TTI: 0-6968

MASH TL-4 TESTING AND EVALUATION OF FREE-STANDING SINGLE SLOPE CONCRETE BARRIER WITH CROSS-BOLT CONNECTION

ACCREDITED
ISO 17025 Laboratory
Testing Certificate # 2821.01
Crash testing performed at:
TTI Proving Ground
3100 SH 47, Building 7091
Bryan, TX 77807

Test Report 0-6968-R5

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE

COLLEGE STATION, TEXAS

in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
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16. Abstract

The purpose of the testing reported herein was to assess the performance of the free-standing single slope concrete barrier (SSCB) with cross-bolt connections according to the safety-performance evaluation guidelines included in American Association of State Highway and Transportation Officials' *Manual for Assessing Safety Hardware (MASH)* for Test Level Four (TL-4). The crash test performed was in accordance with *MASH* Test 4-12 criteria, which involves a 10000S single unit truck impacting the barrier at a target impact speed and angle of 56 mi/h and 15°, respectively.

The free-standing SSCB with cross-bolt connection successfully contained and redirected the single unit truck. The barrier performed acceptably for *MASH* Test 4-12. The maximum dynamic and permanent barrier deflections were each 33.0 inches.

In addition to the TL-4 crash test, researchers performed a detailed finite element analysis to determine the expected lateral deflection of the barrier under *MASH* Test 4-11 conditions, which involve impacting the barrier with a 2270P pickup truck vehicle with a target impact speed and angle of 62 mi/h and 25°, respectively. The maximum lateral barrier deflection for the pickup truck impact was estimated to be in the range of 12.5 inches to 16.8 inches.

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DISCLAIMER

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This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Nauman M. Sheikh, P.E. Texas #105155.

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CHAPTER 1: INTRODUCTION

1.1 PROBLEM

Portable concrete barriers (PCBs) are often used in work zones to reduce the probability of a motorist entering a work zone. Currently there are no PCB designs available that meet safety testing and evaluation criteria specified in American Association of State Highway and Transportation Officials' (AASHTO's) *Manual for Assessing Safety Hardware* (*MASH*) for Test Level Four (TL-4) (*1*).

1.2 BACKGROUND

In 2018, TTI researchers developed and crash tested a single slope PCB with cross-bolt connections that was restrained with regularly spaced vertical anchor bars. These bars were partially embedded in an underlying reinforced concrete pavement. The barrier was tested under *MASH* Test 4-12 impact conditions with a 10000S single unit truck (*2*). This barrier design also had potential to pass the *MASH* TL-4 performance criteria in an unrestrained and free-standing condition. The cross-bolt connection used in this barrier to connect adjacent barrier segments was expected to result in significantly reduced barrier deflections compared to other connection types.

1.3 OBJECTIVE/SCOPE OF RESEARCH

The purpose of the testing reported herein was to assess the performance of the free-standing single slope concrete barrier (SSCB) with cross-bolt connection according to the safety-performance evaluation guidelines included in AASHTO *MASH* for TL-4. The crash test performed was in accordance with *MASH* Test 4-12, which involves a 10000S vehicle impacting the barrier at a target impact speed and angle of 56 mi/h and 15°, respectively.

In addition to performing the crash test, finite element analysis was used to determine an estimated deflection of the SSCB barrier under *MASH* Test 4-11 impact conditions, which involves impacting a 2270P pickup truck vehicle with nominal impact speed and angle of 62 mi/h and 25°, respectively.

CHAPTER 2:
ORGANIZATION AND STYLES

2.1 TEST ARTICLE AND INSTALLATION DETAILS

The installation consisted of seven 30-ft long by 42-inch tall reinforced concrete barrier segments, each 8 inches wide at top and tapering on each side to 24 inches wide at the bottom. The total installation length of the barrier test installation was 210 ft. These barrier segments were placed free-standing on an existing concrete apron without any restraints. Adjacent barrier segments were connected to each other using the cross-bolt connection, which was comprised of two ⅞-inch diameter threaded rods that passed through each segment in an X pattern, restrained on each end with hex nuts and plate washers.

Figure 2.1 presents overall details on the free-standing SSCB with cross-bolt connection, and Figure 2.2 provides photographs of the installation. Appendix A provides further details of the free-standing SSCB with cross-bolt connection.

2.2 MATERIAL SPECIFICATIONS

The concrete of the barrier segments was specified to be TxDOT Class S concrete with a minimum unconfined compressive strength of 4,000 psi. The compressive strength of the concrete on the date of the test was 7330 psi. Appendix B provides material certification documents for the materials used to construct the free-standing SSCB with cross-bolt connection.

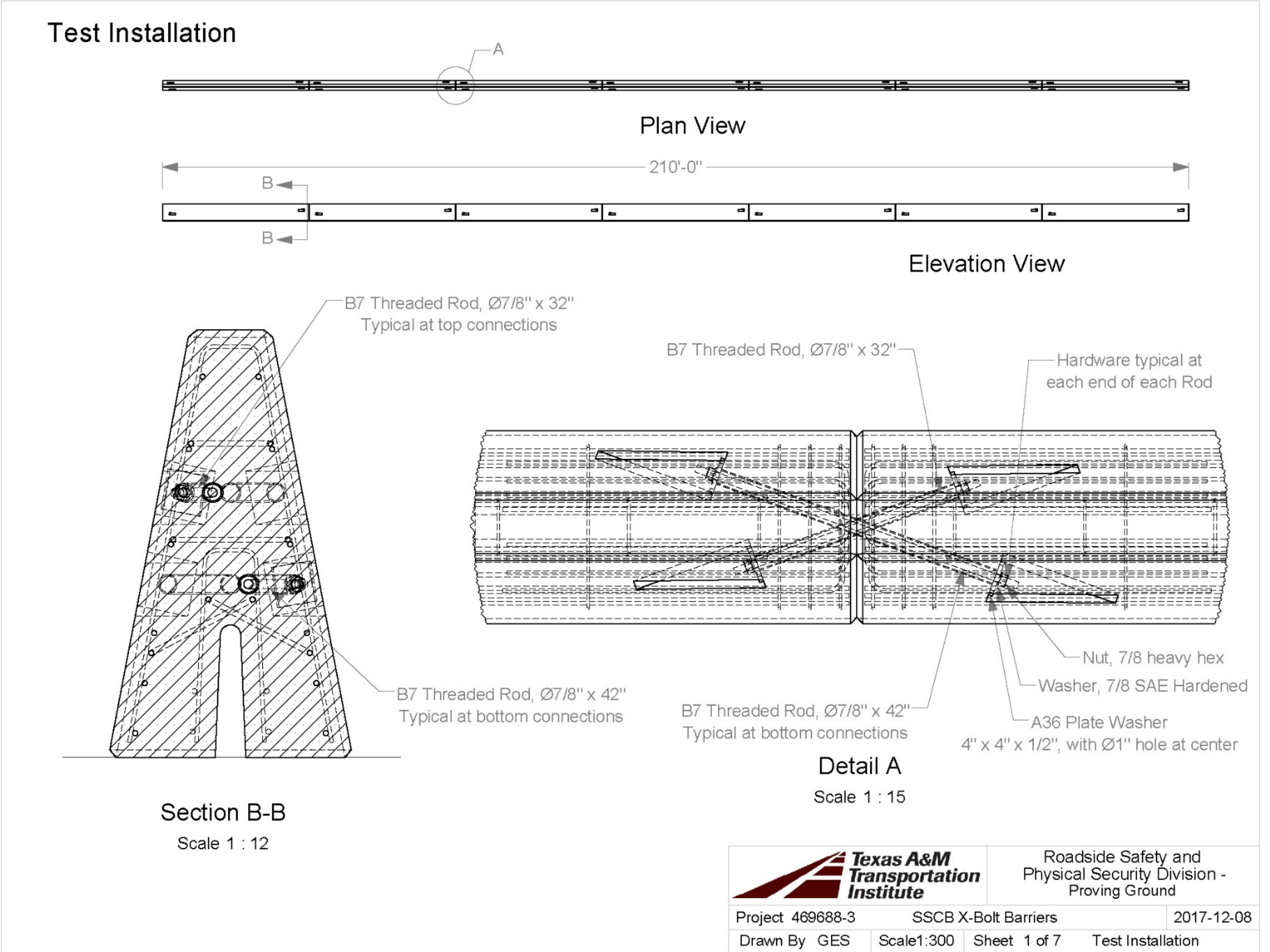


Figure 2.1. Overall Details of the Free-Standing SSCB with Cross-Bolt Connection.

Figure 2.2. Free-Standing SSCB with Cross-Bolt Connection prior to Testing.

CHAPTER 3:
TEST REQUIREMENTS AND EVALUATION CRITERIA

3.1. CRASH TEST MATRIX

Table 3.1 shows the test conditions and evaluation criteria for *MASH* TL-4. This report presents testing of the SSCB with cross-bolt connection in accordance with *MASH* Test 4-12 testing and evaluation criteria. *MASH* Test 4-12 involves a 10000S vehicle weighing 22,046 lb ±660 lb and impacting the critical impact point (CIP) of the barrier at a target impact speed of 56 mi/h ±2.5 mi/h and an angle of 15° ±1.5°. The target CIP selected for the test was determined according to the information provided in *MASH* Section 2.2.1 and 2.3.2.2, and was 5 ft upstream of the joint between the third and fourth barrier segments.

Table 3.1. Test Conditions and Evaluation Criteria Specified for *MASH* Test 4-12.

Test Article	Test Designation	Test Vehicle	Impact Conditions		Evaluation Criteria
			Speed	Angle	
Longitudinal Barrier	4-10	1100C	62 mi/h	25	A, D, F, H, I
	4-11	2270P	62 mi/h	25	A, D, F, H, I
	4-12	10000S	56 mi/h	15	A, D, G

The crash test and data analysis procedures were in accordance with guidelines presented in *MASH*. Chapter 4 presents brief descriptions of these procedures.

3.2. EVALUATION CRITERIA

The appropriate safety evaluation criteria from Tables 2-2A and 5-1A through 5-1C of *MASH* were used to evaluate the crash test reported herein. The test conditions and evaluation criteria required for *MASH* Test 4-12 are listed in Table 3.1, and the substance of the evaluation criteria in Table 3.2. An evaluation of the crash test results is presented in detail under the section Assessment of Test Results.

Table 3.2. Evaluation Criteria Required for *MASH* Test 4-12.

Evaluation Factors	Evaluation Criteria
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.*
Occupant Risk	*D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present 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.*
	G. It is preferable, although not essential, that the vehicle remain upright during and after the collision.

CHAPTER 4: TEST CONDITIONS

4.1 TEST FACILITY

The full-scale crash test reported herein was performed at Texas A&M Transportation Institute (TTI) Proving Ground, an International Standards Organization (ISO) 17025-accredited laboratory with American Association for Laboratory Accreditation (A2LA) Mechanical Testing Certificate 2821.01. The full-scale crash test was performed according to TTI Proving Ground quality procedures, and according to the *MASH* guidelines and standards.

The test facilities of the TTI Proving Ground are located on the Texas A&M University RELLIS Campus, which consists of a 2000-acre complex of research and training facilities situated 10 miles northwest of the flagship campus of Texas A&M University. The site, formerly a United States Army Air Corps base, has large expanses of concrete runways and parking aprons well suited for experimental research and testing in the areas of vehicle performance and handling, vehicle-roadway interaction, durability and efficacy of highway pavements, and evaluation of roadside safety hardware and perimeter protective devices. The site selected for testing of the barrier was on one of these out-of-service aprons. The apron consists of an unreinforced jointed-concrete pavement in 12.5-ft × 15-ft blocks that are nominally 6 inches deep. The apron was built in 1942 and the joints have some displacement, but are otherwise flat and level.

4.2 VEHICLE TOW AND GUIDANCE SYSTEM

The test vehicle was towed into the test installation using a steel cable guidance and reverse tow system. A steel cable for guiding the test vehicle was tensioned along the path, anchored at each end, and threaded through an attachment to the front wheel of the test vehicle. An additional steel cable was connected to the test vehicle, passed around a pulley near the impact point, through a pulley on the tow vehicle, and then anchored to the ground such that the tow vehicle moved away from the test site. A 2:1 speed ratio between the test and tow vehicle existed with this system. Just prior to impact with the installation, the test vehicle was released and ran unrestrained. The vehicle remained freewheeling (i.e., no steering or braking inputs) until it cleared the immediate area of the test site (no sooner than 2 s after impact), after which the brakes were activated, if needed, to bring the test vehicle to a safe and controlled stop.

4.3 DATA ACQUISITION SYSTEMS

4.3.1 Vehicle Instrumentation and Data Processing

The test vehicle was instrumented with a self-contained, on-board data acquisition system. The signal conditioning and acquisition system is a 16-channel, Tiny Data Acquisition System (TDAS) Pro produced by Diversified Technical Systems, Inc. The accelerometers, which measure the x, y, and z axis of vehicle acceleration, are strain gauge type with linear millivolt output proportional to acceleration. Angular rate sensors, measuring vehicle roll, pitch, and yaw rates, are ultra-small, solid state units designed for crash test service. The TDAS Pro hardware and software conform to the latest SAE J211, Instrumentation for Impact Test. Each of the 16 channels is capable of providing precision amplification, scaling, and filtering based on transducer specifications and calibrations. During the test, data are recorded from each channel at a rate of 10,000 values per second with a resolution of one part in 65,536. Once data are recorded, internal batteries back these up inside the unit should the primary battery cable be severed. Initial contact of the pressure switch on the vehicle bumper provides a time zero mark and initiates the recording process. After each test, the data are downloaded from the TDAS Pro unit into a laptop computer at the test site. The Test Risk Assessment Program (TRAP) software then processes the raw data to produce detailed reports of the test results.

Each of the TDAS Pro units is returned to the factory annually for complete recalibration and all instrumentation used in the vehicle conforms to all specifications outlined by SAE J211. All accelerometers are calibrated annually by means of an ENDEVCO® 2901, precision primary vibration standard. This standard and its support instruments are checked annually and receive a National Institute of Standards Technology (NIST) traceable calibration. The rate transducers used in the data acquisition system receive a calibration via a Genisco Rate-of-Turn table. The subsystems of each data channel are also evaluated annually, using instruments with current NIST traceability, and the results are factored into the accuracy of the total data channel, per SAE J211. Calibrations and evaluations are also made any time data are suspect. Acceleration data are measured with an expanded uncertainty of ±1.7 percent at a confidence factor of 95 percent (k=2).

TRAP uses the data from the TDAS Pro to compute occupant/compartment impact velocities, time of occupant/compartment impact after vehicle impact, and the highest 10-millisecond (ms) average ridedown acceleration. TRAP calculates change in vehicle velocity at the end of a given impulse period. In addition, maximum average accelerations over 50-ms intervals in each of the three directions are computed. For reporting purposes, the data from the vehicle-mounted accelerometers are filtered with a 60-Hz low-pass digital filter, and acceleration versus time curves for the longitudinal, lateral, and vertical directions are plotted using TRAP.

TRAP uses the data from the yaw, pitch, and roll rate transducers to compute angular displacement in degrees at 0.0001-s intervals, then plots yaw, pitch, and roll versus time. These displacements are in reference to the vehicle-fixed coordinate system with the initial position and orientation of the vehicle-fixed coordinate systems being initial impact. Rate of rotation data is measured with an expanded uncertainty of ±0.7 percent at a confidence factor of 95 percent (k=2).

