Research Project Number TPF-5(193) Supplement #113
WisDOT Sponsoring Agency Code RPFP-WISC-6

DYNAMIC TESTING AND EVALUATION OF CULVERT-MOUNTED, STRONG-POST MGS TO TL-3 GUIDELINES OF MASH 2016

Submitted by

Mojdeh Asadollahi Pajouh, Ph.D., P.E.
Research Assistant Professor

Jennifer D. Rasmussen, Ph.D., P.E.
Research Associate Professor

Ronald K. Faller, Ph.D., P.E.
Research Professor and MwRSF Director

Robert W. Bielenberg, M.S.M.E., E.I.T.
Research Engineer

Fengtao Bai, Ph.D.
Former Post-Doctoral Research Associate

James C. Holloway, M.S.M.E., E.I.T.
Research Engineer & Assistant Director –
Physical Testing Division

MIDWEST ROADSIDE SAFETY FACILITY
Nebraska Transportation Center
University of Nebraska-Lincoln

Main Office
Prem S. Paul Research Center at Whittier School
Room 130, 2200 Vine Street
Lincoln, Nebraska 68583-0853
(402) 472-0965

Outdoor Test Site
4630 N.W. 36th Street
Lincoln, Nebraska 68524

Submitted to

WISCONSIN DEPARTMENT OF TRANSPORTATION
4802 Sheboygan Avenue
Madison, Wisconsin 53707

MwRSF Research Report No. TRP-03-383-20-R1

November 2, 2020

TESTING CERT # 2937.01

November 2020 ADDENDUM / ERRATA

to MwRSF Report No. TRP-03-383-20
"Dynamic Testing and Evaluation of Culvert-Mounted, Strong-Post MGS to TL-3 Guidelines of MASH 2016"
Published October 26, 2020

Page	Revision
90	Test no. CMGS-1 impact location changed from 76 in. to 92 in. upstream from post no. 19.
143	Test no. CMGS-1 impact location changed from 76 in. to 92 in. upstream from post no. 19.

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TRP-03-383-20-R1		

4. Title and Subtitle
Dynamic Testing and Evaluation of Culvert-Mounted, Strong-Post MGS to TL-3 Guidelines of MASH 2016

5. Report Date
November 2, 2020

6. Performing Organization Code

7. Author(s)
Asadollahi Pajouh, M., Bielenberg, R.W., Rasmussen, J.D., Bai, F., Faller, R.K., and Holloway, J.C.

8. Performing Organization Report No.
TRP-03-383-20-R1

9. Performing Organization Name and Address
Midwest Roadside Safety Facility (MwRSF)
Nebraska Transportation Center
University of Nebraska-Lincoln

Main Office:
Prem S. Paul Research Center at Whittier School
Room 130, 2200 Vine Street
Lincoln, Nebraska 68583-0853

Outdoor Test Site:
4630 N.W. 36th Street
Lincoln, Nebraska
68524

10. Work Unit No.

11. Contract
TPF-5(193) Supplement #113

12. Sponsoring Agency Name and Address
Wisconsin Department of Transportation
4802 Sheboygan Avenue
Madison, Wisconsin 53707

13. Type of Report and Period Covered
Final Report: 2017-2020

14. Sponsoring Agency Code
RPFP–WISC-6

15. Supplementary Notes
Prepared in cooperation with U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

A modified design of the MGS was evaluated for installation on a low-fill culvert with a strong-post attachment using to the culvert, half-post spacing, and a 12-in. (305-mm) offset from the back of the post to the culvert headwall through full-scale crash testing. A four-cell, concrete culvert with 8-in. (203-mm) thick slab and 9-in. (229-mm) deep soil fill was utilized. The test installation consisted of 182.3-ft (55.6-m) long MGS with a 31-in. (787-mm) top rail height, supported by twenty-three W6x8.5 by 72-in. (1,829-mm) long posts upstream and downstream of the culvert and fourteen W6x9 by 41-in. (1,041-mm) long posts attached to the culvert's top slab using a deformable baseplate and through-bolts.

Two crash tests were conducted according to the American Association of State Highway Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware* 2016 (MASH) Test Level 3 (TL-3) impact safety criteria. In test no. CMGS-1, a 2,428-lb (1,101-kg) car impacted the culvert-mounted MGS at a speed of 61.3 mph (98.7 km/h) and at an angle of 25.1 degrees. In test no. CMGS-2, a 5,013-lb (2,274-kg) pickup truck impacted the MGS attached to the culvert at a speed of 62.8 mph (101.1 km/h) and an angle of 25.7 degrees. In both tests, the vehicle was safely redirected and captured. Both tests were deemed acceptable according to TL-3 safety criteria in MASH. Recommendations were made for the implementation of MGS on low-fill culverts as well as transitioning from the standard MGS to the culvert-mounted MGS.

17. Key Words
Highway Safety, Crash Test, Roadside Appurtenances, Compliance Test, MASH 2016, Longitudinal Barrier, Culvert-Mounted, TL-3, Strong Post MGS.

18. Distribution Statement
No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	253	

DISCLAIMER STATEMENT

This material is based upon work supported by the Federal Highway Administration, U.S. Department of Transportation and the Nebraska and Wisconsin Departments of Transportation under TPF-5(193) Supplement #113. The contents of this report reflect the views and opinions of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Nebraska or Wisconsin Departments of Transportation nor the Federal Highway Administration, U.S. Department of Transportation. This report does not constitute a standard, specification, or regulation. Trade or manufacturers' names, which may appear in this report, are cited only because they are considered essential to the objectives of the report. The United States (U.S.) government and the States of Nebraska and Wisconsin do not endorse products or manufacturers.

UNCERTAINTY OF MEASUREMENT STATEMENT

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

INDEPENDENT APPROVING AUTHORITY

The Independent Approving Authority (IAA) for the data contained herein was Dr. Cody Stolle, E.I.T., Research Assistant Professor.

ACKNOWLEDGEMENTS

The authors wish to acknowledge several sources that made a contribution to this project: (1) Wisconsin Department of Transportation for sponsoring the project; (2) Nebraska Department of Transportation for management and facilitation of the Midwest Pooled Fund and project; (3) MwRSF personnel for constructing the barriers and conducting the crash tests; and (4) the Holland Computing Center at the University of Nebraska for the high-performance computing resources.

Acknowledgement is also given to the following individuals who contributed to the completion of this research project.

Midwest Roadside Safety Facility
K.A. Lechtenberg, M.S.M.E., E.I.T., Research Engineer
S.K. Rosenbaugh, M.S.C.E., E.I.T., Research Engineer
C.S. Stolle, Ph.D., E.I.T., Research Assistant Professor
J.S. Steelman, Ph.D., P.E., Associate Professor
A.T. Russell, B.S.B.A., Testing and Maintenance Technician II
E.W. Krier, B.S., Construction and Testing Technician II
S.M. Tighe, Construction and Testing Technician I
D.S. Charroin, Construction and Testing Technician I
R.M. Novak, Construction and Testing Technician I
T.C. Donahoo, Construction and Testing Technician I
J.T. Jones, Construction and Testing Technician I
C.I. Sims, Former Construction and Testing Technician I
J.E. Kohtz, B.S.M.E., CAD Technician
E.L. Urbank, B.A., Research Communication Specialist
Z.Z. Jabr, Engineering Technician
Undergraduate and Graduate Research Assistants

Wisconsin Department of Transportation
Jerry Zogg, P.E., Former Chief Roadway Standards Engineer
Erik Emerson, P.E., Standards Development Engineer
Rodney Taylor, P.E., Roadway Design Standards Unit Supervisor

Nebraska Department of Transportation
Jodi Gibson, Former Research Coordinator
Mark Fischer, P.E., Research Program Manager

TABLE OF CONTENTS

TECHNICAL REPORT DOCUMENTATION PAGE i

DISCLAIMER STATEMENT ii

UNCERTAINTY OF MEASUREMENT STATEMENT ii

INDEPENDENT APPROVING AUTHORITY ii

ACKNOWLEDGEMENTS iii

TABLE OF CONTENTS iv

LIST OF FIGURES vi

LIST OF TABLES xii

1 INTRODUCTION 1
  1.1 Background 1
  1.2 Research Objective 5
  1.3 Scope 5

2 TEST REQUIREMENTS AND EVALUATION CRITERIA 6
  2.1 Test Requirements 6
  2.2 Evaluation Criteria 6
  2.3 Soil Strength Requirements 7

3 DESIGN DETAILS 8
  3.1 Culvert Design and Construction 8
  3.2 Culvert-Mounted, Strong Post MGS 28

4 TEST CONDITIONS 51
  4.1 Test Facility 51
  4.2 Vehicle Tow and Guidance System 51
  4.3 Test Vehicles 51
  4.4 Simulated Occupant 61
  4.5 Data Acquisition Systems 61
    4.5.1 Accelerometers 61
    4.5.2 Rate Transducers 61
    4.5.3 Retroreflective Optic Speed Trap 61
    4.5.4 Digital Photography 62

5 FULL-SCALE CRASH TEST NO. CMGS-1 65
  5.1 Static Soil Test 65
  5.2 Weather Conditions 65
  5.3 Test Description 65
  5.4 Barrier Damage 74
  5.5 Vehicle Damage 82

5.6 Occupant Risk 88
5.7 Discussion 89

6 FULL-SCALE CRASH TEST NO. CMGS-2 91
6.1 Static Soil Test 91
6.2 Weather Conditions 91
6.3 Test Description 91
6.4 Barrier Damage 100
6.5 Vehicle Damage 111
6.6 Occupant Risk 117
6.7 Discussion 118

7 STIFFNESS TRANSITION FROM MGS TO CULVERT-MOUNTED MGS 120
7.1 Transition from Half-Post Spacing MGS to Culvert-Mounted MGS 121
7.2 Transition from Standard MGS to Half-Post Spacing MGS 124
7.2.1 Evaluation of MGS to Half-Post Spacing MGS 127
7.2.2 Simulation of Culvert-Mounted Midwest Guardrail System 127
7.2.3 Determination of Critical Impact Point 139
7.3 Transition Recommendations for Culvert Mounted MGS System 142

8 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS 143
8.1 Recommendations 144

9 MASH EVALUATION 148
9.1 MASH Crash Test Matrix 148
9.2 Full-Scale Crash Testing 148
9.3 MASH 2016 Evaluation 149

10 REFERENCES 150

11 APPENDICES 153
Appendix A. Material Specifications 154
Appendix B. Vehicle Center of Gravity Determination 198
Appendix C. Static Soil Tests 201
Appendix D. Vehicle Deformation Records 206
Appendix E. Accelerometer and Rate Transducer Data Plots, Test No. CMGS-1 219
Appendix F. Accelerometer and Rate Transducer Data Plots, Test No. CMGS-2 236

LIST OF FIGURES

Figure 1. Side-Mounted Configuration for Guardrail on Culvert Headwalls [4] 2
Figure 2. NCHRP Report No. 350-Compliant, Modified G4(1S) Guardrail Attachment to Low-Fill Culvert [5]..3
Figure 3. MASH-Compliant, MGS Guardrail Attachment to Low-Fill Culvert [8].........................4
Figure 4. Culvert System Overview, Test Nos. CMGS-1 and CMGS-2 10
Figure 5. Top Slab and Vertical Support Wall Details, Test Nos. CMGS-1 and CMGS-2...........11
Figure 6. Concrete Rebar Connections, Test Nos. CMGS-1 and CMGS-2..................................12
Figure 7. Concrete Rebar Connections (Cont.), Test Nos. CMGS-1 and CMGS-2 13
Figure 8. Top Slab, Soil Retaining Wall, Interior Vertical Support Wall Details, Test Nos. CMGS-1 and CMGS-2 14
Figure 9. Top Slab, Soil Retaining Wall, Right Exterior Vertical Support Wall Details, Test Nos. CMGS-1 and CMGS-2..15
Figure 10. Concrete Culvert in Ground Details, Test Nos. CMGS-1 and CMGS-2 16
Figure 11. Concrete Top Slab Details, Test Nos. CMGS-1 and CMGS-2 17
Figure 12. Interior and Exterior Support Wall Details, Test Nos. CMGS-1 and CMGS-2...........18
Figure 13. Exterior Support Wall Details, Test Nos. CMGS-1 and CMGS-2..............................19
Figure 14. Concrete Soil Retaining Wall Details, Test Nos. CMGS-1 and CMGS-2 20
Figure 15. Rebar Details, Test Nos. CMGS-1 and CMGS-2...21
Figure 16. Rebar Details (Cont.), Test Nos. CMGS-1 and CMGS-2 22
Figure 17. Bill of Materials, Test Nos. CMGS-1 and CMGS-2 23
Figure 18. Concrete Culvert Support Walls Framework, Test Nos. CMGS-1 and CMGS-2........24
Figure 19. Concrete Top Slab, Headwall, and Soil Retaining Wall Framework, Test Nos. CMGS-1 and CMGS-2 25
Figure 20. Concrete Top Slab and Headwall Construction, Test Nos. CMGS-1 and CMGS-2..26
Figure 21. Concrete Culvert Superstructure, Top Slab, Headwall, and Vertical Supports, Test Nos. CMGS-1 and CMGS-2 27
Figure 22. System Layout, Test No. CMGS-1..29
Figure 23. System Layout, Test No. CMGS-2..30
Figure 24. Post Nos. 13 through 15, 17 through 22, and 24 through 26 Details, Test Nos. CMGS-1 and CMGS-2 31
Figure 25. Post Nos. 16 and 23 Details, Test Nos. CMGS-1 and CMGS-2 32
Figure 26. Splice and Post Details, Test Nos. CMGS-1 and CMGS-2...33
Figure 27. End Section Details, Test Nos. CMGS-1 and CMGS-2..34
Figure 28. BCT Anchor Details, Test Nos. CMGS-1 and CMGS-2...35
Figure 29. Foundation Tube and BCT Timber Post Details, Test Nos. CMGS-1 and CMGS-2..36
Figure 30. Post Nos. 1 through 12 and 27 through 41 Component Details, Test Nos. CMGS-1 and CMGS-2 37
Figure 31. Post Nos. 13 through 26 Assembly Details, Test Nos. CMGS-1 and CMGS-2...........38
Figure 32. Post Nos. 13 through 26 Component Details, Test Nos. CMGS-1 and CMGS-2........39
Figure 33. BCT Anchor Cable, Test Nos. CMGS-1 and CMGS-2...40
Figure 34. BCT Post Components and Anchor Bracket, Test Nos. CMGS-1 and CMGS-2.........41
Figure 35. Ground Strut and Bearing Plate, Test Nos. CMGS-1 and CMGS-2 42
Figure 36. Rail Section Details, Test Nos. CMGS-1 and CMGS-2..43

Figure 37. System Hardware Details, Test Nos. CMGS-1 and CMGS-2....44
Figure 38. System Hardware Details, Test Nos. CMGS-1 and CMGS-2....45
Figure 39. Bill of Materials, Test Nos. CMGS-1 and CMGS-2....46
Figure 40. Bill of Materials (Cont.), Test Nos. CMGS-1 and CMGS-2....47
Figure 41. System Installation, Test Nos. CMGS-1 and CMGS-2....48
Figure 42. Posts Attached to Culvert, Test Nos. CMGS-1 and CMGS-2....49
Figure 43. Bottom-Side Steel Post Connection Details and End Anchorage Systems, Test Nos. CMGS-1 and CMGS-2....50
Figure 44. Test Vehicle, Test No. CMGS-1....53
Figure 45. Test Vehicle's Undercarriage and Interior Floorboards, Test No. CMGS-1....54
Figure 46. Vehicle Dimensions, Test No. CMGS-1....55
Figure 47. Test Vehicle, Test No. CMGS-2....56
Figure 48. Test Vehicle's Undercarriage and Interior Floorboards, Test No. CMGS-2....57
Figure 49. Vehicle Dimensions, Test No. CMGS-2....58
Figure 50. Target Geometry, Test No. CMGS-1....59
Figure 51. Target Geometry, Test No. CMGS-2....60
Figure 52. Camera Locations, Speeds, and Lens Settings, Test No. CMGS-1....63
Figure 53. Camera Locations, Speeds, and Lens Settings, Test No. CMGS-2....64
Figure 54. Impact Location, Test No. CMGS-1....66
Figure 55. Sequential Photographs, Test No. CMGS-1....69
Figure 56. Sequential Photographs, Test No. CMGS-1....70
Figure 57. Additional Sequential Photographs, Test No. CMGS-1....71
Figure 58. Documentary Photographs, Test No. CMGS-1....72
Figure 59. Vehicle Trajectory and Final Position, Test No. CMGS-1....73
Figure 60. System Damage, Test No. CMGS-1....75
Figure 61. Damage to Post Nos. 15 through 22, Test No. CMGS-1....76
Figure 62. Damage to Post and Base Plate Nos. 17 through 21 (After Removal of Soil Fill Post and Base), Test No. CMGS-1....77
Figure 63. Damage to Post and Base Plate Nos. 18 and 19, Test No. CMGS-1....78
Figure 64. Damage to Post and Base Plate No. 21, Test No. CMGS-1....79
Figure 65. Washer Plate Nos. 18 through 22 After Test, Test No. CMGS-1....80
Figure 66. (a) Upstream Anchorage System After Test, and (b) Downstream Anchorage System After Test, Test No. CMGS-1....81
Figure 67. Permanent Set Deflection, Dynamic Deflection, and Working Width, Test No. CMGS-1....82
Figure 68. Vehicle Damage, Test No. CMGS-1....83
Figure 69. Additional Vehicle Damage, Test No. CMGS-1....84
Figure 70. Vehicle Windshield Damage, (a) on Test Site on Test Day, (b) in Vehicle Shop Prior to Measurement, Test No. CMGS-1....85
Figure 71. Occupant Compartment Damage, Test No. CMGS-1....86
Figure 72. Vehicle Undercarriage Damage, Test No. CMGS-1....87
Figure 73. Summary of Test Results and Sequential Photographs, Test No. CMGS-1....90
Figure 74. Impact Location, Test No. CMGS-2....92
Figure 75. Sequential Photographs, Test No. CMGS-2....95
Figure 76. Additional Sequential Photographs, Test No. CMGS-2....96
Figure 77. Additional Sequential Photographs, Test No. CMGS-2....97
Figure 78. Documentary Photographs, Test No. CMGS-2....98

Figure 79. Vehicle Trajectory and Final Position, Test No. CMGS-2 99
Figure 80. System Damage, Test No. CMGS-2....................101
Figure 81. Damage to Post Nos. 15 through 21, Test No. CMGS-2 102
Figure 82. Guardrail Damage, Post Nos. 15 through 19, Test No. CMGS-2 103
Figure 83. Guardrail Damage, Post Nos. 15 through 22, Test No. CMGS-2 104
Figure 84. Rail Tears at Post No. 16, Test No. CMGS-2 105
Figure 85. Damage to Base Plates of Post Nos. 17 through 22, Test No. CMGS-2....................106
Figure 86. Damage to Base Plate Nos. 16 through 18 – After Soil Removal, Test No. CMGS-2....................107
Figure 87. Damage to Post Nos. 17 through 22 Damage – After Soil Removal, Test No. CMGS-2....................108
Figure 88. Culvert Deck after Removal of Soil Fill and Posts and Downstream Anchorage System Deformation, Test No. CMGS-2....................109
Figure 89. Damage to Upstream Anchorage System, Test No. CMGS-2 110
Figure 90. Permanent Set Deflection, Dynamic Deflection, and Working Width, Test No. CMGS-2....................111
Figure 91. Vehicle Damage, Test No. CMGS-2....................112
Figure 92. Additional Vehicle Damage, Test No. CMGS-2....................113
Figure 93. Vehicle Windshield Damage, Test No. CMGS-2 114
Figure 94. Vehicle Occupant Compartment Damage, Test No. CMGS-2....................115
Figure 95. Vehicle Undercarriage Damage, Test No. CMGS-2....................116
Figure 96. Summary of Test Results and Sequential Photographs, Test No. CMGS-2 119
Figure 97. System Sections within Test Installation....................121
Figure 98. (a) Soil Embedment Post Test Nos. MH-1 and MH-4; (b) Concrete-Mounted Post Test No. CGSA-4....................122
Figure 99. Load-Deflection Curves Comparison....................123
Figure 100. Energy-Deflection Curves Comparison 123
Figure 101. System Details and Layout, Test No. MWTSP-2....................125
Figure 102. (a) System Installation; (b) Impact Location, Test No. MWTSP-2 126
Figure 103. Culvert-Mounted MGS Model: (a) Transition from Half-Post Spacing MGS to Culvert-Mounted MGS; and (b) System Installation Model Overview....................128
Figure 104. Culvert-Mounted Post Simulation Details....................128
Figure 105. LS-DYNA Model for Test No. CMGS-2: (a) Isometric View; and (b) Overhead View....................130
Figure 106. Downstream Vehicle Position Comparison, Baseline CMGS Simulation and Test No. CMGS-2....................131
Figure 107. Velocity Comparison, Test and Baseline Simulation (No Wheel Disengagement): (a) Longitudinal Change in Velocity; (b) Lateral Change in Velocity....................134
Figure 108. Deflection Comparison, Test and Baseline Simulation (No Wheel Disengagement) 135
Figure 109. Roll, Pitch and Yaw Angles Comparison, Baseline Simulation 136
Figure 110. Simulation without Wheel Disengagement (Left), Simulation with Wheel Disengaged (Middle), and Test No. CMGS-2 (Right)....................137
Figure 111. Change of Velocity Comparison, Baseline and Wheel Disengaged Models 138
Figure 112. Illustration of Impact Points at Transition from Standard MGS to Half-Post Spacing MGS with Critical Impact Point Denoted in Blue 139

Figure A-1. 12-ft – 6-in. (3,810-mm) 12-gauge (2.7-mm) W-Beam MGS Section and End Section, Test Nos. CMGS-1 and CMGS-2 158
Figure A-2. 6-ft – 3-in. (1,905-mm) 12-gauge (2.7-mm) W-Beam MGS Section, Test Nos. CMGS-1 and CMGS-2 159
Figure A-3. 72-in. (1,829-mm) Long Foundation Tube, Test Nos. CMGS-1 and CMGS-2 160
Figure A-4. BCT Timber Posts, Test Nos. CMGS-1 and CMGS-2 161
Figure A-5. W6x8.5 (152x12.6), 72-in. (1,829-mm) Long Steel Posts, Test Nos. CMGS-1 and CMGS-2 162
Figure A-6. Timber Blockouts for Steel Posts, Test Nos. CMGS-1 and CMGS-2 163
Figure A-7. Timber Blockouts for Steel Posts, Test Nos. CMGS-1 and CMGS-2 164
Figure A-8. Timber Blockouts for Steel Posts, Test Nos. CMGS-1 and CMGS-2 165
Figure A-9. Timber Blockouts for Steel Posts, Test Nos. CMGS-1 and CMGS-2 166
Figure A-10. W6x9 (W150x13.5) 40½-in. (1,029-mm) Long Post, Test No. CMGS-1 and CMGS-2 167
Figure A-11. 8½-in. x 12-in. x ½-in. (216-mm x305-mm x 13-mm) Top Base Plate, Test No. CMGS-1 and CMGS-2 168
Figure A-12. 8½-in. x 11-in. x ¼-in. (216-mm x 280-mm x 6-mm) Bottom Post Plates, Test No. CMGS-1 169
Figure A-13. 8½-in. x 11-in. x ¼-in. (216-mm x 280-mm x 6-mm) Bottom Post Plates, Test No. CMGS-2 170
Figure A-14. ⅝-in. (16-mm) Diameter, 10-in. Hex Head Bolts, Test Nos. CMGS-1 and CMGS-2 171
Figure A-15. ⅝-in. (16-mm) Diameter, Hex Head Nuts, Test Nos. CMGS-1 and CMGS-2 172
Figure A-16. ⅞-in. (22-mm) Diameter, 8-in. (203-mm) Long Hex Head Bolts, Test Nos. CMGS-1 and CMGS-2 173
Figure A-17. ⅞-in. (22-mm) Diameter, Hex Head Nuts, Test Nos. CMGS-1 and CMGS-2 174
Figure A-18. 1-in. (25-mm) Diameter, 10½-in. (267-mm) Long Hex Head Bolts, Test Nos. CMGS-1 and CMGS-2 175
Figure A-19. 1-in. (25-mm) Diameter, 10-in. (254-mm) Long Threaded Rod, Test Nos. CMGS-1 and CMGS-2 176
Figure A-20. 1-in. (25-mm) Diameter Hex Nut, Test Nos. CMGS-1 and CMGS-2 177
Figure A-21. ⅝-in. (16-mm) Diameter, 1½-in. (38-mm) Long Hex Head Bolts, Test Nos. CMGS-1 and CMGS-2 178
Figure A-22. ⅝-in. (16-mm) Diameter, 14-in. (356-mm) Long Guardrail Bolts, Test Nos. CMGS-1 and CMGS-2 179
Figure A-23. ⅝-in. (16-mm) Diameter Guardrail Nuts, Test Nos. CMGS-1 and CMGS-2 180
Figure A-24. ⅝-in. (16-mm) Diameter, 1¼ in. (32-mm) Long Guardrail Bolt, Test Nos. CMGS-1 and CMGS-2 181
Figure A-25. 16D Double Head Nail, Test Nos. CMGS-1 and CMGS-2 182
Figure A-26. ⅝-in. (16-mm) Diameter, 10-in. (254-mm) Long Guardrail Bolt, Test Nos. CMGS-1 and CMGS-2 183
Figure A-27. BCT Anchor Cable, Test Nos. CMGS-1 and CMGS-2 184
Figure A-28. BCT Cable Washers, Test Nos. CMGS-1 and CMGS-2 185
Figure A-29. BCT Cable Nuts, Test Nos. CMGS-1 and CMGS-2 186
Figure A-30. BCT Post Sleeves, Test Nos. CMGS-1 and CMGS-2 187
Figure A-31. North-Side Anchor Bearing Plate and Anchor Bracket Assembly, Test Nos. CMGS-1 and CMGS-2 188

Figure A-32. South-Side Anchor Bearing Plate and North-Side Ground Strut Assembly, Test Nos. CMGS-1 and CMGS-2 189
Figure A-33. South-Side Ground Strut Assembly, Test Nos. CMGS-1 and CMGS-2....190
Figure A-34. South-Side Anchor Bearing Plate, Test Nos. CMGS-1 and CMGS-2....191
Figure A-35. Anchor Bracket Assembly, Test Nos. CMGS-1 and CMGS-2....192
Figure A-36. Concrete Culvert, Test Nos. CMGS-1 and CMGS-2....193
Figure A-37. Concrete Culvert, Test Nos. CMGS-1 and CMGS-2....194
Figure A-38. Concrete Culvert, Test Nos. CMGS-1 and CMGS-2....195
Figure A-39. #4 (#13) Rebar, Test Nos. CMGS-1 and CMGS-2....196
Figure A-40. #4 (#13) Bent Rebar, L-Shaped, 4 ft – 6 in. (1,372 mm) Total Length, Unbent, Test Nos. CMGS-1 and CMGS-2....197
Figure B-1. Vehicle Mass Distribution, Test No. CMGS-1....199
Figure B-2. Vehicle Mass Distribution, Test No. CMGS-2....200
Figure C-1. Soil Strength, Initial Calibration Tests, Test No. CMGS-1....202
Figure C-2. Static Soil Test, Test No. CMGS-1....203
Figure C-3. Soil Strength, Initial Calibration Tests, Test No. CMGS-2....204
Figure C-4. Static Soil Test, Test No. CMGS-2....205
Figure D-1. Floor Pan Deformation Data – Set 1, Test No. CMGS-1....207
Figure D-2. Floor Pan Deformation Data – Set 2, Test No. CMGS-1....208
Figure D-3. Occupant Compartment Deformation Data – Set 1, Test No. CMGS-1....209
Figure D-4. Occupant Compartment Deformation Data – Set 2, Test No. CMGS-1....210
Figure D-5. Exterior Vehicle Crush (NASS) - Front, Test No. CMGS-1....211
Figure D-6. Exterior Vehicle Crush (NASS) - Side, Test No. CMGS-1....212
Figure D-7. Floor Pan Deformation Data – Set 1, Test No. CMGS-2....213
Figure D-8. Floor Pan Deformation Data – Set 2, Test No. CMGS-2....214
Figure D-9. Occupant Compartment Deformation Data – Set 1, Test No. CMGS-2....215
Figure D-10. Occupant Compartment Deformation Data – Set 2, Test No. CMGS-2....216
Figure D-11. Exterior Vehicle Crush (NASS) - Front, Test No. CMGS-2....217
Figure D-12. Exterior Vehicle Crush (NASS) - Side, Test No. CMGS-2....218
Figure E-1. 10-ms Average Longitudinal Deceleration (SLICE-1), Test No. CMGS-1....220
Figure E-2. Longitudinal Change in Velocity (SLICE-1), Test No. CMGS-1....221
Figure E-3. Longitudinal Change in Displacement (SLICE-1), Test No. CMGS-1....222
Figure E-4. 10-ms Average Lateral Deceleration (SLICE-1), Test No. CMGS-1....223
Figure E-5. Lateral Change in Velocity (SLICE-1), Test No. CMGS-1....224
Figure E-6. Lateral Change in Displacement (SLICE-1), Test No. CMGS-1....225
Figure E-7. Vehicle Angular Displacements (SLICE-1), Test No. CMGS-1....226
Figure E-8. Acceleration Severity Index (SLICE-1), Test No. CMGS-1....227
Figure E-9. 10-ms Average Longitudinal Deceleration (SLICE-2), Test No. CMGS-1....228
Figure E-10. Longitudinal Change in Velocity (SLICE-2), Test No. CMGS-1....229
Figure E-11. Longitudinal Change in Displacement (SLICE-2), Test No. CMGS-1....230
Figure E-12. 10-ms Average Lateral Deceleration (SLICE-2), Test No. CMGS-1....231
Figure E-13. Lateral Change in Velocity (SLICE-2), Test No. CMGS-1....232
Figure E-14. Lateral Occupant Displacement (SLICE-2), Test No. CMGS-1....233
Figure E-15. Vehicle Angular Displacements (SLICE-2), Test No. CMGS-1....234
Figure E-16. Acceleration Severity Index (SLICE-2), Test No. CMGS-1....235
Figure F-1. 10-ms Average Longitudinal Deceleration (SLICE-2), Test No. CMGS-2....237
Figure F-2. Longitudinal Change in Velocity (SLICE-2), Test No. CMGS-2....238

Figure F-3. Longitudinal Change in Displacement (SLICE-2), Test No. CMGS-2 239
Figure F-4. 10-ms Average Lateral Deceleration (SLICE-2), Test No. CMGS-2.......................240
Figure F-5. Lateral Change in Velocity (SLICE-2), Test No. CMGS-2.....................................241
Figure F-6. Lateral Change in Displacement (SLICE-2), Test No. CMGS-2 242
Figure F-7. Vehicle Angular Displacements (SLICE-2), Test No. CMGS-2..............................243
Figure F-8. Acceleration Severity Index (SLICE-2), Test No. CMGS-2 244
Figure F-9. 10-ms Average Longitudinal Deceleration (SLICE-1), Test No. CMGS-2 245
Figure F-10. Longitudinal Change in Velocity (SLICE-1), Test No. CMGS-2 246
Figure F-11. Longitudinal Change in Displacement (SLICE-1), Test No. CMGS-2..................247
Figure F-12. 10-ms Average Lateral Deceleration (SLICE-1), Test No. CMGS-2.....................248
Figure F-13. Lateral Change in Velocity (SLICE-1), Test No. CMGS-2...................................249
Figure F-14. Lateral Change in Displacement (SLICE-1), Test No. CMGS-2 250
Figure F-15. Vehicle Angular Displacements (SLICE-1), Test No. CMGS-2............................251
Figure F-16. Acceleration Severity Index (SLICE-1), Test No. CMGS-2 252

LIST OF TABLES

Table 1. MASH TL-3 Crash Test Conditions for Longitudinal Barriers..6
Table 2. MASH 2016 Evaluation Criteria for Longitudinal Barrier..7
Table 3. Weather Conditions, Test No. CMGS-1..65
Table 4. Sequential Description of Impact Events, Test No. CMGS-1 67
Table 5. Sequential Description of Impact Events, Test No. CMGS-1 68
Table 6. Maximum Occupant Compartment Deformations by Location, Test No. CMGS-1.......88
Table 7. Summary of OIV, ORA, THIV, PHD, and ASI Values, Test No. CMGS-1...................89
Table 8. Weather Conditions, Test No. CMGS-2..91
Table 9. Sequential Description of Impact Events, Test No. CMGS-2 93
Table 10. Sequential Description of Impact Events, Test No. CMGS-2 94
Table 11. Maximum Occupant Compartment Intrusions by Location, Test No. CMGS-2.........117
Table 12. Summary of OIV, ORA, THIV, PHD, and ASI Values, Test No. CMGS-2...............118
Table 13. Load-Deflection Comparison 122
Table 14. List of Simulation Model Parts and LS-DYNA Parameters.......................................129
Table 15. Comparison of Test No. CMGS-2 and Simulation Results..132
Table 16. Transition Simulated Impacts Comparison...140
Table 17. Transition Simulated Impacts Comparison, Cont...141
Table 18. Summary of Safety Performance Evaluation...147
Table A-1. Bill of Materials, Test Nos. CMGS-1 and CMGS-2 155
Table A-2. Bill of Materials, Test Nos. CMGS-1 and CMGS-2, Cont.......................................156
Table A-3. Bill of Materials, Culvert, Test Nos. CMGS-1 and CMGS-2 157

1 INTRODUCTION

1.1 Background

Concrete box culverts are routinely installed under roadways to allow water drainage without affecting the motoring public. The ends of these culverts and their associated drop-offs can also represent a hazard on the roadside when they do not extend outside of the clear zone and often require shielding in the form of roadside barriers. The most common safety barriers utilized to shield these areas are W-beam guardrail systems. However, low-fill culverts with less than 40 in. (1,016 mm) of soil fill prevent the proper installation of standard guardrail posts due to a lack of available embedment depth. Previous crash testing has shown that in some cases W-beam installations with shallow post embedment do not perform adequately and are prone to vehicle override [1]. Therefore, low-fill culverts require specialized guardrail systems to safely treat the hazard. Currently, three types of guardrail systems are being used to treat cross-drainage box culverts: (1) long-span guardrail systems; (2) guardrail systems anchored to the culvert headwall; and (3) guardrail systems anchored to the top slab of the culvert.

Long-span guardrail systems contain unsupported lengths of W-beam rail that span over the top of culverts. These barrier systems do not require attachment to the culvert, thus allowing the culvert and the barrier system to operate independently. One *Manual for Assessing Safety Hardware* (MASH) compliant long-span system, developed at the Midwest Roadside Safety Facility (MwRSF), consists of a single layer of 12-gauge (2.67-mm thick), 31-in. (787-mm) tall W-beam guardrail centered over a 25-ft (7.6-m) unsupported span length [2-3]. The long-span systems do not require additional components for attachment to the culvert and provide a cost-effective method for shielding culverts. However, these long-span systems are limited to a maximum unsupported span length of 25 ft (7.6 m).

For low-fill culverts of widths exceeding the maximum unsupported length of long-span systems, few W-beam guardrail designs are available for direct attachment to the culvert's headwalls. One such guardrail system was a side-mounted socket system for weak-post Midwest Guardrail System (MGS) attached to the outside face of culvert headwalls developed by MwRSF in 2014, as shown in Figure 1 [4]. The posts were inserted into side-mounted, steel sockets that would remain undamaged during impacts. The system utilized a top rail height of 31 in. (787 mm) supported by S3x5.7 (S76x8.5) posts, spaced 37½ in. (953 mm) on center and positioned within HSS4x4x⅜ steel socket tubes attached to the outside face of the culvert headwall.

Figure 1. Side-Mounted Configuration for Guardrail on Culvert Headwalls [4]

There are many installations where the culvert or roadway geometry is not compatible with the side-mounted system. Additionally, there may be a fill slope between the edge of the roadway and the culvert headwall, and the side-mounted guardrail system was only designed for level terrain applications. Therefore, there was a need for guardrail systems attached to the top slab of the low-fill culverts. One such guardrail system was developed by MwRSF in 2002, as shown in Figure 2 [5]. This system utilized a 27¾-in. (705-mm) top rail height, a 37½-in. (953-mm) post spacing, a deformable ½-in. (13-mm) thick steel plate welded to the bottom of each guardrail post with a $^{5}/_{16}$-in. (8-mm) three-pass fillet weld on the front (tension) flange and a ¼-in. (6-mm) fillet weld on the web and back (compression) flange. The post assembly was anchored to the culvert slab using four 1-in. (25-mm) diameter through bolts. Finally, the system posts were spaced 3 ft – 1½ in. (953-mm) on centers, and the back side of the posts were offset 18 in. (457 mm) from the inside of the culvert headwall to prevent interaction between the posts and the rigid headwall as the system deflects during an impact event. This system was successfully developed and full-scale crash tested according to the Test Level 3 (TL-3) safety performance guidelines found in National Cooperative Highway Research Program (NCHRP) Report No. 350 [6].

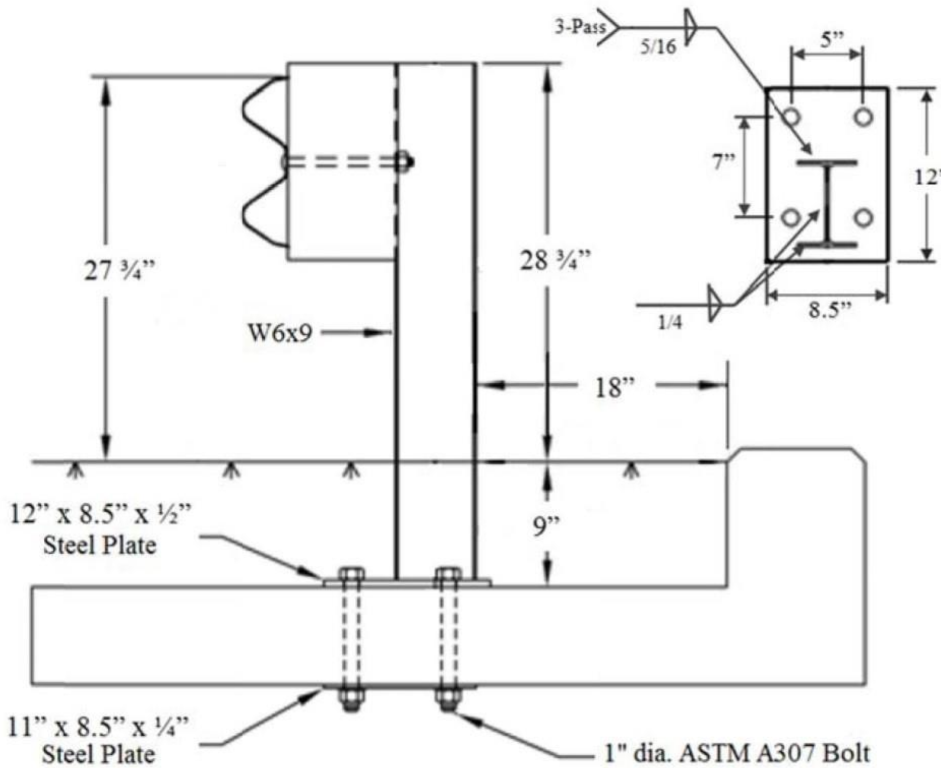


Figure 2. NCHRP Report No. 350-Compliant, Modified G4(1S) Guardrail Attachment to Low-Fill Culvert [5]

During evaluation of the barrier system it was shown that a potential exists for vehicular instabilities or rollover to occur if the guardrail is placed too close to the culvert headwall. This phenomenon was the result of the system's posts being unable to rotate near the base due to contact with the top of the headwall, thus resulting in wheel snag on the posts. From analysis of the crash test results, it was recommended that the back-side face of the steel posts be positioned a minimum of 10 in. (254 mm) away from the front face of the culvert's headwall with a minimum soil fill depth of 9 in. (229 mm) to maintain acceptable barrier performance [5].

For further investigation, an identical culvert-mounted MGS was crash tested with a ¾-ton pickup truck according to TL-3 safety performance criteria presented in NCHRP Report No. 350 [5]. For this design, the steel posts were spaced 1 in. (25 mm) away from the front of the culvert's headwall. During vehicle redirection, the pickup truck rolled over and the test was determined to be unacceptable. The vehicle's instability was attributed to the interaction of the vehicle's front tire and suspension with the steel post immediately downstream from impact. The headwall of the culvert prevented the post from continuing to rotate backward, and subsequently caused a snag point for the vehicle's tire.

Following the NCHRP Report No. 350 evaluation of the culvert-mounted guardrail system, a subsequent research effort was undertaken to determine alternatives to the original attachment design [7]. The first objective was to determine if an alternative weld detail could be utilized to simplify the three-pass fillet weld on the front flange of the post. The second objective was to develop an epoxy anchor alternative to bolting through the top slab of the culvert. These system modifications were evaluated through a series of four dynamic bogie tests conducted under the same impact conditions utilized in the original development study. The study found that proposed changes to the weld details were not feasible, but that epoxy anchorages could be used successfully. This research led to the development of an epoxy anchoring option for the post anchor utilizing 1-in. (25-mm) diameter, ASTM A307 threaded rods and an 8-in. (203-mm) embedment depth. Anchor pullout was encountered for an embedment depth of 6 in. (152 mm), while an 8-in. (203-mm) embedment showed no signs of anchor failure. Thus, an 8-in. (203-mm) minimum embedment depth was recommended for the epoxied anchorage design.

In 2011, the Texas A&M Transportation Institute (TTI) developed and tested a slightly different version of the strong-post culvert attachment for use with a 31-in. (787-mm) tall W-beam guardrail with midspan splices at standard post spacing, as shown in Figure 3 [8]. For this design, W6x9 steel posts were welded to ⅞-in. (22-mm) thick steel base plates and spaced 6 ft – 3 in. (1,905 mm) on centers with midspan rail splices. The posts were attached to the culvert using four ⅞-in. (22-mm) diameter rods that were epoxied into the concrete with a 6-in. (152-mm) minimum embedment depth and a Hilti chemical adhesive anchoring system. The posts were also located 18 in. (457 mm) from the culvert headwall. The guardrail system was designed for use with a minimum soil fill depth of 9 in. (229 mm). Testing of this design under the MASH 2009 TL-3 criteria [9] with the 2770P vehicle was successful. However, it should be noted that partial tearing of the rail was observed in the impact region, which indicated that the rail tensile forces were high, and the potential exists for rail rupture. The thicker base plate used in this system may have increased the stiffness of the barrier and led to the increased rail loads.

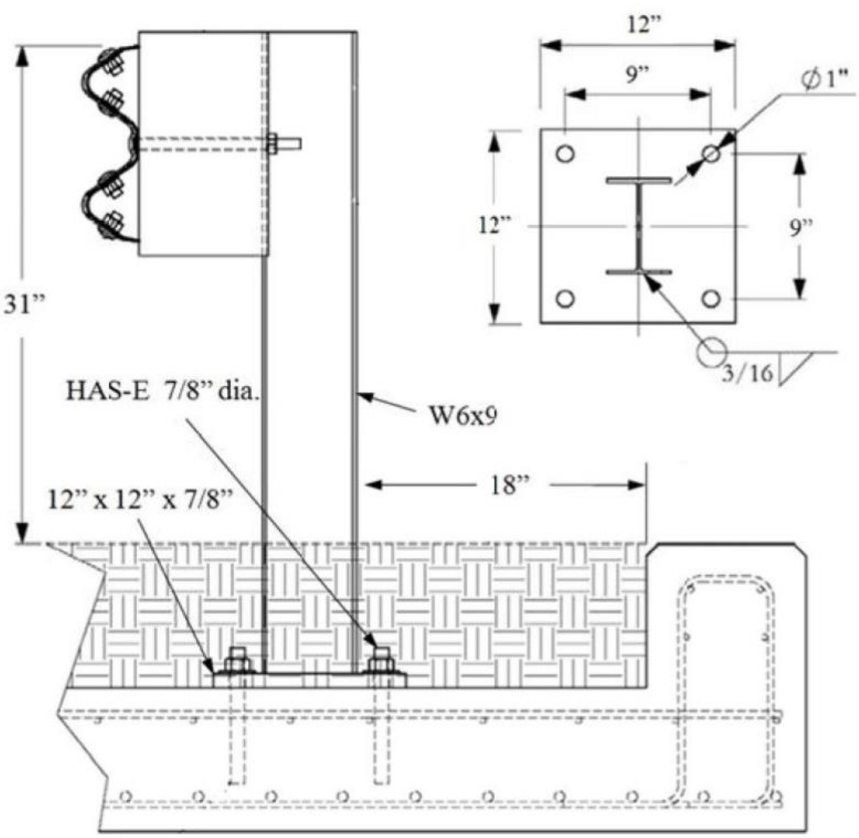


Figure 3. MASH-Compliant, MGS Guardrail Attachment to Low-Fill Culvert [8]

MwRSF provided previous, un-tested guidance on using the MwRSF version of the strong-post attachment to meet MASH 2016 criteria [10] when used with the MGS. Based on the successful testing of the TTI mounting system, it was believed that there would be a good potential for the system to perform safely under the MASH 2016 criteria. However, MwRSF recommended the following if the states wish to use the design: (1) the half-post spacing of the NCHRP Report No. 350 tested system be retained and (2) the minimum offset from the back of the post to the headwall be increased to 18 in. (457 mm).

These recommendations were made to provide a conservative approach to using the MwRSF version of the strong-post attachment based on the original testing of that system and the subsequent testing the TTI design. However, the performance of the MwRSF version of the strong-post attachment under MASH 2016 TL-3 criteria could not be fully determined without full-scale crash testing.

Based on the previous NCHRP Report No. 350 and MASH 2009 testing of similar culvert-mounted guardrail systems, Wisconsin Department of Transportation desired to evaluate the MGS installed on a culvert with the MwRSF version of the strong-post attachment, half-post spacing, and a 12-in. (305-mm) offset from the back of the post to the culvert headwall.

1.2 Research Objective

The objective of this research effort was to conduct full-scale crash testing on the MGS installed on a culvert with the MwRSF version of the strong-post attachment using through-bolts and epoxy anchorage, half-post spacing, and a 12-in. (305-mm) offset from the back of the post to the culvert headwall. All tests were performed according to the TL-3 impact safety standards found in MASH 2016 [10]. Additionally, the transition from standard MGS to the culvert-mounted MGS was to be analyzed and recommendations were made regarding the potential performance of the transition.

1.3 Scope

The research began with development of the design details for the modified MGS installed on a low-fill culvert with the MwRSF version of the strong-post attachment with through-bolts and epoxy anchorage, half-post spacing, and a 12-in. (305-mm) offset from the back of the post to the culvert headwall was recommended for full-scale crash testing. MASH 2016 guidance was utilized to determine the critical impact points for full-scale crash testing. Two full-scale crash tests were conducted according to the MASH 2016 test designation nos. 3-10 and 3-11 to evaluate the length-of-need of the designed culvert-mounted, MGS attachment. Finally, the test results were analyzed, evaluated, and documented. Conclusions and recommendations were then made pertaining to the safety performance of the tested version of culvert-mounted, strong-post MGS. Additionally, the transition from the standard MGS to the culvert-mounted MGS was analyzed and recommendations relative to that transition performance were given.

2 TEST REQUIREMENTS AND EVALUATION CRITERIA

2.1 Test Requirements

Longitudinal barriers, such as W-beam guardrail systems attached to concrete box culverts, must satisfy impact safety standards in order to be declared eligible for federal reimbursement by the Federal Highway Administration (FHWA) for use on the National Highway System (NHS). For new hardware, these safety standards consist of the guidelines and procedures published in MASH 2016 [10]. Note that there is no difference between MASH 2009 and MASH 2016 for longitudinal barriers such as the system tested in this project, except that additional occupant compartment deformation measurements, photographs, and documentation are required by MASH 2016. According to TL-3 of MASH 2016, longitudinal barrier systems must be subjected to two full-scale vehicle crash tests, as summarized in Table 1.

Critical impact points (CIPs) for both impacts were determined based on calculated post and guardrail beam strengths and the use of MASH 2016 Figures 2-8 and 2-11 for the 1100C and 2270P vehicle impacts, respectively.

Table 1. MASH TL-3 Crash Test Conditions for Longitudinal Barriers

Test Article	Test Designation No.	Test Vehicle	Vehicle Weight, lb (kg)	Impact Conditions		Evaluation Criteria [1]
				Speed, mph (km/h)	Angle, deg.	
Longitudinal Barrier	3-10	1100C	2,425 (1,100)	62 (100)	25	A,D,F,H,I
	3-11	2270P	5,000 (2,268)	62 (100)	25	A,D,F,H,I

[1] Evaluation criteria explained in Table 2.

2.2 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 culvert-mounted MGS to contain and redirect impacting vehicles. In addition, controlled lateral deflection of the test article is acceptable. Occupant risk evaluates the degree of hazard to occupants in the impacting vehicle. Post-impact vehicle trajectory is a measure of the potential of the vehicle to result in a secondary collision with other vehicles and/or fixed objects, thereby increasing the risk of injury to the occupants of the impacting vehicle and/or other vehicles. These evaluation criteria are summarized in Table 2 and defined in greater detail in MASH 2016. The full-scale vehicle crash test documented herein was conducted and reported in accordance with the procedures provided in MASH 2016.

In addition to the standard occupant risk measures, the Post-Impact Head Deceleration (PHD), the Theoretical Head Impact Velocity (THIV), and the Acceleration Severity Index (ASI) were determined and reported. Additional discussion on PHD, THIV and ASI is provided in MASH 2016.

Table 2. MASH 2016 Evaluation Criteria for Longitudinal Barrier

<table>
<tr><td>Structural Adequacy</td><td>A.</td><td colspan="3">Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td></tr>
<tr><td rowspan="12">Occupant Risk</td><td>D.</td><td colspan="3">Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of MASH 2016.</td></tr>
<tr><td>F.</td><td colspan="3">The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.</td></tr>
<tr><td rowspan="5">H.</td><td colspan="3">Occupant Impact Velocity (OIV) (see Appendix A, Section A5.2.2 of MASH 2016 for calculation procedure) should satisfy the following limits:</td></tr>
<tr><td colspan="3">Occupant Impact Velocity Limits</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>30 ft/s</td><td>40 ft/s</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td rowspan="5">I.</td><td colspan="3">The Occupant Ridedown Acceleration (ORA) (see Appendix A, Section A5.2.2 of MASH 2016 for calculation procedure) should satisfy the following limits:</td></tr>
<tr><td colspan="3">Occupant Ridedown Acceleration Limits</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>15.0 g’s</td><td>20.49 g’s</td></tr>
</table>

2.3 Soil Strength Requirements

In accordance with Chapter 3 and Appendix B of MASH 2016, foundation soil strength must be verified before any full-scale crash testing can occur. During the installation of a soil dependent system, W6x16 (W150x24) posts were installed near the impact region utilizing the same installation procedures as the system itself. Prior to full-scale testing, dynamic impact testing was conducted to verify a minimum dynamic soil resistance of 7.5 kips (33.4 kN) at post deflections between 5 and 20 in. (127 and 508 mm) measured at a height of 25 in. (635 mm) above the ground line. If dynamic testing near the system is not desired, MASH 2016 permits a static test to be conducted instead and compared against the results of a previously established baseline test. In this situation, the soil must provide a resistance of at least 90% of the static baseline test at deflections of 5, 10, and 15 in. (127, 254, and 381 mm). Further details can be found in Appendix B of MASH 2016.

3 DESIGN DETAILS

For test nos. CMGS-1 and CMGS-2, a simulated four-cell concrete box culvert system was constructed at MwRSF's Outdoor Test Site. The four-cell system was selected to ensure that the research results were representative of actual box culvert site conditions. The strong post MGS was then mounted on the culvert. In the following sections, design details for the test installation are provided.

3.1 Culvert Design and Construction

The basic design of the box culvert was based on the design used in the original NCHRP Report No. 350 full-scale testing and evaluation of the strong post culvert attachment for W-beam guardrail [5]. In this study, the researchers reviewed a variety of culvert design used by state DOTs and selected a culvert configuration with a 7-in. (178-mm) thick concrete top slab. Additionally, the simulated test culvert utilized no. 4 steel reinforcement bars spaced on 12-in. (305-mm) centers and placed in two rows throughout the 7-in. (178-mm) thick slab. This combination of slab thickness and steel reinforcement were believed to provide a non-conservative slab design for resisting dead and live loads but still provide sufficient capacity to minimize concrete damage. Therefore, if satisfactory barrier performance were observed in the crash testing program, then comparable barrier performance would be expected for top slab designs with capacities equal to or greater than that used in the crash tests. Review of Wisconsin standard culvert details found that their culvert designs utilized a minimum thickness of 8 in. (203 mm). In order to be consistent with the Wisconsin details while still providing a relatively non-conservative design, the simulated culvert design for the barrier systems evaluated herein was constructed with the same basic layout and reinforcement as the original NCHRP Report No. 350 tested system, but an 8-in. (203-mm) thick slab was utilized to match the Wisconsin standards. Additionally, the vertical support width was increased to 12 in. (305 mm) to provide increased soil bearing beneath the supports.

A soil test pit was excavated to a depth of approximately 66 in. (1,674 mm) to provide enough clearance for constructing the concrete box culvert. After the soil was excavated from the test pit, five reinforced concrete vertical support walls and a soil retaining wall were constructed on the bottom of the test pit, as shown in Figure 4. Design details of the culvert and bill of materials are shown in Figures 4 through 17. Construction photographs of the culvert are shown in Figures 18 through 21.

The three inner concrete vertical supports had a center-to-center spacing of 127 in. (3,226 mm). The vertical supports were constructed perpendicular to the roadway. As shown in Figure 8, the inner vertical supports measured 12 in. (305 mm) wide, 60 in. (1,524 mm) long, and 48 in. (1,219 mm) high. The two exterior concrete vertical supports measured 12 in. (305 mm) wide, 128 in. (3,251 mm) long, and 48 in. (1,219 mm) high, as shown in Figure 9. The soil retaining wall measured 8 in. (203 mm) wide, 43 ft – 4 in. (13.2 m) long, and 48 in. (1,219 mm) high and was constructed on the front of the culvert to prevent the soil from filling in beneath the simulated culvert, as shown in Figure 14.

The top slab measured 68 in. (1,727 mm) wide, 8 in. (203 mm) thick, and 43 ft – 4 in. (13.2 m) long, as shown in Figure 11. The headwall, constructed above the top slab, measured 10 in. (254 mm) wide, 10 in. (254 mm) high, and 43 ft – 4 in. (13.2 m) long and was located at the back side of the deck. A 9-in. (229-mm) deep soil fill was used to create a level ground surface for testing.

The concrete used for the concrete vertical supports, the soil retaining wall, top slab, and headwall consisted of a Nebraska 47-BD Mix with a minimum compressive strength of 4,000 psi (27.6 MPa). The actual concrete compressive strength of the vertical supports on test day, as determined from concrete cylinder testing, was found to be approximately 4,665 psi (32.1 MPa). A minimum concrete cover of 1½ in. (38 mm) was used for all rebar placed within the concrete vertical supports, soil retaining wall, top slab and headwall. All steel reinforcement was ASTM A615 Grade 60 epoxy-coated rebar.

The steel reinforcement for the vertical supports utilized No. 4 bars for the transverse, vertical, and bent vertical bars, as shown in Figures 5 through 9 and 12 through 16. The transverse bars of the inner vertical wall supports were 76 in. (1,930 mm) long and spaced 15½ in. (394 mm) apart, as shown in Figure 8. The bent vertical bars of the inner vertical supports were 64 in. (1,626 mm) long and spaced 12 in. (305 mm) apart on center, as shown in Figures 9, 11, and 17. The transverse bars of the exterior vertical walls were 130¾ in. (3,321 mm) long and spaced 16¾ in. (425 mm) apart on center, as shown in Figure 9. The vertical dowel bars in the exterior vertical supports were 45 in. (1,143 mm) long and spaced 20 in. (508 mm) apart on center. The long and short bent vertical bars of the two exterior vertical supports were 64 in. (1,626 mm) and 60½ in. (1,537 mm) long, respectively, and they were spaced 18 in. (457 mm) apart on center, as shown in Figure 9.

The steel reinforcement for the soil retaining wall also utilized No. 4 bars for the longitudinal and vertical bars, as shown in Figures 14 through 16. Each of the six longitudinal rebar in the soil retaining wall was 43 ft (13.1 m) long. The length of the longitudinal bar can be varied as long as the minimum lap length of 18 in. (457 mm) is maintained. The vertical dowel bars were 64 in. (1,626 mm) long and spaced 32 in. (813 mm) apart on center, as shown in Figure 14.

The steel reinforcement for the top slab utilized No. 4 bars for the longitudinal and transverse bars, as shown in Figures 5, 11, 15, and 16. Each of the fourteen longitudinal rebar in the top slab was 43 ft (13.1 m) long. The transverse bars in the top slab were 57 in. (1,448 mm) long, and their spacing varied longitudinally. At the outside vertical supports, the loop bars were spaced 11¾ in. (298 mm) apart on center, as shown in Figure 5. The loop bar spacing on either side of the inside vertical supports was 10 in. (254 mm) on center. Between the supports, the spacing of the loop bars was 12 in. (305 mm) apart on center. The vertical spacing between the transverse bars was 4½ in. (114 mm) apart on center.

The steel reinforcement for the headwall utilized No. 4 bars for the longitudinal and loop bars. Each of the four longitudinal rebar in the headwall were 43 ft (13.1 m) long. The headwall loop bars were 53⅜ in. (1,356 mm) long, and their spacing varied longitudinally, as shown in Figures 5, 11, 15, and 16.

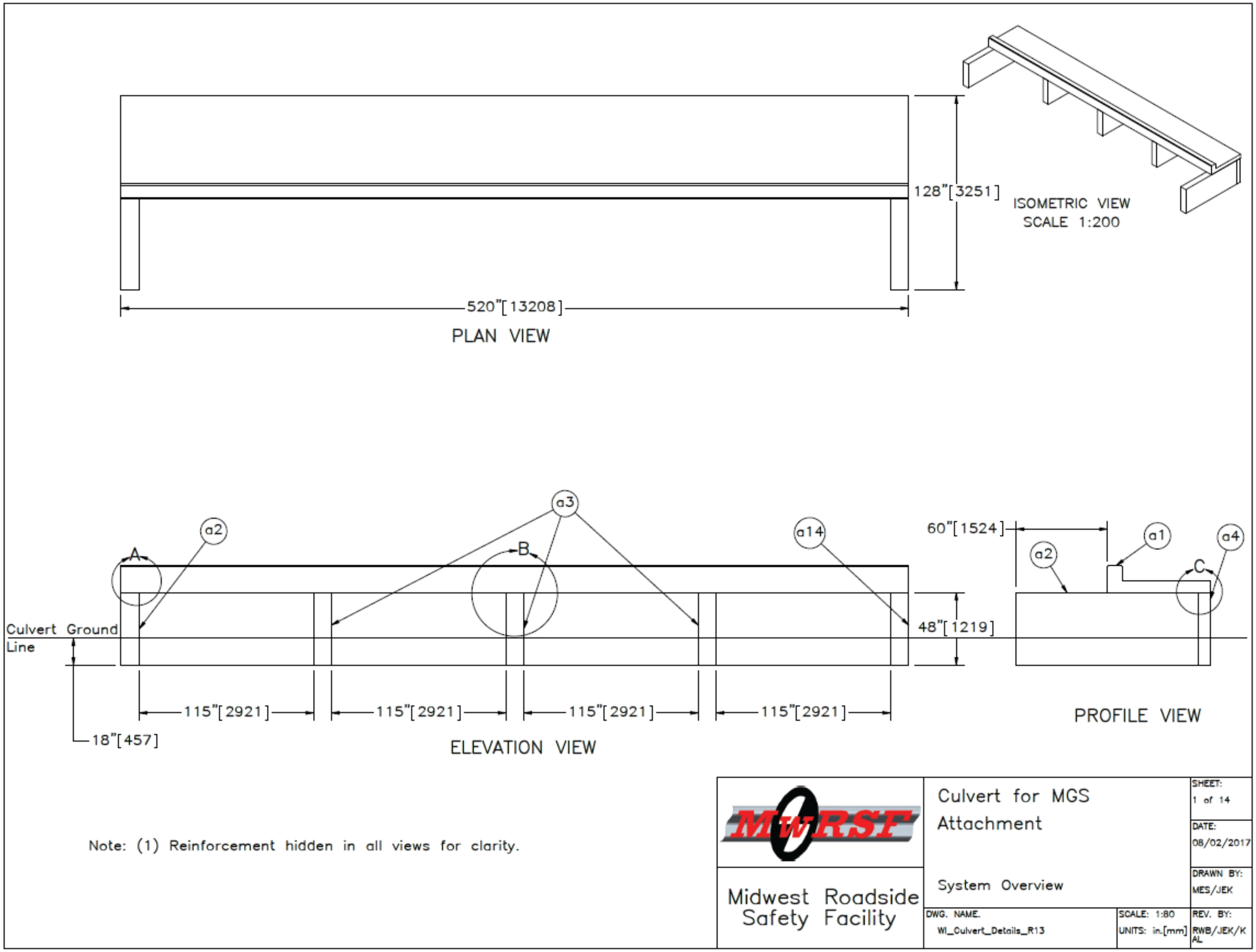


Figure 4. Culvert System Overview, Test Nos. CMGS-1 and CMGS-2

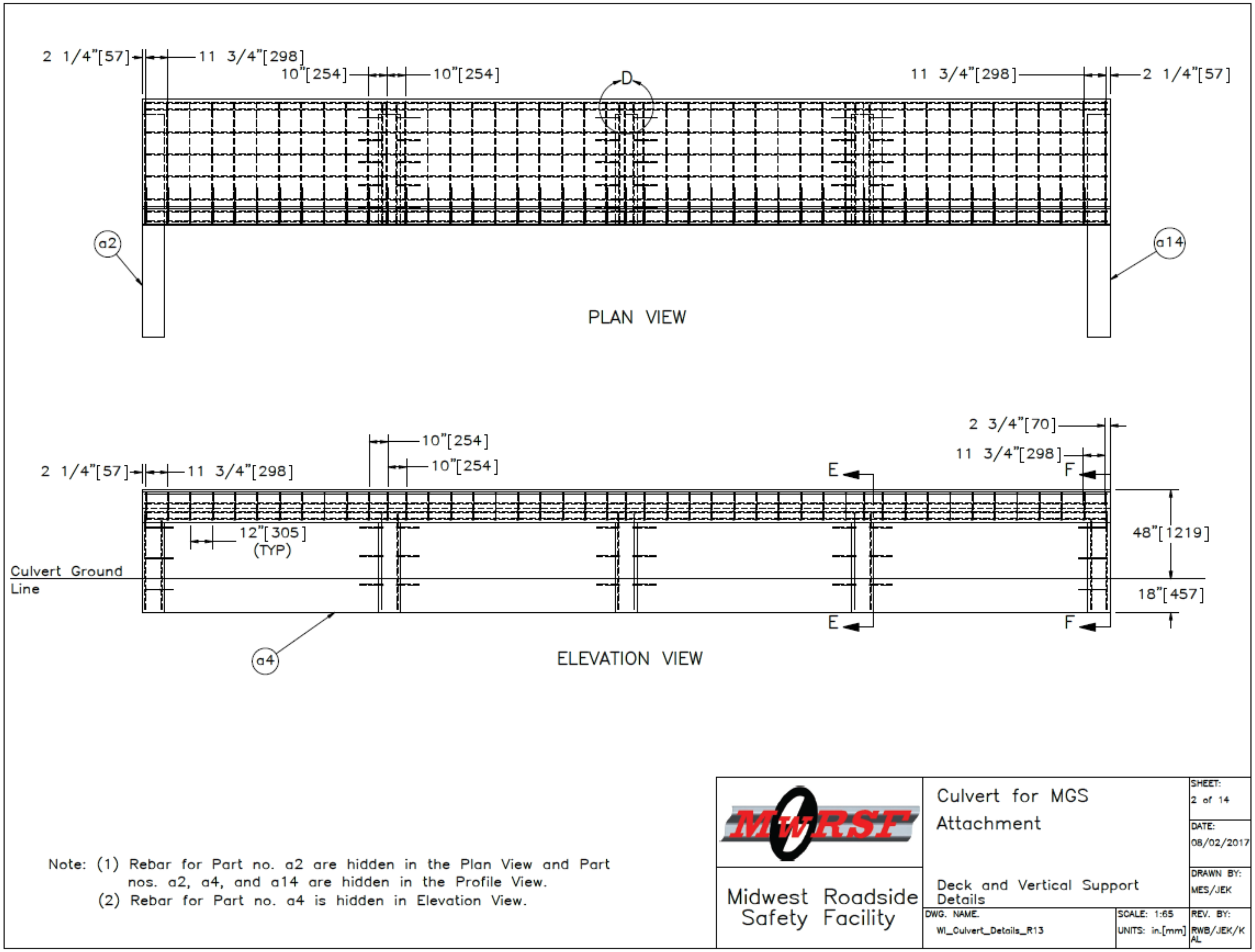


Figure 5. Top Slab and Vertical Support Wall Details, Test Nos. CMGS-1 and CMGS-2

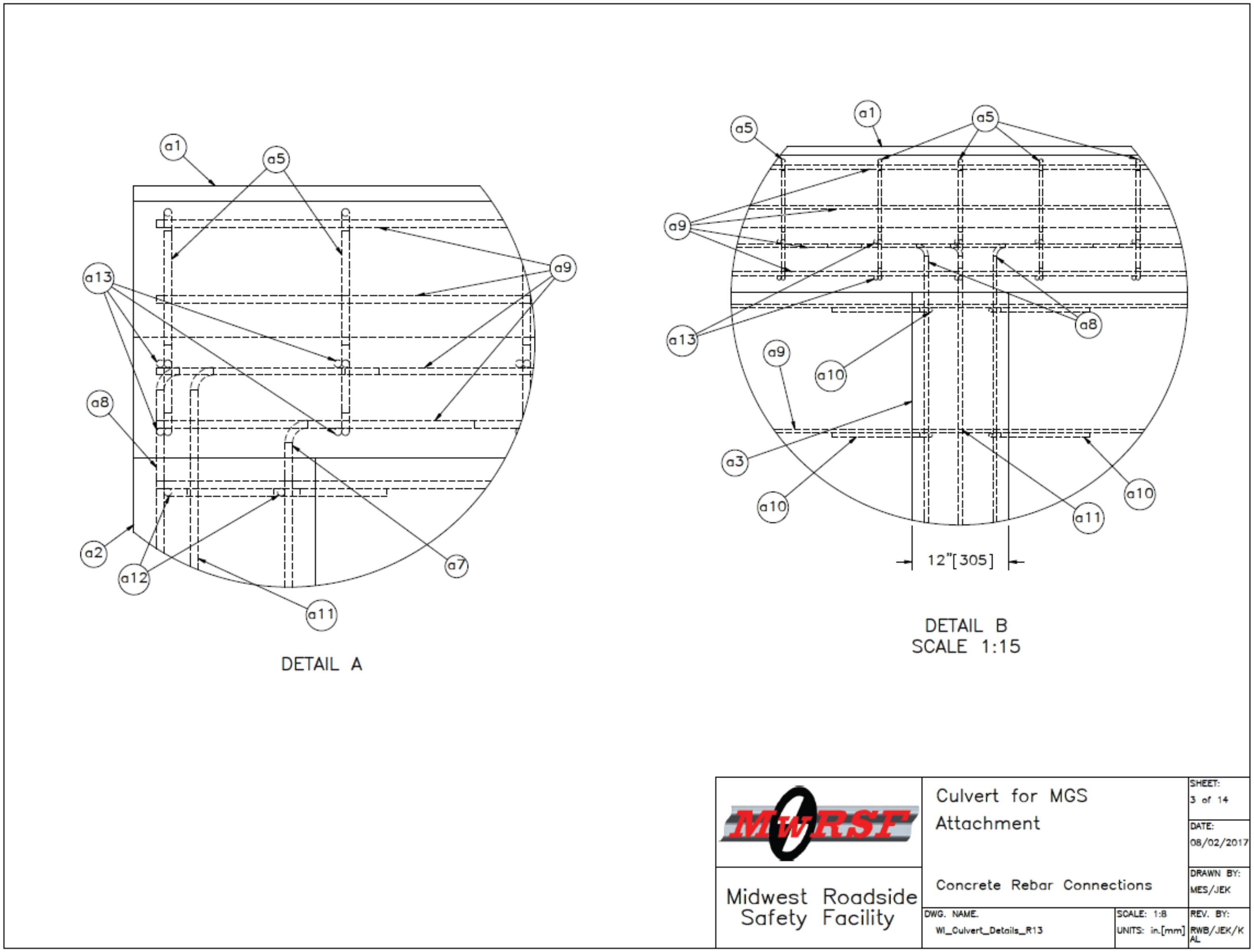


Figure 6. Concrete Rebar Connections, Test Nos. CMGS-1 and CMGS-2

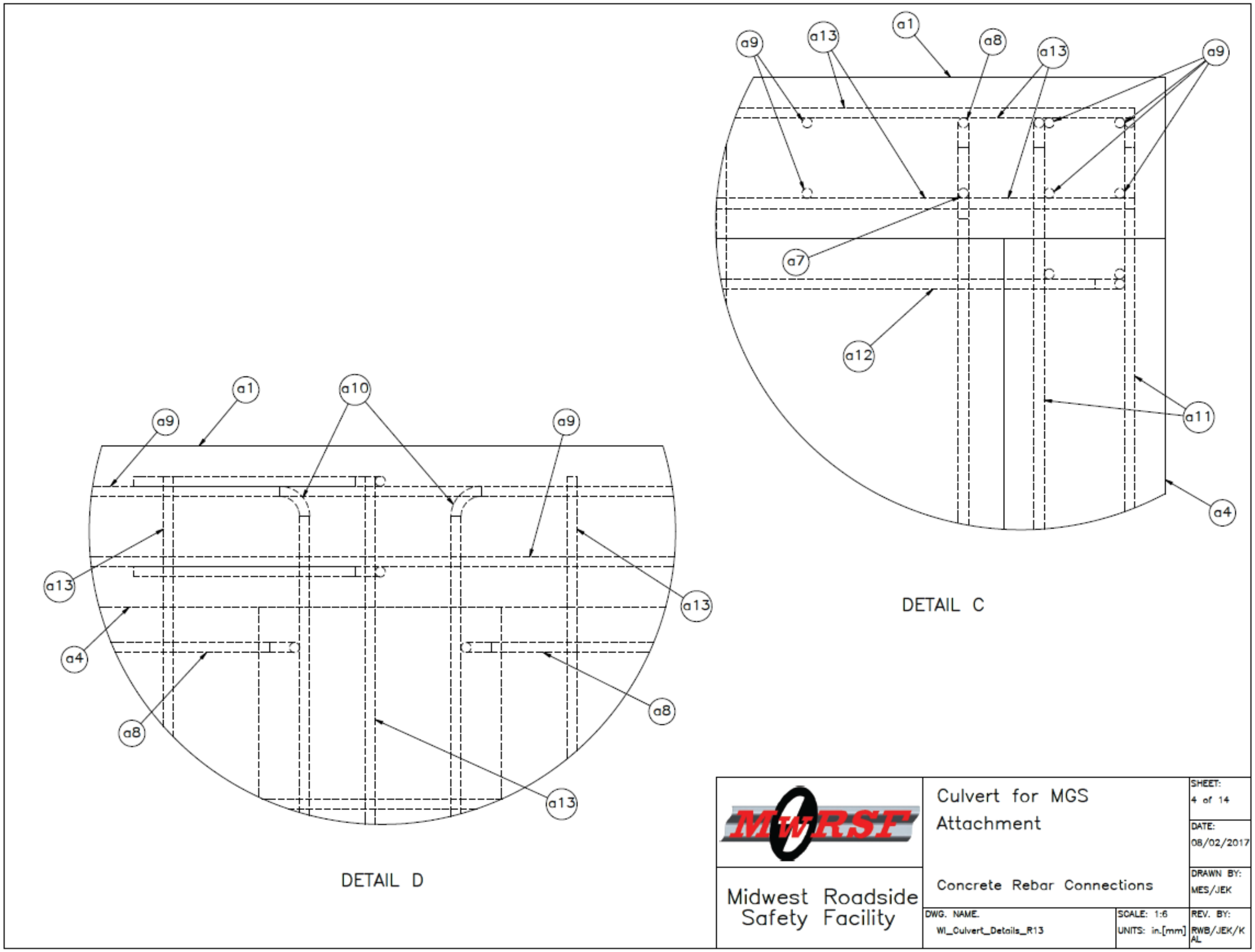


Figure 7. Concrete Rebar Connections (Cont.), Test Nos. CMGS-1 and CMGS-2

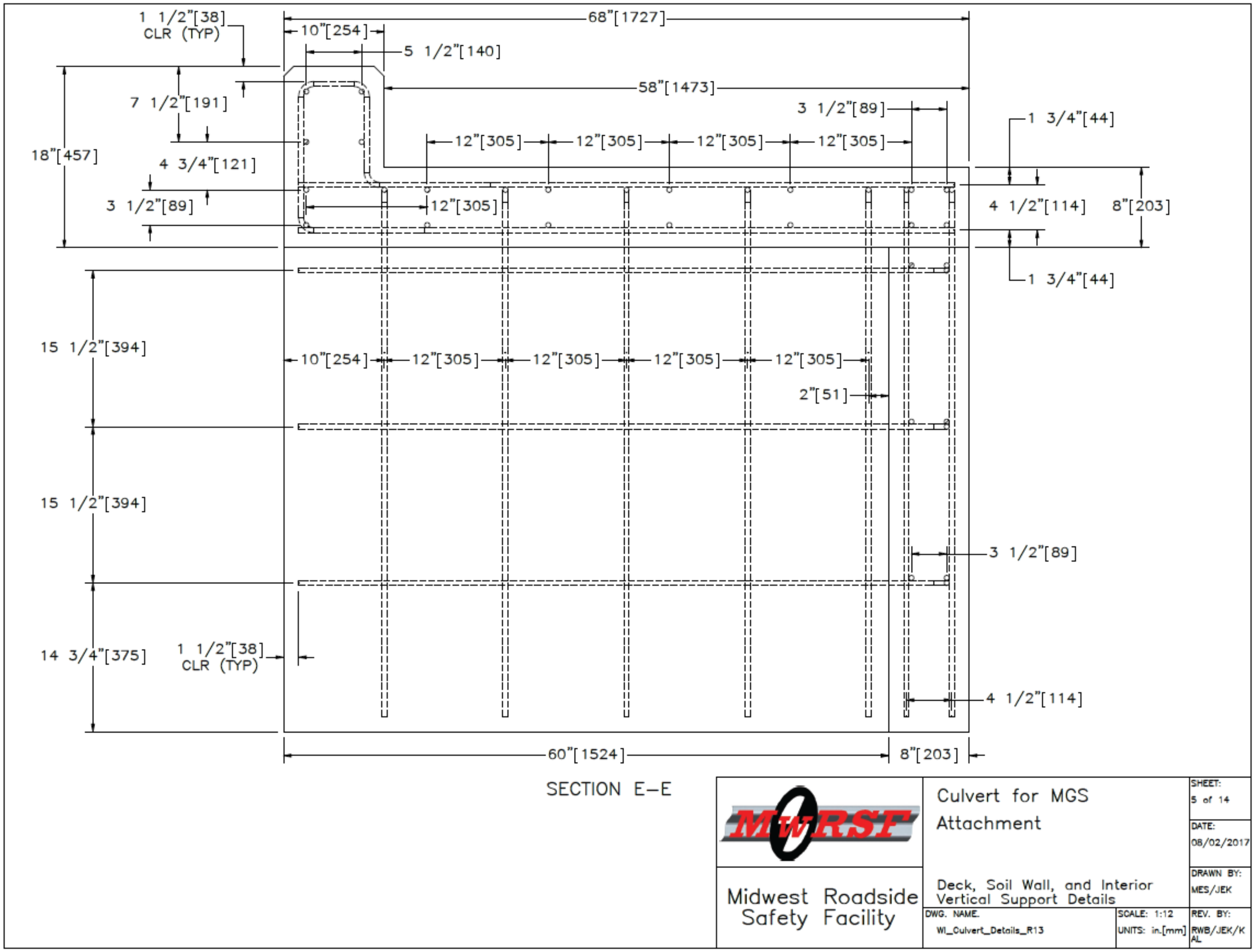


Figure 8. Top Slab, Soil Retaining Wall, Interior Vertical Support Wall Details, Test Nos. CMGS-1 and CMGS-2

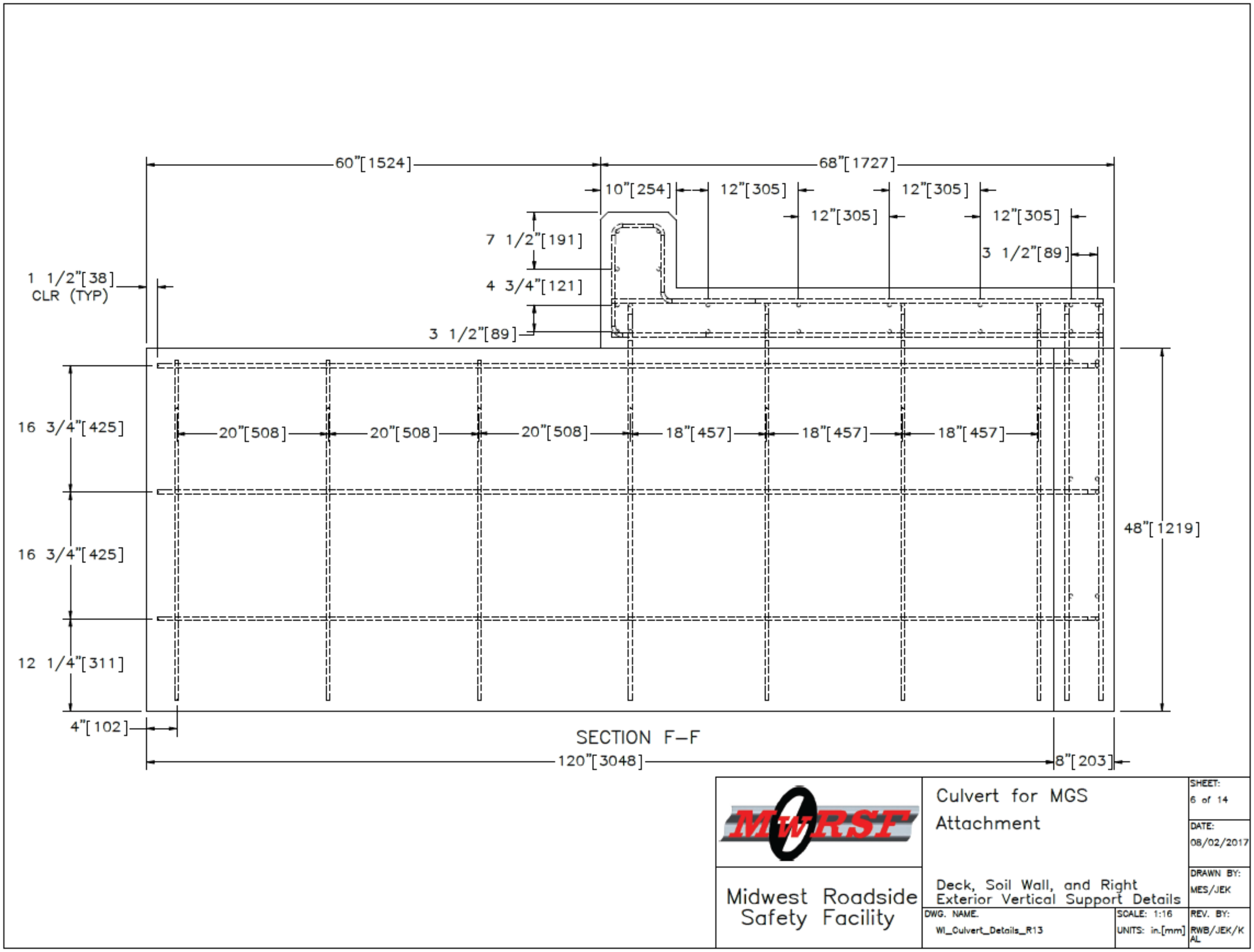


Figure 9. Top Slab, Soil Retaining Wall, Right Exterior Vertical Support Wall Details, Test Nos. CMGS-1 and CMGS-2

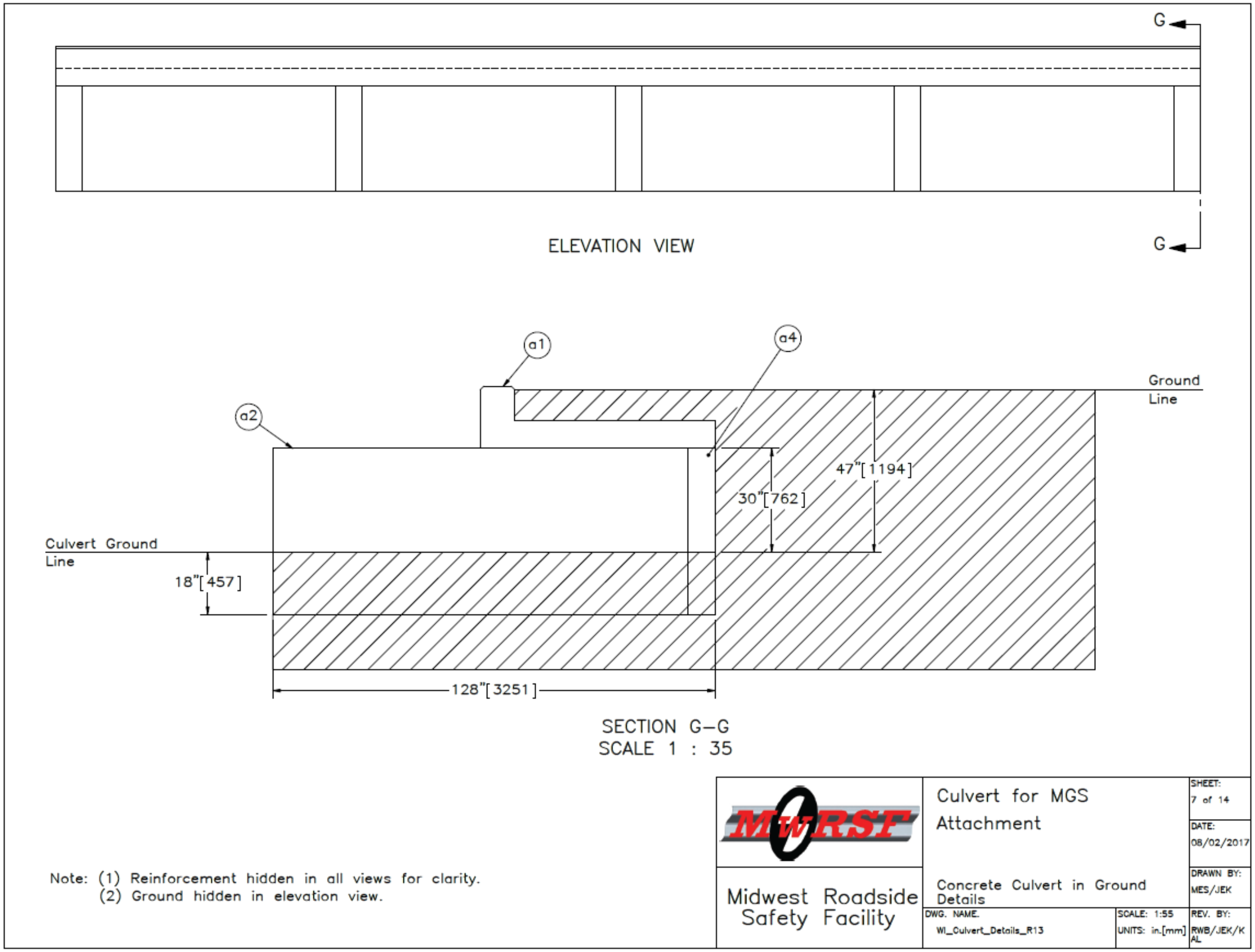


Figure 10. Concrete Culvert in Ground Details, Test Nos. CMGS-1 and CMGS-2

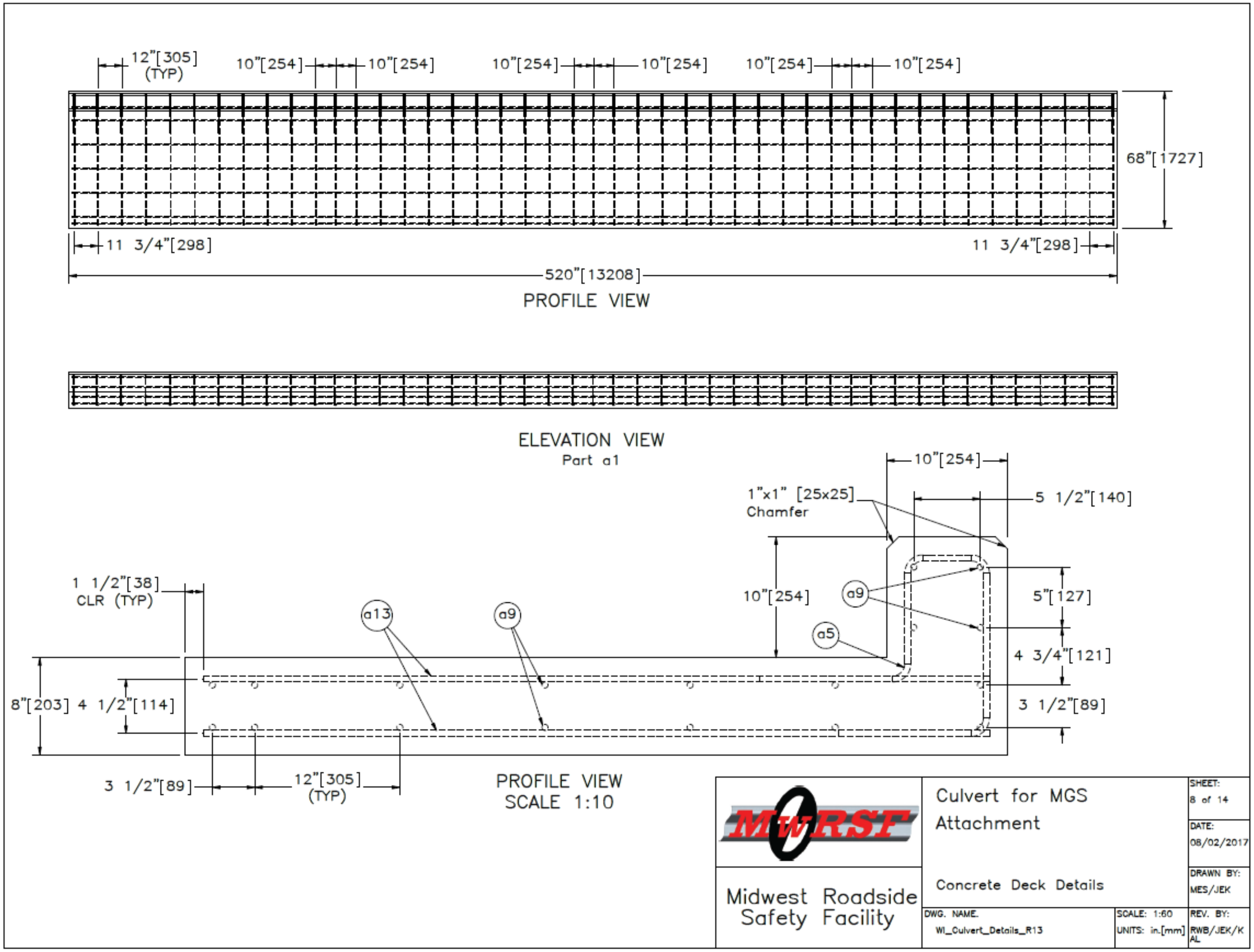


Figure 11. Concrete Top Slab Details, Test Nos. CMGS-1 and CMGS-2

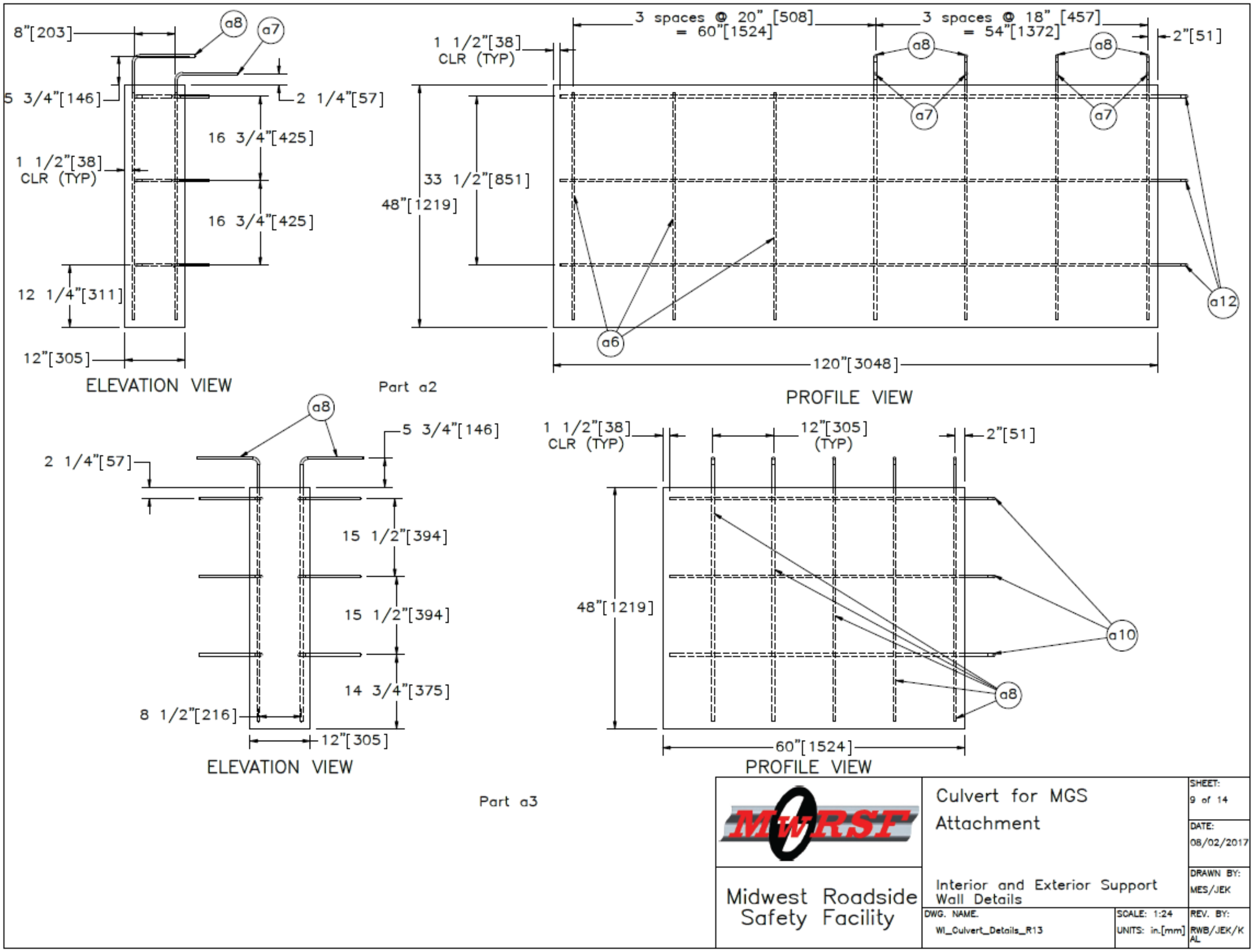


Figure 12. Interior and Exterior Support Wall Details, Test Nos. CMGS-1 and CMGS-2

