FINAL REPORT

ANALYSIS, DESIGN, AND DYNAMIC EVALUATION OF A TL-2 ROUGH STONE MASONRY GUARDWALL

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16. Abstract (Limit: 200 words)

This research study was performed to determine the minimum mounting height for the rough stone masonry guardwall to allow it to meet the Test Level 2 (TL-2) safety performance criteria found in NCHRP Report No. 350. A literature review was conducted to determine whether any relevant research had been performed on low-height, rigid parapets and rough stone masonry guardwalls. LS-DYNA computer simulations were performed on a rigid, vertical-faced barrier with varying heights to evaluate the propensity for vehicular instabilities and barrier override. Several design concepts were considered for providing shear transfer between the top capstones and the inner core wall. The new design utilized steel angle segments anchored to the core wall with the upper leg recessed into saw-cuts placed in the bottom of the capstones. Two TL-2 crash tests were performed on rough stone masonry guardwalls according to NCHRP Report No. 350. The first test was performed on a 22-in. (559-mm) tall, guardwall using a 2000P pickup truck impacting at a speed of 44.4 mph (71.4 km/h) and at an angle of 24.2 degrees. The second test was performed on a 20-in. (508-mm) tall, guardwall using another 2000P vehicle impacting at a speed of 43.6 mph (70.1 km/h) and at an angle of 24.4 degrees. Both crash tests provided acceptable safety performance according to NCHRP Report No. 350. Although the 20-in. (508-mm) tall, parapet adequately contained and redirected the pickup truck at the TL-2 conditions, barrier performance was slightly degraded over that observed in the 2000P testing of the 22-in. (559-mm) tall parapet. Based on the results of this study and for new construction, it is recommended that the rough stone masonry guardwall system be implemented using a nominal top mounting height of 22 in. (559 mm) relative to the traveled way. Finally, roadways that require resurfacing could be accommodated using a 2-in. (51-mm) pavement overlay placed adjacent to the barrier system as long as the rough stone masonry guardwall was originally installed using the 22-in. (559-mm) nominal mounting height relative to the traveled way.

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UNCERTAINTY OF MEASUREMENT STATEMENT

The Midwest Roadside Safety Facility (MwRSF) has determined the uncertainty of measurement for several parameters involved in non-standard testing of roadside safety hardware as well as in standard full-scale crash testing of roadside safety features. Information regarding the uncertainty of measurement for critical parameters is available upon request by the sponsor and the Federal Highway Administration.

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1 INTRODUCTION

1.1 Background

For many years, the Federal Lands Highway Division (FLHD), Federal Highway Administration (FHWA), and the National Park Service (NPS) have been implementing and/or recommending the use of aesthetic bridge railings and barriers along our nation's scenic highways and roadways. Many of these aesthetic barriers, consisting of both rigid and semi-rigid systems, have been full-scale crash tested, evaluated, and accepted for use on the National Highway System (NHS), as denoted in FHWA acceptance letter no. HSA-10/B64-D (1). Two stone masonry guardwalls were included therein – one with a smooth stone face and another with a rough stone face. Both stone masonry guardwalls were successfully evaluated according to the Test Level 3 (TL-3) impact conditions found in the National Cooperative Highway Research Program (NCHRP) Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features* (2).

For the TL-3 rough stone masonry guardwall system, the inner core wall and slab foundation were fabricated using precast, reinforced concrete construction, while a stone masonry veneer was applied to the exterior surfaces of the vertical parapet in order to provide the aesthetic appearance (3). Current design details (Standard Nos. 620-1 through 620-3) for the TL-3 rough stone masonry guardwall are provided in Figures 1 through 3. Details for both the single- and double-face barriers are provided in Standard Nos. 620-1 through 620-3. It should be noted that the barrier and foundation system can also be configured using cast-in-place concrete construction. The overall barrier height was 27 in. (686 mm), while the overall barrier width was 24 in. (610 mm). The inner core wall measured 20 in. (508 mm) tall by 16½ in. (419 mm) wide.

Currently, the TL-3 rough stone masonry guardwall can be utilized along high-speed, high-volume roadways. However, some scenic roadways and highways may only require the use of aesthetic, crashworthy barriers that have met the TL-2 impact safety standards. For the rough stone masonry guardwall, it is believed that the overall top mounting height could be reduced when located along roadways requiring the use of TL-2 barriers. Unfortunately, no research has been performed in order to determine the minimum top mounting height for the rough stone masonry guardwall which would allow the barrier to meet the TL-2 safety performance criteria. As such, there exists a need for a reduced-height, TL-2, rough stone masonry guardwall that maintains the aesthetic qualities of the taller, crashworthy, stone veneer barrier system.

1.2 Research Objective

For this study, the research objective was to determine the minimum top mounting height for the rough stone masonry guardwall in order to allow the aesthetic barrier system to meet the TL-2 safety performance criteria of NCHRP Report No. 350. The minimum top mounting height was to be identified by utilizing any relevant research results published in the literature, the research team's engineering expertise, LS-DYNA finite element analysis, as well as full-scale vehicle crash testing.

1.3 Research Approach

This project began with a review of prior full-scale vehicle crash tests performed on barriers and bridge railings containing aesthetic features and/or those configured with barrier heights less than or equal to 27 in. (686 mm). Subsequently, LS-DYNA computer simulations were performed on a rigid, vertical-faced barrier with varying heights in order to help determine the minimum top mounting height to prevent vehicular instabilities and barrier override. Following the completion of the literature review and LS-DYNA analyses, the research team identified probability ranges for successfully containing and redirecting vehicles using different barrier heights. A 22-in. (559-mm) tall barrier was then selected based on feedback from the research sponsor. Later, the research team, in cooperation with the sponsor, brainstormed several methods for improving the anchorage method and shear transfer for the stone masonry placed on top of the inner core wall. Once the anchorage method was chosen, the final design was completed, including CAD details. A rough stone masonry guardwall system, measuring 74 ft - 4 in. (22.66 m) long, was constructed. Next, one full-scale vehicle crash test was successfully performed according to the Test Level 2 (test designation no. 2-11) guidelines provided in NCHRP Report No. 350. Following the successful crash test on the 22-in. (559-mm) tall, aesthetic barrier, a second 2000P compliance test was performed on a 20-in. (508-mm) tall barrier according to test designation no. 2-11. Once again, a satisfactory result was obtained. Finally, the test results were analyzed, and conclusions were made pertaining to the safety performance evaluation of the aesthetic barrier system.

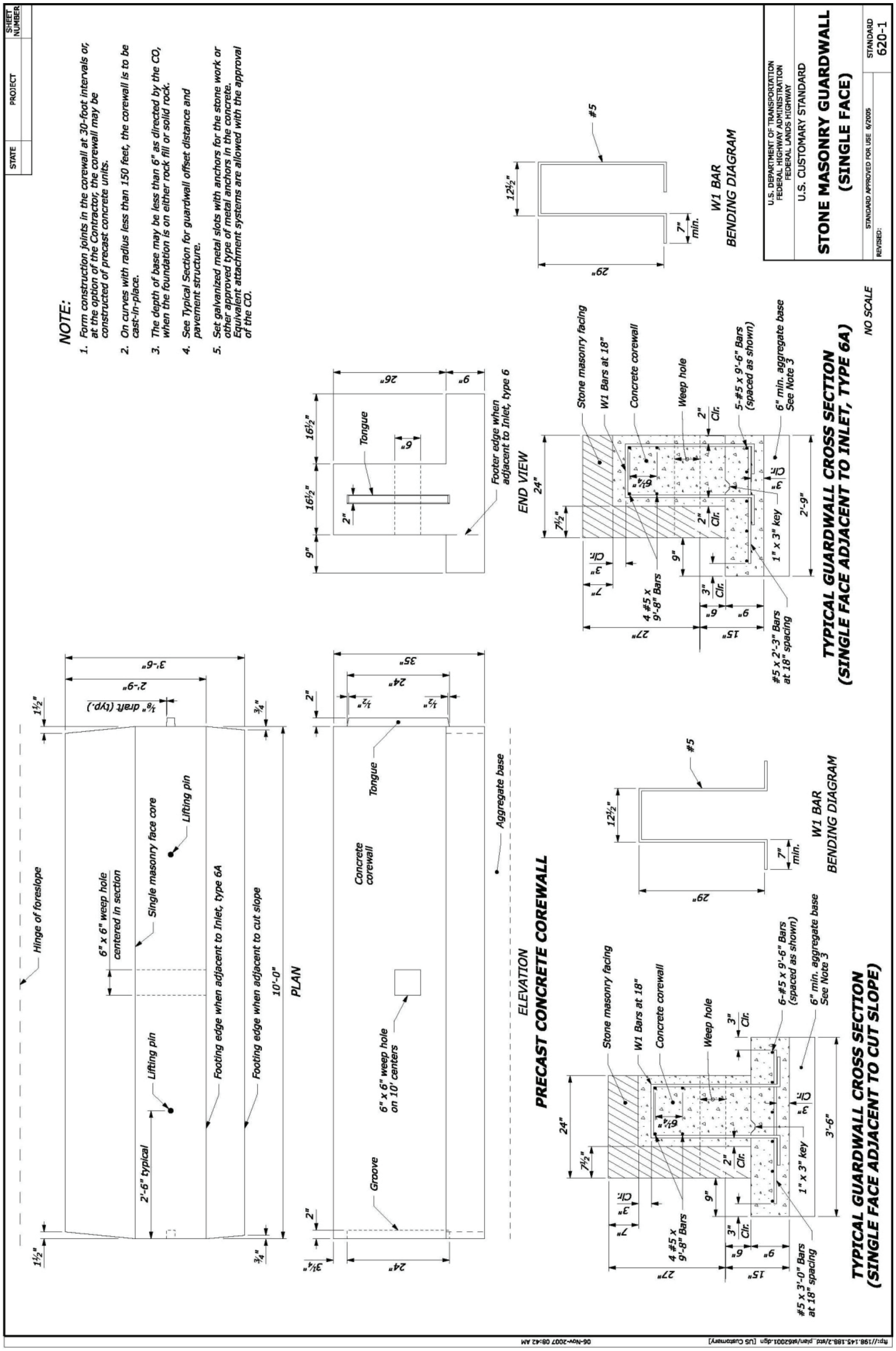


Figure 1. Stone Masonry Guardwall (Single Face) – Standard 620-1

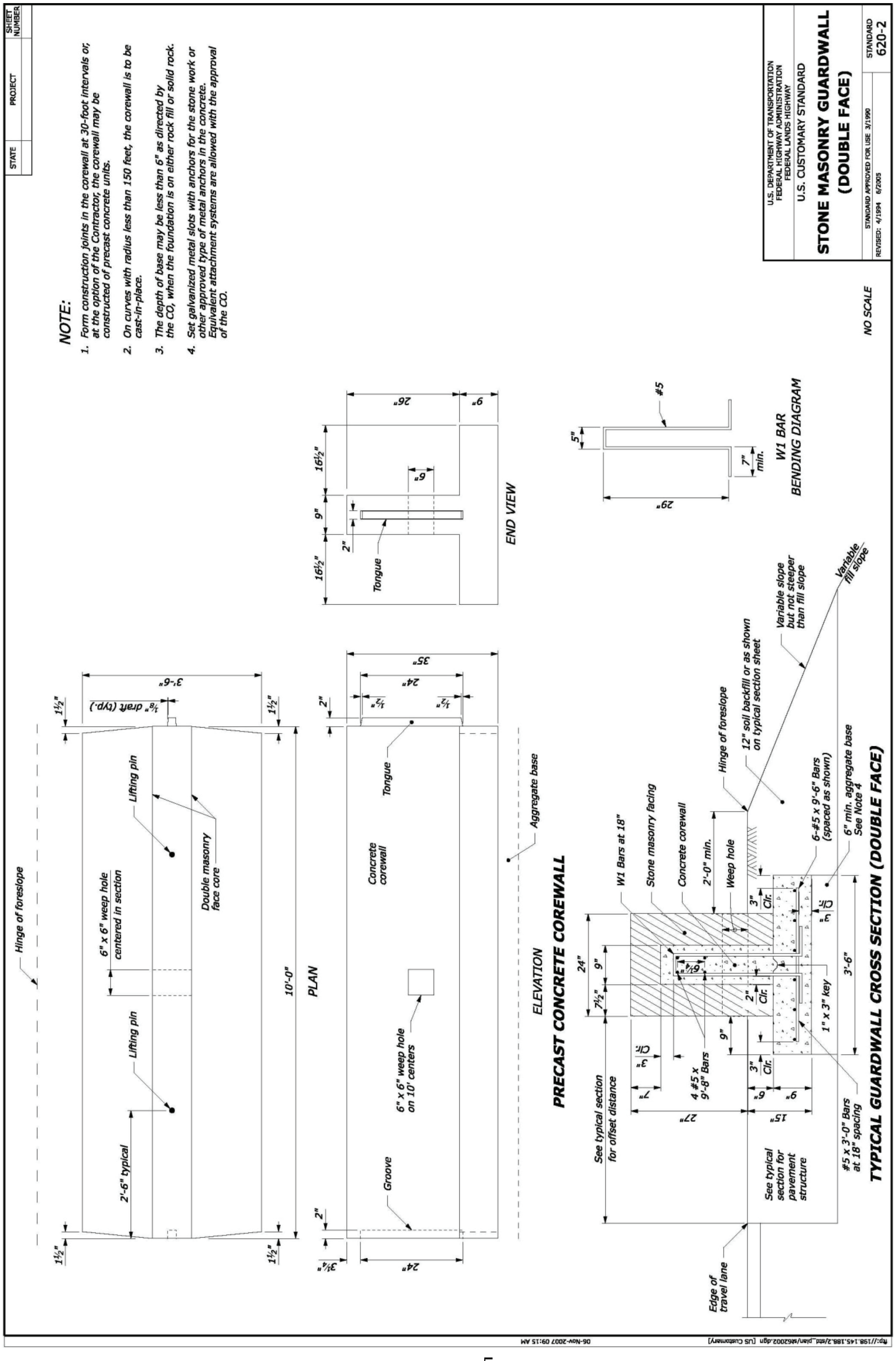


Figure 2. Stone Masonry Guardwall (Double Face) – Standard 620-2

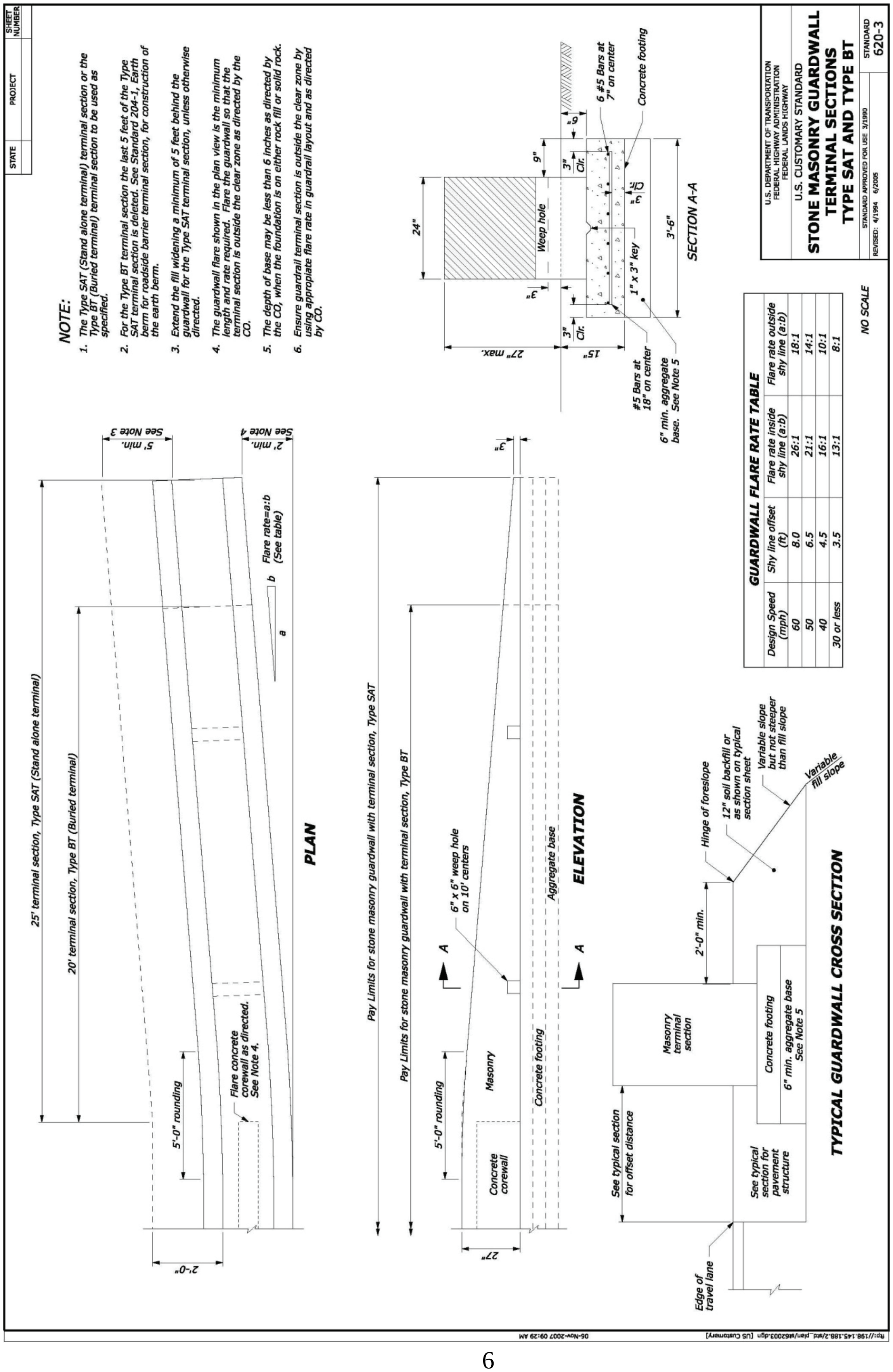


Figure 3. Stone Masonry Guardwall Terminal Sections Types SAT and BT – Standard 620-3

2 LITERATURE REVIEW

2.1 Low-Height Concrete Barriers

A 75-ft (22.86-m) long, low-profile, reinforced concrete bridge railing was designed and crash tested by the Midwest Roadside Safety Facility (MwRSF) in 2001 (4). The 20-in. (508-mm) tall barrier system was successfully evaluated according to the Test Level 2 (TL-2) criteria set forth in the National Cooperative Highway Research Program (NCHRP) Report No. 350 *Recommended Procedures for the Safety Performance Evaluation of Highway Features* (2). The barrier system was impacted with a ¾-ton pickup weighing approximately 4,449 lbs (2,018 kg) at a speed of 43.5 mph (70.0 km/h) and an angle of 27.1 degrees.

In 1991, the Texas Transportation Institute (TTI) and the Texas Department of Transportation developed a low-profile portable concrete barrier (PCB) for temporary and permanent applications (5). The low-profile PCB measured 20 in. (508 mm) tall and was produced in 20-ft (6.10-m) long segments. The low-profile PCB was crash tested using modifications to the criteria found in NCHRP Report No. 230, *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances* (6). As a result, a ¾-ton pickup truck test was used in lieu of the sedan test. Both the small car and the pickup truck full-scale vehicle crash tests met the NCHRP Report No. 230 criteria.

In 1993, NCHRP Report No. 350 was implemented thereby requiring the low-profile PCB, which was acceptable according to the NCHRP Report No. 230 criteria, to be re-evaluated according to the new safety performance criteria. According to NCHRP Report No. 350, a longitudinal barrier must be subjected to two full-scale vehicle crash tests, specifically a 1,808-lb (820-kg) small car impacting with a speed of 43.5 mph (70.0

km/h) and at an angle of 20 degrees and a 4,409-lb (2,000-kg) pickup truck impacting with a speed of 43.5 mph (70.0 km/h) and an angle of 25 degrees. The first conducted test (test designation no. 2-11) involved a 4,504-lb (2,043-kg) pickup that impacted the low-profile PCB at a speed of 44.4 mph (71.4 km/h) and an angle of 26.1 degrees. The second test (test designation no. 2-10) involved a 1,801-lb (817-kg) small car impacting with a speed of 45.7 mph (73.5 km/h) and at an angle of 21.3 degrees. For both full-scale crash tests, the vehicles were smoothly redirected and the collected data fell within the acceptable limits of the occupant risk and vehicle deceleration criteria found in NCHRP Report No. 350. Therefore, these tests demonstrated that the low-profile PCB successfully met the NCHRP Report No. 350 test level 2 criteria and was suitable for use on most local and collector roads and many work zones as defined in NCHRP Report No. 350 (7).

A low-profile, work-zone, curb system was developed by the University of Florida's Department of Civil and Coastal Engineering (8). This low-profile, barrier system measured 18 in. (457 mm) tall and was produced in 12-ft (3.66-m) long segments that had a truncated, slanted triangular cross section. The low-profile, curb system was crash tested according to NCHRP Report No. 350 for use in roadside work-zone situations. The small car and pickup truck crash tests met the NCHRP Report No. 350 criteria. One advantage of this barrier was that its configuration does not require barrier to roadway anchorage since it utilizes inertial resistance to redirect impacting vehicles.

2.2 Rough Stone Masonry Guardwalls

In 1990, ENSCO, Inc. completed the final reporting of FHWA's Guardrail Testing Program (9). For this study, three full-scale vehicle crash tests were performed on two rough stone masonry guardwalls according to the NCHRP Report No. 230 criteria. The first crash test, test no. 1818-5-3-87, was successfully performed using a 1,810-lb (822-kg) small car impacting at 61.2 mph (98.5 km/h) and 20.2 degrees into a 27-in. (686-mm) tall by 24-in. (610-mm) wide by 90-ft (27.43-m) long, single-face, rough stone masonry guardwall which utilized an 18-in. (457-mm) high, inner core wall. For the second test, test no. 1818-5-4-87, a 4,311-lb (1,957-kg) sedan impacted the same barrier at 60.8 mph (97.8 km/h) and 25 degrees. During this test, approximately 20 ft (6.10 m) of stone masonry was dislodged from the top of the barrier system, thus resulting in an unacceptable test result according to the research team. The barrier system was modified to include a 20-in. (508-mm) tall inner core wall which resulted in a 27-in. (686-mm) overall height. The third crash test, test no. 1818-5-88, utilized a 4,325-lb (1,964-kg) sedan impacting the modified barrier at 61.0 mph (98.2 km/h) and 24 degrees. From this research program, the 27-in. (6860-mm) tall, rough stone masonry guardwall with a 20-in. (508-mm) tall inner core wall was found to meet the NCHRP Report No. 230 guidelines. It should be noted that the research team provided additional recommendations for increasing the shear resistance between the inner core wall and the top surface stone masonry. These suggestions included the incorporation of a keyway in the top center of inner core wall, using a stronger mortar for attaching the stone masonry, and the placement of vertical dowels in the inner core wall.

In 1994, the Southwest Research Institute (SwRI) completed a crash testing program on a variable-height, stone masonry guardwall according to the TL-1 and TL-2 impact conditions of NCHRP Report No. 350 as well as to non-compliant impact conditions (10). For this program, five full-scale crash tests were performed on the stone masonry guardwall. The variable-height, stone masonry barrier measured 18 in. (457 mm) wide with the height staggered from 18 in. (457 mm) to 24 in. (610 mm) tall and back to 18 in. (457 mm), using a repeating pattern and a sloped transition between the two heights. A reinforced, inner concrete core wall was placed within the stone masonry barrier. For the three NCHRP Report No. 350 crash tests, two tests were successful at the TL-1 impact conditions – a 2000P pickup truck and an 820C small car. However, the third test was unsuccessful using a 4,495-lb (2,039-kg) pickup truck impacting at 43.5 mph (70.0 km/h) and 25 degrees (i.e., TL-2 impact conditions). In this test, test no. RW-3, the pickup truck impacted an 18-in. (457-mm) high section of the parapet and overrode the barrier, thus coming to stop on the back side of the system. This test demonstrated that an 18-in. (457-mm) tall, rigid, vertical parapet is unable to safely contain and redirect the 2000P vehicle at the TL-2 impact conditions.

In 2000, TTI researchers completed a safety performance evaluation of a double-face, rough stone masonry guardwall system according to the TL-3 criteria found in NCHRP Report No. 350 (3,11). For this project, eight precast concrete segments were placed end to end, each consisting of an inner core wall and slab foundation. The inner core wall measured 20 in. (508 mm) tall by 9 in. (229 mm) wide. Subsequently, a stone masonry veneer was applied to the exterior surfaces of the vertical parapet in order to provide the aesthetic appearance. The overall barrier height was 27 in. (686 mm), while the overall barrier width was 24 in. (610 mm). One full-scale vehicle crash test, test no. 405181-1, was successfully performed using a 4,577-lb (2,076-kg) pickup truck impacting at 61.6 mph (99.1 km/h) and 24.9 degrees. This test demonstrated that a 27-in.

(686-mm) tall, rigid, vertical parapet can safely contain and redirect the 2000P vehicle at the TL-3 impact conditions.

3 LS-DYNA SIMULATION

3.1 Introduction

A limited study was performed using nonlinear, finite element analysis (FEA) to help determine a recommended height for the stone masonry guardwall. LS-DYNA was the software code used for the simulation effort (12). The simulation study was limited due to project funding, research scope, sponsor priorities, and project schedule.

The truck model used for simulation effort consisted of the UNL 2000P pickup truck model that was based off of the National Crash Analysis Center (NCAC) C2500 model. Substantial changes were made to the NCAC model in prior studies, many of which were documented in the noted references (13-14) and will not be repeated here. For the most part, the crash event that was simulated corresponded to the Test Level 2 test condition found in NCHRP Report No. 350 which involved a 4,409-lb (2000-kg) pickup truck impacting at 43.5 mph (70 km/h) and 25 degrees.

Solid, rigid elements were used to model the 24-in. (610-mm) wide, stone masonry wall. The barrier height was varied in order to analyze the affects of using different height walls for redirecting the 2000P test vehicle.

3.2 Initial Efforts

Initial modeling efforts consisted of simulating barrier heights of 27 in. (686 mm), 24 in. (610 mm), 21 in. (533 mm), and 18 in. (457 mm). The simulation results demonstrated that the tire and suspension behavior play a critical role in the impact event. Thus, it was determined that a validation effort was deemed necessary in order to build confidence in any conclusion or recommendation that would be made during the FEA study.

3.3 Validation Effort

3.3.1 Background

In order to validate the models that were used for this research project, a TL-2 low-profile bridge railing was simulated using full-scale crash test no. LPBR-1 (4). This railing system was developed by MwRSF researchers for the Nebraska Department of Roads (NDOR). The top mounting height for this bridge railing was 20 in. (508 mm).

During LPBR-1, the tire blew-out and 2 of the 3 suspension joints connecting the wheel assembly to the vehicle fractured. These all appeared to occur relatively early in the event, sometime between 25 and 50 ms. It is also possible that a limited amount of wheel climb occurred prior to tire blow-out.

Unfortunately, current state-of-the-art vehicle models can not accurately predict (1) wheel climb, (2) tire blow-out, or (3) suspension joint failure. All of these events can be simulated with LS-DYNA, but the engineer has to initiate these events with selective modeling techniques. Thus, current simulation capabilities alone cannot predict this behavior.

3.3.2 Wheel Climb

Wheel climb is primarily a function of tire-barrier interaction and is controlled by the surface of the barrier, the surface of the tire, including tire tread, and by the mesh density for both the barrier and tire. Since it was deemed unnecessary to allow this FEA investigation to become an expensive and time consuming research project, this study was limited to smooth geometric surfaces for both the barrier and tire, and a relatively coarse mesh density. Wheel climb may be induced by changing the friction parameter between the surfaces. However, there are no guidelines on how to do this accurately and allow the model to be predictive. Further, increasing the friction value not only increases the vertical loading on the tire, thus causing it to climb, but it also increases longitudinal friction forces, causing the tire to steer more into the barrier as the tread edge and sidewall “grab hold” of the barrier.

By doing a parameter study (i.e., changing one parameter while holding all other parameters constant) with the tire-barrier friction coefficient, the analyst can obtain a general idea of the affects that this critical parameter plays in the behavior of the barrier system. Based both on a limited parametric study for this project and on previous knowledge, the coefficients of friction between the tire and the barrier and between the remainder of the truck components and the barrier were set to 0.4 and 0.05, respectively.

3.3.3 Tire Blow-Out

Based on film analysis and a limited simulation study, tire blow-out may be the most critical aspect of determining vehicle behavior during test no. LPBR-1. Unfortunately, only crude and inexact methods exist for simulating tire blow-out, including: (1) stopping the simulation at some point, deleting the tire from the model, and then continuing the run without the tire; (2) stopping the simulation at some point and only deleting a few of the tire elements to let the tire air out – although this method sounds promising, it has not been done effectively; (3) stopping the simulation at some point and deleting a portion of the connections between the tire and the wheel; and (4) experimenting with various features of the pressure-volume relationship used to define the pressurized tire.

Attempts to model tire blow-out on this project showed promise. However, model instabilities were observed in those attempts and prevented the simulations from running long enough to draw conclusions as to how accurate they were. Tire blow-out needs much more investigation if it is to be used on simulation projects such as this one.

3.3.4 Suspension Joint Failure

Suspension joints in the pickup truck model use rigid body joint constraints available in LS-DYNA, more specifically, revolute and spherical joints. These joints are relatively simple as compared to modeling the actual joints in detail.

Suspension joint fracture can be specified by defining the failure criteria within the joint definition. This criterion is a function of forces and moments that are imparted through the joint during simulation. If the forces/moments reach a certain value, then the joint constraint is set free, i.e., it is considered failed.

A parameter study was performed on the suspension joint failure force criteria while simulating test no. LPBR-1. Significantly different vehicle behavior was observed during this study as the joint strengths were varied from relatively weak joints to joints so strong they could not fail. As an example, simulation results from two different joint strengths are shown in Figure 4.

Test no. LPBR-1 was not simulated with sufficient accuracy to claim that it was thoroughly “validated”. However, it was believed that general conclusions and recommendations could be made by simulating various heights for the stone masonry guardwall using various suspension joint failure strengths. Therefore, two barrier heights were evaluated within the remaining simulation effort. These heights were deemed reasonable for redirecting the pickup truck at the TL-2 impact condition and included both 22-in. (559-mm) and 20-in. (508-mm) tall barriers.

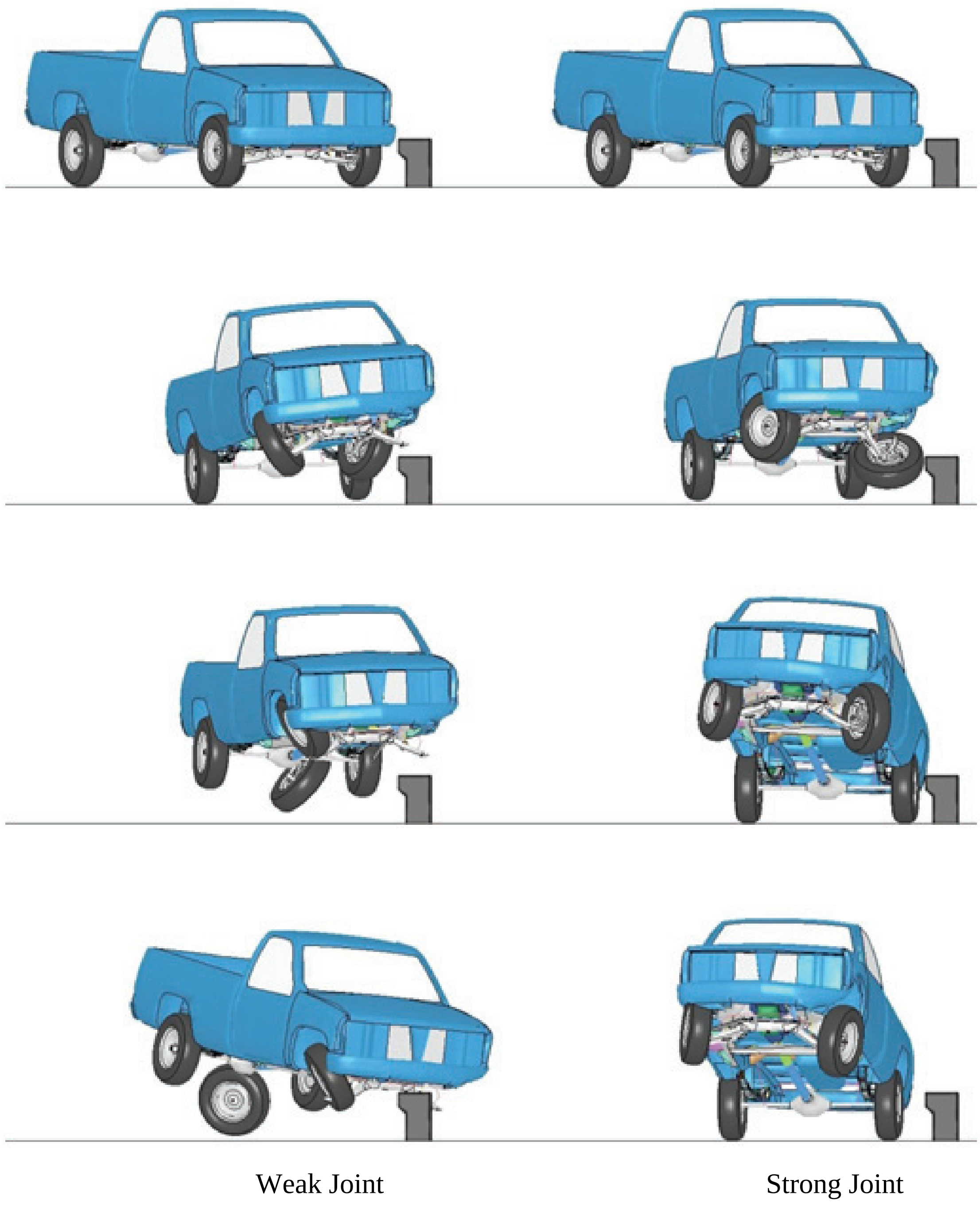


Figure 4. LPBR-1 Simulations Using Different Suspension Joint Strengths - Shown at Times 0, 200, 400, & 600 ms

3.4 Comparison for 22-in. (559-mm) and 20-in. (508-mm) Barrier Heights

Because it cannot be predicted whether or not the suspension joints will fail in an actual full-scale crash test, recommendations for the stone wall height must be prepared in a somewhat subjective manner. To that end, two general considerations were established based on simulations of various wall heights and various suspension joint failure criteria. The general considerations were:

- use a more aggressive approach with a 20-in. (508-mm) tall parapet and a reasonable chance of passing and
- use a more conservative approach with a 22-in. (559-mm) tall parapet and a higher probability of passing.

Time-sequential images from the impact simulations using three different suspension failure criteria were compared for both 22 in. (559 mm) and 20 in. (508 mm) tall walls, as shown in Figures 5 through 7. For the most part, it was evident from the sequential images that the truck impacting the 22-in. (559-mm) wall remained stable throughout all cases; whereas the truck impacting the 20-in. (508-mm) parapet showed potential instabilities not seen in the taller wall.

It should be noted that tire blow-out was not simulated accurately enough to have a major influence on the analysis. However, it is believed that tire blow-out plays a major role on whether or not the truck overrides the lower-height walls. Although simulation results from the 20-in. (508-mm) high parapet show reasonably good results, they are considered to be aggressive. In addition, the results from the simulation analysis should be used as just one part of the overall analysis for determining the minimum top mounting height for the rough stone masonry guardwall.

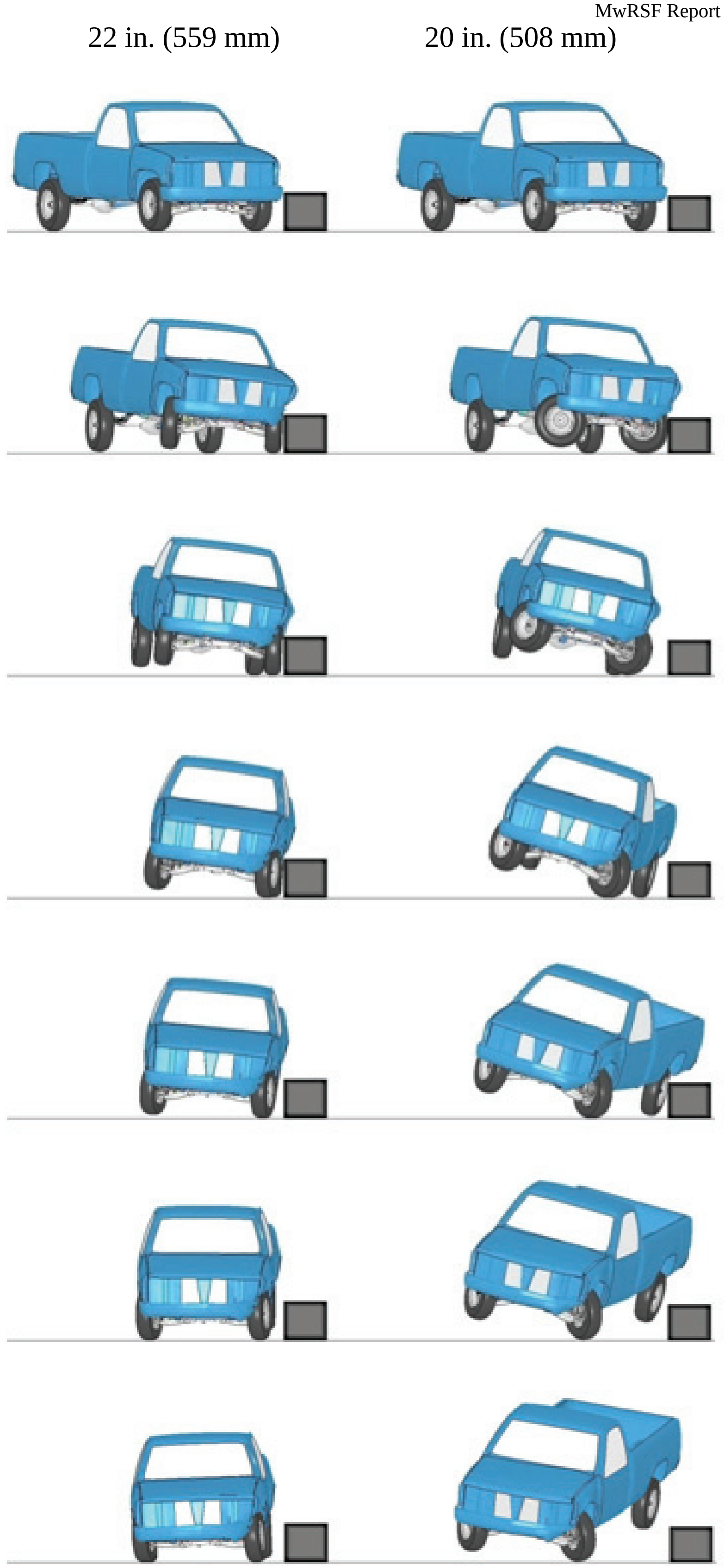


Figure 5. No Suspension Failure: 0 to 600 ms in 100-ms Increments

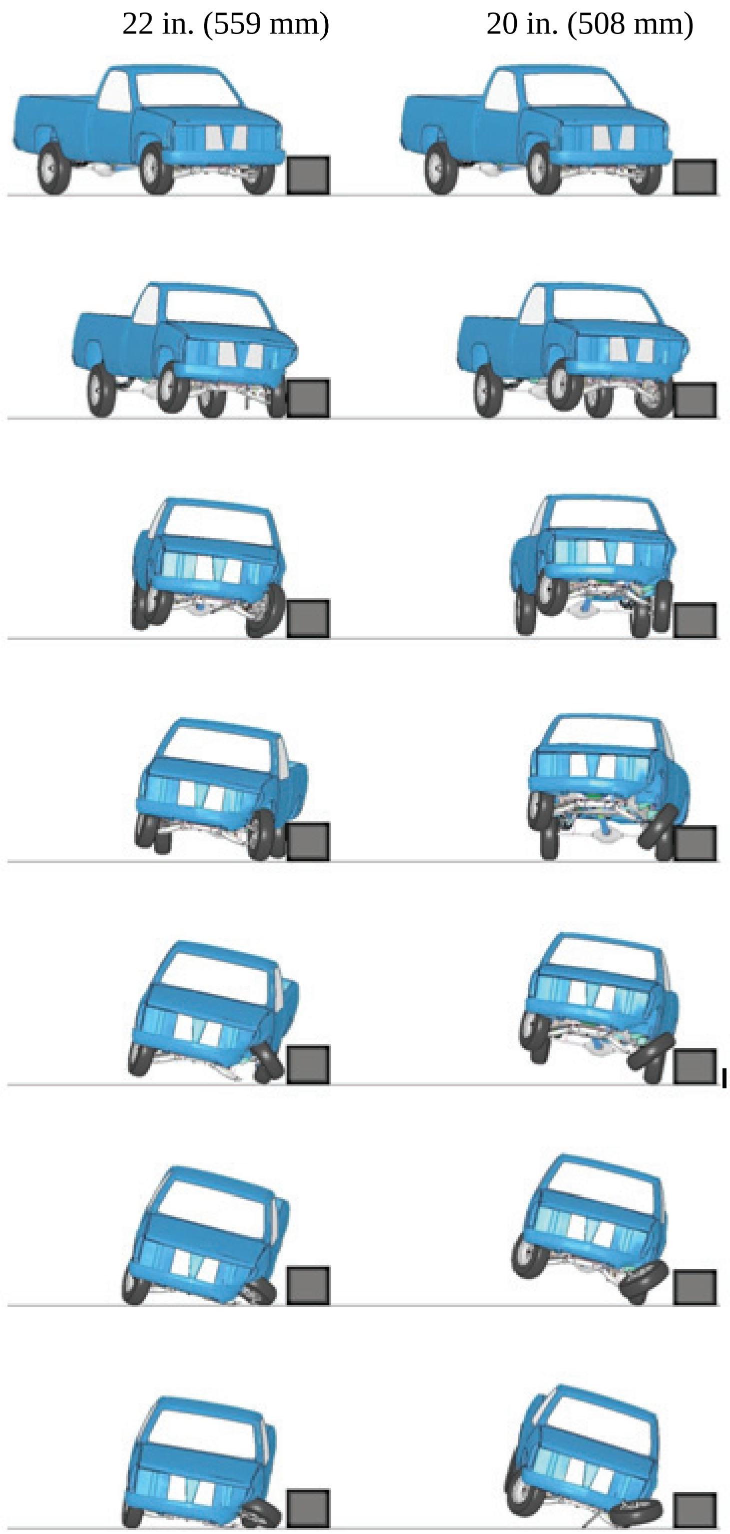


Figure 6. Baseline Suspension Failure – Results in Left-Front Wheel Assembly Detachment

22 in. (559 mm) 20 in. (508 mm)

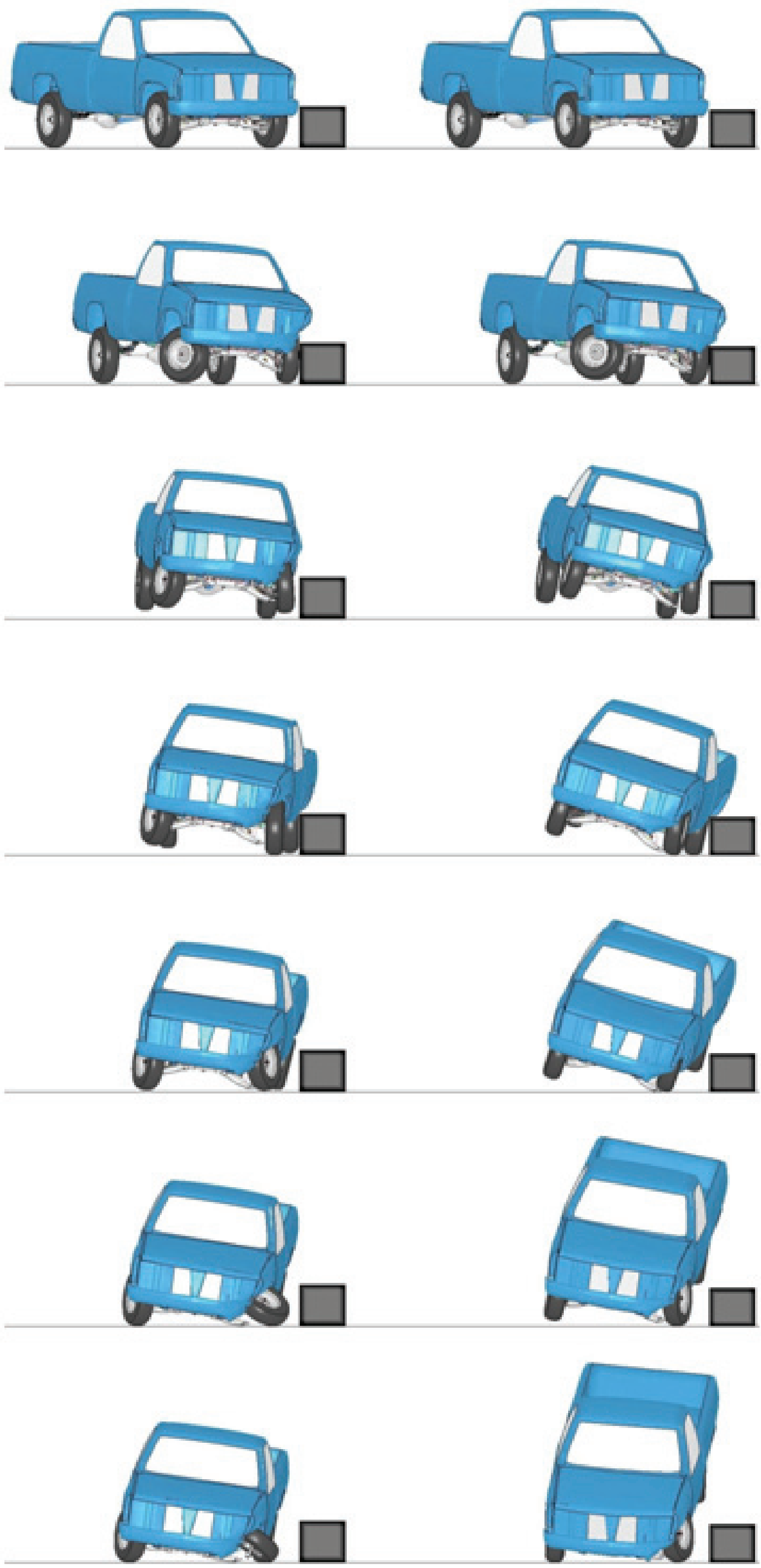


Figure 7. Strengthened Suspension – Results in Limited Failure of Suspension Joints

4 CONSTRUCTION AND DESIGN CONSIDERATIONS

4.1 Barrier Height

As noted previously, the LS-DYNA simulation results revealed a higher likelihood for safely containing and smoothly redirecting the 2000P vehicle at the TL-2 test conditions when using the 22-in. (559-mm) tall parapet as compared to the 20-in. (508-mm) barrier. From the literature review, it was found that 20-in. (508-mm) tall, rigid, vertical parapets were capable of containing and redirecting 2000P vehicles at the TL-2 impact conditions, while 18-in. (457-mm) high parapets allowed the same vehicle to override the barrier. Based on the simulation results, knowledge garnered from prior crash tests into low-height, rigid, vertical parapets, as well as the research team's engineering expertise, additional general height guidance for TL-2 rigid, vertical barriers was provided as follows:

- 18 in. (457 mm) – 0 percent probability of successful test result;
- 19 in. (483 mm) – 5 to 10 percent probability of successful test result;
- 20 in. (508 mm) – 40 to 60 percent probability of successful test result;
- 21 in. (533 mm) – 60 to 75 percent probability of successful test result;
- 22 in. (559 mm) – 75 to 90 percent probability of successful test result; and
- 27 in. (686 mm) – 100 percent probability of successful test result.

For the barrier heights noted above, the guidance assumed that the stone masonry remains intact and attached to the inner concrete core wall during the crash test and contributes to the redirection of the pickup truck. Based on the considerations noted above, the CFLHD, FHWA, and NPS selected the 22-in. (559-mm) tall, rough stone masonry guardrail for use in the crash testing program.

4.2 Inner Core Wall

The TL-3 rough stone masonry guardwall crash tested by TTI utilized a 27-in. (686-mm) tall parapet with a 20-in. tall inner core wall (3,11). For this TL-2 research program, the parapet height was reduced by 5 in. (127 mm). Therefore, it was deemed necessary to also reduce the inner core wall height by the same value, or to a height of 15 in. (381 mm). This change allowed for the use of a 7 in. (178 mm) layer of stone and mortar, similar to that used in the TL-3 version of the parapet. The height reduction of the inner core wall also required the vertical stirrup bars to be shortened and the longitudinal steel reinforcing bars to be shifted downward.

Weep holes, measuring 6 in. x 6 in. (152 mm x 152 mm) square, were placed transversely through the TL-3 parapet, spaced on 10 ft (3.05 m) centers, and positioned with the bottom edge at the ground-line surface. With the noted changes to the inner core wall, it was necessary to modify the size of the weep holes. Therefore, the TL-2 parapet was modified to include 4-in. x 6-in. (102-mm x 152-mm) weep holes spaced on 10.5 ft (3.20 m) centers.

4.3 Stone Masonry Guardwall

Stone masonry guardwalls are to be constructed using rubble masonry, as provided in Section 620 of the noted reference (15). The inner core wall and foundation slab may be constructed using either precast or cast-in-place methods using concrete with a minimum 28-day compressive strength of 3,500 psi (24.13 MPa). For this study, cast-in-place construction was used for the slab and inner core wall, and the stone veneer was attached to the front and top sides. For rubble masonry, the stones are to: vary in size and shape; be roughly dressed; and be laid in random courses of mortar. In general, rubble masonry specifies that the mortar bed and mortar joint thicknesses should each range from ½ to 2½ in. (13 to 64 mm). In addition, guardwalls are to be constructed true and uniform along its length with no stone projecting outward more than 1½ in. (38 mm). All joints and beds are to be raked to a depth of 2 in. (51 mm) on the front and top sides and to 1½ in. (38 mm) on the back side.

When the concrete is placed prior to the stone veneer, the contractor must allow for the facing thickness in order to achieve the required barrier width. The concrete surface shall be continuously wet for 2 hours preceding the placement of the stone veneer. In addition, galvanized metal anchor slots with anchors are to be set into each vertical concrete face in order to allow for the attachment of the stone veneer. The horizontal spacing of the vertical anchor slots shall not exceed 24 in. (610 mm). A temporary filling of felt, foam, or other materials shall be placed in the anchor slots in order to prevent filling of concrete during casting. For 27-in. tall, TL-3 guardwalls, the stone veneer was attached to the front face using metal anchors tightly placed in the slots at an average vertical spacing of 24 in. (610 mm). The proposed TL-2 guardwall system will be constructed with a 22-in. (559-mm) barrier height and a 15-in. (381-mm) inner core wall height above grade. The inner core wall extends 6 in. (152 mm) below grade, resulting in a total core wall height of 21 in. (533 mm) for the proposed TL-2 guardwall. As such, one or more anchors shall be placed in the vertical slots without exceeding a 24 in. (610 mm) average spacing.

At least 25 percent of the anchors are to be bent at short right angles in order to engage recess cuts placed in the stones. The anchors are to extend to within 3 in. (76 mm) of the exposed face of the stone veneer. It is also recommended that 9-gauge (3.80-mm) iron wire ties be used in regions where the concrete face is unsuitable for using metal anchor slots. In these locations, the wire ties are to be used at a rate of 6 ties for each square yard of exposed surface and installed after the concrete has cured using a gun.

For stone placement, one-piece capstones are to be used for the full width of the guardwall along at least 25 percent of the barrier length. Two-piece capstones are to be used with a joint within 4 in. (102 mm) of the center of the guardwall for the remaining barrier length. All stones, including capstones, are to be randomly placed to avoid a pattern. Various stone sizes are to be used to coin or key the corners of the guardwall.

For masonry structures, sound and durable rock shall be furnished, as provided in Section 705 of the noted reference (15). The rock shall be native to the vicinity of the project or similar in texture and color to the native rock. The rock shall be free of reeds, rifts, seams, laminations, and minerals that may cause discoloration or deterioration from weathering. It is important to avoid using rock with depressions or projections that may weaken it or prevent it from being properly bedded. The rock fragments are to use: (1) a minimum thickness of 5 in. (127 mm); (2) a minimum width of 12 in. (305 mm) or 1.5 times the thickness, whichever is greater; and (3) a minimum length equal to 1.5 times the width. The rock shall be properly dressed to remove all thin and weak portions. The face rock bed and joint lines are to be dressed to a maximum variation of 1½ in. (38 mm) from a true line. Additional guidelines for preparing the bed and joint surfaces are published in the Section 705 of the noted reference (15).

4.4 Top Capstone Attachment and Prevention of Barrier Override

The TL-2 guardwall system was configured using a 22-in. (559-mm) tall barrier, including a 15-in. (381-mm) tall inner core wall and a 7-in. (178-mm) thick, stone masonry layer. As noted previously, the full height of the TL-2 barrier was deemed necessary to allow for successful containment and redirection of the 2000P vehicle since the majority of the wheel impact load would be imparted to the top-front region of the guardwall.