4.3.2 Anthropomorphic Dummy Instrumentation

MASH does not recommend or require use of an anthropomorphic dummy in the 10000S vehicle. A dummy was thus not used in the test.

4.3.3 Photographic Instrumentation and Data Processing

Photographic coverage of the test included three high-speed cameras:

- One overhead with a field of view perpendicular to the ground and directly over the impact point.

- One placed behind the installation at an angle.
- A third placed to have a field of view parallel to and aligned with the installation at the downstream end.

A flashbulb on the impacting vehicle was activated by a pressure-sensitive tape switch to indicate the instant of contact with the barrier. The flashbulb was visible from each camera. The video files from these digital high-speed cameras were analyzed to observe phenomena occurring during the collision and to obtain time-event, displacement, and angular data. A digital camera recorded and documented conditions of each test vehicle and the installation before and after the test.

CHAPTER 5:
MASH TEST 4-12 (CRASH TEST NO. 469688-3-1)

5.1 TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

MASH Test 4-12 involves a 10000S vehicle weighing 22,046 lb ±660 lb impacting the CIP of the barrier at an impact speed of 56 mi/h ±2.5 mi/h and an angle of 15° ±1.5°. The target CIP for *MASH* Test 4-12 on the free-standing SSCB with cross-bolt connection was 5 ft ±1 ft upstream of the joint between the third and fourth barrier segments.

The 2006 GMC C7500 single-unit box-van truck used in the test weighed 22,290 lb, and the actual impact speed and angle were 57.0 mi/h and 14.7°, respectively. The actual impact point was 4.9 ft upstream of the joint between segments 3 and 4. Minimum target impact severity (IS) was 142 kip-ft, and actual IS was 156 kip-ft.

5.2 WEATHER CONDITIONS

The test was performed on the morning of February 8, 2018. Weather conditions at the time of testing were as follows: wind speed: 4 mi/h; wind direction: 44° with respect to the vehicle (vehicle was traveling in a northerly direction); temperature: 45°F; relative humidity: 77 percent.

5.3 TEST VEHICLE

Figures 5.1 and 5.2 show the 2006 GMC C7500 single-unit box-van truck used for the crash test. The vehicle's test inertia weight was 22,290 lb, and its gross static weight was 22,290 lb. The height to the lower edge of the vehicle bumper was 18.5 inches, and height to the upper edge of the bumper was 33.5 inches. The height to the ballast's center of gravity was 64.0 inches. Table C.1 in Appendix C1 gives additional dimensions and information on the vehicle. The vehicle was directed into the installation using a cable reverse tow and guidance system, and was released to be freewheeling and unrestrained just prior to impact.

Figure 5.1. Barrier/Test Vehicle Geometrics for Test No. 469688-3-1.

Figure 5.2. Test Vehicle before Test No. 469688-3-1.

5.4 TEST DESCRIPTION

The test vehicle contacted the barrier 4.9 ft upstream of the joint between segments 3 and 4 at an angle of 14.7° while traveling at a speed of 57.0 mi/h. Table 5.1 lists events that occurred during Test No. 469688-3-1. Figures C.1 and C.2 in Appendix C2 present sequential photographs during the test.

Table 5.1. Events during Test No. 469688-3-1.

TIME (s)	EVENT
0.014	Vehicle wheels begin to turn left
0.055	Vehicle begins to redirect
0.063	Barrier begins to deflect toward the field side
0.112	Vehicle’s front right tire lifted from pavement
0.252	Vehicle’s rear right tire lifted from pavement
0.289	Vehicle begins to travel parallel with the barrier
0.516	Vehicle’s box has maximum displacement beyond barrier
0.609	Barrier is at maximum displacement
0.760	Vehicle’s front right tire lands back on pavement
0.997	Vehicle loses contact with barrier while traveling at 49.5 mi/h and 2.6°

For longitudinal barriers, it is desirable that the vehicle redirects, and exits the barrier within the exit box criteria (not less than 65.6 ft downstream from impact for heavy vehicles). The 10000S vehicle exited within the exit box criteria defined in *MASH*. After loss of contact with the barrier, the vehicle yawed counterclockwise and came to rest 342 ft downstream of the impact and 71 ft toward the field side.

5.5 DAMAGE TO TEST INSTALLATION

Figures 5.3 and 5.4 show the damage to the barrier. Segment 1 and the upstream end of segment 2 were pulled downstream 0.5 inch, and the joint between segments 2 and 3 deflected 2.0 inches toward the field side and 2.5 inches downstream. The segments at joint 3–4 deflected toward the field side 33.0 inches, and the segments at joint 4–5 deflected 14.0 inches toward the field side. No movement was noted at segments 5 and 6. Segment 4 developed vertically oriented hairline cracks in several places near its center. Working width for the test was 47.0 inches, and the height of the working width was 119.8 inches, both attributable to the top of the cargo box. Maximum dynamic deflection during the test was 33.0 inches, and maximum permanent deformation was 33.0 inches.

Figure 5.3. Barrier after Test No. 469688-3-1.

Figure 5.4. Traffic Side of Segment 4 after Test No. 469688-3-1.

5.6 DAMAGE TO TEST VEHICLE

Figure 5.5 shows the damage sustained by the vehicle. The front bumper, hood, left front spring, left front tire and rim, and left front corner of the box were damaged. Maximum exterior crush to the vehicle was 7.0 inches in the side plane at the left front corner at bumper height. Maximum occupant compartment deformation was 4.0 inches in the left kick panel/firewall area. Figure 5.6 shows the interior of the vehicle.

Figure 5.5. Test Vehicle after Test No. 469688-3-1.

Before Test

After Test

Figure 5.6. Interior of Test Vehicle for Test No. 469688-3-1.

5.7 OCCUPANT RISK FACTORS

Data from the accelerometer (located at the vehicle horizontal, near the lateral centerline, and just below the vertical center of gravity) were digitized for evaluation of occupant risk and results are shown in Table 5.2. Figure 5.7 summarizes these data and other pertinent information from the test. Figure C.3 in Appendix C3 shows the vehicle angular displacements, and Figures C.4 through C.9 in Appendix C4 show accelerations versus time traces.

Table 5.2. Occupant Risk Factors for Test No. 469688-3-1.

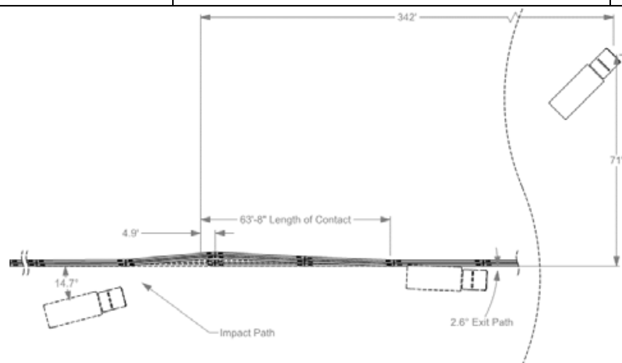
Occupant Risk Factor	Value	Time
Occupant Impact Velocity (OIV)		
Longitudinal	**5.6 ft/s**	at 0.1990 s on left side of interior
Lateral	**10.5 ft/s**	
10-ms Occupant Ridedown Accelerations		
Longitudinal	**3.8 g**	0.3439–0.3539 s
Lateral	**26.3 g**	0.3236–0.3336 s
Theoretical Head Impact Velocity (THIV)	**13.1 km/h** **3.6 m/s**	at 0.1913 s on left side of interior
Post Head Deceleration (PHD)	**26.3 g**	0.3236–0.3336 s
Acceleration Severity Index (ASI)	**0.73**	0.3273–0.3773 s
Maximum 50-ms Moving Average		
Longitudinal	**−1.4 g**	0.0114–0.0614 s
Lateral	**6.1 g**	0.3226–0.3726 s
Vertical	**−2.7 g**	1.1813–1.2313 s
Maximum Roll, Pitch, and Yaw Angles		
Roll	**15°**	0.5709 s
Pitch	**5°**	0.8274 s
Yaw	**20°**	0.5466 s

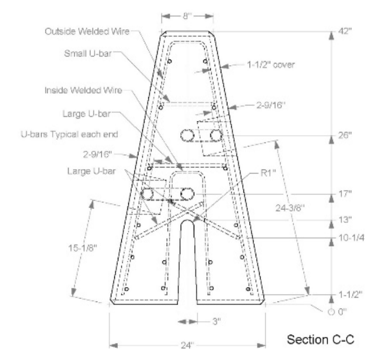
0.000 s

0.300 s

0.600 s

1.000 s





General Information	
Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard Test No.	MASH Test 4-12
TTI Test No.	469688-3-1
Test Date	2018-02-08
Test Article	
Type	Portable Concrete Barrier
Name	SSCB with Cross-Bolt Connection
Installation Length	210 ft
Material or Key Elements	Seven 30-ft long single-slope concrete barriers, 8 inches wide at top, tapering on each side to 24 inches wide at bottom, and 42 inches tall
Soil Type and Condition	Placed on concrete surface, damp
Test Vehicle	
Type/Designation	10000S
Make and Model	2006 GMC C7500 Single-Unit Truck
Curb	13,810 lb
Test Inertial	22,290 lb
Dummy	No dummy
Gross Static	22,290 lb

Impact Conditions	
Speed	57.0 mi/h
Angle	14.7°
Location/Orientation	4.9 ft upstream of joint 3-4
Impact Severity	156 kip-ft
Exit Conditions	
Speed	49.5 mi/h
Angle	2.6°
Occupant Risk Values	
Longitudinal OIV	5.6 ft/s
Lateral OIV	10.5 ft/s
Longitudinal Ridedown	3.8 g
Lateral Ridedown	26.3 g
THIV	13.1 km/h
PHD	26.3 g
ASI	0.73
Max. 0.050-s Average	
Longitudinal	−1.4 g
Lateral	6.1 g
Vertical	−2.7 g

Post-Impact Trajectory	
Stopping Distance	342 ft downstream 71 ft twd field side
Vehicle Stability	
Maximum Yaw Angle	20°
Maximum Pitch Angle	5°
Maximum Roll Angle	15°
Vehicle Snagging	No
Vehicle Pocketing	No
Test Article Deflections	
Dynamic	33.0 inches
Permanent	33.0 inches
Working Width	47.0 inches
Height of Working Width	119.8 inches
Vehicle Damage	
VDS	NA
CDC	11FLEW4
Max. Exterior Deformation	7.0 inches
OCDI	NA
Max. Occupant Compartment Deformation	4.0 inches

Figure 5.7. Summary of Results for *MASH* Test 4-12 on Free-Standing SSCB with Cross-Bolt Connection.

CHAPTER 6: SIMULATION ANALYSIS[1]

6.1 INTRODUCTION

While the full-scale crash testing was only performed with the single unit truck, TxDOT wished to determine the free-standing barrier's estimated maximum deflection for a *MASH* pickup truck impact (Test 4-11). For this purpose, researchers developed a finite element model of the free-standing SSCB barrier system and performed an impact simulation under *MASH* Test 4-12 conditions using a single unit truck model. The ratio between the test and simulation deflection was noted. Researchers then used the same barrier model to perform an impact simulation with a pickup truck model under *MASH* Test 4-11 conditions (i.e., impact at a speed and angle of 62 mi/h and 25 degrees, respectively). The deflection of the barrier from the pickup truck impact simulation was scaled using the ratio determined from the single unit truck impact simulation. This scaled deflection is the estimated deflection of the free-standing single slope barrier with cross-bolt connections for a *MASH* Test 4-11 impact. Details of the finite element modeling and results of the simulation analyses are presented in this chapter.

6.2. FINITE ELEMENT MODELING AND ANALYSIS

The simulations were performed using the finite element method. LS-DYNA, which is a commercially available general purpose finite element analysis software, was used for all simulations.

The 42-inch tall, 30 ft long single slope barrier segments were modeled using rigid material representation. A 13-inch vertical slot was modeled at the base of the barrier along its centerline. As in the full-scale crash test, the overall system model was comprised of seven (7) barrier segments to achieve a total barrier length of 210 ft. Adjacent barrier segments were connected using cross-bolt connections. The threaded rods in these connections were modeled with elastic-plastic material representation. Material properties for these threaded rods were obtained from mill test reports of the rods used in the single-unit truck test (presented in Appendix B).

Figure 6.1 shows various details of the finite element model. The cross-bolt connections are shown. Also shown are views of the full system model and the impact vehicle for *MASH* Test 4-12.

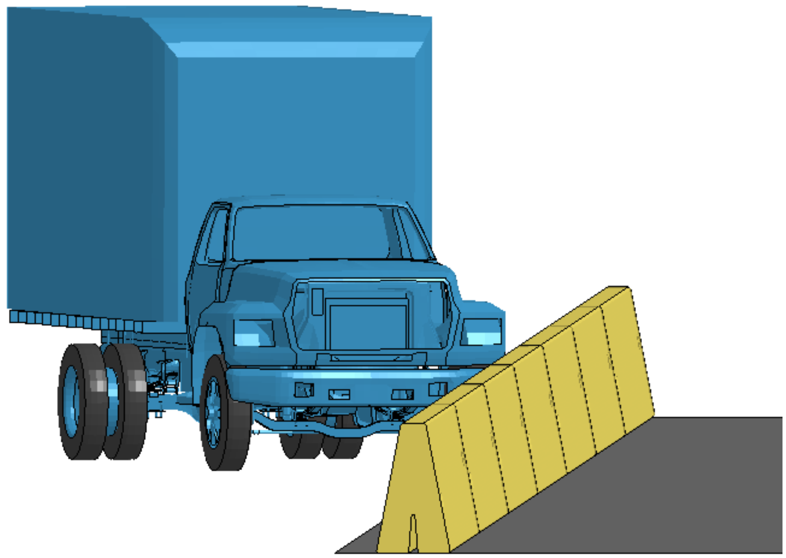
The single-unit truck simulations were performed for *MASH* Test 4-12 impact conditions, which involve the vehicle impacting the barrier at 56 mi/h and 15 degrees. The vehicle model used in the simulations was originally developed by National Crash Analysis Center and Battelle under sponsorship from the Federal Highway Administration. This model has subsequently been modified to meet *MASH* 10000S specifications and improved for greater accuracy and robustness by Texas A&M Transportation Institute (TTI) over the course of many research projects involving simulation and testing with the single unit truck.

[1] The simulations discussed in this chapter are outside the scope of TTI Proving Ground's A2LA Accreditation.

Figure 6.2 shows the results of the simulation analysis for *MASH* Test 4-12 with the single-unit truck. The free-standing barrier successfully contained and redirected the vehicle as in the full-scale test. The permanent deflection of the barrier was 44.6 inches in the simulation, which is 1.35 times greater than the 33-inch maximum deflection observed in the full-scale crash test. Some of the differences in the test and simulation deflection can be attributed to the failure and cracking of the barrier concrete during the impact, which dissipates some of the impact energy and reduces the bending load on the threaded rods comprising the barrier’s cross-bolt connections. The barrier segments in the simulations were modeled with rigid material representation for simplicity. This resulted in greater load being transferred to the cross-bolt connections, resulting in greater bending of the threaded rods and, therefore, a larger deflection in the simulation compared to the test.