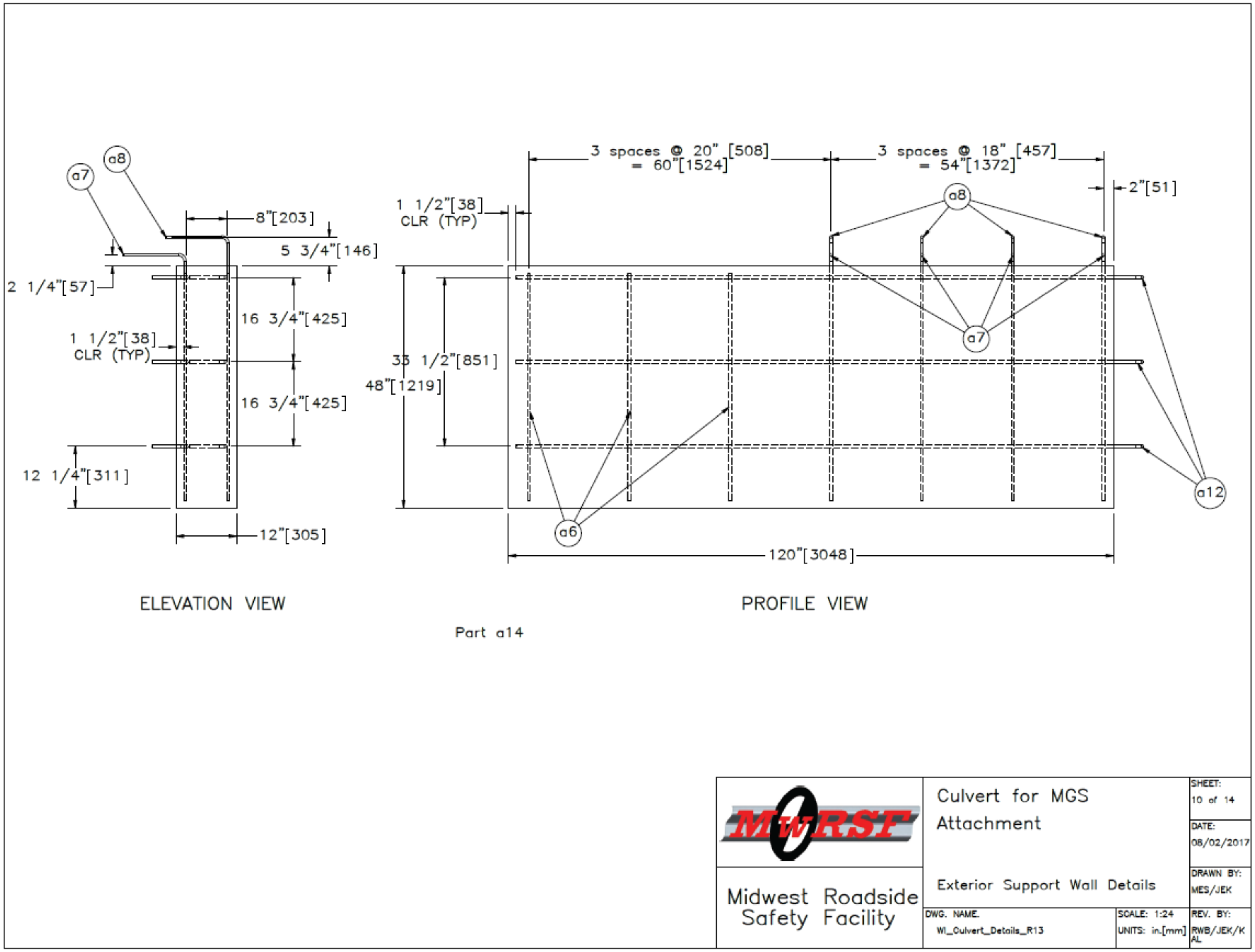


Figure 13. Exterior Support Wall Details, Test Nos. CMGS-1 and CMGS-2

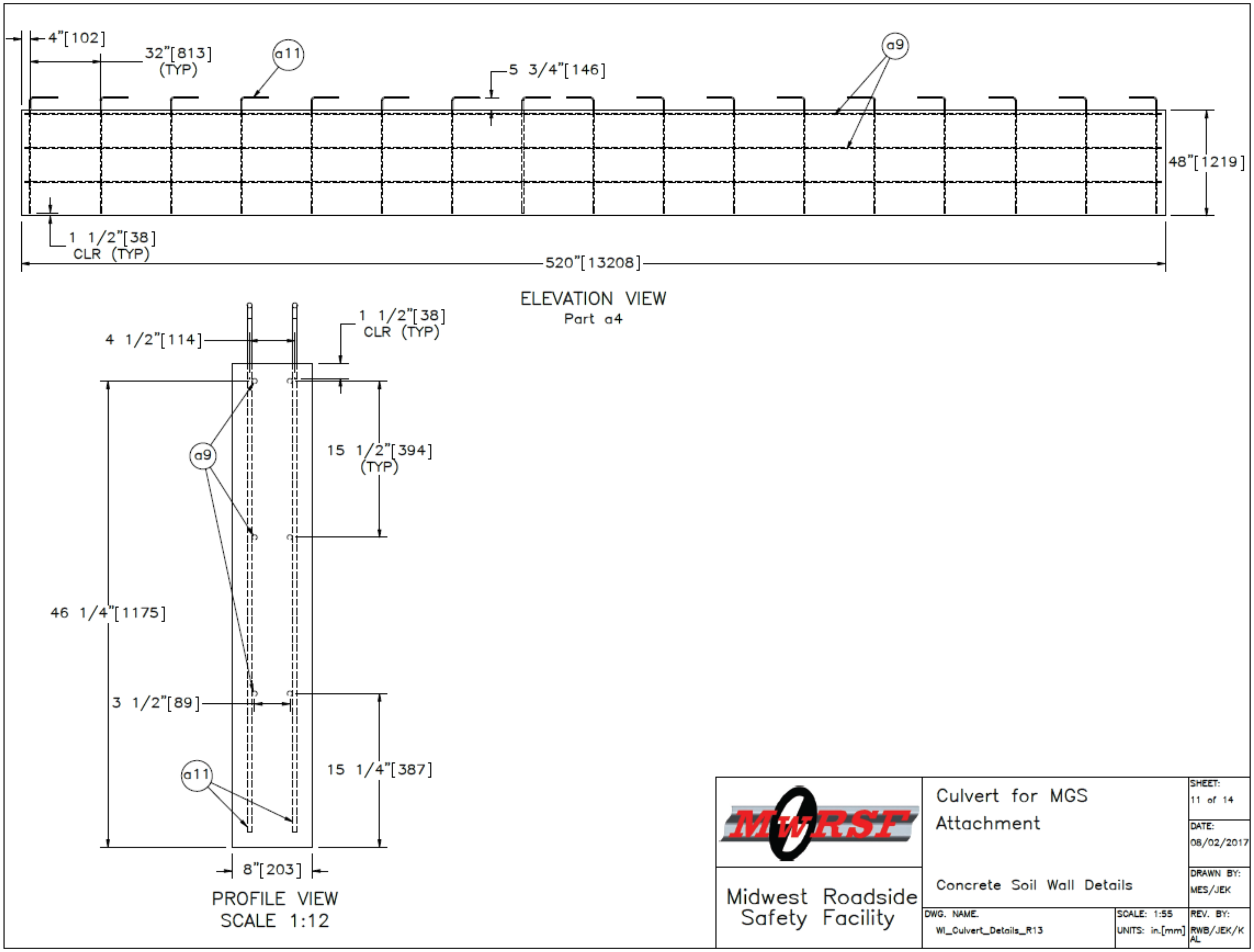
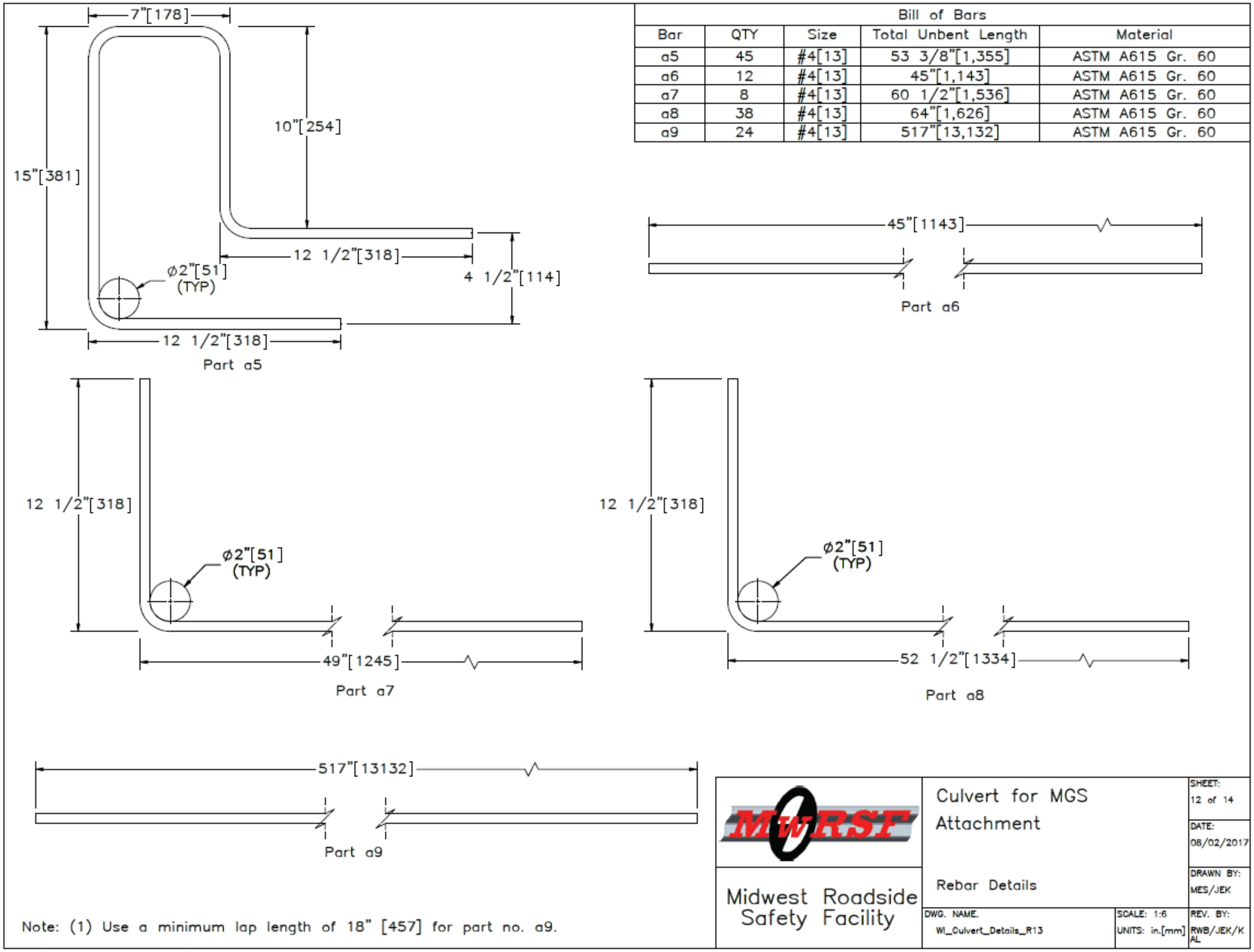


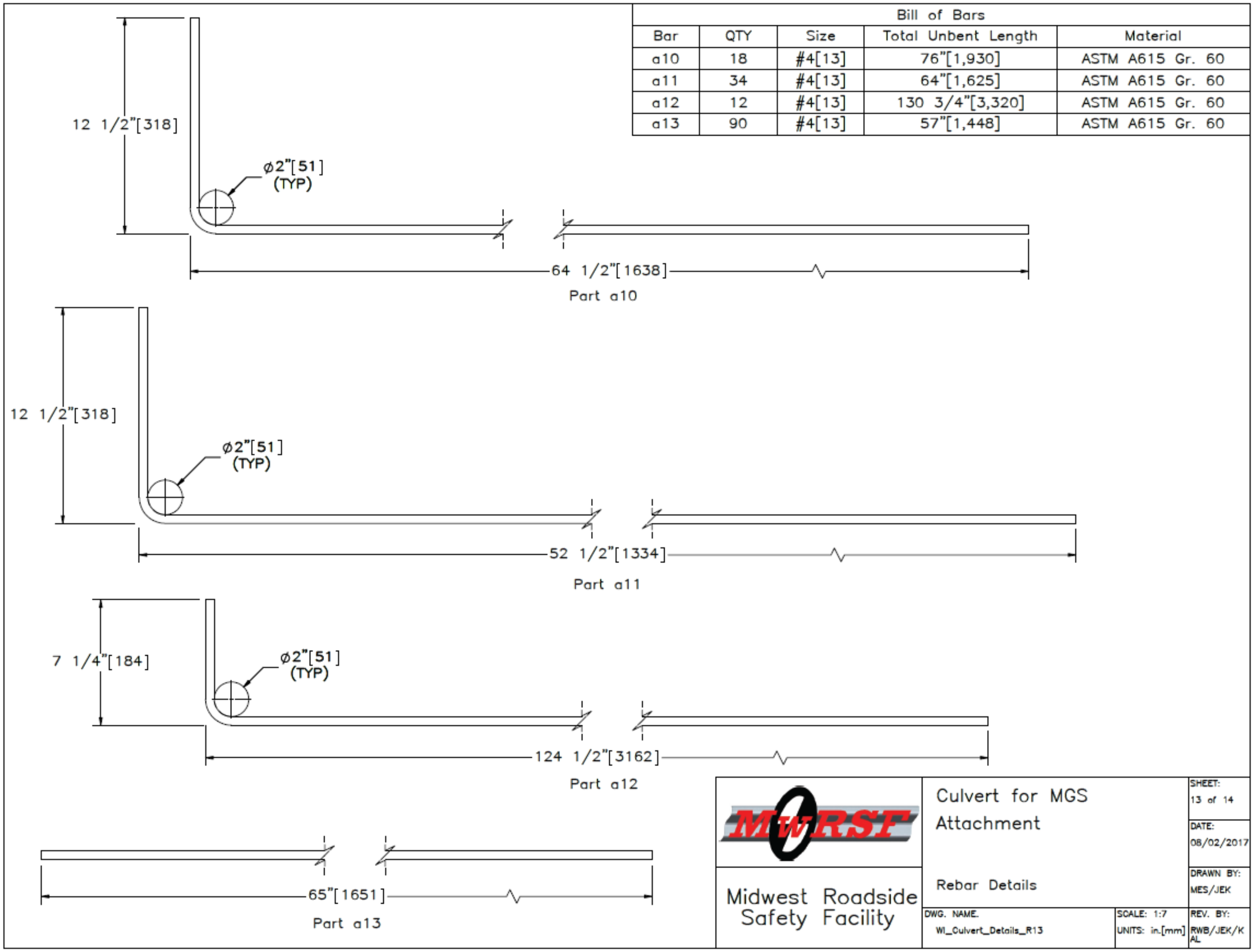
Figure 14. Concrete Soil Retaining Wall Details, Test Nos. CMGS-1 and CMGS-2



Bill of Bars

Bar	QTY	Size	Total Unbent Length	Material
a5	45	#4[13]	53 3/8"[1,355]	ASTM A615 Gr. 60
a6	12	#4[13]	45"[1,143]	ASTM A615 Gr. 60
a7	8	#4[13]	60 1/2"[1,536]	ASTM A615 Gr. 60
a8	38	#4[13]	64"[1,626]	ASTM A615 Gr. 60
a9	24	#4[13]	517"[13,132]	ASTM A615 Gr. 60

Figure 15. Rebar Details, Test Nos. CMGS-1 and CMGS-2



Bill of Bars

Bar	QTY	Size	Total Unbent Length	Material
a10	18	#4[13]	76"[1,930]	ASTM A615 Gr. 60
a11	34	#4[13]	64"[1,625]	ASTM A615 Gr. 60
a12	12	#4[13]	130 3/4"[3,320]	ASTM A615 Gr. 60
a13	90	#4[13]	57"[1,448]	ASTM A615 Gr. 60

Figure 16. Rebar Details (Cont.), Test Nos. CMGS-1 and CMGS-2

Item No.	QTY.	Description	Material Spec	Galvanization Spec
a1	1	520"x17"x60" [13,208x432x1,524] Reinforce Concrete Culvert Deck/Headwall	Min. f'c = 4,000 psi [27.6 MPa] NE Mix 47BD	–
a2	1	12"x48"x120" [305x1,219x3,048] Reinforced Concrete Exterior Support Wall	Min. f'c = 4,000 psi [27.6 MPa] NE Mix 47BD	–
a3	3	12"x48"x60" [305x1,219x1,524] Reinforce Concrete Interior Support Wall	Min. f'c = 4,000 psi [27.6 MPa] NE Mix 47BD	–
a4	1	8"x48"x520" [203x1,219x13,208] Reinforced Concrete Soil Wall	Min. f'c = 4,000 psi [27.6 MPa] NE Mix 47BD	–
a5	45	#4 [#13] Bent Rebar, Vertical Loop, 53 3/8" [1,355] Total Length Unbent	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)
a6	12	#4 [#13] Straight Rebar, 45" [1,143] Long	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)
a7	8	#4 [#13] Bent Rebar, Support Wall Hook, 60 1/2" [1,536] Total Length Unbent	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)
a8	38	#4 [#13] Bent Rebar, Support Wall Hook, 64" [1,626] Total Length Unbent	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)
a9	24	#4 [#13] Straight Rebar, 517" [13,132] Long	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)
a10	18	#4 [#13] Bemt Rebar, Support Wall Hook, 76" [1,930] Total Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)
a11	34	#4 [#13] Bent Rebar, Soil Wall Hook, 64" [1,625] Total Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)
a12	12	#4 [13] Bent Rebar, Support Wall Hook, 130 3/4" [3,320] Total Length	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)
a13	90	#4 [#13] Straight Rebar, 65" [1,651] Long	ASTM A615 Gr. 60	Epoxy Coated (ASTM A775 or A934)
a14	1	12"x48"x120" [305x1,219x3,048] Reinforced Concrete Exterior Support Wall	Min. f'c = 4,000 psi [27.6 MPa] NE Mix 47BD	–

Midwest Roadside Safety Facility

Culvert for MGS Attachment

Bill of Materials

SHEET: 14 of 14

DATE: 08/02/2017

DRAWN BY: MES/JEK

DWG. NAME. WI_Culvert_Details_R13

SCALE: None
UNITS: in.[mm]

REV. BY: RWB/JEK/KAL

Figure 17. Bill of Materials, Test Nos. CMGS-1 and CMGS-2

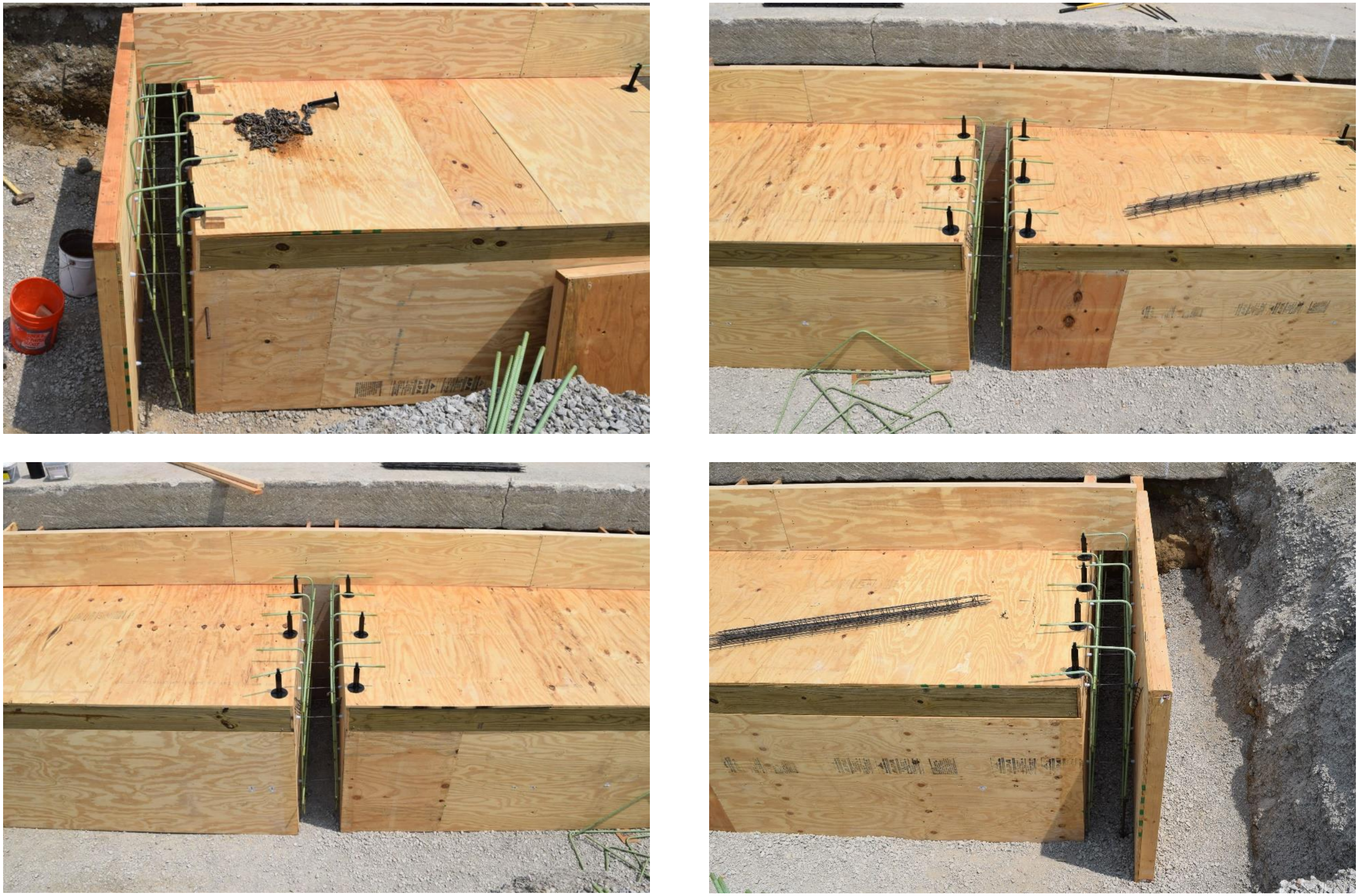


Figure 18. Concrete Culvert Support Walls Framework, Test Nos. CMGS-1 and CMGS-2

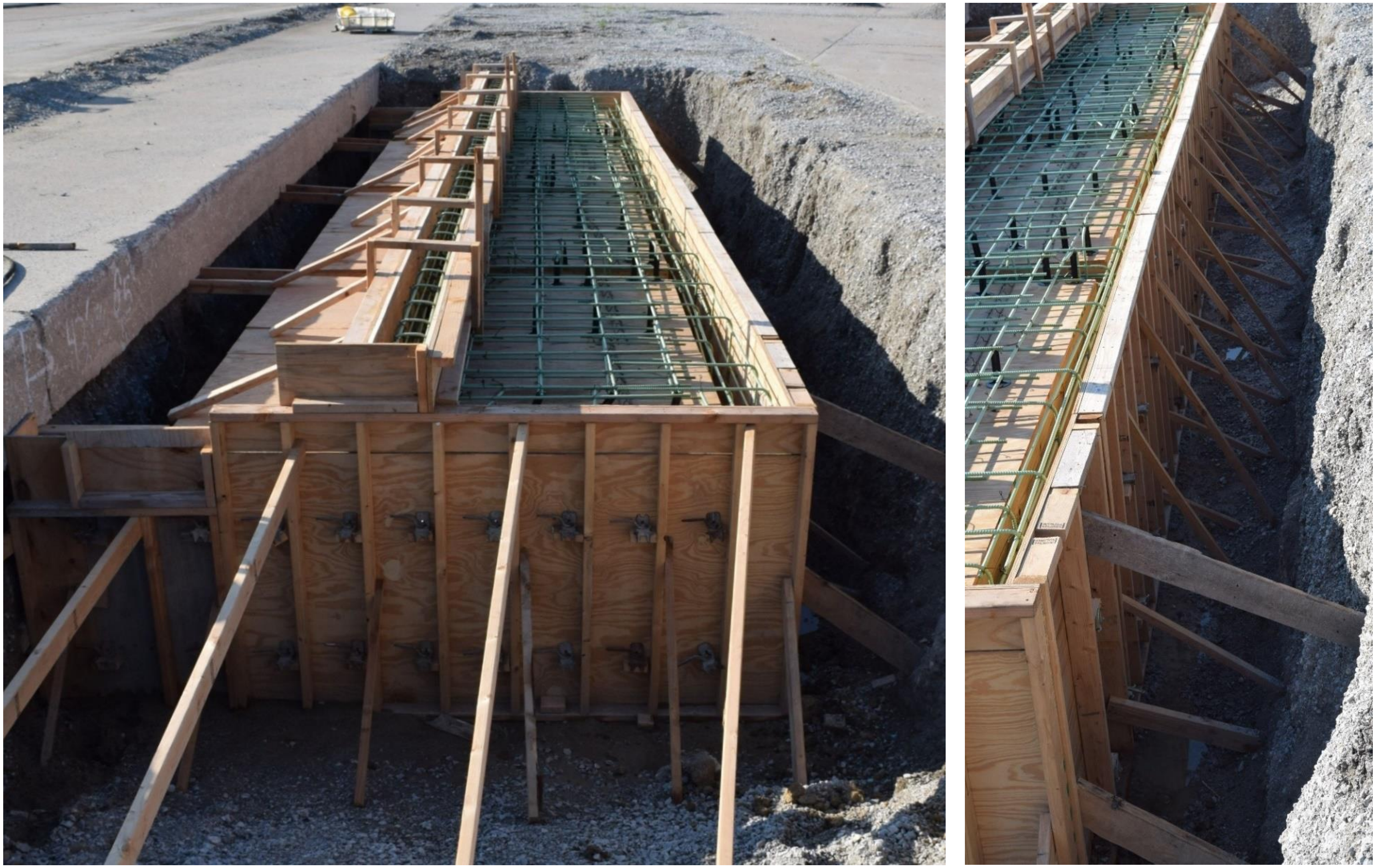


Figure 19. Concrete Top Slab, Headwall, and Soil Retaining Wall Framework, Test Nos. CMGS-1 and CMGS-2

Figure 20. Concrete Top Slab and Headwall Construction, Test Nos. CMGS-1 and CMGS-2

Figure 21. Concrete Culvert Superstructure, Top Slab, Headwall, and Vertical Supports, Test Nos. CMGS-1 and CMGS-2

3.2 Culvert-Mounted, Strong Post MGS

The test installation consisted of 182.3 ft (55.6 m) of MGS supported by steel posts with a top mounting rail height of 31 in. (787 mm), as shown in Figures 22 through 40. The test installation is shown in Figures 41 through 43. Test nos. CMGS-1 and CMGS-2 were conducted on the same installation; however, post nos. 14 through 21 were replaced before conducting test no. CMGS-2.

Anchorage systems similar to those used on tangent guardrail terminals were utilized on both the upstream and downstream ends of the guardrail system. The system was constructed using 41 posts. Post nos. 3 through 12 and 27 through 39 were galvanized ASTM A992 steel W6x8.5 sections measuring 72 in. (1,829 mm) long. Post nos. 13 through 26 were ASTM A992 steel W6x9 sections measuring 40½ in. (1,029 mm) long. Post nos. 1, 2, 40, and 41 were BCT posts measuring 5½ in. x 7½ in. x 46 in. (140 mm x 191 mm x 1,168 mm) and were placed in a steel foundation tube. Post nos. 1 through 8 and 32 through 41 were spaced 75 in. (1,905 mm) apart on center. Post nos. 8 through 32 were spaced 37½ in. (952 mm) apart on center, as shown in Figure 22. For post nos. 3 through 12 and 27 through 39, the soil embedment depth was 40 in. (1,016 mm). For post nos. 13 through 26, the soil embedment depth was 9 in. (229 mm). The posts were placed in a compacted, coarse, crushed limestone material with a strength that satisfied MASH 2016 criteria. For all posts, 6-in. x 12-in. x 14¼-in. (152-mm x 305-mm x 362-mm) wood blockouts were used to offset the rail away from the front face of the steel posts.

Post nos. 13 through 26 were anchored to the top of the concrete culvert using welded steel plates. A ½-in. thick x 8½-in. wide x 12-in. long (13-mm thick x 216-mm wide x 305-mm long) ASTM A572 steel plate was welded to the bottom of each post. The thickness of the baseplate was selected to allow some deformation of the base plate and corresponding energy absorption. In order to fully develop the connection between the baseplate and the W6x9 post sections, a special weld detail was utilized that incorporated a 3-pass, $^{5}/_{16}$-in. (8-mm) fillet weld on the front flange of the post and a ¼-in. (6-mm) fillet weld on the web and back flange of the post. The backside of these posts was positioned 12 in. (305 mm) from the culvert's headwall.

Post nos. 13 through 15, 17 through 22, and 24 through 26 were anchored to the top concrete slab using four through-bolts, as shown in Figure 24. Four 1-in. (25-mm) diameter by 10½-in. (267-mm) long ASTM A307 hex head bolts were placed through each top base plate and the concrete deck and were held in place with 8½-in. wide x 12-in. long x ¼-in. (216-mm wide x 305-mm long x 6-mm) thick steel washer plates below the top slab. Note that the one-piece washer plate below the top slab used for testing could be replaced by individual 3½-in. wide x 3½-in. long x ¼-in. (89-mm wide x 89-mm long x 6-mm) square washer plates if desired. Post nos. 16 and 23 were anchored using 10-in. (254-mm) long epoxied threaded rods with an 8-in. (203 mm) embedded length due to the presence of the culvert's interior wall support, as shown in Figure 25. This alternative anchorage detail was developed in previous research effort [7].

A concrete culvert, as previously described in Section 3.1, was constructed at the center of the system. The maximum dimensions of the culvert's top slab were 60 in. (1,524 mm) wide and 8 in. (203 mm) thick with a 10-in. (254-mm) wide x 9-in. (229-mm) high headwall positioned flush with the backside of the top slab, as previously described. The length of the culvert was 43 ft – 4 in. (13.2 m) long, and the culvert spanned from 16¼ in. (413 mm) upstream from the center of post no. 13 to 16¼ in. (413 mm) downstream from the center of post no. 26.

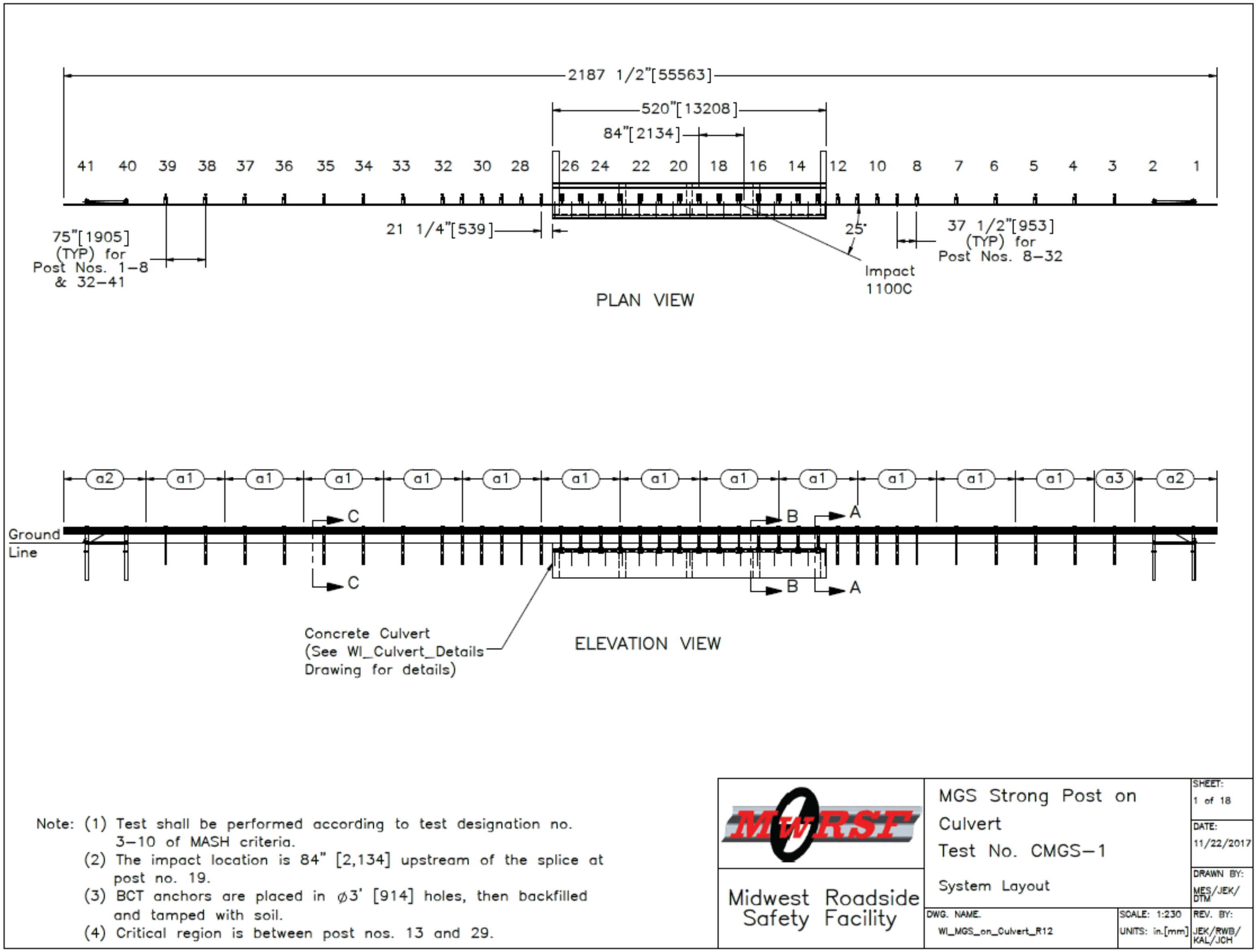


Figure 22. System Layout, Test No. CMGS-1

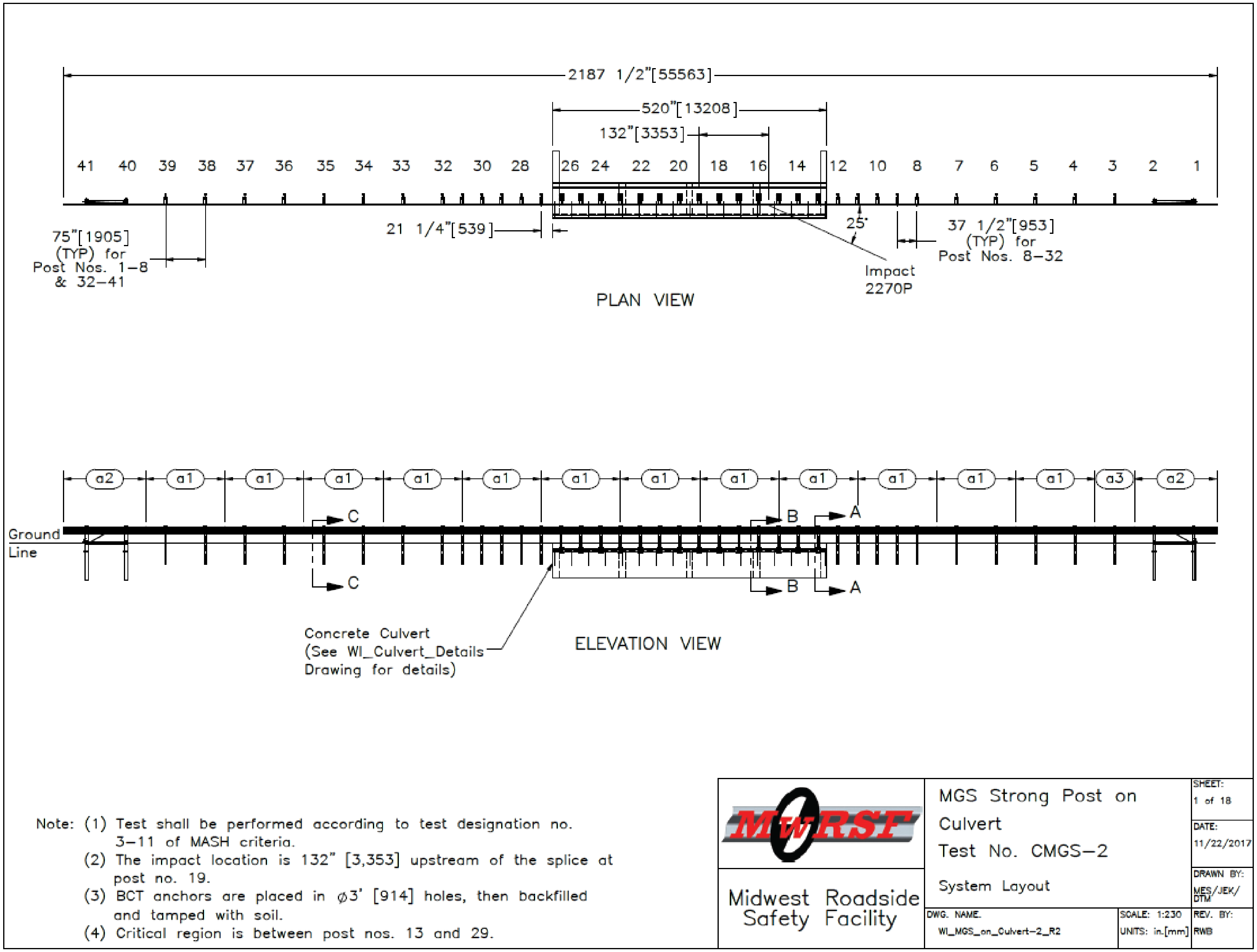


Figure 23. System Layout, Test No. CMGS-2

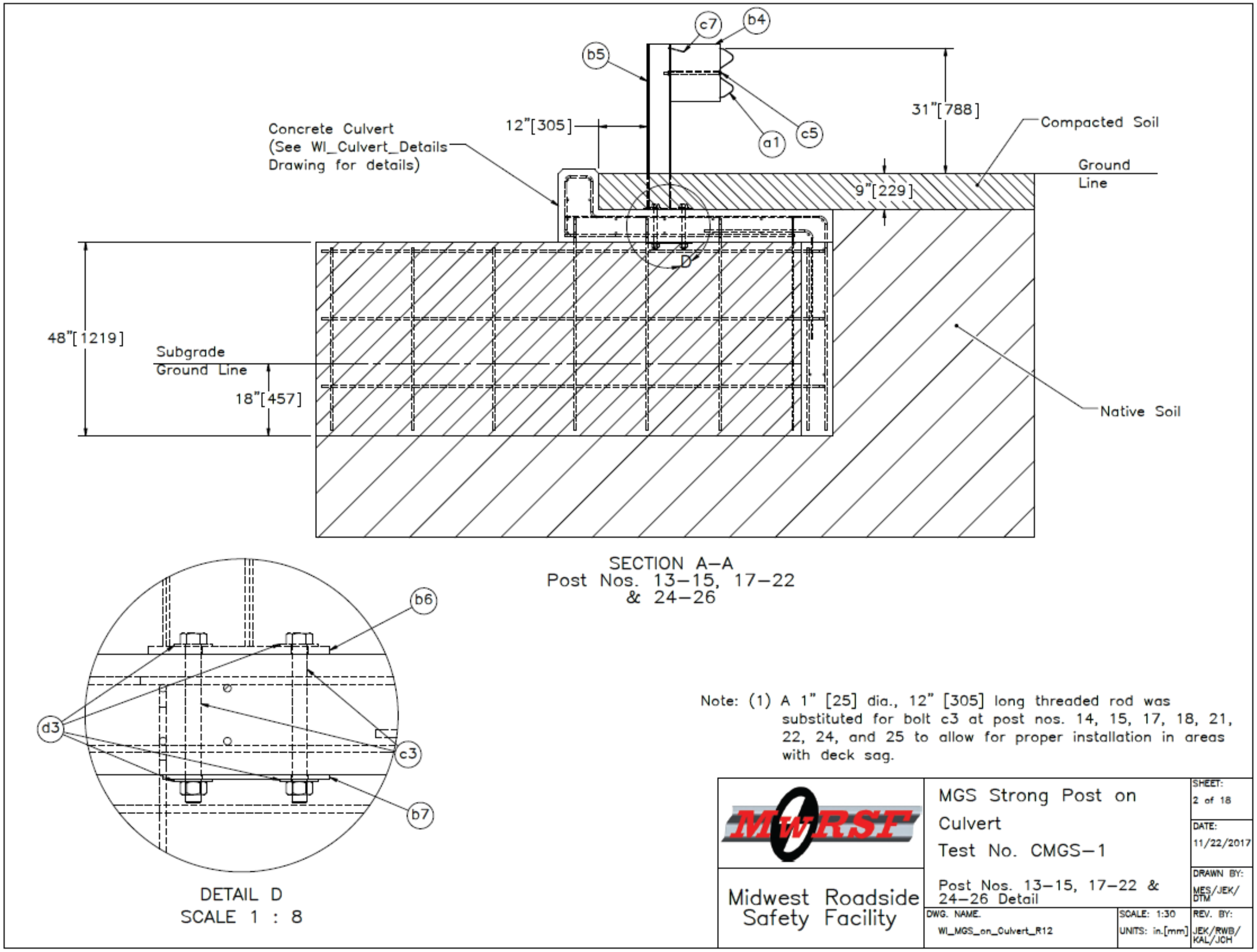


Figure 24. Post Nos. 13 through 15, 17 through 22, and 24 through 26 Details, Test Nos. CMGS-1 and CMGS-2

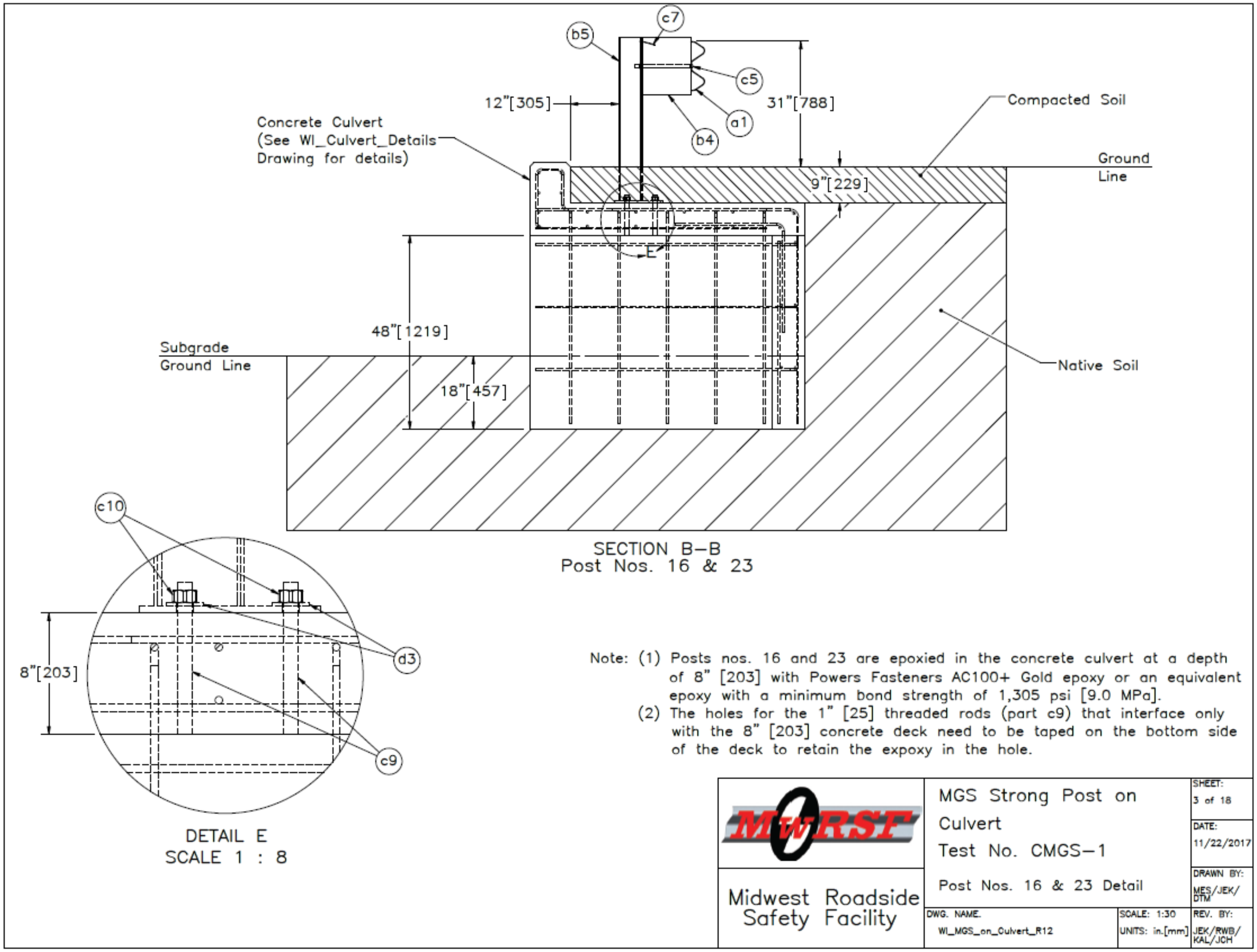


Figure 25. Post Nos. 16 and 23 Details, Test Nos. CMGS-1 and CMGS-2

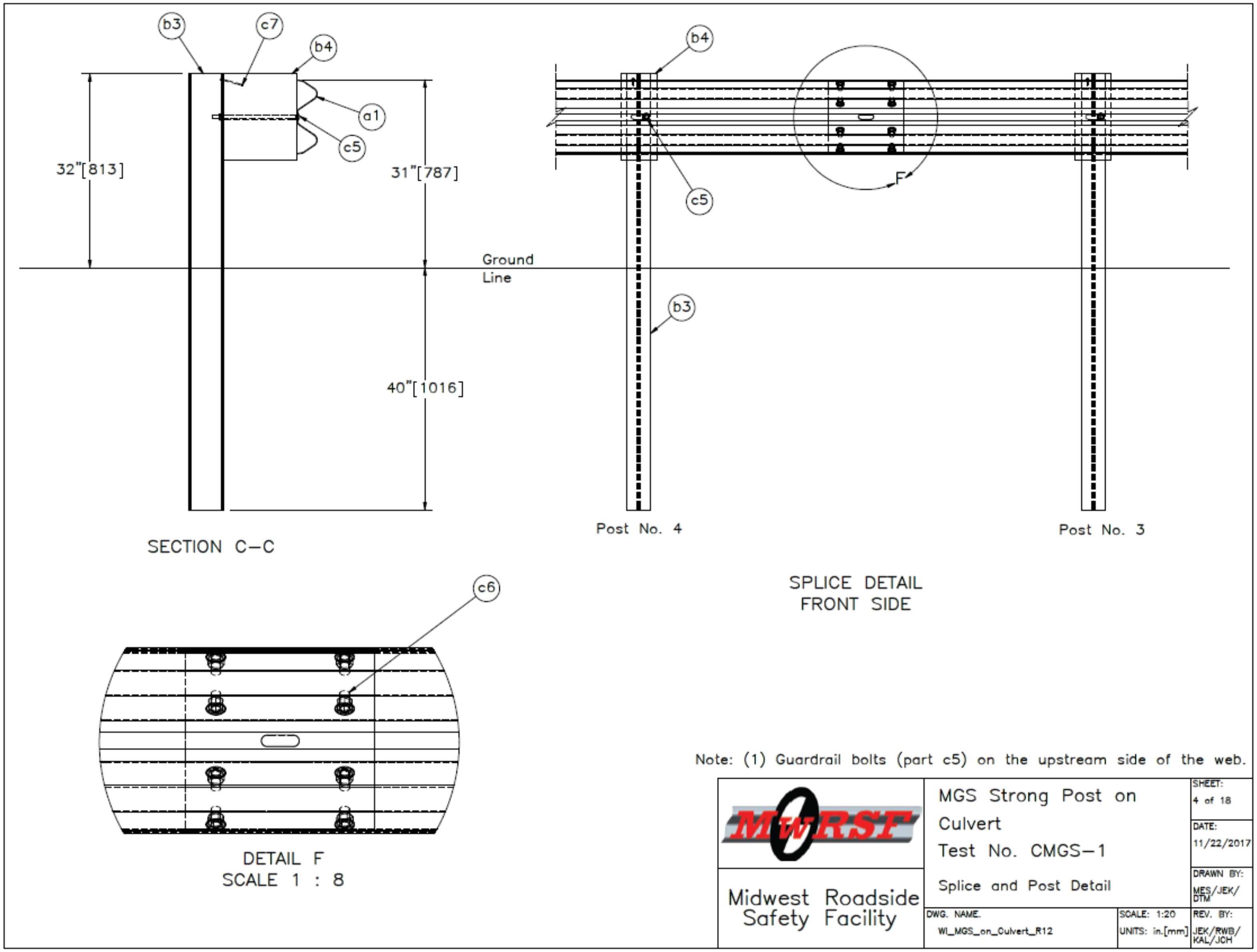


Figure 26. Splice and Post Details, Test Nos. CMGS-1 and CMGS-2

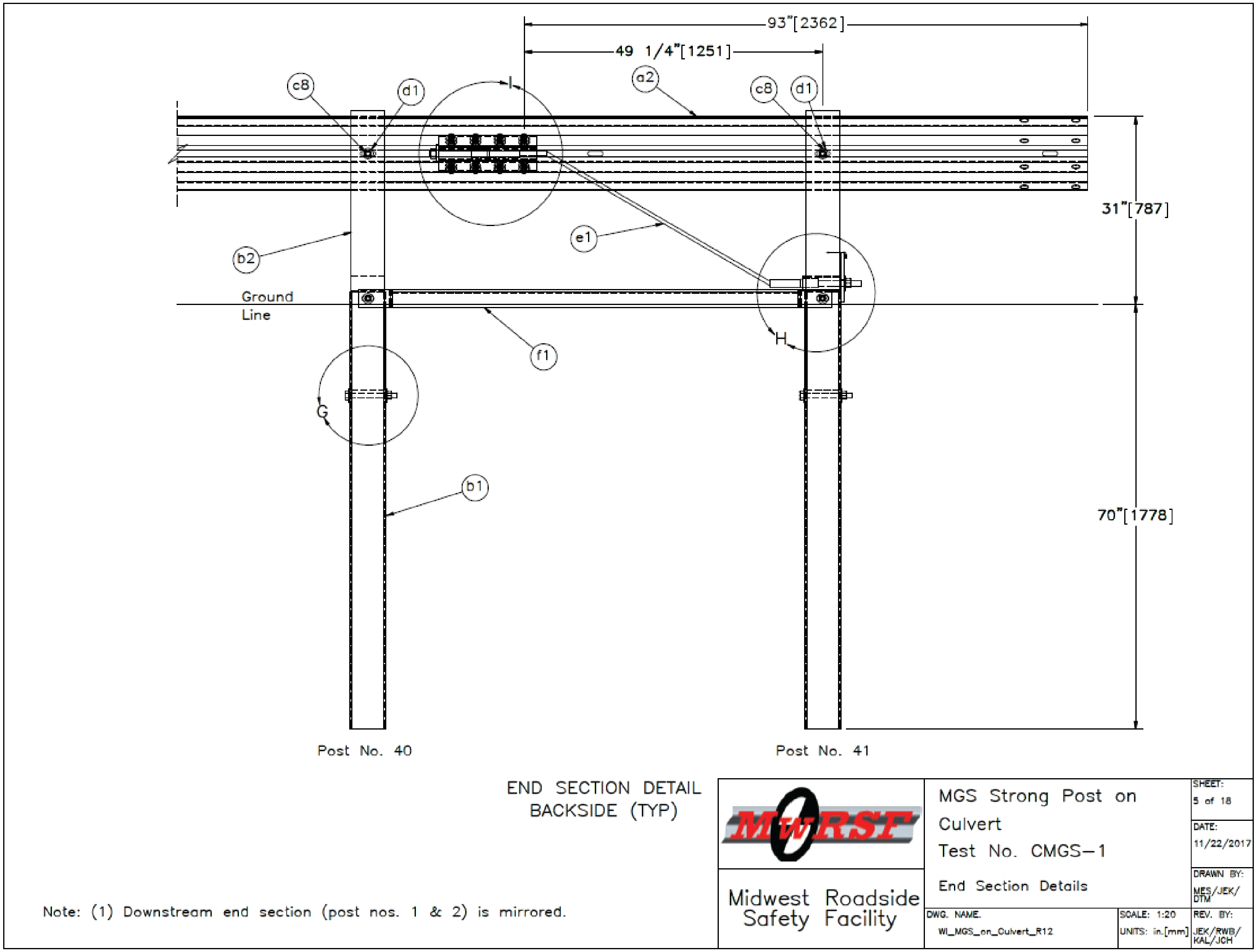


Figure 27. End Section Details, Test Nos. CMGS-1 and CMGS-2

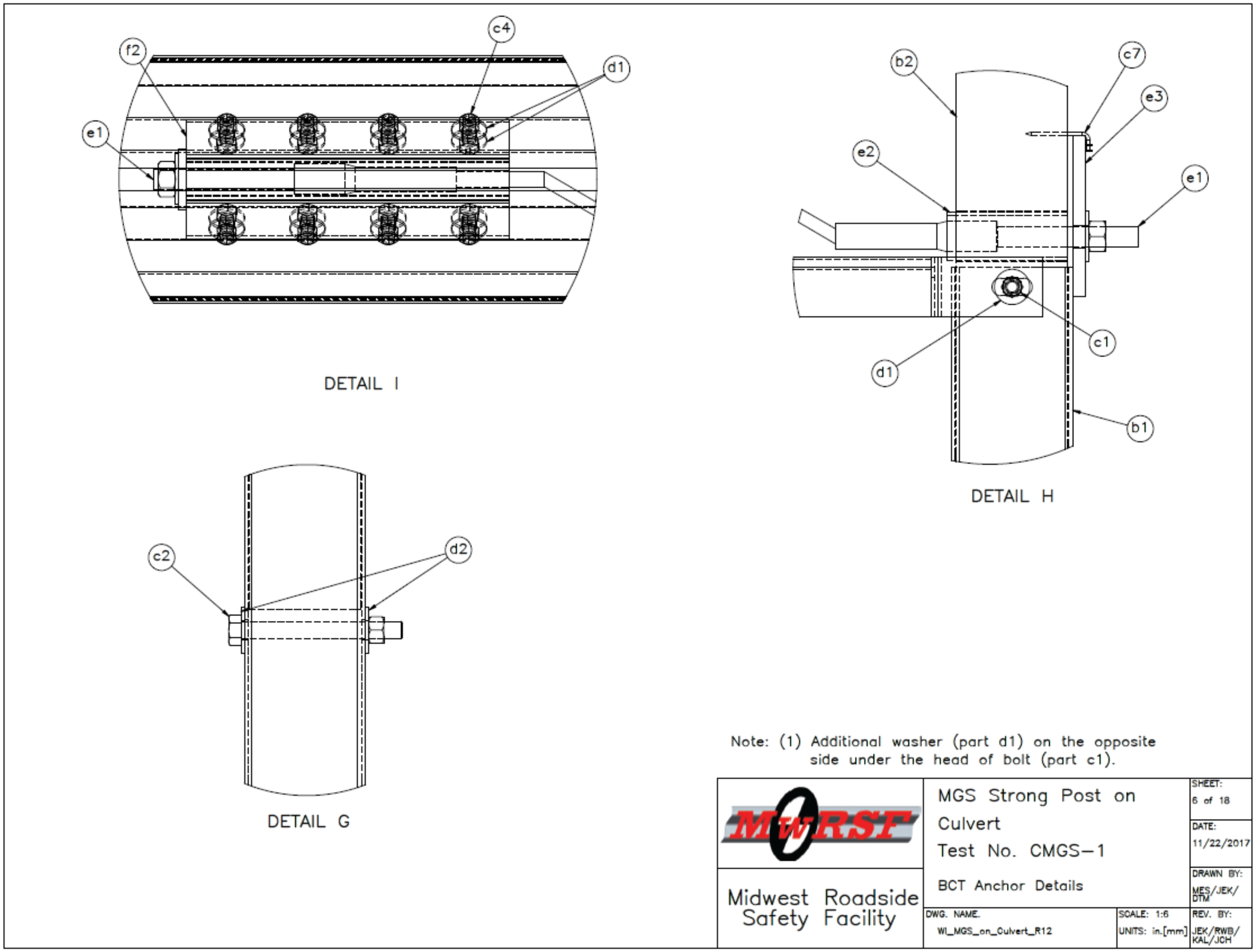


Figure 28. BCT Anchor Details, Test Nos. CMGS-1 and CMGS-2

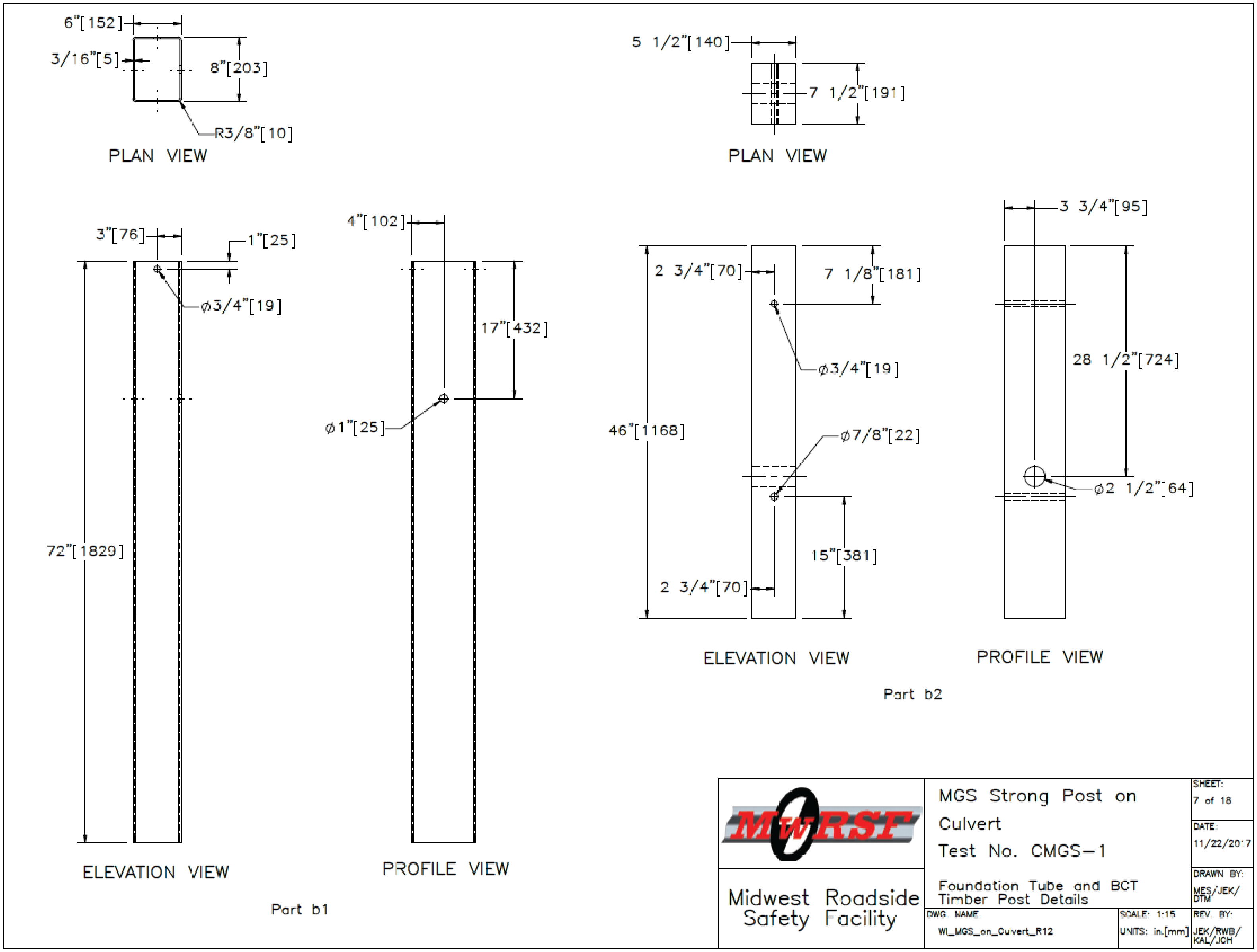


Figure 29. Foundation Tube and BCT Timber Post Details, Test Nos. CMGS-1 and CMGS-2

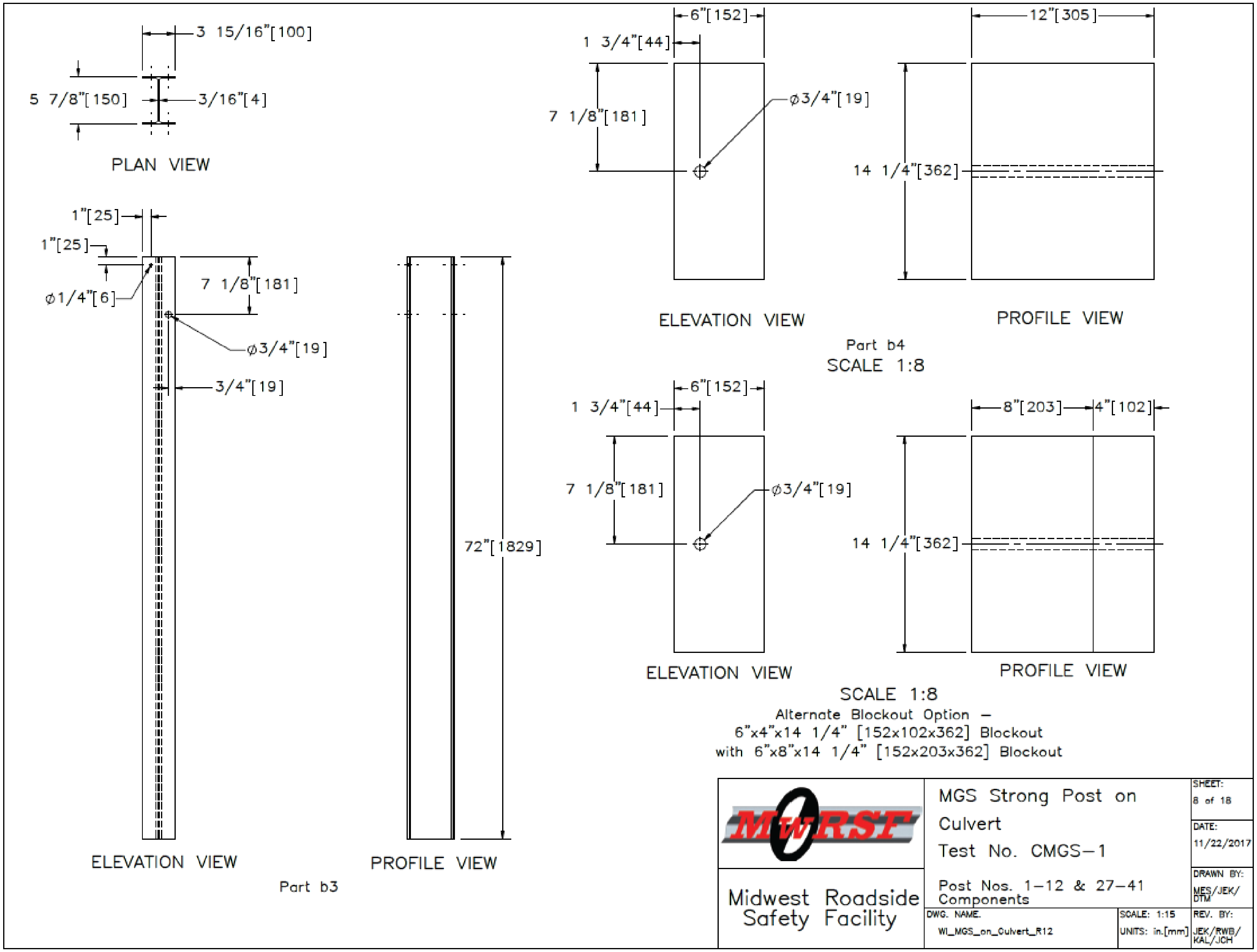


Figure 30. Post Nos. 1 through 12 and 27 through 41 Component Details, Test Nos. CMGS-1 and CMGS-2

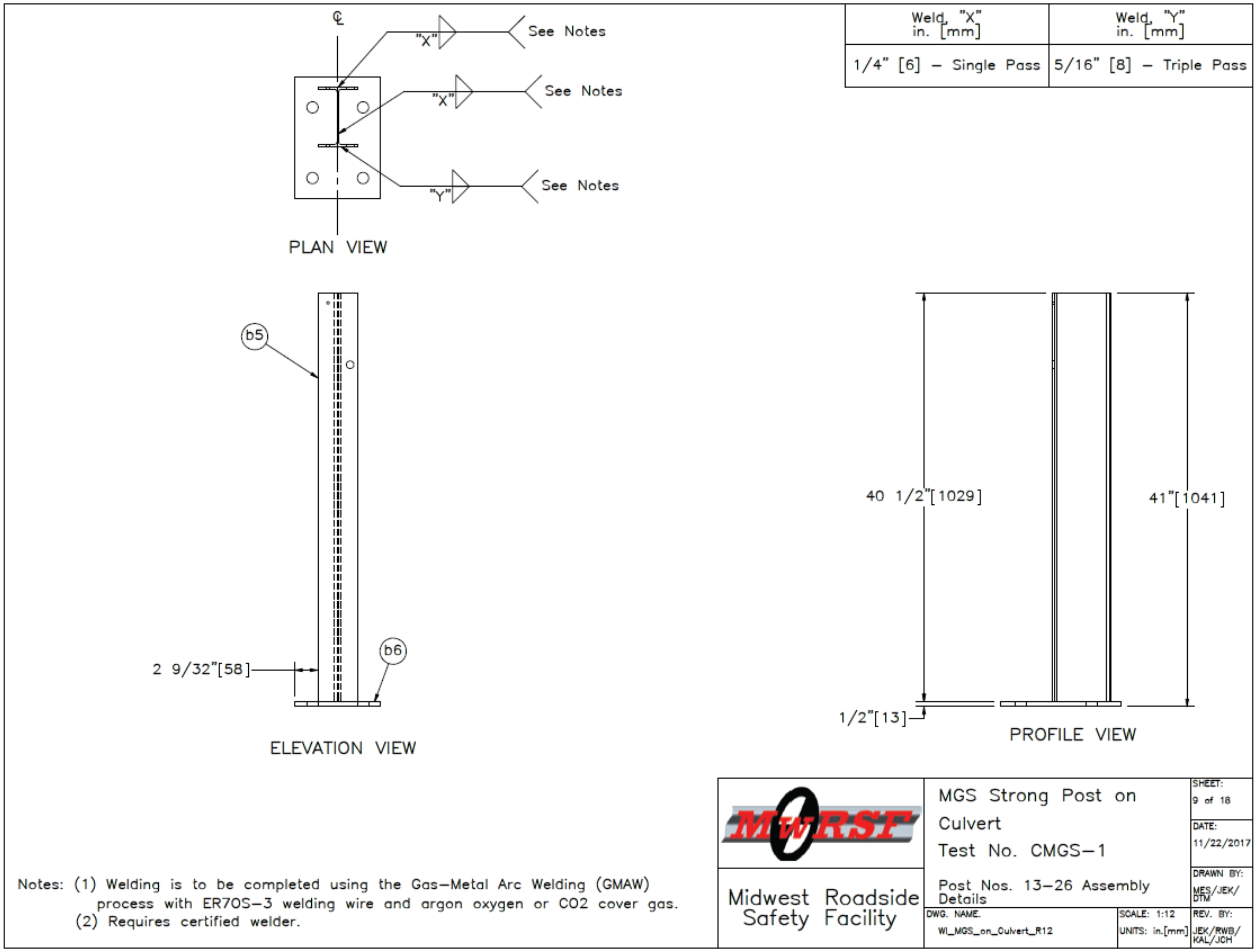


Figure 31. Post Nos. 13 through 26 Assembly Details, Test Nos. CMGS-1 and CMGS-2

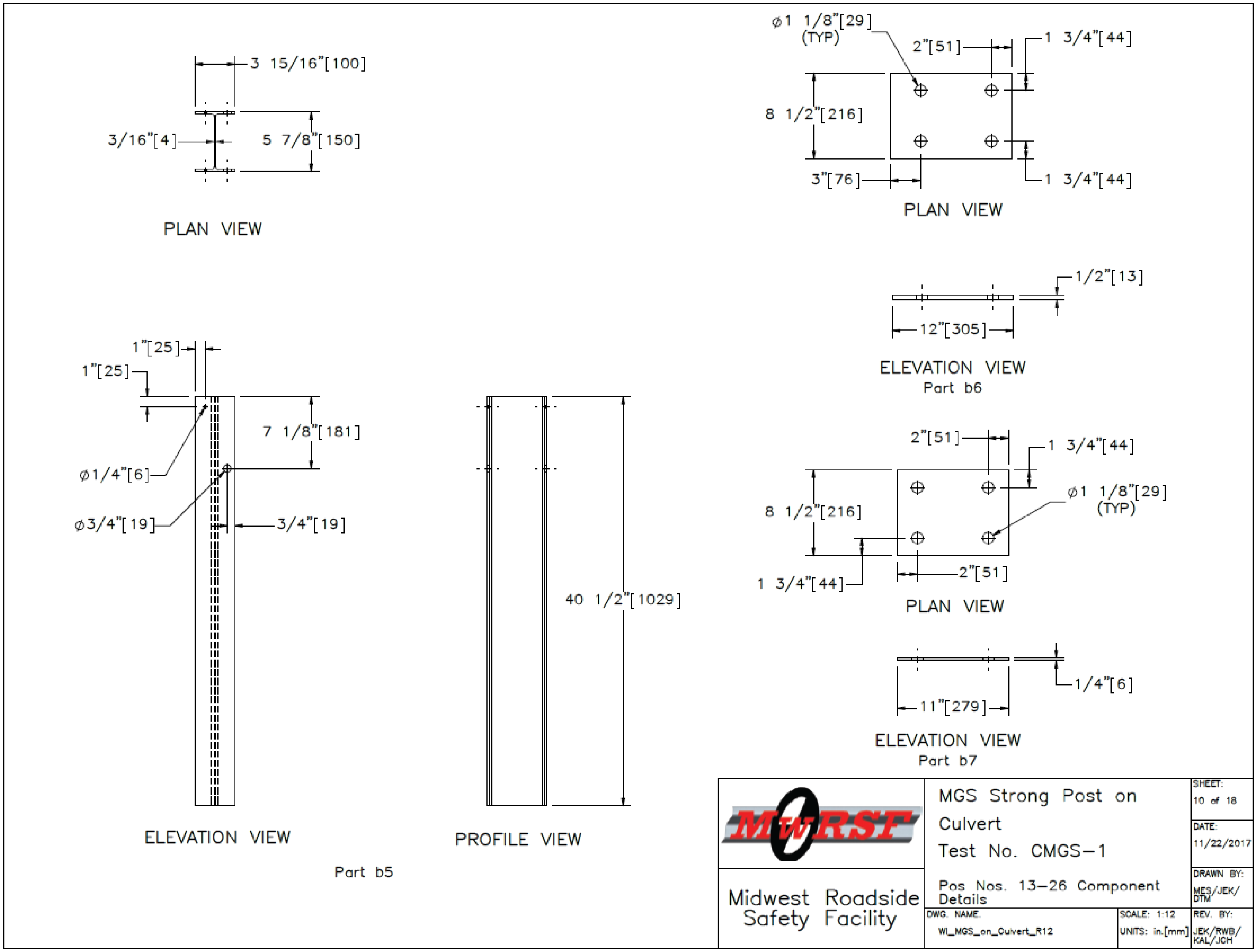


Figure 32. Post Nos. 13 through 26 Component Details, Test Nos. CMGS-1 and CMGS-2

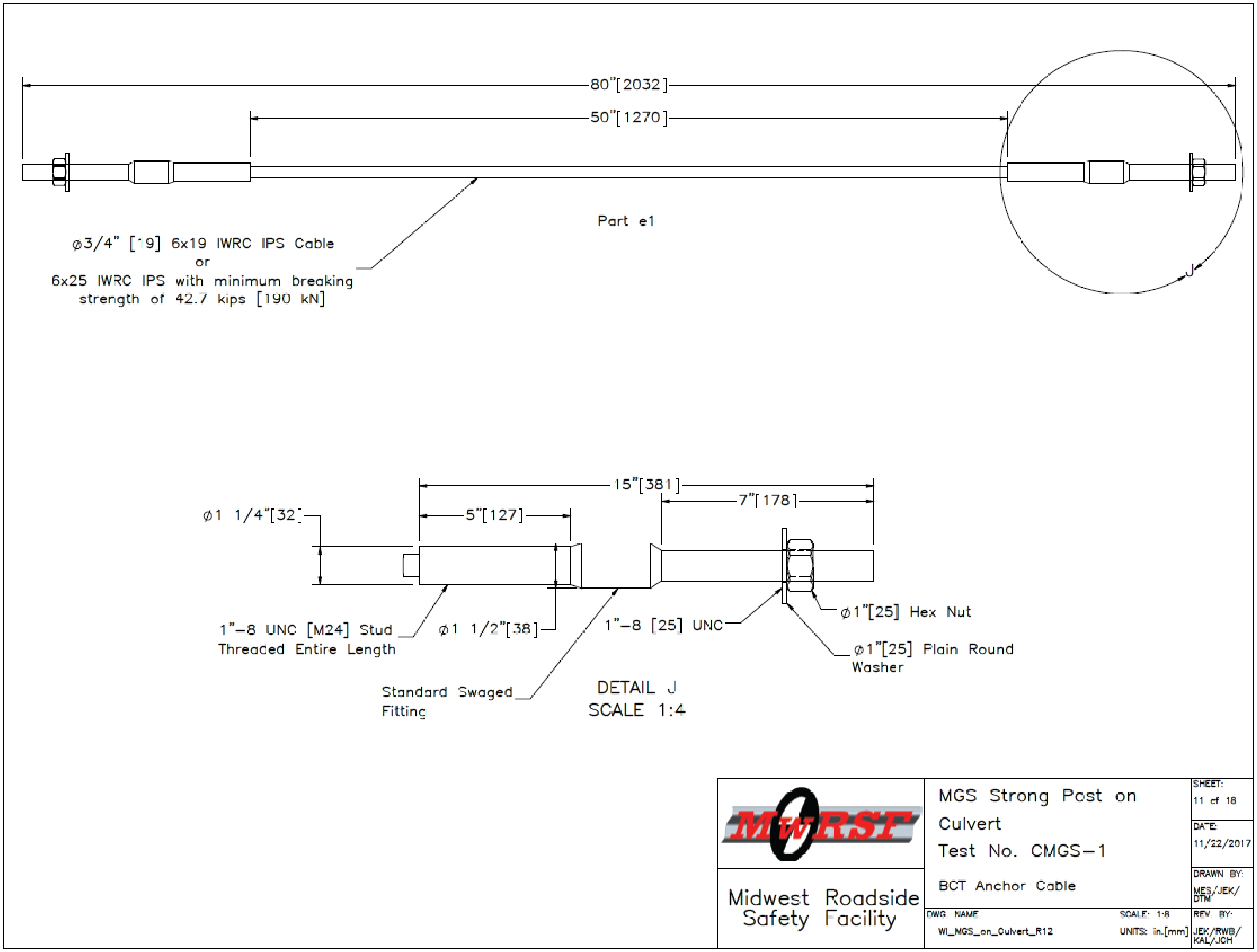


Figure 33. BCT Anchor Cable, Test Nos. CMGS-1 and CMGS-2

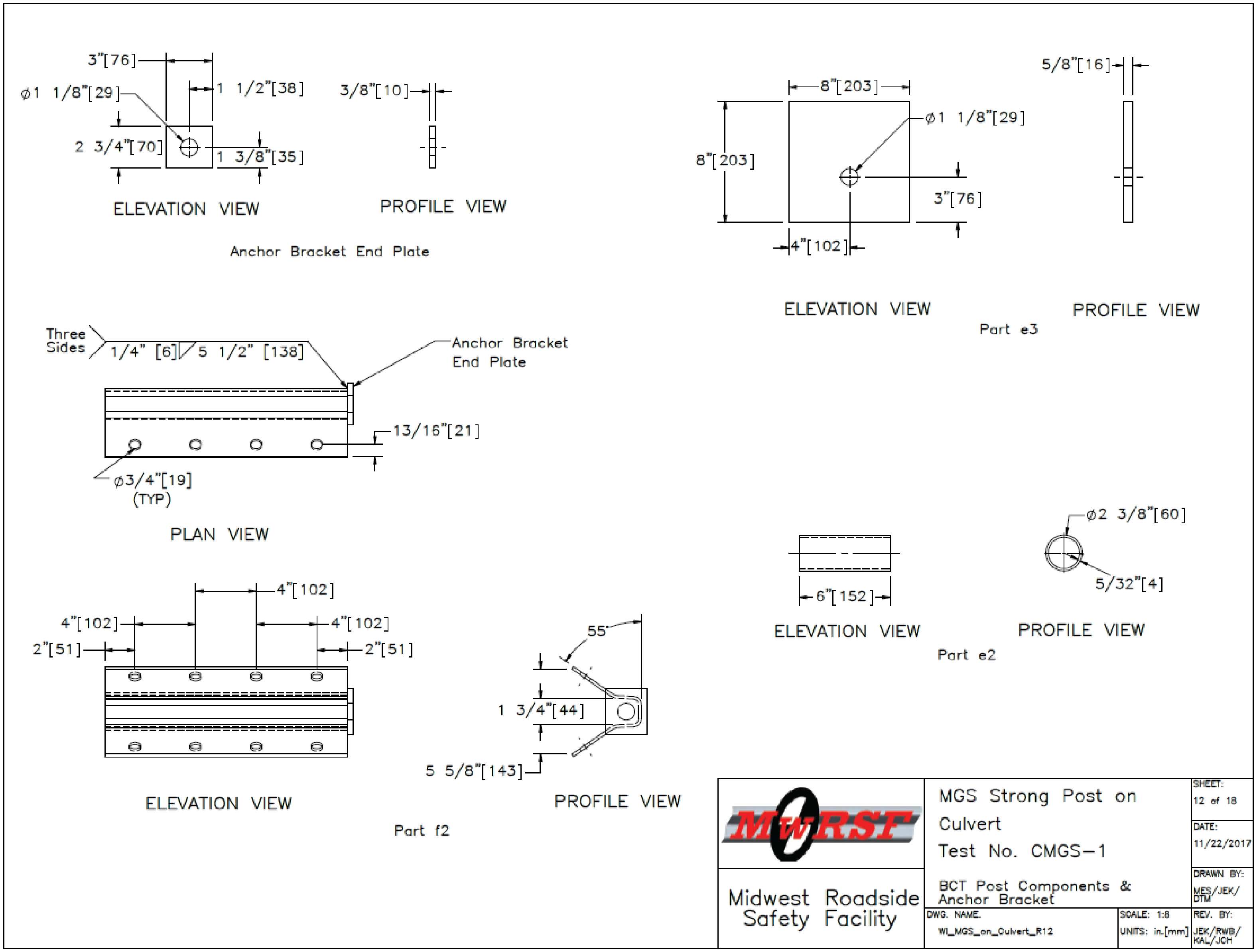


Figure 34. BCT Post Components and Anchor Bracket, Test Nos. CMGS-1 and CMGS-2

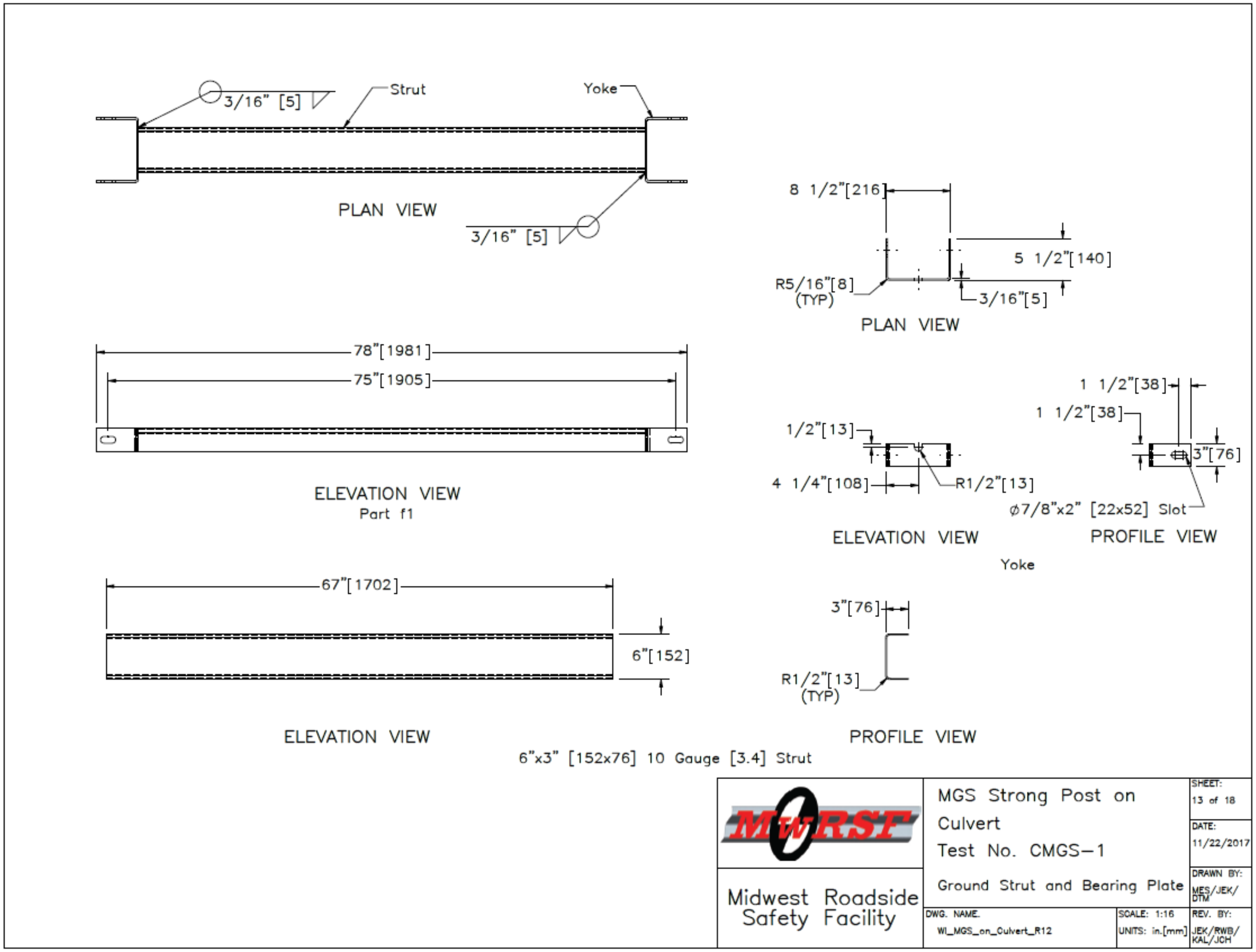


Figure 35. Ground Strut and Bearing Plate, Test Nos. CMGS-1 and CMGS-2

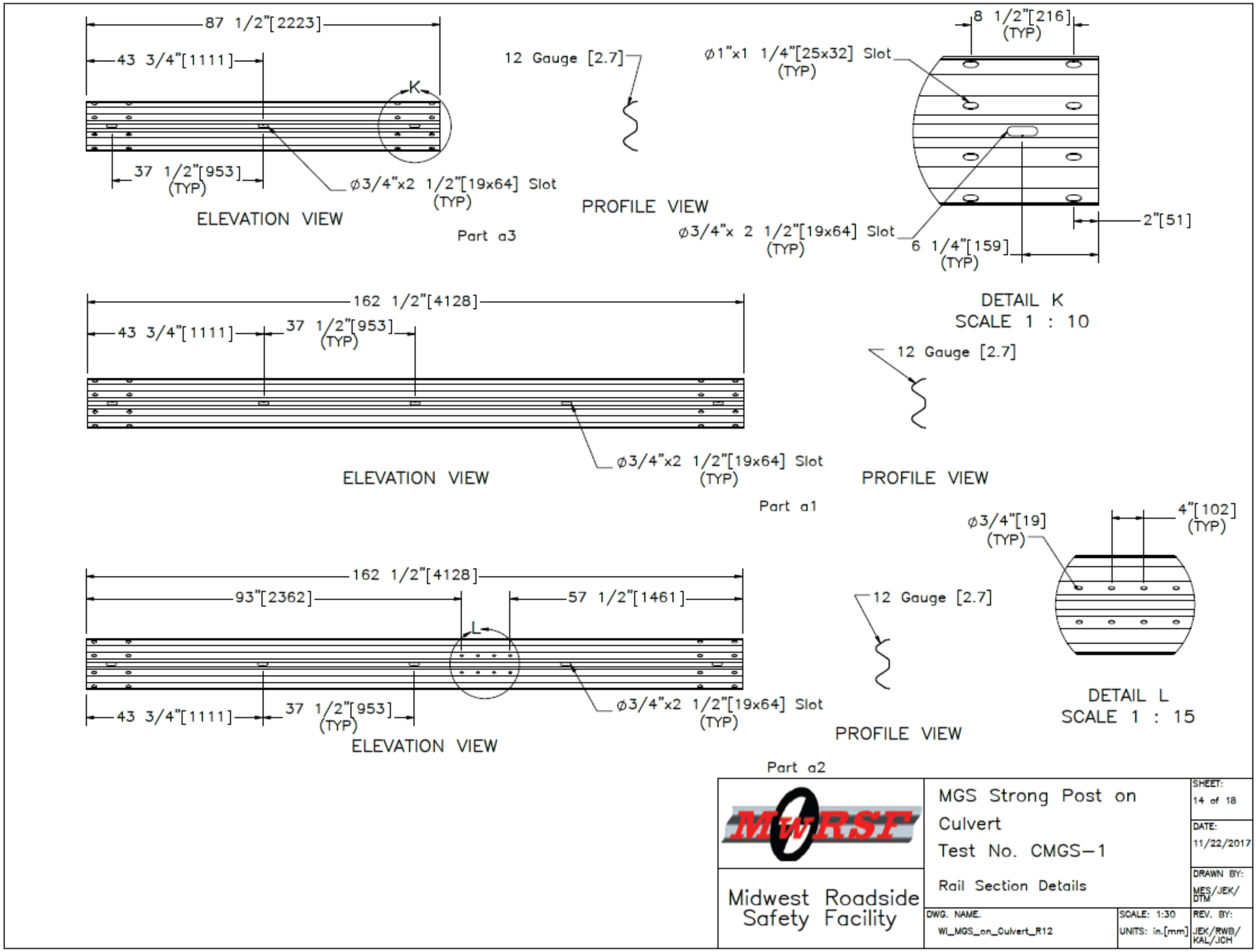


Figure 36. Rail Section Details, Test Nos. CMGS-1 and CMGS-2

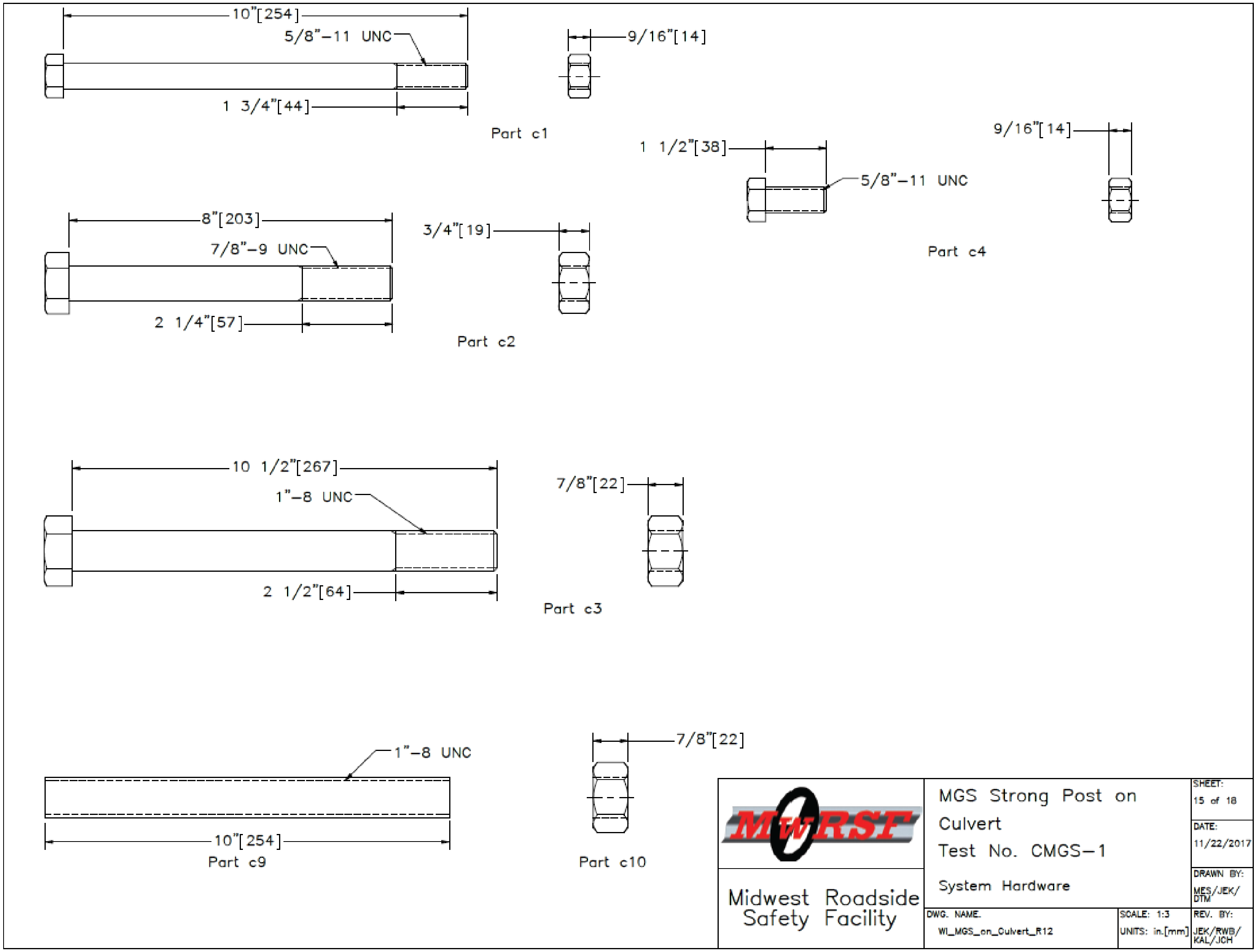


Figure 37. System Hardware Details, Test Nos. CMGS-1 and CMGS-2

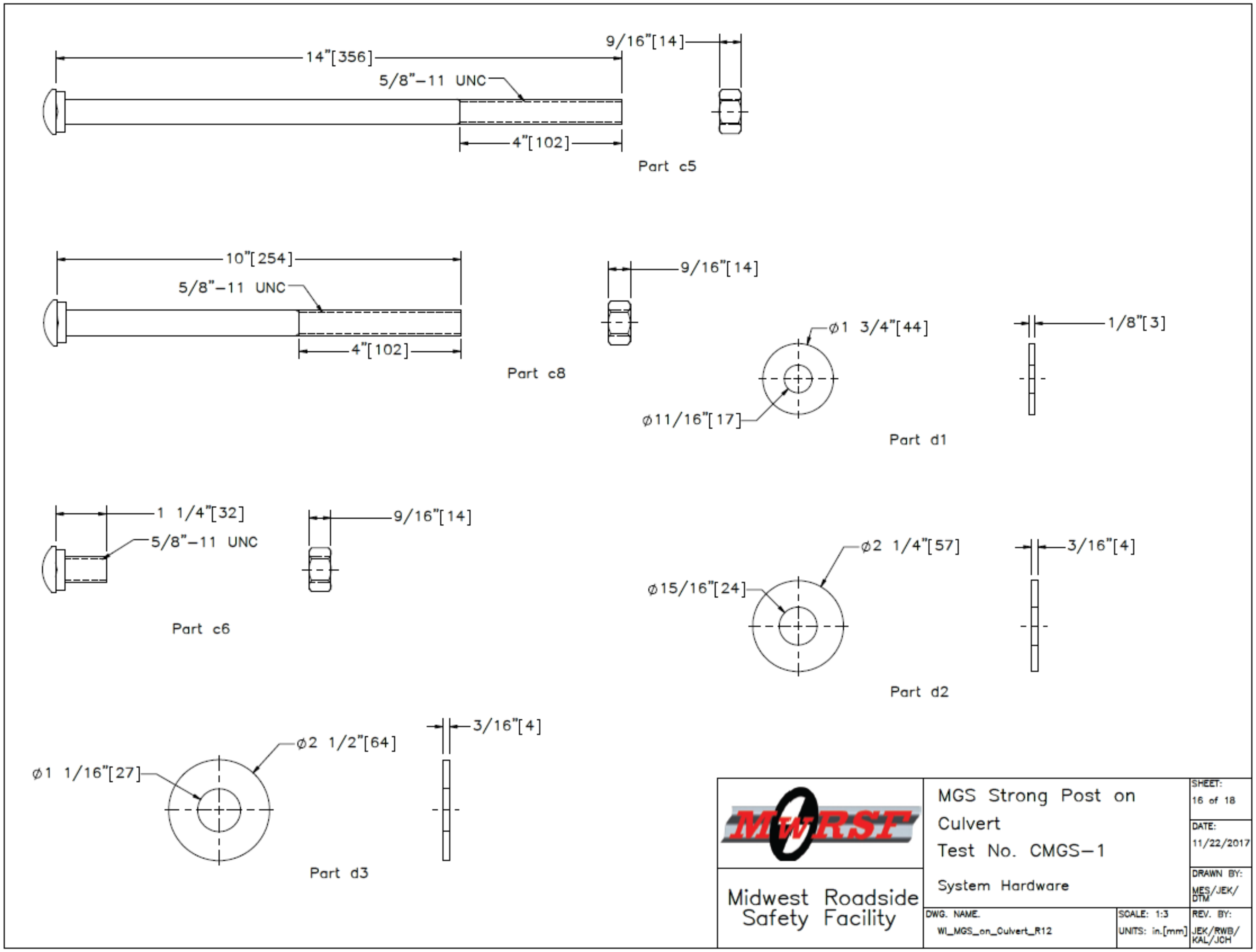


Figure 38. System Hardware Details, Test Nos. CMGS-1 and CMGS-2

Item No.	QTY.	Description	Material Specification	Galvanization Specification	Hardware Guide
a1	12	12'–6" [3,810] 12 gauge [2.7] W–Beam MGS Section	AASHTO M180	ASTM A123 or A653	RWM04a
a2	2	12'–6" [3,810] 12 gauge [2.7] W–Beam MGS End Section	AASHTO M180	ASTM A123 or A653	RWM14a
a3	1	6'–3" [1,905] 12 gauge [2.7] W–Beam MGS Section	AASHTO M180	ASTM A123 or A653	RWM04a
b1	4	72" [1829] Long Foundation Tube	ASTM A500 Gr. B	ASTM A123	PTE06
b2	4	BCT Timber Post – MGS Height	SYP Grade No. 1 or better (No knots 18" [457] above or below ground tension face)	–	PDF01
b3	23	W6x8.5 [152x12.6] or W6x9 [W152x13.4], 72" [1,829] Long Steel Post	ASTM A992	ASTM A123	PWE06
b4	37	6"x12"x14 1/4" [152x305x368] Timber Blockout for Steel Posts	SYP Grade No. 1 or better	–	PDB10a
b5	14	W6x8.5 [W152x12.6] or W6x9 [W152x13.4] Post, 40 1/2" [1029] Long	ASTM A992	ASTM A123	SGR25
b6	14	8 1/2"x12"x1/2" [216x305x13] Top Base Plate	ASTM A572 Gr. 50	ASTM A123	SGR25
b7	13	8 1/2"x11"x1/4" [216x280x6] Bottom Post Plate	ASTM A572 Gr. 50	ASTM A123	SGR25
c1	4	5/8" [16] Dia. UNC, 10" [254] Long Hex Head Bolt and Nut	Bolt – ASTM A307 Gr. A Nut – ASTM A563A	ASTM A153 or B695 Class 55 or F2329	FBX16a
c2	4	7/8" [22] Dia. UNC, 8" [203] Long Hex Head Bolt and Nut	Bolt – ASTM A307 Gr. A Nut – ASTM A563A	ASTM A153 or B695 Class 55 or F2329	–
c3	52	1" [25] Dia. UNC, 10 1/2" [267] Long Hex Head Bolt and Nut	Bolt – ASTM A307 Gr. A Nut – ASTM A563A	ASTM A153 or B695 Class 55 or F2329	FBX24a
c4	16	5/8" [16] Dia. UNC, 1 1/2" [38] Long Hex Head Bolt and Nut	Bolt – ASTM A307 Gr. A Nut – ASTM A563A	ASTM A153 or B695 Class 55 or F2329	FBX16a
c5	37	5/8" [16] Dia. UNC, 14" [356] Long Guardrail Bolt and Nut	Bolt – ASTM A307 Gr. A Nut – ASTM A563A	ASTM A153 or B695 Class 55 or F2329	FBB06
c6	112	5/8" [16] Dia. UNC, 1 1/4" [32] Long Guardrail Bolt and Nut	Bolt – ASTM A307 Gr. A Nut – ASTM A563A	ASTM A153 or B695 Class 55 or F2329	FBB01
c7	39	16D Double Head Nail	–	–	–
c8	4	5/8" [16] Dia. UNC, 10" [254] Long Guardrail Bolt and Nut	Bolt – ASTM A307 Gr. A Nut – ASTM A563A	ASTM A153 or B695 Class 55 or F2329	FBB03
c9	4	1" [25] Dia. UNC, 10" [254] Long Threaded Rod	ASTM A307 Gr. A	ASTM A153 or B695 Class 55 or F2329	FRR24a
c10	8	1" [25] Dia. Hex Nut	ASTM A563A	ASTM A153 or B695 Class 55 or F2329	FNX24a

Note: (1) A 25' [7.6 m] guardrail segment may be used in place of two 12.5' [3.8 m] segments outside of the critical region.