The research team was concerned with this load condition, especially for the configuration where the top capstones are placed with the front-vertical edge aligned with the traffic-side face of the guardwall. During pickup truck impacts, a high impulse loading would be imparted into the top stone masonry, while only limited loading would be distributed to the barrier's front face. The high loading condition would pose a significant risk for shearing off the top stone masonry layer, thus lowering the effective barrier height and increasing the propensity for vehicle override. Therefore, an effective shear transfer mechanism must be developed and utilized to anchor the stone masonry facade to the top surface of the inner core wall. Based on the concerns noted above, the research team and sponsors brainstormed several concepts for anchoring the top stone masonry layer. These concepts included:

(1) place Grade 60, No. 4 vertical steel bars (epoxy-coated) into the top surface at 12 in. (305 mm) centers and in a staggered pattern in order to engage the mortar pad and possibly some stones;
(2) Option (1) in combination with longitudinal steel reinforcement tied to the vertical studs and embedded in the mortar pad;
(3) place a ⅜ to ½-in. (10 to 13-mm) thick, longitudinal steel angle at the back of the wall and anchored to the top surface to increase shear capacity and form edge for masonry, although there are concerns for water seeping down vertical angle seam at back edge and causing deterioration of stone masonry layer due to freeze-thaw cycles;
(4) use an excessive number of drill-in masonry anchors/ties in the top surface of the inner core wall in order to engage the mortar pad;
(5) place mechanical anchors in the top surface of the core wall for use in attaching longitudinal, steel angle segments using 1 to 1½-in. (25 to 38-mm) vertical leg and placed within the mortar bed and completely covered by mortar on all sides;
(6) place mechanical anchors in the top surface of the core wall for use with variable-length, hex head bolts to engage the mortar pad;
(7) place raised, trapezoid-shaped, compression blocks on top of the inner core wall in order to provide lateral resistance for the stone masonry layer;
(8) place a longitudinal, steel angle with a 3 to 5-in. (76 to 127 mm) vertical leg, on the top surface of the inner core wall to engage the face stone and mortar pad near the front face of the inner core wall, although a continuous, longitudinal mortar joint will appear on the top surface;
(9) install a 5-in. (127-mm) wide by 7-in. (178-mm) tall, continuous, raised reinforced concrete shelf on the upper back side of the inner core wall;
(10) install mechanical anchor slots and anchors on the upper surface of the inner core wall in order to engage the stones, although there is concern regarding the bending and tear-out capacities of the thin, steel anchor tabs; and
(11) attach a longitudinal, steel angle to the top surface of the inner core wall and recessed into saw-cuts or kerfs placed in the bottom of the capstones and filled with excess mortar.

Following a discussion on the proposed concepts, the research team and sponsors determined that the Option 11 provided the best solution for anchoring the upper stone masonry to the inner core wall. As such, 5-in. x 3-in. x ½-in. (127-mm x 76-mm x 13-mm) galvanized steel angle segments were anchored to the inner core wall using ¾-in. (19.0-mm) diameter by 6-in. (152-mm) long, galvanized, carbon steel Wedge-Bolt screw anchors. The mechanical anchors were spaced on 18 in. (457 mm) centers at interior angle locations and using a reduced spacing at exterior locations. The anchors were placed at the centerline of the inner core wall, or 8¼ in. (210 mm) from the sides. Final design details for the stone masonry barrier and top capstone attachment system are provided in Chapter 7.

5 TEST REQUIREMENTS AND EVALUATION CRITERIA

5.1 Test Requirements

Longitudinal barriers, such as rough stone masonry guardwalls, must satisfy the impact safety standards provided in National Cooperative Highway Research Program (NCHRP) Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features,* (2) in order to be accepted by the Federal Highway Administration (FHWA) for use on National Highway System (NHS) new construction projects or as a replacement for existing designs not meeting current safety standards. According to Test Level 2 (TL-2) of NCHRP Report No. 350, longitudinal barrier systems must be subjected to two full-scale vehicle crash tests. The two full-scale crash tests are as follows:

1. Test Designation 2-10 consisting of a 1,808-lb (820-kg) small car impacting the barrier at a nominal speed and angle of 43.5 mph (70.0 km/h) and 20 degrees, respectively.

2. Test Designation 2-11 consisting of a 4,409-lb (2,000-kg) pickup truck impacting the barrier at a nominal speed and angle of 43.5 mph (70.0 km/h) and 25 degrees, respectively.

The test conditions for TL-2 longitudinal barriers are summarized in Table 1.

Table 1. NCHRP Report No. 350 Test Level 2 Crash Test Conditions

Test Article	Test Designation	Test Vehicle	Impact Conditions			Evaluation Criteria[1]
			Speed		Angle (deg)	
			mph	km/h		
Longitudinal Barrier	2-10	820C	43.5	70.0	20	A,D,F,H,I,(J),K,M
Longitudinal Barrier	2-11	2000P	43.5	70.0	25	A,D,F,K,L,M

[1] Evaluation criteria are explained in Table 2 for those crash tests performed – 2000P tests.

The small car crash test condition is a requirement of the TL-2 safety performance criteria provided in NCHRP Report No. 350. However, this test was not believed to be critical nor needed to garner FHWA acceptance for the modified, rough stone masonry guardwall. When impacted by small cars, several low-height, rigid, vertical-face barriers have been shown to meet safety performance standards (4,5,8,10). Therefore, the 1,808-lb (820-kg) small car crash test, test designation no. 2-10, was deemed unnecessary for this project and was not performed.

5.2 Evaluation Criteria

Evaluation criteria for full-scale vehicle crash testing are based on three appraisal areas: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after collision. Criteria for structural adequacy are intended to evaluate the ability of the barrier system to contain and redirect impacting vehicles. Occupant risk evaluates the degree of hazard to occupants in the impacting vehicle. Vehicle trajectory after collision evaluates the potential risk for the crashed vehicle to become involved in secondary collisions with other vehicles or fixed objects. These evaluation criteria are summarized in Table 2 and defined in greater detail in NCHRP Report No. 350. The full-scale vehicle crash testing program was conducted and reported in accordance with the procedures provided in NCHRP Report 350.

Table 2. NCHRP 350 Test Level-2 Evaluation Criteria for Longitudinal Barriers

Structural Adequacy	A.	Test article should contain and redirect the vehicle; 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 an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted. See discussion in Section 5.3 and Appendix E of NCHRP Report 350.
	F.	The vehicle should remain upright during and after collision although moderate rolling, pitching, and yawing are acceptable.
Vehicle Trajectory	K.	After collision, it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.
	L.	The occupant impact velocity in the longitudinal direction should not exceed 39.37 ft/sec (12 m/sec) and the occupant ridedown acceleration in the longitudinal direction (see Appendix A, Section A5.3 in NCHRP Report 350 for calculation procedure) should not exceed 20 g's.
	M.	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at time of vehicle loss of contact with test device.

6 TEST CONDITIONS

6.1 Test Facility

The testing facility is located at the Lincoln Air Park on the northwest side of the Lincoln Municipal Airport and is approximately 5 miles (8 km) northwest of the University of Nebraska-Lincoln.

6.2 Vehicle Tow and Guidance System

A reverse cable tow system, configured with a 1:2 mechanical advantage, propelled the test vehicle. The tow vehicle's travel distance and speed were one-half that of those parameters for 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 (16) 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 0.375-in. (9.5-mm) diameter guide cable was tensioned to approximately 3,500 lbf (15.6 kN) and supported both laterally and vertically every 100 ft (30.5 m) by hinged stanchions. The hinged stanchions stood upright while holding up the guide cable. However, the guide-flag struck and knocked each stanchion to the ground as the vehicle was towed down the line. For test nos. RSMG-1 and RSMG-2, the vehicle guidance systems were 798 ft (243 m) and 800 ft (244 m) long, respectively.

6.3 Test Vehicles

For test no. RSMG-1, a 1999 Chevrolet ¾-ton pickup truck was used as the test vehicle. The test inertial and gross static weights were 4,456 lbs (2,021 kg). The test vehicle is shown in Figure 8, and vehicle dimensions are shown in Figure 9.

For test no. RSMG-2, a 1999 Chevrolet ¾-ton pickup truck was used as the test vehicle. The test inertial and gross static weights were 4,440 lbs (2,014 kg). The test vehicle is shown in Figure 10, and vehicle dimensions are shown in Figure 11.

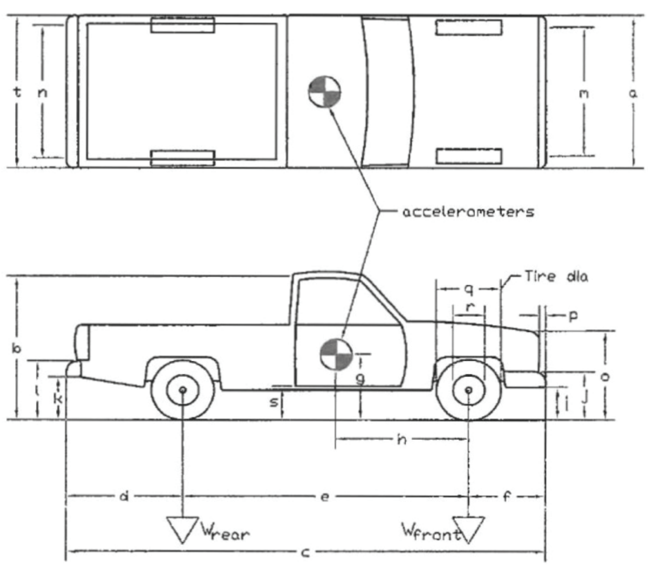
Square, black and white, checkered targets were placed on the vehicle to aid in the analysis of the high-speed VITcam videos, as shown in Figures 12 and 13. Round, checkered targets were placed on the center of gravity, on the left-side door, the right-side door, and the roof of the vehicle. The c.g. was determined using the measured axle weights. The locations of the final centers of gravity for both test vehicles are shown in Figures 12 and 13. The remaining targets were located as references that could be viewed from the high-speed cameras for video analysis.

The front wheels of the test vehicles were aligned for camber, caster, and toe-in values of zero so that the vehicles would track properly along the guide cable. A 5B flash bulb was mounted on the left-side of the vehicle's dash to pinpoint the time of impact with the barrier system on the high-speed VITcam videos. The flash bulb was fired by a pressure tape switch mounted on the front face of the bumper. A remote controlled brake system was installed in the test vehicle so the vehicle could be safely brought to a stop after the test.

Figure 8. Test Vehicle, Test No. RSMG-1

Date:	11/5/2008	Test Number:	RSMG-1	Model:	2000p/C2500
Make:	Chevrolet	Vehicle I.D.#:	1GCGC24R8XR715091		
Tire Size:	LT245/75 R16	Year:	1999	Odometer:	217319

*(All Measurements Refer to Impacting Side)



Vehicle Geometry -- mm (in.)

a	1879.6 (74.0)	b	72.25
c	5549.9 (218.5)	d	51
e	3327.4 (131.0)	f	36.5
g	711.2 (28.0)	h	55
i	444.5 (17.5)	j	26
k	584.2 (23.0)	l	30.5
m	1590.7 (62.625)	n	64
o	1066.8 (42.0)	p	3.5
q	749.3 (29.5)	r	17.5
s	438.15 (17.25)	t	72.5

Wheel Center Height Front	14.25
Wheel Center Height Rear	14.75
Wheel Well Clearance (FR)	35.25
Wheel Well Clearance (RR)	37.75
Frame Height (FR)	13.75
Frame Height (RR)	27
Engine Type	8 CYL. GAS
Engine Size	5.7L

Transmission Type:

Automatic

RWD

GVWR	
F	4100
R	6000
Tot.	8600

Weights kg (lbs)	Curb	Test Inertial	Gross Static
W-front	1229.2 (2710)	(2592)	1175.7 (2592)
W-rear	911.72 (2010)	845.5 (1864)	845.5 (1864)
W-total	2141 (4720)	2021.2 (4456)	2021.2 (4456)

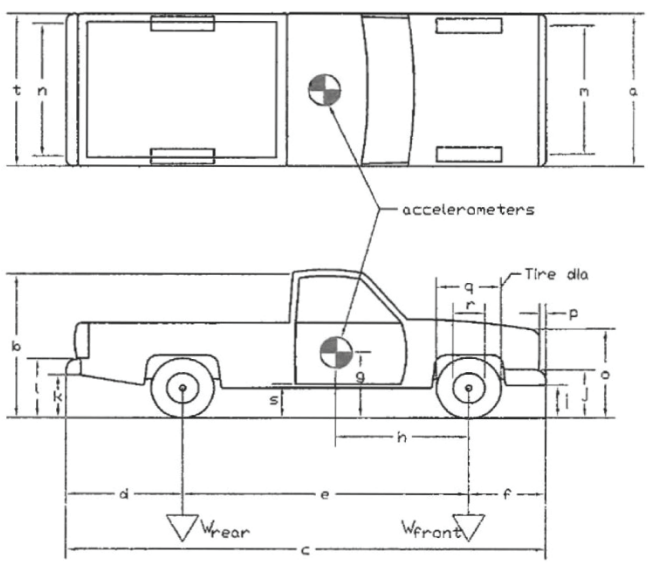
Note any damage prior to test: None

Figure 9. Vehicle Dimensions, Test No. RSMG-1

Figure 10. Test Vehicle, Test No. RSMG-2

Date:	1/8/2009	Test Number:	RSMG-2	Model:	2000p/C2500
Make:	Chevrolet	Vehicle I.D.#:	1GCGC24RXXR715125		
Tire Size:	LT245/75 R16	Year:	1999	Odometer:	205534

*(All Measurements Refer to Impacting Side)



Vehicle Geometry -- mm (in.)

a	1905 (75.0)	b	0 (72.25)
c	5537.2 (218.0)	d	0 (51.25)
e	3333.8 (131.25)	f	0 (35.5)
g	669.93 (26.375)	h	0 (55.5)
i	444.5 (17.5)	j	0 (26.0)
k	609.6 (24.0)	l	0 (31.0)
m	1578 (62.125)	n	0 (64.0)
o	1092.2 (43.0)	p	0 (4.0)
q	742.95 (29.25)	r	0 (17.0)
s	495.3 (19.5)	t	0 (72.75)

Wheel Center Height Front	0 (14.25)
Wheel Center Height Rear	0 (14.5)
Wheel Well Clearance (FR)	0 (35.5)
Wheel Well Clearance (RR)	0 (37.75)
Frame Height (FR)	0 (14.0)
Frame Height (RR)	0 (27.25)
Engine Type	8 CYL. GAS
Engine Size	5.7L

Transmission Type:

Automatic

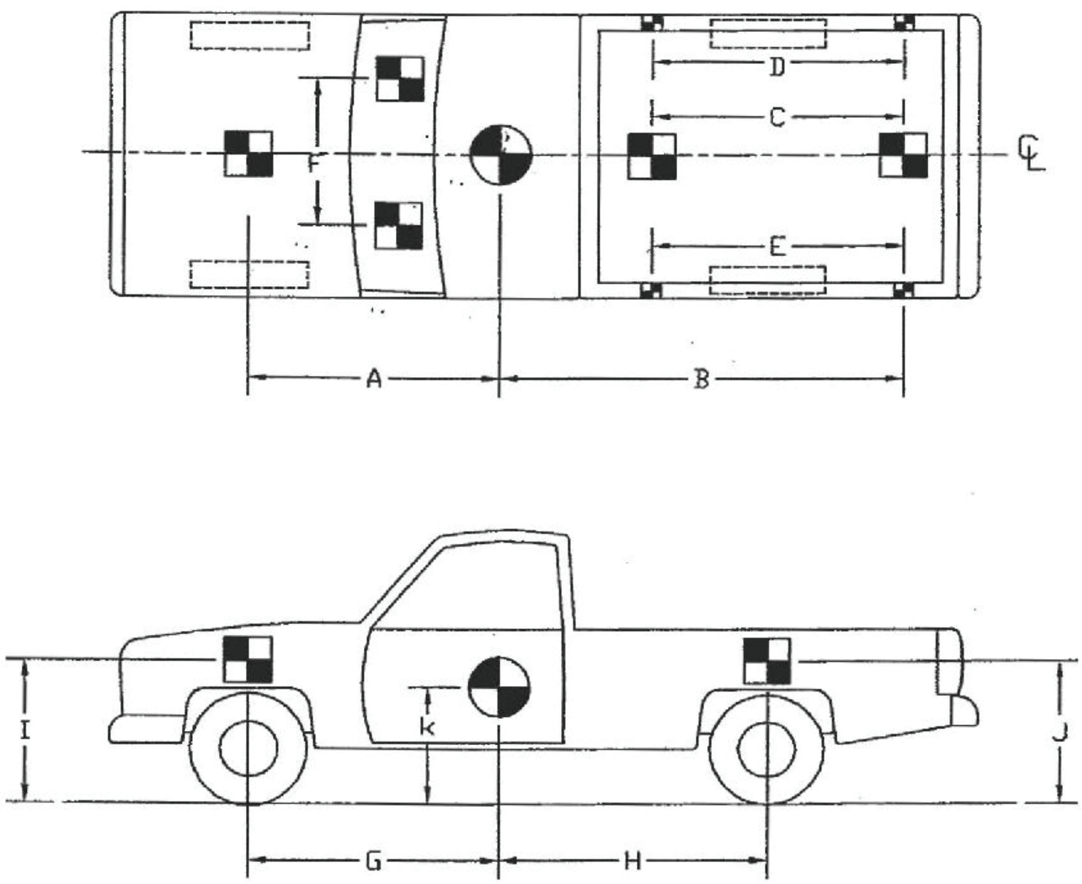
RWD

GVWR		
	F	4100
	R	6000
	Tot.	8600

Weights kg (lbs)	Curb	Test Inertial	Gross Static
W-front	1206.1 (2659)	1179.3 (2600)	1179.3 (2600)
W-rear	880.42 (1941)	834.61 (1840)	834.61 (1840)
W-total	2086.5 (4600)	2014 (4440)	2014 (4440)

Note any damage prior to test: None

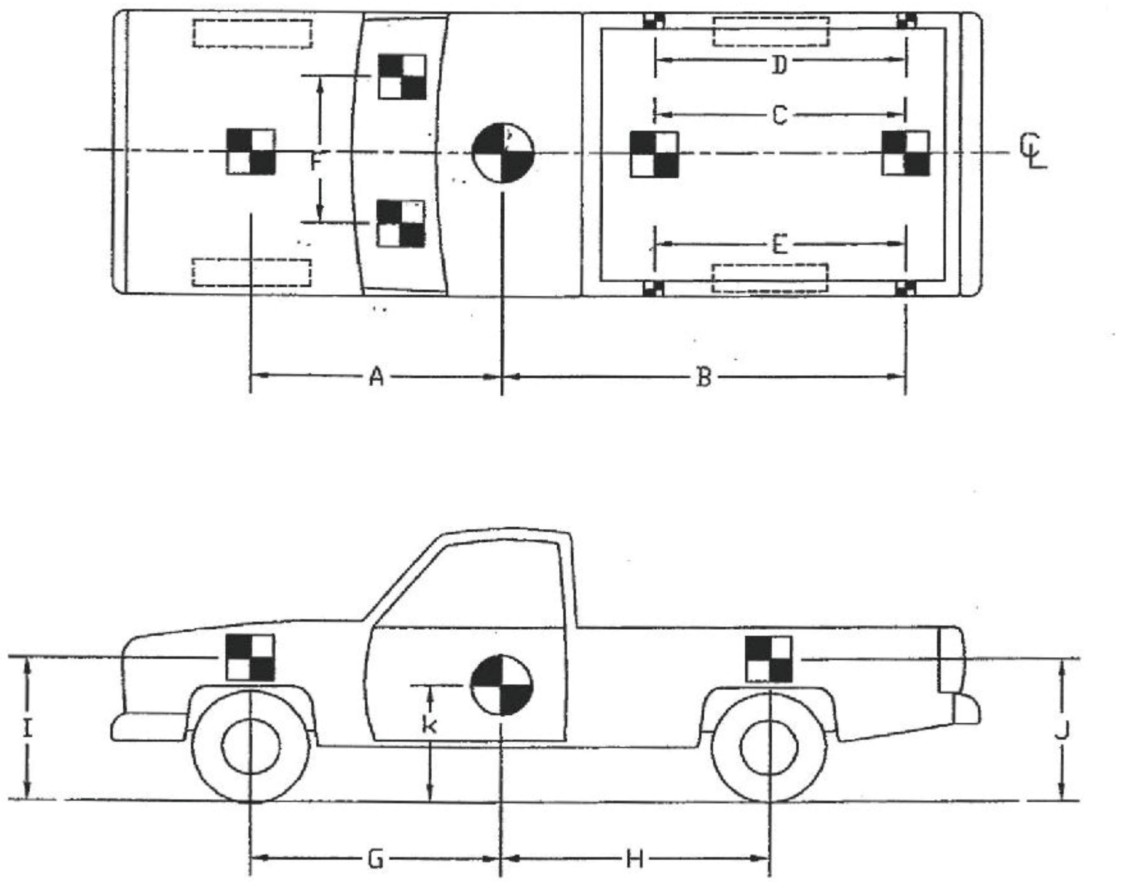
Figure 11. Vehicle Dimensions, Test No. RSMG-2



TEST #: RSMG-1
TARGET GEOMETRY-- mm (in.)

A	1588	(62.5)	E	2286	(90.0)	I	984	(38.75)
B	2591	(102.0)	F	1156	(45.5)	J	1054	(41.5)
C	1219	(48.0)	G	1397	(55.0)	K	711	(28.0)
D	2286	(90.0)	H	1930	(76.0)			

Figure 12. Target Geometry, Test No. RSMG-1



TEST #: RSMG-2

TARGET GEOMETRY-- mm (in.)

A	1588 (62.5)	E	2153 (84.75)	I	1003 (39.5)
B	2502 (98.5)	F	1181 (46.5)	J	1060 (41.75)
C	1372 (54.0)	G	1410 (55.5)	K	670 (26.375)
D	2153 (84.75)	H	1924 (75.75)		

Figure 13. Target Geometry, Test No. RSMG-2

6.4 Data Acquisition Systems

6.4.1 Accelerometers

Two environmental shock and vibration sensor/recorder systems, developed and manufactured by Instrumented Sensor Technology (IST) of Okemos, Michigan, were used to measure the accelerations in the longitudinal, lateral, and vertical directions. The first system consisted of a triaxial, piezoresistive, accelerometer system, Model EDR-4-6DoF-500/1200, which included three differential channels as well as three single-ended channels. The EDR-4-6DoF-500/1200 was configured with 6 MB of RAM memory, a range of ±500 g's, a sample rate of 10,000 Hz, and a 1,650 Hz lowpass filter. The EDR-4-6DoF-500/1200 was used in both crash tests. The second system consisted of a triaxial, piezoresistive, accelerometer system, Model EDR-3, also developed and manufactured by IST. The EDR-3 was configured with 256 kB of RAM memory, a range of ±200 g's, a sample rate of 3,200 Hz, and a 1,120 Hz lowpass filter. The EDR-3 was only used in test no. RSMG-1. Data from both EDR accelerometer systems was analyzed and plotted using "DynaMax 1 (DM-1)", "DADiSP", as well as a customized Microsoft Excel computer software program.

A third system utilized two-Arm, triaxial, piezoresistive accelerometers, developed and manufactured by Endevco of San Juan Capistrano, California. Three accelerometers independently measured accelerations in the longitudinal, lateral, and vertical directions 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. (DTS) 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 memory and 8 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 back-up battery. Both the SIM and module rack were crashworthy. The DTS and Endevco Accelerometer system was used in both crash tests. "DTS TDAS Control", "DADiSP", and a customized Microsoft Excel computer software program were used to analyze and plot the accelerometer data from the DTS unit. All of the accelerometers were mounted near the center of gravities of the test vehicles.

6.4.2 Rate Transducers

An Analog Systems, three-axis rate transducer, with a range of 1,200 degrees/sec in each of the three directions (pitch, roll, and yaw), was used to measure the rates of motion for the test vehicles. The rate transducer was mounted inside the body of the EDR-4-6DoF-500/1200. Data was recorded at 10,000 Hz to a second data acquisition board inside the EDR-4-6DoF-500/1200 housing. The raw data measurements were then downloaded, converted to the appropriate Euler angles for analysis, and plotted. "DynaMax 1", "DADiSP", and a customized Microsoft Excel computer software program were used to analyze and plot the angular rate transducer data.

An additional angle rate sensor, the ARS-1500, with a range of 1,500 degrees/sec in each of the three directions, was used to measure the rates of rotation for the test vehicles. The angular rate sensor was mounted on an aluminum block placed within the test vehicle near the center of gravity. Data was recorded at 10,000 Hz to the SIM unit. The raw data measurements were then downloaded, converted to the proper Euler angles for analysis, and plotted. "DTS TDAS Control", "DADiSP", and a customized Microsoft Excel computer software program were used to analyze and plot the angular rate transducer data.

6.4.3 Pressure Tape Switches

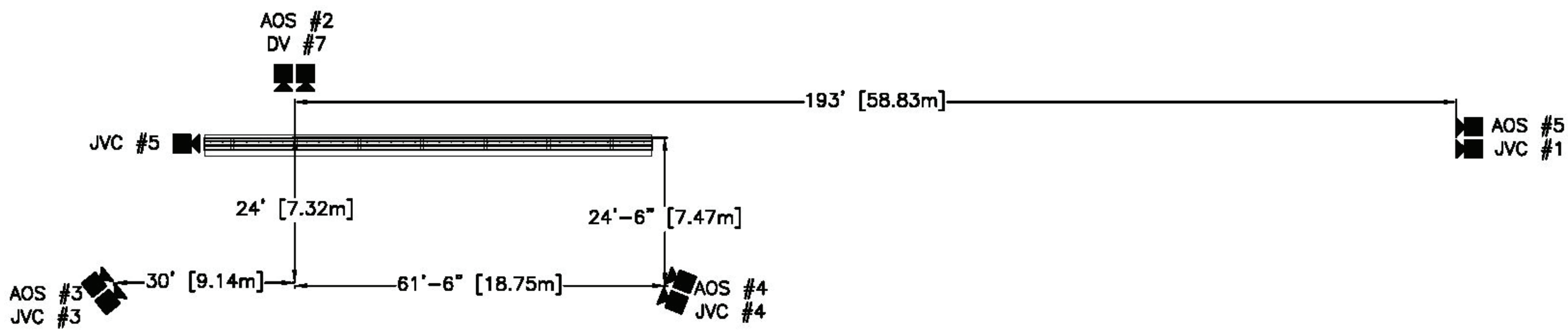
For test nos. RSMG-1 and RSMG-2, five pressure-activated tape switches, spaced at 6.56-ft (2-m) intervals, were used to determine the speed of the vehicle before impact. Each tape switch fired a strobe light which sent an electronic timing signal to the data acquisition system as the right-front tire of the test vehicle passed over it. Test vehicle speeds were determined from electronic timing mark data recorded using either the TestPoint or LabView software programs. Strobe lights and high-speed video analysis are only used as a backup in the event that vehicle speeds cannot be determined from the electronic data.

6.4.4 High-Speed Photography

Four high-speed AOS VITcam digital video cameras, five JVC digital video cameras, and two Canon digital video cameras were utilized to film test no. RSMG-1. Camera details, lens information, and camera operating speeds, along with a schematic of the camera locations, are shown in Figure 14.

For test no. RSMG-2, five high-speed AOS VITcam digital video cameras, four JVC digital video cameras, and two Canon digital video cameras were utilized. Camera details, lens information, and camera operating speeds, along with a schematic of the camera locations, are shown in Figure 15.

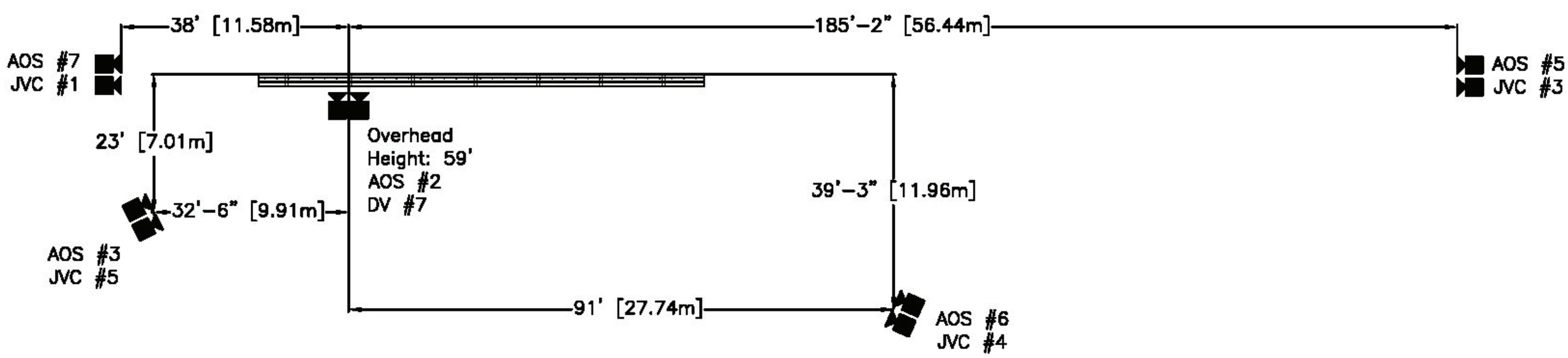
The VITcam videos were analyzed using the ImageExpress MotionPlus analysis software. Camera speed and camera divergence factors were considered in the analysis of the high-speed videos.



Camera Summary - RSMG-1

	No.	Type	Operating Speed (frames/sec)	Lens	Lens Setting
High-Speed Video	2	Vitcam CTM	500	Fixed 12.5mm	-
	3	Vitcam CTM	500	Sigma 24-135	50
	4	Vitcam CTM	500	Sigma 24-70	70
	5	Vitcam Gigabit	500	Sigma 70-200	200
Digital Video	1	JVC - GZ-MC500 (Everio)	29.97		
	2	JVC - GZ-MC40u (Everio)	29.97		
	3	JVC - GZ-MC40u (Everio)	29.97		
	4	JVC - GZ-MC40u (Everio)	29.97		
	5	JVC - GZ-MC27u (Everio)	29.97		
	7	Canon-ZR90	29.97		
	8	Canon-ZR90	29.97		

Figure 14. Camera Locations, Speeds, and Lens Settings, Test No. RSMG-1



Camera Summary - RSMG-2

	No.	Type	Operating Speed (frames/sec)	Lens	Lens Setting
High-Speed Video	2	Vitcam CTM	500	Cosmicar 12.5mm fixed	-
	3	Vitcam CTM	500	Sigma 24-70	50
	5	Vitcam Gigabit	500	Sigma 70-200	100
	6	Vitcam Gigabit	500	Sigma 50mm fixed	-
	7	Vitcam Gigabit	500	Sigma 24-135	24
Digital Video	1	JVC - GZ-MC500 (Everio)	29.97		
	3	JVC - GZ-MC40u (Everio)	29.97		
	4	JVC - GZ-MC40u (Everio)	29.97		
	5	JVC - GZ-MC27u (Everio)	29.97		
	7	Canon-ZR90	29.97		
	8	Canon-ZR90	29.97		

Figure 15. Camera Locations, Speeds, and Lens Settings, Test No. RSMG-2

7 BARRIER DESIGN DETAILS – TEST NO. RSMG-1

7.1 Overview

The test installation consisted of a 74-ft 4-in. (22.66-m) long, rough stone masonry guardwall system. The barrier system consisted of three main sub-systems: (1) the reinforced concrete foundation slab and supporting aggregate base; (2) the inner, reinforced concrete, core wall; and (3) the rough stone masonry façade and attachment systems. Final design details are provided in Figures 16 through 30. Photographs of the phased construction and final test installation are shown in Figures 31 through 39.

7.2 Concrete Foundation Slab

A reinforced concrete, foundation slab was constructed on top of a 6-in. (152-mm) thick, compacted, crushed limestone aggregate base. The 9-in. thick concrete slab measured 3 ft – 6 in. (1,067 mm) wide by 74 ft – 4 in. (22.66 m) long. The top of the slab was positioned 6 in. (152 mm) below soil grade. Steel reinforcing bars, conforming to ASTM A615 Grade 60, were placed in the slab as well as extended upward for use in strengthening the inner core wall. Both bent and straight bars were used, as shown in the CAD details and photographs. The concrete slab was configured using an L-3500 (NDOR 47B) mix design with a minimum 28-day concrete compression strength of 3,500 psi (24.13 MPa). The actual 55-day concrete compressive strength for the foundation slab was 4,083 psi (28.15 MPa). Test no. RSMG-1 was performed on day 47 of the slab curing process.

7.3 Inner Concrete Core Wall

A reinforced concrete, core wall was constructed on top of the foundation slab. The core wall was rigidly attached to the slab using the vertical steel reinforcing bars which extended out of the slab. In addition, a shear keyway was placed between the two concrete surfaces and within the rebar cage. The inner core wall measured 16½ in. (419 mm) wide by 21 in. tall (533 mm). However, the lower 6 in. (152 mm) of the wall was placed below the soil grade, thus leaving 15 in. (381 mm) above grade. ASTM A615 Grade 60 longitudinal, steel reinforcing bars were tied within the vertical bent bars. The concrete core wall was configured using an L-3500 (NDOR 47B) mix design with a minimum 28-day concrete compression strength of 3,500 psi (24.13 MPa). The 49-day concrete compressive strength for the inner core wall was 4,405 psi (30.37 MPa). Test no. RSMG-1 was performed on day 41 of the core wall curing process.

Weep holes, measuring 4 in. x 6 in. (102 mm x 152 mm), were placed transversely through the parapet, spaced on 10.5 ft (3.20 m) centers, and positioned with the bottom edge at the ground-line surface. It should be noted that the weep holes also extended through the stone masonry veneer placed on front of the inner core wall.

7.4 Rock Material

The stone mason subcontractor acquired a sound and durable, rock material from U.S. Stone Industries, LLC, of Herrington, Kansas. The material consisted of Flint Hills Gray Limestone. Test results were acquired for this rock material from the quarry. Material testing was performed by SGS U.S. Testing Company, Inc. and documented in a November 1, 2004, test report. Using Test Procedure ASTM C 241, the abrasion resistance index was found to be 12.41. Based on Test Procedure C 170, the compressive strength was determined to be 13,393 psi (92.34 MPa). From Test Procedure ASTM C 99, the modulus of rupture was calculated as 1,955 psi (13.48 MPa). Finally, using Test Procedure ASTM C 97, the water absorption, density, and specific gravity were found to be 2.26 percent, 155.2 lbs/ft^3 (2,486 kg/m^3), and 2.488, respectively.

7.5 Rough Stone Masonry Façade and Anchorage Systems

The rough stone material was attached to the inner core wall using: (1) a mortar bed on the front and top faces of the inner core wall as well as a narrow region on the surface of the foundation slab; (2) Dovetail Anchor Slots with Dovetail Anchor Ties on the front face of the core wall; (3) Dovetail Anchor Ties wedged under the steel angles that were anchored to the top surface of the core wall; (4) stainless steel, Z-clips attached to the top surface of the core wall using masonry anchors; and (5) ASTM A36 steel angles attached to the top surface of the core wall using Wedge-Bolt Screw Anchors with the upper angle leg extending into a kerf cut into the bottom side of the top capstone, with the void space filled with mortar. Details and specifications for the anchorage systems are provided in the attached drawings, as shown in Figures 16 through 30.

The mortar bed utilized a PROMIX Stone Veneer Mortar conforming to the ASTM C-270 Type S specifications. The PROMIX Mortar consists of a Portland cement and Lime mix that is pre-blended with finely-graded sand. According to ASTM C-270 Type S, the minimum 28-day compressive strength for the mortar is 1,800 psi (12.41 MPa), while the minimum water retention and maximum water content are 12 percent and 75 percent, respectively.

Carbon Steel, Wedge-Bolt screw anchors were used to anchor the steel angles to the top of the inner core wall. The blue-tip anchors were manufactured by Powers Fasteners and measured ¾ in. (19.0 mm) in diameter by 6 in. (152 mm) long. Zinc-plate or galvanized anchor hardware should be utilized in actual field installations.

Eleven ASTM A36 black steel angles, measuring 5 in. x 3 in. x ½ in. (127 mm x 76 mm x 13 mm), were placed on top of the core wall. For interior regions, the segment lengths were 5 ft – 11½ in. (1,816 mm) long. At the ends of the guardwall, shorter segment lengths were chosen for the steel angles, as shown on the included CAD details. In general, the interior angles were attached using screws anchors spaced on 18-in. (457-mm) centers, except for the adjacent anchors located across the gap between two different angles. For the exterior angles located at the ends of the guardwall, a reduced spacing was utilized for selected screw anchors. The upstream and downstream angle lengths were 54 in. (1,372 mm) and 42 in. (1,067 mm), respectively. The slots in the angles were originally configured to be 1 in. (25 mm) wide by 2 in. (51 mm) long. However, the steel fabricator had a standard punch to produce slots measuring 1¼ in. (32 mm) x 1 $^{15}/_{16}$ in. (49 mm). Thus, the actual slot size used in the steel angles conformed to the later dimensions. Although black angles were used in the crash testing program, the steel angles should be galvanized when placed in actual field installations.

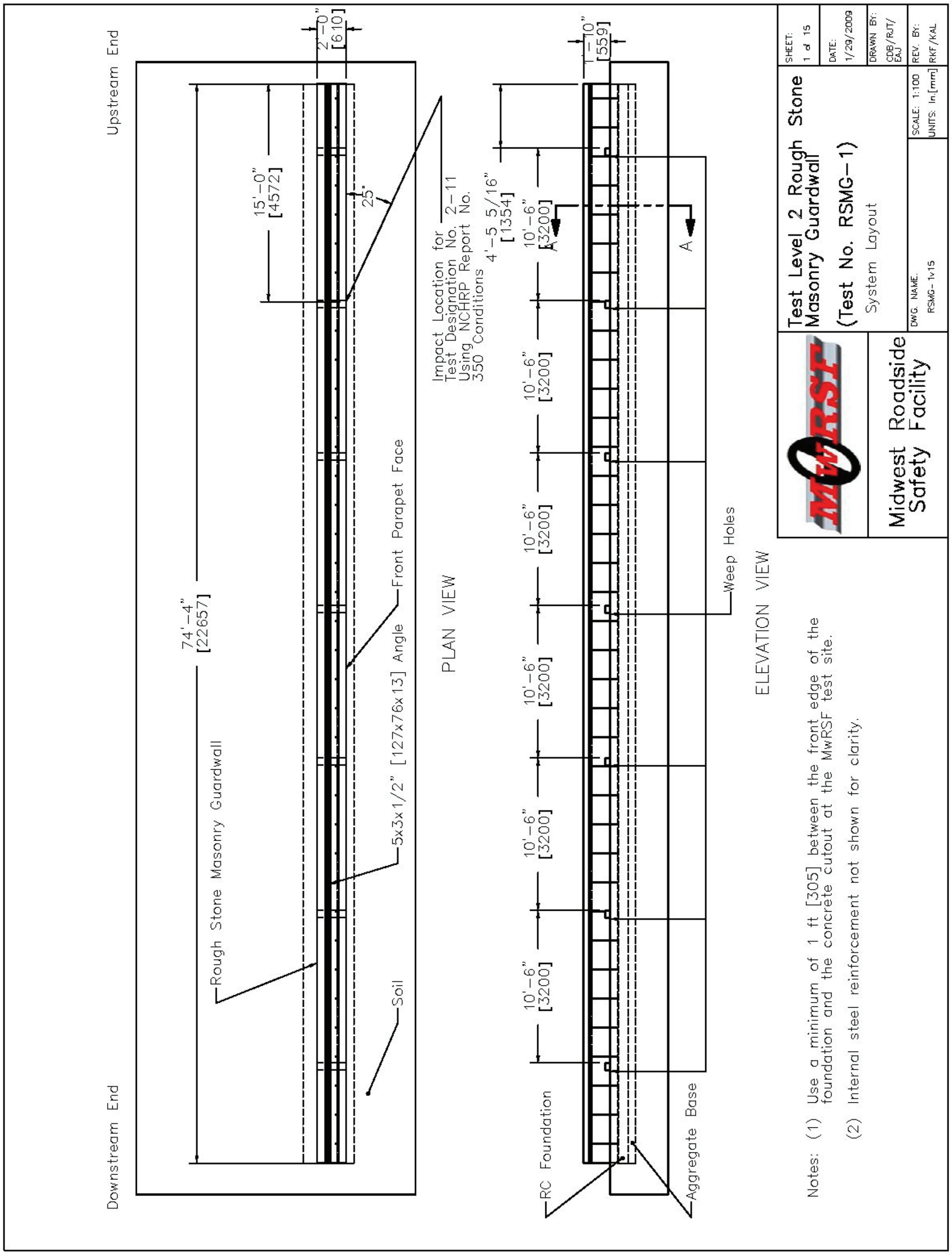


Figure 16. System Layout, Test No. RSMG-1

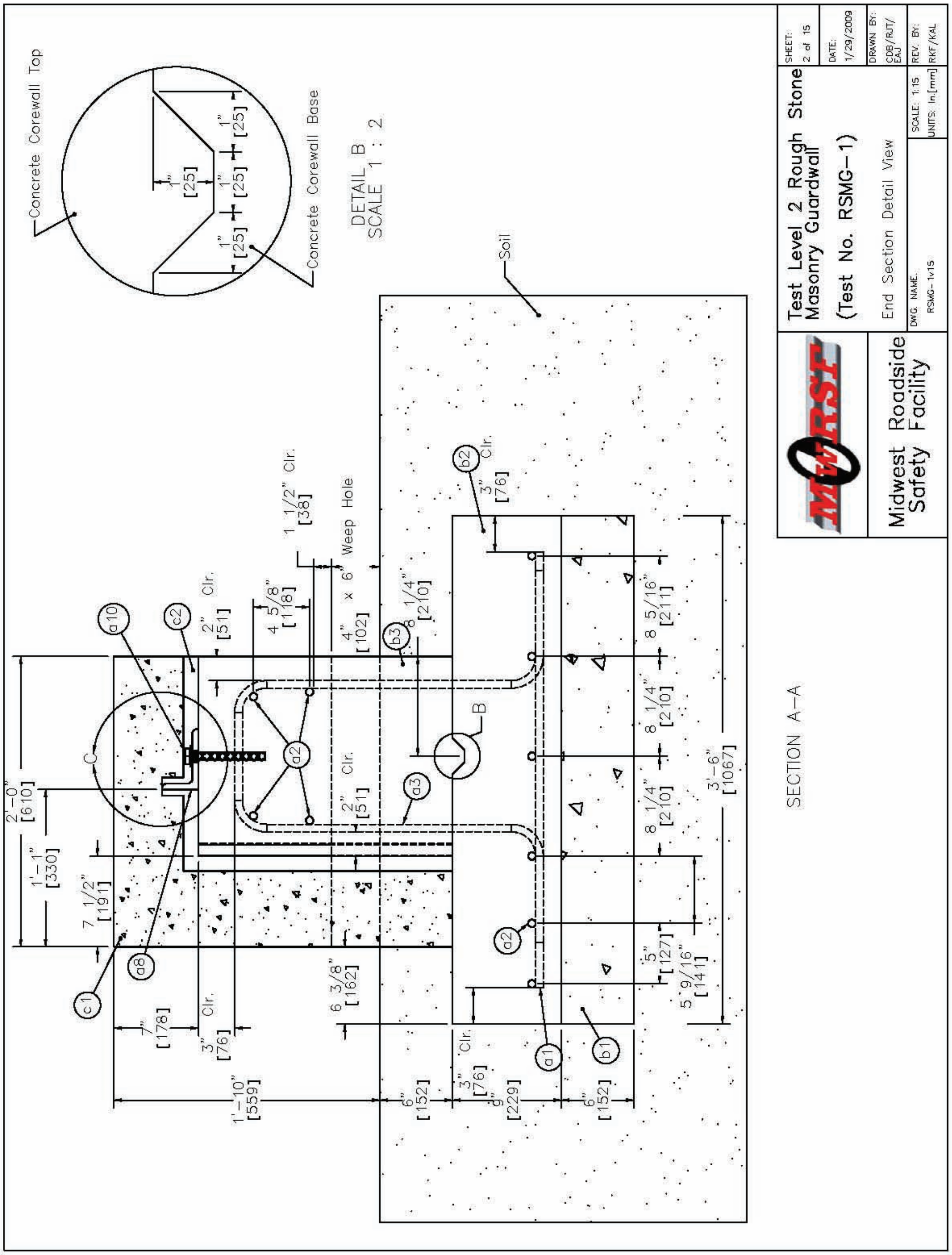
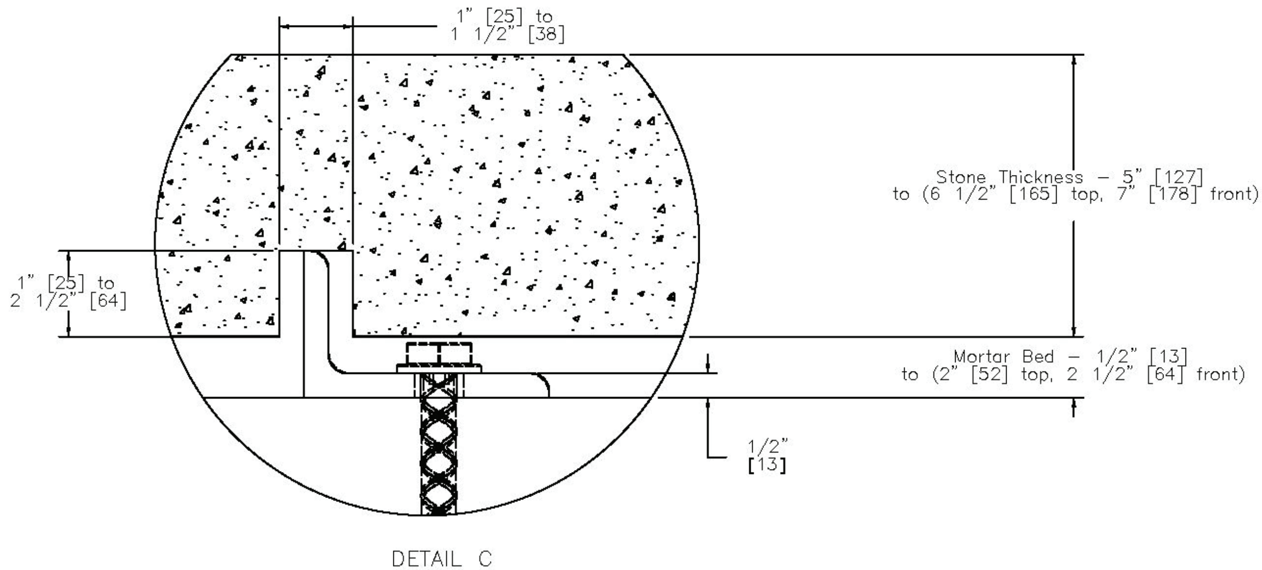


Figure 17. End Section Detail View, Test No. RSMG-1



Notes:

(1) The capstones placed on the top of the barrier shall be kerfed to allow for their placement over the steel angle. The kerf width shall be approximately 1 to 1 1/2 in. [25 to 38] wide. The maximum kerf depth shall be 2 1/2 in. [64] although thinner kerf depths are allowed as long as all other geometries are met.

(2) The top mortar bed thickness shall range between 1/2 and 2 in. [13 and 52] for rubble stone masonry. The top capstone thickness shall range between 5 to 6 1/2 in. [127 to 165].

(3) Morter shall fill the void region surrounding the angle's vertical leg when the capstones are set in place.

(4) The first 36 to 38 ft [10.9 to 11.6 m] of barrier shall be constructed with capstones covering the entire barrier width of 24 in. [610], thus revealing a mortar joint on the front face.

(5) The remaining barrier length shall be constructed using alternating face and top stones to meet up at the top–front corner of the barrier.

(6) For top capstone thicknesses greater than 5 7/8 in. [149], it will be necessary to chisle the bottom of the stone to form a dish to allow its placement over the heads of the Wedge–Bolt anchors.

(7) Two types of steel anchors were used to provide vertical attachment of the stone masonry to the top of the inner core wall. Type 106 corrugated Dovetail Anchor Ties (16 gauge [1.5] by 5 1/2" [140] long) were wedged under the top–mounting angles and bent upward to engage the mortar. The Type 106 Ties were spaced approximately on 2 ft [610] centers, alternating sides of the steel angles. Stainless steel (SS 304) Z–clips were also used to anchor the stone using 1/4" [6.4] diameter by 2 3/4" [70] long, heavy–weight, stainless steel Tapcon masonry anchors. The Z–clips were spaced approximately on 2 ft [610] centers, alternating sides of the steel angles, and used to engage a recess cut in the stone.

(8) Dovetail Anchor Ties shall be mill galvanized steel ASTM A653 or hot dip glavanized ASTM A153.