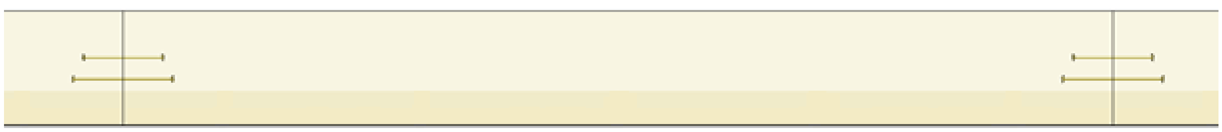
Figure 6.3 shows results of the impact simulation with the pickup truck model under *MASH* Test 4-11 conditions. The vehicle impacted the barrier 4.3 ft upstream of the connection between the third and fourth barrier segment. The impact point was selected using the CIP recommendations provided in the Section 2.2 and 2.3 of *MASH*. The barrier successfully contained and redirected the vehicle in the simulation. The maximum permanent lateral deflection of the barrier was 16.8 inches. This deflection was scaled using the ratio observed for the single unit truck impact to arrive at the expected pickup truck deflection of 12.5 inches.

Thus, using the results of the simulations, the estimated lateral deflection of the free-standing single slope barrier with cross-bolt connections ranges between 12.5 and 16.8 inches.



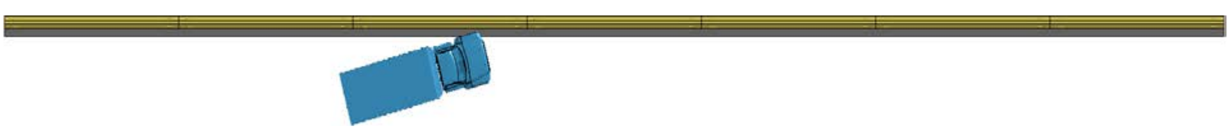
Overall System Model

Top View of a Connected Barrier Segment*



Side View of a Connected Barrier Segment*

System Model (Side View)



System Model (Top View)

*Barrier segments shown with transparency to show connections

Figure 6.1. Simulation Model Details of Tested Design.

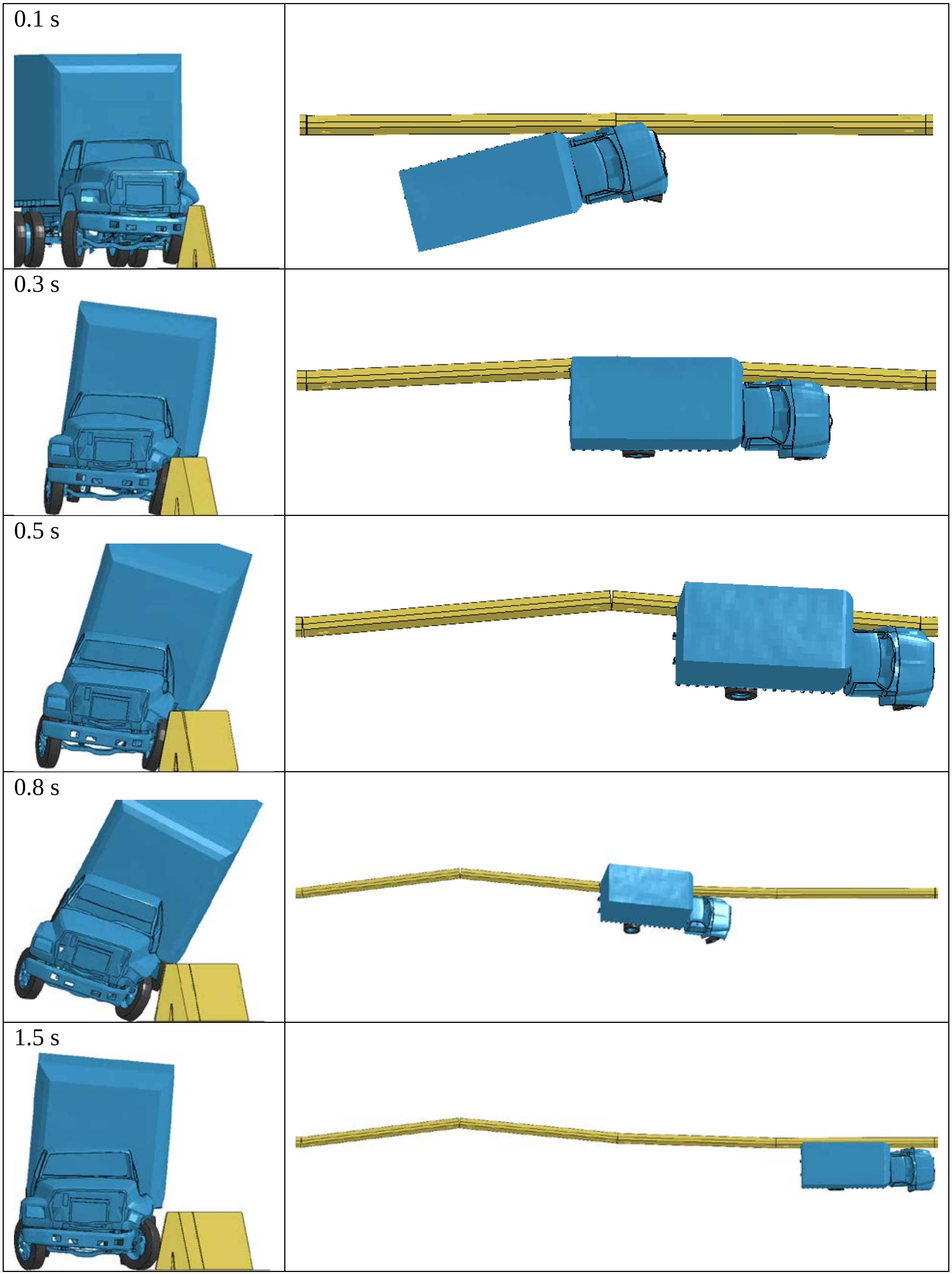


Figure 6.2. Sequential Images of the Simulation for *MASH* Test 4-12.

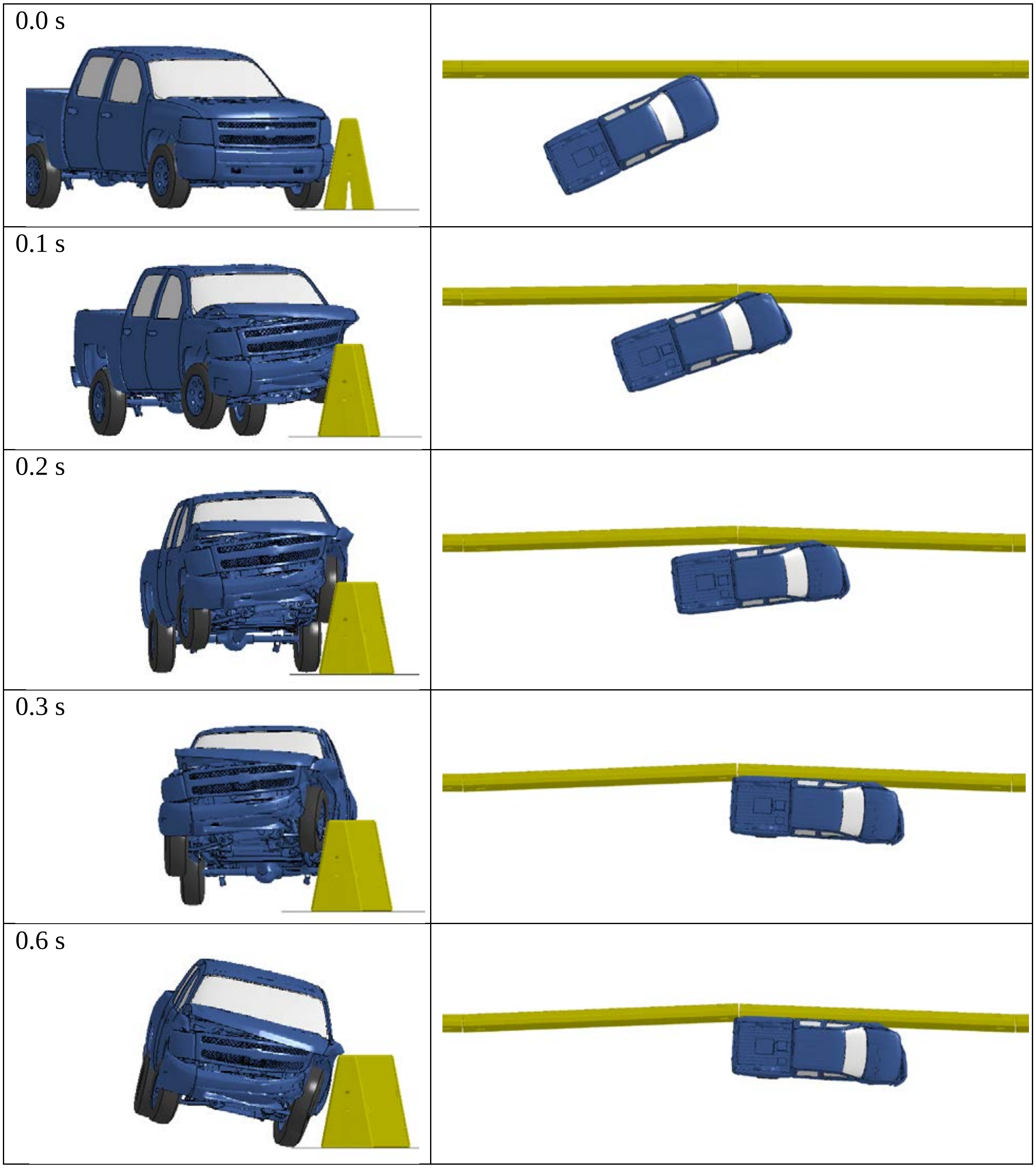


Figure 6.3. Sequential Images of the Simulation for *MASH* Test 4-11.

CHAPTER 7: SUMMARY AND CONCLUSIONS

7.1 SUMMARY OF RESULTS

An assessment of the test based on the applicable safety evaluation criteria for *MASH* Test 4-12 is provided in Table 7.1.

7.2 CONCLUSIONS

The free-standing SSCB with cross-bolt connection performed acceptably for *MASH* Test 4-12.

Table 7.1. Performance Evaluation Summary for *MASH* Test 4-12 on Free-Standing SSCB with Cross-Bolt Connection.

Test Agency: Texas A&M Transportation Institute | Test No.: 469688-3-1 | Test Date: 2018-02-08

***MASH* Test 4-12 Evaluation Criteria**	**Test Results**	**Assessment**
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*	The free-standing SSCB with cross-bolt connection contained and redirected the 10000S vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection during the test was 33.0 inches.	Pass
Occupant Risk *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.*	Small pieces of concrete spalled from two of the joints. However, these fragments did not penetrate or show potential for penetrating the occupant compartment, or to present undue hazard for others in the area.	Pass
Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.	Maximum occupant compartment deformation was 4.0 inches in the left kick panel/firewall area.	
G. It is preferable, although not essential, that the vehicle remain upright during and after collision.	The 10000S vehicle remained upright during and after the collision event. Maximum roll and pitch were 15° and 5°, respectively.	Pass

CHAPTER 8: IMPLEMENTATION STATEMENT[2]

Based on the results of the testing and evaluation reported herein, the free-standing single slope concrete barrier with cross-bolt connections is considered suitable for implementation as a *MASH* Test Level 4 barrier system. For *MASH* Test 4-12 performed under this project, the barrier had a deflection of 33 inches.

MASH also recommends performing Test 4-10 and 4-11 with the small passenger car and a pickup truck, respectively. However, the barrier is not expected to be imparted with greater lateral loading in the small car or the pickup truck tests compared to the single unit truck impact of Test 4-12. Based on the performance of the single slope barrier in past testing, Test 4-10 and 4-11 were not considered critical. As an example, Whitesel et al. preformed a *MASH* Test 3-10, which is equivalent to *MASH* Test 4-10, on a permanent single slope barrier with 9.1° face slope (*3*). This test passed the occupant risk criteria and the vehicle was contained and redirected in a stable manner. Similarly, Sheikh et al. performed a *MASH* Test 3-11, which is equivalent to Test 4-11, on single slope barrier segments that were restrained by embedding in soil (*4*). The pickup truck was successfully contained and redirected in this test and the occupant risk evaluation criteria met *MASH* requirements. Supported by these past tests and the simulation analysis performed under this project for Test 4-11 conditions, the single slope barrier with cross-bolt connection was only evaluated for *MASH* Test 4-12 criteria. *MASH* Tests 4-10 and 4-11 were not considered critical and were therefore not performed.

Based on the simulation analysis performed under this project, the barrier is expected to have a deflection range of 12.5 to 16.8 inches for pickup truck impact under *MASH* Test 4-11 (which is an equivalent test condition to *MASH* Test Level 3, Test 3-11). This low deflection makes this TL-4 barrier suitable for use as a work zone barrier.

Statewide implementation of this barrier can be achieved by TxDOT's Design Division through the development and issuance of a new standard detail sheet. The barrier details provided in Appendix A can be used for this purpose.

[2] The opinions/interpretations identified/expressed in this chapter are outside the scope of TTI Proving Ground's A2LA Accreditation.

REFERENCES

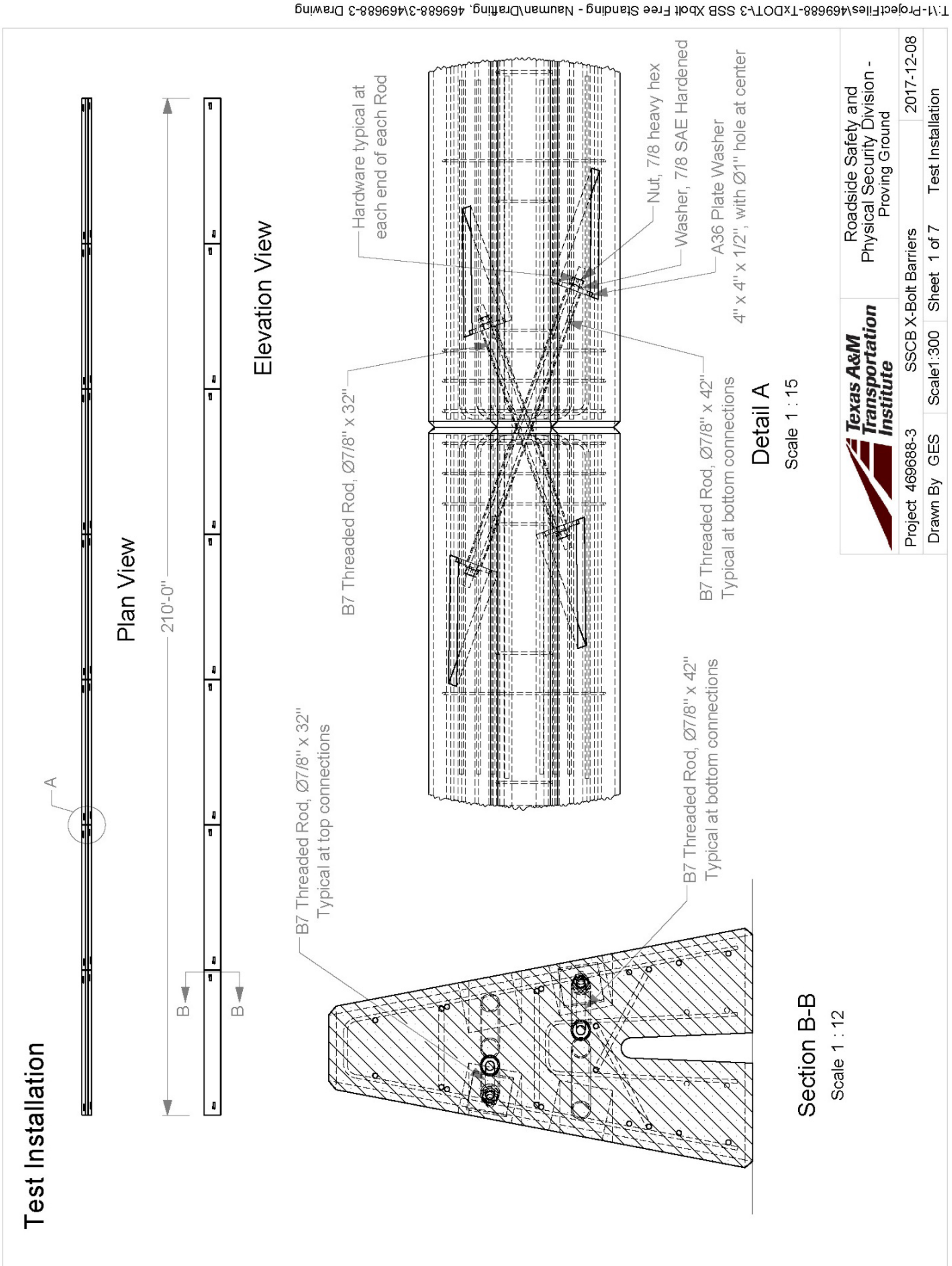
1. AASHTO. *Manual for Assessing Roadside Safety Hardware.* Second Edition, 2016, American Association of State Highway and Transportation Officials: Washington, D.C.

