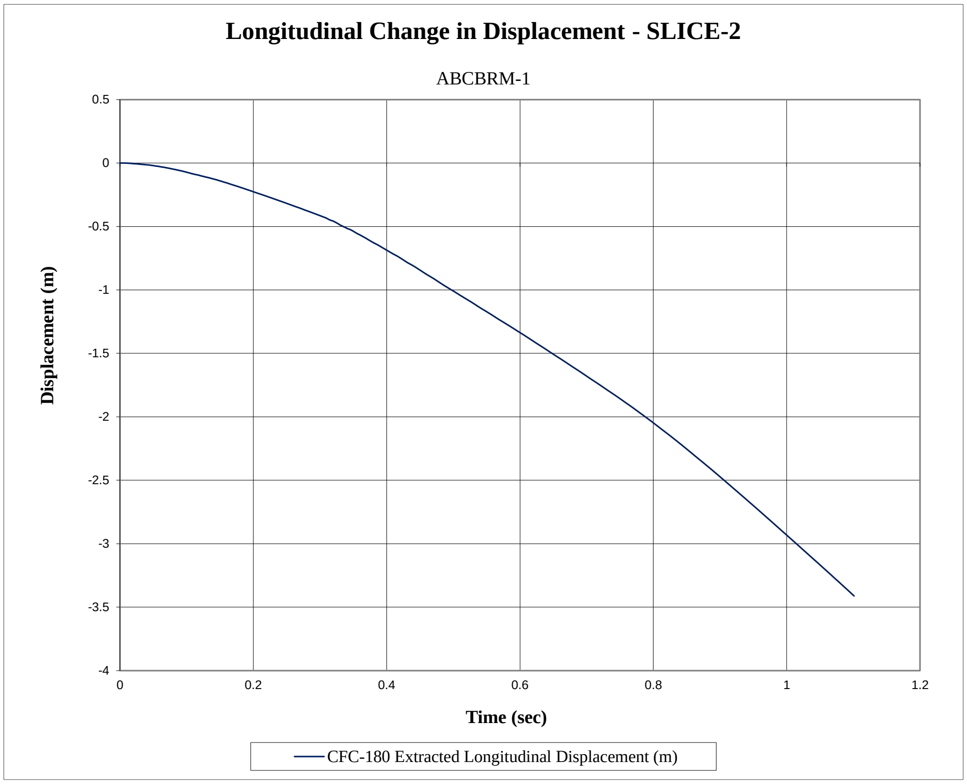


Figure I-11. Longitudinal Occupant Displacement (SLICE-2, C.G.), Test No. ABCBRM-1