Midwest Roadside Safety Facility	Test Level 2 Rough Stone Masonry Guardwall (Test No. RSMG–1) Mortar Bed Details		SHEET: 3 of 15
			DATE: 1/29/2009
			DRAWN BY: CDB/RJT/EAJ
	DWG. NAME. RSMG–1v15	SCALE: 1:3 UNITS: In.[mm]	REV. BY: RKF/KAL

Figure 18. Mortar Bed and Stone Veneer Attachment Details, Test No. RSMG-1

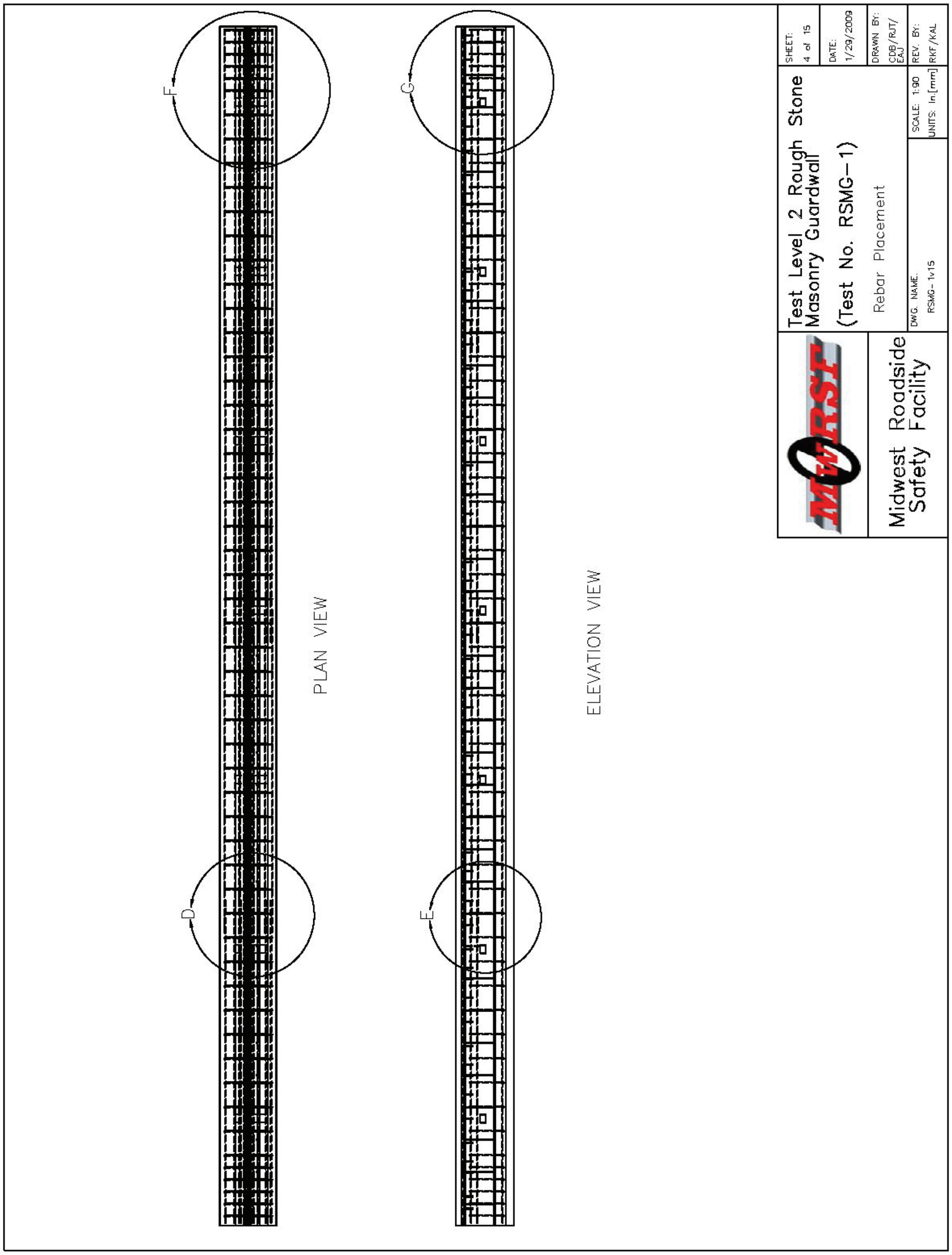


Figure 19. Rebar Placement, Test No. RSMG-1

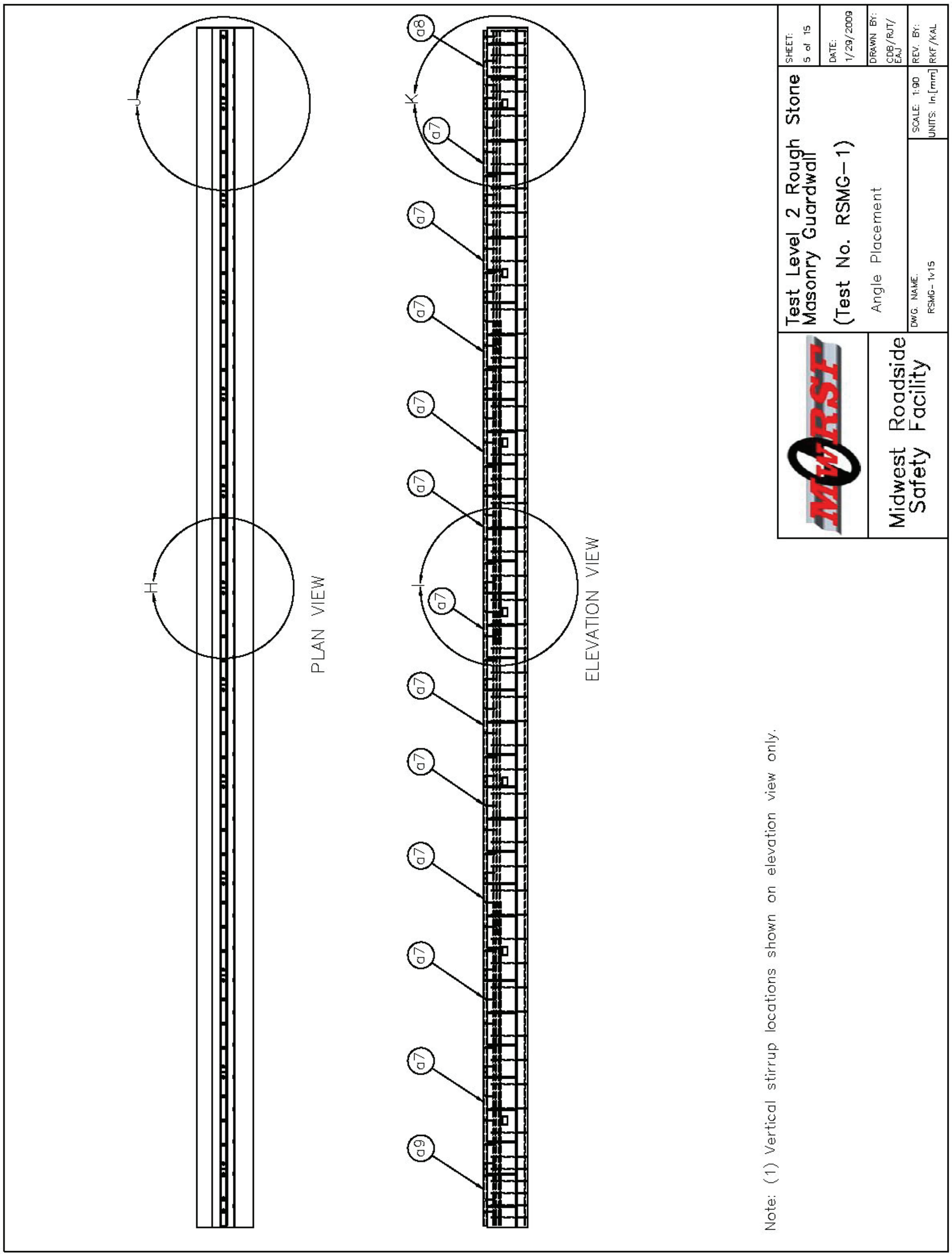


Figure 20. Angle Placement, Test No. RSMG-1

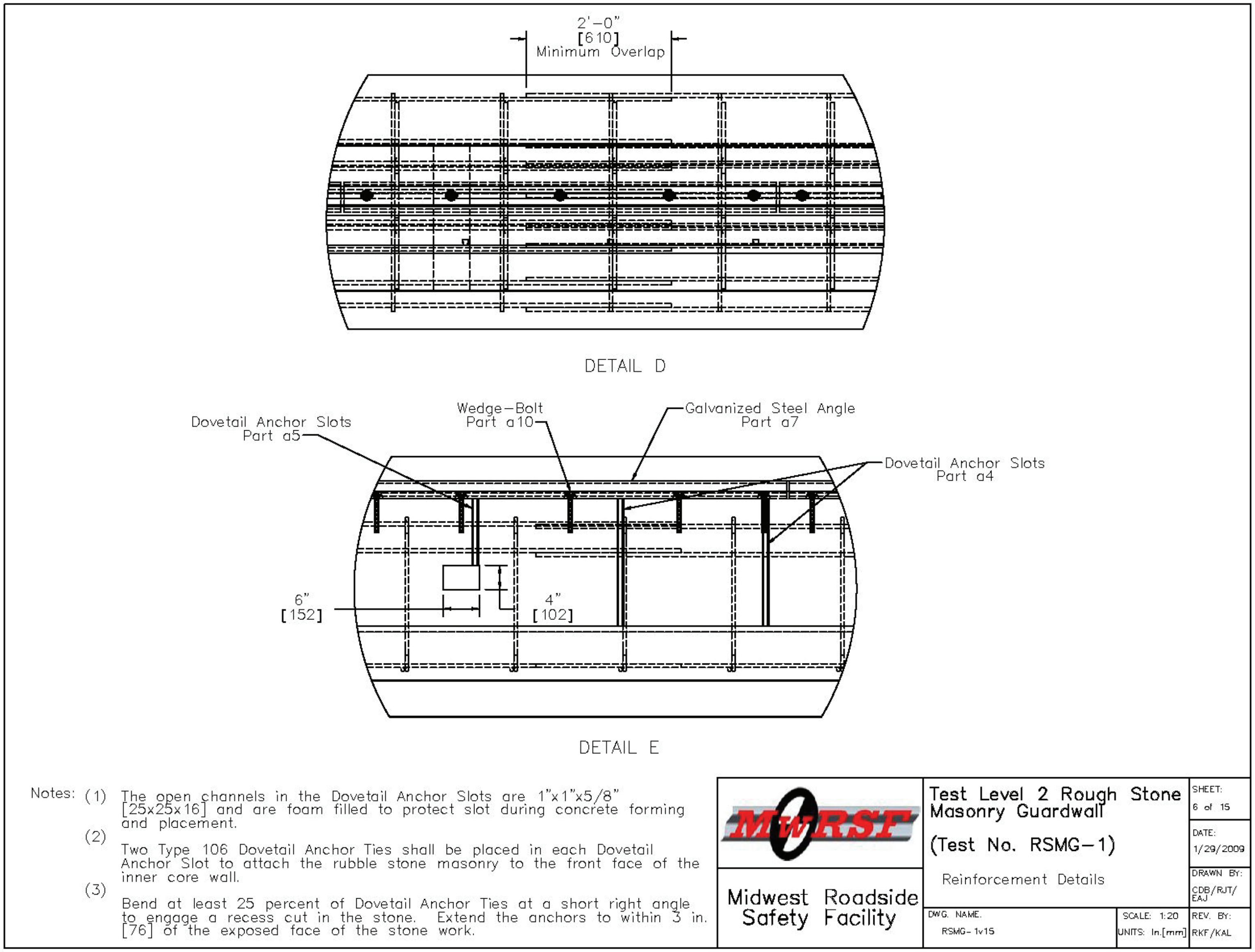


Figure 21. Reinforcement and Angle Attachment Details, Test No. RSMG-1

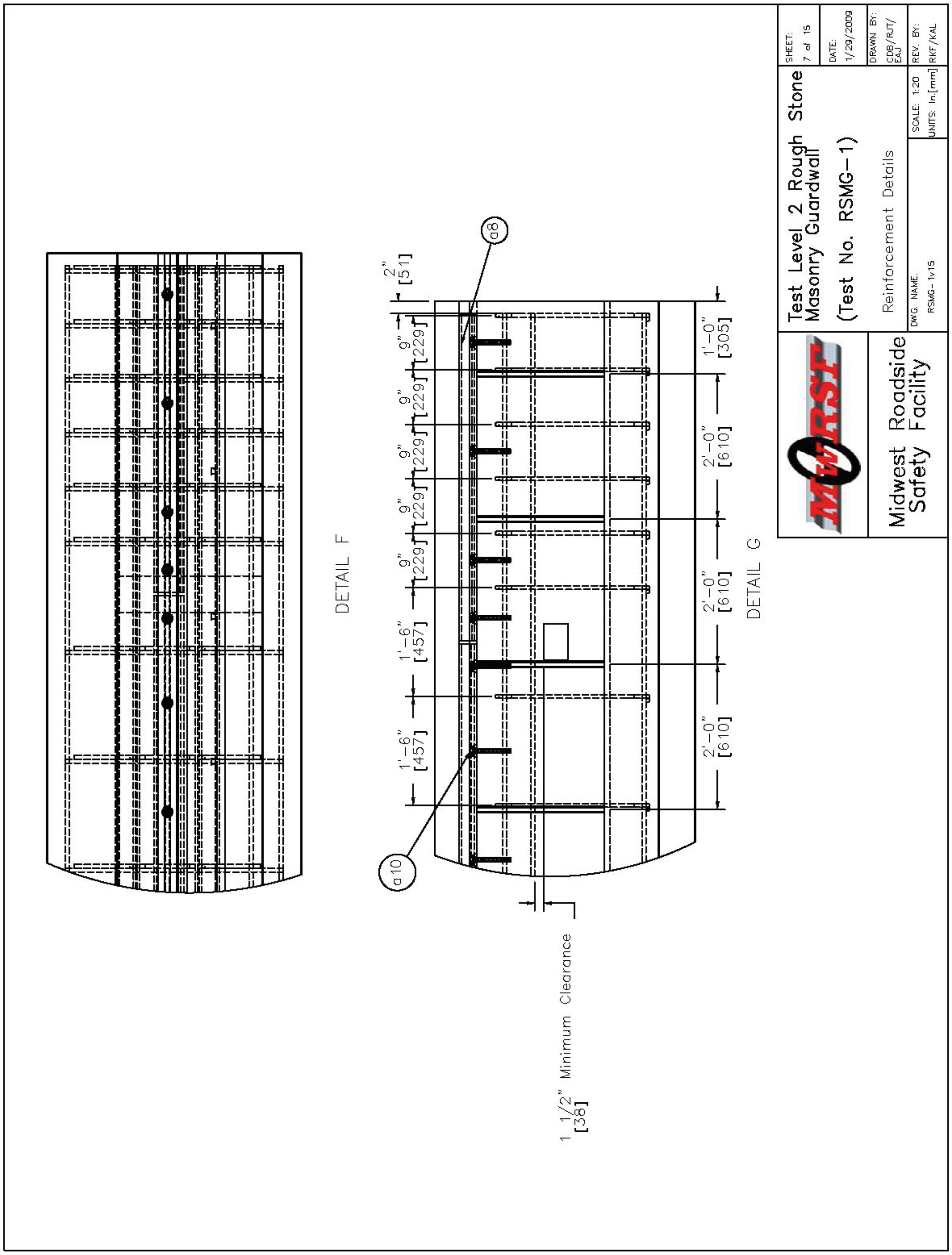


Figure 22. Reinforcement and Angle Attachment Details, Test No. RSMG-1

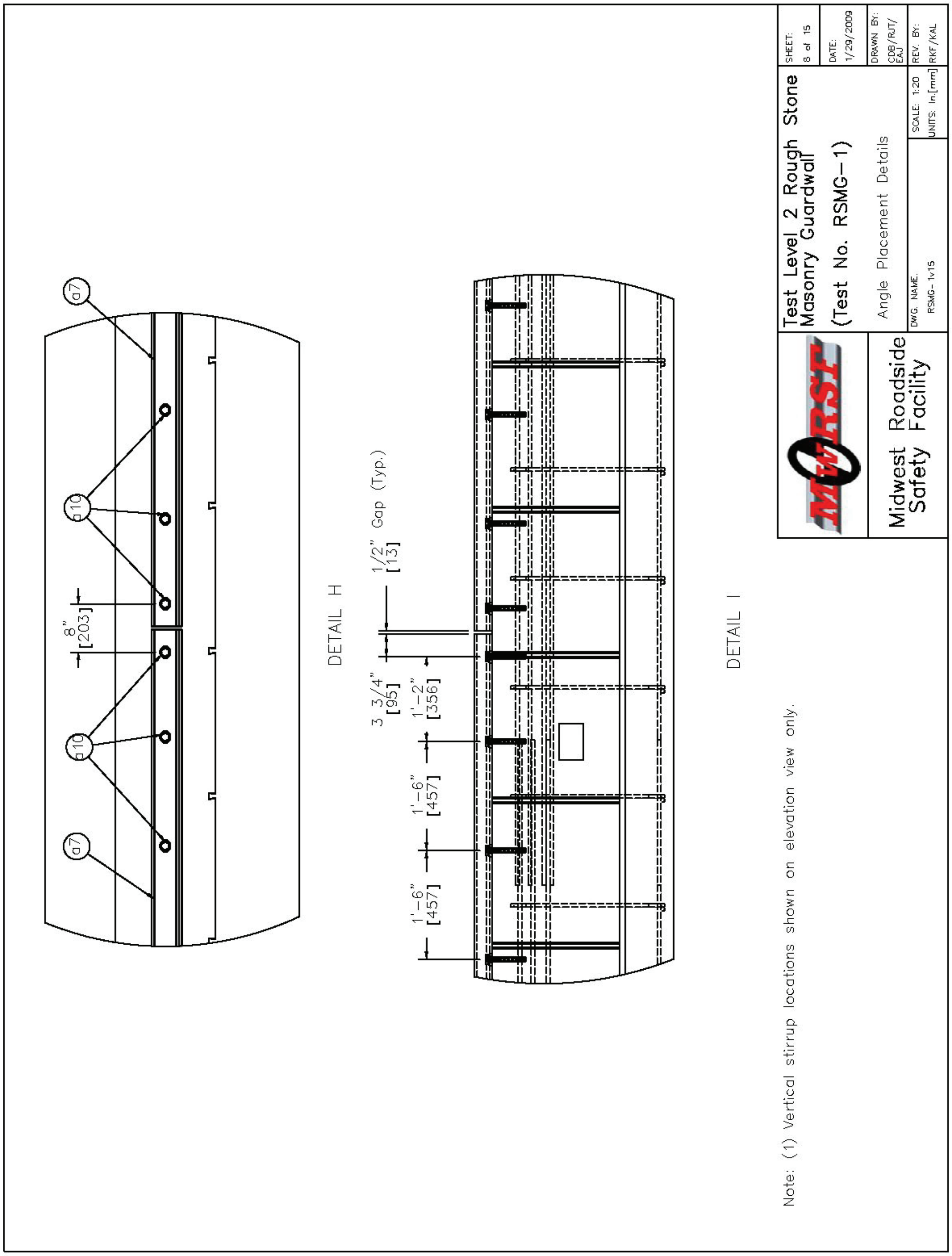


Figure 23. Angle Placement Details, Test No. RSMG-1

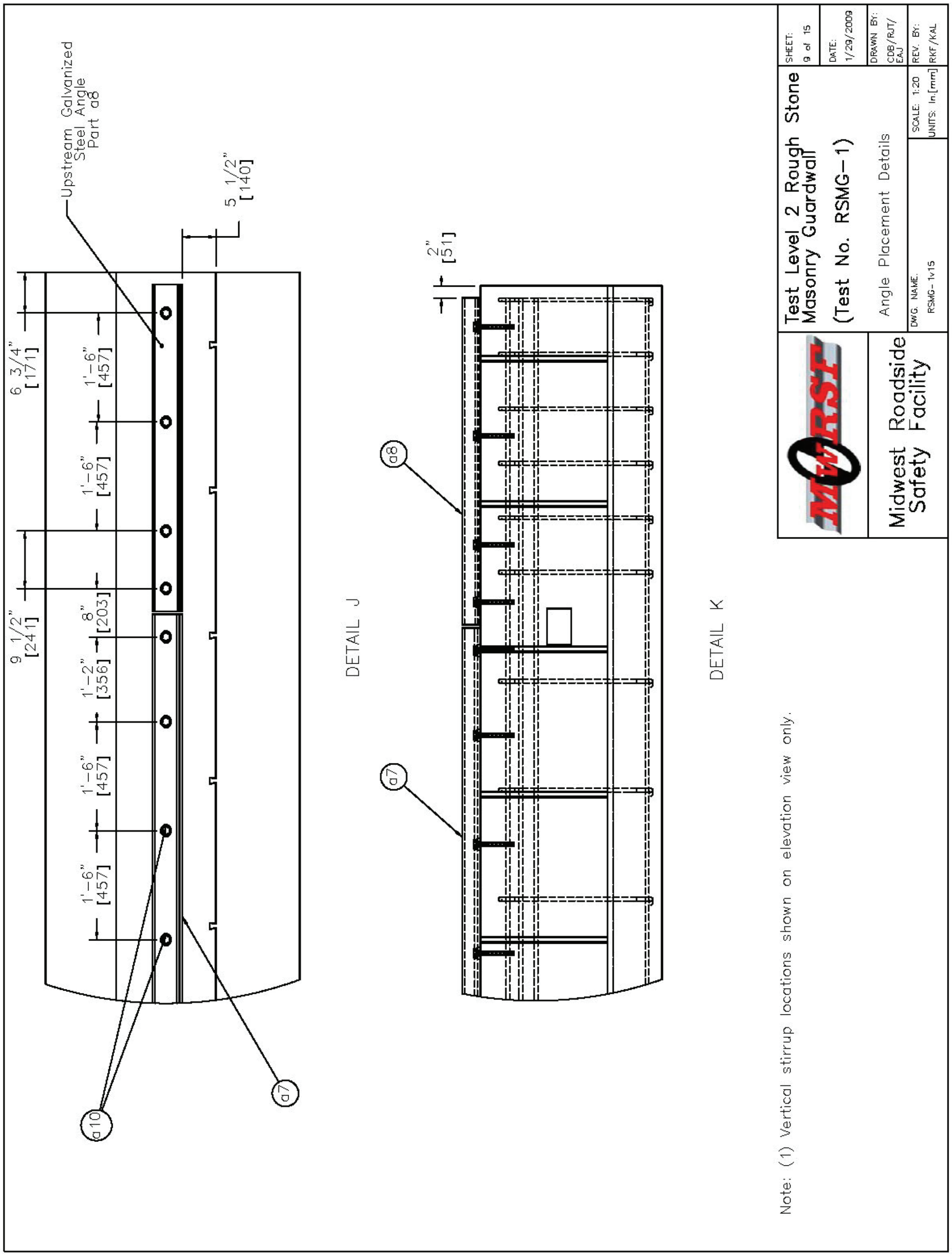


Figure 24. Angle Placement Details, Test No. RSMG-1

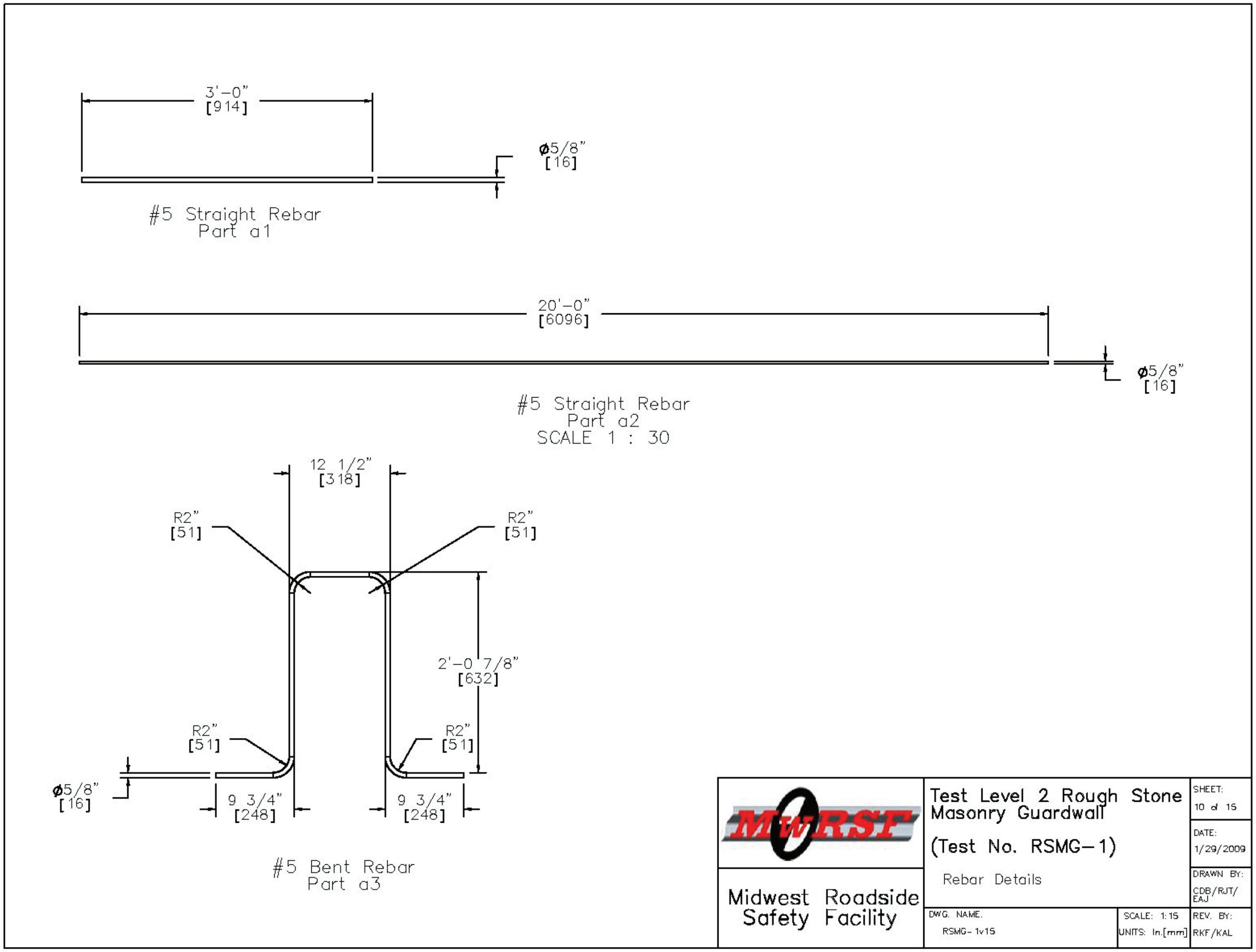


Figure 25. Rebar Details, Test No. RSMG-1

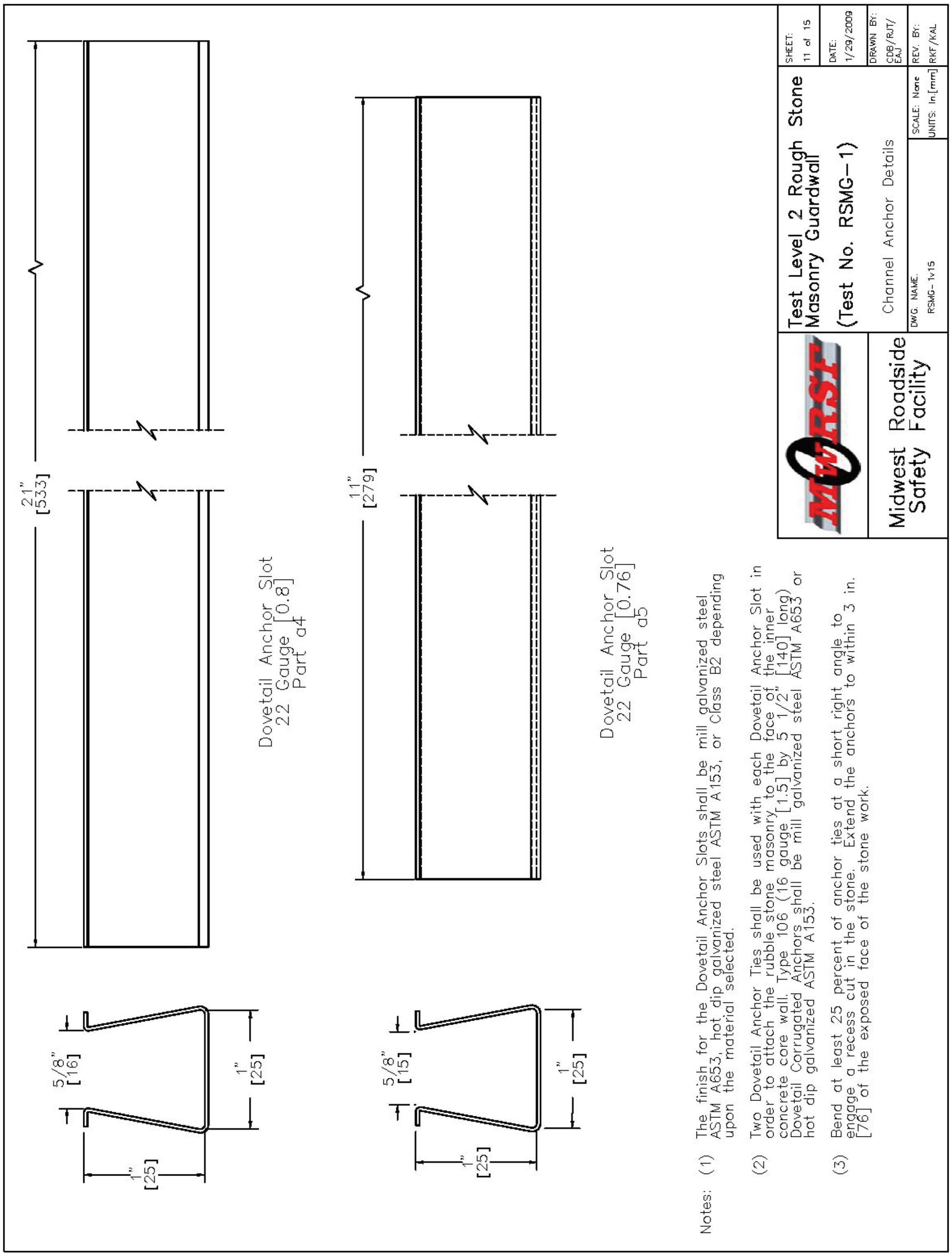


Figure 26. Dovetail Anchor Details, Test No. RSMG-1

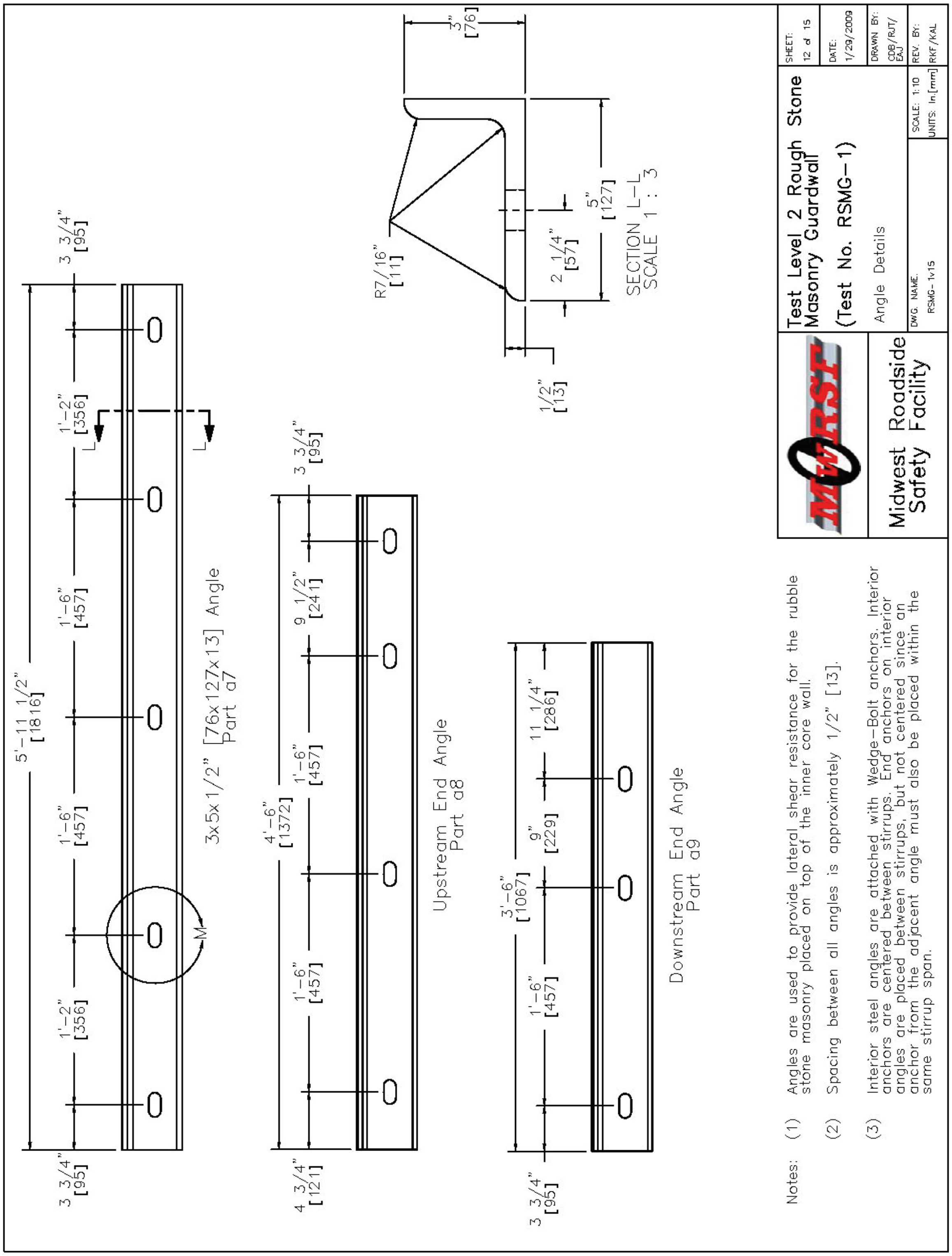


Figure 27. Steel Angle Details, Test No. RSMG-1

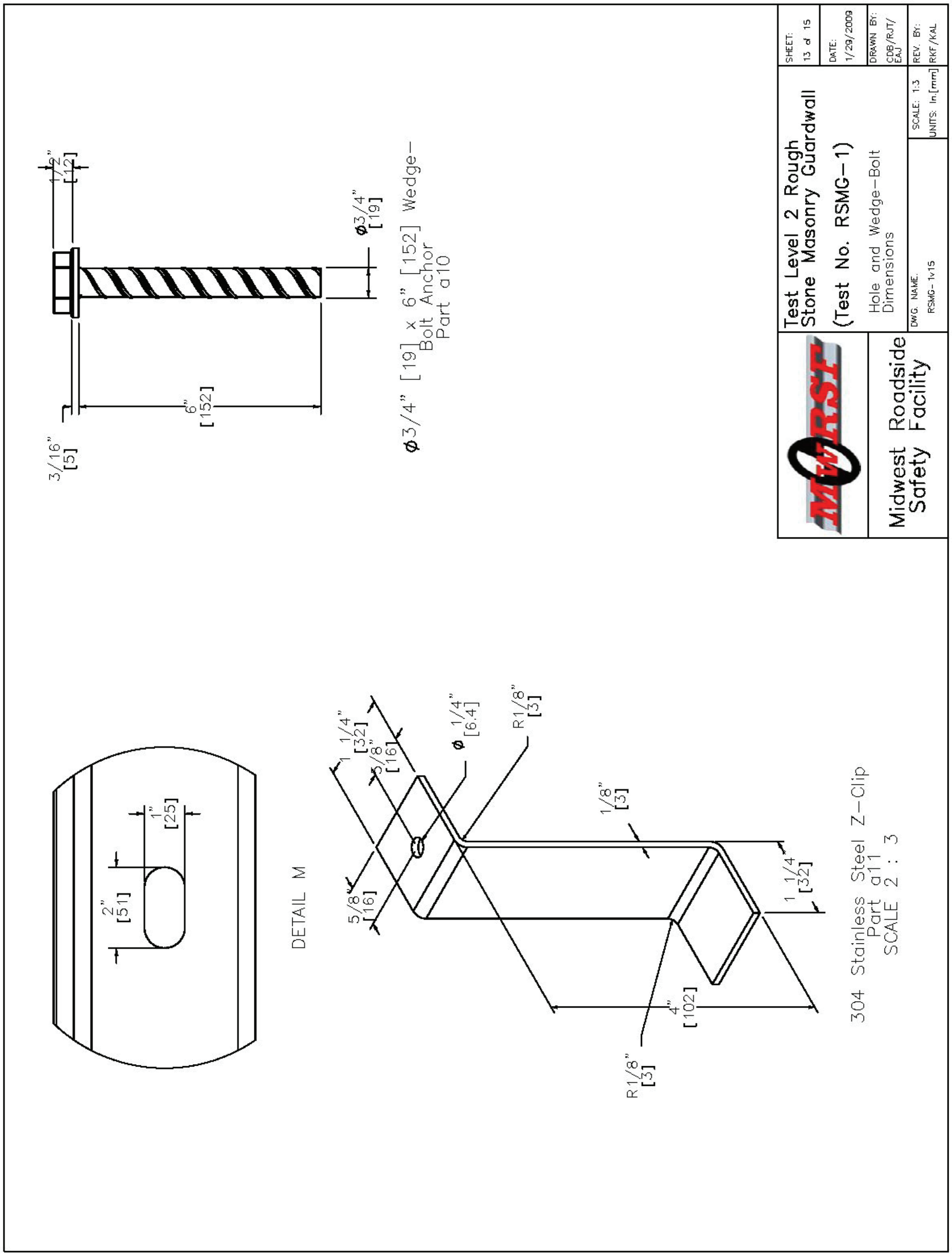


Figure 28. Angle Slot, Z-Clip Bracket, and Wedge-Bolt Screw Anchor Dimensions, Test No. RSMG-1

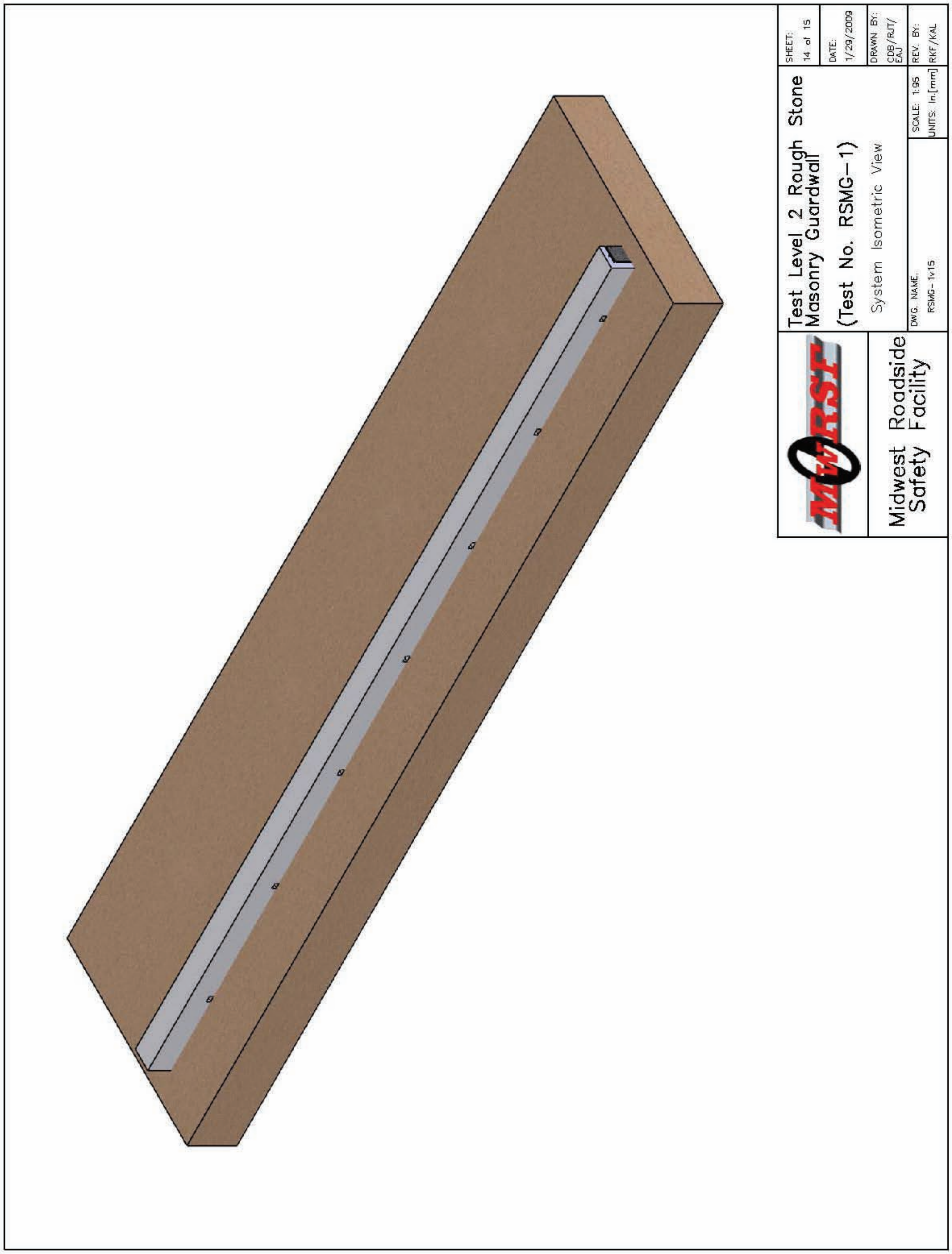


Figure 29. System Isometric View, Test No. RSMG-1

Test Level 2 Rough Stone Masonry Guardwall			
Item No.	QTY.	Description	Material Specifications
a1	55	#5 Straight Rebar, 3' [914] long	Grade 60
a2	40	#5 Straight Rebar, 20' [6096] long	Grade 60
a3	55	#5 Bent Rebar	Grade 60
a4	35	Dovetail Anchor Slot 21" [533] long (22 gauge [0.8])–Galvanized	ASTM A1008, A109, or A1011
a5	2	Dovetail Anchor Slot 11" [279] long (22 gauge [0.8])–Galvanized	ASTM A1008, A109, or A1011
a7	11	5x3x1/2" [127x76x13] Interior Angle	Galvanized, ASTM A36 Steel
a6	111	Dovetail Anchor Tie (16 gauge [1.5] by 5 1/2" [140] long by 1" [25] wide)	Galvanized Steel
a8	1	5x3x1/2" [127x76x13] Upstream End Angle	Galvanized, ASTM A36 Steel
a9	1	5x3x1/2" [127x76x13] Downstream End Angle	Galvanized, ASTM A36 Steel
a10	62	3/4" [19] Dia. by 6" [152] long Wedge–Bolt Anchor	Galvanized, Carbon Steel
a11	37	Z–Clips	304 Stainless Steel
a12	37	Heavy–Weight, Tapcon Masonry Anchors – 1/4" [6.4] Diam. x 2 3/4" [70] long	Stainless Steel
b1	1	3'–6" x 74'–4" x 6" [1.1mx22.7mx152mm] Aggregate Base	Aggregate
b2	1	Concrete Corewall Base	f'c = 3,500 psi [24.1 MPa]
b3	1	Concrete Corewall Top	f'c = 3,500 psi [24.1 MPa]
c1	1	Rough Stone Masonry Facade (Rubble Masonry)	Sound, Durable Rock with Mortar
c2	1	Mortar Bed – PROMIX Stone Veneer Mortar conforming to ASTM C–270 Type S Specifications	FHWA Section 712.05(a)

Midwest Roadside Safety Facility

Test Level 2 Rough Stone Masonry Guardwall
(Test No. RSMG–1)
Bill Of Materials

SHEET: 15 of 15	DATE: 1/29/2009	DRAWN BY: CDB/RJT/EAJ
DWG. NAME. RSMG–1v15	SCALE: None UNITS: In.[mm]	REV. BY: RKF/KAL

Figure 30. Bill of Materials, Test No. RSMG-1

Figure 31. Aggregate Base and Foundation Slab Formwork and Steel Reinforcement

Figure 32. Cast-In-Place Construction for Inner Concrete Core Wall

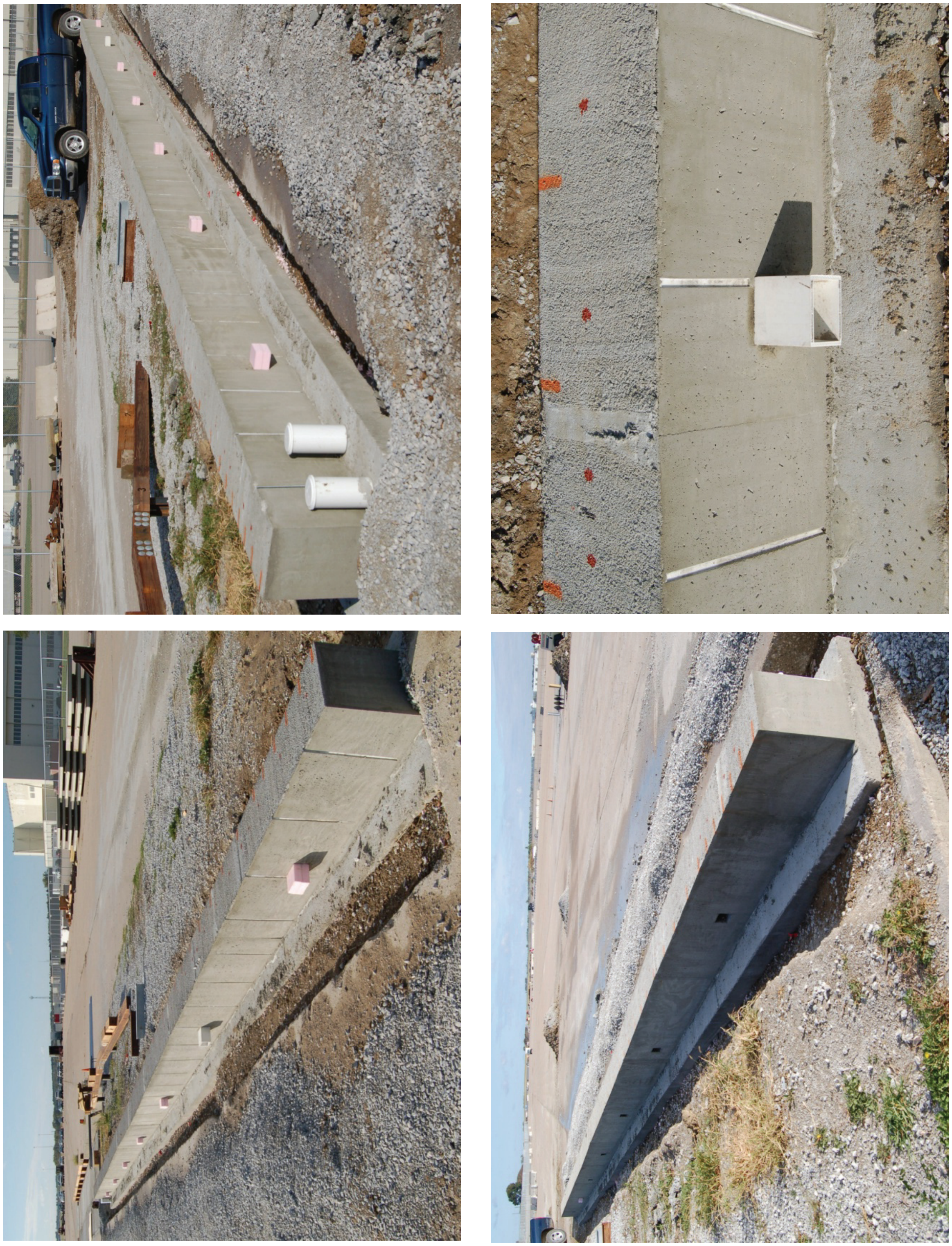


Figure 33. Inner Concrete Core Wall

Figure 34. Construction of Rough Stone Masonry Facade

Figure 35. Anchorage for Rough Stone Masonry Facade

Figure 36. Preparation and Placement of Top Capstones

Figure 37. Rough Stone Masonry Guardwall

Figure 38. Rough Stone Masonry Guardwall (Continued)

Figure 39. Rough Stone Masonry Guardwall (Continued)

8 FULL-SCALE CRASH TEST NO. 1

8.1 Test No. RSMG-1

The 4,456-lb (2,021-kg) pickup truck impacted the rough stone masonry guardwall system at a speed of 44.4 mph (71.4 km/h) and at an angle of 24.2 degrees. A summary of the test results and sequential photographs are shown in Figure 40. Additional sequential photographs are shown in Figures 41 and 42. Documentary photographs of the crash test are shown in Figures 43 and 44.

8.2 Weather Conditions

Test no. RSMG-1 was conducted on November 5, 2008 at approximately 12:30 pm. The weather conditions were reported as follows:

Pavement Surface: Dry
Sky Conditions: Overcast
Visibility: 10 Statute Miles
Air (Dry-Bulb) Temperature: 71 Degrees Fahrenheit
Relative Humidity: 57%
Wind Speed: 23 mph
Wind Direction: 180 Degrees from True North

8.3 Test Description

Initial vehicle impact was to occur 15 ft (4.57 m) downstream of the upstream end of the barrier, as shown in Figure 45. The actual point of impact was 15 ft – 2 in. (4.62 m) downstream from the upstream end. At 0.002 sec after impact, the front-right bumper cover deflected upward. At 0.008 sec, the front end of the vehicle pitched upward. At 0.016 sec, the front-right hood corner rode over the traffic-side face of the barrier. At 0.018 sec, a gap formed between the top-right corner of the engine hood and the vehicle. At 0.030 sec, a gap formed between the left-front bumper cover and the vehicle. At 0.032 sec, the base of the passenger-side A-pillar deflected, and the vehicle rolled toward the driver side of the vehicle. At 0.042 sec, the right-front wheel ceased lateral movement. At 0.052 sec, the right-front tire blew out, and the right-front quarter panel deflected. At 0.060 sec, the vehicle began to redirect. At 0.066 sec, a gap formed between the top-rear corner of the passenger-side door and the B-pillar. At 0.072 sec, the vehicle rolled toward the passenger side of the vehicle. At 0.094 sec, the bottom-front corner of the passenger-side door contacted the barrier. At 0.110 sec, the vehicle reached its maximum lateral displacement, and the left-front tire became airborne. At 0.174 sec, the left-rear tire became airborne. At 0.238 sec, the right-front corner of the truck bed contacted the barrier. At 0.242 sec, the vehicle ceased to pitch upward and began to pitch downward. At 0.280 sec, the right-rear bumper cover contacted the barrier slightly upstream of the impact location. At 0.294 sec, the right-front tire lost contact with the barrier. At 0.306 sec, the vehicle was parallel to the barrier. At 0.372 sec, the vehicle exited the system. The vehicle came to rest 154 ft – 9 in. (47.17 m) downstream from the impact location and 2 ft – 7.5 in. (0.80 m) laterally away from the traffic-side face of the barrier. The trajectory and final position of the vehicle are shown in Figure 46.

8.4 Barrier Damage

Damage to the barrier was minimal, as shown in Figures 47 and 48. Damage consisted only of contact marks along the barrier. Contact marks were found beginning at impact and continuing downstream for 141 in. (3.58 m). The contact marks extended from the top to the bottom of the barrier for the first 98 in. (2.49 m).

The maximum lateral permanent set deflection was negligible. The maximum lateral dynamic barrier deflection was less than 0.25 in. (6.4 mm), as determined from high-speed digital video analysis. The working width of the system was found to be less than 24.25 in. (616 mm).

8.5 Vehicle Damage

The damage to the vehicle was moderate, as shown in Figures 49 through 52. Damage was concentrated primarily at the right-front corner of the vehicle. The right-front bumper was crushed inward, and the frame connection was bent upward. The right-front quarter panel was folded inward. The top of the quarter panel was detached slightly from the hood, and the bottom of the quarter panel was scratched and dented inward. The right-front fog lights were scratched and cracked, and the front-right steel rim was bent and dented inward. The right-front tire was detached at the bottom part of the rim and deflated.

The bottom of the right-side door was slightly crushed inward, extending to the right-rear wheel well. The right-rear end of the truck bed was crushed inward at the bottom. The right-rear hubcap was cracked, and the right-rear rim was dented. There was slight buckling on the right-side floor in the occupant compartment. The right-side door was separated from the cab along the top frame. Some vehicle damage may have resulted from the secondary impact with the temporary concrete barriers located downstream from the guardwall system. The maximum interior occupant compartment deformation was 1½ in. (32 mm) located near the far right side of the floor pan. Complete occupant compartment deformations and the corresponding locations are provided in Appendix B.

8.6 Occupant Risk

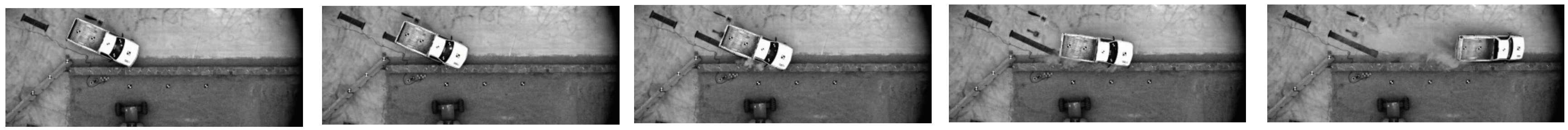
The occupant impact velocities (OIVs) and 0.010-sec average occupant ridedown acecelerations (ORAs) are summarized in Table 3. It is noted that the occupant impact velocities (OIVs) and occupant ridedown accelerations (ORAs) were within the suggested limits provided in NCHRP Report No. 350. The results of the occupant risk, as determined from the accelerometer data, are also summarized in Figure 40. The recorded data from all three accelerometers and the rate transducer are shown graphically in Appendix C.

Table 3. Summary of OIV and ORA, Test No. RSMG-1

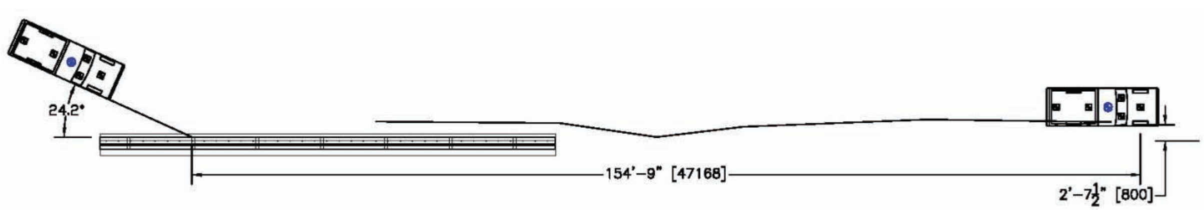
Transducer	Longitudinal		Lateral	
	OIV [ft/s (m/s)]	ORA [g's]	OIV [ft/s (m/s)]	ORA [g's]
EDR-3	-16.92 (-5.16)	-6.37	13.57 (4.14)	9.08
EDR-4	-15.02 (-4.58)	-7.35	16.26 (4.96)	9.33
DTS	-16.67 (-5.08)	-6.67	-16.86 (-5.14)	-10.40

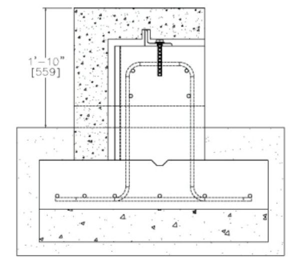
8.7 Discussion

The analysis of the test results for test no. RSMG-1 showed that the 22-in. (559-mm) tall, rough stone masonry guardwall system, including a reinforced concrete inner core wall and foundation slab, adequately contained and redirected the ¾-ton pickup truck without significant permanent set deflection of the barrier system. No detached elements nor fragments showed the potential for penetrating the occupant compartment nor presented an undue risk for being hazardous to other traffic. The deformation of, or intrusion into, the occupant compartment was minimal. These deformations did not pose a risk for causing serious injuries. The test vehicle did not penetrate nor ride over the barrier and remained upright during and after the collision. As shown in Appendix C, vehicle roll, pitch, and yaw angular displacements were noted and deemed acceptable. These angular motions did not adversely influence the evaluation of occupant risk nor cause a vehicle rollover. After impact, the vehicle exited the barrier at an angle of 2.8 degrees, which is less than 60 percent of the impact angle, and did not intrude into adjacent traffic lanes. Therefore, test no. RSMG-1 was determined to be acceptable according to the TL-2 safety performance criteria found in NCHRP Report No. 350. A summary of the safety performance criteria is shown in Table 5.