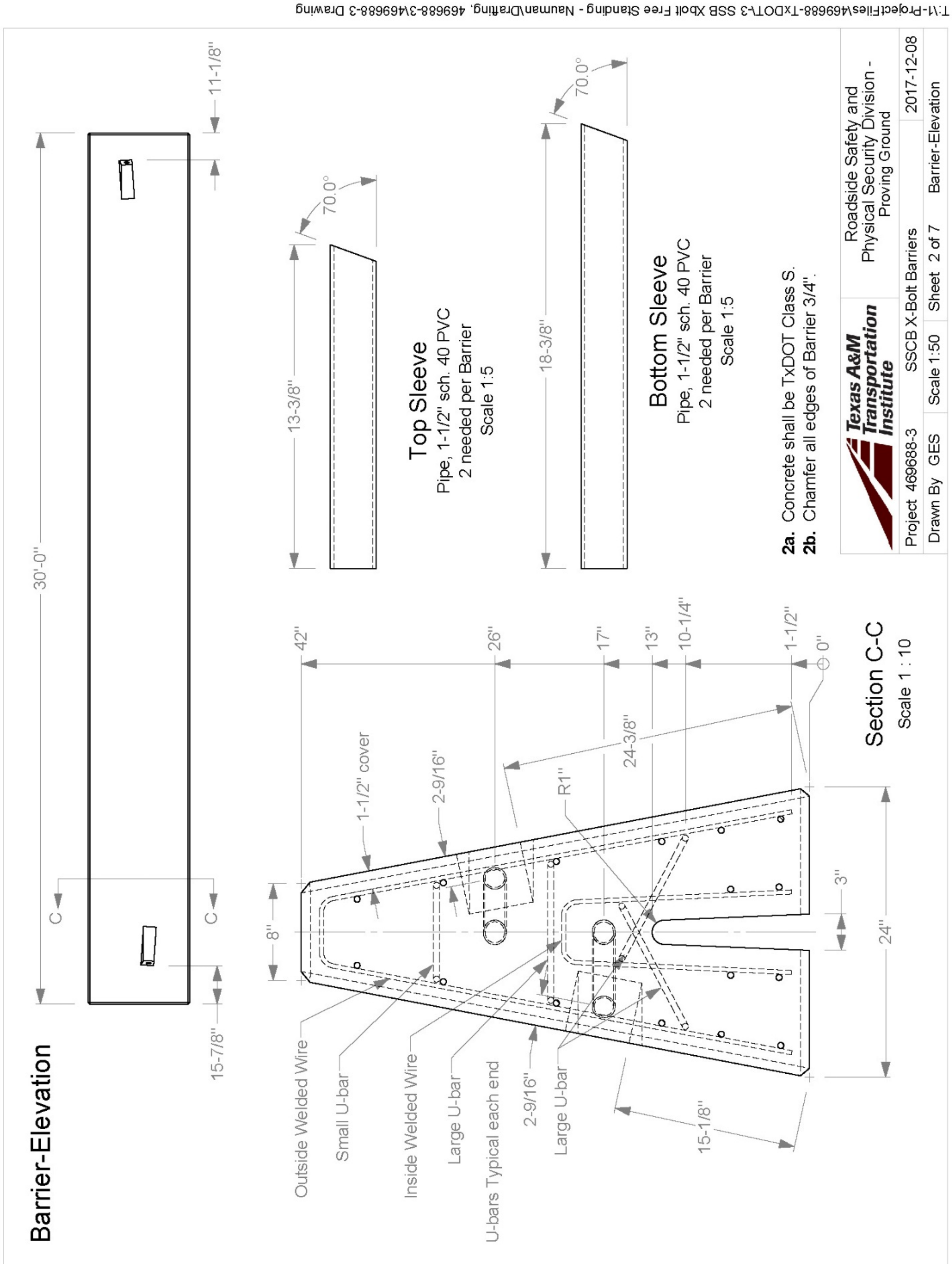
2. W.F. Williams, N.M. Sheikh, W.L. Menges, D.L. Kuhn, and R.P. Bligh, *Crash Test and Evaluation of Restrained Safety Shape Concrete Barriers on Concrete Bridge Deck*. Research Report 9-1002-15, Texas A&M Transportation Institute, College Station, TX, January 2018.

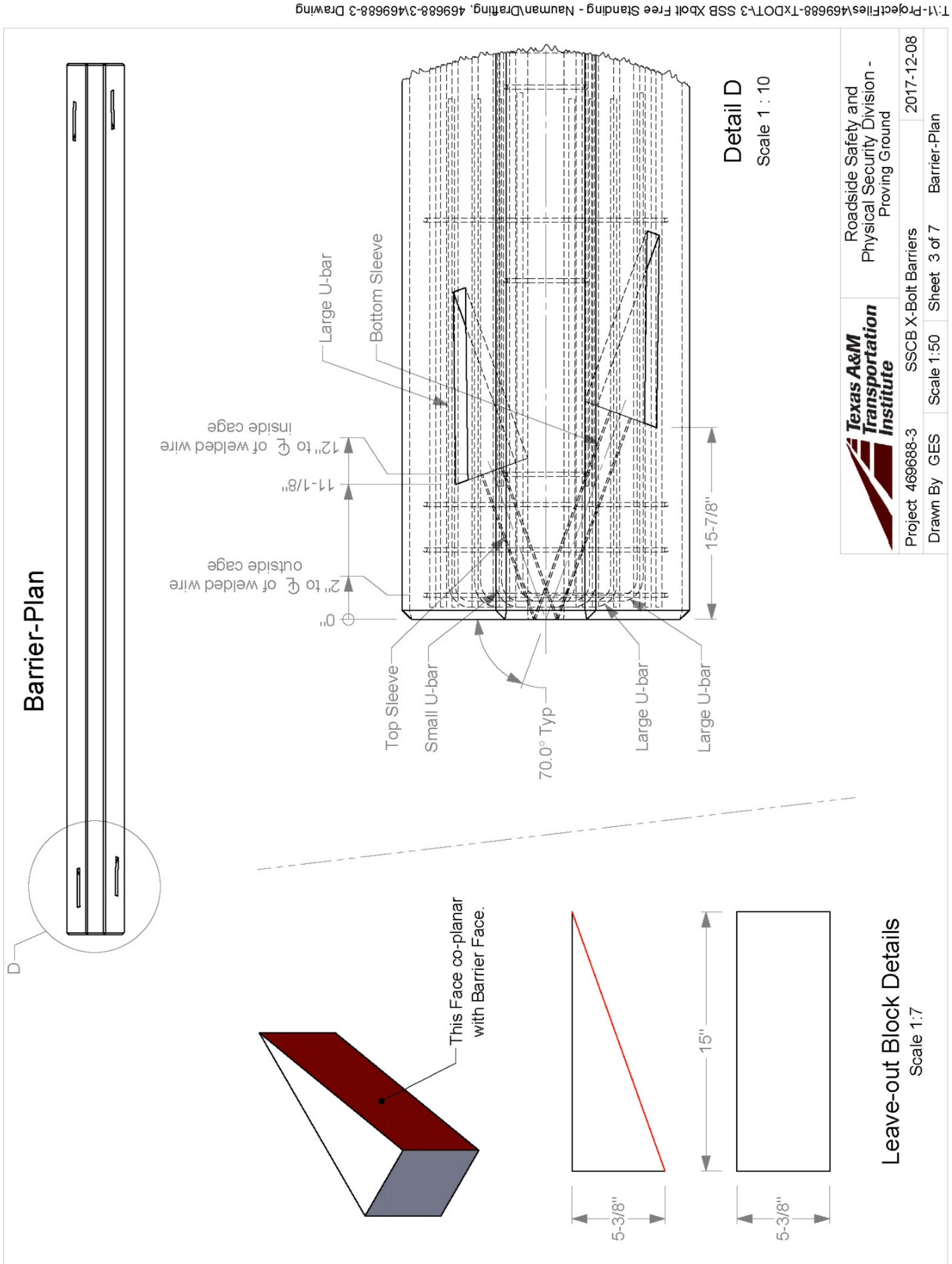
3. D. Whitesel, J. Jewell, and R. Meline, *Compliance Crash Testing of the Type 60 Median Barrier, Test 140MASH3C16-04.* Research Report FHWA/CA17-2654, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, May 2018.

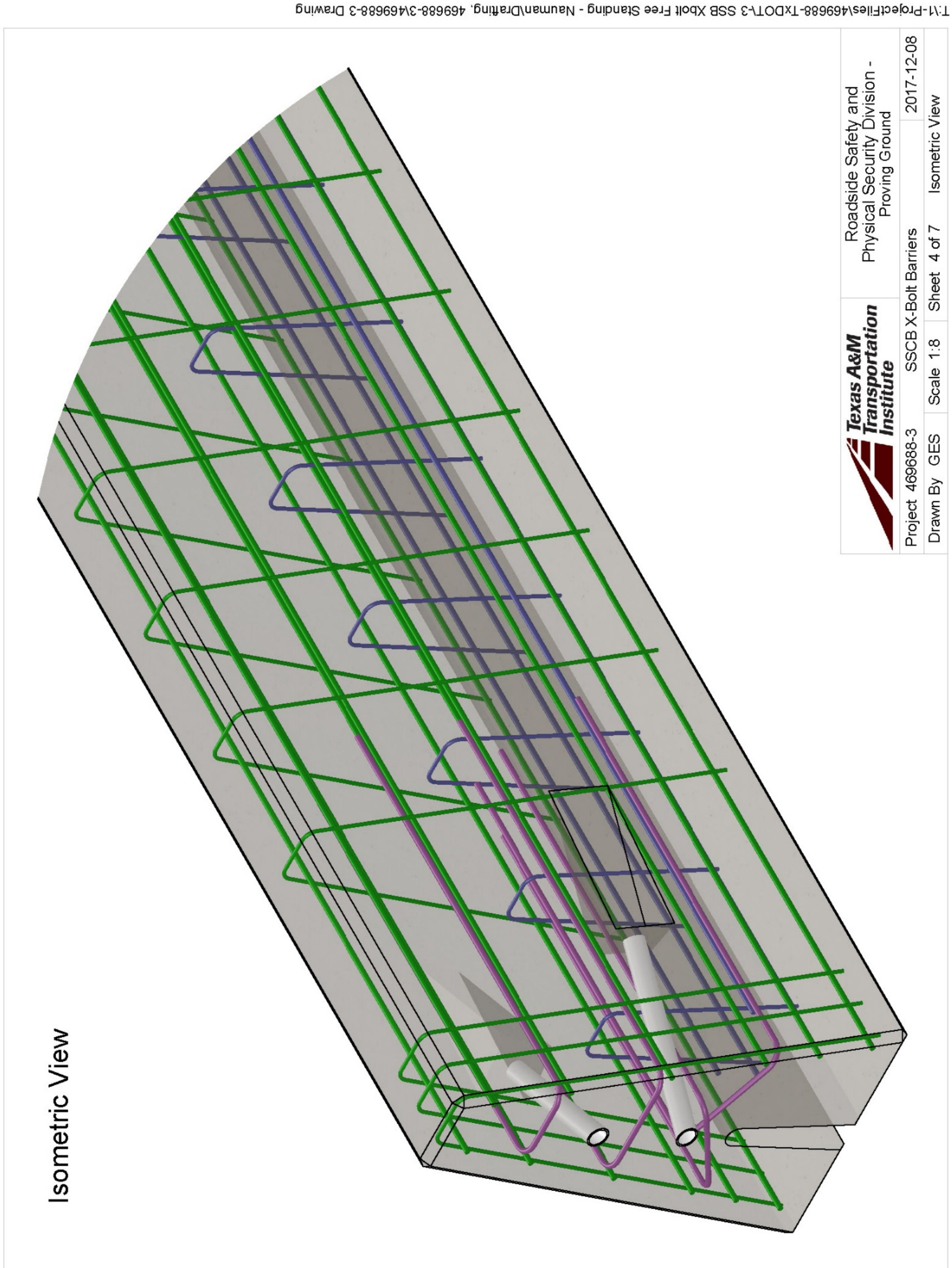
4. N.M. Sheikh, R.P. Bligh, and W.L. Menges, *Development and Testing of a Concrete Barrier Design for use in Front of Slope or on MSE Wall*. Research Report 405160-13-1, Texas A&M Transportation Institute, College Station, TX, August 2009.