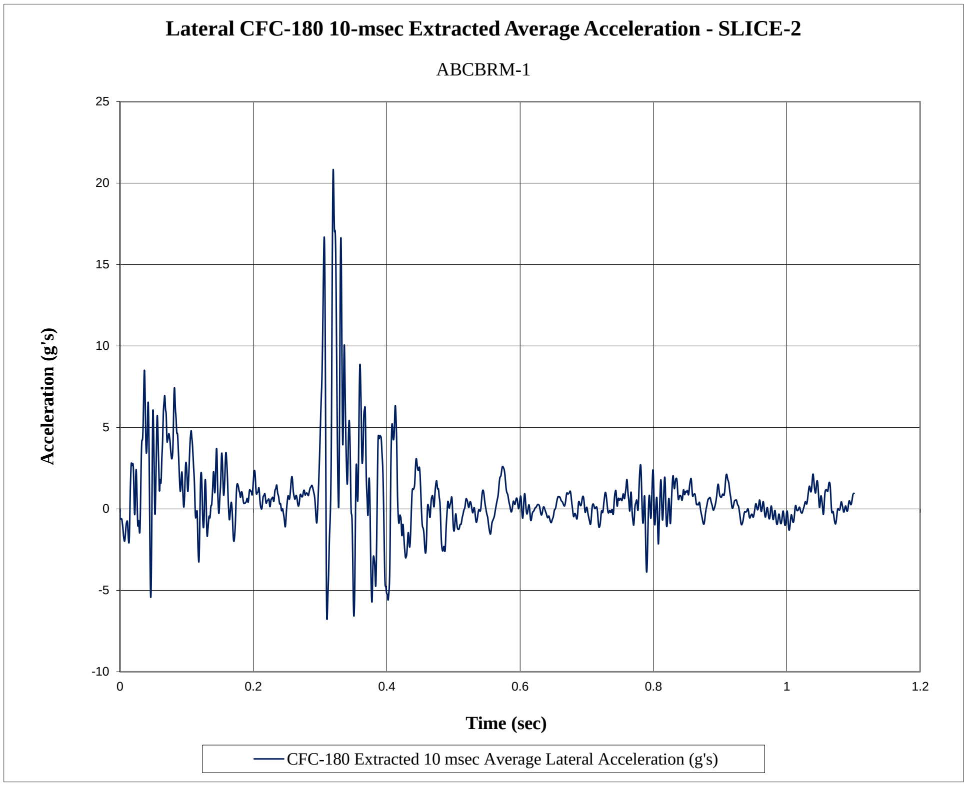


Figure I-12. Figure D-12. 10-ms Average Lateral Acceleration (SLICE-2, C.G.), Test No. ABCBRM-1

