Roadside Safety Pooled Fund

Texas A&M Transportation Institute Proving Ground

Test Report No. 614721-01-1&2
Test Report Date: August 2023

DETERMINATION OF LENGTH-OF-NEED FOR GUARDRAIL WITHOUT ANCHORAGE

by

James C. Kovar
Assistant Research Scientist

William Schroeder
Engineering Research Associate

Daniel Curran
Student Technician

and

Heath Buttery
Student Technician

Contract No.: T4541-DZ
Test Nos.: 614721-01-1 and 614271-01-2
Test Dates: 2022-10-26 and 2021-04-06

Sponsored by
Roadside Safety Research Program Pooled Fund
Study No. TPF-5(343)

TEXAS A&M TRANSPORTATION INSTITUTE PROVING GROUND

Mailing Address:
Roadside Safety & Physical Security
Texas A&M University System
3135 TAMU
College Station, TX 77843-3135

Located at:
Texas A&M University System RELLIS Campus
Building 7091
1254 Avenue A
Bryan, TX 77807

ACCREDITED
ISO 17025 Laboratory
Testing Certificate # 2821.01

DISCLAIMER

The contents of this report reflect the views of the authors, who are solely responsible for the facts and accuracy of the data and the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Roadside Safety Pooled Fund Group, Washington State Department of Transportation (WSDOT), The Texas A&M University System, or the Texas A&M Transportation Institute (TTI). This report does not constitute a standard, specification, or regulation. In addition, the above listed agencies/companies assume no liability for its contents or use thereof. The names of specific products or manufacturers listed herein do not imply endorsement of those products or manufacturers.

The results reported herein apply only to the article tested. The full-scale crash tests were performed according to TTI Proving Ground quality procedures and *Manual for Assessing Safety Hardware* guidelines and standards.

The Proving Ground Laboratory within TTI's Roadside Safety and Physical Security Division ("TTI Lab") strives for accuracy and completeness in its crash test reports. On rare occasions, unintentional or inadvertent clerical errors, technical errors, omissions, oversights, or misunderstandings (collectively referred to as "errors") may occur and may not be identified for corrective action prior to the final report being published and issued. If, and when, the TTI Lab discovers an error in a published and issued final report, the TTI Lab will promptly disclose such error to the Roadside Safety Pooled Fund Group, WSDOT, and all parties shall endeavor in good faith to resolve this situation. The TTI Lab will be responsible for correcting the error that occurred in the report, which may be in the form of errata, amendment, replacement sections, or up to and including full reissuance of the report. The cost of correcting an error in the report shall be borne by the TTI Lab. Any such errors or inadvertent delays that occur in connection with the performance of the related testing contract will not constitute a breach of the testing contract.

THE TTI LAB WILL NOT BE LIABLE FOR ANY INDIRECT, CONSEQUENTIAL, PUNITIVE, OR OTHER DAMAGES SUFFERED BY THE ROADSIDE SAFETY POOLED FUND GROUP, WSDOT, OR ANY OTHER PERSON OR ENTITY, WHETHER SUCH LIABILITY IS BASED, OR CLAIMED TO BE BASED, UPON ANY NEGLIGENT ACT, OMISSION, ERROR, CORRECTION OF ERROR, DELAY, OR BREACH OF AN OBLIGATION BY THE TTI LAB.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DETERMINATION OF LENGTH-OF-NEED FOR GUARDRAIL WITHOUT ANCHORAGE		5. Report Date August 2023 6. Performing Organization Code
7. Author(s) James C. Kovar, Daniel Curran, Heath Buttery, William Schroeder, and Bill L. Griffith		8. Performing Organization Report No. Test Report No. 614721-01-1&2
9. Performing Organization Name and Address Texas A&M Transportation Institute Proving Ground 3135 TAMU College Station, Texas 77843-3135		10. Work Unit No. (TRAIS) 11. Contract or Grant No. TPF-5(343)
12. Sponsoring Agency Name and Address Washington State Department of Transportation Research Office MS 47372, Transportation Building Olympia, WA 98504-7372		13. Type of Report and Period Covered Technical Report: September 2019—October 2022 14. Sponsoring Agency Code

15. Supplementary Notes

Project Title: Determination of Length-of-Need for Guardrail without Anchorage
Name of Contacting Representative: Joe Hall, Ted Whitmore, and Donna Hardy

16. Abstract

The objective of this project was to determine the minimum length-of-need of a Midwest Guardrail System (MGS) without downstream anchorage required to provide *MASH* compliant redirective behavior. In pursuit of this objective, the research team performed computer simulations to predict the minimum length-of-need prior to full-scale crash testing. After a crash test which failed to meet project objectives, the research team improved the predictive capability of the simulations by improving the modeling of the guardrail bolt head and rail slot interaction. Following the improved modeling effort, the minimum length-of-need was again predicted through computer simulation. The research team then investigated a reduction in this length-of-need by including guardrail washers on the downstream end posts. This system was then evaluated through full-scale crash testing, but it again failed to meet the project objectives. Consequently, the research team prepared recommendations for future research efforts. This report documents the efforts discussed above and the resulting recommendations for future research.

17. Key Words	18. Distribution Statement		
Longitudinal barrier, W-beam guardrail, guardrail without downstream anchorage, crash testing, roadside safety, *MASH*	Copyrighted. Not to be copied or reprinted without consent from the Roadside Safety Pooled Fund.		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 222	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized.

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

*SI is the symbol for the International System of Units

ACKNOWLEDGEMENTS

This research project was performed under a pooled fund program between the following States and Agencies. The authors acknowledge and appreciate their guidance and assistance.

Roadside Safety Research Pooled Fund Committee
Revised May 2023

ALABAMA

Wade Henry, P.E.
Assistant State Design Engineer
Design Bureau, Final Design Division
Alabama Dept. of Transportation
1409 Coliseum Boulevard, T-205
Montgomery, AL 36110
(334) 242-6464
henryw@dot.state.al.us

Stanley (Stan) C. Biddick, P.E.
State Design Engineer
Design Bureau, Final Design Division
Alabama Dept. of Transportation
1409 Coliseum Boulevard, T-205
Montgomery, AL 36110
(334) 242-6833
biddicks@dot.state.al.us

ALASKA

Mary F. McRae
Design and Construction Standards Engineer
Alaska Depart. of Transportation & Public Facilities
3132 Channel Drive
P.O. Box 112500
Juneau, AK 99811-2500
(907) 465-1222
mary.mcrae@alaska.gov

Cole Carnahan
Design and Construction Standards Engineering Assistant
Alaska Depart. of Transportation & Public Facilities
3132 Channel Drive
P.O. Box 112500
Juneau, AK 99811-2500
(907) 465-6955
cole.carnahan@alaska.gov

CALIFORNIA

Bob Meline, P.E.
Caltrans
Office of Materials and Infrastructure
Division of Research and Innovation
5900 Folsom Blvd
Sacramento, CA 95819
(916) 227-7031
Bob.Meline@dot.ca.gov

John Jewell, P.E.
Senior Crash Testing Engineer
Office of Safety Innovation & Cooperative Research
(916) 227-5824
John_Jewell@dot.ca.gov

COLORADO

Andy Pott, P.E.
Senior Bridge Design and Construction Engineer
Division of Project Support, Staff Bridge Design and Construction Management
Colorado Dept. of Transportation (CDOT)
4201 E Arkansas Ave, 4th Floor
Denver, CO 80222
303-512-4020
andrew.pott@state.co.us

Shawn Yu, P.E.
Miscellaneous (M) Standards and Specifications Unit Manager
Division of Project Support, Construction Engineering Services (CES) Branch
Colorado Dept. of Transportation (CDOT)
4201 E Arkansas Ave, 4th Floor
Denver, CO 80222
303-757-9474
shawn.yu@state.co.us

David Kosmiski, P.E.
Miscellaneous (M) Standards Engineer
Division of Project Support, Construction Engineering Services (CES) Branch
Colorado Dept. of Transportation (CDOT)
4201 E Arkansas Ave, 4th Floor
Denver, CO 80222
303-757-9021
david.kosmiski@state.co.us

Amin Fakhimalizad
Assistant Miscellaneous (M) Standards Engineer
Division of Project Support, Construction Engineering Services (CES) Branch
Colorado Dept. of Transportation (CDOT)
303-757-9229
amin.fakhimalizad@state.co.us

CONNECTICUT

David Kilpatrick
State of Connecticut Depart. of Transportation
2800 Berlin Turnpike
Newington, CT 06131-7546
(806) 594-3288
David.Kilpatrick@ct.gov

DELAWARE

Craig Blowers
Construction Resource Engineer
Construction Section
Delaware DOT
(302)760-2336
Craig.Blowers@delaware.gov

James Osborne
Traffic Safety Programs Manager
Traffic Operations
Delaware DOT
(302)659-4651
James.Osborne@delaware.gov

FLORIDA

Richard Stepp
Florida Department of Transportation
Richard.Stepp@dot.state.fl.us

Derwood C. Sheppard, Jr., P.E.
State Roadway Design Engineer
Florida Depart. of Transportation
Roadway Design Office
605 Suwannee Street, MS-32
Tallahassee, FL 32399-0450
(850) 414-4334
Derwood.Sheppard@dot.state.fl.us

IDAHO

Marc Danley, P.E.
Technical Engineer
(208) 334-8558
Marc.danley@itd.idaho.gov

Kevin Sablan
Design/Traffic Engineer
Idaho Transportation Department
(208) 334-8558
Kevin.sablan@itd.idaho.gov

ILLINOIS

Martha A. Brown, P.E.
Safety Design Bureau Chief
Bureau of Safety Programs and Engineering
Illinois Depart. of Transportation
2300 Dirksen Parkway, Room 005
Springfield, IL 62764
(217) 785-3034
Martha.A.Brown@illinois.gov

Edgar Galofre
Safety Design Engineer
(217) 558-9089
edgar.glofre@illinois.gov

IOWA

Daniel Harness
Office of Design – Methods
Iowa Department of Transportation
Daniel.Harness@iowadot.us

Chris Poole
State Traffic Engineer
Traffic and Safety Bureau
Iowa Department of Transportation
Chris.Poole@iowadot.us

LOUISIANA

Chris Guidry
Bridge Manager
Louisiana Transportation Center
Bridge & Structural Design Section
P.O. Box 94245
Baton Rouge, LA 79084-9245
(225) 379-1933
Chris.Guidry@la.gov

Carl Gaudry
Bridge Design Manager
Bridge & Structural Design Section
Louisiana Department of Transportation & Development
Carl.Gaudry@la.gov

MARYLAND

Matamba Kabengele
Traffic Engineer
Office of Traffic and Safety
Maryland State Highway Administration
MKabengele@mdot.maryland.gov

MASSACHUSETTS

Alex Bardow
Director of Bridges and Structure
Massachusetts Depart. of Transportation
10 Park Plaza, Room 6430
Boston, MA 02116
(517) 335-9430
Alexander.Bardow@state.ma.us

James Danila
State Traffic Engineer
(857) 368-9640
James.danilla@state.ma.us

MICHIGAN

Carlos Torres, P.E.
Crash Barrier Engineer
Geometric Design Unit, Design Division
Michigan Depart. of Transportation
P. O. Box 30050
Lansing, MI 48909
(517) 335-2852
TorresC@michigan.gov

MINNESOTA

Khamsai Yang
Design Standards Engineer
Office of Project Management and Technical Support
(651) 366-4622
Khamsai.Yang@state.mn.us

Brian Tang
Assistant Design Standards Engineer
Office of Project Management and Technical Support
Minnesota Department of Transportation
(651) 366-4684
brian.tang@state.mn.us

MISSOURI

Sarah Kleinschmit, P.E.
Policy and Innovations Engineer,
Missouri Department of Transportation
P.O. Box 270
Jefferson City, MO 65102
(573) 751-7412
sarah.kleinschmit@modot.mo.gov

Kaitlyn (Katy) Bower
Roadside Design Specialist
Missouri Department of Transportation
573-472-9028
kaitlyn.bower@modot.mo.gov

NEW MEXICO

Brad Julian
Traffic Technical Support Engineer
(505) 827-3263
Brad.Julian@state.nm.us

OHIO

Don P. Fisher, P.E.
Ohio Depart. of Transportation
1980 West Broad Street
Mail Stop 1230
Columbus, OH 43223
(614) 387-6214
Don.fisher@dot.ohio.gov

OREGON

Christopher Henson
Senior Roadside Design Engineer
Oregon Depart. of Transportation
Technical Service Branch
4040 Fairview Industrial Drive, SE
Salem, OR 97302-1142
(503) 986-3561
Christopher.S.Henson@odot.state.or.us

PENNSYLVANIA

James A. Borino, Jr., P.E.
Chief, Standards and Criteria Unit
Highway Design and Technology Division
Pennsylvania DOT
(717) 612-4791
jborino@pa.gov

Evan Pursel
Senior Civil Engineer
Highway Design and Technology Division
Pennsylvania DOT
(717) 705-8535
epursel@pa.gov

Nina Ertel
Project Development Engineer
Highway Design and Technology Division
Pennsylvania DOT
(717) 425-7679
nertel@pa.gov

TEXAS

Chris Lindsey
Transportation Engineer
Design Division
Texas Department of Transportation
125 East 11th Street
Austin, TX 78701-2483
(512) 416-2750
Christopher.Lindsey@txdot.gov

Taya Retterer
TxDOT Bridge Standards Engineer
Bridge Division
Texas Department of Transportation
(512) 416-2719
Taya.Retterer@txdot.gov

UTAH

Shawn Debenham
Traffic and Safety Division
Utah Depart. of Transportation
4501 South 2700 West
PO Box 143200
Salt Lake City UT 84114-3200
(801) 965-4590
sdebenham@utah.gov

WASHINGTON

Mustafa Mohamedali
Assistant Research Project Manager
P.O. Box 47372
Olympia, WA 98504-7372
(360) 704-6307
mohamem@wsdot.wa.gov

Tim Moeckel
Roadside Safety Engineer
Washington State Department of
Transportation
Development Division
P.O. Box 47329
Olympia, WA 98504-7246
(360) 704-6377
moecket@wsdot.wa.gov

WEST VIRGINIA

Donna J. Hardy, P.E.
Safety Programs Engineer
West Virginia Depart. of
Transportation – Traffic Engineering
Building 5, Room A-550
1900 Kanawha Blvd E.
Charleston, WV 25305-0430
(304) 558-9576
Donna.J.Hardy@wv.gov

Ted Whitmore
Traffic Services Engineer
Traffic Engineering
WV Division of Highways
(304)414-7373
Ted.J.Whitmore@wv.gov

WISCONSIN

Erik Emerson, P.E.
Standards Development Engineer –
Roadside Design
Wisconsin Department of Transportation
Bureau of Project Development
4802 Sheboygan Avenue, Room 651
P. O. Box 7916
Madison, WI 53707-7916
(608) 266-2842
Erik.Emerson@wi.gov

CANADA – ONTARIO

Kenneth Shannon, P. Eng.
Senior Engineer, Highway Design (A)
Ontario Ministry of Transportation
301 St. Paul Street
St. Catharines, ON L2R 7R4
CANADA
(904) 704-3106
Kenneth.Shannon@ontario.ca

FEDERAL HIGHWAY ADMINISTRATION (FHWA)

WebSite: safety.fhwa.dot.gov

Richard B. (Dick) Albin, P.E.
Safety Engineer
FHWA Resource Center Safety & Design
Technical Services Team
711 S. Capital
Olympia, WA 98501
(303) 550-8804
Dick.Albin@dot.gov

Eduardo Arispe
Research Highway Safety Specialist
U.S. Department of Transportation
Federal Highway Administration
Turner-Fairbank Highway Research Center
Mail Code: HRDS-10
6300 Georgetown Pike
McLean, VA 22101
(202) 493-3291
Eduardo.arispe@dot.gov

Christine Black
Highway Safety Engineer
Central Federal Lands Highway Division
12300 West Dakota Ave.
Lakewood, CO 80228
(720) 963-3662
Christine.black@dot.gov

Isbel Ramos-Reyes
Lead Safety and Transportation Operations Engineer
(703) 948-1442
isbel.ramos-reyes@dot.gov

Matt Hinshaw, M.S., P.E.
Highway Safety Engineer
Central Federal Lands Highway Division
(360)619-7677
matthew.hinshaw@dot.gov

TEXAS A&M TRANSPORTATION INSTITUTE (TTI)

WebSite: tti.tamu.edu
www.roadsidepooledfund.org

D. Lance Bullard, Jr., P.E.
Senior Research Engineer
Roadside Safety & Physical Security Div.
Texas A&M Transportation Institute
3135 TAMU
College Station, TX 77843-3135
(979) 317-2855
L-Bullard@tti.tamu.edu

Roger P. Bligh, Ph.D., P.E.
Senior Research Engineer
(979) 317-2703
R-Bligh@tti.tamu.edu

Nauman Sheikh
Research Scientist
Roadside Safety and Physical Security
Texas A&M Transportation Institute
n-sheikh@tti.tamu.edu

Ariel Sheil
Research Assistant
Roadside Safety and Physical Security
Texas A&M Transportation Institute
A-Sheil@tti.tamu.edu

REPORT AUTHORIZATION

REPORT REVIEWED BY:

DocuSigned by:
Glenn Schroeder
E692F9CB5047487...

Glenn Schroeder, Research Specialist
Drafting & Reporting

DocuSigned by:
Ken Reeves
60D556935596468...

Ken Reeves, Research Specialist
Electronics Instrumentation

DocuSigned by:
Adam Mayer
F7A06F754E02430...

Adam Mayer, Research Specialist
Construction

DocuSigned by:
Richard Badillo
0F51DA60AB144F9...

Richard Badillo, Research Specialist
Photographic Instrumentation

DocuSigned by:
Robert Kocman
6CF2C47B60EB409...

Robert Kocman, Research Specialist
Mechanical Instrumentation

DocuSigned by:
25F29E1BAD624E8...

William J. L. Schroeder, Research Engineering Associate
Research Evaluation and Reporting

DocuSigned by:
Bill Griffith
44A122CB271845B...

Bill L. Griffith, Research Specialist
Quality Manager

DocuSigned by:
Matt Robinson
EAA22BFA5BFD417...

Matthew N. Robinson, Research Specialist
Test Facility Manager & Technical Manager

DocuSigned by:
James Kovar
4204176432C64A8...

James C. Kovar
Assistant Research Scientist

This page intentionally left blank.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

This page intentionally left blank.

CHAPTER 1. INTRODUCTION

Typical Midwest Guardrail Systems (MGS) are anchored at both ends with a termination that is designed to resist the tensile load caused by vehicular impacts. Certain situations may dictate a guardrail system be left without this termination hardware at one end. This most frequently occurs during a construction or repair phase when there is a temporary interruption in work prior to the installation of one termination. Since both anchors have not been installed in these situations, the posts in the guardrail system must successfully resist the tensile load caused by the impact. Therefore, the guardrail system will need to be of sufficient length to successfully resist this impact loading.

The primary objective of this study is to determine the minimum required length of guardrail installation which does not have anchorage at the downstream end but still provides redirective behavior. This system must maintain connectivity between the w-beam rail and the most downstream post. This would promote the ability of the guardrail system to successfully redirect vehicles during impact.

This report documents the test installations, the computer simulation effort, the crash test results, and the performance assessment of the guardrail without downstream anchorage for Manual for Assessing Safety Hardware (*1*) *MASH* Test 3-11 evaluation criteria.

This page intentionally left blank.

CHAPTER 2. COMPUTER SIMULATION EFFORT EVALUATING MINIMUM LENGTH-OF-NEED

2.1. INTRODUCTION

A finite element analysis (FEA) model was developed to replicate the test installation used by the Midwest Roadside Safety Facility (MwRSF) in test number 2214MG-2 (*2*). This test article consisted of a 175-ft long installation of w-beam guardrail. The top of rail was positioned at 31-inches above grade. The splices between rail sections were located at midspan between posts. The W6x9 posts were embedded 40-inches below grade.

The model developed in this computer simulation effort replicated the conditions stated above, with the exception of the installation length. The guardrail system was modeled as 162.5-ft, instead of 175-ft due to the specific modeling technique used to represent the end terminations in full-scale testing. Instead of explicitly modeling the end terminations, the researchers used spring elements to provide the tensile resistance. These spring elements have been used in previous simulation efforts and have been verified as reasonably representing the tensile load resistance exhibited in full-scale testing. With the spring elements, the length of guardrail was shortened to represent that of the guardrail evaluated in the crash test, excluding the end terminations. Figure 2.1 shows an overhead view of the FEA model of the guardrail installation. The initial simulations were intended to verify the predictive performance of the FEA models using the data collected during the MwRSF Crash Test 2214MG-2. The vehicle models utilized in the simulation efforts were originally developed by George Mason University through the Center for Collision Safety and Analysis, later refined by TTI researchers, and successfully implemented in previous simulation efforts.

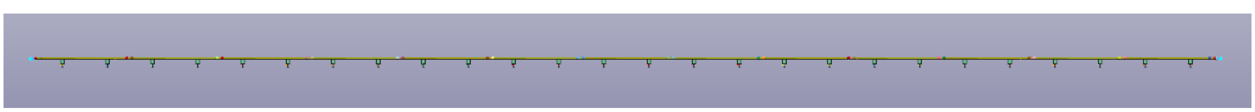


Figure 2.1 Overhead View of 162.5-ft Long Guardrail System

The system was evaluated using a computer simulated MASH Test 3-11 (*3*). The 2270P MASH pickup truck impacted the guardrail system at 62.94 mi/h with an impact angle of 25.5˚, which matched the impact conditions in MwRSF Test 2214MG-2. The impact point was 104-ft from the downstream end of the rail and is shown below in Figure 2.2.

Figure 2.2. Overhead View of Impact Point for 162.5-ft Long Guardrail System Simulation

The system reasonably predicted the performance of the guardrail system evaluated in MwRSF Test 2214MG-2. Figure 2.3 and Figure 2.4 show a comparison of the sequential images from both the computer simulation and the physical crash test. The researchers further confirmed the predictive performance of the individual model components in other research projects for the Roadside Safety Pooled Fund, including the *Testing of Midwest Guardrail Systems with Reduced Post Spacing for MASH Compliance* and the *Design and Testing of a MASH TL-3 Thrie-Beam System for Roadside and Median Applications.* These projects utilized components from this model and were compared against various crash tests to ensure adequate predictive performance.

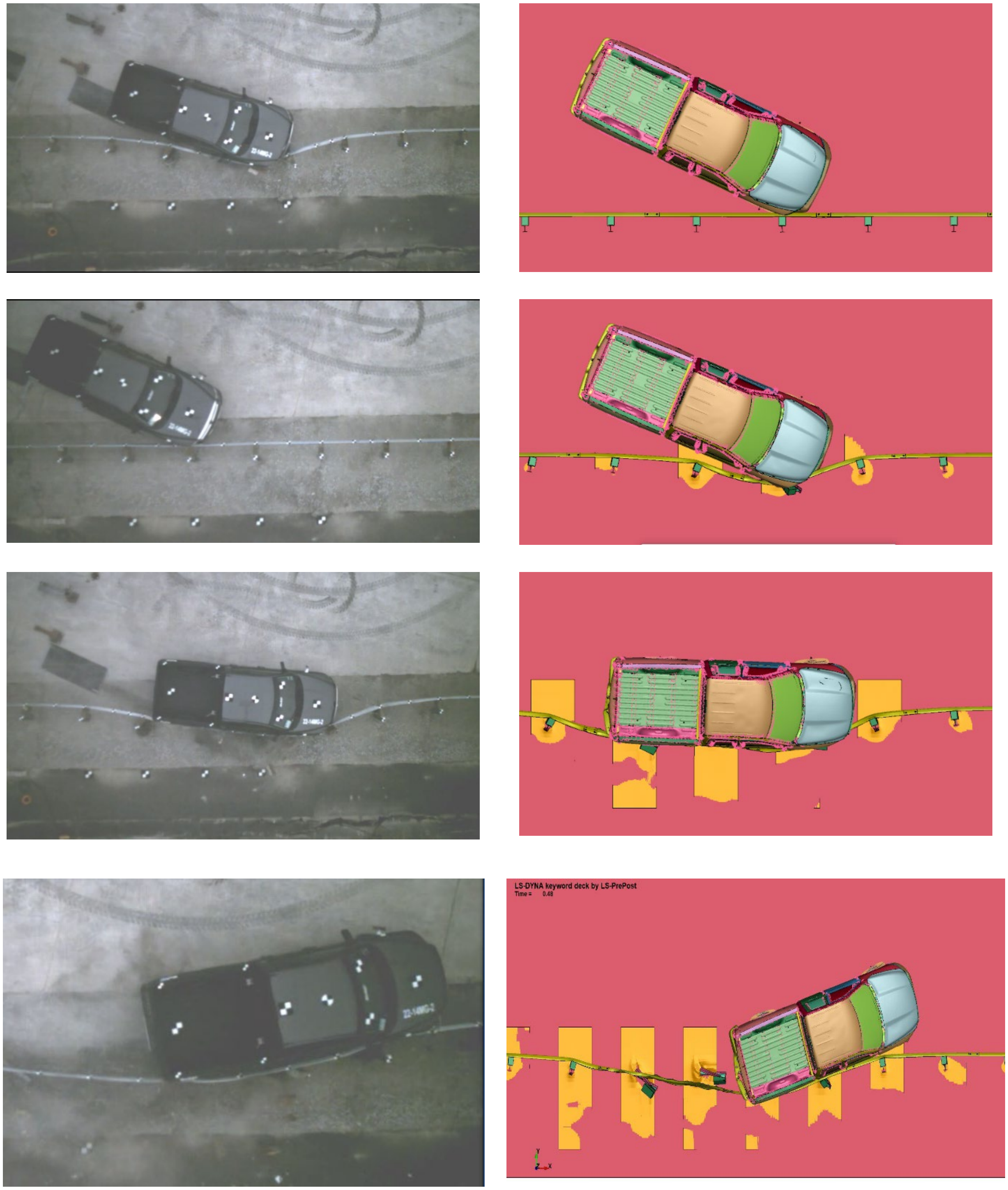


Figure 2.3. Overhead View Sequential Image Comparison

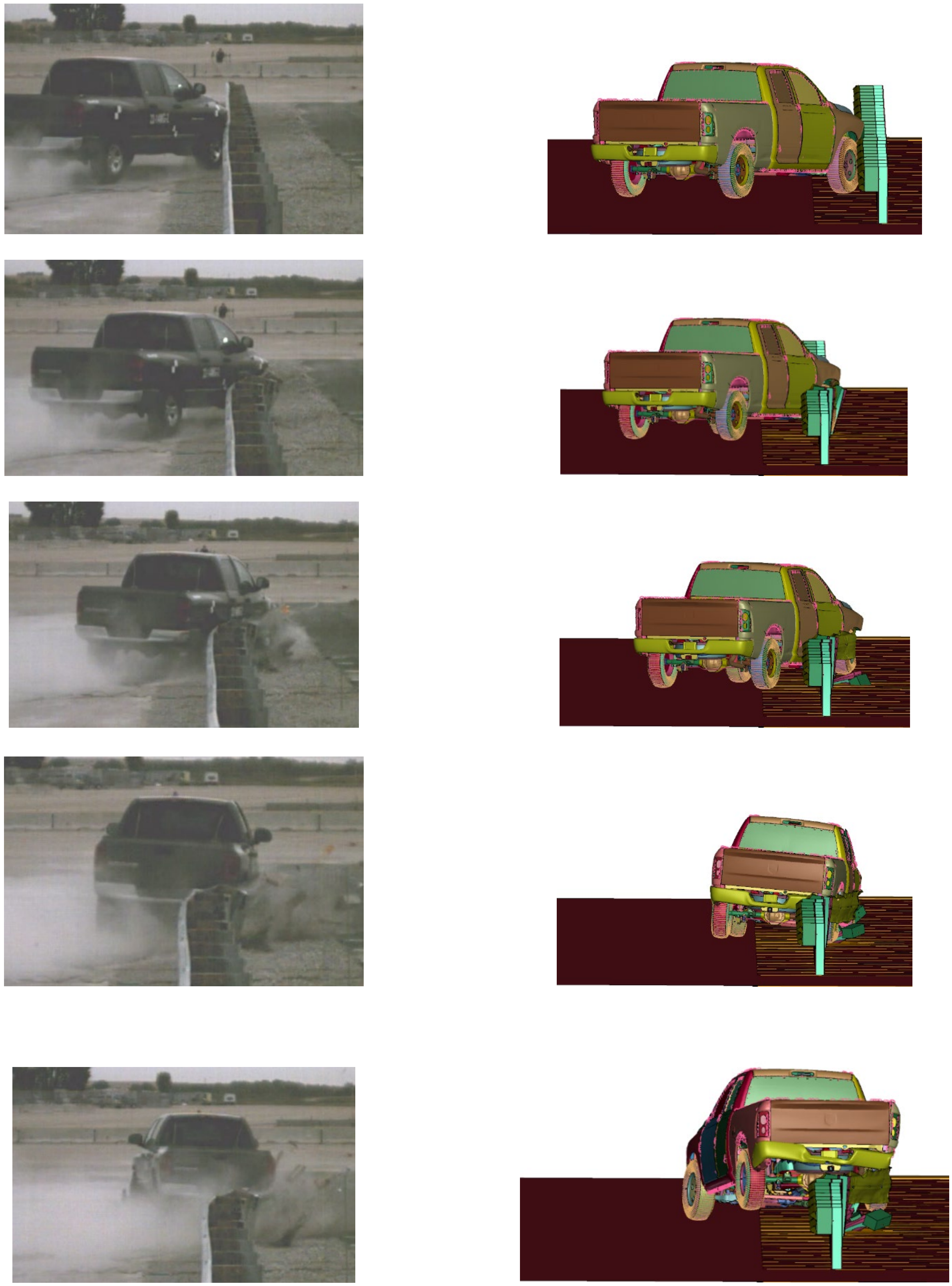


Figure 2.4. Upstream View Sequential Image Comparison

2.2. COMPUTER SIMULATION RESULTS

To evaluate the minimum required length-of-need for a MGS without downstream anchorage, a parametric analysis was completed with computer simulations. Each iteration of computer simulations adjusted the overall length of the guardrail system to achieve a crashworthy result. If the test vehicle successfully contained and redirected the vehicle, and the downstream end of the guardrail maintained connectivity to the posts, the length of the system was shortened. This process was repeated until the downstream end of the guardrail system lost connectivity to the posts or the guardrail failed to stably contain and redirect the test vehicle.

2.2.1. 162.5-ft Installation Without Downstream Anchorage

This simulation included a 162.5-ft long guardrail system without downstream anchorage. Figure 2.5 shows an overhead view of the finite element model. The system was evaluated using a computer simulated MASH Test 3-11. The 2270P MASH pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 103.8-ft from the downstream end of the rail and is shown below in Figure 2.6.

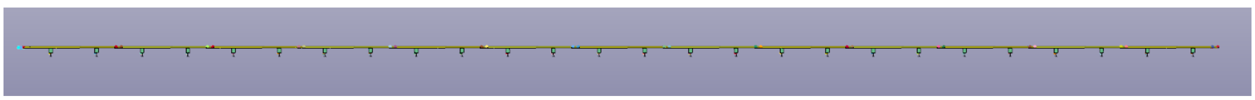


Figure 2.5. Overhead View of the 162.5-ft Guardrail System

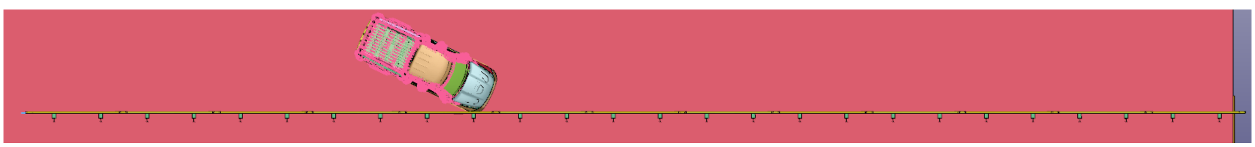


Figure 2.6. Overhead View of Impact Point for the 162.5-ft Guardrail System

Sequential photos of the computer simulation can be seen in the figures below. The system performed well in the simulated MASH Test 3-11 by successfully containing and redirecting the test vehicle. After exiting the system, the test vehicle remained upright and stable. Because of the successful performance, the guardrail system was shortened, and this resulting iteration can be found in the following section.

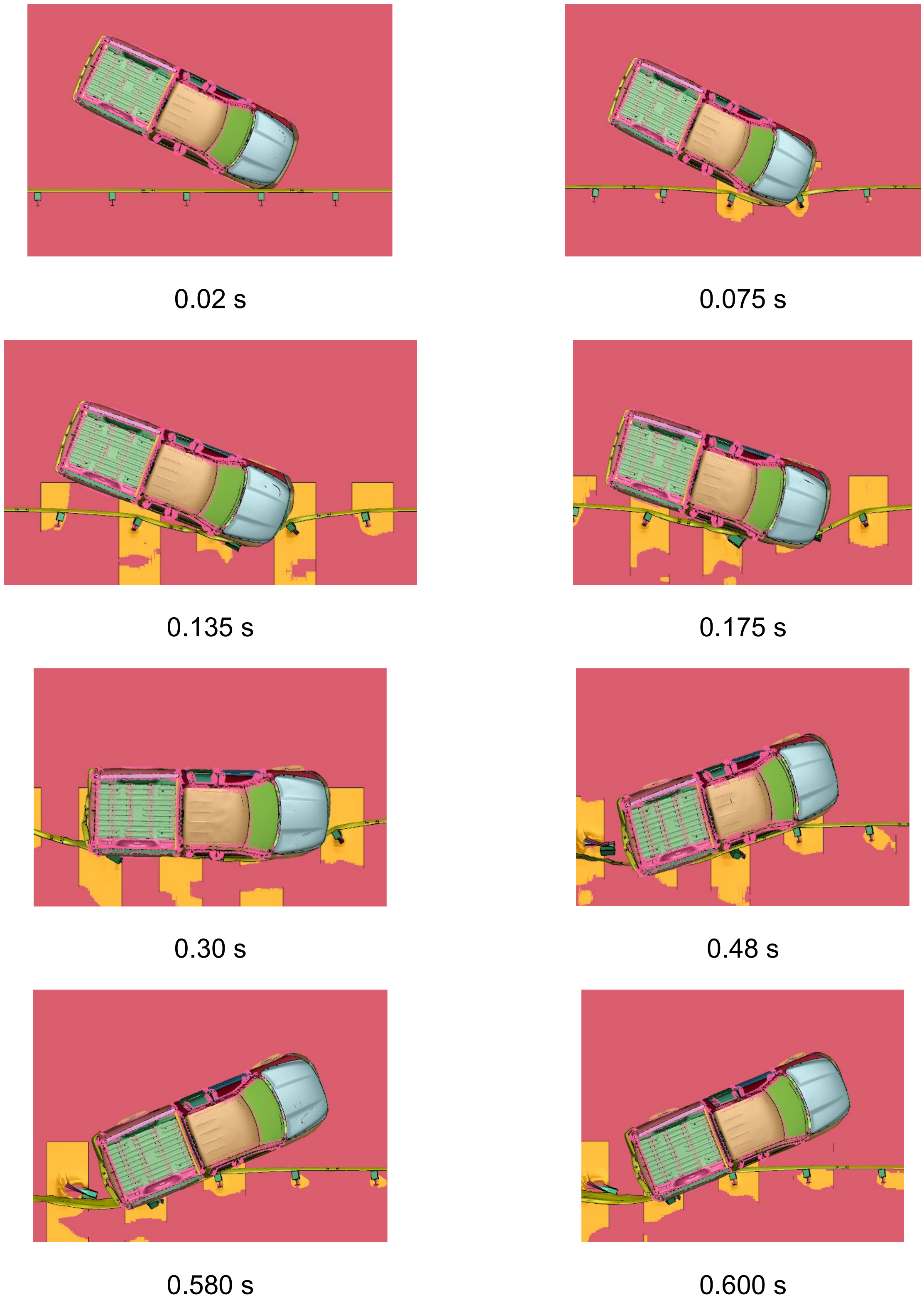
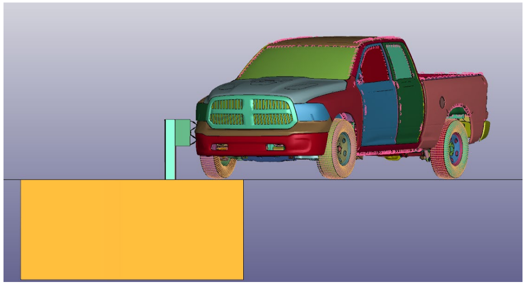
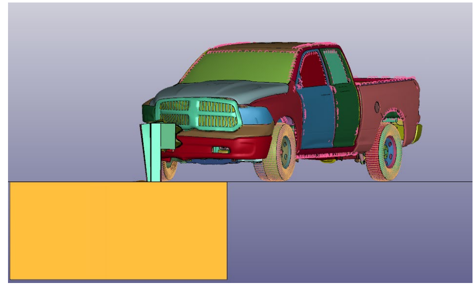


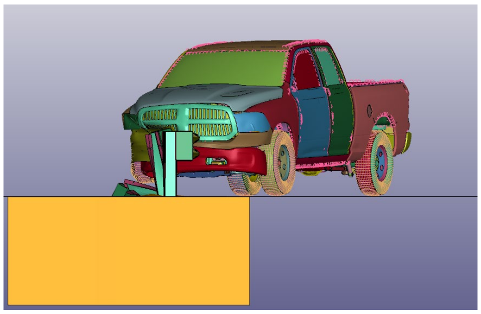
Figure 2.7. 162.5-ft Guardrail System – Overhead View



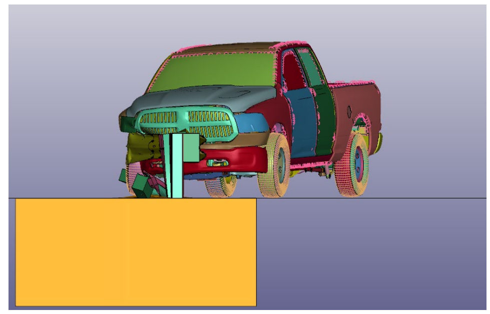
0.02 s



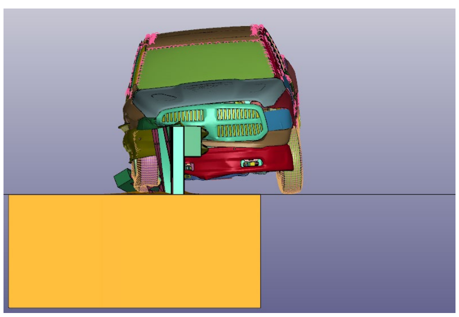
0.075 s



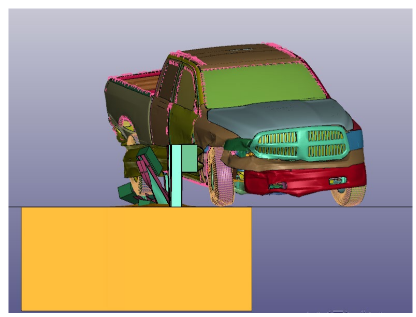
0.135 s



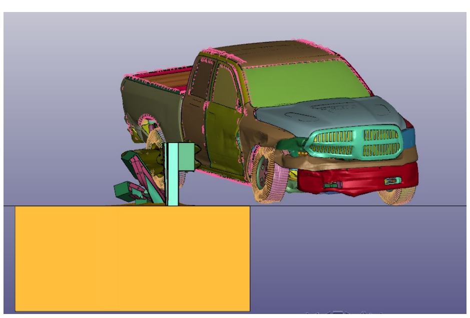
0.175 s



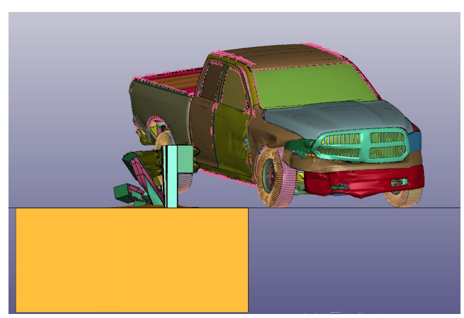
0.30 s



0.48 s



0.580 s



0.600 s

Figure 2.8. 162.5-ft Guardrail System – Downstream View

2.2.2. 137.5-ft Installation Without Downstream Anchorage

The FEA model discussed above in section 2.2.1 was shortened by removing two 12.5-ft long rail sections from the downstream side. Therefore, this model included a 137.5-ft long guardrail installation. Figure 2.9 shows an overhead view of the finite element model.

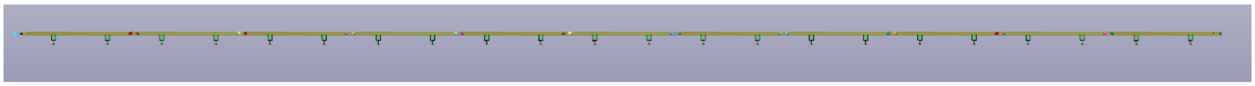


Figure 2.9. Overhead View of 137.5 ft Guardrail System

The system was evaluated using a simulated MASH test 3-11. The 2270P MASH pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 79-ft from the downstream end of the rail and is shown below in Figure 2.10.