Midwest Roadside Safety Facility

MGS Strong Post on Culvert
Test No. CMGS–1

Bill of Materials

SHEET: 17 of 18
DATE: 11/22/2017
DRAWN BY: MES/JEK/DTM
REV. BY: JEK/RWB/KAL/JCH
DWG. NAME. WI_MGS_on_Culvert_R12
SCALE: None
UNITS: in.[mm]

Figure 39. Bill of Materials, Test Nos. CMGS-1 and CMGS-2

Item No.	QTY.	Description	Material Specification	Galvanization Specification	Hardware Guide
d1	44	5/8" [16] Dia. Plain Round Washer	ASTM F844	ASTM A123 or A153 or F2329	FWC16a
d2	8	7/8" [22] Dia. Plain Round Washer	ASTM F844	ASTM A123 or A153 or F2329	–
d3	104	1" [25] Dia. Plain Round Washer	ASTM F844	ASTM A123 or A153 or F2329	FWC24a
e1	2	BCT Anchor Cable	–	–	FCA01
e2	2	2 3/8" [60] O.D. x 6" [152] Long BCT Post Sleeve	ASTM A53 Gr. B Schedule 40	ASTM A123	FMM02
e3	2	8"x8"x5/8" [203x203x16] Anchor Bearing Plate	ASTM A36	ASTM A123	FPB01
f1	2	Ground Strut Assembly	ASTM A36	ASTM A123	PFP01
f2	2	Anchor Bracket Assembly	ASTM A36	ASTM A123	FPA01
–	1	Concrete Culvert*	Min. f'c = 4,000 psi [27.6 MPa] NE Mix 47BD	–	–

* See WI_Culvert_Details_as_built drawing for details on concrete culvert.

MwRSF Midwest Roadside Safety Facility

MGS Strong Post on Culvert
Test No. CMGS-1
Bill of Materials

SHEET: 18 of 18
DATE: 11/22/2017
DRAWN BY: MES/JEK/DTM
REV. BY: JEK/RWB/KAL/JCH
DWG. NAME. WI_MGS_on_Culvert_R12
SCALE: None
UNITS: in.[mm]

Figure 40. Bill of Materials (Cont.), Test Nos. CMGS-1 and CMGS-2

Figure 41. System Installation, Test Nos. CMGS-1 and CMGS-2

Figure 42. Posts Attached to Culvert, Test Nos. CMGS-1 and CMGS-2

Figure 43. Bottom-Side Steel Post Connection Details and End Anchorage Systems, Test Nos. CMGS-1 and CMGS-2

4 TEST CONDITIONS

4.1 Test Facility

The outdoor test site is located at the Lincoln Air Park on the northwest side of the Lincoln Municipal Airport and is approximately 5 miles (8.0 km) northwest of the University of Nebraska-Lincoln.

4.2 Vehicle Tow and Guidance System

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

A vehicle guidance system developed by Hinch [11] was used to steer the test vehicle. A guide flag, attached to the right-front wheel and the guide cable, was sheared off before impact with the barrier system. The ⅜-in. (9.5-mm) diameter guide cable was tensioned to approximately 3,500 lb (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, but as the vehicle was towed down the line, the guide flag struck and knocked each stanchion to the ground.

4.3 Test Vehicles

For test no. CMGS-1, a 2010 Hyundai Accent was used as the test vehicle. The curb, test inertial, and gross static vehicle weights were 2,471 lb (1,121 kg), 2,428 lb (1,101 kg), and 2,588 lb (1,174 kg), respectively. The test vehicle is shown in Figures 44 and 45, and vehicle dimensions are shown in Figure 46.

For test no. CMGS-2, a 2010 Dodge Ram 1500 Crew Cab was used as the test vehicle. The curb, test inertial, and gross static vehicle weights were 5,292 lb (2,400 kg), 5,013 lb (2,274 kg), and 5,175 lb (2,347 kg), respectively. The test vehicle is shown in Figures 47 and 48, and vehicle dimensions are shown in Figure 49. It should be noted that the test vehicles used were within six years of the research project contract date.

The longitudinal component of the center of gravity (c.g.) was determined using the measured axle weights. The vertical component of the c.g. for the 1100C vehicle was determined utilizing a procedure published by SAE [12]. The location of the final c.g. is shown in Figures 46 and 50. Data used to calculate the location of the c.g. and ballast information is shown in Appendix B.

Square, black- and white-checkered targets were placed on the test vehicles for reference to be viewed from the high-speed digital video cameras and aid in the video analysis, as shown in Figures 50 and 51. Round, checkered targets were placed at the c.g. on the left-side door, the right-side door, and the roof of the vehicles.

The front wheels of the test vehicles were aligned to vehicle standards except the toe-in value was adjusted to zero so that the vehicle would track properly along the guide cable. A 5B flash bulb was mounted under the vehicles' right-side and left-side windshield wipers for test nos. CMGS-1 and CMGS-2, respectively, and was fired by a pressure tape switch mounted at the impact corner of the bumper. The flash bulb was fired upon initial impact with the test article to create a visual indicator of the precise time of impact on the high-speed digital videos. A remote-controlled brake system was installed in the test vehicle so the vehicles could be brought safely to a stop after the test.

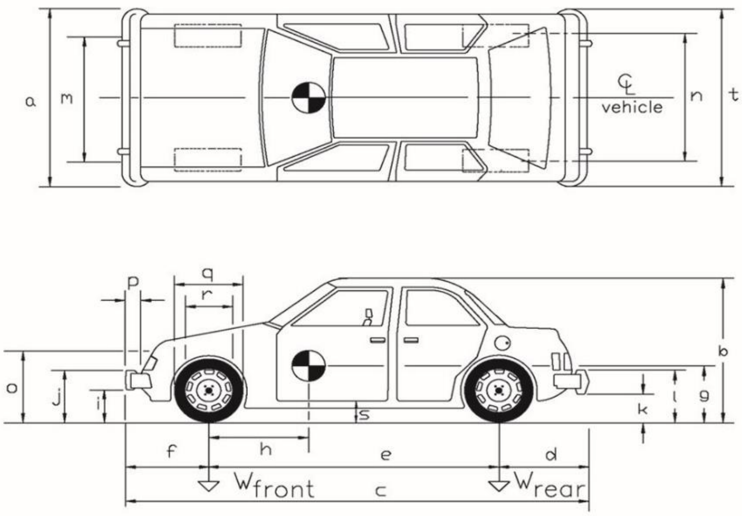

Figure 44. Test Vehicle, Test No. CMGS-1

Figure 45. Test Vehicle's Undercarriage and Interior Floorboards, Test No. CMGS-1

Date: 10/26/2017 | Test Number: CMGS-1 | VIN: KMHCN4ACOAU423259

Year: 2010 | Make: Hyundai | Model: Accent

Tire Size: 185\65 R14 | Tire Inflation Pressure: 32 Psi | Odometer: 140104



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

a:	63 1/8 (1603) 65±3 (1650±75)	b:	57 3/4 (1467)
c:	168 3/4 (4286) 169±8 (4300±200)	d:	36 3/4 (933)
e:	98 3/4 (2508) 98±5 (2500±125)	f:	33 1/4 (845) 35±4 (900±100)
g:	23 (584)	h:	36 3/8 (924) 39±4 (990±100)
i:	14 (356)	j:	20 3/4 (527)
k:	16 1/4 (413)	l:	23 1/4 (591)
m:	57 3/8 (1457) 56±2 (1425±50)	n:	57 1/4 (1454) 56±2 (1425±50)
o:	26 (660) 24±4 (600±100)	p:	3 3/4 (95)
q:	23 (584)	r:	15 1/2 (394)
s:	12 (305)	t:	65 (1651)

Mass Distribution lb. (kg)

Gross Static	LF	795 (361)	RF	819 (371)
	LR	483 (219)	RR	491 (223)

Weights lb. (kg)	Curb	Test Inertial	Gross Static
W-front	1582 (718)	1534 (696)	1614 (732)
W-rear	889 (403)	894 (406)	974 (442)
W-total	2471 (1121)	2428 (1101) 2420±55 (1100±25)	2588 (1174) 2585±55 (1175±50)

Top of radiator core support:	28 7/8 (733)
Wheel Center Height (Front):	10 1/2 (267)
Wheel Center Height (Rear):	11 1/8 (283)
Wheel Well Clearance (Front):	25 3/8 (645)
Wheel Well Clearance (Rear):	25 (635)
Bottom Frame Height (Front):	7 1/2 (191)
Bottom Frame Height (Rear):	15 5/8 (397)
Engine Type:	Gasoline
Engine Size:	1.4L 4 cyl.
Transmission Type:	Automatic
Drive Type:	FWD

GVWR Ratings lb.

Front: 1918

Rear: 1874

Total: 3638

Dummy Data

Type: Hybrid II

Mass: 160

Seat Position: Passenger/Right

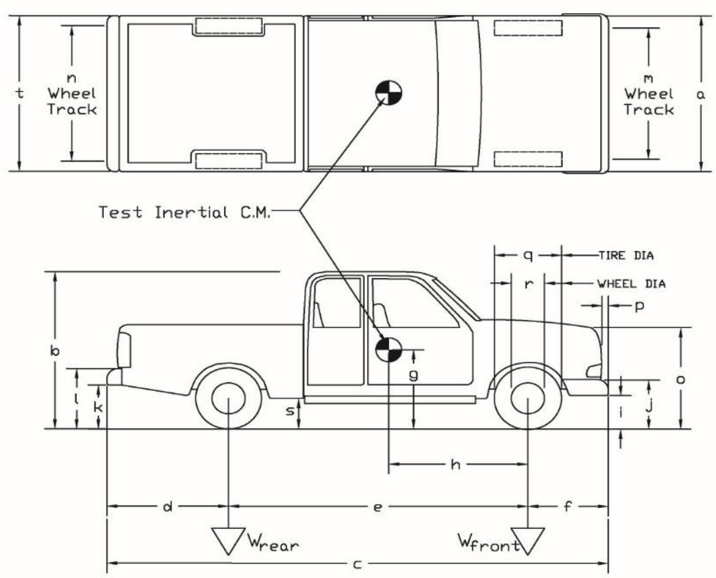
Note any damage prior to test: none

Figure 46. Vehicle Dimensions, Test No. CMGS-1

Figure 47. Test Vehicle, Test No. CMGS-2

Figure 48. Test Vehicle’s Undercarriage and Interior Floorboards, Test No. CMGS-2

Date:	1/3/2018	Test Name:	CMGS-2	VIN No:	1D7RB1CTXAS115553
Year:	2010	Make:	DODGE	Model:	RAM 1500 CREW CAB
Tire Size:	275/60 R20	Tire Inflation Pressure:	35 Psi	Odometer:	211977



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

a:	76 1/8	(1934)	b:	75	(1905)
	78±2 (1950±50)				
c:	229 1/4	(5823)	d:	47 1/2	(1207)
	237±13 (6020±325)				
e:	140 3/8	(3566)	f:	41 3/8	(1051)
	148±12 (3760±300)			39±3 (1000±75)	
g:	29 9/16	(751)	h:	60 1/4	(1530)
	min: 28 (710)			63±4 (1575±100)	
i:	13 1/8	(333)	j:	24 3/4	(629)
k:	21	(533)	l:	29	(737)
m:	68 1/8	(1730)	n:	67 1/2	(1715)
	67±1.5 (1700±38)			67±1.5 (1700±38)	
o:	45 1/4	(1149)	p:	4 5/8	(117)
	43±4 (1100±75)				
q:	32 1/2	(826)	r:	21 1/2	(546)
s:	14 1/2	(368)	t:	76 1/2	(1943)

Wheel Center Height (Front):	15 5/8	(397)
Wheel Center Height (Rear):	15 5/8	(397)
Wheel Well Clearance (Front):	35 1/2	(902)
Wheel Well Clearance (Rear):	38 3/8	(975)
Bottom Frame Height (Front):	18 3/4	(476)
Bottom Frame Height (Rear):	26	(660)
Engine Type:	8cyl. Gas	
Engine Size:	5.7L	
Transmission Type:	Automatic	
Drive Type:	RWD	
Cab Style:	Crew Cab	
Bed Length:	67"	

Mass Distribution lb. (kg)

Gross Static	LF	1480 (671)	RF	1483 (673)
	LR	1069 (485)	RR	1143 (518)

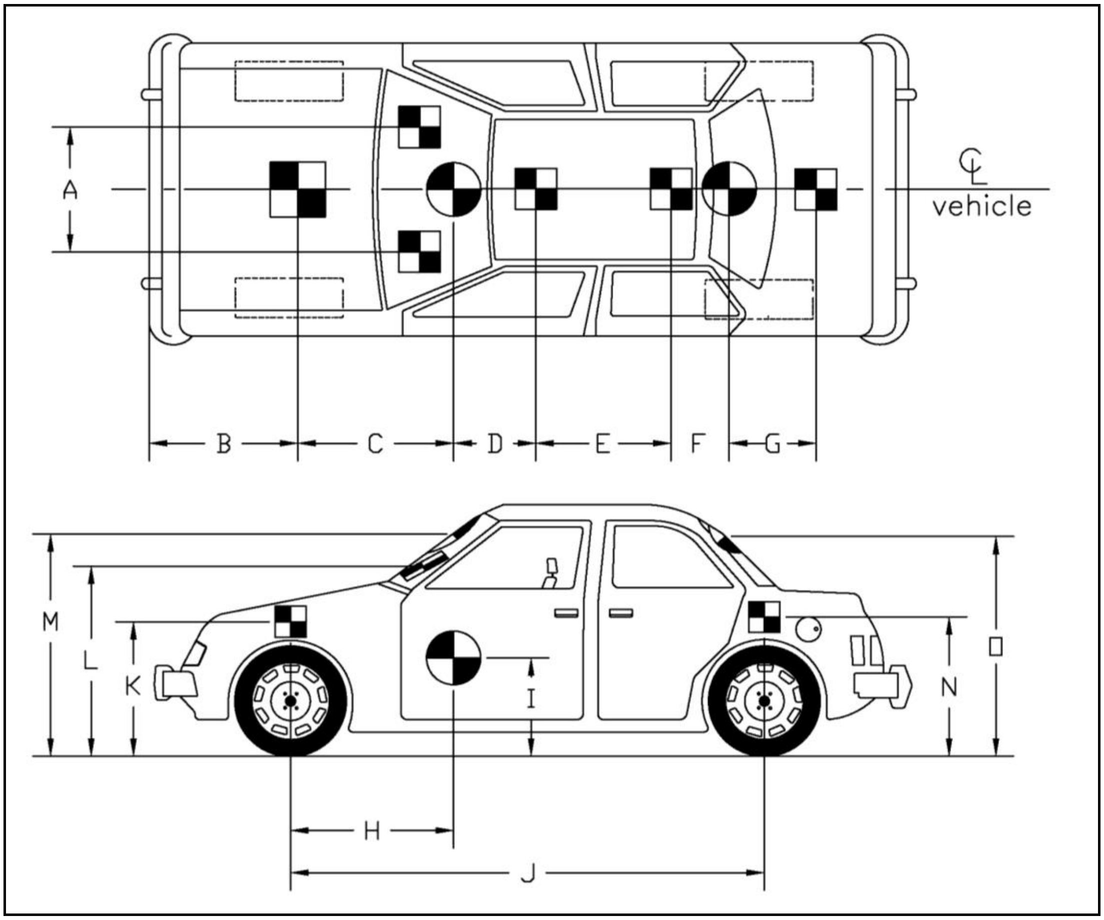
Weights lb. (kg)	Curb	Test Inertial	Gross Static
W-front	2946 (1336)	2862 (1298)	2963 (1344)
W-rear	2346 (1064)	2151 (976)	2212 (1003)
W-total	5292 (2400)	5013 (2274) 5000±110 (2270±50)	5175 (2347) 5165±110 (2343±50)

GVWR Ratings lb.		Dummy Data	
Front	3700	Type:	Hybrid II
Rear	3900	Mass:	162 lbs.
Total	6800	Seat Position:	Right

Note any damage prior to test: None

Figure 49. Vehicle Dimensions, Test No. CMGS-2

Date:	12/1/2017	Test Name:	CMGS-1	VIN:	KMHCN4ACOAU423259
Year:	2010	Make:	Hyundai	Model:	Accent

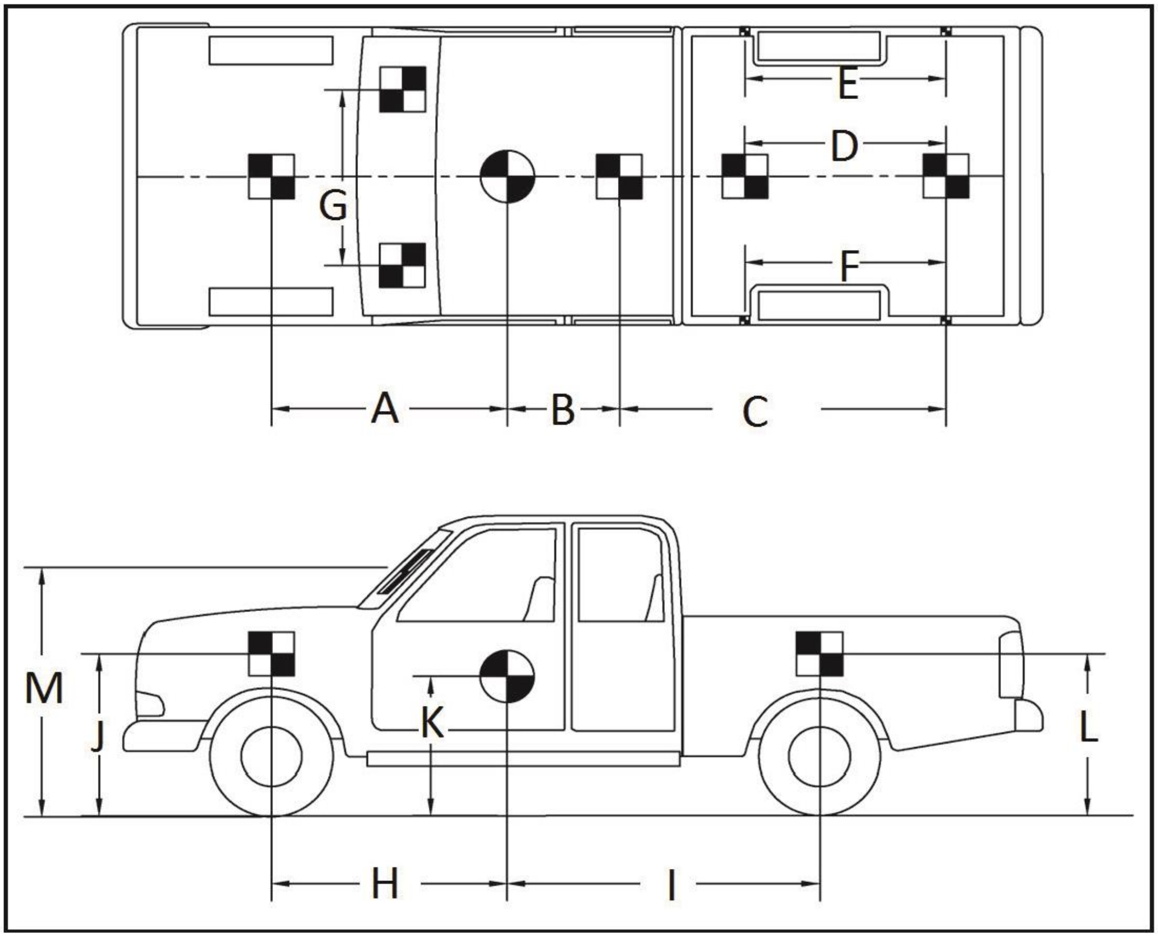


TARGET GEOMETRY - in. (mm)

A	29 1/8	(740)	F	14 1/8	(359)	K	29	(737)
B	23 1/4	(591)	G	21 5/8	(549)	L	49 1/8	(1248)
C	45 7/8	(1165)	H	36 3/8	(924)	M	52 3/4	(1340)
D	14 5/8	(371)	I	23	(584)	N	28 3/4	(730)
E	33 3/4	(857)	J	98 3/4	(2508)	O	52 1/2	(1334)

Figure 50. Target Geometry, Test No. CMGS-1

Date:	1/3/2018	**Test Name:**	CMGS-2	**VIN:**	1D7RB1CTXAS115553
Year:	2010	**Make:**	DODGE	**Model:**	RAM 1500 CREW CAB



TARGET GEOMETRY-- in. (mm)

A:	75 1/2	(1918)	E:	53 1/2	(1359)	J:	39 1/4	(997)
B:	31 5/8	(803)	F:	53 7/8	(1368)	K:	29 1/2	(749)
C:	69 1/4	(1759)	G:	36 1/2	(927)	L:	42 1/4	(1073)
D:	24 1/4	(616)	H:	60 1/4	(1530)	M:	64 1/2	(1638)
			I:	80 1/8	(2035)			

Figure 51. Target Geometry, Test No. CMGS-2

4.4 Simulated Occupant

For test nos. CMGS-1 and CMGS-2, a Hybrid II 50th-Percentile, Adult Male Dummy, equipped with clothing and footwear, was placed in the right-front seat of the test vehicles with the seat belt fastened. The simulated occupant had a final weight of 160 lb (72.6 kg) and 162 (73.5 kg) in test nos. CMGS-1 and CMGS-2, respectively. As recommended by MASH 2016, the simulated occupant was not included in calculating the c.g. location.

4.5 Data Acquisition Systems

4.5.1 Accelerometers

Two environmental, shock and vibration, sensor/recorder systems were used to measure the accelerations in the longitudinal, lateral, and vertical directions. Both accelerometer systems were mounted near the c.g. of the test vehicle. The electronic accelerometer data obtained in dynamic testing was filtered using the SAE Class 60 and the SAE Class 180 Butterworth filter conforming to the SAE J211/1 specifications [13].

The two accelerometer systems, the SLICE-1 and SLICE-2 units, were modular data acquisition systems manufactured by Diversified Technical Systems, Inc. (DTS) of Seal Beach, California. In test nos. CMGS-1 and CMGS-2, the SLICE-1 and the SLICE-2 unit was designated as the primary system, respectively. The acceleration sensors were mounted inside the bodies of custom-built SLICE 6DX event data recorders and recorded data at 10,000 Hz to the onboard microprocessor. Each SLICE 6DX was configured with 7 GB of non-volatile flash memory, a range of ±500 g's, a sample rate of 10,000 Hz, and a 1,650 Hz (CFC 1000) anti-aliasing filter. The "SLICEWare" computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

4.5.2 Rate Transducers

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

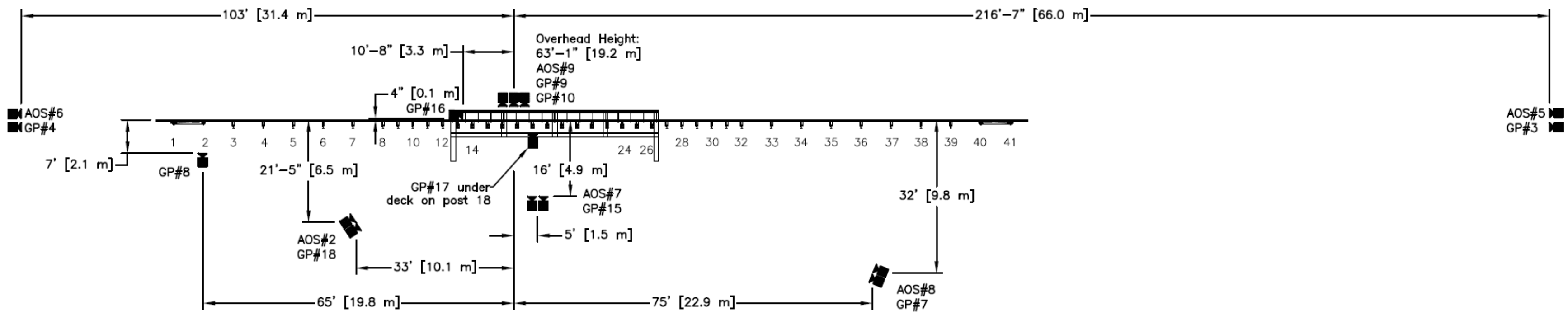
4.5.3 Retroreflective Optic Speed Trap

The retroreflective optic speed trap was used to determine the speed of the test vehicle before impact. Five retroreflective targets, spaced at approximately 18-in. (457-mm) intervals, were applied to the side of the vehicle. When the emitted beam of light was reflected by the targets and returned to the Emitter/Receiver, a signal was sent to the data acquisition computer, recording at 10,000 Hz, as well as the external LED box activating the LED flashes. The speed was then calculated using the spacing between the retroreflective targets and the time between the signals. LED lights and high-speed digital video analysis are only used as a backup in the event that vehicle speeds cannot be determined from the electronic data.

4.5.4 Digital Photography

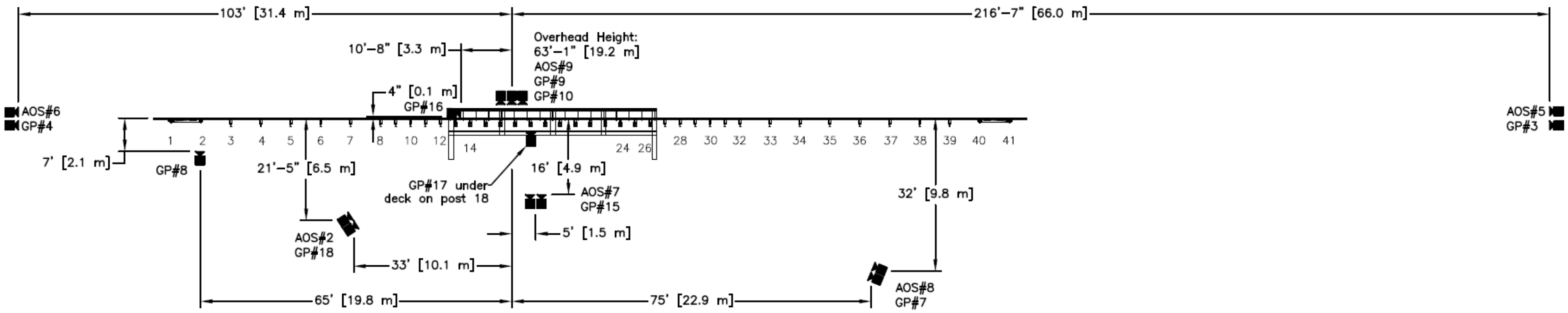
Six AOS high-speed digital video cameras and twelve GoPro digital video cameras were utilized to film test nos. CMGS-1 and CMGS-2. Camera details, camera operating speeds, lens information, and a schematic of the camera locations relative to the system are shown in Figures 52 and 53.

The high-speed digital videos were analyzed using TEMA Motion and Redlake MotionScope software programs. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed videos. A digital still camera was also used to document pre- and post-test conditions for all tests.



No.	Type	Operating Speed (frames/sec)	Lens	Lens Setting
AOS-2	AOS Vitcam CTM	500	Fujinon 35mm Fixed	–
AOS-5	AOS X-PRI Gigabit	500	Fujinon 135mm Fixed	–
AOS-6	AOS X-PRI Gigabit	500	Fujinon 50mm Fixed	–
AOS-7	AOS X-PRI Gigabit	500	Kowa 16mm Fixed	–
AOS-8	AOS S-VIT 1531	500	Sigma 28-70	50
AOS-9	AOS TRI-VIT 2236	1000	Kowa 12mm Fixed	–
GP-3	GoPro Hero 3+	120		
GP-4	GoPro Hero 3+	120		
GP-5	GoPro Hero 3+	120		
GP-6	GoPro Hero 3+	120		
GP-7	GoPro Hero 4	240		
GP-8	GoPro Hero 4	120		
GP-9	GoPro Hero 4	120		
GP-10	GoPro Hero 4	240		
GP-15	GoPro Hero 4	240		
GP-16	GoPro Hero 4	120		
GP-17	GoPro Hero 4	120		
GP-18	GoPro Hero 4	240		

Figure 52. Camera Locations, Speeds, and Lens Settings, Test No. CMGS-1



No.	Type	Operating Speed (frames/sec)	Lens	Lens Setting
AOS-2	AOS Vitcam CTM	500	Fujinon 35mm Fixed	–
AOS-5	AOS X-PRI Gigabit	500	Fujinon 135mm Fixed	–
AOS-6	AOS X-PRI Gigabit	500	Fujinon 50mm Fixed	–
AOS-7	AOS X-PRI Gigabit	500	Kowa 16mm Fixed	–
AOS-8	AOS S-VIT 1531	500	Sigma 28-70	50
AOS-9	AOS TRI-VIT 2236	1000	Kowa 12mm Fixed	–
GP-3	GoPro Hero 3+	120		
GP-4	GoPro Hero 3+	120		
GP-5	GoPro Hero 3+	120		
GP-6	GoPro Hero 3+	120		
GP-7	GoPro Hero 4	240		
GP-8	GoPro Hero 4	120		
GP-9	GoPro Hero 4	120		
GP-10	GoPro Hero 4	240		
GP-15	GoPro Hero 4	240		
GP-16	GoPro Hero 4	120		
GP-17	GoPro Hero 4	120		
GP-18	GoPro Hero 4	240		

Figure 53. Camera Locations, Speeds, and Lens Settings, Test No. CMGS-2

5 FULL-SCALE CRASH TEST NO. CMGS-1

5.1 Static Soil Test

Before full-scale crash test no. CMGS-1 was conducted, the strength of the foundation soil was evaluated with a static test, as described in MASH 2016. The static test results, as shown in Appendix C, demonstrated a soil resistance above the baseline test limits. Thus, the soil provided adequate strength, and full-scale crash testing could be conducted on the barrier system.

5.2 Weather Conditions

Test no. CMGS-1 was conducted on December 1, 2017 at approximately 2:30 p.m. The weather conditions as per the National Oceanic and Atmospheric Administration (station 14939/LNK) were reported and are shown in Table 3.

Table 3. Weather Conditions, Test No. CMGS-1

Temperature	59° F
Humidity	29%
Wind Speed	13 mph
Wind Direction	210° from True North
Sky Conditions	Sunny
Visibility	10 Statute Miles
Pavement Surface	Dry
Previous 3-Day Precipitation	0.00 in.
Previous 7-Day Precipitation	0.00 in.

5.3 Test Description

Initial vehicle impact was to occur at 84 in. (2,134 mm) upstream from post no. 19, as shown in Figure 54, which was selected using Table 2-8 of MASH 2016. The 2,428-lb (1,101-kg) Hyundai Accent impacted the test installation at a speed of 61.3 mph (98.7 km/h) and at an angle of 25.1 degrees, resulting in an impact severity of 54.8 kip-ft (74.3 kJ). The actual point of impact was 8 in. (203 mm) upstream from the target impact. As the vehicle was redirected, a partial rail tear occurred through the lower hump of the W-beam rail at the downstream end of the rail splice at post no. 19. This tear did not rupture the rail nor compromise the integrity of the W-beam rail element. At 0.259 sec after impact, the vehicle became parallel to the system with a speed of 26.5 mph (42.6 km/h). At 0.464 sec, the vehicle exited the system at a speed of 24.7 mph (39.8 km/h) and at angle of 17.0 degrees. The vehicle came to rest approximately 173 ft – 6 in. (52.9 m) downstream and 43 ft – 11 in. laterally in front of the system from the point of impact. The vehicle was successfully contained and redirected.

A detailed sequential description of the impact events is contained in Table 4. Sequential photographs are shown in Figures 55 through 57. Documentary photographs of the crash test are shown in Figure 58. The vehicle trajectory and final position are shown in Figure 59.

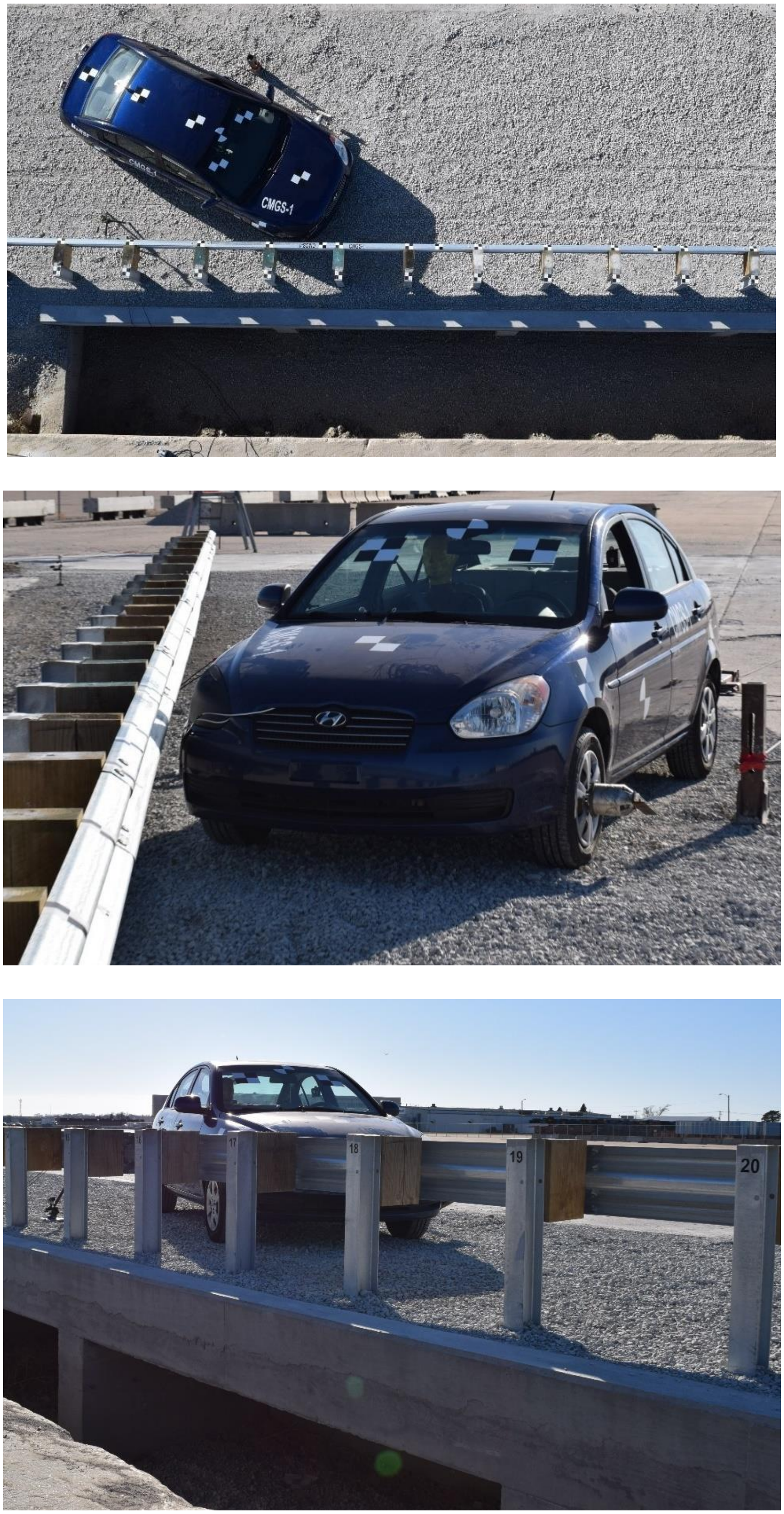


Figure 54. Impact Location, Test No. CMGS-1

Table 4. Sequential Description of Impact Events, Test No. CMGS-1

TIME (sec)	EVENT
0.000	Vehicle’s right-front bumper contacted rail between post nos. 16 and 17.
0.008	Vehicle’s right fender contacted rail and right headlight deformed.
0.012	Vehicle’s hood deformed.
0.016	Post nos. 16 and 17 deflected backward.
0.018	Post no. 18 deflected backward.
0.022	Vehicle’s right headlight shattered and vehicle’s right fender and grille deformed.
0.024	Post no. 18 deflected downstream.
0.026	Vehicle’s right fender shattered.
0.028	Vehicle’s front bumper deformed.
0.034	Vehicle’s right-front door deformed.
0.041	Vehicle yawed away from barrier.
0.042	Post no. 18 rotated counterclockwise.
0.044	Post no. 19 deflected downstream.
0.050	Post no. 17 rotated backward. Vehicle rolled away from barrier. Right-side airbags deployed.
0.054	Vehicle pitched downward. Blockout no. 18 fractured.
0.056	Vehicle right-front wheel snagged on post no. 18.
0.058	Rail disengaged from bolt at post no. 18.
0.060	Blockout disengaged from post no. 18.
0.062	Post no. 19 deflected backward. Right-front airbag deployed.
0.064	Vehicle’s right-rear tire became airborne.
0.070	Vehicle’s right-front tire contacted post no. 18.
0.072	Post no. 18 bent downstream.
0.076	Post no. 19 rotated downstream. Post no. 20 deflected backward.
0.080	Post no. 19 twisted counterclockwise.
0.098	Rail disengaged from bolt at post no. 19.
0.104	Post no. 21 deflected backward.
0.112	Post no. 20 deflected downstream.
0.116	Vehicle’s right-front wheel snagged on post no. 18.
0.120	Vehicle’s front bumper contacted ground.
0.144	Rail disengaged from bolt at post no. 20.
0.196	Blockout no. 21 fractured.
0.259	Vehicle was parallel to system at a speed of 26.5 mph (42.6 km/h).

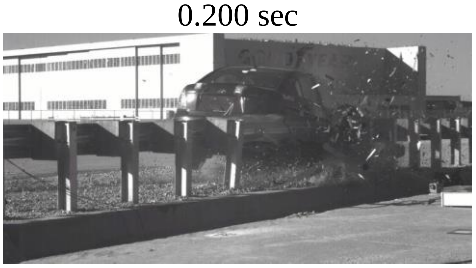
Table 5. Sequential Description of Impact Events, Test No. CMGS-1

TIME (sec)	EVENT
0.262	Vehicle's left-rear tire became airborne.
0.280	Vehicle pitched upward.
0.316	Vehicle's right-rear tire regained contact with ground.
0.333	Vehicle's right quarter panel contacted rail.
0.338	Vehicle's right-rear door deformed.
0.370	Vehicle's rear bumper contacted rail.
0.382	Vehicle's left-front tire became airborne.
0.428	Vehicle rolled away from barrier.
0.464	Vehicle exited system at a speed of 24.7 mph (39.8 km/h) and an angle of 17.0 degrees.
0.502	Vehicle's left-front tire regained contact with ground.
0.686	Vehicle's left-rear tire regained contact with ground.
0.794	Disengaged right-front tire contacted culvert headwall.
0.915	Vehicle yawed toward barrier.

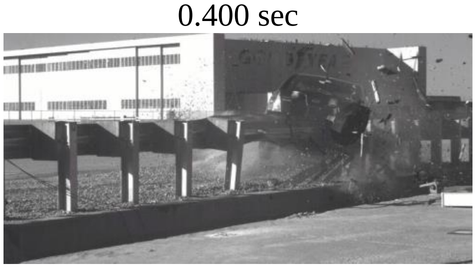

0.000 sec


0.100 sec


0.200 sec


0.300 sec


0.400 sec

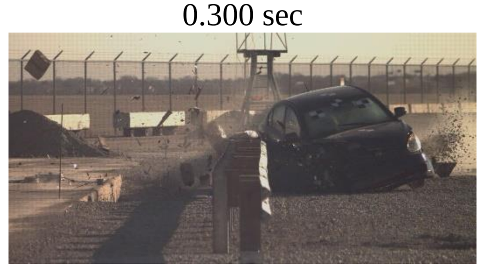

0.500 sec


0.000 sec


0.100 sec


0.200 sec


0.300 sec


0.400 sec


0.500 sec

Figure 55. Sequential Photographs, Test No. CMGS-1


0.000 sec


0.000 sec


0.100 sec

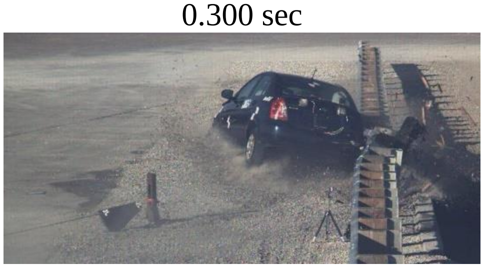

0.100 sec


0.200 sec

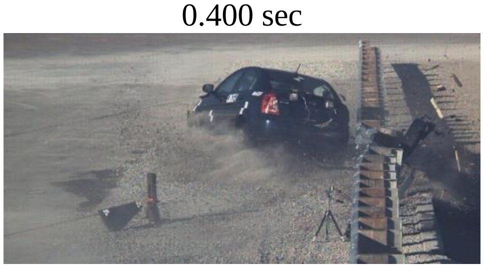

0.200 sec


0.300 sec


0.300 sec


0.400 sec


0.400 sec


0.500 sec


0.500 sec

Figure 56. Sequential Photographs, Test No. CMGS-1

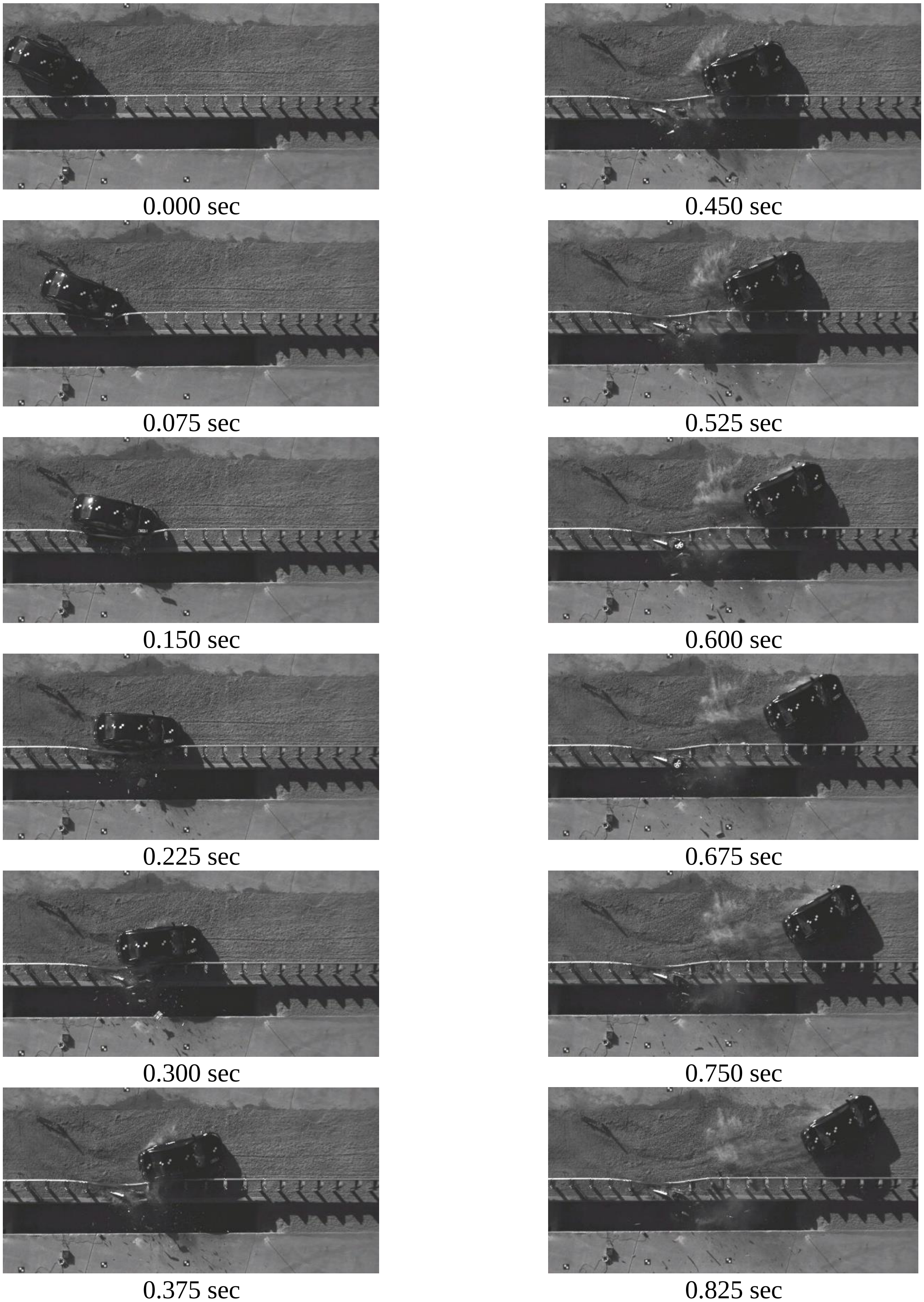


Figure 57. Additional Sequential Photographs, Test No. CMGS-1

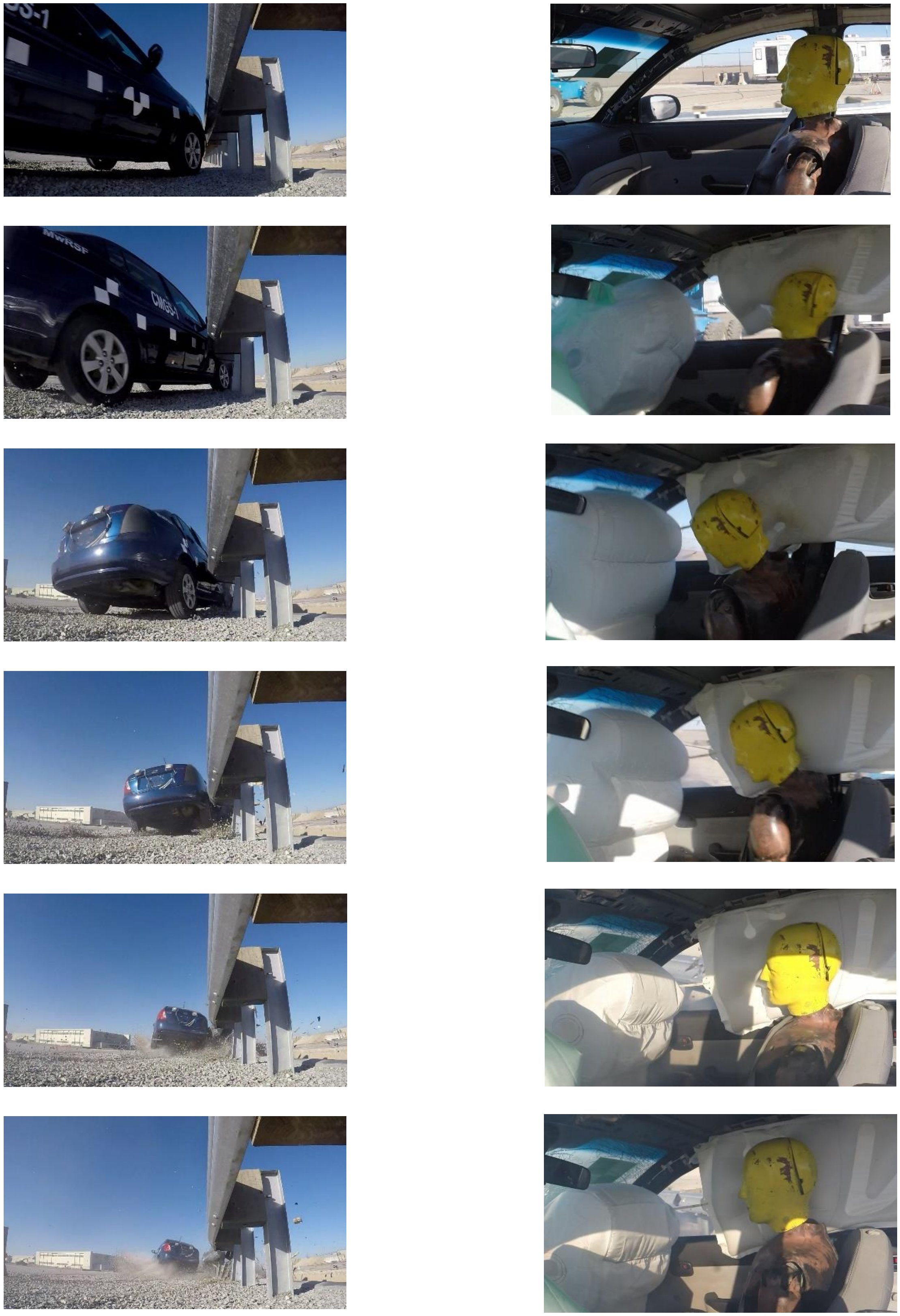


Figure 58. Documentary Photographs, Test No. CMGS-1

Figure 59. Vehicle Trajectory and Final Position, Test No. CMGS-1

5.4 Barrier Damage

Damage to the barrier was moderate, as shown in Figures 60 through 66. Barrier damage consisted mostly of deformed W-beam, contact marks on the guardrail sections, and deformed posts. The length of vehicle contact along the barrier was approximately 16 ft which spanned from 12⅝ in. (321 mm) downstream from post no. 16 to 15½ in. (394 mm) downstream from post no. 21.

The guardrail damage consisted moderate deformation and flattening of the impacted section of the W-beam between post nos. 16 and 22. The W-beam was pulled out from the bolts at post nos. 18 through 21. Contact marks were found on the guardrail between post nos. 16 through 21. A partial rail tear was observed through the lower hump of the W-beam rail at the downstream end of the rail splice at post no. 19, as shown in Figures 60 and 61. No significant guardrail damage occurred upstream from post no. 16 nor downstream from post no. 22.

Post no. 17 slightly deflected backward. Post nos. 18 and 19 were bent longitudinally toward the ground in the downstream direction. Post no. 20 was bent slightly longitudinally downstream. Contact marks were found on the front face of post nos. 18 and 19. No significant post damage occurred to post nos. 1 through 16 nor 21 through 41. The upstream and downstream anchorage systems remained unmoved and te posts in both nchorage systems were not damaged. The wooden blockout at post nos. 18, 19, and 21 disengaged from the system. The blockout at post no. 20 rotated but did not disengage. The blockouts at post nos. 3 through 17 and 22 through 39 were undamaged.

Following the test, the soil on top of the culvert headwall was removed for inspection of the damage to the posts and base plates as well as to review any potential damage to the culvert. Deformation of the post base plates was observed on post nos. 17 through 21. Minor cracking was observed on the weld at the front flange of the base plate of post no. 17. The upstream side of the front flange of post no. 18 was torn up to the web near the base plate weld. All anchorage bolts and epoxied threaded rods were intact and remained secure, although some minor deformation of the bolts and rods was observed. No damage was observed to the concrete culvert slab or the headwall.

The maximum lateral permanent set of the barrier system was 11⅞ in. (302 mm), which occurred at the back of post no. 18, as measured in the field. The maximum lateral dynamic deflection was 12 in. (305 mm) at post no. 18, as determined from high-speed digital video analysis. The working width of the system was 33.1 in. (842 mm) at post no. 18, also determined from high-speed digital video analysis. A schematic of the permanent set, dynamic deflection, and working width is shown in Figure 67.

Figure 60. System Damage, Test No. CMGS-1

Figure 61. Damage to Post Nos. 15 through 22, Test No. CMGS-1

Figure 62. Damage to Post and Base Plate Nos. 17 through 21 (After Removal of Soil Fill Post and Base), Test No. CMGS-1

Figure 63. Damage to Post and Base Plate Nos. 18 and 19, Test No. CMGS-1

Figure 64. Damage to Post and Base Plate No. 21, Test No. CMGS-1

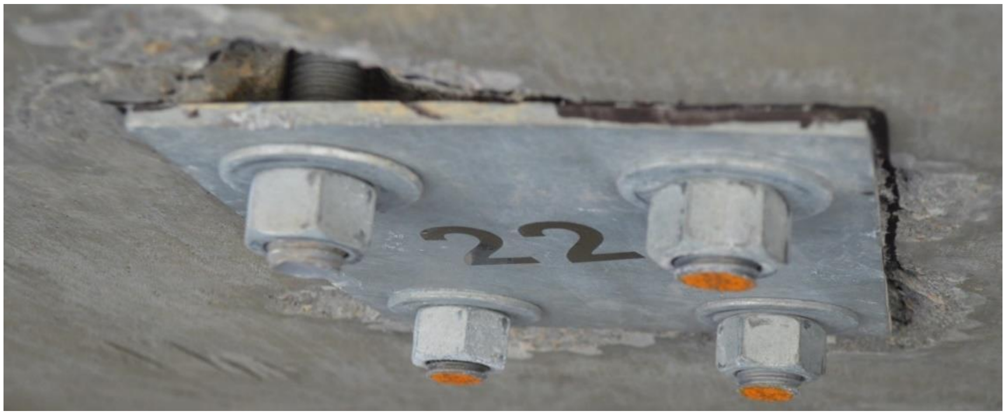


Figure 65. Washer Plate Nos. 18 through 22 After Test, Test No. CMGS-1

(a)

(b)

Figure 66. (a) Upstream Anchorage System After Test, and (b) Downstream Anchorage System After Test, Test No. CMGS-1

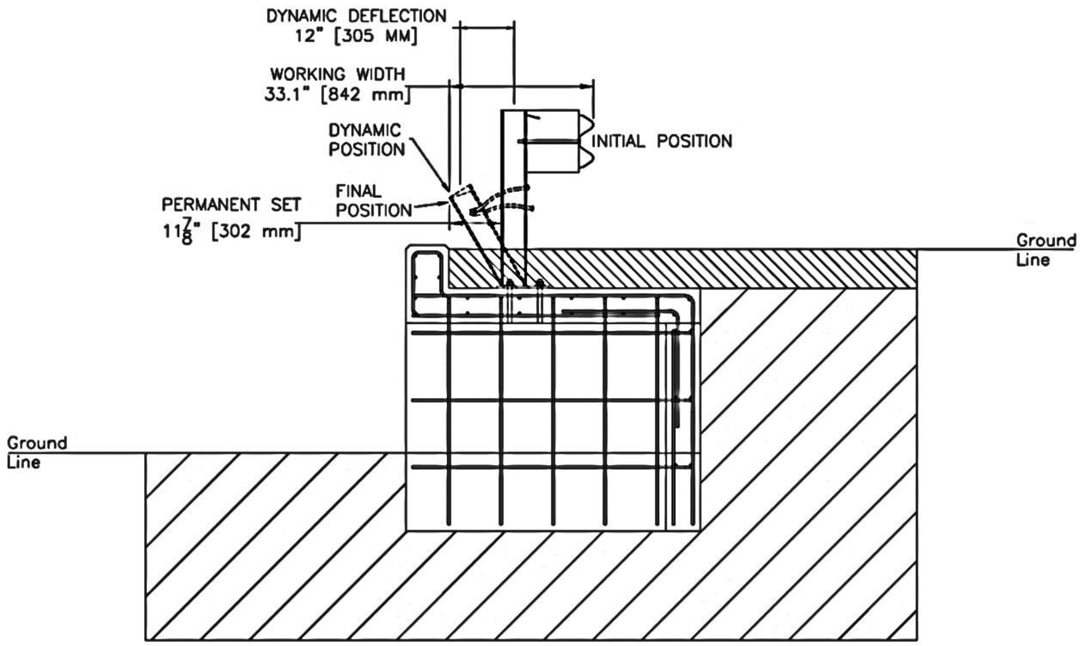


Figure 67. Permanent Set Deflection, Dynamic Deflection, and Working Width, Test No. CMGS-1

5.5 Vehicle Damage

The damage to the vehicle was moderate, as shown in Figures 68 through 72. The maximum occupant compartment deformations are listed in Table 6 along with the intrusion limits established in MASH 2016 for various areas of the occupant compartment. MASH 2016 defines intrusion or deformation as the occupant compartment being deformed and reduced in size with no observed penetration. The maximum deformation of the windshield was measured to be 3⅜ in. (86 mm) which was not observed on the test day, as shown in Figure 70. Prior to the vehicle deformation measurements, the snow and ice on the windshield caused an additional caving in deformation. Therefore, this deformation exceeding the MASH deformation criteria was not due to the impact event and is not critical to the test evaluation. All other occupant compartment deformations were within MASH limits. Complete occupant compartment and vehicle deformations as well as the corresponding locations are provided in Appendix D.

Majority of the vehicle damage was concentrated on the right-front corner, where primary impact occurred. The right-front wheel contacted post nos. 18 and 19 and was disengaged, and the left-front tire was deflated. The right corner of the hood buckled. The side and front airbags on both the passenger and driver side deployed, which caused the windshield on the passenger side to shatter but remain intact. The right-rear quarter panel was crushed inward.

The roof, the left side, and the rear of the vehicle remained undamaged. The left-side and rear window glass also remained undamaged. The front right strut broke at the weld point on the top of the gas cylinder, and only the top portion of the shock absorber was still intact. The right-side wheel hub attachment point detached from the steering rack, and the tie rod was bent. The right-front brake assembly disengaged from the car. There was no damage to the vehicle's frame, rear suspension, or rear shocks and springs.

Figure 68. Vehicle Damage, Test No. CMGS-1

Figure 69. Additional Vehicle Damage, Test No. CMGS-1

(a) (b)

Figure 70. Vehicle Windshield Damage, (a) on Test Site on Test Day, (b) in Vehicle Shop Prior to Measurement, Test No. CMGS-1

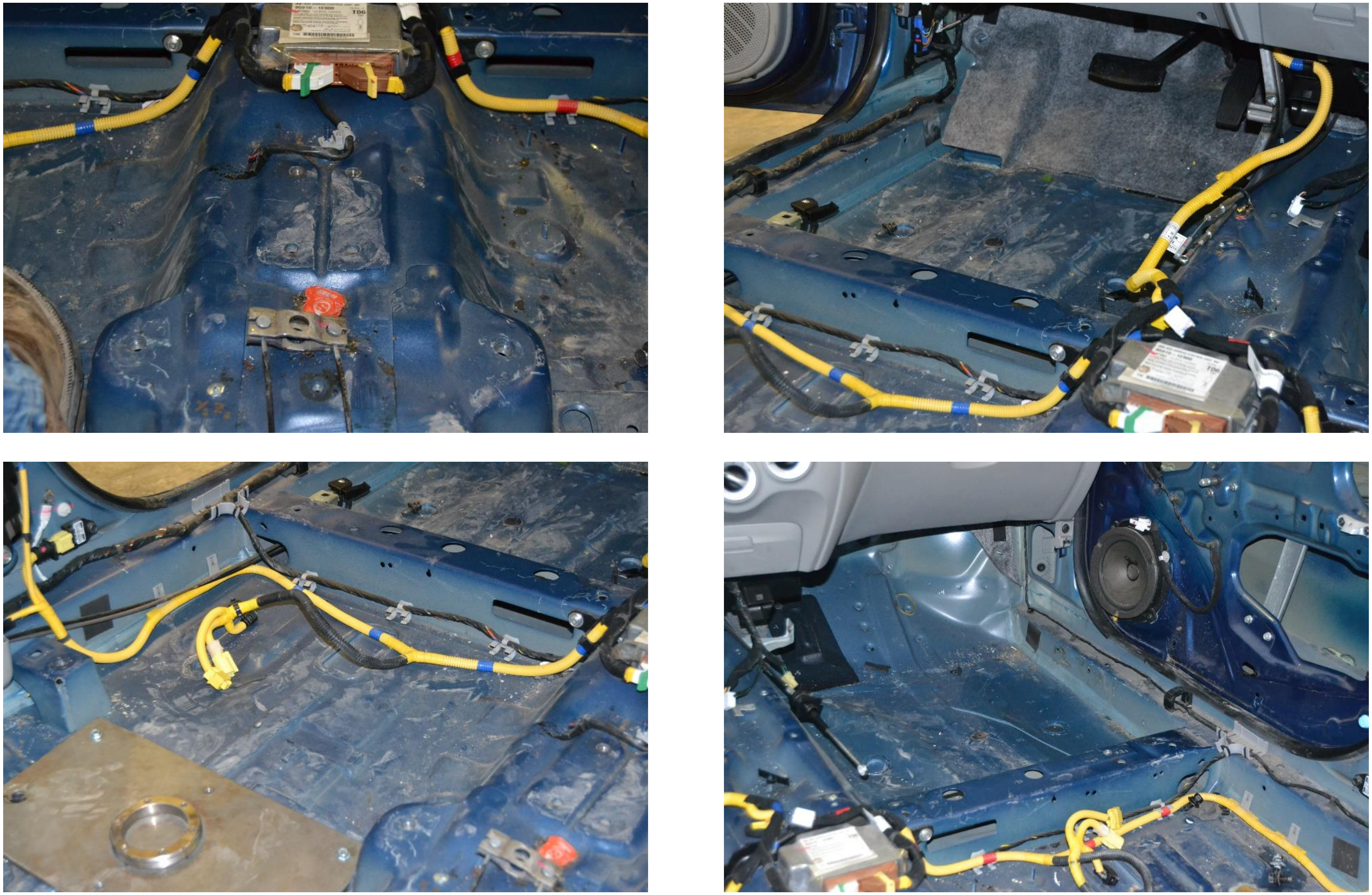


Figure 71. Occupant Compartment Damage, Test No. CMGS-1

Figure 72. Vehicle Undercarriage Damage, Test No. CMGS-1

Table 6. Maximum Occupant Compartment Deformations by Location, Test No. CMGS-1

LOCATION	MAXIMUM INTRUSION in. (mm)	MASH 2016 ALLOWABLE INTRUSION in. (mm)
Wheel Well & Toe Pan	1⅞ (48)	≤ 9 (229)
Floor Pan & Transmission Tunnel	¾ (19)	≤ 12 (305)
A-Pillar	1⅛ (29)	≤ 5 (127)
A-Pillar (Lateral)	⅞ (22)	≤ 3 (76)
B-Pillar	1⅜ (35)	≤ 5 (127)
B-Pillar (Lateral)	¾ (19)	≤ 3 (76)
Side Front Panel (in Front of A-Pillar)	¼ (6)	≤ 12 (305)
Side Door (Above Seat)	¾ (19)	≤ 9 (229)
Side Door (Below Seat)	1 (25)	≤ 12 (305)
Roof	¼ (6)	≤ 4 (102)
Windshield	3⅜ (86)[2]	≤ 3 (76)
Side Window	No shattering of side windows occurred	No shattering resulting from contact with structural member of test article
Dash	⅞ (22)	N/A[1]

[1] – N/A - No MASH 2016 criteria exist for this location
[2] – Deformation was not present on test day but occurred after snow and ice on windshield caused deformation prior to measurement

5.6 Occupant Risk

The calculated occupant impact velocities (OIVs) and maximum 0.010-sec average occupant ridedown accelerations (ORAs) in both the longitudinal and lateral directions are shown in Table 7. Note that the OIVs and ORAs were within suggested limits, as provided in MASH 2016. The calculated THIV, PHD, and ASI values are also shown in Table 7. The results of the occupant risk analysis, as determined from the accelerometer data, are summarized in Table 7. The recorded data from the accelerometers and the rate transducers are shown graphically in Appendix E.

Table 7. Summary of OIV, ORA, THIV, PHD, and ASI Values, Test No. CMGS-1

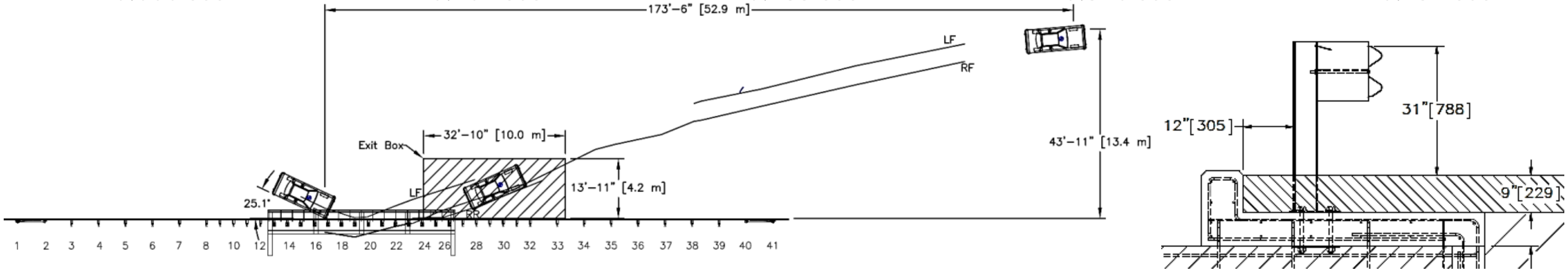
Evaluation Criteria		Transducer		MASH 2016 Limits
		SLICE-1 (Primary)	SLICE-2	
OIV ft/s (m/s)	Longitudinal	-27.34 (-8.33)	-27.57 (-8.40)	± 40 (12.2)
	Lateral	-20.01 (-6.10)	-19.49 (-5.94)	± 40 (12.2)
ORA g's	Longitudinal	-16.96	-15.45	± 20.49
	Lateral	-11.51	-11.18	± 20.49
MAX ANGULAR DISPLACEMENT deg.	Roll	15.2	-11.3	± 75
	Pitch	-6.9	-4.7	± 75
	Yaw	-53.4	-53.7	not required
THIV ft/s (m/s)		33.47 (10.20)	31.49 (9.60)	not required
PHD g's		18.32	17.61	not required
ASI		1.37	1.34	not required

5.7 Discussion

The analysis of the test results for test no. CMGS-1 showed that the strong post MGS attached to the culvert's top slab adequately contained and redirected the 1100C vehicle with controlled displacement of the barrier. A summary of the test results and sequential photographs are shown in Figure 73. Detached elements, fragments, or other debris from the test article did not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or work-zone personnel. Deformations of, or intrusions into, the occupant compartment that could have caused serious injury did not occur. Note, the maximum windshield deformation of 3⅜ in. (86 mm) was not from the impact event, and therefore, it was not critical to the test evaluation.

The test vehicle did not penetrate nor ride over the barrier and remained upright during and after the collision. Vehicle roll, pitch, and yaw angular displacements, as shown in Appendix E, were deemed acceptable because they did not adversely influence occupant risk safety criteria nor cause rollover. After impact, the vehicle exited the barrier at an angle of 17 degrees, and its trajectory did not violate the bounds of the exit box. Therefore, test no. CMGS-1 conducted on the culvert mounted, strong post MGS was determined to be acceptable according to the MASH 2016 safety performance criteria for test designation no. 3-10.

0.000 sec 0.104 sec 0.259 sec 0.370 sec 0.794 sec



- Test Agency .... MwRSF
- Test Number CMGS-1
- Date 12/01/2017
- MASH Test Designation No. 3-10
- Test Article .... Culvert-Mounted, Strong Post MGS
- Total Length .... 182.3 ft (55.6 m)
- Distance between Posts and Headwall .... 12 in. (305 mm)
- Key Component – MGS Rail
  - Thickness .... 12 gauge (2.7 mm)
  - Top Mounting Height .... 31 in. (787 mm)
- Key Component – Steel Posts
  - Post Type .... W6x9 by 40½ in. (1,029 mm)
  - Post Spacing .... 37½ in. (952 mm) on center
- Soil Type .... Compacted, coarse, crushed limestone
- Vehicle Make /Model .... 2010 Hyundai Accent
  - Curb .... 2,471 lb (1,121 kg)
  - Test Inertial .... 2,428 lb (1,101 kg)
  - Gross Static .... 2,588 lb (1,174 kg)
- Impact Conditions
  - Speed .... 61.3 mph (98.7 km/h)
  - Angle .... 25.1 deg
  - Impact Location .... 92 in. (2,337 mm) upstream from post no. 19
- Impact Severity .... 58.5 kip-ft (79.3 kJ) > 51 kip-ft (69.1 kJ) Limit from MASH
- Exit Conditions
  - Speed .... 24.7 mph (39.8 km/h)
  - Angle .... 17 deg
- Exit Box Criterion .... Pass
- Vehicle Stability .... Satisfactory
- Vehicle Stopping Distance .... 173 ft - 6 in. (52.9 m) Downstream within the system
- Vehicle Damage .... Moderate
  - VDS [14] 1-RFQ-6
  - CDC [15] 1-RZAK-5
  - Maximum Interior Deformation .... 3⅜ in. (86 mm)
- Test Article Damage .... Moderate
- Maximum Test Article Deflections
  - Dynamic .... 12.0 in. (305 mm)
  - Working Width .... 33.1 in. (842 mm)
  - Permanent Set .... 11⅞ in. (302 mm)
- Transducer Data

Evaluation Criteria		Transducer		MASH 2016 Limit
		SLICE-1 (primary)	SLICE-2	
OIV ft/s (m/s)	Longitudinal	-27.34 (-8.33)	-27.57 (-8.40)	± 40 (12.2)
	Lateral	-20.01 (-6.10)	-19.49 (-5.94)	± 40 (12.2)
ORA g's	Longitudinal	-16.96	-15.45	± 20.49
	Lateral	-11.51	-11.18	± 20.49
MAX ANGULAR DISPLACEMENT deg.	Roll	15.2	-11.4	±75
	Pitch	-6.9	-4.7	±75
	Yaw	-53.4	-53.7	not required
THIV – ft/s (m/s)		33.47 (10.20)	31.49 (9.60)	not required
PHD – g's		18.32	17.60	not required
ASI		1.37	1.34	not required

Figure 73. Summary of Test Results and Sequential Photographs, Test No. CMGS-1

6 FULL-SCALE CRASH TEST NO. CMGS-2

6.1 Static Soil Test

Before full-scale crash test no. CMGS-2 was conducted, the strength of the foundation soil was evaluated with a static test, as described in MASH 2016. The static test results, as shown in Appendix C, demonstrated a soil resistance above the baseline test limits. Thus, the soil provided adequate strength, and full-scale crash testing could be conducted on the barrier system.

6.2 Weather Conditions

Test no. CMGS-2 was conducted on February 14, 2018 at approximately 12:45 p.m. The weather conditions as per the National Oceanic and Atmospheric Administration (station 14939/LNK) were reported and are shown in Table 8.

Table 8. Weather Conditions, Test No. CMGS-2

Temperature	42° F
Humidity	79%
Wind Speed	9 mph
Wind Direction	210° from True North
Sky Conditions	Sunny
Visibility	7 Statute Miles
Pavement Surface	Dry
Previous 3-Day Precipitation	0.00 in.
Previous 7-Day Precipitation	0.15 in.

6.3 Test Description

Initial vehicle impact was to occur 132 in. (3,353 mm) upstream from post no. 19, as shown in Figure 74, which was selected using Table 2-8 of MASH 2016. The 5,013-lb (2,274-kg) crew cab pickup truck impacted the test installation at a speed of 62.8 mph (101.1 km/h) and at an angle of 25.7 degrees, resulting in an impact severity of 124.7 kip-ft (169.1 kJ). The actual point of impact was 129.1 in. (3,279 mm) upstream from post no. 19. During the impact event, the right-front wheel snagged on post nos. 17 through 19 and was disengaged, but the vehicle remained stable and was safely redirected. At 0.270 sec after impact, the vehicle became parallel to the system with a speed of 36.9 mph (59.5 km/h). At 0.520 sec, the vehicle exited the system at a speed of 33.1 mph (53.2 km/h) and at an angle of 17.4 degrees. The vehicle came to rest approximately 173 ft – 6 in. (52.9 m) downstream from the point of impact.

A detailed sequential description of the impact events is shown in Table 9. Sequential photographs are shown in Figures 75 and 76. Documentary photographs of the crash test are shown in Figure 78. The vehicle trajectory and final position are shown in Figure 79.

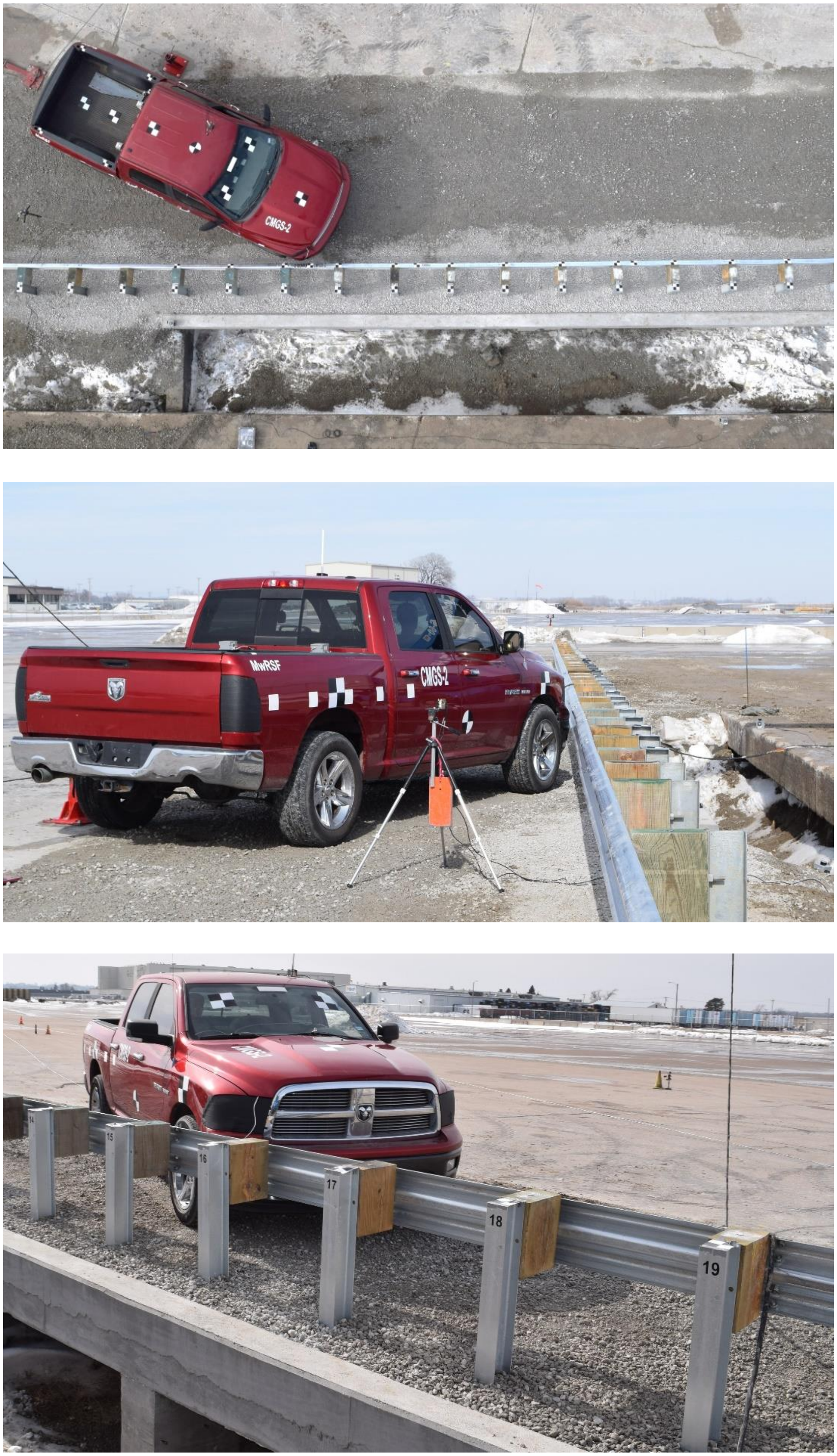


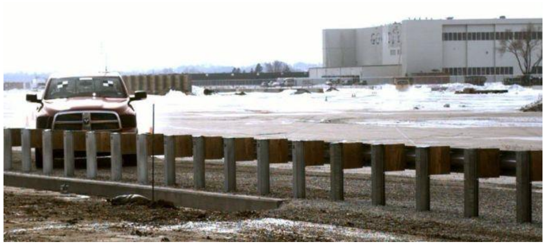
Figure 74. Impact Location, Test No. CMGS-2

Table 9. Sequential Description of Impact Events, Test No. CMGS-2

TIME (sec)	EVENT
0.000	Vehicle’s front bumper contacted rail between post nos. 15 and 16.
0.002	Vehicle’s front bumper deformed.
0.006	Vehicle's right fender contacted rail and deformed.
0.012	Vehicle’s right-front tire contacted rail.
0.014	Post no. 16 deflected backward.
0.016	Post no. 15 deflected backward.
0.018	Post no. 17 deflected backward. Soil heave formed on non-traffic flange of post no. 16. Vehicle's right headlight shattered.
0.020	Vehicle’s grille deformed.
0.022	Vehicle’s right-front wheel rim deformed.
0.032	Post no. 14 deflected backward.
0.040	Post no. 17 deflected downstream.
0.046	Post no. 18 deflected backward.
0.048	Post no. 17 rotated counterclockwise.
0.060	Vehicle yawed away from system.
0.070	Post no. 18 twisted counterclockwise. Vehicle’s right-front tire contacted post no. 17.
0.076	Post no. 17 bent downstream.
0.078	Rail disengaged from bolt at post no. 17.
0.086	Post nos. 19 and 20 deflected backward. Rail disengaged from bolt at post no. 18. Blockout no. 17 fractured.
0.090	Blockout disengaged from post no. 17.
0.094	Post no. 19 rotated counterclockwise.
0.104	Post no. 17 contacted culvert headwall.
0.108	Post no. 19 deflected downstream.
0.110	Vehicle pitched downward.
0.114	Vehicle rolled toward system.
0.120	Post no. 17 pulled out of soil.
0.124	Rail disengaged from bolt at post no. 19.
0.128	Post no. 21 deflected backward. Post no. 20 twisted counterclockwise.
0.133	Vehicle’s right-front tire contacted post no. 18.
0.134	Blockout disengaged from post no. 18.
0.136	Vehicle’s right-front wheel became disengaged.
0.140	Post no. 20 deflected downstream.
0.144	Post no. 22 deflected backward. Soil heave formed on non-traffic flange of post no. 21.

Table 10. Sequential Description of Impact Events, Test No. CMGS-2

TIME (sec)	EVENT
0.148	Blockout disengaged from post no. 19.
0.152	Vehicle’s right-front tire contacted blockout no. 19.
0.158	Post no. 20 rotated downstream.
0.160	Post no. 18 contacted culvert headwall.
0.168	Blockout no. 19 fractured. Rail disengaged from bolt at post no. 20.
0.172	Post no. 18 pulled out of soil.
0.174	Post no. 19 bent downstream.
0.176	Vehicle’s right-rear tire contacted rail.
0.184	Post no. 21 deflected downstream.
0.194	Vehicle’s rear bumper contacted rail and deformed.
0.202	Blockout disengaged from post no. 20.
0.204	Blockout no. 20 fractured. Post no. 21 rotated counterclockwise.
0.210	Vehicle’s right-front tire contacted blockout no. 20.
0.214	Vehicle’s right-front tire contacted post no. 20. Vehicle’s left-rear tire became airborne.
0.216	Post no. 20 bent downstream.
0.238	Rail disengaged from bolt at post no. 21.
0.244	Vehicle rolled away from system.
0.270	Vehicle was parallel to system at a speed of 36.9 mph (59.5 km/h).
0.384	Vehicle’s left-front tire became airborne.
0.456	Vehicle’s left-front tire regained contact with ground.
0.520	Vehicle’s right-rear tire became airborne. Vehicle exited system at a speed of 33.1 mph (53.2 km/h) and at an angle of 17.4 degrees.