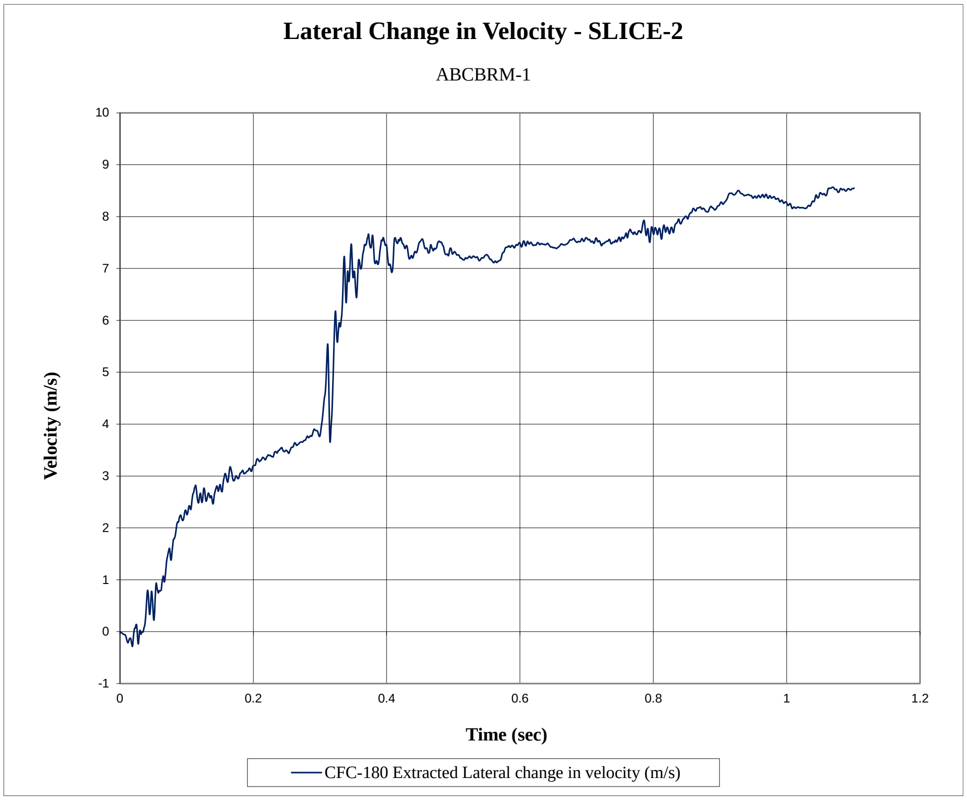


Figure I-13. Lateral Change in Velocity (SLICE-2, C.G.), Test No. ABCBRM-1

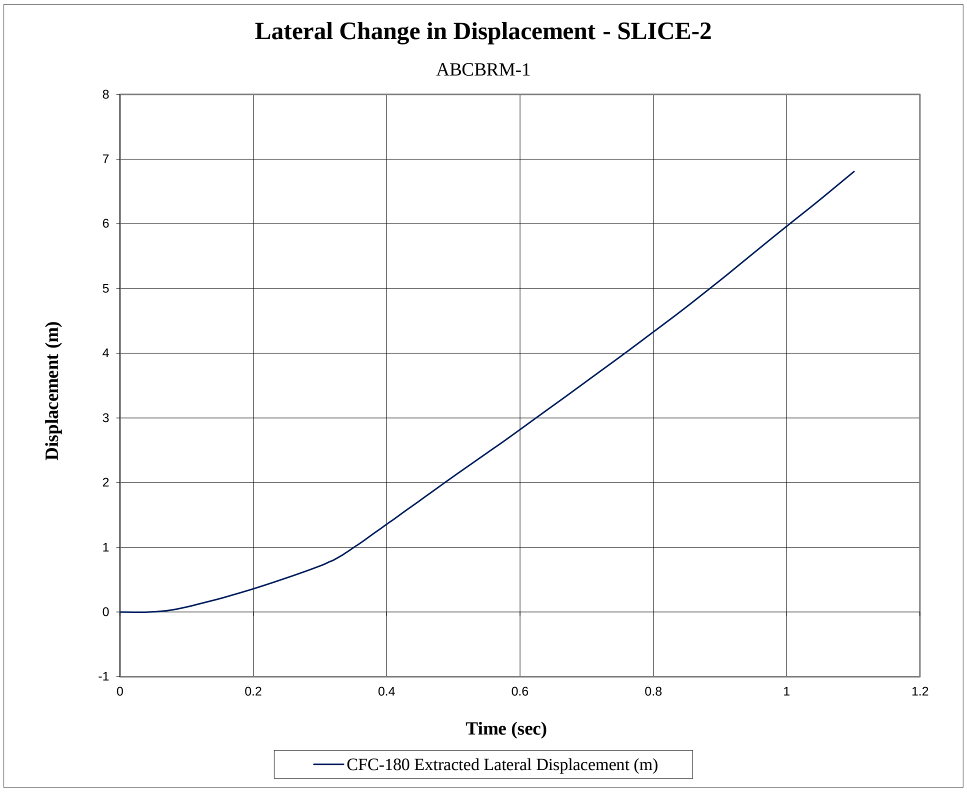


Figure I-14. Lateral Occupant Displacement (SLICE-2, C.G.), Test No. ABCBRM-1

Figure I-15. Vehicle Angular Displacements (SLICE-2, C.G.), Test No. ABCBRM-1