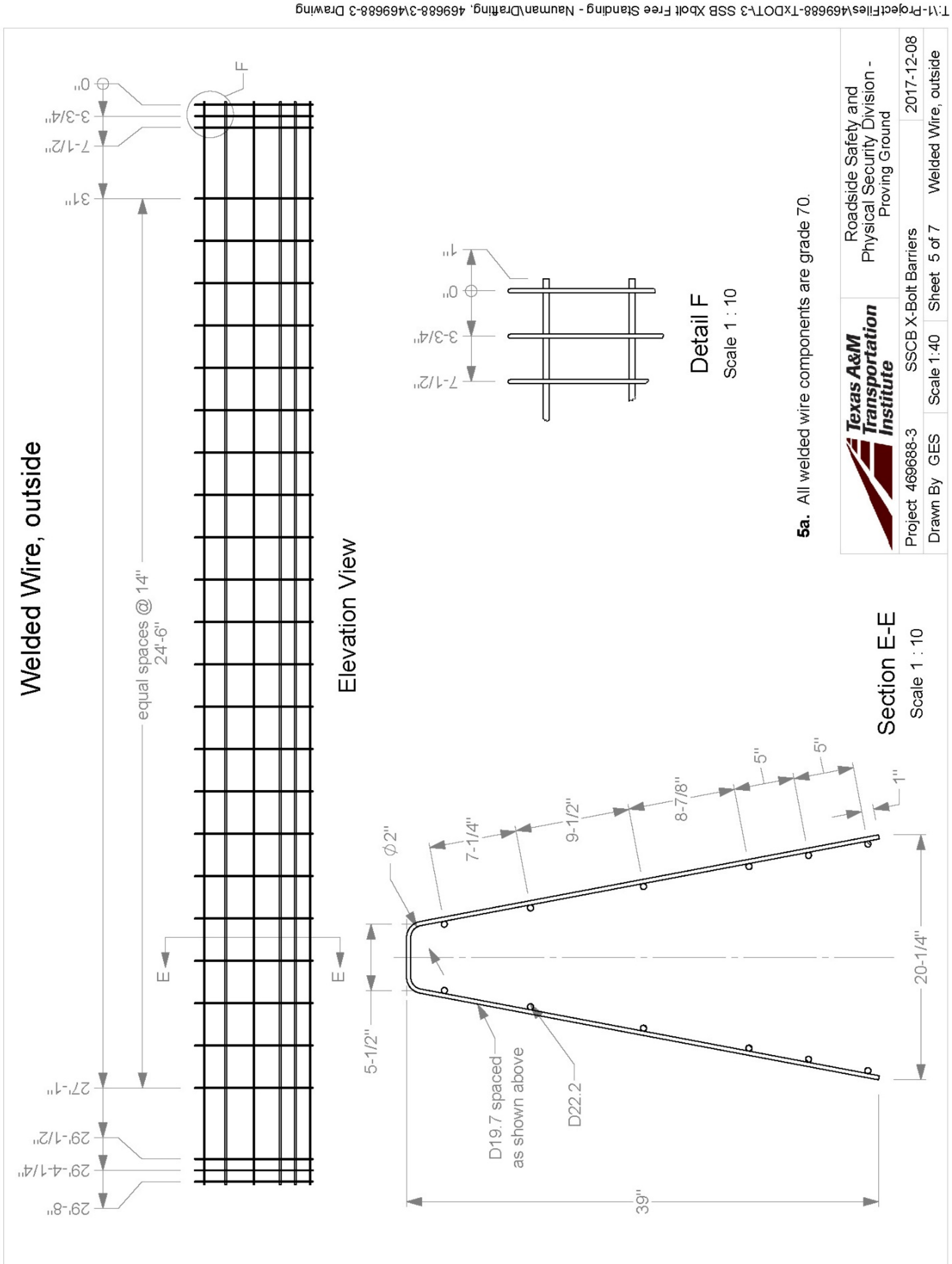
APPENDIX A. DETAILS OF FREE-STANDING SSCB WITH CROSS-BOLT CONNECTION

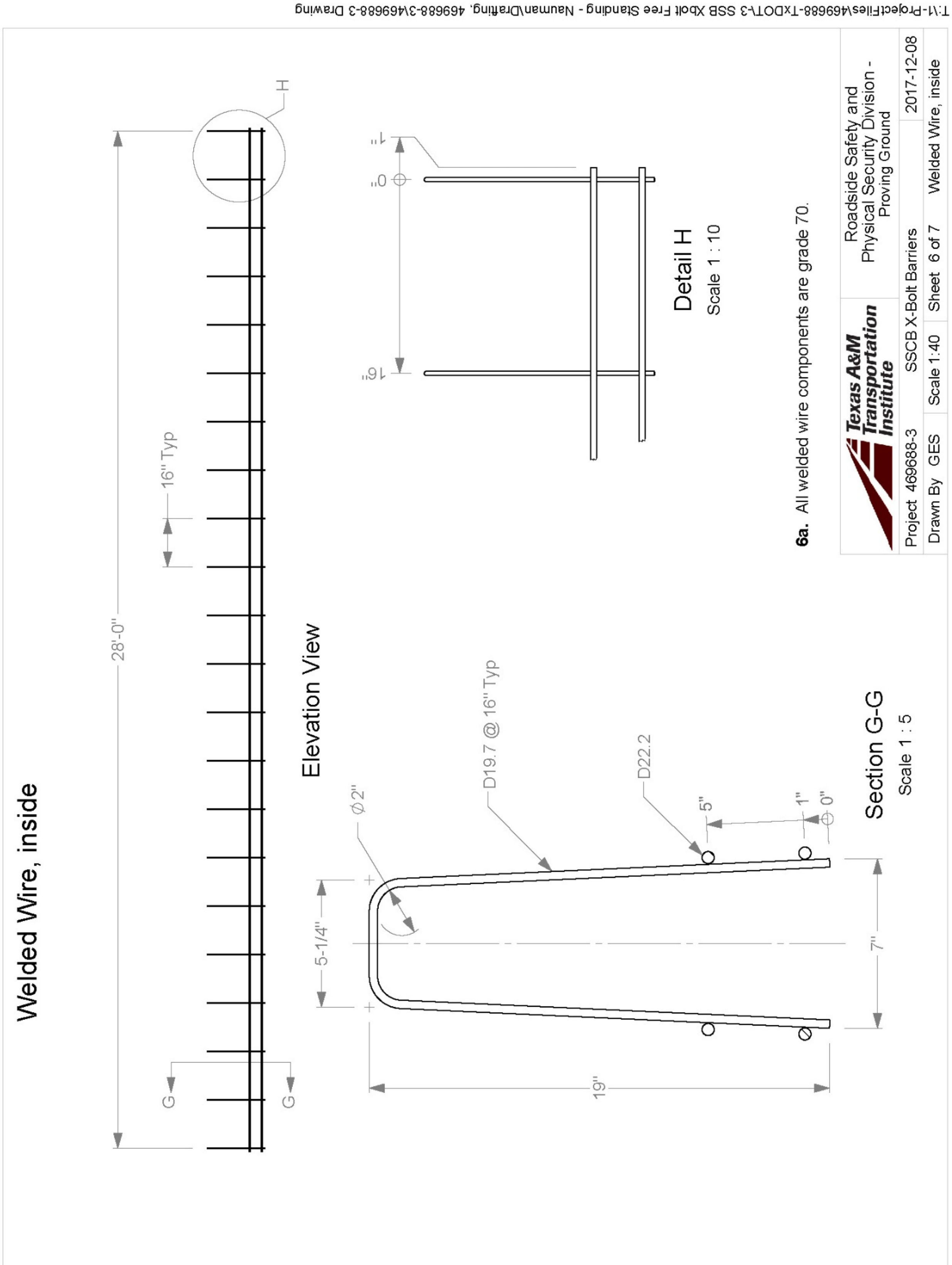


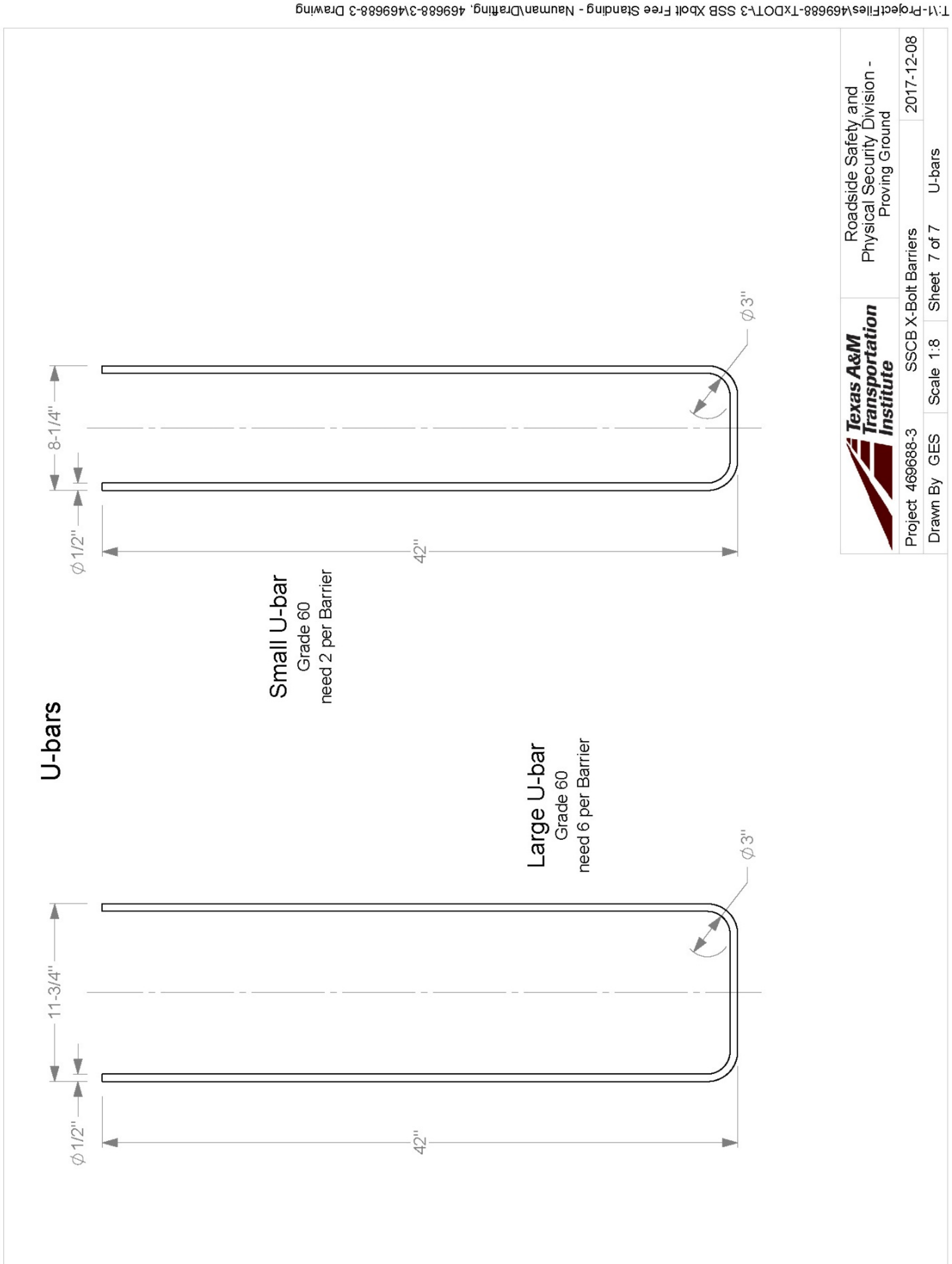

T:\1-ProjectFiles\469688-TxDOT-3 SSB Xbolt Free Standing - Nauman\Drafting, 469688-3\469688-3 Drawing
Barrier-Elevation
30'-0"
11-1/8"
15-7/8"
C
C
Top Sleeve
Pipe, 1-1/2" sch. 40 PVC
2 needed per Barrier
Scale 1:5
13-3/8"
70.0°
Bottom Sleeve
Pipe, 1-1/2" sch. 40 PVC
2 needed per Barrier
Scale 1:5
18-3/8"
70.0°
2a. Concrete shall be TxDOT Class S.
2b. Chamfer all edges of Barrier 3/4".
Section C-C
Scale 1 : 10
42"
26"
17"
13"
10-1/4"
1-1/2"
0"
8"
3"
24"
24-3/8"
15-1/8"
R1"
1-1/2" cover
2-9/16"
2-9/16"
Outside Welded Wire
Small U-bar
Inside Welded Wire
Large U-bar
U-bars Typical each end
Large U-bar
Texas A&M Transportation Institute
Roadside Safety and Physical Security Division - Proving Ground
2017-12-08
Project 469688-3
SSCB X-Bolt Barriers
Drawn By GES
Scale 1:50
Sheet 2 of 7
Barrier-Elevation


T:\1-ProjectFiles\469688-TxDOT\-3 SSB Xbolt Free Standing - Nauman\Drafting, 469688-3\469688-3 Drawing
Barrier-Plan
D
Detail D
Scale 1 : 10
Large U-bar
Bottom Sleeve
12" to ℄ of welded wire
inside cage
11-1/8"
2" to ℄ of welded wire
outside cage
0"
15-7/8"
Top Sleeve
Small U-bar
70.0° Typ
Large U-bar
Large U-bar
This Face co-planar
with Barrier Face.
15"
5-3/8"
5-3/8"
Leave-out Block Details
Scale 1:7
Roadside Safety and
Physical Security Division -
Proving Ground
Texas A&M
Transportation
Institute
Project 469688-3
SSCB X-Bolt Barriers
2017-12-08
Drawn By GES
Scale 1:50
Sheet 3 of 7
Barrier-Plan


T:\1-ProjectFiles\469688-TxDOT\-3 SSB Xbolt Free Standing - Nauman\Drafting, 469688-3\469688-3 Drawing
Isometric View
Texas A&M Transportation Institute
Roadside Safety and Physical Security Division - Proving Ground
Project 469688-3
SSCB X-Bolt Barriers
2017-12-08
Drawn By GES
Scale 1:8
Sheet 4 of 7
Isometric View


T:\1-ProjectFiles\469688-TxDOT\-3 SSB Xbolt Free Standing - Nauman\Drafting, 469688-3\469688-3 Drawing
Welded Wire, outside
Elevation View
equal spaces @ 14"
24'-6"
0"
3-3/4"
7-1/2"
31"
27'-1"
29'-1/2"
29'-4-1/4"
29'-8"
F
E
Detail F
Scale 1 : 10
1"
Section E-E
Scale 1 : 10
⌀2"
7-1/4"
9-1/2"
8-7/8"
5"
5"
1"
5-1/2"
20-1/4"
39"
D19.7 spaced
as shown above
D22.2
5a. All welded wire components are grade 70.
Texas A&M Transportation Institute
Roadside Safety and Physical Security Division - Proving Ground
Project 469688-3
SSCB X-Bolt Barriers
2017-12-08
Drawn By GES
Scale 1:40
Sheet 5 of 7
Welded Wire, outside


T:\1-ProjectFiles\469688-TxDOT-3 SSB Xbolt Free Standing - Nauman\Drafting, 469688-3\469688-3 Drawing
Welded Wire, inside
28'-0"
16" Typ
H
G
G
Elevation View
Detail H
Scale 1 : 10
0"
1"
16"
Ø2"
D19.7 @ 16" Typ
D22.2
5"
1"
0"
5-1/4"
7"
19"
Section G-G
Scale 1 : 5
6a. All welded wire components are grade 70.
Texas A&M Transportation Institute
Roadside Safety and Physical Security Division - Proving Ground
Project 469688-3
SSCB X-Bolt Barriers
2017-12-08
Drawn By GES
Scale 1:40
Sheet 6 of 7
Welded Wire, inside


T:\1-ProjectFiles\469688-TxDOT\-3 SSB Xbolt Free Standing - Nauman\Drafting, 469688-3\469688-3 Drawing
U-bars
Small U-bar
Grade 60
need 2 per Barrier
Large U-bar
Grade 60
need 6 per Barrier
8-1/4"
11-3/4"
ϕ1/2"
ϕ3"
42"
Texas A&M Transportation Institute
Roadside Safety and Physical Security Division - Proving Ground
Project 469688-3
SSCB X-Bolt Barriers
2017-12-08
Drawn By GES
Scale 1:8
Sheet 7 of 7
U-bars

APPENDIX B. SUPPORTING CERTIFICATION DOCUMENTS

Texas A&M Transportation Institute Proving Ground, 3100 SH 47, Bldg 7091, Bryan, TX 77807 Texas A&M University, College Station, TX 77843, Phone 979-845-6375	5.7.2 Concrete Break	Doc. No. QPF 5.7.2	Revision Date: 2012-09-17
Quality Policy Form	Revised by: G. E. Schroeder Approved by: C. E. But	Revision: 5	Page: 1 of 1

Project No.: 469688-3 **Casting Date:** 2018-1-11

Placement: SINGLE SLOPE **Mix Design P.S.I.:** CLASS C

Truck No.	Batch Ticket	Yards
1		

Printed name of Technician taking sample: GREGORY FRITZ

Signature of Technician taking sample:

Printed name of Technician breaking sample: GREGORY FRITZ

Signature of Technician breaking sample:

Break Date	Cylinder Age	Truck No.	Total Load (Pounds)	PSI Break	Average
2018-2-8	28 DAYS	1	197,000	6970	
↓	↓	1	214,500	7590	7330
		1	210,000	7430	

ZHEJIANG JUNYUE STANDARD PART CO.,LTD.