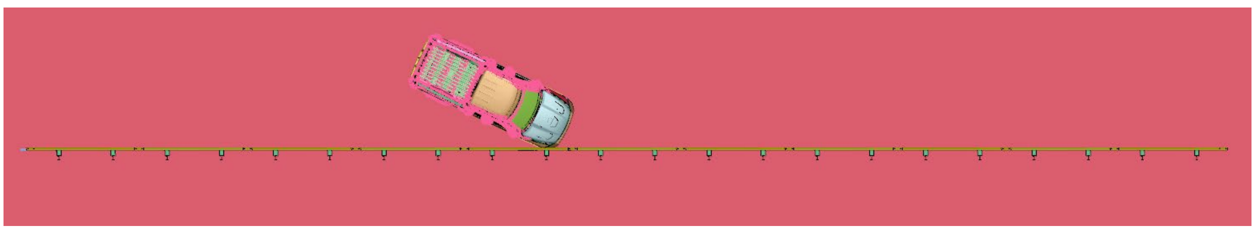


Figure 2.10. Overhead View of Impact Point for 137.5 ft Guardrail System

Sequential photos of the computer simulation can be seen in the figures below. The system performed well in the simulated MASH Test 3-11. The guardrail system without downstream anchorage successfully contained and redirected the test vehicle. After exiting the system, the test vehicle remained upright and stable. Because of the successful performance, the guardrail system was shortened, and this resulting iteration can be found in section 2.2.3.

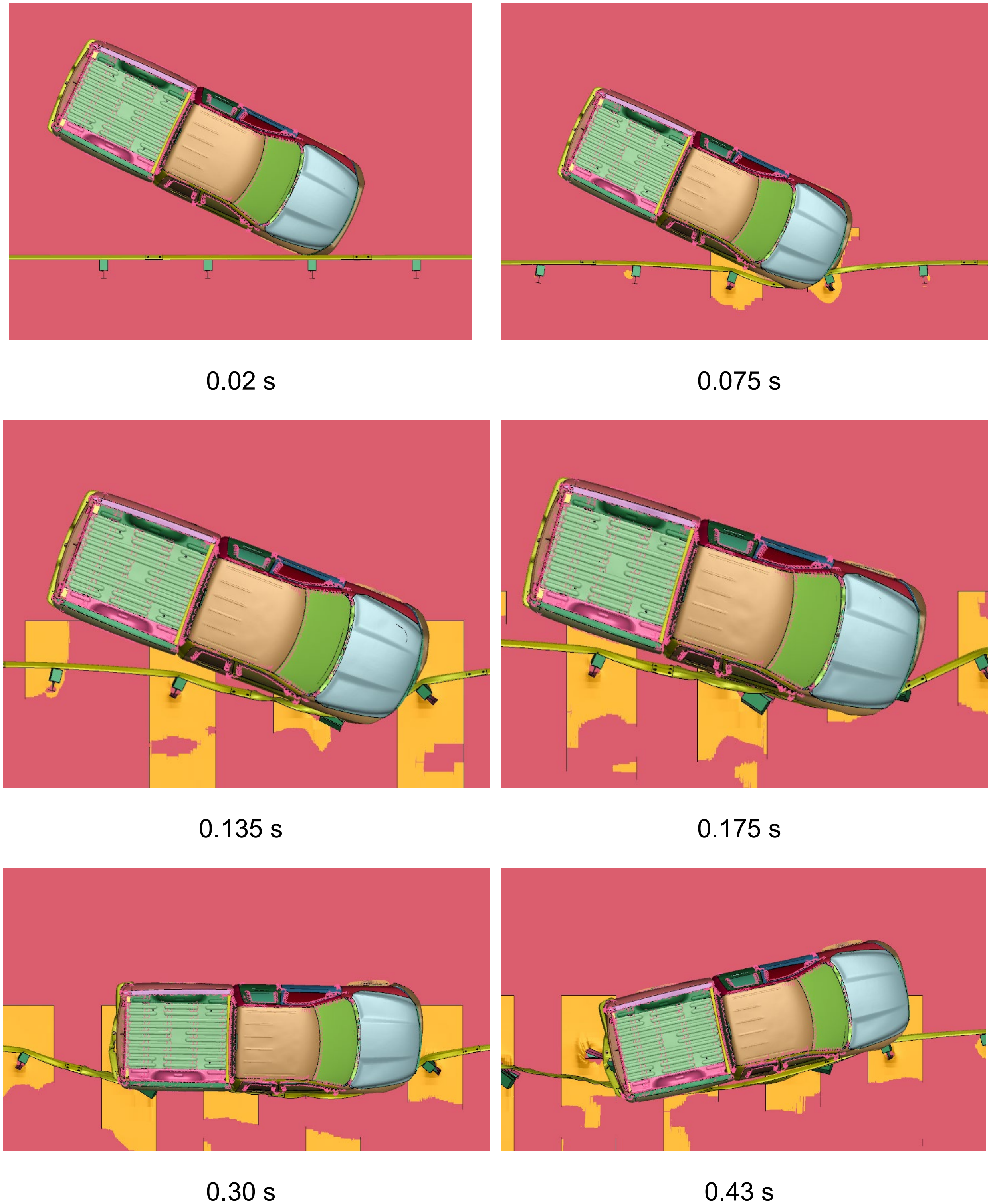
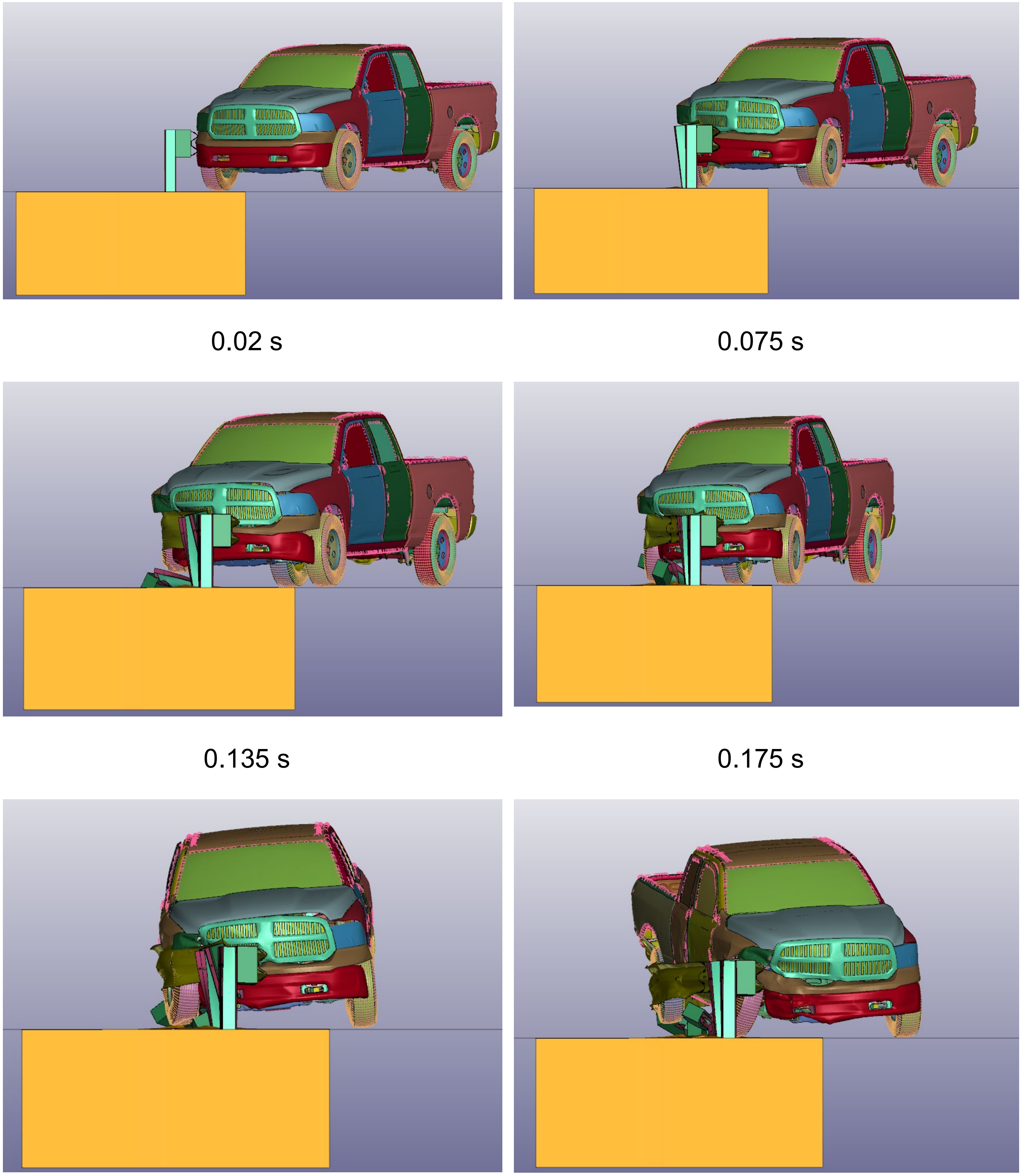


Figure 2.11. 137.5 ft Guardrail System – Overhead View



0.02 s 0.075 s

0.135 s 0.175 s

0.30 s 0.43 s

Figure 2.12. 137.5 ft Guardrail System – Downstream View

2.2.3. 125-ft Installation Without Downstream Anchorage

The FEA model discussed above in section 2.2.2 was shortened by removing one 12.5-ft long rail section from the downstream side. Therefore, this model included a 125-ft long guardrail installation. Figure 2.13 shows an overhead view of the finite element model.

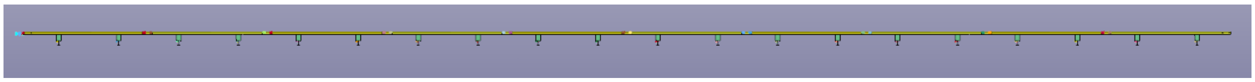


Figure 2.13. Overhead View of 125 ft Guardrail System

The system was evaluated using a computer simulated MASH Test 3-11. The 2270P MASH pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 66.3-ft from the downstream end of the rail and is shown below in Figure 2.14.

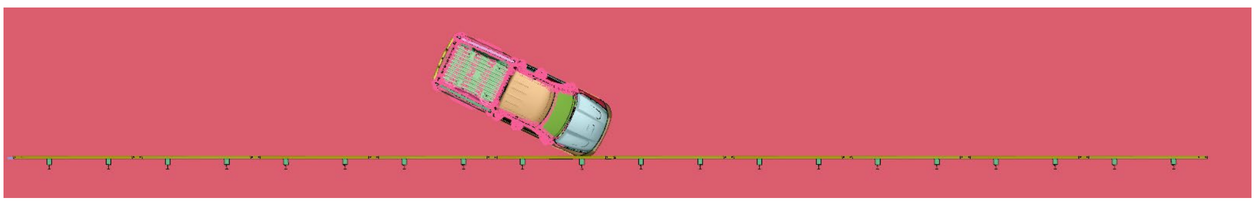


Figure 2.14. Overhead View of Impact Point for 125 ft Guardrail System

Sequential photos of the computer simulation can be seen in the figures below. The system performed well in the simulated MASH Test 3-11. The guardrail system without downstream anchorage successfully contained and redirected the test vehicle. After exiting the system, the test vehicle remained upright and stable. Because of the successful performance, the guardrail system was shortened, and this resulting iteration can be found in section 2.2.4.

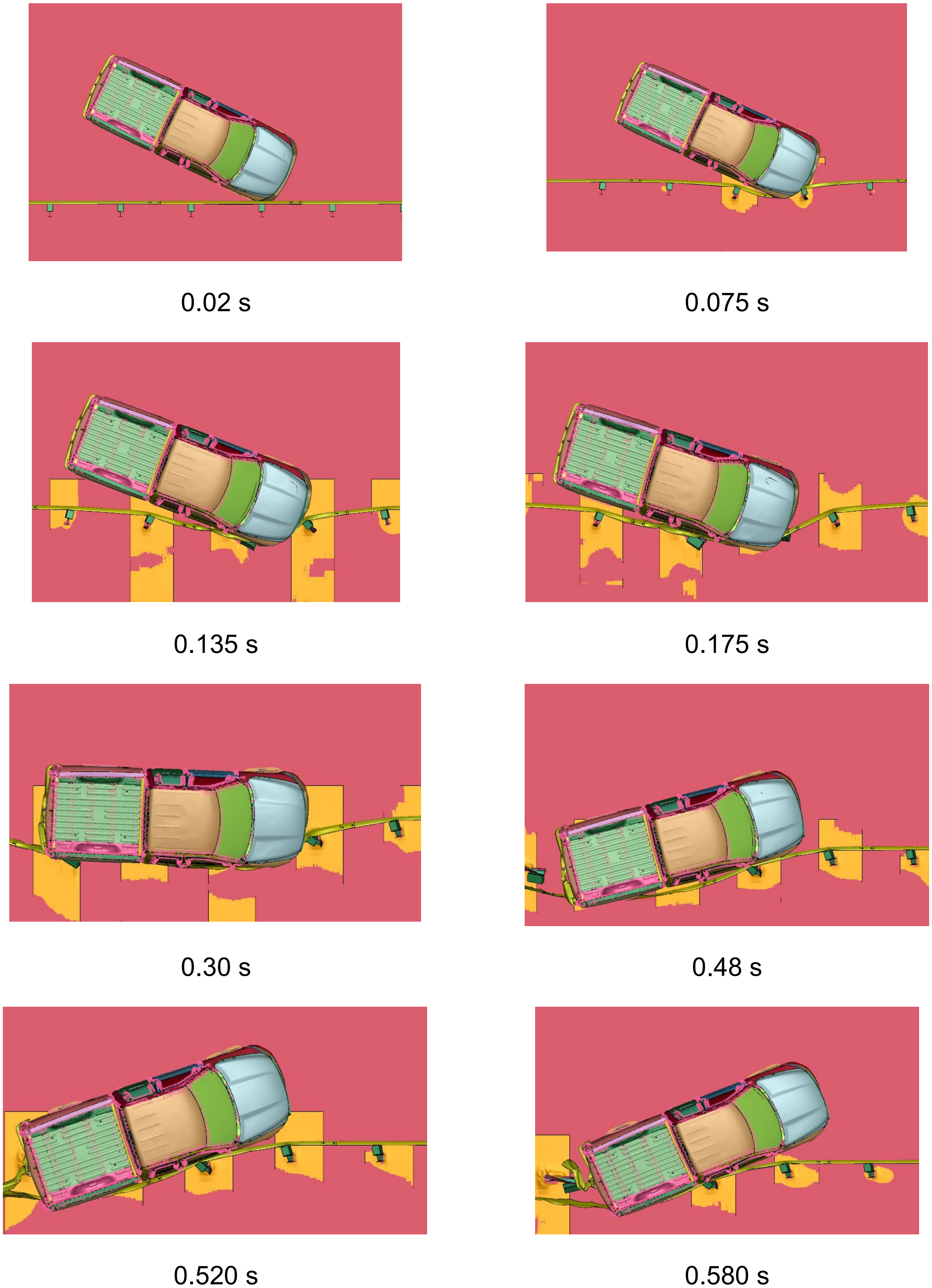
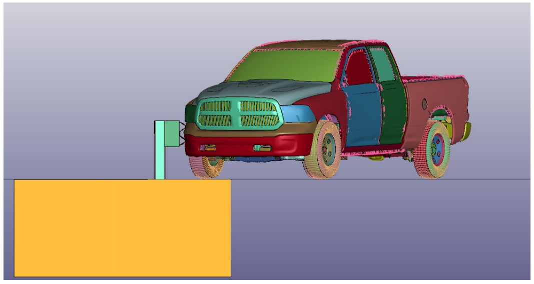
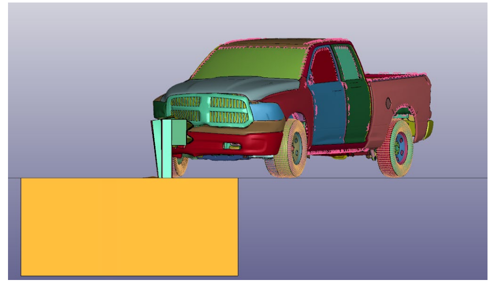


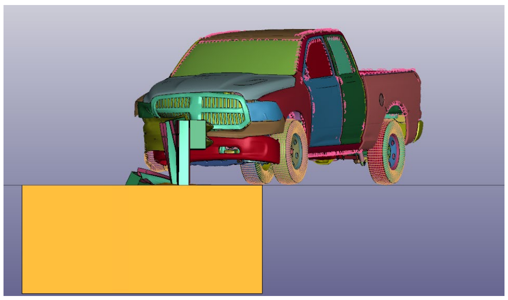
Figure 2.15. 125 ft Guardrail System – Overhead View



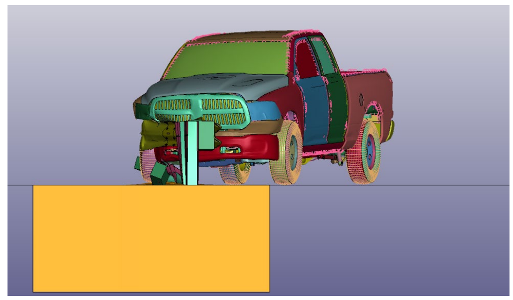
0.02 s



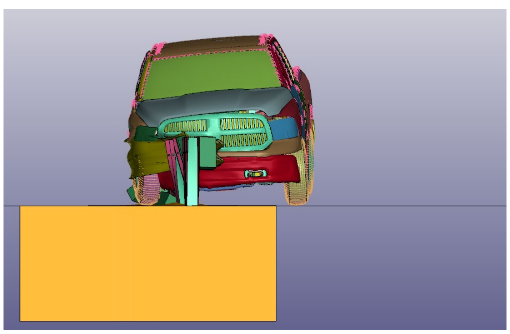
0.075 s



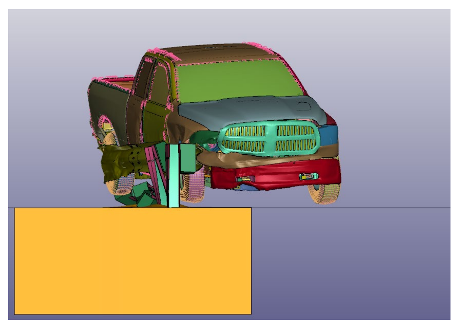
0.135 s



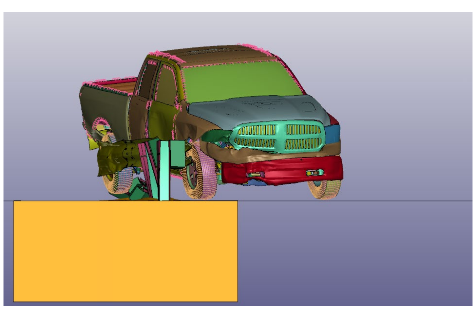
0.175 s



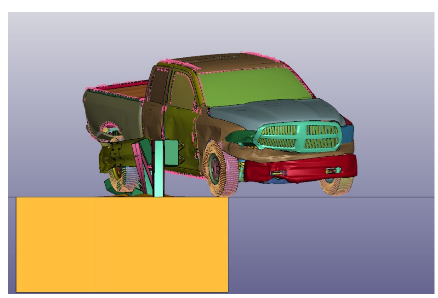
0.30 s



0.48 s



0.520 s



0.580 s

Figure 2.16. 125 ft Guardrail System – Downstream View

2.2.4. 87.5-ft Installation Without Downstream Anchorage

The iterative process of shortening the guardrail system after successful runs was repeated several more times. Consequently, the FEA model discussed above in section 2.2.3 was shortened by removing several 12.5-ft long rail sections from both the downstream and upstream side. This model resulted in an 87.5-ft long guardrail installation. Figure 2.17 shows an overhead view of the finite element model.

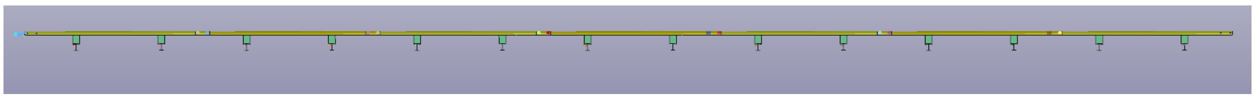


Figure 2.17. Overhead View of 87.5 ft Guardrail System

The system was evaluated using a computer simulated MASH Test 3-11. The 2270P MASH pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 66.4-ft from the downstream end of the rail and is shown below in Figure 2.18.

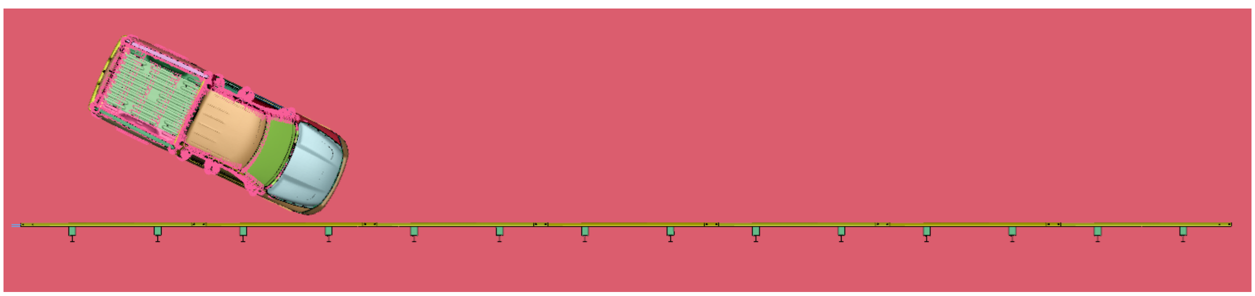
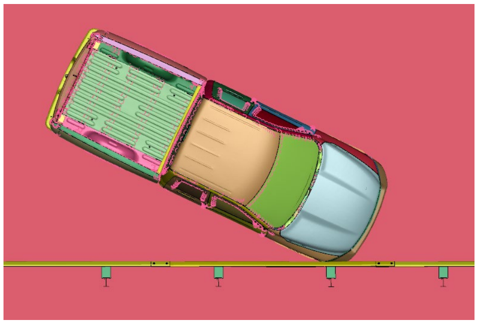
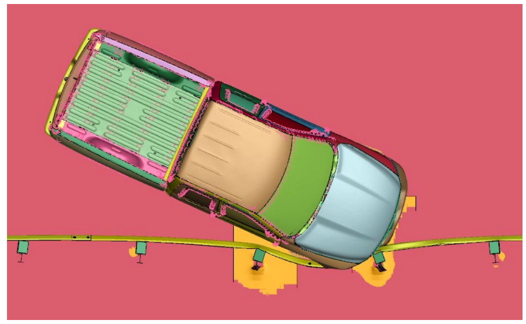


Figure 2.18. Overhead View of Impact Point for 87.5 ft Guardrail System

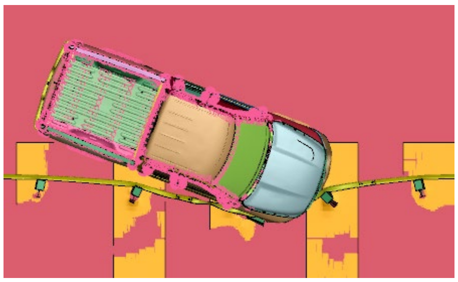
Sequential photos of the computer simulation can be seen in the figures below. The system performed well in the simulated MASH Test 3-11. The guardrail system without downstream anchorage successfully contained and redirected the test vehicle. After exiting the system, the test vehicle remained upright and stable. Because of the successful performance, the guardrail system was shortened, and this resulting iteration can be found in section 2.2.5.



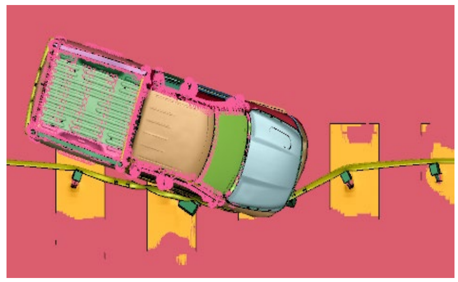
0.02 s



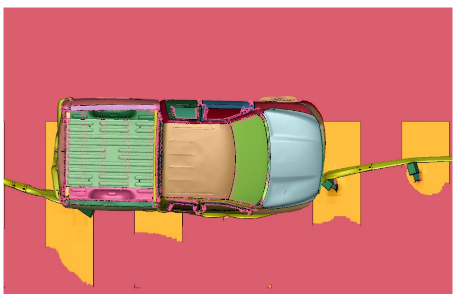
0.075 s



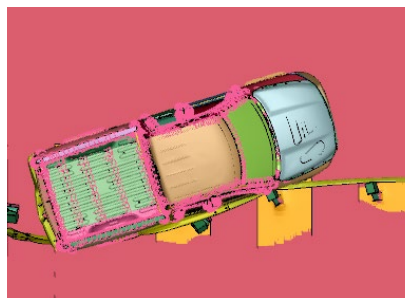
0.135 s



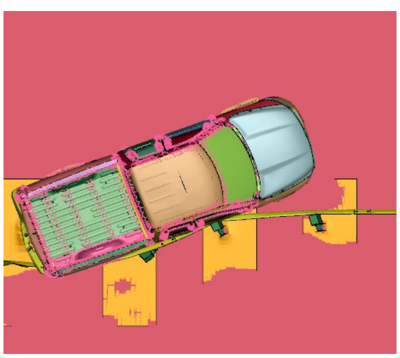
0.175 s



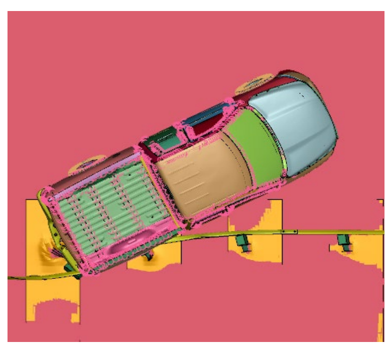
0.30 s



0.48 s

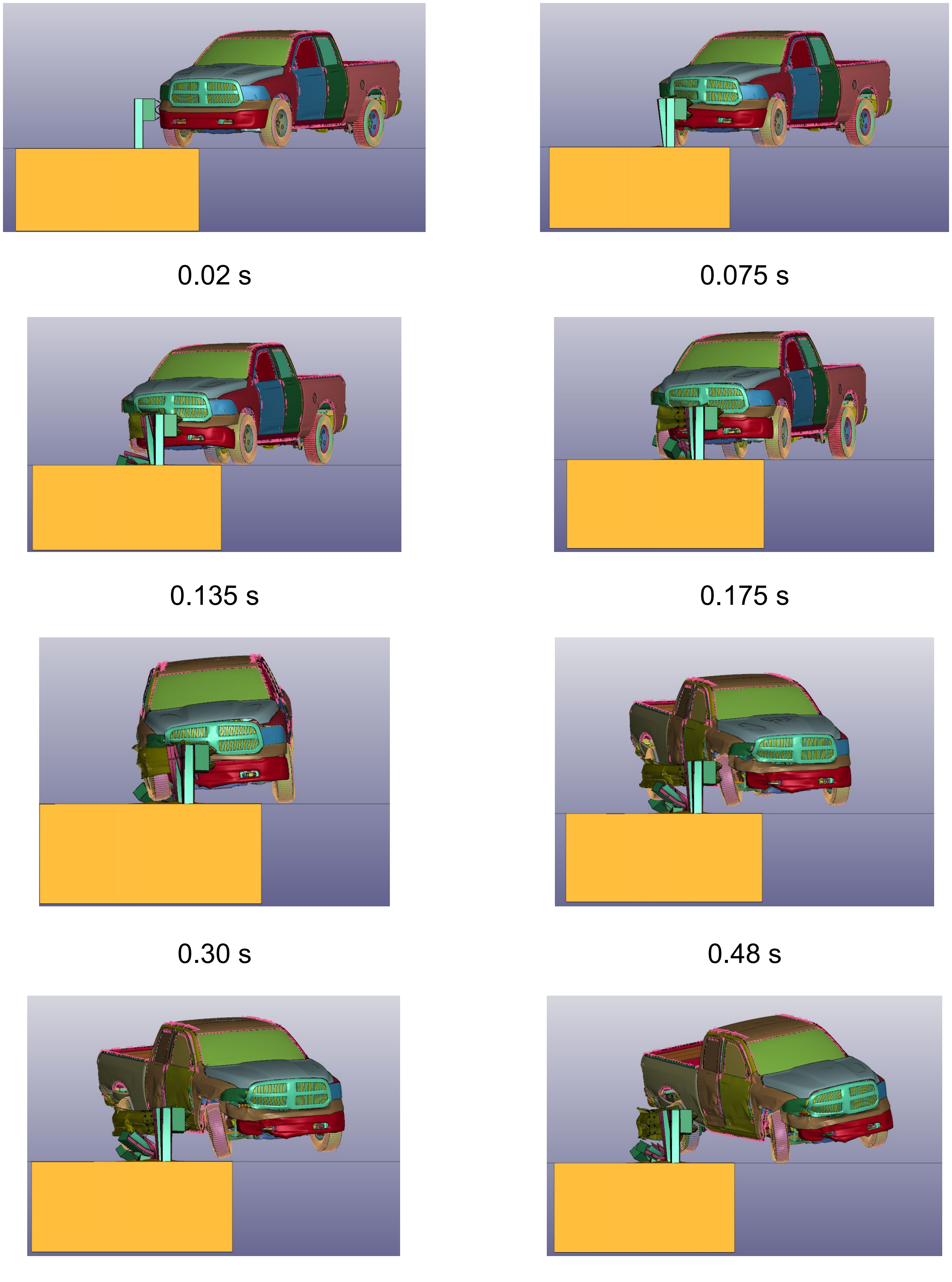


0.520 s



0.640 s

Figure 2.19. 87.5-ft Guardrail System – Overhead View



0.640 s

Figure 2.20. 87.5-ft Guardrail System – Downstream View

2.2.5. 75-ft Installation Without Downstream Anchorage

The FEA model discussed above in section 2.2.4 was shortened by removing one 12.5-ft long rail section from the downstream side. Therefore, this model included a 75-ft long guardrail installation. Figure 2.21 shows an overhead view of the finite element model.

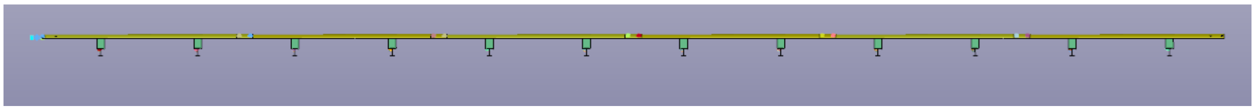


Figure 2.21. Overhead View of 75 ft Guardrail System

The system was evaluated using a simulated MASH Test 3-11. The 2270P MASH pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 53.8-ft from downstream end of the rail and is shown below in Figure 2.22.

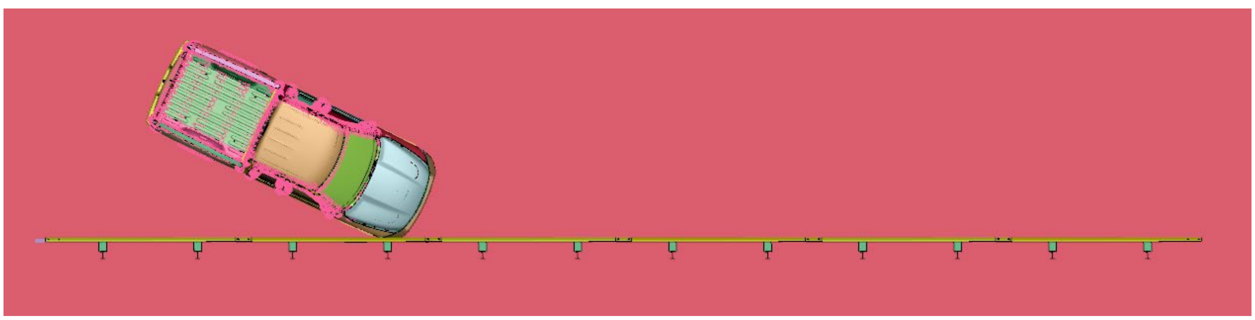
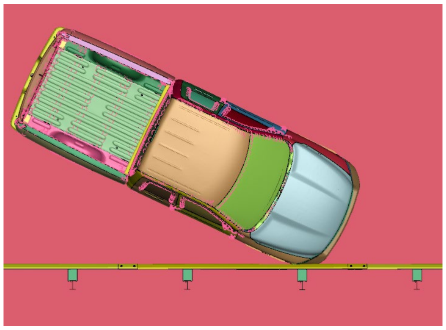
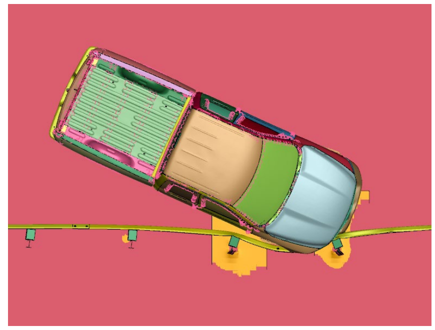


Figure 2.22. Overhead View of Impact Point for 75 ft Guardrail System

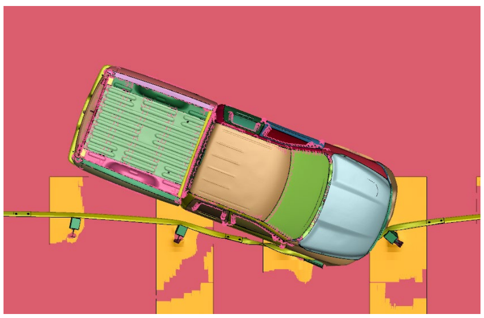
Sequential photos of the computer simulation can be seen in the figures below. During the impact, the w-beam rail was pulled off the downstream end posts and consequently lost its ability to redirect the pickup truck. Additionally, the end of the simulation showed the truck overrode the guardrail. Because of these two behaviors, the researchers deemed this length to be unacceptable. Therefore, the 87.5-ft length discussed in 2.2.4 was determined to be the shortest length required to provide redirective behavior.



0.02 s

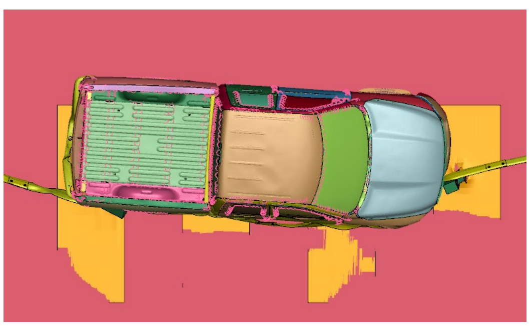


0.075 s

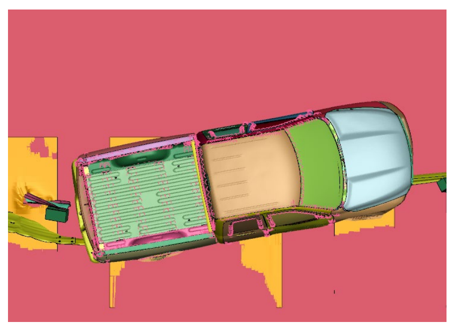


0.135 s

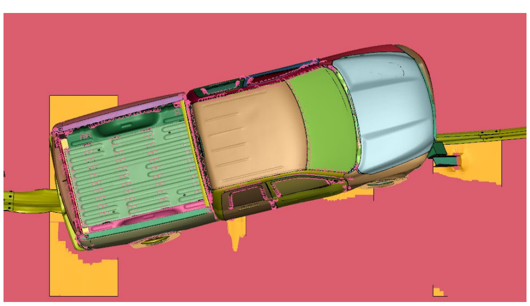
0.175 s



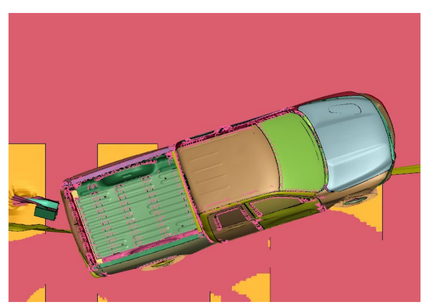
0.30 s



0.48 s

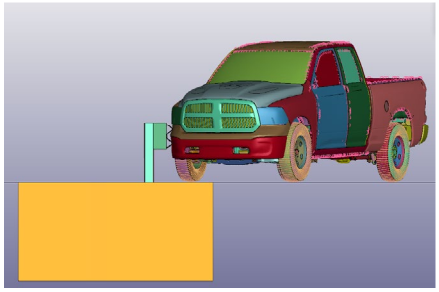


0.520 s

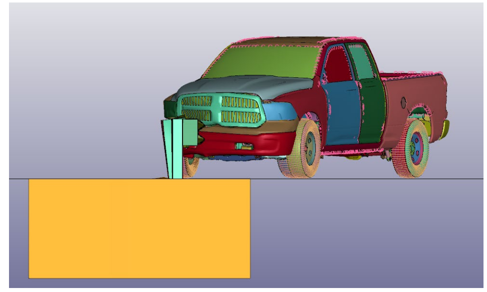


0.600 s

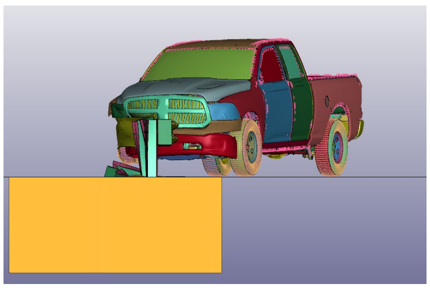
Figure 2.23. 75 ft Guardrail System – Overhead View



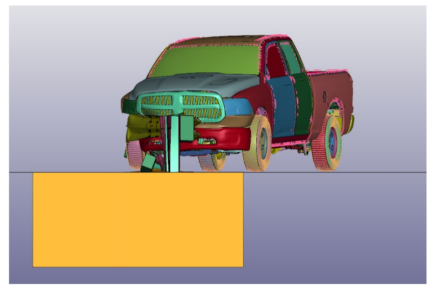
0.02 s



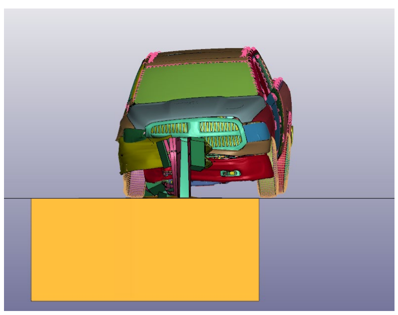
0.075 s



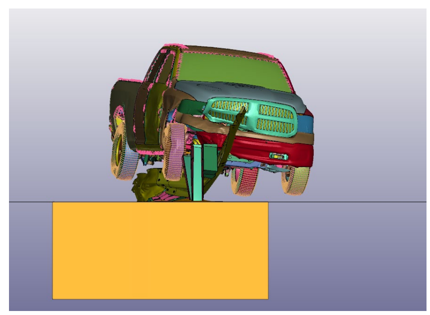
0.135 s



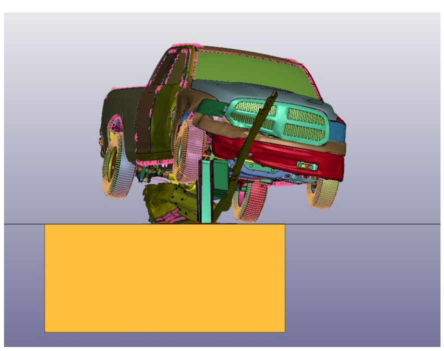
0.175 s



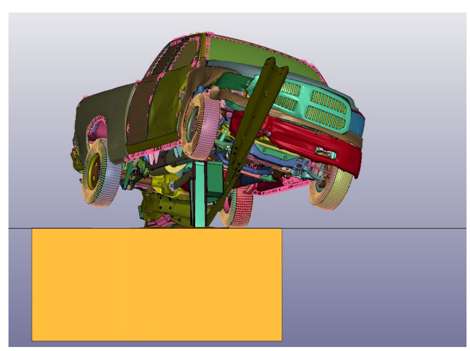
0.30 s



0.48 s



0.520 s



0.600 s

Figure 2.24. 75 ft Guardrail System – Downstream View

2.2.6. 87.5-ft Installation Without Downstream Anchorage – 37.5 inches Downstream Impact Point

In the previous simulations, the shortest length of guardrail installation to provide redirective behavior was determined to be 87.5-ft. The researchers began to then determine the location on the installation which causes an vehicle to gate through or override the guardrail system. In this pursuit, this simulation was performed with the impact point 37.5-inches downstream from the impact point used in section 2.2.4. This equates to 63.3-ft from the downstream end of the installation. Figure 2.25 shows an overhead view of the finite element model.