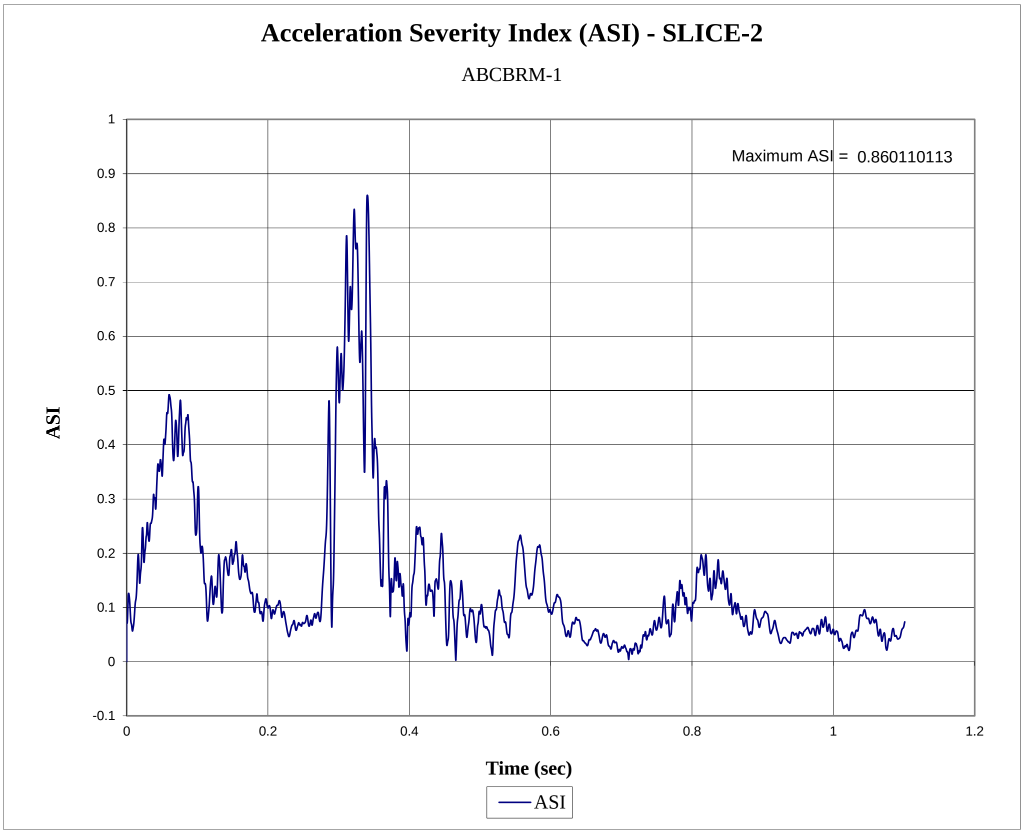


Figure I-16. Acceleration Severity Index (SLICE-2, C.G.), Test No. ABCBRM-1

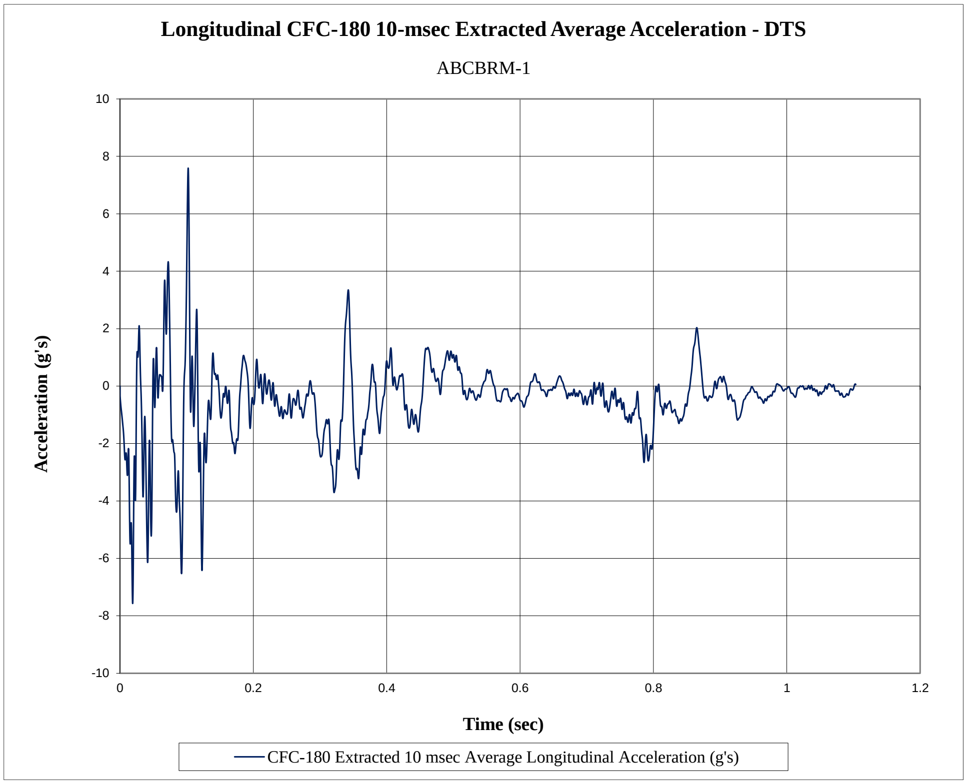


Figure I-17. 10-ms Average Longitudinal Acceleration (TDAS, Cab), Test No. ABCBRM-1