0.000 sec 0.052 sec 0.110 sec 0.238 sec 0.648 sec





- Test Agency .... MwRSF
- Test Number RSMG-1
- Date 11/5/2008
- NCHRP 350 Test Designation 2-11
- Test Article .... Rough Stone Masonry Guardwall
- Total Length .... 74 ft – 4 in. [22.66 m]
- Barrier Height .... 22 in. [559 mm]
- Barrier Width .... 24 in. [610 mm]
- Weep Hole Spacing .... 10.5 ft [3.20 m]
- Key Component – Rough Stone Masonry Wall
  - Rough Stone Masonry Facade .... Sound, Durable Rock with Mortar
  - Interior Angles ....5x3x1/2" by 5 ft - 11.5 in. [127x76x13 by 1,816 mm]
  - Upstream Angle .... 5x3x1/2" by 4.5 ft [127x76x13 by 1,372 mm]
  - Downstream Angle .... 5x3x1/2" by 3.5 ft [127x76x13 by 1,067 mm]
  - Wedge-Bolt Screw Anchors .... 0.75x6" [19.0 x152 mm]
- Key Component – Rough Stone Masonry Foundation Slab and Core Wall
  - Concrete (f'c) .... 3,500 psi [24.13 MPa]
  - Aggregate Base .... 3.5 x74.33x0.5 ft [1.1x22.67x0.152 m]
- Vehicle Model .... 1999 Chevrolet 2500 ¾-ton pickup
  - Curb .... 4,720 lbs [2,141 kg]
  - Test Inertial .... 4,456 lbs [2,021 kg]
  - Gross Static .... 4,456 lbs [2,021 kg]
- Impact Conditions
  - Speed .... 44.4 mph [71.4 km/h]
  - Angle .... 24.2 deg
  - Target Impact Location .... 15 ft [4.57 m] D.S. from U.S. end
- Exit Conditions
  - Speed .... 33.3 mph [53.6 km/h]
  - Angle .... 2.8 deg
- Vehicle Stability .... Satisfactory
- Vehicle Stopping Distance .... 154 ft - 10 in. [47.17 m] DS from Impact
- EDR-3
  - o Occupant Ridedown Acceleration
    - Longitudinal .... -6.37 g's < 20 g's
    - Lateral .... 9.08 g's < 20 g's
  - o Occupant Impact Velocity
    - Longitudinal .... -16.92 ft/s [-5.16 m/s] < 39.4 ft/s [12 m/s]
    - Lateral .... 13.57 ft/s [4.14 m/s] < 39.4 ft/s [12 m/s]
- EDR-4
  - o Occupant Ridedown Acceleration
    - Longitudinal .... -7.35 g's < 20 g's
    - Lateral .... 9.33 g's < 20 g's
  - o Occupant Impact Velocity
    - Longitudinal .... -15.02 ft/s [-4.58 m/s] < 39.4 ft/s [12 m/s]
    - Lateral .... 16.26 ft/s [4.96 m/s] < 39.4 ft/s [12 m/s]
- DTS
  - o Occupant Ridedown Acceleration
    - Longitudinal .... -6.67 g's < 20 g's
    - Lateral .... -10.40 g's < 20 g's
  - o Occupant Impact Velocity
    - Longitudinal .... -16.67 ft/s [-5.08 m/s] < 39.4 ft/s [12 m/s]
    - Lateral .... -16.86 ft/s [-5.14 m/s] < 39.4 ft/s [12 m/s]
- THIV .... 20.75 ft/s [6.326 m/s]
- PHD .... 10.423 g's < 20 g's
- Vehicle Damage .... Moderate
  - VDS[17] 1-FR-1
  - CDC[18] 01-RRLN1
  - Maximum Deformation .... 1.25 in. [32 mm]
- Test Article Damage .... Minimal
- Maximum Deflections
  - Permanent Set .... negligible
  - Dynamic .... less than 0.25 in. [6.4 mm]
- Working Width .... less than 24.25 in. [616 mm]

Figure 40. Summary of Test Results and Sequential Photographs, Test No. RSMG-1

0.000 sec

0.052 sec

0.098 sec

0.158 sec

0.372 sec

0.000 sec

0.104 sec

0.184 sec

0.242 sec

0.372 sec

Figure 41. Additional Sequential Photographs, Test No. RSMG-1

0.000 sec

0.110 sec

0.294 sec

0.592 sec

1.132 sec

Figure 42. Additional Sequential Photographs, Test No. RSMG-1

Figure 43. Documentary Photographs, Test No. RSMG-1

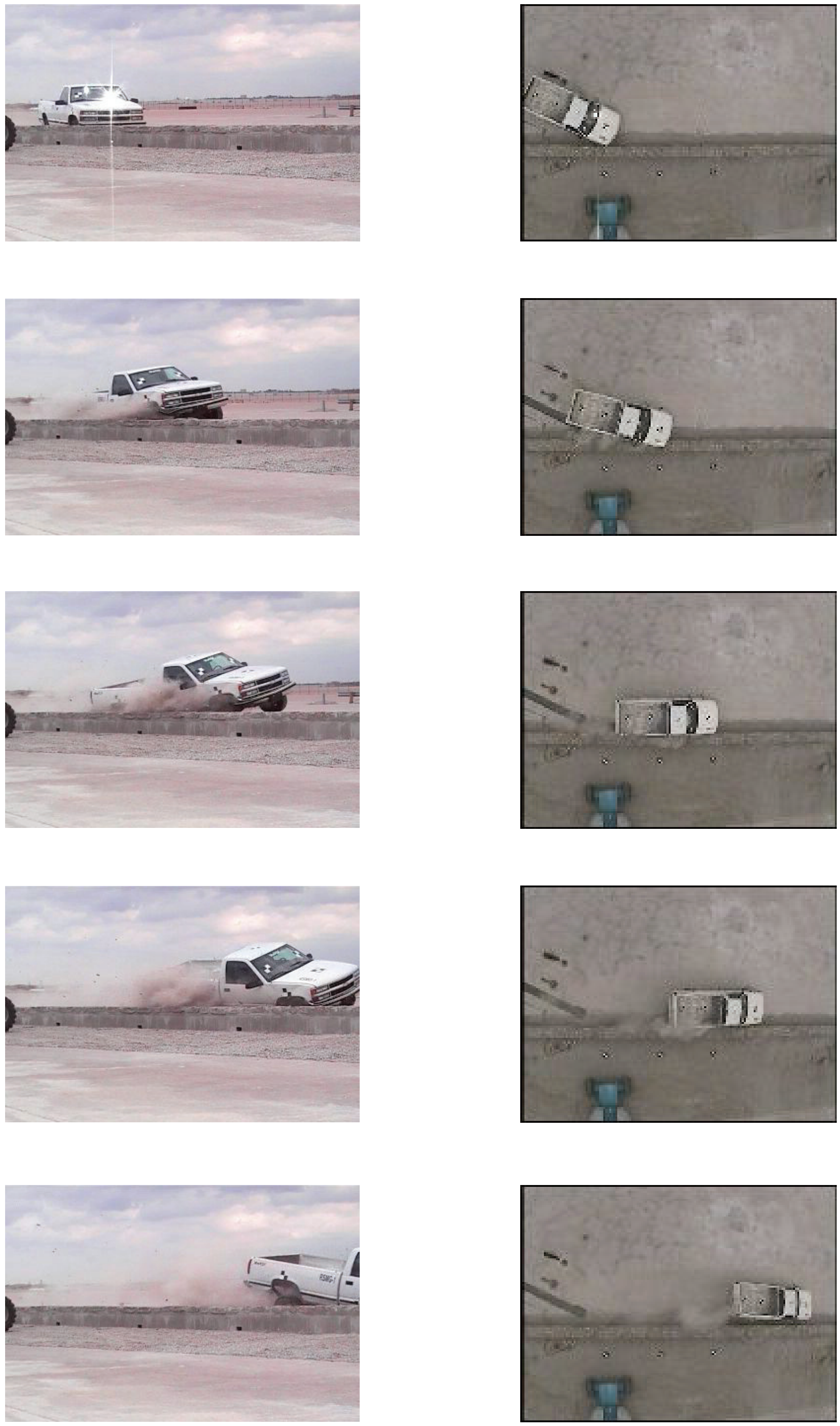


Figure 44. Documentary Photographs, Test No. RSMG-1

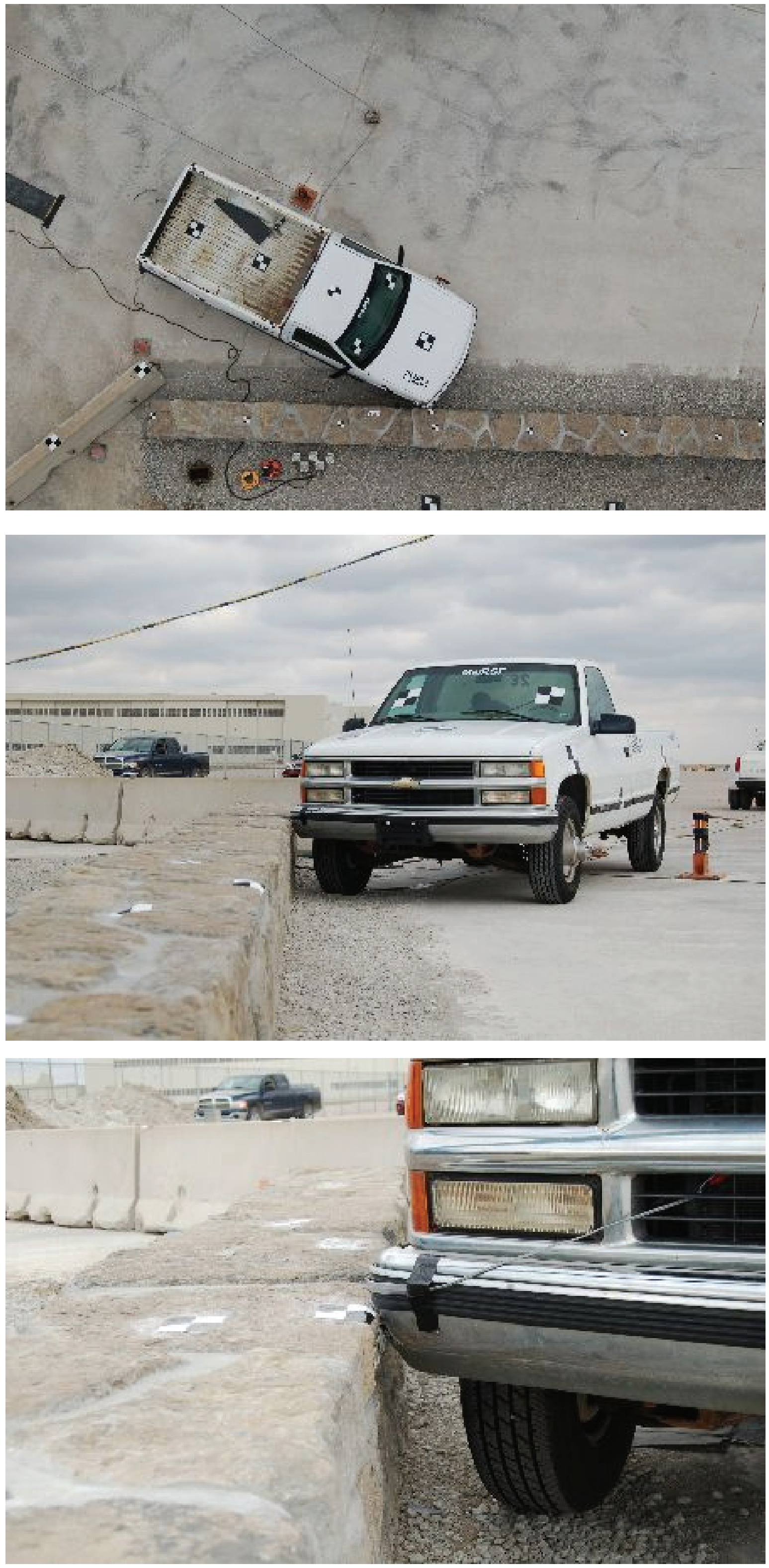


Figure 45. Impact Location, Test No. RSMG-1

Figure 46. Vehicle Final Position and Trajectory Marks, Test No. RSMG-1

Figure 47. System Damage, Test No. RSMG-1

Figure 48. System Damage, Test No. RSMG-1

Figure 49. Vehicle Damage, Test No. RSMG-1

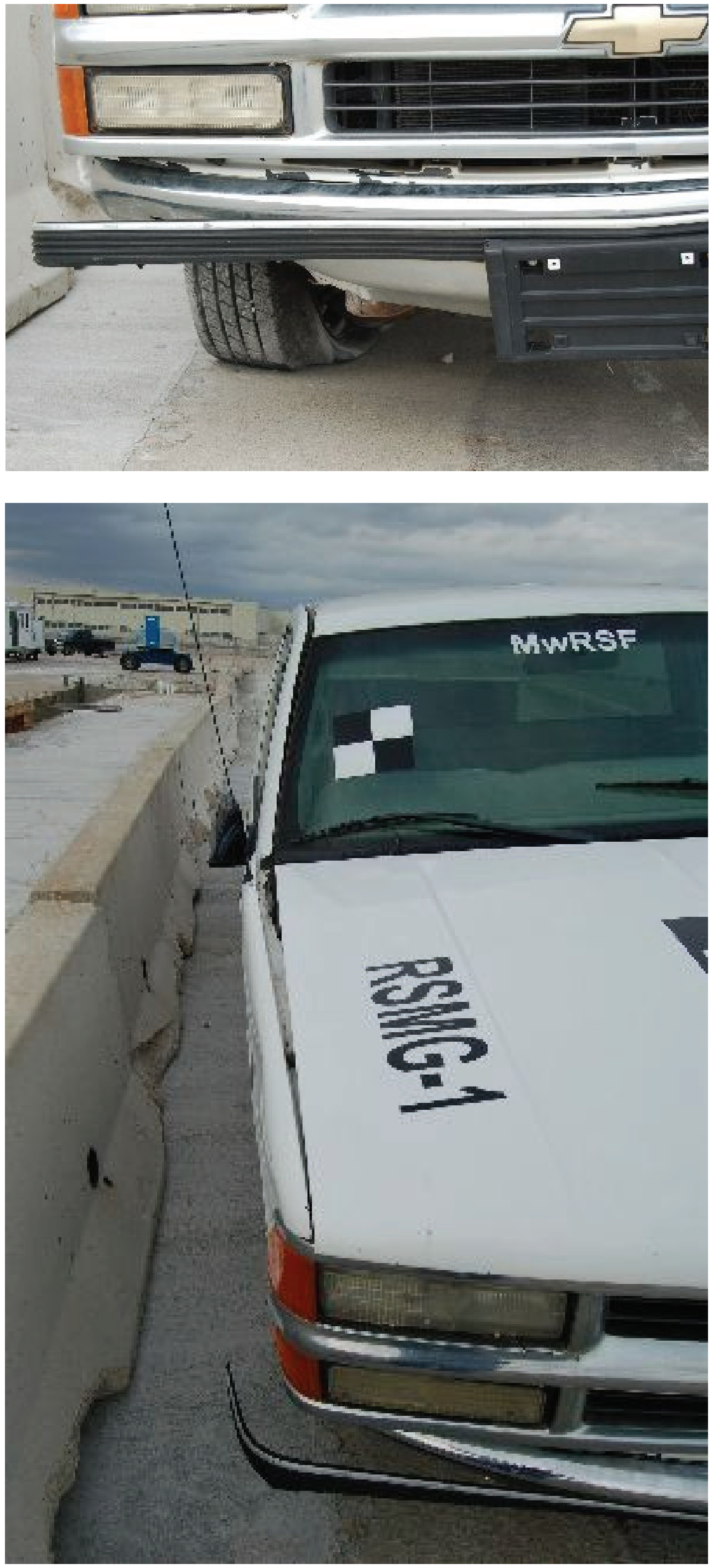


Figure 50. Vehicle Damage, Test No. RSMG-1

Figure 51. Vehicle Damage, Test No. RSMG-1

Figure 52. Vehicle Damage, Occupant Compartment, Test No. RSMG-1

9 BARRIER DESIGN DETAILS - TEST NO. RSMG-2

9.1 Design Discussion

For test no. RSMG-1, the 22-in. (559-mm) tall, rough stone masonry guardwall successfully redirected the pickup truck at the TL-2 impact conditions provided in NCHRP Report No. 350. Based on this success as well as the existence of an undamaged guardwall, the research team and sponsors discussed whether there was a benefit in conducting one additional pickup truck crash test using a lower barrier height, such as at 20 in. (508 mm).

For this project, the research objective was to determine the lowest barrier height that would meet the TL-2 test conditions. As noted previously, MwRSF researchers estimated that a 20-in. (508-mm) high, rough stone masonry guardwall had a 40 to 60 percent probability for successfully containing and smoothly redirecting the pickup truck. Therefore, a second crash test performed on a 20-in. (508-mm) tall, barrier would yield valuable information regarding the performance limits of the TL-2 guardwall system. If the second test were successful, then the barrier could be implemented in actual field installations using a nominal height of 22 in. (559 mm) with the existence of a 2-in. (51-mm) downside, construction tolerance. Second, a successful test at the reduced height would also allow for the future placement of a 2-in. (51-mm) pavement overlay on the roadway adjacent to the barrier system. As such, the project sponsors deemed it valuable to conduct another crash test using a 20-in. (508-mm) tall, barrier system.

9.2 Design Modifications

For the second test, the rough stone masonry guardwall system was identical to the barrier system used in test no. RSMG-1, except that the barrier height was 20 in. (508 mm) instead of 22 in. (559 mm). For test no. RSMG-2, a 2 in. (51 mm) wearing surface was installed adjacent to the barrier system in order to allow the existing barrier to be reused in the crash testing program. In addition, the 2-in. (51-mm) thick, wearing surface extended outward from the barrier for more that 150 ft (45.72 m) along the 25-degree approach angle. At the end of the simulated wearing surface pad, a 20-ft (6.10-m) long, ramp was used to raise the test vehicle to the appropriate elevation. The length of wearing surface and ramp were selected in order to allow for the test vehicle to reach its stable, equilibrium position, or within ¼ in. (6 mm). Details for the wearing surface and new barrier height are provided in Figures 53 and 54. A full set of CAD details for test no. RSMG-2 is shown in Appendix E.

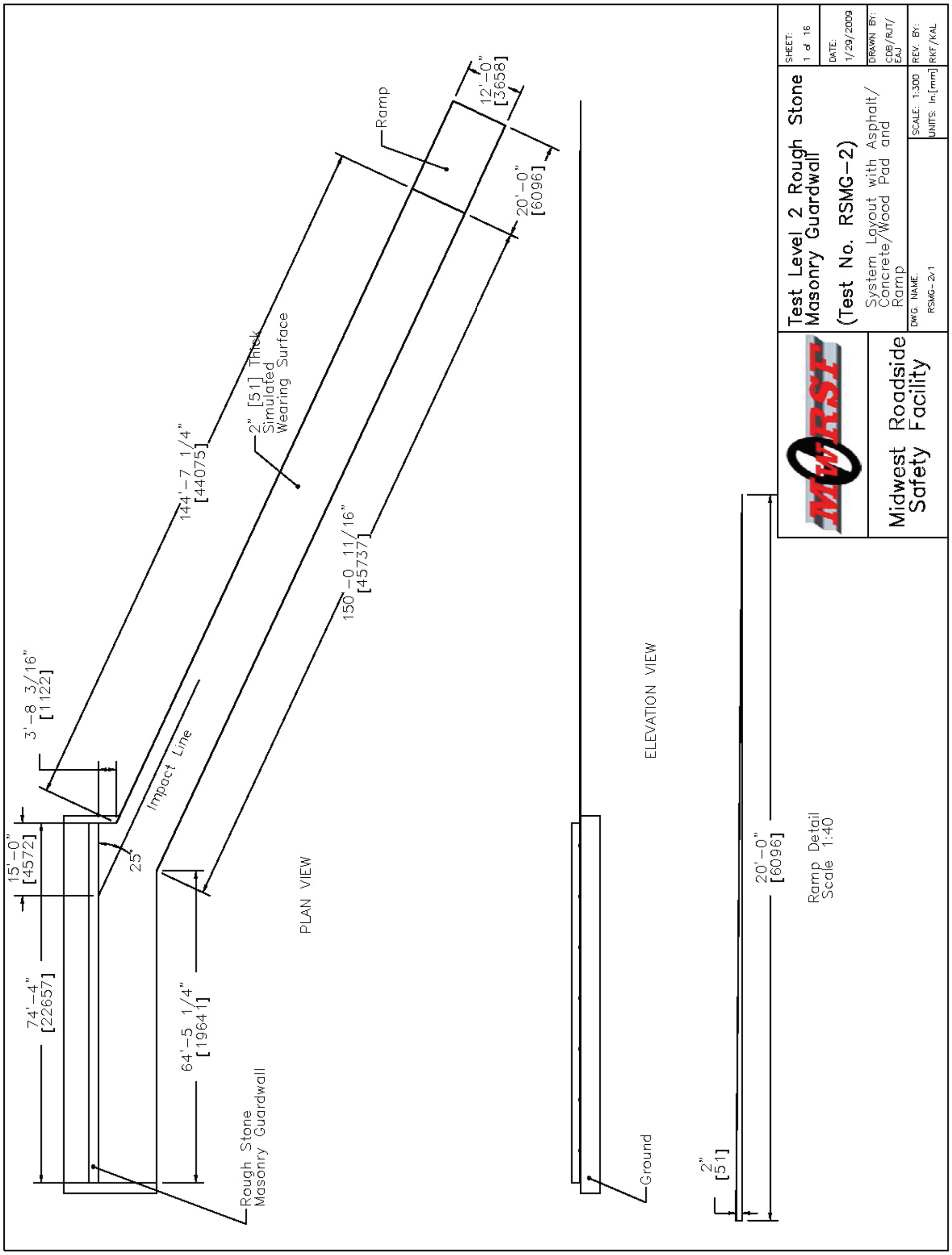


Figure 53. System Layout with Wearing Surface Pad and Ramp, Test No. RSMG-2

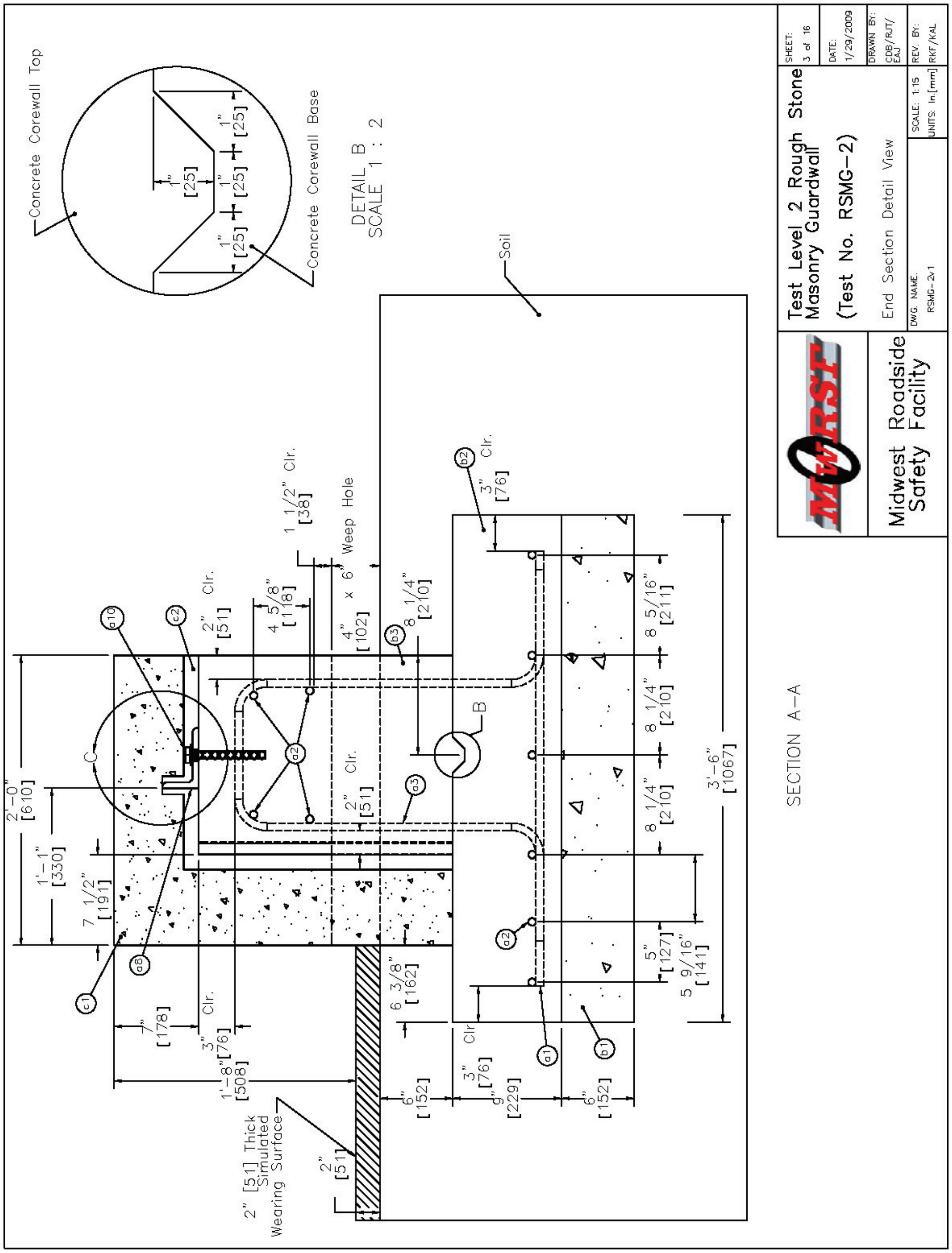


Figure 54. End Section Details and Effective Barrier Height, Test No. RSMG-2

10 FULL-SCALE CRASH TEST NO. 2

10.1 Test No. RSMG-2

The 4,440-lb (2,014-kg) pickup truck impacted the rough stone masonry guardwall at a speed of 43.6 mph (70.1 km/h) and at an angle of 24.4 degrees. A summary of the test results and sequential photographs are shown in Figure 55. Additional sequential photographs are shown in Figures 56 and 57. Documentary photographs of the crash test are shown in Figures 58 and 59.

10.2 Weather Conditions

Test no. RSMG-2 was conducted on January 8, 2009 at approximately 1:15 pm. The weather conditions were reported as follows:

Pavement Surface: Dry
Sky Conditions: Scattered Clouds
Visibility: 10 Statute Miles
Air (Dry-Bulb) Temperature: 28 Degrees Fahrenheit
Relative Humidity: 56%
Wind Speed: 8 mph
Wind Direction: 170 Degrees from True North

10.3 Test Description

Initial vehicle impact was to occur 15 ft (4.57 m) downstream of the upstream end of the barrier, as shown in Figure 60. The actual point of impact was 15 ft – 2½ in. (4.64 m) downstream of the upstream end. At 0.002 sec after impact, the right-front bumper cover began to crush inward. At 0.012 sec, the right-front tire contacted the barrier. At 0.016 sec, the front grill was forced upward, and the right-front bumper cover was on top of the barrier. At 0.038 sec, the right-front tire was forced backward. At 0.068 sec, the right-side body panel of the vehicle was on top of the barrier, and the vehicle began to redirect. At 0.072 sec, the truck began to roll toward the barrier. At 0.078 sec, the truck began to pitch upward. At 0.104 sec, the front tires lost contact with the ground. At 0.150 sec, the front bumper lost contact with the barrier. At 0.218

sec, the right-front tire lost contact with the system, and the truck exited the system for the first time. At 0.328 sec, the right-rear bumper cover contacted the barrier, and the truck began to pitch downward. At 0.486 sec, the right-front tire contacted the ground. At 0.582 sec, the pickup truck began to roll away from the barrier. At 0.912 sec, the left-front tire contacted the ground. At 0.940 sec, the right-front bumper cover contacted the barrier for the second time. At 1.426, the right-front bumper cover contacted the top face of the barrier. The vehicle came to rest 80 ft – 7½ in. (24.57 m) downstream from the impact location and 4 in. (102 mm) laterally away from the traffic-side face of the barrier. The trajectory and final position of the vehicle are shown in Figure 61.

10.4 Barrier Damage

Damage to the barrier was minimal, as shown in Figures 62 through 64. Damage consisted of contact marks and scratches along the barrier. Scratches were found along the vertical face of the wall at the location of impact and along the top face of the wall beginning 15 ft (4.6 m) from the upstream end of the barrier and continuing downstream for 5 ft (1.5 m). A scratch was found on the vertical face of the wall 20 ft (6.1 m) from the upstream end. A large scratch was observed on the top edge of the guardwall 24-ft 8-in. (7.52 m) from the upstream end. Scratches were also found on the top and vertical faces of the wall 54-ft 8-in. (16.67 m) from the upstream end. Black contact marks were found on the vertical face of the barrier at 58 ft (17.7 m), and a large scratch was found on the top face of the barrier at 61 ft (18.6 m). A 3 ft (0.9 m) long scratch was observed on the top face of the barrier's downstream end.

The maximum lateral permanent set deflection for the barrier was negligible. The maximum lateral dynamic barrier deflection was 0.25 in. (6.4 mm), as determined from high-speed digital video analysis. The working width of the system was 24.25 in. (616 mm).

10.5 Vehicle Damage

The damage to the vehicle was moderate, as shown in Figures 65 through 68. Damage was concentrated primarily to the right-front corner of the vehicle. The front grill was removed from the vehicle, and the bumper was dislocated and crushed on the right side. The right-side headlight and blinker were destroyed. The right-front quarter panel was severely damaged, and the right-front tire was deflated. The right-front wheel was still attached but had been pushed underneath the vehicle. There were also some scrapes found on the lower edge of the right-side door.

The right-rear quarter panel had scrapes along the lower edge, and there were also scrapes on the right edge of the rear bumper. The right-rear rim was scraped and deformed. The maximum occupant compartment deformation was 1 in. (25 mm) located near the middle of the right-side floor pan. Complete occupant compartment deformations and the corresponding locations are provided in Appendix B.

10.6 Occupant Risk

The occupant impact velocities (OIVs) and 0.010-sec average occupant ridedown accelerations (ORAs) are summarized in Table 4. It is noted that the occupant impact velocities (OIVs) and occupant ridedown accelerations (ORAs) were within the suggested limits provided in NCHRP Report No. 350. The results of the occupant risk, as determined from the accelerometer data, are also summarized in Figure 55. The recorded data from both the accelerometers and the rate transducer are shown graphically in Appendix D.

Table 4. Summary of OIV and ORA, Test No. RSMG-2

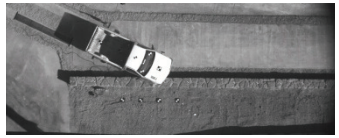
Transducer	Longitudinal		Lateral	
	OIV [ft/s (m/s)]	ORA [g's]	OIV [ft/s (m/s)]	ORA [g's]
EDR-4	-16.27 (-4.96)	-6.49	-16.46 (-5.02)	-9.44
DTS	-15.55 (-4.74)	-5.90	-16.35 (-4.98)	-9.58

10.7 Discussion

The analysis of the test results for test no. RSMG-2 showed that the 20-in. (508-mm) tall, rough stone masonry guardwall system, including a reinforced concrete inner core wall and foundation slab, adequately contained and redirected the ¾-ton pickup truck without significant permanent set deflection of the barrier system. No detached elements nor fragments showed the potential for penetrating the occupant compartment nor presented an undue risk for being hazardous to other traffic. The deformation of, or intrusion into, the occupant compartment was minimal. These deformations did not pose a risk for causing serious injuries. The test vehicle did not penetrate nor ride over the barrier and remained upright during and after the collision. As shown in Appendix D, vehicle roll, pitch, and yaw angular displacements were noted and deemed acceptable. These angular motions did not adversely influence the evaluation of occupant risk nor cause a vehicle rollover. After impact, the vehicle exited the barrier at an angle of 0.3 degrees, which is less than 60 percent of the impact angle, and did not intrude into adjacent traffic lanes. The exit angle was negative after the vehicle lost contact with the end of the system. Therefore, test no. RSMG-2 was determined to be acceptable according to the TL-2 safety performance criteria found in NCHRP Report No. 350. A summary of the safety performance criteria is shown in Table 5.

Although the 20-in. (508-mm) tall, parapet demonstrated a successful safety performance, it is unlikely that 18 to 19 in. (457 to 483 mm) parapet heights would be capable of meeting the TL-2 impact conditions.

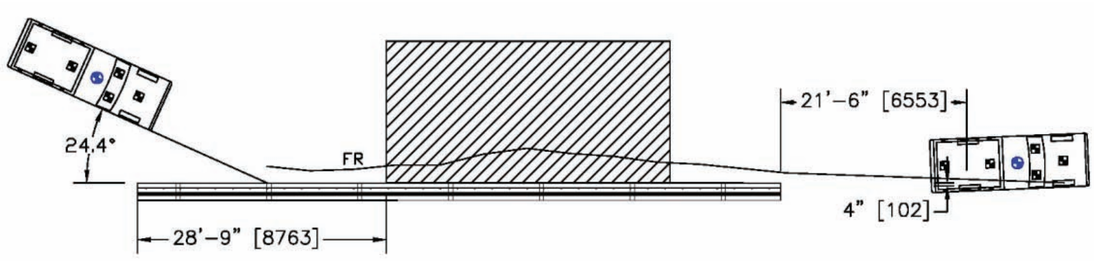

0.000 sec

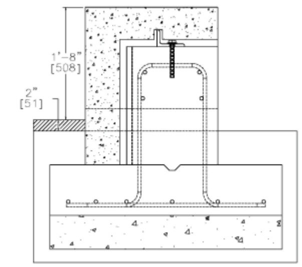

0.068 sec


0.120 sec


0.162 sec


0.218 sec





- Test Agency ....MwRSF
- Test Number RSMG-2
- Date 1/8/2009
- NCHRP 350 Test Designation 2-11
- Test Article ....Rough Stone Masonry Guardwall
- Total Length ....74 ft – 4 in. [22.66 m]
- Barrier Height ....20 in. [508 mm]
- Barrier Width ....24 in. [610 mm]
- Weep Hole Spacing ....10.5 ft [3200 mm]
- Key Component – Rough Stone Masonry Wall
  - Rough Stone Masonry Facade ....Sound, Durable Rock with Mortar
  - Interior Angles ....5x3x1/2" by 5 ft - 11.5 in. [127x76x13 by 1,816 mm]
  - Upstream Angle .... 5x3x1/2" by 4.5 ft [127x76x13 by 1,372 mm]
  - Downstream Angle.......... 5x3x1/2" by 3.5 ft [127x76x13 by 1,067 mm]
  - Wedge-Bolt Screw Anchors............................. 0.75x6" [19.0 x152 mm]
- Key Component – Rough Stone Masonry Foundation Slab and Core Wall
  - Concrete (f'c) ....3,500 psi [24.13 MPa]
  - Aggregate Base ....3.5 x74.33x0.5 ft [1.1x22.67x0.152 m]
- Vehicle Model ....1999 Chevrolet 2500 ¾-ton pickup
  - Curb ....4,600 lbs [2,087 kg]
  - Test Inertial ....4,440 lbs [2,014 kg]
  - Gross Static ....4,440 lbs [2,014 kg]
- Impact Conditions
  - Speed ....43.6 mph [70.1 km/h]
  - Angle ....24.4 deg
  - Target Impact Location ....15 ft [4.57 m] D.S. from U.S. end
- Exit Conditions
  - Speed ....34.6 mph [55.6 km/h]
  - Angle ....0.3 deg
- Vehicle Stability ....Satisfactory
- Vehicle Stopping Distance ....80 ft – 7.5 in. [24.57 m] DS from impact
- EDR-4
  - o Occupant Ridedown Acceleration
    - Longitudinal ....-6.49 g's < 20 g's
    - Lateral ....-9.44 g's < 20 g's
  - o Occupant Impact Velocity
    - Longitudinal ....-16.27 ft/s [-4.96 m/s] < 39.4 ft/s [12 m/s]
    - Lateral ....-16.46 ft/s [-5.02 m/s] < 39.4 ft/s [12 m/s]
- DTS
  - o Occupant Ridedown Acceleration
    - Longitudinal ....-5.90 g's < 20 g's
    - Lateral ....-9.58 g's < 20 g's
  - o Occupant Impact Velocity
    - Longitudinal ....-15.55 ft/s [-4.74 m/s] < 39.4 ft/s [12 m/s]
    - Lateral ....-16.35 ft/s [-4.98 m/s] < 39.4 ft/s [12 m/s]
- THIV ....24.06 ft/s [7.332 m/s]
- PHD ....9.586 g's < 20 g's
- Vehicle Damage ....Moderate
  - VDS[17] 1-FR-2
  - CDC[18] 01-RREN2
  - Maximum Deformation ....1.0 in. [25 mm]
- Test Article Damage ....Minimal
- Maximum Deflections
  - Permanent Set ....negligible
  - Dynamic ....0.25 in. [6.4 mm]
- Working Width ....24.25 in. [616 mm]

Figure 55. Summary of Test Results and Sequential Photographs, Test No. RSMG-2


0.000 sec


0.582 sec


0.068 sec


0.940 sec


0.150 sec


1.216 sec


0.218 sec


1.426 sec


0.328 sec


2.134 sec

Figure 56. Additional Sequential Photographs, Test No. RSMG-2

0.000 sec

0.000 sec

0.068 sec

0.038 sec

0.120 sec

0.122 sec

0.154 sec

0.162 sec

0.218 sec

0.218 sec

Figure 57. Additional Sequential Photographs, Test No. RSMG-2

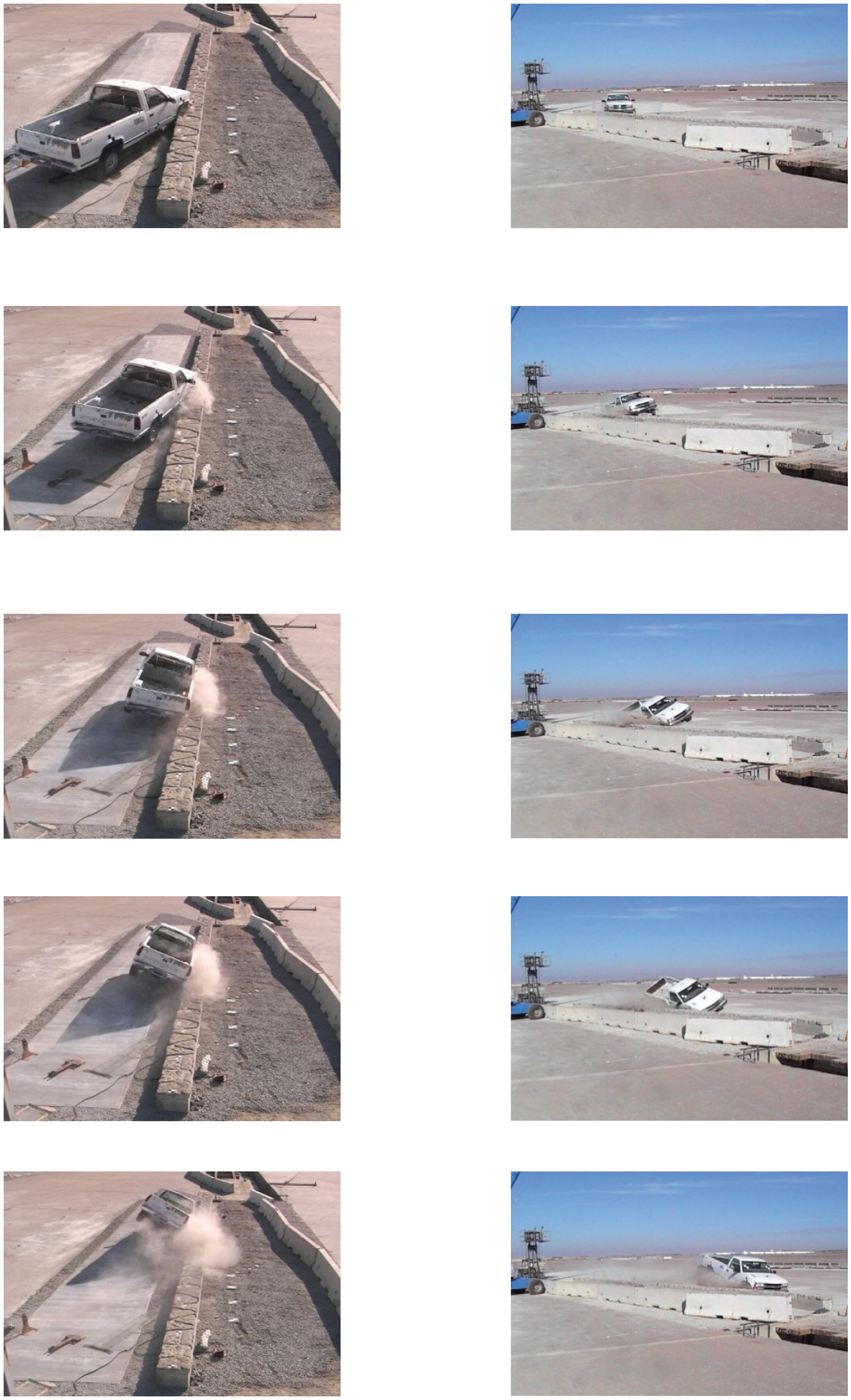


Figure 58. Documentary Photographs, Test No. RSMG-2

Figure 59. Documentary Photographs, Test No. RSMG-2

Figure 60. Impact Location, Test No. RSMG-2

Figure 61. Vehicle Final Position and Trajectory Marks, Test No. RSMG-2

Figure 62. System Damage, Test No. RSMG-2

Figure 63. System Damage, Test No. RSMG-2

Figure 64. System Damage, Test No. RSMG-2

Figure 65. Vehicle Damage, Test No. RSMG-2

Figure 66. Vehicle Damage, Test No. RSMG-2

Figure 67. Vehicle Damage, Test No. RSMG-2

Figure 68. Vehicle Damage, Occupant Compartment, Test No. RSMG-2

11 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

For this study, the research team was tasked with determining the minimum top mounting height for the rough stone masonry guardwall in order to allow the aesthetic barrier system to meet the TL-2 safety performance criteria of NCHRP Report No. 350. To complete this task, several efforts were utilized. First, a literature review was performed in order to determine whether any relevant research had been performed on either low-height, rigid parapets or rough stone masonry guardwalls. From this review, it was found that 20-in. (508-mm) tall, rigid, smooth face, vertical parapets were capable of containing and redirecting 2000P vehicles at the TL-2 impact conditions, while 18-in. (457-mm) high parapets allowed the same vehicle to override a rough stone masonry barrier at the TL-2 impact conditions.

Next, a very limited study using nonlinear, finite element analysis (FEA) was performed to assist in the determination of the recommended height for the stone masonry guardwall. However, the simulation study was limited due to project funding, research scope, sponsor priorities, and project schedule. LS-DYNA computer simulations were performed on a rigid, vertical-faced barrier with varying heights in order to help determine the minimum top mounting height to prevent vehicular instabilities and barrier override. From this effort, two general considerations were established based on simulations of various wall heights and various suspension joint failure criteria. The general considerations were to (1) use a more aggressive approach with a 20-in. (508-mm) tall parapet and a reasonable chance of passing and (2) use a more conservative approach with a 22-in. (559-mm) tall parapet and a higher probability of passing.

Following the completion of the literature review and LS-DYNA analyses, the research team identified probability ranges for successfully containing and redirecting vehicles using different barrier heights. Based on the simulation results, knowledge garnered from prior crash tests into low-height, rigid, vertical parapets, as well as the research team's engineering expertise, additional general height guidance for TL-2 rigid, vertical barriers was provided as follows:

- 18 in. (457 mm) – 0 percent probability of successful test result;
- 19 in. (483 mm) – 5 to 10 percent probability of successful test result;
- 20 in. (508 mm) – 40 to 60 percent probability of successful test result;
- 21 in. (533 mm) – 60 to 75 percent probability of successful test result;
- 22 in. (559 mm) – 75 to 90 percent probability of successful test result; and
- 27 in. (686 mm) – 100 percent probability of successful test result.

For the barrier heights noted above, the guidance assumed that the stone masonry remained intact and attached to the inner concrete core wall during the crash testing program and would contribute to the redirection of the pickup truck. Based on the considerations noted above, the CFLHD, FHWA, and NPS selected the 22-in. (559-mm) tall, rough stone masonry guardrail for use in the initial crash testing program.

Several design concepts were brainstormed for providing adequate shear transfer between the top capstones and the top surface of the inner core wall. However, the best alternative consisted of steel angle segments anchored to the top surface of the core wall with the upper leg of the angle recessed into saw-cuts or kerfs placed in the bottom of the top capstones and filled with excess mortar. The interior angles measured 5 in. x 3 in. x ½ in. (127 mm x 76 mm x 13 mm). Galvanized, carbon steel Wedge-Bolt screw anchors, measuring ¾-in. (19.0-mm) diameter by 6-in. (152-mm) long, were placed through slots in the angles and rigidly attached to the core wall.

Two Test Level 2 (TL-2) full-scale vehicle crash tests were performed on rough stone masonry guardwall systems according to the NCHRP Report No. 350 safety performance guidelines. The first test was performed on a 22-in. (559-mm) tall, guardwall system using a 4,456-lb (2,021-kg) pickup truck impacting at a speed of 44.4 mph (71.4 km/h) and at an angle of 24.2 degrees. The second test was performed on a 20-in. (508-mm) tall, guardwall system using a 4,440-lb (2,014-kg) pickup truck impacting at a speed of 43.6 mph (70.1 km/h) and at an angle of 24.4 degrees. Both crash tests provided an acceptable safety performance according to the evaluation criteria provided in NCHRP Report No. 350. A summary for each safety performance evaluation is provided in Table 5.

Although the 20-in. (508-mm) tall, parapet demonstrated a successful safety performance, it is unlikely that 18 to 19 in. (457 to 483 mm) parapet heights would be capable of meeting the TL-2 impact conditions. This opinion is based on: (1) the unsuccessful safety performance of an 18-in. tall, stone masonry guardwall conducted by SwRI according to the TL-2 impact conditions (10); (2) the crash test results obtained from other research studies conducted on low-height, rigid parapets; (3) the results obtained from the limited LS-DYNA analysis effort reported herein; and (4) the research team’s engineering expertise.

For actual field installations, it is recommended that the rough stone masonry guardwall system be implemented using a nominal top mounting height of 22 in. (559 mm) relative to the traveled way. With this configuration, a downside construction or performance tolerance would be available in the amount of 2 in. (51 mm). Finally, roadways requiring a 2-in. (51-mm) pavement overlay adjacent to the barrier system could be accommodated as long as the rough stone masonry guardwall was originally installed using the 22-in. (559-mm) nominal mounting height relative to the traveled way.

Table 5. Summary of NCHRP Report No. 350 Safety Performance Evaluation Results (Test Designation No. 2-11)

Evaluation Factors		Evaluation Criteria	Test RSMG-1	Test RSMG-2
Structural Adequacy	A.	Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	S	S
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. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted. See discussion in Section 5.3 and Appendix E of NCHRP Report 350.	S	S
	F.	The vehicle should remain upright during and after collision although moderate roll, pitching and yawing are acceptable.	S	S
Vehicle Trajectory	K.	After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	S	S
	L.	The occupant impact velocity (OIV) in the longitudinal direction should not exceed 39.37 ft/sec (12 m/sec) and the occupant rideown acceleration (ORA) in the longitudinal direction (see Appendix A, Section A5.3 in NCHRP Report 350 for calculation procedure) should not exceed 20 g's.	S	S
	M.	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at time of vehicle loss of contact with test device.	S	S

S – Satisfactory U – Unsatisfactory
M - Marginal NA - Not Available

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13 APPENDICES

Appendix A. Vehicle Center of Gravity Determination

Test: RSMG-1 **Vehicle:** 1999 GMC C2500

Vehicle CG Determination

VEHICLE	Equipment	Weight	Long CG	Vert CG	HOR M	Vert M
+	Unbalasted Truck	4720	56.11	26.25	264817.5	123900
+	Brake receivers/wires	5	80	37	400	185
+	Brake Frame	7	35	31	245	217
+	Brake Cylinder	29	96	37	2784	1073
+	Strobe Battery	6	72	29	432	174
+	Hub	25	0	14.5	0	362.5
+	CG Plate (EDRs)	10	58	28	580	280
-	Battery	-40	-15	38	600	-1520
-	Oil	-6	6	18.5	-36	-111
-	Interior	-89	57	31	-5073	-2759
-	Fuel	-125	84	20	-10500	-2500
-	Coolant	-10	-20	31	200	-310
-	Exhaust	-53	70	20	-3710	-1060
-	Washer fluid	-8	-18	27	144	-216
BALLAST	Water (fuel tank)				0	0
	Misc. DTS	15	63	30	945	450
	Misc.		0		0	0
					251828.5	118165.5
	TOTAL WEIGHT	4486			56.136536	26.34095

131.75

NCHRP 350 Targets		CURRENT	Difference
Test Inertial Weight	4410 (+/-)100	4486	76.0
Long CG	55 (+/-)6	56.13654	1.13654
Vert CG	28 (+/-)2	26.34095	-1.65905

Note, Long. CG is measured from front axle of test vehicle

Curb Weight

	Left	Right
Front	1352	1358
Rear	1006	1004
FRONT	2710	
REAR	2010	
TOTAL	4720	

Actual test inertial weight

	Left	Right
Front	1318	1273
Rear	905	959
FRONT	2591	
REAR	1864	
TOTAL	4455	

Figure A-1. Vehicle Mass Distribution, Test No. RSMG-1

Test: RSMG-2 **Vehicle:** 1999 GMC C2500

Vehicle CG Determination

VEHICLE	Equipment	Weight	Long CG	Vert CG	HOR M	Vert M
+	Unbalasted Truck	4600	55.62	26.25	255858.5	120750
+	Brake receivers/wires	5	80	37	400	185
+	Brake Frame	7	35	31	245	217
+	Brake Cylinder	29	96	37	2784	1073
+	Strobe Battery	6	72	29	432	174
+	Hub	25	0	14.5	0	362.5
+	CG Plate (EDRs)	10	58	28	580	280
-	Battery	0	-15	38	0	0
-	Oil	-8	6	18.5	-48	-148
-	Interior	-101	57	31	-5757	-3131
-	Fuel	-57	84	20	-4788	-1140
-	Coolant	-14	-20	31	280	-434
-	Exhaust	-56	70	20	-3920	-1120
-	Washer fluid	-12	-18	27	216	-324
BALLAST	Water (fuel tank)				0	0
	Misc. DTS	15	63	30	945	450
	Misc.		0		0	0
					247227.5	117194.5
	TOTAL WEIGHT	4449			55.569229	26.34176

131.75

NCHRP 350 Targets		CURRENT	Difference
Test Inertial Weight	4410 (+/-)100	4449	39.0
Long CG	55 (+/-)6	55.56923	0.56923
Vert CG	28 (+/-)2	26.34176	-1.65824

Note, Long. CG is measured from front axle of test vehicle

Curb Weight

	Left	Right
Front	1343	1315
Rear	969	973
FRONT	2658	
REAR	1942	
TOTAL	4600	

Actual test inertial weight

	Left	Right
Front	1324	1276
Rear	910	930
FRONT	2600	
REAR	1840	
TOTAL	4440	

Figure A-2. Vehicle Mass Distribution, Test No. RSMG-2

Appendix B. Occupant Compartment Deformation Data

VEHICLE PRE/POST CRUSH INFO
Set-1

TEST: RSMG-1
VEHICLE: 1999 Chevy C2500

Note: If impact is on driver side need to enter negative number for Y

POINT	X	Y	Z	X'	Y'	Z'	DEL X	DEL Y	DEL Z
1	27.5	4.75	1	27.5	5	1.25	0	0.25	0.25
2	31	11	0	31.25	10.5	0	0.25	-0.5	0
3	34.75	17	-1.25	35	16.5	-1	0.25	-0.5	0.25
4	32.25	27	0	32	26.5	0	-0.25	-0.5	0
5	23.75	5.75	-2.25	23.75	5.75	-1.5	0	0	0.75
6	27.75	12	-5.75	27.75	11	-5.75	0	-1	0
7	28.25	22.25	-5.5	28	21.5	-5	-0.25	-0.75	0.5
8	28	28.25	-5.5	27.75	27	-5.5	-0.25	-1.25	0
9	18.5	1.5	-2.75	18.5	1.75	-2.25	0	0.25	0.5
10	18.5	6	-3	18.5	6.25	-2.25	0	0.25	0.75
11	20.5	11	-8.25	20.5	10	-8	0	-1	0.25
12	21	18.25	-8.25	21	17	-8.25	0	-1.25	0
13	21.25	23.75	-8	21.25	22.5	-8.25	0	-1.25	-0.25
14	22	29	-7.75	22	28	-8	0	-1	-0.25
15	14	1	-3.25	14	1	-2.75	0	0	0.5
16	13.75	6.25	-3.5	13.75	6	-2.75	0	-0.25	0.75
17	14.75	10.75	-8.25	14.75	9.5	-8	0	-1.25	0.25
18	15.5	17.25	-8.5	15.5	16.5	-7.5	0	-0.75	1
19	15.75	23	-8	15.5	21.75	-8	-0.25	-1.25	0
20	17	28	-8.5	17	27	-9	0	-1	-0.5
21	8	1	-4	8	1	-3.5	0	0	0.5
22	8.75	6	-4	8.75	6	-3	0	0	1
23	9.5	10.75	-8.25	9.5	10.25	-8	0	-0.5	0.25
24	10.5	18.5	-8.25	10.25	17.5	-7.75	-0.25	-1	0.5
25	11.25	28	-8.5	11.25	27	-9	0	-1	-0.5
26	2	1	-4.5	1.75	1	-4	-0.25	0	0.5
27	1.75	5.75	-4.5	1.75	6	-3.5	0	0.25	1
28	1	10	-8	1	9.25	-7	0	-0.75	1
29	0.5	19.5	-7.75	0.5	18.5	-8	0	-1	-0.25
30									

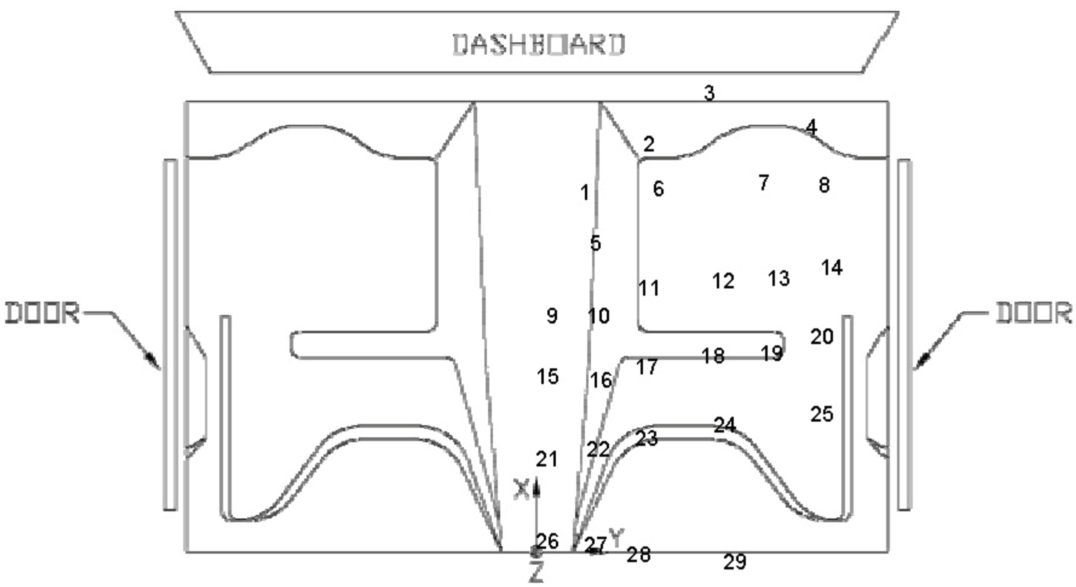


Figure B-1. Occupant Compartment Deformation Data – Set 1, Test No. RSMG-1

VEHICLE PRE/POST CRUSH INFO
Set-2

TEST: RSMG-1
VEHICLE: 1999 Chevy C2500

Note: If impact is on driver side need to enter negative number for Y

	-19.5	-10							
POINT	X	Y	Z	X'	Y'	Z'	DEL X	DEL Y	DEL Z
1	47.75	14.75	0.75	47.75	14.75	1.25	0	0	0.5
2	51.25	21	0	51.5	20.25	0	0.25	-0.75	0
3	55	27	-1	55.25	26.25	-1	0.25	-0.75	0
4	52.5	37	0	52.25	36.25	0	-0.25	-0.75	0
5	44	15.75	-2.5	44	15.5	-1.75	0	-0.25	0.75
6	48	22	-5.75	48	20.75	-5.75	0	-1.25	0
7	48.5	32.25	-5.5	48.25	31.25	-5	-0.25	-1	0.5
8	48.25	38.25	-5.25	48	36.75	-5.25	-0.25	-1.5	0
9	38.75	11.5	-3	38.75	11.5	-2.5	0	0	0.5
10	38.75	16	-3.25	38.75	16	-2.25	0	0	1
11	40.75	21	-8.5	40.75	19.75	-7.75	0	-1.25	0.75
12	41.25	28.25	-8.25	41.25	26.75	-8.25	0	-1.5	0
13	41.5	33.75	-8	41.5	32.25	-8	0	-1.5	0
14	42.25	39	-7.75	42.25	37.75	-8	0	-1.25	-0.25
15	34.25	11	-3.5	34.25	10.75	-3	0	-0.25	0.5
16	34	16.25	-3.75	34	15.75	-2.75	0	-0.5	1
17	35	20.75	-8.5	35	19.25	-8	0	-1.5	0.5
18	35.75	27.25	-8.5	35.75	26.25	-7.75	0	-1	0.75
19	36	33	-8	35.75	31.5	-7.75	-0.25	-1.5	0.25
20	37.25	38	-8.5	37.25	36.75	-9	0	-1.25	-0.5
21	28.25	11	-4.25	28.25	10.75	-3.75	0	-0.25	0.5
22	29	16	-4.25	29	15.75	-3.25	0	-0.25	1
23	29.75	20.75	-8.5	29.75	20	-8	0	-0.75	0.5
24	30.75	28.5	-8.25	30.5	27.25	-7.75	-0.25	-1.25	0.5
25	31.5	38	-8.5	31.5	36.75	-8.75	0	-1.25	-0.25
26	22.25	11	-4.75	22	10.75	-4.25	-0.25	-0.25	0.5
27	22	15.75	-4.5	22	15.75	-3.5	0	0	1
28	21.25	20	-8	21.25	19	-7	0	-1	1
29	20.75	29.5	-7.75	20.75	28.25	-7.75	0	-1.25	0
30									