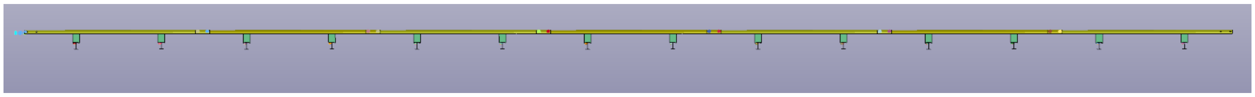


Figure 2.25. Overhead View of 87.5 ft Guardrail System with 37.5 inches Downstream Impact Point

The system was evaluated using a simulated MASH Test 3-11. The 2270P MASH pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 63.3-ft from the downstream end of the rail and is shown below in Figure 2.26.

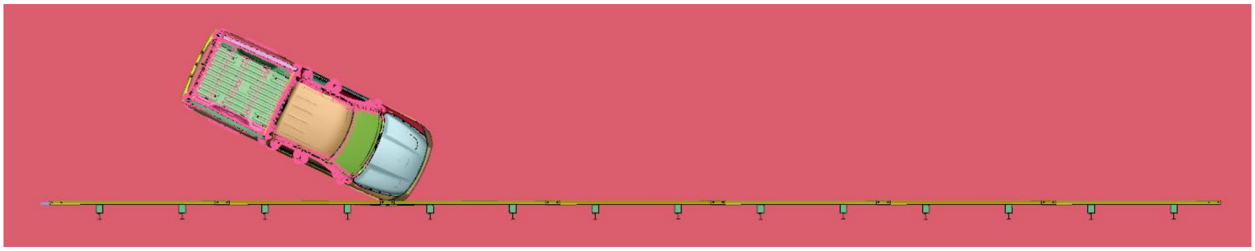


Figure 2.26. Overhead View of Impact Point for 87.5 ft Guardrail System with 37.5 inches Downstream Impact Point

Sequential photos of the computer simulation can be seen in the figures below. The system performed well in the computer simulated MASH Test 3-11. The guardrail system without downstream anchorage successfully contained and redirected the test vehicle. After exiting the system, the test vehicle remained upright and stable. Because of the successful performance, the impact point was shifted 37.5-inches downstream and this resulting iteration can be found in section 2.2.7.

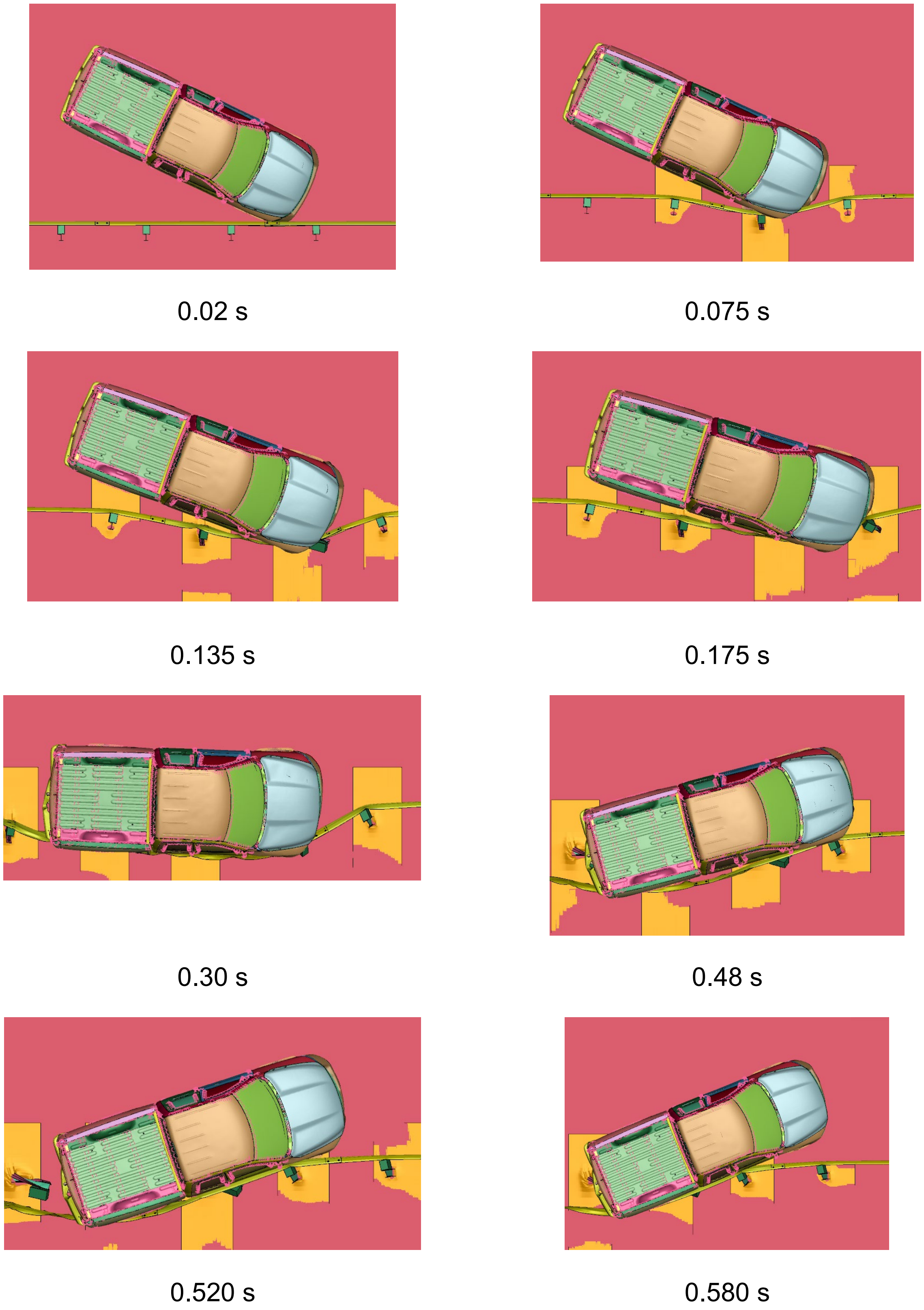
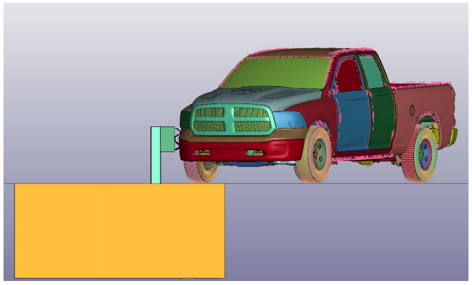
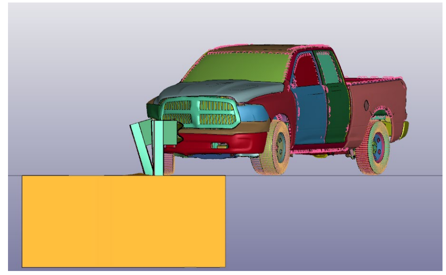


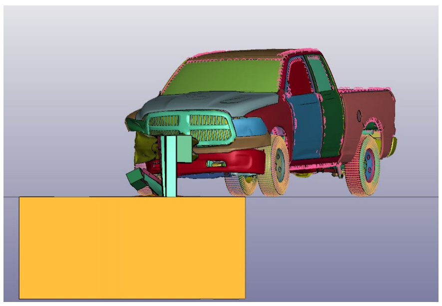
Figure 2.27. 87.5 ft Guardrail System with 37.5 inches Downstream Impact Point – Overhead View



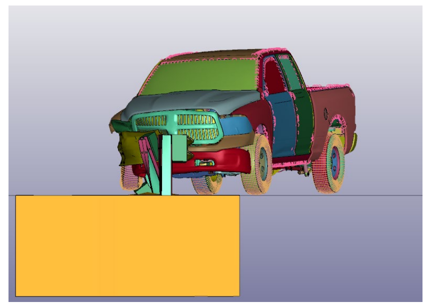
0.02 s



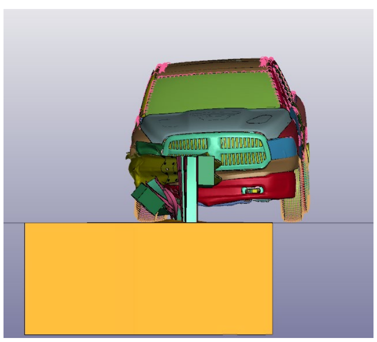
0.075 s



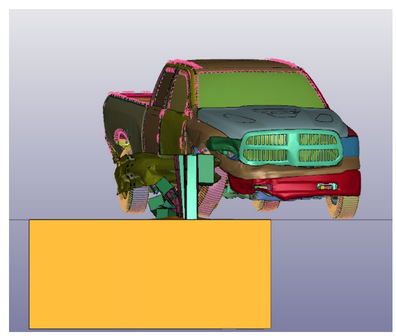
0.135 s



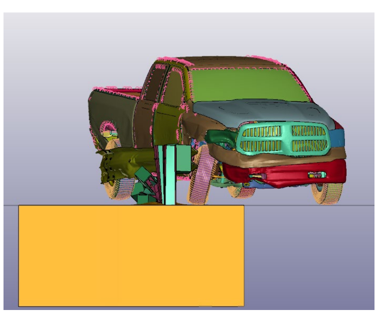
0.175 s



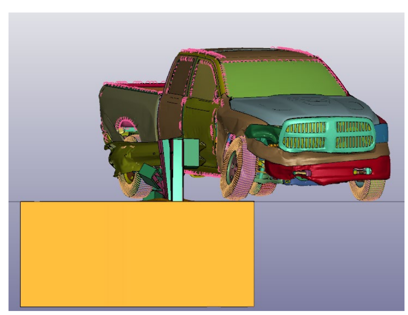
0.30 s



0.48 s



0.520 s



0.580 s

Figure 2.28. 87.5 ft Guardrail System with 37.5 inches Downstream Impact Point–Downstream View

2.2.7. 87.5-ft Installation Without Downstream Anchorage – 75-inches Downstream Impact Point

After successful redirection in section 2.2.6, the researchers decided to further move the impact point downstream by 37.5 inches. Therefore, this simulation was performed with the impact point 75-inches downstream from the impact point used in section 2.2.4. This equates to 60.0-ft from the downstream end of the installation. Figure 2.29 shows an overhead view of the finite element model.

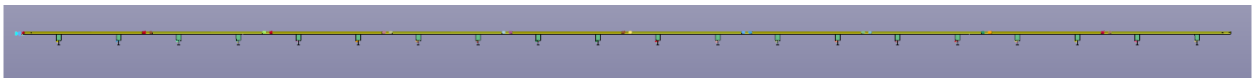


Figure 2.29. Overhead View of 87.5 ft Guardrail System with 75 inches Downstream Impact Point

The system was evaluated using a simulated MASH Test 3-11. The 2270P MASH pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 60.0-ft from the downstream end of the rail and is shown below in Figure 2.30.

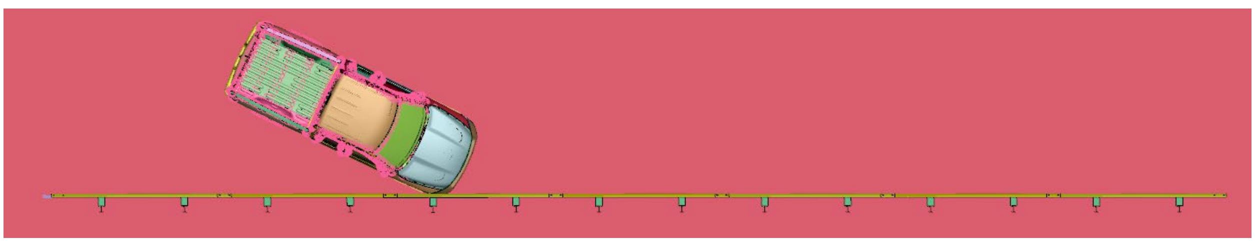
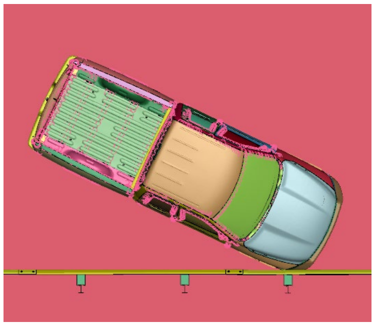
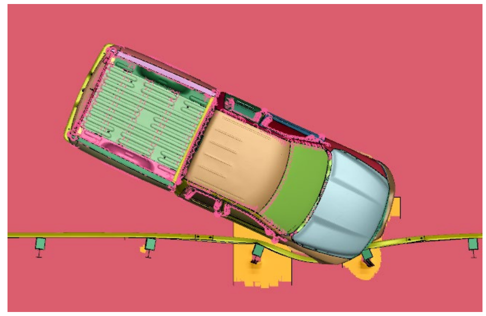


Figure 2.30. Overhead View of Impact Point for 87.5 ft Guardrail System with 75 inches Downstream Impact Point

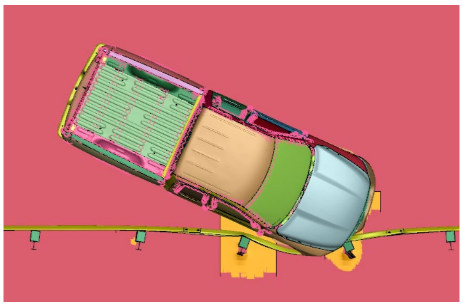
Sequential photos of the computer simulation can be seen in the figures below. During the impact, the w-beam rail was pulled off the downstream end posts and consequently lost its ability to redirect the pickup truck. Therefore, the researchers deemed the impact point 63.3-ft from the downstream end of the rail (see section 2.2.6) to be the furthest downstream impact point which would provide redirective behavior. Any impact point downstream of this location could not be assumed to provide redirective behavior.



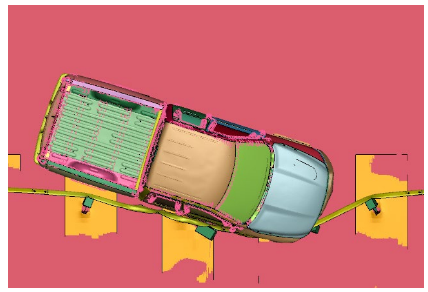
0.02 s



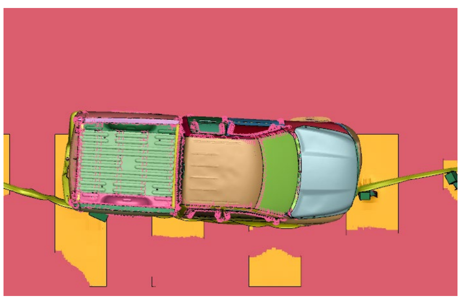
0.075 s



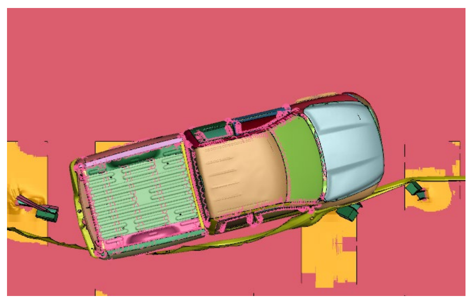
0.135 s



0.175 s

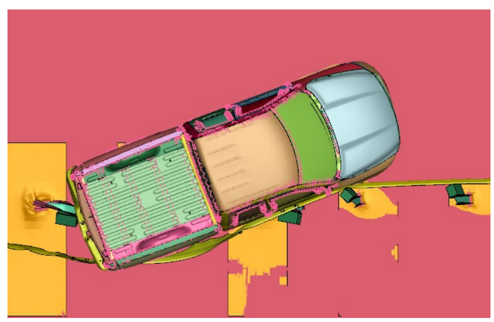


0.30 s



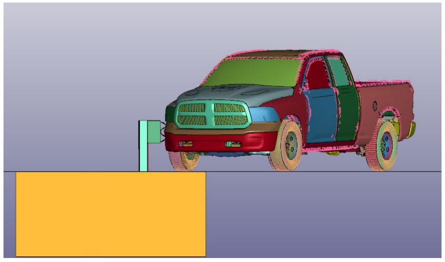
0.48 s

0.520 s

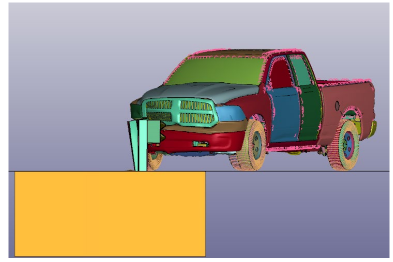


0.580 s

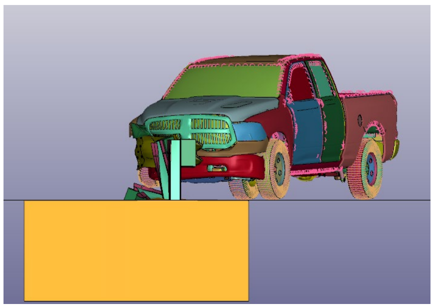
Figure 2.31. of 87.5 ft Guardrail System with 75-inches Downstream Impact Point – Overhead View



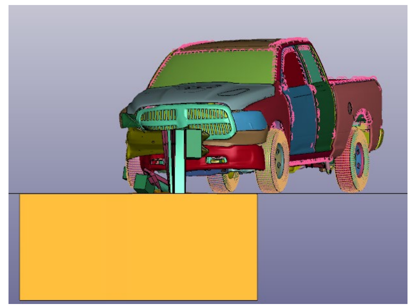
0.02 s



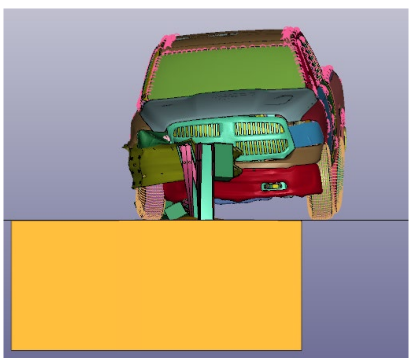
0.075 s



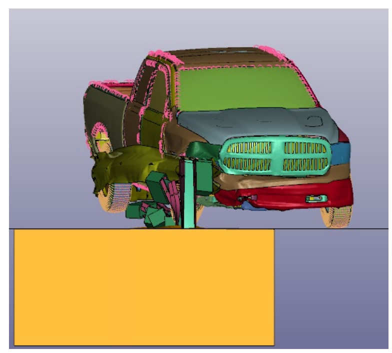
0.135 s



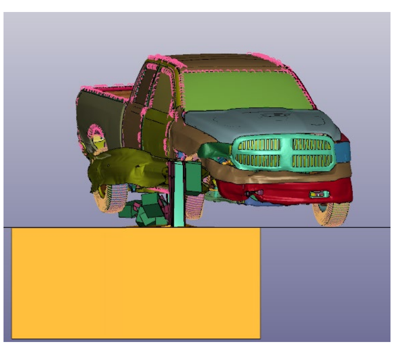
0.175 s



0.30 s



0.48 s



0.520 s

0.580 s

Figure 2.32. 87.5 ft Guardrail System with 75 inches Downstream Impact Point–Downstream View

2.3. COMPUTER SIMULATION CONCLUSIONS

Based on the results of the previous computer simulations, the research team proceeded to develop test installation drawings for full-scale crash testing. The selected system incorporated 87.5 ft of w-beam guardrail, as was determined to be the minimum length-of-need by computer simulation. The critical impact point was selected to be the 37.5-inches downstream impact point, as discussed above. The research team determined 12.5 ft of this 87.5 ft minimum length can be accounted for in the length of the guardrail terminal. Therefore, only 75 ft of additional length beyond a MASH compliant terminal is needed. The crash testing of this system is discussed in the following chapter.

CHAPTER 3. SYSTEM DETAILS

3.1. TEST ARTICLE AND INSTALLATION DETAILS

In Crash Test No. 614721-01-2 on April 6, 2021, the installation consisted of a 125 ft-9½ inch long W-beam guardrail system with a length-of-need of 75 ft (with an additional 12.5 ft of length-of-need accounted for in a *MASH* compliant terminal). It was anchored on the upstream end by a SoftStop® end terminal. The downstream end of the system was not anchored. Posts 9 through 20 were standard 72-inch long wide flange steel guardrail posts spaced at 75 inches. The height of the w-beam rail top edge was 31 inches above grade. Section A.1 in Appendix A provides further details on the guardrail without downstream anchorage.

For the second Crash Test No. 614721-01-1 on October 26, 2022, the installation was the same as the first test except that a rectangular plate washer was added and attached in front of the guardrail at posts 19 and 20. Section A.2 in Appendix A provides further details on the guardrail without downstream anchorage.

Figure 3.1 presents the overall information on the guardrail without downstream anchorage, and Figure 3.2 provides photographs of the installation. Drawings were provided by the Texas A&M Transportation Institute (TTI) Proving Ground, and construction was performed by approved vendors and supervised by TTI Proving Ground personnel.

3.2. DESIGN MODIFICATIONS DURING TESTS

No modifications were made during testing

3.3. MATERIAL SPECIFICATIONS

Appendix B provides material certification documents for the materials used to install/construct the Guardrail without downstream anchorage.

3.4. SOIL CONDITIONS

The test installation was installed in standard soil meeting grading B of AASHTO standard specification M147-17 "Materials for Aggregate and Soil-Aggregate Subbase, Base and Surface Courses."

In accordance with Appendix B of *MASH*, soil strength was measured the day of the crash test. During installation of the guardrail without downstream anchorage for full-scale crash testing, two 6-ft long W6×16 posts were installed in the immediate vicinity of the Guardrail without downstream anchorage using the same fill materials and installation procedures used in the test installation and the standard dynamic test. Table B.1 in Appendix B presents minimum soil strength properties established through the dynamic testing performed in accordance with *MASH* Appendix B.

As determined by the tests summarized in Appendix B, Table B.1, the minimum post loads are shown in Table 3..

On the day of Test 3-11, April 4, 2021, the measured post loading proved the backfill material in which the Guardrail without downstream anchorage was installed met minimum *MASH* requirements for soil strength.

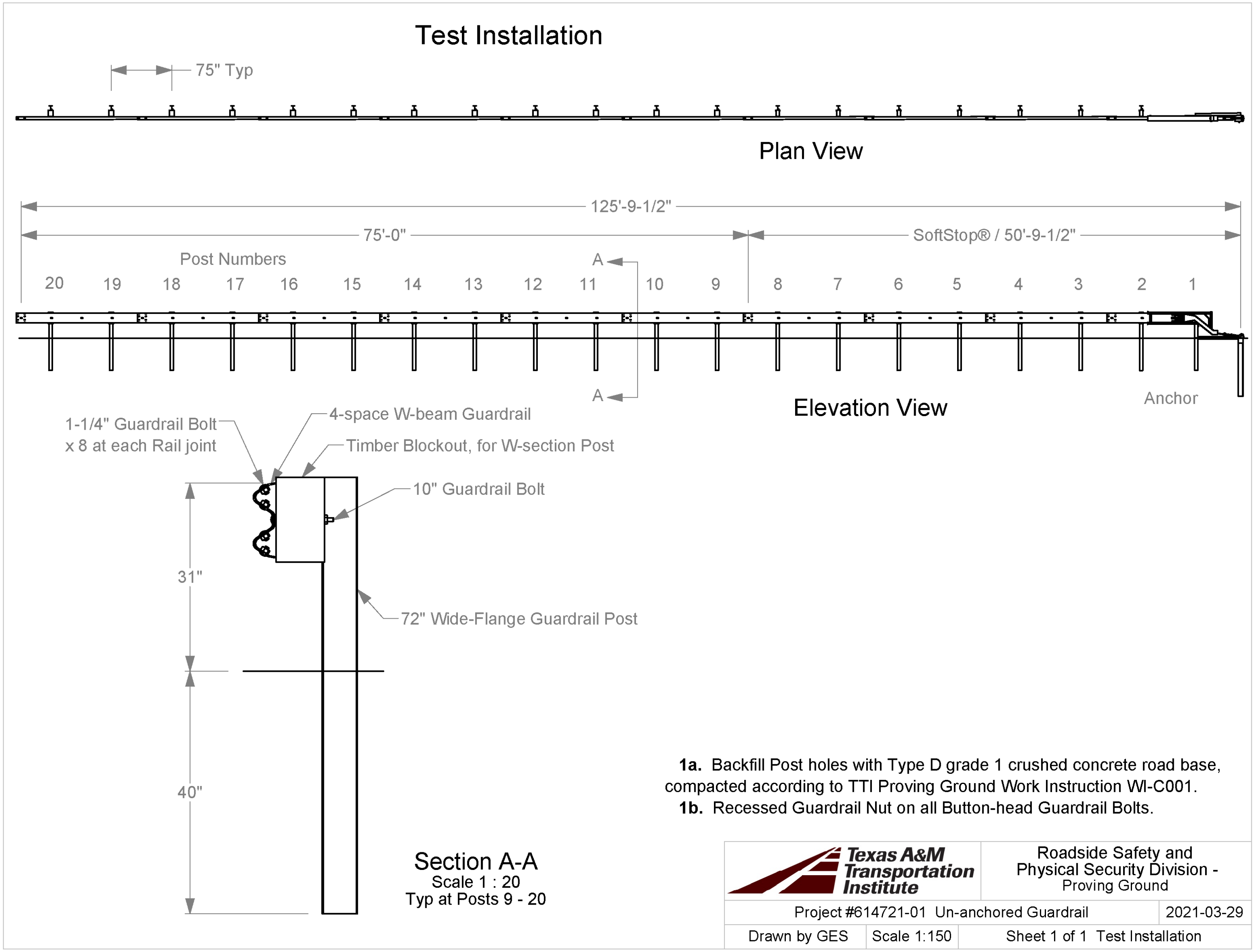
Table 3.2. Soil Strength, Test 614721-01-2.

Displacement (in)	Minimum Load (lb)	Actual Load (lb)
5	4420	7777
10	4981	8939
15	5282	9595

On the day of Test 3-11, October 26, 2022, the measured post loading proved the backfill material in which the Guardrail without downstream anchorage was installed met minimum *MASH* requirements for soil strength.

Table 3.1. Soil Strength, Test 614721-01-1.

Displacement (in)	Minimum Load (lb)	Actual Load (lb)
5	4420	7696
10	4981	6969
15	5282	5697



Q:\Accreditation-17025-2017\EIR-000 Project Files\614721-01 - Un-anchored Guardrail - Kovar\Drafting, 614721-01\614721-01 Drawing

Figure 3.1. Details of Guardrail without downstream anchorage.

Figure 3.2. Guardrail without downstream anchorage prior to Testing.

This page intentionally left blank.

CHAPTER 4. TEST REQUIREMENTS AND EVALUATION CRITERIA

4.1. CRASH TEST PERFORMED/MATRIX

Table 4.1. shows the test conditions and evaluation criteria for *MASH* TL-3 for longitudinal barriers. The target critical impact points (CIPs) for each test were determined through computer simulation. Figure 4.1 shows the target CIP for *MASH* Test 3-11 on the guardrail without downstream anchorage.

Table 4.1. Test Conditions and Evaluation Criteria Specified for *MASH* TL-3 Longitudinal Barriers.

Test Article	Test Designation	Test Vehicle	Impact Conditions		Evaluation Criteria
			Speed	Angle	
Longitudinal Barrier	3-11	2270P	62 mi/h	25°	A, D, F, H, I

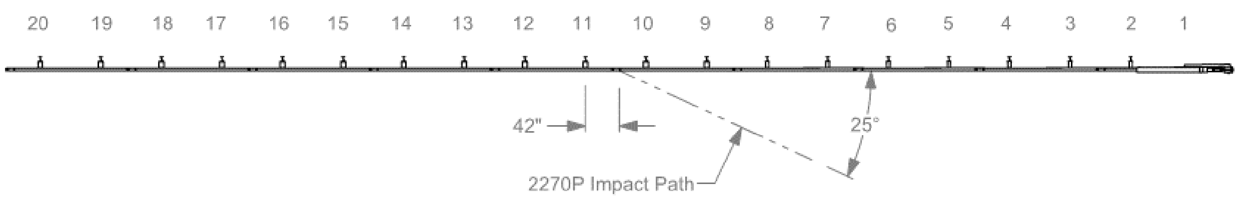


Figure 4.1. Target CIP for *MASH* Test 3-11 (Crash Test Nos. 614721-01-1 & 2) on Guardrail without downstream anchorage.

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

4.2. EVALUATION CRITERIA

The appropriate safety evaluation criteria from Tables 2-2 and 5-1 of *MASH* were used to evaluate the crash tests reported herein. Table 4.1. lists the test conditions and evaluation criteria required for *MASH* TL-3, and Table 4.2 provides detailed information on the evaluation criteria. An evaluation of the crash test results is presented in Chapter 7.

Table 4.2. Evaluation Criteria Required for *MASH* TL-3 Longitudinal Barriers.

Evaluation Factors	Evaluation Criteria	*MASH* Test
Structural Adequacy	*A. Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.*	*3-10 and 3-11*
Occupant Risk	*D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone.* *Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of MASH.*	*3-10 and 3-11*
	F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.	*3-10 and 3-11*
	H. Occupant impact velocities (OIV) should satisfy the following limits: Preferred value of 30 ft/s, or maximum allowable value of 40 ft/s.	*3-10 and 3-11*
	I. The occupant ridedown accelerations should satisfy the following: Preferred value of 15.0 g, or maximum allowable value of 20.49 g.	*3-10 and 3-11*

CHAPTER 5. TEST CONDITIONS

5.1. TEST FACILITY

The full-scale crash tests reported herein were performed at the TTI Proving Ground, an International Standards Organization (ISO)/International Electrotechnical Commission (IEC) 17025-accredited laboratory with American Association for Laboratory Accreditation (A2LA) Mechanical Testing Certificate 2821.01. The full-scale crash tests were performed according to TTI Proving Ground quality procedures, as well as *MASH* guidelines and standards.

The test facilities of the TTI Proving Ground are located on The Texas A&M University System RELLIS Campus, which consists of a 2000-acre complex of research and training facilities situated 10 mi northwest of the flagship campus of Texas A&M University. The site, formerly a United States Army Air Corps base, has large expanses of concrete runways and parking aprons well suited for experimental research and testing in the areas of vehicle performance and handling, vehicle-roadway interaction, highway pavement durability and efficacy, and roadside safety hardware and perimeter protective device evaluation. The site selected for construction and testing of the Guardrail without downstream anchorage was along the edge of an out-of-service apron. The apron consists of an unreinforced jointed-concrete pavement in 12.5-ft × 15-ft blocks nominally 6 inches deep. The aprons were built in 1942, and the joints have some displacement but are otherwise flat and level.

5.2. VEHICLE TOW AND GUIDANCE SYSTEM

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

5.3. DATA ACQUISITION SYSTEMS

5.3.1. Vehicle Instrumentation and Data Processing

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

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

TRAP uses the DAS-captured data to compute the occupant/compartment impact velocities, time of occupant/compartment impact after vehicle impact, and highest 10-millisecond (ms) average ridedown acceleration. TRAP calculates change in vehicle velocity at the end of a given impulse period. In addition, maximum average accelerations over 50-ms intervals in each of the three directions are computed. For reporting purposes, the data from the vehicle-mounted accelerometers are filtered with an SAE Class 180-Hz low-pass digital filter, and acceleration versus time curves for the longitudinal, lateral, and vertical directions are plotted using TRAP.

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

5.3.2. Anthropomorphic Dummy Instrumentation

According to *MASH*, use of a dummy in the 2270P vehicle is optional, and no dummy was used in the test.

5.3.3. Photographic Instrumentation Data Processing

Photographic coverage of each test included three digital high-speed cameras:

- One overhead with a field of view perpendicular to the ground and directly over the impact point.
- One placed upstream from the installation at an angle to have a field of view of the interaction of the rear of the vehicle with the installation.
- A third placed with a field of view parallel to and aligned with the installation at the downstream end.

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

CHAPTER 6. *MASH* TEST 3-11 (CRASH TEST NO. 614721-01-2)

6.1. TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

MASH Test 3-11 involves a 2270P vehicle weighing 5000 lb ± 110 lb impacting the CIP of the longitudinal barrier at an impact speed of 62 mi/h ± 2.5 mi/h and an angle of 25 degrees ± 1.5 degrees. The CIP for *MASH* Test 3-11 on the guardrail without downstream anchorage was 42 inches ± 12 inches upstream of the centerline of post 11. Figure 4.1 and Figure 6.1 depict the target impact setup.

Figure 6.1. Guardrail without downstream anchorage/Test Vehicle Geometrics for Test No. 614721-01-2.

The 2270P vehicle weighed 5035 lb, and the actual impact speed and angle were 62.8 mi/h and 25.4 degrees. The actual impact point was 46.3 inches upstream of the centerline of post 11. Minimum target IS was 106 kip-ft, and actual IS was 122.1 kip-ft.

6.2. WEATHER CONDITIONS

The test was performed on the morning of April 6, 2021. Weather conditions at the time of testing were as follows: wind speed: 11 mi/h; wind direction: 163 degrees (vehicle was traveling at a heading of 195 degrees); temperature: 72°F; relative humidity: 88 percent.

6.3. TEST VEHICLE

Figure 6.2 shows the 2017 RAM 1500 pickup truck used for the crash test. The vehicle's test inertia weight was 5035 lb, and its gross static weight was 5035 lb. The height to the lower edge of the vehicle bumper was 11.75 inches, and height to the upper edge of the bumper was 27.0 inches. The height to the vehicle's center of gravity was 28.25 inches. Tables C.1 and C.2 in Appendix C.1 give additional dimensions and information on the vehicle. The vehicle was directed into the installation using a cable reverse tow and guidance system and was released to be freewheeling and unrestrained just prior to impact.

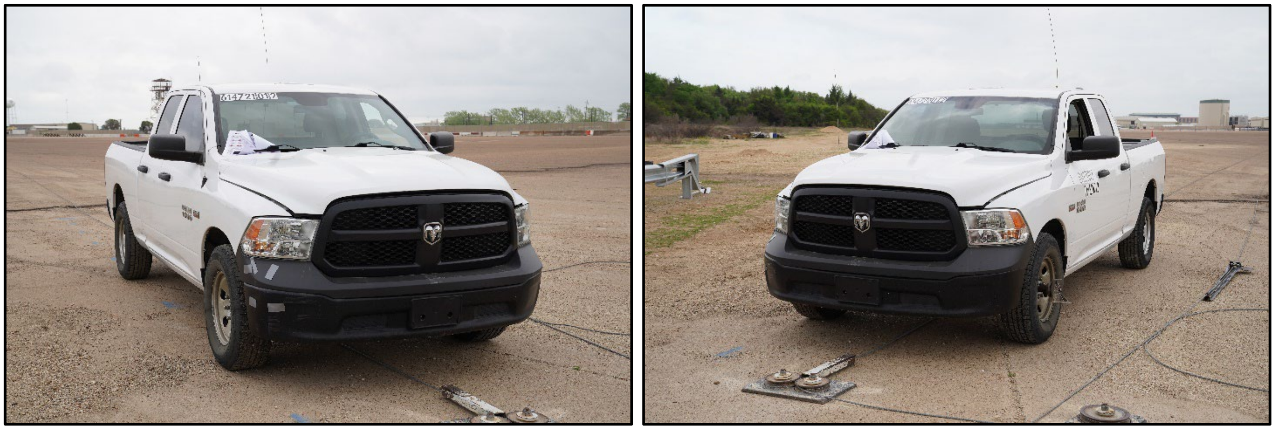


Figure 6.2. Test Vehicle before Test No. 614721-01-2.

6.4. TEST DESCRIPTION

Table 6.1 lists events that occurred during Test No. 614721-01-2. Figures C.1 and C.2 in Appendix C.2 present sequential photographs during the test.

Table 6.1. Events during Test No. 614721-01-2.

Time (s)	Events
0.0000	Vehicle impacted the guardrail
0.0188	Post 11 began to deflect towards the field side
0.0510	Vehicle began to redirect
0.0980	Rail element released from the downstream blockouts

For longitudinal barriers, it is desirable for the vehicle to redirect and exit the barrier within the exit box criteria (not less than 32.8 ft downstream from loss of contact for cars and pickups). The test vehicle did not exit within the exit box criteria defined in *MASH*. Brakes on the vehicle were not applied after impact. The vehicle subsequently came to rest 35 ft downstream of the point of impact and 19 ft toward the field side.

6.5. DAMAGE TO TEST INSTALLATION

Figure 6.3 shows the damage to the guardrail without downstream anchorage. The rail deformed and was partially torn in several places. The rail element released from the posts and blockouts from post 12 until the end of the installation. The blockout released from the rail element and post at posts 12, 13, and 15. The soil was disturbed at post 1, and 4 through 8. Please see Table 6.2 for measurements of post behavior.

Figure 6.3. Guardrail without downstream anchorage after Test No. 614721-01-2.

Table 6.2. Post Movement/Lean after Test No. 614721-01-2.

Post #	Post Lean	Soil Gap
Anchor	1½ inches u/s	-
2	-	1° f/s
9	¼-inch t/s	-
10	1¼ inches t/s; ½-inch f/s	2° f/s
11	7 inches t/s; ¼-inch f/s	20° f/s
12	-	64° d/s
13	-	68° d/s
14	-	77° d/s
15	-	66° d/s
16	-	64° d/s
17	¼-inch t/s; ¼-inch f/s	1° d/s

t/s=traffic side; f/s=field side; u/s=upstream; d/s=downstream

6.6. DAMAGE TO TEST VEHICLE

Figure 6.4 shows the damage sustained by the vehicle. The front bumper, hood, grill, radiator and support, right and left front fenders, right front tire and rim, right front and rear doors, right rear exterior bed, left rear door, left rear cab corner, and left rear exterior bed were damaged. No fuel tank damage was observed. Maximum exterior crush to the vehicle was 11.0 inches in the front plane at the right front corner at bumper height. No occupant compartment deformation or intrusion was observed. Figure 6.5 shows the interior of the vehicle. Tables C.3 and C.4 in Appendix C.1 provide exterior crush and occupant compartment measurements.

Figure 6.4. Test Vehicle after Test No. 614721-01-2.

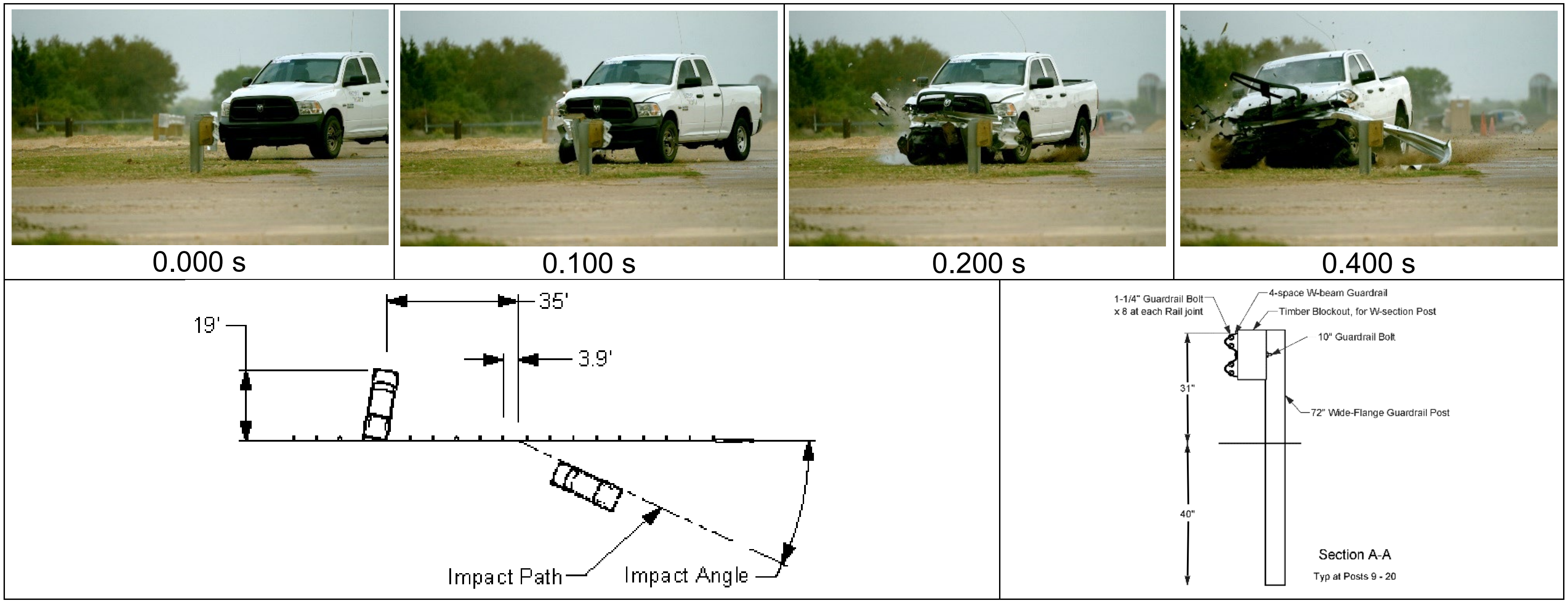
Figure 6.5. Interior of Test Vehicle after Test No. 614721-01-2.