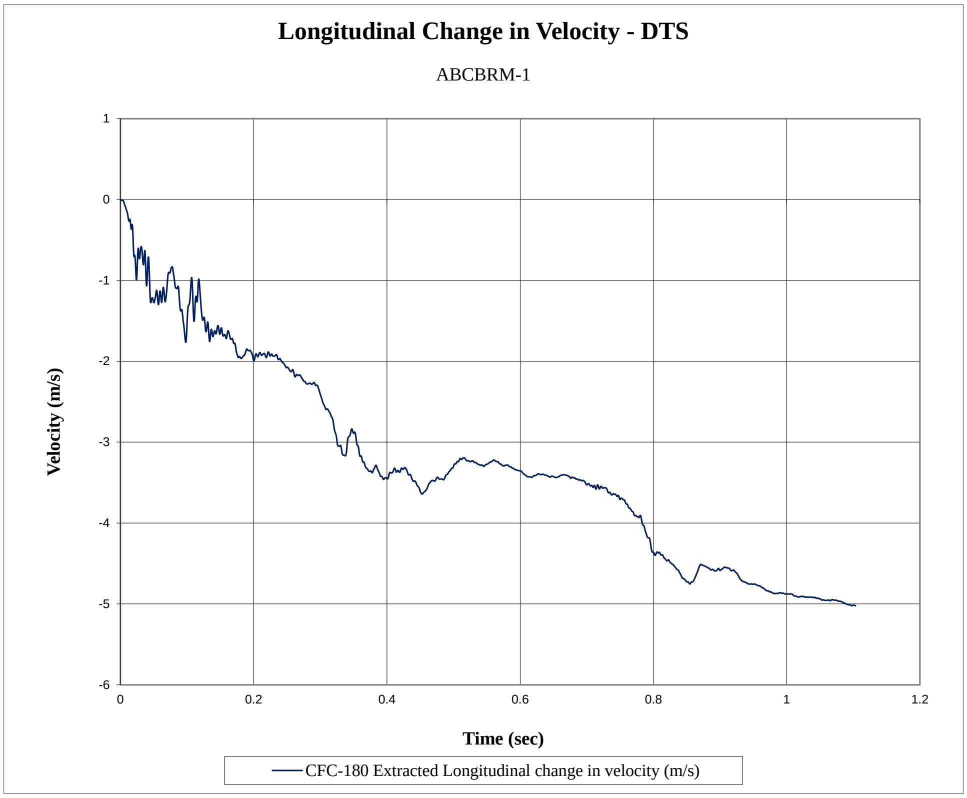


Figure I-18. Longitudinal Change in Velocity (TDAS, Cab), Test No. ABCBRM-1

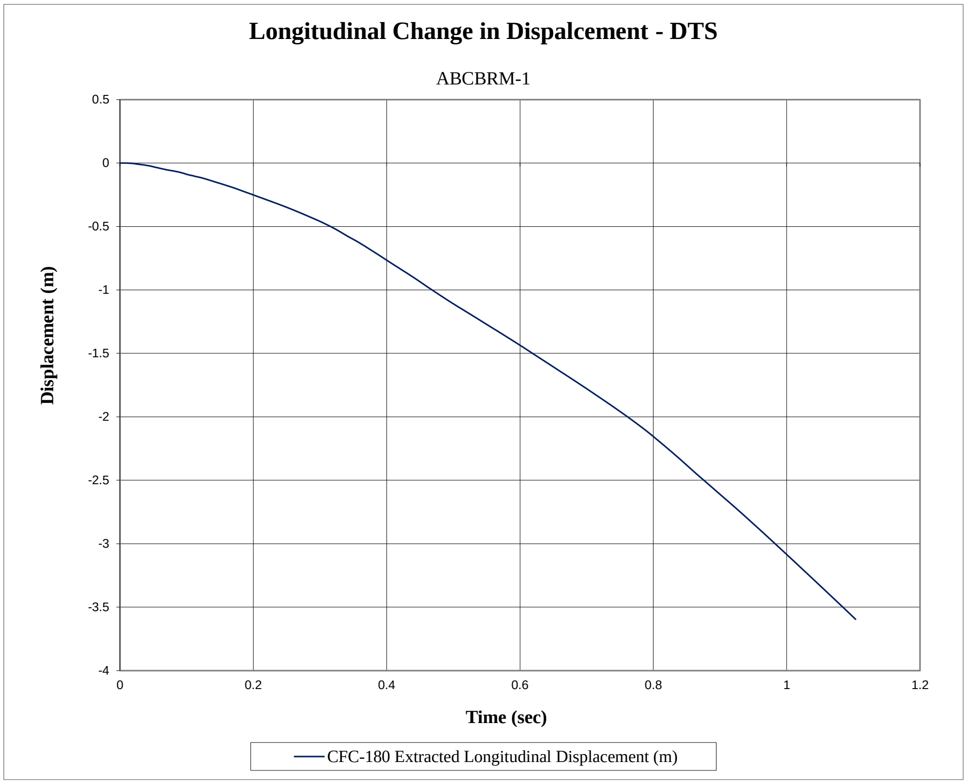


Figure I-19. Longitudinal Occupant Displacement (TDAS, Cab), Test No. ABCBRM-1