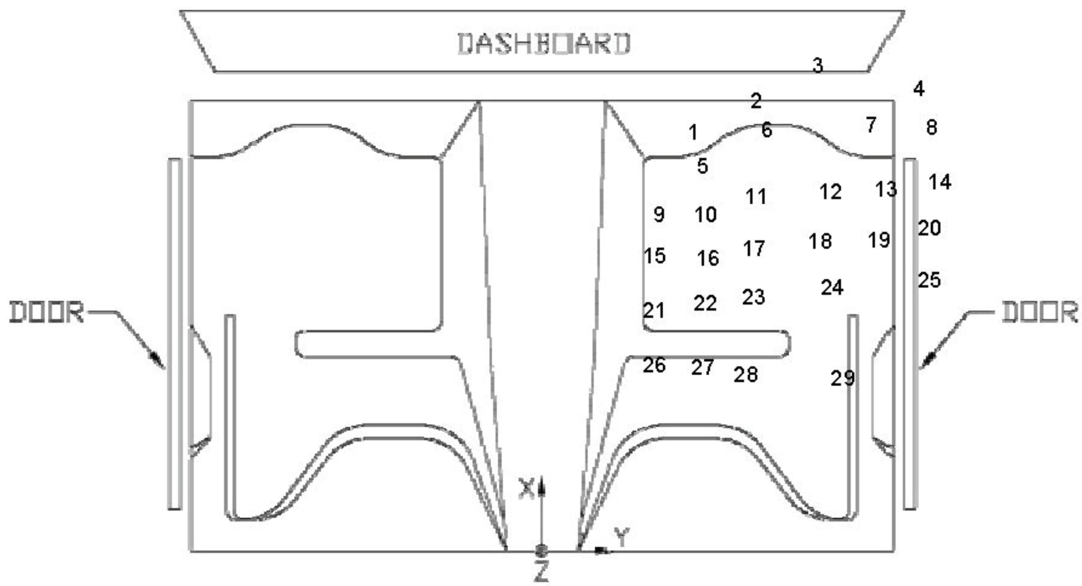


Figure B-2. Occupant Compartment Deformation Data – Set 2, Test No. RSMG-1

Occupant Compartment Deformation Index (OCDI)

Test No. RSMG-1
Vehicle Type: 1999 Chevy C2500

OCDI = XXABCDEFGHI

XX = location of occupant compartment deformation

A = distance between the dashboard and a reference point at the rear of the occupant compartment, such as the top of the rear seat or the rear of the cab on a pickup

B = distance between the roof and the floor panel

C = distance between a reference point at the rear of the occupant compartment and the motor panel

D = distance between the lower dashboard and the floor panel

E = interior width

F = distance between the lower edge of right window and the upper edge of left window

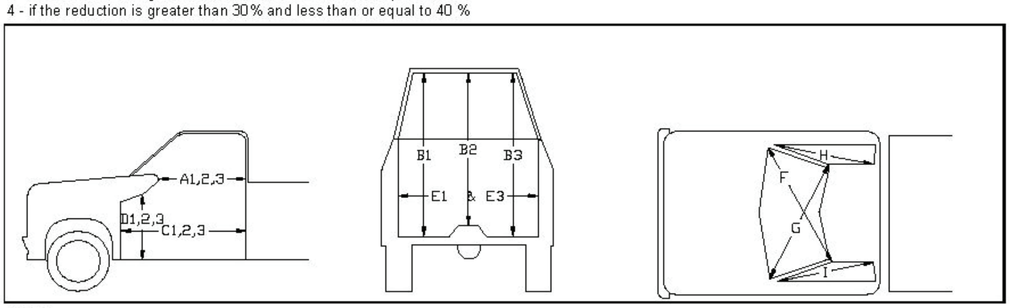
G = distance between the lower edge of left window and the upper edge of right window

H= distance between bottom front corner and top rear corner of the passenger side window

I= distance between bottom front corner and top rear corner of the driver side window

Severity Indices

0 - if the reduction is less than 3%
1 - if the reduction is greater than 3% and less than or equal to 10 %
2 - if the reduction is greater than 10% and less than or equal to 20 %
3 - if the reduction is greater than 20% and less than or equal to 30 %
4 - if the reduction is greater than 30% and less than or equal to 40 %



where,
1 = Passenger Side
2 = Middle
3 = Driver Side

Location:

Measurement	Pre-Test (in.)	Post-Test (in.)	Change (in.)	% Difference	Severity Index
A1	43.25	43.50	0.25	0.58	0
A2	41.50	42.00	0.50	1.20	0
A3	43.50	43.50	0.00	0.00	0
B1	44.00	44.00	0.00	0.00	0
B2	39.50	39.00	-0.50	-1.27	0
B3	44.25	44.25	0.00	0.00	0
C1	52.50	52.50	0.00	0.00	0
C2	44.25	44.00	-0.25	-0.56	0
C3	53.00	53.00	0.00	0.00	0
D1	22.50	22.50	0.00	0.00	0
D2	16.50	16.50	0.00	0.00	0
D3	22.25	22.50	0.25	1.12	0
E1	62.25	62.00	-0.25	-0.40	0
E3	63.50	63.50	0.00	0.00	0
F	57.00	56.75	-0.25	-0.44	0
G	57.00	57.00	0.00	0.00	0
H	41.50	41.50	0.00	0.00	0
I	41.25	41.25	0.00	0.00	0

Note: Maximum sevrity index for each variable (A-I) is used for determination of final OCDI value

	XX	A	B	C	D	E	F	G	H	I
Final OCDI:	RF	0	0	0	0	0	0	0	0	0

Figure B-3. Occupant Compartment Deformation Index (OCDI), Test No. RSMG-1

VEHICLE PRE/POST CRUSH INFO
Set-1

TEST: RSMG-2
VEHICLE: 1999 Chevy C2500

Note: If impact is on driver side need to enter negative number for Y

POINT	X	Y	Z	X'	Y'	Z'	DEL X	DEL Y	DEL Z
1	30.5	9.5	0	31	9.5	0	0.5	0	0
2	33.75	16	-1.25	34	16	-1.5	0.25	0	-0.25
3	34	21.75	-1.25	33.75	22	-1.25	-0.25	0.25	0
4	33	25.75	-0.25	32.75	25.75	-0.5	-0.25	0	-0.25
5	32.5	29.5	0.25	32.75	29.5	0	0.25	0	-0.25
6	24.25	6.5	-2.5	24.25	6.5	-2	0	0	0.5
7	26.25	11	-7.25	26	10.5	-7	-0.25	-0.5	0.25
8	26.75	16.5	-7	26.75	15.5	-7	0	-1	0
9	26.5	24	-7	26.25	23.5	-6.75	-0.25	-0.5	0.25
10	27.5	29	-5.5	27.5	29	-5.75	0	0	-0.25
11	19.75	6.75	-3.25	19.75	6.5	-2.75	0	-0.25	0.5
12	19.5	10.75	-8.5	19.5	10.5	-8.5	0	-0.25	0
13	19.75	16.75	-8.75	19.75	16.5	-8.5	0	-0.25	0.25
14	20.25	24.5	-8	20.25	24	-8.25	0	-0.5	-0.25
15	21	30.5	-8.25	21	30	-8.5	0	-0.5	-0.25
16	15	6.75	-4	15	6.75	-3.5	0	0	0.5
17	15.5	11.25	-9	15.5	11	-8.5	0	-0.25	0.5
18	16	17	-9	16	16.5	-9	0	-0.5	0
19	16.25	24.5	-8.5	16.25	24.25	-8.5	0	-0.25	0
20	17	29.5	-8.75	17	29	-9.25	0	-0.5	-0.5
21	10	6.75	-5	10	6.75	-4.5	0	0	0.5
22	10.5	11.25	-9.5	10.5	11	-8.75	0	-0.25	0.75
23	10.5	17.25	-9.5	10.5	17	-9	0	-0.25	0.5
24	11.5	25.5	-9	11.75	25	-9	0.25	-0.5	0
25	1	5.75	-6.5	1	5.75	-5.75	0	0	0.75
26	1.25	11.5	-10	1.5	11.25	-9	0.25	-0.25	1
27	1	17	-9.5	1	16.75	-9	0	-0.25	0.5
28	1	21	-9.25	1	21	-9.25	0	0	0
29							0	0	0
30									

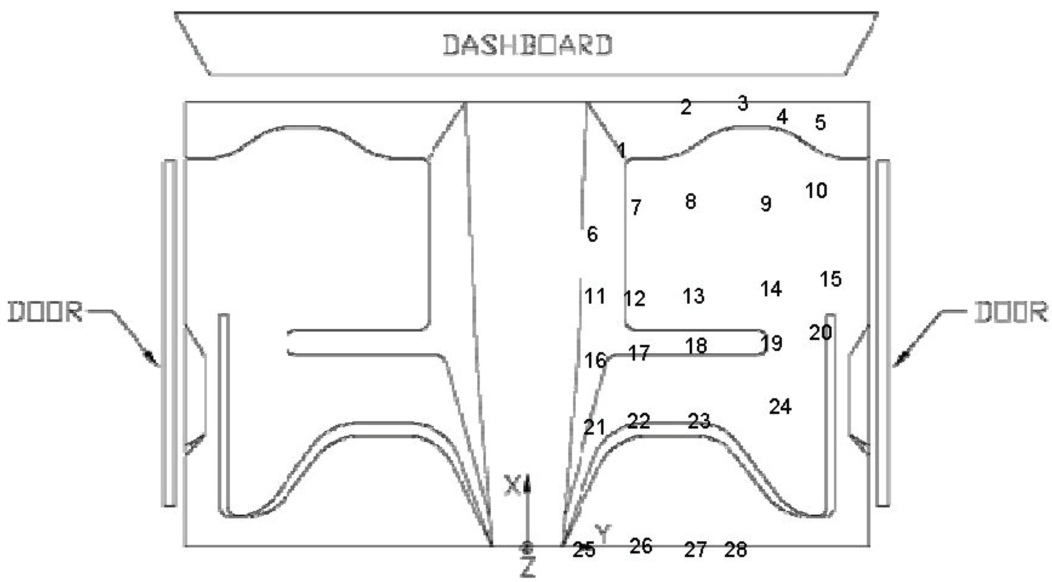


Figure B-4. Occupant Compartment Deformation Data – Set 1, Test No. RSMG-2

VEHICLE PRE/POST CRUSH INFO
Set-2

TEST: RSMG-2
VEHICLE: 1999 Chevy C2500

Note: If impact is on driver side need to enter negative number for Y

POINT	X	Y	Z	X'	Y'	Z'	DEL X	DEL Y	DEL Z
1	11.25	18	0	11.75	18	0	0.5	0	0
2	14.5	24.5	-1.5	14.75	24.5	-1	0.25	0	0.5
3	14.75	30.25	-1	14.5	30.5	-0.5	-0.25	0.25	0.5
4	13.75	34.25	0	13.5	34.25	0.25	-0.25	0	0.25
5	13.25	38	0.5	13.5	38	0.75	0.25	0	0.25
6	5	15	-2.5	5	15	-2	0	0	0.5
7	7	19.5	-7.25	6.75	19	-7	-0.25	-0.5	0.25
8	7.5	25	-7	7.5	24	-7	0	-1	0
9	7.25	32.5	-6.75	7	32	-6.5	-0.25	-0.5	0.25
10	8.25	37.5	-5.25	8.25	37.5	-5	0	0	0.25
11	0.5	15.25	-3.25	0.5	15	-2.5	0	-0.25	0.75
12	0.25	19.25	-8.5	0.25	19	-8.25	0	-0.25	0.25
13	0.5	25.25	-8.75	0.5	25	-8.25	0	-0.25	0.5
14	1	33	-8	1	32.5	-7.75	0	-0.5	0.25
15	1.75	39	-8	1.75	38.5	-8	0	-0.5	0
16	-4.25	15.25	-4	-4.25	15.25	-3.5	0	0	0.5
17	-3.75	19.75	-9	-3.75	19.5	-8.25	0	-0.25	0.75
18	-3.25	25.5	-9	-3.25	25	-8.5	0	-0.5	0.5
19	-3	33	-8.5	-3	32.75	-8.5	0	-0.25	0
20	-2.25	38	-8.75	-2.25	37.5	-8.75	0	-0.5	0
21	-9.25	15.25	-5	-9.25	15.25	-4.25	0	0	0.75
22	-8.75	19.75	-9.25	-8.75	19.5	-8.75	0	-0.25	0.5
23	-8.75	25.75	-9.5	-8.75	25.5	-9	0	-0.25	0.5
24	-7.75	34	-9	-7.5	33.5	-8.75	0.25	-0.5	0.25
25	-18.25	14.25	-6	-18.25	14.25	-5.75	0	0	0.25
26	-18	20	-9.75	-17.75	19.75	-8.75	0.25	-0.25	1
27	-18.25	25.5	-9.75	-18.25	25.25	-9.25	0	-0.25	0.5
28	-18.25	29.5	-9.5	-18.25	29.5	-9.25	0	0	0.25
29							0	0	0
30									

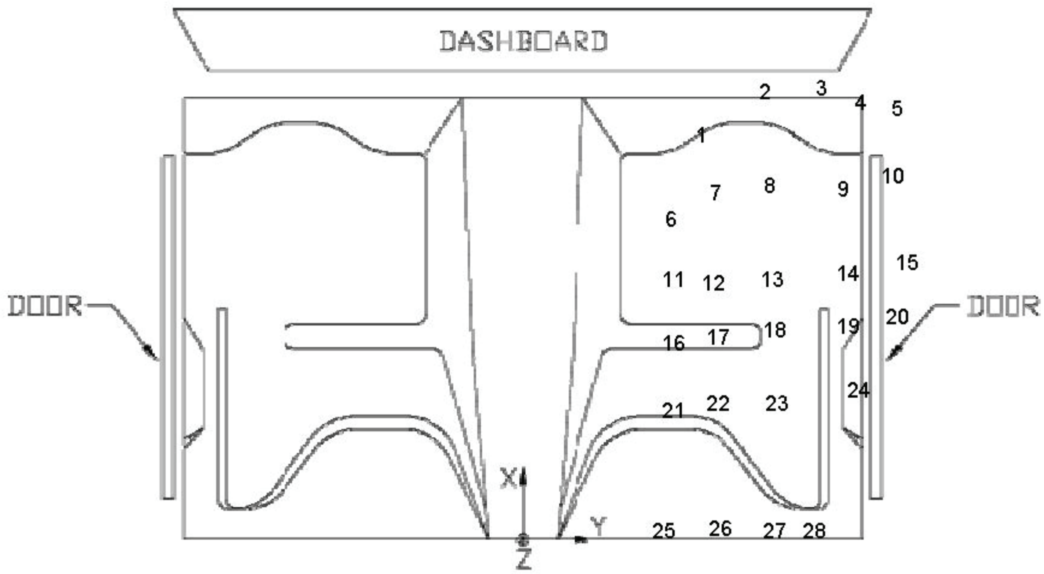


Figure B-5. Occupant Compartment Deformation Data – Set 2, Test No. RSMG-2

Occupant Compartment Deformation Index (OCDI)

Test No. RSMG-2
Vehicle Type: 1999 Chevy C2500

OCDI = XXABCDEFGHI

XX = location of occupant compartment deformation

A = distance between the dashboard and a reference point at the rear of the occupant compartment, such as the top of the rear seat or the rear of the cab on a pickup

B = distance between the roof and the floor panel

C = distance between a reference point at the rear of the occupant compartment and the motor panel

D = distance between the lower dashboard and the floor panel

E = interior width

F = distance between the lower edge of right window and the upper edge of left window

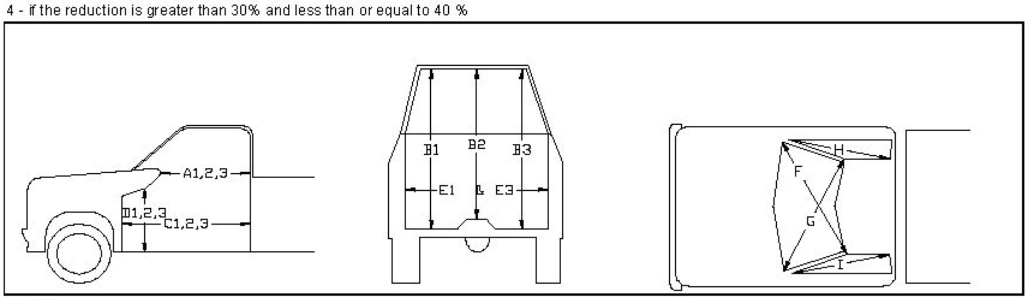
G = distance between the lower edge of left window and the upper edge of right window

H= distance between bottom front corner and top rear corner of the passenger side window

I= distance between bottom front corner and top rear corner of the driver side window

Severity Indices

0 - if the reduction is less than 3%
1 - if the reduction is greater than 3% and less than or equal to 10 %
2 - if the reduction is greater than 10% and less than or equal to 20 %
3 - if the reduction is greater than 20% and less than or equal to 30 %
4 - if the reduction is greater than 30% and less than or equal to 40 %



where,
1 = Passenger Side
2 = Middle
3 = Driver Side

Location:

Measurement	Pre-Test (in.)	Post-Test (in.)	Change (in.)	% Difference	Severity Index
A1	37.00	37.00	0.00	0.00	0
A2	41.25	41.25	0.00	0.00	0
A3	38.25	38.00	-0.25	-0.65	0
B1	44.50	44.25	-0.25	-0.56	0
B2	40.25	40.00	-0.25	-0.62	0
B3	44.75	44.50	-0.25	-0.56	0
C1	58.00	58.00	0.00	0.00	0
C2	52.25	52.50	0.25	0.48	0
C3	57.75	57.50	-0.25	-0.43	0
D1	21.50	21.50	0.00	0.00	0
D2	16.50	16.00	-0.50	-3.03	1
D3	22.25	22.25	0.00	0.00	0
E1	62.50	62.00	-0.50	-0.80	0
E3	63.50	63.50	0.00	0.00	0
F	56.00	56.00	0.00	0.00	0
G	56.50	56.50	0.00	0.00	0
H	40.25	39.50	-0.75	-1.86	0
I	40.25	40.25	0.00	0.00	0

Note: Maximum sevrity index for each variable (A-I) is used for determination of final OCDI value

	XX	A	B	C	D	E	F	G	H	I
Final OCDI:	RF	0	0	0	1	0	0	0	0	0

Figure B-6. Occupant Compartment Deformation Index (OCDI), Test No. RSMG-2

Appendix C. Accelerometer and Rate Transducer Data Plots, Test No. RSMG-1

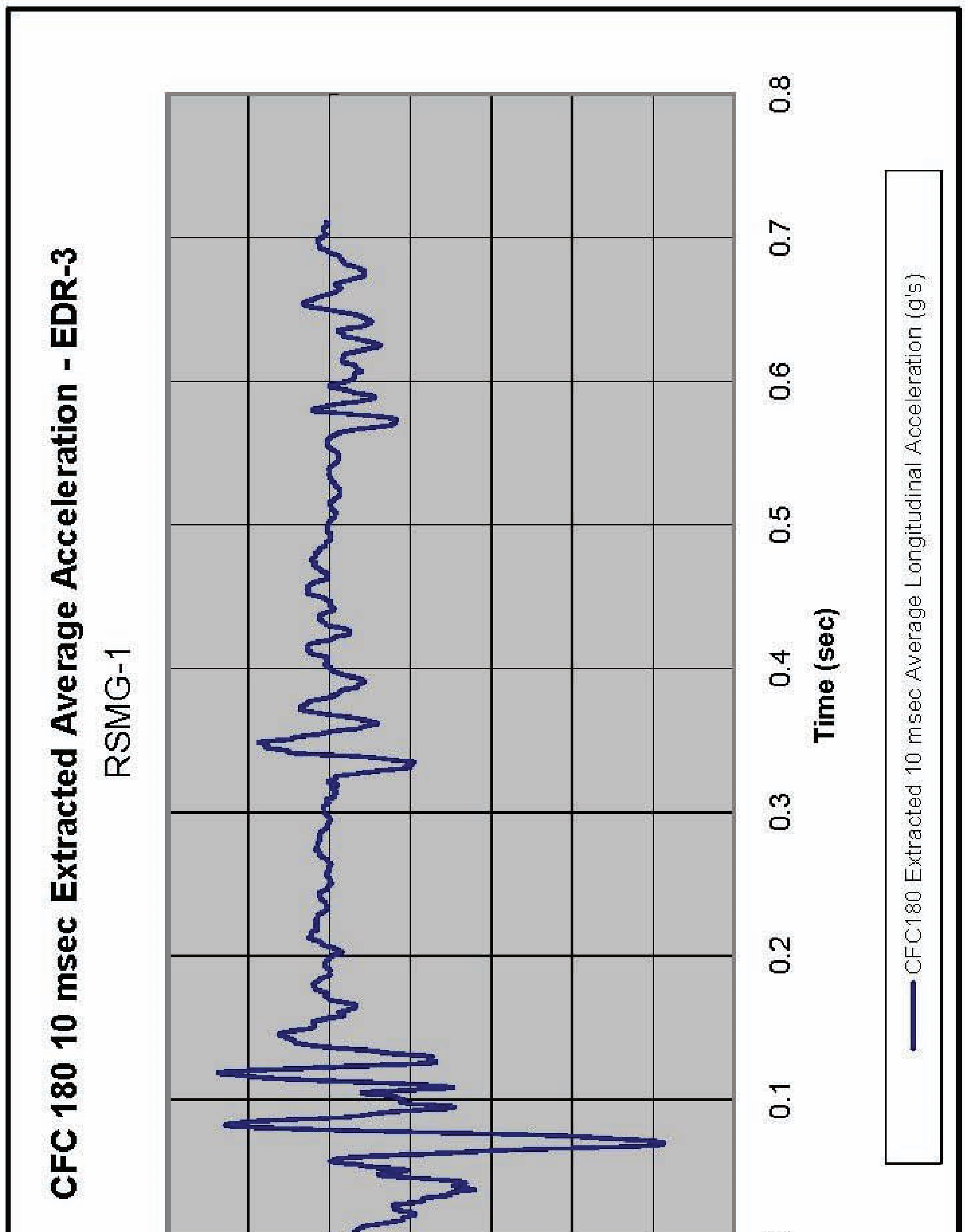


Figure C-1. Graph of 10-ms Average Longitudinal Acceleration – EDR-3, Test No. RSMG-1

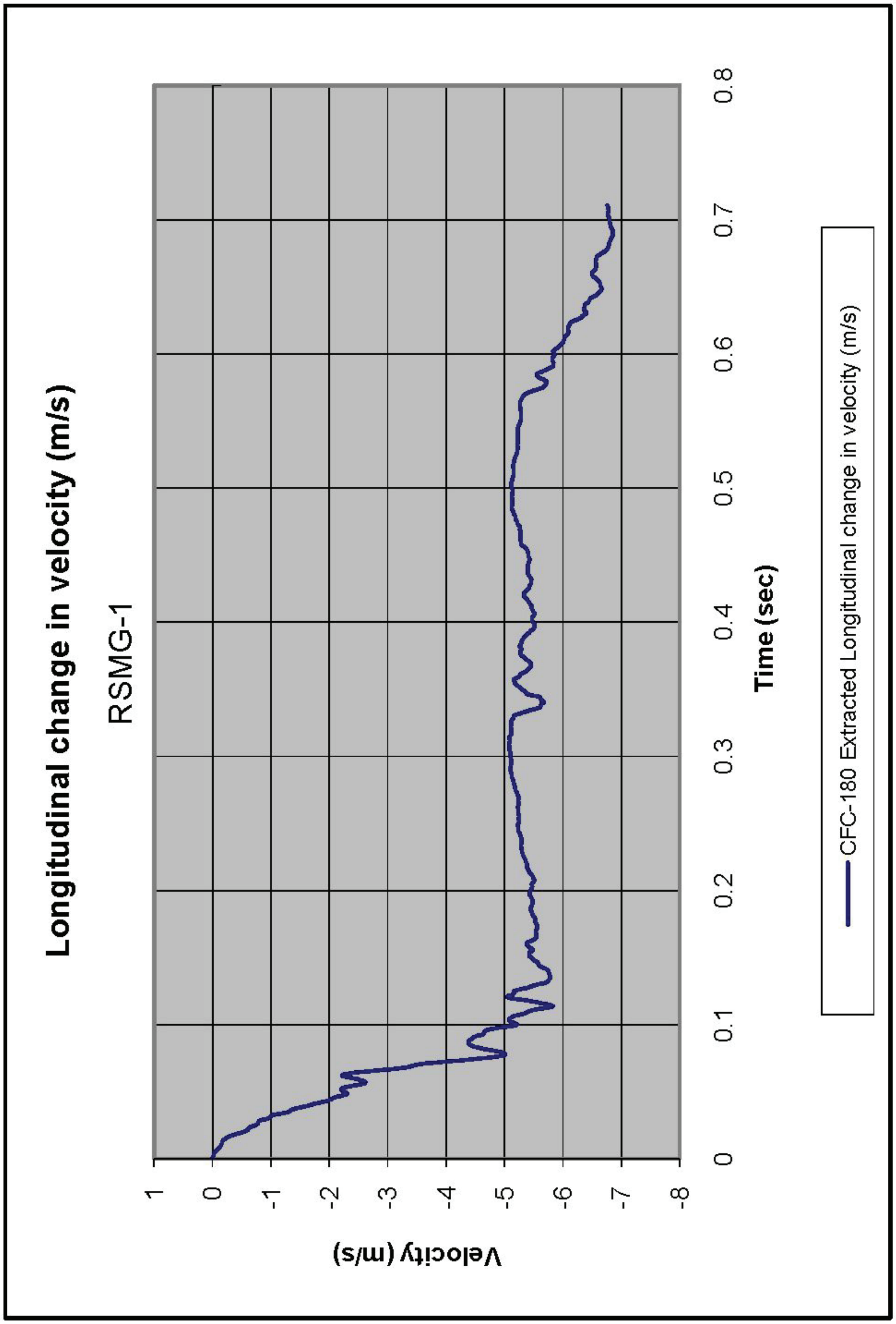


Figure C-2. Graph of Longitudinal Occupant Impact Velocity – EDR-3, Test No. RSMG-1

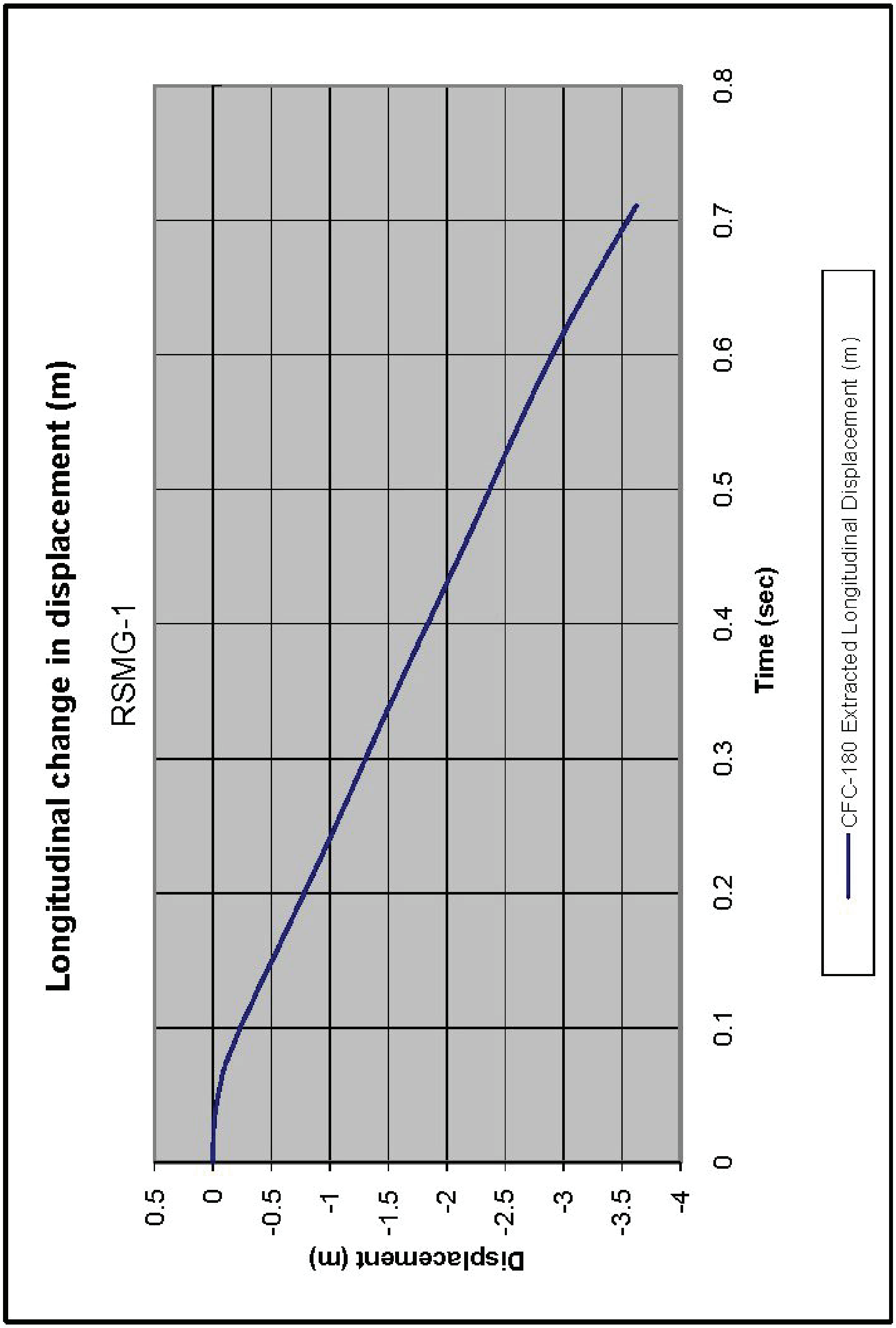


Figure C-3. Graph of Longitudinal Occupant Displacement – EDR-3, Test No. RSMG-1

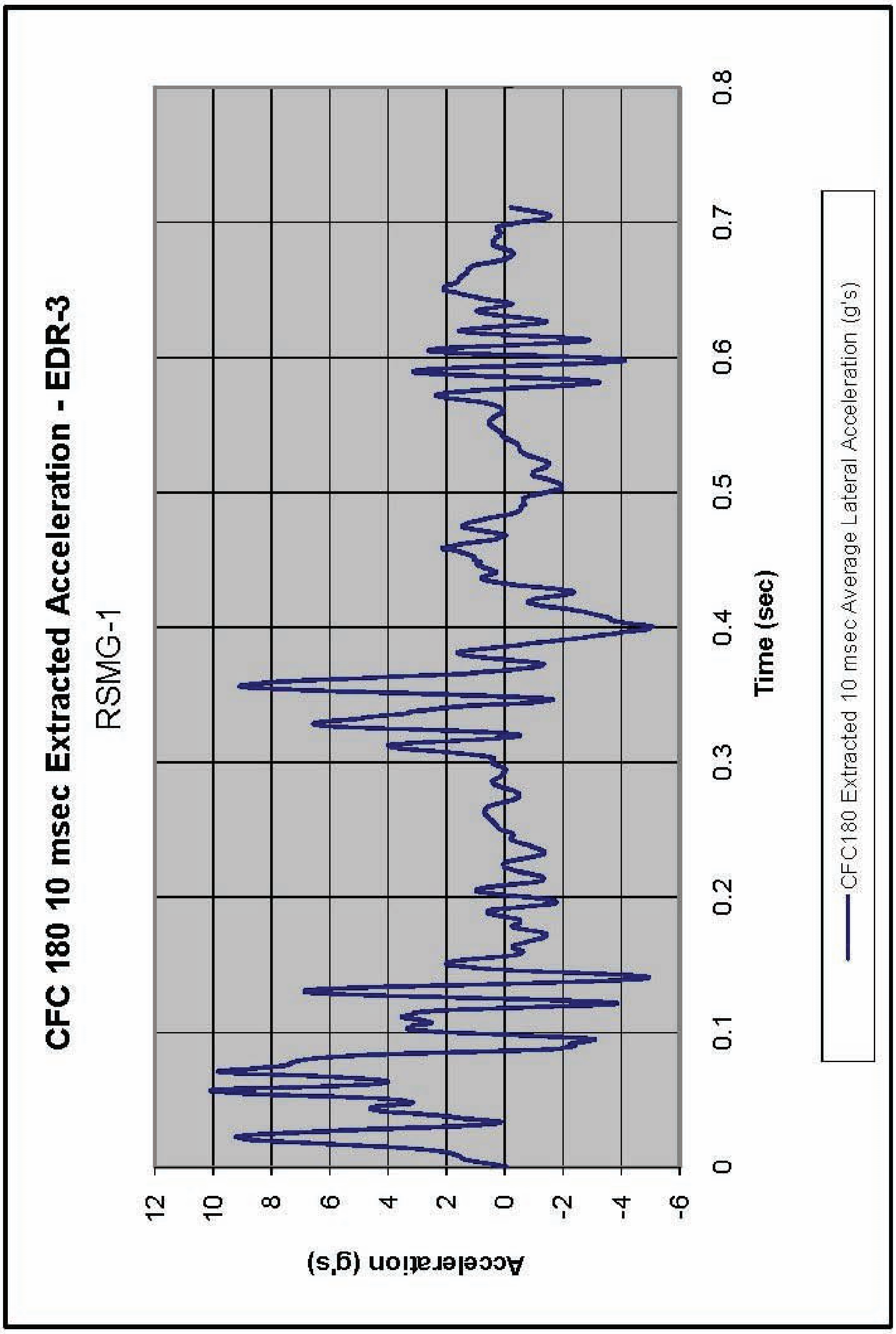


Figure C-4. Graph of 10 ms Average Lateral Acceleration – EDR-3, Test No. RSMG-1

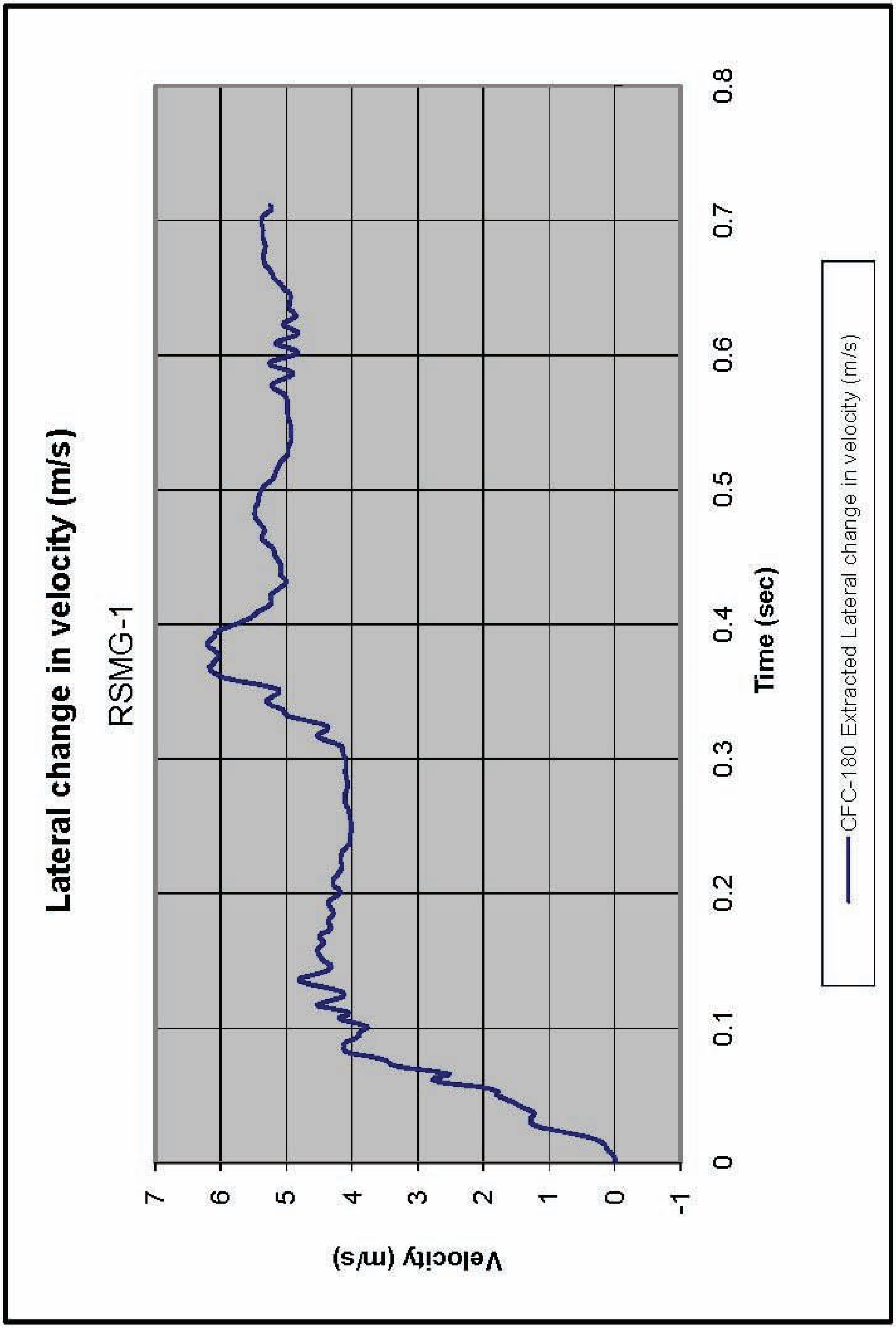


Figure C-5. Graph of Lateral Occupant Impact Velocity – EDR-3, Test No. RSMG-1

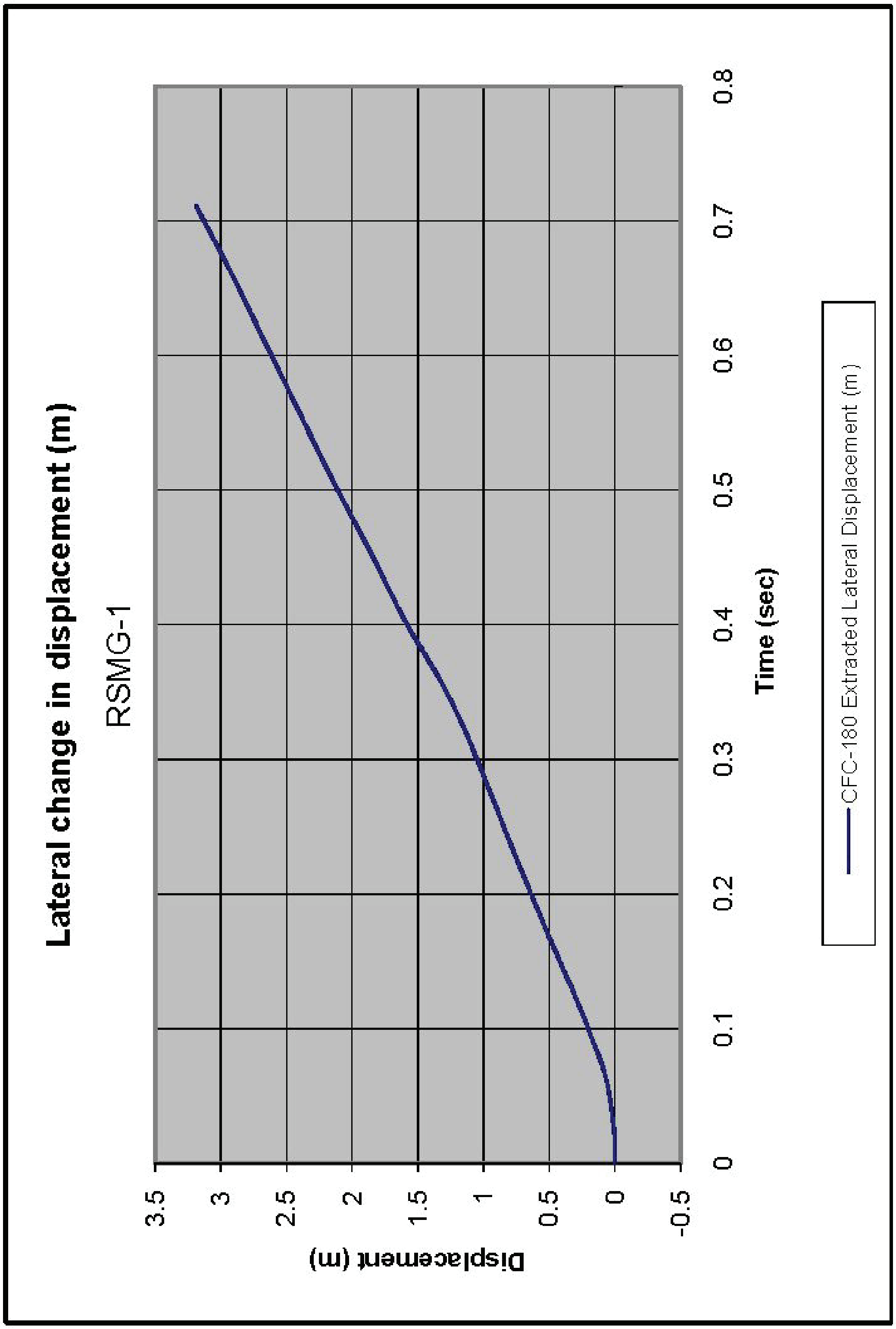


Figure C-6. Graph of Lateral Occupant Displacement – EDR-3, Test No. RSMG-1

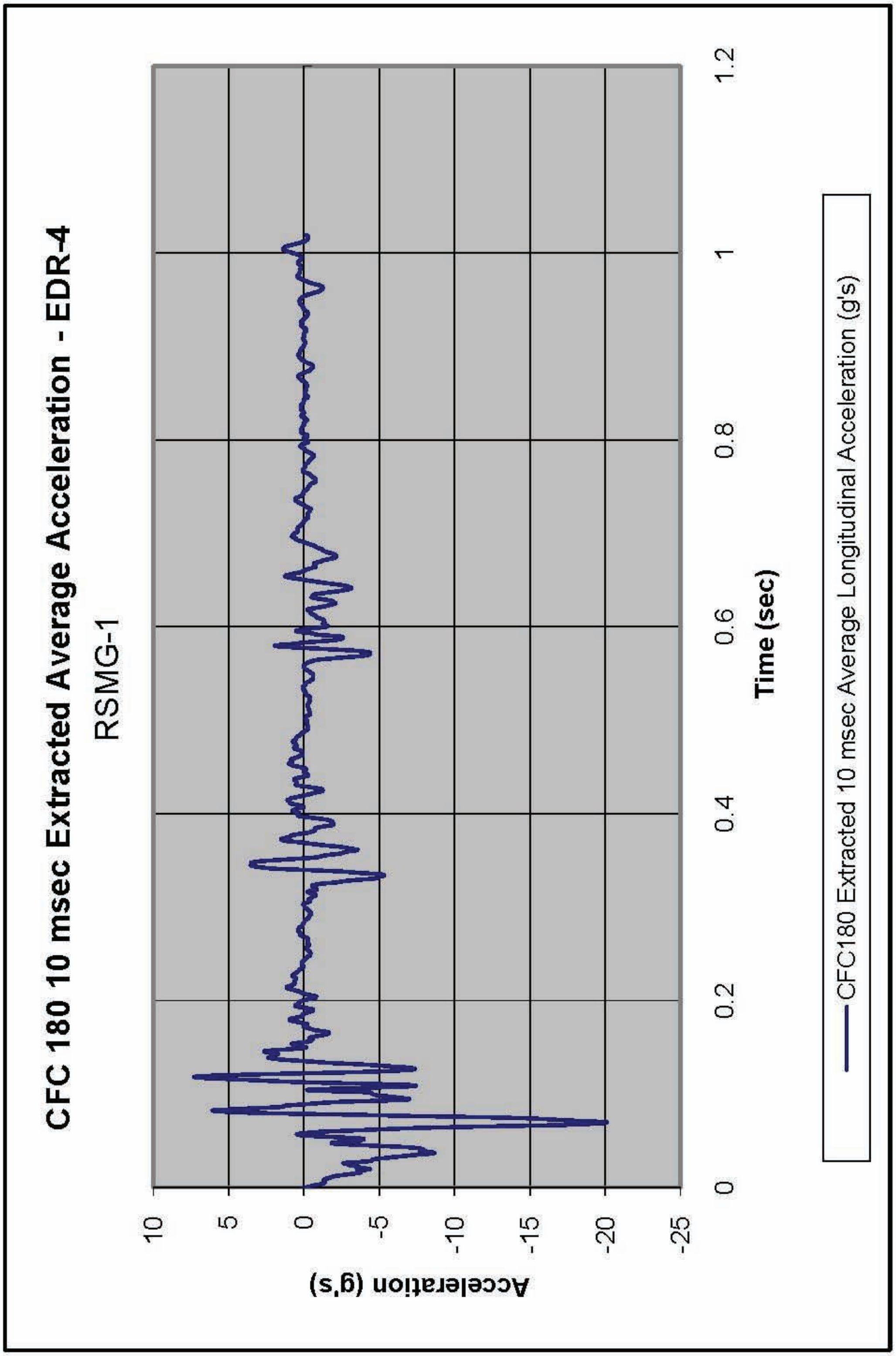


Figure C-7. Graph of 10-ms Average Longitudinal Acceleration – EDR-4, Test No. RSMG-1

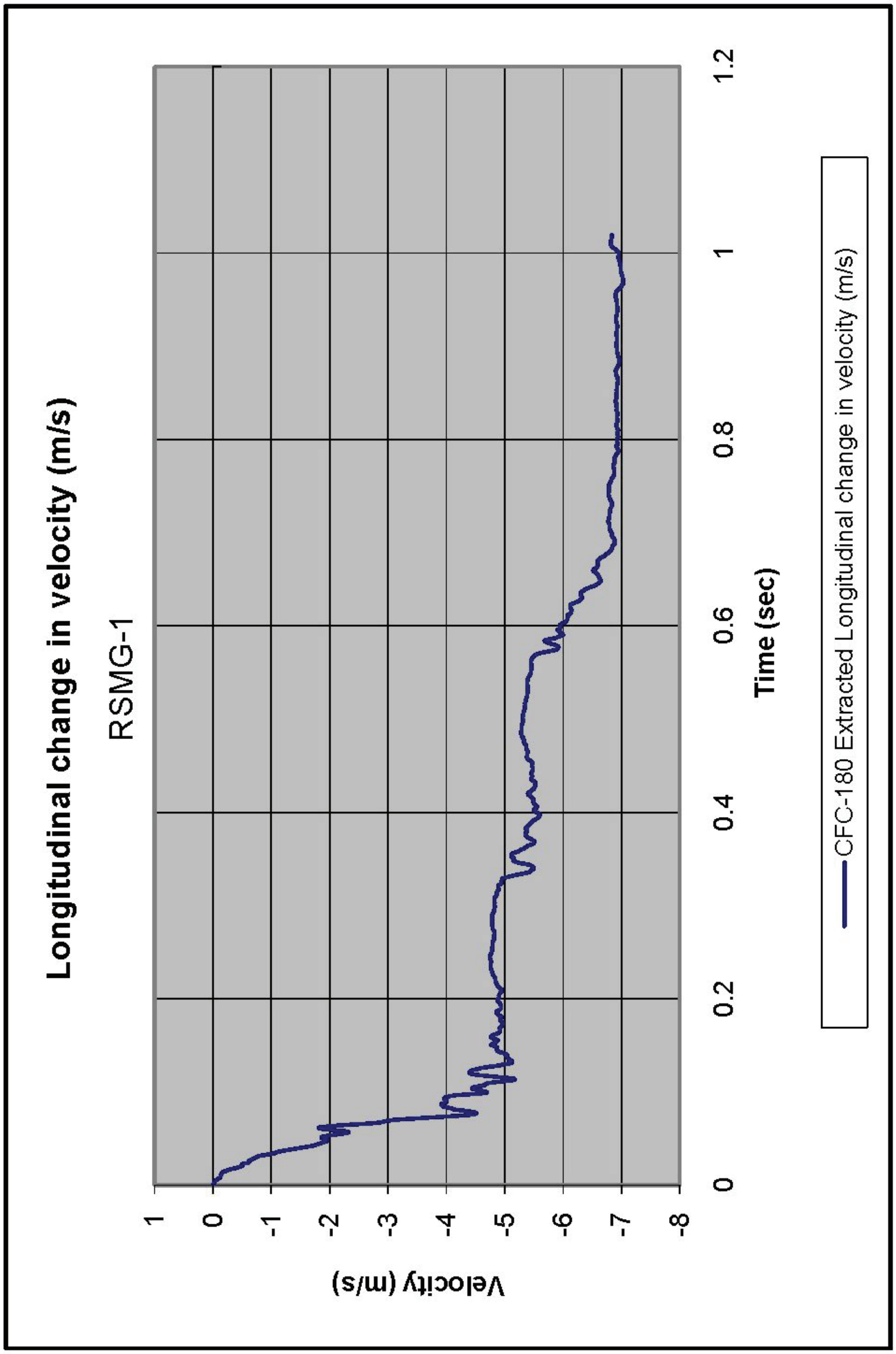


Figure C-8. Graph of Longitudinal Occupant Impact Velocity – EDR-4, Test No. RSMG-1

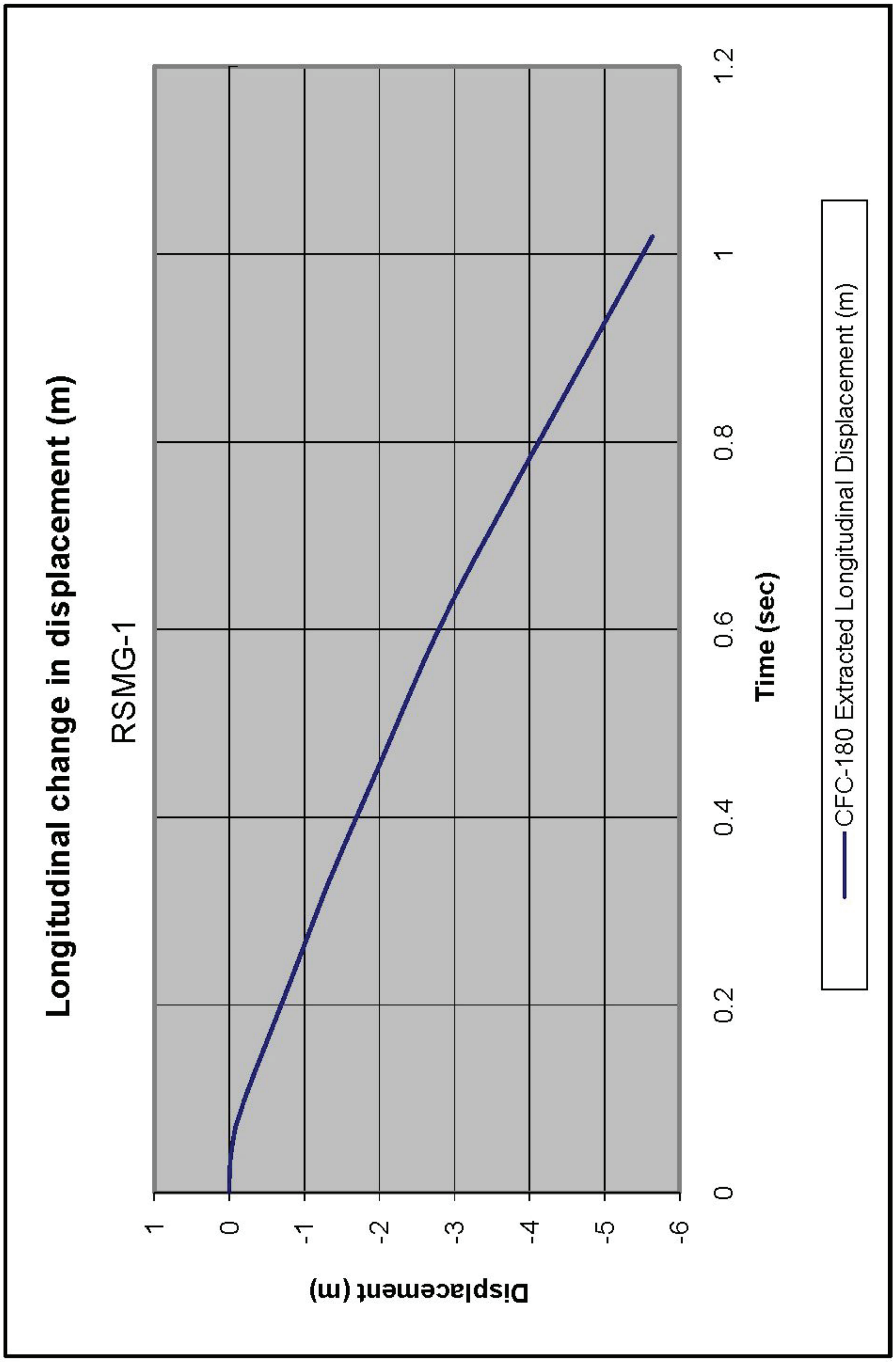


Figure C-9. Graph of Longitudinal Occupant Displacement – EDR-4, Test No. RSMG-1

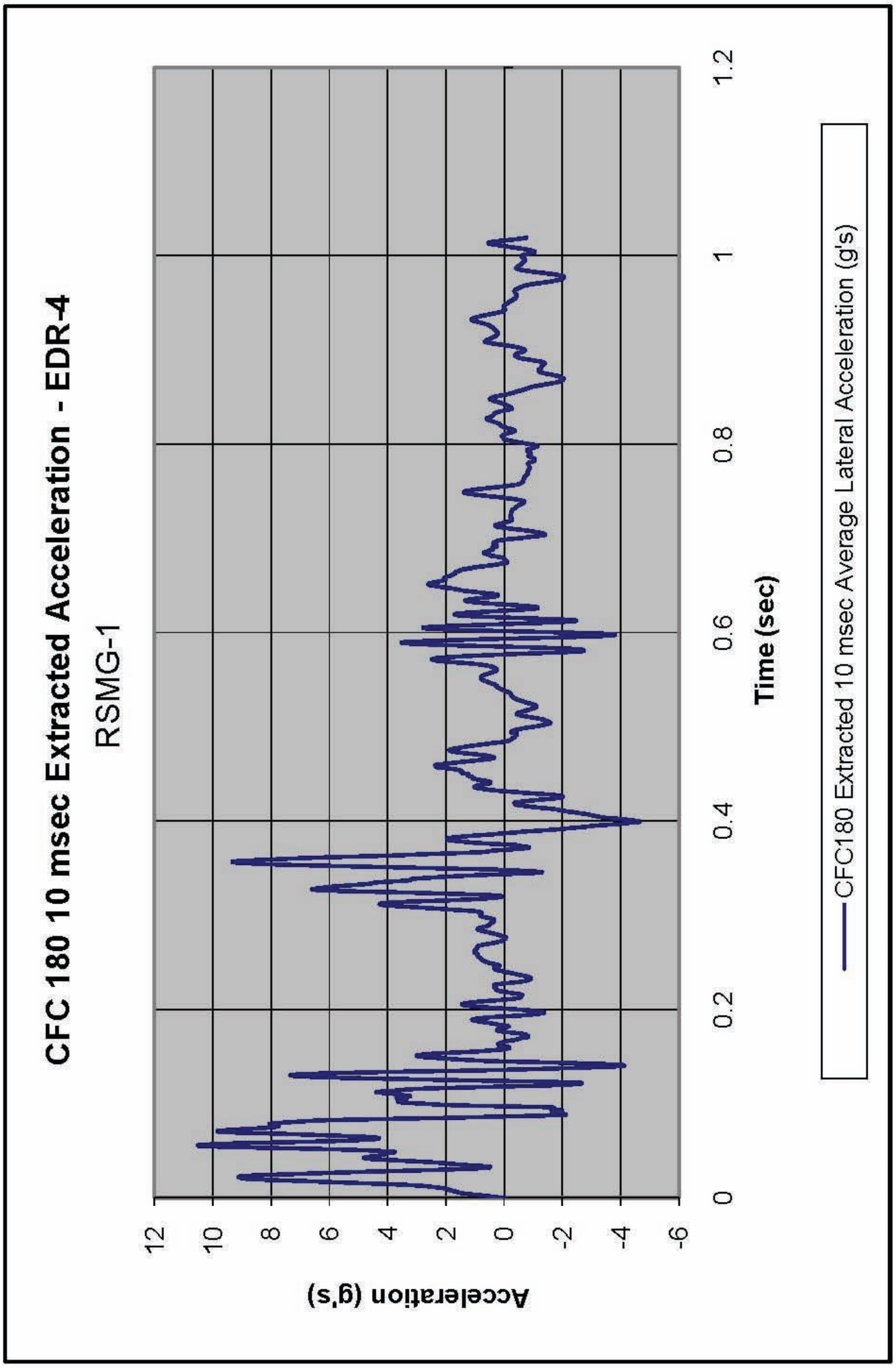


Figure C-10. Graph of 10 ms Average Lateral Acceleration – EDR-4, Test No. RSMG-1