6.7. OCCUPANT RISK FACTORS

Data from the accelerometers were digitized for evaluation of occupant risk, and the results are shown in Table 6.3. Figure C.3 in Appendix C.3 shows the vehicle angular displacements, and Figures C.4 through C.6 in Appendix C.4 show acceleration versus time traces. Figure 6.6 summarizes pertinent information from the test.

Table 6.3. Occupant Risk Factors for Test No. 614721-01-2.

Occupant Risk Factor	Value	Time
Occupant Impact Velocity (OIV)		
Longitudinal	16.4 ft/s	at 0.1707 s on right side of interior
Lateral	9.4 ft/s	
Occupant Ridedown Accelerations		
Longitudinal	8.4 g	0.4806 - 0.4906 s
Lateral	4.3 g	0.4192 - 0.4292 s
Theoretical Head Impact Velocity (THIV)	5.4 m/s	at 0.1619 s on right side of interior
Acceleration Severity Index (ASI)	0.6	0.0747 - 0.1247 s
Maximum 50-ms Moving Average		
Longitudinal	−6.1 g	0.5209 - 0.5709 s
Lateral	−4.6 g	0.0478 - 0.0978 s
Vertical	−2.9 g	0.1634 - 0.2134 s
Maximum Yaw, Pitch, and Roll Angles		
Roll	12°	1.0313 s
Pitch	9°	1.9637 s
Yaw	76°	1.3715 s



General Information	
Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard Test No.	*MASH* Test 3-11
TTI Test No.	614721-01-2
Test Date	2021-04-06
Test Article	
Type	Longitudinal Barrier—Guardrail
Name	Guardrail without downstream anchorage
Installation Length	125 ft-9½ inches
Material or Key Elements	W-beam rail element mounted at 31 inches on 72-inch long wide flange steel guardrail posts without downstream anchorage
Soil Type and Condition	Crushed concrete, dry
Test Vehicle	
Type/Designation	2270P
Make and Model	2017 RAM 1500 Pickup
Curb	5117 lb
Test Inertial	5035 lb
Dummy	No dummy
Gross Static	5035 lb

Impact Conditions	
Speed	62.8 mi/h
Angle	25.4°
Location/Orientation	46.3 inches upstream of post 11
Impact Severity	122.1 kip-ft
Exit Conditions	
Speed	Not Measurable
Trajectory/Heading Angle	Not Measurable
Occupant Risk Values	
Longitudinal OIV	16.4 ft/s
Lateral OIV	9.4 ft/s
Longitudinal Ridedown	8.4 g
Lateral Ridedown	4.3 g
THIV	5.4 m/s
ASI	0.6
Max. 0.050-s Average	
Longitudinal	−6.1 g
Lateral	−4.6 g
Vertical	−2.9 g

Post-Impact Trajectory	
Stopping Distance	35 ft downstream 19 ft twd field side
Vehicle Stability	
Maximum Roll Angle	12°
Maximum Pitch Angle	9°
Maximum Yaw Angle	76°
Vehicle Snagging	No
Vehicle Pocketing	No
Test Article Deflections	
Dynamic	Not Measurable
Permanent	Not Measurable
Working Width	Not Measurable
Height of Working Width	Not Measurable
Vehicle Damage	
VDS	01RFQ4
CDC	01FREW3
Max. Exterior Deformation	11.0 inches
Max. Occupant Compartment Deformation	None

Figure 6.6. Summary of Results for *MASH* Test 3-11 on Guardrail without downstream anchorage.

CHAPTER 7. COMPUTER SIMULATION EFFORT TO IMPROVE REDIRECTIVE CAPABILITY

7.1. INTRODUCTION

After the failed *MASH* test 3-11, the research team compared the predictive simulations discussed in Chapter 2 and the results of the physical crash test. The computer simulations failed to adequately represent the tensile resistance the w-beam guardrail slots provide for the guardrail bolt head. The physical crash test showed the w-beam guardrail slots allowed the bolts to pull through the rail sooner than what the simulation was predicting. Therefore, the research team initiated an effort to improve the predictive capability of the simulations, specifically the interaction between the w-beam guardrail slots and the guardrail bolt heads. Once the improvements were added to the FEA model, the researchers investigated methods to maintain connectivity between the w-beam guardrail and the downstream end posts.

7.2. SIMULATION MODEL IMPROVEMENTS

Following the failed crash test, the research team modified the finite element model to improve its predictive capability. This primarily focused on the ability of the computer simulations to predict the interaction between the guardrail bolts and the w-beam guardrail slots. To improve the predictive capability of this interaction, the research team refined the mesh size and the thickness of the elements around the slot.

7.2.1. 87.5-ft Guardrail System with 2.3 mm Slot Elements

To improve the accuracy of the simulated interaction between the bolts and w-beam rail, the researchers reduced the w-beam rail’s mesh size around the slot location. Furthermore, the researchers reduced the thickness of the elements around the slot to 2.3 mm from the original 2.6 mm. Figure 7.1 shows an overhead view of the finite element model.

Figure 7.1. Overhead View of 2.2.8 Guardrail System

The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 63.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.2.

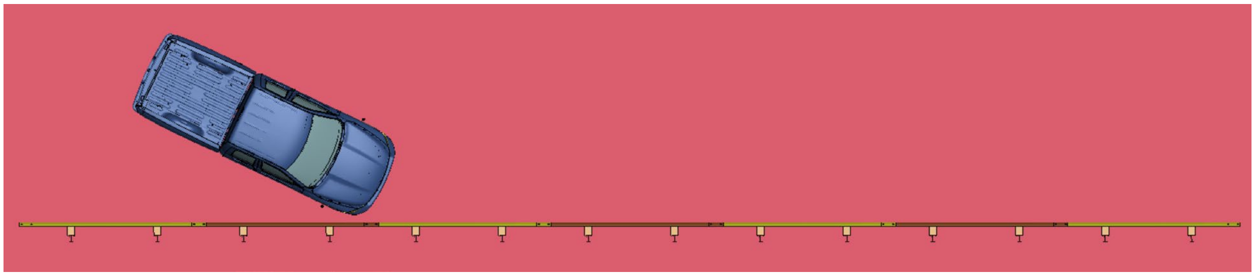


Figure 7.2. Overhead View of Impact Point for 2.2.8 Guardrail System

Figure 7.3, Figure 7.4, Figure 7.5, and Figure 7.6 show the sequential frames of *MASH* Test 3-11 on the 87.5-ft system with refined slot mesh. During the impact, the w-beam rail was pulled from the downstream end posts and consequently lost its ability to redirect the pickup truck. The simulation could have improved in similarity to the physical crash test, and therefore, the researchers further refined the model as discussed in the following section.

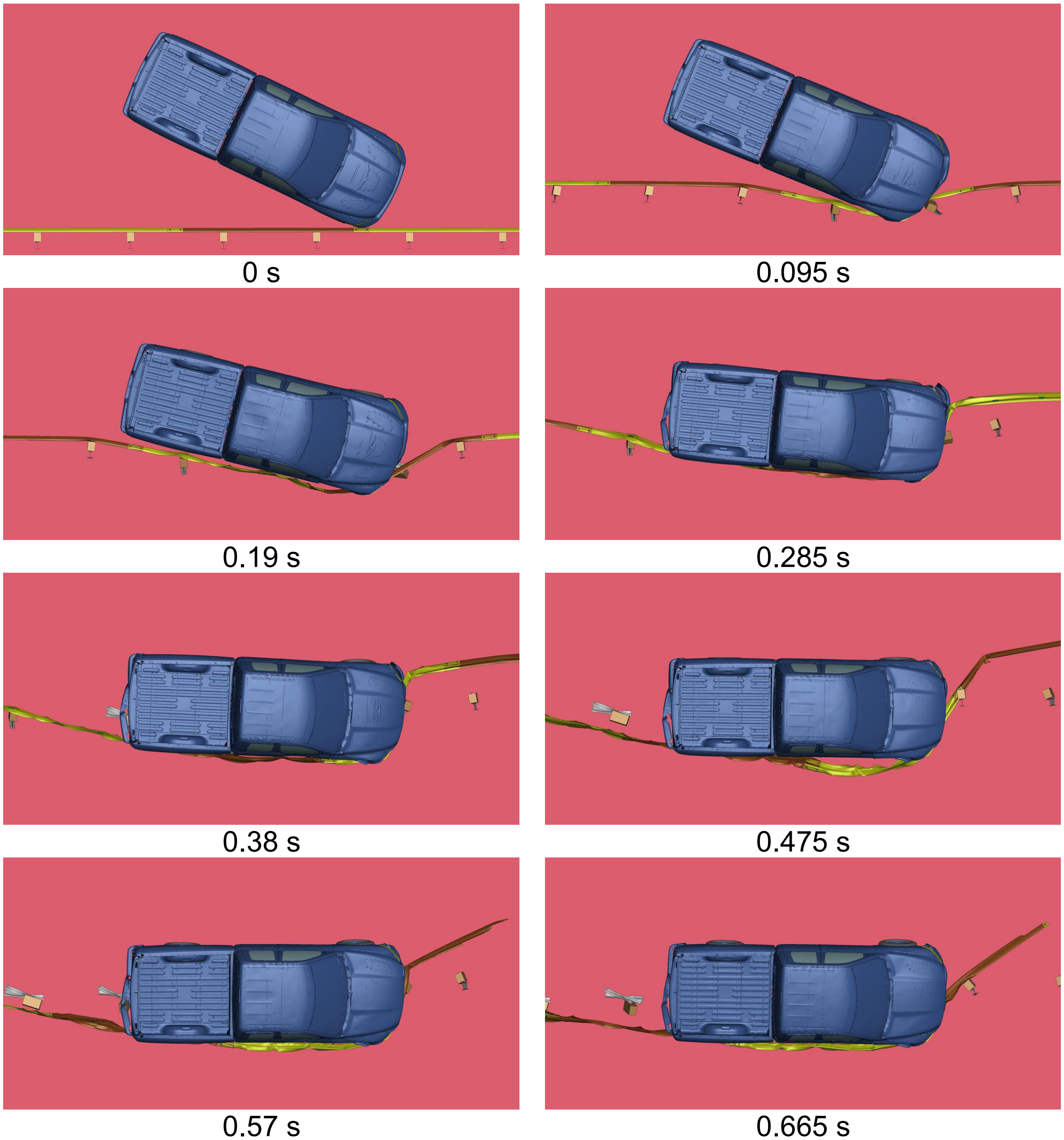


Figure 7.3. 87.5-ft Guardrail System with 2.3 mm Slot Elements – Overhead View of MASH Test 3-11

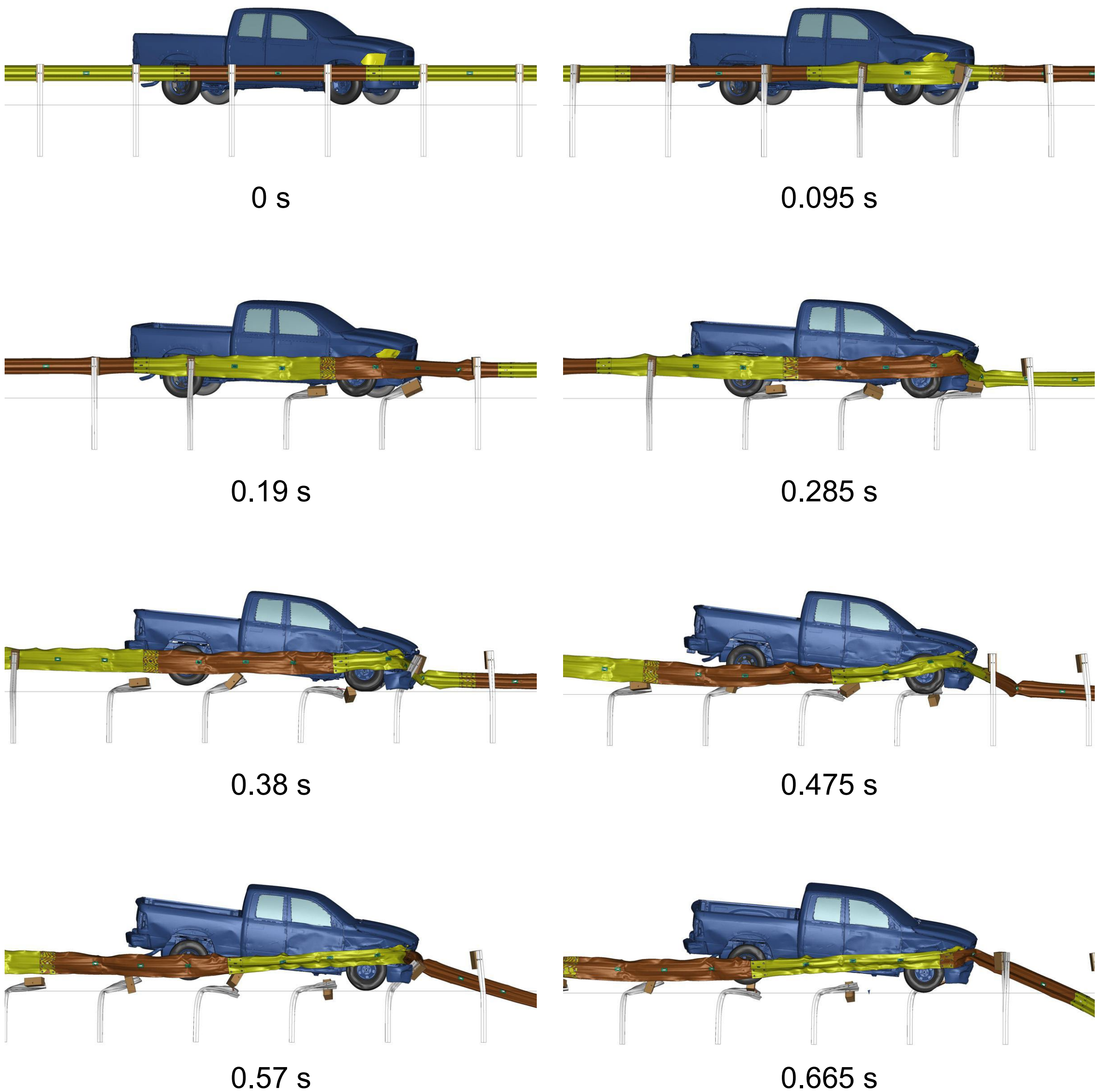


Figure 7.4. 87.5-ft Guardrail System with 2.3 mm Slot Elements – Rear View of *MASH* Test 3-11

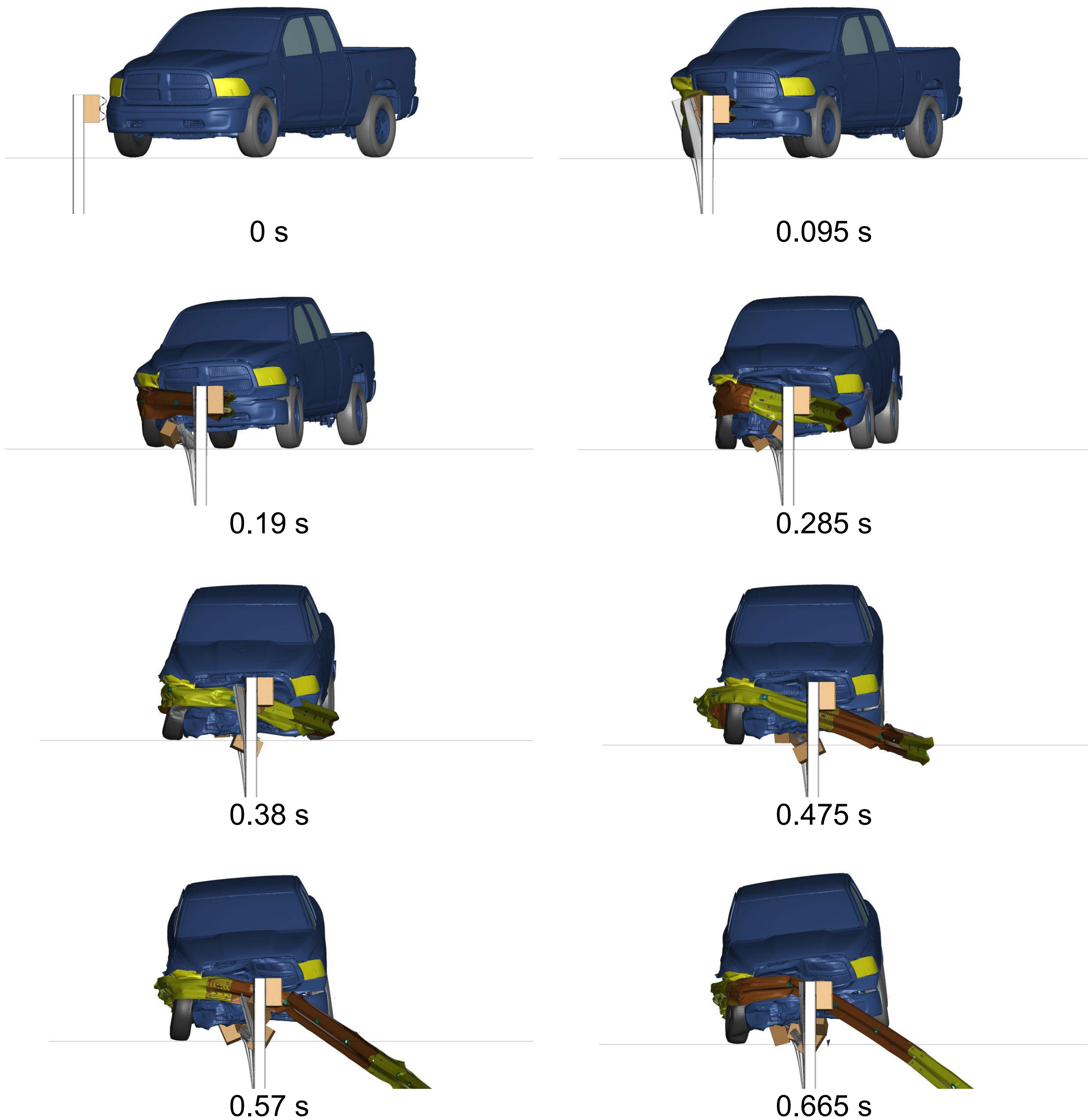


Figure 7.5. 87.5-ft Guardrail System with 2.3 mm Slot Elements – Downstream View of *MASH* Test 3-11

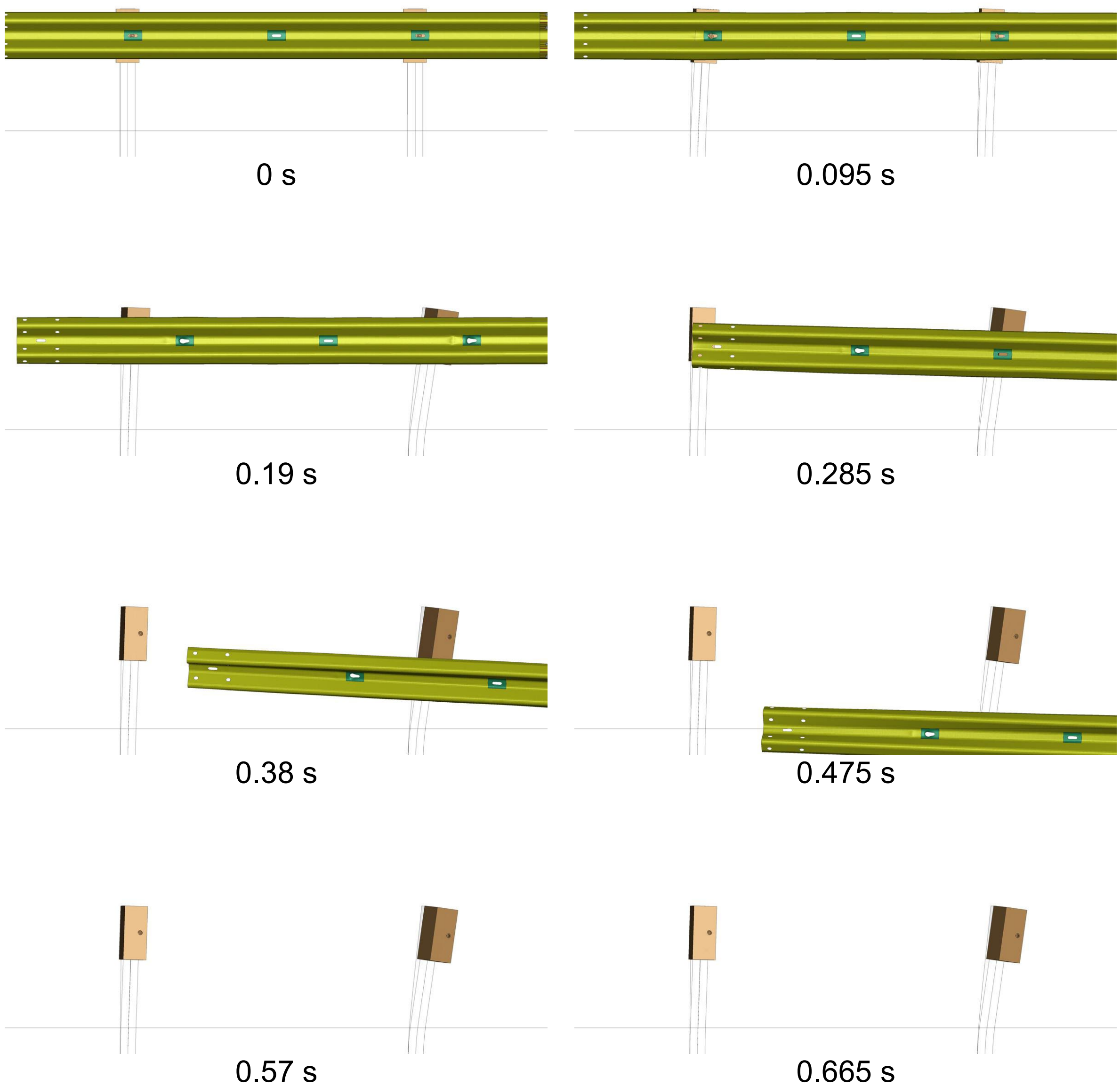


Figure 7.6. 87.5-ft Guardrail System with 2.3 mm Slot Elements – Front View of Downstream End Posts During *MASH* Test 3-11

7.2.2. 87.5-ft Guardrail System with 2.4 mm Slot Elements

The thickness of the refined mesh slot elements was increased from 2.3 mm, simulated in 2.2.8, to 2.4 mm. Figure 7.7 shows an overhead view of the finite element model.

Figure 7.7. Overhead View of 87.5-ft Long Guardrail System

The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 63.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.8.

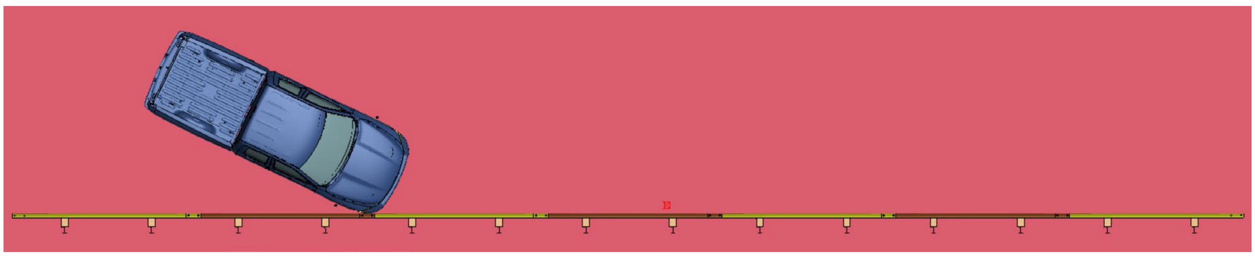


Figure 7.8. Overhead View of Impact Point for 87.5-ft Long Guardrail System

Figure 7.9, Figure 7.10, Figure 7.11, and Figure 7.12 show the sequential frames of *MASH* Test 3-11 on the 87.5-ft system with 2.4 mm thick refined slot elements. During the impact, the w-beam rail was pulled off the posts downstream of impact and consequently lost its ability to redirect the pickup truck. The simulation needed improvement in similarity to the physical crash test, and therefore, the researchers further refined the model as discussed in the following section. The truck did exhibit node entanglement simulation issues with the w-beam rail, but these occurred after the w-beam rail was pulled off the downstream posts.

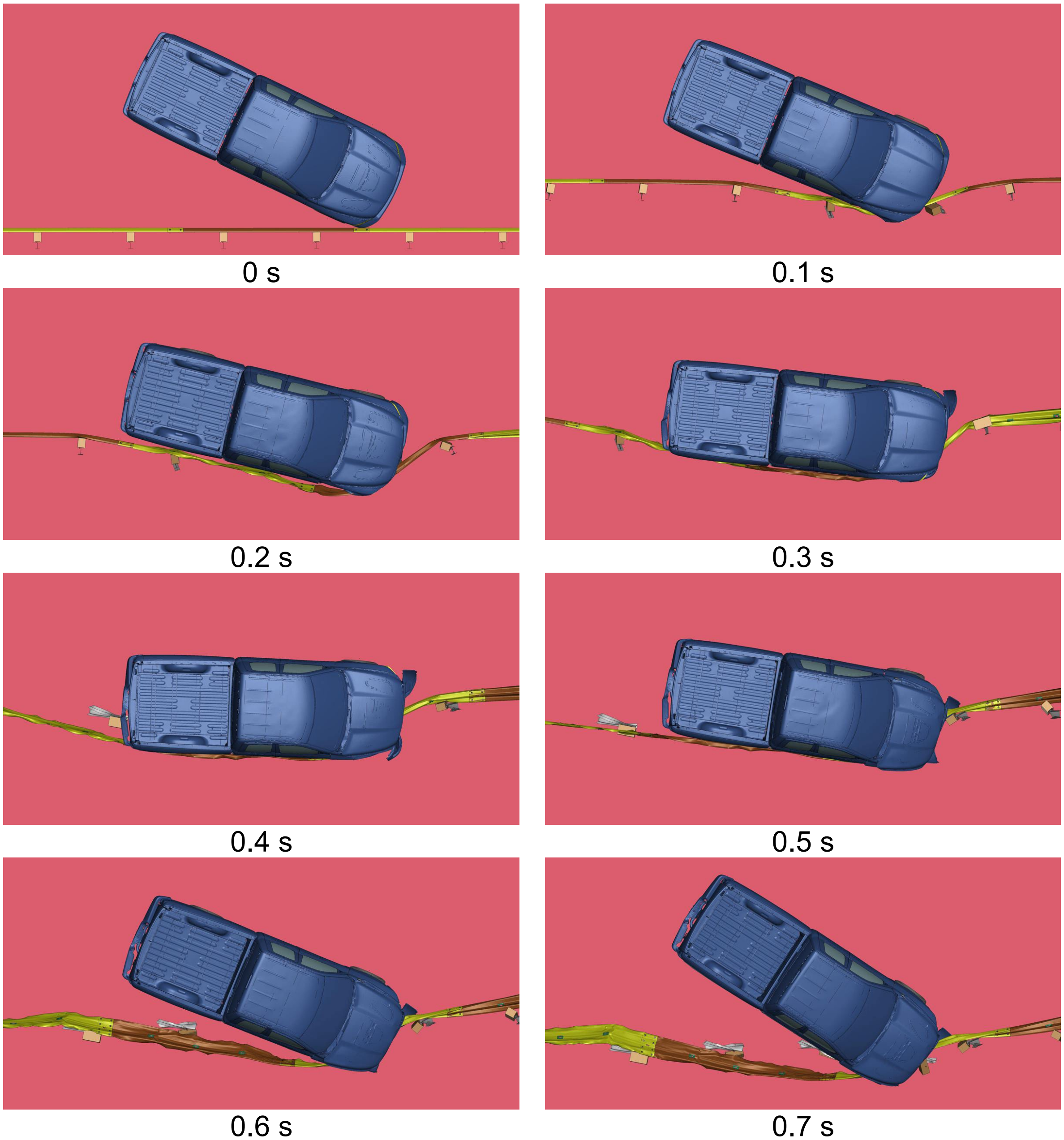


Figure 7.9. 87.5-ft Guardrail System with 2.4 mm Slot Elements – Overhead View of *MASH* Test 3-11

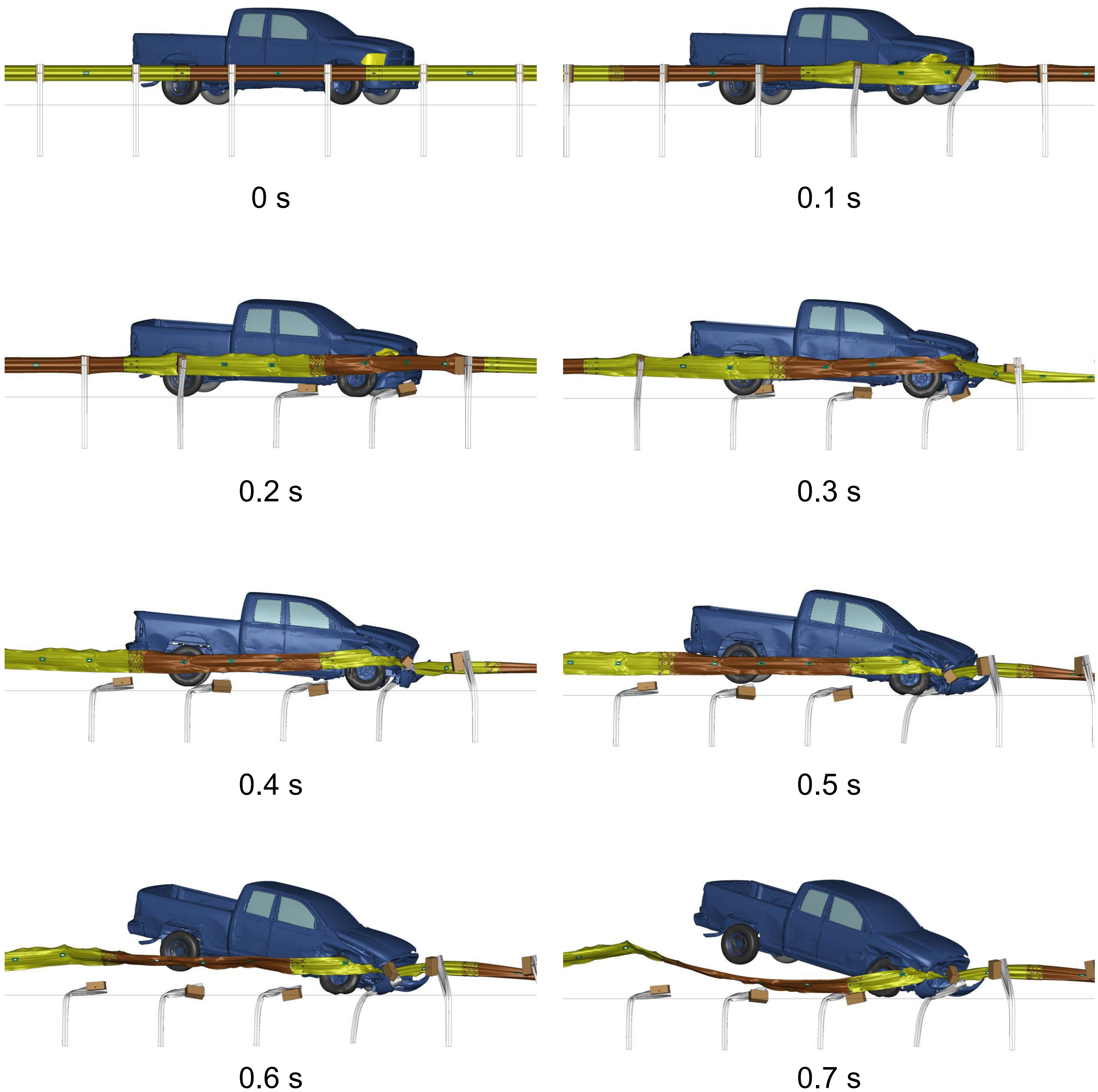


Figure 7.10. 87.5-ft Guardrail System with 2.4 mm Slot Elements – Rear View of *MASH* Test 3-11

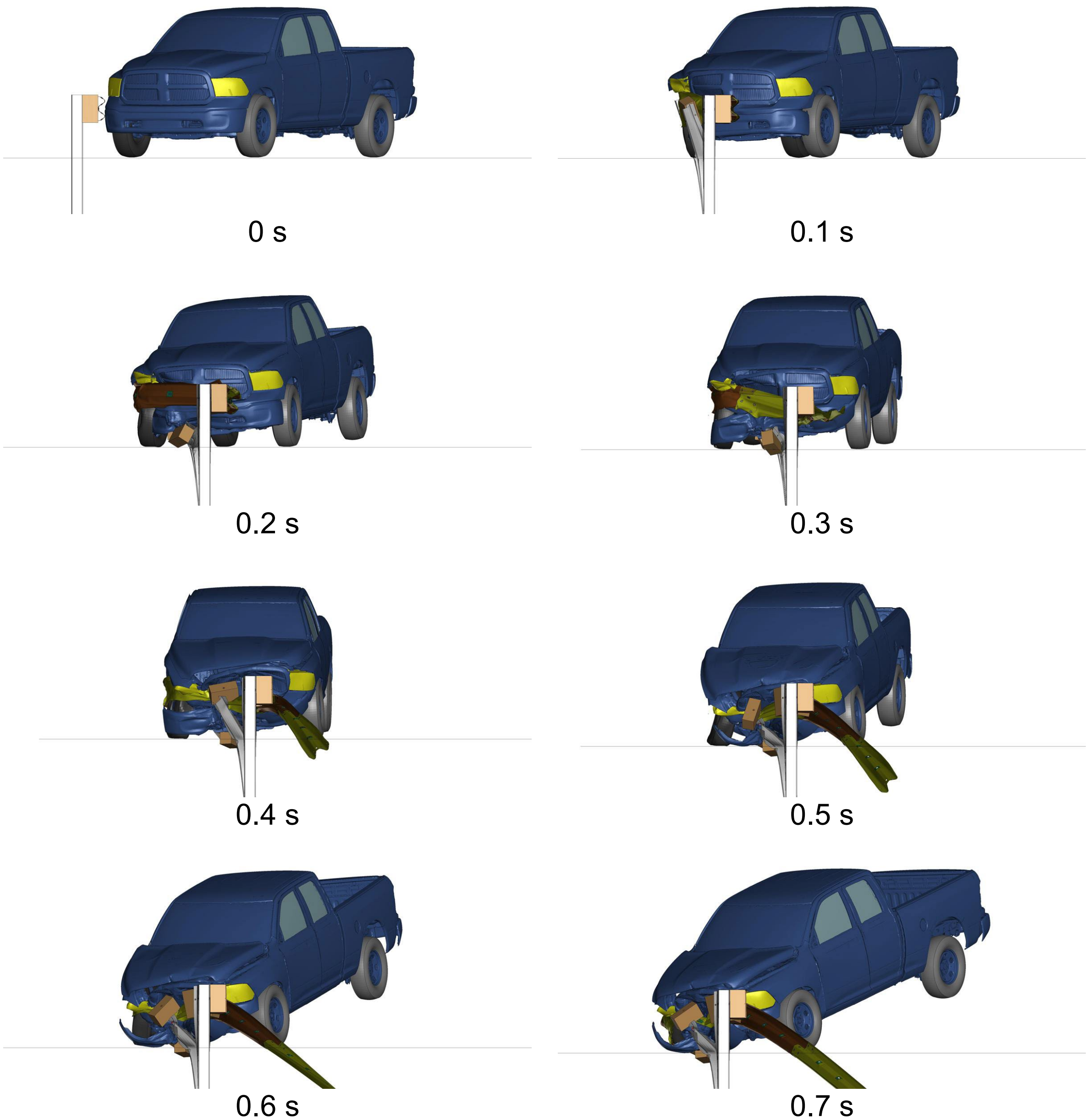


Figure 7.11. 87.5-ft Guardrail System with 2.4 mm Slot Elements – Downstream View of *MASH* Test 3-11

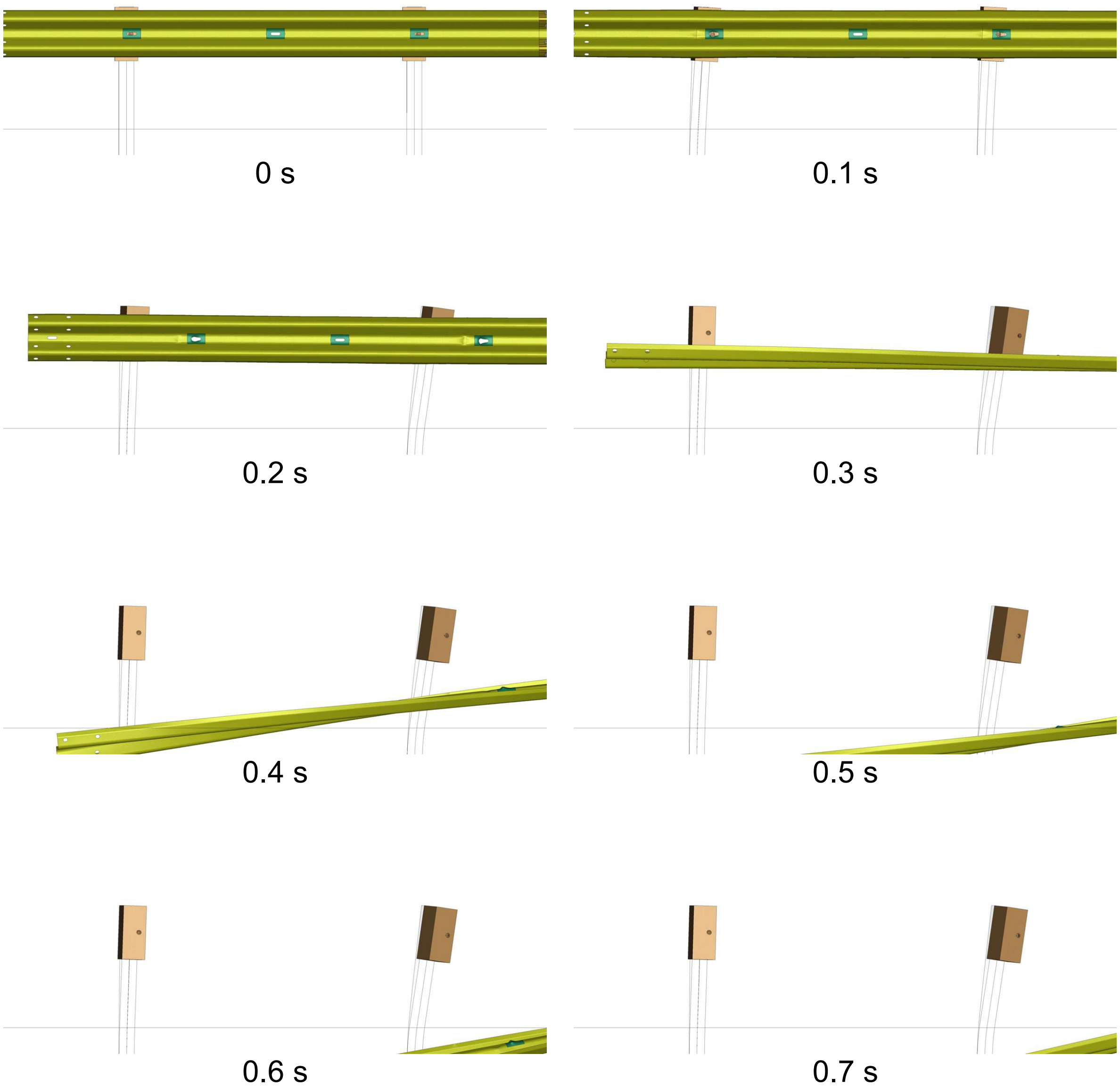


Figure 7.12. 87.5-ft Guardrail System with 2.4 mm Slot Elements – Front View of Downstream Posts During *MASH* Test 3-11

7.2.3. 87.5-ft Guardrail System with 2.5 mm Slot Elements

The thickness of the refined mesh slot was increased from 2.4 mm, simulated in 2.2.9, to 2.5 mm. Figure 7.13 shows an overhead view of the finite element model.

Figure 7.13. Overhead View of 87.5-ft Long Guardrail System

The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 63.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.14.