0.000 sec

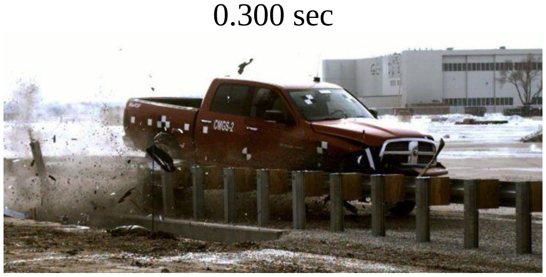

0.000 sec

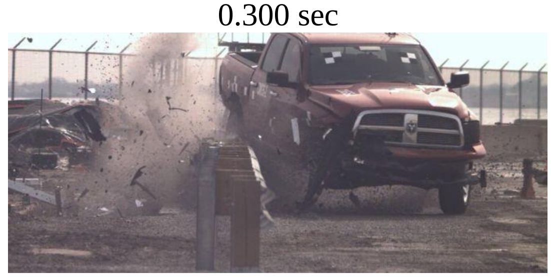

0.150 sec


0.150 sec


0.300 sec


0.300 sec


0.450 sec


0.450 sec


0.600 sec


0.600 sec


0.750 sec


0.750 sec

Figure 75. Sequential Photographs, Test No. CMGS-2


0.000 sec

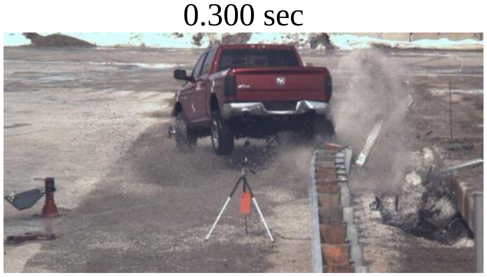

0.000 sec

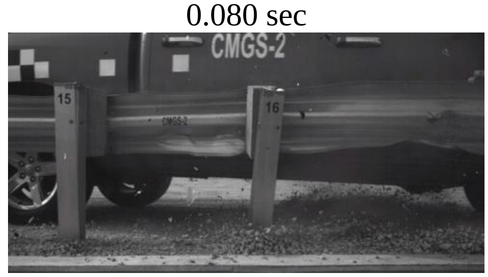

0.150 sec

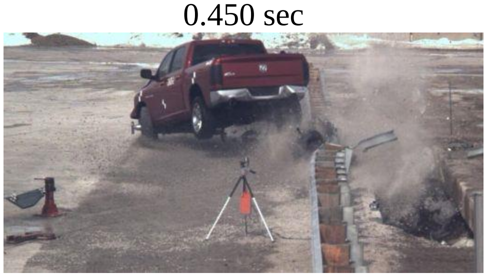

0.040 sec

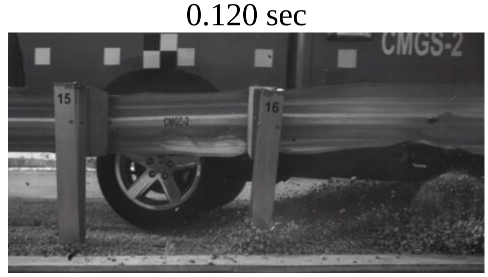

0.300 sec

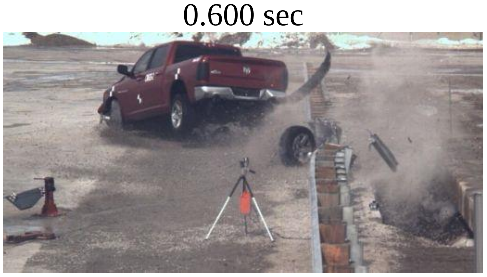

0.080 sec


0.450 sec


0.120 sec


0.600 sec


0.160 sec


0.750 sec

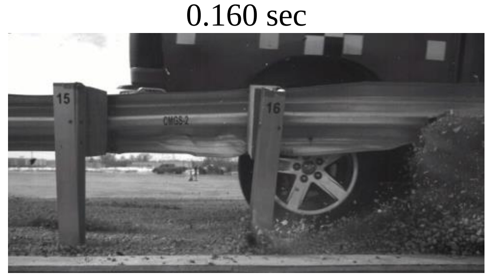
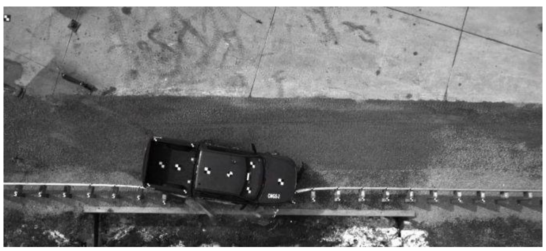
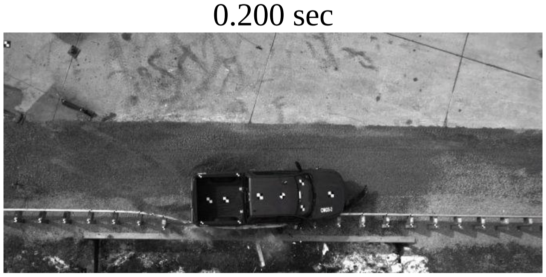

0.200 sec

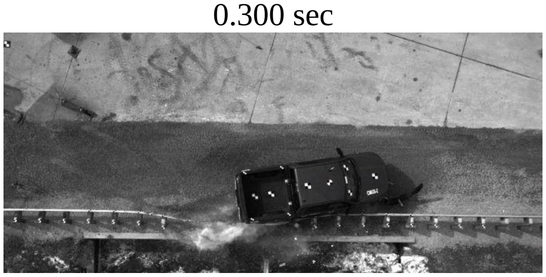
Figure 76. Additional Sequential Photographs, Test No. CMGS-2

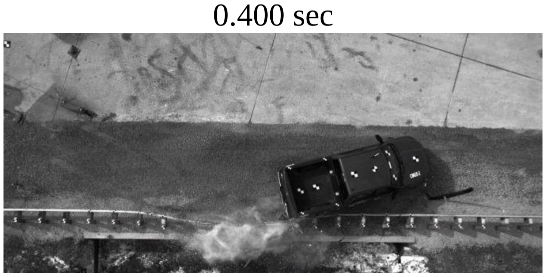

0.000 sec

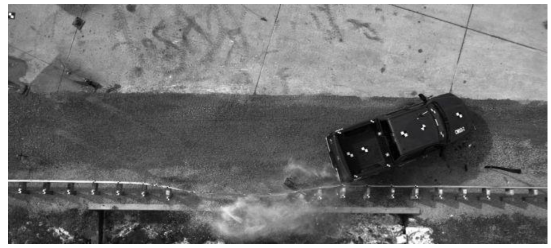

0.100 sec


0.200 sec


0.300 sec

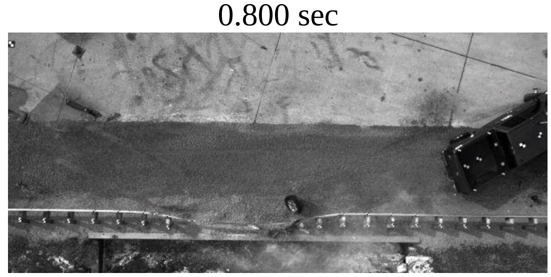

0.400 sec

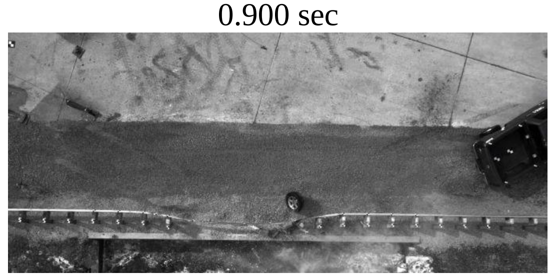

0.500 sec


0.600 sec


0.700 sec


0.800 sec


0.900 sec


1.000 sec

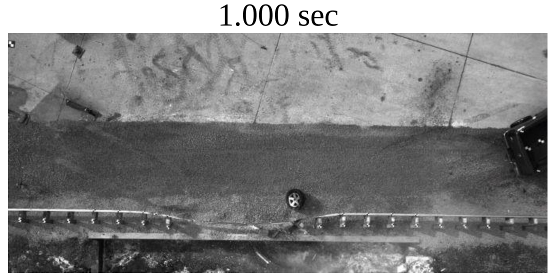

1.100 sec

Figure 77. Additional Sequential Photographs, Test No. CMGS-2

Figure 78. Documentary Photographs, Test No. CMGS-2

Figure 79. Vehicle Trajectory and Final Position, Test No. CMGS-2

6.4 Barrier Damage

Damage to the barrier was moderate, as shown in Figures 80 through 89. Barrier damage consisted mostly of deformed W-beam, contact marks on the guardrail sections, and deformed posts. The length of vehicle contact along the barrier was approximately 24 ft – 1 in. (7.3 m) which spanned from 7 in. (178 mm) downstream from post no. 15 to the downstream edge of the rail splice at post no. 23.

The guardrail damage consisted moderate deformation and flattening of the impacted section of the W-beam between post nos. 15 and 23. The W-beam disengaged from post nos. 17 through 21. Contact marks were found on the guardrail between post nos. 15 through 23. Small horizontal rail tearing was observed at and upstream from post no. 16, as shown in Figure 84. No significant guardrail damage occurred upstream from post no. 15 nor downstream from post no. 23.

Post nos. 15 and 16 slightly deflected backward. Post nos. 17 and 18 broke away from the base plate and were pulled out of the soil. However, this did not adversely affect the system's performance, and the disengaged posts did not pose secondary hazard to traffic. Post nos. 19 through 21 also deflected longitudinally toward the ground in the downstream direction but remained attached to the culvert. Contact marks were found on the front face of post nos. 18 and 19. No significant post damage occurred to post nos. 1 through 15 or 24 through 41. The upstream anchorage system was displaced nearly 1 in. (25 mm) and the downstream anchorage system remained unmoved. The posts in both the upstream and downstream anchorage systems were not damaged. The wooden blockouts at post nos. 17 through 20 disengaged from the system. The blockout at post no. 21 rotated but did not disengage from the rail. The blockouts at post nos. 3 through 16 and 22 through 39 remained undamaged.

Following the test, the soil on top of the culvert headwall was removed for inspection of the damage to the posts and base plates as well as to review any potential damage to the culvert. Deformation of the post base plates was observed on post nos. 16 through 22. Post nos. 17 and 18 fractured at the base of the post above the weld line at the front flange and web of the post and through the weld at the back flange of the post. The upstream side of the front flange of post nos. 20 and 21 was torn up to the web near the base plate weld. All anchorage bolts and epoxied threaded rods were intact and remained secure, although some minor deformation of the bolts and rods was observed. No damage was observed to the concrete culvert slab or the headwall.

The maximum lateral permanent set of the barrier system was 15¾ in. (400 mm) which occurred at the back of rail at post no. 19, as measured in the field. The maximum dynamic barrier deflection was 29.6 in. (752 mm) at post no. 17. The working width of the system was 50.8 in. (1,290 mm) at post no. 17, also determined from high-speed digital video analysis. A schematic of the permanent set deflection, dynamic deflection, and working width is shown in Figure 90.

Figure 80. System Damage, Test No. CMGS-2

Figure 81. Damage to Post Nos. 15 through 21, Test No. CMGS-2

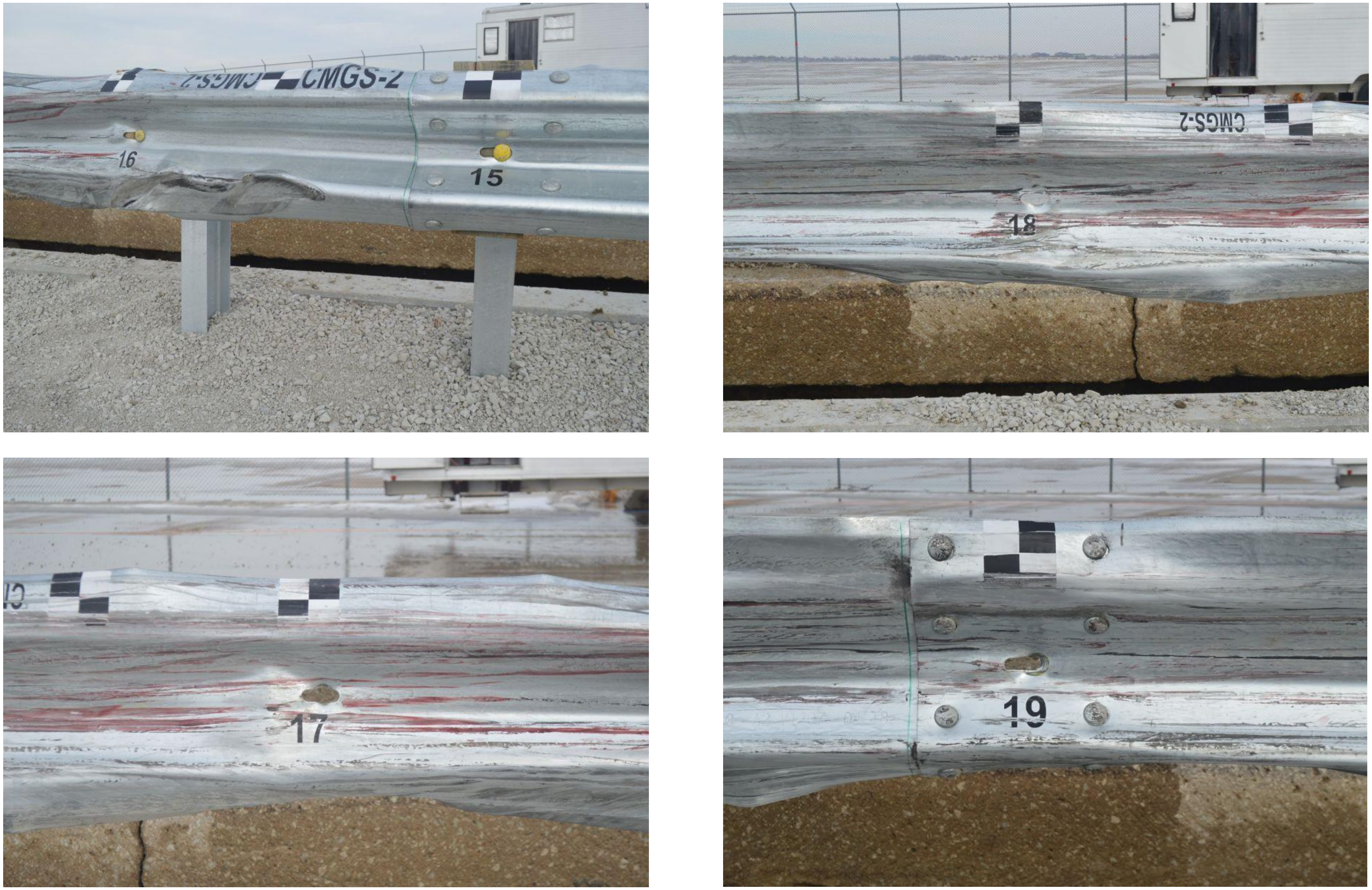


Figure 82. Guardrail Damage, Post Nos. 15 through 19, Test No. CMGS-2

Figure 83. Guardrail Damage, Post Nos. 15 through 22, Test No. CMGS-2

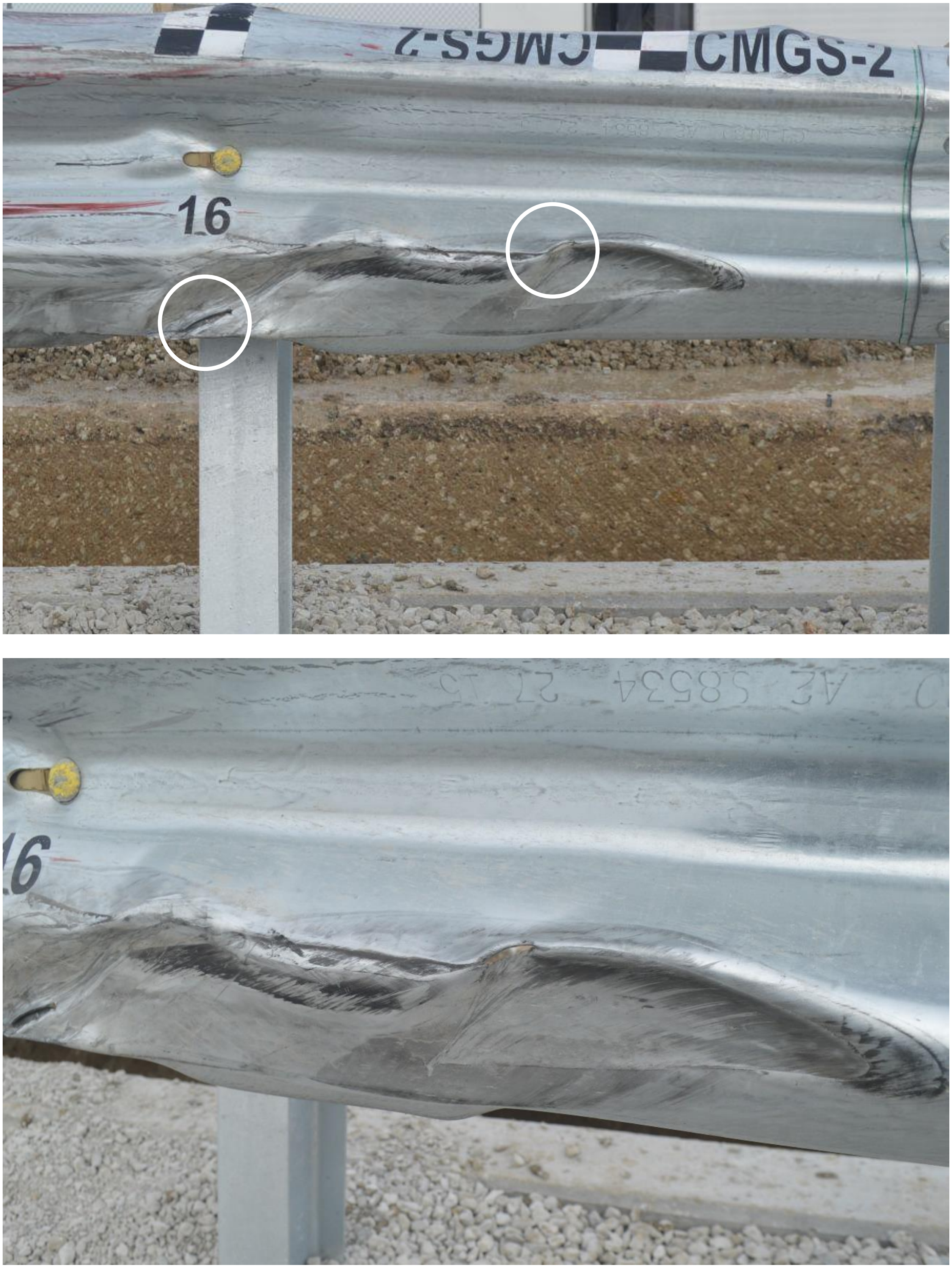


Figure 84. Rail Tears at Post No. 16, Test No. CMGS-2

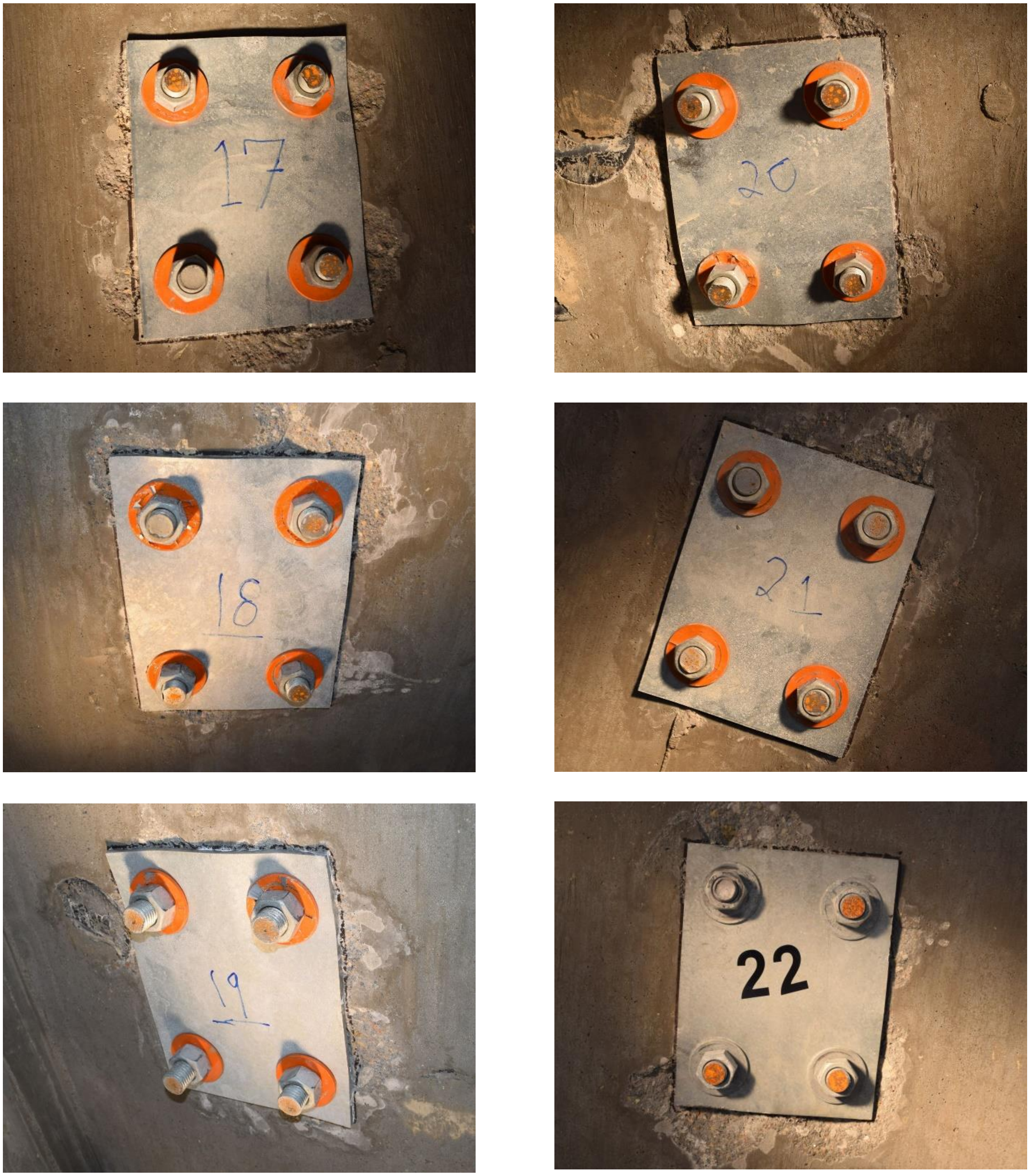


Figure 85. Damage to Base Plates of Post Nos. 17 through 22, Test No. CMGS-2

Figure 86. Damage to Base Plate Nos. 16 through 18 – After Soil Removal, Test No. CMGS-2

Figure 87. Damage to Post Nos. 17 through 22 Damage – After Soil Removal, Test No. CMGS-2

Figure 88. Culvert Deck after Removal of Soil Fill and Posts and Downstream Anchorage System Deformation, Test No. CMGS-2

Figure 89. Damage to Upstream Anchorage System, Test No. CMGS-2

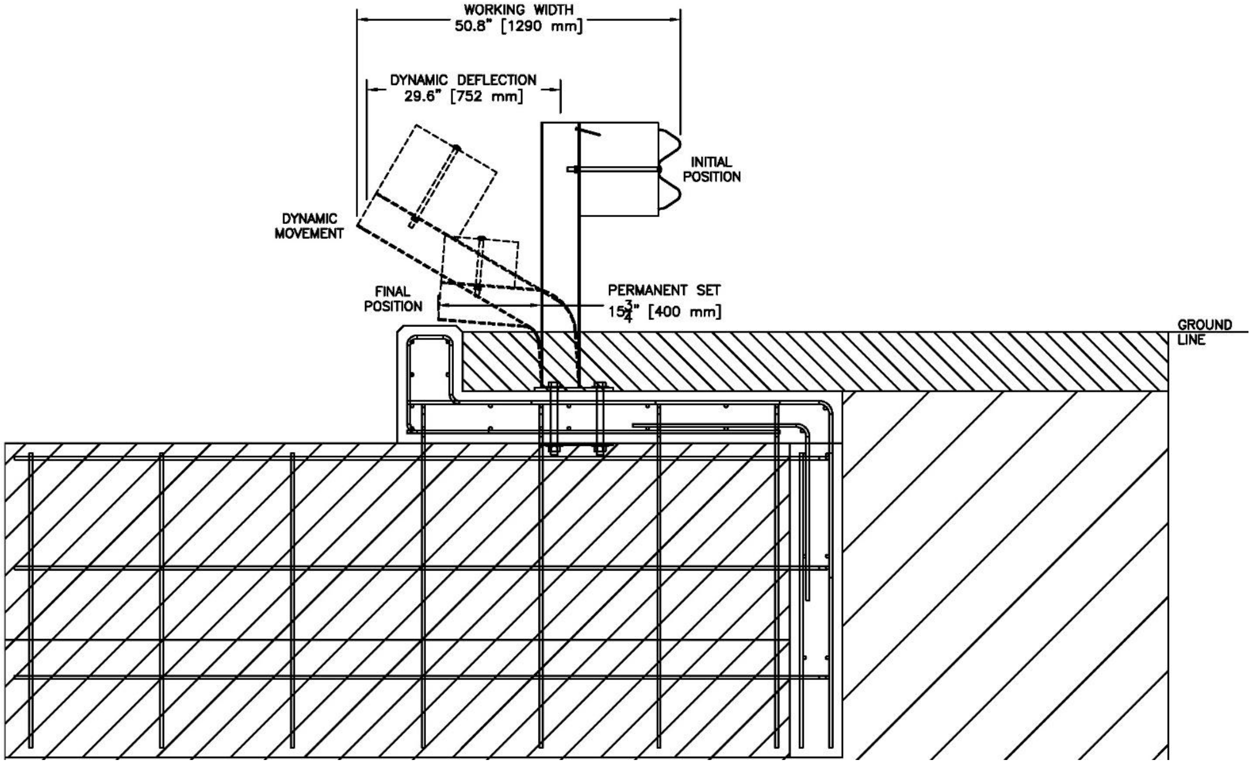


Figure 90. Permanent Set Deflection, Dynamic Deflection, and Working Width, Test No. CMGS-2

6.5 Vehicle Damage

The damage to the vehicle was moderate, as shown in Figures 91 through 95. The maximum occupant compartment deformations are listed in Table 11 along with the intrusion limits established in MASH 2016 for various areas of the occupant compartment. MASH 2016 defines intrusion or deformation as the occupant compartment being deformed and reduced in size with no observed penetration. Complete occupant compartment and vehicle deformations as well as the corresponding locations are provided in Appendix D.

The majority of the vehicle damage was concentrated on the right-front corner, where primary impact occurred. The vehicle's front bumper was crushed inward. The lower passenger side grille was broken. The front bumper cover was torn off except for the two bolts on the driver side. The vehicle right-front wheel was disengaged, and right-rear tire was deflated. The airbags did not deploy during the impact. The right corner of the rear bumper on the passenger side buckled inward and the rear corner of the right-rear fender was deformed from the impact with the barrier.

The roof, the hood, and the left side remained undamaged. The left-side and rear window glass also remained undamaged. The airbags did not deploy during the impact. The overall undercarriage damage included a 2-in. (51 mm) bend in the lower control arm, and the steering knuckle broke along with the steering arm on the passenger side. The front passenger-side brake line was disconnected. Interior occupant compartment deformations were moderate with a maximum of 1⅛ in. (29 mm), which did not violate the limits established in MASH 2016.

Figure 91. Vehicle Damage, Test No. CMGS-2

Figure 92. Additional Vehicle Damage, Test No. CMGS-2

Figure 93. Vehicle Windshield Damage, Test No. CMGS-2

Figure 94. Vehicle Occupant Compartment Damage, Test No. CMGS-2

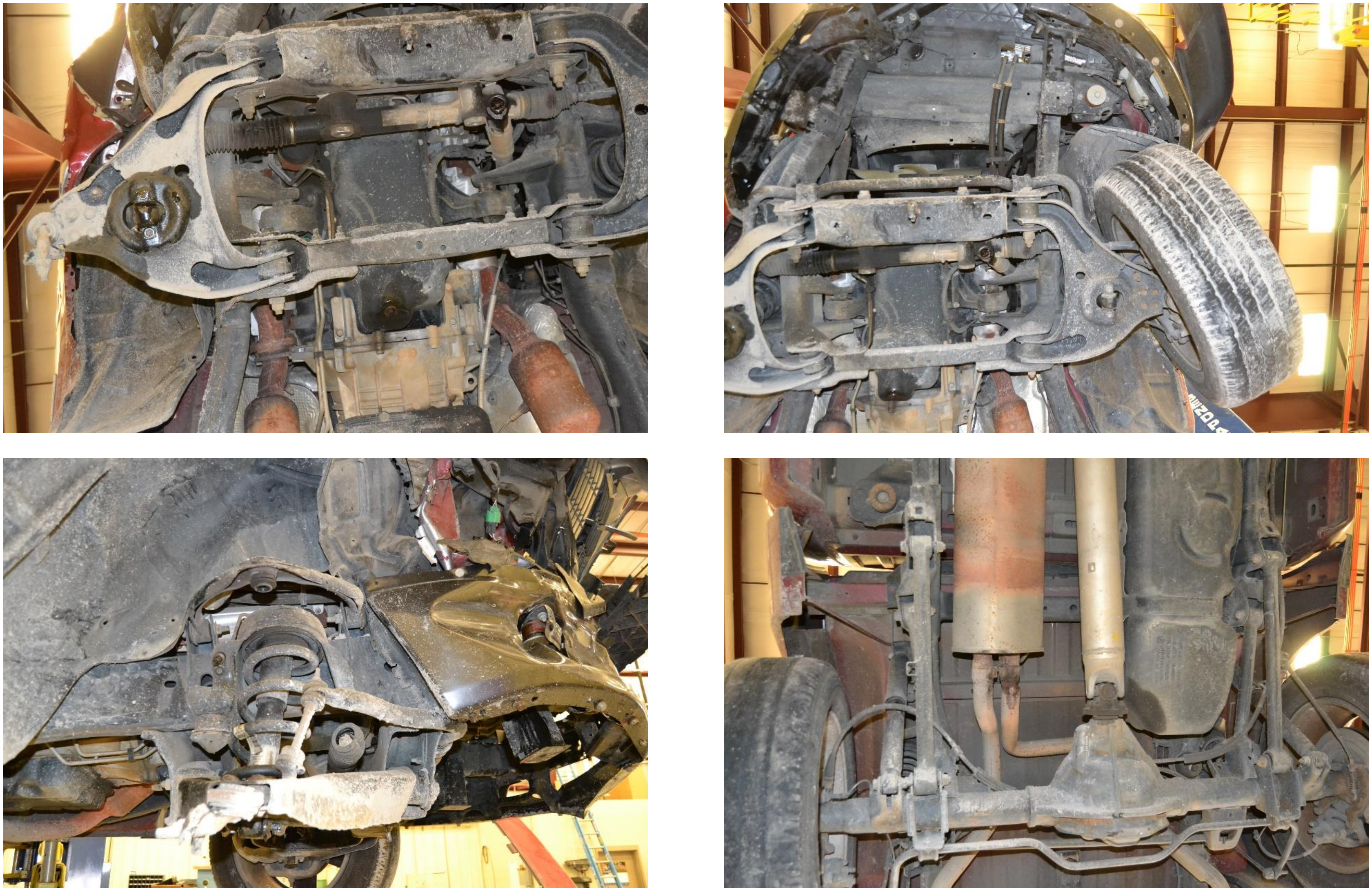


Figure 95. Vehicle Undercarriage Damage, Test No. CMGS-2

Table 11. Maximum Occupant Compartment Intrusions by Location, Test No. CMGS-2

LOCATION	MAXIMUM INTRUSION in. (mm)	MASH ALLOWABLE INTRUSION in. (mm)
Wheel Well & Toe Pan	½ (13)	≤ 9 (229)
Floor Pan & Transmission Tunnel	½ (13)	≤ 12 (305)
A-Pillar	⅜ (10)	≤ 5 (127)
A-Pillar (Lateral)	¼ (6)	≤ 3 (76)
B-Pillar	¼ (6)	≤ 5 (127)
B-Pillar (Lateral)	¼ (6)	≤ 3 (76)
Side Front Panel (in Front of A-Pillar)	⅞ (22)	≤ 12 (305)
Side Door (Above Seat)	1⅛ (29)	≤ 9 (229)
Side Door (Below Seat)	¾ (19)	≤ 12 (305)
Roof	½ (13)	≤ 4 (102)
Windshield	0	≤ 3 (76)
Side Window	No shattering of side windows occurred	No shattering resulting from contact with structural member of test article
Dash	¼ (6)	N/A[1]

N/A[1] – No MASH 2016 criteria exist for this location

6.6 Occupant Risk

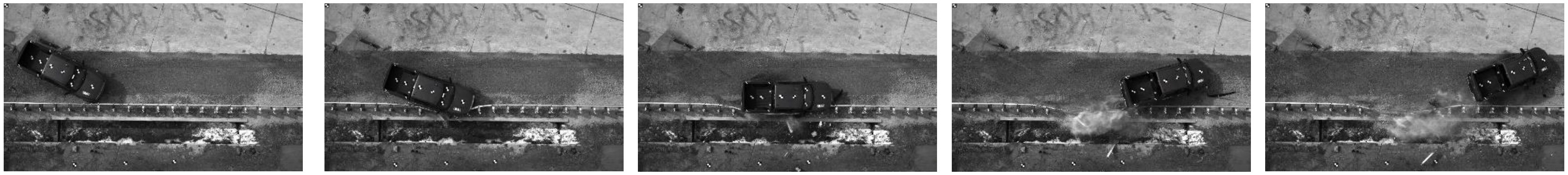
The calculated occupant impact velocities (OIVs) and maximum 0.010-sec average occupant ridedown accelerations (ORAs) in both the longitudinal and lateral directions are shown in Table 12. Note that the OIVs and ORAs were within suggested limits, as provided in MASH 2016. The calculated THIV, PHD, and ASI values are also shown in Table 12. The results of the occupant risk analysis, as determined from the accelerometer data, are summarized in Figure 96. The recorded data from the accelerometers and the rate transducers are shown graphically in Appendix F.

Table 12. Summary of OIV, ORA, THIV, PHD, and ASI Values, Test No. CMGS-2

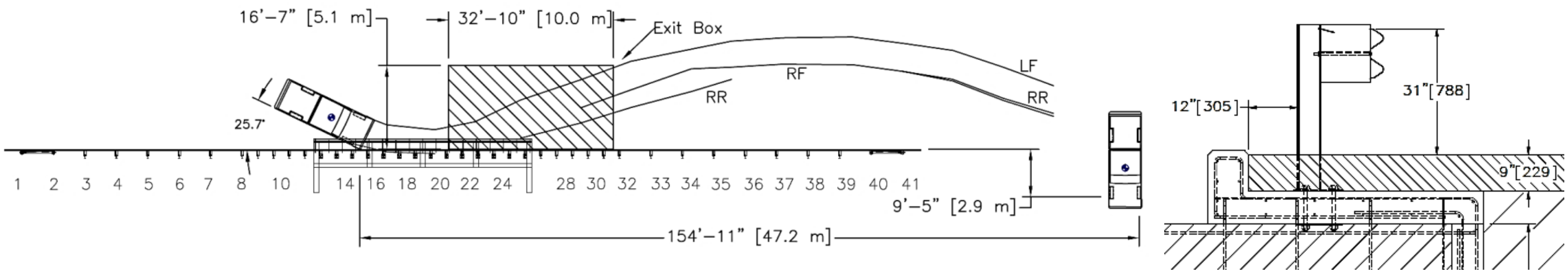
Evaluation Criteria		Transducer		MASH 2016 Limits
		SLICE-1	SLICE-2 (Primary)	
OIV ft/s (m/s)	Longitudinal	-21.86 (-6.66)	-19.60 (-5.97)	± 40 (12.2)
	Lateral	-15.36 (-4.68)	-16.58 (-5.05)	± 40 (12.2)
ORA g's	Longitudinal	-12.88	-13.78	± 20.49
	Lateral	-11.05	-10.24	± 20.49
MAX ANGULAR DISPLACEMENT deg.	Roll	22.6	15.4	± 75
	Pitch	-7.9	-9.5	± 75
	Yaw	-57.0	-57.4	not required
THIV ft/s (m/s)		24.66 (7.52)	23.68 (7.22)	not required
PHD g's		16.11	16.22	not required
ASI		1.02	0.96	not required

6.7 Discussion

The analysis of the test results for test no. CMGS-2 showed that the strong post MGS attached to the culvert's top slab using through-bolts adequately contained and redirected the 2270P vehicle with controlled displacement of the barrier. A summary of the test results and sequential photographs are shown in Figure 96. Detached elements, fragments, or other debris from the test article did not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or work-zone personnel. Two posts in the system were disengaged from their base plates and ejected laterally behind the barrier system. It is not anticipated that these disengaged posts would pose a hazard to other traffic, pedestrians, or work-zone personnel when ejected behind the system and into the flow channel of the culvert. Deformations of, or intrusions into, the occupant compartment that could have caused serious injury did not occur. The test vehicle did not penetrate nor ride over the barrier and remained upright during and after the collision. Vehicle roll, pitch, and yaw angular displacements, as shown in Appendix E, were deemed acceptable because they did not adversely influence occupant risk safety criteria nor cause rollover. After impact, the vehicle exited the barrier at an angle of 17.4 degrees, and its trajectory did not violate the bounds of the exit box. Therefore, test no. CMGS-2 conducted on the culvert mounted, strong post MGS was determined to be acceptable according to the MASH 2016 safety performance criteria for test designation no. 3-11.



0.000 sec   0.126 sec   0.270 sec   0.520 sec   0.652 sec



- Test Agency .... MwRSF
- Test Number CMGS-2
- Date 2/14/2018
- MASH Test Designation No. 3-11
- Test Article .... Culvert-Mounted, Strong Post MGS
- Total Length .... 182.3 ft (55.6 m)
- Distance between Posts and Headwall .... 12 in. (305 mm)
- Key Component – MGS Rail
  - Thickness .... 12 gauge (2.7 mm)
  - Top Mounting Height .... 31 in. (787 mm)
- Key Component – Steel Posts
  - Post Type .... W6x9 by 40½ in. (1,029 mm)
  - Post Spacing .... 37½ in. (952 mm) on center
- Soil Type .... Compacted, coarse, crushed limestone
- Vehicle Make /Model .... 2010 Dodge Ram
  - Curb .... 5,292 lb (2,400 kg)
  - Test Inertial .... 5,013 lb (2,274 kg)
  - Gross Static .... 5,175 lb (2,347 kg)
- Impact Conditions
  - Speed .... 62.8 mph (101.1 km/h)
  - Angle .... 25.7 deg
  - Impact Location .... 129.1 in. (3,279 mm) upstream from post no. 19
- Impact Severity .... 124.7 kip-ft (169.1 kJ) > 106 kip-ft (144 kJ) Limit from MASH
- Exit Conditions
  - Speed .... 33.1 mph (53.2 km/h)
  - Angle .... 17.4 deg
- Exit Box Criterion .... Pass
- Vehicle Stability .... Satisfactory
- Vehicle Stopping Distance .... 173 ft - 6 in. (52.9 m) Downstream within the system
- Vehicle Damage .... Moderate
  - VDS [14] 1-RFQ-6
  - CDC [15] 1-RZAK-5
  - Maximum Interior Deformation .... 1⅛ in. (29 mm)
- Test Article Damage .... Moderate
- Maximum Test Article Deflections
  - Dynamic .... 29.6 in. (752 mm)
  - Working Width .... 50.8 in. (1,290 mm)
  - Permanent Set .... 15¾ in. (400 mm)
- Transducer Data

Evaluation Criteria		Transducer		MASH 2016 Limit
		SLICE-1 (primary)	SLICE-2	
OIV ft/s (m/s)	Longitudinal	-21.86 (-6.66)	-19.60 (-5.97)	± 40 (12.2)
	Lateral	-15.36 (-4.68)	-16.58 (-5.05)	± 40 (12.2)
ORA g's	Longitudinal	-12.88	-13.78	± 20.49
	Lateral	-11.05	-10.24	± 20.49
MAX ANGULAR DISPLACEMENT deg.	Roll	22.6	15.4	±75
	Pitch	-7.9	-9.5	±75
	Yaw	-57.0	-57.4	not required
THIV – ft/s (m/s)		24.66 (7.52)	23.68 (7.22)	not required
PHD – g's		16.11	16.22	not required
ASI		1.02	0.96	not required

Figure 96. Summary of Test Results and Sequential Photographs, Test No. CMGS-2

7 STIFFNESS TRANSITION FROM MGS TO CULVERT-MOUNTED MGS

Following two successful full-scale crash tests on culvert-mounted MGS, it was desired to evaluate the performance of the transition between the standard MGS and the culvert-mounted MGS. This system installation consists of four sections, including the anchorage system, standard MGS, half-post spacing MGS, and culvert-mounted MGS, as shown in Figure 97.

The anchorage systems consisted of timber posts (post nos. 1 and 2, 40 and 41) measuring 5½ in. wide x 7½ in. deep x 46 in. long (140 mm wide x 191 mm deep x 1,168 mm long) and were placed in 6-ft (1.8-m) long steel foundation tubes. The timber BCT posts and foundation tubes were part of the end anchor systems that are representative of a tangent guardrail terminal. The safety performance of these downstream anchorage systems also has been evaluated to MASH through full-scale crash testing [16]. Alternative crashworthy anchorage systems, including energy-absorbing end terminals are also acceptable.

The culvert-mounted MGS, as described in detail in Section 3.2, consisted of MGS with a 31-in. top rail height, supported by fourteen steel W6x9 posts (post nos. 13 through 26), measuring 40½ in. (1,029 mm) long, spaced at 37½ in. (953 mm) on center, attached to a low-fill culvert's top slab with a 12-in. (305-mm) offset from the back of the post to the culvert headwall. For culvert-mounted MGS posts, the soil embedment depth was 9 in. (229 mm). Two successful crash tests were conducted according to MASH 2016 Test Level 3 impact safety criteria.

The standard MGS consisted of steel W6x8.5 guardrail posts measuring 6 ft (1.8 m) long with a top mounting rail height of 31 in. (787 mm). The posts were spaced at 75 in. (1,905 mm) on center with a soil embedment depth of 40 in. (1,016 mm). For posts within the MGS, 6-in. wide x 12-in. deep x 14¼-in. long (152-mm wide x 305-mm deep x 362-mm long) wood spacer blockouts were used to offset the rail away from the front face of the steel posts. The standard MGS has been previously successfully crash tested to MASH TL-3 criteria [17-18].

The half-post spacing MGS was identical to the standard MGS except that the original guardrail system utilizes a post spacing of 37½ in. (953 mm) on center. This configuration was previously considered crashworthy under NCHRP Report No. 350 evaluation criteria and was carried over to the design evaluated herein to provide for a more conservative transition between standard MGS and the culvert-mounted system. However, half-post spacing MGS has not been successfully evaluated to MASH 2016. Thus, it desired to compare the behavior of standard 40-in. (1,016-mm) embedded posts to the culvert-mounted posts to verify that the behavior of half-post spacing MGS and the transition between half-post spacing MGS and culvert-mounted MGS would be similar.

When transitioning from the standard MGS to half-post spacing MGS, the reduced post spacing increases the system stiffness, and consequently, potential for vehicle snag. Therefore, further investigation was needed to confirm the safety performance of the transition in redirection of vehicles. Additionally, it was unknown if there was a change in system stiffness when transitioning from the half-post spacing MGS with 40-in (1,016-mm) soil embedded posts to culvert-mounted MGS with 9-in (229-mm) soil embedded post. Thus, further analysis was conducted to evaluate these two transitions: (1) transition from standard MGS to half-post spacing MGS; and (2) transition from half-post spacing MGS to culvert-mounted MGS.

It should be noted that, recent full-scale crash testing of stiffened or reduced deflection MGS systems have resulted in rail ruptures. Texas A&M Transportation Institute (TTI) has recently conducted testing on the MGS with reduced post spacing and transitions from standard post spacing to reduced post spacing. TTI researchers first evaluated a quarter-post spacing system (18¾ in.) with MASH test designation nos. 3-11 and 3-10. The quarter-post spacing system successfully passed both MASH tests. TTI researchers also tested a transition between quarter-(18¾ in.) and full-(75 in.) spacing according to MASH test designation no. 3-21 impact conditions. This transition used single, W-beam rail elements and did not incorporate any nested rail sections. In this test, the pickup truck ruptured the rail and penetrated beyond the barrier. TTI researchers attributed the failure to rail pocketing caused by the short transition in lateral barrier stiffness. Finally, TTI researchers also tested a half-post spacing (37½ in.) variation of the MGS under this project. In this test, the pickup truck ruptured the rail and penetrated beyond the barrier. Published reports for these research efforts are not yet available and are not referenced herein.

These recent test failures involving 2270P impacts into the MGS with reduced post spacing suggests that the there is potential for rail failure during impacts into stiffened MGS applications and/or applications where increased localized rail deflection and pocketing may occur.

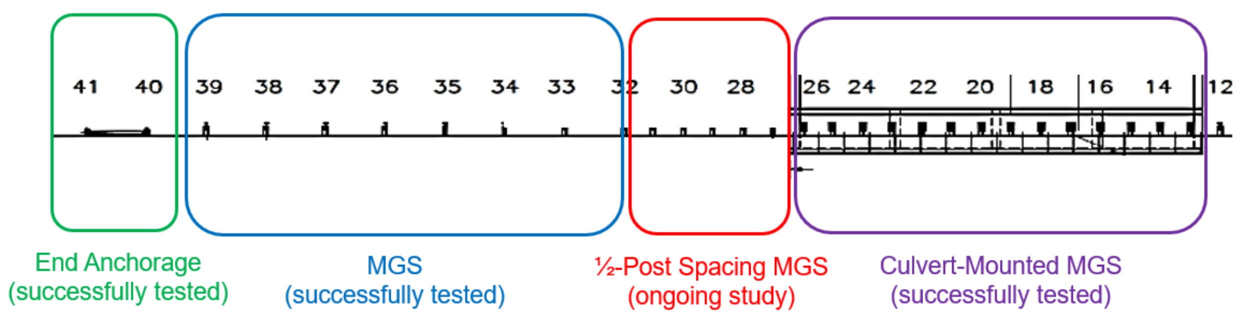


Figure 97. System Sections within Test Installation

7.1 Transition from Half-Post Spacing MGS to Culvert-Mounted MGS

For the stiffness transition from culvert-mounted posts to soil-embedded posts within the MGS, the load-deflection curve of each post is the key parameter to determine its resistance. The load-deflection curves from previous W6x8.5 posts embedded 40 in. (1,016 mm) in soil were compared to a W6x9 culvert-mounted post.

MwRSF researchers previously conducted a similar component test, namely, test no. CGSA-4, which was conducted on an ASTM A992 W6x9 (W152x13.4) steel post with the same geometry of the culvert-mounted posts in test no. CMGS-2, as shown in Figure 98a [7]. The post was bolted on the concrete grade. The impact height for the CGSA-4 post was 30⅝ in. (778 mm), which would correspond to an impact height of 21⅝ in. (549 mm) above grade for a 9-in (229 mm) embedment. Component level bogie tests, test nos. MH-1 and MH-4 had been previously conducted on a similar post embedded 40 in. (1,016 mm) in soil, as shown in Figure 98b. Details of these tests can be found in reports [19-20]. The bogie test key parameters are summarized in Table 13. The load- and energy-deflection results are plotted in Figures 99 and 100, respectively. Note that the force and deflection data from test no. CGSA-4 was adjusted to account for the difference in impact height between the two tests. In test no. CGSA-4, the post was bolted to the concrete, and upon impact the bogie had large vibrations, as shown in Figure 99, whereas in test nos. MH-1 and MH-4, the soil damped out some of the bogie vibrations, so less force variation occurred.

The culvert-mounted post and standard 40-in. (1,016-mm) embedded posts had very similar average forces, as shown in Table 13 and Figure 99. Additionally, the culvert-mounted post had nearly identical energy dissipation to the standard posts. Based on the similar stiffness and energy dissipation between the culvert mounted post and standard guardrail posts, it was believed that no stiffness transition would be required between the standard 40-in. (1,016-mm) embedded posts at half-post spacing and the culvert-mounted posts as half-post spacing.

(a) (b)

Figure 98. (a) Soil Embedment Post Test Nos. MH-1 and MH-4; (b) Concrete-Mounted Post Test No. CGSA-4

Table 13. Load-Deflection Comparison

Test No.	Embedment Depth in. (mm)	Actual Impact Height in. (mm)	Steel Post Size	Post Grade	Impact speed mph (km/h)	Bogie Weight lb (kg)	Peak Force Kips (kN)	Average Force kips (kN) at displacement		
								10 in.	15 in.	20 in.
MH-1	40.0 (1,016)	24⅞ (632)	W6x8.5 (W152x12.6)	A36	20.0 (32.2)	1,745 (792)	14.0 (62.3)	9.8 (43.6)	9.5 (42.3)	8.8 (39.1)
MH-4	40.0 (1,016)	24⅞ (632)	W6x8.5 (W152x12.6)	A36	20.0 (32.2)	1,745 (792)	12.9 (57.4)	9.6 (42.7)	9.5 (42.3)	8.9 (39.6)
CGSA-4	N.A.*	30⅝ (778)	W6x9 (W152x13.4)	A992	10.0 (16)	4,888 (2217)	19.0 (85.3)	10.7 (47.6)	10.9 (48.4)	9.8 (43.6)

*N.A. = not available on bolted connection

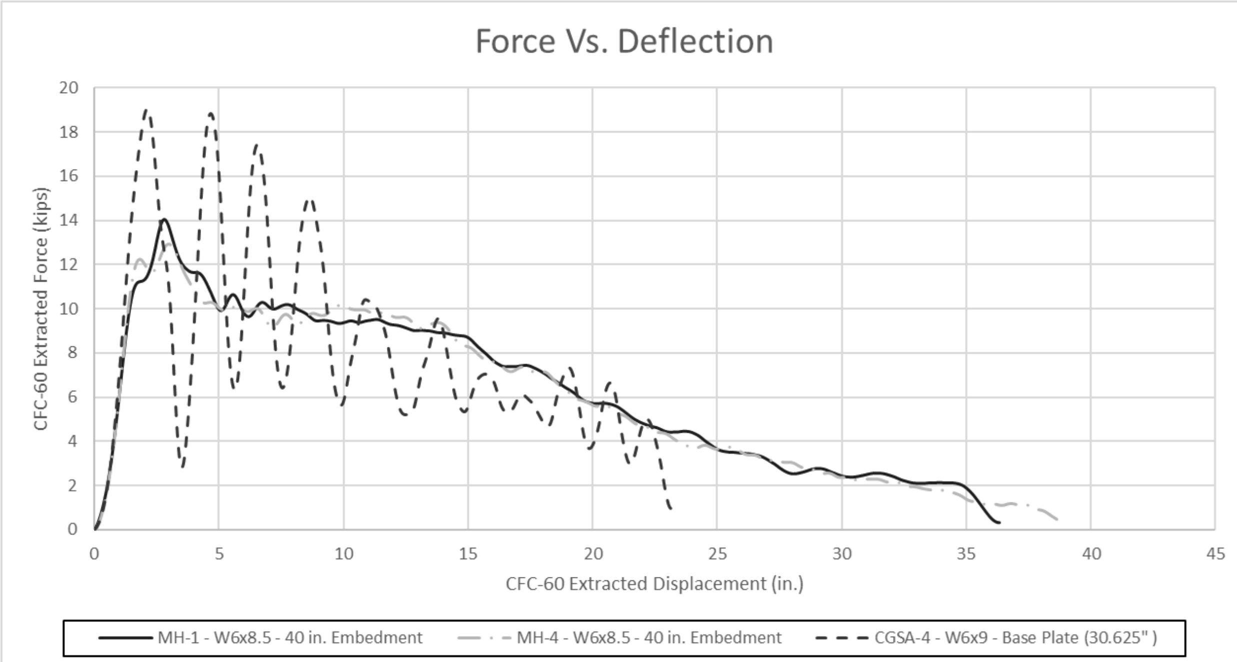


Figure 99. Load-Deflection Curves Comparison

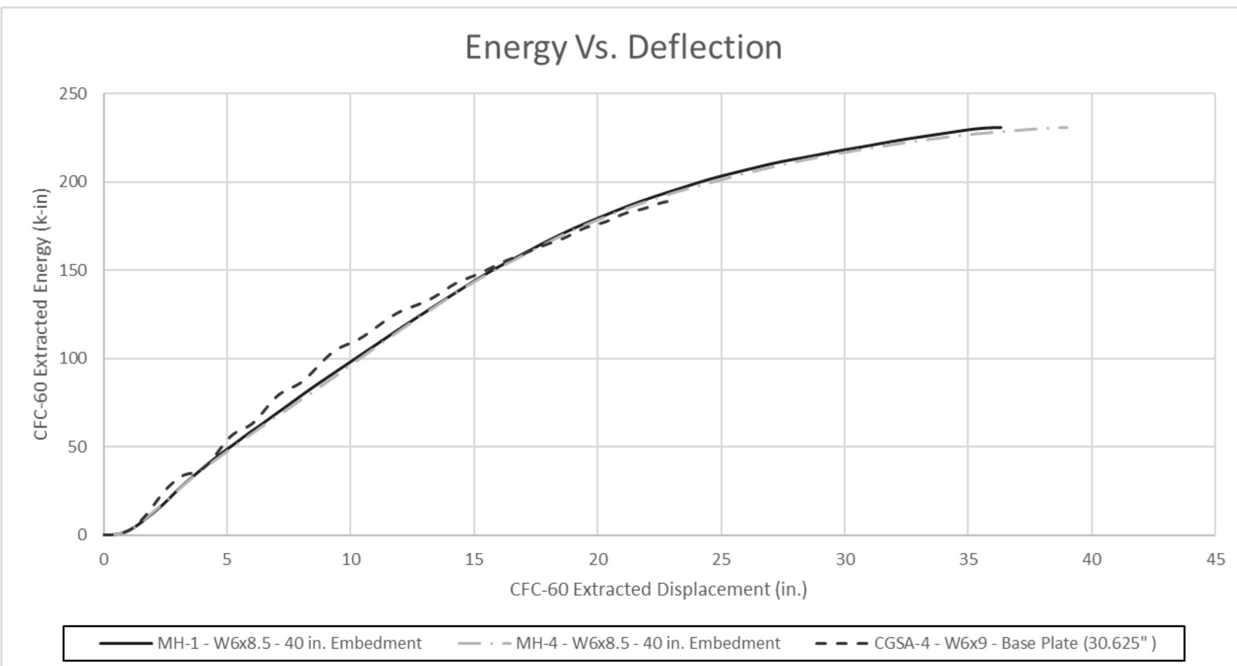


Figure 100. Energy-Deflection Curves Comparison

7.2 Transition from Standard MGS to Half-Post Spacing MGS

In transition from the standard MGS to half-post spacing MGS, the potential for rail pocketing, wheel snag, and higher accelerations exists due to the increased barrier stiffness of the half-post spacing region. MwRSF researchers previously conducted research and full-scale crash testing of a similar MGS transition, namely, test no. MWTSP-2 [21].

In test no. MWTSP-2, an upstream stiffness transition between the MGS and a thrie beam approach guardrail transition was crash tested according to TL-3 safety performance criteria set forth in MASH 2009, as shown in Figure 101. The barrier was constructed with several components, including (1) standard W-beam rail; (2) asymmetrical, W-beam to thrie-beam transition element; (3) standard thrie-beam guardrail; (4) nested thrie-beam guardrail; and (5) thrie-beam and channel bridge railing system, as shown in Figure 102a. All guardrails had a top rail height of 31 in. (787 mm). Post nos. 1 through 8 and 8 through 12 were ASTM A36 W6x9 posts embedded 40 in. (1,016 mm) and were spaced 75 in. (1,905 mm) and 37½ in. (953 mm), respectively. In test no. MWTSP-2, a 5,158-lb (2,340-kg) pickup truck impacted the upstream stiffness transition at a speed of 61.2 mph (98.5 km/h) and at an angle of 26.3 degrees. The barrier was impacted in the span where the full post spacing MGS approached the half-post spacing MGS 37.5 in. (953 mm) upstream from post no. 8), as shown in Figure 102b, which was determined to be the critical impact point for snag and rail pocketing based on a Barrier VII analysis. In test no. MWTSP-2, the pickup truck was safely contained, and test no. MWTSP-2 was determined to be acceptable according to test designation no. 3-21 of MASH.

The transition in test no. MWTSP-2 is similar to the transition between standard MGS and half-post spacing MGS in terms of the post configuration and rail section. Thus, test no. MWTSP-2 was considered as a reference to evaluate the transition from standard MGS to half-post spacing MGS within the test installation in test nos. CMGS-1 and CMGS-2. Since test no. MWTSP-2 was tested to be at a critical point for snag and rail pocketing relative to the transition from standard MGS and half-post spacing MGS and it was successful, it was also believed that the standard MGS to half-post spacing MGS utilized upstream of the culvert-mounted MGS would also be adequate. Therefore, the transition between standard MGS and half-post spacing MGS was believed to not expose errant vehicles to any additional hazards. Additionally, numerical simulations were carried out to confirm the critical impact point and evaluate the need for a separate transition from standard MGS to half-post spacing MGS.

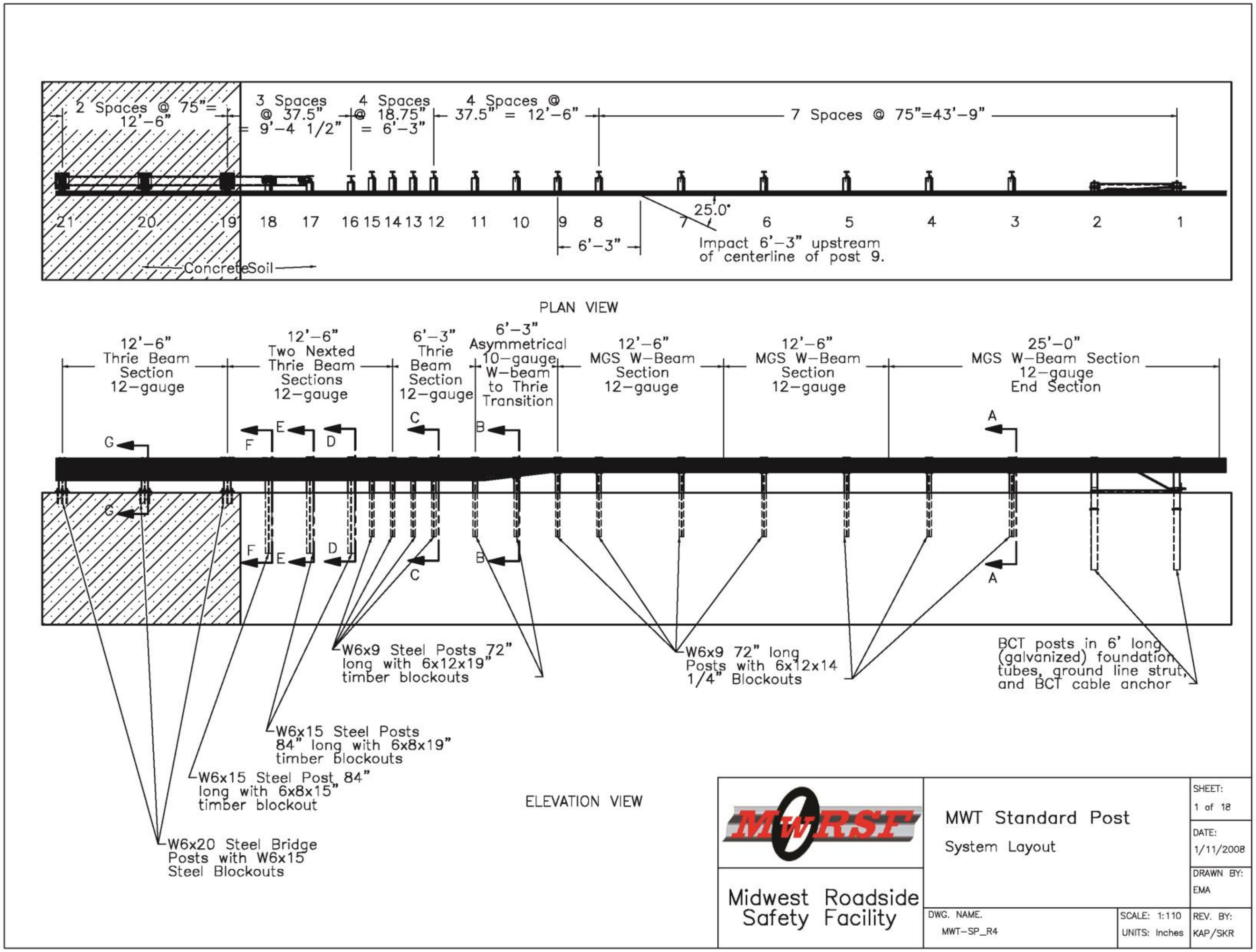
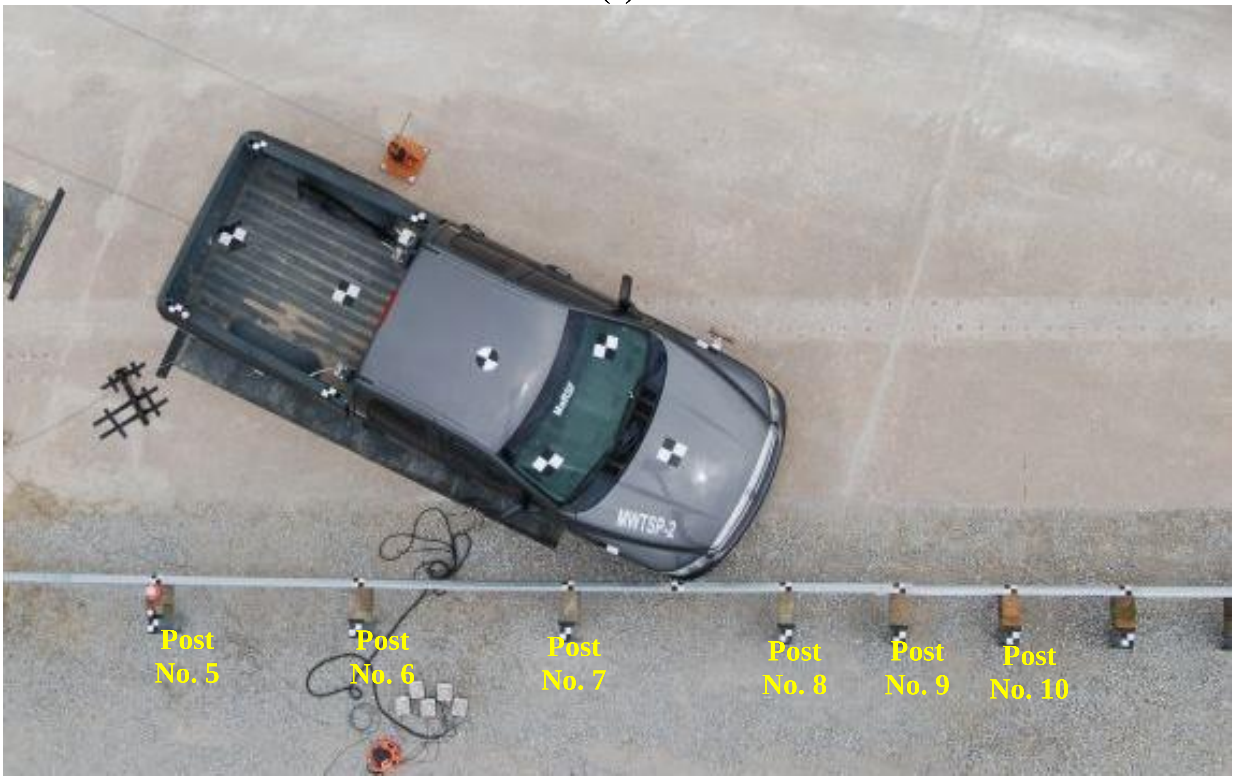


Figure 101. System Details and Layout, Test No. MWTSP-2

(a)



(b)

Figure 102. (a) System Installation; (b) Impact Location, Test No. MWTSP-2

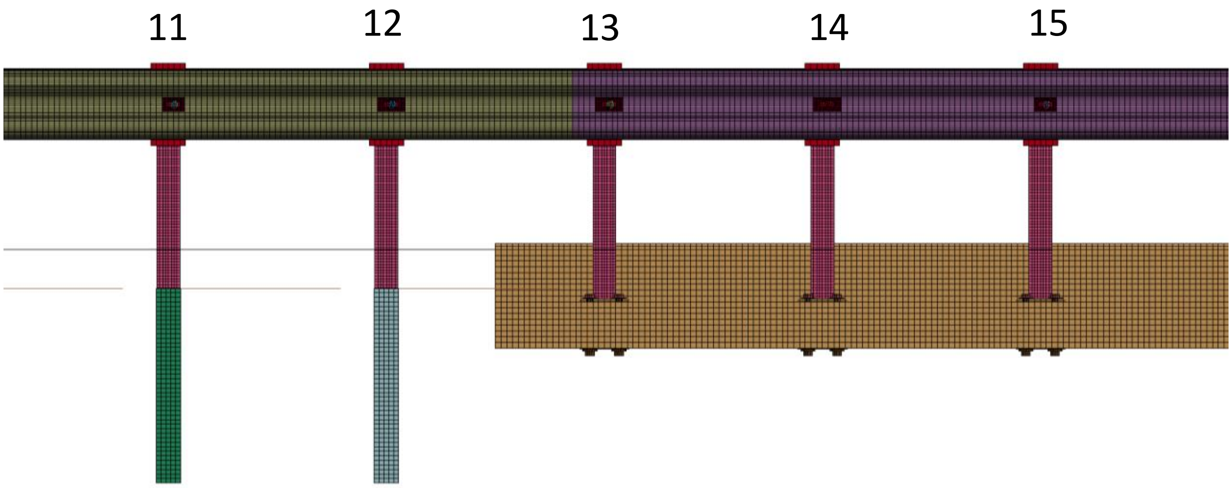
7.2.1 Evaluation of MGS to Half-Post Spacing MGS

A baseline simulation of MGS was modified to simulate the culvert-mounted MGS impacted by a 2270P pickup truck and was compared to crash test no. CMGS-2 [22]. Then, several impact points in the transition area from full-post spacing MGS to half-post spacing MGS were evaluated. The analysis focused on impacts with the 2270P vehicle as the pickup truck was expected to deflect the barrier more as compared to the small car, leading to increased pocketing and vehicle snag in the transition region. Two cases with and without wheel and tire disengagement were considered in order to bracket the simulation analysis.

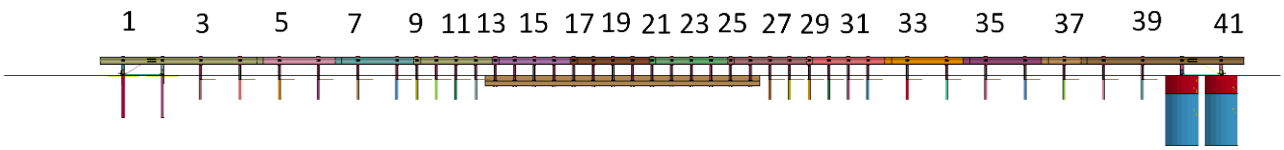
7.2.2 Simulation of Culvert-Mounted Midwest Guardrail System

The culvert-mounted MGS model was developed by modifying the standard MGS model. The standard MGS model consisted of twenty-nine steel posts with a 75 in. (1,905 mm) post spacing. The soil was modeled with soil springs in both guardrail longitudinal and lateral directions that provided equivalent resistance to soil. The standard MGS model was validated in a previous project using NCHRP Report No. W179 procedures for verification and validation of computer simulations used for roadside safety applications [22]. The standard MGS model was modified by reducing the post spacing at the culvert location and the transition areas, as shown in Figure 103, to represent test installation in test no. CMGS-2. The culvert-mounted MGS consisted of a total of forty-one steel posts. The standard post spacing of 75 in. (1,905 mm) occurred from post nos. 1 through 8 and 32 through 41. The reduced post span length of 37½ in. (952.5 mm) occurred from post nos. 8 through 32 at the culvert and the transition. The bolted connections between culvert-mounted post base plates and the culvert were explicitly modeled. The welds between the culvert-mounted posts and base plates were simplified by merging nodes between the two parts, as shown in Figure 104. Since no damage occurred to the culvert in test nos. CMGS-1 and CMGS-2, the culvert was modeled with rigid material. The parts, elements, and materials used in the culvert-mounted MGS model are shown in Table 14. Note that the components added to the existing standard MGS model are described in Table 14. Further details of the baseline MGS model can be found in NCHRP Report No. W179 [22].

The reduced-element, 2270P Chevrolet Silverado pickup truck model, originally developed by the National Crash Analysis Center (NCAC) and modified by MwRSF, was previously validated with an MGS test, test no. 2214MG-2 [17, 22]. The standard vehicle model does not incorporate failure in the suspension parts, nor tire deflation or wheel disengagement capacities. This vehicle model was used for the baseline culvert-mounted MGS model.



(a)



(b)

Figure 103. Culvert-Mounted MGS Model: (a) Transition from Half-Post Spacing MGS to Culvert-Mounted MGS; and (b) System Installation Model Overview

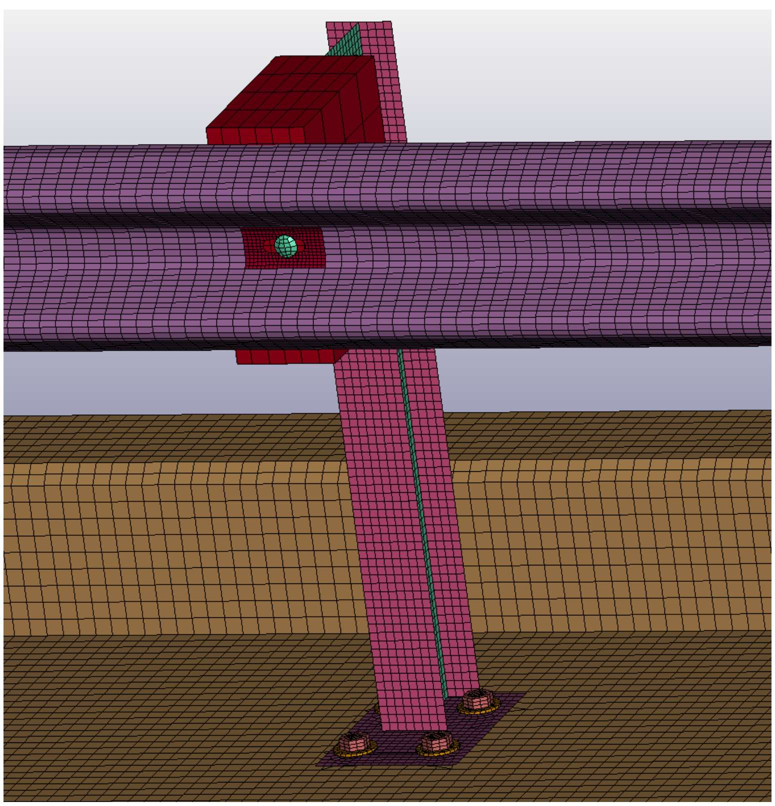


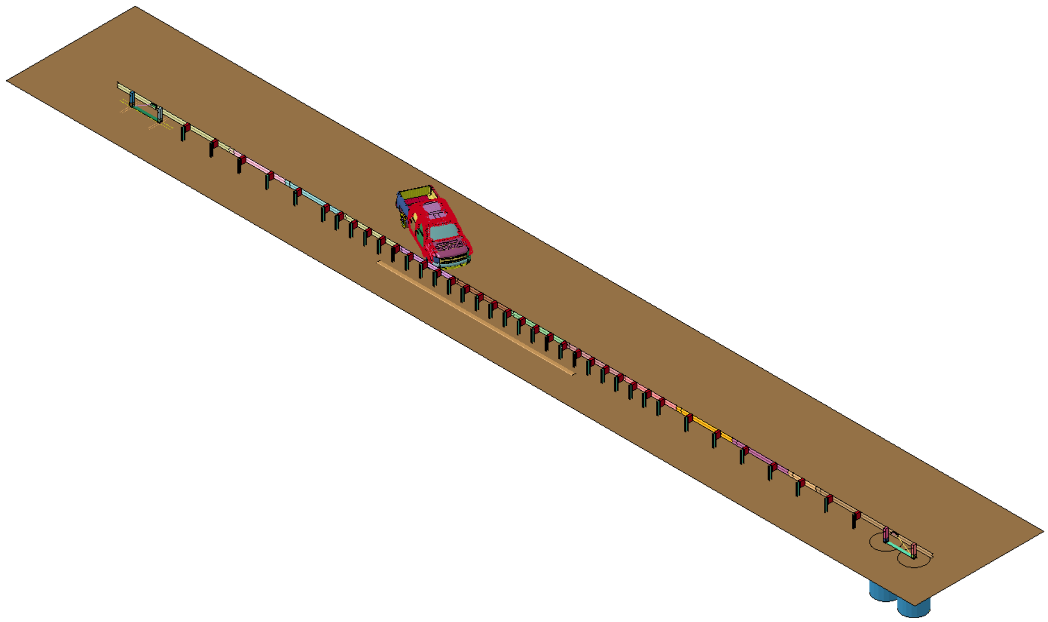
Figure 104. Culvert-Mounted Post Simulation Details

Table 14. List of Simulation Model Parts and LS-DYNA Parameters

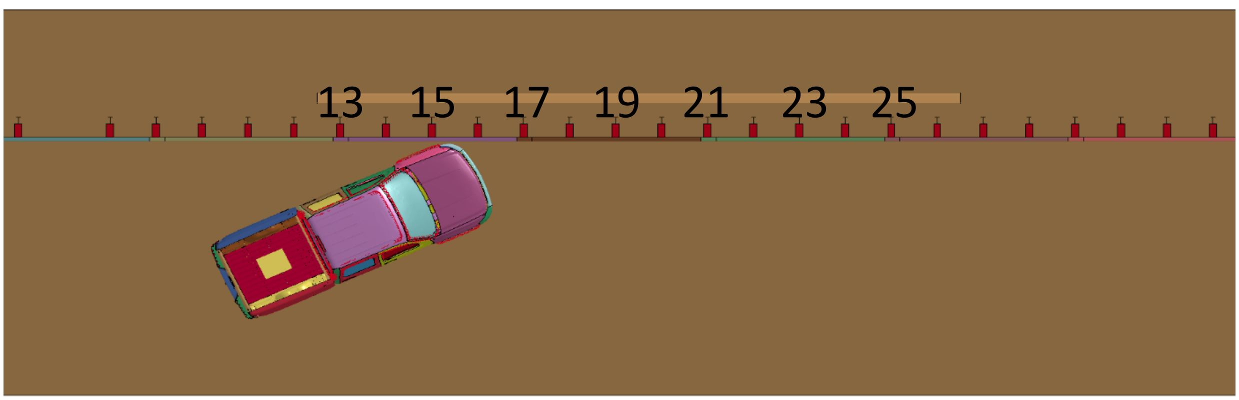
Part Name	Element Type	Element Formulation	Material Type	Material Formulation
Concrete Culvert	Solid	Constant Stress	Normal Weight Concrete	Rigid Solid
Base plates	Shell	Hughes-Liu	ASTM A572 Steel	Piecewise, Linear Plasticity
Washers	Solid	Fully Integrated	ASTM F844 Steel	Piecewise, Linear Plasticity
Bolts	Solid	Fully Integrated	ASTM A307 Steel	Piecewise, Linear Plasticity
Nuts	Solid	Fully Integrated	A563 Steel	Piecewise, Linear Plasticity

In test no. CMGS-2, the vehicle was a 5,013-lb (2,274-kg) Dodge Ram 1500, while the simulated vehicle was a 5,005-lb (2,270-kg) Chevrolet Silverado 1500. The impact angle and speed in the numerical model were 25 degrees and 62.8 mph (101.1 km/h), whereas the impact angle and speed in the test no. CMGS-2 were 25.7 degrees and 62.8 mph (101.1 km/h). The impact point in both test and numerical models was 129 in. (3,277 mm) upstream of post no. 19. The simulated system before the impact and the sequential comparison of test CMGS-2 and baseline CMGS simulation are shown in Figures 105 and 106, respectively.

The data obtained from test no. CMGS-2 was compared to the two baseline simulations' results: one with wheel disengagement and one without, as shown in Table 15. Specifically, change in velocities, deflections, and vehicle Euler angles were compared in detail.



(a)



(b)

Figure 105. LS-DYNA Model for Test No. CMGS-2: (a) Isometric View; and (b) Overhead View

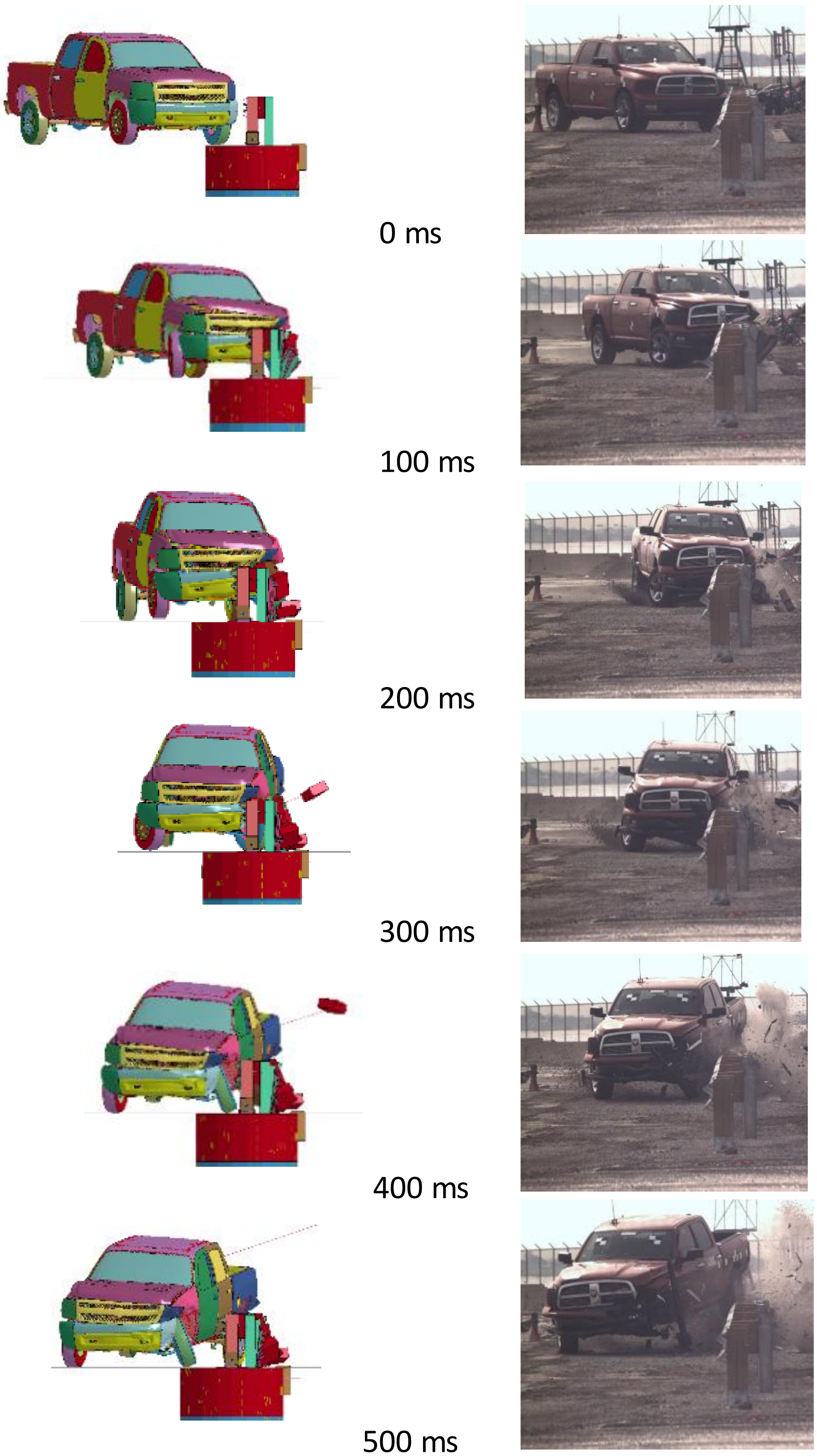


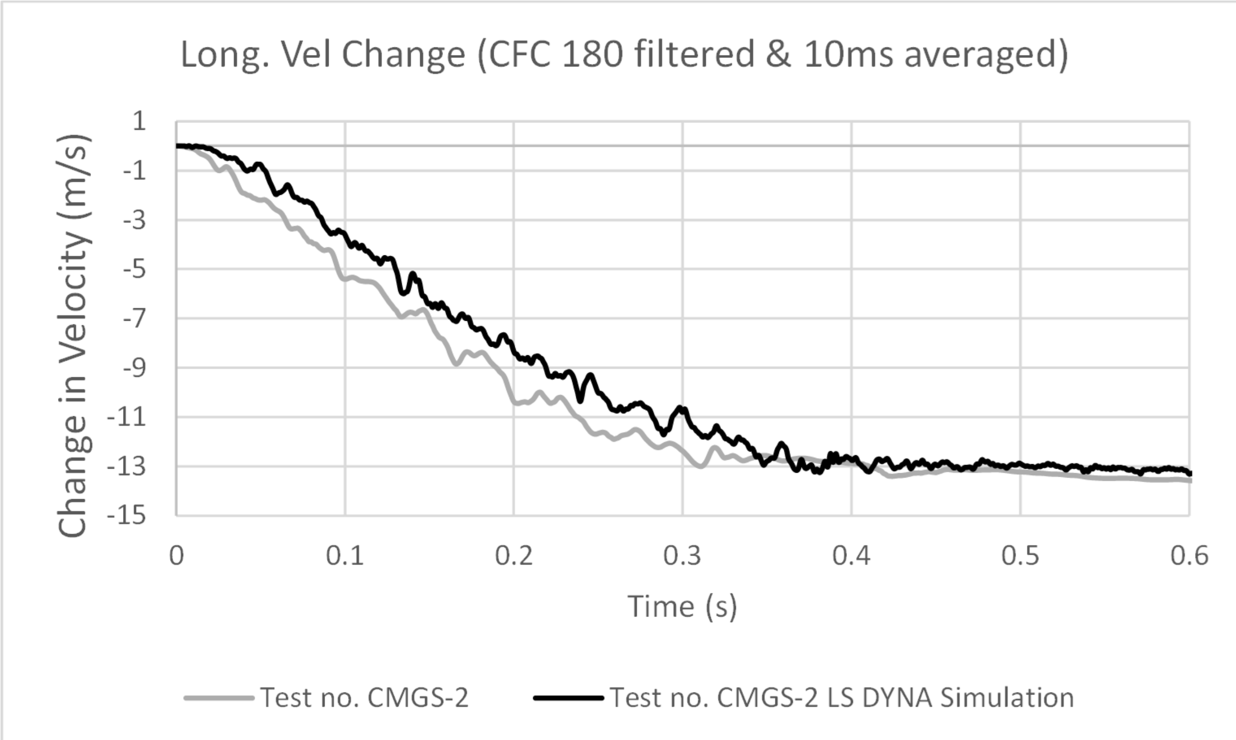
Figure 106. Downstream Vehicle Position Comparison, Baseline CMGS Simulation and Test No. CMGS-2

Table 15. Comparison of Test No. CMGS-2 and Simulation Results

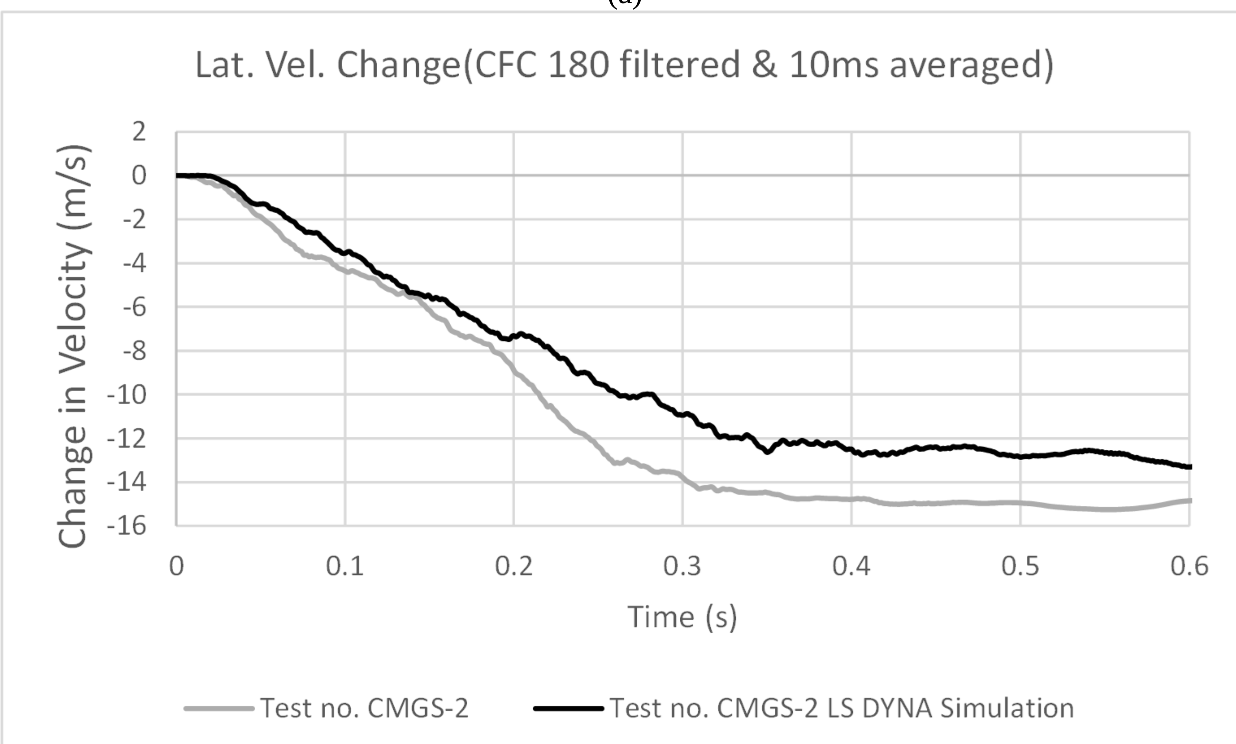
		Test	Simulation	Simulation
Parameters		Test No. CMGS-2	Baseline CMGS	Baseline CMGS Wheel Disengaged
Vehicle	Year, Make, and Model	2010, Dodge, RAM 1500	Chevrolet, Silverado 1500	Chevrolet, Silverado 1500
	Test Inertial Weight, lb (kg)	5,013 (2,274)	5,005 (2,270)	5,005 (2,270)
Impact Conditions	Speed, mph (km/h)	62.8 (101.1)	62.8 (101.1)	62.8 (101.1)
	Angle, deg	25.7	25.0	25.0
	Impact Point in. (mm), from upstream from Post 19	129.1 (3,279)	129.0 (3,277)	129.0 (3,277)
Impact Severity, kip-ft (kN-m)		124.7 (169.1)	117.9 (159.9)	117.9 (159.9)
Parallel Conditions	Speed, mph (km/h)	36.9 (59.5)	38.2 (61.5)	39.6 (63.7)
	Time, ms	270	253	250
Exit Conditions	Speed, mph (km/h)	33.1 (53.2)	33.2 (53.4)	33.2 (53.4)
	Angle, deg	19.5	15.4	15.7
	Time, (ms)	520	660	620
t*, seconds		0.1225	0.1324	0.1324
ORA, g's	Longitudinal	-13.78	-12.30	-12.54
	Lateral	-10.24	-7.44	-8.64
OIV, ft/s (m/s)	Longitudinal	-19.60 (-6.0)	-19.03 (-5.8)	-19.03 (-5.8)
	Lateral	-16.58 (-5.1)	-17.39 (-5.3)	-17.4 (-5.3)
Test Article Deflection	Max Rail deflection, in. (mm)	22.4 (569)	25.3 (643)	26.8 (681)
	Max Rail deflection Time, ms	192	177	350
	Max Post deflection, in. (mm)	29.6 (752)	15.3 (389)	15.6 (396)
	Max Post deflection Time, ms	137	110	110
	Working Width, in. (mm)	50.8 (1,290)	42.5 (1,080)	41.5 (1,054)
	Working Width Location (Post No.)	17	18	18
Euler Angles	Max Roll, Deg	3.4	6.1	11.6
	Max Roll Time, ms	257	350	626
	Max Pitch, Deg	-9.0	-4.7	-6.1
	Max Pitch Time, ms	600	360	473
	Max Yaw, Deg	-40.7	-40.7	-42.2
	Max Yaw Time, ms	600	621	651
Disengaged Post Nos.		18, 19	N.A.	N.A.
Posts Impacted by Leading Tire		18, 19	17 through 21	17 through 21
Deflected Posts		15 through 23	15 through 23	15 through 23
Total Length of Vehicle Contact, in. (mm)		289 (7,341)	300 (7,620)	300 (7,620)
Time Leading Tire Disengaged, ms		155	N.A.	150-160

Initial comparisons were made between the full-scale crash test and the baseline simulation model without wheel disengagement. The maximum tested and simulated dynamic rail deflection was 22.4 in. (569 mm) and 25.3.8 in. (643 mm), respectively. The Euler angles for the test and the model also have similar results before the wheel completely disengaged during the test. As shown in Figure 107, the tested and simulated vehicle longitudinal velocity changes were similar. However, there was some discrepancy in the lateral velocity change after 200 ms. This discrepancy may have been caused by wheel disengagement during the test. Failure of control arms, wheels, and tires was not incorporated in the standard vehicle model, as it was computationally expensive and could not be reliably predicted.

The deflected rail shape for test no. CMGS-2 and the baseline simulation model without wheel disengagement were compared at 192 ms, when the maximum rail dynamic deflection occurred, as shown in Figure 108. The tested rail deflection was obtained using high-speed videos. The maximum tested and simulated rail deflections at 192 ms were generally in good agreement.