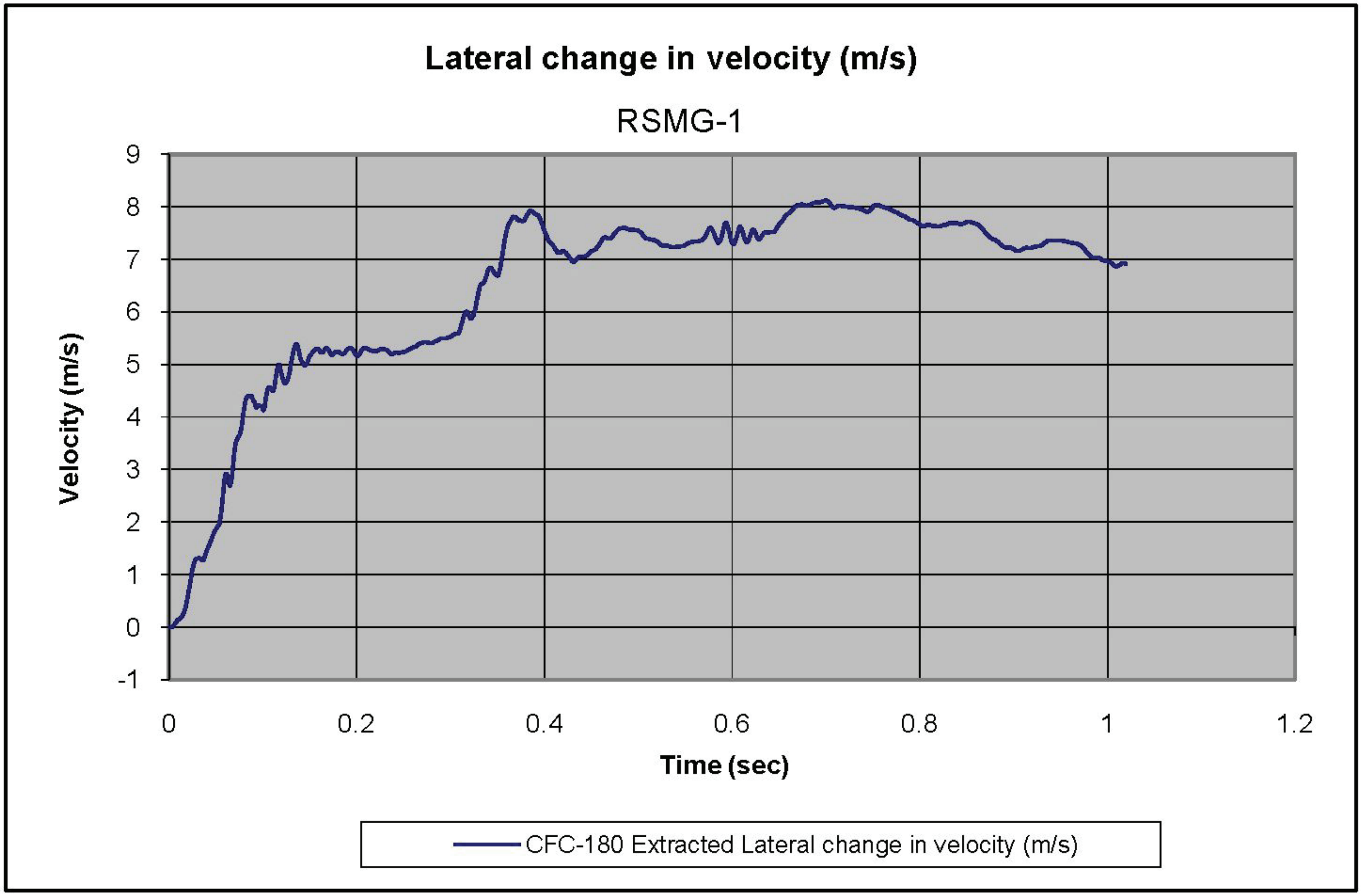


Figure C-11. Graph of Lateral Occupant Impact Velocity – EDR-4, Test No. RSMG-1

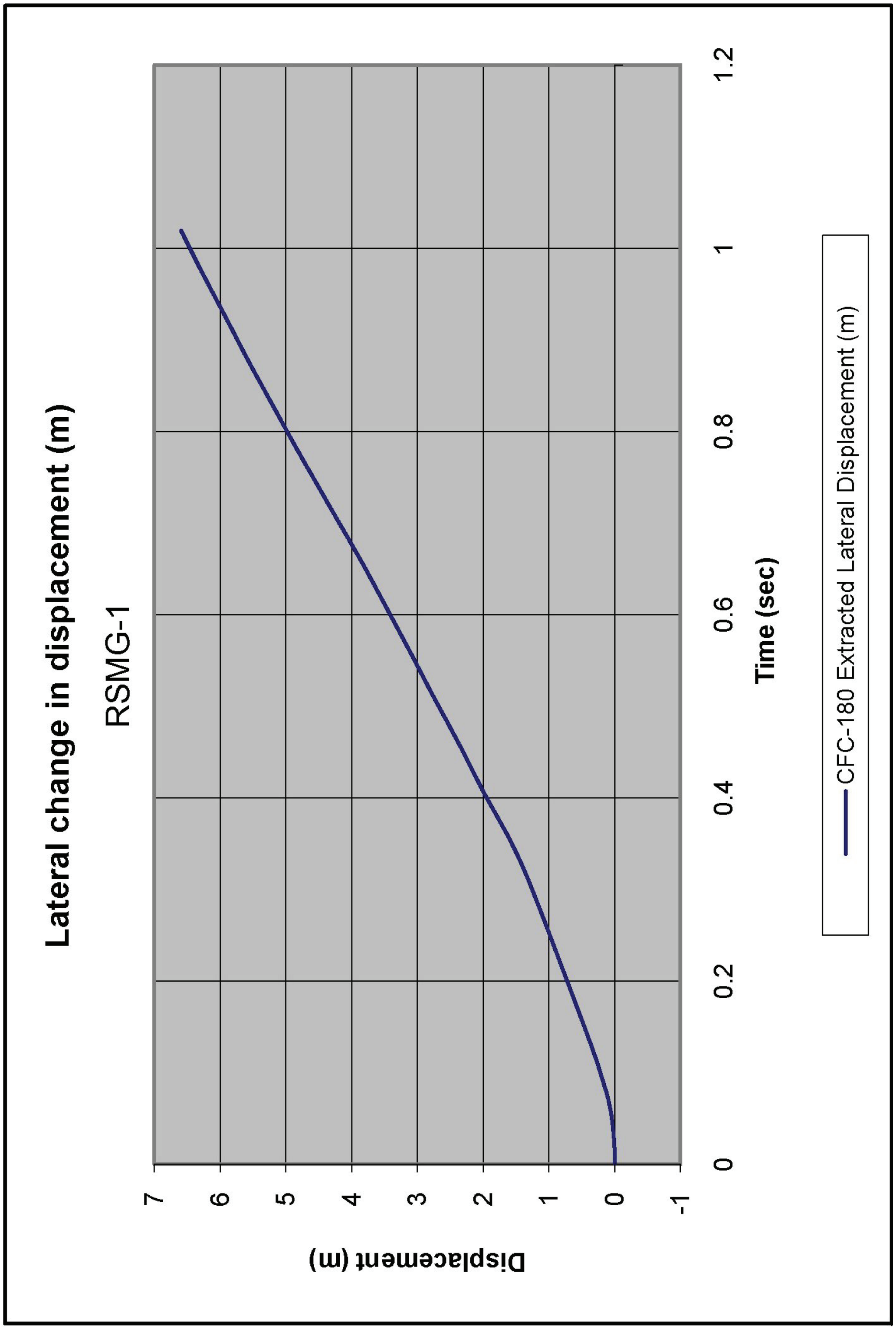


Figure C-12. Graph of Lateral Occupant Displacement – EDR-4, Test No. RSMG-1

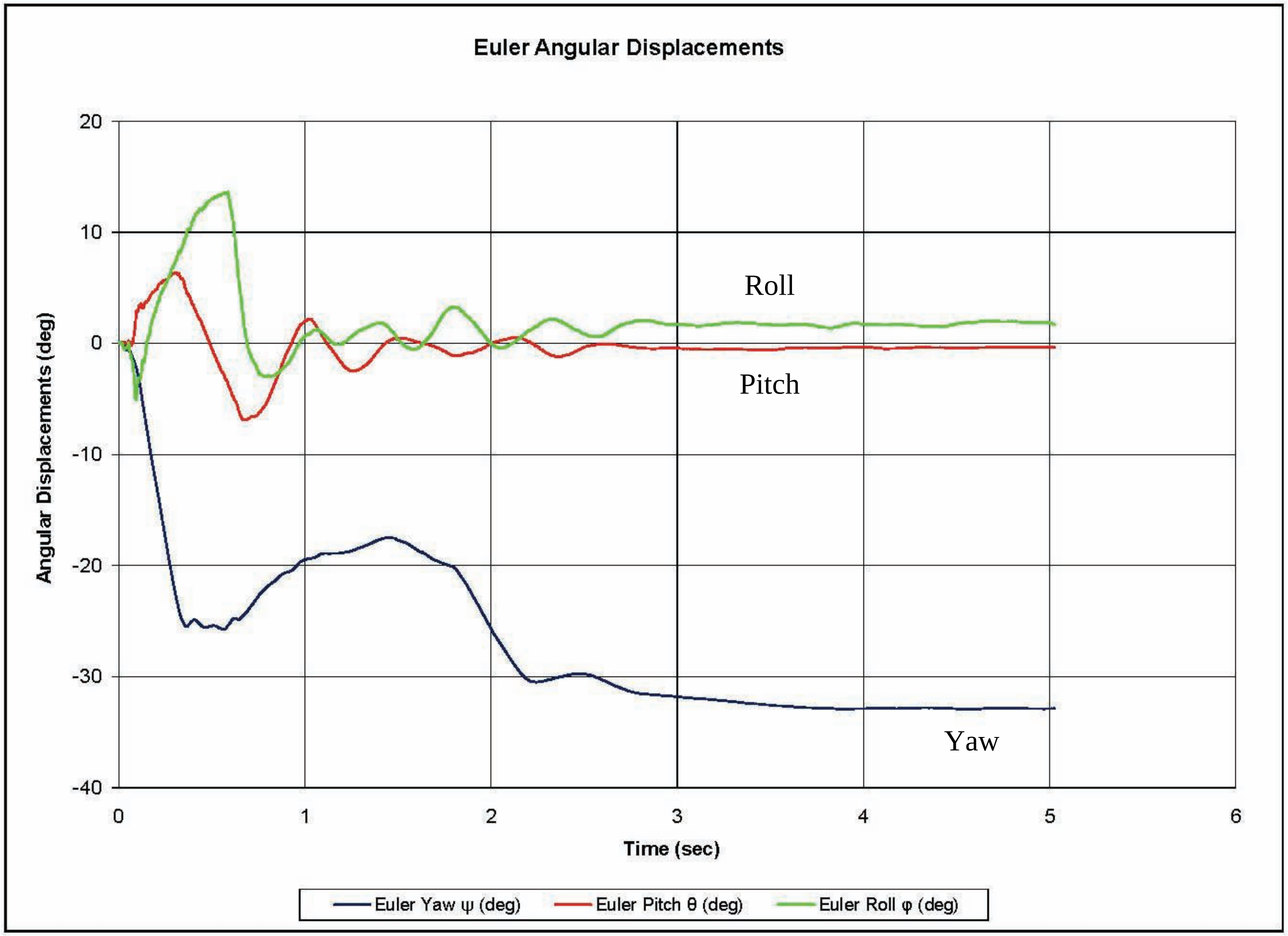


Figure C-13. Graph of Euler Angular Displacements – EDR-4, Test No. RSMG-1

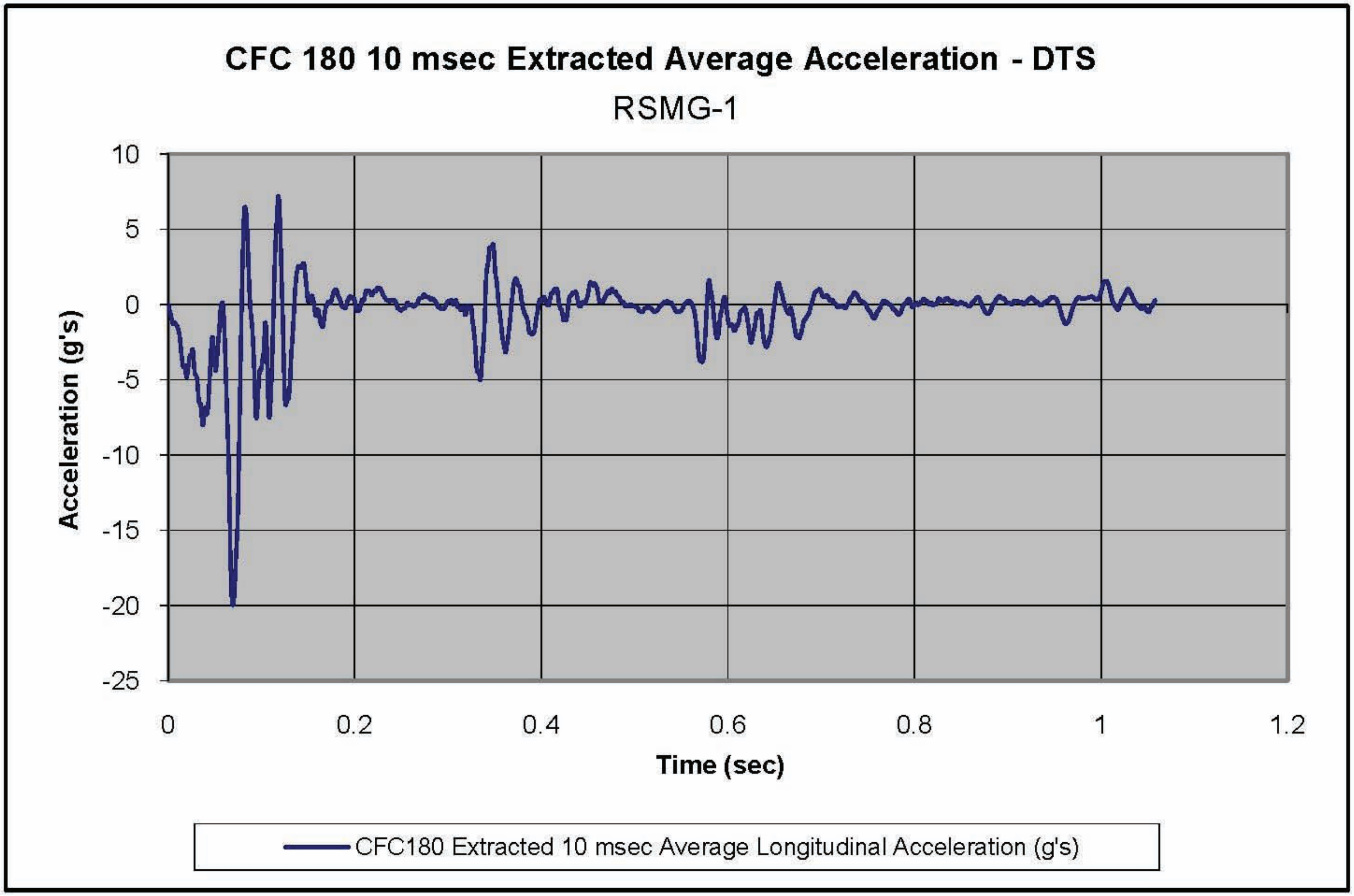


Figure C-14. Graph of 10-ms Average Longitudinal Acceleration – DTS, Test No. RSMG-1

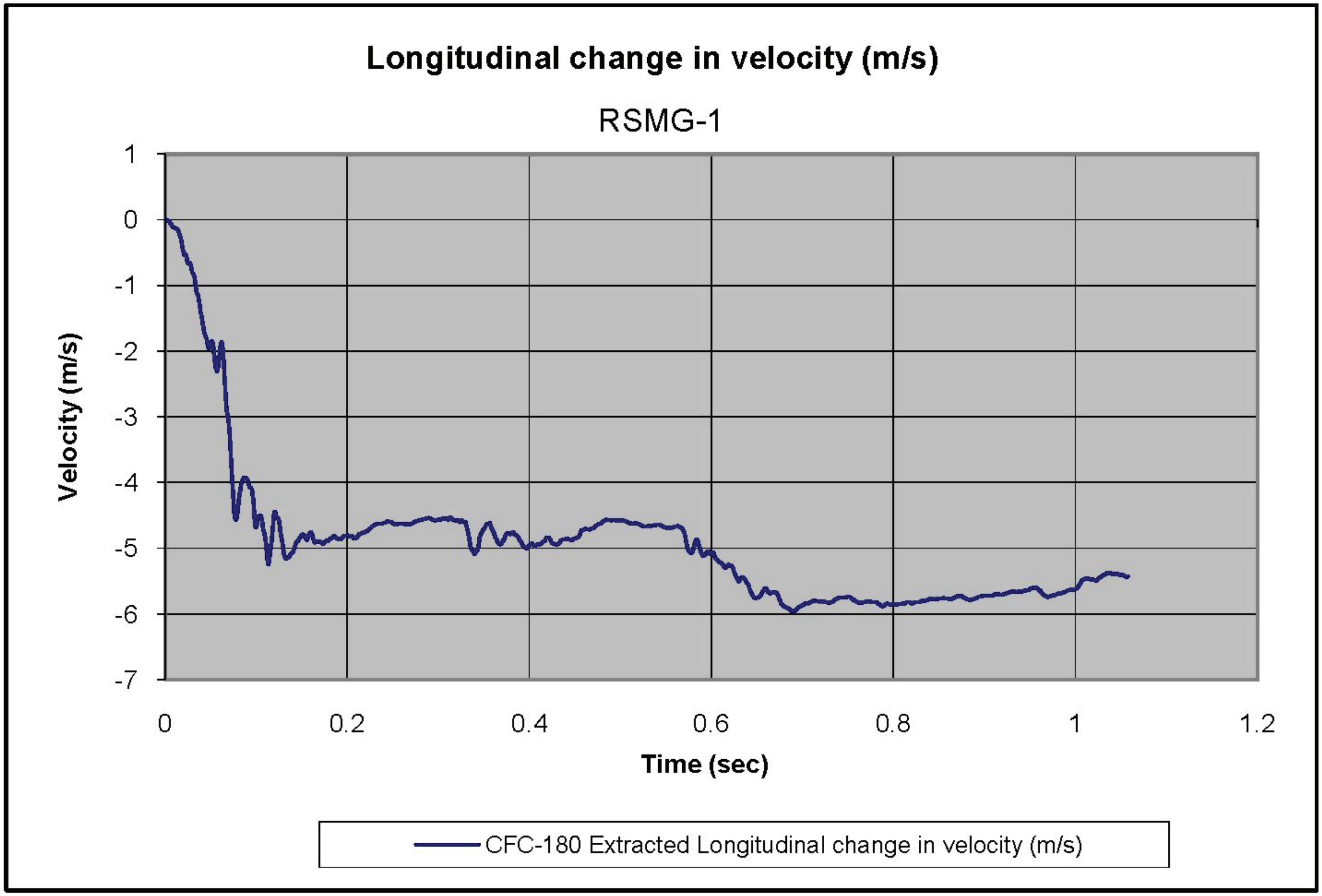


Figure C-15. Graph of Longitudinal Occupant Impact Velocity – DTS, Test No. RSMG-1

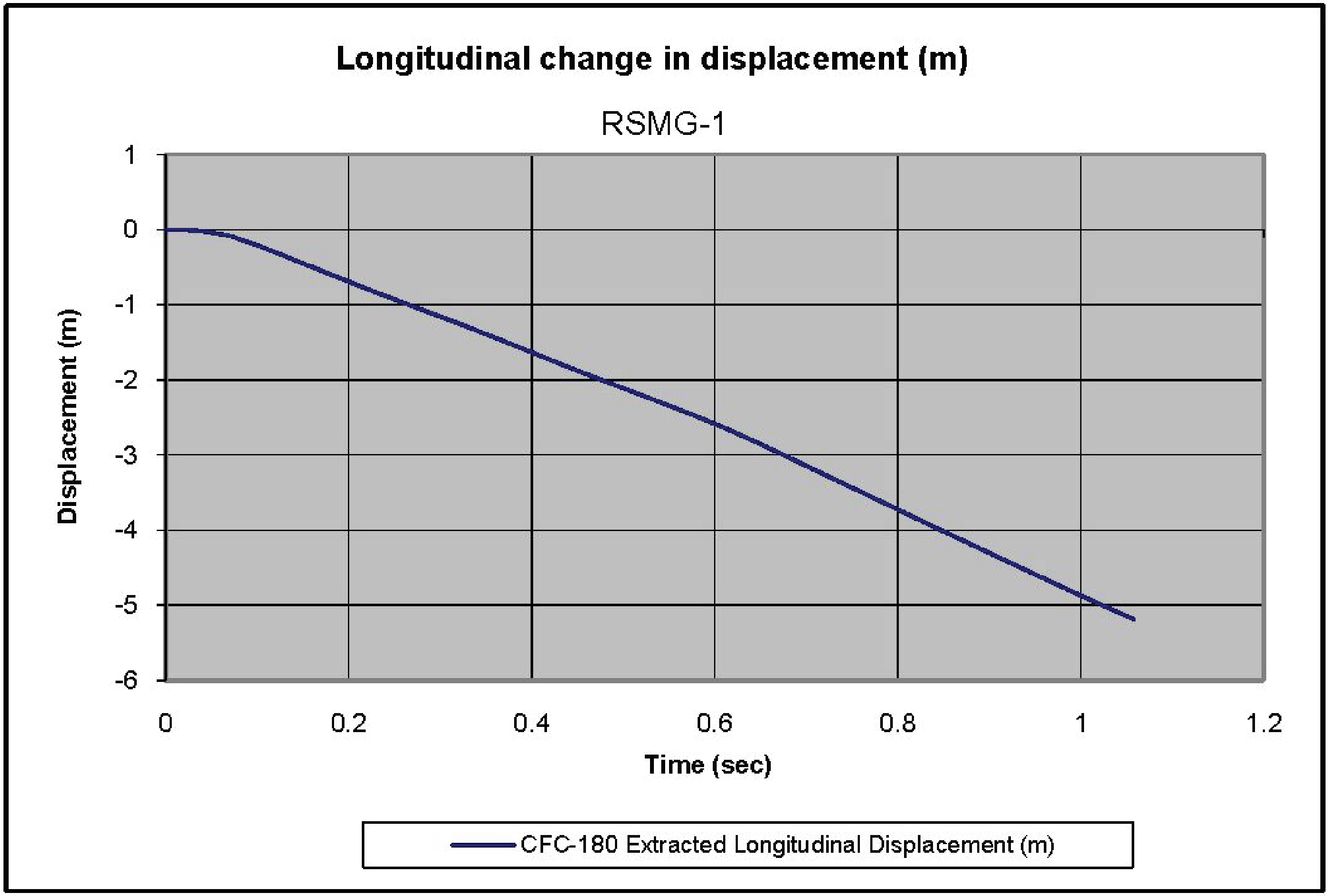


Figure C-16. Graph of Longitudinal Occupant Displacement – DTS, Test No. RSMG-1

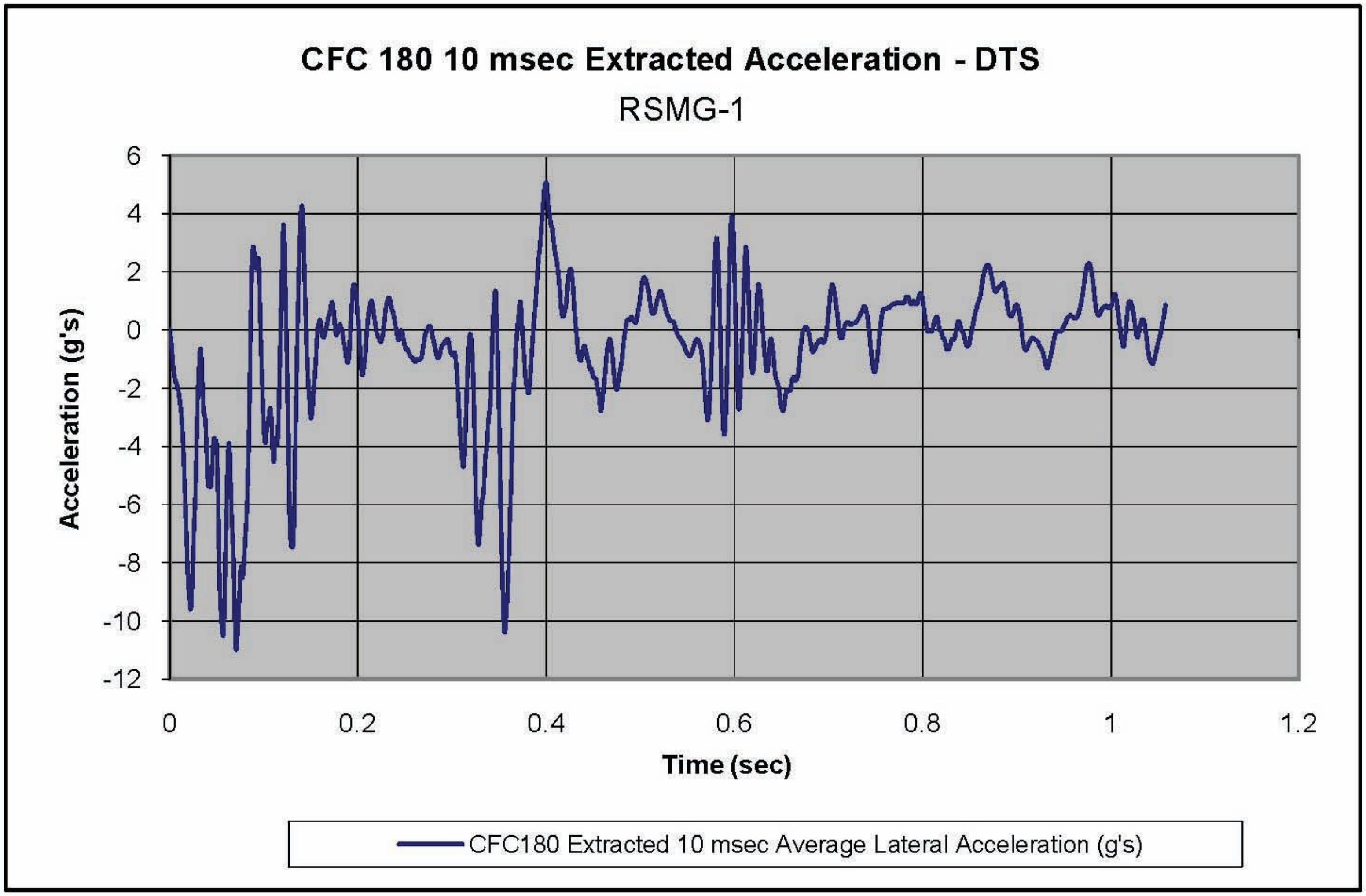


Figure C-17. Graph of 10 ms Average Lateral Acceleration – DTS, Test No. RSMG-1

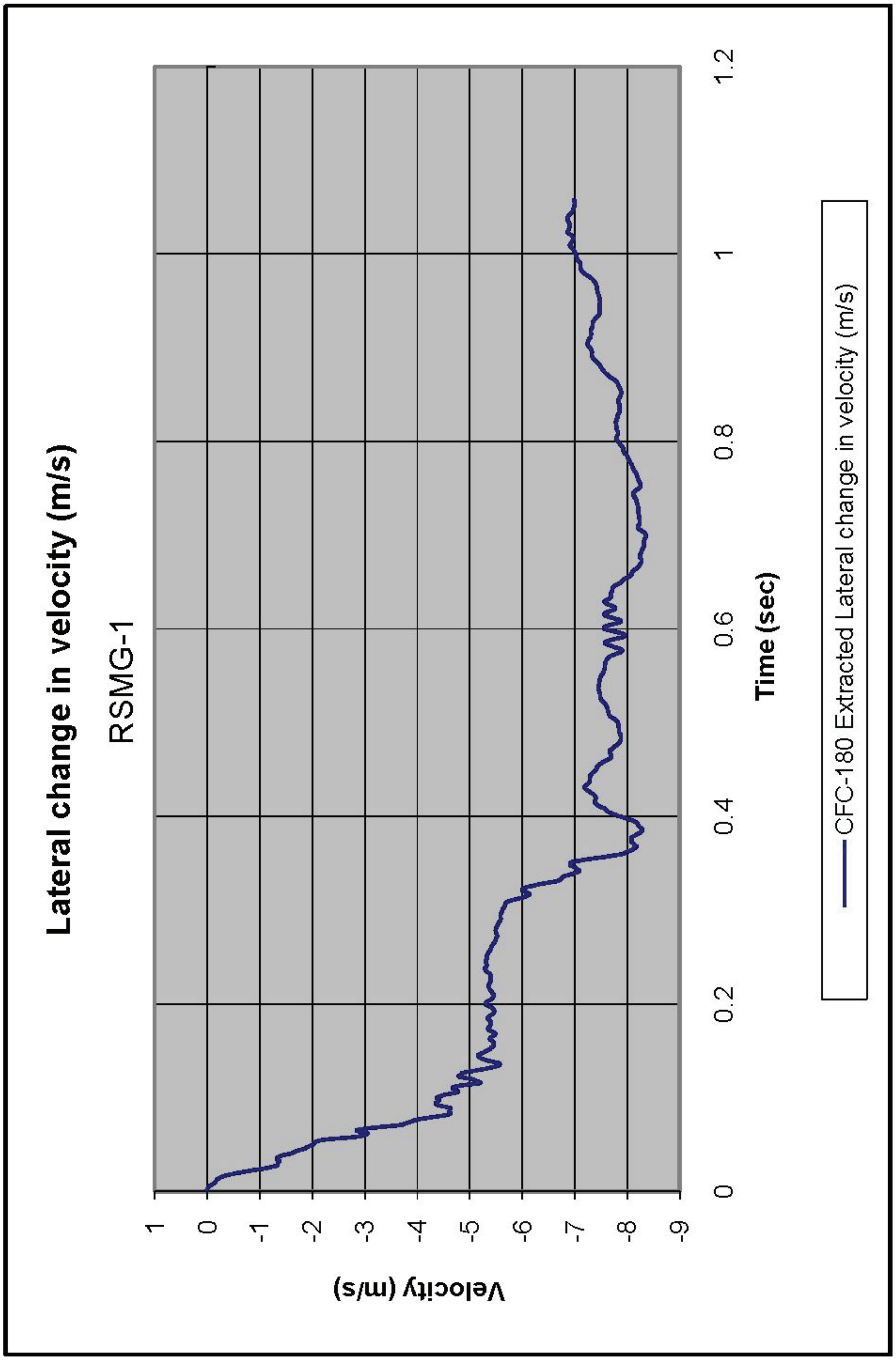


Figure C-18. Graph of Lateral Occupant Impact Velocity – DTS, Test No. RSMG-1

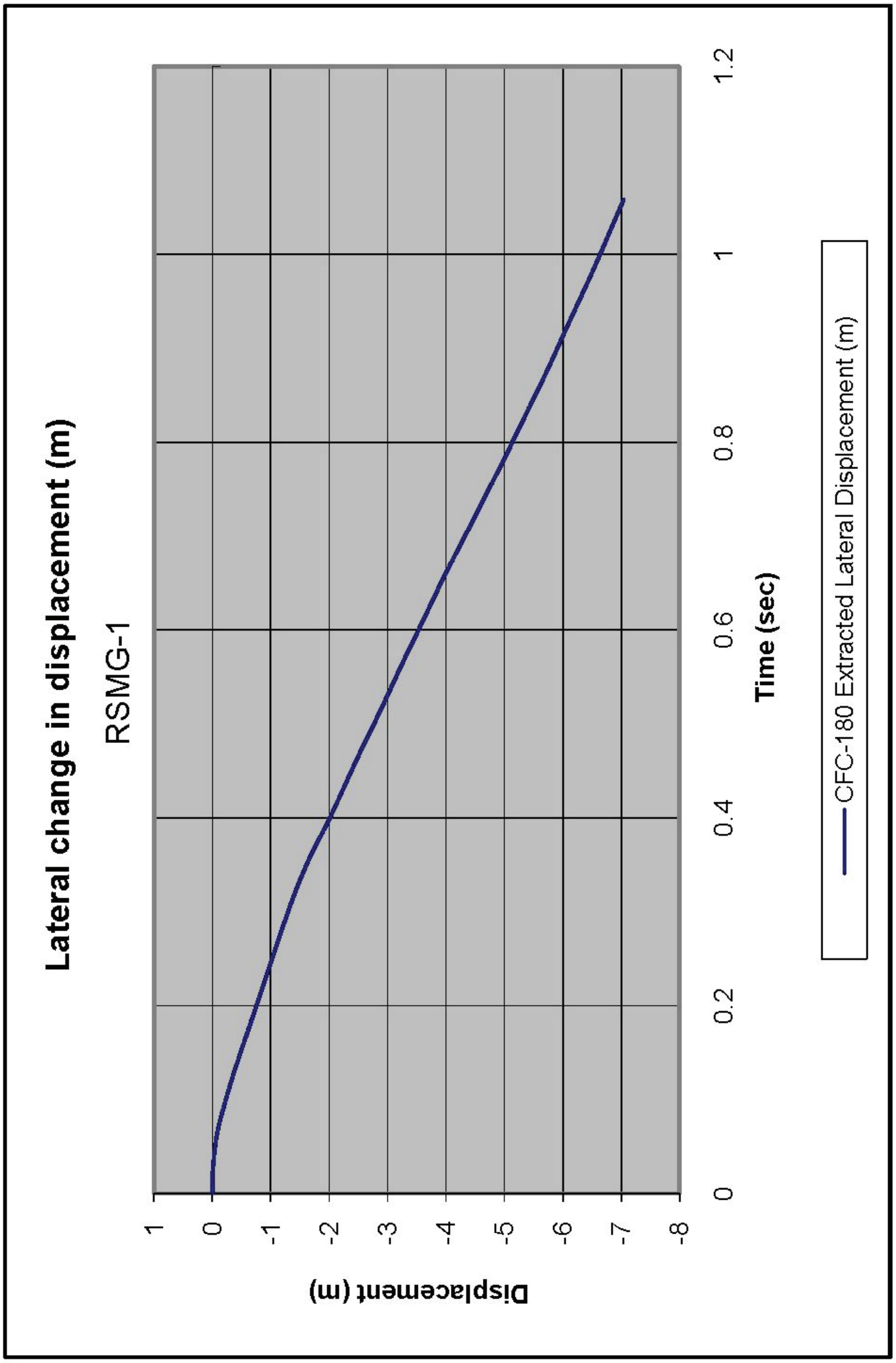


Figure C-19. Graph of Lateral Occupant Displacement – DTS, Test No. RSMG-1

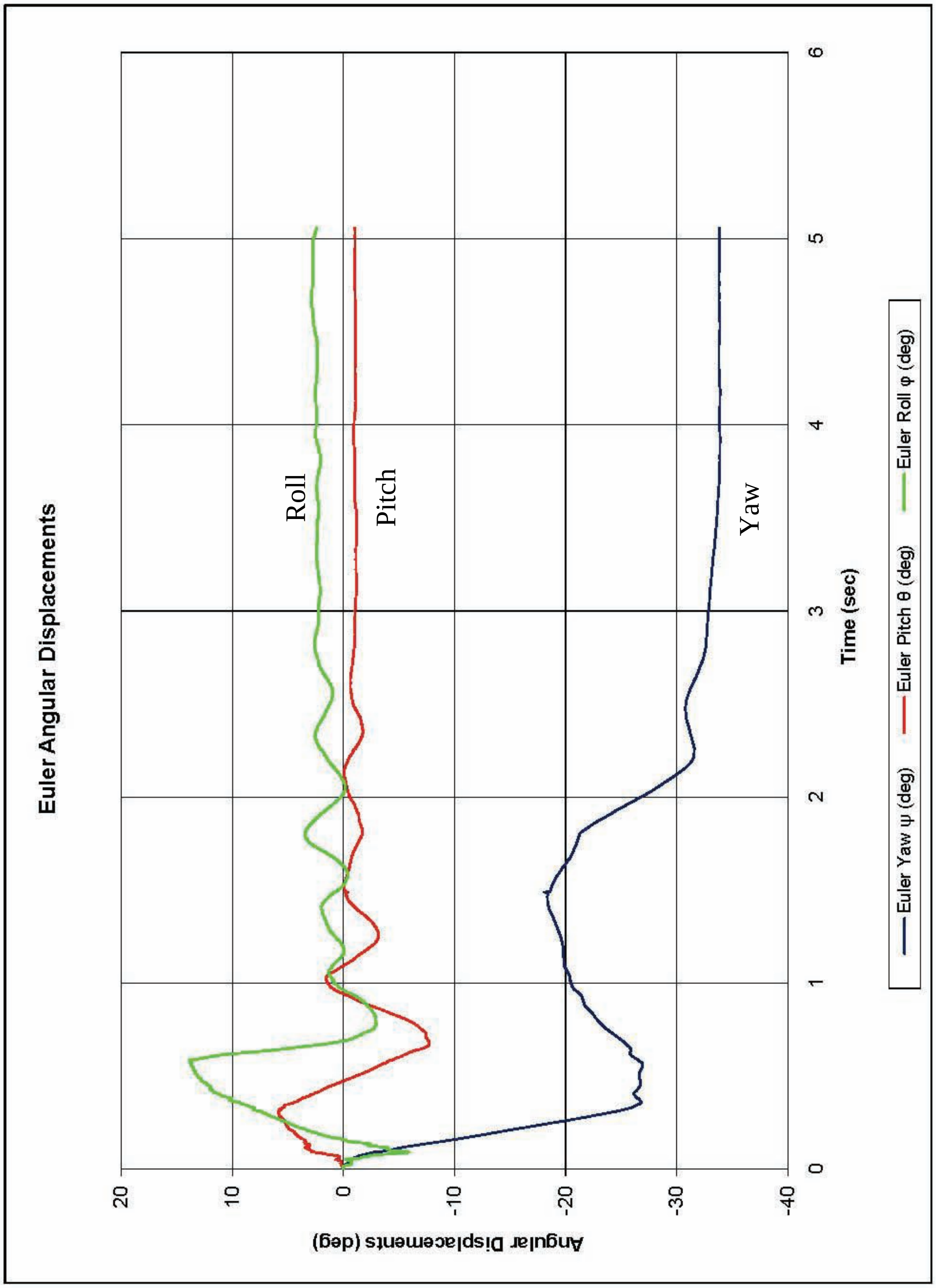


Figure C-20. Graph of Euler Angular Displacements - DTS, Test No. RSMG-1

Appendix D. Accelerometer and Rate Transducer Data Plots, Test No. RSMG-2

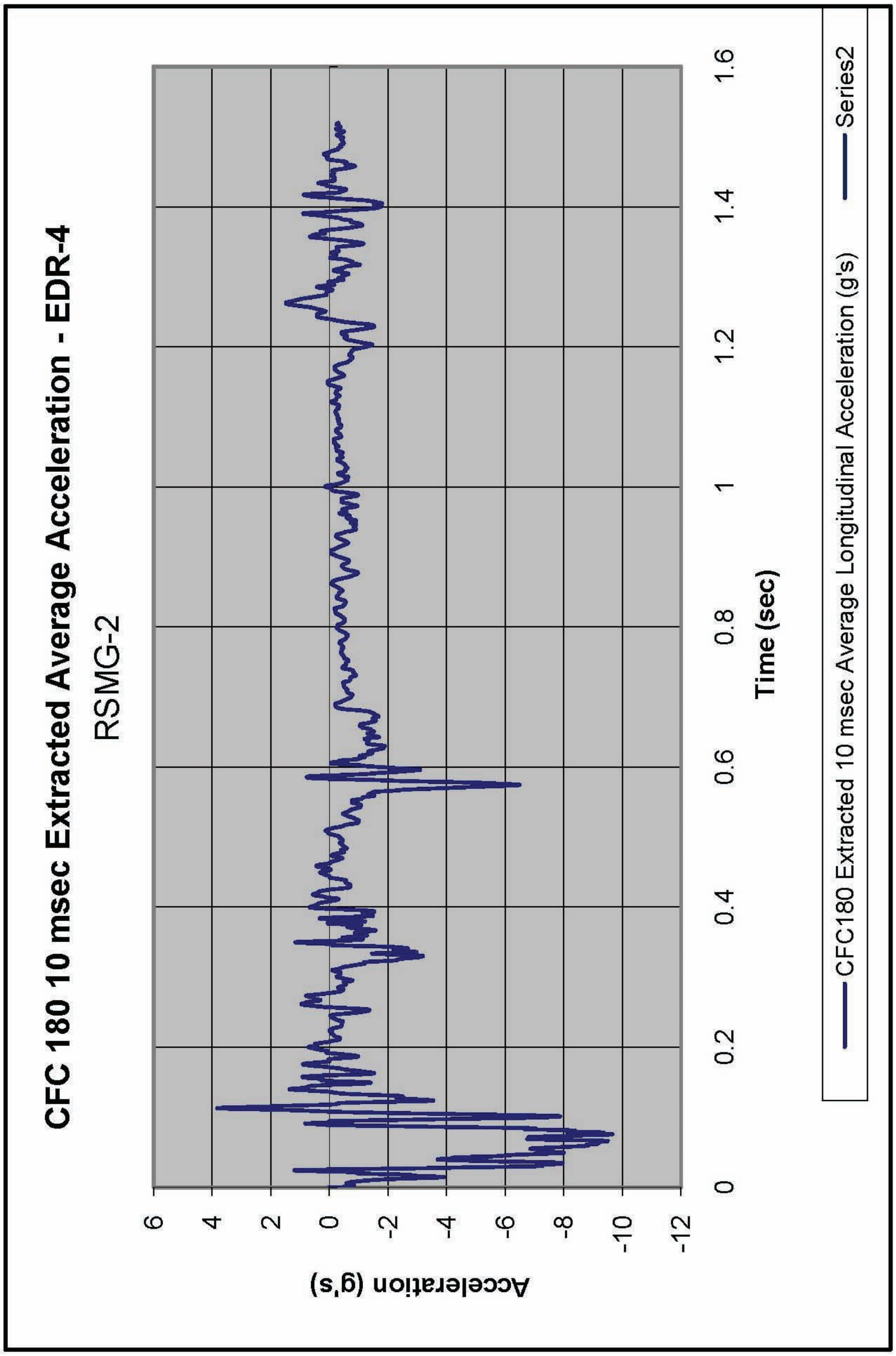


Figure D-1. Graph of 10-ms Average Longitudinal Acceleration – EDR-4, Test No. RSMG-2

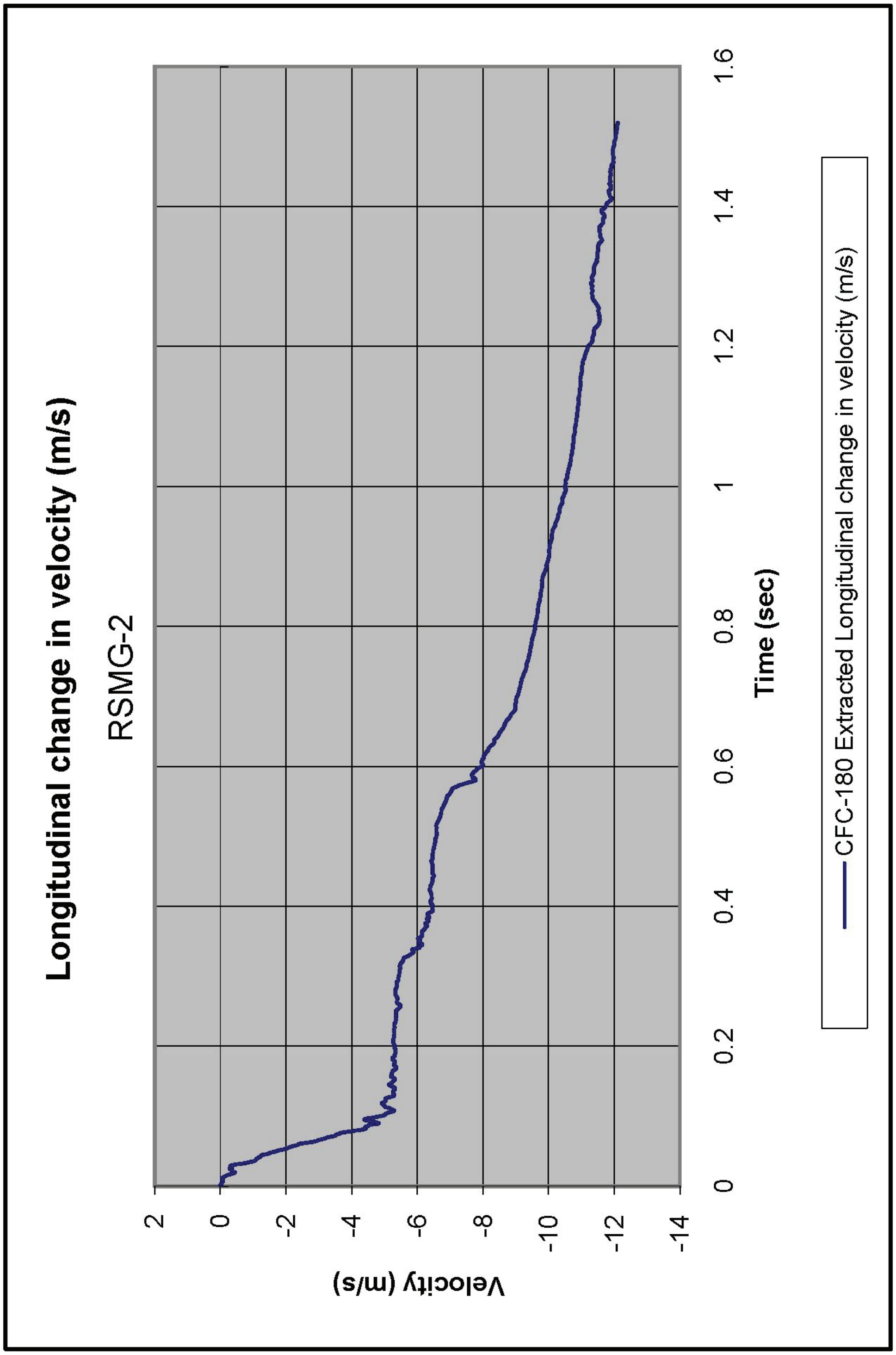


Figure D-2. Graph of Longitudinal Occupant Impact Velocity – EDR-4, Test No. RSMG-2