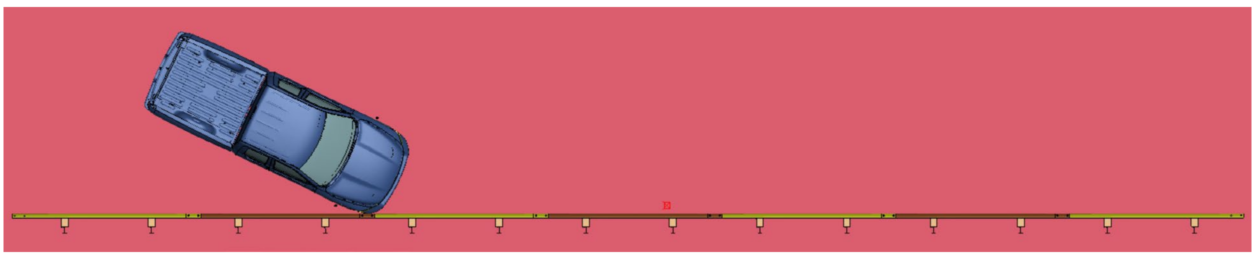
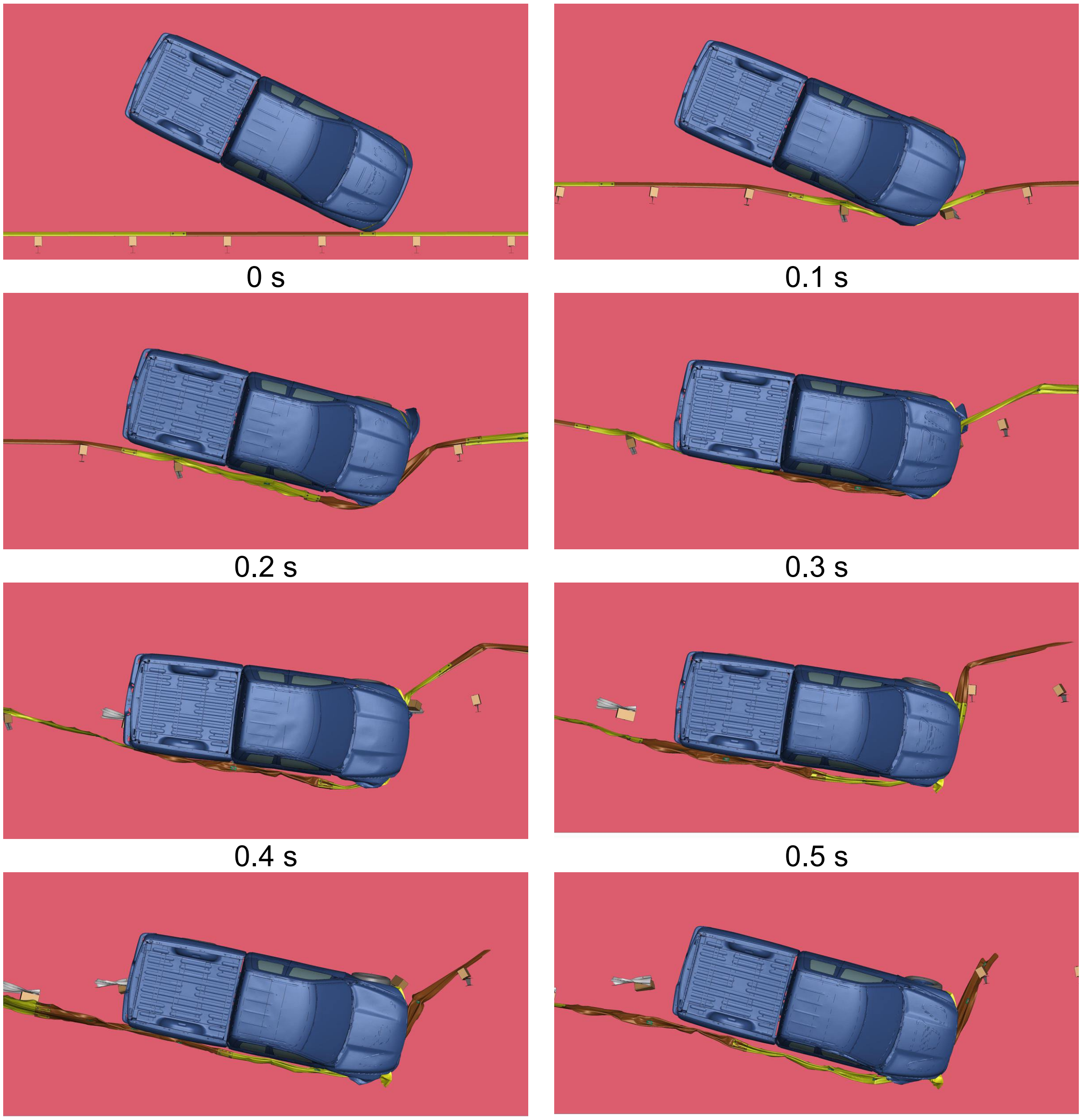


Figure 7.14. Overhead View of Impact Point for 87.5-ft Long Guardrail System

Figure 7.15, Figure 7.16, Figure 7.17, and Figure 7.18 show the sequential frames of *MASH* Test 3-11 on the 87.5-ft system with 2.5 mm thick refined slot elements. During the impact, the w-beam rail was pulled off the posts downstream of impact and consequently lost its ability to redirect the pickup truck. The simulation could have improved in similarity to the physical crash test, and therefore, the researchers further refined the model as discussed in the following section.



0 s
0.1 s
0.2 s
0.3 s
0.4 s
0.5 s
0.6 s
0.7 s

Figure 7.15. 87.5-ft Guardrail System with 2.5 mm Slot Elements – Overhead View of *MASH* Test 3-11

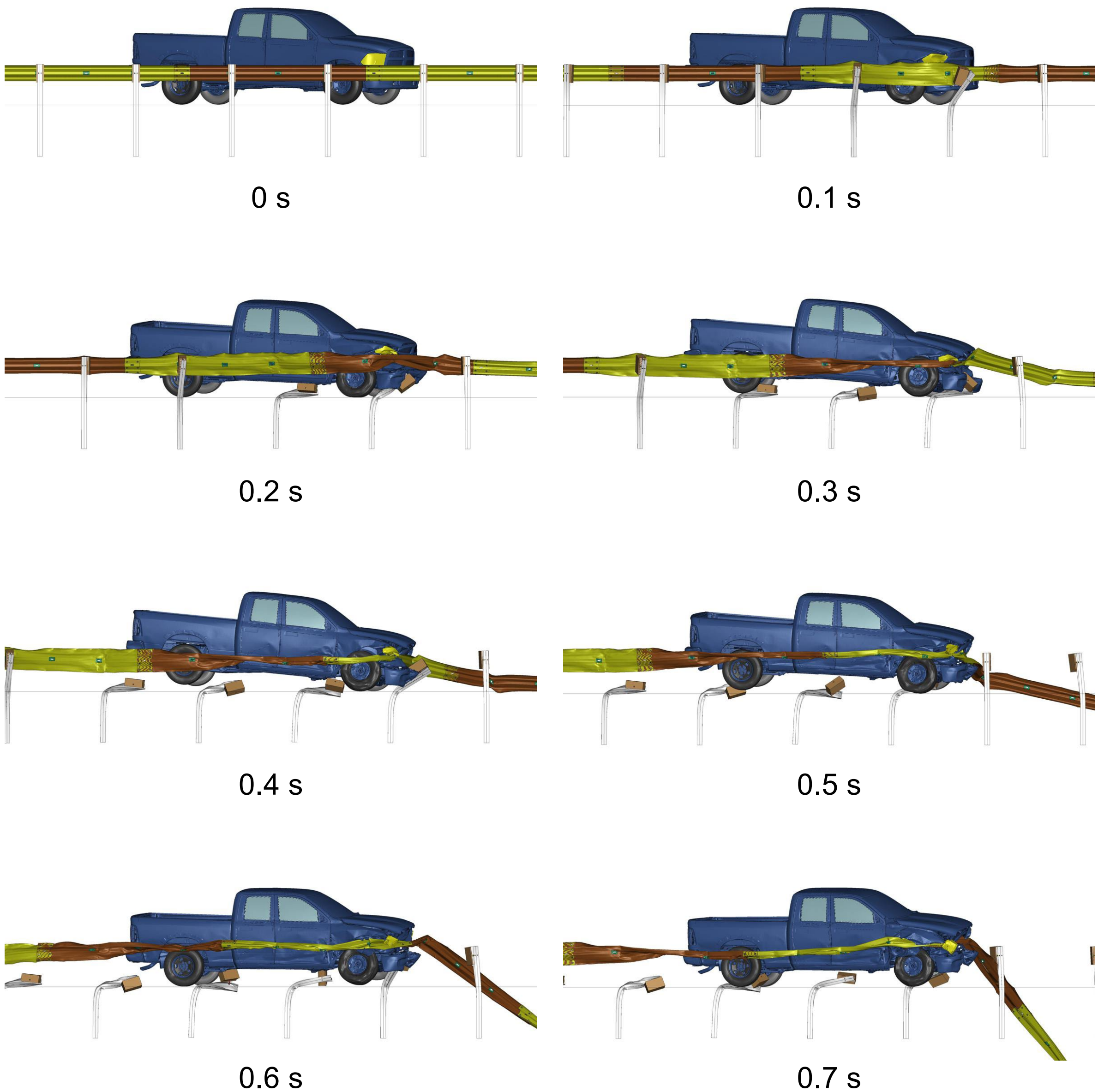


Figure 7.16. 87.5-ft Guardrail System with 2.5 mm Slot Elements – Rear View of *MASH* Test 3-11

Figure 7.17. 87.5-ft Guardrail System with 2.5 mm Slot Elements – Downstream View of *MASH* Test 3-11

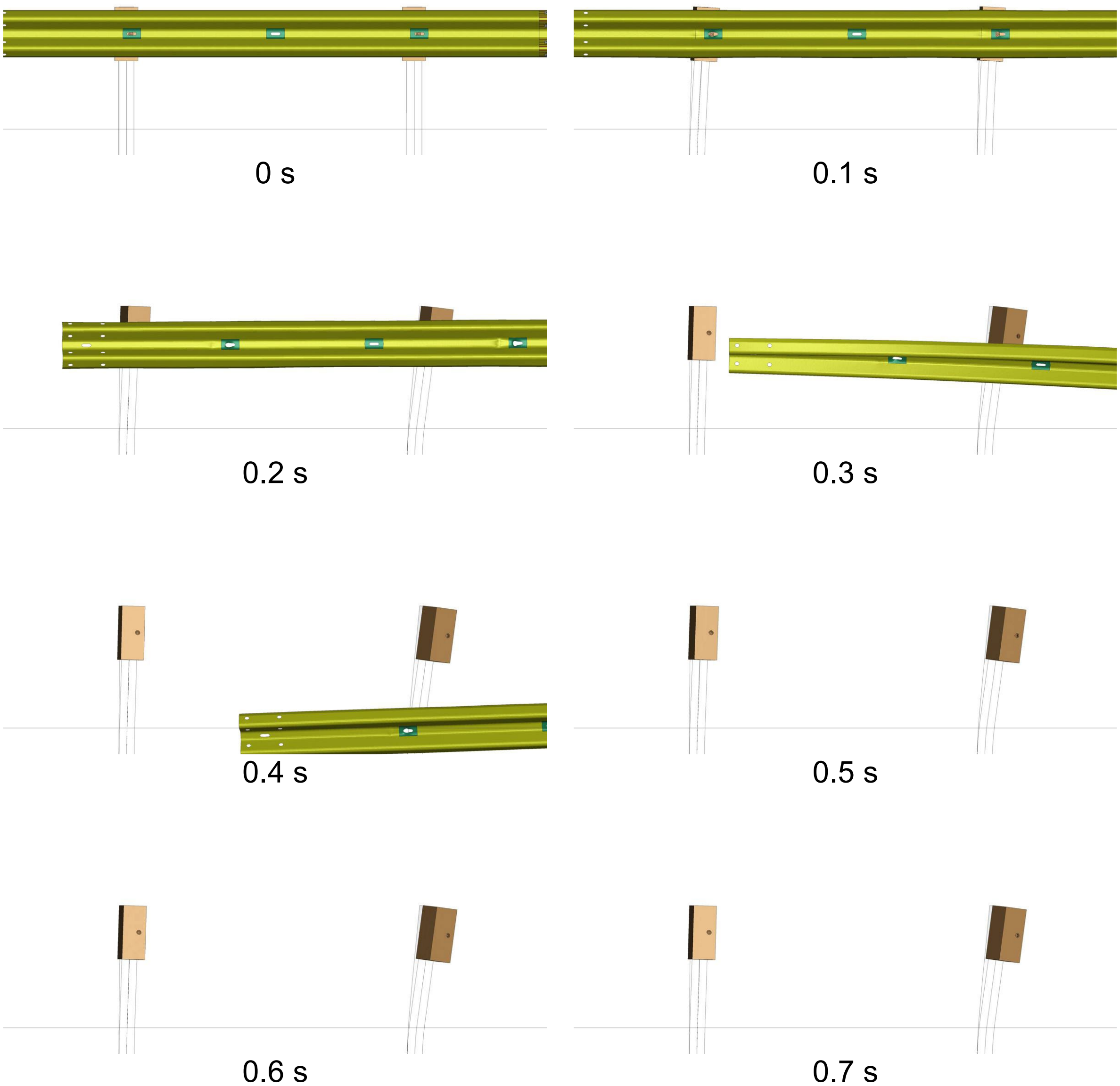


Figure 7.18. 87.5-ft Guardrail System with 2.5 mm Slot Elements – Front View of Downstream Posts During *MASH* Test 3-11

7.2.4. 87.5-ft Guardrail System with 2.6 mm Slot Elements

To reflect the results of physical crash testing more accurately, the thickness of the refined mesh slot was increased from 2.5 mm, simulated in 2.2.10, to 2.6 mm. Figure 7.19 shows an overhead view of the finite element model.

Figure 7.19. Overhead View of 87.5-ft Long Guardrail System

The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 63.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.20.

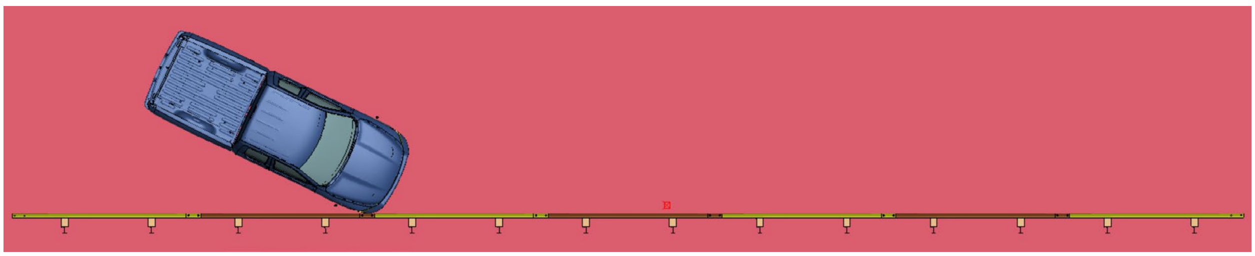


Figure 7.20. Overhead View of Impact Point for 87.5-ft Long Guardrail System

Figure 7.21, Figure 7.22, Figure 7.23, and Figure 7.24 show the sequential frames of *MASH* Test 3-11 on the 87.5-ft system with 2.6 mm thick refined slot elements. During the impact, the w-beam rail was pulled off the posts downstream of impact and consequently lost its ability to redirect the pickup truck. The simulation could have improved in similarity to the physical crash test, and therefore, the researchers further refined the model as discussed in the following section.

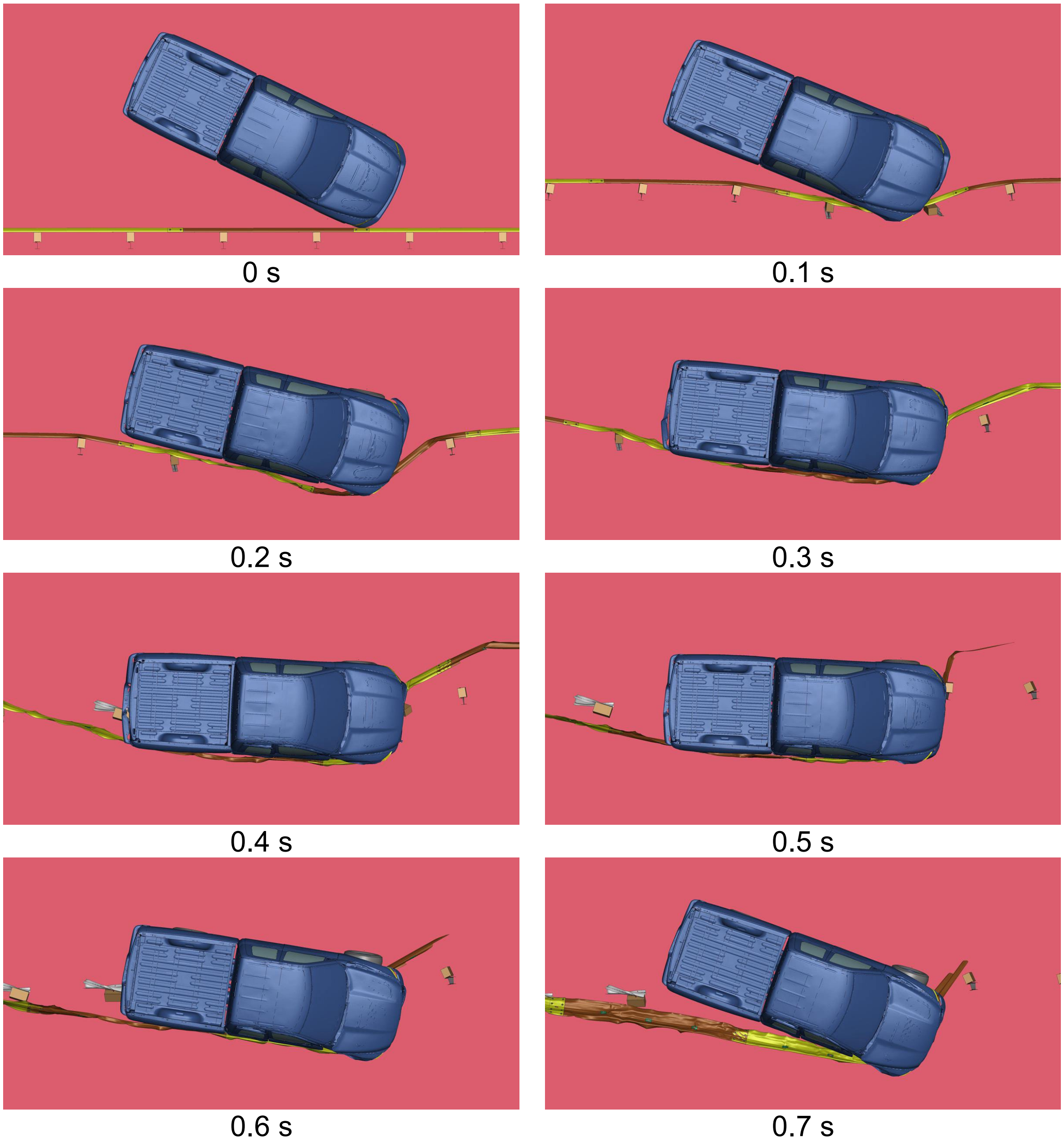


Figure 7.21. 87.5-ft Guardrail System with 2.6 mm Slot Elements – Overhead View of *MASH* Test 3-11

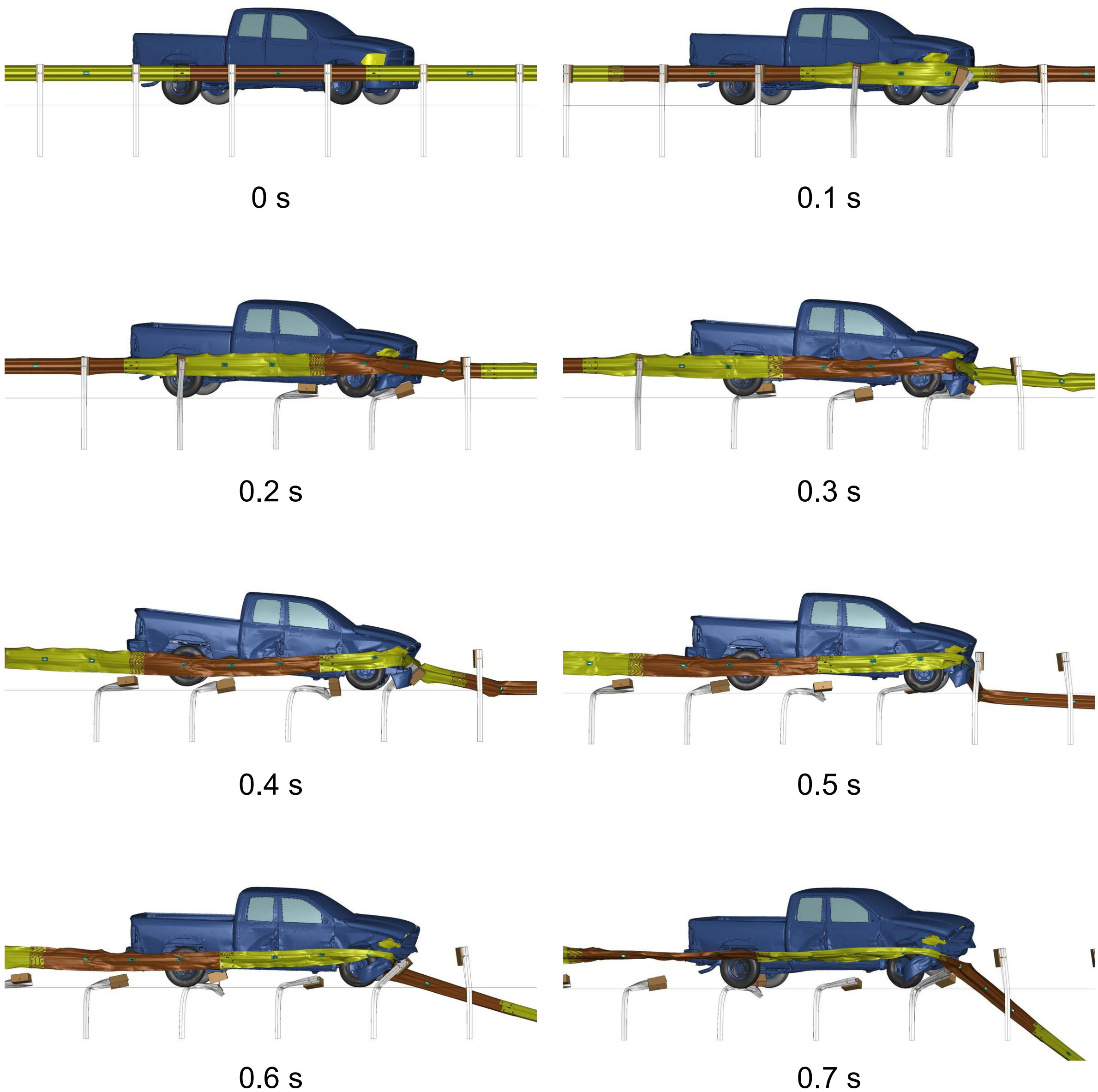


Figure 7.22. 87.5-ft Guardrail System with 2.6 mm Slot Elements – Rear View of *MASH* Test 3-11

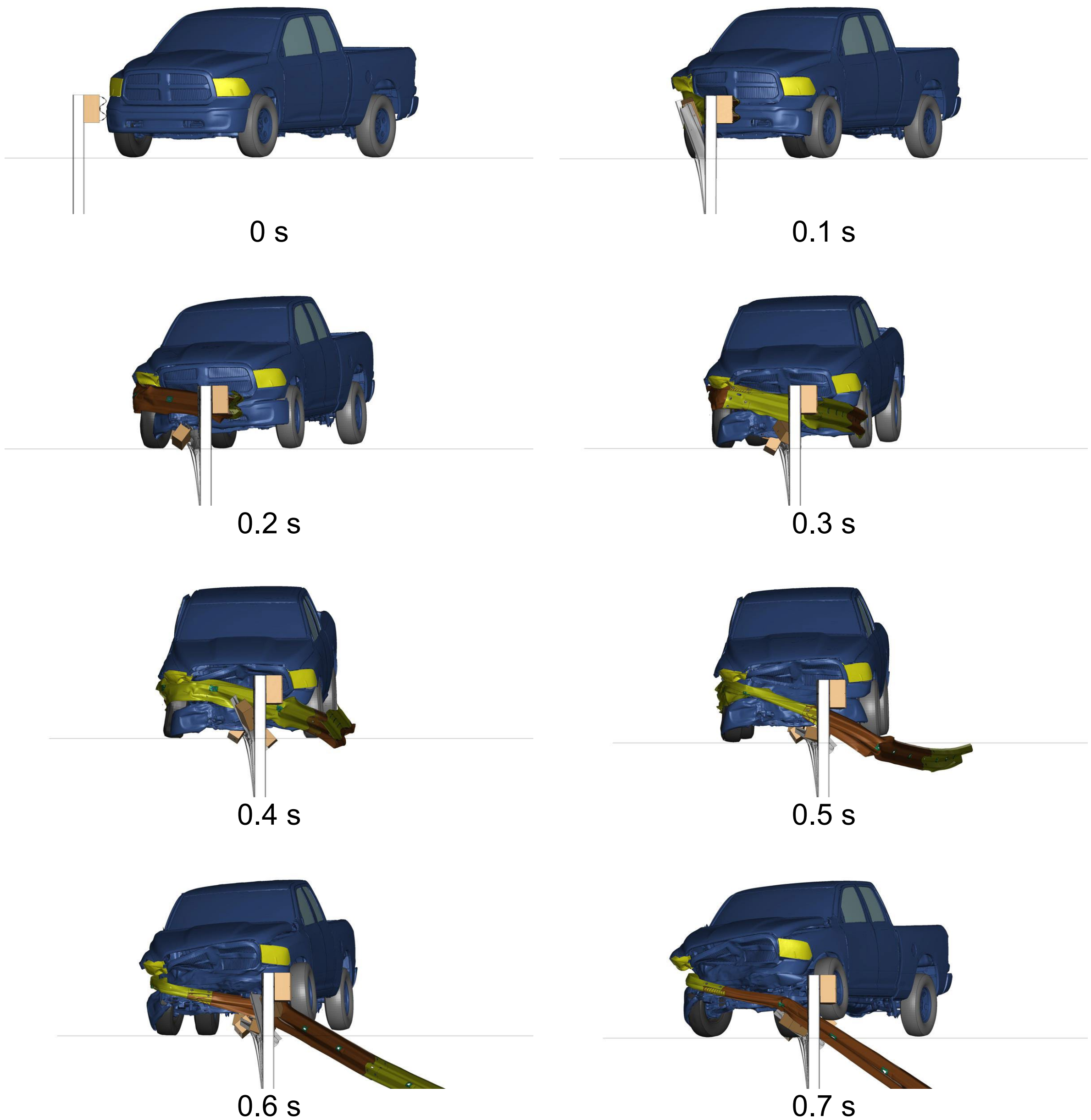


Figure 7.23. 87.5-ft Guardrail System with 2.6 mm Slot Elements – Downstream View of *MASH* Test 3-11

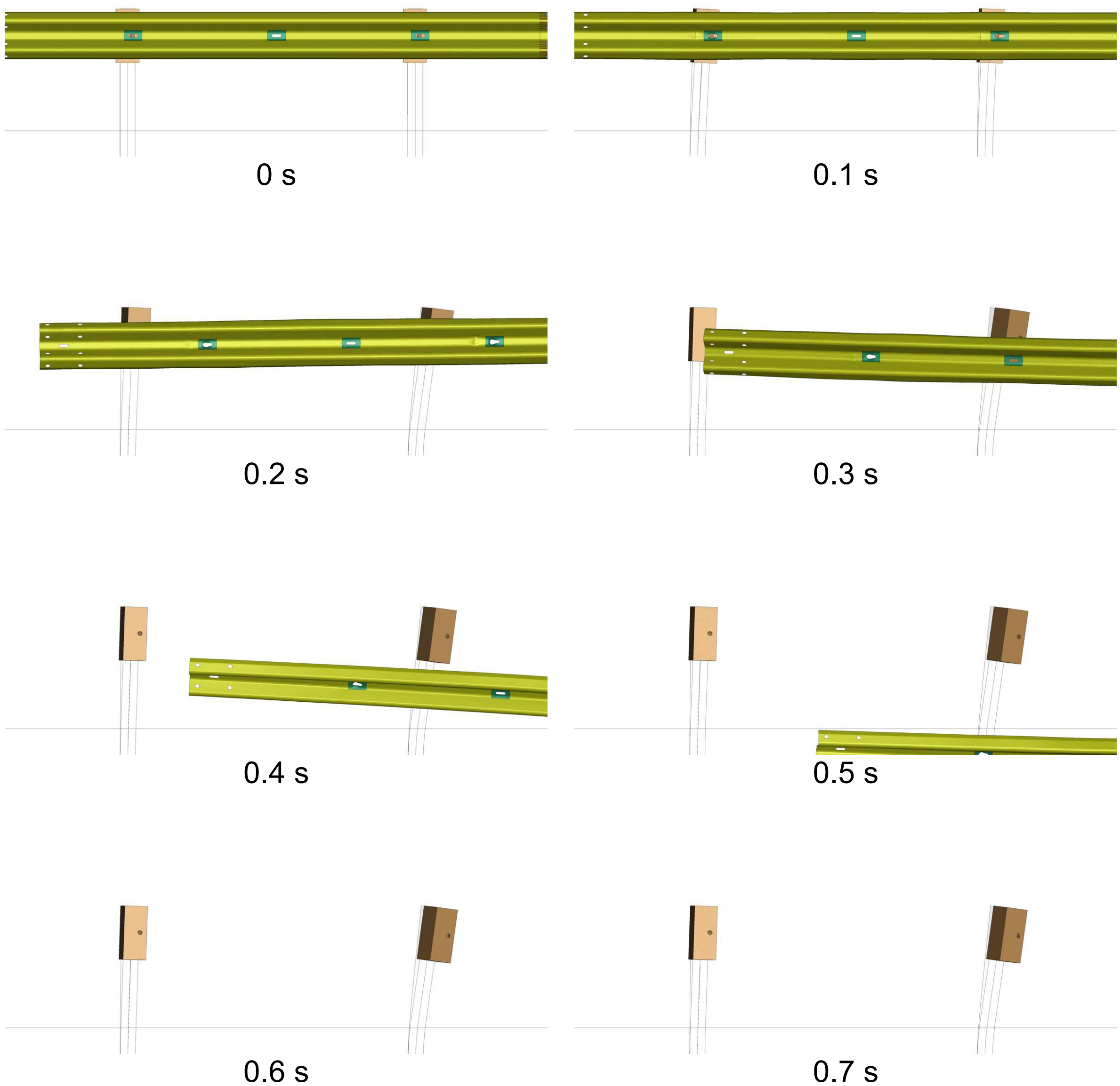


Figure 7.24. 87.5-ft Guardrail System with 2.6 mm Slot Elements – Front View of Downstream Posts During *MASH* Test 3-11

7.2.5. 87.5-ft Guardrail System with 1 mm Slot Elements

The thickness of the refined mesh slot was decreased from 2.6 mm, simulated in 2.2.11, to 1 mm. Figure 7.25 shows an overhead view of the finite element model.

Figure 7.25. Overhead View of 87.5-ft Long Guardrail System

The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 63.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.26.

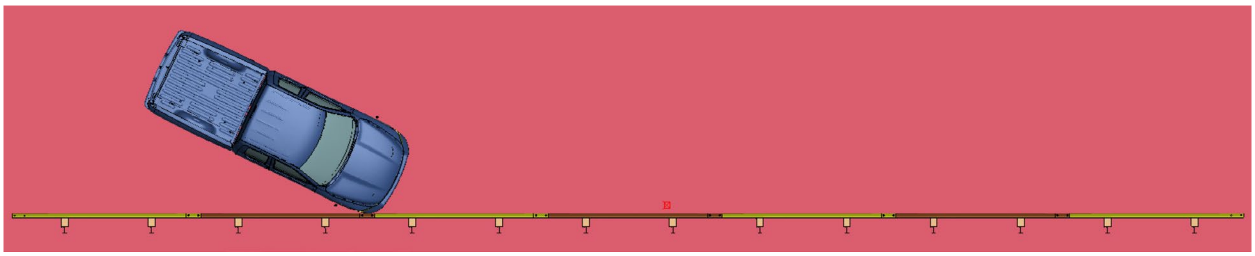


Figure 7.26. Overhead View of Impact Point for 87.5-ft Long Guardrail System

Figure 7.27, Figure 7.28, Figure 7.29, and Figure 7.30 show the sequential frames of *MASH* Test 3-11 on the 87.5-ft system with 2.6 mm thick refined slot elements. During the impact, the w-beam rail was pulled off the posts downstream of impact and consequently lost its ability to redirect the pickup truck. This simulation most closely matched the previous physical crash test. Therefore, a refined mesh slot element thickness of 1 mm was utilized in future simulations.

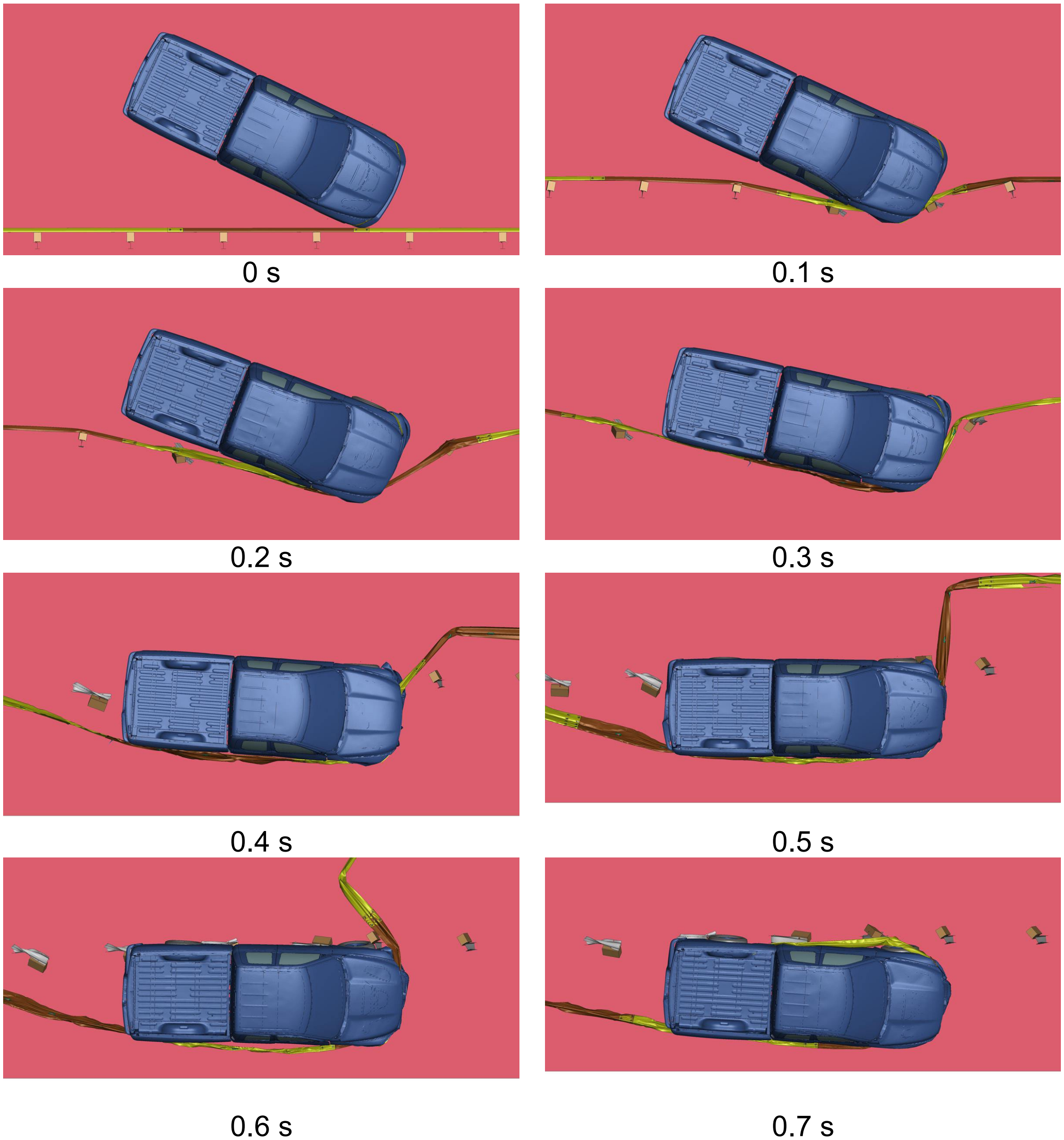


Figure 7.27. 87.5-ft Guardrail System with 1 mm Slot Elements – Overhead View of *MASH* Test 3-11

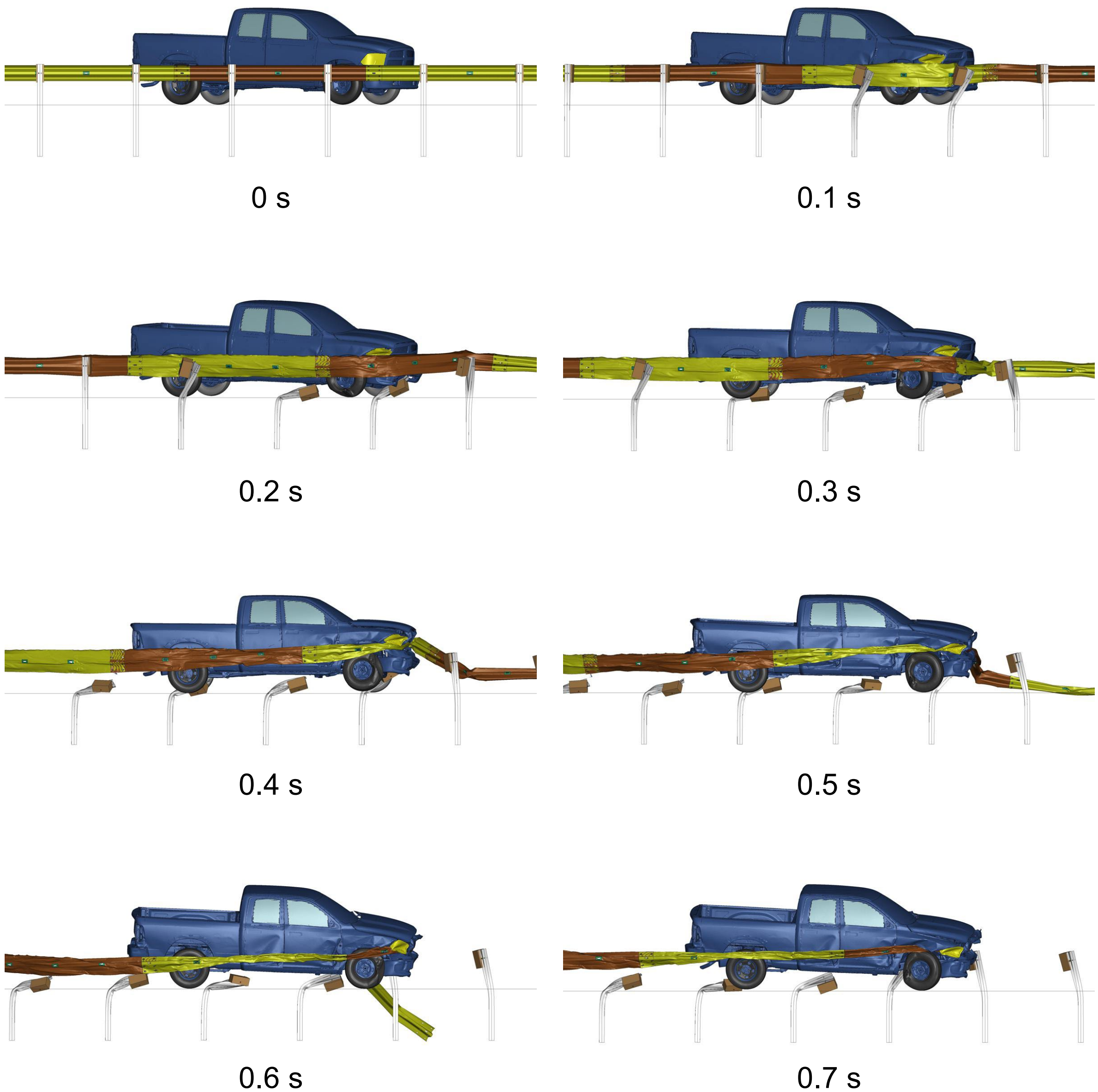


Figure 7.28. 87.5-ft Guardrail System with 1 mm Slot Elements – Rear View of *MASH* Test 3-11

Figure 7.29. 87.5-ft Guardrail System with 1 mm Slot Elements – Downstream View of *MASH* Test 3-11

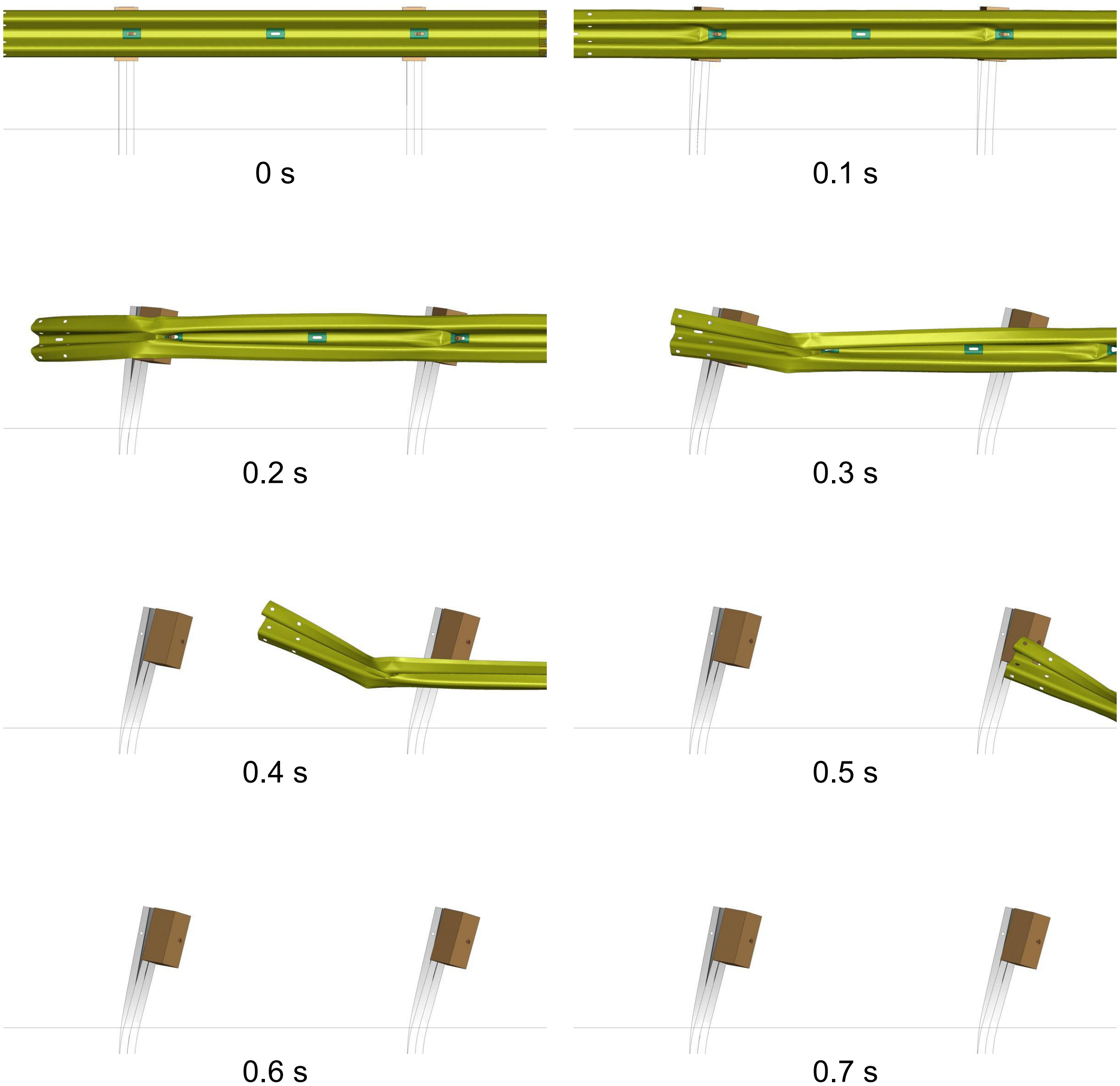


Figure 7.30. 87.5-ft Guardrail System with 1 mm Slot Elements – Front View of Downstream Posts During *MASH* Test 3-11

7.3. DETERMINATION OF REQUIRED ADDITIONAL LENGTH

After the model with refined mesh was shown to adequately predict the outcome of the previous physical crash test, the researchers evaluated what additional measures were needed to maintain connectivity between the w-beam guardrail and the downstream end posts. First, the researchers evaluated the required additional length to maintain connectivity, compared to the physical crash test installation. Next, the researchers evaluated the effectiveness of guardrail washers for maintaining the connectivity.