(a)



(b)

Figure 107. Velocity Comparison, Test and Baseline Simulation (No Wheel Disengagement): (a) Longitudinal Change in Velocity; (b) Lateral Change in Velocity

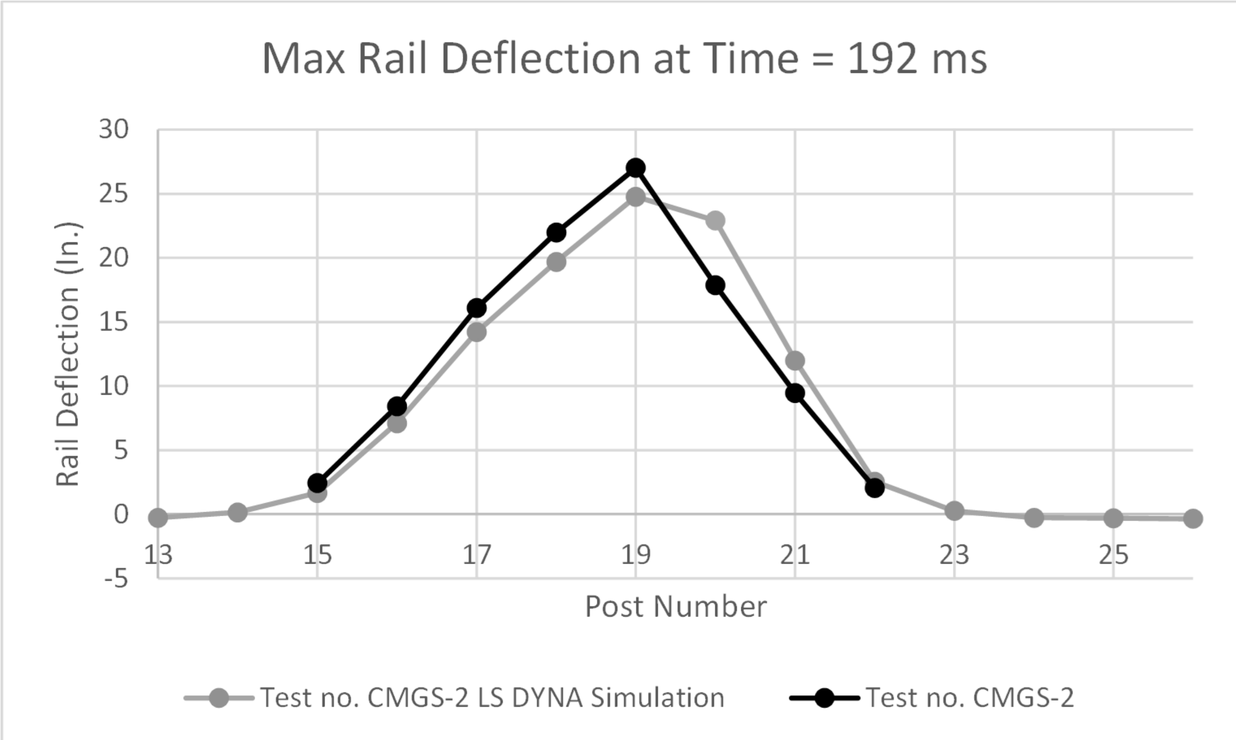
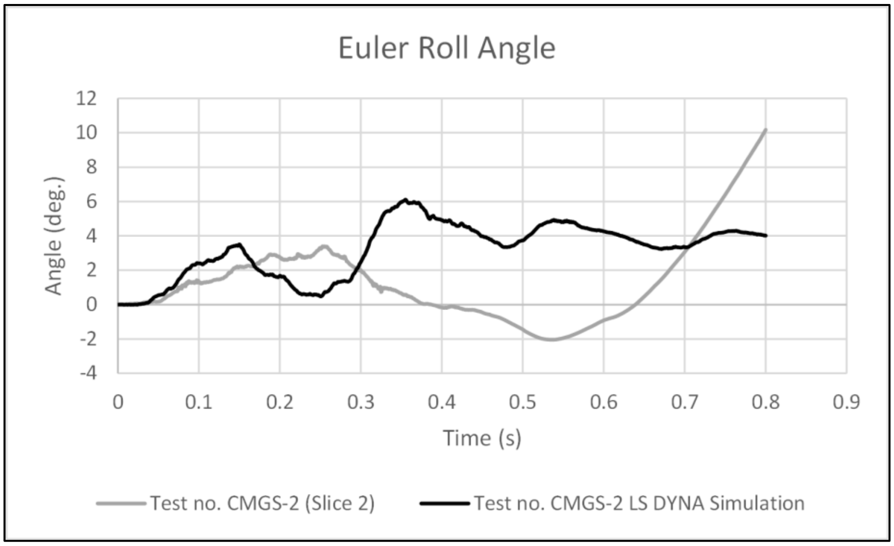
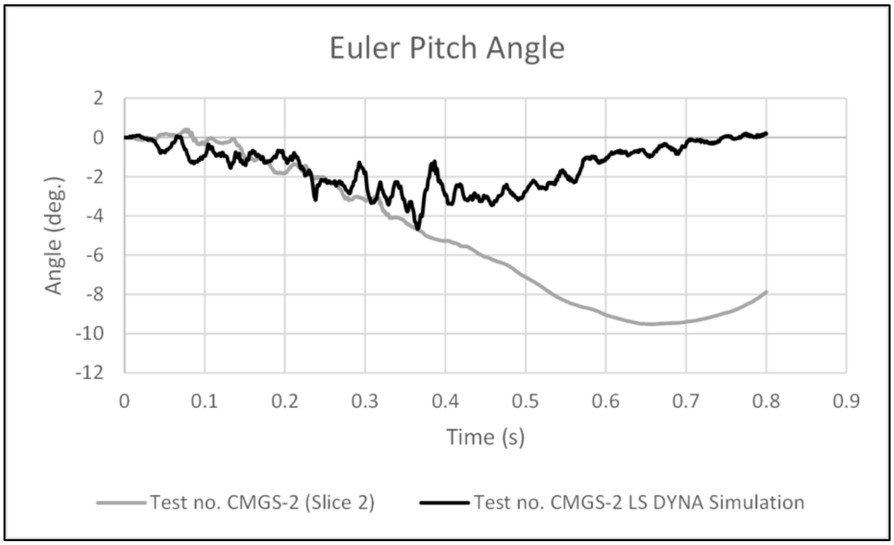


Figure 108. Deflection Comparison, Test and Baseline Simulation (No Wheel Disengagement)

The roll, pitch and yaw angles were compared between the test and baseline simulation model without wheel disengagement, as shown in Figure 109. The simulated vehicle had a maximum roll of 6.1 degrees, while the maximum vehicle roll during test no. CMGS-2 was 3.4 degrees while in contact with barrier, and 10.2 degrees after exiting the barrier. The simulated vehicle pitch was -4.6 degrees while it was still in contact with the barrier. Whereas the test vehicle pitch was -9.5 degrees after the vehicle exited the barrier. The simulated and test vehicle yaw angles agreed well until 300 ms but the difference remained within 20% until the simulated vehicle exited the barrier at 660 ms. Overall, the roll, pitch, and yaw in test no. CMGS-2 and simulation agreed well before 300 ms. However, after 300 ms, the trajectory of the vehicle in the test and simulation deviated.





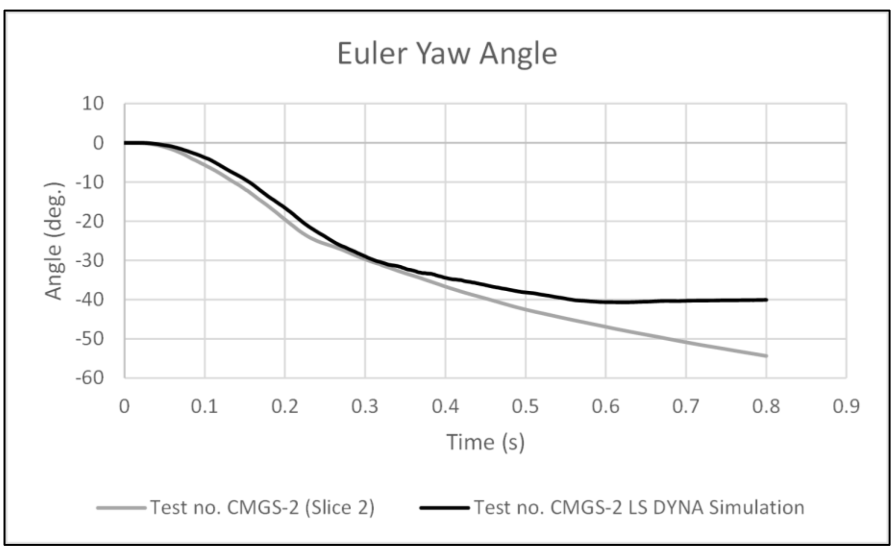


Figure 109. Roll, Pitch and Yaw Angles Comparison, Baseline Simulation

In test no. CMGS-2, the impact-side wheel of the test vehicle snagged on posts nos. 18 and 19 and was disengaged. However, the initial baseline model did not have wheel disengagement enabled. Thus, a modified model with wheel disengagement capabilities was configured. Note that failure of wheel and suspension parts cannot be reliably predicted. Thus, time-based failure was enabled in the vehicle model. This wheel disengagement model required a prescribed time to initialize the three-stage wheel disengagement process, which involves disengaging upper, lower, and steering control arms from the vehicle model. The disengagement time was estimated using test videos. Specifically, the front wheel at the guardrail side started disengaging at time 150 ms and the wheel was completely disengaged at time 160 ms. This wheel disengagement time corresponded to the approximate wheel disengagement time of 155 ms during the test. Other than the wheel disengagement, everything else in the barrier and vehicle models was kept the same with the initial baseline model. Sequential time comparisons of the baseline model without wheel disengagement, the modified model with wheel disengagement, and test no. CMGS-2 are shown in Figure 110.

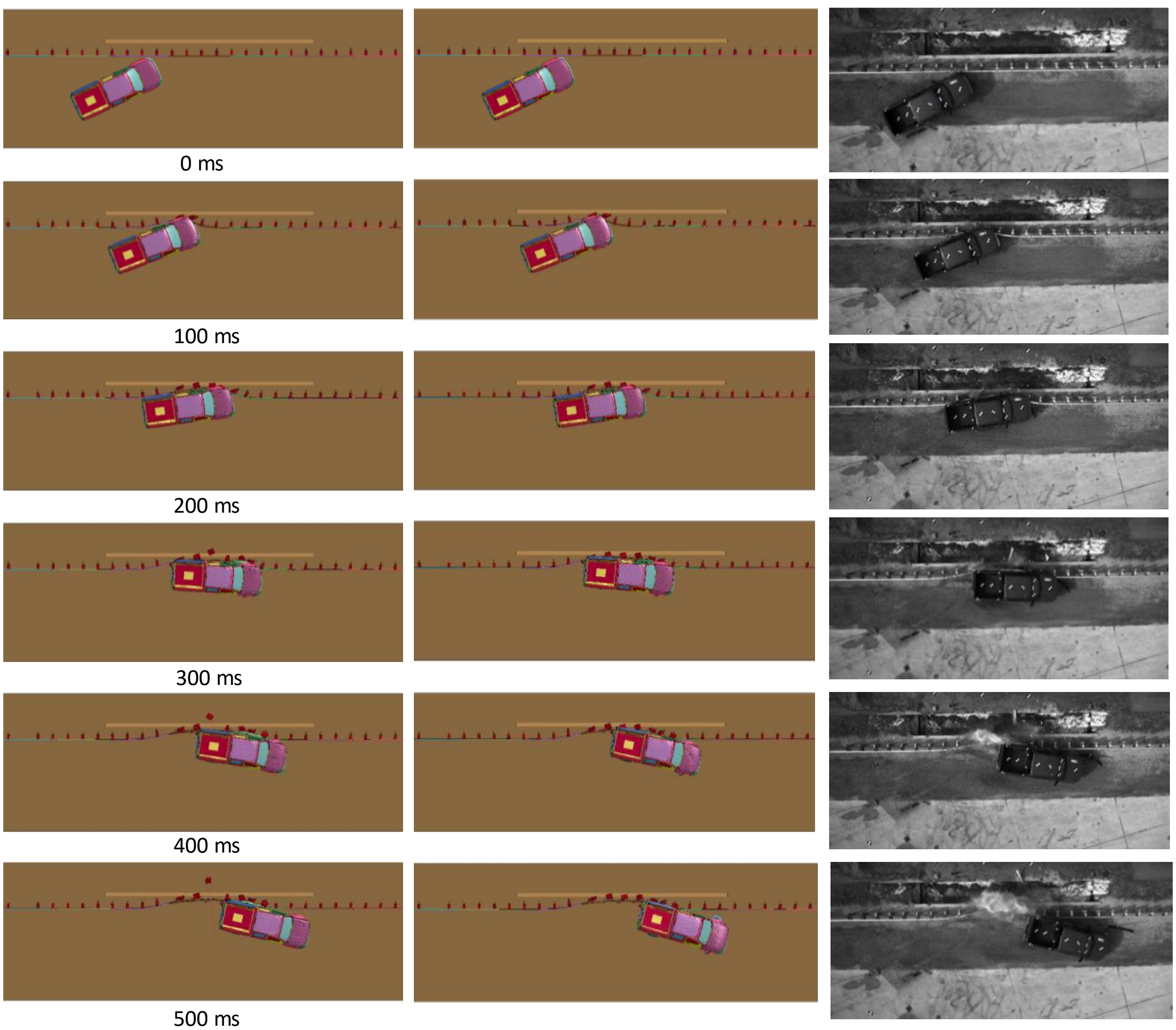


Figure 110. Simulation without Wheel Disengagement (Left), Simulation with Wheel Disengaged (Middle), and Test No. CMGS-2 (Right)

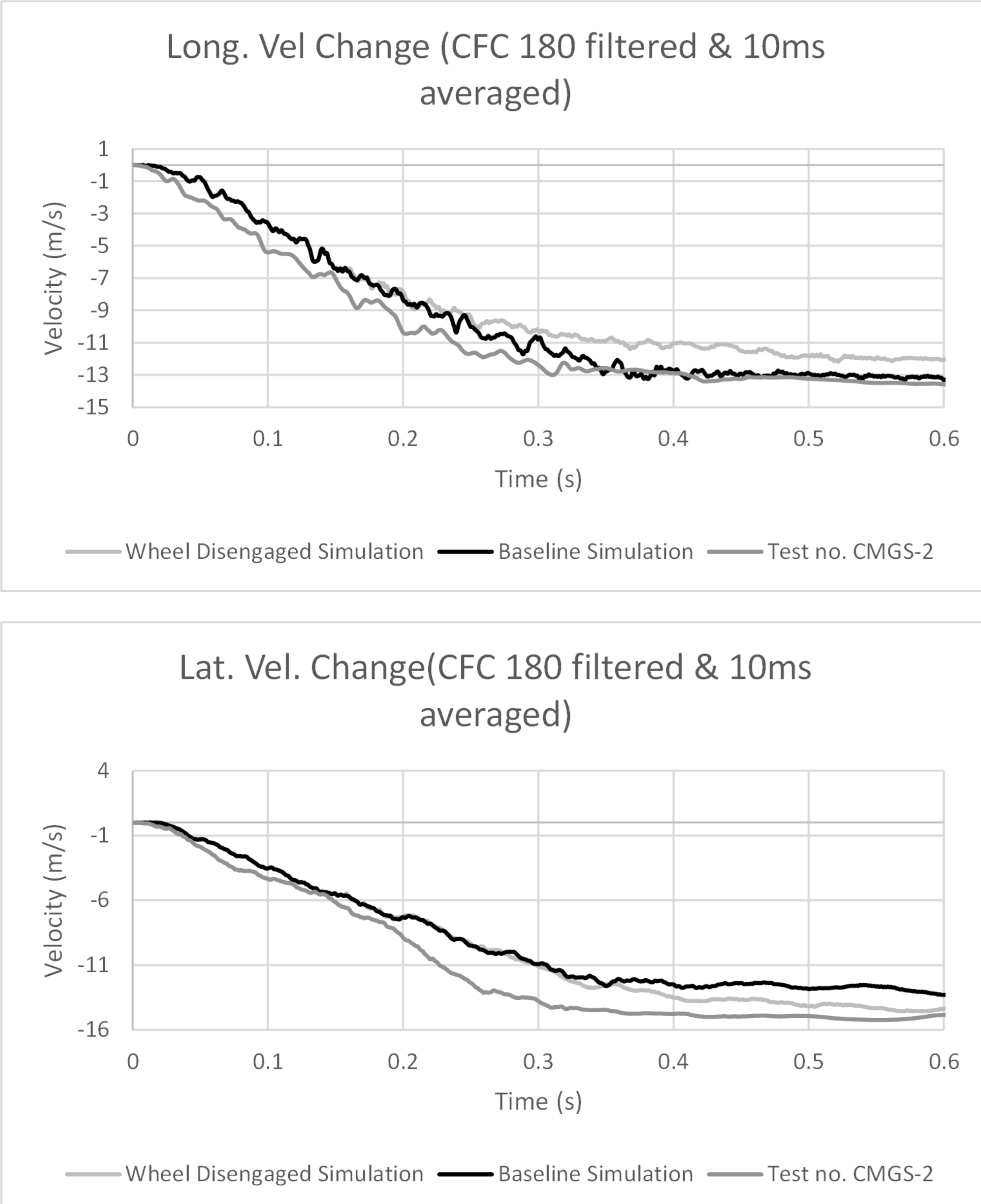


Figure 111. Change of Velocity Comparison, Baseline and Wheel Disengaged Models

The lateral change in velocity in the wheel disengaged model was closer to test no. CMGS-2 than the baseline model, as shown in Figure 111. However, the longitudinal change in velocity deviated more significantly. Additionally, several other wheel failure times were explored, but none of them were able to replicate the wheel disengagement behavior that occurred in test no. CMGS-2.

Important metrics were similar in Table 15, and the tested and simulated velocity and Euler angle curves also agreed well. However, the wheel disengaged during test no. CMGS-2, and the current modeling techniques could not replicate the wheel disengagement. Note that the baseline model accurately represented rail deformation and deflection, which was believed to be the most important metric when evaluating the transition. Additionally, the standard MGS model had been previously validated, and the impact points for the transition areas were located near the standard MGS. Thus, the culvert MGS model was considered sufficient to evaluate the impact point in transition between the standard MGS to half-post spacing MGS.

7.2.3 Determination of Critical Impact Point

After development of the culvert-mounted MGS model, eight impact points at the transition area from standard MGS to half-post spacing MGS were simulated, as illustrated in Figure 112. The detailed results are summarized in Table 16.

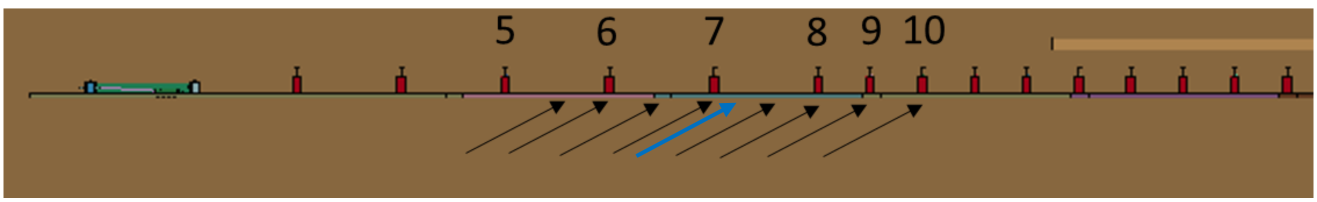


Figure 112. Illustration of Impact Points at Transition from Standard MGS to Half-Post Spacing MGS with Critical Impact Point Denoted in Blue

Starting from the midspan of post nos. 5 and 6, eight impact points were selected at an interval of 37½ in. (953 mm) through post no. 10. The results of eight cases are summarized and compared to the baseline model in Table 16. As shown in Table 16, longitudinal ORA at the mid-span of post nos. 7 and 8 had the largest value, which corresponded with significant wheel snag. At this impact point, other metrics including OIV (both lateral and longitudinal), anchor force, roll and pitch angles also had higher values. Thus, the critical impact point in this transition area was determined as the mid-span of post nos. 7 and 8 (i.e., 37½ in. (953 mm) from the first reduced span post).

This critical impact point was the same as impact point in test no. MWTSP-2. Since test no. MWTSP-2 was successful and had similar post sections, posts spacing, and rail sections in the impact region, the standard MGS to half-post spacing MGS transition region was believed to not expose errant vehicles to any additional hazards. Thus, a separate transition was not believed to be necessary between standard MGS and half-post spacing MGS based on the simulation analysis and comparison with existing test no. MWTSP-2. However, as noted previously, recent research at TTI with reduced post spacings suggests that the potential for rail rupture exists in regions with reduced posts spacings or transitions in post spacing under MASH TL-3 impact conditions. Thus, the researchers finding that a separate transition region is not needed between the standard MGS and half-post spacing MGS may need revision based on new full-scale crash test results or further findings from the ongoing TTI studies.

Table 16. Transition Simulated Impacts Comparison

Comparison of Results		Stiffness Transition Simulations								Baseline Simulation
Vehicle	Year, Make, Model	Chevy, Silverado 1500								
	Test Inertial Weight, lb (kg)	5005 (2270)								
Impact Conditions	Speed, mph (km/h)	62.1 (100.0)								62.8 (101.1)
	Angle, Deg	25								
	Impact Post No.	5.5*	6	6.5	7	7.5	8	9	10	15.57
Impact Severity, kip-ft (kN-m)		115.2 (156.3)								117.9 (159.8)
Parallel Conditions	Speed, mph (km/h)	43.8 (70.5)	37.0 (59.5)	40.7 (65.5)	40.7 (65.5)	39.2 (63.1)	39.2 (63.1)	38.4 (61.8)	40.0 (64.4)	37.5 (60.3)
	Time, ms	258	258	252	255	254	254	268	263	250
t*, seconds		0.1551	0.1567	0.1525	0.1516	0.1474	0.1422	0.1402	0.1394	0.1324
ORA, g's	Longitudinal	-8.5	-10.9	-11.9	-14.8	-16.1	-10.2	-14.3	-15.	-12.3
	Lateral	-10.1	-7.8	-9.7	-8.4	-9.5	-8.5	-9.4	-7.9	-7.4
OIV, ft/s (m/s)	Longitudinal	-16.8 (-5.1)	-17.5 (-5.3)	-18.2 (-5.6)	-20.3 (-6.2)	-19.2 (-5.9)	-20.8 (-6.3)	-19.4 (-5.9)	-16.9 (-5.2)	-19.0 (-5.8)
	Lateral	-16.7 (-5.1)	-16.5 (-5.0)	-17.2 (-5.2)	-17.2 (-5.2)	-18.1 (-5.5)	-17.8 (-5.4)	-16.9 (-5.2)	-16.2 (-4.9)	-17.4 (-5.3)
Test Article Deflections	Max Rail Deflection, in (mm.)	35.5 (902)	36.3 (922)	32.9 (836)	32.3 (820)	30.4 (772)	28.1 (714)	28.8 (732)	28.4 (721)	25.3 (643)
	Max Rail Location, from Post No. 5, in. (mm)	182.4 (4,633)	211.2 (5,364)	259.2 (6,584)	288.0 (7,315)	326.4 (8,291)	384.0 (9,754)	403.2 (10,241)	441.6 (11,217)	637.5 (16,193)
	Max Rail Deflection Time, ms	360	350	173	160	160.00	200	170	173	177

Table 17. Transition Simulated Impacts Comparison, Cont.

Comparison of Results		Stiffness Transition Simulations								Baseline Simulation
Euler Angles	Max Roll, Deg	5.5	4.1	5.5	4.2	6.5	4.1	5.7	5.0	6.1
	Max Roll Time, ms	363	414	372	194	420	186	377	389	350
	Max Pitch, Deg	-3.9	-4.3	-3.7	-4.4	-5.2	-4.2	-4.7	-5.1	-4.7
	Max Pitch Time, ms	395	360	338	241	336	275	291	393	360
	Max Yaw, Deg	-45.8	-47.0	-47.2	-49.4	-43.0	-45.2	-457	-38.9	-40.7
	Max Yaw Time, ms	524	529	795	795	568	526	753	792	621
Pocketing Angle	Angle, Deg	-25.8	-24.6	-22.7	-24.1	-23.0	-23.8	-23.7	-24.1	-21.4
	Time, ms	500	500	340	430	190	150	530	470	150
Section Forces	Max Upstream Anchor, kips (kN)	40.1 (178.4)	39.3 (174.8)	38.6 (171.7)	39.9 (177.5)	35.2 (156.6)	37.0 (164.6)	36.9 (164.1)	33.1 (174.2)	26.1 (116.1)
	Time, ms	131	143	164	147	155	118	158	119	116
	Max Downstream Anchor, kips (kN)	11.2 (49.8)	11.3 (50.3)	11.6 (51.6)	10.9 (48.5)	12.4 (55.2)	10.3 (45.8)	11.7 (52.0)	12.5 (55.6)	13.8 (61.4)
	Time, ms	162	170	137	165	160	139	137	88	114
	Max Neighboring Upstream Rail, kips (kN)	57.3 (254.9)	52.9 (235.3)	50.0 (222.4)	49.9 (222.0)	51.7 (230.0)	53.0 (235.8)	48.9 (217.5)	48.1 (214.0)	N.A.**
	Time, ms	129	134	161	137	133	138	93	117	N.A.
	Max section force right after post no. 2, kips (kN)	52.5 (233.5)	47.4 (210.8)	44.1 (196.2)	46.1 (205.1)	43.6 (193.9)	42.8 (190.4)	39.0 (173.5)	38.7 (172.1)	28.1
	Time, ms	129	149	162	156	151	136	114	114	151

*5.5 represents the mid-span between post nos. 5 and 6
** N.A. = not available

7.3 Transition Recommendations for Culvert Mounted MGS System

The strong post, culvert mounted MGS system utilized a stiffened barrier configuration as comparted to the standard MGS. This design uses W6x9 posts as half-post spacing bolted to the top of the culvert slab. Attachment of this system to the standard MGS on each end of the culvert utilized a minimum of five posts at half-post spacing in soil prior to the culvert mounted posts. This transition required analysis of two distinct transition regions on the approach to the culvert mounted guardrail: 1) the transition from half-post spaced posts in soil to half-post spaced culvert mounted posts; and 2) the transition from standard MGS to half-posts spacing MGS. The downstream transition was not considered in the analysis as transitioning from a stiffened to a less stiff region of the barrier system is not considered a hazard. The analysis of the two transition regions led to the following recommendations.

1. For the transition from half-post spaced posts in soil to half-post spaced culvert mounted posts, no additional transition was recommended as comparison of the stiffness and energy dissipation of the W6x8.5 posts embedded 40 in. (1,016 mm) in soil and the W6x9 culvert-mounted post were virtually identical. This would indicate that there would be little difference in barrier stiffness and performance in that region of the system.

2. For the transition from standard MGS to half-posts spacing MGS, LS-DYNA analysis was used to determine the critical impact point of the transition region. The simulation analysis indicated that the critical impact point for this transition region was the mid-span of post nos. 7 and 8 (i.e., 37½ in. (953 mm) from the first reduced span post). This point was the same impact point that was previously impacted in test no. MWTSP-2 on the MGS upstream stiffness transition for thrie beam approach guardrail transitions. The upstream stiffness transition in test no. MWTSP-2 similar post sections, posts spacing, and rail sections in the impact region as the proposed transition region in the culvert mounted MGS design. Based on comparison with this similar, successful full-scale crash test, it was recommended that no additional transition was needed between the standard MGS and the half-post spacing MGS system. However, it was noted that further research may be needed to alleviate concerns raised in parallel ongoing research conducted at TTI. The results of those research studies are ongoing and may affect future recommendations for the culvert-mounted guardrail transition.

8 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The objective of this research was to evaluate the safety performance of the MGS installed on a culvert with a strong-post attachment using W6x9 steel posts welded to anchored baseplates at half-post spacing and offset 12 in. (305 mm) from the back of the post to the culvert headwall. Test nos. CMGS-1 and CMGS-2 were conducted according to MASH 2016 test designation nos. 3-10 and 3-11, respectively. The installation in each test consisted of 182.3 ft (55.6 m) of guardrail constructed atop a 43.3-ft (13.2-m) long simulated four-cell concrete box culvert. The culvert-mounted MGS was supported by steel posts with a top mounting rail height of 31 in. (787 mm). A summary of the test evaluation is shown in Table 18.

In test no. CMGS-1, the 2,428-lb (1,101-kg) car impacted the culvert-mounted MGS system at a speed of 61.3 mph (98.7 km/h), an angle of 25.1 degrees, and at a location of 92 in. (2,337 mm) upstream from post no. 19, thus resulting in an impact severity of 54.8 kip-ft (74.3 kJ). The vehicle was successfully contained and smoothly redirected with moderate damage to both the barrier system and the vehicle. All occupant crush, ORAs, and OIVs fell within the recommended safety limits established in MASH 2016. The vehicle trajectory did not violate the bounds of the exit box. Therefore, test no. CMGS-1 was successful according to the safety criteria of MASH 2016 test designation no. 3-10.

In test no. CMGS-2, the 5,013-lb (2,274-kg) pickup truck impacted the culvert-mounted MGS system at a speed of 62.8 mph (101.1 km/h), an angle of 25.7 degrees, and at a location of 129.1 in. (3,279 mm) upstream from post no. 19, thus resulting in an impact severity of 124.7 kip-ft (169.1kJ) The vehicle was successfully contained and smoothly redirected with moderate damage to both the barrier system and the vehicle. All occupant crush, ORAs, and OIVs fell within the recommended safety limits established in MASH 2016. Therefore, test no. CMGS-2 was successful according to the safety criteria of MASH 2016 test designation no. 3-11. Therefore, the culvert-mounted MGS with a 12-in. (305-mm) offset from the back of the post to the culvert headwall met all the requirements of MASH 2016 test designation nos. 3-10 and 3-11.

Following two successful full-scale crash tests on culvert-mounted MGS, the performance of the transition between the MGS and the culvert-mounted MGS was evaluated. Two stiffness transitions in this system were further investigated: (1) transition from half-post spacing MGS to culvert-mounted MGS; and (2) transition from the standard MGS to half-post spacing MGS.

For transition from the half-post spacing MGS to culvert-mounted MGS, a separate transition system is not necessary, because the resistance of the culvert-mounted posts and the posts embedded 40 in. (1,016 mm) in soil were found very similar through component-level bogie tests.

For transitioning from the standard MGS to the culvert-mounted MGS, at least five posts embedded 40 in. (1,016 mm) in soil at half-post spacing are recommended to be installed both upstream and downstream from the culvert-mounted posts.

For transition from the standard MGS and half-post spacing MGS, no additional stiffness transition is required, as this transition has been successfully tested during a previous similar test, test no. MWTSP-2 [21]. In test no. MWTSP-2, a 5,158-lb (2,340-kg) pickup truck impacted the full-spacing MGS that was transitioned to half-post spacing MGS at a speed of 61.2 mph (98.5

km/h) and at an angle of 26.3 degrees. The pickup truck was safely contained, and test no. MWTSP-2 was determined to be acceptable according to test designation no. 3-21 of MASH. Additional LS-DYNA numerical simulations confirmed the critical impact point as similar to the impact point in test no. MWTSP-2. Since the transition from standard MGS to half-post spacing MGS with this critical impact point did not result in any out of limit metrics specified in MASH in test no. MWTSP-2, this transition was believed to not expose errant vehicles to any additional hazards. However, it was noted that further research may be needed to alleviate concerns raised in parallel ongoing research conducted at TTI. The results of those research studies are ongoing and may affect future recommendations for the culvert-mounted guardrail transition.

8.1 Recommendations

The culvert-mounted MGS is unrestricted in terms of increased system length and could be implemented on culverts with lengths longer than the as-tested culvert. In terms of shorter installation lengths, there would be no reason that system lengths could not theoretically be as short as a single post. However, other solutions such as the MGS long span guardrail system and the MGS with an omitted post would likely be more practical solutions for very short culvert type post obstructions. Additionally, it is recommended to retain the half-post spacing transition region adjacent to the culvert mounted MGS system regardless of the system length.

It is recommended that at least five posts embedded 40 in. (1,016 mm) in soil at half-post spacing are installed both upstream and downstream from the culvert-mounted posts. This half-post spacing region outside of the culvert mounted posts was utilized in the original NCHRP Report No. 350 tested system and was carried over to this design to provide a more conservative transition between standard MGS and the culvert-mounted system. There is potential that this transition region could be omitted, but further research into the would be recommended prior to implementing a less conservative transition region. In order to prevent interference with post rotation in soil, the first guardrail post within the half-post spacing MGS adjacent to the culvert should have a minimum 12-in. (305-mm) clear distance to any part of the culvert. This clearance should limit a rotated and displaced guardrail post from interacting with the culvert.

The culvert mounted MGS system evaluated herein was tested utilizing an 8-in. (203-mm) thick culvert slab with non-conservative reinforcement. No damage was noted to the culvert slab following the full-scale crash testing. Installation of the system on culvert slabs with equal or greater thickness and structural reinforcement are expected to provide similar performance. The original NCHRP Report No. 350 full-scale crash testing of this design utilized a 7-in. (178-mm) thick culvert slab with similar reinforcement and displayed little to no damage. Because this system the same post section, baseplate, and anchorage, it is believed that the previously tested 7-in. (178-mm) thick culvert slab would also perform acceptably. Installations on thinner culvert slabs with lesser reinforcement may result in increased culvert slab damage and potential changes in post behavior. Thus, it is recommended that the system be implemented on culvert designs with similar or greater structural capacity than the simulated culvert slabs previously full-scale crash tested.

The culvert mounted MGS system evaluated herein was tested utilizing an embedment depth of 9 in. (229 mm). This should be considered the minimum allowable embedment depth for the culvert mounted MGS system. Installing the posts at shallower embedments shortens the moment arm of the post and stiffens the response of each post. This, in turn, can lead to increased rail loads and pocketing which may degrade the performance of the system. Additionally, installation of the posts at shorter embedment increases the propensity for wheel snag on the posts as the lower section of the post cannot rotate and displace as much. This also can degrade the system performance. Soil fill deeper than 9 in. (229 mm) over the deck offers more support to culvert-mounted posts, therefore it does not cause concern. Greater depth of soil material would result in a post more similar to an embedded steel post in soil within the standard MGS. As such, larger embedments less than 40 in. (1016 mm) would be allowable. The top mounting height of the guardrail should remain at 31 in. (787 mm) above the top of the soil fill.

Similarly, the culvert mounted MGS system evaluated herein was tested utilizing an offset from back of the post to the culvert headwall of 12 in. (305 mm). Shorter offsets are not recommended at this time as they would tend to limit post rotation and may result in increased rail pocketing and rail loading. Offsets larger than 12 in. (305 mm) would be considered acceptable.

The culvert mounted guardrail post should not be placed too close to the upstream or downstream ends of a culvert. If a post and anchorage is placed near the end of a headwall, the attachment anchors may not have enough concrete cover to develop the required shear and/or tension loads. Thus, a minimum of 4 in. (102 mm) should be used between a free end of a culvert headwall and the center of any attachment anchor.

Anchorage of the culvert mounted posts in the full-scale crash tested barrier system was primarily accomplished with through bolts. In areas of the installation where slab support walls interfered with through bolting, an alternative epoxy anchorage was utilized than had previously be developed for the culvert post attachment through a series of dynamic bogie tests. The dynamic bogie testing demonstrated that the alternative epoxy anchorage was capable of fully developing the capacity of the culvert-mounted W6X9 post would be considered acceptable for installation of the culvert-mounted MGS system. However, it should be noted that the epoxy anchorage requires 8 in. (203mm) of embedment. As such, installation of the epoxy anchorage should ensure that the culvert slab has sufficient thickness to adequately install the anchor. Full details and recommendations for the installation of the epoxy anchorage for the culvert mounted W6x9 posts can be found in the original research report [7].

Often, culvert headwalls may extend 6.0 in. (152 mm) or more above the groundline. Headwall extensions of this magnitude would represent a vertical curb adjacent to the barrier and could pose a stability hazard or adversely affect barrier performance. Thus, it is recommended that the culvert headwall extend no higher than 2.0 in. (51 mm) above the groundline and that any extensions greater than 2.0 in. (51 mm) be ground down to match the ground profile.

It may be desired to install the culvert-mounted MGS system adjacent to a fill-slope. Placement of the culvert mounted posts adjacent to or at the slope break point of a fill slope may change the lateral resistance of the post due to the reduction of soil fill behind the post and subsequently affect the barrier performance. Because the effect of placement of the culvert-mounted posts adjacent to a fill slope is not currently quantified, it is recommended to use a minimum of 2 ft (610 mm) of level terrain from the back of the post to the start of the fill slope in order to provide consistent post response. Additionally, the system was designed and evaluated for use on low-fill culverts with relatively flat grading. It is recommended that the system only be used with approach slopes of 10H:1V or flatter.

Finally, installations should be implemented with the guardrail terminals (or end anchorages) located a sufficient distance from the culvert to prevent the two systems from interfering with the proper performance of one another. As such, the following implementation guidelines should be considered in addition to guardrail length of need requirements:

1. A recommended minimum length of 12 ft – 6 in. (3.8 m) of standard MGS between the first post at half-post spacing and the interior end of an acceptable TL-3 guardrail end terminal.

2. A recommended minimum barrier length of 50 ft (15.2 m) before the first post at half-post spacing, which includes standard MGS and a crashworthy guardrail end terminal. This guidance applies to the downstream end as well.

3. For flared guardrail applications, a minimum length of 25 ft (7.6 m) is recommended between the first post at half-post spacing and the start of the flared section (i.e. bend between flared and tangent sections).

Table 18. Summary of Safety Performance Evaluation

<table>
<tr><th>Evaluation Factors</th><th colspan="2">Evaluation Criteria</th><th>Test No. CMGS-1</th><th>Test No. CMGS-2</th></tr>
<tr><td>Structural Adequacy</td><td>A.</td><td>Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>S</td><td>S</td></tr>
<tr><td rowspan="6">Occupant Risk</td><td rowspan="2">D.</td><td>1. Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone.</td><td>S</td><td>S</td></tr>
<tr><td>2. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of MASH 2016.</td><td>S</td><td>S</td></tr>
<tr><td>F.</td><td>The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.</td><td>S</td><td>S</td></tr>
<tr><td>H.</td><td>Occupant Impact Velocity (OIV) (see Appendix A, Section A5.2.2 of MASH 2016 for calculation procedure) should satisfy the following limits:<table><tr><th colspan="3">Occupant Impact Velocity Limits</th></tr><tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr><tr><td>Longitudinal and Lateral</td><td>30 ft/s (9.1 m/s)</td><td>40 ft/s (12.2 m/s)</td></tr></table></td><td>S</td><td>S</td></tr>
<tr><td>I.</td><td>The Occupant Ridedown Acceleration (ORA) (see Appendix A, Section A5.2.2 of MASH 2016 for calculation procedure) should satisfy the following limits:<table><tr><th colspan="3">Occupant Ridedown Acceleration Limits</th></tr><tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr><tr><td>Longitudinal and Lateral</td><td>15.0 g's</td><td>20.49 g's</td></tr></table></td><td>S</td><td>S</td></tr>
<tr><td colspan="2"></td><td></td><td></td></tr>
<tr><td colspan="3">MASH Test Designation No.</td><td>3-10</td><td>3-11</td></tr>
<tr><td colspan="3">Final Evaluation (Pass or Fail)</td><td>Pass</td><td>Pass</td></tr>
</table>

S – Satisfactory U – Unsatisfactory NA - Not Applicable

9 MASH EVALUATION

In this study, the safety performance of the MGS installed on a culvert with a strong-post attachment using W6x9 steel posts welded to anchored baseplates at half-post spacing and offset 12 in. (305 mm) from the back of the post to the culvert headwall was evaluated through full-scale crash testing. The system consisted of strong post MGS mounted on a simulated four-cell concrete box culvert system. Anchorage systems were utilized at both the upstream and downstream ends of the guardrail system. Steel post nos. 3 through 12 and 27 through 39 were embedded in soil a depth of 40 in. (1,016 mm). Post nos. 13 through 26 were embedded a depth of 9 in. (229 mm) and anchored to the top of the concrete culvert using welded steel baseplates. Post nos. 13 through 15, 17 through 22, and 24 through 26 were anchored to the top concrete slab using four through-bolts, and post nos. 16 and 26 were anchored using 10-in. (254-mm) long epoxied threaded rods with an 8-in. (203 mm) embedded length due to the presence of the culvert's interior wall support.

9.1 MASH Crash Test Matrix

According to TL-3 evaluation criteria in MASH 2016, two tests are required for evaluation of longitudinal barrier systems: (1) test designation no. 3-10 – an 1100C small car and (2) test designation no. 3-11 – a 2270P pickup truck. Critical impact points (CIPs) for both impacts were determined based on calculated post and guardrail beam strengths and the use of MASH 2016 Figures 2-8 and 2-11 for the 1100C and 2270P vehicle impacts, respectively.

9.2 Full-Scale Crash Testing

In test no. CMGS-1, a 2,428-lb (1,101-kg) sedan with a simulated occupant seated in the right-front passenger seat, impacted the MGS atop culvert system at a speed of 61.3 mph (98.7 km/h) and at an angle of 25.1 degrees, resulting in an impact severity of 54.8 kip-ft (74.3 kJ). At 0.259 sec after impact, the vehicle became parallel to the system with a speed of 26.5 mph (42.6 km/h). At 0.464 sec, the vehicle exited the system at a speed of 24.7 mph (39.8 km/h) and at an angle of 17.0 degrees. The vehicle was successfully contained and smoothly redirected.

Exterior vehicle damage was moderate. Interior occupant compartment deformations were moderate with a maximum of 3⅜ in. (86 mm), which was not observed on the test day. Prior to the vehicle deformations' measurements, the snow and ice on the windshield caused an additional caving in deformation. Therefore, this deformation exceeding the MASH deformation criteria was not from the impact event and was not critical to the test evaluation.

Damage to the system was also moderate, consisting mostly of deformed W-beam, contact marks on the guardrail sections, and deformed posts. The maximum lateral permanent set of the barrier system was 11⅞ in. (302 mm). The maximum dynamic barrier deflection was 12.0 in. (305 mm), which included vehicle overhang along the MGS. The working width of the system was 33.1 in. (842 mm). All occupant risk measures were within the recommended limits, and the occupant compartment deformations were also deemed acceptable. Therefore, the MGS atop culvert system successfully met all the safety performance criteria of MASH 2016 test designation no. 3-10.

In test no. CMGS-2, a 5,013-lb (2,274-kg) pickup truck with a simulated occupant seated in the right-front passenger seat, impacted the MGS atop culvert system at a speed of 62.8 mph (101.1 km/h) and at an angle of 25.7 degrees, resulting in an impact severity of 124.7 kip-ft (169.1

kJ). At 0.270 sec after impact, the vehicle became parallel to the system with a speed of 36.9 mph (59.5 km/h). At 0.520 sec, the vehicle exited the system at a speed of 33.1 mph (53.2 km/h) and at an angle of 17.4 degrees. The vehicle was successfully contained and smoothly redirected.

Exterior vehicle damage was moderate. Interior occupant compartment deformations were moderate with a maximum of 1⅛ in. (29 mm), which did not violate the limits established in MASH 2016. Damage to the system was also moderate, consisting of contact marks on the front face of the guardrail sections and deformation of W-beam and posts. The maximum lateral permanent set of the barrier system was 15¾ in. (400 mm). The maximum dynamic barrier deflection was 29.6 in. (753 mm), which included vehicle overhang along the MGS. The working width of the system was 50.8 in. (1,290 mm). All occupant risk measures were within the recommended limits, and the occupant compartment deformations were also deemed acceptable. Therefore, the MGS atop culvert system successfully met all the safety performance criteria of MASH 2016 test designation no. 3-11.

9.3 MASH 2016 Evaluation

Based on the results of the two successful full-scale crash tests conducted herein, the culvert-mounted MGS system meets all of the safety requirements for MASH 2016 TL-3.

Additionally, an analysis of the transition between the MGS and the culvert-mounted MGS was completed. Two stiffness transitions in this system were investigated: (1) transition from half-post spacing MGS to culvert-mounted MGS; and (2) transition from the standard MGS to half-post spacing MGS. For transition from the half-post spacing MGS to culvert-mounted MGS, a separate transition system was not necessary, because the resistance of the culvert-mounted posts and the posts embedded 40 in. (1,016 mm) in soil were found very similar through component-level bogie tests [19-20].

For transitioning from the standard MGS to the culvert-mounted MGS, at least five posts embedded 40 in. (1,016 mm) in soil at half-post spacing were recommended to be installed both upstream and downstream from the culvert-mounted posts. No additional stiffness transition was believed to be required, as a similar transition region had been successfully tested during a full-scale crash testing of the MGS upstream stiffness transition to thrie beam approach guardrail transitions in test no. MWTSP-2 [21]. Additional LS-DYNA numerical simulations confirmed the critical impact point for the transition from standard to half-post spacing MGS as similar to the impact point in test no. MWTSP-2. Since the transition from standard MGS to half-post spacing MGS with this critical impact point did not result in any out of limit metrics specified in MASH in test no. MWTSP-2, this transition was believed to not expose errant vehicles to any additional hazards. However, it was noted that further research may be needed to alleviate concerns raised in parallel ongoing research conducted at TTI. The results of those research studies are ongoing and may affect future recommendations for the culvert-mounted guardrail transition.

10 REFERENCES

1. Hirsch, T.J. and Beggs, D., Use of Guardrails on Low Fill Bridge Length Culverts, *Transportation Research Record No. 1198, Journal of Transportation Research Board*, Washington, D.C., 1988.

2. Bielenberg, B.W., Faller, R. K., Rohde, J.R., Reid, J.D., Sicking, D.L., Holloway, J.C., Allison, E.M., and Polivka, K.A., *Midwest Guardrail System for Long-Span Culvert Applications*, Research Report No. TRP-03-187-07, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, November 16, 2007.

3. Bielenberg, R.W., Faller, R.K., Sicking, D.L., Rhode, J.R., and Reid, J.D., Midwest Guardrail System for Long-Span Culvert Applications, *Transportation Research Record No. 2025, Journal of Transportation Research Board*, Washington, D.C., 2007.

4. Schneider, A.J., Rosenbaugh, S.K., Faller, R.K., Sicking, D.L., Lechtenberg, K.A., and Reid, J.D., *Safety Performance Evaluation of Weak-Post, W-Beam Guardrail Attached to Culvert*, Research Report No. TRP-03-277-14, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, February 12, 2014.

5. Polivka, K.A., Faller, R.K., Sicking, D.L., Rohde, J.R., Reid, J.D., and Holloway, J.C., *NCHRP 350 Development and Testing of a Guardrail Connection to Low-Fill Culverts*, Research Report No. TRP-03-114-02, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, November 1, 2002.

6. Ross, H.E., Sicking, D.L., Zimmer, R.A., and Michie, J.D., *Recommended Procedures for the Safety Performance Evaluation of Highway Features*, National Cooperative Highway Research Program (NCHRP) Report 350, Transportation Research Board, Washington, D.C., 1993.

7. Price, C.W., Rosenbaugh, S.K., Faller, R.K., Sicking, D.L., Reid, J.D., and Bielenberg, R.W., *Post Weld and Epoxy Anchorage Variations for W-Beam Guardrail Attached to Low-Fill Culverts*, Research Report No. TRP-03-278-13, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, August 12, 2013.

8. Williams, W.F., and Menges, W.L., *MASH Test 3-11 of the W-beam Guardrail on Low-Fill Box Culvert*, Test Report No. 405160-23-2, Texas A&M Transportation Institute, Texas A&M University, College Station, TX, November 11, 2011.

9. *Manual for Assessing Safety Hardware*, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2009.

10. *Manual for Assessing Safety Hardware, Second Edition*, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.

11. Hinch, J., Yang, T.L., and Owings, R., *Guidance Systems for Vehicle Testing*, ENSCO, Inc., Springfield, VA, 1986.

12. Mac Innis, D., Cliff, W., and Ising, K., *A Comparison of the Moment of Inertia Estimation Techniques for Vehicle Dynamics Simulation*, SAE Technical Paper Series – 970951, Society of Automotive Engineers, Inc., Warrendale, PA, 1997.

13. Society of Automotive Engineers (SAE), *Instrumentation for Impact Test – Part 1 – Electronic Instrumentation*, SAE J211/1 MAR95, New York City, NY, July 2007.

14. *Vehicle Damage Scale for Traffic Investigators*, Second Edition, Technical Bulletin No. 1, Traffic Accident Data (TAD) Project, National Safety Council, Chicago, IL, 1971.

15. *Collision Deformation Classification – Recommended Practice J224 March 1980*, Handbook Volume 4, Society of Automotive Engineers (SAE), Warrendale, PA, 1985.

16. Mongiardini, M., Faller, R.K., Reid, J.D., Sicking, D.L., Stolle, C.S., and Lechtenberg, K.A. *Downstream Anchoring Requirements for The Midwest Guardrail System*, Research Report No. TRP-03-279-13, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 28, 2013.

17. Polivka, K.A., Faller, R.K., Sicking, D. L., Rohde, J.R., Bielenberg, R.W., and Reid, J.D., *Performance Evaluation of the Midwest Guardrail System – Update to NCHRP 350 Test No. 3-11 with 28" C.G. Height (2214MG-2)*, National Cooperative Highway Research Program, Research Report No. TRP-03-171-06, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 2006.

18. Polivka, K.A., Faller, R.K., Sicking, D.L., Rohde, J.R., Bielenberg, R.W., and Reid, J.D., *Performance Evaluation of the Midwest Guardrail System – Update to NCHRP 350 Test No. 3-10 (2214MG-3)*, National Cooperative Highway Research Program, Research Report No. TRP-03-172-06, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, October 2006.

19. Schmidt, T.L., Bielenberg, R.W., Reid, J.D., Mongiardini, M., Lechtenberg, K.A., and Faller, R.K., *Dynamic Testing of MGS W6x8.5 Posts at Decreased Embedment*, Research Report No. TRP-03-271-12, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, December 17, 2012.

20. Price, C.W., Rosenbaugh, S.K., Faller, R.K., Sicking, D.L., Reid, J.D., and Bielenberg, R.W., *Post Weld and Epoxy Anchorage Variations for W-Beam Guardrail Attached to Low-Fill Culverts*, Research Report No. TRP-03-278-13, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, August 12, 2013.

21. Rosenbaugh, S.K., Lechtenberg, K.A., Faller, R.K., Sicking, D.L., Bielenberg, R.W., and Reid, J.D., *Development of the MGS Approach Guardrail Transition Using Standardized Steel Posts*, Research Report No. TRP-03-210-10, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, December 21, 2010.

22. Asadollahi Pajouh, M., Bielenberg, R.W., Schmidt, J.D., Lingenfelter, J.L., Faller, R.K., and Reid, J.D., *Placement of Breakaway Light Poles Located Directly Behind Midwest Guardrail System (MGS)*, Research Report No. TRP-03-361-17, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, NE, June 29, 2017.

11 APPENDICES

Appendix A. Material Specifications

Table A-1. Bill of Materials, Test Nos. CMGS-1 and CMGS-2

Item No.	Description	Material Specification	References
a1	12'-6" [3,810] 12 gauge [2.7] W-Beam MGS Section	AASHTO M180	H#9411949
a2	12'-6" [3,810] 12 gauge [2.7] W-Beam MGS End Section	AASHTO M180	H#9411949
a3	6'-3" [1,905] 12 gauge [2.7] W-Beam MGS Section	AASHTO M180	R#12-0368 Red Paint
b1	72" [1829] Long Foundation Tube	ASTM A500 Gr. B	H#0173175
b2	BCT Timber Post - MGS Height	SYP Grade No. 1 or better (No knots 18" [457] above or below ground tension face)	R#17-505 Orange Paint
b3	W6x8.5 [152x12.6] or W6x9 [W152x13.4], 72" [1,829] Long Steel Post	ASTM A992	R#16-692 Black Paint H#55044251
b4	6"x12"x14¼" [152x305x368] Timber Blockout for Steel Posts	SYP Grade No. 1 or better	R#16-692 Black, Charge#23422 R#18-288 White, R#17-282 Light Blue, R#14-0554 Green
b5	W6x8.5 [W152x12.6] or W6x9 [W152x13.4 Post, 40½" [1029] Long	ASTM A992	H#A134108
b6	8½"x12"x½" [216x305x13] Top Base Plate	ASTM A572 Gr. 50	H#A7D898
b7	8½"x11"x¼" [216x280x6] Bottom Post Plate	ASTM A572 Gr. 50	CMGS-1: H#A608874 CMGS-2: H#A7R1834-02
c1	⅝" [16] Dia. UNC, 10" [254] Long Hex Head Bolt and Nut	Bolt - ASTM A307 Gr. A Nut - ASTM A563A	Bolts: R#16-692 H#DL15107048 L#208977 Orange Paint Nuts: R#16-0217 P#36713 C#210101526
c2	⅞" [22] Dia. UNC, 8" [203] Long Hex Head Bolt and Nut	Bolt - ASTM A307 Gr. A Nut - ASTM A563A	Bolts: R#15-0600 H#2038622 L#39685 Nuts: R#15-0600 H#NF12101054 L#WA651
c3	1" [25] Dia. UNC, 10½" [267] Long Hex Head Bolt and Nut REPLACED BY PART C9	Bolt - ASTM A307 Gr. A Nut - ASTM A563A	CMGS-1: P#47657 Control#200125104 CMGS-2: Bolts: P#47641 Nuts: P#36719
c4	⅝" [16] Dia. UNC, 1½" [38] Long Hex Head Bolt and Nut	Bolt - ASTM A307 Gr. A Nut - ASTM A563A	Bolts: R#17-507 H#816070039 Nuts: R#16-0217 P#36713 C#210101526

Table A-2. Bill of Materials, Test Nos. CMGS-1 and CMGS-2, Cont.

Item No.	Description	Material Specification	References
c5	⅝" [16] Dia. UNC, 14" [356] Long Guardrail Bolt and Nut	Bolt - ASTM A307 Gr. A Nut - ASTM A563A	H#NF16202178 Yellow Paint Nuts: H#20479830
c6	⅝" [16] Dia. UNC, 1¼" [32] Long Guardrail Bolt and Nut	Bolt - ASTM A307 Gr. A Nut - ASTM A563A	Bolts: H#20460760 Nuts: H#20479830
c7	16D Double Head Nail	-	COC PO E000357170
c8	⅝" [16] Dia. UNC, 10" [254] Long Guardrail Bolt and Nut	Bolt - ASTM A307 Gr. A Nut - ASTM A563A	R#16-692 H#20351510 L#150424L Orange Paint
c9	1" [25] Dia. UNC, 10" [254] Long Threaded Rod	ASTM A307 Gr. A	Part#47641 H#604061
c10	1" [25] Dia. Hex Nut	ASTM A563A	P#36719 H#1623764; NUTS: 36719 120282576 GL17036-5 R#17-732
d1	⅝" [16] Dia. Plain Round Washer	ASTM F844	n/a
d2	⅞" [22] Dia. Plain Round Washer	ASTM F844	n/a
d3	1" [25] Dia. Plain Round Washer	ASTM F844	n/a
e1	BCT Anchor Cable	-	Yellow Paint R#17-700 Washers: R#17-715 L#16H-168236-30 Orange Paint Nuts: P#38210 H#DL15105591
e2	2⅜" [60] O.D. x 6" [152] Long BCT Post Sleeve	ASTM A53 Gr. B Schedule 40	H#A79999
e3	8"x8"x⅝" [203x203x16] Anchor Bearing Plate	ASTM A36	North: R#17-282 South: R#09-0453
f1	Ground Strut Assembly	ASTM A36	North: R#09-0453 South: H#163375
f2	Anchor Bracket Assembly	ASTM A36	R#17-282
-	Concrete Culvert	Min. f'c = 4,000 psi [27.6 MPa] NE Mix 47BD	See Table A-3

Table A-3. Bill of Materials, Culvert, Test Nos. CMGS-1 and CMGS-2

Item No.	Description	Material Specification	References
a1	520"x17"x60" [13,208x432x1,524] Reinforce Concrete Culvert Deck/Headwall	Min. f'c = 4,000 psi [27.6 MPa] NE Mix 47BD	R#18-250
a2	8"x48"x120" [203x1,219x3,048] Reinforced Concrete Exterior Support Wall	Min. f'c = 4,000 psi [27.6 MPa] NE Mix 47BD	R#18-250
a3	12"x48"x60" [305x1,219x1,524] Reinforce Concrete Interior Support Wall	Min. f'c = 4,000 psi [27.6 MPa] NE Mix 47BD	R#18-250
a4	8"x48"x520" [203x1,219x13,208] Reinforced Concrete Soil Wall	Min. f'c = 4,000 psi [27.6 MPa] NE Mix 47BD	R#18-250
a5	#4 [#13] Bent Rebar, Vertical Loop, 53⅜" [1,355] Total Length, Unbent	ASTM A615 Gr. 60	H#KN15106961
a6	#4 [#13] Straight Rebar, 57" [1,448] Long	ASTM A615 Gr. 60	H#KN15106961
a7	#4 [#13] Straight Rebar, 517" [13,132] Long	ASTM A615 Gr. 60	H#KN15106961
a8	#4 [#13] Straight Rebar, 45" [1,143] Long	ASTM A615 Gr. 60	H#KN15106961
a9	#4 [13] Straight Rebar, 117" [2,972] Long	ASTM A615 Gr. 60	H#KN15106961
a10	#4 [#13] Bent Rebar, Support Wall Hook, 64" [1,626] Total Length, Unbent	ASTM A615 Gr. 60	H#KN15106961
a11	#4 [#13] Bent Rebar, Support Wall Hook, 60½" [1,536] Total Length, Unbent	ASTM A615 Gr. 60	H#KN15106961
a12	8"x48"x120" [203x1,219x3,048] Reinforced Concrete Exterior Support Wall	Min. f'c = 4,000 psi [27.6 MPa] NE Mix 47BD	R#18-250
a13	#4 [#13] Bent Rebar, L-Shaped, 4' 6" Total Length, Unbent	ASTM A615 Gr. 60	H#62139047

GREGORY HIGHWAY PRODUCTS, INC.
4100 13th St. SW
Canton, Ohio 44710

Customer:	UNIVERSITY OF NEBRASKA-LINCOLN 401 CANFIELD ADMIN BLDG P O BOX 880439 LINCOLN,NE,68588-0439	Test Report Ship Date: Customer P.O.: Shipped to: Project: GHP Order No.:	 7/9/2015 4500274709/ 07/07/2015 UNIVERSITY OF NEBRASKA-LINCOLN TESTING COIL 183306

HT # code	Heat #	C.	Mn.	P.	S.	Si.	Tensile	Yield	Elong.	Quantity	Class	Type	Description
8534	9411949	0.21	0.75	0.01	0.006	0.01	75774	56527	27.15	10	A	2	12GA 25FT WB T2 MGS ANCHOR PANEL
8534	9411949	0.21	0.75	0.01	0.006	0.01	75774	56527	27.15	100	A	2	12GA 12FT6IN/3FT1 1/2IN WB T2
8534	9411949	0.21	0.75	0.01	0.006	0.01	75774	56527	27.15	20	A	2	12GA 25FT0IN 3FT1 1/2IN WB T2

Bolts comply with ASTM A-307 specifications and are galvanized in accordance with ASTM A-153, unless otherwise stated.
Nuts comply with ASTM A-563 specifications and are galvanized in accordance with ASTM A-153, unless otherwise stated.
All other galvanized material conforms with ASTM-123 & ASTM-653
All Galvanizing has occurred in the United States
All steel used in the manufacture is of Domestic Origin, "Made and Melted in the United States"
All Steel used meets Title 23CFR 635.410 - Buy America
All Guardrail and Terminal Sections meets AASHTO M-180, All structural steel meets AASHTO M-183 & M270
All Bolts and Nuts are of Domestic Origin
All material fabricated in accordance with Nebraska Department of Transportation
All controlled oxidized/corrosion resistant Guardrail and terminal sections meet ASTM A606, Type 4.

By:____________________
Andrew Artar, VP of Sales & Marketing
Gregory Highway Products, Inc.

STATE OF OHIO: COUNTY OF STARK
Sworn to and subscribed before me, a Notary Public by Andrew Artar this 17 day of July 2015.

Notary Public, State of Ohio

NOTARIAL SEAL
STATE OF OHIO

DAWN R. BATTON
NOTARY PUBLIC
STATE OF OHIO
Comm. Expires
March 03, 2018
Recorded in
Portage County

Figure A-1. 12-ft – 6-in. (3,810-mm) 12-gauge (2.7-mm) W-Beam MGS Section and End Section, Test Nos. CMGS-1 and CMGS-2

Certified Analysis

Trinity Highway Products , LLC
550 East Robb Ave.
Lima, OH 45801
Customer: MIDWEST MACH.& SUPPLY CO.
P. O. BOX 703

MILFORD, NE 68405
Project: RESALE

Order Number: 1164746
Customer PO: 2563
BOL Number: 69500
Document #: 1
Shipped To: NE
Use State: KS

As of: 5/16/12

Qty	Part #	Description	Spec	CL	TY	Heat Code/ Heat #	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
50	6G	12/6'3/S	M-180	A	2	515691	64,000	72,300	27.0	0.060	0.740	0.009	0.008	0.010	0.021	0.04	0.032	0.000	4
			M-180	A	2	4111321	63,100	80,200	29.0	0.210	0.710	0.009	0.007	0.010	0.030	0.000	0.030	0.000	4
			M-180	A	2	515659	67,000	75,200	26.0	0.064	0.790	0.012	0.008	0.008	0.022	0.000	0.025	0.000	4
			M-180	A	2	515660	66,800	74,300	27.0	0.064	0.740	0.012	0.006	0.009	0.017	0.000	0.025	0.000	4
			M-180	A	2	515662	63,900	72,900	28.0	0.064	0.770	0.010	0.006	0.009	0.016	0.000	0.025	0.000	4
			M-180	A	2	515663	64,900	76,500	21.0	0.064	0.740	0.009	0.007	0.007	0.023	0.000	0.026	0.000	4
			M-180	A	2	515668	66,700	75,500	27.0	0.063	0.770	0.014	0.007	0.010	0.024	0.000	0.030	0.000	4
			M-180	A	2	515668	70,200	80,800	21.0	0.063	0.770	0.014	0.007	0.010	0.024	0.000	0.030	0.000	4
			M-180	A	2	515669	64,500	74,100	26.0	0.063	0.790	0.014	0.007	0.009	0.017	0.000	0.028	0.000	4
			M-180	A	2	515687	63,400	74,100	30.0	0.068	0.750	0.012	0.010	0.008	0.025	0.000	0.060	0.000	4
			M-180	A	2	515687	65,100	74,400	28.0	0.068	0.750	0.012	0.010	0.008	0.025	0.000	0.060	0.000	4
			M-180	A	2	515690	63,000	71,800	27.0	0.059	0.720	0.010	0.008	0.013	0.024	0.000	0.042	0.000	4
			M-180	A	2	515696	62,900	72,500	28.0	0.058	0.740	0.013	0.008	0.011	0.029	0.000	0.046	0.000	4
			M-180	A	2	515696	63,900	73,400	29.0	0.058	0.740	0.013	0.008	0.011	0.029	0.000	0.046	0.000	4
			M-180	A	2	515700	67,800	77,700	28.0	0.065	0.800	0.013	0.009	0.012	0.036	0.000	0.035	0.000	4
			M-180	A	2	616068	62,900	71,600	27.0	0.061	0.740	0.013	0.010	0.012	0.027	0.000	0.064	0.000	4
			M-180	A	2	616068	66,700	74,200	30.0	0.061	0.740	0.013	0.010	0.012	0.027	0.000	0.064	0.000	4
			M-180	A	2	616071	64,000	74,000	28.0	0.061	0.760	0.016	0.007	0.011	0.021	0.000	0.028	0.000	4
			M-180	A	2	616072	63,800	74,200	29.0	0.066	0.750	0.014	0.009	0.010	0.026	0.000	0.039	0.000	4
			M-180	A	2	616073	63,900	73,300	27.0	0.064	0.760	0.016	0.009	0.012	0.024	0.000	0.041	0.000	4
			M-180	A	2	616073	65,000	74,500	28.0	0.064	0.760	0.016	0.009	0.012	0.024	0.000	0.041	0.000	4
30	60G	12/25/6'3/S	M-180	A	2	4111321	63,100	80,200	29.0	0.210	0.710	0.009	0.007	0.010	0.030	0.00	0.030	0.000	4
			M-180	A	2	515656	63,600	73,600	27.0	0.066	0.720	0.012	0.006	0.011	0.021	0.000	0.026	0.000	4
			M-180	A	2	515658	64,800	74,300	26.0	0.069	0.740	0.010	0.006	0.011	0.022	0.000	0.021	0.000	4
			M-180	A	2	515659	67,000	75,200	26.0	0.064	0.790	0.012	0.008	0.008	0.022	0.000	0.025	0.000	4
			M-180	A	2	515663	64,900	76,500	21.0	0.064	0.740	0.009	0.007	0.007	0.023	0.000	0.026	0.000	4

Figure A-2. 6-ft – 3-in. (1,905-mm) 12-gauge (2.7-mm) W-Beam MGS Section, Test Nos. CMGS-1 and CMGS-2

Certified Analysis

Trinity Highway Products , LLC
550 East Robb Ave.
Lima, OH 45801
Customer: MIDWEST MACH.& SUPPLY CO.
P. O. BOX 703

MILFORD, NE 68405
Project: STOCK

Order Number: 1215324 Prod Ln Grp: 9-End Terminals (Dom)
Customer PO: 2884
BOL Number: 80821 Ship Date:
Document #: 1
Shipped To: NE
Use State: KS

As of: 4/14/14

Foundation Tubes Green Paint
R#15-0157 September 2014 SMT

Qty	Part #	Description	Spec	CL	TY	Heat Code/ Heat	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
10	701A	.25X11.75X16 CAB ANC	A-36			A3V3361	48,600	69,000	29.1	0.180	0.410	0.010	0.005	0.040	0.270	0.000	0.070	0.001	4
	701A		A-36			JJ4744	50,500	71,900	30.0	0.150	1.060	0.010	0.035	0.240	0.270	0.002	0.090	0.021	4
12	729G	TS 8X6X3/16X8'-0" SLEEVE	A-500			0173175	55,871	74,495	31.0	0.160	0.610	0.012	0.009	0.010	0.030	0.000	0.030	0.000	4
15	736G	5'/TUBE SL/.188"X6"X8"FLA	A-500			0173175	55,871	74,495	31.0	0.160	0.610	0.012	0.009	0.010	0.030	0.000	0.030	0.000	4
12	749G	TS 8X6X3/16X6'-0" SLEEVE	A-500			0173175	55,871	74,495	31.0	0.160	0.610	0.012	0.009	0.010	0.030	0.000	0.030	0.000	4
5	783A	5/8X8X8 BEAR PL 3/16 STP	A-36			10903960	56,000	79,500	28.0	0.180	0.810	0.009	0.005	0.020	0.100	0.012	0.030	0.000	4
	783A		A-36			DL13106973	57,000	72,000	22.0	0.160	0.720	0.012	0.022	0.190	0.360	0.002	0.120	0.050	4
20	3000G	CBL 3/4X6'6/DBL	HW			99692													
25	4063B	WD 6'0 POST 6X8 CRT	HW			43360													
15	4147B	WD 3'9 POST 5.5"X7.5"	HW			2401													
20	15000G	6'0 SYT PST/8.5/31" GR HT	A-36			34940	46,000	66,000	25.3	0.130	0.640	0.012	0.043	0.220	0.310	0.001	0.100	0.002	4
10	19948G	.135(10Ga)X1.75X1.75	HW			P34744													
2	33795G	SYT-3"AN STRT 3-HL 6'6	A-36			JJ6421	53,600	73,400	31.3	0.140	1.050	0.009	0.028	0.210	0.280	0.000	0.100	0.022	4
4	34053A	SRT-31 TRM UP PST 2'6.625	A-36			JJ5463	56,300	77,700	31.3	0.170	1.070	0.009	0.016	0.240	0.220	0.002	0.080	0.020	4

1 of 3

Figure A-3. 72-in. (1,829-mm) Long Foundation Tube, Test Nos. CMGS-1 and CMGS-2

CENTRAL
NEBRASKA
WOOD PRESERVERS, INC.

P. O. Box 630 • Sutton, NE 68979
Pone 402-773-4319
FAX 402-773-4513

R#17-505
BCT Posts
Orange Paint March 2017 SMT

Date: 3/2/17

CERTIFICATE OF COMPLIANCE

Shipped TO: Midwest Machinery + Supply BOL# 10056187

Customer PO# 3396 Preservative: CCA – C 0.60 pcf AWPA UC4B

Part #	Physical Description	# of Pieces	Charge #	Tested Retention
656806.5PST	6x8-6.5 Rub PosT	168	23489	.649
656806.5PST	6x8-6.5' Rub Post	42	23490	.724
656806.5PST	6x8.5-CRT PST	42	23490	.724
65684GPST	6x8-46" BCT	42	23491	.651

I certify the above referenced material has been produced, treated and tested in accordance with AWPA standards and conforms to AASHTO M133 & M168.

VA: Central Nebraska Wood Preservers certifies that the treated wood products listed above have been treated in accordance with AWPA standards, Section 236 of the VDOT Road & Bridge Specifications and meets the applicable minimum penetration and retention requirements.

Nick Sowl, General Counsel

3/2/17
Date

Figure A-4. BCT Timber Posts, Test Nos. CMGS-1 and CMGS-2

GERDAU

US-ML-CARTERSVILLE
384 OLD GRASSDALE ROAD NE
CARTERSVILLE, GA 30121
USA

CERTIFIED MATERIAL TEST REPORT

Page 1/1

CUSTOMER SHIP TO	CUSTOMER BILL TO	GRADE	SHAPE / SIZE	DOCUMENT ID:
HIGHWAY SAFETY CORP 473 W FAIRGROUND ST MARION,OH 43302-1701 USA	HIGHWAY SAFETY CORP GLASTONBURY,CT 06033-0358 USA	A992/A709-36	Wide Flange Beam / 6 X 8.5# / 150 X 13.0	0000006197

LENGTH	WEIGHT	HEAT / BATCH
42'00"	44,982 LB	55044251/02

SALES ORDER	CUSTOMER MATERIAL Nº	SPECIFICATION / DATE or REVISION
3399484/000010	IB-B0600800	ASTM A6-14 ASTM A709-13A ASTM A992-11 CSA G40.21-13 345WM

CUSTOMER PURCHASE ORDER NUMBER	BILL OF LADING	DATE
000167 PO#1677003	1323-0000066391	03/16/2016

CHEMICAL COMPOSITION

C %	Mn %	P %	S %	Si %	Cu %	Ni %	Cr %	Mo %	Sn %	V %	Nb %
0.14	0.90	0.014	0.019	0.19	0.28	0.08	0.09	0.023	0.012	0.017	0.000

MECHANICAL PROPERTIES

YS 0.2% PSI	UTS PSI	YS MPa	UTS MPa	G/L Inch	Elong. %
56700	77700	391	536	8.000	21.30
54800	75700	378	522	8.000	22.60

COMMENTS / NOTES

The above figures are certified chemical and physical test records as contained in the permanent records of company. We certify that these data are correct and in compliance with specified requirements. This material, including the billets, was melted and manufactured in the USA. CMTR complies with EN 10204 3.1.

BHASKAR YALAMANCHILI
QUALITY DIRECTOR

YAN WANG
QUALITY ASSURANCE MGR.

Figure A-5. W6x8.5 (152x12.6), 72-in. (1,829-mm) Long Steel Posts, Test Nos. CMGS-1 and CMGS-2

CENTRAL NEBRASKA WOOD PRESERVERS, INC.

P. O. Box 630 • Sutton, NE 68979
Pone 402-773-4319
FAX 402-773-4513

R#16-692 6x12x14 Timber Blockouts
COC June2016 SMT Black Paint Tags

Date: 10/29/15

CERTIFICATE OF COMPLIANCE

Shipped TO: Midwest Machinery. BOL# 18052937

Customer PO# 3161 Preservative: CCA – C 0.60 pcf AWPA UC4B

Part #	Physical Description	# of Pieces	Charge #	Tested Retention
	6x12 – 14" ocd Block	84	21327	.658 pcf

I certify the above referenced material has been produced, treated and tested in accordance with AWPA standards and conforms to AASHTO M133 & M168.

VA: Central Nebraska Wood Preservers certifies that the treated wood products listed above have been treated in accordance with AWPA standards, Section 236 of the VDOT Road & Bridge Specifications and meets the applicable minimum penetration and retention requirements.

[signature] G.M
Nick Sowl, General Counsel

10/29/15
Date

Figure A-6. Timber Blockouts for Steel Posts, Test Nos. CMGS-1 and CMGS-2

CNWP
CENTRAL NEBRASKA WOOD PRESERVERS

1098 East Maple St
Sutton, NE 68979
Phone: 402.773.4319
Email: nick@nebraskawood.com

CERTIFICATE OF COMPLIANCE

Shipped To: Midwest Machinery and Supply
BOL# 10057873
Customer PO# 3475
Preservative: CCA – C 0.60D pcf AWPA UC4B

Part #	Physical Description	# of Pieces	Charge #	Tested Retention
GR61219 BLK	6x12-19" TRANS Hole BLK	56	24245	.616
GR6819 BLK	6x8-19" OCD BLOCK	168	24253	.611
GR61214 BLK	6x12-14" Thrie Hole BLK OCD	84	23422	.660

I certify the above referenced material has been produced, treated and tested in accordance with and conforms to AASHTO M133 & M168 standards.

VA: Iowa Wood Preservers certifies that the treated wood products listed above have been treated in accordance with AWPA standards, Section 236 of the VDOT Road & Bridge Specifications and meets the applicable minimum penetration and retention requirements.

Nicholas Sowl, General Counsel

9/1/2017
Date

Figure A-7. Timber Blockouts for Steel Posts, Test Nos. CMGS-1 and CMGS-2

CENTRAL NEBRASKA WOOD PRESERVERS, INC.

P. O. Box 630 • Sutton, NE 68979
Pone 402-773-4319
FAX 402-773-4513

R#17-282 BCT Posts 70 Acct AND Wood Blocks for Bullnose
Nov2016 SMT Wood Blockouts are painted Light Blue

Date: 11/11/16

CERTIFICATE OF COMPLIANCE

Shipped TO: Midwest Machinery + Supply BOL# 10055387

Customer PO# 3339 Preservative: CCA – C 0.60 pcf AWPA UC4B

Part #	Physical Description	# of Pieces	Charge #	Tested Retention
GR6806.5PST	6x8-6.5" PST	35	22973	.679
GR6806.5CRT	6x8-6.5" CRT	35	22973	.679
GS6846PST	5.5-7.5-46" BCT	42	22927	.638
GR61214BCK	6x12-14" OCD	168	22927	.638

I certify the above referenced material has been produced, treated and tested in accordance with AWPA standards and conforms to AASHTO M133 & M168.

VA: Central Nebraska Wood Preservers certifies that the treated wood products listed above have been treated in accordance with AWPA standards, Section 236 of the VDOT Road & Bridge Specifications and meets the applicable minimum penetration and retention requirements.

Nick Sowl, General Counsel

11/11/16
Date

Figure A-8. Timber Blockouts for Steel Posts, Test Nos. CMGS-1 and CMGS-2

CENTRAL NEBRASKA WOOD PRESERVERS, INC.

P. O. Box 630 • Sutton, NE 68979
Pone 402-773-4319
FAX 402-773-4513

CWNP Invoice 10048570
Shipped To MIDWEST-MILFORD
Customer PO 2892

Central Nebraska Wood Preservers, Inc.
Certification of Inspection

Date: 4/23/14

Specifications: Highway Construction Use

Preservative: CCA – C 0.60 pcf

Charge #	Date Treated	Grade	Material Size, Length & Dressing	# Pieces	White Moisture Readings	Penetration # of Borings & % Conforming	Actual Retentions % Conforming
18379	4/16/14	#1	6x12-14" Blocks	756	19	1/20 95%	.651 pcf
18379	4/16/14	#1	6x8-22" Blocks	84	19	1/20 95%	.651 pcf

Number of pieces rejected and reason for rejection:
None

Statement: The above reference material was treated and inspected in accordance with the above referenced specifications.

Kurt Andres, General Manager

4/23/14
Date

MGS Wood Blockouts 6x12x14" R#14-0554
GREEN TAGS don't mistaken these for the 2part blockouts because they are also GREEN. July 2014 SMT

Figure A-9. Timber Blockouts for Steel Posts, Test Nos. CMGS-1 and CMGS-2

Steel Dynamics, Inc.
Long Products Group

(260) 625-8100 (260) 625-8950 FAX
Quality Steel 100% EAF Melted and Manufactured in the USA
Recycled content: PC = 79.6%, PI = 18.0%
ISO 9001:2008 and ABS Certified

CERTIFIED MILL TEST REPORT

Printed: **05 / 29 / 2017**
Produced: **04 / 11 / 2017**

Ship to:
Steel & Pipe Supply
401 New Century Parkway
New Century KS, 66031 US
Attn: Receiving

Customer # 000058

Bill to:
Steel & Pipe Supply - Kansas
555 Poyntz Avenue
PO Box 1688
Manhattan KS, 66505 US
Attn: David Chizek

GENERAL INFORMATION

Product Wide Flange Beam
Size W6X9
W150X13.5
Heat Number A134108
Condition(s) As-Rolled
Fine Grained
Fully Killed
No Weld Repair

SPECIFICATIONS

Standards	Grades
ASTM A6/A6M - 16a	
» ASTM A992/A992M - 11	A992 / A992M
ASTM A709/A709M - 16a	A709 gr50/gr345
ASTM A572/A572M - 15	A572 gr50/gr345
AASHTO M270M/M270 - 12	M270 gr345/gr50
CSA G40.21-13	50WM/345WM

SHIPMENT DETAILS

BOL # 0000455326 - 7200.00 lbs

Bundle / ASN #	Length	pcs	Cust PO | Recv PO | Job
060763251	50' 0"	16	4500287984

CHEMICAL ANALYSIS (weight percent)

C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Sn	V	Nb/Cb	Al	N	B	*C1	*C2	*C3	*PC	*I	Analysis Type
.06	.93	.015	.011	.25	.30	.12	.11	.035	.012	.023	<.001	.002	.0100	.0003	.28	.32	.26	.15	5.75	Heat

MECHANICAL TESTING

Test	Yield (fy) Strength ksi / MPa	Tensile (fu) Strength ksi / MPa	fy / fu ratio	% Elong. (8" gage)
1	63 / 436	80 / 550	.79	26
2	64 / 444	80 / 554	.80	25
3				
4				

CHARPY IMPACT TESTS (available only when specified at time of order)

Test	Temp F / C	Absorbed Energy ft-lbf / J Specimen 1	Specimen 2	Specimen 3	Average	Minimum
1						
2						
3						
4						
5						
6						
7						

Notes: *Calculated Chemistry Values Carbon Equivalents (C1 C2 C3, PC) Corrosion Index (I) I (ASTM G101)= 26 01(Cu)+3 88(Ni)+1 20(Cr)+1 49(Si)+17 29(P)-7 29(Cu)(Ni)-9 10(Ni)(P)-33 39(Cu²)
CE1 (IIW)=C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15 CE2 (AWS)=C+(Mn+Si)/6+(Cr+Mo+V)/5+(Ni+Cu)/15 CE3 (CET) = C + (Mn/6) + (Si/24) + (Cr/5) + (Ni/40) +(Mo/4) + (V/14) Pcm(AWS) = C+Si/30+Mn/20+Cu/20+Ni/60+Cr/20+mo/15+V/10+5B

I hereby certify that the material described herein has been made to the applicable specification by the electric arc furnace/continuous cast process and tested in accordance with the requirements of American Bureau of Shipping Rules with satisfactory results.

Signed:

ABS CERTIFICATION

I hereby certify that the content of this report are accurate and correct. All tests and operations performed by this material manufacturer are in compliance with the requirements of the material specifications and applicable purchaser designated requirements.

Signed: **Todd Bashford**
Quality Manager

Form F-6100-002-054 rev 8

State of Indiana, County of Whitley Sworn to and subscribed before me

this ________ day of ________________

Signed: ________________ My commission expires: ________
Notary Public

ASTM A6 - 14 6 A signature is not required on the test report; however the document shall clearly identify the organization submitting the report. Notwithstanding the absence of a signature the organization submitting the report is responsible for the content of the report.

Page 3 of 7

Figure A-10. W6x9 (W150x13.5) 40½-in. (1,029-mm) Long Post, Test No. CMGS-1 and CMGS-2

SSAB

Preliminary Test Certificate

1770 Bill Sharp Boulevard, Muscatine, IA 52761-9412, US **Official copy to follow**

Form TC1: Revision 2: Date 23 Apr 2014

Customer: STEEL & PIPE SUPPLY P.O. BOX 1688 MANHATTAN KS 66502	Customer P.O. No.: 4500287649	Mill Order No.: 41-504804-02	Shipping Manifest: MT318692
	Product Description: ASTM A572-50/M345(15)/A709-50/M345(16A)	Ship Date: 21 Jun 17 Cert Date: 21 Jun 17	Cert No: 061649975 (Page 1 of 1)
	Size: 0.500 X 96.00 X 240.0 (IN)		

Tested Pieces			Tensiles									Charpy Impact Tests						
Heat Id	Piece Id	Tested Thickness	Tst Loc	YS (KSI)	UTS (KSI)	%RA	Elong % 2in	Elong % 8in	Tst Dir	Hardness	Abs. Energy(FTLB) 1 2 3 Avg	% Shear 1 2 3 Avg	Tst Tmp	Tst Dir	Tst Siz (mm)	BDWTT Tmp	BDWTT %Shr
A7D898	D19	0.496 (DISCRT)	L	61	73		38		T								
A7F058	D31	0.497 (DISCRT)	L	55	68		37		T								
B7D657	D18	0.507 (DISCRT)	L	57	77		28		T								

Chemical Analysis

Heat Id	C	Mn	P	S	Si	Tot Al	Cu	Ni	Cr	Mo	Cb	V	Ti	ORGN
A7D898	.05	1.32	.014	.004	.10	.034	.30	.14	.15	.03	.024	.027	.008	USA
A7F058	.05	1.21	.012	.006	.02	.028	.31	.14	.10	.04	.002	.053	.001	USA
B7D657	.16	1.14	.013	.007	.03	.029	.30	.15	.17	.04	.002	.033	.006	USA

KILLED STEEL
MERCURY IS NOT A METALLURGICAL COMPONENT OF THE STEEL AND NO MERCURY WAS INTENTIONALLY ADDED DURING THE MANUFACTURE OF THIS PRODUCT.
MTR EN 10204:2004 INSPECTION CERTIFICATE 3.1 COMPLIANT
100% MELTED AND MANUFACTURED IN THE USA.
PRODUCTS SHIPPED:

B7D657	D18	PCES: 2,	LBS: 6534	A7F058	D31	PCES: 1,	LBS: 3267
A7D898	D19	PCES: 3,	LBS: 9801				

Cust Part # : 721696240A2

WE HEREBY CERTIFY THAT THIS MATERIAL WAS TESTED IN ACCORDANCE WITH, AND MEETS THE REQUIREMENTS OF, THE APPROPRIATE SPECIFICATION

SENIOR METALLURGIST - PRODUCT

Figure A-11. 8½-in. x 12-in. x ½-in. (216-mm x305-mm x 13-mm) Top Base Plate, Test No. CMGS-1 and CMGS-2

STEEL AND PIPE SUPPLY
SPS Coil Processing Tulsa
5275 Bird Creek Ave.
Port of Catoosa, OK 74015

METALLURGICAL TEST REPORT

PAGE 1 of 1
DATE 10/07/2016
TIME 20:41:17
USER GIANGRER

SOLD TO
66031-1127

SHIP TO
13716
Kansas City Warehouse
401 New Century Parkway
NEW CENTURY KS

Order	Material No.	Description	Quantity	Weight	Customer Part	Customer PO	Ship Date
40272379-0010	70860240A2	1/4 60 X 240 A572GR50 STP MIL PLT	4	4,084			10/07/2016

Chemical Analysis

Heat No. A608874 Vendor STEEL DYNAMICS COLUMBUS DOMESTIC Mill STEEL DYNAMICS COLUMBUS **Melted and Manufactured in the USA**

Produced from Coil

Carbon	Manganese	Phosphorus	Sulphur	Silicon	Nickel	Chromium	Molybdenum	Boron	Copper	Aluminum	Titanium	Vanadium	Columbium	Nitrogen	Tin
0.0600	0.8100	0.0160	0.0010	0.0400	0.0300	0.0600	0.0100	0.0001	0.1100	0.0220	0.0010	0.0030	0.0160	0.0068	0.0040

Mechanical / Physical Properties

Mill Coil No. 16B640645

Tensile	Yield	Elong	Rckwl	Grain	Charpy	Charpy Dr	Charpy Sz	Temperature	Olsen
73500.000	62300.000	30.00			0	NA			
72600.000	63500.000	26.30			0	NA			
71900.000	61500.000	33.20			0	NA			
71900.000	62200.000	29.80			0	NA			

Batch 0004493721 4 EA 4,084 LB

THE CHEMICAL, PHYSICAL, OR MECHANICAL TESTS REPORTED ABOVE ACCURATELY REFLECT INFORMATION AS CONTAINED IN THE RECORDS OF THE CORPORATION.
The material is in compliance with EN 10204 Section 4.1 Inspection Certificate Type 3.1

Figure A-12. 8½-in. x 11-in. x ¼-in. (216-mm x 280-mm x 6-mm) Bottom Post Plates, Test No. CMGS-1

NUCOR

NUCOR STEEL TUSCALOOSA, INC.

MILL TEST CERTIFICATE

1700 HOLT RD N.E.
Tuscaloosa, AL 35404-1000
800 800-8204
customerservice@nucortusk.com

Page: 1 of 1

Load Number	Tally	Mill Order Number	PO NO | Line NO	Part Number	Certificate Number	Prepared
B152559	00000000725694	N-155738-023	P0181329-09 23		S72569401-1	05/07/2017 13:20

Grade

Order Description:
Hot Roll Plate From Coil
A572 50, 0.2500 IN x 96.000 IN x 240.000 IN

Quality Plan Description:
A57250 LO SI IMP: ASTM A572-50-15/A70950-15/M27050 H Freq impacts

Customer:

Sold TO:
SUPERIOR SUPPLY AND STEEL CATOOSA OK

Ship TO:
SUPERIOR SUPPLY AND STEEL Catoosa OK

Sent TO:

Shipped Item	Heat/Slab Number	Certified By	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	Cb	V	Al	Ti	N2	B	Ca	Sn	CEV	ACI
7E0085B	A7R1834-02 ***	A7R1834	0.07	1.14	0.011	0.005	0.03	0.17	0.06	0.23	0.023	0.038	0.005	0.026	0.011	0.009	0.0001	0.0015		0.33	

Shipped Item	Certified By	Heat Number	Yield ksi	Tensile ksi	Y/T %	ELONGATION % 2"	ELONGATION % 8"	Bend OK?	Hard HB	Charpy Impacts (ft-lbs) Size mm	1	2	3	Avg	Shear % 1	2	3	Avg	Test Temp
7E0085B	S7E0085FTT	A7R1834 ***	58.3	69.4	84.0	30.6													
7E0085B	S7E0085BLI	A7R1834 ***								5.0	90	89	77	85.3					-22 F
7E0085B	S7E0085FLI	A7R1834 ***								5.0	82	83	88	84.3					-22 F
7E0085B	S7E0085MLI	A7R1834 ***								5.0	88	102	72	87.3					-22 F
7E0085B	S7E0085MTT	A7R1834 ***	63.1	72.1	87.5	25.4													

Items: 1 PCS: 5 Weight: 8168 LBS

Mercury has not come in contact with this product during the manufacturing process nor has any mercury been used by the manufacturing process. Certified in accordance with EN 10204 3.1. No weld repair has been performed on this material. Manufactured to a fully killed fine grain practice. NUTEMPER TEMPER PASSED plate from coil
ISO 9001:2015 Registered, PED Certified

"***" indicates Heats melted and Manufactured in the U.S.A.

We hereby certify that the product described above passed all of the tests required by the specifications.

Dr. Quilin Yu - Metallurgist

Figure A-13. 8½-in. x 11-in. x ¼-in. (216-mm x 280-mm x 6-mm) Bottom Post Plates, Test No. CMGS-2

NUCOR

NUCOR CORPORATION
NUCOR STEEL SOUTH CAROLINA

Mill Certification
3/11/2016

MTR #: C1-366222
300 Steel Mill Road
DARLINGTON, SC 29540
(843) 393-5841
Fax: (843) 395-8701

Sold To: BIRMINGHAM FASTENER & SUPPLY
PO BOX 10323
BIRMINGHAM, AL 35202-0323
(205) 595-3511
Fax: (205) 591-0244

Ship To: BIRMINGHAM FASTENER & SUPPLY
931 AVE W
PO BOX 10323
BIRMINGHAM, AL 35202-0000
(205) 595-3511
Fax: (205) 591-0244

Customer P.O.	M7812	Sales Order	238747.1
Product Group	Merchant Bar Quality	Part Number	30000562480DES0
Grade	ASTM A307-55, F1554-07a gr 55, S1, AASHTO M314 GR 55, S1	Lot #	DL1510704804
Size	9/16" (.5625) Round	Heat #	DL15107048
Product	9/16" (.5625) Round 40' A307-55	B.L. Number	C1-686468
Description	A307-55	Load Number	C1-366222
Customer Spec		Customer Part #	

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

Roll Date: 1/28/2016 Melt Date: 12/5/2015 Qty Shipped LBS: 17,494 Qty Shipped Pcs: 517

Melt Date: 12/5/2015

C	Mn	V	Si	S	P	Cu	Cr	Ni	Mo	Cb	CE1554
0.22%	0.82%	0.0410%	0.27%	0.010%	0.007%	0.20%	0.10%	0.06%	0.015%	0.001%	0.37%

CE1554: CE per F1554 GR55, S1

Roll Date: 1/28/2016

Yield 1: 67,000psi	Tensile 1: 87,000psi	Elongation: 21% in 8"(% in 203.3mm)
Yield 2: 66,000psi	Tensile 2: 88,000psi	Elongation 21% in 8"(% in 203.3mm)
Reduction of Area: 50.43%	Reduction of Area #2: 53.52%	

Specification Comments:

1. WELDING OR WELD REPAIR WAS NOT PERFORMED ON THIS MATERIAL
2. MELTED AND MANUFACTURED IN THE USA
3. MERCURY, RADIUM, OR ALPHA SOURCE MATERIALS IN ANY FORM HAVE NOT BEEN USED IN THE PRODUCTION OF THIS MATERIAL

James H. Blew
Division Metallurgist

NBMG-10 January 1, 2012

Page 1 of 2

Figure A-14. ⅝-in. (16-mm) Diameter, 10-in. Hex Head Bolts, Test Nos. CMGS-1 and CMGS-2

Certified Material Test Report to BS EN 10204-2004 3.1
FOR ASTM A563, GRADE A HEX FIN NUTS

FACTORY: IFI & Morgan Ltd. Haiyan Office
ADDRESS: No.583-28，CHANG'AN NORTH ROAD
WUYUAN TOWN,HAIYAN,ZHEJIANG CHINA
Tel:#(852)2542 3366
CUSTOMER:

REPORT DATE:2017-7-20

MFG LOT NUMBER: GL17089-2

SAMPLE SIZE: ACC. TO ASME B18.18-11;ASTM F1470-12
SIZE: 1-8 HDG QTY: 15150 PCS

PO NUMBER:210133243

PART NO: 36719

STEEL PROPERTIES
STEEL GRADE: ML08AL

HEAT NUMBER:1623764

	C %*100	Mn%*100	P %*1000	S %*1000
CHEMISTRY SPEC: ASTM A563 GRADE A	0.55max	min	0.12max	0.15max
TEST:	0.06	0. 4	0.01	0.006

DIMENSIONAL INSPECTIONS SPECIFICATION: ASME-B18.2.2-2010

CHARACTERISTICS	TEST METHOD	SPECIFIED	ACTUAL RESULT	ACC.	REJ.
**********************	*****************	*******************	*******************	********	********
APPEARANCE	ASTM F812-2013		PASSED	29	0
THREAD	ASME B1.3-2003 2B		PASSED	15	0
WIDTH A/F	1.500-1.450		1.488-1.485	4	0
WIDTH A/C	1.732-1.653		1.708-1.704	4	0
HEIGHT	0.887-0.831		0.856-0.852	4	0

MECHANICAL PROPERTIES: 1/4" to 1 1/2" SPECIFICATION: ASTM A563-07a GR-A

CHARACTERISTICS	TEST METHOD	SPECIFIED	ACTUAL RESULT	ACC.	REJ.
*********************	******************	******************	******************	********	********
HARDNESS :	ASTM F606-2014	B68-C32 Max(107HRB)	C25-27	15	0
PROOF LOAD :	ASTM F606-2014	Min 68 Ksi	70-72 Ksi	4	0

CHARACTERISTICS	TEST METHOD	SPECIFIED	ACTUAL RESULT	ACC.	REJ.
*********************	****************	*******************	*****************	********	********
HOT DIP GALVANIZED	ASTM F2329-05	MIN 2.10miu	2.3-2.5miu	4	0

ALL TESTS IN ACCORDANCE WITH THE METHODS PRESCRIBED IN THE APPLICABLE ASTM OR SAE SPECIFICATION. WE CERTIFY THAT THIS DATA IS A TRUE REPRESENTATION OF INFORMATION PROVIDED BY THE MATERIAL SUPPLIER AND OUR TESTING LABORATORY.