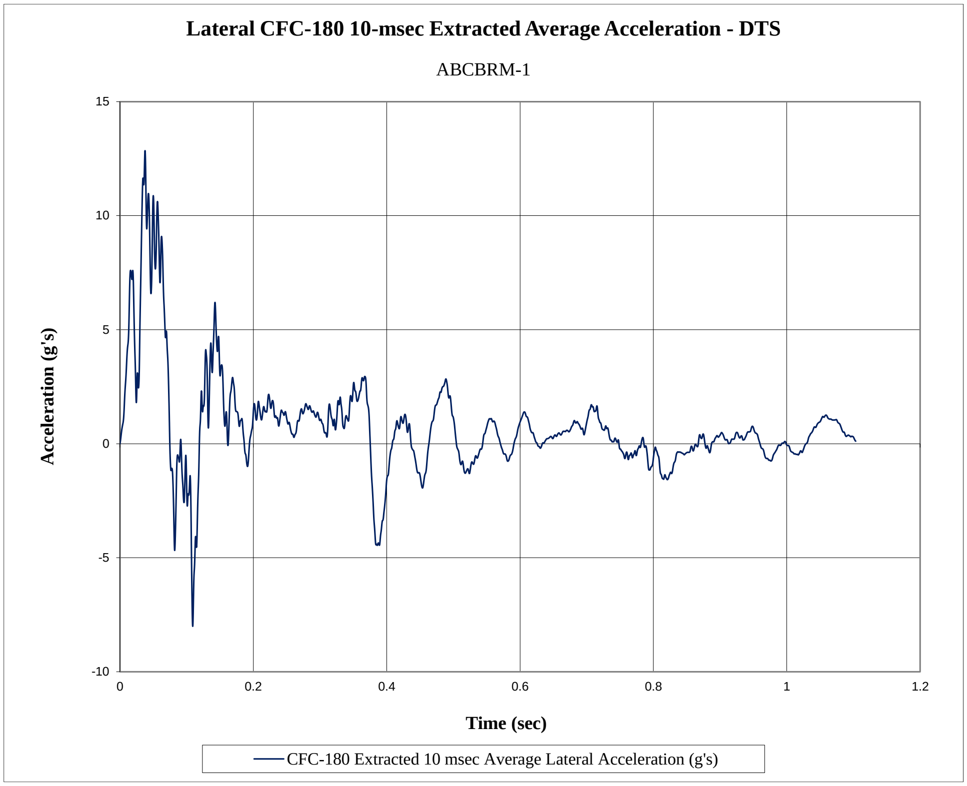


Figure I-20. 10-ms Average Lateral Acceleration (TDAS, Cab), Test No. ABCBRM-1

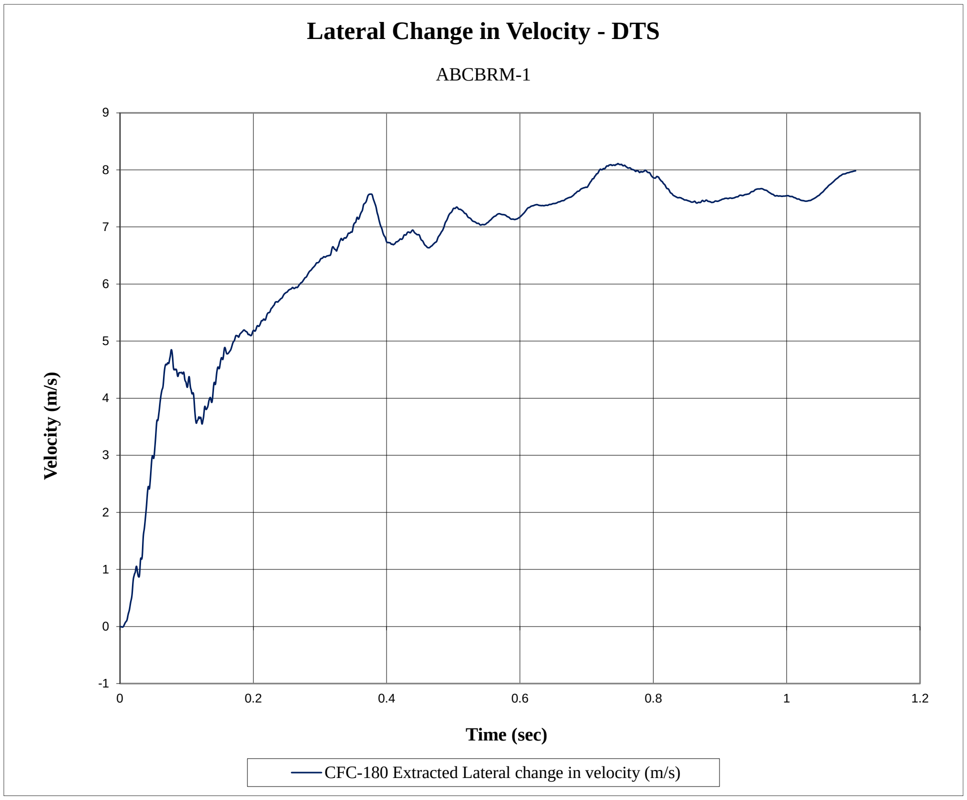


Figure I-21. Lateral Change in