7.3.1. 112.5-ft Guardrail System with Refined Slot Mesh

This model and the following models have the refined mesh, as discussed earlier, incorporated to the w-beam guardrail slot locations. The length of the guardrail system was increased by adding 25-ft to the downstream side for a total length of 112.5-ft. Figure 7.31 shows an overhead view of the finite element model. The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 88.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.32.

Figure 7.31. Overhead View of 112.5-ft Long Guardrail System

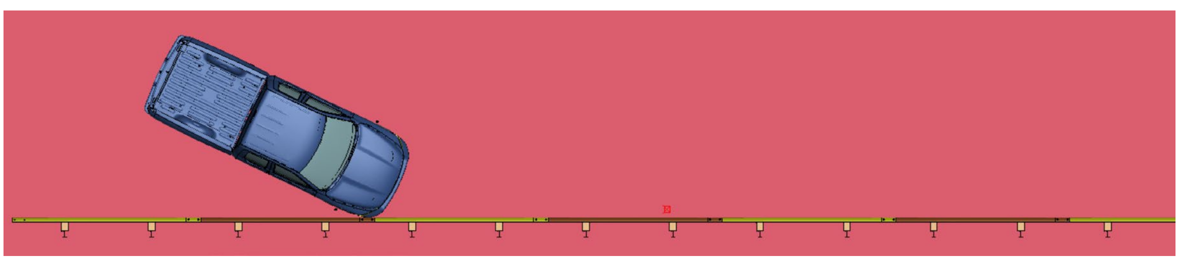


Figure 7.32. Overhead View of Impact Point for 112.5-ft Long Guardrail System

Figure 7.33, Figure 7.34, Figure 7.35, and Figure 7.36 show the sequential frames of *MASH* Test 3-11 on the 112.5-ft system with 1 mm thick refined slot elements. During the impact, the w-beam rail was pulled off the posts downstream of impact and consequently lost its ability to redirect the pickup truck. The researchers then increased the length of the guardrail system, and this model is discussed in the next section.

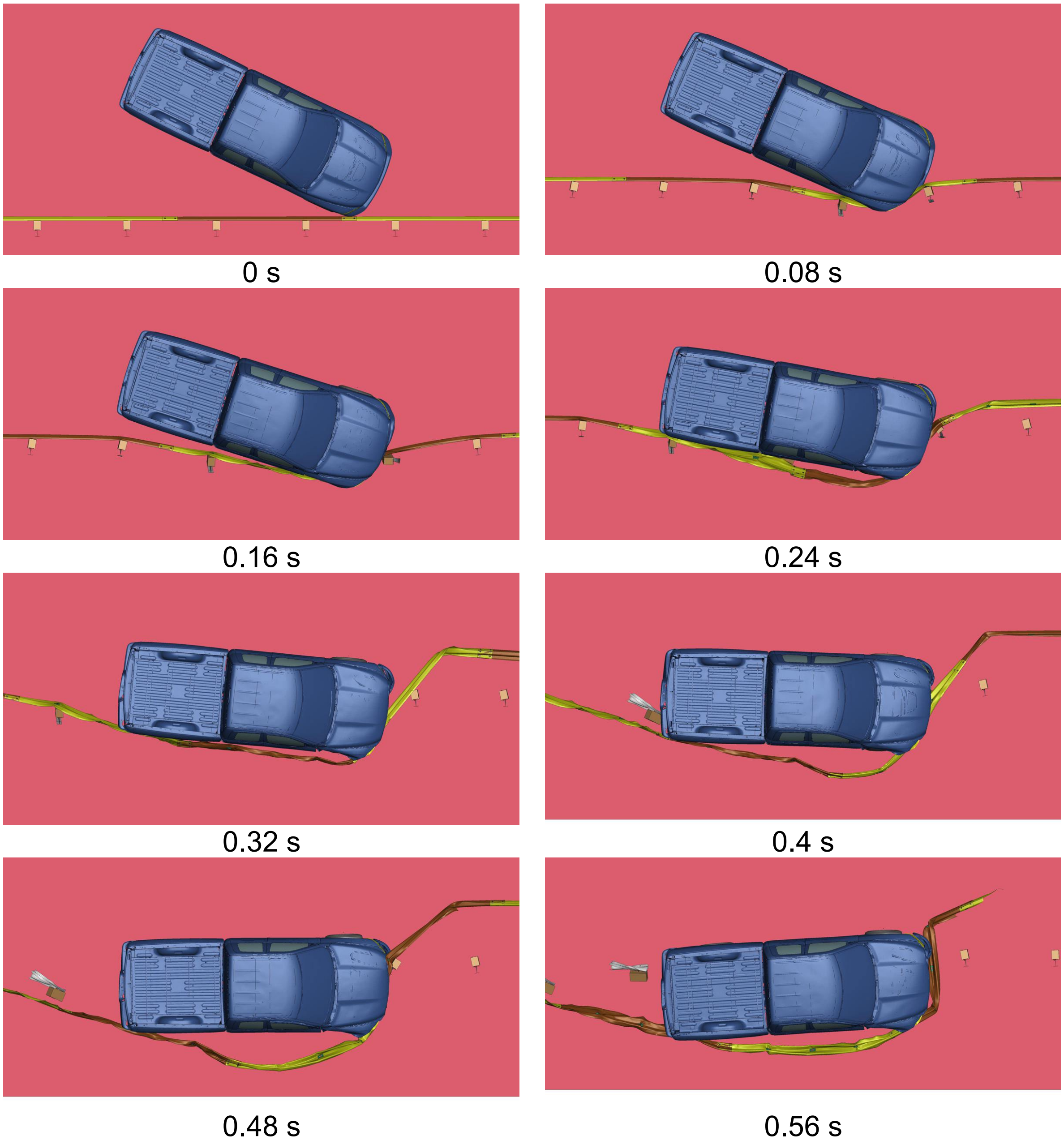


Figure 7.33. 112.5-ft Guardrail System with Refined Slot Mesh – Overhead View of *MASH* Test 3-11

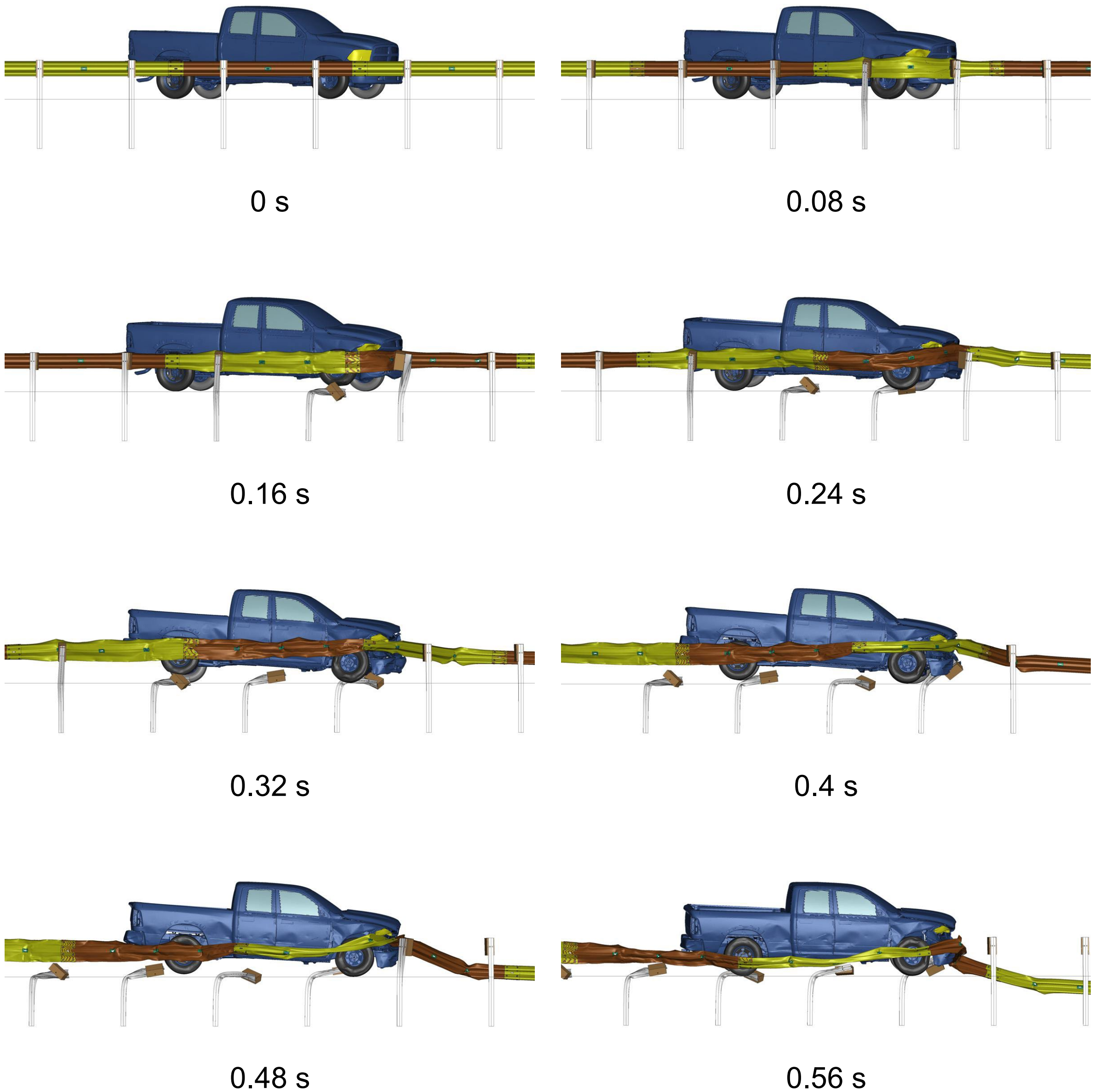


Figure 7.34. 112.5-ft Guardrail System with Refined Slot Mesh – Rear View of *MASH* Test 3-11

Figure 7.35. 112.5-ft Guardrail System with Refined Slot Mesh – Downstream View of *MASH* Test 3-11

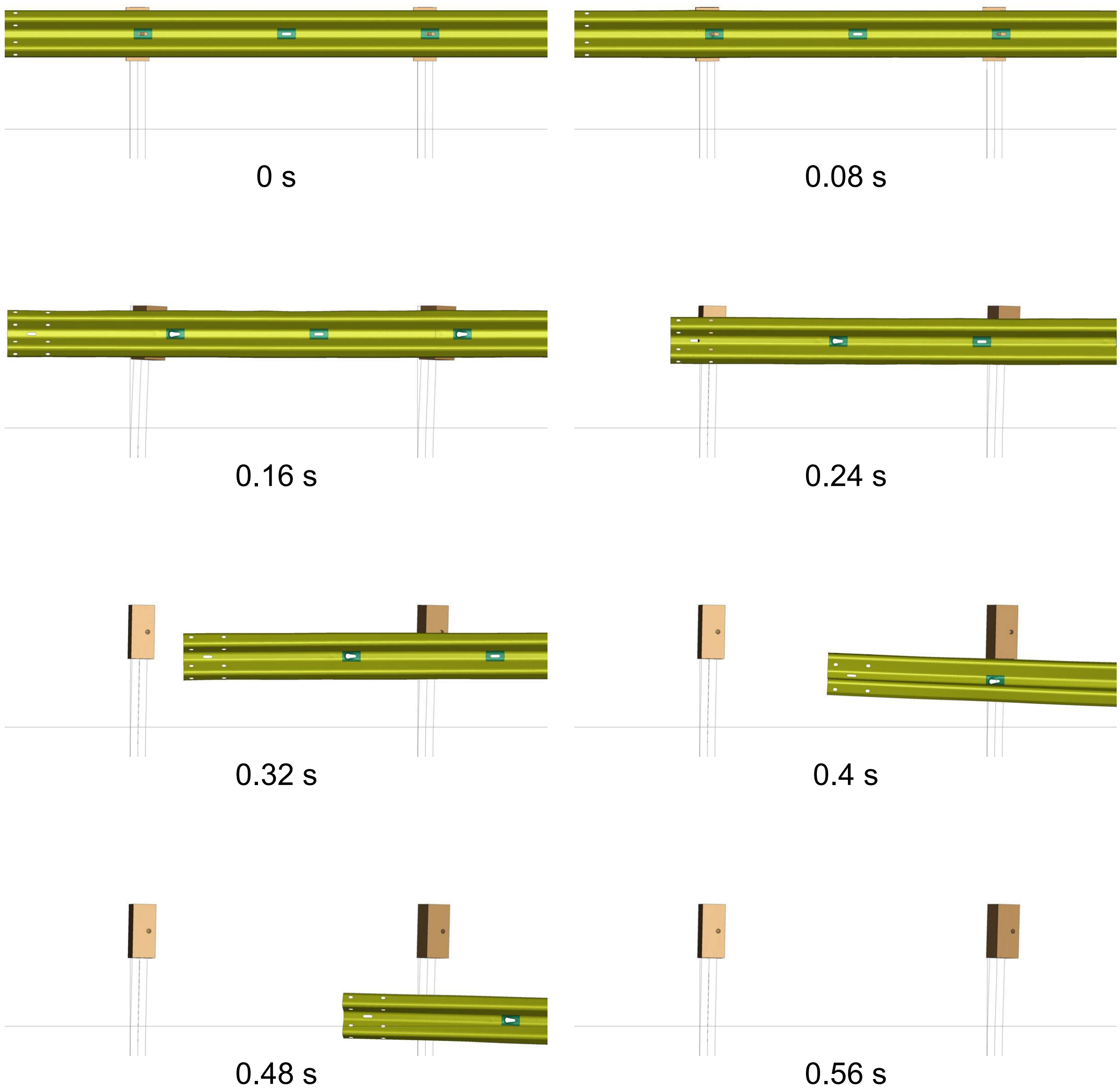


Figure 7.36. 112.5-ft Guardrail System with Refined Slot Mesh – Front View of Downstream Posts During *MASH* Test 3-11

7.3.2. 137.5-ft Guardrail System with Refined Slot Mesh

The length of the guardrail system was increased by adding 25-ft to the downstream side for a total length of 137.5-ft. Figure 7.37 shows an overhead view of the finite element model. The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 113.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.38.

Figure 7.37. Overhead View of 137.5-ft Long Guardrail System

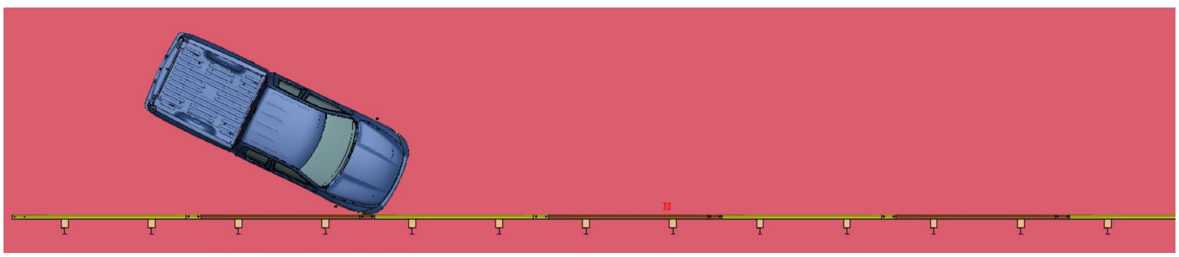


Figure 7.38. Overhead View of Impact Point for 137.5-ft Long Guardrail System

Figure 7.39, Figure 7.40, Figure 7.41., and Figure 7.42 show the sequential frames of *MASH* Test 3-11 on the 137.5-ft system with 1 mm thick refined slot element. During the impact, the w-beam rail was pulled off the posts downstream of impact and consequently lost its ability to redirect the pickup truck. The researchers then increased the length of the guardrail system, and this model is discussed in the next section.

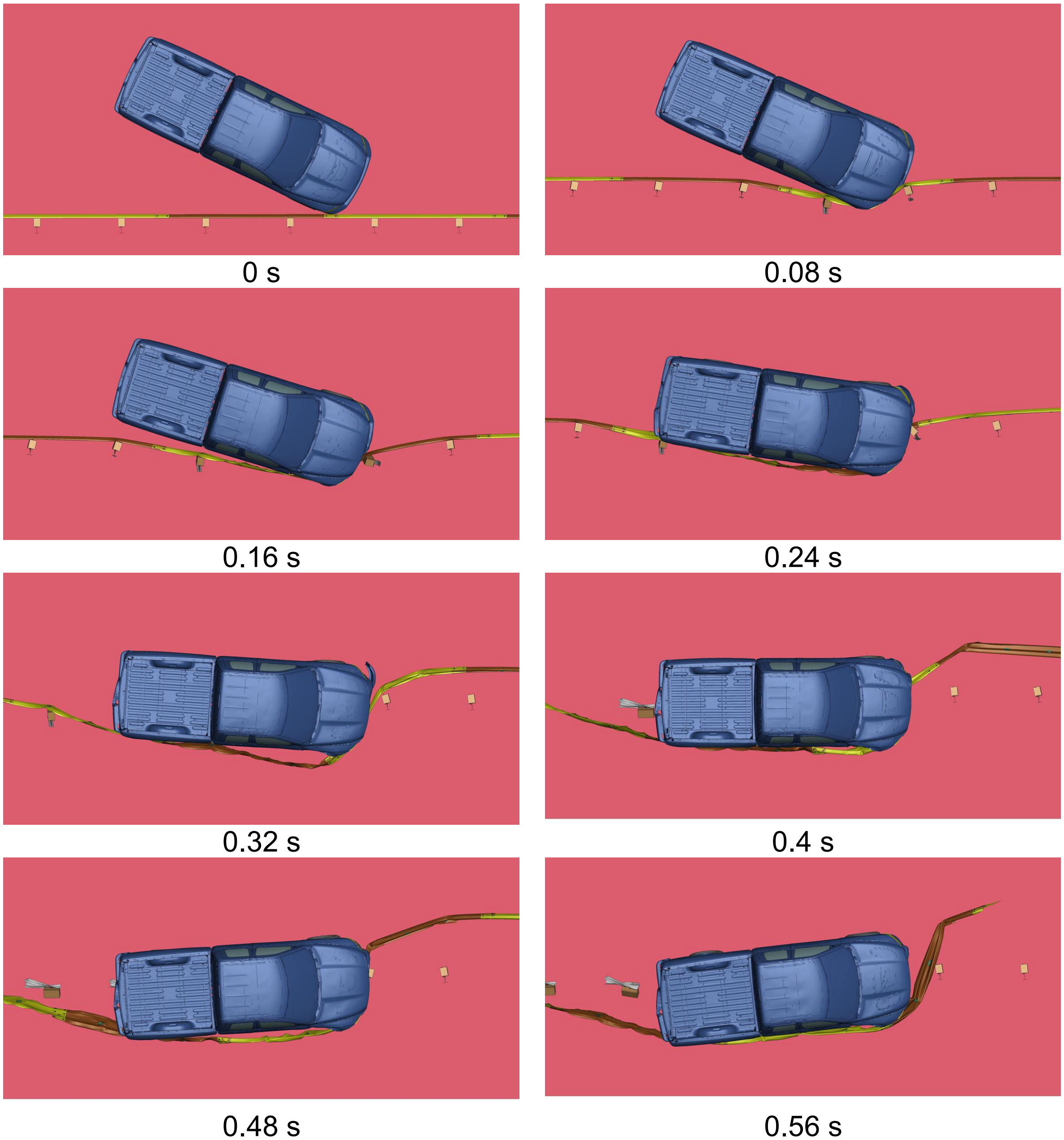


Figure 7.39. 137.5-ft Guardrail System with Refined Slot Mesh – Overhead View of *MASH* Test 3-11

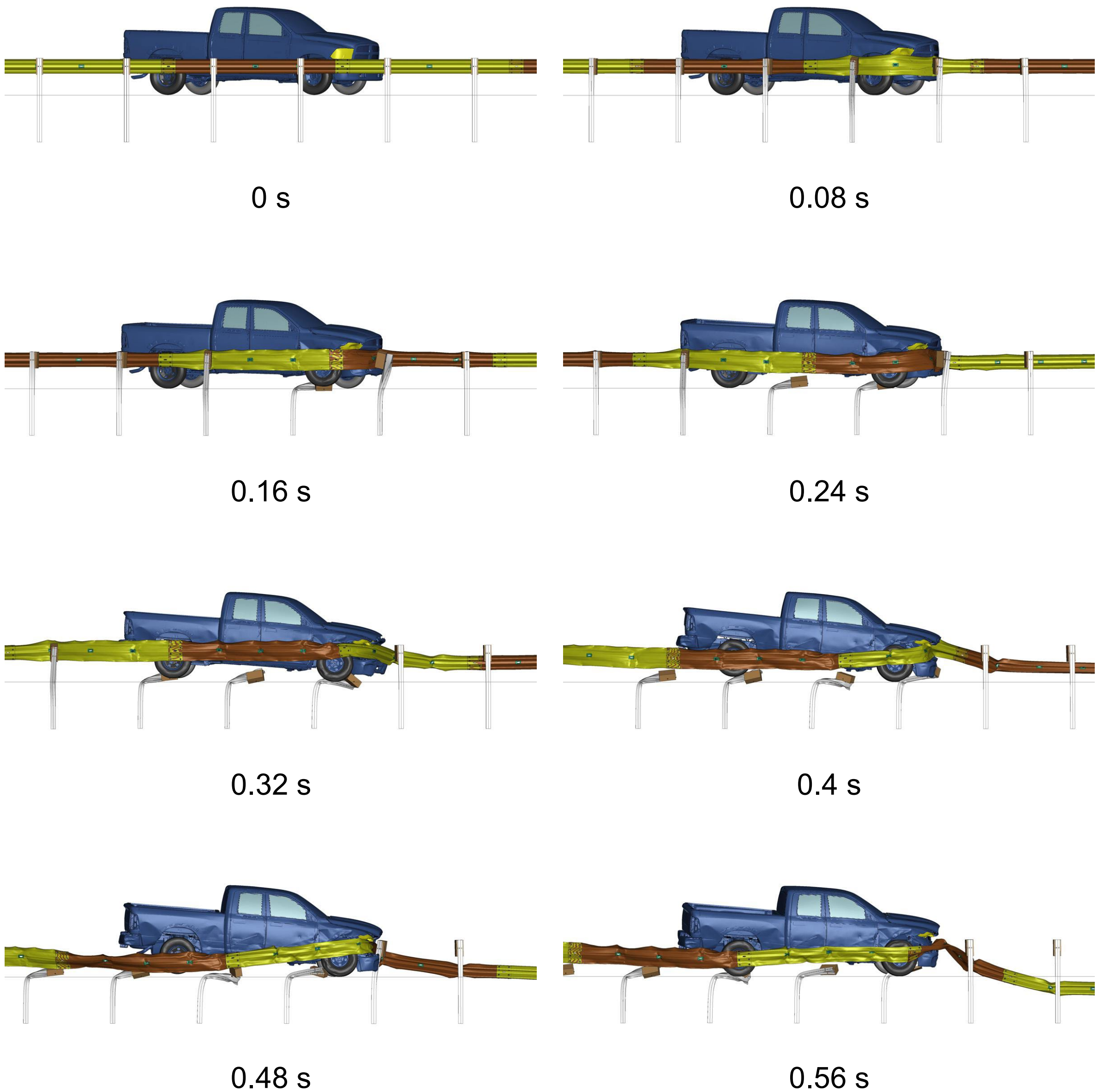


Figure 7.40. 137.5-ft Guardrail System with Refined Slot Mesh – Rear View of *MASH* Test 3-11

Figure 7.41. 137.5-ft Guardrail System with Refined Slot Mesh – Downstream View of *MASH* Test 3-11

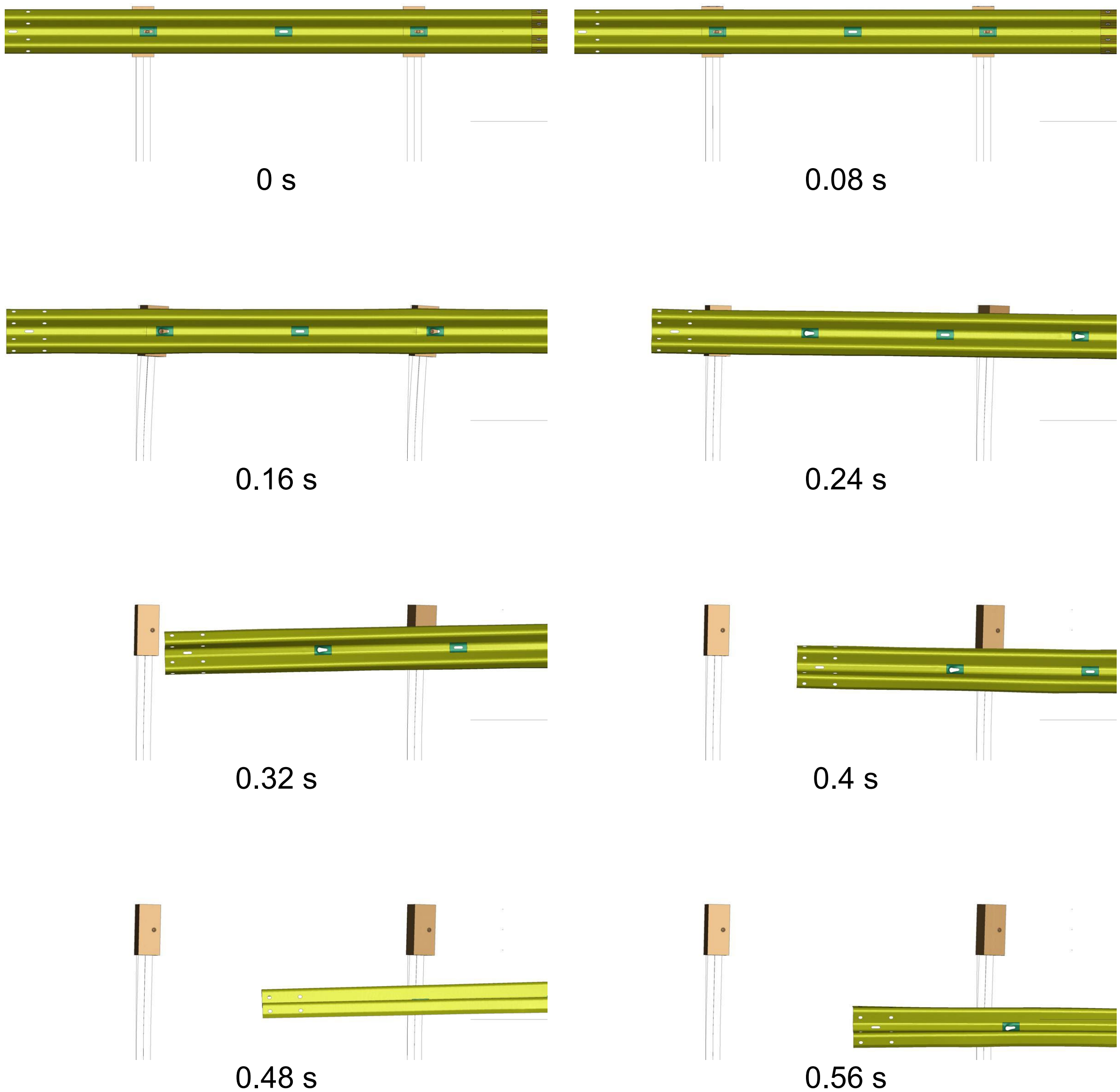


Figure 7.42. 137.5-ft Guardrail System with Refined Slot Mesh – Front View of Downstream Posts During *MASH* Test 3-11

7.3.3. 162.5-ft Guardrail System with Refined Slot Mesh

The length of the guardrail system was increased by adding 25-ft to the downstream side for a total length of 162.5-ft. Figure 7.43 shows an overhead view of the finite element model. The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 138.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.44.

Figure 7.43. Overhead View of 162.5-ft Long Guardrail System

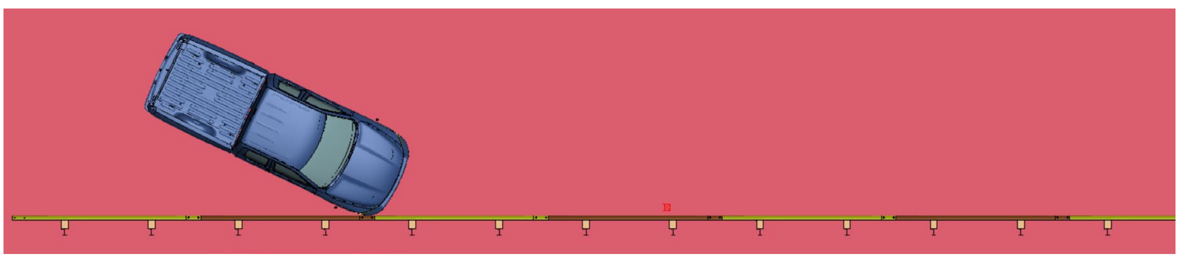


Figure 7.44. Overhead View of Impact Point for 162.5-ft Long Guardrail System

Figure 7.45, Figure 7.46, Figure 7.47, and Figure 7.48 show the sequential frames of *MASH* Test 3-11 on the 162.5-ft system with 1 mm thick refined slot elements. During the impact, the w-beam rail was pulled off the posts downstream of impact and consequently lost its ability to redirect the pickup truck. The researchers then increased the length of the guardrail system, and this model is discussed in the next section.

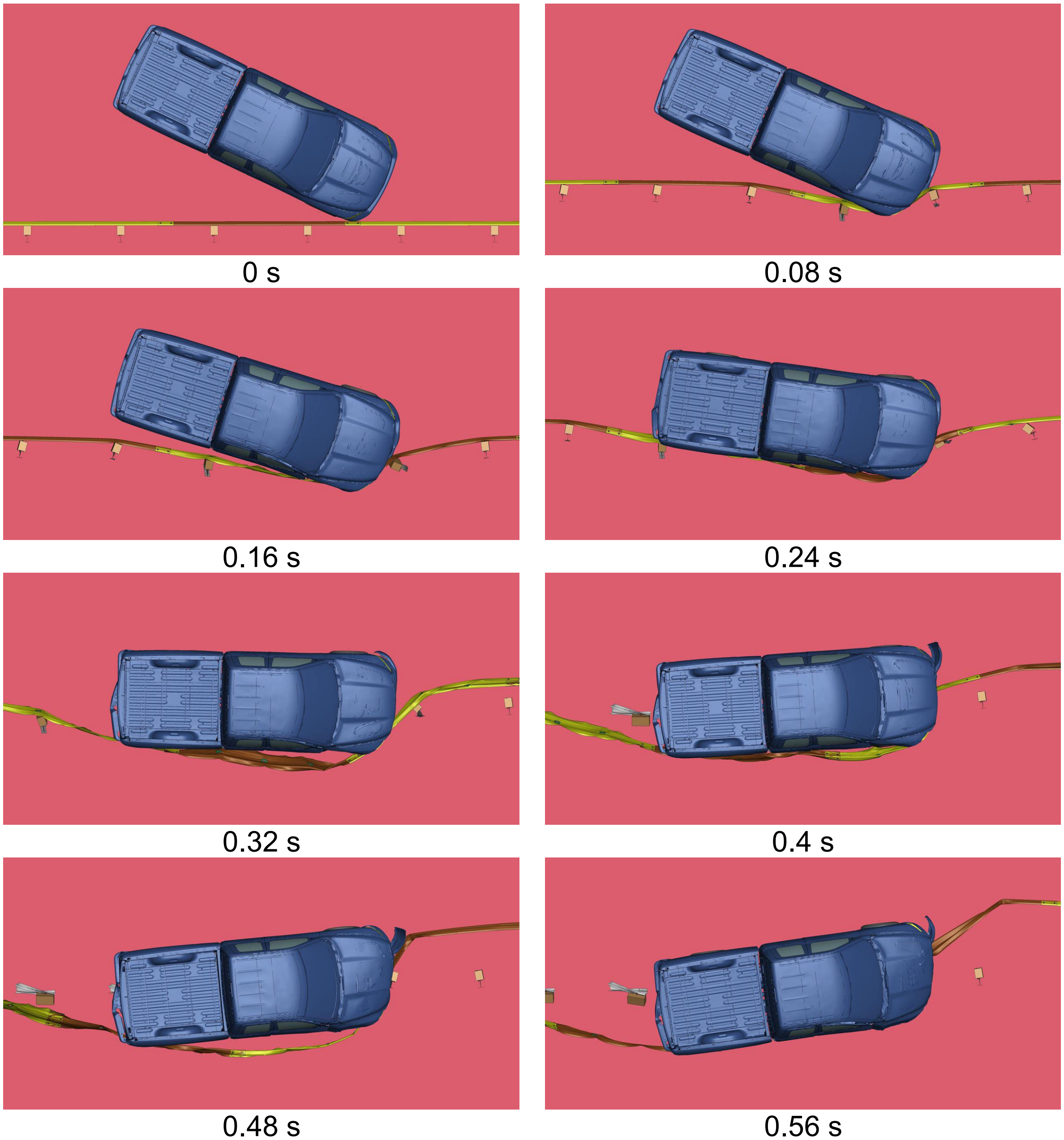


Figure 7.45. 162.5-ft Guardrail System with Refined Slot – Overhead View of *MASH* Test 3-11

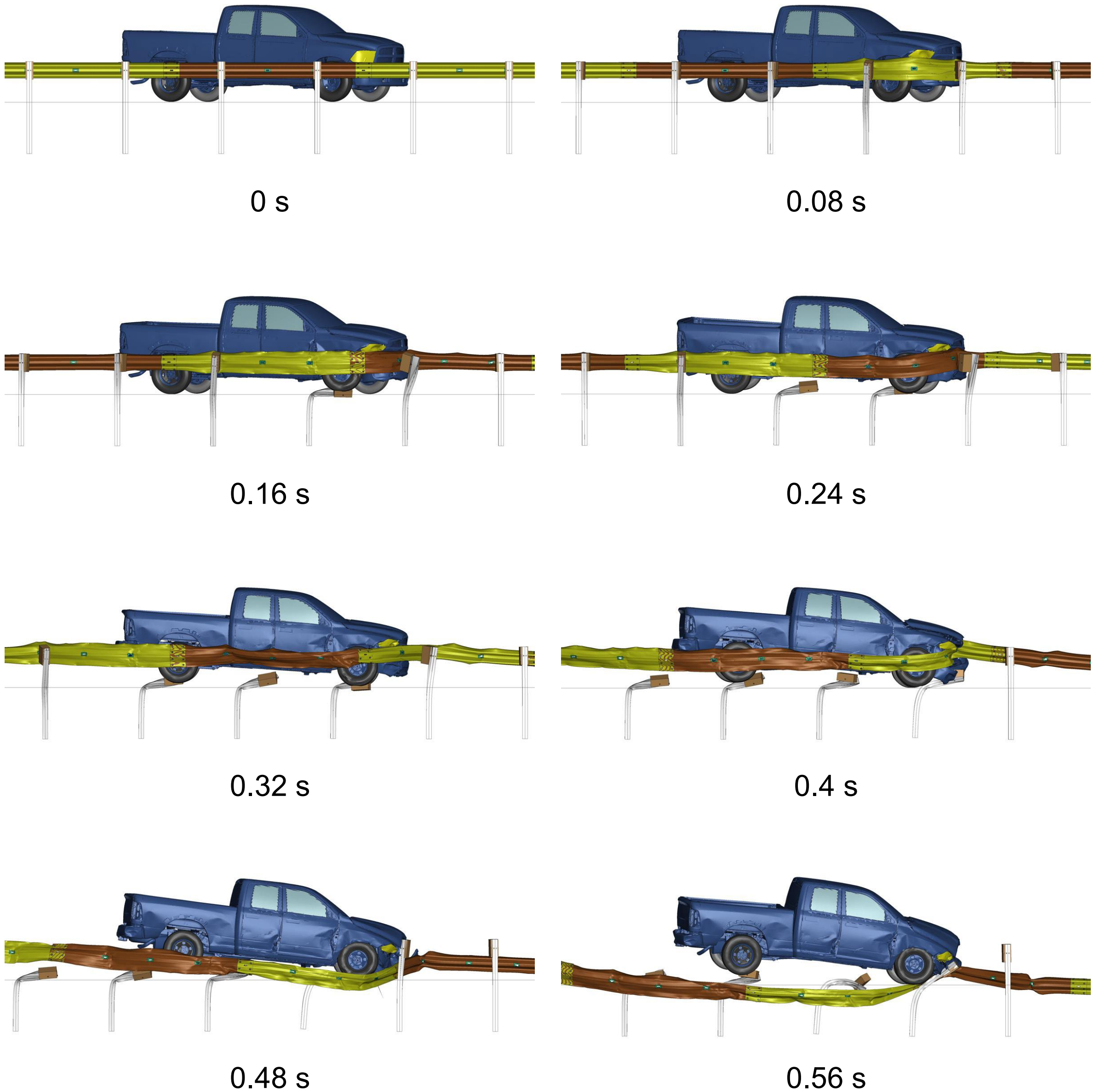


Figure 7.46. 162.5-ft Guardrail System with Refined Slot – Rear View of *MASH* Test 3-11

Figure 7.47. 162.5-ft Guardrail System with Refined Slot – Gut View of *MASH* Test 3-11

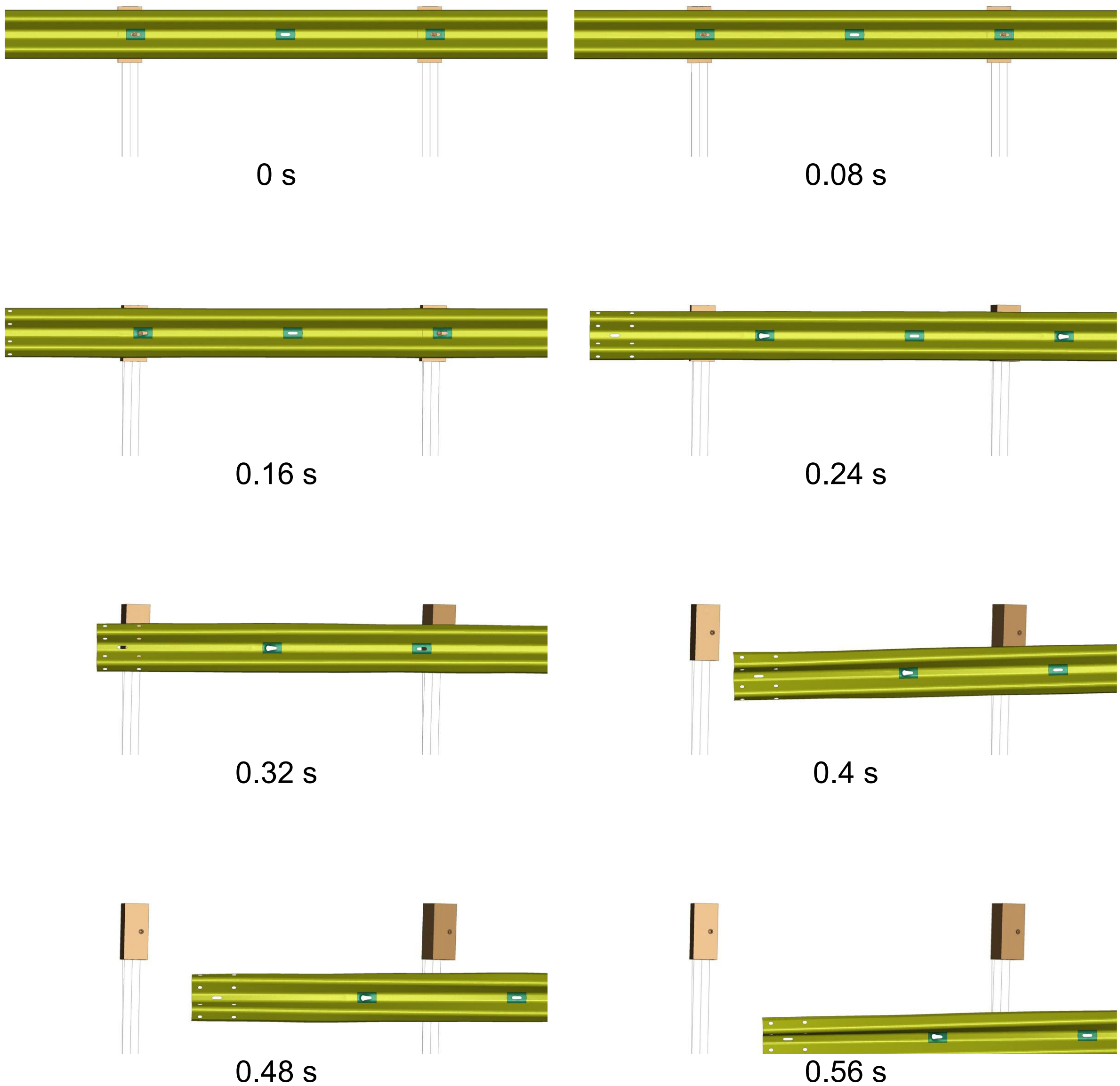


Figure 7.48. 162.5-ft Guardrail System with Refined Slot – Front View of Downstream Posts During *MASH* Test 3-11

7.3.4. 175-ft Guardrail System with Refined Slot Mesh

The length of the guardrail system was increased by adding 25-ft to the downstream side for a total length of 175-ft. Figure 7.49 shows an overhead view of the finite element model. The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 150.8-ft from the unanchored downstream end of the rail and is shown below in Figure 7.50.