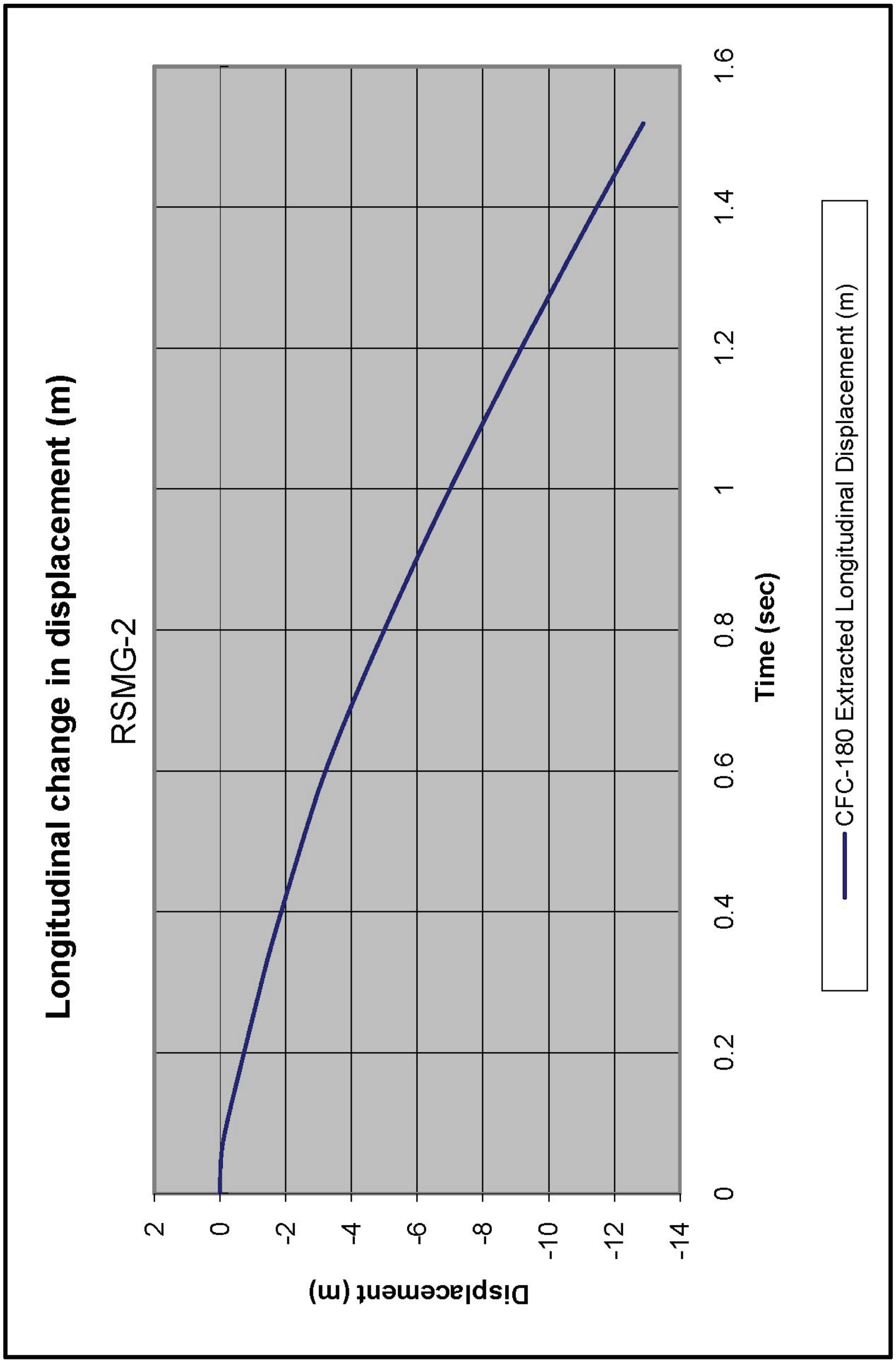


Figure D-3. Graph of Longitudinal Occupant Displacement – EDR-4, Test No. RSMG-2

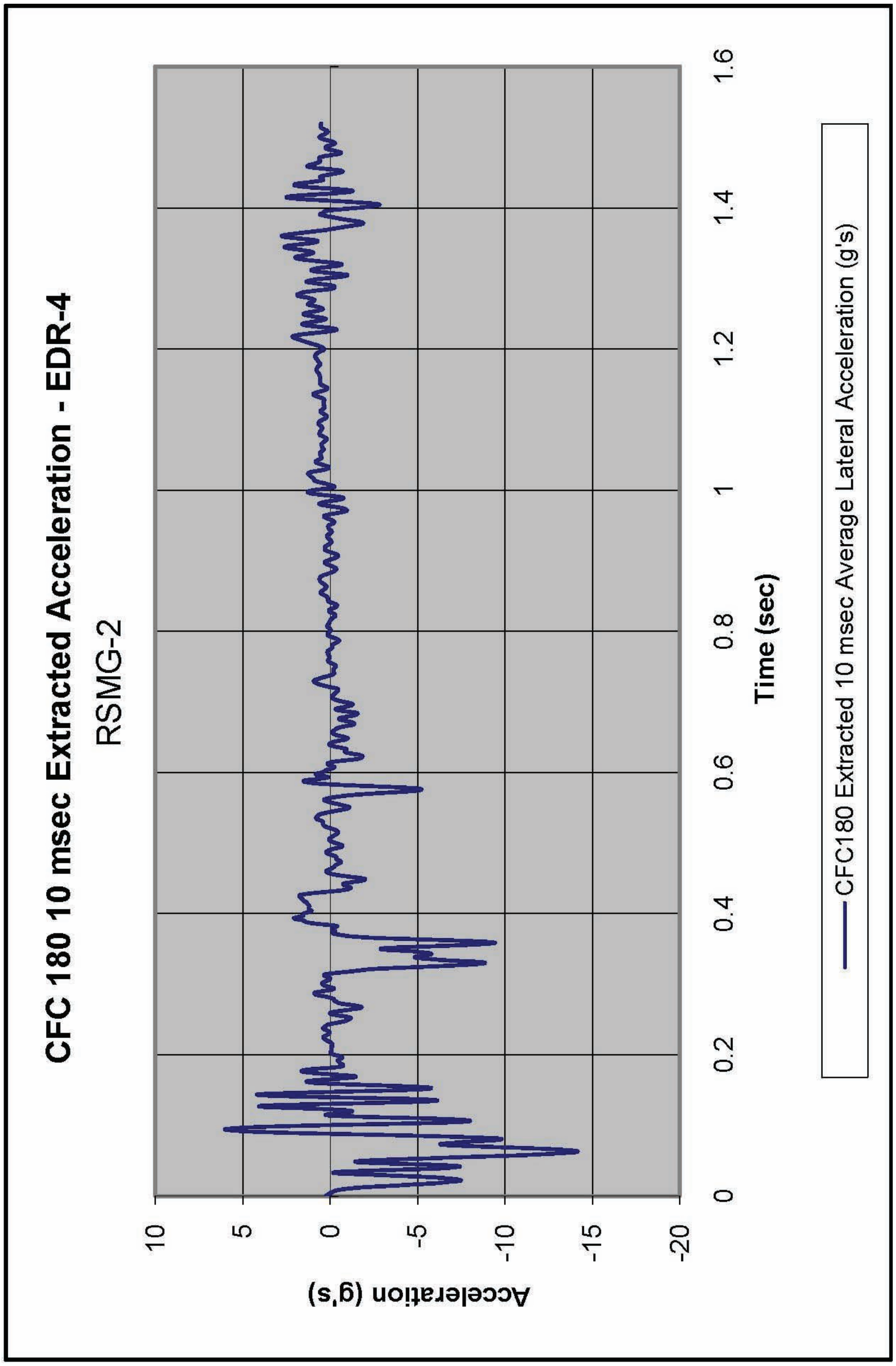


Figure D-4. Graph of 10 ms Average Lateral Acceleration – EDR-4, Test No. RSMG-2

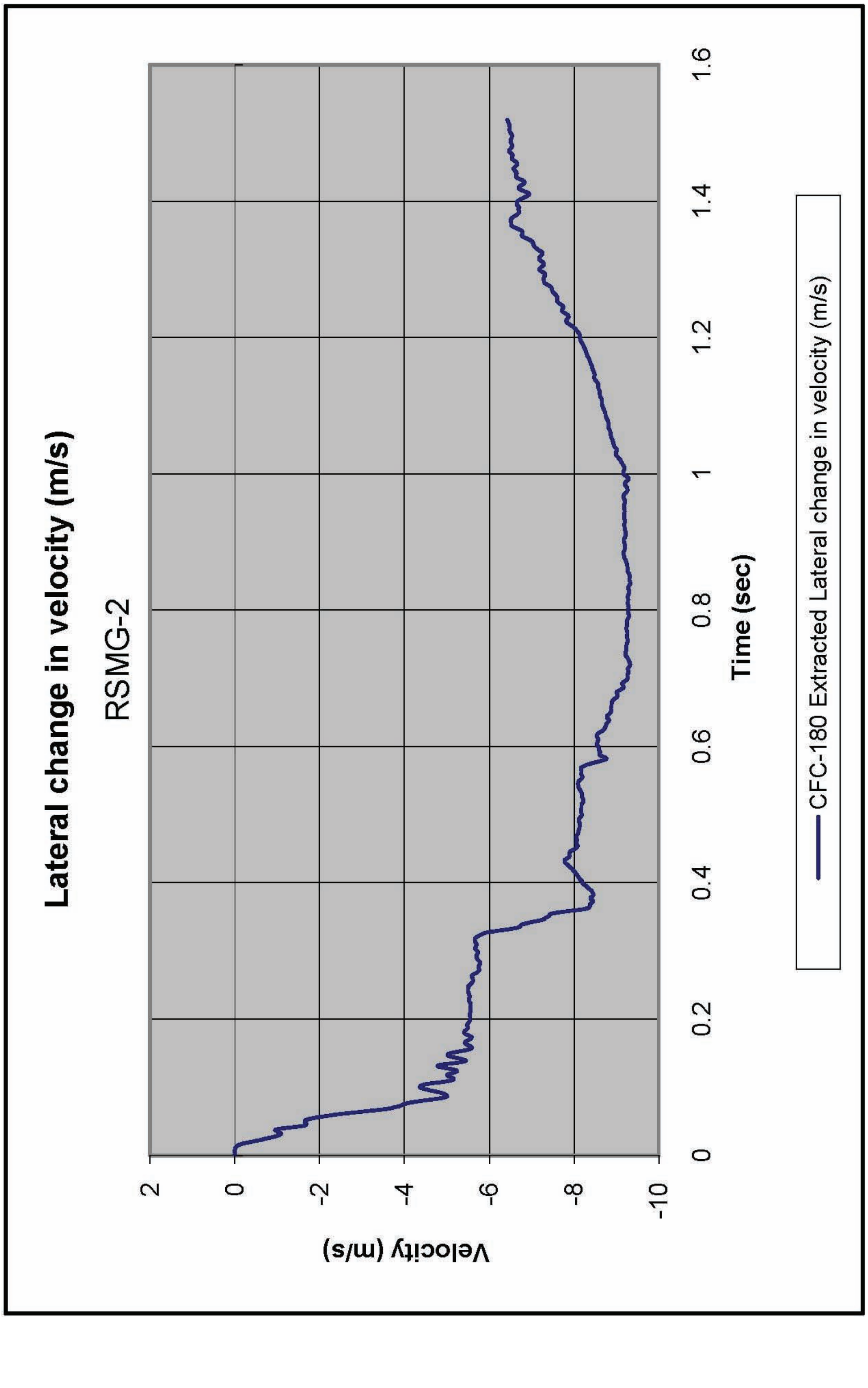


Figure D-5. Graph of Lateral Occupant Impact Velocity – EDR-4, Test No. RSMG-2

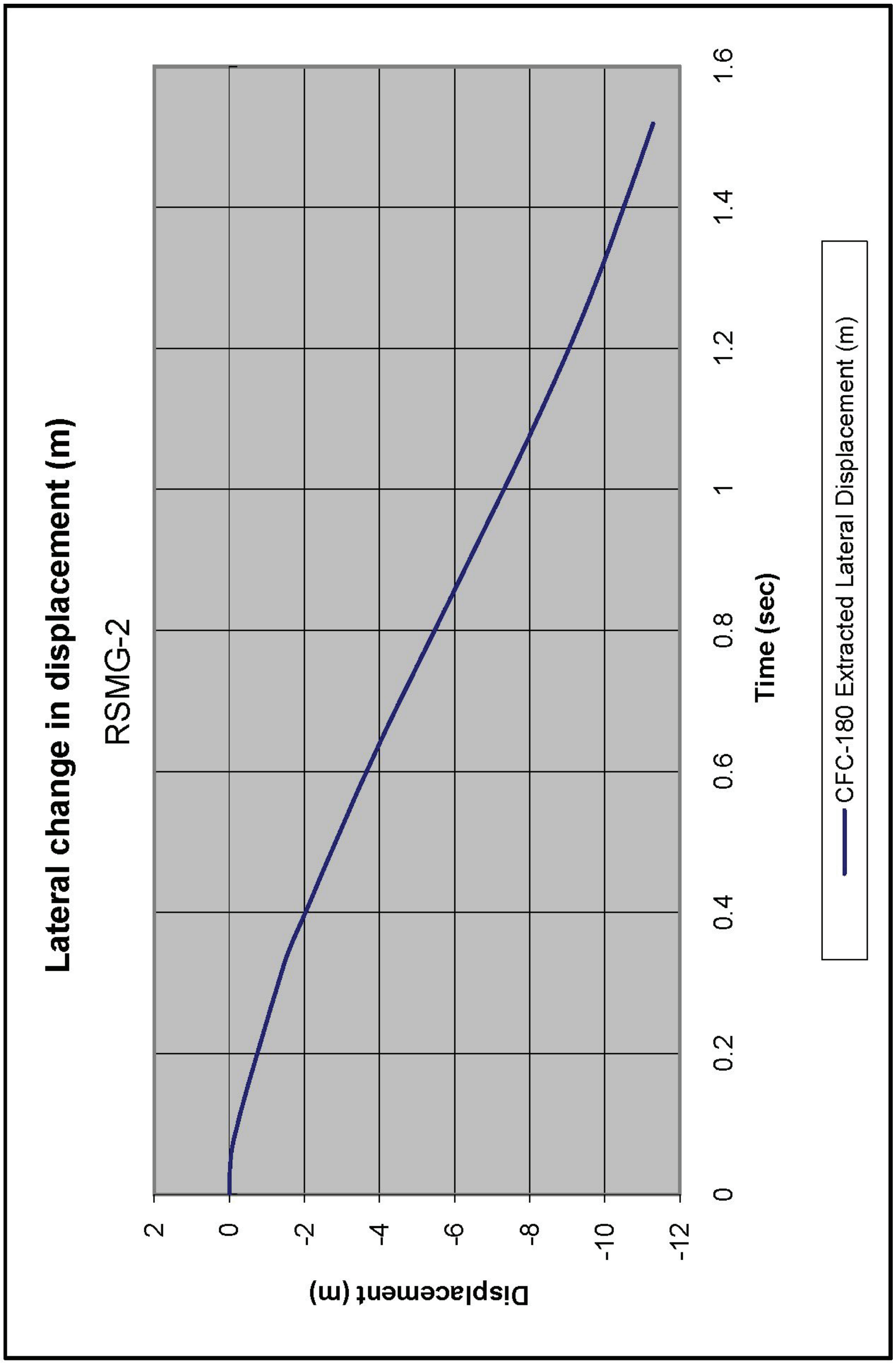


Figure D-6. Graph of Lateral Occupant Displacement – EDR-4, Test No. RSMG-2

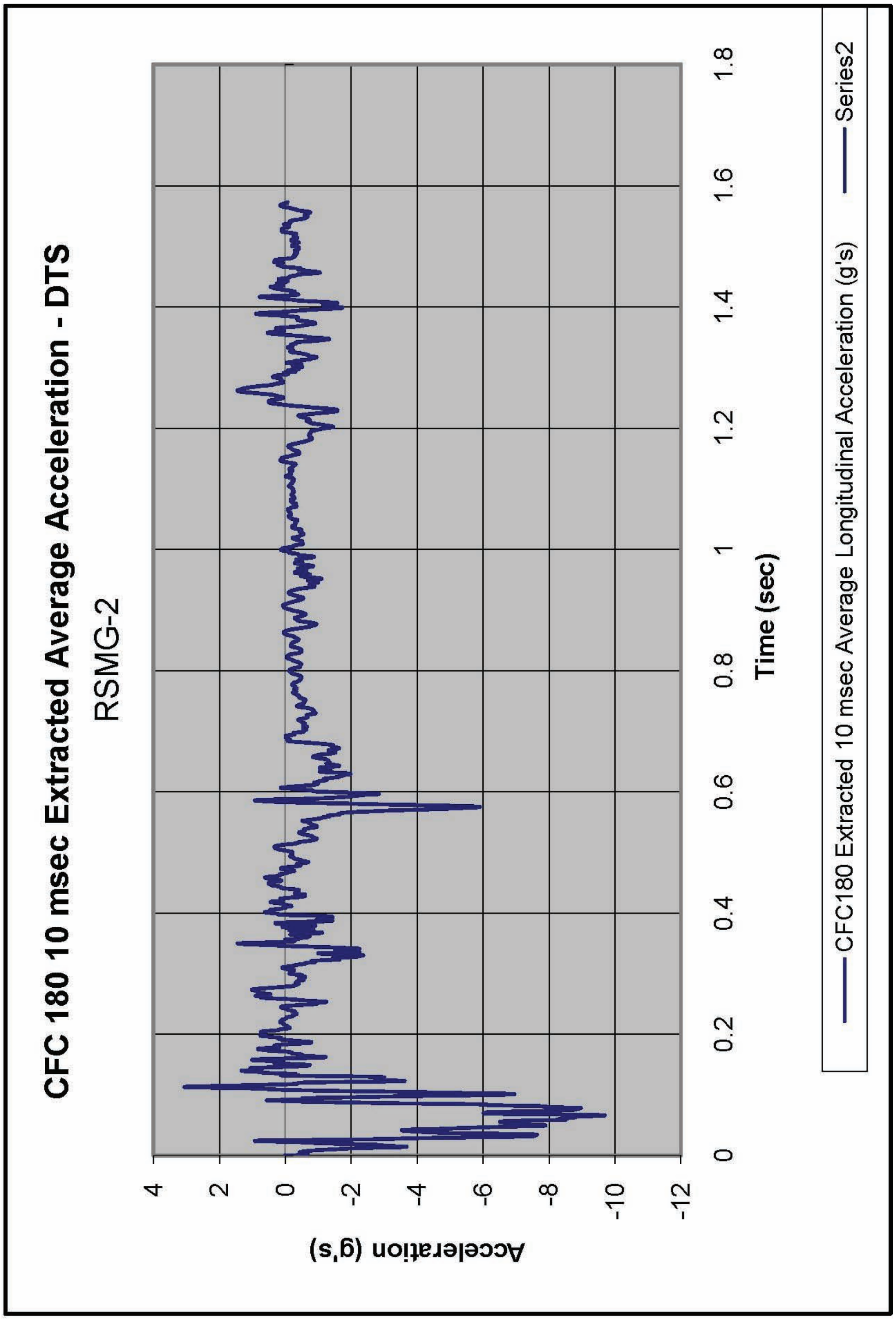


Figure D-7. Graph of 10-ms Average Longitudinal Acceleration - DTS, Test No. RSMG-2

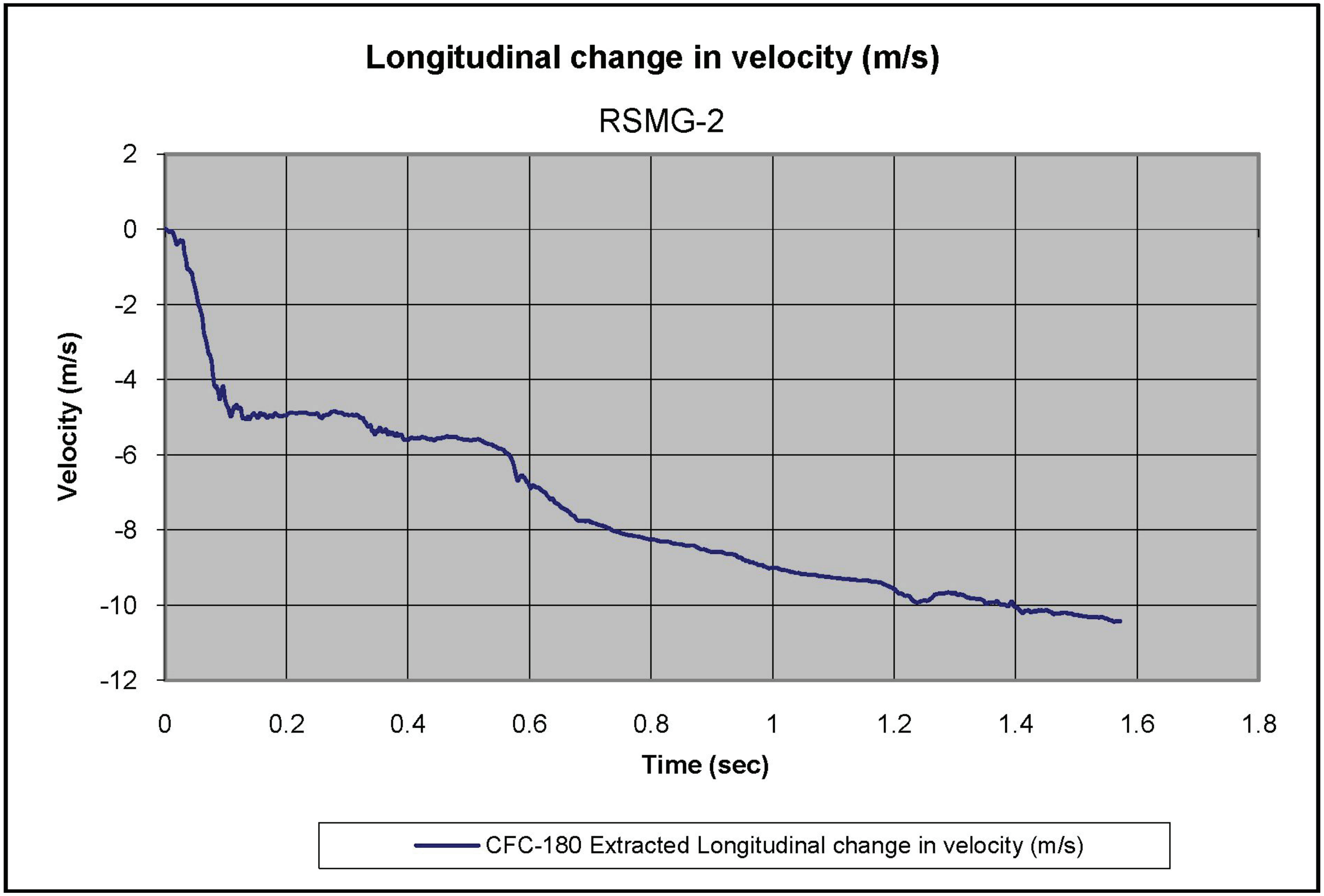


Figure D-8. Graph of Longitudinal Occupant Impact Velocity - DTS, Test No. RSMG-2

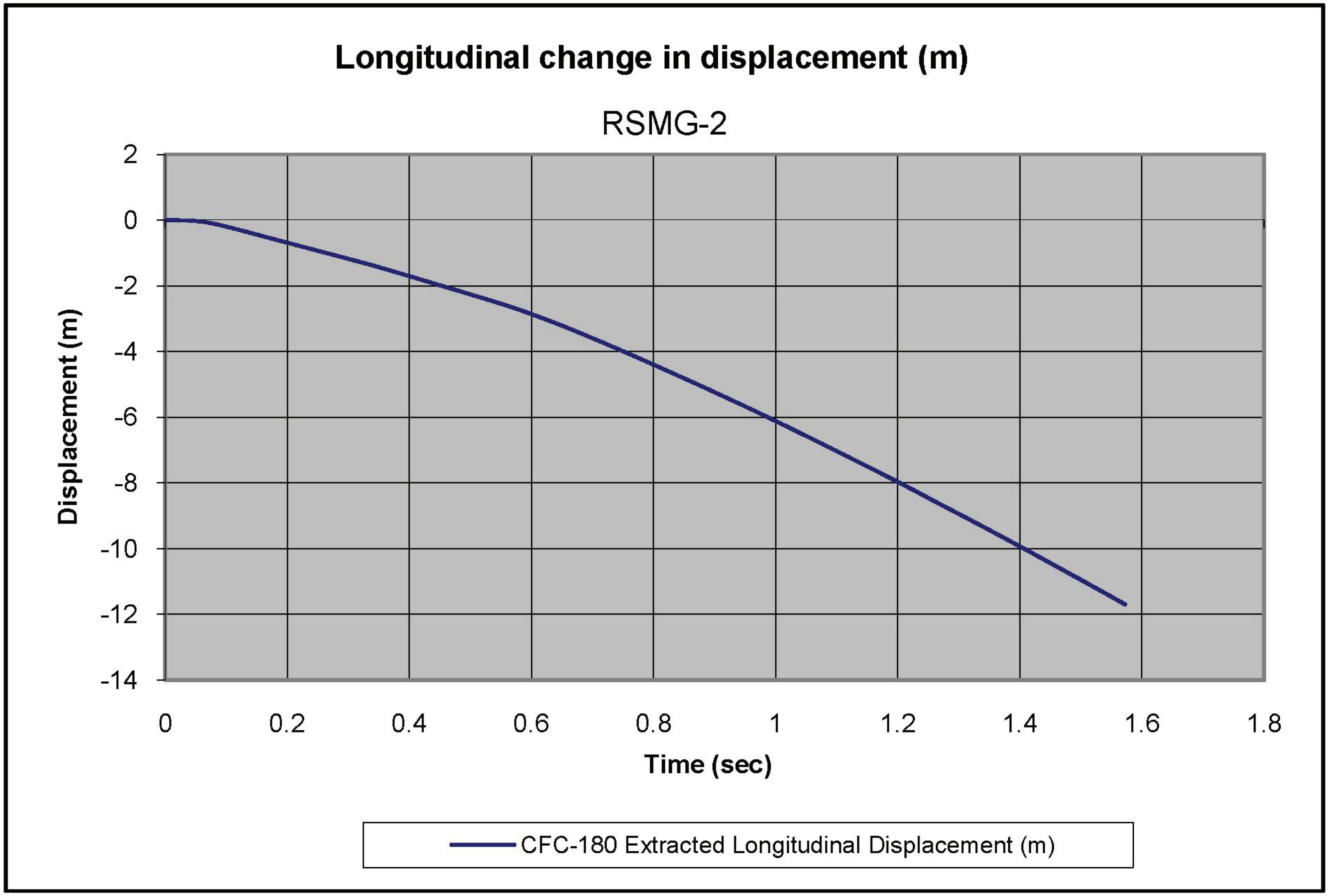


Figure D-9. Graph of Longitudinal Occupant Displacement - DTS, Test No. RSMG-2

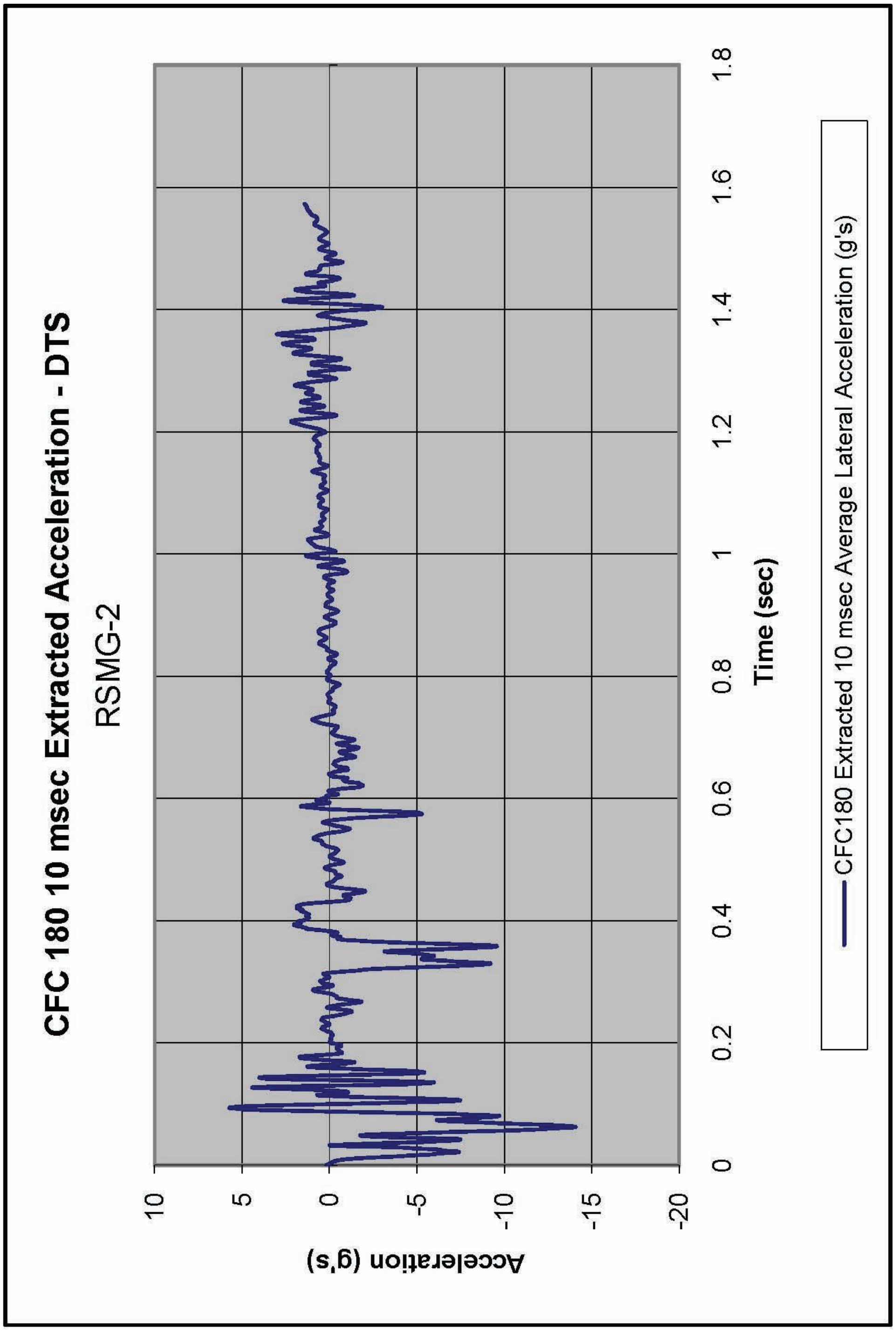


Figure D-10. Graph of 10 ms Average Lateral Acceleration - DTS, Test No. RSMG-2

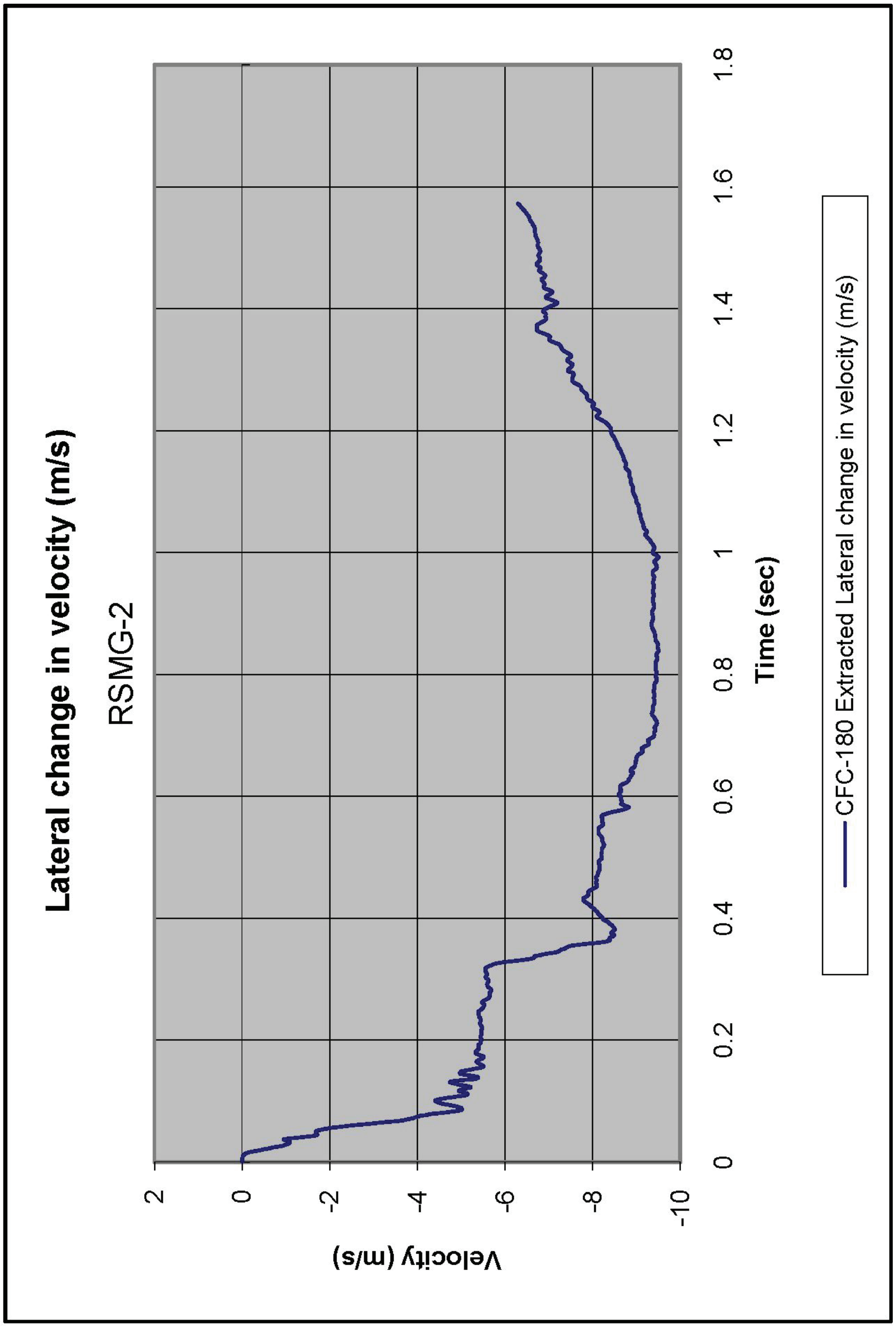


Figure D-11. Graph of Lateral Occupant Impact Velocity - DTS, Test No. RSMG-2

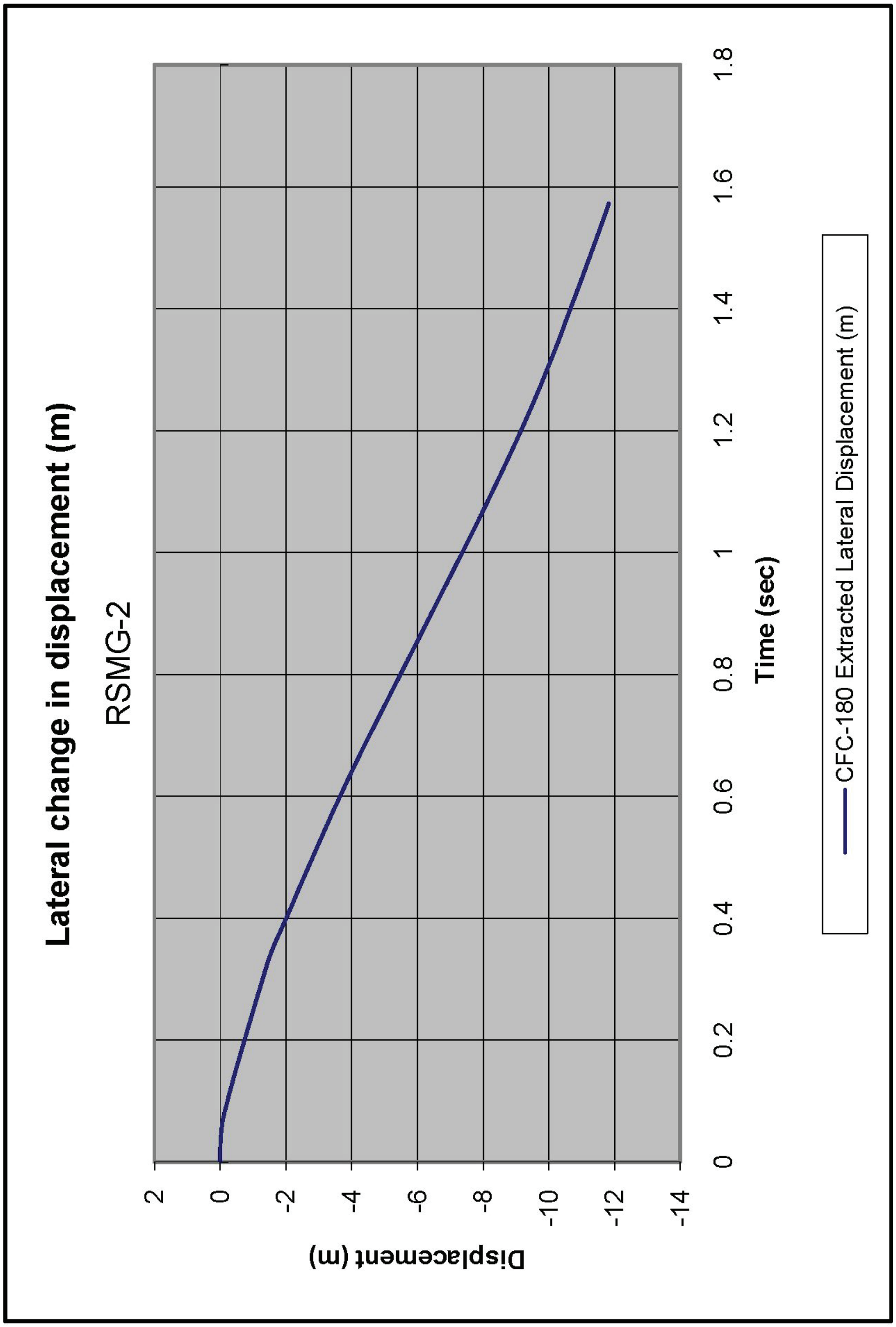


Figure D-12. Graph of Lateral Occupant Displacement - DTS, Test No. RSMG-2

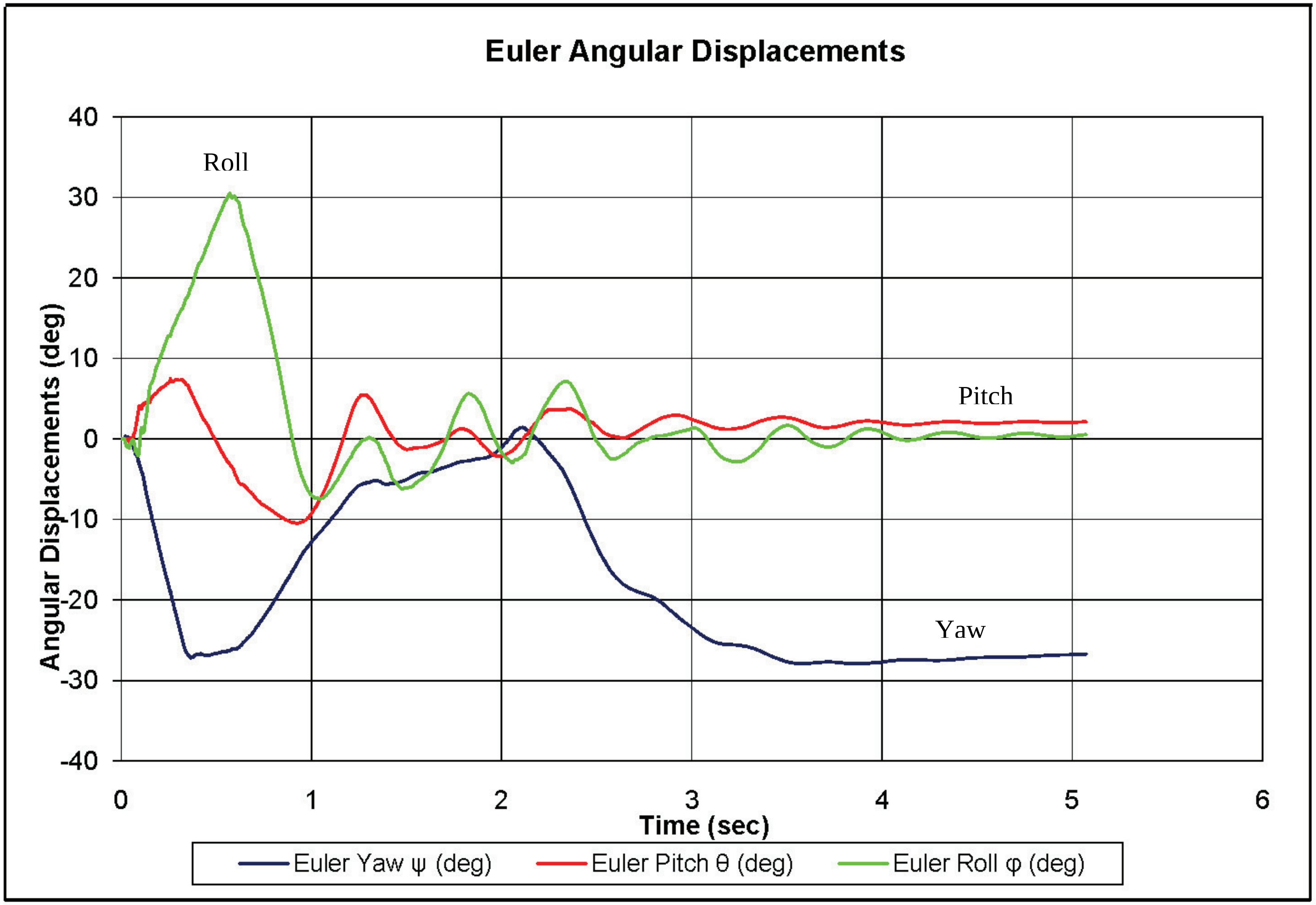


Figure D-13. Graph of Euler Angular Displacements - DTS, Test No. RSMG-2

Appendix E. System Drawings, Test No. RSMG-2

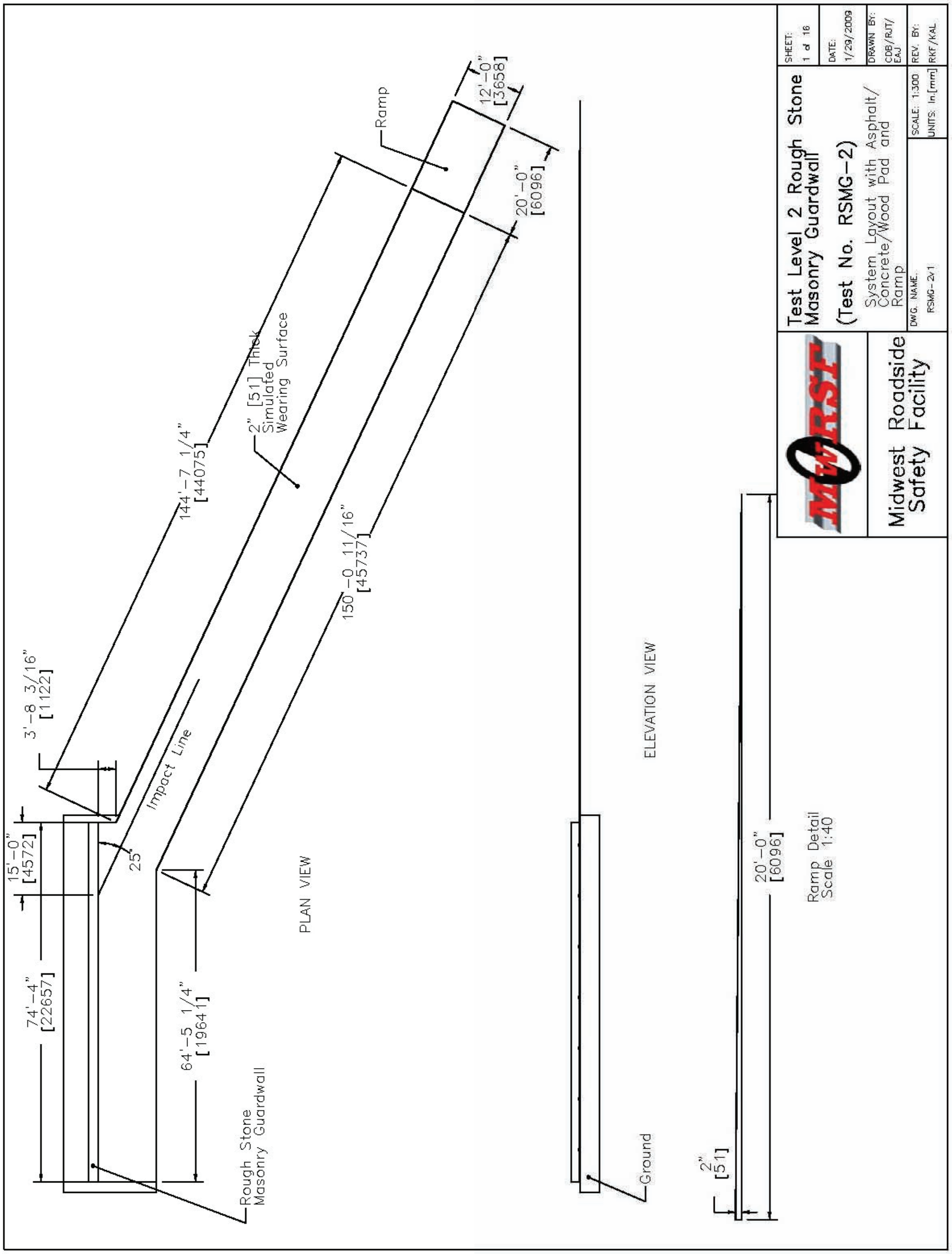


Figure E-1. System Layout with Wearing Surface Pad and Ramp, Test No. RSMG-2

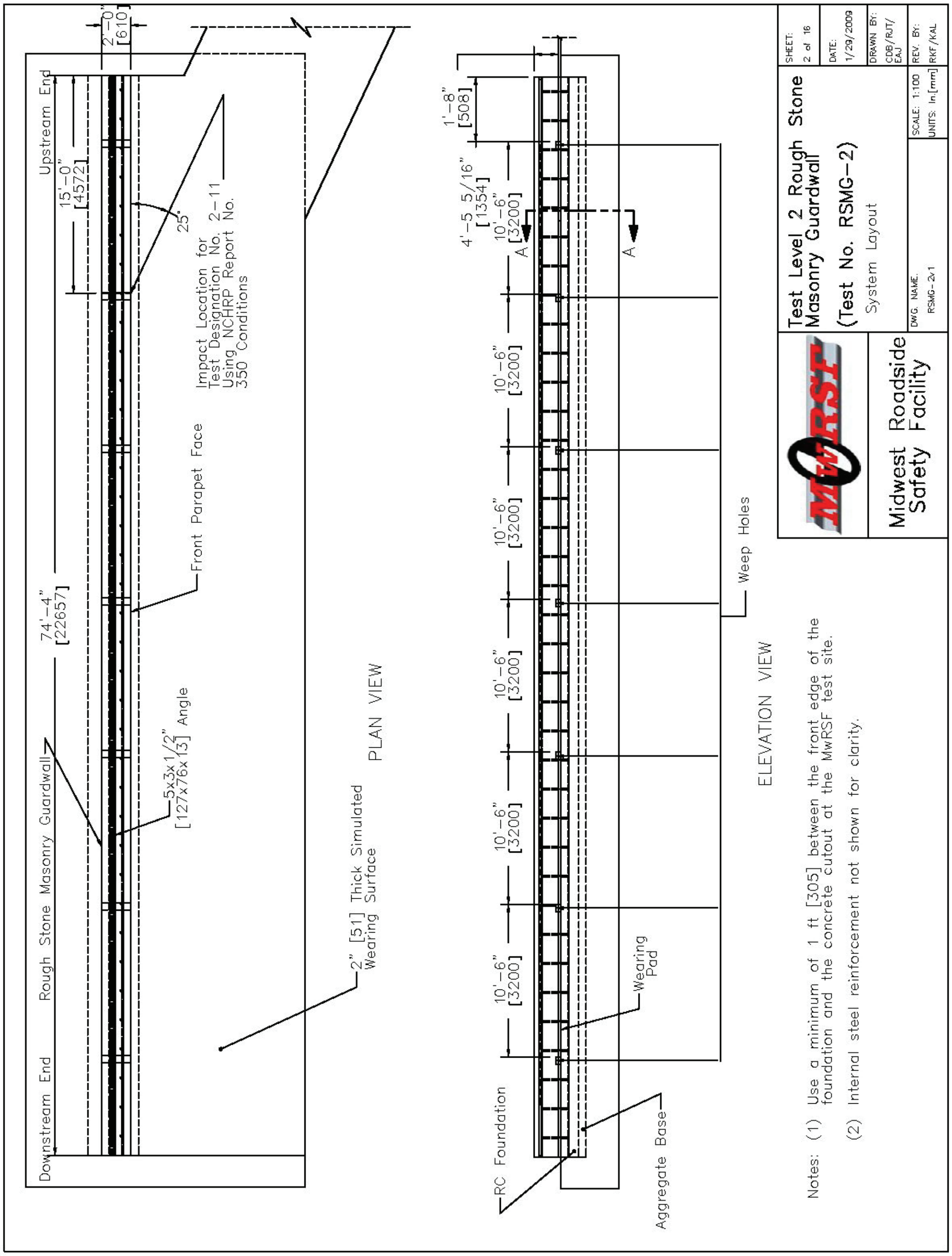


Figure E-2. System Layout, Test No. RSMG-2

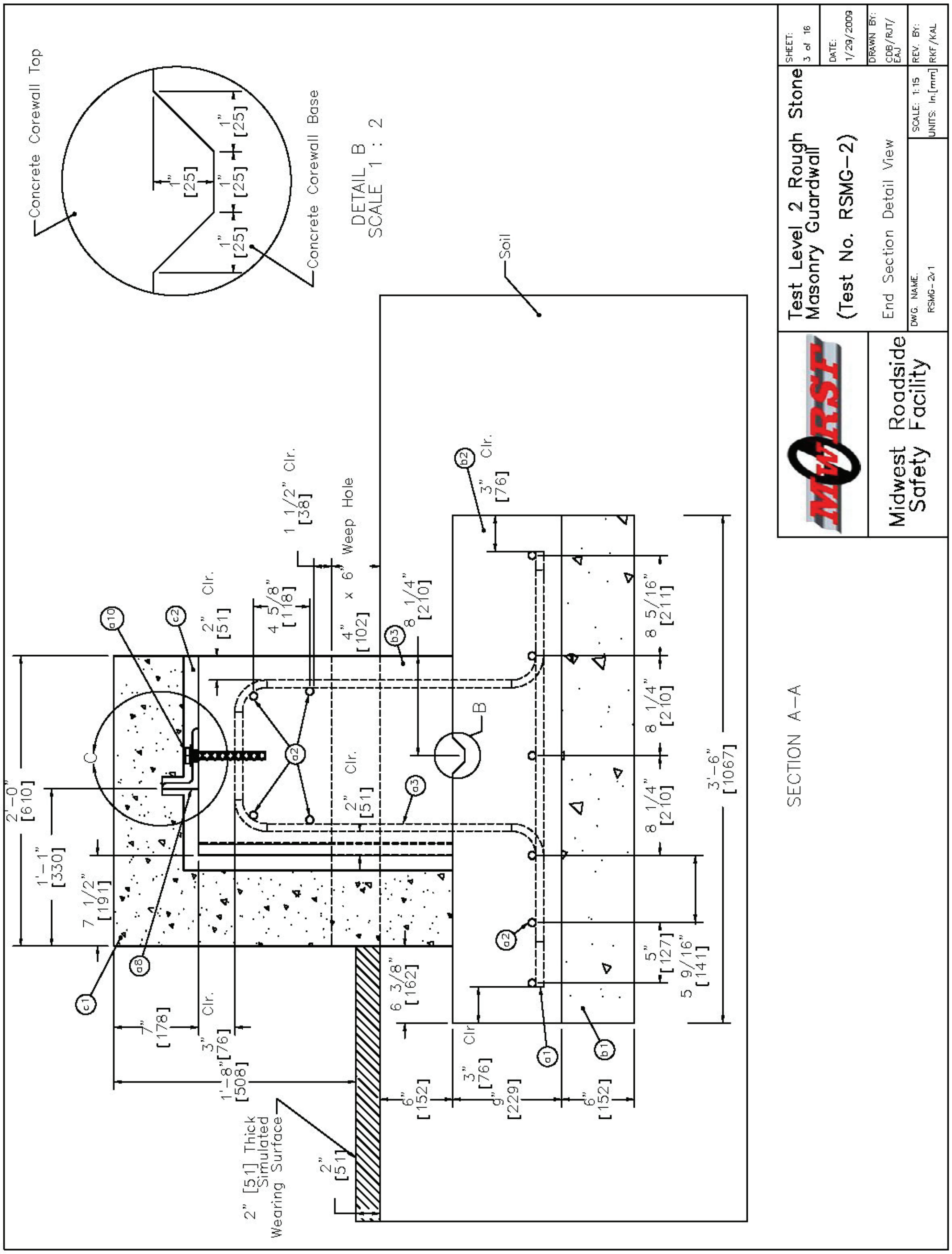
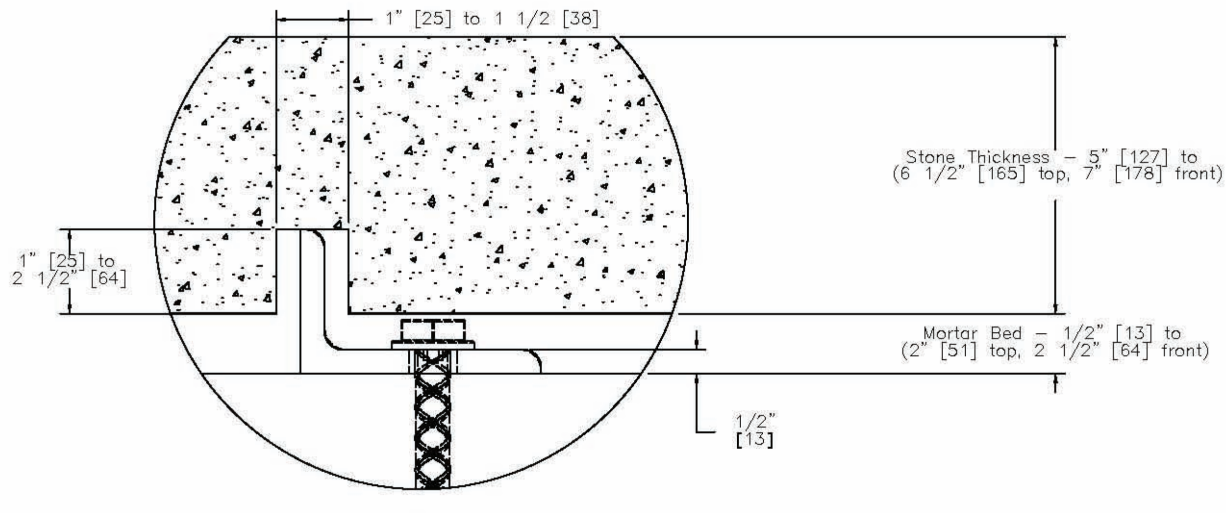


Figure E-3. End Section Detail View with Effective Barrier Height, Test No. RSMG-2



DETAIL C

Notes:

(1) The capstones placed on the top of the barrier shall be kerfed to allow for their placement over the steel angle. The kerf width shall be approximately 1 to 1 1/2 in. [25 to 38] wide. The maximum kerf depth shall be 2 1/2 in. [64] although thinner kerf depths are allowed as long as all other geometries are met.

(2) The top mortar bed thickness shall range between 1/2 and 2 in. [13 and 51] for rubble stone masonry. The top capstone thickness shall range between 5 to 6 1/2 in. [127 to 165].

(3) Morter shall fill the void region surrounding the angle's vertical leg when the capstones are set in place.

(4) The first 36 to 38 ft [10.9 to 11.6m] of barrier shall be constructed with capstones covering the entire barrier width of 24 in. [51], thus revealing a mortar joint on the front face.

(5) The remaining barrier length shall be constructed using alternating face and top stones to meet up at the top–front corner of the barrier.

(6) For top capstone thicknesses greater than 5 7/8 in. [149], it will be necessary to chisle the bottom of the stone to form a dish to allow its placement over the heads of the Wedge–Bolt anchors.

(7) Two types of steel anchors were used to provide vertical attachment of the stone masonry to the top of the inner core wall. Type 106 corrugated Dovetail Anchor Ties (16 gauge [1.5] by 5 1/2" [140] long) were wedged under the top–mounting angles and bent upward to engage the mortar. The Type 106 Ties were spaced approximately on 2 ft [610] centers, alternating sides of the steel angles. Stainless steel (SS 304) Z–clips were also used to anchor the stone using 1/4" [6.4] diameter by 2 3/4" [70] long, heavy–weight, stainless steel Tapcon masonry anchors. The Z–clips were spaced approximately on 2 ft [610] centers, alternating sides of the steel angles, and used to engage a recess cut in the stone.

(8) Dovetail Anchor Ties shall be mill galvanized steel ASTM A653 or hot dip glavanized ASTM A153.