CERTIFIED MATERIAL TEST REPORT

COMMODITY: STUD SIZE: 7/8-9×144" STANDARD: ASTM A193-06

Order No: B13120306 QTY: 3200 PCS) HEAD MARKS: XL B7

LOT NO.: JY70317_778087 PART NO. 778087

一、CHEMICAL ELEMENTS (%) HEAT NO: 6612040219 MATERIAL:B7/4140

CHEMICAL ELEMENT	C	Mn	Si	P	S	Cr	Mo
SPEC	0.37	0.65	0.15	max	max	0.75	0.15
	0.49	1.10	0.35	0.035	0.04	1.20	0.25
TEST REPORT	0.41	0.77	0.22	0.012	0.007	0.92	0.19

二、MACHINICAL PROPERTIES BATCH NO 3P7051902 TEST NO: A193-06 B7

ITEM	TENSILE STRENGTH min (Mpa)	YIELD STRENGTH min (Mpa)	ELONGATION min (%)	REDUCE min (%)	TEMPERING min (^0C)	QUENCHING (^0C)	HARDNESS max (HRC)
STANDARD	860	724	16	50	593	820~880	35
TEST REPORT	933	810	18	56	640	860	29

三、TESTED SIZE

ITEM		LENGTH	MAJORDIA	GO	NO		STRAIGHTNESS	ADD
STANDARD		3663.95	22.177	2A	2A		max	
		3651.25	21.824			MACROETCH	18.29	
TEST REPORT	①	3656.00	21.90	OK	OK		OK	
	②	3656.00	21.92	OK	OK		OK	
	③	3657.00	21.95	OK	OK		OK	
PCS: 4	④	3656.00	21.90	OK	OK	S2/R2/C2	OK	OK

PARTS ARE MANUFACTURED AND TESTED IN ACCORDANCE WITH ASTM A193-06 B7
ALSO MEET THE REQUIREMENTS OF ASME SA-95 SECTION 2 IN YOUR MTR.
ALL TESTS IN ACCORDANCE WITH THE METHODS PRESCRIBED IN THE APPLICABLE ASTM SPECIFICATION. WE CERTIFY THAT THIS DATA IS TRUE REPRESENTATION OF INFORMATION PROVIDED BY THE MATERIAL SUPPLIES AND OUR TESTING LABORATORY.

MADE IN CHINA

浙江君悦标准件有限公司 质量检验章

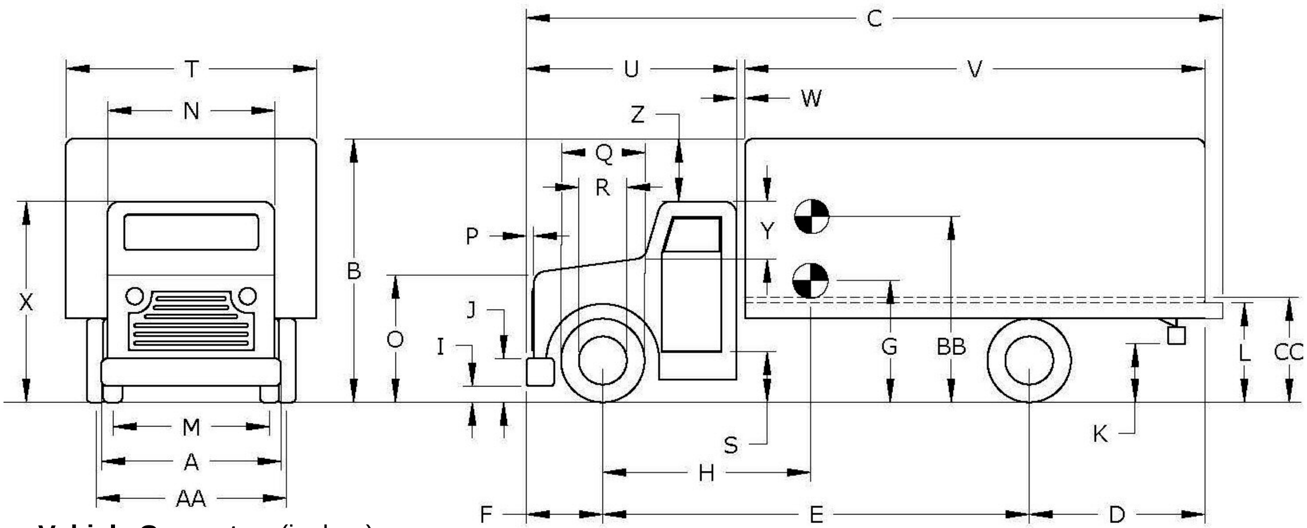
QC: ZHANG GUANG
ZHEJIANG JUNYUE STANDARD PART CO., LTD.
QUALITY DEPARTMENT

APPENDIX C. *MASH* TEST 4-12 (CRASH TEST NO. 469688-3-1)

C.1 VEHICLE PROPERTIES AND INFORMATION

Table C.1. Vehicle Properties for Test No. 469688-3-1.

Date:	2018-02-07	Test No.:	469688-3-1	VIN No.:	1GDJC1366F406621
Year:	2006	Make:	GMC	Model:	C7500
Odometer:	292568	Tire Size Front:	11 R-22.5	Tire Size Rear:	11 R-22.5



Vehicle Geometry: (inches)

A	Front Bumper Width:	93.50	K	Rear Bumper Bottom:		U	Cab Length:	102.00
B	Overall Height:	150.00	L	Rear Frame Top:	39.00	V	Trailer/Box Length:	222.50
C	Overall Length:	329.50	M	Front Track Width:	82.00	W	Gap Width:	3.00
D	Rear Overhang:	86.50	N	Roof Width:	60.00	X	Overall Front Height:	99.50
E	Wheel Base:	206.00	O	Hood Height:	61.00	Y	Roof-Hood Distance:	26.00
F	Front Overhang:	37.00	P	Bumper Extension:	2.00	Z	Roof-Box Height Difference:	49.00
G	C.G. Height:		Q	Front Tire Width:	41.50	AA	Rear Track Width:	72.00
H	C.G. Horizontal Dist. w/Ballast:	131.70	R	Front Wheel Width:	23.00	BB	Ballast Center of Mass:	64.00
I	Front Bumper Bottom:	18.50	S	Bottom Door Height:	35.50	CC	Cargo Bed Height:	50.50
J	Front Bumper Top:	33.50	T	Overall Width:	101.75			

Wheel Center Height Front	19.50	Wheel Well Clearance (Front)	11.50	Bottom Frame Height (Front)	26.25
Wheel Center Height Rear	19.50	Wheel Well Clearance (Rear)	5.00	Bottom Frame Height (Rear)	29.00

Table C.1. Vehicle Properties for Test No. 469688-3-1 (Continued).

Date: 2018-02-07 Test No.: 469688-3-1 VIN No.: 1GDJC1366F406621

Year: 2006 Make: GMC Model: C7500

WEIGHTS (lb)	CURB	TEST INERTIAL
$W_{front\ axle}$	6880	8030
$W_{rear\ axle}$	6930	14260
W_{TOTAL}	13810	22290

Ballast: 8480 (lb)

Mass Distribution
(lb): **LF:** 4000 **RF:** 4030 **LR:** 7160 **RR:** 7100

Engine Type: DURAMAX Diesel

Engine Size: 475 CID

Transmission Type:

x Auto or ___ Manual

___ FWD x RWD ___ 4WD

Accelerometer Locations (inches)

	x[3]	**y**	**z**[4]
Front:			
Center:	131.70	0	49.00
Rear:	231.70	0	49.00

Describe any damage to the vehicle prior to test:

None

Other notes to include ballast type, dimensions, mass, location, center of mass, and method of attachment:

Block 30 inches high x 60 inches wide x 30 inches long

Block 30 inches high x 60 inches wide x 30 inches long

Centered in middle of bed

Tied down with four 5/16-inch cables per block

[3] Referenced to the front axle
[4] Above ground

C.2 SEQUENTIAL PHOTOGRAPHS

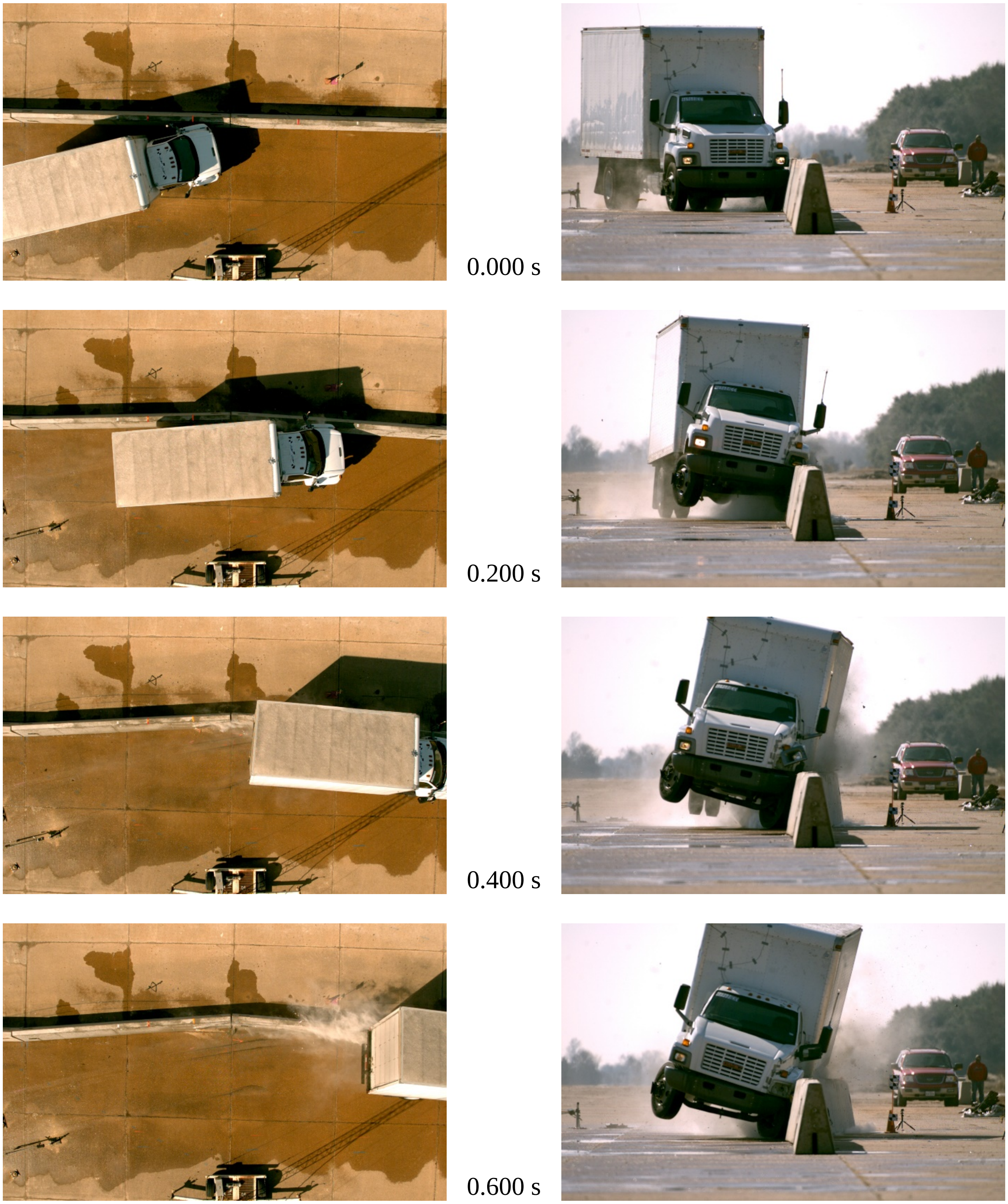
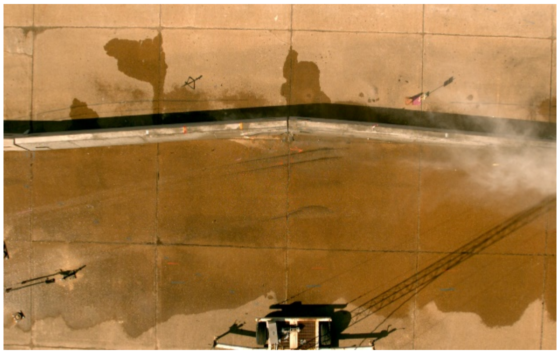


Figure C.1. Sequential Photographs for Test No. 469688-3-1 (Overhead and Frontal Views).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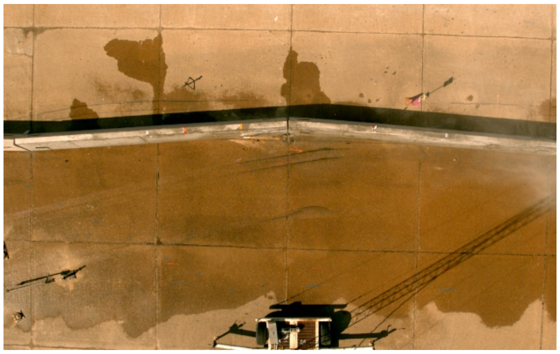
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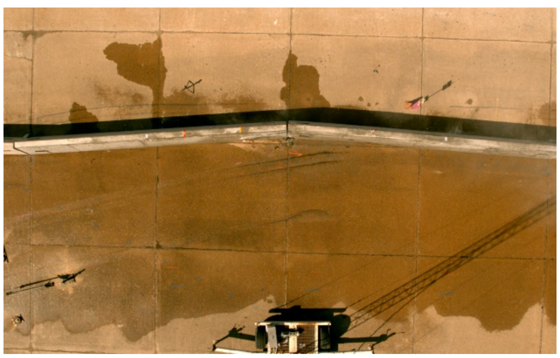
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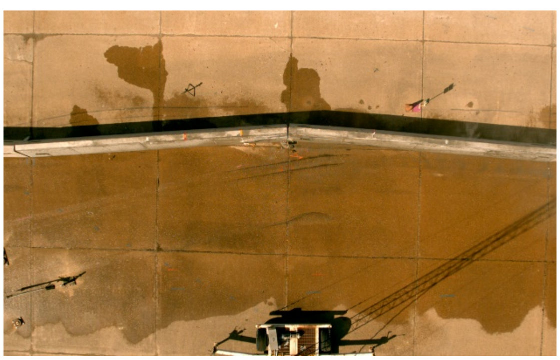
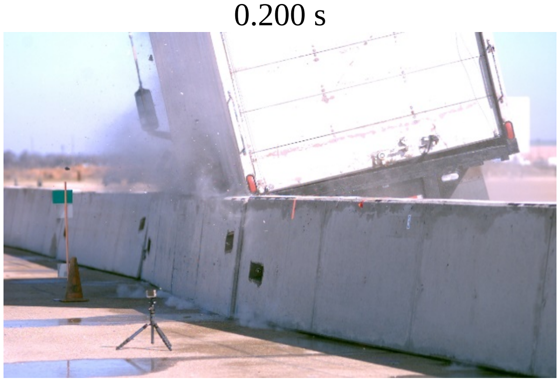

1.400 s

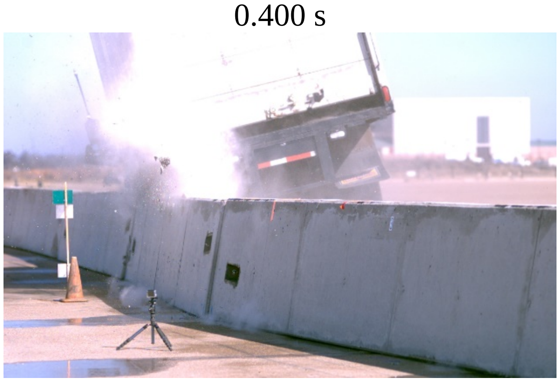

Figure C.1. Sequential Photographs for Test No. 469688-3-1 (Overhead and Frontal Views) (Continued).