Figure 7.49. Overhead View of 175-ft Long Guardrail System

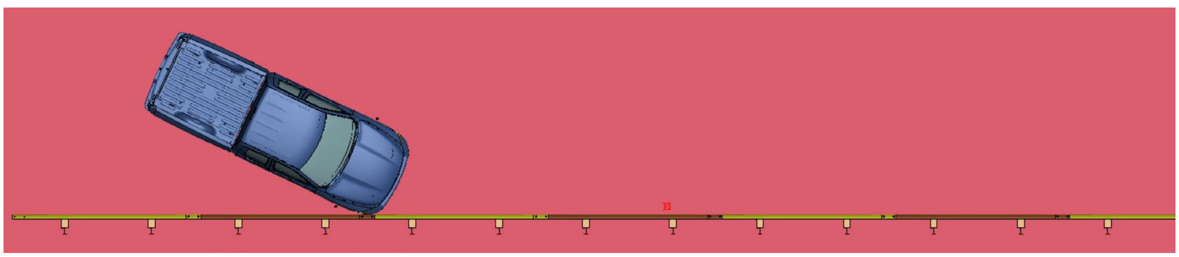


Figure 7.50. Overhead View of Impact Point for 175-ft Long Guardrail System

Figure 7.51, Figure 7.52, Figure 7.53, and Figure 7.54 show the sequential frames of *MASH* Test 3-11 on the 175-ft system with 1 mm thick refined slot elements. During the impact, the w-beam rail was pulled off the posts downstream of impact and consequently lost its ability to redirect the pickup truck. The researchers then increased the length of the guardrail system, and this model is discussed in the next section.

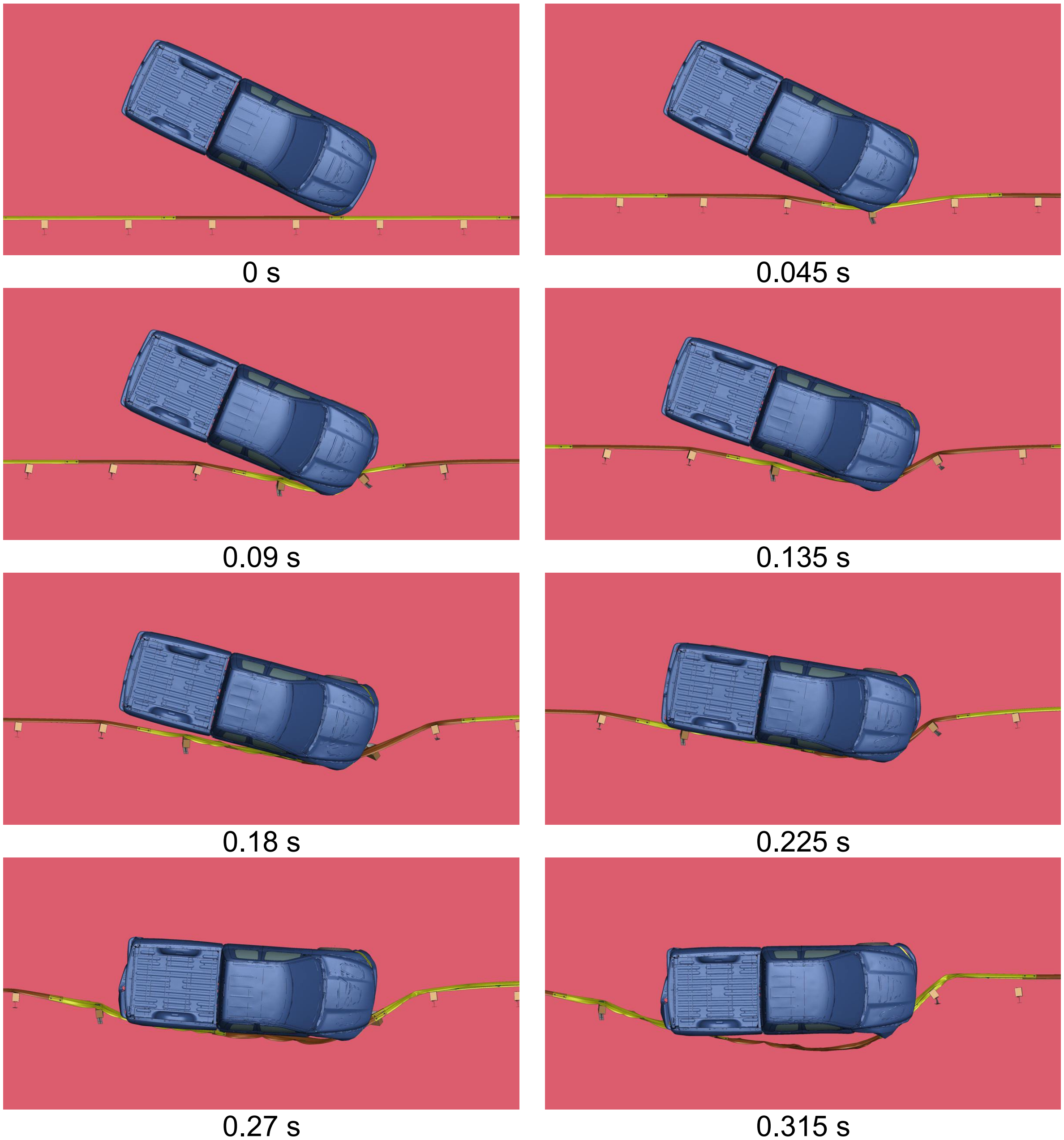


Figure 7.51. 175-ft Guardrail System with Refined Slot Mesh – Overhead View of *MASH* Test 3-11

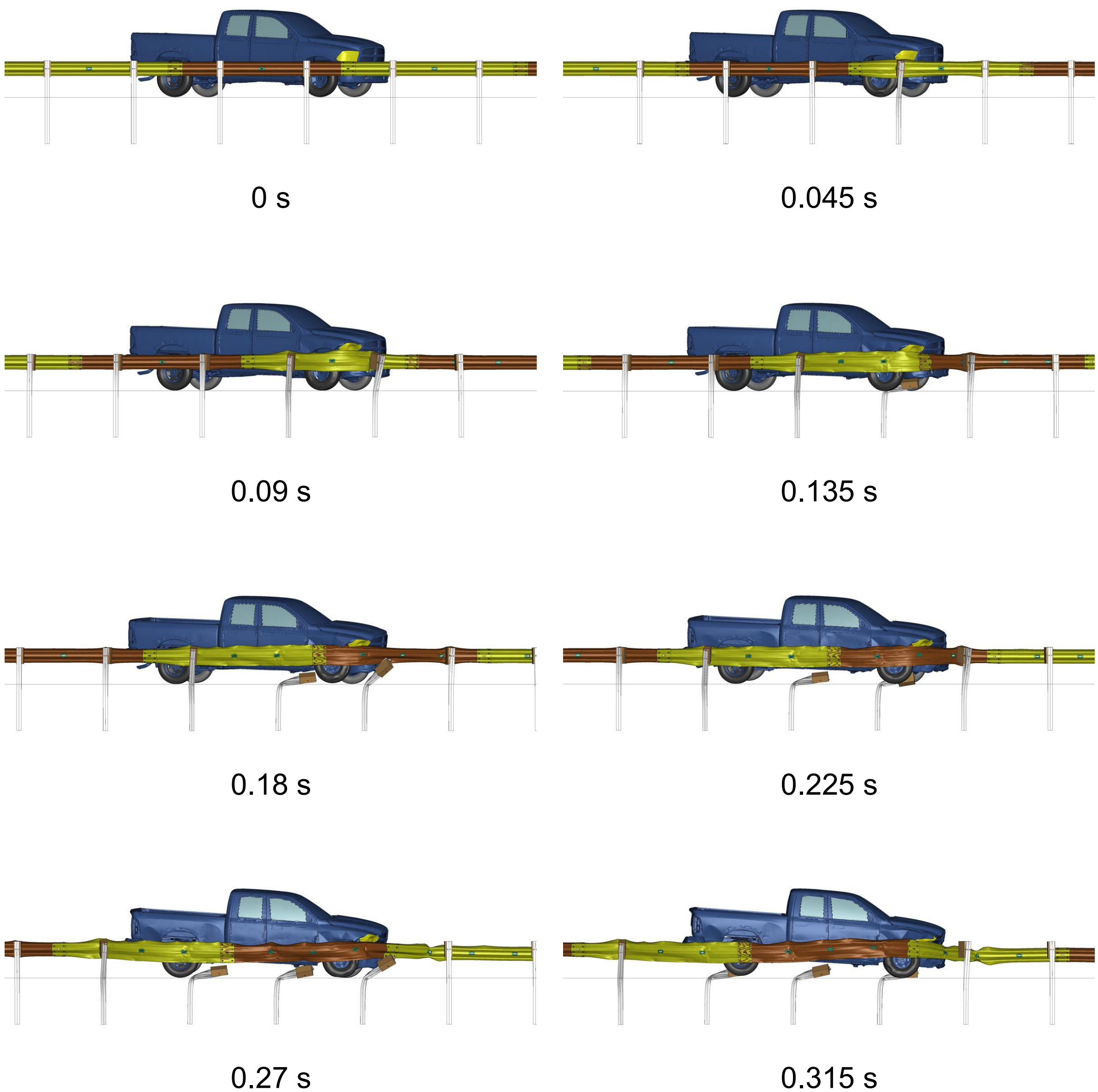


Figure 7.52. 175-ft Guardrail System with Refined Slot Mesh – Rear View of *MASH* Test 3-11

Figure 7.53. 175-ft Guardrail System with Refined Slot Mesh – Downstream View of *MASH* Test 3-11

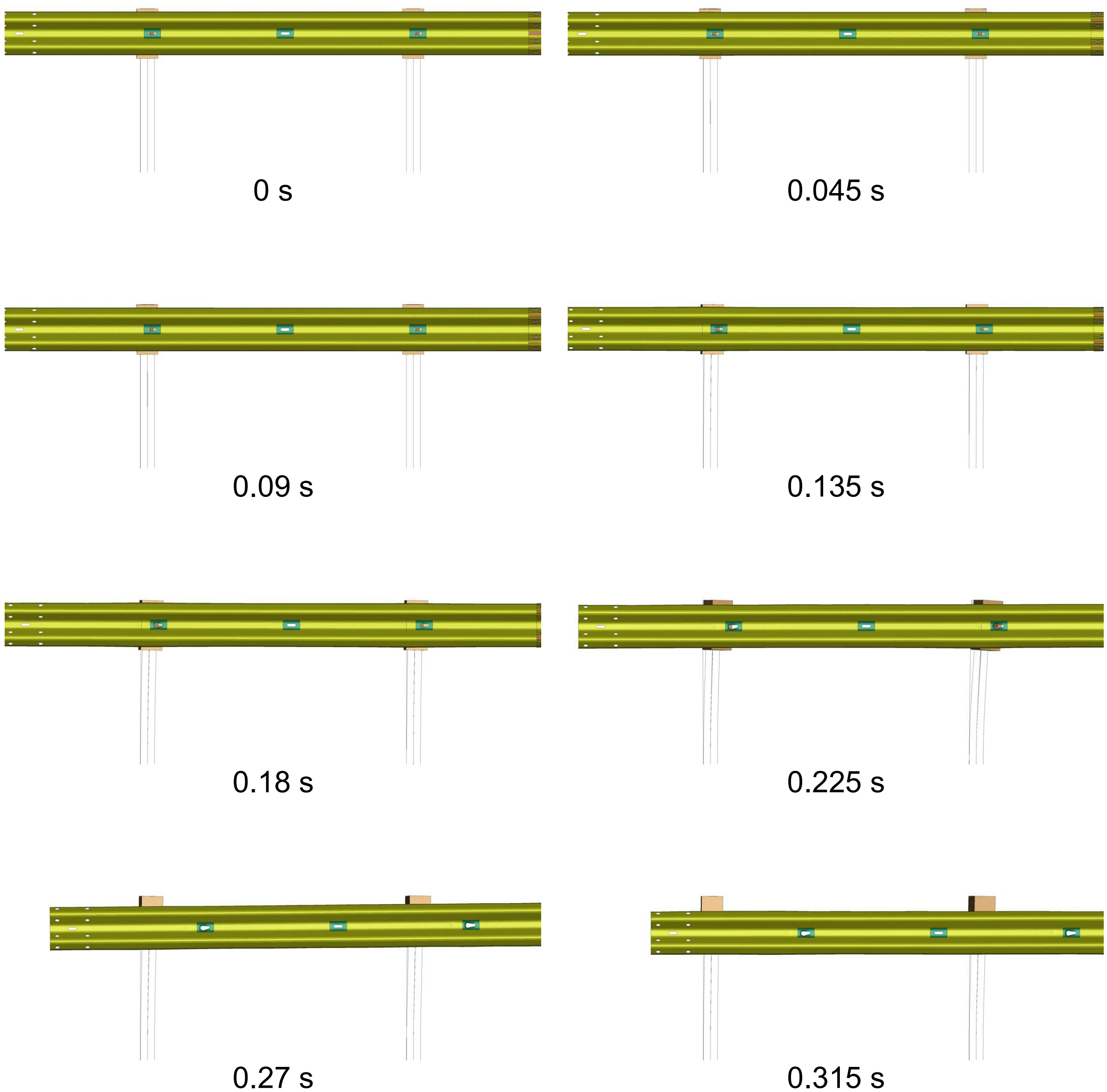


Figure 7.54. 175-ft Guardrail System with Refined Slot Mesh – Front View of Downstream Posts During *MASH* Test 3-11

7.3.5. 187.5-ft Guardrail System with Refined Slot Mesh

The length of the guardrail system was increased by adding 12.5-ft to the downstream side for a total length of 187.5-ft. Figure 7.55 shows an overhead view of the finite element model. The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 163.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.56.

Figure 7.55. Overhead View of 187.5-ft Long Guardrail System

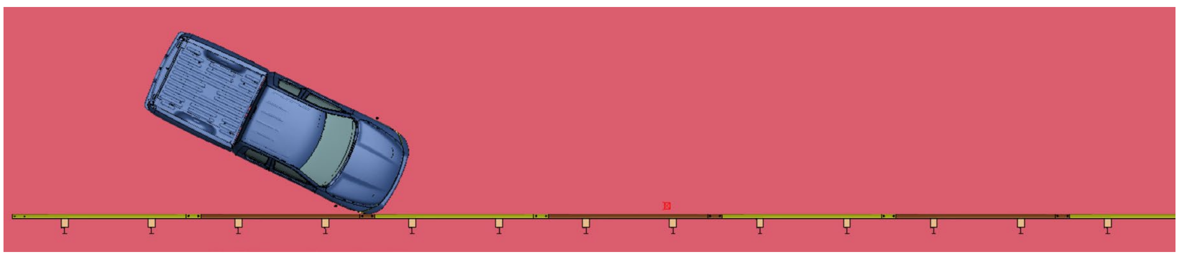


Figure 7.56. Overhead View of Impact Point for 187.5-ft Long Guardrail System

Figure 7.57, Figure 7.58, Figure 7.59, and Figure 7.60 show the sequential frames of *MASH* Test 3-11 on the 187.5-ft system with 1 mm thick refined slot element. During the impact, the w-beam rail was pulled off the posts downstream of impact and failed to meet the project objective. The researchers then increased the length of the guardrail system, and this model is discussed in the next section.

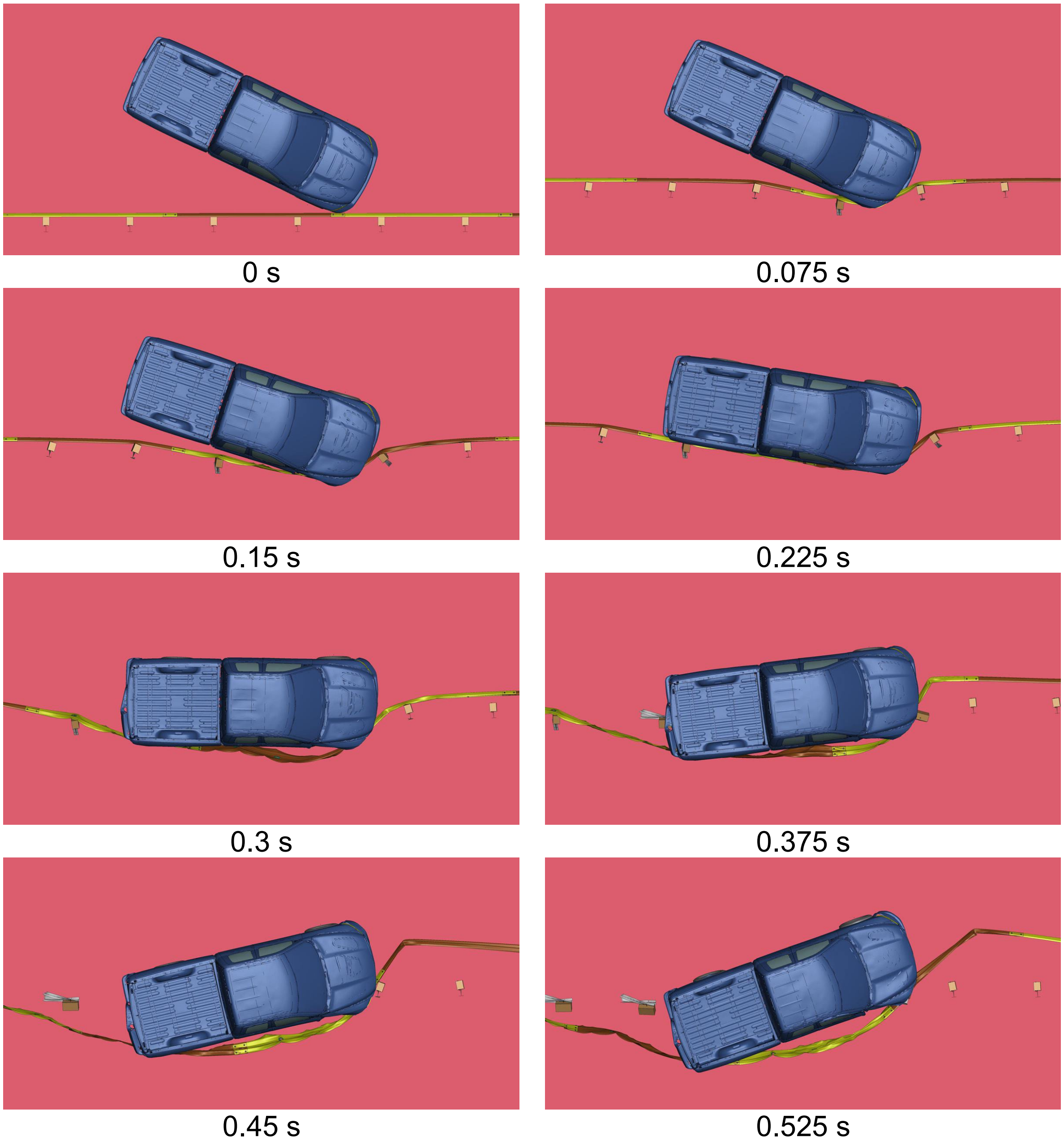


Figure 7.57. 187.5-ft Guardrail System with Refined Slot – Overhead View of *MASH* Test 3-11

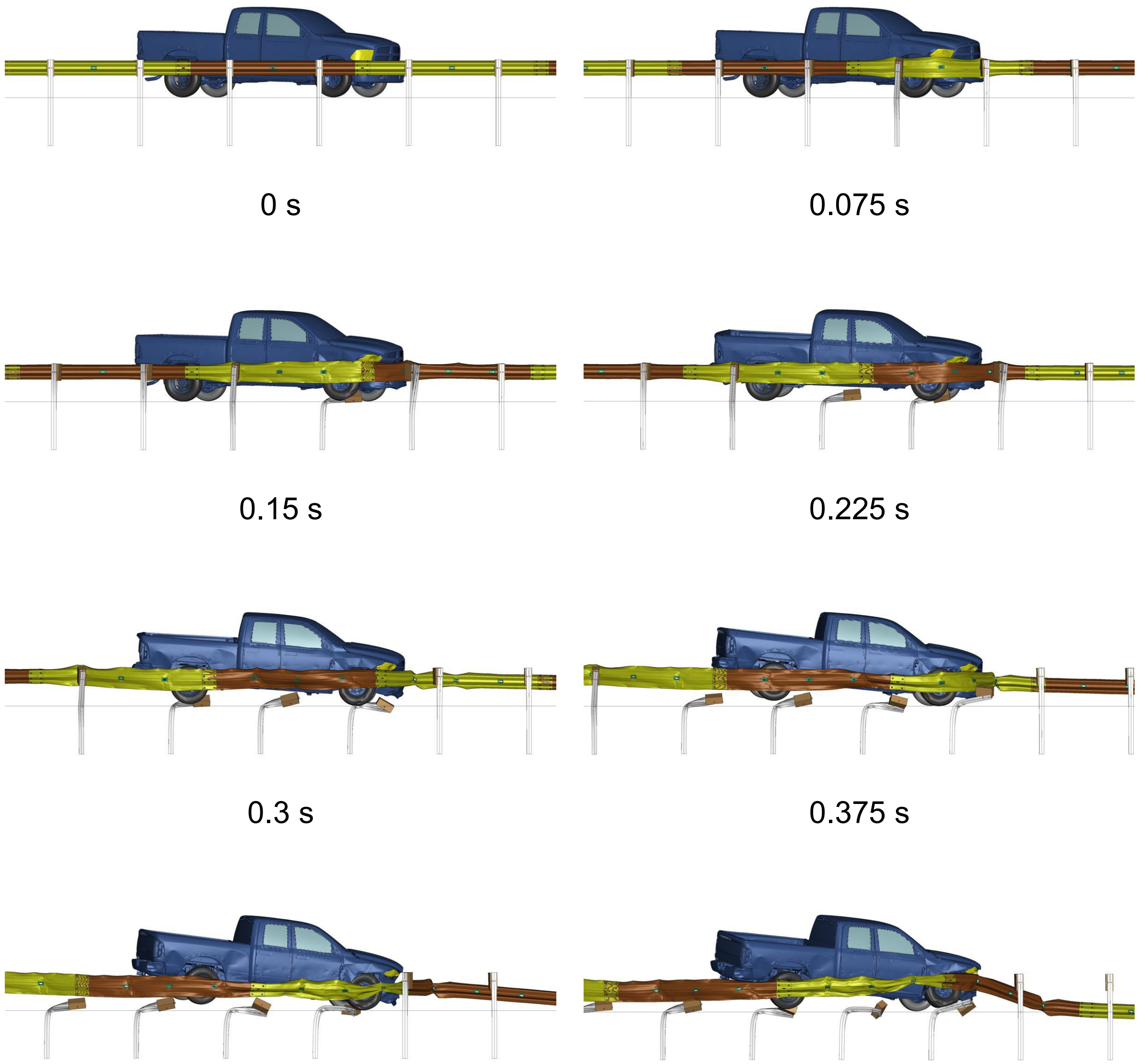


Figure 7.58. 187.5-ft Guardrail System with Refined Slot – Rear View of *MASH* Test 3-11

Figure 7.59. 187.5-ft Guardrail System with Refined Slot – Downstream View of *MASH* Test 3-11

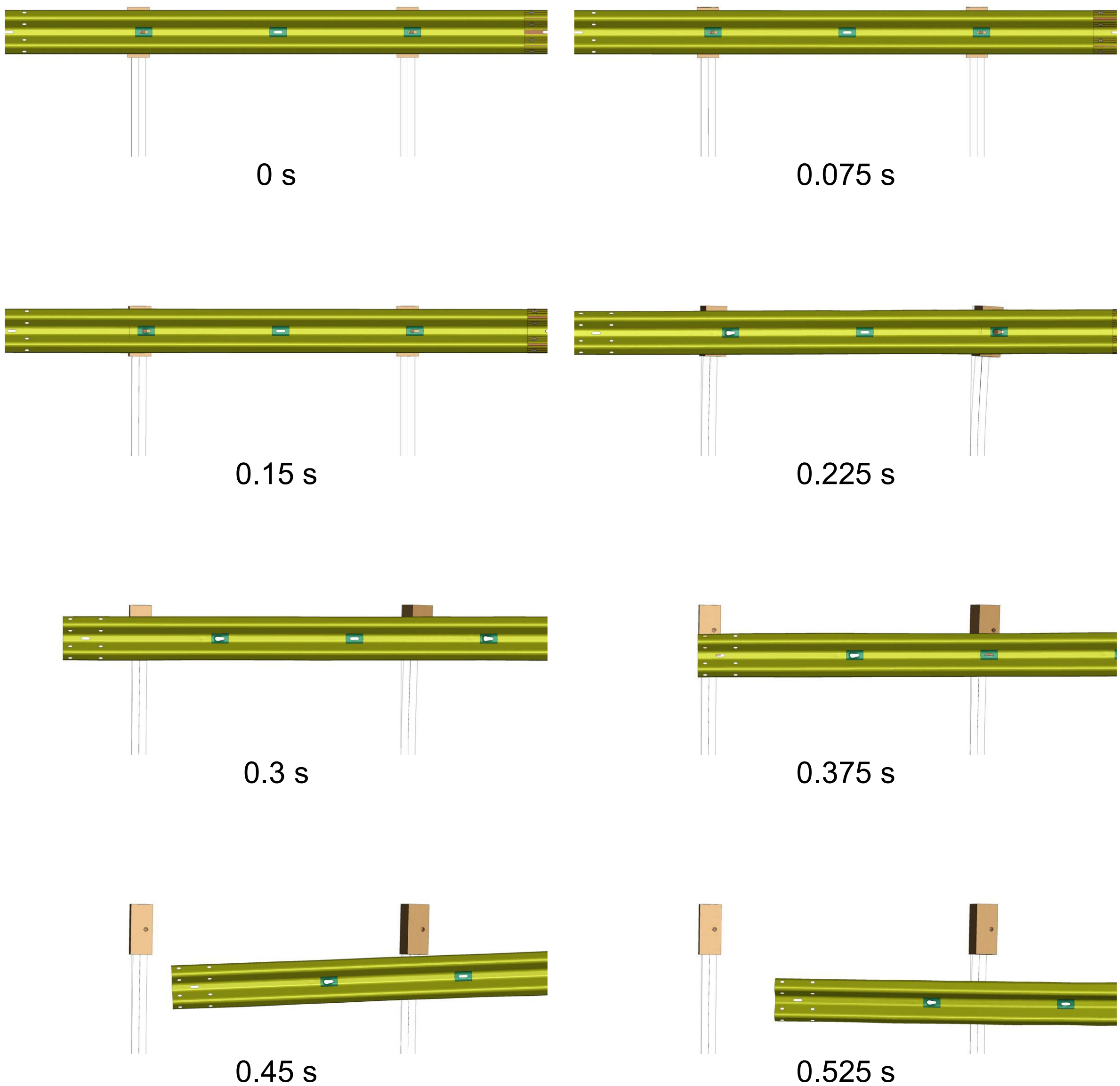


Figure 7.60. 187.5-ft Guardrail System with Refined Slot – Front View of Downstream Posts During *MASH* Test 3-11

7.3.6. 212.5-ft Guardrail System with Refined Slot Mesh

The length of the guardrail system was increased by adding 25-ft to the downstream side for a total length of 212.5-ft. Figure 7.61 shows an overhead view of the finite element model. The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 188.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.62.

Figure 7.61. Overhead View of 212.5-ft Long Guardrail System

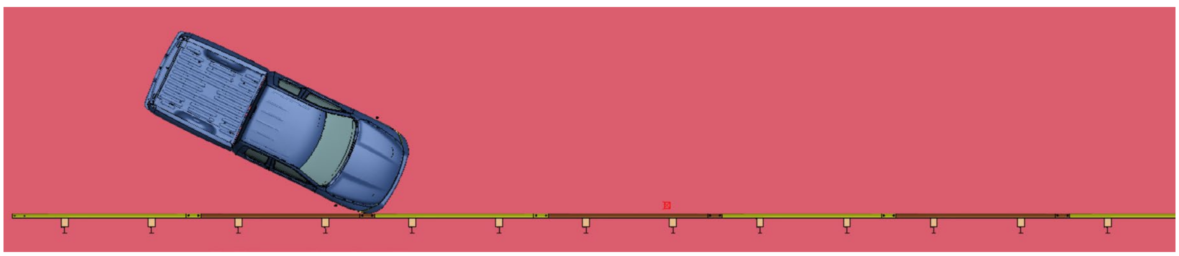


Figure 7.62. Overhead View of Impact Point for 212.5-ft Long Guardrail System

Figure 7.63, Figure 7.64, Figure 7.65, and Figure 7.66 show the sequential frames of *MASH* Test 3-11 on the 212.5-ft system with 1 mm thick refined slot element. During the impact, the w-beam rail was pulled off the posts downstream of impact and failed to meet the project objective. The researchers then increased the length of the guardrail system, and this model is discussed in the next section.

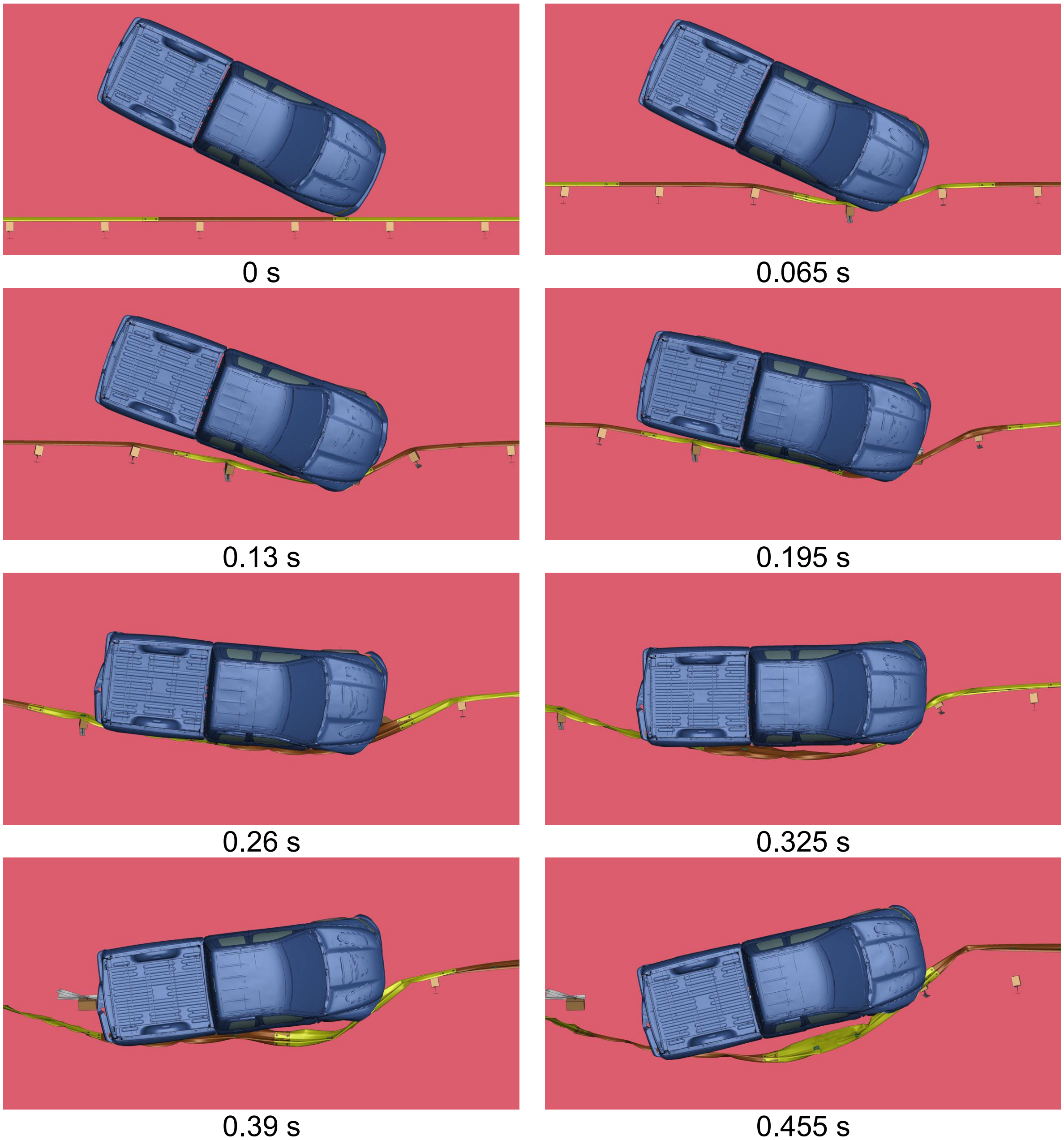


Figure 7.63. 212.5-ft Guardrail System with Refined Slot – Overhead View of *MASH* Test 3-11

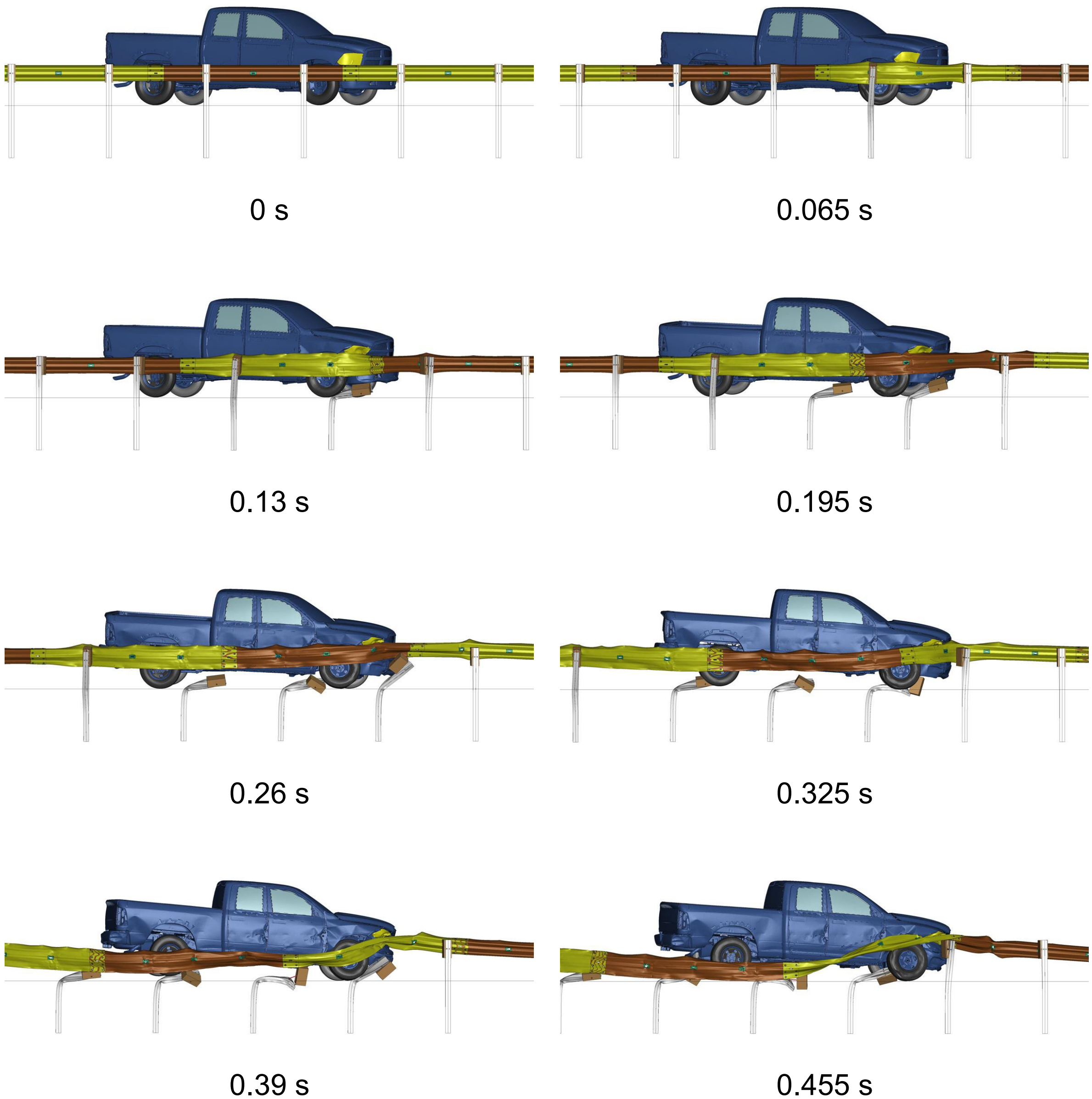


Figure 7.64. 212.5-ft Guardrail System with Refined Slot – Rear View of *MASH* Test 3-11

Figure 7.65. 212.5-ft Guardrail System with Refined Slot – Downstream View of *MASH* Test 3-11

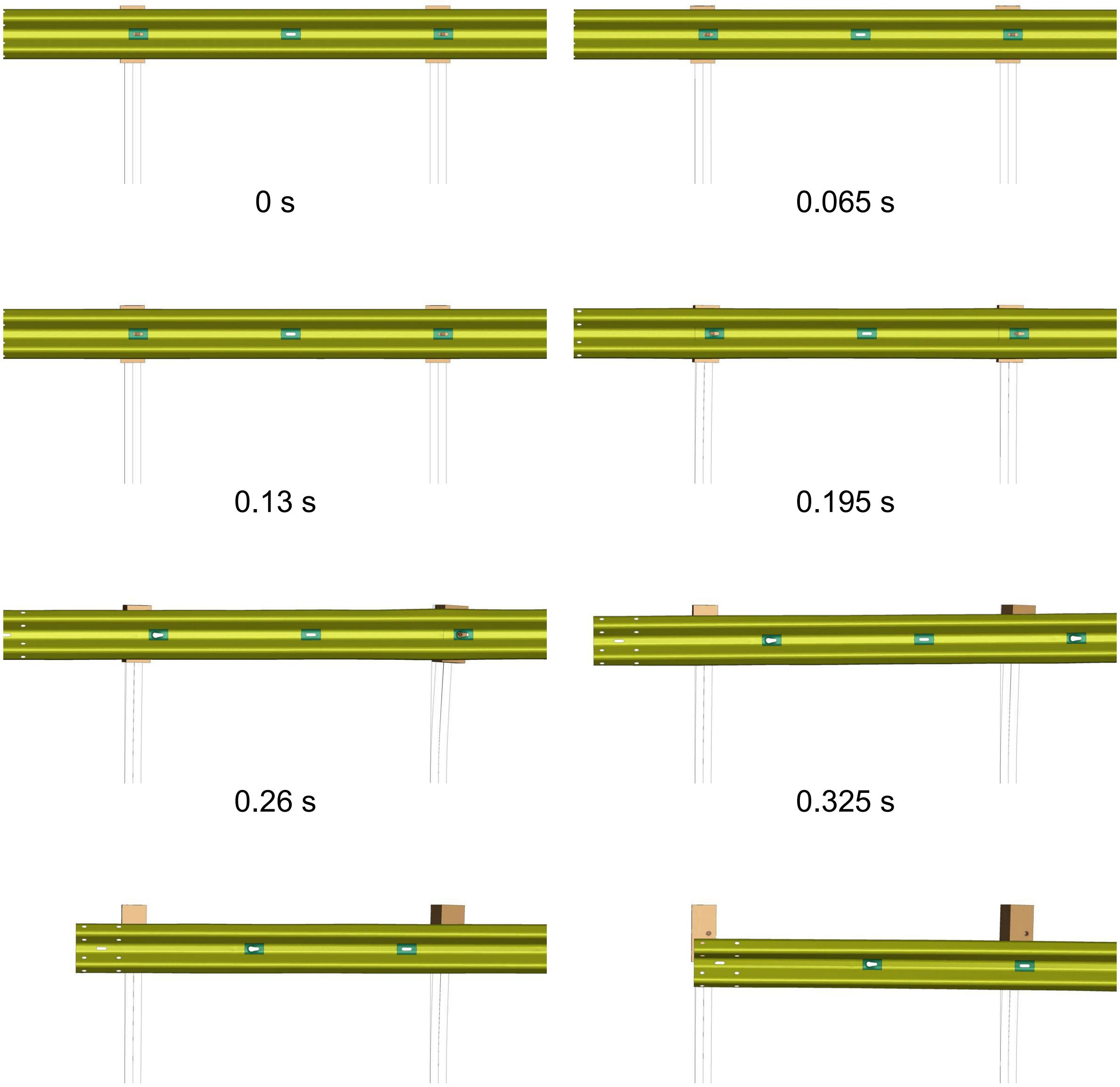

0 s
0.065 s
0.13 s
0.195 s
0.26 s
0.325 s
0.39 s
0.455 s

Figure 7.66. 212.5-ft Guardrail System with Refined Slot – Front View of Downstream Posts During *MASH* Test 3-11

7.3.7. 225-ft Guardrail System with Refined Slot Mesh

The length of the guardrail system was increased by adding 12.5-ft to the downstream side for a total length of 225-ft. Figure 7.67 shows an overhead view of the finite element model. The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 200.8-ft from the unanchored downstream end of the rail and is shown below in Figure 7.68.