IFI & MORGAN LTD.
检验专用章
QUALITY CONTROL

(SIGNATURE OF Q.A. LAB MGR.)
(NAME OF MANUFACTURER)

Figure A-15. ⅝-in. (16-mm) Diameter, Hex Head Nuts, Test Nos. CMGS-1 and CMGS-2

From: FAXmaker To: 1-815-877-0734 Page: 1/1 Date: 5/14/2015 4:00:16 PM

Customer Name	Customer PO#	Invoice No	Shipper No	Heat Number
GAFFNEY BOLT CO.	5-7-2015 MIKE	701917	680907	2038622

CMC

1SERIES-BPS ®

CMC STEEL SOUTH CAROLINA
310 New State Road
Cayce SC 29033-3704

CERTIFIED MILL TEST REPORT
For additional copies call
800-637-3227

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

Richard S. Ray
Richard S. Ray - CMC Steel SC
Quality Assurance Manager

	SOLD TO	SHIP TO	
HEAT NO.:2038622 SECTION: ROUND 7/8 x 40'0" A36/52950 GRADE: ASTM A36-12/A529-05 Gr 50 ROLL DATE: 09/09/2014 MELT DATE: 09/08/2014	Infra-Metals - Mars 1601 Broadway St Marseilles IL US 61341-9326 8009875283	Infra-Metals - Mars 1601 Broadway St Marseilles IL US 61341-9326 8009875283	Delivery#: 81471569 BOL#: 70533247 CUST PO#: CE-485729 CUST P/N: DLVRY LBS / HEAT: 9075.000 LB DLVRY PCS / HEAT: 111 EA

Characteristic	Value	Characteristic	Value	Characteristic	Value
C	0.16%	Elongation Gage Lgth test 1	8IN		
Mn	0.73%	Reduction of Area test 1	58%		
P	0.013%	Yield to tensile ratio test1	0.75		
S	0.021%	Yield Strength test 2	56.9ksi		
Si	0.22%	Tensile Strength test 2	76.5ksi		
Cu	0.32%	Elongation test 2	25%		
Cr	0.13%	Elongation Gage Lgth test 2	8IN		
Ni	0.10%	Reduction of Area test 2	57%		
Mo	0.027%	Yield to tensile ratio test2	0.74		
V	0.000%	C+(Mn/6)	0.28%		
Cb	0.026%				
Sn	0.010%				
Al	0.000%				
Ti	0.001%				
N	0.0084%				
Carbon Eq A529	0.38%				
Yield Strength test 1	57.1ksi				
Tensile Strength test 1	76.3ksi				
Elongation test 1	23%				

THIS MATERIAL IS FULLY KILLED, 100% MELTED AND MANUFACTURED IN THE USA, WITH NO WELD REPAIR OR MERCURY CONTAMINATION IN THE PROCESS.

REMARKS :

ALSO MEETS ASTM GRADE A36 REV-03A, A529 GR.50, A572-2013A GR.50, A709 GR.36, A709 GR.50, A992, AASHTO GRADE M270 GR.36, M270 GR.50, CSA G40.21-04 GRADE 44W, 50WASME SA-36 2008A ADDEND A.

03/18/2015 14:05:35
Page 1 OF 1

Figure A-16. ⅞-in. (22-mm) Diameter, 8-in. (203-mm) Long Hex Head Bolts, Test Nos. CMGS-1 and CMGS-2

INSPECTION CERTIFICATE

Customer	Specification	Size	Lot No.	Date
	ASTM A-563 GRADE DH HEAVY HEX NUT	7/8- 9 UNC	WA651	Jun. 29,'12

UNYTITE, INC.
One Unytite Drive
Peru, Illinois 61354
815-224-2221 — FAX# 815-224-3434

Mechanical properties tested in accordance to ASTM F606/F606M, ASTM A370, ASTM E18

Chemical Composition (%)

Mill Maker	Material Size	Heat No.	Spec.	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	
NUCOR	CARBON			0.20 0.55	-	MIN. 0.60	MAX. 0.040	MAX. 0.050	-	-	-	-	-
STEEL	STEEL	12101054		0.43	0.24	0.87	0.015	0.020	0.09	0.04	0.08	-	-

Shape & Dimension	
Inspection	ANSI B18.2.2 GOOD
Thread Precision Inspection	ANSI B1.1 CLASS 2B GOOD
Appearance Inspection	GOOD

Mechanical Property Inspection

Item	Proof Load	Cone stripping	Hardness	After Heat Treatment Hardness	Absorbed Energy	Heat Treatment
Spec.	80,850 lbf	- kN·kgf·lbf	24-38 HrC	HrB·HB	j·kgfm·ftlbf	T:MIN.800 F
Results	n 5 Results GOOD	n - Results -	29.4 28.9 29.7 29.7 29.5 29.4	5 Piece Average After Heat Treament Hardness Treatment After 24 Hr.X °F(°C)	at °F(°C)	Q:FORGING Q (W.Q.) T:1058 F/45M. (W.C.) Q: Quenching T: Tempering ST: Solution Treatment

OFFICIAL SEAL
JEAN MARGHERIO
NOTARY PUBLIC - STATE OF ILLINOIS
MY COMMISSION EXPIRES:10/18/13
07-10-12

Remarks:

"DH U"

Production Quantity
22,391 pcs.

BCT Foundation Tube
Keeper Bolt Nuts
R#15-0600 June 2015 SMT

Material used for the nut was melted and manufactured in the USA. The nut was manufactured in the USA to the above specification.

We hereby certify that the material described has been manufactured and inspected satisfactorily with the requirement of the above specification.

Chief of Quality Assurance Section

Figure A-17. ⅞-in. (22-mm) Diameter, Hex Head Nuts, Test Nos. CMGS-1 and CMGS-2

Feb. 14. 2018 11:23AM Fastenal-NELIN No. 4249 P. 2

FASTENAL®

Certificate of Compliance

Sold To:

UNL TRANSPORTATION

Purchase Order: tighe picking up

Job:

Invoice Date: 10/23/2017

THIS IS TO CERTIFY THAT WE HAVE SUPPLIED YOU WITH THE FOLLOWING PARTS.
THESE PARTS WERE PURCHASED TO THE FOLLOWING SPECIFICATIONS.

50 PCS 1"-8 A-563 Grade DH Hot Dip Galvanized Heavy Hex Nut SUPPLIED UNDER OUR TRACE NUMBER 210119800 AND UNDER PART NUMBER 36761

4 PCS 1"-8 x 12 ft ASTM A307 Gr A Hot Dip Galvanized Low Carbon Steel Threaded Rod SUPPLIED UNDER OUR TRACE NUMBER 200125104 AND UNDER PART NUMBER 47657

This is to certify that the above document is true and accurate to the best of my knowledge.

S Morgan

Fastenal Account Representative Signature

Sean Morgan

Printed Name

2/14/18

Date

Please check current revision to avoid using obsolete copies.

This document was printed on 02/14/2018 and was current at that time.

Fastenal Store Location/Address

3201 N. 23rd Street STE 1
LINCOLN, NE 68521
Phone #: (402)476-7900
Fax #: 402/476-7958

Page 1 of 1

Figure A-18. 1-in. (25-mm) Diameter, 10½-in. (267-mm) Long Hex Head Bolts, Test Nos. CMGS-1 and CMGS-2

MANGAL STEEL ENTERPRISES LTD.

FINAL INSPECTION CERTIFICATE

DATE : 20.06.2017

CUSTOMER : **FASTENAL COMPANY PURCHASING IMPORT TRAFFIC**

PART NAME : CARBON STEEL ALL THREADED RODS

SIZE : 1" - 8 X 10 FT | **DATE :** 09.03.2017

PART NO. (Customer) : 47641 | **REPORT NO. :** M 18

MATERIAL/DIA : 25 MM | **SHIPPING NO.** 120280178 (LOT#3)

HEAT NO. : 604061 | **ORDER NO. :** 120280178

LOT QTY. : 30 PCS | **LOT NO. :** 25 V - 5/16

SPECIFICATION : **ASTM A 307 GRADE A; 1A THREAD FIT**

QUANTITY TESTED : 2 PCS

	INSPECTION ITEM	SPECIFICATION		INSPECTION RESULT		REMARKS
		Min	Max	1st Sample	2nd Sample	
1	TENSILE (ksi)	60	-	74.6	74.7	OK
2	YIELD STRENGTH					
3	ELONGATION					
4	HARDNESS	69 - 100 HRB		84 HRB	84 HRB	OK
5	COATING (HDG)	45 µ		48 µ	50 µ	OK
6	APPEARANCE	VISUAL		OK	OK	OK

	PHYSICAL DIMENSIONS	SPECIFICATION		INSPECTION RESULT		REMARKS
		Min	Max	1st Sample	2nd Sample	
1	MAJOR DIA (inches)	0.975"	0.998"	0.992"	0.993"	OK
2	PITCH DIA (inches)	0.906"	0.916"	0.909"	0.910"	OK
3	LENGTH (ft)	10'	(± 1/8")	10'	10'	OK
4	GO GAUGE	PASS		PASS	PASS	OK
5	NO-GO GAUGE	DOES NOT PASS		DOES NOT PASS	DOES NOT PASS	OK

INSPECTED BY : | CERTIFIED BY :

Figure A-19. 1-in. (25-mm) Diameter, 10-in. (254-mm) Long Threaded Rod, Test Nos. CMGS-1 and CMGS-2

Certified Material Test Report to BS EN 10204-2004 3.1
FOR ASTM A563, GRADE A HEX FIN NUTS

FACTORY: IFI & Morgan Ltd. Haiyan Office
ADDRESS: No.583-28，CHANG'AN NORTH ROAD
WUYUAN TOWN,HAIYAN,ZHEJIANG CHINA
Tel:#(852)2542 3366
CUSTOMER:

REPORT DATE:2017-4-15

MFG LOT NUMBER: GL17036-5

SAMPLE SIZE: ACC. TO ASME B18.18-11;ASTM F1470-12
SIZE: 1"-8 HDG QTY: 10800 PCS

PO NUMBER:120282576

PART NO: 36719

STEEL PROPERTIES
STEEL GRADE: ML08Al

HEAT NUMBER:1623764

	C %*100	Mn%*100	P %*1000	S %*1000
CHEMISTRY SPEC: ASTM A563 GRADE A	0.55max	min	0.12max	0.15max
TEST:	0.06	0.4	0.01	0.006

DIMENSIONAL INSPECTIONS SPECIFICATION: ASME-B18.2.2-2010

CHARACTERISTICS	TEST METHOD	SPECIFIED	ACTUAL RESULT	ACC.	REJ.
**********************	*****************	*******************	*******************	********	********
APPEARANCE	ASTM F812-2013		PASSED	22	0
THREAD	ASME B1.3-2003 2B		PASSED	15	0
WIDTH A/F	1.500-1.450		1.478-1.475	4	0
WIDTH A/C	1.732-1.653		1.722-1.720	4	0
HEIGHT	0.887-0.831		0.853-0.851	4	0

MECHANICAL PROPERTIES: 1/4" to 1 1/2" SPECIFICATION: ASTM A563-07a GR-A

CHARACTERISTICS	TEST METHOD	SPECIFIED	ACTUAL RESULT	ACC.	REJ.
*********************	*****************	******************	******************	********	********
HARDNESS :	ASTM F606-2014	B68-C32 Max(107HRB)	C20-23	15	0
PROOF LOAD :	ASTM F606-2014	Min68 Ksi	70-72 Ksi	4	0

CHARACTERISTICS	TEST METHOD	SPECIFIED	ACTUAL RESULT	ACC.	REJ.
*********************	****************	*******************	*****************	********	********
HOT DIP GALVANIZED	ASTM F2329-05	MIN 0.0017"	0.0020-0.0021	4	0

ALL TESTS IN ACCORDANCE WITH THE METHODS PRESCRIBED IN THE APPLICABLE ASTM OR SAE SPECIFICATION. WE CERTIFY THAT THIS DATA IS A TRUE REPRESENTATION OF INFORMATION PROVIDED BY THE MATERIAL SUPPLIER AND OUR TESTING LABORATORY.

IFI & MORGAN LTD. 检验专用章 QUALITY CONTROL

(SIGNATURE OF Q.A. LAB MGR.)
(NAME OF MANUFACTURER)

Figure A-20. 1-in. (25-mm) Diameter Hex Nut, Test Nos. CMGS-1 and CMGS-2

CERTIFIED MATERIAL TEST REPORT
FOR ASTM A307, GRADE A - MACHINE BOLTS

FACTORY: NINGBO ECONOMIC & TECHNICAL DEVELOPMENT ZONE YONGGANG FASTENERS CO., LTD. REPORT DATE:2016/12/29
R#17-507 H#816070039
ADDRESS: FuShan South Road No.17,BeiLun NingBo China BCT Cable Bracket Bolts
MANUFACTURE DATE:2016/12/2
TEL#(852)25423366
CUSTOMER: FASTENAL MFG LOT NUMBER:M-2016HT927-9
SAMPE SIZE: ACC.TO Dimension:ASME B18.18-11;Mechanical Properties:ASTM F1470-12
MANU QTY: 4800PCS SHIPPED QTY: 4800PCS
SIZE: 5/8-11X1 1/2 HDG
HEADMARKS: 307A PLUS NY PO NUMBER:220023115
PART NO:1191919

STEEL PROPERTIES:
MATERIAL TYPE:Q195 HEAT NUMBER: 816070039

CHEMISTRY SPEC:	C %*100	Mn%*100	P %*1000	S %*1000
Grade A ASTM A307-12	0.29max	1.20 max	0.04max	0.15max
TEST:	0.07	0.28	0.016	0.003

DIMENSIONAL INSPECTIONS Unit:inch SPECIFICATION: ASME B18.2.1 - 2012

CHARACTERISTICS	SPECIFIED	ACTUAL RESULT	ACC.	REJ.
VISUAL	ASTM F788-2013	PASSED	22	0
THREAD	ASME B1.1-2003,3A GO,2A NOGO	PASSED	15	0
WIDTH FLATS	0.906-0.938	0.915-0.928	4	0
WIDTH A/C	1.033-1.083	1.048-1.057	4	0
HEAD HEIGHT	0.378-0.444	0.394-0.424	4	0
THREAD LENGTH	1.420-1.560	1.435-1.541	15	0
LENGTH	1.420-1.560	1.435-1.541	15	0

MECHANICAL PROPERTIES: SPECIFICATION: ASTM A307-2012 GR-A

CHARACTERISTICS	TEST METHOD	SPECIFIED	ACTUAL RESULT	ACC.	REJ.
CORE HARDNESS :	ASTM F606-2014	69-100 HRB	76-79 HRB	4	0
WEDGE TENSILE:	ASTM F606-2014	Min 60 KSI	65-69 KSI	4	0

CHARACTERISTICS	TEST METHOD	SPECIFIED	ACTUAL RESULT	ACC.	REJ.
COATINGS OF ZINC:	SPECIFIATION:ASTM F2329-2013				
HOT DIP GALVANIZED	ASTM B568-98(2104)	Min 0.0017"	0.0017" -0.0018"	4	0

ALL TESTS IN ACCORDANCE WITH THE METHODS PRESCRIBED IN THE APPLICABLE ASTM SPECIFICATION. WE CERTIFY THAT THIS DATA IS A TRUE REPRESENTATION OF INFORMATION PROVIDED BY THE MATERIAL SUPPLIER AND OUR TESTING LABORATORY.

Maker's ISO# 00109Q16722R3M/3302

NINGBO ECONOMIC & TECHNICAL DEVELOPMENT ZONE YONGGANG FASTENERS CO., LTD

(SIGNATURE Q.A. LAB MGR.)
(NAME OF MANUFACTURER)

Figure A-21. ⅝-in. (16-mm) Diameter, 1½-in. (38-mm) Long Hex Head Bolts, Test Nos. CMGS-1 and CMGS-2

3540G

CERTIFICATE OF COMPLIANCE

ROCKFORD BOLT & STEEL CO.
126 MILL STREET
ROCKFORD, IL 61101
815-968-0514 FAX# 815-968-3111

CUSTOMER NAME: TRINITY INDUSTRIES

CUSTOMER PO: 178379

SHIPPER #: 058326
DATE SHIPPED: 08/03/2016

LOT#: 28899-B

SPECIFICATION: ASTM A307, GRADE A MILD CARBON STEEL BOLTS

TENSILE: SPEC: 60,000 psi*min RESULTS: 77,659 / 76,735

HARDNESS: 100 max 91.30 / 90.70

*Pounds Per Square Inch.

COATING: ASTM SPECIFICATION F-2329 HOT DIP GALVANIZE
ROGERS GALVANIZE: 28899-B

CHEMICAL COMPOSITION

MILL	GRADE	HEAT#	C	Mn	P	S	Si
NUCOR	1010	NF16202178	.12	.54	.007	.035	.17

QUANTITY AND DESCRIPTION:

3,325 PCS 5/8" X 14" GUARD RAIL BOLT
P/N 3540G

WE HEREBY CERTIFY THE ABOVE BOLTS HAVE BEEN MANUFACTURED BY ROCKFORD BOLT AND STEEL AT OUR FACILITY IN ROCKFORD, ILLINOIS, USA. THE MATERIAL USED WAS MELTED AND MANUFACTURED IN THE USA. WE FURTHER CERIFY THAT THIS DATA IS A TRUE REPRESENTATION OF INFORMATION PROVIDED BY THE MATERIALS SUPPLIER, AND THAT OUR PROCEDURES FOR THE CONTROL OF PRODUCT QUALITY ASSURE THAT ALL ITEMS FURNISHED ON THIS ORDER MEET OR EXCEED ALL APPLICABLE TESTS, PROCESS, AND INSPECTION REQUIREMENT PER ABOVE SPECIFICATION.

STATE OF ILLINOIS
COUNTY OF WINNEBAGO
SIGNED BEFORE ME ON THIS
4th DAY OF August 20 16
Merry F Shane

Linda McComas
APPROVED SIGNATORY

8/4/16
DATE

OFFICIAL SEAL
MERRY F. SHANE
NOTARY PUBLIC – STATE OF ILLINOIS
MY COMMISSION EXPIRES OCTOBER 3, 2018

Figure A-22. ⅝-in. (16-mm) Diameter, 14-in. (356-mm) Long Guardrail Bolts, Test Nos. CMGS-1 and CMGS-2

CHARTER STEEL

A Division of Charter Manufacturing Company, Inc.

EMAIL

1658 Cold Springs Road
Saukville, Wisconsin 53080
(262) 268-2400
1-800-437-8789
Fax (262) 268-2570

CHARTER STEEL TEST REPORT

Melted in USA Manufactured in USA

Cust P.O.	91893
Customer Part #	AXA18CB-5/16
Charter Sales Order	30124802
Heat #	20479830
Ship Lot #	2117839
Grade	1018 X AK FG RHQ 5/16
Process	HR
Finish Size	5/16
Ship date	13-JAN-17

Johnstown Wire Technologies
124 Laurel Ave.
Johnstown,PA-15906

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed below and that it satisfies these requirements. The recording of false, fictitious and fraudulent statements or entries on this document may be punishable as a felony under federal statute.

Test results of Heat Lot # 20479830

Lab Code: 125544

CHEM	C	MN	P	S	SI	NI	CR	MO	CU	SN	V
%Wt	.16	.84	.008	.004	.060	.03	.05	.01	.04	.003	.001

AL	N	B	TI	NB
.051	.0050	.0001	.001	.001

CAT DI=.35

Test results of Rolling Lot # 2117839

	# of Tests	Min Value	Max Value	Mean Value	
TENSILE (KSI)	1	68.6	68.6	68.6	TENSILE LAB = 0358-04
REDUCTION OF AREA (%)	1	72	72	72	RA LAB = 0358-04

NUM DECARB=1
REDUCTION RATIO=637:1

AVE DECARB (inch)=.000

Specifications: Manufactured per Charter Steel Quality Manual Rev Date 12/12/13
Charter Steel certifies this product is indistinguishable from background radiation levels by having process radiation detectors in place to measure for the presence of radiation within our process & products.
Meets customer specifications with any applicable Charter Steel exceptions for the following customer documents:
Customer Document = RW007-RW100 Revision = Dated = 08-NOV-13

Additional Comments:

Melt Source:
Charter Steel
Cuyahoga Heights, OH, USA

Rem: Load1,Fax0,Mail0

A2LA ACCREDITED Testing Laboratory

Page 1 of 2

This MTR supersedes all previously dated MTRs for this order

Janice Barnard Division Mgr. of Quality Assurance
barnardJ@chartersteel.com
Printed Date : 01/13/2017

Figure A-23. ⅝-in. (16-mm) Diameter Guardrail Nuts, Test Nos. CMGS-1 and CMGS-2

CHARTER STEEL
A Division of Charter Manufacturing Company, Inc.

LOAD

1658 Cold Springs Road
Saukville, Wisconsin 53080
(262) 268-2400
1-800-437-8789
Fax (262) 268-2570

Melted in USA Manufactured in USA

CHARTER STEEL TEST REPORT

Rockford Bolt & Steel
126 Mill St.
Rockford,IL-61101
Kind Attn :Linda McComas

Cust P.O.	P37098
Customer Part #	100905
Charter Sales Order	70075879
Heat #	20460760
Ship Lot #	3242161
Grade	1010 A AK FG RHQ 19/32
Process	HRSA
Finish Size	19/32
Ship date	01-NOV-16

I hereby certify that the material described herein has been manufactured in accordance with the specifications and standards listed below and that it satisfies these requirements. The recording of false, fictitious and fraudulent statements or entries on this document may be punishable as a felony under federal statute.

Test results of Heat Lot # 20460760

Lab Code: 125544

CHEM	C	MN	P	S	SI	NI	CR	MO	CU	SN	V
%Wt	.09	.33	.006	.003	.060	.03	.06	.01	.08	.006	.001
	AL	N	B	TI	NB						
	.025	.0070	.0001	.001	.001						

Test results of Rolling Lot # 2110397

REDUCTION RATIO=177:1

Specifications: Manufactured per Charter Steel Quality Manual Rev Date 12/12/13
Charter Steel certifies this product is indistinguishable from background radiation levels by having process radiation detectors in place to measure for the presence of radiation within our process & products.
Meets customer specifications with any applicable Charter Steel exceptions for the following customer documents:
Customer Document = ASTM A29/A29M Revision = 15 Dated = 01-NOV-15

Additional Comments: MELTED AND ROLLED IN THE USA

Melt Source:
Charter Steel
Cuyahoga Heights, OH, USA

Rem: Load1,Fax0,Mail0

ACCREDITED
Testing Laboratory

This MTR supersedes all previously dated MTRs for this order

Janice Barnard Division Mgr. of Quality Assurance
barnardJ@chartersteel.com
Printed Date : 11/01/2016

Page 1 of 2

Figure A-24. ⅝-in. (16-mm) Diameter, 1¼ in. (32-mm) Long Guardrail Bolt, Test Nos. CMGS-1 and CMGS-2

Certificate of Compliance

McMASTER-CARR

600 N County Line Rd
Elmhurst IL 60126-2081
630-600-3600
chi.sales@mcmaster.com

University of Nebraska
Midwest Roadside Safety Facility
M W R S F
4630 Nw 36TH St
Lincoln NE 68524-1802
Attention: Shaun M Tighe
Midwest Roadside Safety Facility

Purchase Order
E000357170

Order Placed By
Shaun M Tighe

McMaster-Carr Number
2098331-01

Page 1 of 1

Line		Product	Ordered	Shipped
1	**97812A109**	Steel Double-Headed Nail Size 16D, 3" Length, .16" Shank Diameter, 200 Pieces/Pack, Packs of 5	**5 Packs**	**5**

Certificate of compliance

This is to certify that the above items were supplied in accordance with the description and as illustrated in the catalog. Your order is subject only to our terms and conditions, available at www.mcmaster.com or from our Sales Department.

Sarah Weinberg
Compliance Manager

Figure A-25. 16D Double Head Nail, Test Nos. CMGS-1 and CMGS-2

R#16-692 5/8"x10" GR Bolt
Orange Paint H#20351510 L#150424L

3500G

TRINITY HIGHWAY PRODUCTS, LLC
425 East O'Connor Ave.
Lima, Ohio 45801
419-227-1296

MATERIAL CERTIFICATION

Customer: Stock

Date: December 16, 2015
Invoice Number:
Lot Number: 150424L

Part Number: 3500G
Quantity: 16,702 Pcs.

Description: 5/8" x 10" G.R. Bolt

Heat Numbers: 20351510 16,702

Specification: ASTM A307-A / A153 / F2329

MATERIAL CHEMISTRY

Heat	C	MN	P	S	SI	NI	CR	MO	CU	SN	V	AL	N	B	TI	NB
20351510	.09	.33	.007	.002	.06	.04	.05	.01	.06	.004	.001	.028	.007	.0001	.001	.001

PLATING OR PROTECTIVE COATING

HOT DIP GALVANIZED (Lot Ave.Thickness / Mils) 2.52 (2.0 Mils Minimum)

****THIS PRODUCT WAS MANUFACTURED IN THE UNITED STATES OF AMERICA****

THE MATERIAL USED IN THIS PRODUCT WAS MELTED AND MANUFACTURED IN THE U.S.A

WE HEREBY CERTIFY THAT TO THE BEST OF OUR KNOWLEDGE ALL INFORMATION CONTAINED HEREIN IS CORRECT.

TRINITY HIGHWAY PRODUCTS LLC

STATE OF OHIO, COUNTY OF ALLEN
SWORN AND SUBSCRIBED BEFORE ME THIS 12-17-15

NOTARY PUBLIC

425 E. O'CONNOR AVENUE LIMA, OHIO 419-227-1296

MONIQUE HOLMES
Notary Public, State of Ohio
My Commission Expires
July 5, 2020

Figure A-26. ⅝-in. (16-mm) Diameter, 10-in. (254-mm) Long Guardrail Bolt, Test Nos. CMGS-1 and CMGS-2

COMMERCIAL GROUP LIFTING PRODUCTS

Feb 15th 2017

SOLD TO:
GREGORY INDUSTRIES, INC.
4100 13TH ST. SW
CANTON, OH. 44710

SHIP TO:
HIGHWAY – FINISHED GOODS
GREGORY INDUSTRIES, INC.
ATTN: STEVE PENNINGTON
CANTON, OH 44710

R#17-700

CERTIFICATON BCT Cables Yellow Paint

CGLP ORDER# 256284
GREGORY PO# 36454

THIS LETTER AND THE ENCLOSED ATTACHMENTS ARE TO CERTIFY THAT THE FOLLOWING ITEMS WERE 100% MANUFACTURED IN THE UNITED STATES OF AMERICA.

1,330 PCS, PART# 3012G, 3/4IN X 6FT 6IN DOUBLE SWAGE GUARD RAIL ASSEMBLYS.

THEY SHOW THE DOMESTICITY OF ALL MATERIAL USED, 100% MELTED & MANUFACTURED IN THE USA. THESE ITEMS ARE HOT DIPPED GALVANIZED TO ASTM-153 SPECIFICATIONS AND STANDARDS, GALV PROCESS ALSO TOOK PLACE IN THE U.S.A.

ATTACHMENTS:

(WIRE ROPE) WIRECO WORLD GROUP REEL# 428-671806-1; HEAT# .15R582807; 16R584001; 72987C; 16R586548; 73253F; 16R588160; 16R584967; 16R585464; 16R586547; 14R574048; 14R571682; 16R586549; 16R586401; (ROCKY MOUNTAIN STEEL / EVRAZ)

(END FITTINGS) REMLINGER MFG: HEAT#S 75063022; 75062074; 765063075 (GERDAU NORTH AMERICA)

VERY TRULY YOURS

BILL KOTARSKI
GEN MGR CLEV OFFICE

HEADQUARTERS	FLINT BRANCH	CLEVELAND BRANCH
12801 UNIVERSAL DRIVE TAYLOR, MI 48180 *NEW PH# (734) 947-4000* *NEW FAX# (734) 947-4004*	G2427 E. JUDD ROAD BURTON, MI 48529 PH# (810) 744-4540 FAX# (810) 744-1588	5213 GRANT AVE CLEVELAND, OH 44105 PH# (216) 641-4100 FAX# (216) 641-1814

Figure A-27. BCT Anchor Cable, Test Nos. CMGS-1 and CMGS-2

Certified Material Test Report to BS EN ISO 10204-2004 3.1

FOR USS FLAT WASHER HDG

COUNTRY OF ORIGIN: CHINA
CUSTOMER: FASTENAL
FACTORY NAME: IFI & MORGAN LTD.
FACTORY ADDRESS: Chang'an North Road, Wuyuan Town, Haiyan, Zhejiang, China

DESCRIPTION: 1
INVOICE NBR: TD16680155
PART NBR.: 33188
LOT NO.: 16H-168236-30

DATE: 2016-10-08
ORDER NBR. 210114135
QUANTITY:3240PCS

DIMENSIONS (UNIT:INCH)

	STANDARD	RESULT				
		1	2	3	4	5
INSIDE DIA	1.055-1.092	1.068	1.068	1.067	1.069	1.068
OUTSIDE DIA	2.493-2.530	2.514	2.513	2.514	2.514	2.511
THICKNESS	0.136-0.192	0.146	0.149	0.152	0.152	0.147

WE HEREBY CERTIFY THAT THIS WAS PRODUCED AS PER CUSTOMER'S REQUIREMENT.

CHARACTERISTICS	SPECIFIED	ACTUAL RESULT	ACC.	REJ.
HOT DIP GALVANIZED ASTM F2329	Min 43 um	48-64um	8	0

NOTE

1. QUANTITY OF SAMPLES: 5 PCS

2. JUDGEMENT: GOOD

3. CHIEF INSPECTOR:

IFI & MORGAN LTD.
检验专用章
QUANLITY CONTROL

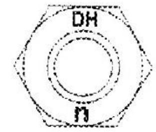
Figure A-28. BCT Cable Washers, Test Nos. CMGS-1 and CMGS-2

NUCOR
FASTENER DIVISION

LOT NO.
371123B

Post Office Box 6100
Saint Joe, Indiana 46785
Telephone 260/337-1600

CUSTOMER NO/NAME
8001 FASTENAL COMPANY-KS — NUCOR ORDER # 978943
TEST REPORT SERIAL# FB488556 — CUST PART # 38210
TEST REPORT ISSUE DATE 3/04/16
DATE SHIPPED 8/17/16 — CUSTOMER P.O. # 210117217
NAME OF LAB SAMPLER: SANDRA NEUMANN-PLUMMER, LAB TECHNICIAN



*****************CERTIFIED MATERIAL TEST REPORT*****************

NUCOR PART NO	QUANTITY	LOT NO.	DESCRIPTION
175647	3600	371123B	1-8 GR DH HV H.D.G.

MANUFACTURE DATE 1/07/16 — HEX NUT H.D.G./GREEN LUBE

--CHEMISTRY MATERIAL GRADE -1045L
**CHEMISTRY COMPOSITION (WT% HEAT ANALYSIS) BY MATERIAL SUPPLIER — NUCOR STEEL - SOUTH CAROL

MATERIAL NUMBER	HEAT NUMBER	C	MN	P	S	SI
RM030412	DL15105591	.44	.64	.005	.020	.20

--MECHANICAL PROPERTIES IN ACCORDANCE WITH ASTM A563-07a

SURFACE HARDNESS (R30N)	CORE HARDNESS (RC)	PROOF LOAD 90900 LBS	TENSILE STRENGTH DEG-WEDGE (LBS)	STRESS (PSI)
N/A	26.6	PASS	N/A	N/A
N/A	27.0	PASS	N/A	N/A
N/A	27.6	PASS	N/A	N/A
N/A	28.9	PASS	N/A	N/A
N/A	26.7	PASS	N/A	N/A

AVERAGE VALUES FROM TESTS
27.4
PRODUCTION LOT SIZE 90800 PCS

--VISUAL INSPECTION IN ACCORDANCE WITH ASTM A563-07a — 80 PCS. SAMPLED — LOT PASSED

--COATING - HOT DIP GALVANIZED TO ASTM F2329-13 - GALVANIZING PERFORMED IN THE U.S.A.

1. 0.00294	2. 0.00311	3. 0.00346	4. 0.00235	5. 0.00218	6. 0.00270	7. 0.00353
8. 0.00322	9. 0.00406	10. 0.00269	11. 0.00275	12. 0.00315	13. 0.00487	14. 0.00253
15. 0.00416						

AVERAGE THICKNESS FROM 15 TESTS .00318
HEAT TREATMENT - AUSTENITIZED, OIL QUENCHED & TEMPERED (MIN 800 DEG F)

--DIMENSIONS PER ASME B18.2.6-2010

CHARACTERISTIC	#SAMPLES TESTED	MINIMUM	MAXIMUM
Width Across Corners	8	1.824	1.844
Thickness	32	0.980	1.001

ALL TESTS ARE IN ACCORDANCE WITH THE LATEST REVISIONS OF THE METHODS PRESCRIBED IN THE APPLICABLE SAE AND ASTM SPECIFICATIONS. THE SAMPLES TESTED CONFORM TO THE SPECIFICATIONS AS DESCRIBED/LISTED ABOVE AND WERE MANUFACTURED FREE OF MERCURY CONTAMINATION. NO INTENTIONAL ADDITIONS OF BISMUTH, SELENIUM, TELLURIUM, OR LEAD WERE USED IN THE STEEL USED TO PRODUCE THIS PRODUCT.
THE STEEL WAS MELTED AND MANUFACTURED IN THE U.S.A. AND THE PRODUCT WAS MANUFACTURED AND TESTED IN THE U.S.A. PRODUCT COMPLIES WITH DFARS 252.225-7014. WE CERTIFY THAT THIS DATA IS A TRUE REPRESENTATION OF INFORMATION PROVIDED BY THE MATERIAL SUPPLIER AND OUR TESTING LABORATORY. THIS CERTIFIED MATERIAL TEST REPORT RELATES ONLY TO THE ITEMS LISTED ON THIS DOCUMENT AND MAY NOT BE REPRODUCED EXCEPT IN FULL.

A2LA ACCREDITED

MECHANICAL FASTENER
CERTIFICATE NO. A2LA 0139.01
EXPIRATION DATE 12/31/17

NUCOR FASTENER
A DIVISION OF NUCOR CORPORATION
John W. Ferguson
JOHN W. FERGUSON
QUALITY ASSURANCE SUPERVISOR

Page 1 of 1

Figure A-29. BCT Cable Nuts, Test Nos. CMGS-1 and CMGS-2

EXLTUBE

1000 BURLINGTON STREET, NORTH KANSAS CITY, MO 64116 1-816-474-5210 TOLL FREE 1-800-892-TUBE

STEEL VENTURES, LLC dba EXLTUBE

Certified Test Report

Customer:	Size:	Customer Order No:	Date:
SPS - New Century 401 New Century Parkway NEW CENTURY KS 66031-1127	02.375	4500269918	07/25/2016
	Gauge: .154	Delivery No: 82799116 Load No: 3774661	
	Specification: ASTM A500-13 Gr.B/C, ASTM A53-12 Gr.B BNT*, ASME SA53 Gr.B BNT*		

Heat No	Yield KSI	Tensile KSI	Elongation % 2 inch
A79999	63.2	67.3	31.00

R#17-175 H#A79999
BCT Post Sleeves QTY 8
Oct 2016 SMT

Heat No	C	MN	P	S	SI	CU	NI	CR	MO	V
A79999	0.0700	0.8400	0.0110	0.0040	0.0200	0.1500	0.0500	0.0600	0.0200	0.0010

This material was melted & manufactured in the U.S.A.
We hereby certify that all test results shown in this report are correct as contained in the records of our company. All testing and manufacturing is in accordance to A.S.T.M. parameters encompassed within the scope of the specifications denoted in the specification and grade tiles above. This product was manufactured in accordance with your purchase order requirements.
BNT=Grade B not pressure tested - meets tensile & chemical properties ONLY.

This material has not come into direct contact with mercury, any of its compounds, or any mercury bearing devices during our manufacturing process, testing, or inspections.

This material is in compliance with EN 10204 Section 4.1 Inspection Certificate Type 3.1

This material has passed NDE (eddy current, A309) testing. This material has passed flattening tests.

Tensile test completed using test specimen with 3/4" reduced area.

STEEL VENTURES, LLC dba EXLTUBE

Jonathan Wolfe
Quality Assurance Manager

Figure A-30. BCT Post Sleeves, Test Nos. CMGS-1 and CMGS-2

Certified Analysis

Trinity Highway Products, LLC
550 East Robb Ave.
Lima, OH 45801 Phn:(419) 227-1296
Customer: MIDWEST MACH.& SUPPLY CO.
P. O. BOX 703

MILFORD, NE 68405
Project: RESALE

Order Number: 1269489 Prod Ln Grp: 3-Guardrail (Dom)
Customer PO: 3346
BOL Number: 97457 Ship Date:
Document #: 1
Shipped To: NE
Use State: NE

As of: 11/7/16

Qty	Part #	Description	Spec	CL	TY	Heat Code/ Heat	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
	701A	Anchor Box	A-36			JK16101488	56,172	75,460	25.0	0.160	0.780	0.017	0.028	0.200	0.280	0.001	0.140	0.028	4
	701A		A-36			535133	43,300	68,500	33.0	0.019	0.460	0.013	0.016	0.013	0.090	0.001	0.090	0.002	4
4	729G	TS 8X6X3/16X8'-0" SLEEVE	A-500			A49248	64,818	78,412	32.0	0.200	0.810	0.014	0.002	0.040	0.020	0.000	0.040	0.001	4
20	738A	5'TUBE SL.188X6X8 1/4 /PL	A-36		2	4182184	45,000	67,900	31.0	0.210	0.760	0.012	0.008	0.010	0.050	0.001	0.030	0.002	4
	738A		A-500			A49248	64,818	78,412	32.0	0.200	0.810	0.014	0.002	0.040	0.020	0.000	0.040	0.001	4
6	749G	TS 8X6X3/16X6'-0" SLEEVE	A-500			A49248	64,818	78,412	32.0	0.200	0.810	0.014	0.002	0.040	0.020	0.000	0.040	0.001	4
6	782G	5/8"X8"X8" BEAR PL/OF	A-36			DL15103543	58,000	74,000	25.0	0.150	0.750	0.013	0.025	0.200	0.360	0.003	0.090	0.000	4
20	783A	5/8X8X8 BEAR PL 3/16 STP	A-36			PL14107973	48,167	69,811	25.0	0.160	0.740	0.012	0.041	0.190	0.370	0.000	0.220	0.002	4
	783A		A-36			DL15103543	58,000	74,000	25.0	0.150	0.750	0.013	0.025	0.200	0.360	0.003	0.090	0.000	4
45	3000G	CBL 3/4X6'6/DBL	HW			119048													
7,000	3340G	5/8" GR HEX NUT	HW			0055551-116146													
4,000	3360G	5/8"X1.25" GR BOLT	HW			0053777-115516													
450	3500G	5/8"X10" GR BOLT A307	HW			28971-B													
1,225	3540G	5/8"X14" GR BOLT A307	HW			29053-B													

Figure A-31. North-Side Anchor Bearing Plate and Anchor Bracket Assembly, Test Nos. CMGS-1 and CMGS-2

Certified Analysis

Trinity Highway Products, LLC
2548 N.E. 28th St.
Ft Worth, TX
Customer: MIDWEST MACH.& SUPPLY CO.
P. O. BOX 81097

LINCOLN, NE 68501-1097
Project: RESALE

Order Number: 1095199
Customer PO: 2041
BOL Number: 24481
Document #: 1
Shipped To: NE
Use State: KS

As of: 6/20/08

Qty	Part#	Description	Spec	CL	TY	Heat Code/ Heat #	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
25	6G	12/6'3/S	M-180	A		84964	64,230	81,300	25.4	0.180	0.720	0.012	0.001	0.040	0.080	0.000	0.060	0.000	4
20	701A	.25X11.75X16 CAB ANC	A-36			4153095	44,900	60,800	34.0	0.240	0.750	0.012	0.003	0.020	0.020	0.000	0.040	0.002	4
10	742G	6'0 TUBE SL/.188X8X6	A-500			A8P1160	74,000	87,000	25.2	0.050	0.670	0.013	0.005	0.030	0.220	0.000	0.060	0.021	4
20	782G	5/8"X8"X8" BEAR PL/OF	A-36			6105195	46,700	69,900	23.5	0.180	0.830	0.010	0.005	0.020	0.230	0.000	0.070	0.006	4
40	907G	12/BUFFER/ROLLED	M-180	A		L0049	54,200	73,500	25.0	0.160	0.700	0.011	0.008	0.020	0.200	0.000	0.100	0.000	4

Upon delivery, all materials subject to Trinity Highway Products, LLC Storage Stain Policy No. LG-002.

ALL STEEL USED WAS MELTED AND MANUFACTURED IN USA AND COMPLIES WITH THE BUY AMERICA ACT.
ALL GUARDRAIL MEETS AASHTO M-180, ALL STRUCTURAL STEEL MEETS ASTM A36
ALL OTHER GALVANIZED MATERIAL CONFORMS WITH ASTM-123.
BOLTS COMPLY WITH ASTM A-307 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.
NUTS COMPLY WITH ASTM A-563 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.

3/4" DIA CABLE 6X19 ZINC COATED SWAGED END AISI C-1035 STEEL ANNEALED STUD 1" DIA ASTM 449 AASHTO M30, TYPE II BREAKING STRENGTH – 49100 LB

State of Texas, County of Tarrant. Sworn and subscribed before me this 20th day of June, 2008

Notary Public:
Commission Expires

RACHEL R. MEDINA
Notary Public
State of Texas
My Commission Expires

Trinity Highway Products, LLC
Certified By: Stefanie Onal.a

Figure A-32. South-Side Anchor Bearing Plate and North-Side Ground Strut Assembly, Test Nos. CMGS-1 and CMGS-2

Certified Analysis

Trinity Highway Products , LLC
550 East Robb Ave.
Lima, OH 45801
Customer: MIDWEST MACH.& SUPPLY CO.
P. O. BOX 703

MILFORD, NE 68405
Project: STOCK

Order Number: 1214903 Prod Ln Grp: 9-End Terminals (Dom)
Customer PO: 2878
BOL Number: 80278 Ship Date:
Document #: 1
Shipped To: NE
Use State: KS

As of: 3/7/14

Qty	Part #	Description	Spec	CL	TY	Heat Code/ Heat	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
36	749G	TS 8X6X3/16X6'-0" SLEEVE	A-500			0173175	55,871	74,495	31.0	0.160	0.610	0.012	0.009	0.010	0.030	0.000	0.030	0.000	4
20	3000G	CBL 3/4X6'6/DBL	HW			98790													
22	9852A	STRUT & YOKE ASSY	A-1011-SS			163375	48,380	64,020	32.9	0.190	0.520	0.011	0.003	0.030	0.110	0.000	0.050	0.000	4
	9852A		A-36			11237730	45,500	70,000	30.0	0.170	0.500	0.010	0.008	0.020	0.080	0.000	0.070	0.001	4

Ground Strut Green Paint
R#15-0157 September 2014 SMT

Upon delivery, all materials subject to Trinity Highway Products , LLC Storage Stain Policy No. LG-002.

ALL STEEL USED WAS MELTED AND MANUFACTURED IN USA AND COMPLIES WITH THE BUY AMERICA ACT.
ALL GUARDRAIL MEETS AASHTO M-180, ALL STRUCTURAL STEEL MEETS ASTM A36
ALL COATINGS PROCESSES OF THE STEEL OR IRON ARE PERFORMED IN USA AND COMPLIES WITH THE "BUY AMERICA ACT"
ALL GALVANIZED MATERIAL CONFORMS WITH ASTM-123 (US DOMESTIC SHIPMENTS)
ALL GALVANIZED MATERIAL CONFORMS WITH ASTM A123 & ISO 1461 (INTERNATIONAL SHIPMENTS)

FINISHED GOOD PART NUMBERS ENDING IN SUFFIX B,P, OR S, ARE UNCOATED
BOLTS COMPLY WITH ASTM A-307 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.
NUTS COMPLY WITH ASTM A-563 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.
WASHERS COMPLY WITH ASTM F-436 SPECIFICATION AND/OR F-844 AND ARE GALVANIZED IN ACCORDANCE WITH ASTM F-2329.
3/4" DIA CABLE 6X19 ZINC COATED SWAGED END AISI C-1035 STEEL ANNEALED STUD 1" DIA ASTM 449 AASHTO M30, TYPE II BREAKING STRENGTH – 46000 LB

Figure A-33. South-Side Ground Strut Assembly, Test Nos. CMGS-1 and CMGS-2

Certified Analysis

Trinity Highway Products , LLC
2548 N.E. 28th St.
Ft Worth, TX
Customer: MIDWEST MACH.& SUPPLY CO.
P. O. BOX 81097

LINCOLN, NE 68501-1097

Project: RESALE

Order Number: 1095199
Customer PO: 2041
BOL Number: 24481
Document #: 1
Shipped To: NE
Use State: KS

As of: 6/20/08

Qty	Part#	Description	Spec	CL	TY	Heat Code/ Heat #	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
25	6G	12/6'3/S	M-180	A		84964	64,230	81,300	25.4	0.180	0.720	0.012	0.001	0.000	0.080	0.000	0.060	0.000	4
20	701A	.25X11.75X16 CAB ANC	A-36			4153095	44,900	60,800	34.0	0.240	0.750	0.012	0.003	0.020	0.020	0.000	0.040	0.002	4
10	742G	6'0 TUBE SL/.188X8X6	A-500			A8P1160	74,000	87,000	25.2	0.050	0.670	0.013	0.005	0.030	0.220	0.000	0.060	0.021	4
20	782G	5/8"X8"X8" BEAR PL/OF	A-36			6105195	46,700	69,900	23.5	0.180	0.830	0.010	0.005	0.020	0.230	0.000	0.070	0.006	4
40	907G	12/BUFFER/ROLLED	M-180	A		L0049	54,200	73,500	25.0	0.160	0.700	0.011	0.008	0.020	0.200	0.000	0.100	0.000	4

Upon delivery, all materials subject to Trinity Highway Products , LLC Storage Stain Policy No. LG-002.

ALL STEEL USED WAS MELTED AND MANUFACTURED IN USA AND COMPLIES WITH THE BUY AMERICA ACT.
ALL GUARDRAIL MEETS AASHTO M-180, ALL STRUCTURAL STEEL MEETS ASTM A36
ALL OTHER GALVANIZED MATERIAL CONFORMS WITH ASTM-123.
BOLTS COMPLY WITH ASTM A-307 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.
NUTS COMPLY WITH ASTM A-563 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.

3/4" DIA CABLE 6X19 ZINC COATED SWAGED END AISI C-1035 STEEL ANNEALED STUD 1" DIA ASTM 449 AASHTO M30, TYPE II BREAKING STRENGTH – 49100 LB

State of Texas, County of Tarrant. Sworn and subscribed before me this 20th day of June, 2008

Notary Public:
Commission Expires

RACHEL R. MEDINA
Notary Public
State of Texas
My Commission Expires

Trinity Highway Products , LLC
Certified By:

Stefanie Ornel.a

Figure A-34. South-Side Anchor Bearing Plate, Test Nos. CMGS-1 and CMGS-2

Certified Analysis

Trinity Highway Products , LLC
550 East Robb Ave.
Lima, OH 45801 Phn:(419) 227-1296
Customer: MIDWEST MACH.& SUPPLY CO.
P. O. BOX 703

MILFORD, NE 68405
Project: RESALE

Order Number: 1269489 Prod Ln Grp: 3-Guardrail (Dom)
Customer PO: 3346
BOL Number: 97457 Ship Date:
Document #: 1
Shipped To: NE
Use State: NE

As of: 11/7/16

Qty	Part #	Description	Spec	CL	TY	Heat Code/ Heat	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
175	3580G	5/8"X18" GR BOLT A307	HW			29145-B													
6	6696G	CBL 5/8"X14'4.75/DBL BTN	HW			248853													
400	6740B	PLYMR BLK 6X12X14 MT	HW			27950													
4	9852A	STRUT & YOKE ASSY	A-36			195070	52,940	69,970	31.1	0.190	0.520	0.014	0.004	0.020	0.110	0.000	0.050	0.000	4
7	12379G	T12/12'6/SPEC/S 34'RCX	RHC		2	L34713													4
			M-180	A	2	172876	55,930	72,020	31.4	0.190	0.720	0.014	0.002	0.020	0.130	0.000	0.080	0.000	4
			M-180	A	2	172876	55,930	72,020	31.4	0.190	0.720	0.014	0.002	0.020	0.130	0.000	0.080	0.000	4
6	12383G	T12/12'6/6'3/SPEC SLOTS/S	RHC			L33814													4
			M-180	A		182997	58,340	76,890	26.9	0.180	0.730	0.014	0.004	0.010	0.130	0.000	0.060	0.001	4
			M-180	A		182998	60,310	78,910	25.4	0.200	0.730	0.012	0.006	0.010	0.140	0.000	0.050	0.001	4
			M-180	A		182997	58,340	76,890	26.9	0.180	0.730	0.014	0.004	0.010	0.130	0.000	0.060	0.001	4
			M-180	A		182998	60,310	78,910	25.4	0.200	0.730	0.012	0.006	0.010	0.140	0.000	0.050	0.001	4
3	12385G	T12/12'6/SPEC/S 5'RCX			2	L34416													
			M-180	A	2	208318	64,140	81,540	24.5	0.190	0.720	0.011	0.003	0.020	0.110	0.000	0.060	0.000	4
24	19361G	BNT PL 3/16X12-5/8X5-1/2	A-36			B4M5475	46,800	70,400	29.1	0.180	0.840	0.007	0.008	0.060	0.170	0.000	0.070	0.001	4

Upon delivery, all materials subject to Trinity Highway Products , LLC Storage Stain Policy QMS-LG-002.

ALL STEEL USED WAS MELTED AND MANUFACTURED IN USA AND COMPLIES WITH THE BUY AMERICA ACT , 23 CFR 635.410.
ALL GUARDRAIL MEETS AASHTO M-180, ALL STRUCTURAL STEEL MEETS ASTM A36 UNLESS OTHERWISE STATED.

Figure A-35. Anchor Bracket Assembly, Test Nos. CMGS-1 and CMGS-2

Ready Mixed Concrete Company
6200 Cornhusker Hwy, Lincoln, NE 68529
Phone: (402) 434-1844 Fax: (402) 434-1877

Customer's Signature: ______________________

PLANT	TRUCK	DRIVER	CUSTOMER	PROJECT	TAX	PO NUMBER	DATE	TIME	TICKET
4	0212	9264	00003	3		HOLLOWAY 450 625	8/17/17	9:20 AM	4197075

Customer	Delivery Address	Special Instructions
CIA---MIDWEST ROADSIDE SAFETY	4630 NW 36TH ST	N/SIDE OF GOODYEAR HANGAR

LOAD QUANTITY	CUMULATIVE QUANTITY	ORDERED QUANTITY	PRODUCT CODE	PRODUCT DESCRIPTION	UOM	UNIT PRICE	EXTENDED PRICE
9.00	9.00	18.00	470031PF	47BD (1PF) WO/R	yd	$118.91	$1,070.19

Water Added On Job At Customer's Request: ______

SLUMP: 4.00 in

Notes:

TICKET SUBTOTAL	$1,070.19
SALES TAX	$0.00
TICKET TOTAL	**$1,070.19**
PREVIOUS TOTAL	
GRAND TOTAL	**$1,070.19**

CAUTION FRESH CONCRETE

KEEP CHILDREN AWAY

Contains Portland cement. Freshly mixed cement, mortar, concrete or grout may cause skin injury. Avoid prolonged contact with skin. Always wear appropriate Personal Protective Equipment (PPE). In case of contact with eyes or skin, flush thoroughly with water. If irritation persists, seek medical attention promptly.

Terms & Conditions

This concrete is produced with the ASTM standard specifications for ready mix concrete. Strengths are based on a 3" slump. Drivers are not permitted to add water to the mix to exceed this slump, except under the authorization of the customer and their acceptance of any decrease in compressive strength and any risk of loss as a result thereof. Cylinder tests must be handled according to ACI/ASTM specifications and drawn by a licensed testing lab and/or certified technician.
Ready Mixed Concrete Company will not deliver any product beyond any curb lines unless expressly told to do so by customer and customer assumes all liability for any personal or property damage that may occur as a result of any such directive.
The purchaser's exceptions and claims shall be deemed waived unless made in writing within 3 days from time of delivery. In such a case, seller shall be given full opportunity to investigate any such claim. Seller's liability shall in no event exceed the purchase price of the materials against which any claims are made.

MATERIAL	DESCRIPTION	DESIGN QTY	REQUIRED	BATCHED	% VAR	% MOISTURE	ACTUAL WATER
G47B	47B GRAVEL	1975.0 lb	17994.9 lb	17960.0 lb	-0.19%	1.24% A	26.3 gl
L47B	47B ROCK	840.0 lb	7635.6 lb	7660.0 lb	0.10%	1.00% M	9.1 gl
CEM1PF	1PF CEMENT	658.0 lb	5922.0 lb	5900.0 lb	-0.37%		
WATER	WATER	31.6 gl	258.0 gl	257.6 gl	-0.14%		257.6 gl
LRWR	POZZ 322N LOV	34.0 oz	306.0 oz	306.0 oz	0.00%		
AIR	MB AE 200 air e	5.9 oz	53.1 oz	53.0 oz	-0.19%		

Actual Load: 33692 lb | Num Batches: 1 | Design W/C: 0.40 | Water/Cement: 0.41 A | Design Water: 284.4 gl | Manual | Actual: 293.0 gl

Slump: 4.00 in # | Water in Truck: 0.0 gl | Adjust Water: 0.0 gl / Load | Trim Water: 0.0 gl / CYDS

Actual W/C Ratio 0.41 | Actual Water: 293 gl | Batched Cement: 5900 lb | Allowable Water: 0 lb | To Add: 0.0 gl

Figure A-36. Concrete Culvert, Test Nos. CMGS-1 and CMGS-2

Ready Mixed Concrete Company
6200 Cornhusker Hwy, Lincoln, NE 68529
Phone: (402) 434-1844 Fax: (402) 434-1877

Customer's Signature:

PLANT	TRUCK	DRIVER	CUSTOMER	PROJECT	TAX	PO NUMBER	DATE	TIME	TICKET
4	0228	5806	00003	3		HOLLOWAY 450 625	8/17/17	9:39 AM	4197078

Customer	Delivery Address	Special Instructions
CIA---MIDWEST ROADSIDE SAFETY	4630 NW 36TH ST	N/SIDE OF GOODYEAR HANGAR

LOAD QUANTITY	CUMULATIVE QUANTITY	ORDERED QUANTITY	PRODUCT CODE	PRODUCT DESCRIPTION	UOM	UNIT PRICE	EXTENDED PRICE
9.00	18.00	18.00	470031PF	47BD (1PF) WO/R	yd	$118.91	$1,070.19

Water Added On Job At Customer's Request:	SLUMP	Notes:		
	4.00 in		TICKET SUBTOTAL SALES TAX TICKET TOTAL	$1,070.19 $0.00 **$1,070.19**
			PREVIOUS TOTAL **GRAND TOTAL**	$1,070.19 **$2,140.38**

CAUTION FRESH CONCRETE

KEEP CHILDREN AWAY

Contains Portland cement. Freshly mixed cement, mortar, concrete or grout may cause skin injury. Avoid prolonged contact with skin. Always wear appropriate Personal Protective Equipment (PPE). In case of contact with eyes or skin, flush thoroughly with water. If irritation persists, seek medical attention promptly.

Terms & Conditions

This concrete is produced with the ASTM standard specifications for ready mix concrete. Strengths are based on a 3" slump. Drivers are not permitted to add water to the mix to exceed this slump, except under the authorization of the customer and their acceptance of any decrease in compressive strength and any risk of loss as a result thereof. Cylinder tests must be handled according to ACI/ASTM specifications and drawn by a licensed testing lab and/or certified technician.
Ready Mixed Concrete Company will not deliver any product beyond any curb lines unless expressly told to do so by customer and customer assumes all liability for any personal or property damage that may occur as a result of any such directive.
The purchaser's exceptions and claims shall be deemed waived unless made in writing within 3 days from time of delivery. In such a case, seller shall be given full opportunity to investigate any such claim. Seller's liability shall in no event exceed the purchase price of the materials against which any claims are made.

MATERIAL	DESCRIPTION	DESIGN QTY	REQUIRED	BATCHED	% VAR	% MOISTURE	ACTUAL WATER
G47B	47B GRAVEL	1975.0 lb	17996.9 lb	17940.0 lb	-0.32%	1.25% A	26.5 gl
L47B	47B ROCK	840.0 lb	7635.6 lb	7600.0 lb	-0.14%	1.00% M	9.0 gl
CEM1PF	1PF CEMENT	658.0 lb	5922.0 lb	5900.0 lb	-0.37%		
WATER	WATER	31.6 gl	257.8 gl	258.6 gl	0.33%		258.6 gl
LRWR	POZZ 322N LOV	34.0 oz	306.0 oz	306.0 oz	0.00%		
AIR	MB AE 200 air e	5.9 oz	53.1 oz	54.0 oz	1.69%		

Actual Load: 33621 lb	Num Batches: 1 Design W/C: 0.40	Water/Cement: 0.42 A	Design Water: 284.4 gl	Manual Actual: 294.1 gl
Slump: 4.00 in #	Water in Truck: 0.0 gl	Adjust Water: 0.0 gl / Load	Trim Water: 0.0 gl / CYDS	
Actual W/C Ratio 0.42	Actual Water: 294 gl	Batched Cement: 5900 lb	Allowable Water: 0 lb	To Add: 0.0 gl

Figure A-37. Concrete Culvert, Test Nos. CMGS-1 and CMGS-2

LINCOLN OFFICE
825 "M" Street Suite 100
Lincoln, NE 68508
Phone: (402) 479-2200
Fax: (402) 479-2276

COMPRESSION TEST OF CYLINDRICAL CONCRETE SPECIMENS - 6x12

ASTM Designation: C 39

Client Name: Midwest Roadside Safety Facility
Project Name: Miscellaneous Concrete Testing
Placement Location: WI MGS Culvert

Date 13-Sep-17

Mix Designation:

Required Strength:

Laboratory Test Data

Laboratory Identification	Field Identification	Date Cast	Date Received	Date Tested	Days Cured in Field	Days Cured in Laboratory	Age of Test, Days	Length of Specimen, in.	Diameter of Specimen, in.	Cross-Sectional Area,sq.in.	Maximum Load, lbf	Compressive Strength, psi.	Required Strength, psi.	Type of Fracture	ASTM Practice for Capping Specimen
URR- 12	A	8/17/2017	9/13/2017	9/13/2017	27	0	27	12	6.02	28.46	132,704	4,660		5	C 1231
URR- 13	1B	8/17/2017	9/13/2017	9/13/2017	27	0	27	12	6.01	28.37	132,547	4,670		5	C 1231

1 cc: Ms. Karla Lechtenberg
Midwest Roadside Safety Facility

Remarks:

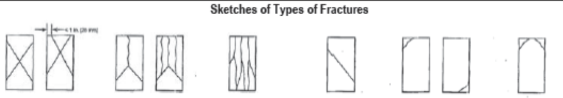
All concrete test data in this report was produced by Benesch personnel using ASTM Standard Methods and Practices unless otherwise noted.

Test results presented relate only to the concrete sampled by Benesch personnel as referenced above.

This report shall not be reproduced except in full, without the written approval of Alfred Benesch & Company.

Report Number 2147369527
Page 1

Sketches of Types of Fractures



Type 1 Reasonably well-formed cones on both ends, less than 1 in. [25 mm] of cracking through caps

Type 2 Well-formed cone on one end, vertical cracks running through caps, no well-defined cone on other end

Type 3 Columnar vertical cracking through both ends, no well-formed cones

Type 4 Diagonal fracture with no cracking through ends; tap with hammer to distinguish from Type 1

Type 5 Side fractures at top or bottom (occur commonly with unbonded caps)

Type 6 Similar to Type 5 but end of cylinder is pointed

ALFRED BENESCH & COMPANY
CONSTRUCTION MATERIALS LABORATORY

By____________________
Brant Wells, Field/Lab Operations Manager

Figure A-38. Concrete Culvert, Test Nos. CMGS-1 and CMGS-2

Concrete Industries
6300 Cornhusker Highway
P.O. Box 29529
Lincoln, NE 68529-
Phone: (402)434-1800 FAX: (402)434-1899

JOB NUMBER: 8000MISC.
RELEASE NUMBER: WES-RSF
REQ. DELIVERY DATE:
PAGE: 1 of 1
JOB NAME: JOB COMPLETE
CC: RSFS
CUSTOMER: MIDWEST ROADSIDE SAFETY FACILITY
BY: wrb

MATERIAL TYPE: Rebar, Grade 60, Epoxy
REFERENCE:
DRAWING ID:
DESCRIPTION: CULVERTS FOR MGS

Itm	Qty	Size	Length	Mark	Shape	Lbs	A	B	C	D	E	F/R	G	H	J	K	O	BC
1	8	4	5-05	A10	S10	29		1-002	4-042									202
2	38	4	5-01	A11	S10	129		1-002	4-01									202
3	45	4	4-09	A5	S5	143	1-002	1-03	0-07	0-10			1-002					110
4	44	4	20-00	A7		588												0
5	12	4	9-09	A9		78												0
6	22	4	6-01	A7LAP		89												0
7	108	4	4-09	A6		343												0
8	46	4	3-09	A8		115												0
	323.					1514.												

Total Weight: 1,514 Lbs

Longest Length: 20-00

INSPECTOR

WEIGHT SUMMARY

	TOTAL			STRAIGHT			LIGHT BENDING			HEAVY BENDING		
SIZE	ITEMS	PIECES	LBS	ITEMS	PIECES	LBS	ITEMS	PIECES	LBS	ITEMS	PIECES	LBS
Rebar, Grade 60, Epoxy												
4	8	323	1,514	5	232	1,213	3	91	301	0	0	0
	8	323	1,514	5	232	1,213	3	91	301	0	0	0

Total Weight: 1,514 Lbs

Longest Length: 20-00

GERDAU 62140165

ALL OTHER #4
IS: NUCOR KN15106961

Reinforcing steel represented by the heat numbers Shown have been tested and approved by Nebraska Department of Roads, Materials & Research Division.

This steel may be incorporated into the Project provided that no damage has occurred by Handling or shipping.

The complete shipping Report covering these materials will be issued by the Materials & Research Division.

Concrete Industries

Mary Berentis

JUN 0 7 2017
FOR CONSTRUCTION

v16.01.021 (T) (LIN) ©2017 aSa UNAUTHORIZED REPRODUCTION PROHIBITED Wednesday, June 07, 2017 1:53 PM

Figure A-39. #4 (#13) Rebar, Test Nos. CMGS-1 and CMGS-2

GERDAU

US-ML-ST PAUL
1678 RED ROCK ROAD
SAINT PAUL, MN 55119
USA

CERTIFIED MATERIAL TEST REPORT

Page 1/1

CUSTOMER SHIP TO	CUSTOMER BILL TO	GRADE	SHAPE / SIZE
SIMCOTE INC 1645 RED ROCK RD SAINT PAUL,MN 55119 USA	SIMCOTE INC 1645 RED ROCK ROAD SAINT PAUL,MN 55119-6014 USA	60 (420)	Rebar / #4 (13MM)

LENGTH	WEIGHT	HEAT / BATCH
60'00"	17,435 LB	62139047/02

SALES ORDER	CUSTOMER MATERIAL N°	SPECIFICATION / DATE or REVISION
2492020/000050		ASTM A615/A615M-14

CUSTOMER PURCHASE ORDER NUMBER	BILL OF LADING	DATE
3621	1332-0000032142	08/26/2015

CHEMICAL COMPOSITION

C %	Mn %	P %	S %	Si %	Cu %	Ni %	Cr %	Mo %	Sn %	V %	Nb %
0.41	1.11	0.015	0.026	0.20	0.26	0.11	0.18	0.023	0.024	0.005	0.002

MECHANICAL PROPERTIES

YS PSI	YS MPa	UTS PSI	UTS MPa	G/L Inch	G/L mm
70000	483	110500	762	8.000	203.2

MECHANICAL PROPERTIES

Elong. %	BendTest
15.00	OK

GEOMETRIC CHARACTERISTICS

%Light %	Def Hgt Inch	Def Gap Inch	DefSpace Inch
2.25	0.033	0.104	0.333

COMMENTS / NOTES

Material 100% melted and rolled in the USA. Manufacturing processes for this steel, which may include scrap melted in an electric arc furnace and hot rolling, has been performed at Gerdau St. Paul Mill. 1678 Red Rock Rd., St. Paul, Minnesota, USA. All products produced from strand cast billets. Silicon killed (deoxidized) steel. No weld repairment performed. Steel not exposed to mercury or any liquid alloy which is liquid at ambient temperatures during processing or while in Gerdau St. Paul Mill's possession. Any modification to this certification as provided by Gerdau St. Paul Mill without the expressed written consent of Gerdau St. Paul Mill negates the validity of this test report. This report shall not be reproduced except in full. without the expressed written consent of Gerdau St. Paul Mill. Gerdau St. Paul Mill is not responsible for the inability of this material to meet specific applications.

The above figures are certified chemical and physical test records as contained in the permanent records of company. We certify that these data are correct and in compliance with specified requirements. This material, including the billets, was melted and manufactured in the USA. CMTR complies with EN 10204 3.1.

BHASKAR YALAMANCHILI
QUALITY DIRECTOR

ALEA BRANDENBURG
QUALITY ASSURANCE MGR.

Figure A-40. #4 (#13) Bent Rebar, L-Shaped, 4 ft – 6 in. (1,372 mm) Total Length, Unbent, Test Nos. CMGS-1 and CMGS-2

Appendix B. Vehicle Center of Gravity Determination

Date:	12/1/2017	Test Name:	CMGS-1	VIN:	KMHCN4ACOAU423259
Year:	2010	Make:	Hyundai	Model:	Accent

Vehicle CG Determination

VEHICLE	Equipment	Weight (lb.)
+	Unbalasted Car (Curb)	2471
+	Hub	19
+	Brake activation cylinder & frame	7
+	Pneumatic tank (Nitrogen)	22
+	Strobe/Brake Battery	5
+	Brake Reciever/Wires	6
+	CG Plate including DAS	13
-	Battery	-31
-	Oil	-12
-	Interior	-57
-	Fuel	-18
-	Coolant	-7
-	Washer fluid	-8
+	Water Ballast (In Fuel Tank)	0
+	Onboard Battery	14

Note: (+) is added equipment to vehicle, (-) is removed equipment from vehicle

Estimated Total Weight (lb.) 2424

Vehicle Dimensions for C.G. Calculations

Roof Height:	57 3/4 in.	Front Track Width:	57 3/8 in.
Wheel Base:	98 3/4 in.	Rear Track Width:	57 1/4 in.

Center of Gravity	1100C MASH Targets	Test Inertial	Difference
Test Inertial Weight (lb.)	2420 ± 55	2428	8
Longitudinal CG (in.)	39 ± 4	36.36017	-2.639827
Lateral CG (in.)	NA	-0.40128	NA
Vertical CG (in.)	NA	23.01861	NA

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

Note: Lateral CG measured from centerline - positive to vehicle right (passenger) side

CURB WEIGHT (lb.)

	Left	Right
Front	804	778
Rear	447	442

FRONT	1582	lb
REAR	889	lb
TOTAL	2471	lb

TEST INERTIAL WEIGHT (lb.)

	Left	Right
Front	775	759
Rear	456	438

FRONT	1534	lb
REAR	894	lb
TOTAL	2428	lb

Figure B-1. Vehicle Mass Distribution, Test No. CMGS-1

Date:	1/3/2018	Test Name:	CMGS-2	VIN:	1D7RB1CTXAS115553
Year:	2010	Make:	DODGE	Model:	RAM 1500 CREW CAB

Vehicle CG Determination

VEHICLE	Equipment	Weight (lb.)	Vertical CG (in.)	Vertical M (lb.-in.)
+	Unballasted Truck (Curb)	5292	29 1/4	154791
+	Hub	19	15 5/8	296.875
+	Brake activation cylinder & frame	7	28 1/2	199.5
+	Pneumatic tank (Nitrogen)	22	27 1/2	605
+	Strobe/Brake Battery	6	26	156
+	Brake Receiver/Wires	5	52 1/2	262.5
+	CG Plate including DAS	50	30 1/8	1506.25
-	Battery	-41	40 1/2	-1660.5
-	Oil	-10	19 1/2	-195
-	Interior	-113	29	-3277
-	Fuel	-161	18	-2898
-	Coolant	-13	36	-468
-	Washer fluid	-6	36 1/2	-219
+	Water Ballast (In Fuel Tank)	0	0	0
+	Onboard Supplemental Battery	13	27 3/4	360.75
	Spare Tire	-66	24	-1584
				147876.38

Note: (+) is added equipment to vehicle, (-) is removed equipment from vehicle

Estimated Total Weight (lb.)	5004
Vertical CG Location (in.)	29.5516

Vehicle Dimensions for C.G. Calculations

Wheel Base:	140 3/8 in.	Front Track Width:	68 1/8 in.
		Rear Track Width:	67 1/2 in.

Center of Gravity	2270P MASH Targets	Test Inertial	Difference
Test Inertial Weight (lb.)	5000 ± 110	5013	13.0
Longitudinal CG (in.)	63 ± 4	60.23272	-2.76728
Lateral CG (in.)	NA	0.0338183	NA
Vertical CG (in.)	28 or greater	29.55	1.55163

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

Note: Lateral CG measured from centerline - positive to vehicle right (passenger) side

CURB WEIGHT (lb.)

	Left	Right
Front	1518	1428
Rear	1155	1191

FRONT	2946	lb.
REAR	2346	lb.
TOTAL	5292	lb.

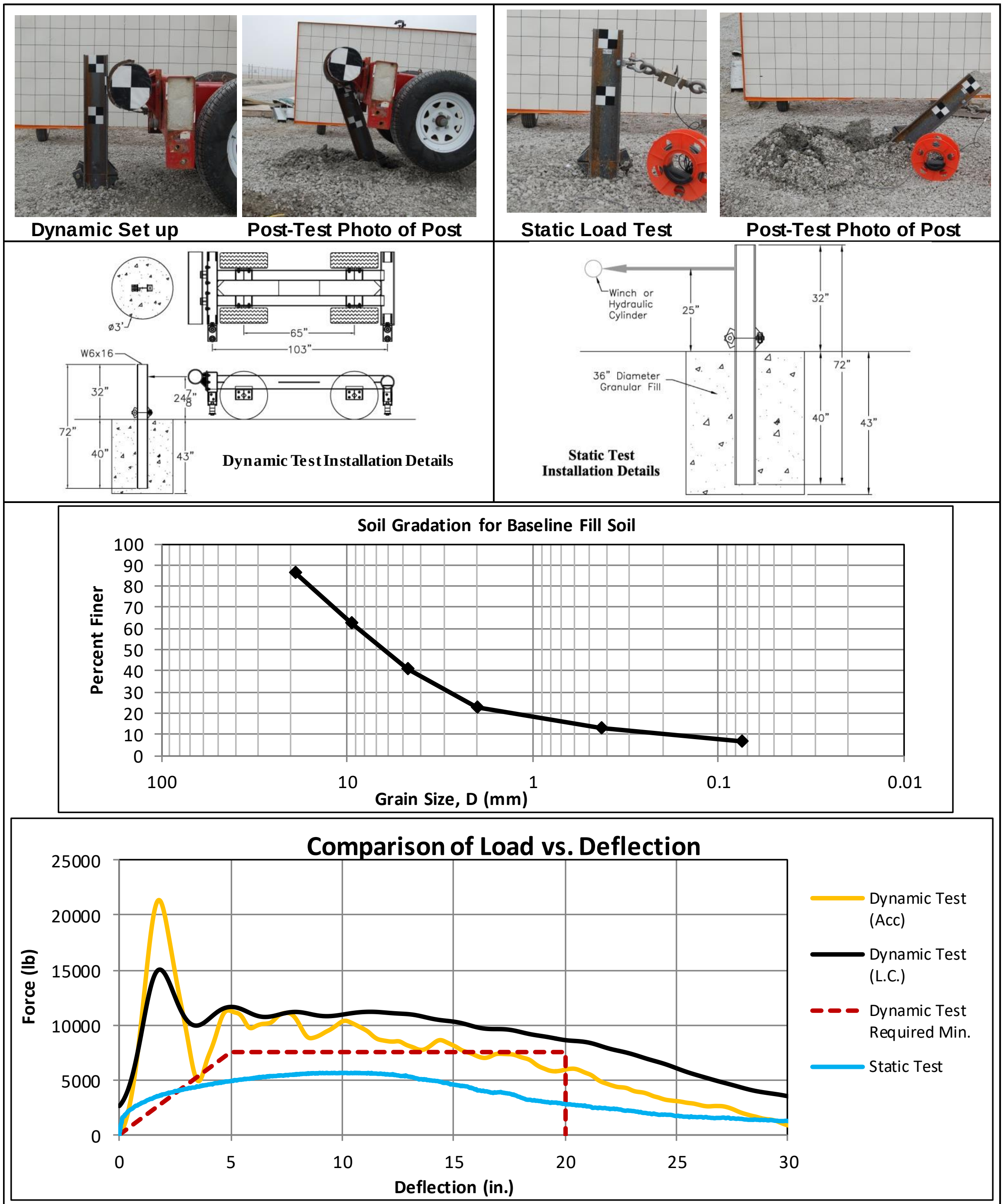
TEST INERTIAL WEIGHT (lb.)

	Left	Right
Front	1459	1403
Rear	1045	1106

FRONT	2862	lb.
REAR	2151	lb.
TOTAL	5013	lb.

Figure B-2. Vehicle Mass Distribution, Test No. CMGS-2

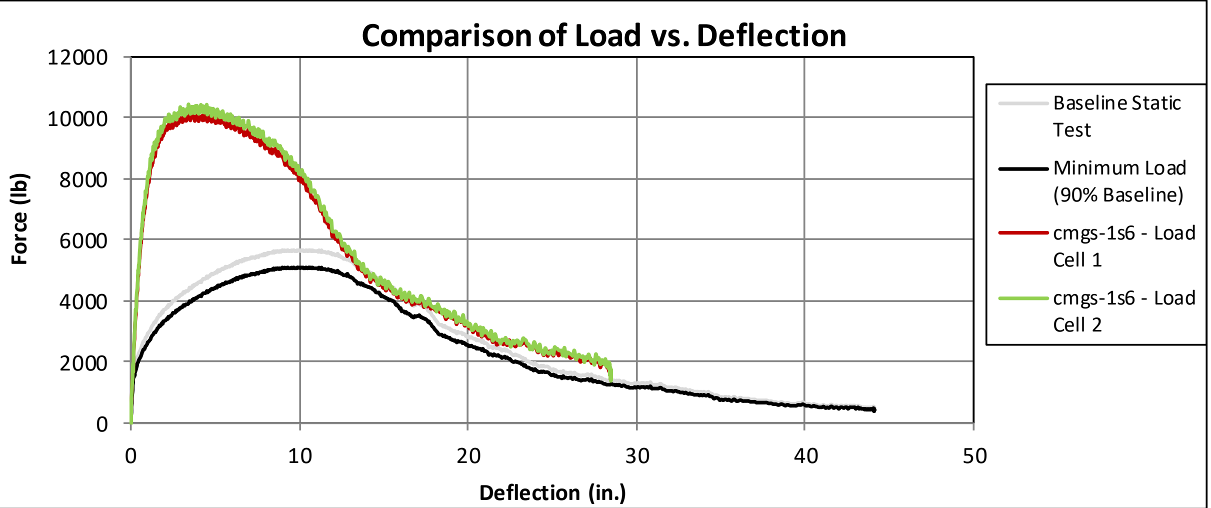
Appendix C. Static Soil Tests

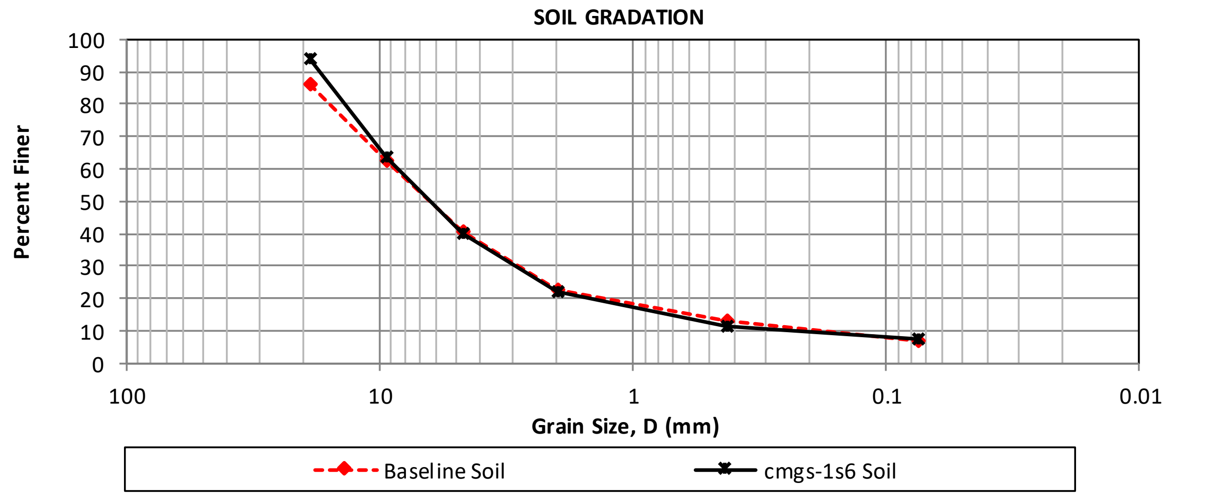


Date...	5/17/2013	
Test Facility & Site Location.....................	Midwest Roadside Safety Facility	
In situ soil description (ASTM D2487).........	Well-Graded Gravel (GW)	
Fill material description (ASTM D2487)......	Well-Graded Gravel (GW) (see sieve analyses above)	
Description of fill placement procedure.....	H.E.-8	
Bogie Weight...	1857 lb	842 kg
Impact Velocity.....................................	20.6 mph	33.2 km/h

Figure C-1. Soil Strength, Initial Calibration Tests, Test No. CMGS-1

Static Load Test Setup	Post-Test Photo of Post
	





Date..	12/1/2017
Test Facility & Site Location....................	Midwest Roadside Safety Facility
In situ soil description (ASTM D2487).........	Well-Graded Gravel (GW)
Fill material description (ASTM D2487)......	Well-Graded Gravel (GW) (see sieve analyses above)
Description of fill placement procedure.....	8-inch lifts tamped with a pneumatic compactor

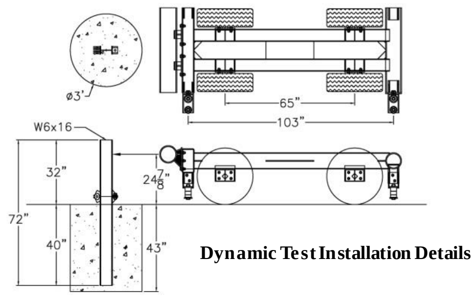
Figure C-2. Static Soil Test, Test No. CMGS-1

Dynamic Set up

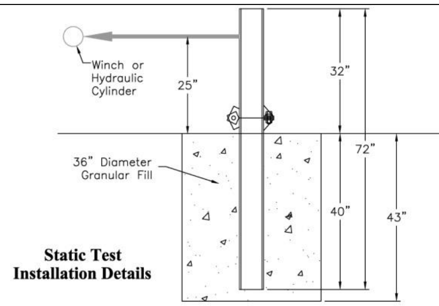
Post-Test Photo of Post

Static Load Test

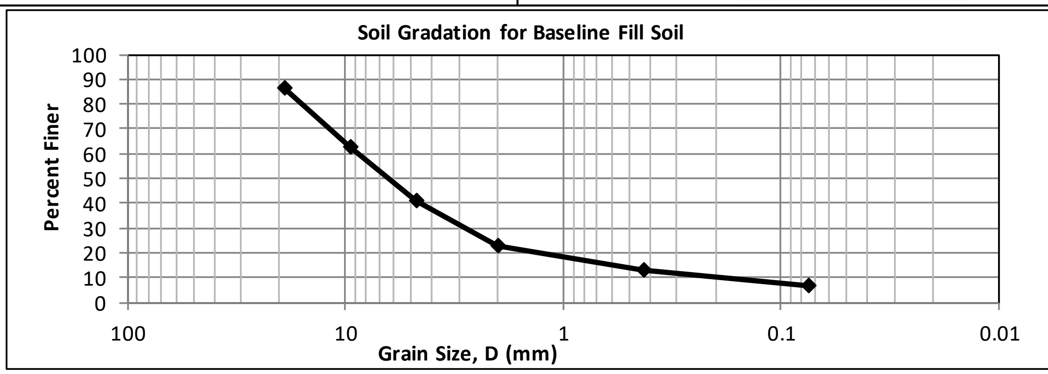
Post-Test Photo of Post

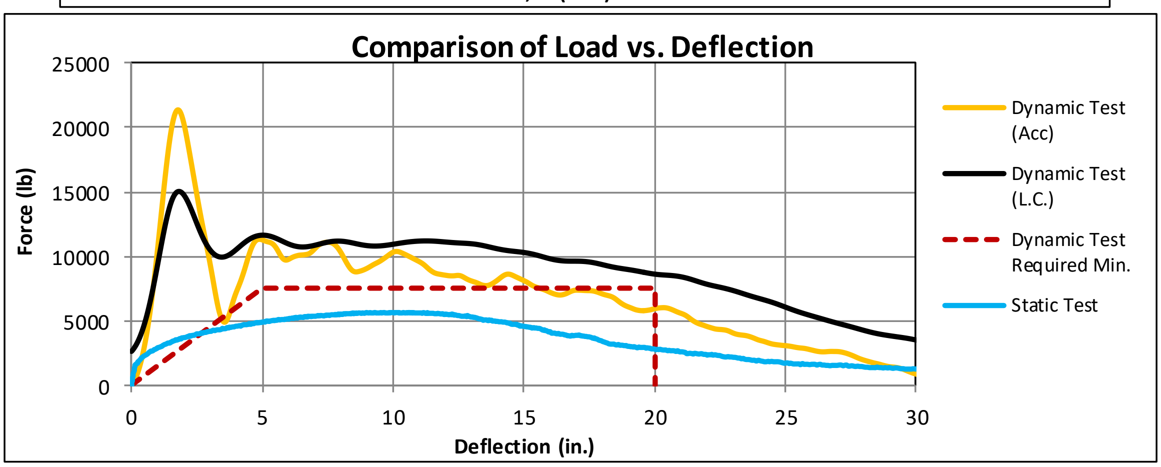


Dynamic Test Installation Details



Static Test Installation Details

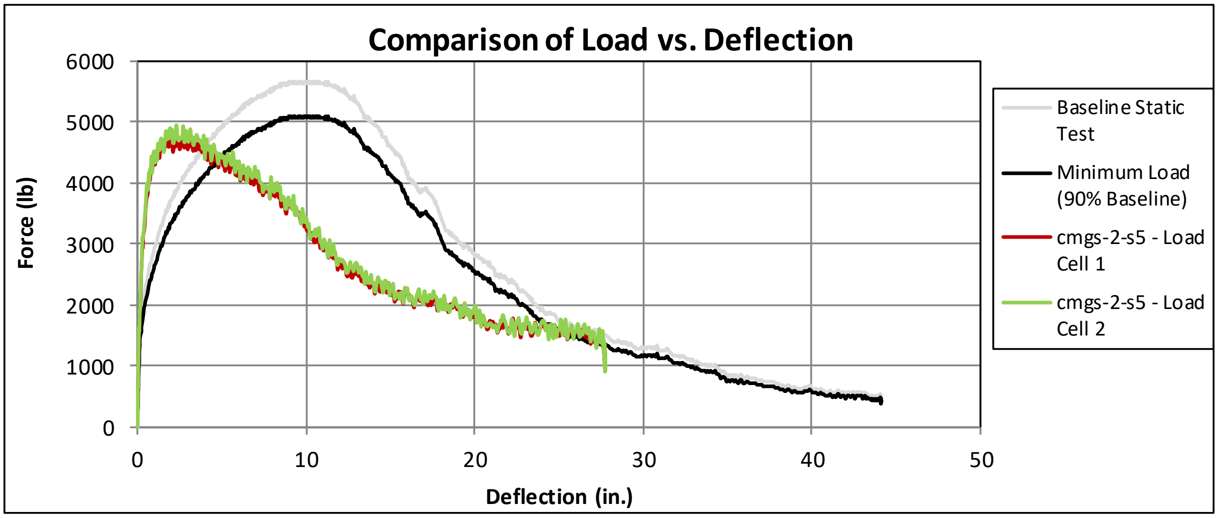


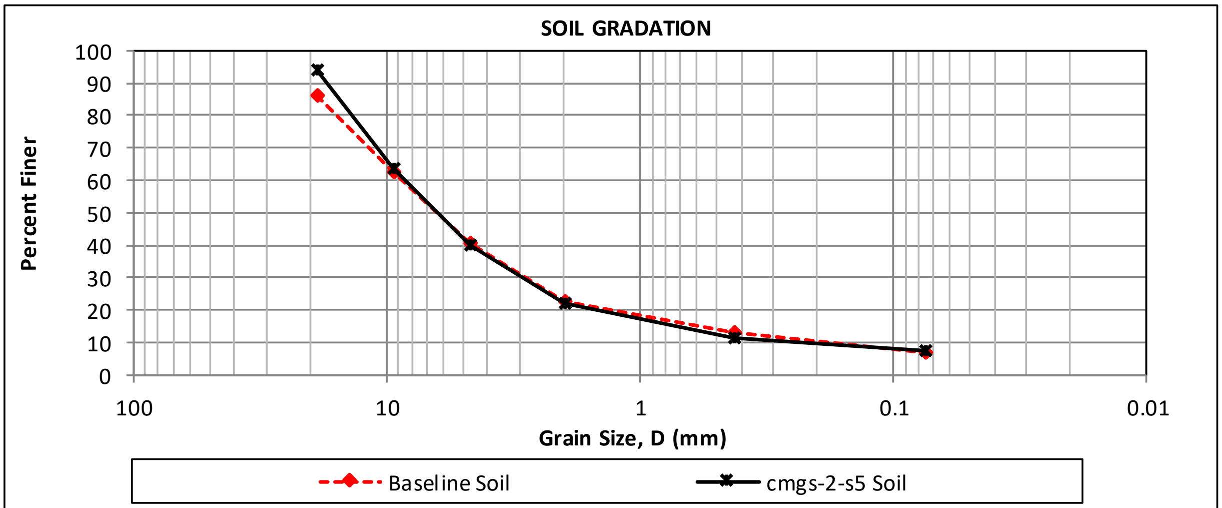


Date	5/17/2013		
Test Facility & Site Location	Midwest Roadside Safety Facility		
In situ soil description (ASTM D2487)	Well-Graded Gravel (GW)		
Fill material description (ASTM D2487)	Well-Graded Gravel (GW) (see sieve analyses above)		
Description of fill placement procedure	H.E.-8		
Bogie Weight	1857	lb	842 kg
Impact Velocity	20.6	mph	33.2 km/h

Figure C-3. Soil Strength, Initial Calibration Tests, Test No. CMGS-2

Static Load Test Setup	Post-Test Photo of Post
	





Date	2/13/2018
Test Facility & Site Location	Midwest Roadside Safety Facility
In situ soil description (ASTM D2487)	Well-Graded Gravel (GW)
Fill material description (ASTM D2487)	Well-Graded Gravel (GW) (see sieve analyses above)
Description of fill placement procedure	8-inch lifts tamped with a pneumatic compactor

Figure C-4. Static Soil Test, Test No. CMGS-2

Appendix D. Vehicle Deformation Records

The following figures and tables describe all occupant compartment measurements taken on the test vehicles used in full-scale crash testing herein. MASH 2016 defines intrusion as the occupant compartment being deformed and reduced in size with no penetration. Outward deformations, which are denoted as negative numbers within this Appendix, are not considered as crush toward the occupant, and are not subject to evaluation by MASH 2016 criteria.