0.000 s

0.200 s



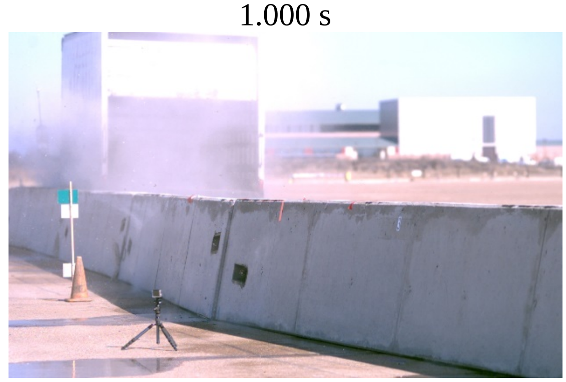
0.400 s



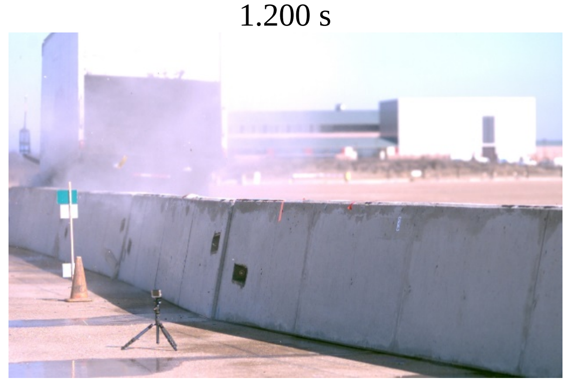
0.600 s

0.800 s

1.000 s



1.200 s



1.400 s

Figure C.2. Sequential Photographs for Test No. 469688-3-1 (Rear View).

C.3 VEHICLE ANGULAR DISPLACEMENT

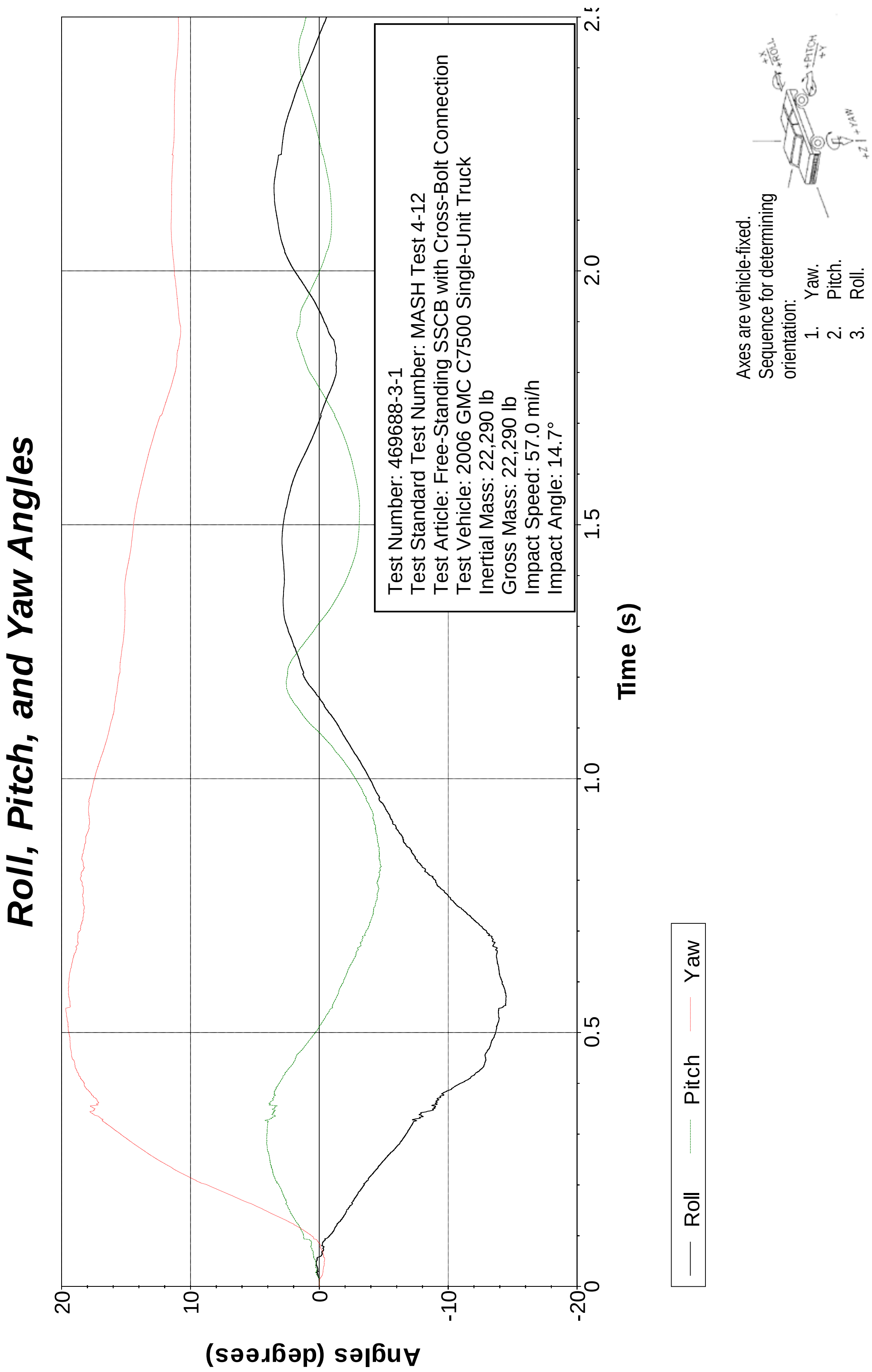


Figure C.3. Vehicle Angular Displacements for Test No. 469688-3-1.

C.4 VEHICLE ACCELERATIONS

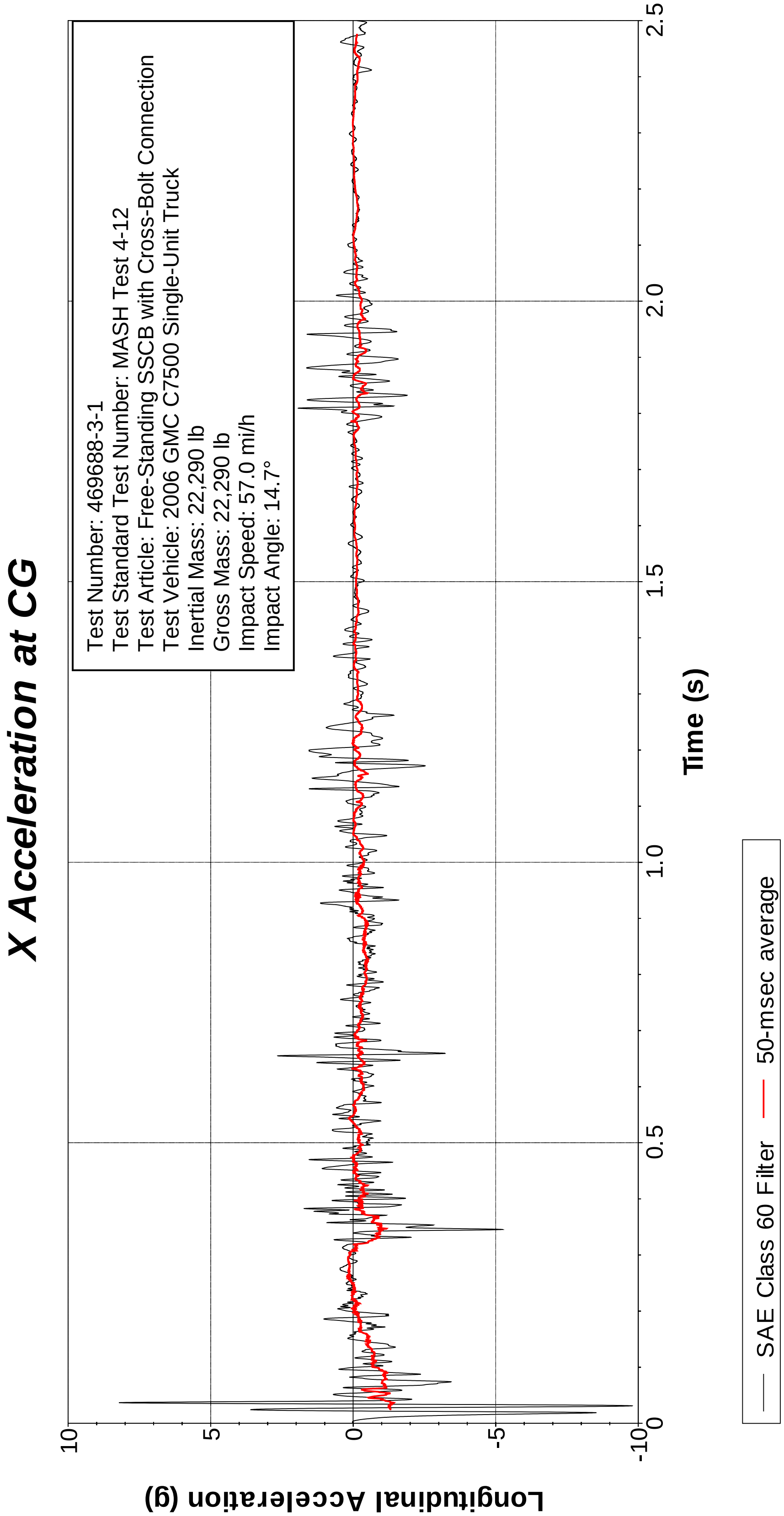


Figure C.4. Vehicle Longitudinal Accelerometer Trace for Test No. 469688-3-1 (Accelerometer Located at Center of Gravity).

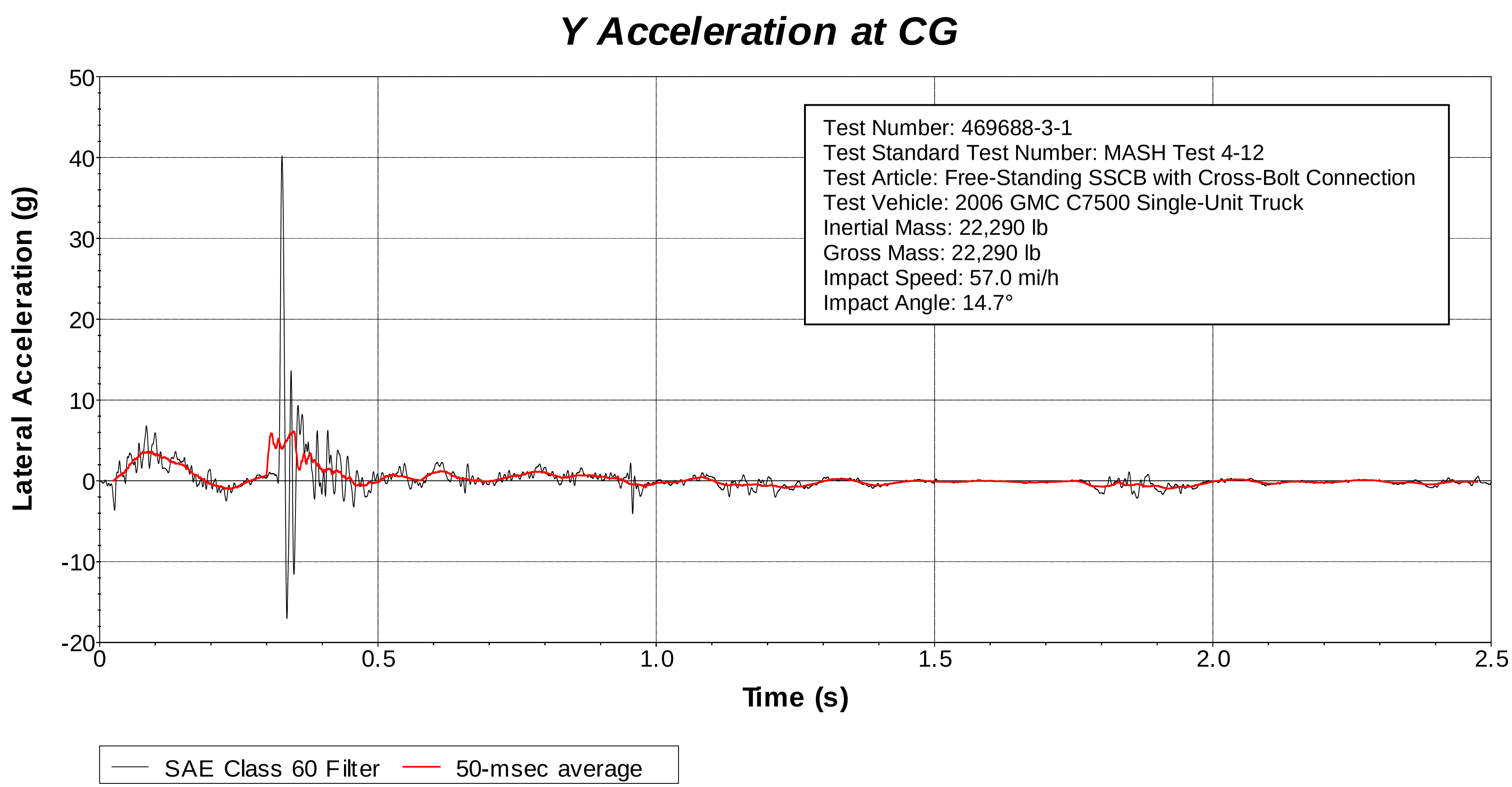


Figure C.5. Vehicle Lateral Accelerometer Trace for Test No. 469688-3-1 (Accelerometer Located at Center of Gravity).