Midwest Roadside Safety Facility	Test Level 2 Rough Stone Masonry Guardwall (Test No. RSMG–2) Mortar Bed Details	SHEET: 4 of 16
		DATE: 1/29/2009
		DRAWN BY: CDB/RJT/EAJ
	DWG. NAME. RSMG–2v1 / SCALE: 1:3 UNITS: In.[mm]	REV. BY: RKF/KAL

Figure E-4. Mortar Bed and Stone Veneer Attachment Details, Test No. RSMG-2

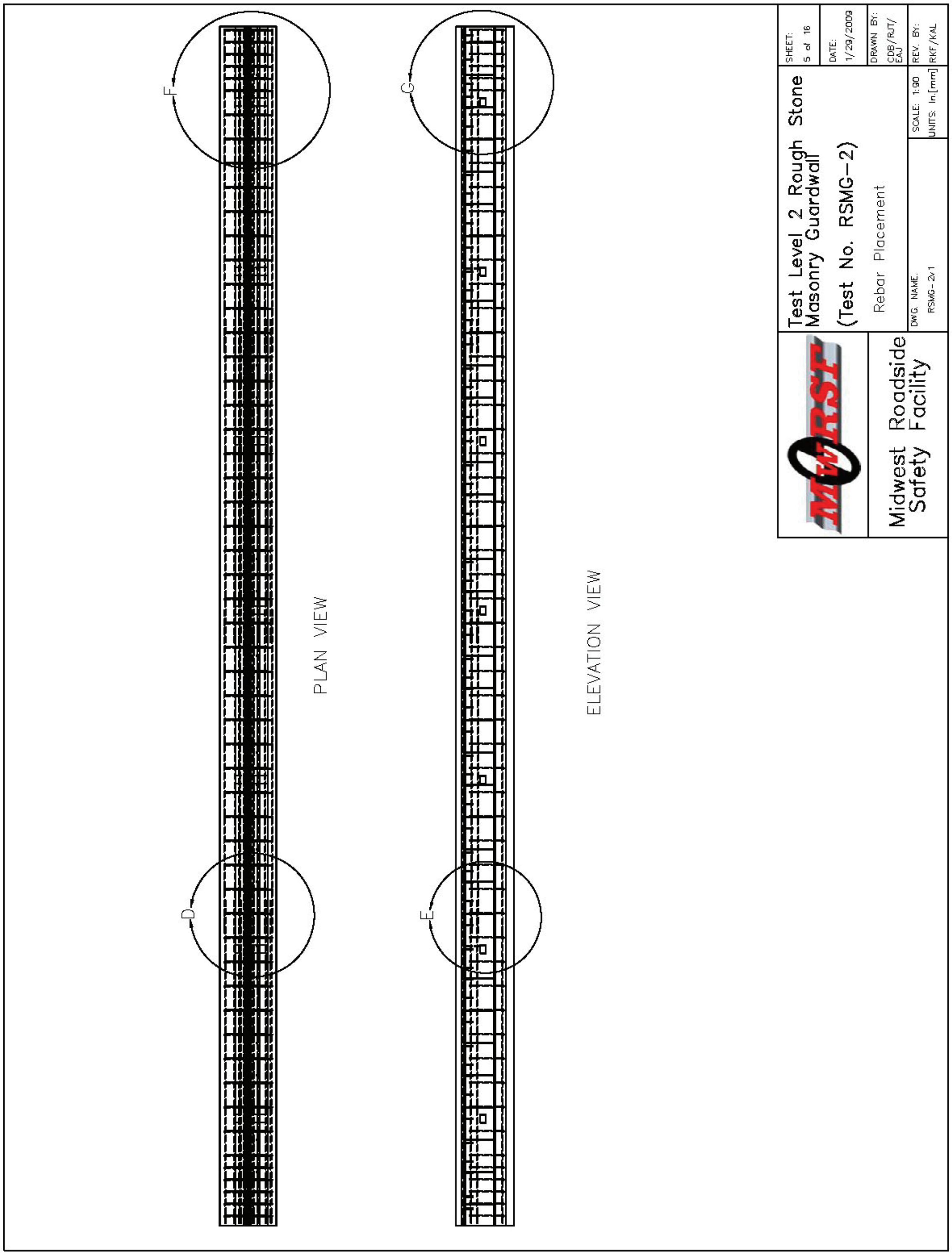


Figure E-5. Rebar Placement, Test No. RSMG-2

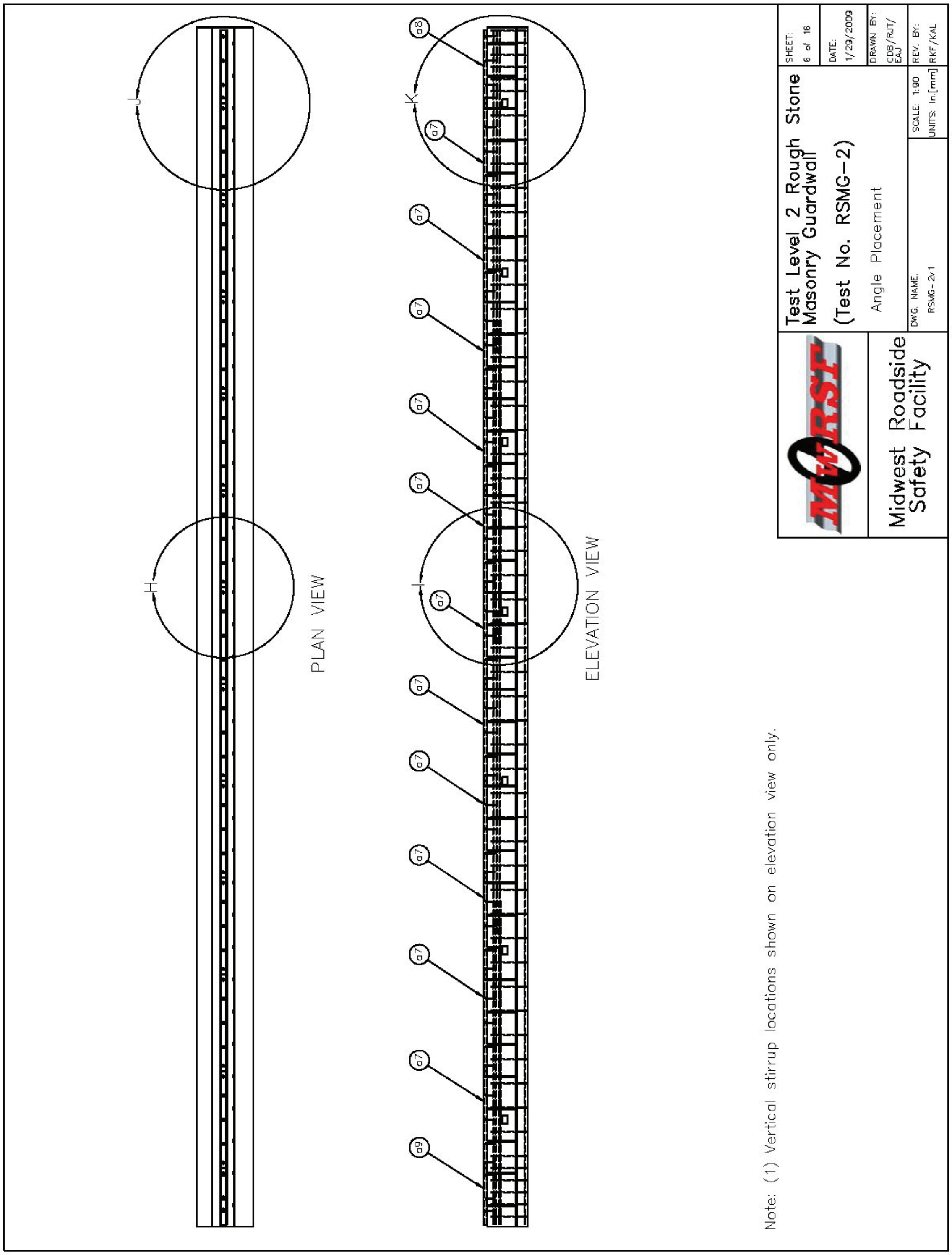


Figure E-6. Angle Placement, Test No. RSMG-2

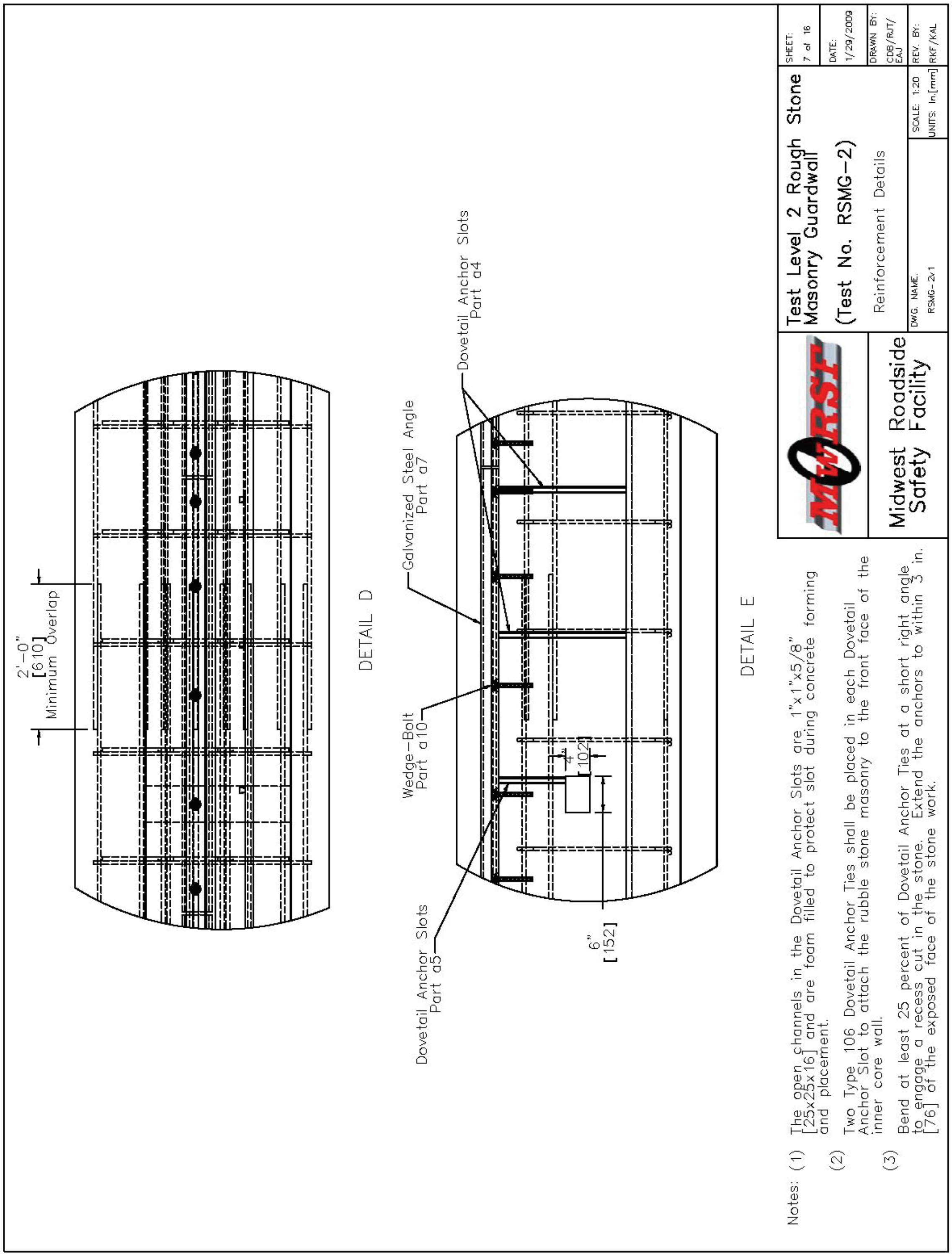


Figure E-7. Reinforcement and Angle Attachment Details, Test No. RSMG-2

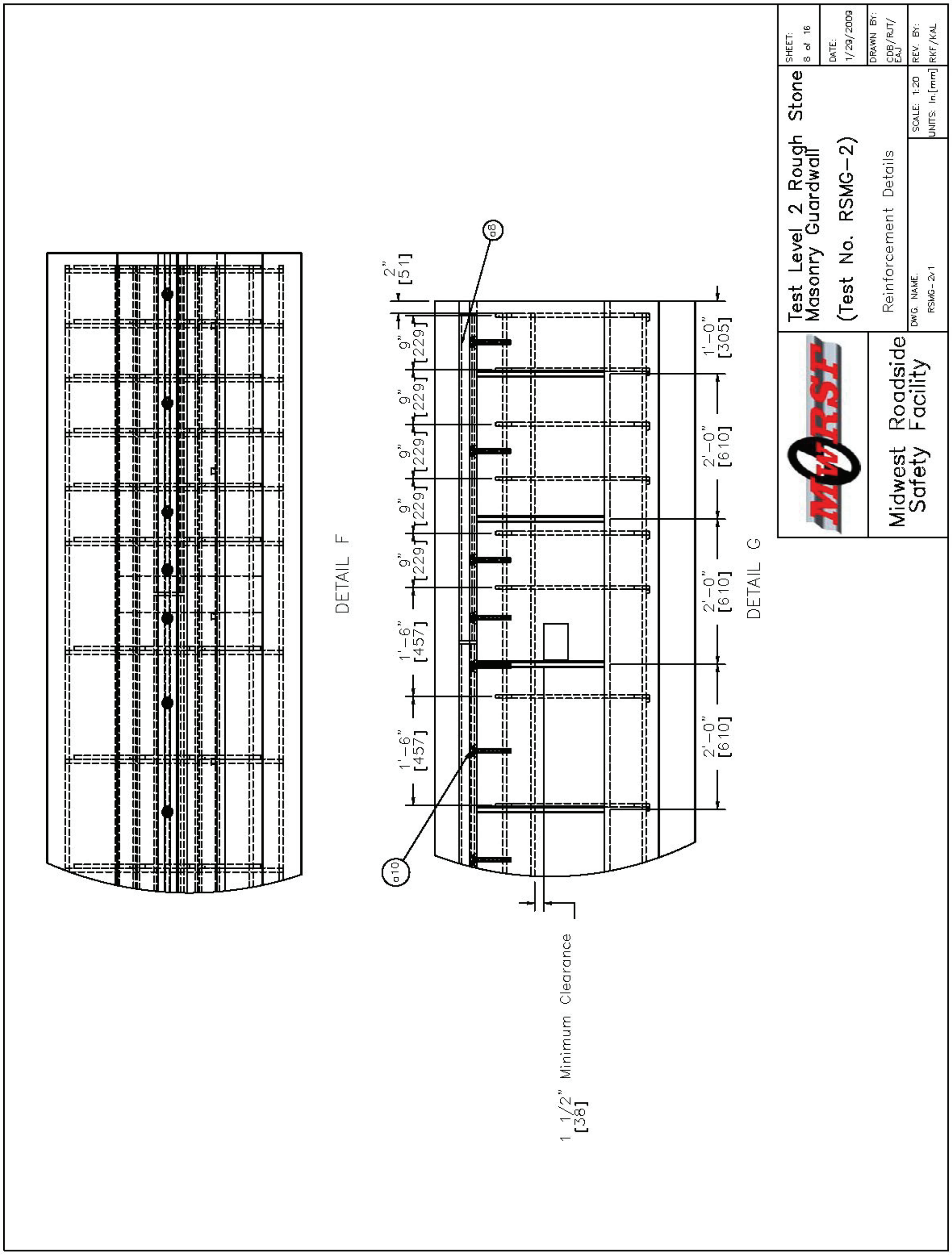


Figure E-8. Reinforcement and Angle Attachment Details, Test No. RSMG-2

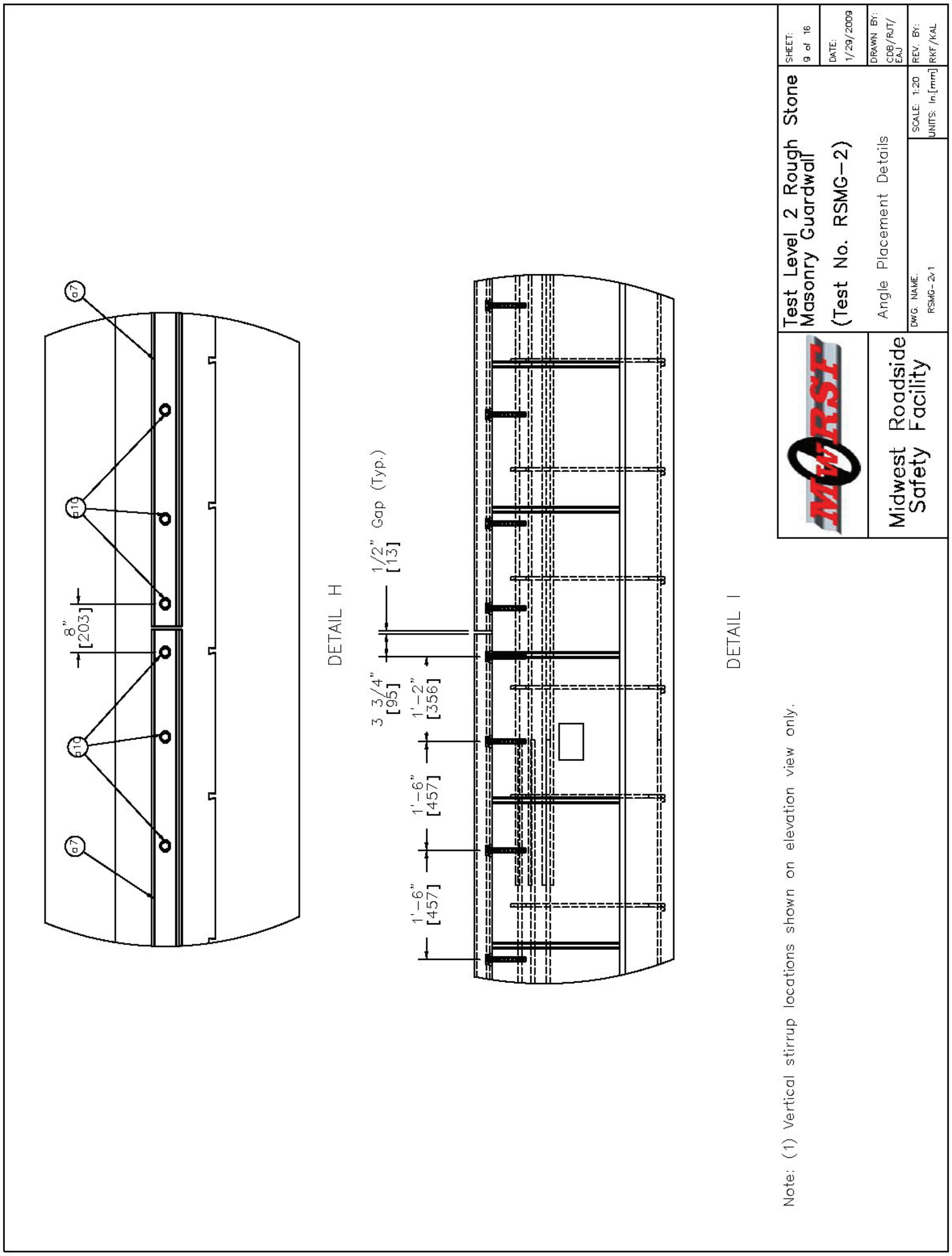


Figure E-9. Angle Placement Details, Test No. RSMG-2

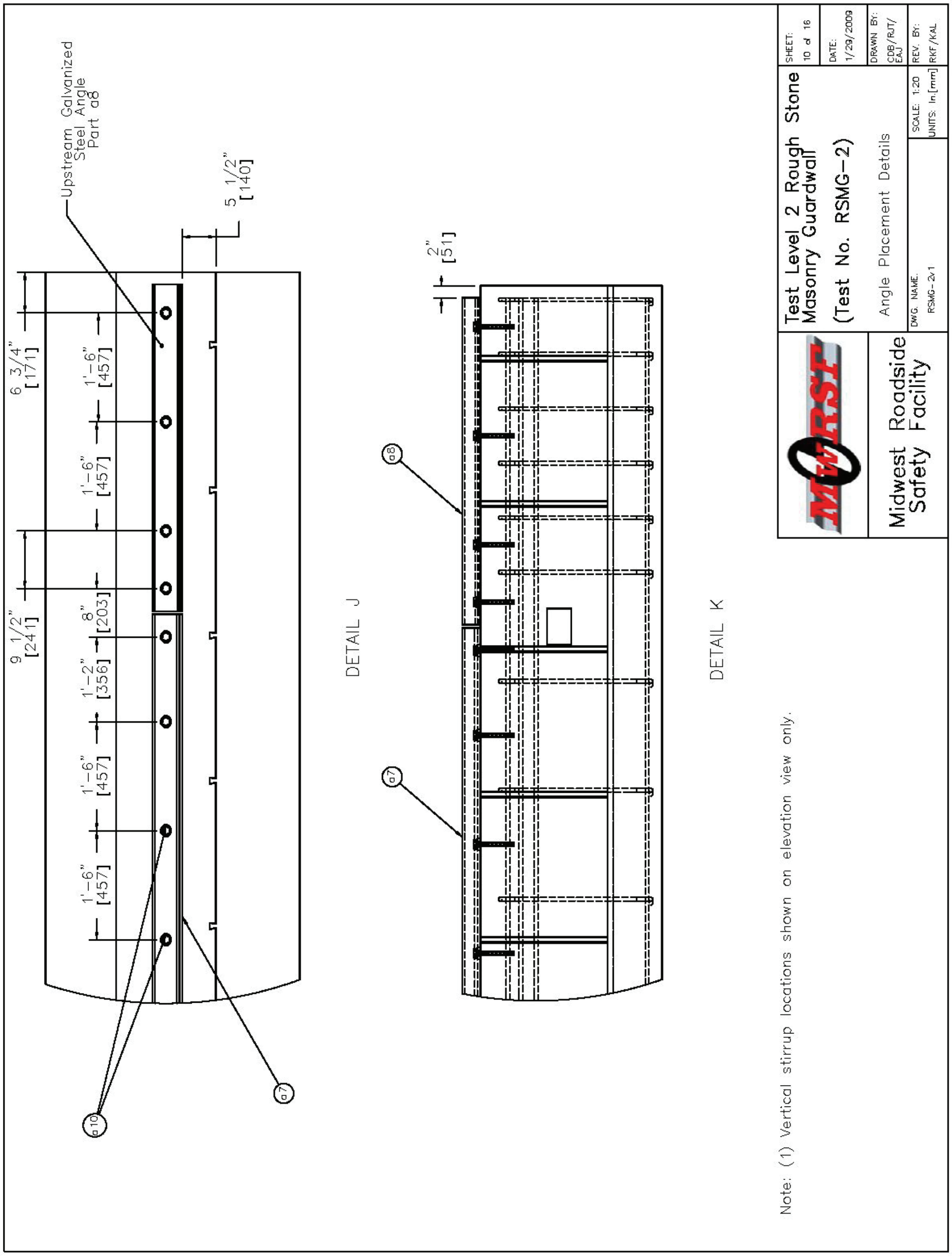


Figure E-10. Angle Placement Details, Test No. RSMG-2

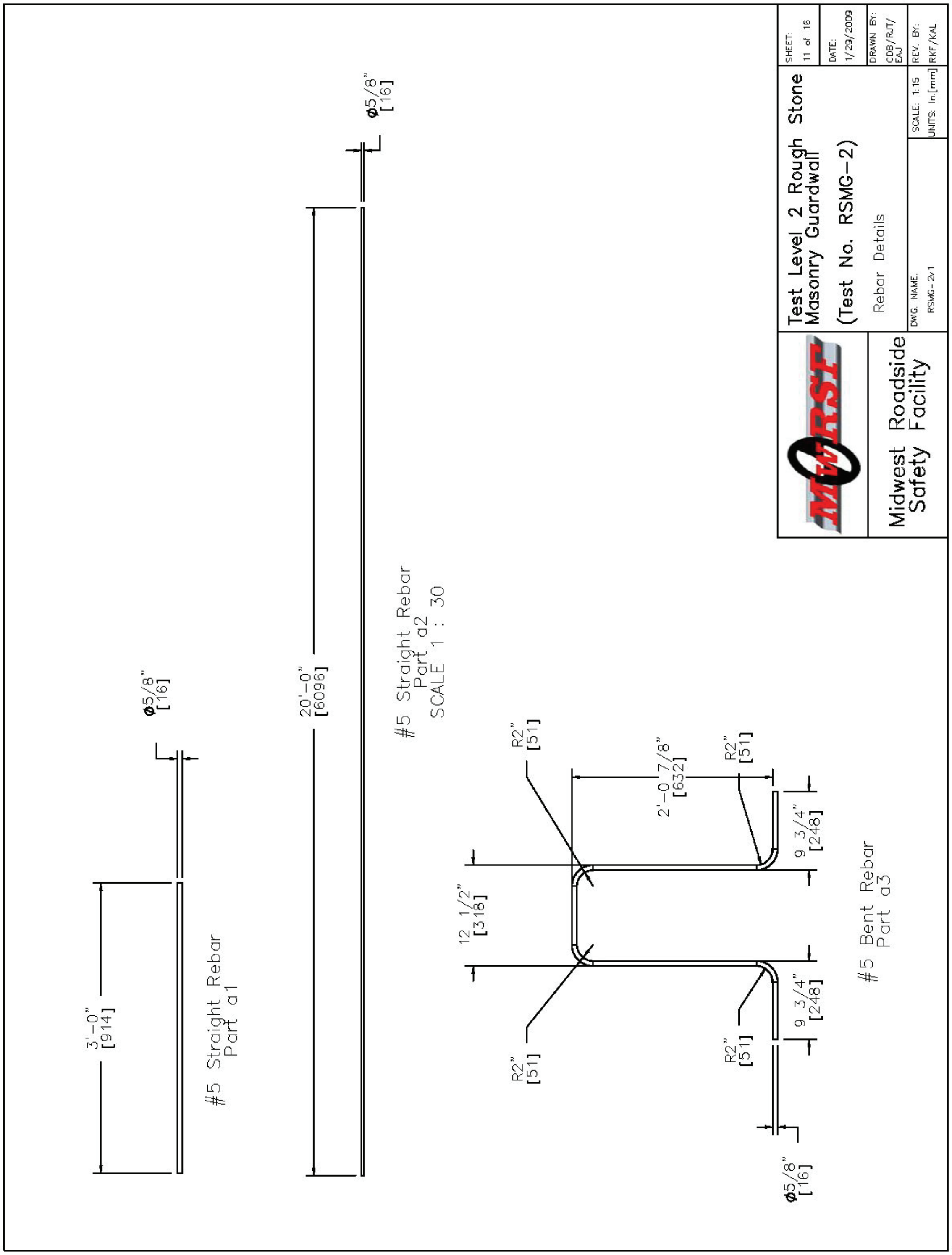


Figure E-11. Rebar Details, Test No. RSMG-2

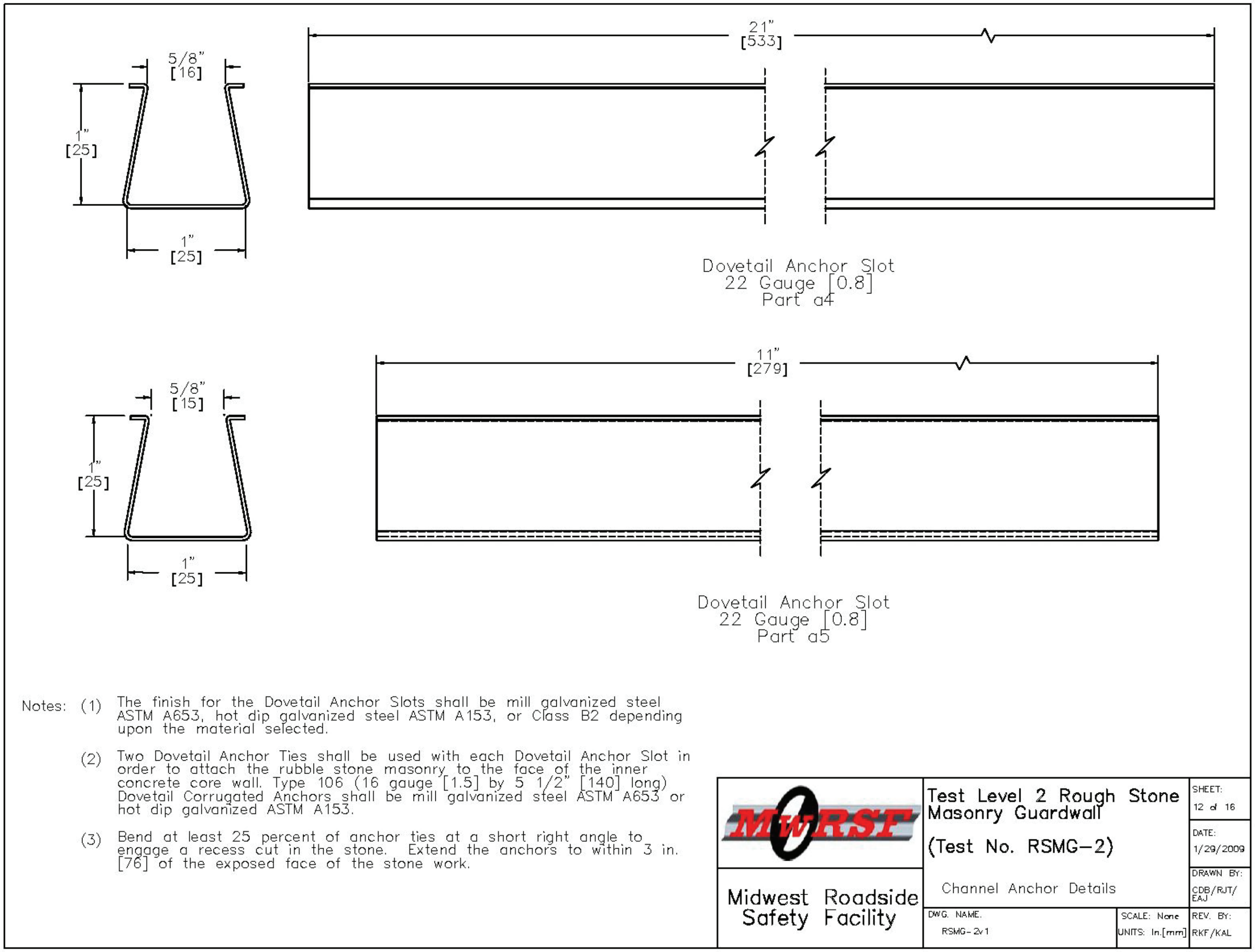


Figure E-12. Dovetail Anchor Details, Test No. RSMG-2

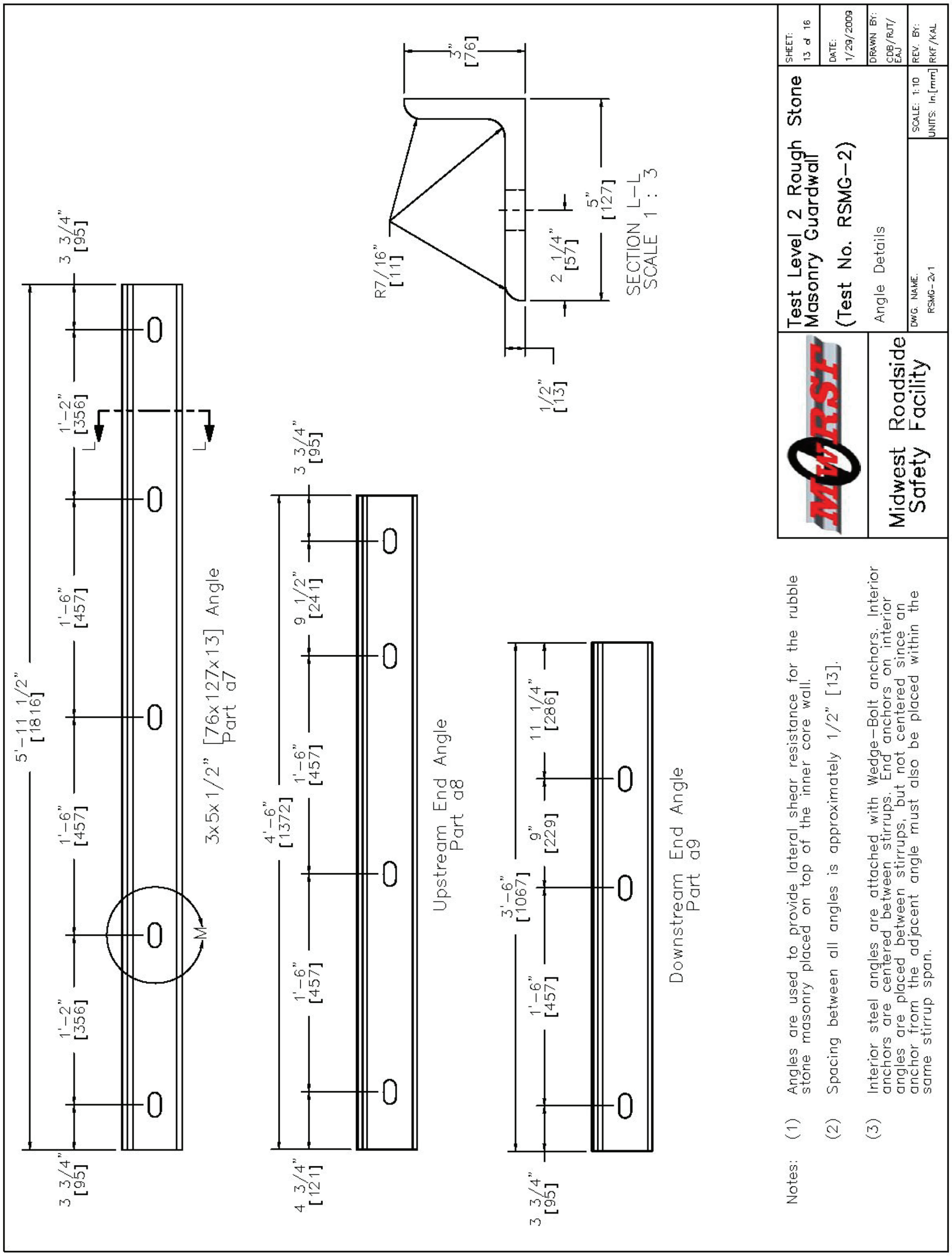


Figure E-13. Steel Angle Details, Test No. RSMG-2

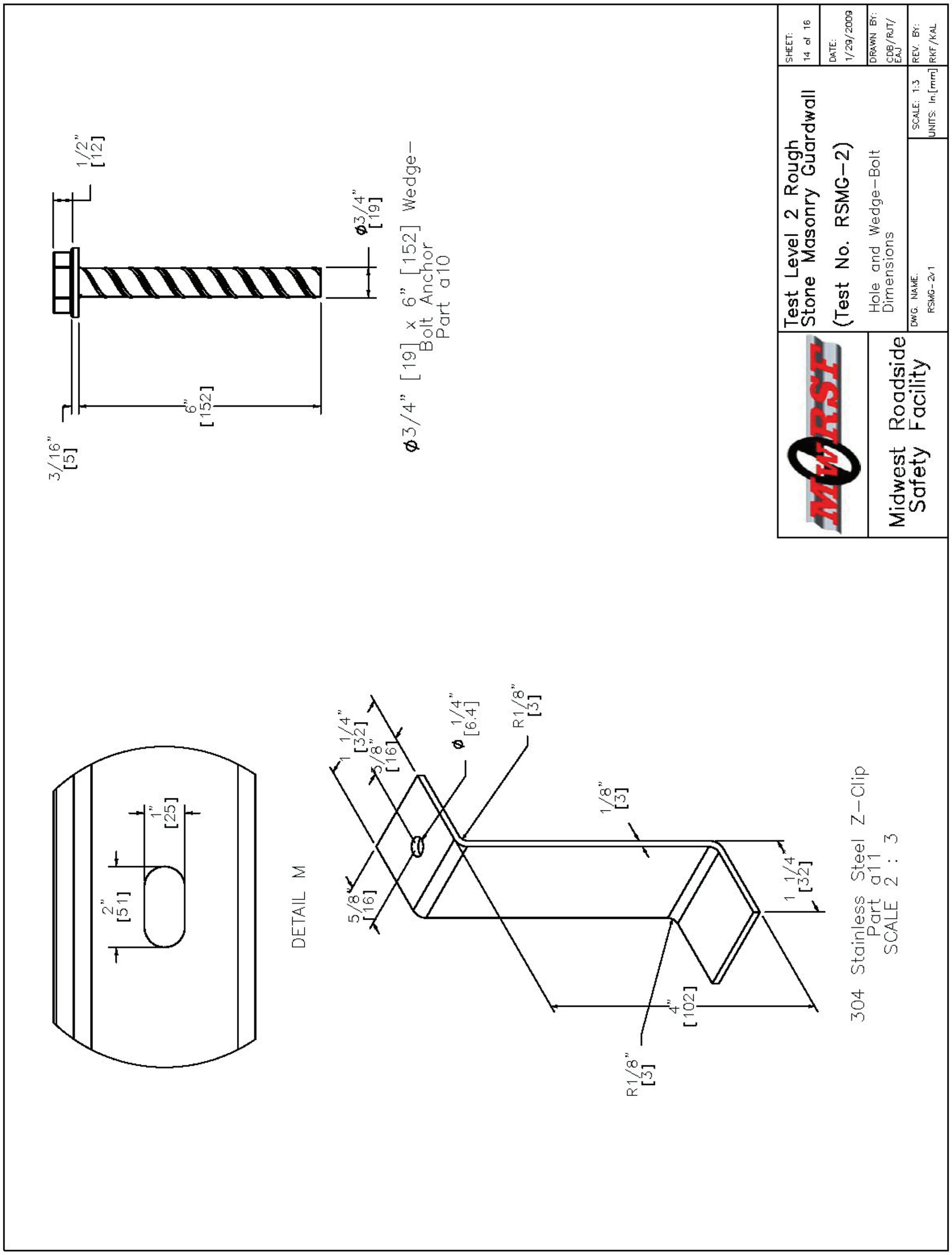


Figure E-14. Angle Slot, Z-Clip Bracket, and Wedge-Bolt Screw Anchor Dimensions, Test No. RSMG-2

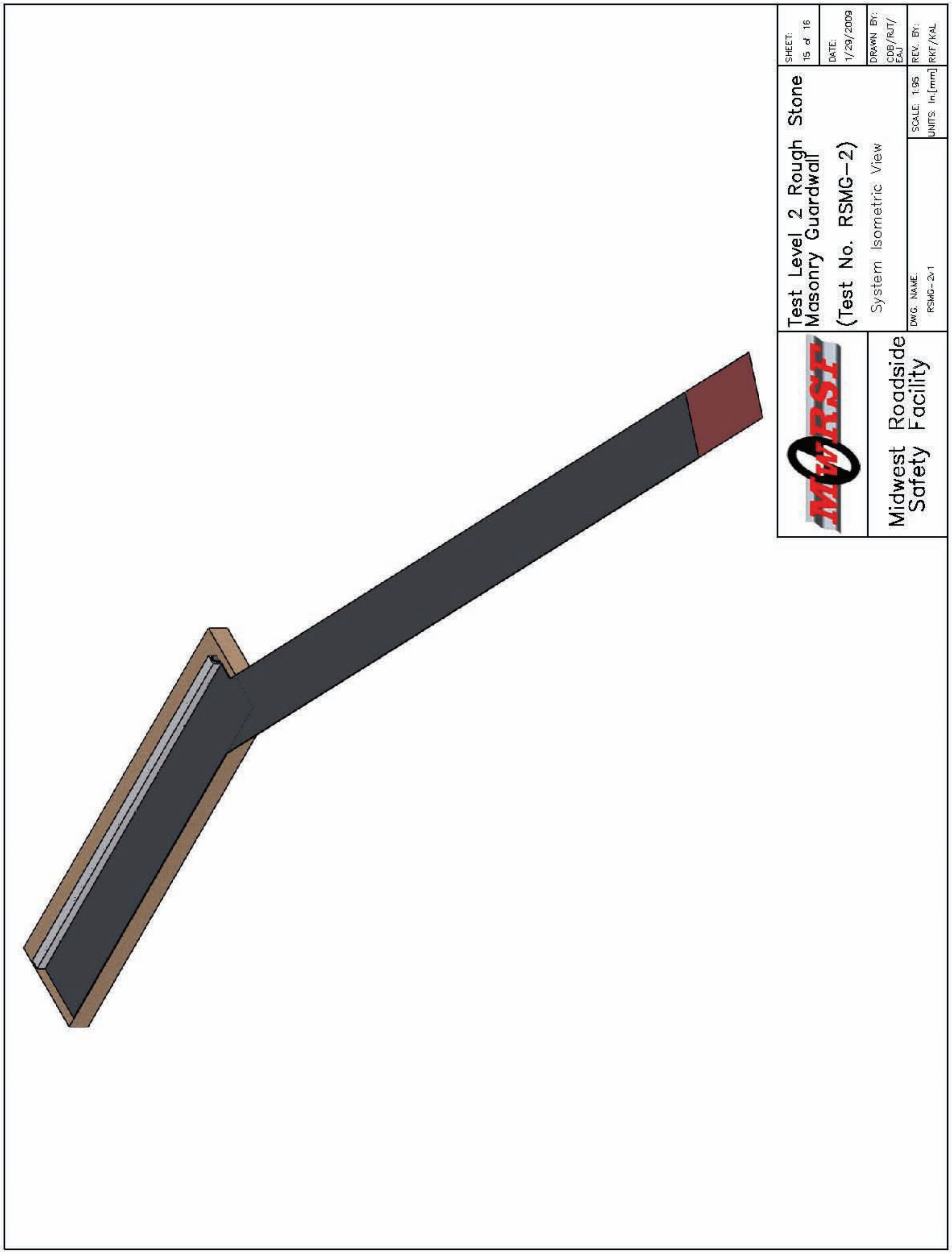


Figure E-15. System Isometric View, Test No. RSMG-2

Test Level 2 Rough Stone Masonry Guardwall			
Item No.	QTY.	Description	Material Specifications
a1	55	#5 Straight Rebar, 3' [914] long	Grade 60
a2	40	#5 Straight Rebar, 20' [6096] long	Grade 60
a3	55	#5 Bent Rebar	Grade 60
a4	35	Dovetail Anchor Slot 21" [533] long (22 gauge [0.8])–Galvanized	ASTM A1008, A109, or A1011
a5	2	Dovetail Anchor Slot 11" [279] long (22 gauge [0.8])–Galvanized	ASTM A1008, A109, or A1011
a7	11	5x3x1/2" [127x76x13] Interior Angle	Galvanized, ASTM A36 Steel
a6	111	Dovetail Anchor Tie (16 gauge by 5 1/2" long by 1" wide)	Galvanized Steel
a8	1	5x3x1/2" [127x76x13] Upstream End Angle	Galvanized, ASTM A36 Steel
a9	1	5x3x1/2" [127x76x13] Downstream End Angle	Galvanized, ASTM A36 Steel
a10	62	3/4" [19] Dia. by 6" [152] long Wedge–Bolt Anchor	Galvanized, Carbon Steel
a11	37	Z–Clips	304 Stainless Steel
a12	37	Heavy–Weight, Tapcon Masonry Anchors – 1/4" [6.4] Diam. x 2 3/4" [70] long	Stainless Steel
b1	1	3'–6" x 74'–4" x 6" [1.1mx22.7mx152mm] Aggregate Base	Aggregate
b2	1	Concrete Corewall Base	f'c = 3,500 psi [24.1 MPa]
b3	1	Concrete Corewall Top	f'c = 3,500 psi [24.1 MPa]
c1	1	Rough Stone Masonry Facade (Rubble Masonry)	Sound, Durable Rock with Mortar
c2	1	Mortar Bed – PROMIX Stone Veneer Mortar conforming to ASTM C–270 Type S Specifications	FHWA Section 712.05(a)

Midwest Roadside Safety Facility

Test Level 2 Rough Stone Masonry Guardwall
(Test No. RSMG–2)
Bill Of Materials

SHEET: 16 of 16
DATE: 1/29/2009
DRAWN BY: CDB/RJT/EAJ
DWG. NAME. RSMG-2v1
SCALE: None
UNITS: In.[mm]
REV. BY: RKF/KAL

Figure E-16. Bill of Materials, Test No. RSMG-2

Appendix F. Material Specifications

Figure F-1. PROMIX Mortar Mix

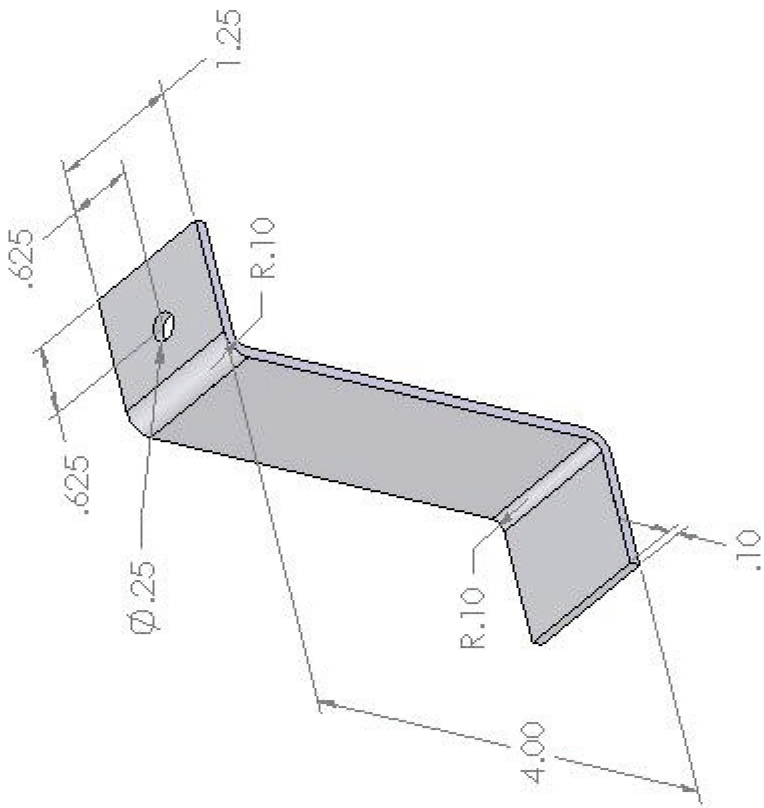


Figure F-2. Stainless Steel Z-Clip

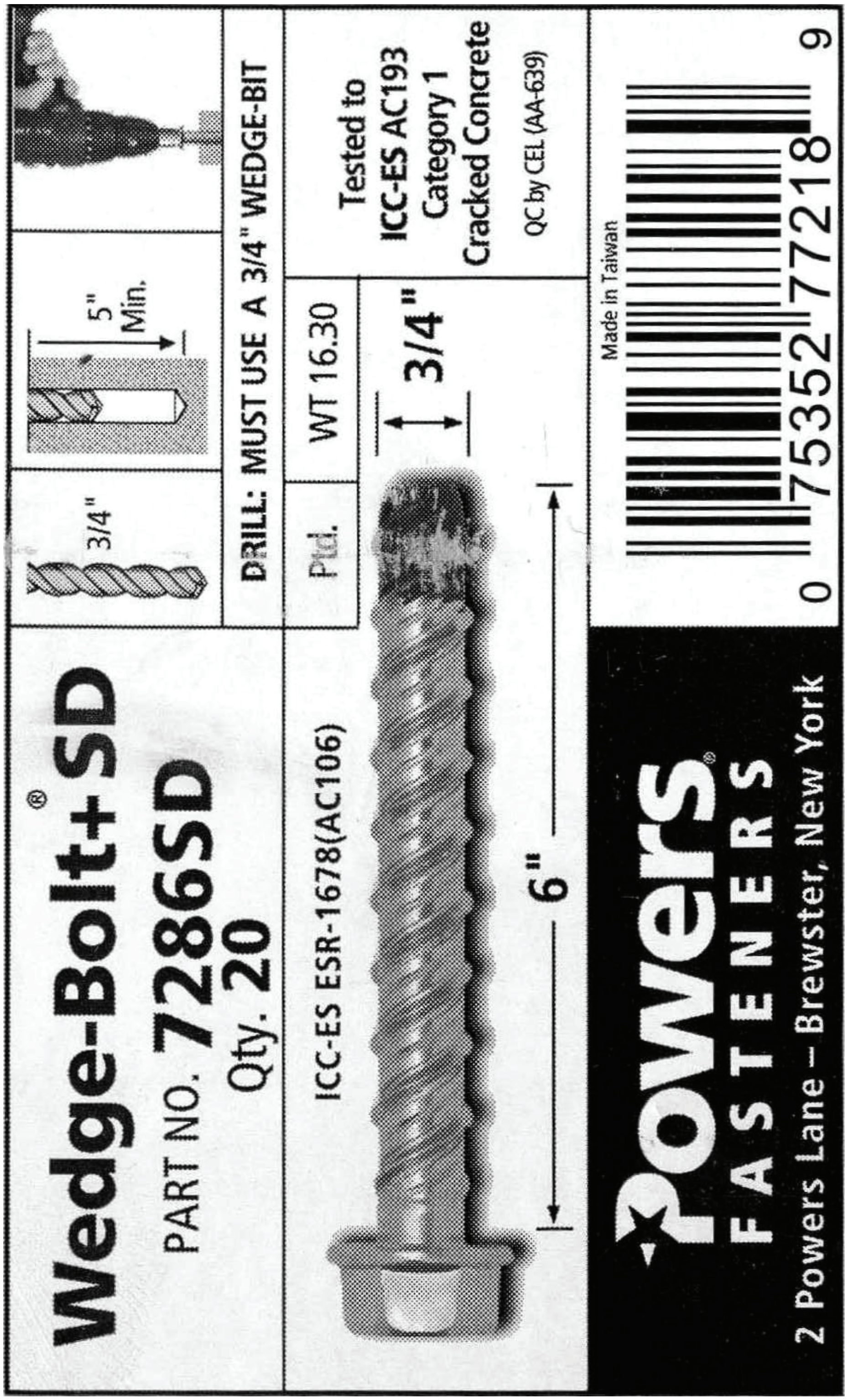
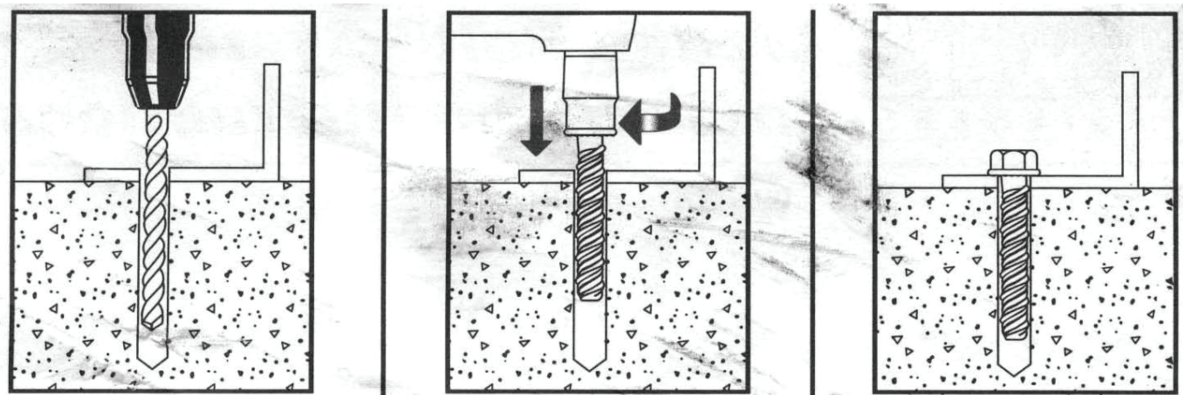


Figure F-3. Wedge-Bolt Material Specifications



1. Using the proper diameter ***Wedge-Bit,*** drill a hole into the base material to a depth of at least 1/2" or one anchor diameter deeper than the embedment required. ***Be sure to use a Wedge-Bit.*** Blow the hole clean of dust and other material. Insert the anchor through the fixture into the anchor hole.

2. Begin tightening the anchor by applying forward pressure when engaging the first few threads. Continue tightening the anchor until the head is firmly seated against the fixture. In extremely dense materials, use of an impact wrench is recommended.

3. Be sure the anchor is at the required embedment depth and that the maximum torque has not been exceeded. The Installation is now complete.

For complete details on the design and installation of anchors, refer to the Fastening Systems Design Manual published by Powers Fasteners, Inc.

Wedge-Bolt™ + Wedge-Bit™ = Proper Installation
Do not use a standard ANSI drill bit

Figure F-4. Wedge-Bolt Material Specifications

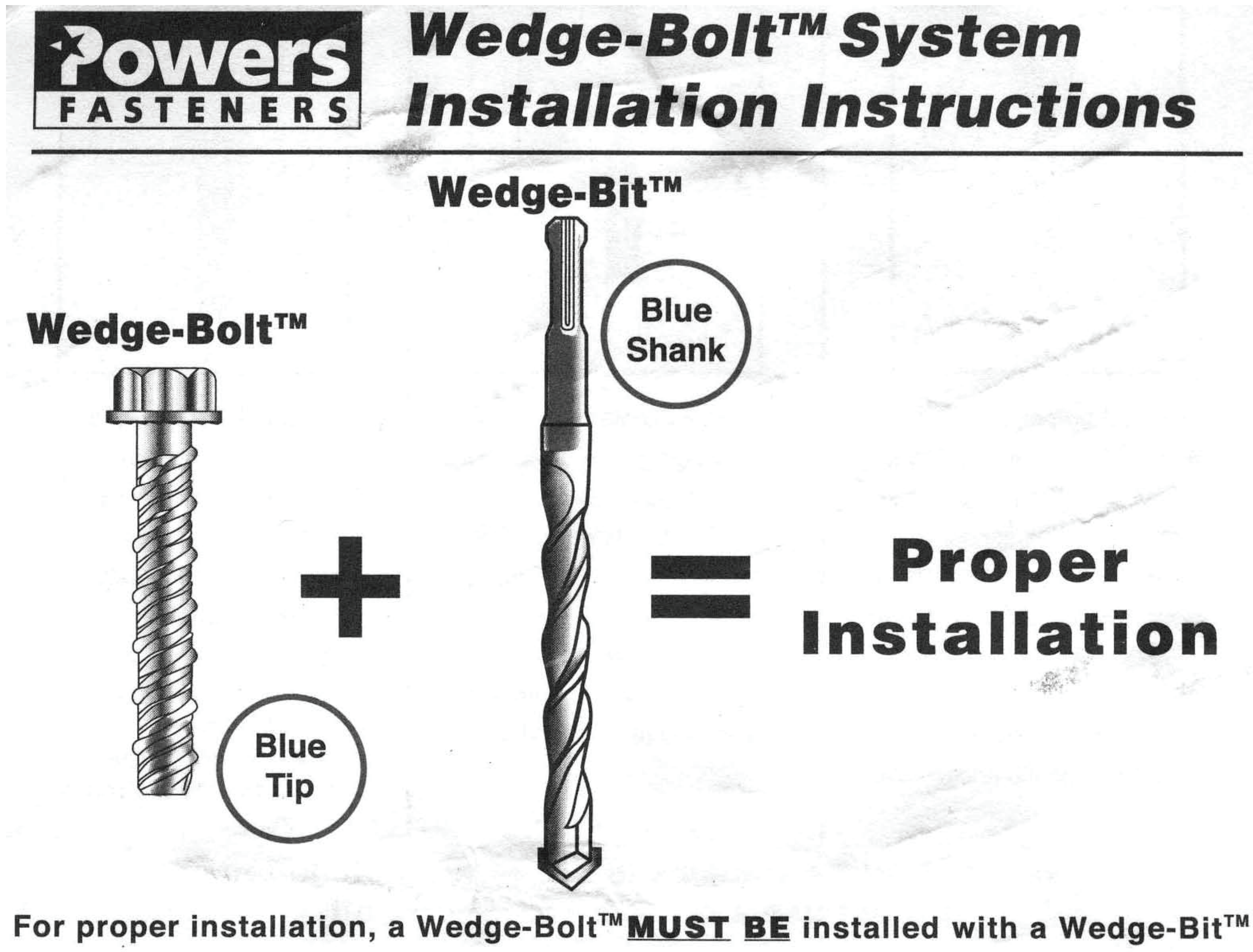


Figure F-5. Wedge-Bolt Material Specification

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