Velocity (TDAS, Cab), Test No. ABCBRM-1

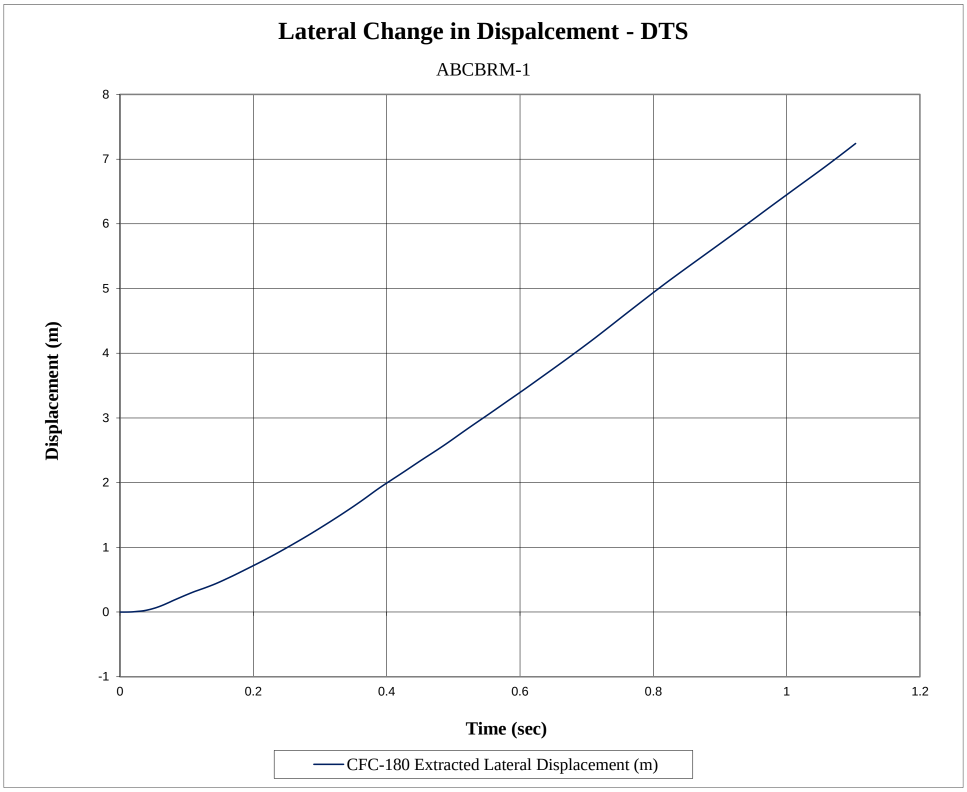


Figure I-22. Lateral Occupant Displacement (TDAS, Cab), Test No. ABCBRM-1

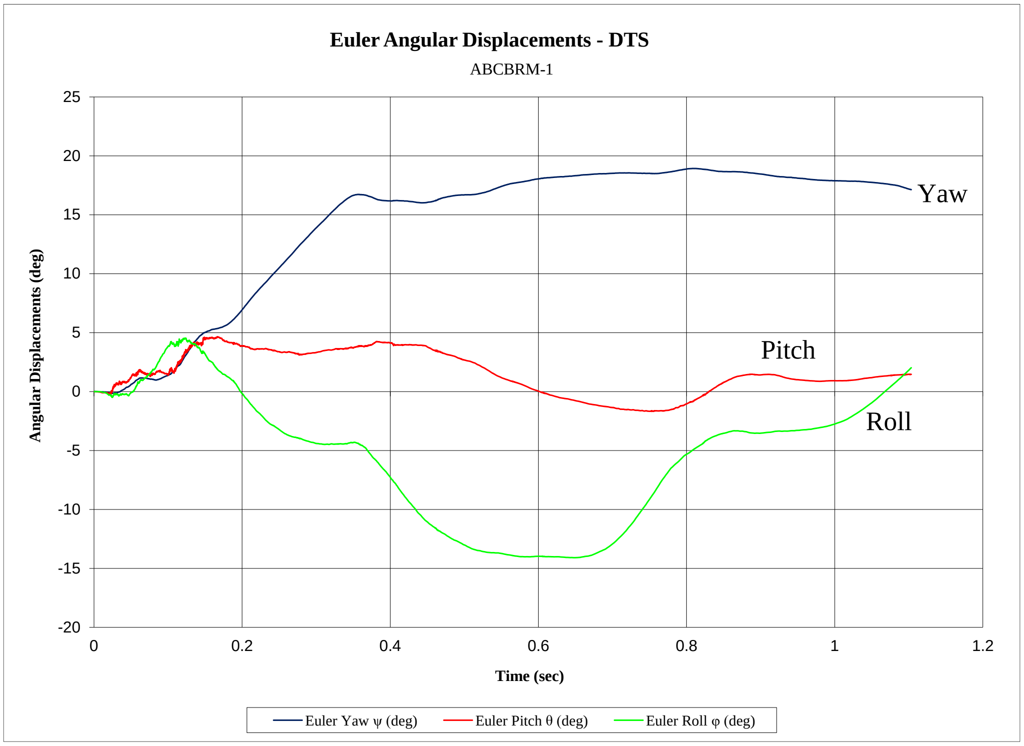