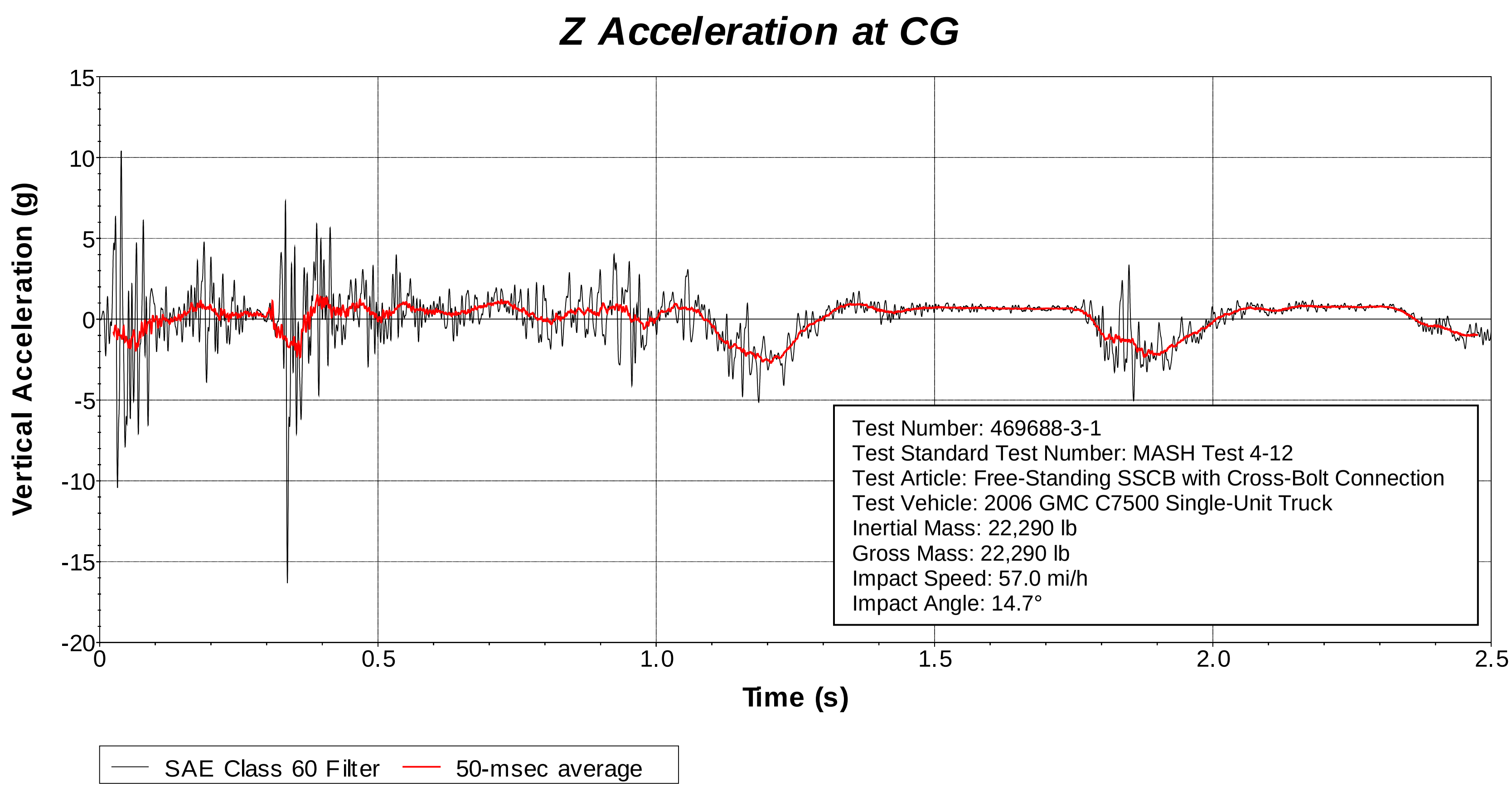


Figure C.6. Vehicle Vertical Accelerometer Trace for Test No. 469688-3-1 (Accelerometer Located at Center of Gravity).

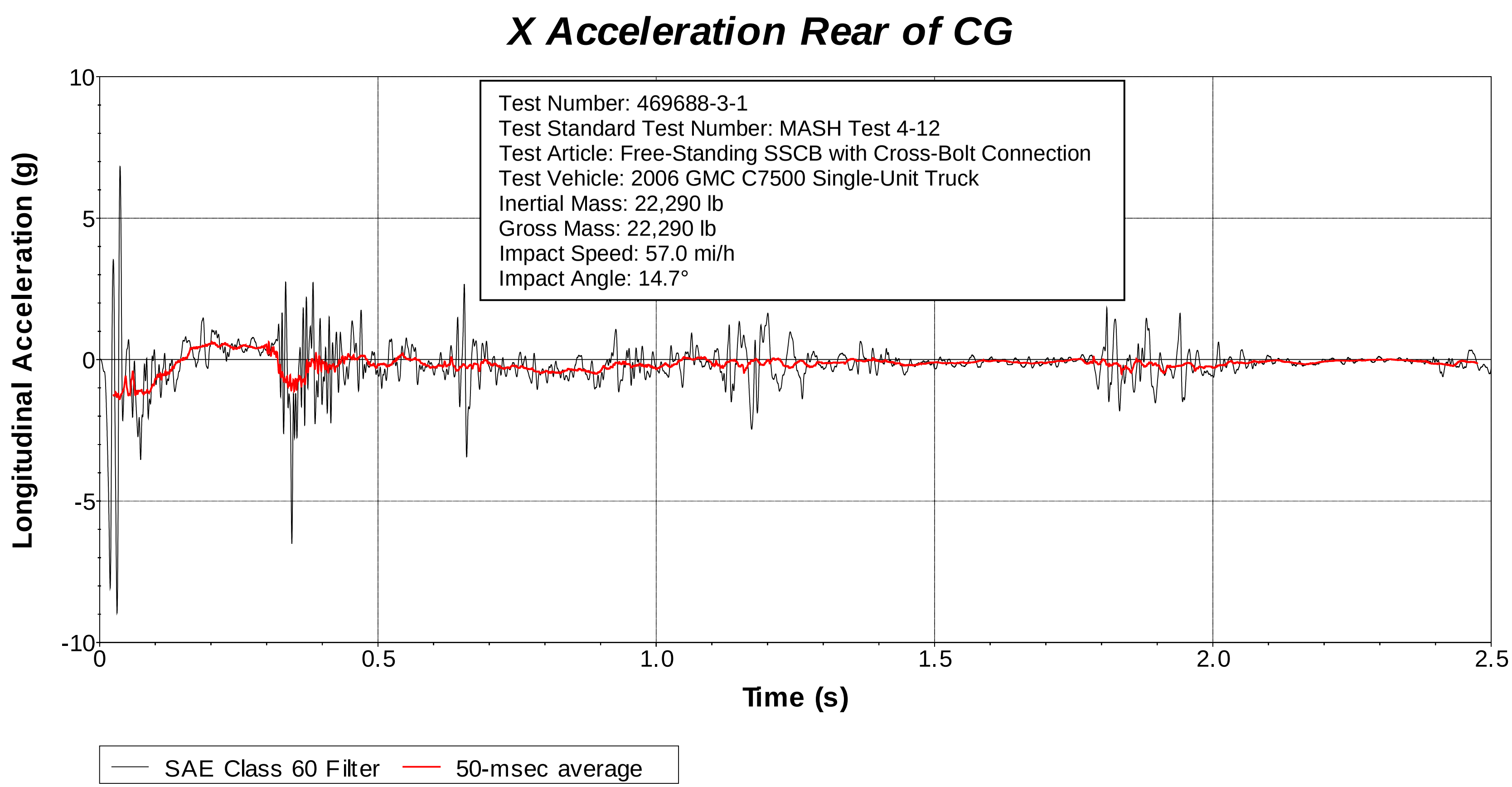


Figure C.7. Vehicle Longitudinal Accelerometer Trace for Test No. 469688-3-1 (Accelerometer Located Rear of Center of Gravity).

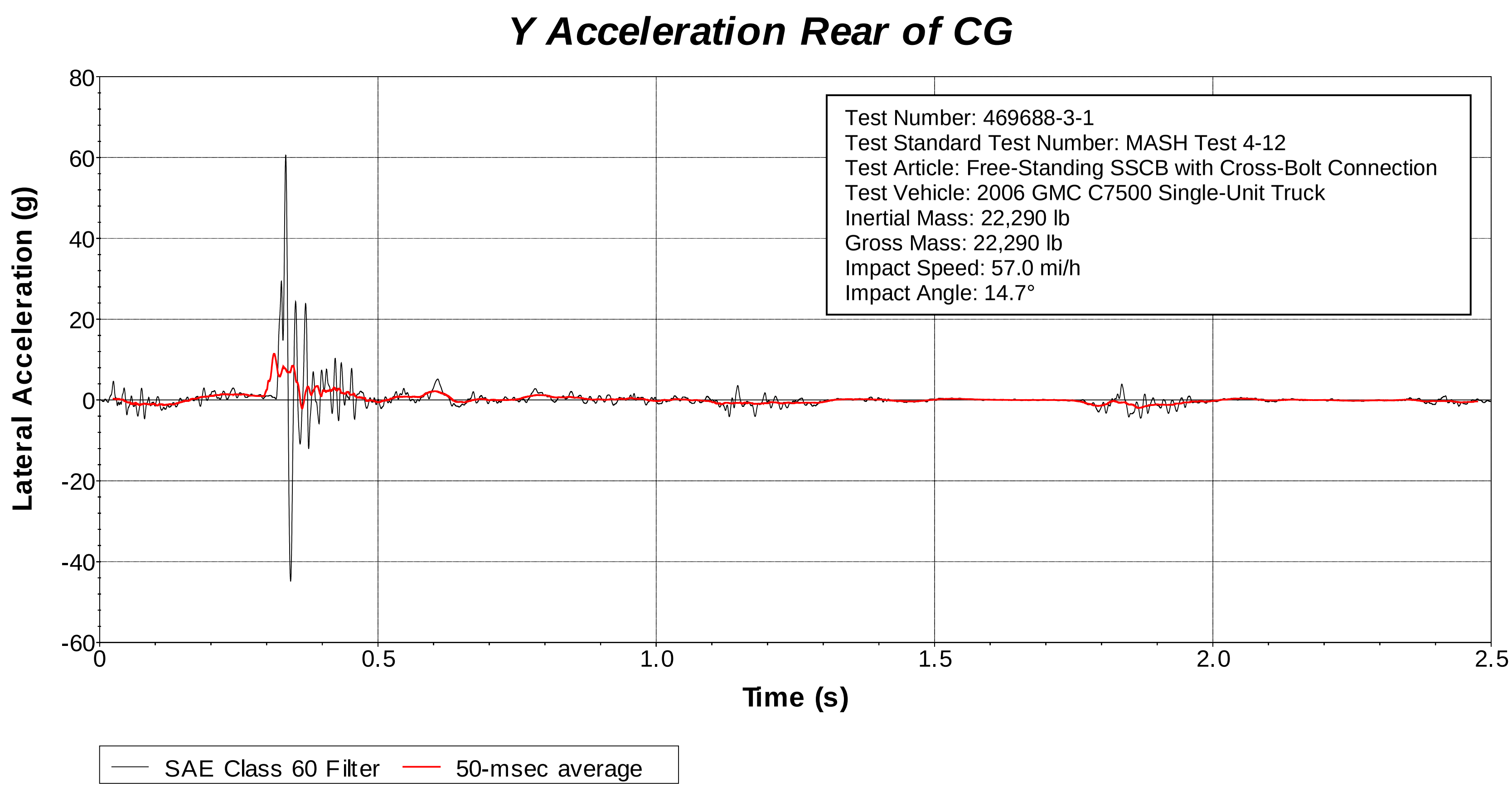


Figure C.8. Vehicle Lateral Accelerometer Trace for Test No. 469688-3-1 (Accelerometer Located Rear of Center of Gravity).

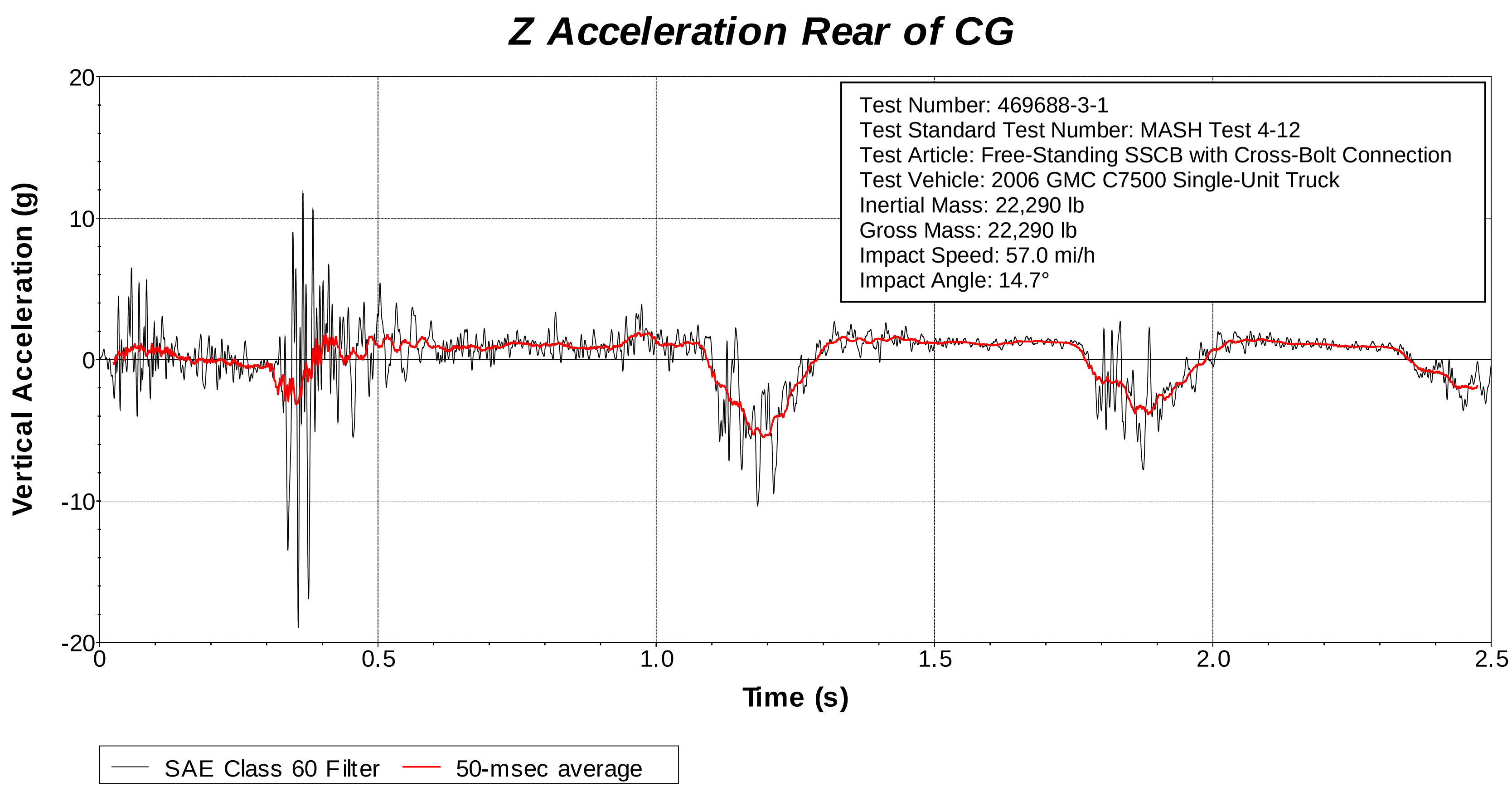


Figure C.9. Vehicle Vertical Accelerometer Trace for Test No. 469688-3-1 (Accelerometer Located Rear of Center of Gravity).