Date: 12/1/2017 Test Name: CMGS-1 VIN: KMHCN4ACOAU423259
Year: 2010 Make: Hyundai Model: Accent

VEHICLE PRE/POST CRUSH
FLOORPAN - SET 1

POINT	X (in.)	Y (in.)	Z (in.)	X' (in.)	Y' (in.)	Z' (in.)	ΔX (in.)	ΔY (in.)	ΔZ (in.)	Total Δ (in.)
1	26.022	10.369	-2.981	24.767	12.320	-2.774	-1.256	1.951	0.208	2.329
2	25.897	15.105	-2.961	24.458	17.093	-2.833	-1.439	1.988	0.128	2.458
3	25.683	19.029	-2.692	24.009	20.935	-2.555	-1.674	1.906	0.137	2.541
4	25.168	23.426	-1.838	23.286	25.291	-1.769	-1.883	1.864	0.070	2.651
5	22.247	10.452	-4.969	21.101	12.316	-4.824	-1.146	1.863	0.145	2.192
6	22.432	14.973	-4.830	21.069	16.817	-4.844	-1.363	1.844	-0.014	2.293
7	22.452	18.834	-4.394	20.823	20.675	-4.285	-1.629	1.841	0.109	2.461
8	22.587	24.128	-4.495	20.735	25.919	-4.400	-1.852	1.791	0.095	2.578
9	19.146	10.691	-5.466	18.689	11.093	-5.300	-0.457	0.402	0.166	0.631
10	18.872	15.054	-5.432	18.387	15.509	-5.285	-0.485	0.455	0.147	0.680
11	18.983	18.555	-5.294	18.393	18.974	-5.144	-0.591	0.418	0.150	0.739
12	18.823	23.251	-5.503	18.321	23.690	-5.328	-0.502	0.439	0.176	0.689
13	16.652	10.752	-5.587	16.304	11.126	-4.873	-0.348	0.374	0.714	0.878
14	16.562	15.192	-5.448	16.034	15.576	-5.326	-0.529	0.384	0.122	0.665
15	16.310	18.887	-5.421	15.716	19.285	-5.295	-0.594	0.398	0.126	0.726
16	16.352	23.481	-5.601	15.798	23.933	-5.445	-0.554	0.452	0.156	0.732
17	14.150	10.659	-5.871	13.807	11.089	-5.320	-0.343	0.430	0.552	0.779
18	13.873	15.404	-5.360	13.308	15.761	-5.259	-0.566	0.357	0.101	0.677
19	13.492	19.773	-5.322	12.906	20.128	-5.191	-0.586	0.355	0.131	0.697
20	13.292	24.331	-5.876	12.663	24.740	-5.725	-0.629	0.409	0.150	0.765
21	8.439	10.574	-5.853	8.067	10.949	-5.616	-0.372	0.375	0.238	0.579
22	8.239	15.454	-5.161	7.765	15.742	-5.064	-0.474	0.288	0.097	0.563
23	7.925	20.084	-5.106	7.401	20.367	-4.986	-0.524	0.283	0.121	0.607
24	7.481	24.511	-5.764	6.968	24.818	-5.588	-0.513	0.306	0.177	0.623
25	-1.031	8.841	-1.228	-1.301	8.980	-1.210	-0.270	0.139	0.018	0.304
26	-1.393	13.778	-1.204	-1.725	14.010	-1.123	-0.332	0.232	0.082	0.413
27	-1.454	18.832	-1.172	-1.882	19.055	-1.026	-0.427	0.223	0.146	0.503
28	-1.913	24.861	-1.104	-2.285	24.889	-0.871	-0.372	0.028	0.233	0.440

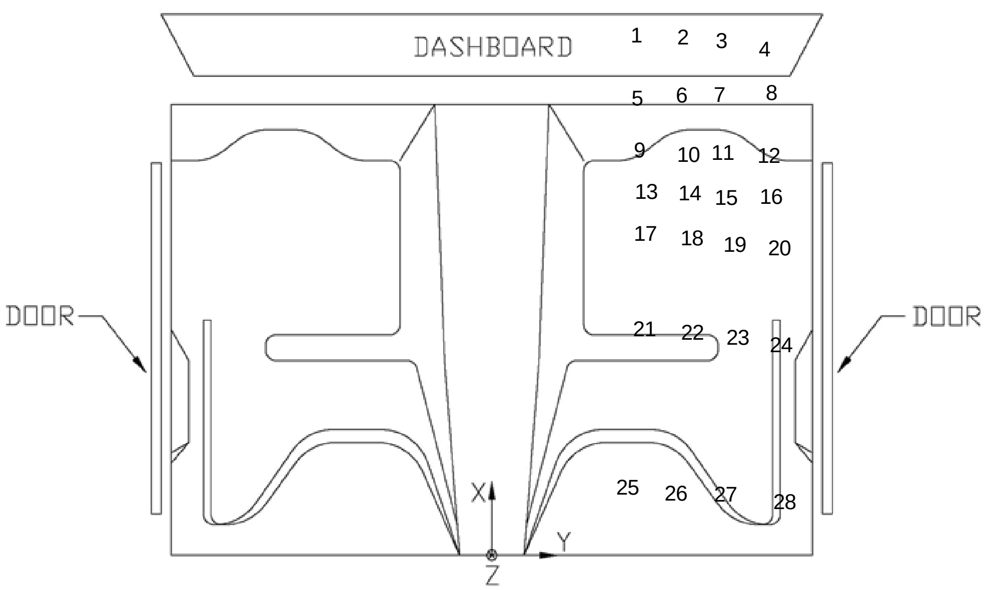


Figure D-1. Floor Pan Deformation Data – Set 1, Test No. CMGS-1

Date: 12/1/2017 Test Name: CMGS-1 VIN: KMHCN4ACOAU423259
Year: 2010 Make: Hyundai Model: Accent

VEHICLE PRE/POST CRUSH
FLOORPAN - SET 2

POINT	X (in.)	Y (in.)	Z (in.)	X' (in.)	Y' (in.)	Z' (in.)	ΔX (in.)	ΔY (in.)	ΔZ (in.)	Total Δ (in.)
1	52.751	11.566	0.776	52.703	11.530	0.842	-0.048	-0.036	0.067	0.090
2	52.683	16.317	0.848	52.647	16.311	0.679	-0.036	-0.006	-0.169	0.173
3	52.457	20.206	1.129	52.384	20.175	0.862	-0.072	-0.031	-0.267	0.278
4	51.891	24.644	1.972	51.847	24.578	1.528	-0.044	-0.066	-0.444	0.451
5	49.086	11.672	-1.386	49.159	11.670	-1.407	0.072	-0.002	-0.020	0.075
6	49.301	16.228	-1.194	49.362	16.166	-1.511	0.061	-0.062	-0.317	0.329
7	49.317	20.106	-0.726	49.287	20.041	-1.036	-0.030	-0.065	-0.311	0.319
8	49.507	25.366	-0.760	49.479	25.280	-1.251	-0.029	-0.085	-0.491	0.499
9	46.019	11.909	-2.018	46.716	10.562	-1.993	0.696	-1.348	0.025	1.517
10	45.797	16.362	-1.962	46.644	14.987	-2.075	0.846	-1.375	-0.112	1.619
11	45.905	19.794	-1.796	46.822	18.449	-1.996	0.917	-1.345	-0.200	1.640
12	45.759	24.484	-1.983	47.006	23.158	-2.270	1.247	-1.327	-0.288	1.843
13	43.584	12.008	-2.248	44.316	10.725	-1.699	0.732	-1.283	0.549	1.576
14	43.469	16.415	-2.090	44.302	15.173	-2.247	0.833	-1.243	-0.157	1.504
15	43.269	20.175	-2.049	44.177	18.893	-2.301	0.907	-1.282	-0.252	1.591
16	43.303	24.755	-2.199	44.508	23.526	-2.531	1.205	-1.228	-0.332	1.752
17	41.064	11.918	-2.665	41.849	10.806	-2.282	0.784	-1.112	0.383	1.413
18	40.748	16.639	-2.136	41.590	15.498	-2.333	0.842	-1.142	-0.197	1.432
19	40.434	21.034	-2.085	41.414	19.880	-2.367	0.980	-1.154	-0.282	1.540
20	40.248	25.588	-2.619	41.439	24.486	-2.998	1.192	-1.102	-0.379	1.667
21	35.371	11.833	-2.924	36.134	10.952	-2.891	0.762	-0.880	0.033	1.165
22	35.163	16.696	-2.208	36.052	15.766	-2.444	0.889	-0.931	-0.236	1.309
23	34.856	21.309	-2.139	35.925	20.403	-2.470	1.069	-0.906	-0.331	1.440
24	34.444	25.806	-2.787	35.757	24.857	-3.176	1.313	-0.950	-0.389	1.667
25	25.705	10.088	1.222	26.451	9.557	1.027	0.746	-0.531	-0.196	0.937
26	25.327	15.109	1.262	26.285	14.602	0.999	0.958	-0.507	-0.264	1.115
27	25.249	20.106	1.326	26.386	19.649	0.995	1.138	-0.456	-0.331	1.270
28	24.878	26.075	1.424	26.279	25.499	1.022	1.401	-0.576	-0.402	1.567

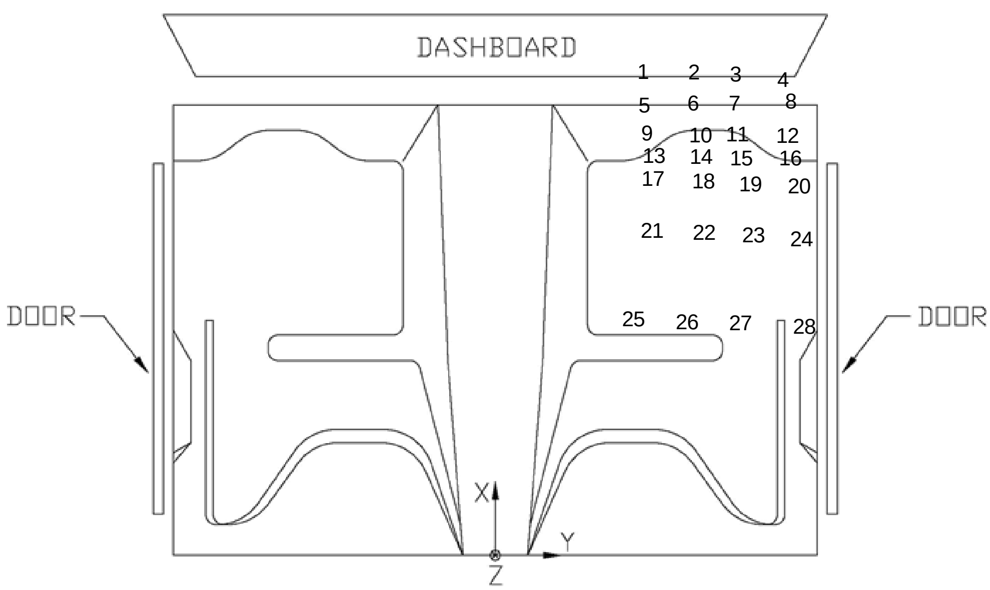


Figure D-2. Floor Pan Deformation Data – Set 2, Test No. CMGS-1

Date: 12/1/2017 Test Name: CMGS-1 VIN: KMHCN4ACOAU423259
Year: 2010 Make: Hyundai Model: Accent

VEHICLE PRE/POST CRUSH
INTERIOR CRUSH - SET 1

	POINT	X (in.)	Y (in.)	Z (in.)	X' (in.)	Y' (in.)	Z' (in.)	ΔX (in.)	ΔY (in.)	ΔZ (in.)	Total Δ (in.)
DASH	1	12.945	3.187	23.438	13.329	3.090	23.536	0.384	-0.097	0.099	0.408
	2	13.442	15.878	21.719	13.761	15.830	21.843	0.319	-0.048	0.125	0.345
	3	12.971	25.434	21.705	13.286	25.306	21.879	0.315	-0.129	0.174	0.382
	4	9.018	2.458	16.202	9.299	2.444	16.339	0.281	-0.014	0.137	0.312
	5	11.505	17.525	16.970	11.770	17.437	17.170	0.265	-0.088	0.201	0.344
	6	10.657	25.550	16.631	10.907	25.389	16.792	0.251	-0.161	0.162	0.339
SIDE PANEL	7	16.772	29.237	0.861	16.874	29.101	1.140	0.103	-0.136	0.279	0.327
	8	16.804	29.243	2.453	16.934	29.098	2.643	0.130	-0.145	0.190	0.272
	9	19.491	29.419	0.009	19.626	29.142	0.392	0.135	-0.277	0.383	0.491
IMPACT SIDE DOOR	10	9.266	29.799	21.090	9.309	29.683	21.303	0.044	-0.116	0.214	0.247
	11	-0.152	29.427	21.983	-0.047	29.468	22.217	0.105	0.041	0.234	0.260
	12	-9.959	28.958	23.071	-9.929	29.111	23.437	0.030	0.153	0.366	0.398
	13	3.598	30.092	9.679	3.566	30.661	10.039	-0.033	0.568	0.360	0.674
	14	-2.810	29.832	11.850	-2.782	30.313	12.171	0.028	0.482	0.322	0.580
	15	-11.617	29.489	12.197	-11.510	29.848	12.572	0.107	0.359	0.375	0.530
ROOF	16	0.412	19.897	38.649	0.480	19.873	38.879	0.068	-0.025	0.230	0.241
	17	1.428	13.605	38.957	1.543	13.608	39.126	0.114	0.003	0.170	0.205
	18	1.993	9.098	39.071	2.074	9.050	39.248	0.081	-0.048	0.177	0.200
	19	2.262	5.670	39.155	2.424	5.579	39.304	0.162	-0.091	0.149	0.238
	20	2.493	1.703	39.171	2.554	1.699	39.349	0.061	-0.004	0.178	0.188
	21	-5.405	18.611	41.227	-5.261	18.557	41.429	0.143	-0.054	0.202	0.253
	22	-4.560	14.266	41.467	-4.511	14.159	41.685	0.049	-0.107	0.218	0.247
	23	-3.895	10.182	41.604	-3.698	10.025	41.773	0.196	-0.156	0.169	0.302
	24	-3.591	6.923	41.691	-3.448	6.774	41.864	0.144	-0.148	0.173	0.269
	25	-3.908	1.858	41.907	-3.655	1.725	42.038	0.252	-0.133	0.131	0.314
	26	-9.902	17.578	42.261	-9.766	17.428	42.456	0.136	-0.151	0.196	0.282
	27	-8.144	13.817	42.301	-7.973	13.687	42.485	0.171	-0.130	0.183	0.283
	28	-7.418	10.099	42.419	-7.267	9.956	42.601	0.151	-0.143	0.182	0.276
	29	-6.588	6.486	42.422	-6.477	6.362	42.604	0.111	-0.124	0.182	0.246
	30	-6.089	2.002	42.422	-5.771	1.788	42.547	0.318	-0.214	0.125	0.403
A PILLAR	31	3.629	24.589	34.809	3.754	24.460	35.116	0.125	-0.130	0.307	0.356
	32	7.160	25.535	32.688	7.287	25.401	33.005	0.126	-0.134	0.317	0.367
	33	9.830	26.269	30.832	9.998	26.137	31.121	0.168	-0.132	0.288	0.359
	34	13.443	27.226	28.258	13.649	27.081	28.596	0.205	-0.145	0.338	0.421
B PILLAR	35	-17.939	27.390	22.735	-17.708	27.463	23.007	0.231	0.072	0.272	0.364
	36	-21.723	27.294	22.333	-21.485	27.242	22.547	0.238	-0.052	0.214	0.325
	37	-18.625	26.517	28.198	-18.362	26.406	28.449	0.263	-0.111	0.250	0.380
	38	-22.485	26.511	27.849	-22.235	26.415	28.127	0.250	-0.096	0.279	0.387
	39	-19.964	23.437	36.441	-19.463	23.414	36.525	0.500	-0.023	0.085	0.508
	40	-22.990	23.524	36.231	-22.621	23.386	36.452	0.369	-0.139	0.221	0.452

Figure D-3. Occupant Compartment Deformation Data – Set 1, Test No. CMGS-1

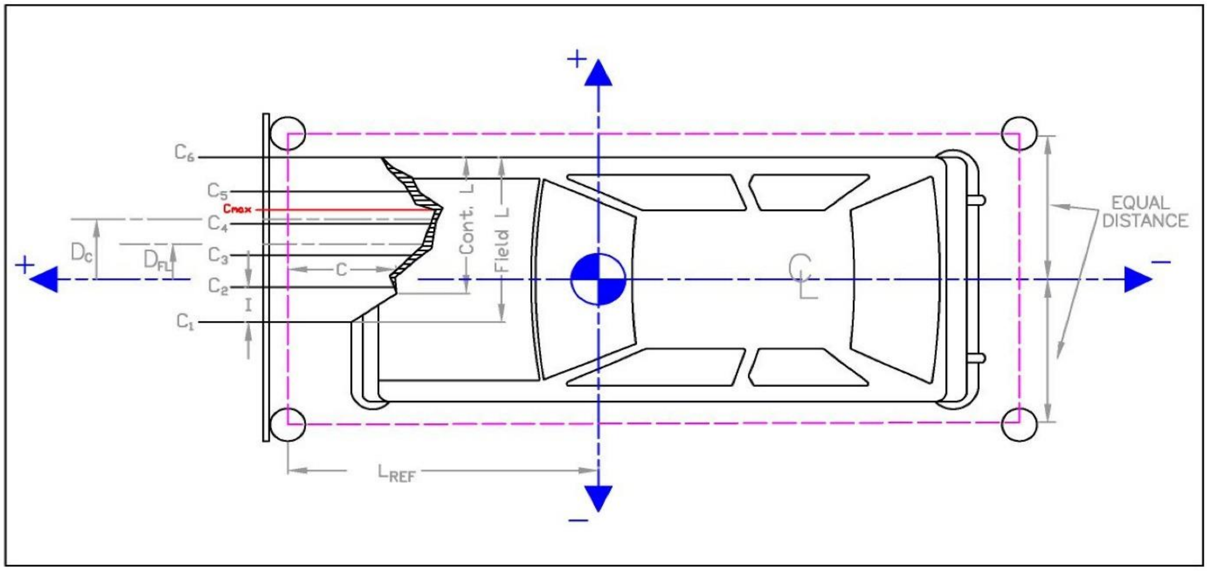
Date: 12/1/2017 Test Name: CMGS-1 VIN: KMHCN4ACOAU423259
Year: 2010 Make: Hyundai Model: Accent

VEHICLE PRE/POST CRUSH
INTERIOR CRUSH - SET 2

	POINT	X (in.)	Y (in.)	Z (in.)	X' (in.)	Y' (in.)	Z' (in.)	ΔX (in.)	ΔY (in.)	ΔZ (in.)	Total Δ (in.)
DASH	1	38.167	4.280	26.554	38.400	5.083	26.570	0.232	0.803	0.016	0.836
	2	38.715	17.003	24.884	38.951	17.789	24.664	0.235	0.785	-0.221	0.849
	3	38.281	26.538	24.948	38.496	27.264	24.495	0.215	0.726	-0.453	0.882
	4	34.575	3.730	19.165	34.764	4.306	19.178	0.189	0.576	0.013	0.606
	5	37.044	18.701	20.101	37.219	19.309	19.860	0.176	0.608	-0.241	0.677
	6	36.229	26.686	19.734	36.396	27.254	19.287	0.167	0.568	-0.447	0.742
SIDE PANEL	7	43.110	30.453	4.357	43.211	30.662	3.914	0.101	0.209	-0.444	0.501
	8	43.086	30.450	5.981	43.189	30.687	5.418	0.103	0.237	-0.564	0.620
	9	45.911	30.622	3.672	45.999	30.685	3.315	0.088	0.063	-0.357	0.373
IMPACT SIDE DOOR	10	34.647	30.908	24.156	34.566	31.634	23.623	-0.081	0.725	-0.533	0.904
	11	25.217	30.555	24.569	25.173	31.447	24.032	-0.044	0.892	-0.537	1.043
	12	15.326	30.099	25.214	15.239	31.126	24.720	-0.086	1.027	-0.494	1.143
	13	29.583	31.290	12.495	29.443	32.405	12.047	-0.139	1.116	-0.448	1.210
	14	23.071	31.034	14.293	22.988	32.106	13.838	-0.082	1.072	-0.455	1.168
	15	14.261	30.703	14.236	14.251	31.659	13.774	-0.010	0.956	-0.462	1.061
ROOF	16	24.800	20.926	41.199	24.776	22.168	40.875	-0.024	1.242	-0.324	1.284
	17	25.783	14.644	41.518	25.810	15.908	41.298	0.027	1.264	-0.220	1.284
	18	26.401	10.104	41.620	26.323	11.353	41.533	-0.077	1.248	-0.086	1.254
	19	26.644	6.712	41.699	26.662	7.883	41.674	0.018	1.171	-0.025	1.172
	20	26.760	2.756	41.744	26.781	4.004	41.799	0.021	1.248	0.056	1.249
	21	18.883	19.681	43.456	18.902	20.908	43.134	0.019	1.227	-0.321	1.269
	22	19.737	15.330	43.706	19.627	16.514	43.513	-0.110	1.185	-0.193	1.206
	23	20.389	11.212	43.851	20.425	12.383	43.723	0.036	1.171	-0.128	1.178
	24	20.705	7.884	43.932	20.663	9.134	43.889	-0.042	1.249	-0.044	1.251
	25	20.358	2.914	44.102	20.435	4.089	44.147	0.077	1.176	0.045	1.179
	26	14.395	18.611	44.241	14.346	19.804	43.937	-0.050	1.193	-0.304	1.232
	27	16.127	14.808	44.348	16.126	16.062	44.133	0.000	1.254	-0.215	1.272
	28	16.746	11.087	44.494	16.817	12.333	44.358	0.071	1.246	-0.136	1.255
	29	17.673	7.485	44.501	17.597	8.739	44.471	-0.076	1.254	-0.030	1.257
	30	18.076	2.998	44.512	18.295	4.164	44.538	0.219	1.165	0.026	1.186
A PILLAR	31	28.196	25.646	37.560	28.259	26.679	37.210	0.063	1.033	-0.351	1.093
	32	31.885	26.595	35.591	31.903	27.576	35.276	0.018	0.981	-0.314	1.031
	33	34.663	27.332	33.892	34.714	28.274	33.528	0.050	0.942	-0.364	1.011
	34	38.420	28.297	31.541	38.498	29.165	31.187	0.078	0.868	-0.354	0.941
B PILLAR	35	7.299	28.541	24.409	7.491	29.478	23.900	0.192	0.938	-0.509	1.084
	36	3.549	28.455	23.808	3.744	29.254	23.240	0.195	0.799	-0.568	0.999
	37	6.293	27.626	29.853	6.541	28.525	29.318	0.249	0.900	-0.535	1.076
	38	2.476	27.640	29.267	2.691	28.533	28.787	0.214	0.893	-0.481	1.037
	39	4.575	24.546	37.883	4.997	25.688	37.378	0.422	1.142	-0.506	1.319
	40	1.608	24.594	37.606	1.848	25.662	37.134	0.240	1.069	-0.472	1.193

Figure D-4. Occupant Compartment Deformation Data – Set 2, Test No. CMGS-1

Date:	2/7/2018	Test Number:	CMGS-1		
Year:	2010	Make:	Hyundai	Model:	Accent



	in.	(mm)
Distance from C.G. to reference line - L_{REF}:	78	(1980)
Total Width of Vehicle:	63 1/8	(1603)
Width of contact and induced crush - Field L:	38 1/2	(978)
Crush measurement spacing interval (L/5) - I:	7 3/4	(197)
Distance from center of vehicle to center of Field L - D_{FL}:	16	(406)
Width of Contact Damage:	20 1/2	(521)
Distance from center of vehicle to center of contact damage - D_C:	22 2/9	(564)

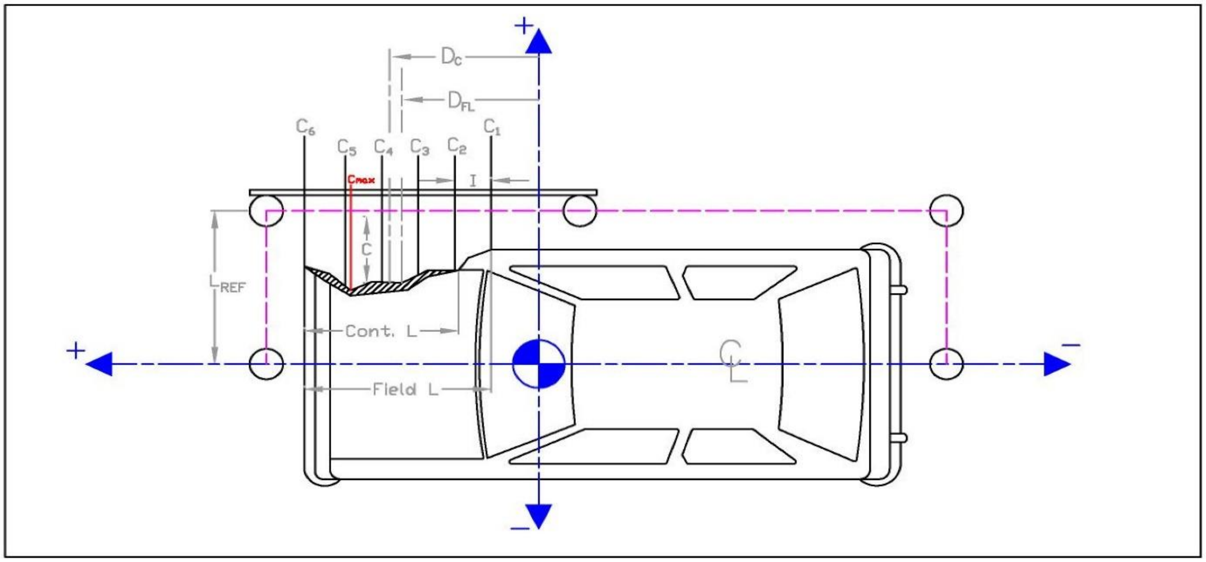
NOTE: Enter "NA" for crush measurement if distance can not be measured (i.e., side of vehicle has been pushed inward)
NOTE: All values must be filled out above before crush measurements are filled out.

	Crush Measurement		Lateral Location		Original Profile Measurement		Dist. Between Ref. Lines		Actual Crush	
	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)
C_1	8 1/2	(216)	-3 1/4	-(83)	1 3/4	(44)	6 4/7	(167)	1/5	(5)
C_2	8 1/2	(216)	4 1/2	(114)	1 7/8	(48)			0	(2)
C_3	8 3/4	(222)	12 1/4	(311)	3	(76)			- 4/5	-(21)
C_4	9 1/2	(241)	20	(508)	4 7/8	(124)			-2	-(49)
C_5	10 3/4	(273)	27 3/4	(705)	10 1/4	(260)			-6	-(154)
C_6	12 1/2	(318)	35 1/2	(902)	19 7/8	(505)			-14	-(354)
C_{MAX}	29	(737)	24 1/2	(622)	7	(178)			15 4/9	(392)

Figure D-5. Exterior Vehicle Crush (NASS) - Front, Test No. CMGS-1

Date: 43138 **Test Number:** CMGS-1

Year: 2010 **Make:** Hyundai **Model:** Accent



	in.	(mm)
Distance from centerline to reference line - L_{REF}:	48	(1219)
Total Vehicle Length:	168 3/4	(4286)
Distance from vehicle c.g. to 1/2 of Vehicle total length:	-14 3/4	-(375)
Width of contact and induced crush - Field L:	76 3/8	(1940)
Crush measurement spacing interval (L/5) - I:	15 1/4	(387)
Distance from vehicle c.g. to center of Field L - D_{FL}:	31 4/9	(799)
Width of Contact Damage:	76 3/8	(1940)
Distance from vehicle c.g. to center of contact damage - D_C:	31 4/9	(799)

NOTE: Enter "NA" for crush measurement if distance can not be measured (i.e., front of vehicle has been pushed inward or tire has been removed)
NOTE: All values must be filled out above before crush measurements are filled out.

	Crush Measurement		Longitudinal Location		Original Profile Measurement		Dist. Between Ref. Lines		Actual Crush	
	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)
C_1	14 1/4	(362)	-6 3/4	-(171)	3 1/4	(83)	12	(305)	-1	-(25)
C_2	14 3/4	(375)	8 1/2	(216)	3 1/4	(83)			- 1/2	-(13)
C_3	17	(432)	23 3/4	(603)	3	(76)			2	(51)
C_4	NA	NA	39	(991)	3 1/2	(89)			NA	NA
C_5	27 1/4	(692)	54 1/4	(1378)	5	(127)			10 1/4	(260)
C_6	42 1/2	(1080)	69 1/2	(1765)	31 7/8	(810)			-1 3/8	-(35)
C_{MAX}	27 1/4	(692)	54 1/4	(1378)	5	(127)			10 1/4	(260)

Figure D-6. Exterior Vehicle Crush (NASS) - Side, Test No. CMGS-1

Date: 2/14/2018 Test Name: CMGS-2 VIN: 1D7RB1CTXAS115553
Year: 2010 Make: DODGE Model: RAM 1500 CREW CAB

VEHICLE PRE/POST CRUSH
FLOORPAN - SET 1

POINT	X (in.)	Y (in.)	Z (in.)	X' (in.)	Y' (in.)	Z' (in.)	ΔX (in.)	ΔY (in.)	ΔZ (in.)	Total Δ (in.)
1	65.518	46.148	6.804	65.168	45.889	6.878	-0.350	-0.259	0.074	0.442
2	66.258	44.195	5.965	66.100	44.039	6.021	-0.158	-0.156	0.056	0.229
3	66.636	42.319	5.191	66.616	42.228	5.335	-0.020	-0.090	0.144	0.171
4	66.385	39.467	5.298	66.274	39.434	5.284	-0.111	-0.033	-0.014	0.117
5	64.722	36.877	6.431	64.579	36.896	6.468	-0.143	0.019	0.038	0.149
6	63.161	34.712	7.485	63.063	34.788	7.573	-0.098	0.076	0.088	0.153
7	62.548	47.661	3.262	62.350	47.428	3.244	-0.198	-0.233	-0.019	0.306
8	62.705	44.748	2.632	62.698	44.641	2.530	-0.007	-0.107	-0.103	0.148
9	62.546	40.947	2.660	62.460	40.793	2.584	-0.086	-0.154	-0.077	0.192
10	62.453	37.434	3.493	62.384	37.386	3.443	-0.068	-0.048	-0.050	0.097
11	61.468	35.368	6.191	61.289	35.393	6.172	-0.179	0.026	-0.018	0.182
12	60.886	33.653	7.206	60.693	33.688	7.203	-0.193	0.035	-0.003	0.196
13	58.414	47.168	0.565	58.359	47.085	0.535	-0.055	-0.083	-0.030	0.104
14	58.533	44.575	0.675	58.498	44.521	0.632	-0.034	-0.054	-0.043	0.077
15	58.501	42.142	0.676	58.545	42.065	0.650	0.044	-0.078	-0.026	0.093
16	58.623	38.645	0.708	58.618	38.573	0.642	-0.005	-0.072	-0.066	0.097
17	57.787	36.394	2.868	57.716	36.339	2.774	-0.071	-0.056	-0.095	0.131
18	56.916	33.060	5.272	56.844	33.005	5.280	-0.072	-0.056	0.008	0.092
19	51.751	48.299	-1.175	51.696	48.235	-1.263	-0.055	-0.064	-0.088	0.122
20	51.643	45.766	-1.035	51.666	45.652	-1.132	0.023	-0.113	-0.098	0.151
21	51.699	42.321	-1.021	51.664	42.200	-1.122	-0.035	-0.121	-0.102	0.162
22	51.727	39.208	-1.018	51.724	39.095	-1.113	-0.003	-0.113	-0.096	0.148
23	51.708	36.446	-0.988	51.629	36.372	-1.083	-0.079	-0.075	-0.095	0.145
24	50.533	30.501	2.091	50.471	30.320	2.016	-0.062	-0.181	-0.075	0.206
25	42.983	46.101	-1.396	42.889	45.952	-1.449	-0.094	-0.149	-0.052	0.184
26	42.879	41.991	-1.329	42.858	41.959	-1.400	-0.021	-0.032	-0.072	0.081
27	42.736	38.281	-1.300	42.716	38.202	-1.374	-0.020	-0.079	-0.075	0.111
28	42.582	34.062	-1.277	42.564	33.946	-1.341	-0.018	-0.117	-0.065	0.134
29	36.114	43.585	2.687	36.159	43.478	2.736	0.046	-0.106	0.049	0.126
30	35.944	34.487	2.765	35.986	34.423	2.726	0.042	-0.065	-0.040	0.087

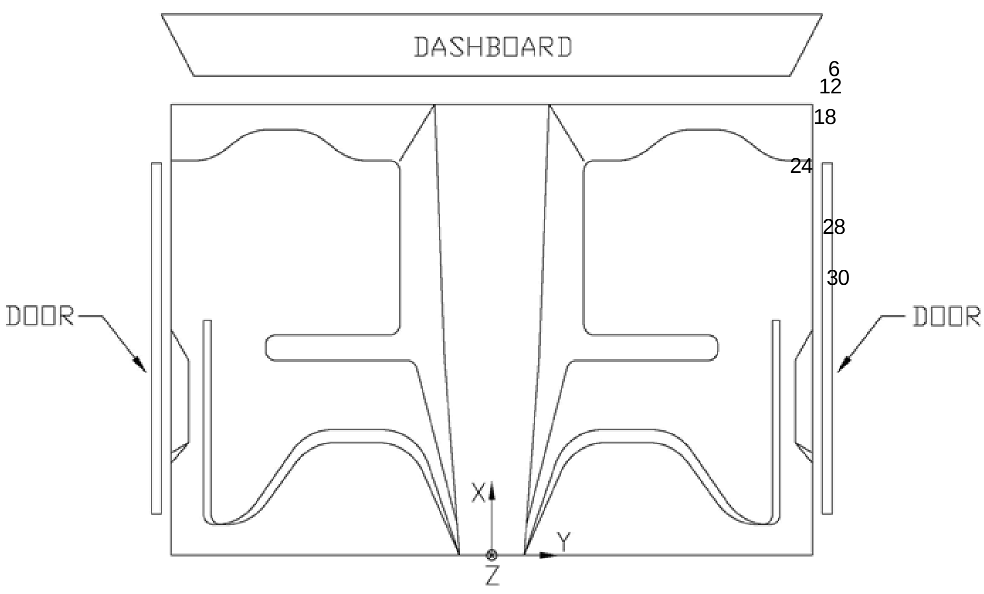


Figure D-7. Floor Pan Deformation Data – Set 1, Test No. CMGS-2

Date: 2/14/2018 Test Name: CMGS-2 VIN: 1D7RB1CTXAS115553
Year: 2010 Make: DODGE Model: RAM 1500 CREW CAB

VEHICLE PRE/POST CRUSH
FLOORPAN - SET 2

POINT	X (in.)	Y (in.)	Z (in.)	X' (in.)	Y' (in.)	Z' (in.)	ΔX (in.)	ΔY (in.)	ΔZ (in.)	Total Δ (in.)
1	62.959	26.617	3.121	62.630	26.661	2.831	-0.329	0.044	-0.290	0.441
2	63.707	24.663	2.236	63.578	24.822	1.968	-0.128	0.159	-0.268	0.337
3	64.143	22.835	1.554	64.110	23.018	1.276	-0.033	0.184	-0.278	0.335
4	63.913	20.007	1.615	63.794	20.221	1.217	-0.119	0.213	-0.398	0.467
5	62.243	17.368	2.678	62.125	17.664	2.397	-0.118	0.296	-0.281	0.425
6	60.744	15.212	3.744	60.630	15.538	3.498	-0.114	0.326	-0.247	0.425
7	59.977	28.183	-0.407	59.793	28.183	-0.795	-0.184	0.000	-0.388	0.430
8	60.189	25.306	-1.028	60.166	25.402	-1.517	-0.023	0.096	-0.489	0.499
9	60.006	21.430	-1.056	59.964	21.552	-1.474	-0.042	0.122	-0.418	0.437
10	59.979	17.926	-0.238	59.922	18.141	-0.624	-0.058	0.215	-0.386	0.446
11	59.020	15.847	2.437	58.849	16.131	2.101	-0.171	0.284	-0.336	0.472
12	58.389	14.090	3.452	58.271	14.418	3.127	-0.119	0.328	-0.324	0.476
13	55.912	27.643	-3.073	55.801	27.810	-3.499	-0.110	0.167	-0.425	0.470
14	56.030	25.116	-2.993	55.965	25.247	-3.409	-0.065	0.131	-0.416	0.441
15	56.058	22.630	-2.990	56.034	22.792	-3.399	-0.024	0.162	-0.410	0.441
16	56.180	19.125	-3.006	56.141	19.301	-3.416	-0.039	0.176	-0.410	0.448
17	55.303	16.809	-0.856	55.263	17.052	-1.290	-0.041	0.243	-0.434	0.499
18	54.528	13.537	1.496	54.426	13.703	1.208	-0.102	0.166	-0.288	0.348
19	49.184	28.682	-4.839	49.125	28.903	-5.284	-0.059	0.221	-0.445	0.500
20	49.124	26.117	-4.715	49.119	26.320	-5.161	-0.005	0.202	-0.446	0.490
21	49.214	22.741	-4.725	49.150	22.867	-5.161	-0.064	0.126	-0.435	0.458
22	49.252	19.636	-4.749	49.239	19.763	-5.161	-0.013	0.127	-0.412	0.431
23	49.216	16.871	-4.743	49.170	17.039	-5.138	-0.046	0.167	-0.395	0.432
24	48.099	10.857	-1.696	48.074	10.967	-2.055	-0.025	0.110	-0.359	0.377
25	40.473	26.438	-5.102	40.340	26.537	-5.464	-0.133	0.099	-0.362	0.399
26	40.438	22.327	-5.064	40.347	22.544	-5.427	-0.091	0.217	-0.364	0.433
27	40.307	18.636	-5.061	40.240	18.786	-5.412	-0.067	0.150	-0.351	0.387
28	40.174	14.416	-5.067	40.129	14.528	-5.391	-0.045	0.112	-0.324	0.346
29	33.606	23.870	-1.058	33.639	23.988	-1.277	0.033	0.118	-0.219	0.251
30	33.537	14.757	-1.045	33.551	14.932	-1.314	0.014	0.174	-0.269	0.321

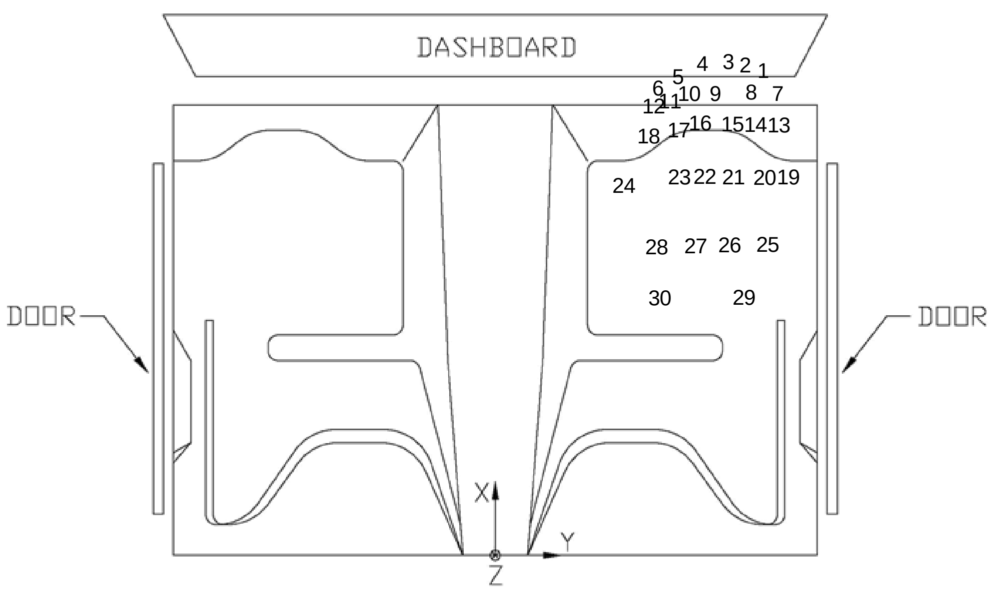


Figure D-8. Floor Pan Deformation Data – Set 2, Test No. CMGS-2

Date: 2/14/2018 Test Name: CMGS-2 VIN: 1D7RB1CTXAS115553
Year: 2010 Make: DODGE Model: RAM 1500 CREW CAB

VEHICLE PRE/POST CRUSH
INTERIOR CRUSH - SET 1

	POINT	X (in.)	Y (in.)	Z (in.)	X' (in.)	Y' (in.)	Z' (in.)	ΔX (in.)	ΔY (in.)	ΔZ (in.)	Total Δ (in.)
DASH	1	-47.020	-48.357	20.164	-46.983	-48.392	20.202	0.037	-0.035	0.038	0.064
	2	-49.089	-38.210	14.643	-49.020	-38.132	14.673	0.069	0.078	0.030	0.109
	3	-46.019	-30.678	20.914	-46.018	-30.621	20.963	0.002	0.056	0.049	0.075
	4	-50.950	-38.078	31.061	-50.938	-38.099	31.102	0.012	-0.021	0.041	0.048
	5	-46.930	-20.267	30.796	-46.917	-20.305	30.740	0.014	-0.038	-0.056	0.069
	6	-44.026	-19.878	19.478	-44.013	-19.977	19.459	0.013	-0.099	-0.019	0.102
SIDE PANEL	7	-56.089	-52.035	8.971	-55.987	-51.153	8.956	0.102	0.881	-0.015	0.887
	8	-59.068	-51.996	6.653	-58.963	-51.312	6.622	0.105	0.683	-0.031	0.692
	9	-60.646	-51.882	4.010	-60.590	-51.374	4.095	0.056	0.508	0.086	0.518
IMPACT SIDE DOOR	10	-21.856	-54.031	26.435	-21.450	-54.944	26.673	0.406	-0.913	0.238	1.027
	11	-34.469	-53.794	26.323	-34.095	-54.301	26.556	0.373	-0.506	0.233	0.671
	12	-44.396	-53.586	26.211	-44.043	-53.756	26.433	0.353	-0.170	0.222	0.451
	13	-26.279	-54.789	16.281	-25.834	-55.314	16.569	0.445	-0.525	0.288	0.746
	14	-37.165	-54.656	16.671	-36.746	-54.849	16.890	0.419	-0.193	0.219	0.510
	15	-36.791	-55.196	6.792	-36.310	-55.184	6.938	0.481	0.012	0.146	0.503
ROOF	16	-35.177	-41.318	47.536	-35.093	-41.328	47.664	0.084	-0.010	0.128	0.153
	17	-36.527	-36.395	47.912	-36.507	-36.424	47.985	0.021	-0.029	0.073	0.081
	18	-37.515	-31.014	48.080	-37.485	-31.127	48.133	0.030	-0.113	0.053	0.128
	19	-37.980	-26.873	48.110	-37.964	-26.897	48.138	0.016	-0.023	0.028	0.040
	20	-29.773	-41.267	49.564	-29.843	-41.375	49.630	-0.071	-0.108	0.066	0.145
	21	-31.020	-35.266	49.936	-31.029	-35.339	49.979	-0.009	-0.073	0.043	0.086
	22	-32.010	-28.878	50.160	-32.143	-28.834	50.179	-0.133	0.044	0.019	0.141
	23	-32.165	-23.898	50.306	-32.274	-23.946	50.304	-0.108	-0.047	-0.002	0.118
	24	-23.272	-39.694	50.229	-23.297	-39.715	50.314	-0.025	-0.022	0.085	0.091
	25	-23.503	-35.851	50.422	-23.507	-35.932	50.504	-0.004	-0.081	0.082	0.115
	26	-22.978	-29.390	50.791	-23.018	-29.467	50.834	-0.040	-0.077	0.043	0.097
	27	-22.738	-25.268	50.939	-22.802	-25.234	50.978	-0.063	0.034	0.038	0.081
	28	-18.962	-39.319	50.441	-19.060	-39.324	50.528	-0.098	-0.005	0.087	0.131
	29	-19.021	-34.949	50.734	-19.086	-34.956	50.801	-0.065	-0.007	0.067	0.094
	30	-18.967	-28.866	51.039	-19.105	-28.911	51.085	-0.138	-0.045	0.045	0.152
A PILLAR	31	-54.374	-50.505	33.075	-54.379	-50.520	33.079	-0.005	-0.015	0.003	0.017
	32	-51.087	-49.824	36.231	-51.023	-49.862	36.270	0.064	-0.038	0.039	0.084
	33	-45.252	-48.770	40.803	-45.086	-48.788	40.885	0.166	-0.017	0.082	0.186
	34	-39.014	-47.418	44.440	-38.913	-47.453	44.565	0.101	-0.035	0.126	0.165
B PILLAR	35	-11.043	-47.050	46.038	-11.038	-47.084	46.234	0.005	-0.034	0.196	0.199
	36	-14.083	-47.060	45.925	-14.116	-47.105	46.145	-0.033	-0.046	0.221	0.228
	37	-11.824	-48.626	41.371	-11.754	-48.680	41.575	0.070	-0.054	0.204	0.222
	38	-14.797	-49.032	40.268	-14.775	-49.139	40.485	0.023	-0.107	0.216	0.243
	39	-12.980	-51.436	32.920	-12.899	-51.515	33.134	0.080	-0.079	0.215	0.243
	40	-14.321	-52.268	29.284	-14.273	-52.382	29.539	0.048	-0.114	0.256	0.284

Figure D-9. Occupant Compartment Deformation Data – Set 1, Test No. CMGS-2

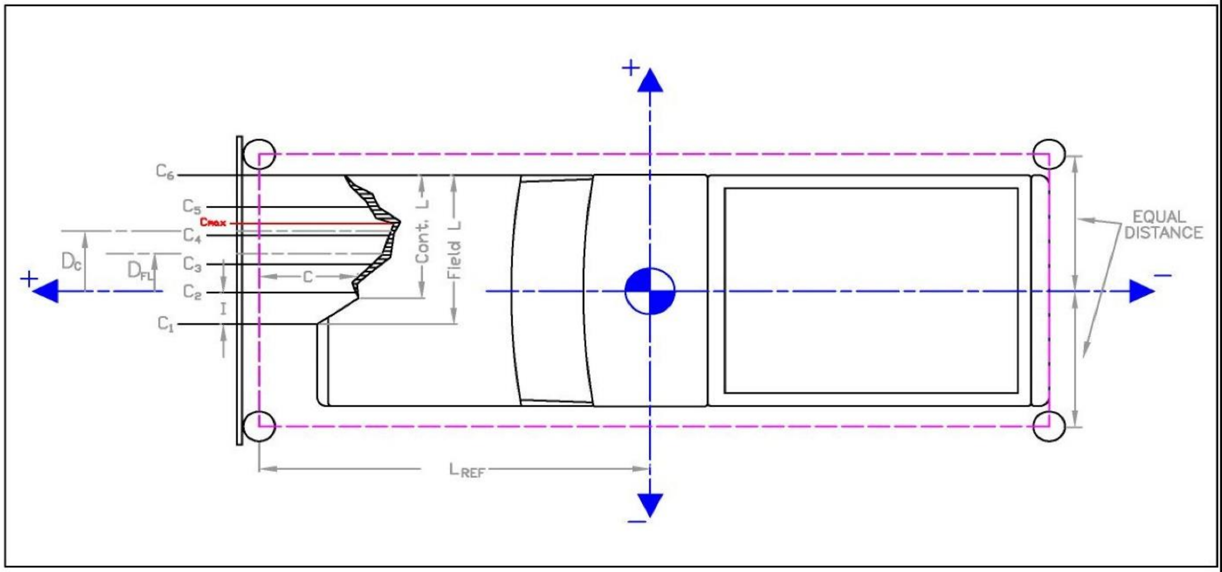
Date: 2/14/2018 Test Name: CMGS-2 VIN: 1D7RB1CTXAS115553
Year: 2010 Make: DODGE Model: RAM 1500 CREW CAB

VEHICLE PRE/POST CRUSH
INTERIOR CRUSH - SET 2

	POINT	X (in.)	Y (in.)	Z (in.)	X' (in.)	Y' (in.)	Z' (in.)	ΔX (in.)	ΔY (in.)	ΔZ (in.)	Total Δ (in.)
DASH	1	44.453	28.840	16.384	44.457	28.947	16.172	0.004	0.107	-0.212	0.237
	2	46.629	18.681	10.818	46.579	18.722	10.611	-0.050	0.041	-0.207	0.217
	3	43.600	11.105	17.077	43.657	11.166	16.885	0.057	0.061	-0.192	0.209
	4	48.436	18.536	27.233	48.525	18.662	27.036	0.089	0.126	-0.197	0.250
	5	44.574	0.655	26.858	44.669	0.832	26.632	0.095	0.177	-0.227	0.302
	6	41.708	0.301	15.539	41.749	0.509	15.355	0.040	0.207	-0.184	0.280
SIDE PANEL	7	53.492	32.644	5.245	53.415	31.823	4.918	-0.077	-0.821	-0.327	0.887
	8	56.492	32.640	2.887	56.385	32.016	2.579	-0.106	-0.625	-0.308	0.704
	9	58.065	32.555	0.292	58.007	32.099	0.050	-0.058	-0.456	-0.242	0.519
IMPACT SIDE DOOR	10	19.306	34.257	22.609	18.875	35.245	22.705	-0.431	0.988	0.095	1.082
	11	31.927	34.127	22.533	31.526	34.719	22.564	-0.401	0.592	0.032	0.715
	12	41.813	33.993	22.495	41.478	34.267	22.423	-0.335	0.273	-0.072	0.439
	13	23.607	35.109	12.535	23.238	35.683	12.594	-0.369	0.574	0.059	0.685
	14	34.586	35.060	12.917	34.155	35.318	12.896	-0.431	0.258	-0.021	0.503
	15	34.201	35.651	2.996	33.698	35.676	2.945	-0.502	0.026	-0.051	0.506
ROOF	16	32.621	21.554	43.688	32.680	21.698	43.634	0.060	0.144	-0.053	0.165
	17	33.991	16.588	44.130	34.140	16.806	43.940	0.149	0.218	-0.190	0.325
	18	34.988	11.296	44.244	35.168	11.518	44.071	0.180	0.222	-0.173	0.334
	19	35.512	7.116	44.172	35.686	7.293	44.064	0.174	0.177	-0.108	0.270
	20	27.109	21.424	45.745	27.434	21.690	45.610	0.325	0.266	-0.135	0.441
	21	28.505	15.531	46.058	28.676	15.665	45.940	0.172	0.134	-0.118	0.248
	22	29.681	9.032	46.238	29.851	9.170	46.120	0.170	0.138	-0.118	0.249
	23	29.797	4.126	46.357	30.027	4.283	46.231	0.230	0.157	-0.126	0.305
	24	20.575	19.806	46.373	20.905	19.969	46.300	0.329	0.162	-0.073	0.374
	25	20.998	16.062	46.549	21.150	16.187	46.480	0.152	0.125	-0.069	0.209
	26	20.507	9.518	46.879	20.722	9.717	46.793	0.214	0.199	-0.086	0.304
	27	20.329	5.381	47.006	20.545	5.481	46.925	0.215	0.100	-0.081	0.251
	28	16.439	19.410	46.570	16.672	19.538	46.520	0.234	0.128	-0.050	0.271
	29	16.518	15.011	46.841	16.739	15.169	46.782	0.221	0.159	-0.059	0.279
	30	16.544	9.011	47.116	16.815	9.124	47.049	0.271	0.113	-0.068	0.301
A PILLAR	31	51.855	31.004	29.426	51.855	31.109	29.042	0.000	0.104	-0.384	0.398
	32	48.521	30.252	32.414	48.511	30.411	32.237	-0.010	0.159	-0.177	0.238
	33	42.648	29.109	36.979	42.592	29.268	36.859	-0.056	0.160	-0.120	0.207
	34	36.408	27.675	40.557	36.439	27.866	40.546	0.031	0.191	-0.011	0.194
B PILLAR	35	8.446	27.089	42.149	8.571	27.234	42.262	0.126	0.145	0.113	0.223
	36	11.502	27.106	42.096	11.649	27.285	42.168	0.147	0.178	0.072	0.242
	37	9.243	28.685	37.532	9.264	28.850	37.606	0.022	0.166	0.074	0.183
	38	12.286	29.119	36.449	12.278	29.341	36.512	-0.007	0.221	0.063	0.230
	39	10.398	31.570	29.058	10.368	31.719	29.172	-0.029	0.150	0.114	0.190
	40	11.740	32.409	25.482	11.728	32.608	25.577	-0.013	0.199	0.094	0.220

Figure D-10. Occupant Compartment Deformation Data – Set 2, Test No. CMGS-2

Date:	2/16/2018	Test Name:	CMGS-2	VIN:	1D7RB1CTXAS115553
Year:	2010	Make:	DODGE	Model:	RAM 1500 CREW CAB



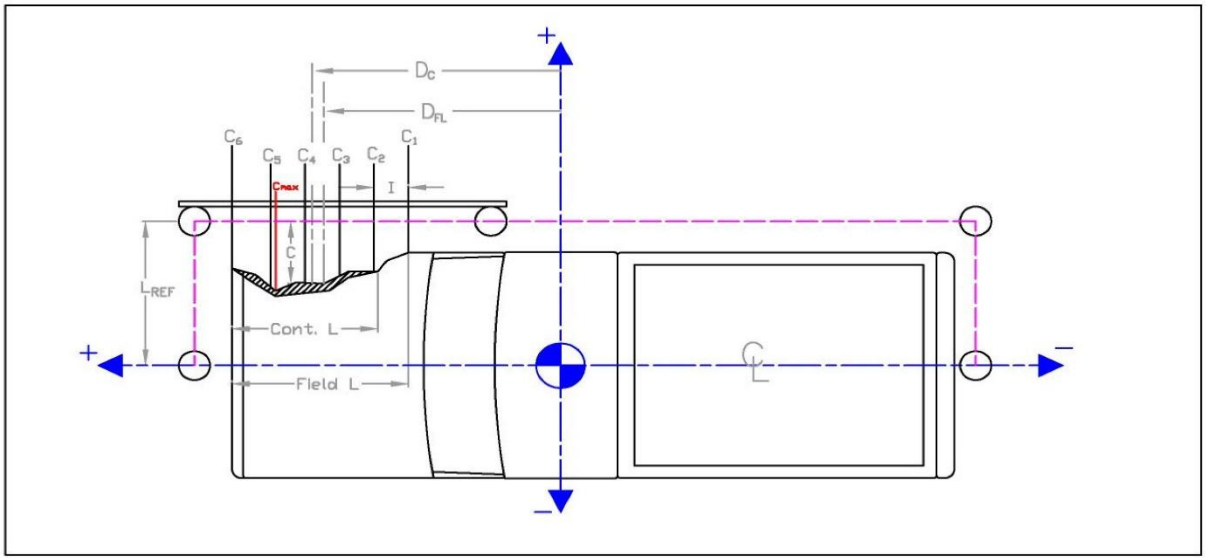
	in.	(mm)
Distance from C.G. to reference line - L_{REF}:	117	(2972)
Total Vehicle Width:	76 1/8	(1934)
Width of contact and induced crush - Field L:	50	(1272)
Crush measurement spacing interval (L/5) - I:	10	(254)
Distance from center of vehicle to center of Field L - D_{FL}:	0	()
Width of Contact Damage:	27	(686)
Distance from center of vehicle to center of contact damage - D_C:	11 1/2	(292)

NOTE: Enter "NA" for crush measurement if distance can not be measured (i.e., side of vehicle has been pushed inward)
NOTE: All values must be filled out above before crush measurements are filled out.

	Crush Measurement		Lateral Location		Original Profile Measurement		Dist. Between Ref. Lines		Actual Crush	
	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)
C_1	24	(610)	-25	-(635)	7	(178)	12 5/8	(321)	4 3/8	(111)
C_2	16	(406)	-15	-(381)	4 7/8	(124)			-1 1/2	-(38)
C_3	12 3/4	(324)	-5	-(127)	4 1/8	(105)			-4	-(102)
C_4	12 1/2	(318)	5	(127)	4 1/8	(105)			-4 1/4	-(108)
C_5	21	(533)	15	(381)	4 7/8	(124)			3 1/2	(89)
C_6	36 1/2	(927)	25	(635)	6 3/4	(171)			17 1/8	(435)
C_{MAX}	36 1/2	(927)	25	(635)	6 3/4	(171)			17 1/8	(435)

Figure D-11. Exterior Vehicle Crush (NASS) - Front, Test No. CMGS-2

Date:	2/16/2018	Test Name:	CMGS-2	VIN:	1D7RB1CTXAS115553
Year:	2010	Make:	DODGE	Model:	RAM 1500 CREW CAB



	in.	(mm)
Distance from centerline to reference line - L_{REF}:	49 1/2	(1257)
Total Vehicle Length:	229 1/4	(5823)
Distance from vehicle c.g. to 1/2 of Vehicle total length:	-13	-(330)
Width of contact and induced crush - Field L:	229 1/4	(5823)
Crush measurement spacing interval (L/5) - I:	45 7/8	(1165)
Distance from vehicle c.g. to center of Field L - D_{FL}:	-12 3/4	-(324)
Width of Contact Damage:	229 1/4	(5823)
Distance from vehicle c.g. to center of contact damage - D_C:	-12 3/4	-(324)

NOTE: Enter "NA" for crush measurement if distance can not be measured (i.e., front of vehicle has been pushed inward or tire has been removed)

NOTE: All values must be filled out above before crush measurements are filled out.

	Crush Measurement		Longitudinal Location		Original Profile Measurement		Dist. Between Ref. Lines		Actual	Crush
	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)
C_1	18	(457)	-127 3/8	-(3235)	33 1/2	(851)	5 1/2	(140)	-21	-(533)
C_2	N/A	N/A	-81 1/2	-(2070)	5 1/4	(133)			N/A	N/A
C_3	7 1/2	(191)	-35 5/8	-(905)	5 1/2	(140)			-3 1/2	-(89)
C_4	7	(178)	10 1/4	(260)	5 1/8	(130)			-3 5/8	-(92)
C_5	N/A	N/A	56 1/8	(1426)	5 1/8	(130)			N/A	N/A
C_6	37	(940)	102	(2591)	33 1/2	(851)			-2	-(51)
C_{MAX}	37	(940)	102	(2591)	33 1/2	(851)			-2	-(51)