Figure I-23. Vehicle Angular Displacements (TDAS, Cab), Test No. ABCBRM-1

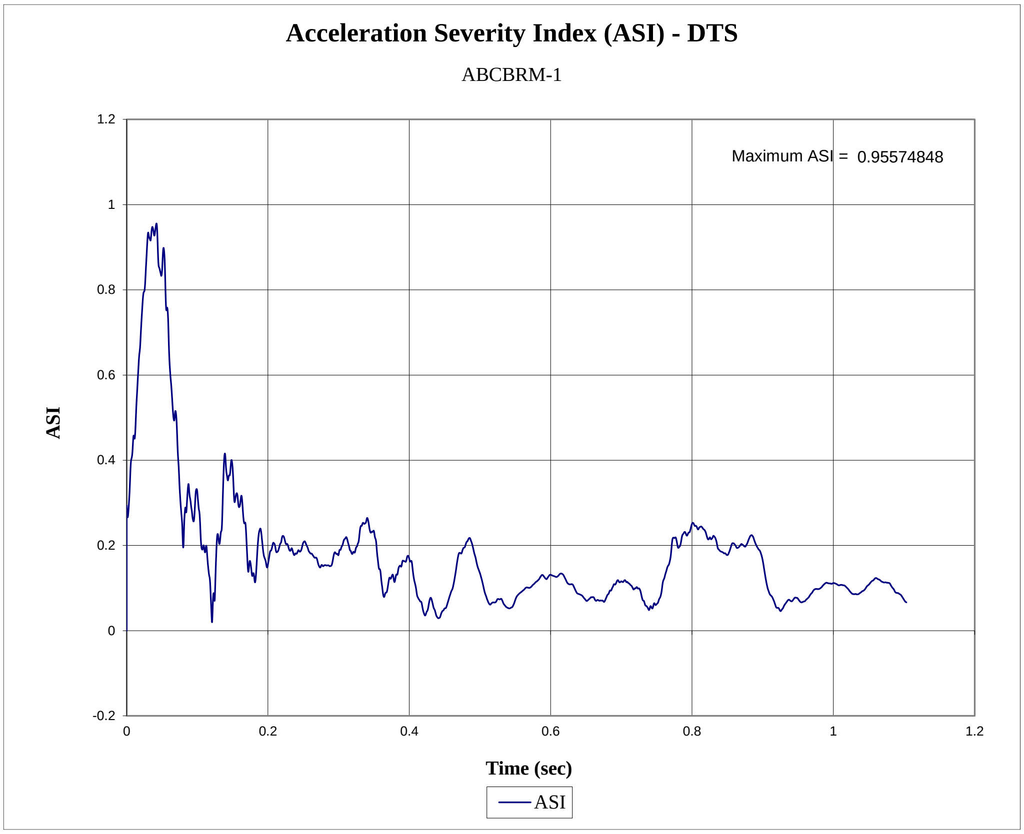


Figure I-24. Acceleration Severity Index (TDAS, Cab), Test No. ABCBRM-1

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