Figure D-12. Exterior Vehicle Crush (NASS) - Side, Test No. CMGS-2

Appendix E. Accelerometer and Rate Transducer Data Plots, Test No. CMGS-1

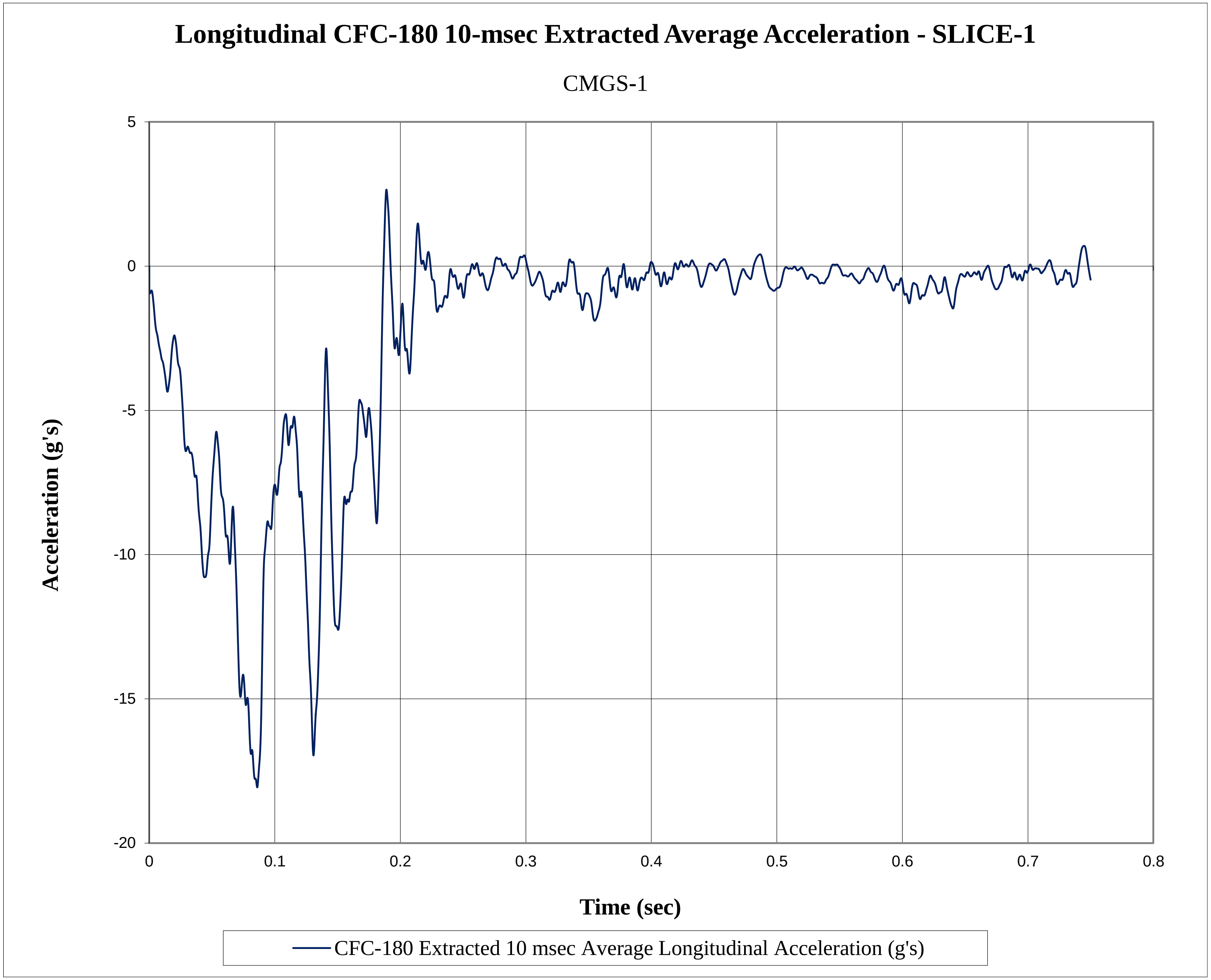


Figure E-1. 10-ms Average Longitudinal Deceleration (SLICE-1), Test No. CMGS-1

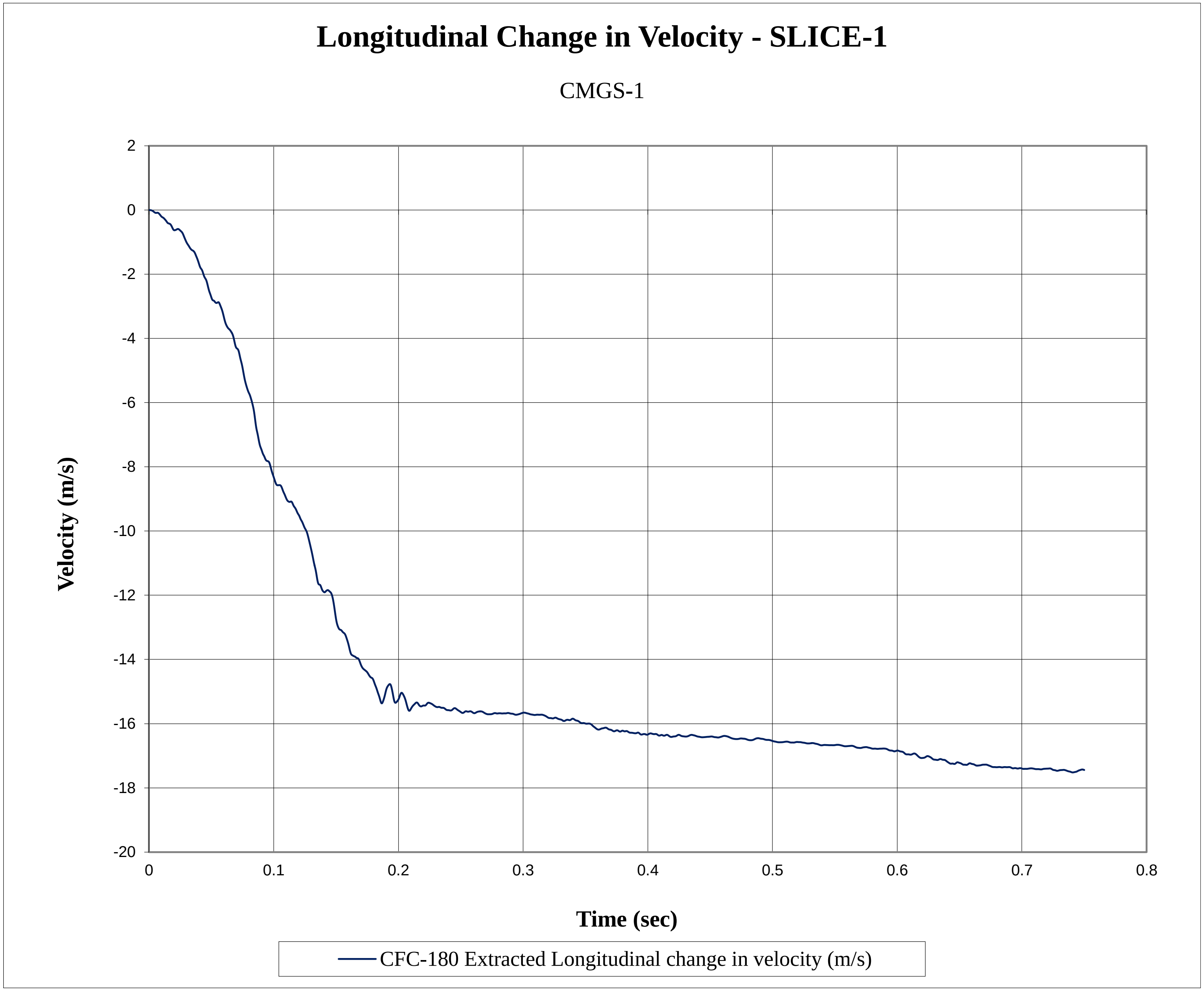


Figure E-2. Longitudinal Change in Velocity (SLICE-1), Test No. CMGS-1

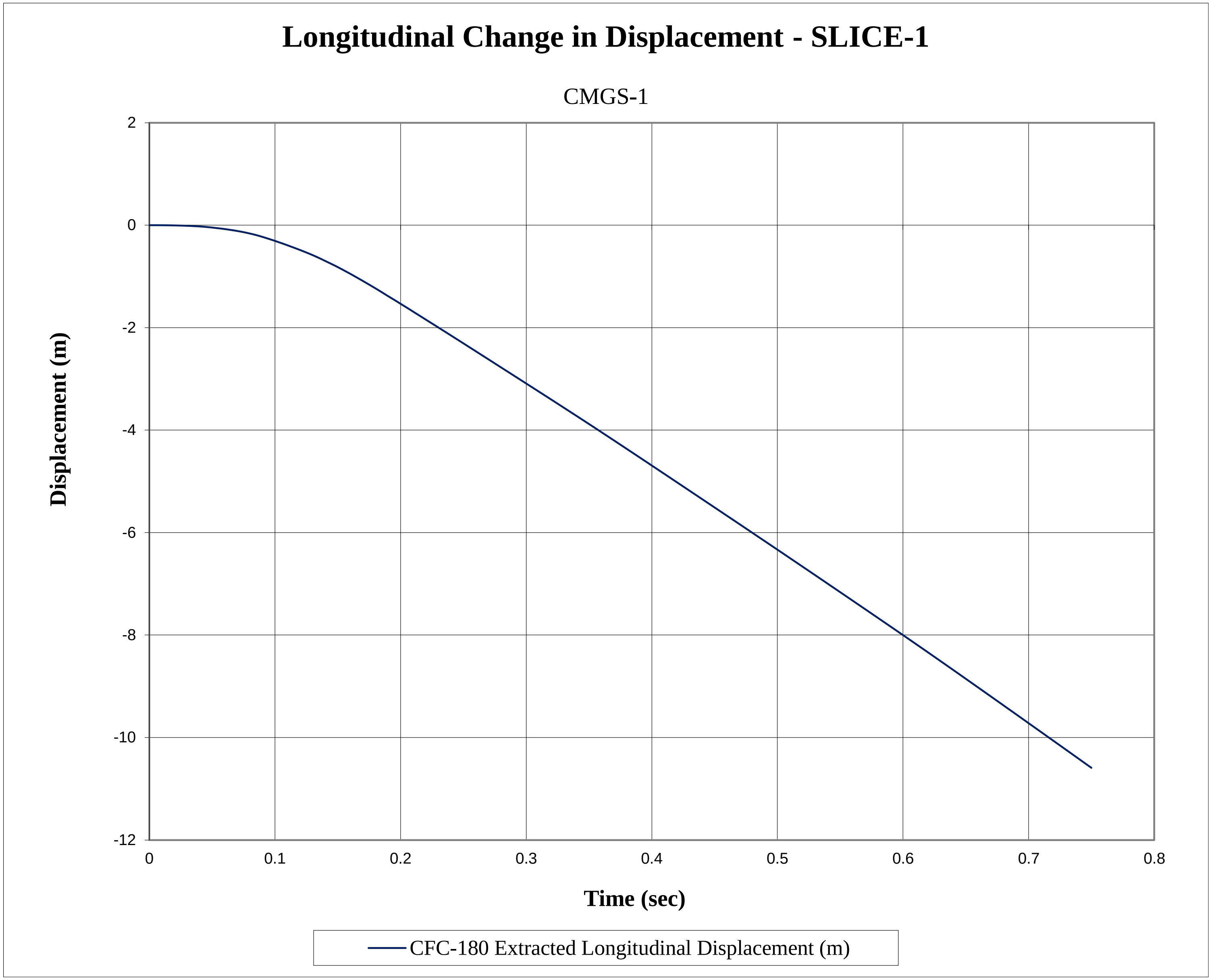


Figure E-3. Longitudinal Change in Displacement (SLICE-1), Test No. CMGS-1

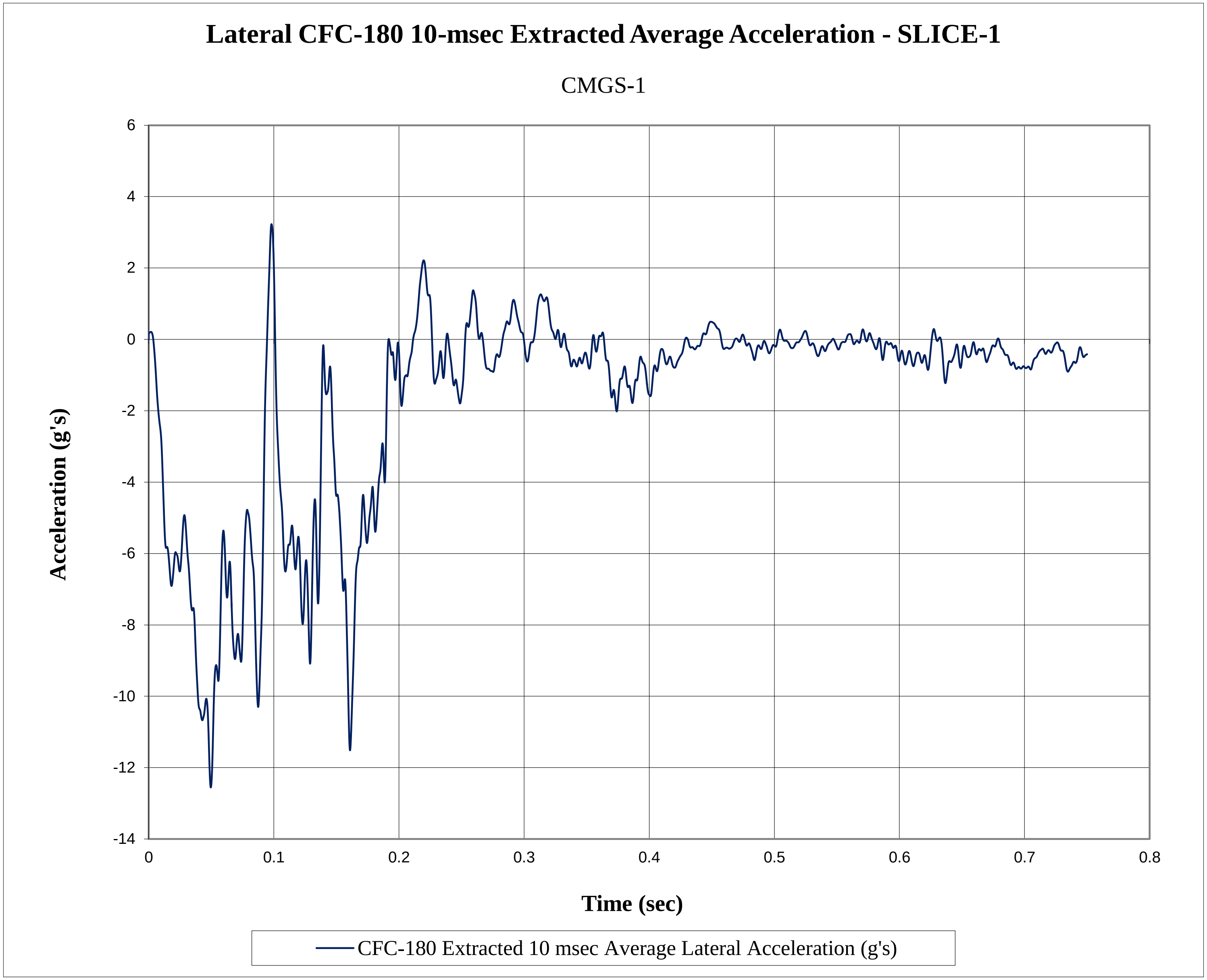


Figure E-4. 10-ms Average Lateral Deceleration (SLICE-1), Test No. CMGS-1

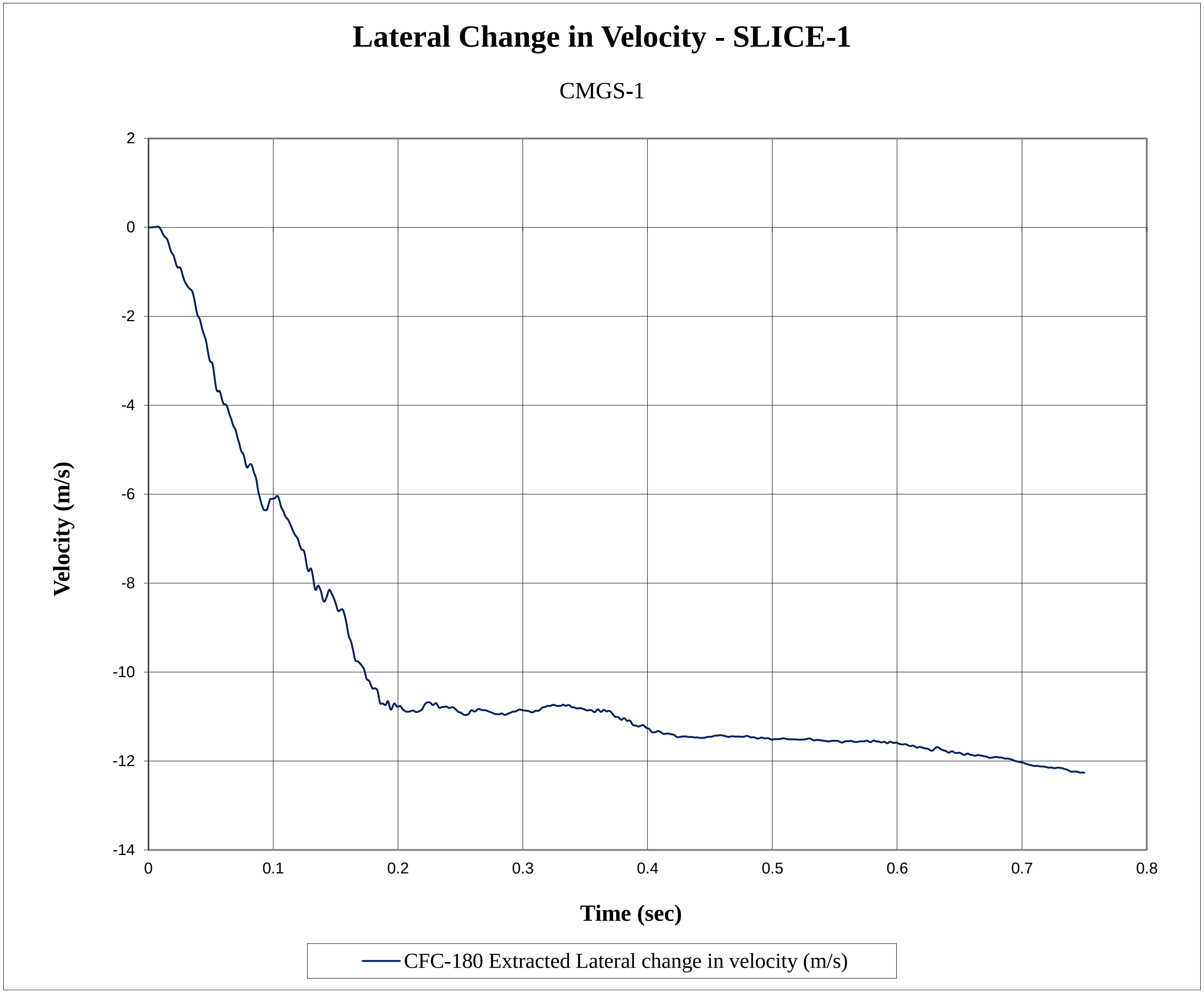


Figure E-5. Lateral Change in Velocity (SLICE-1), Test No. CMGS-1

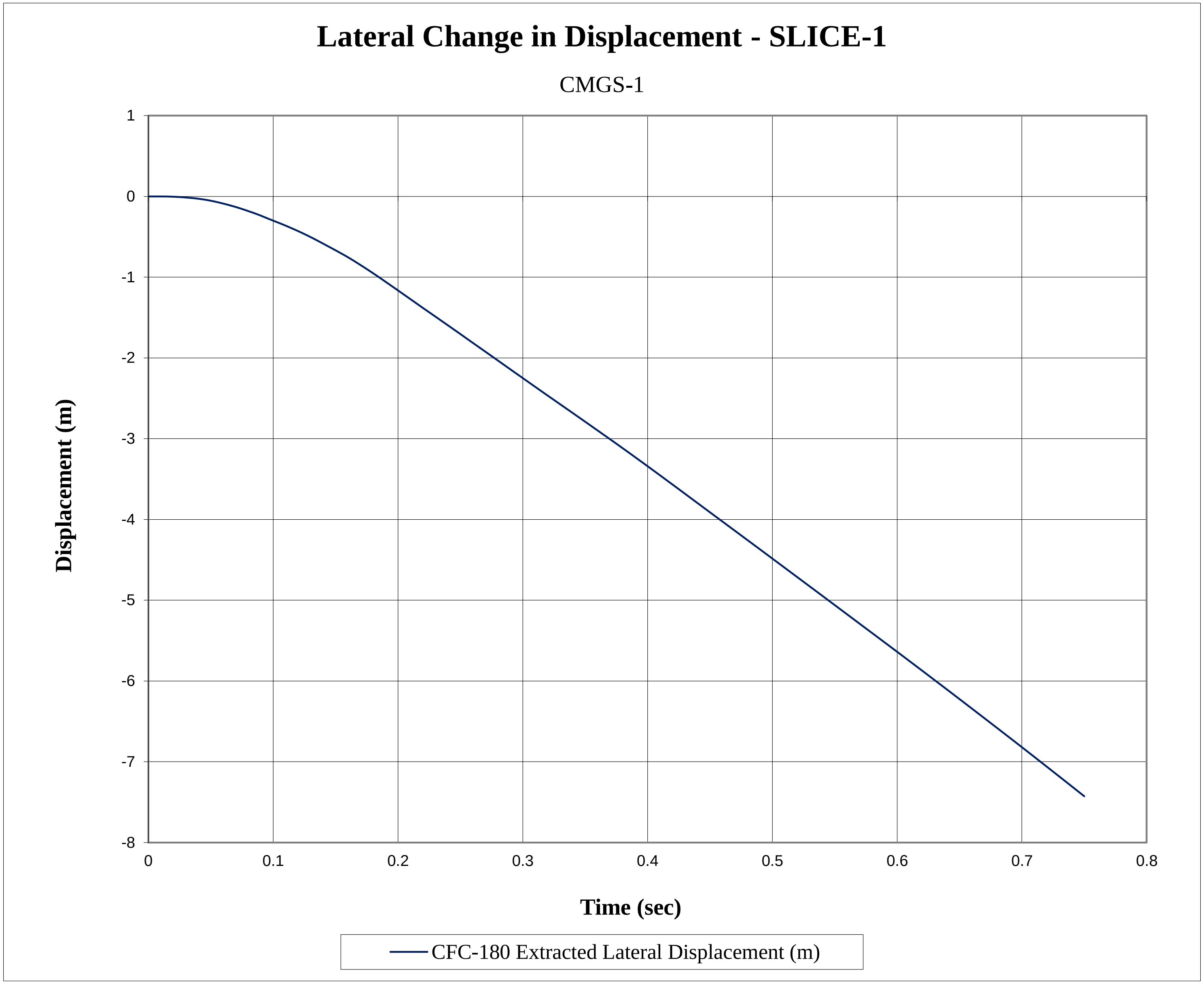


Figure E-6. Lateral Change in Displacement (SLICE-1), Test No. CMGS-1

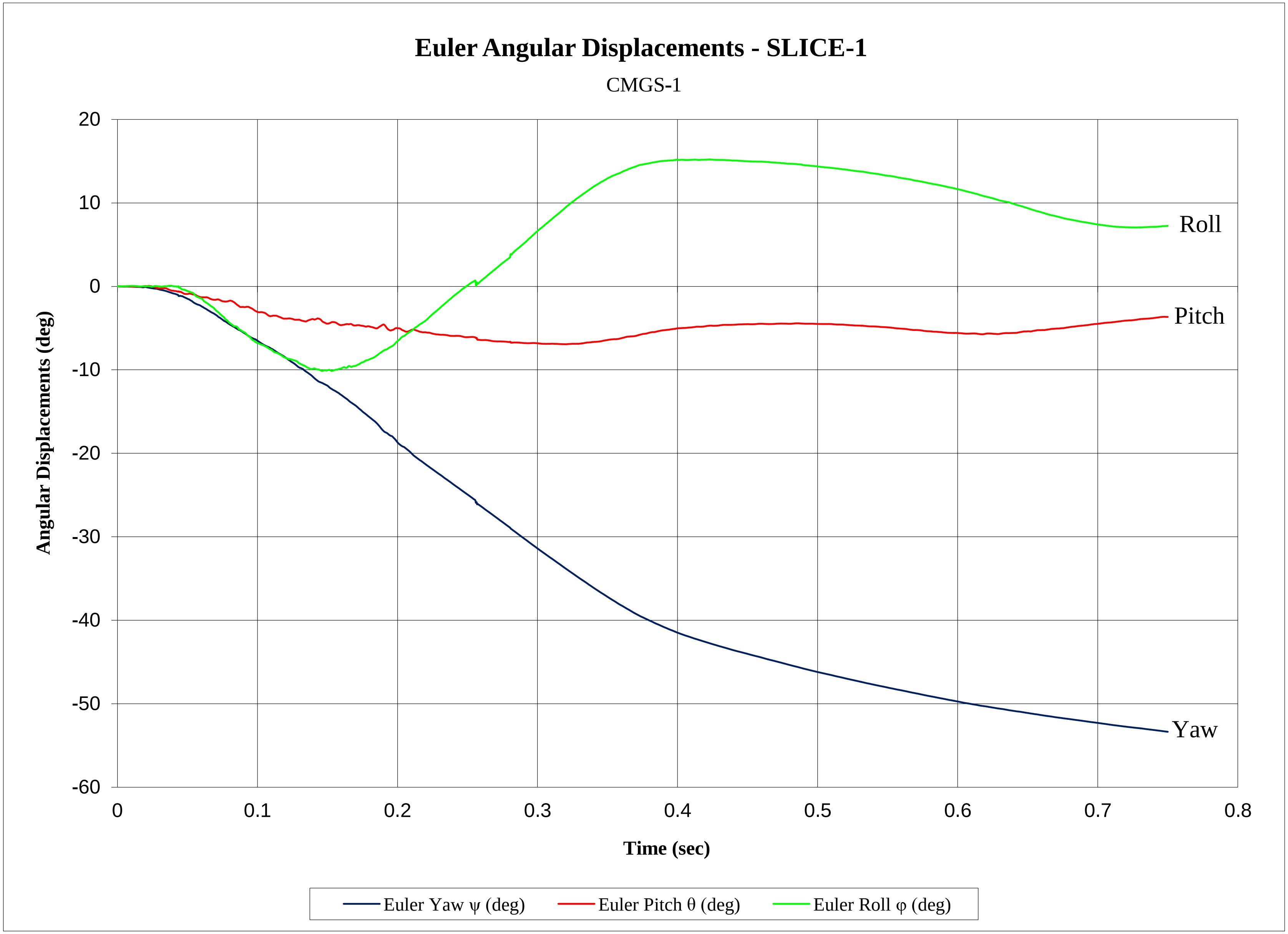


Figure E-7. Vehicle Angular Displacements (SLICE-1), Test No. CMGS-1

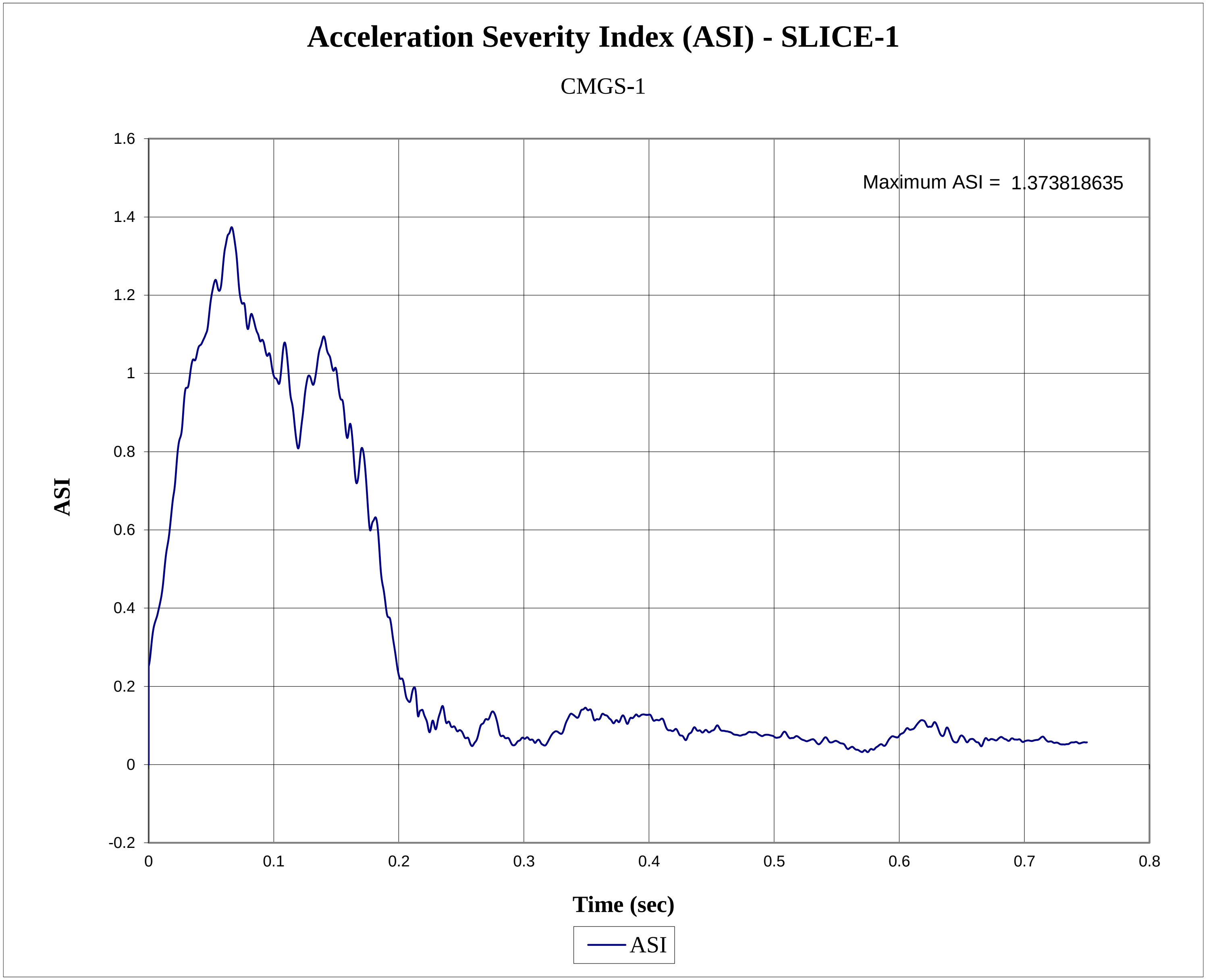


Figure E-8. Acceleration Severity Index (SLICE-1), Test No. CMGS-1

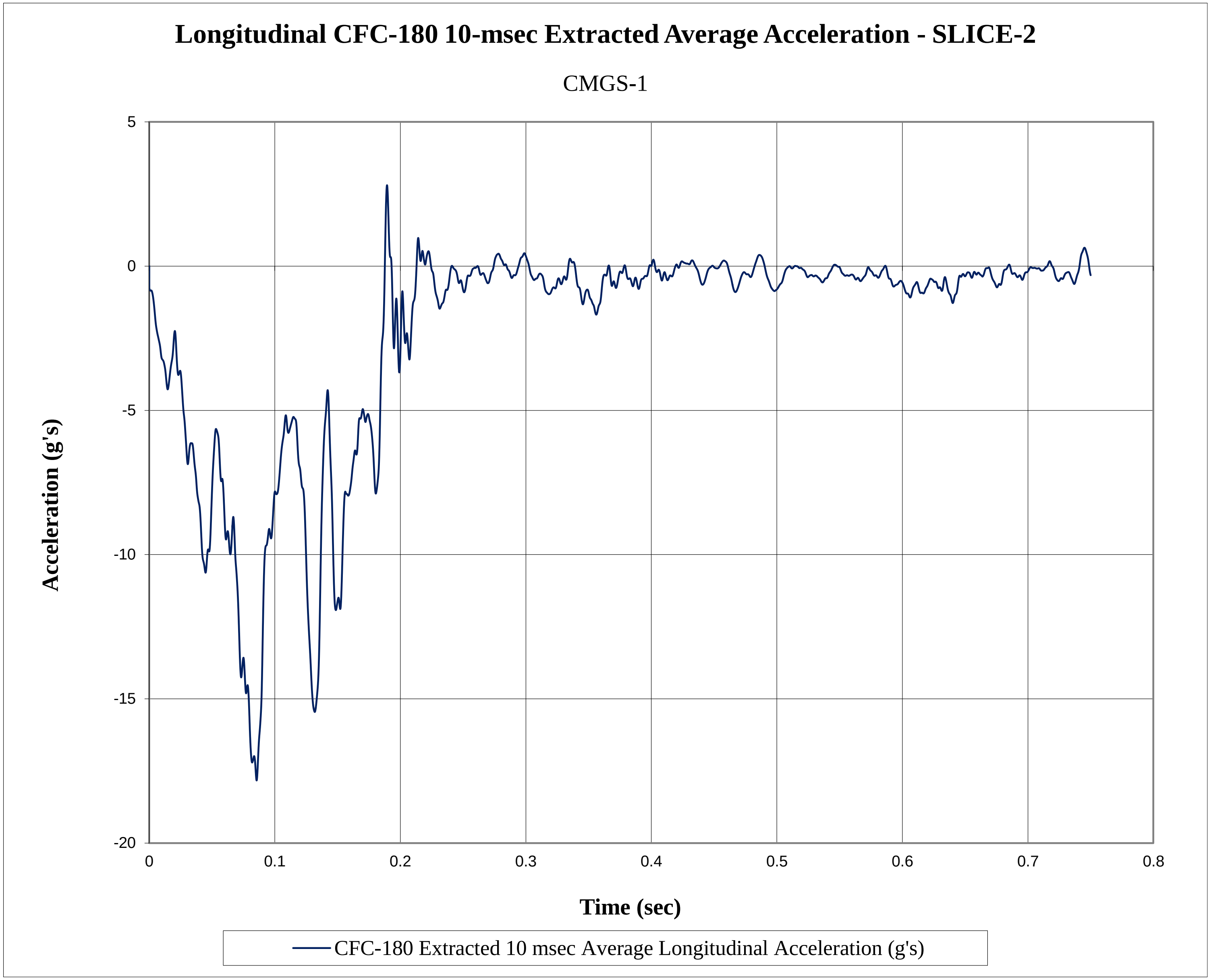


Figure E-9. 10-ms Average Longitudinal Deceleration (SLICE-2), Test No. CMGS-1

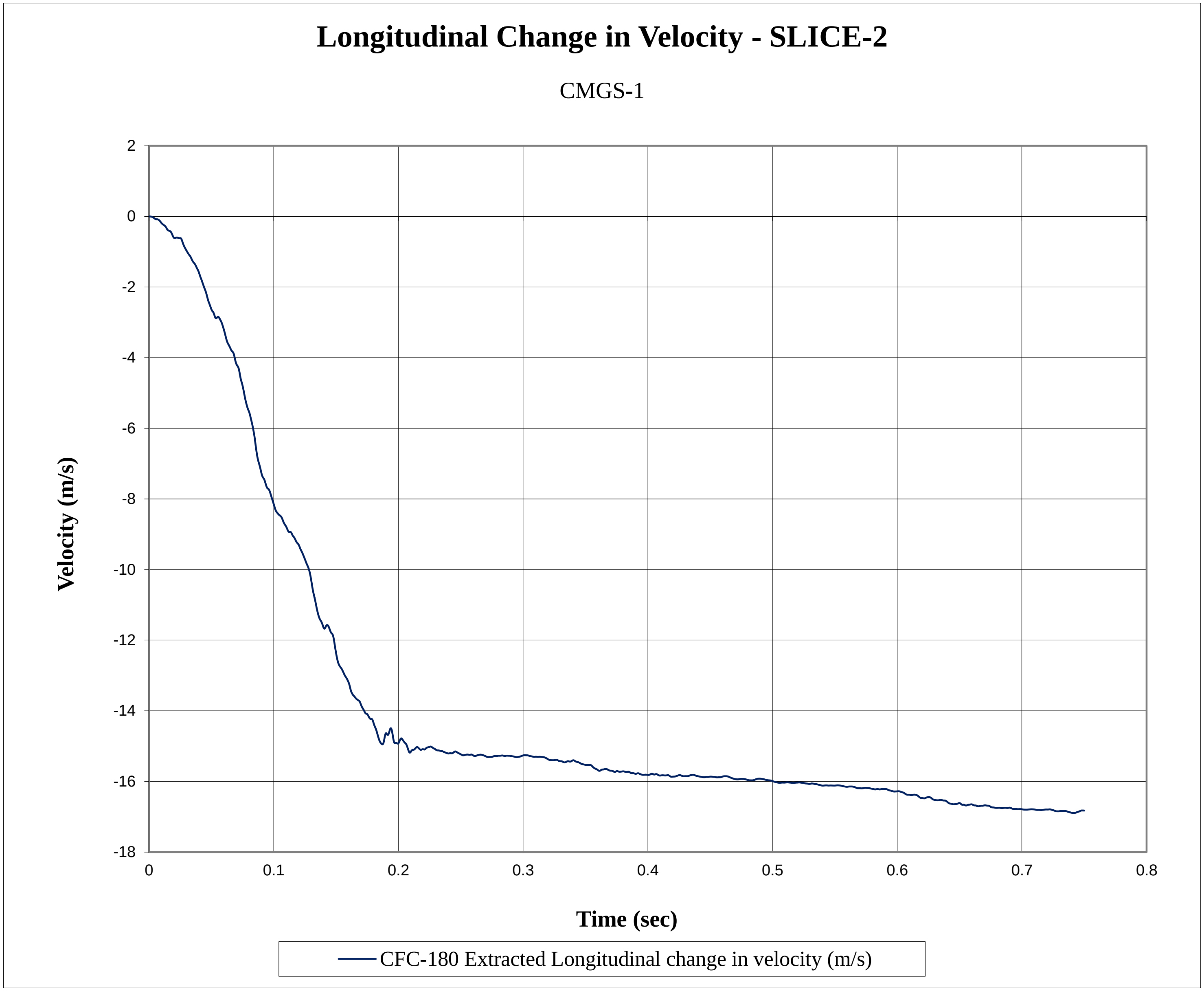


Figure E-10. Longitudinal Change in Velocity (SLICE-2), Test No. CMGS-1

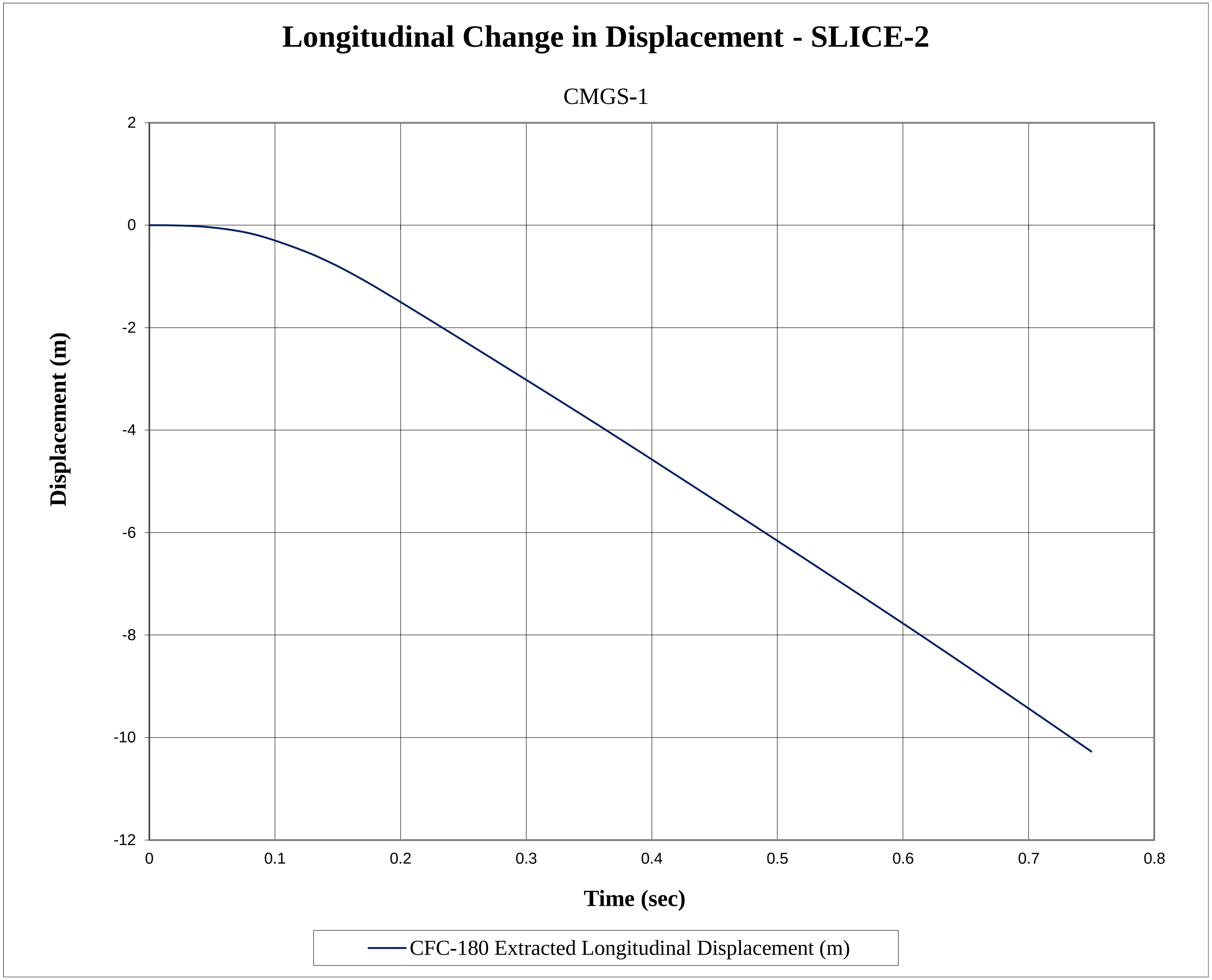


Figure E-11. Longitudinal Change in Displacement (SLICE-2), Test No. CMGS-1

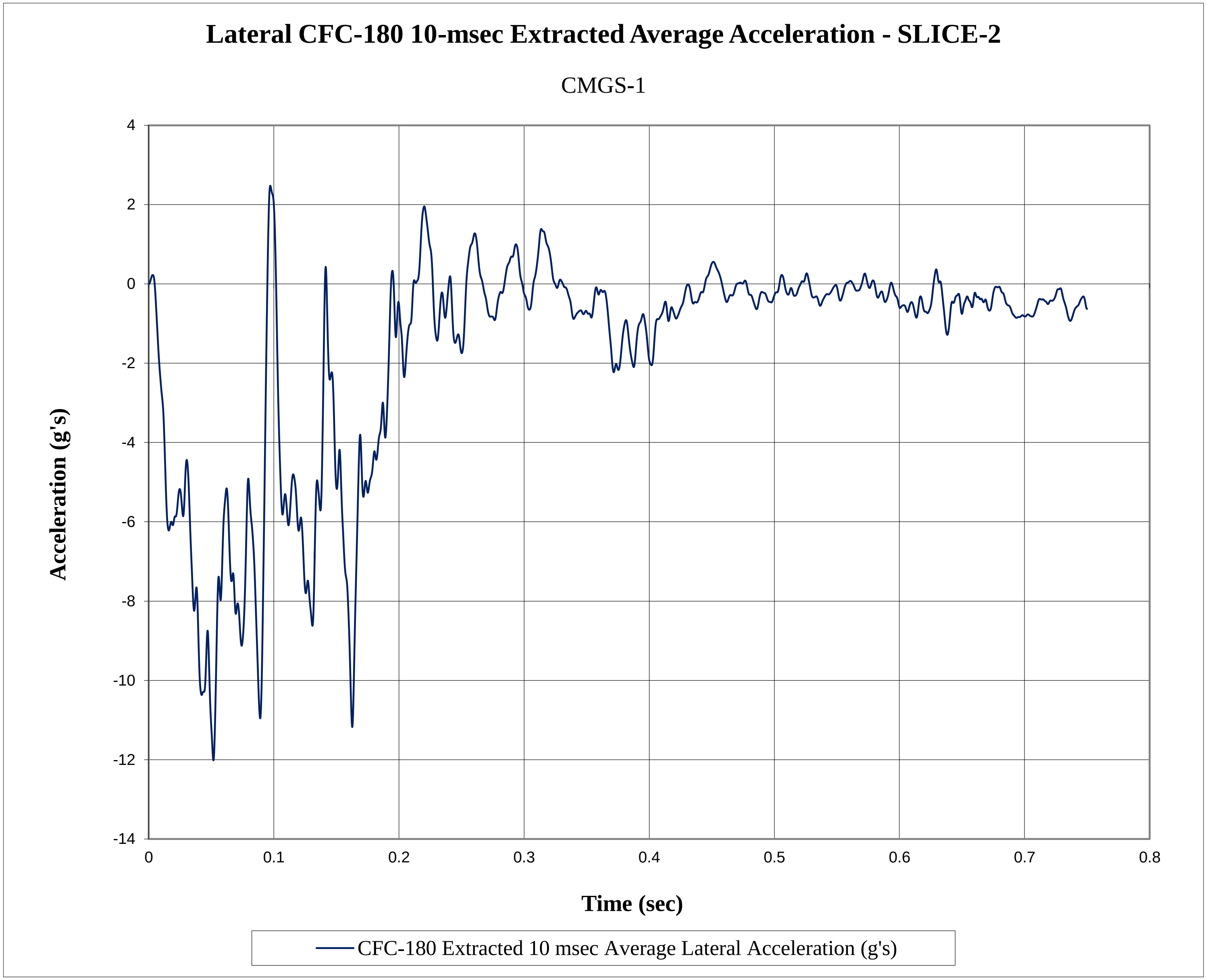


Figure E-12. 10-ms Average Lateral Deceleration (SLICE-2), Test No. CMGS-1

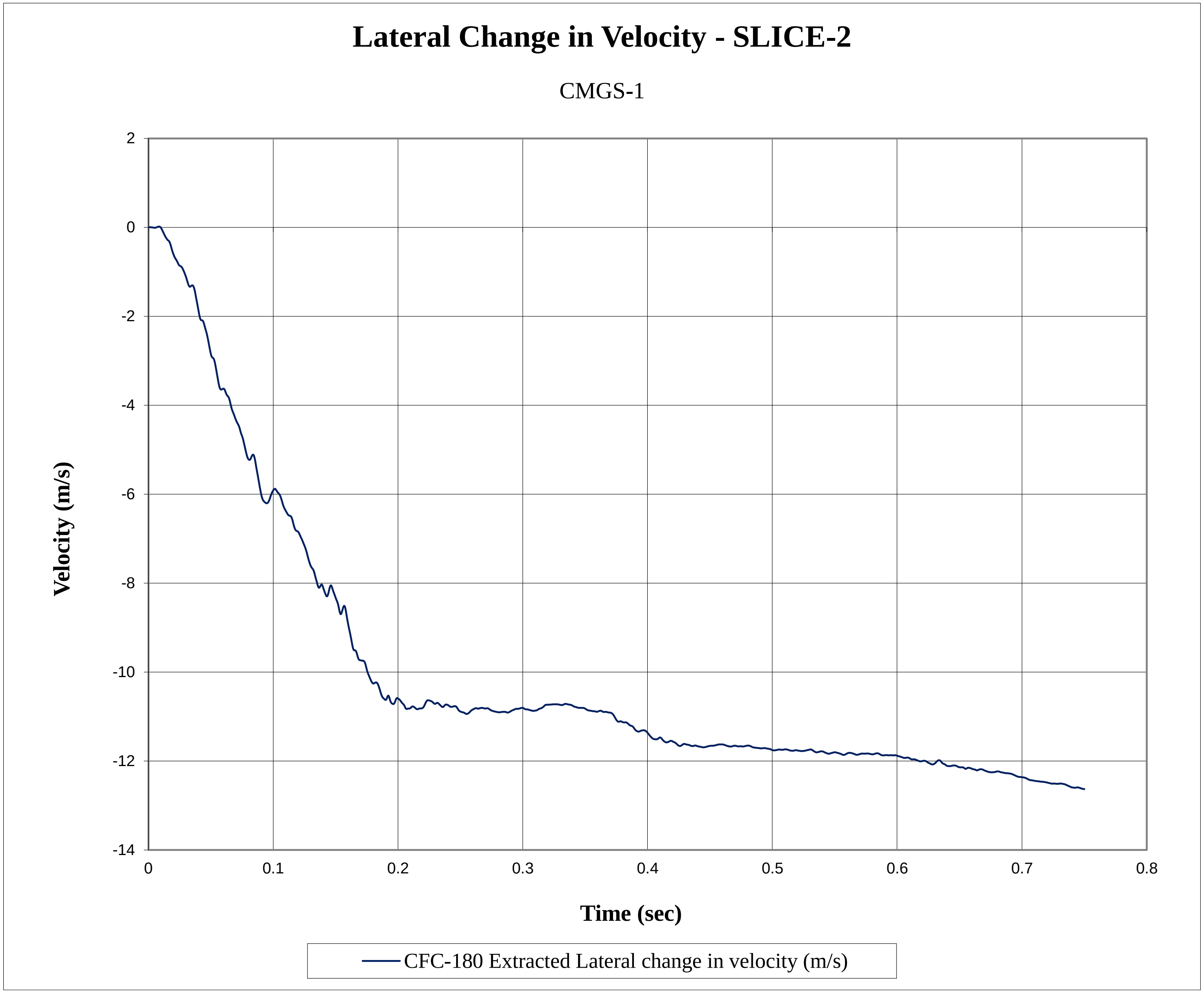


Figure E-13. Lateral Change in Velocity (SLICE-2), Test No. CMGS-1

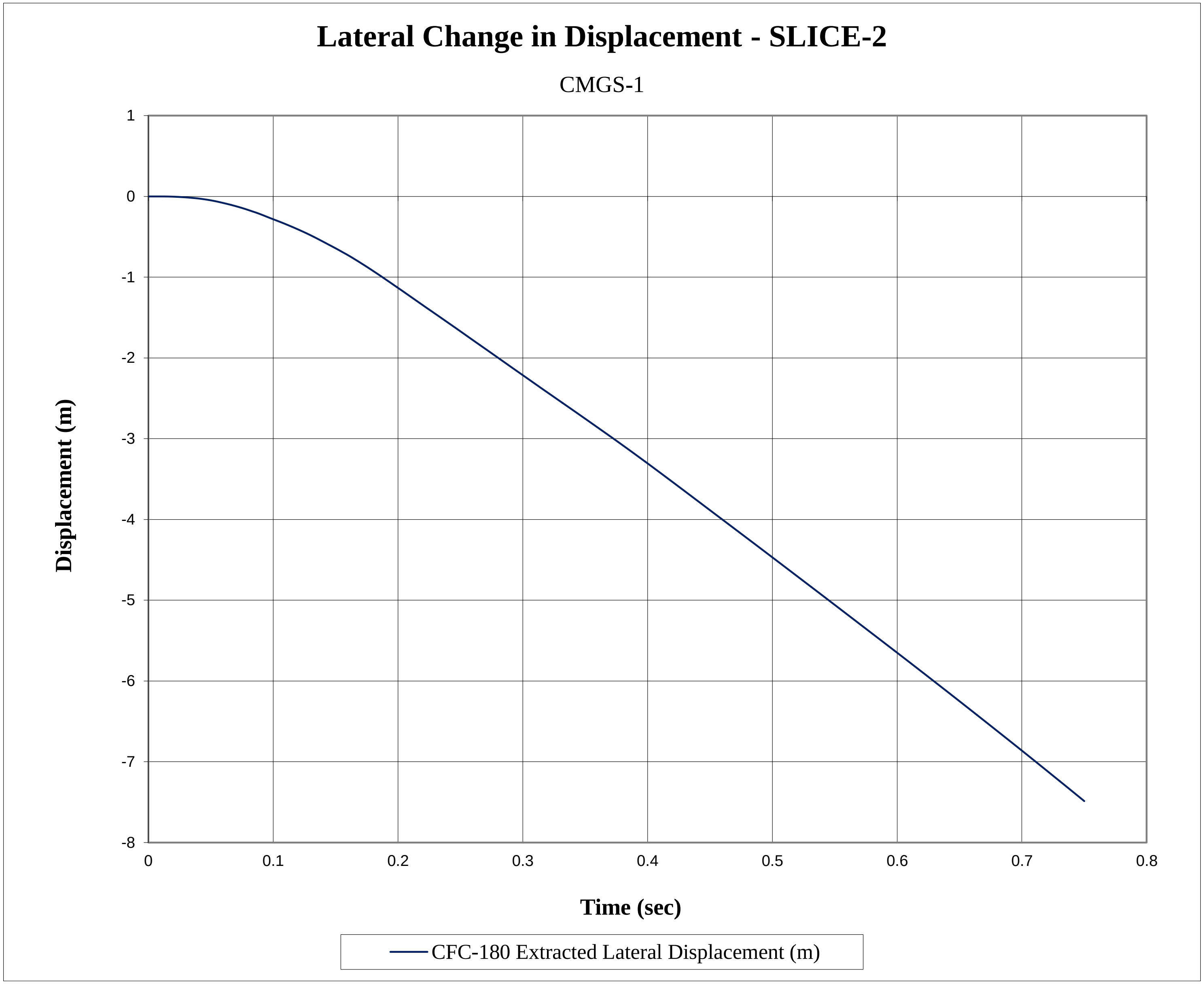


Figure E-14. Lateral Occupant Displacement (SLICE-2), Test No. CMGS-1

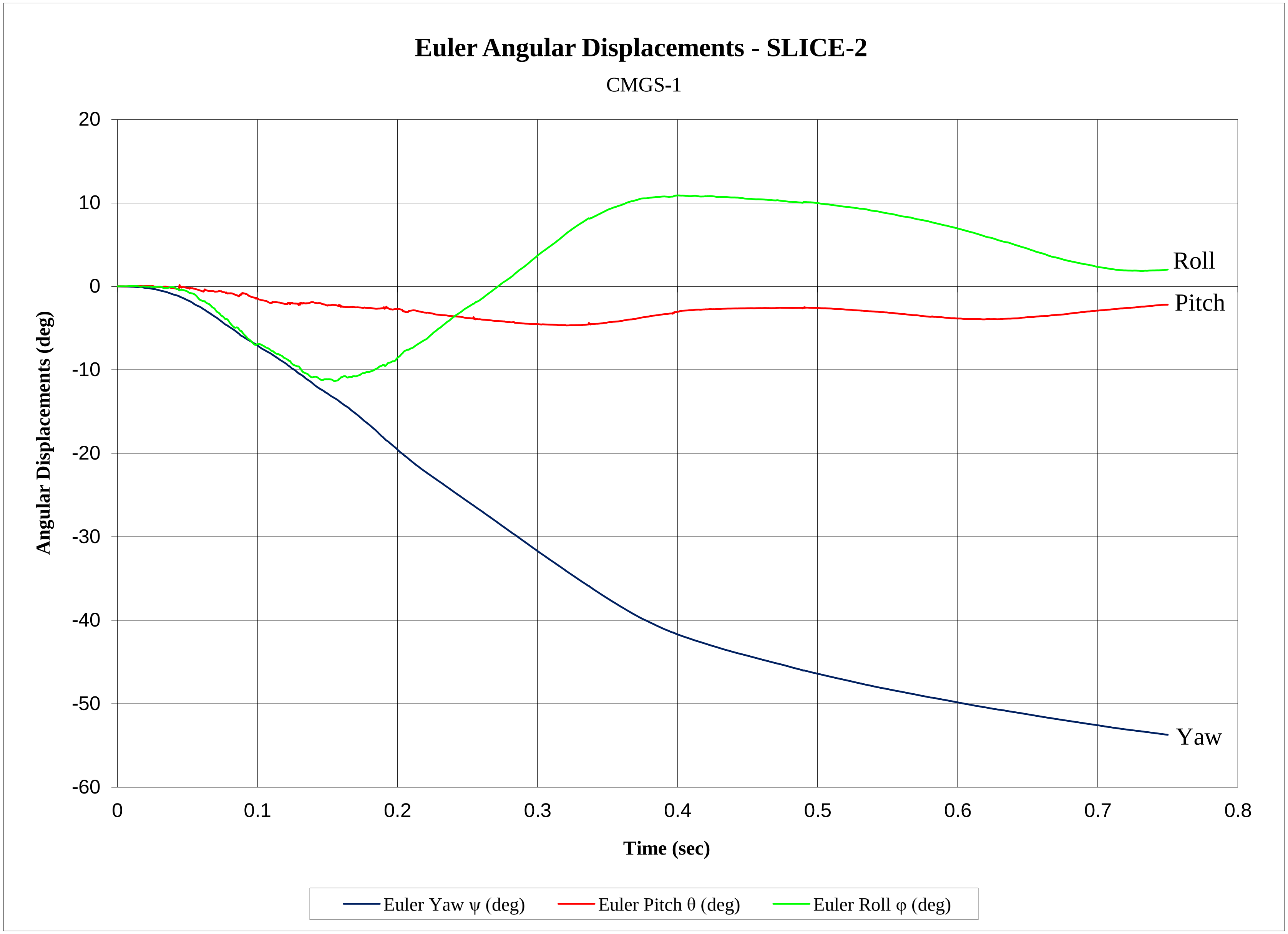


Figure E-15. Vehicle Angular Displacements (SLICE-2), Test No. CMGS-1

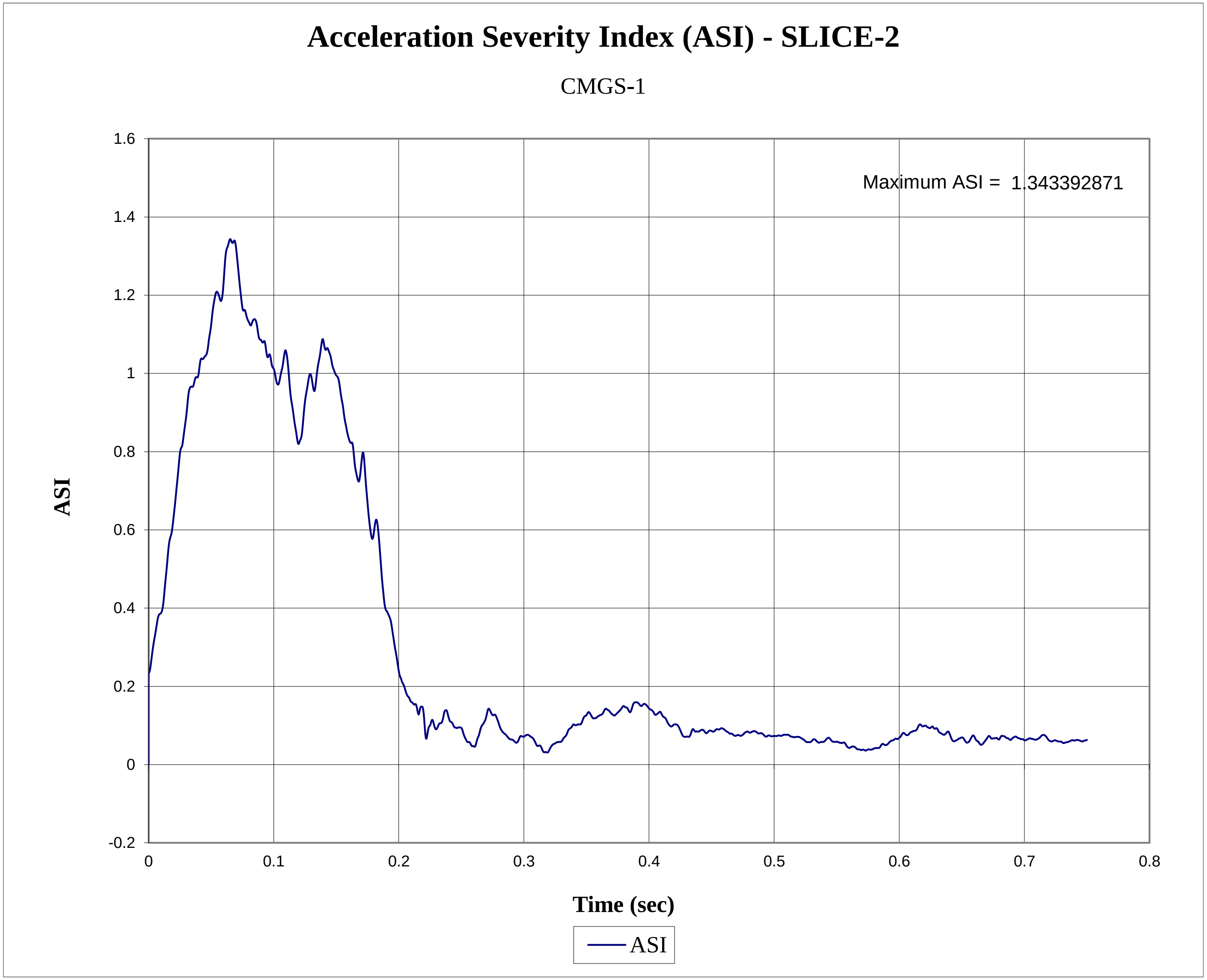


Figure E-16. Acceleration Severity Index (SLICE-2), Test No. CMGS-1

Appendix F. Accelerometer and Rate Transducer Data Plots, Test No. CMGS-2

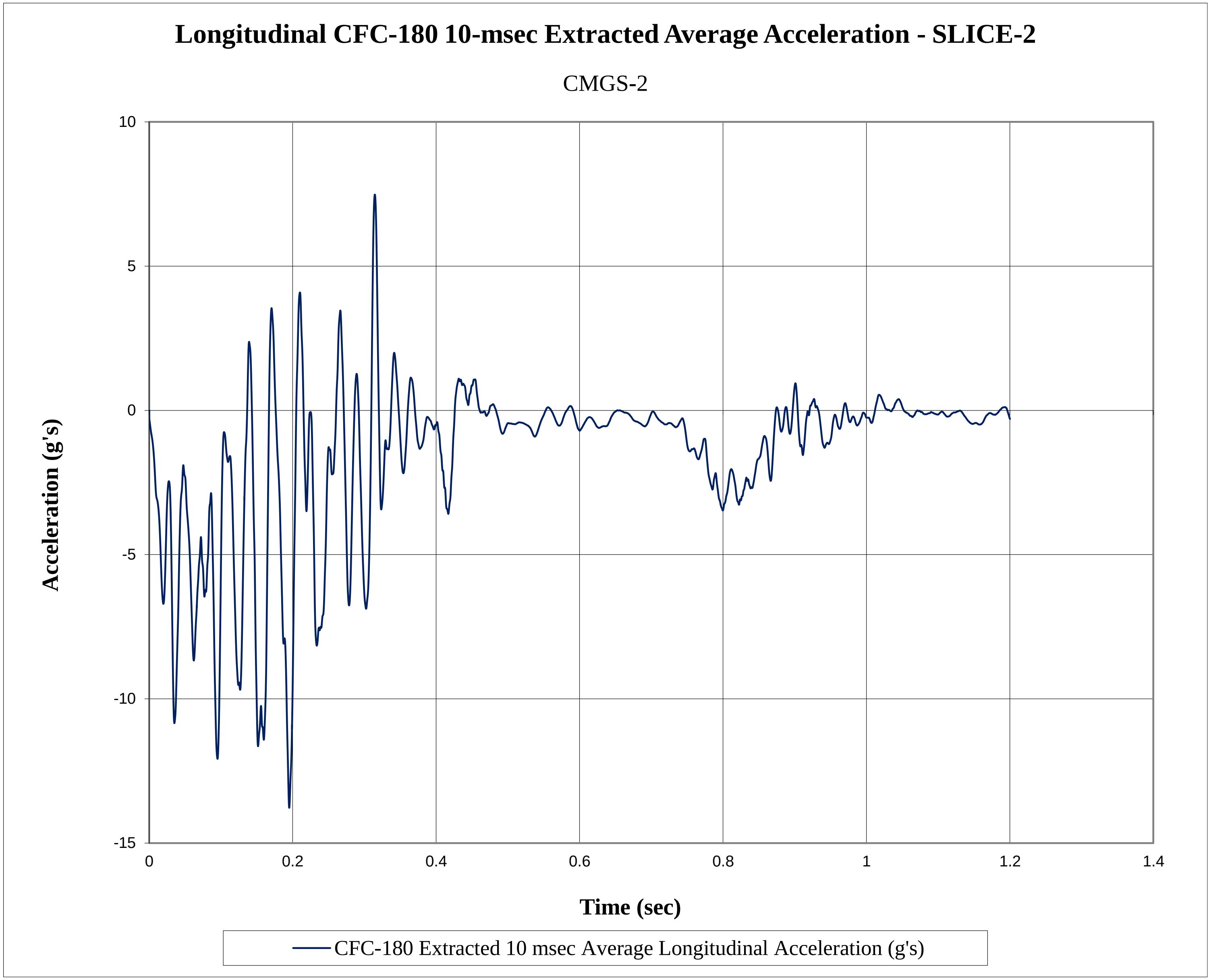


Figure F-1. 10-ms Average Longitudinal Deceleration (SLICE-2), Test No. CMGS-2

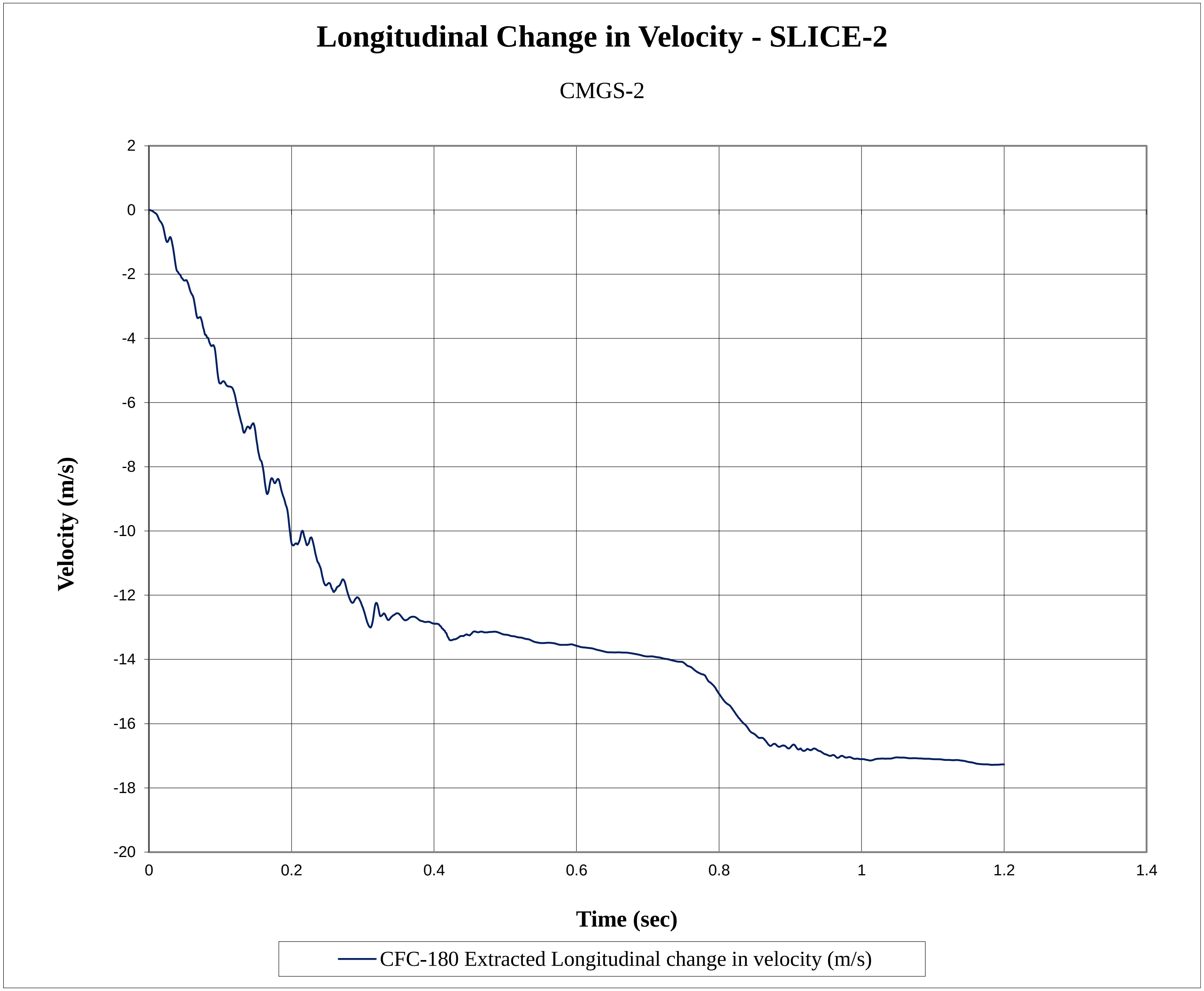


Figure F-2. Longitudinal Change in Velocity (SLICE-2), Test No. CMGS-2

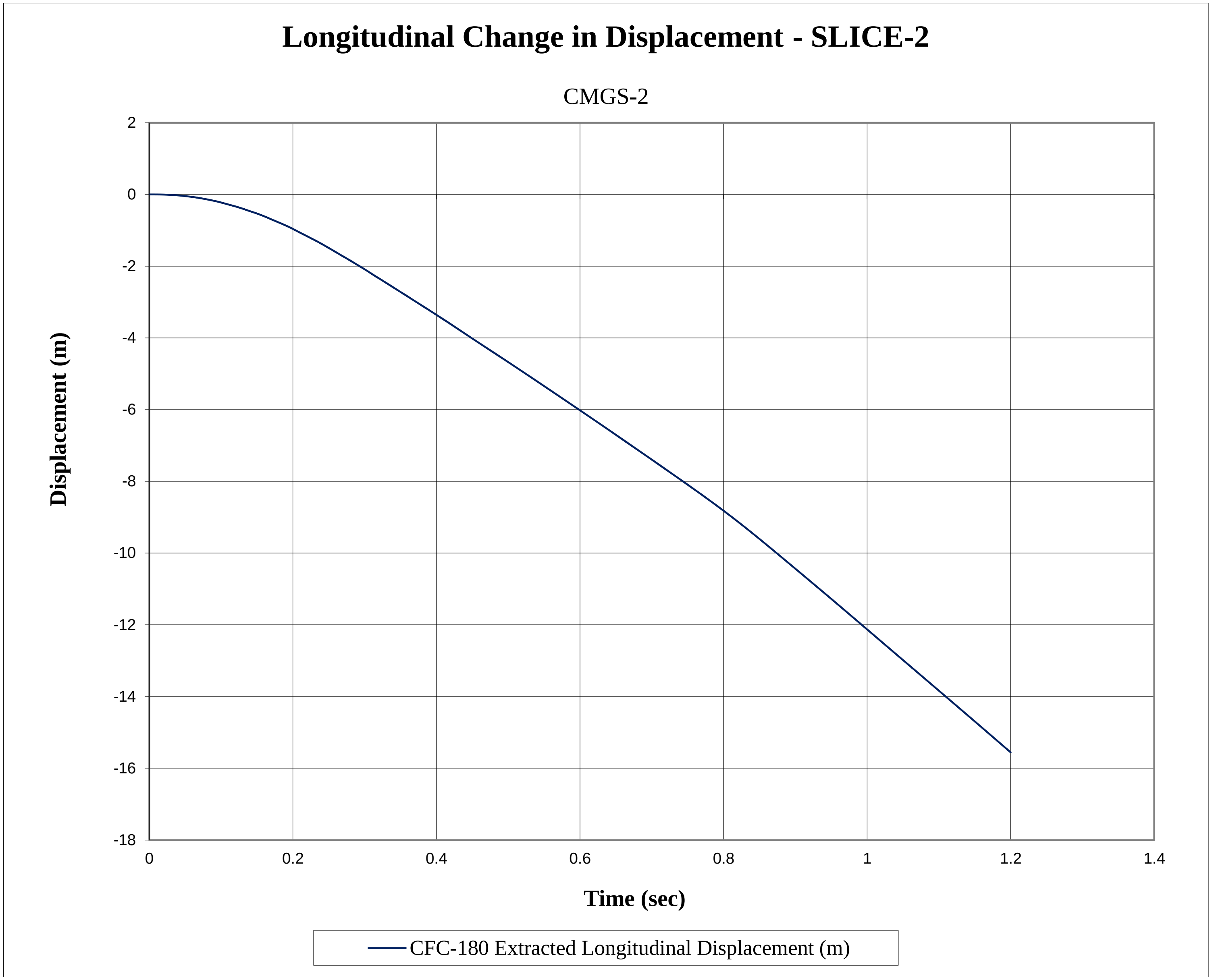


Figure F-3. Longitudinal Change in Displacement (SLICE-2), Test No. CMGS-2

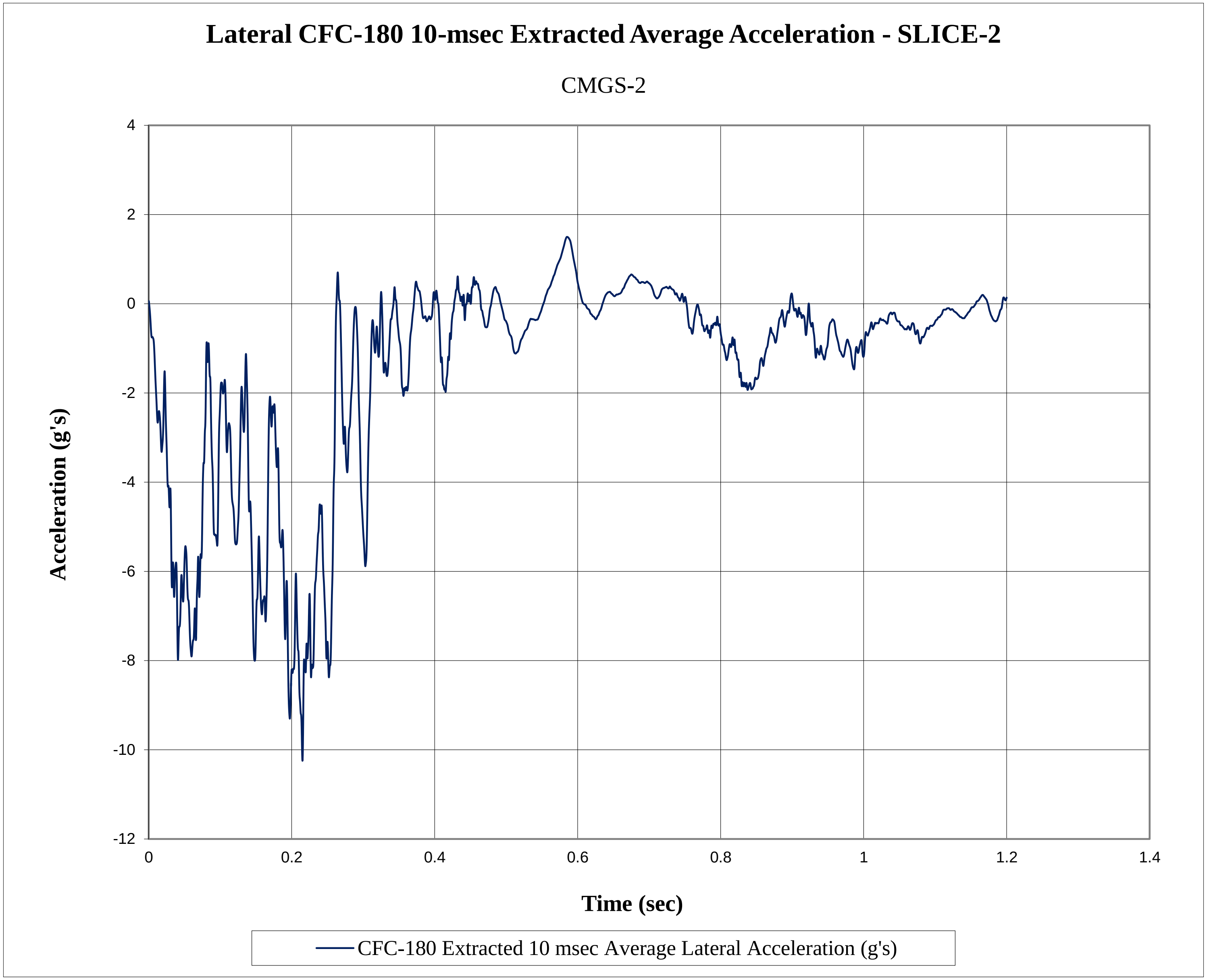


Figure F-4. 10-ms Average Lateral Deceleration (SLICE-2), Test No. CMGS-2

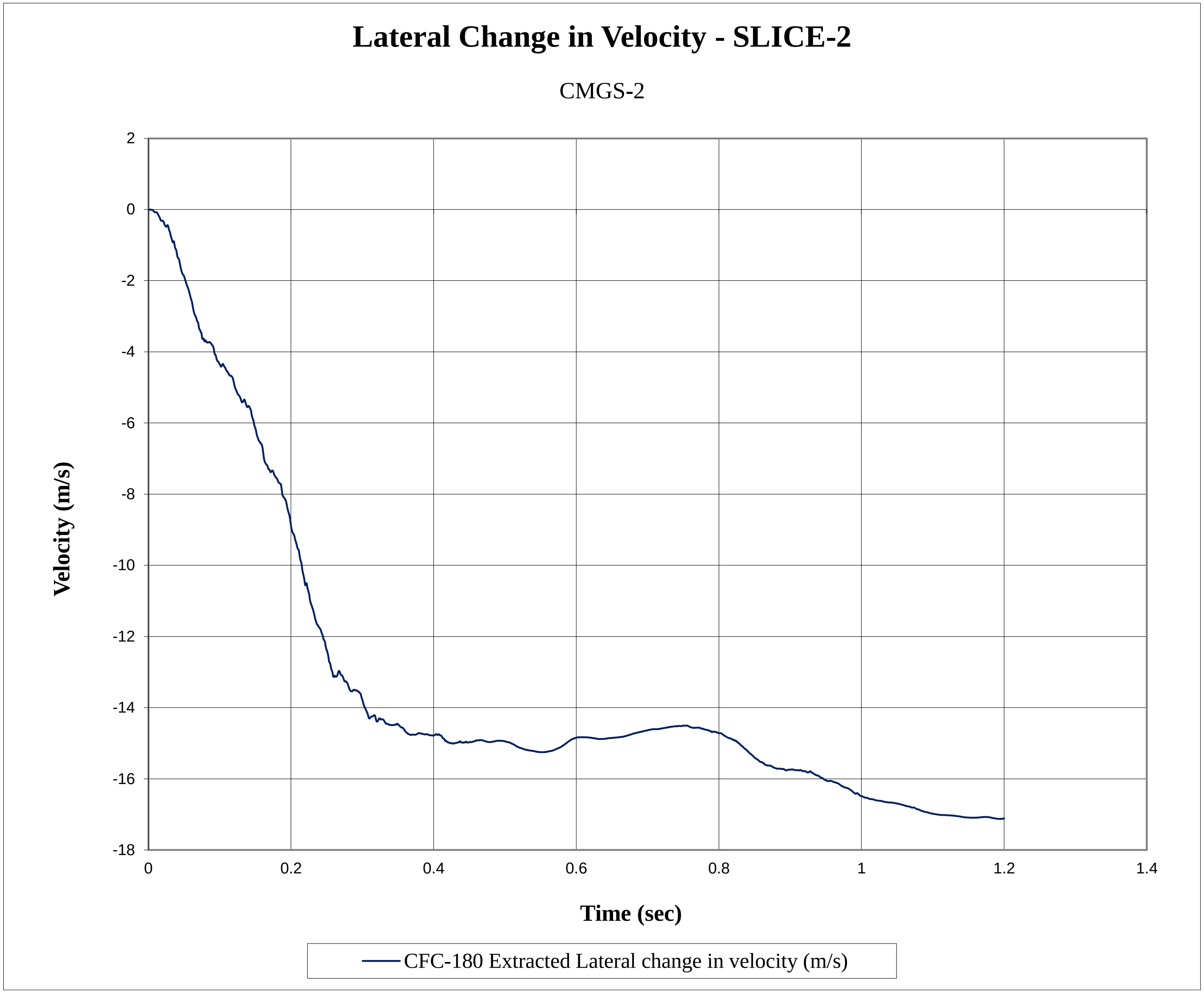


Figure F-5. Lateral Change in Velocity (SLICE-2), Test No. CMGS-2

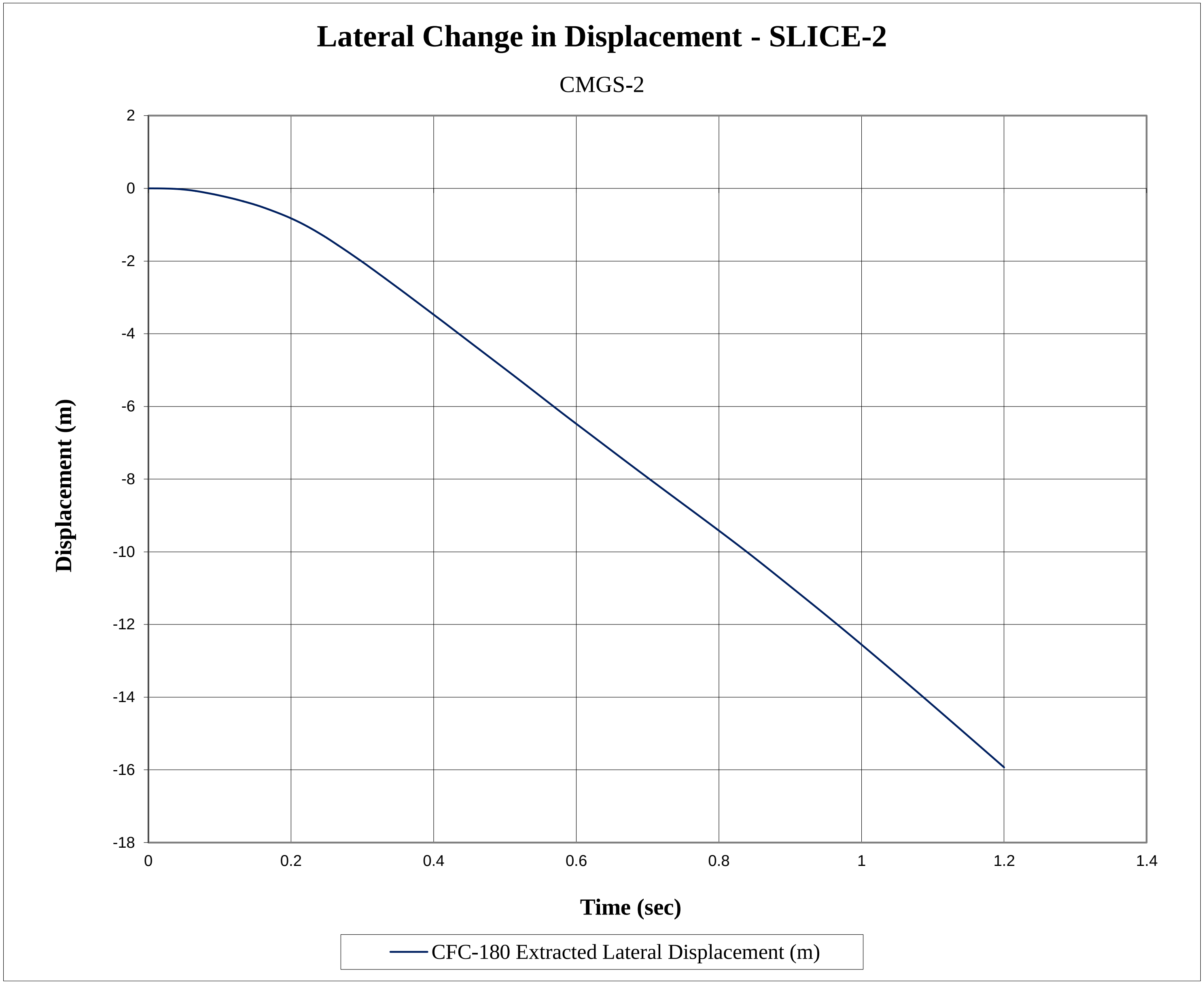


Figure F-6. Lateral Change in Displacement (SLICE-2), Test No. CMGS-2

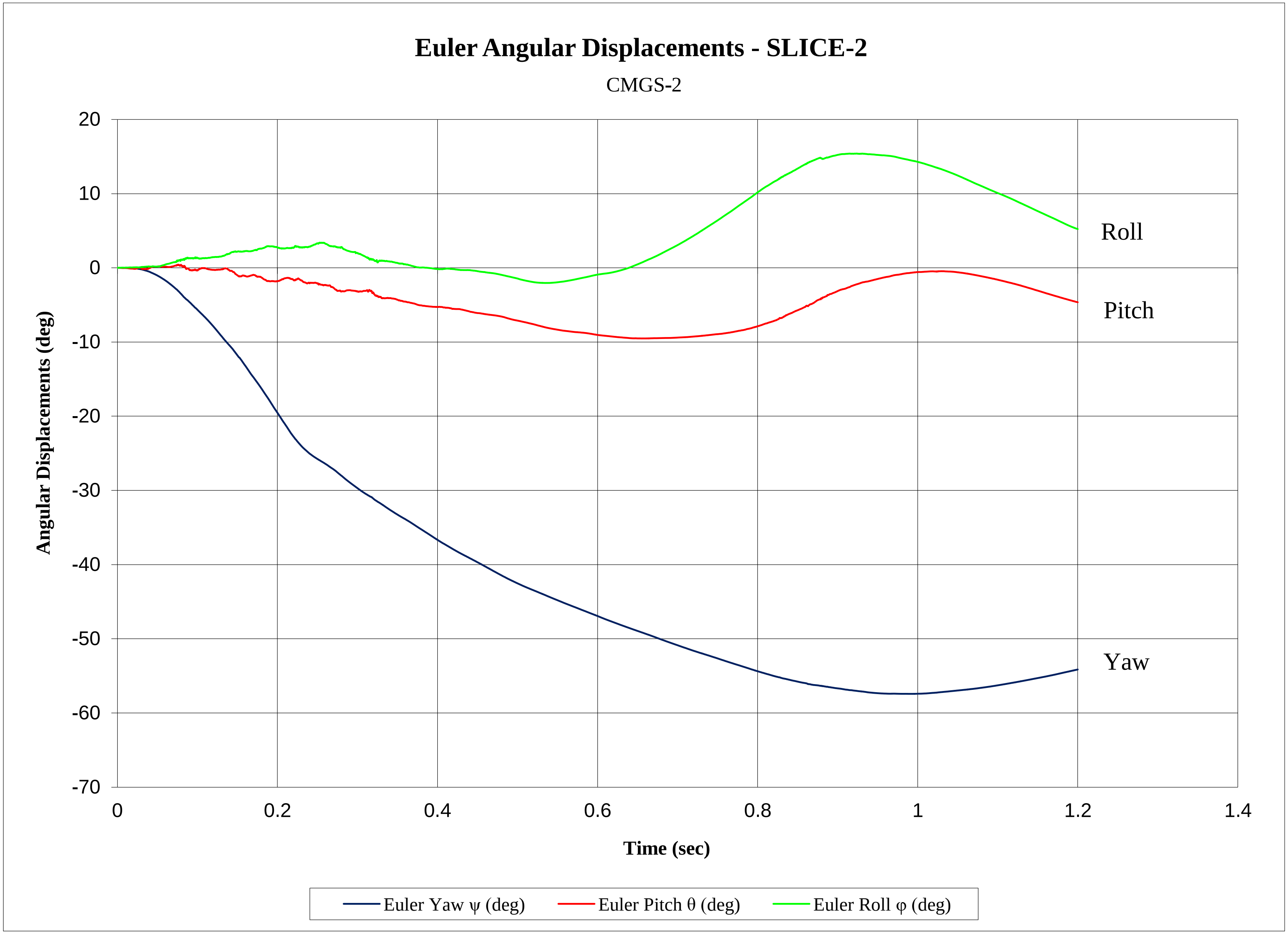


Figure F-7. Vehicle Angular Displacements (SLICE-2), Test No. CMGS-2

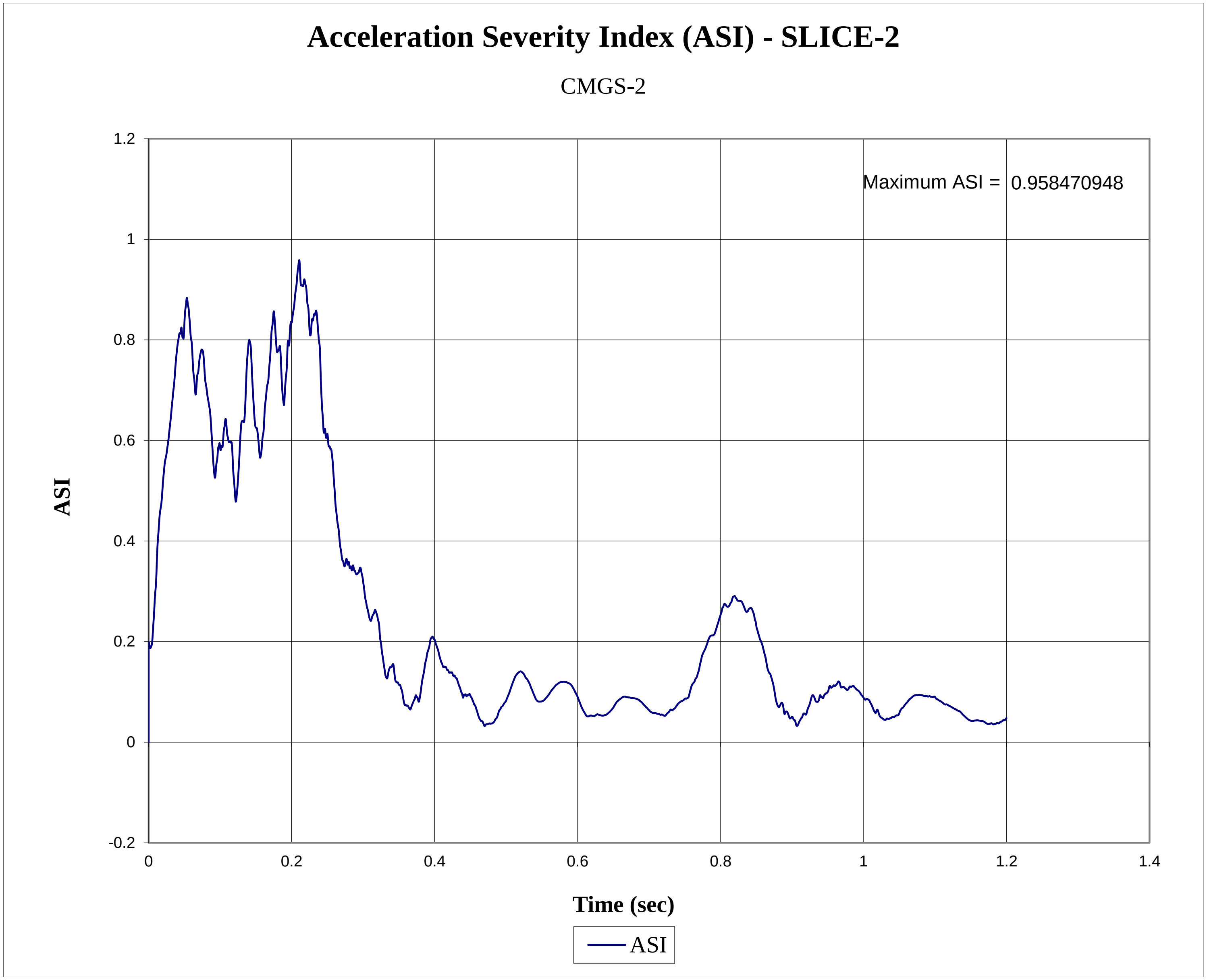


Figure F-8. Acceleration Severity Index (SLICE-2), Test No. CMGS-2

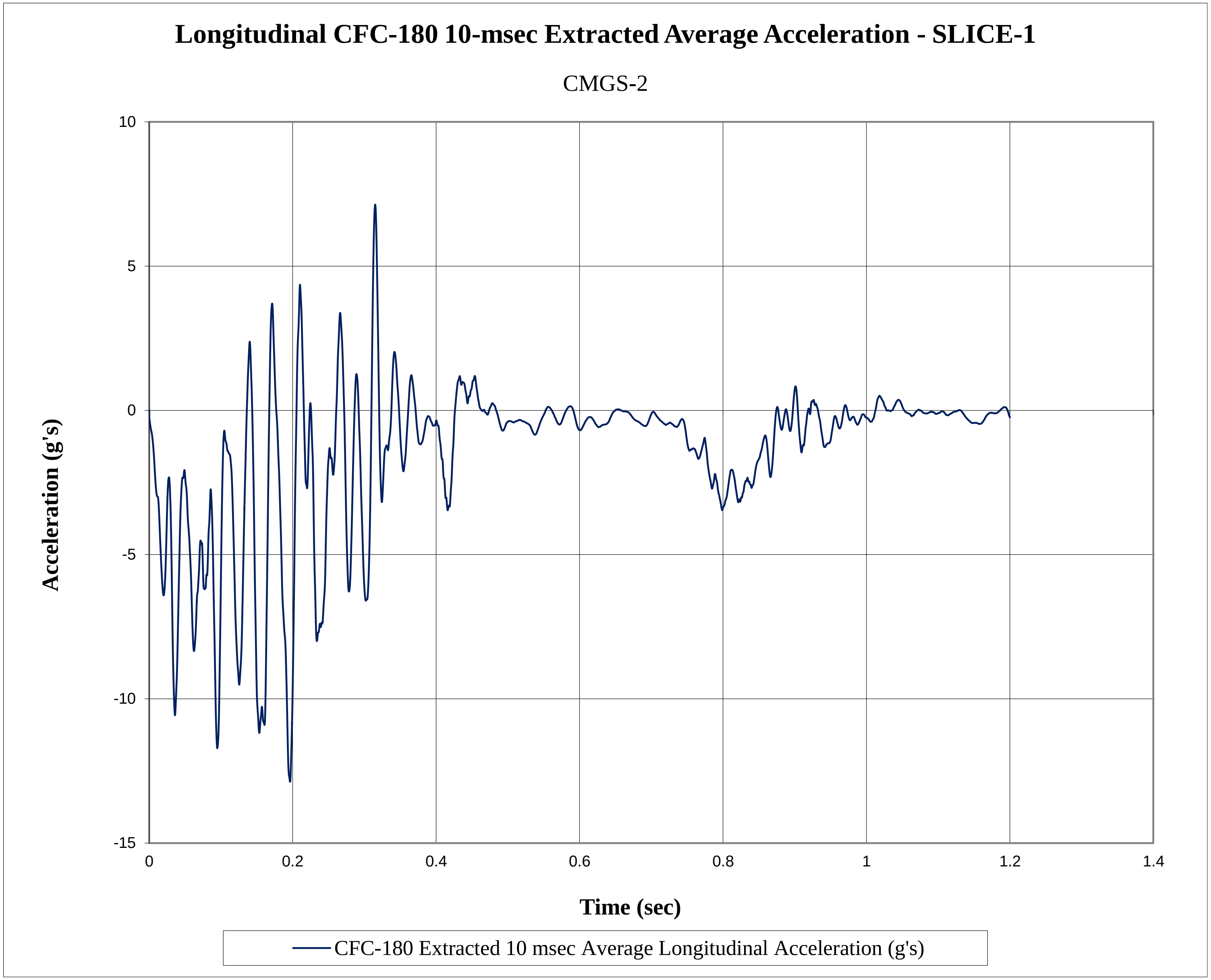


Figure F-9. 10-ms Average Longitudinal Deceleration (SLICE-1), Test No. CMGS-2

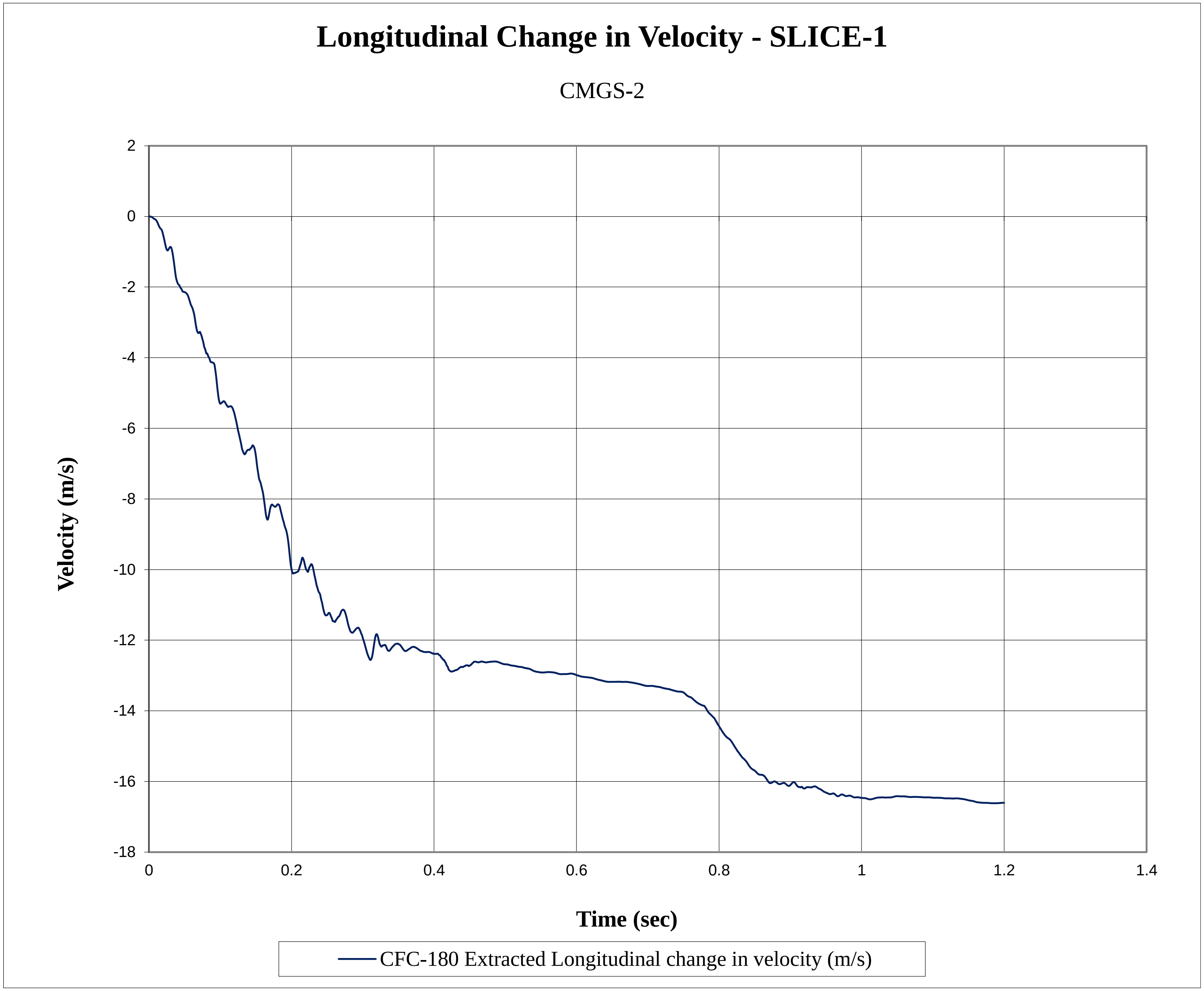


Figure F-10. Longitudinal Change in Velocity (SLICE-1), Test No. CMGS-2

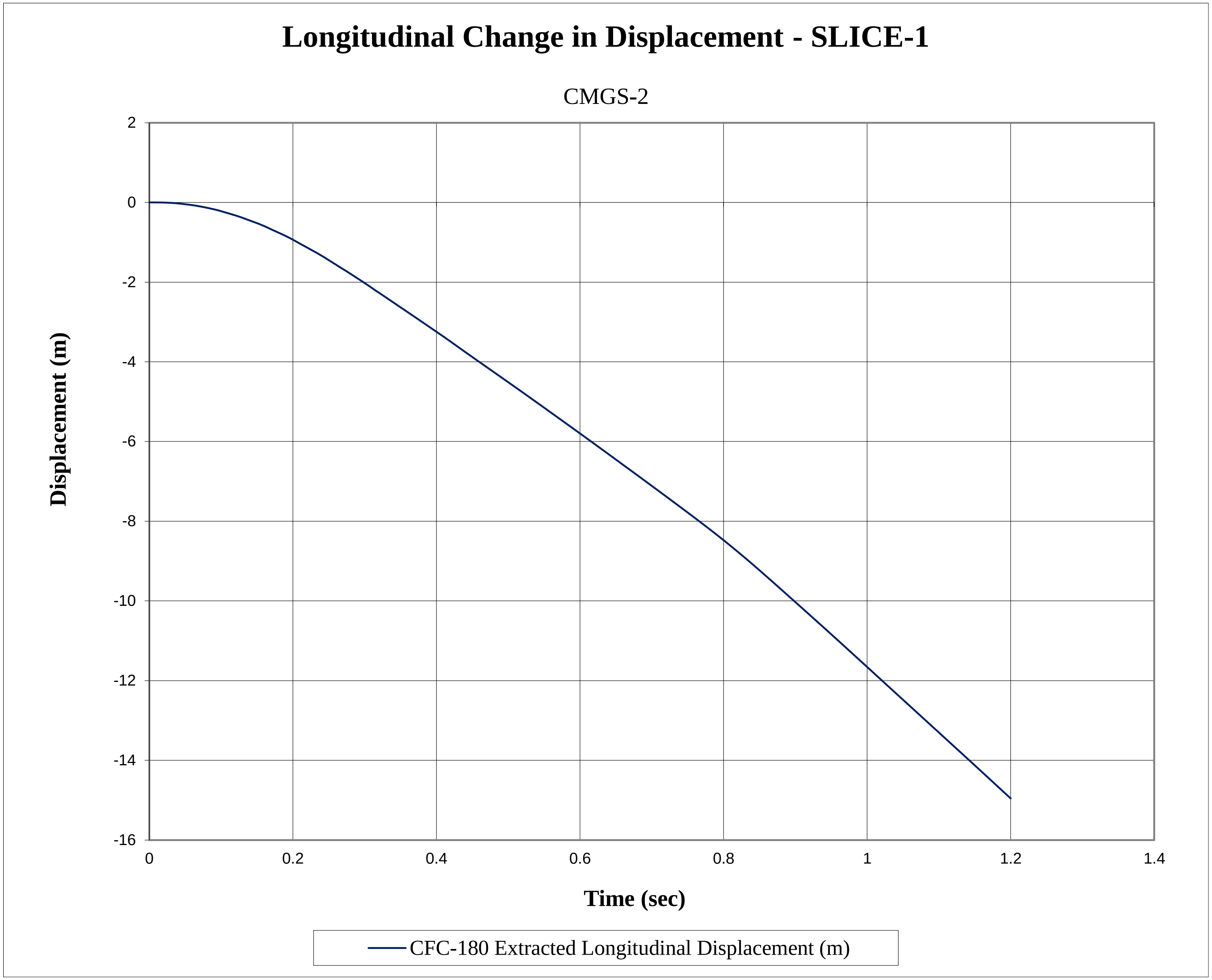


Figure F-11. Longitudinal Change in Displacement (SLICE-1), Test No. CMGS-2

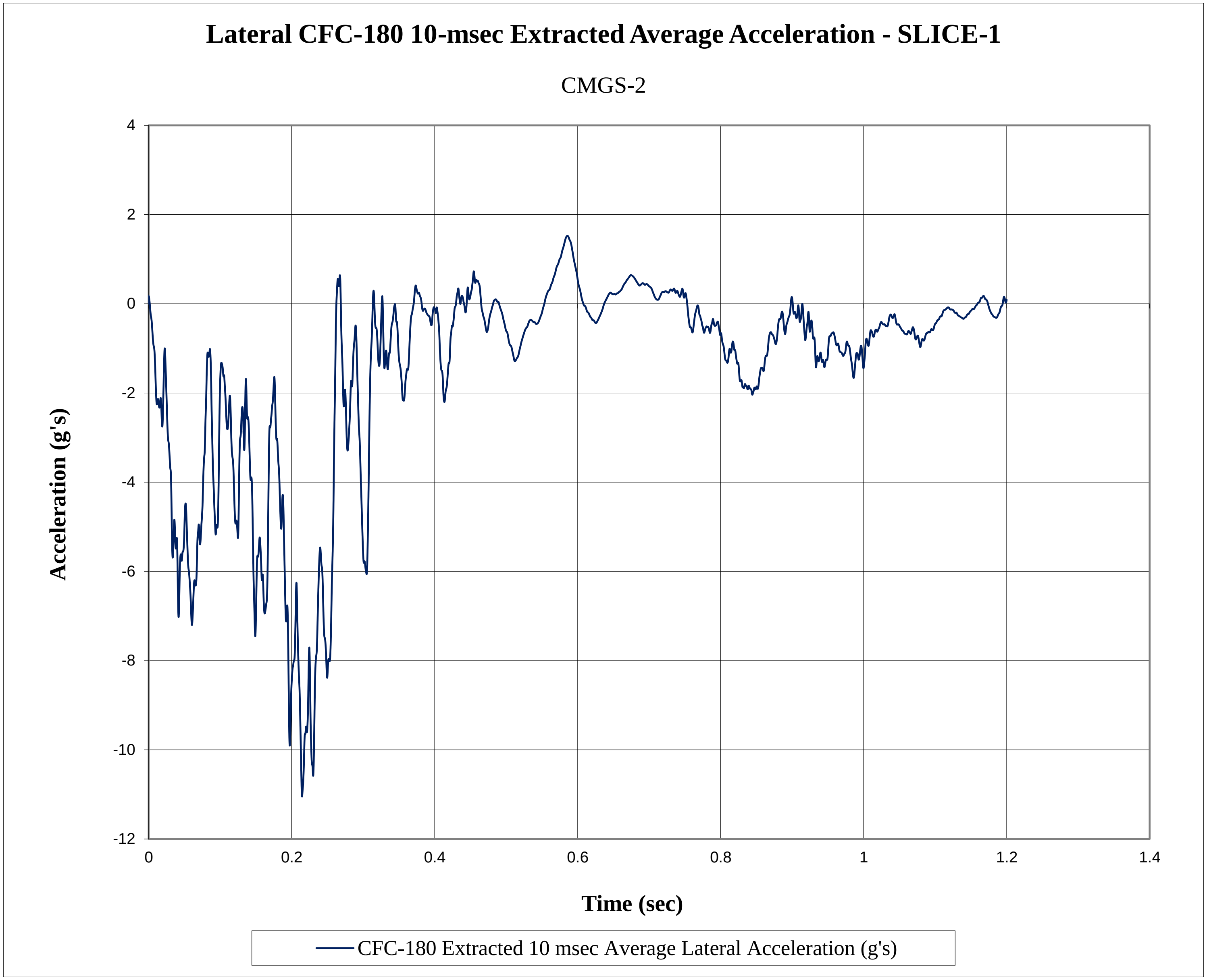


Figure F-12. 10-ms Average Lateral Deceleration (SLICE-1), Test No. CMGS-2

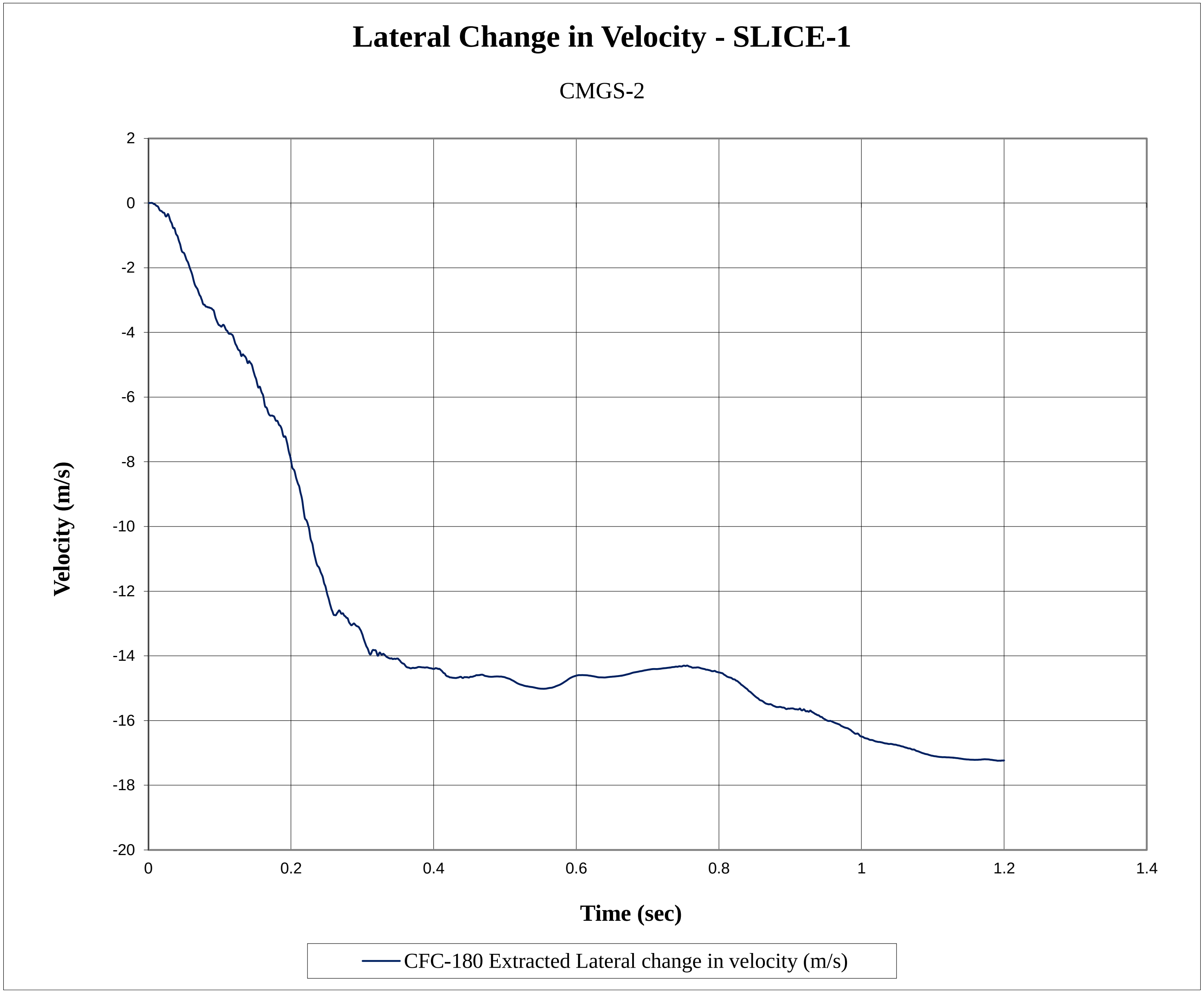


Figure F-13. Lateral Change in Velocity (SLICE-1), Test No. CMGS-2

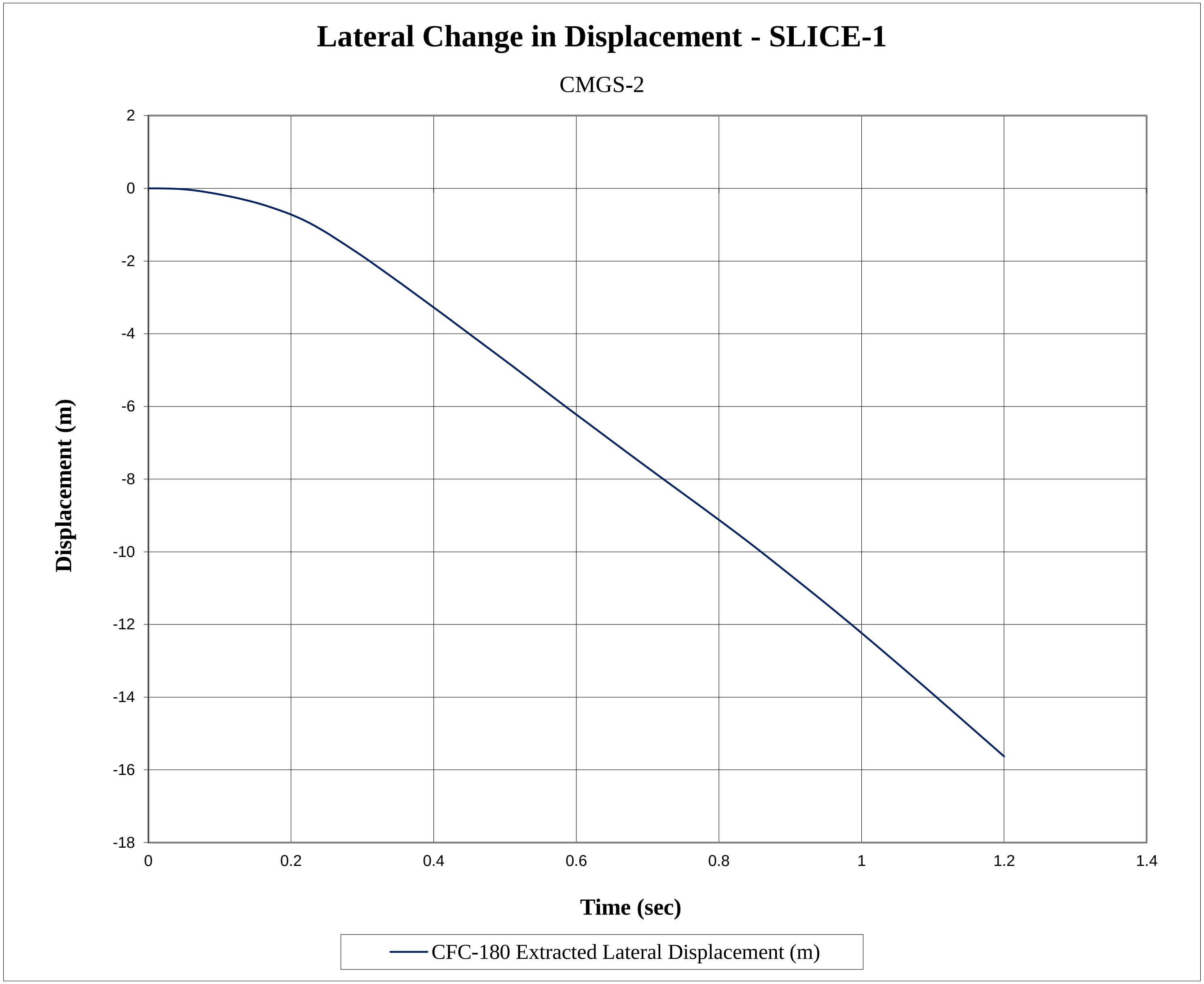


Figure F-14. Lateral Change in Displacement (SLICE-1), Test No. CMGS-2

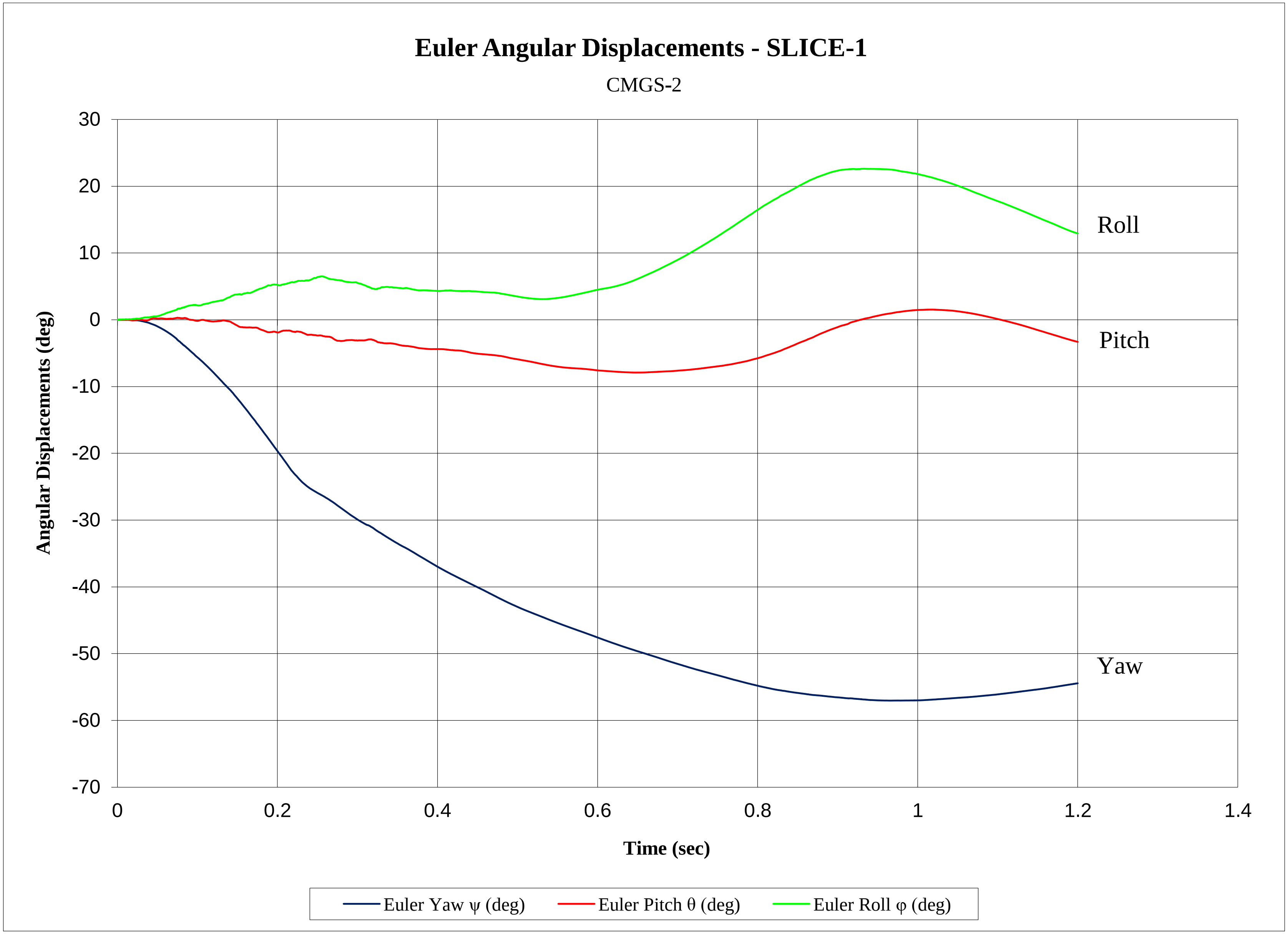


Figure F-15. Vehicle Angular Displacements (SLICE-1), Test No. CMGS-2

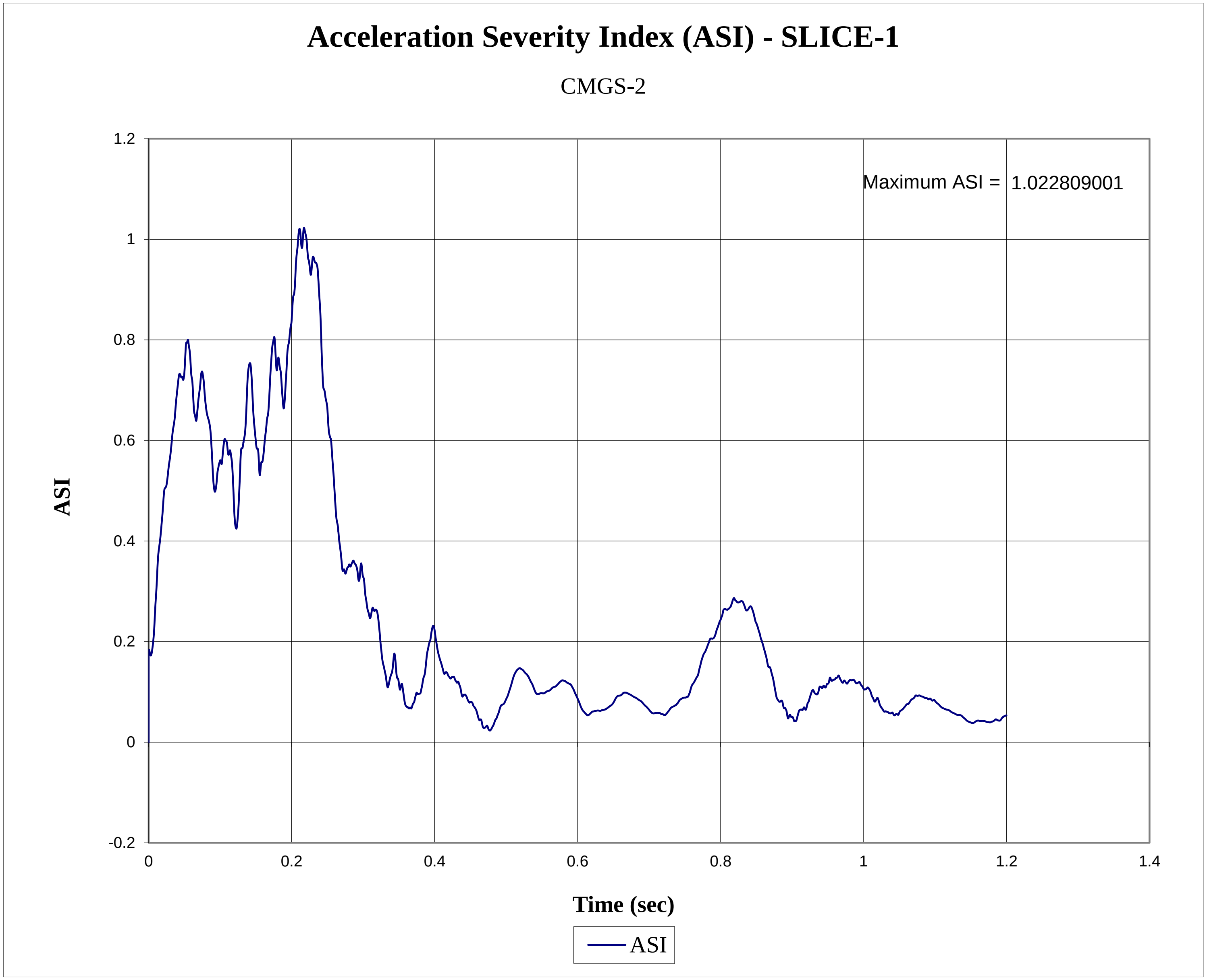


Figure F-16. Acceleration Severity Index (SLICE-1), Test No. CMGS-2

END OF DOCUMENT