Figure 7.67. Overhead View of 225-ft Long Guardrail System

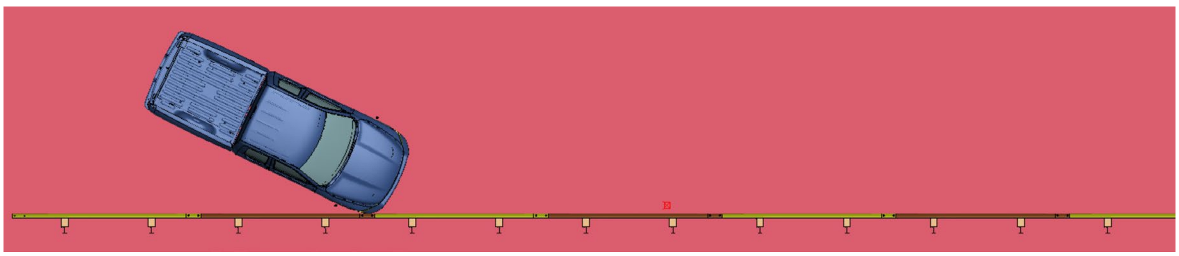


Figure 7.68. Overhead View of Impact Point for 225-ft Long Guardrail System

Figure 7.69, Figure 7.70, Figure 7.71, and Figure 7.72 show the sequential frames of *MASH* Test 3-11 on the 225-ft system with 1 mm thick refined slot element. During the impact, the w-beam rail was pulled off the posts downstream of impact and failed to meet the project objective. The researchers then increased the length of the guardrail system, and this model is discussed in the next section.

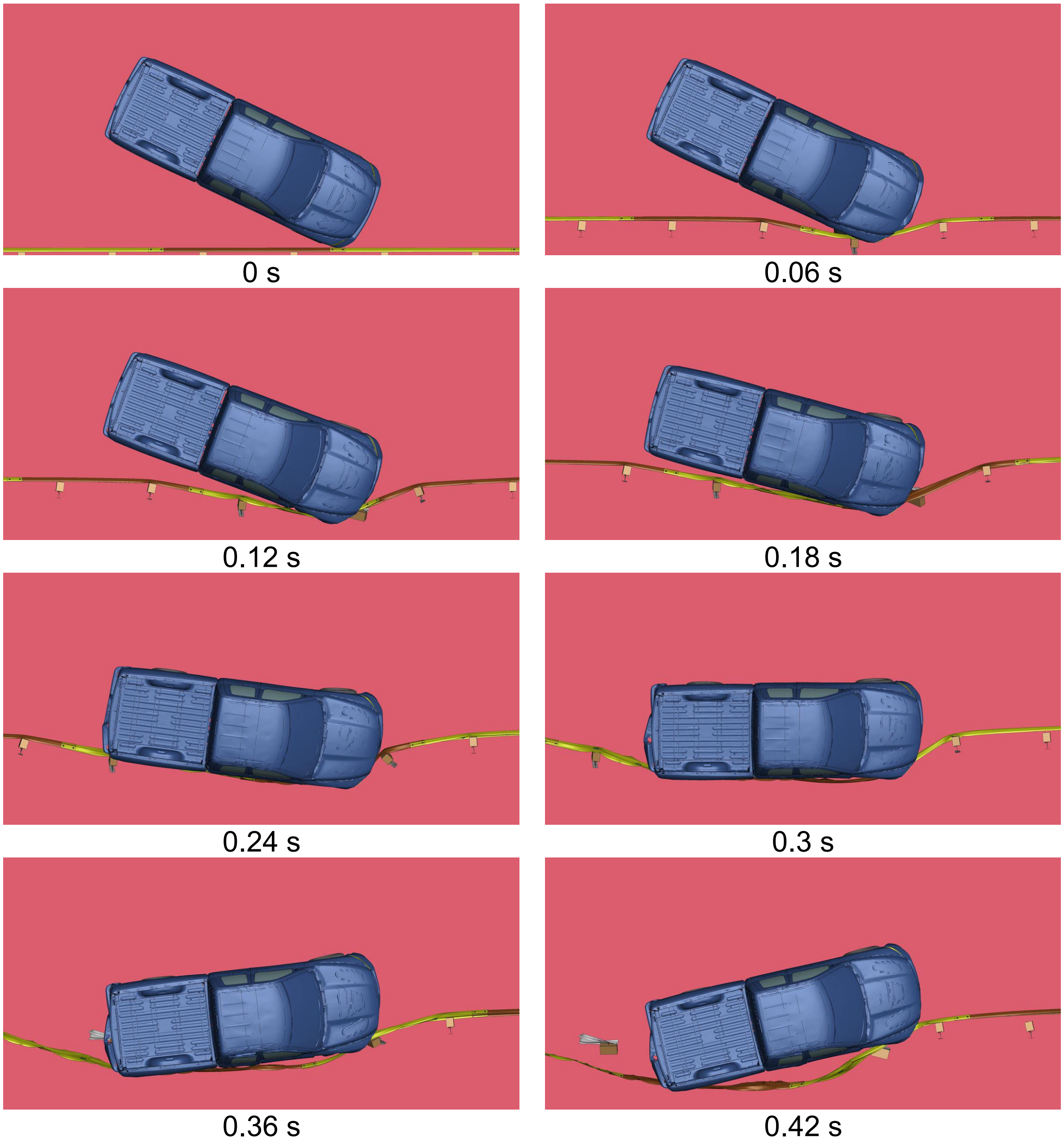


Figure 7.69. 225-ft Guardrail System with Refined Slot – Overhead View of *MASH* Test 3-11

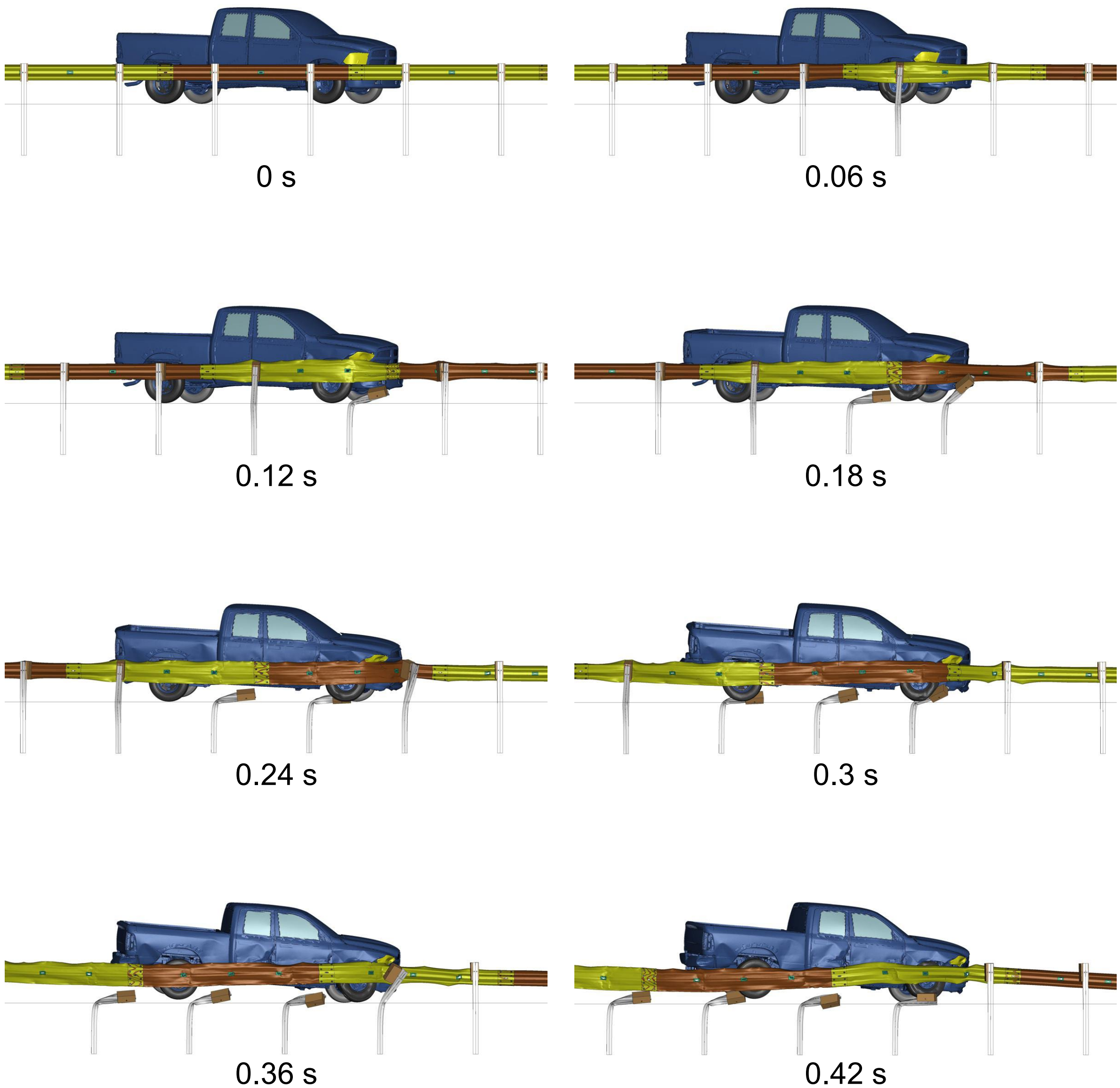


Figure 7.70. 225-ft Guardrail System with Refined Slot – Rear View of *MASH* Test 3-11

Figure 7.71. 225-ft Guardrail System with Refined Slot – Downstream View of *MASH* Test 3-11

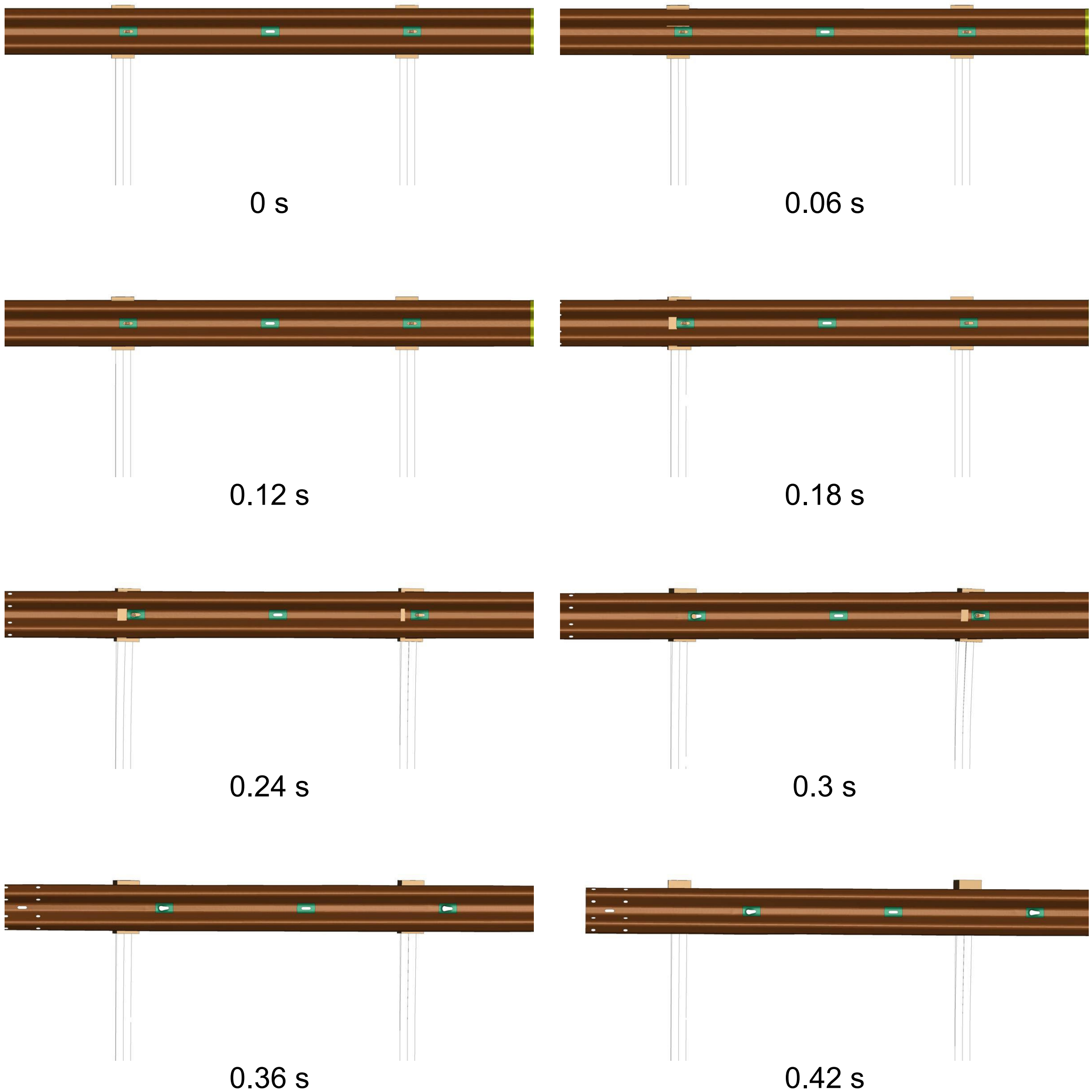


Figure 7.72. 225-ft Guardrail System with Refined Slot – Front View of Downstream Posts During *MASH* Test 3-11

7.3.8. 237.5-ft Guardrail System with Refined Slot Mesh

The length of the guardrail system was increased by adding 12.5-ft to the downstream side for a total length of 237.5-ft. Figure 7.73 shows an overhead view of the finite element model. The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 213.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.74.

Figure 7.73. Overhead View of 237.5-ft Long Guardrail System

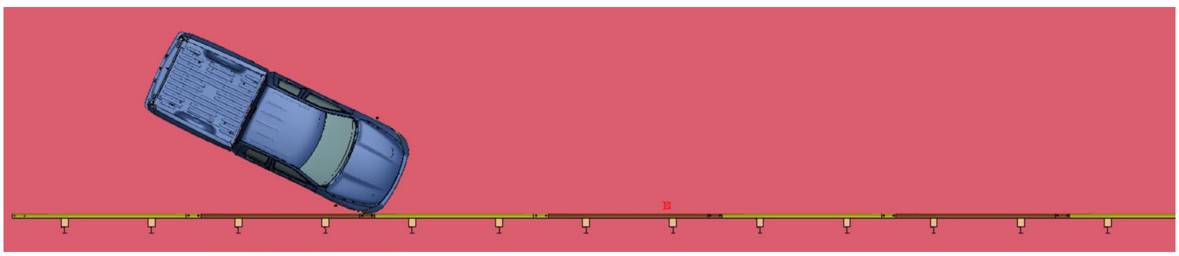


Figure 7.74. Overhead View of Impact Point for 237.5-ft Long Guardrail System

Figure 7.75, Figure 7.76, Figure 7.77, and Figure 7.78 show the sequential frames of *MASH* Test 3-11 on the 237.5-ft system with 1 mm thick refined slot element. During the impact, the w-beam rail was pulled off the posts downstream of impact and failed to meet the project objective. The researchers then increased the length of the guardrail system, and this model is discussed in the next section.

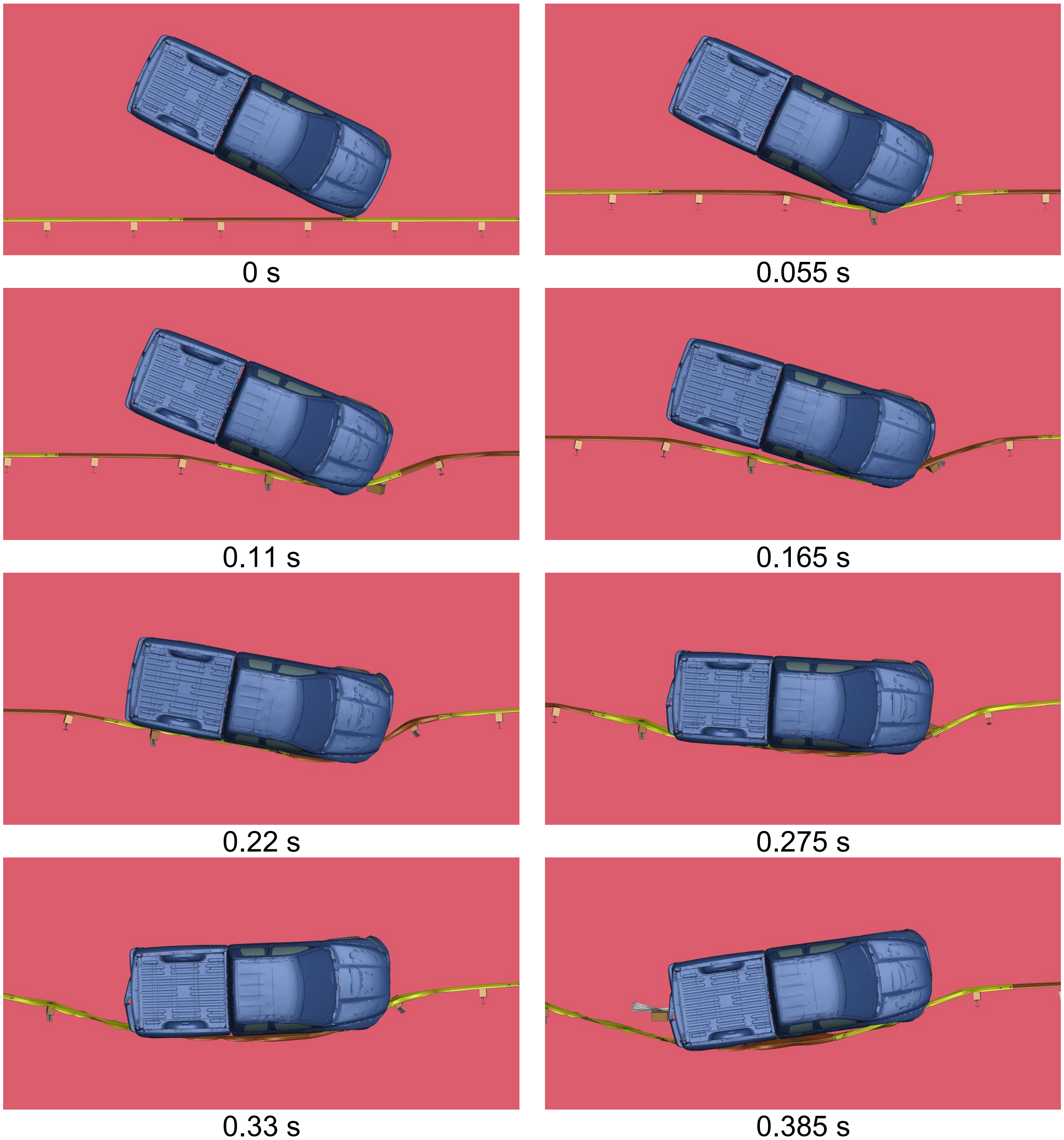


Figure 7.75. 237.5-ft Guardrail System with Refined Slot – Overhead View of *MASH* Test 3-11

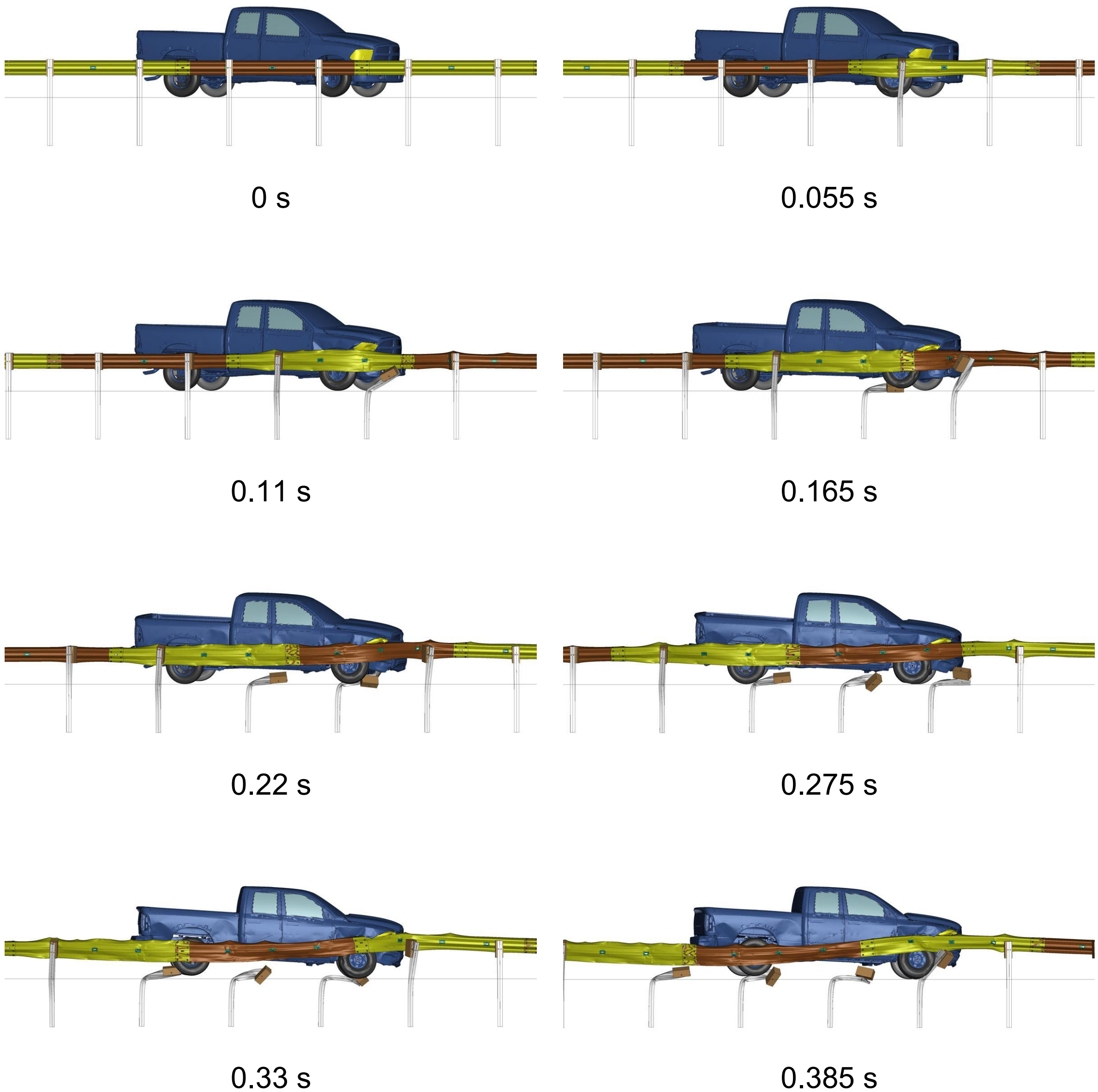


Figure 7.76. 237.5-ft Guardrail System with Refined Slot – Rear View of *MASH* Test 3-11

Figure 7.77. 237.5-ft Guardrail System with Refined Slot – Downstream View of *MASH* Test 3-11

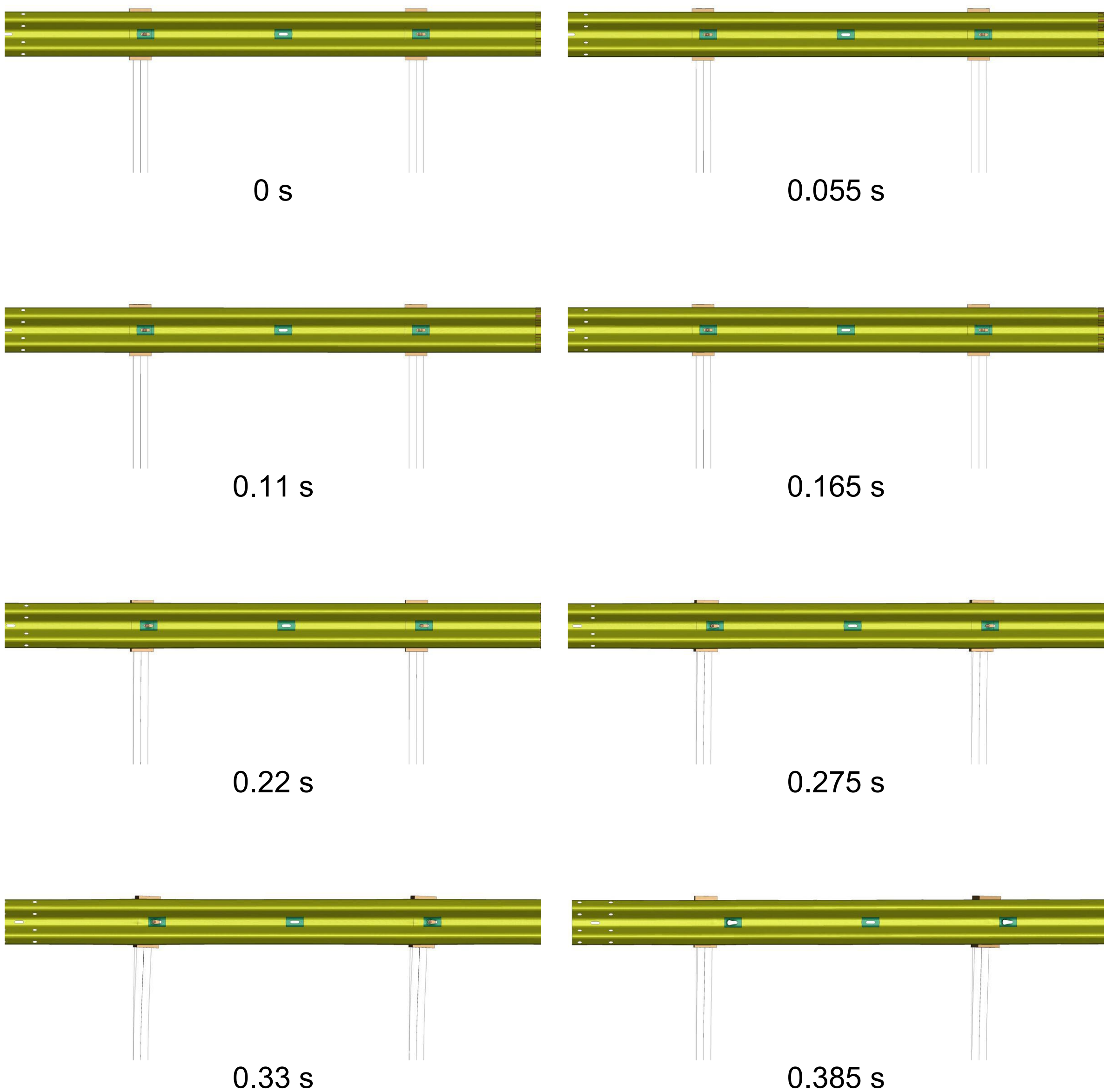


Figure 7.78. 237.5-ft Guardrail System with Refined Slot – Front View of Downstream Posts During *MASH* Test 3-11

7.3.9. 237.5-ft Guardrail System with Refined Slot Mesh and Increased Bolt Retention

The length of the guardrail system was the same as the previous model, but the guardrail bolt was adjusted to reduce the gap between the bolt head and the slot in the rail to ensure a snug fit. This was intended to improve retention between the rail and the post. In the field, guardrail bolts are often extremely tight against the rail and blockout, and the research team wanted to investigate this effect on the redirective performance of the system. **Figure 7.79** shows an overhead view of the finite element model. The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 213.3-ft from the unanchored downstream end of the rail and is shown below in **Figure 7.80**.

Figure 7.79. Overhead View of 237.5-ft Long Guardrail System

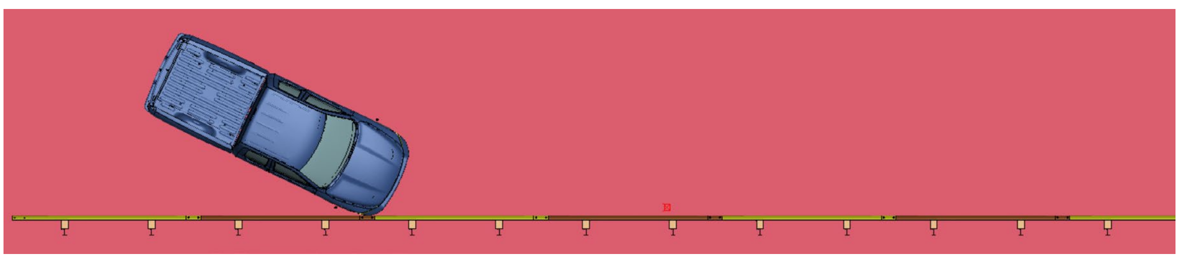


Figure 7.80. Overhead View of Impact Point for 237.5-ft Long Guardrail System

Figure 7.81, Figure 7.82, Figure 7.83, and Figure 7.84 show the sequential frames of *MASH* Test 3-11 on the 237.5-ft system with 1 mm thick refined slot element and increased bolt retention. The OIV was calculated to be 5.5 m/s (preferred limit is 9.1 m/s). The RDA was calculated to be 8.5 G's (preferred limit is 15.0 G's). The simulation showed improved retention between the rail and the post members compared to the previous simulation. Because the simulations of a 250-ft guardrail system (see following section) showed the posts pulled off of the posts, the research team decided to continue the evaluation longer guardrail systems.

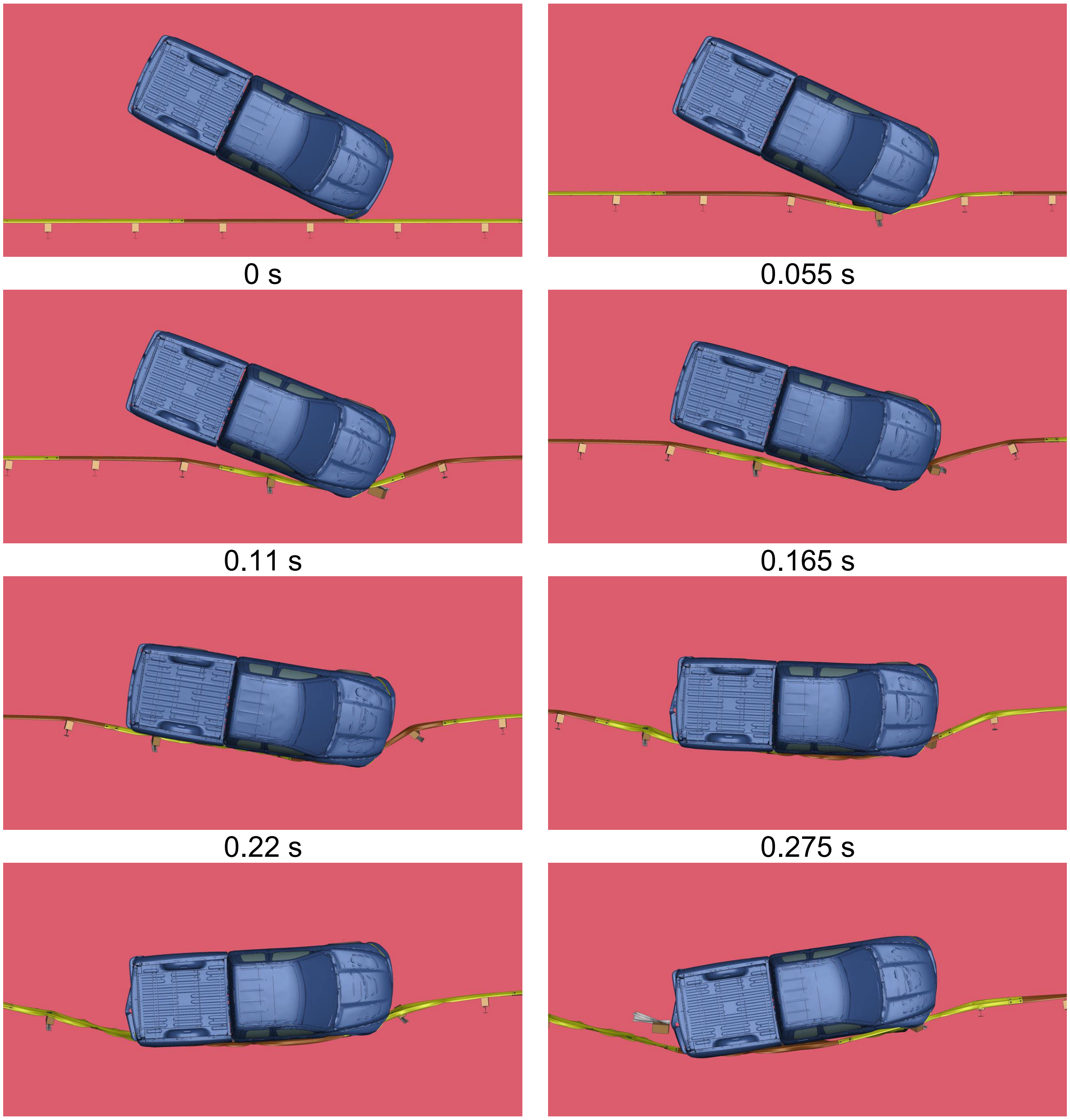


Figure 7.81. 237.5-ft Guardrail System with Refined Slot and Improved Bolt Retention– Overhead View of *MASH* Test 3-11

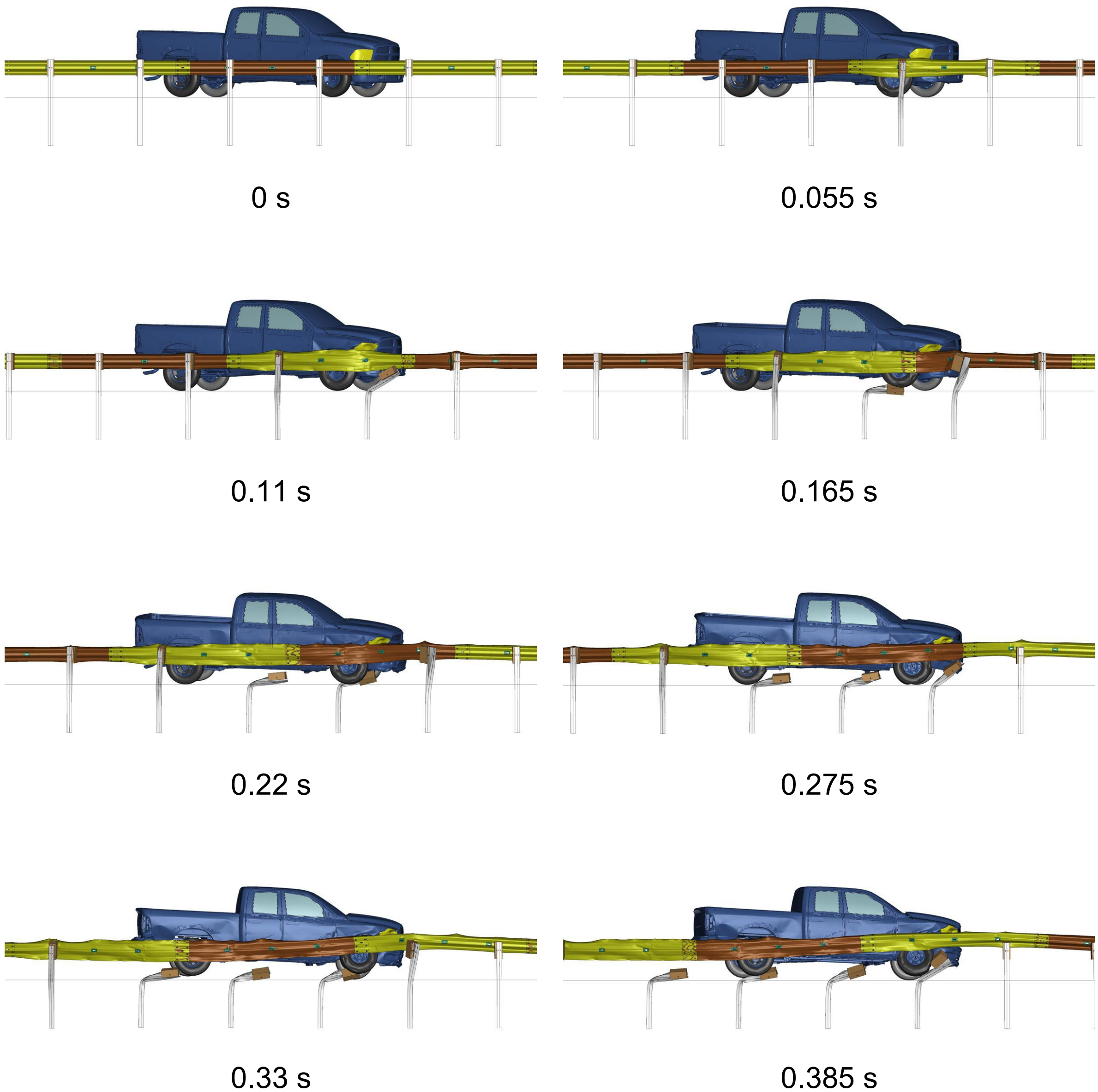


Figure 7.82. 237.5-ft Guardrail System with Refined Slot and Improved Bolt Retention – Rear View of *MASH* Test 3-11

Figure 7.83. 237.5-ft Guardrail System with Refined Slot and Improved Bolt Retention – Downstream View of *MASH* Test 3-11

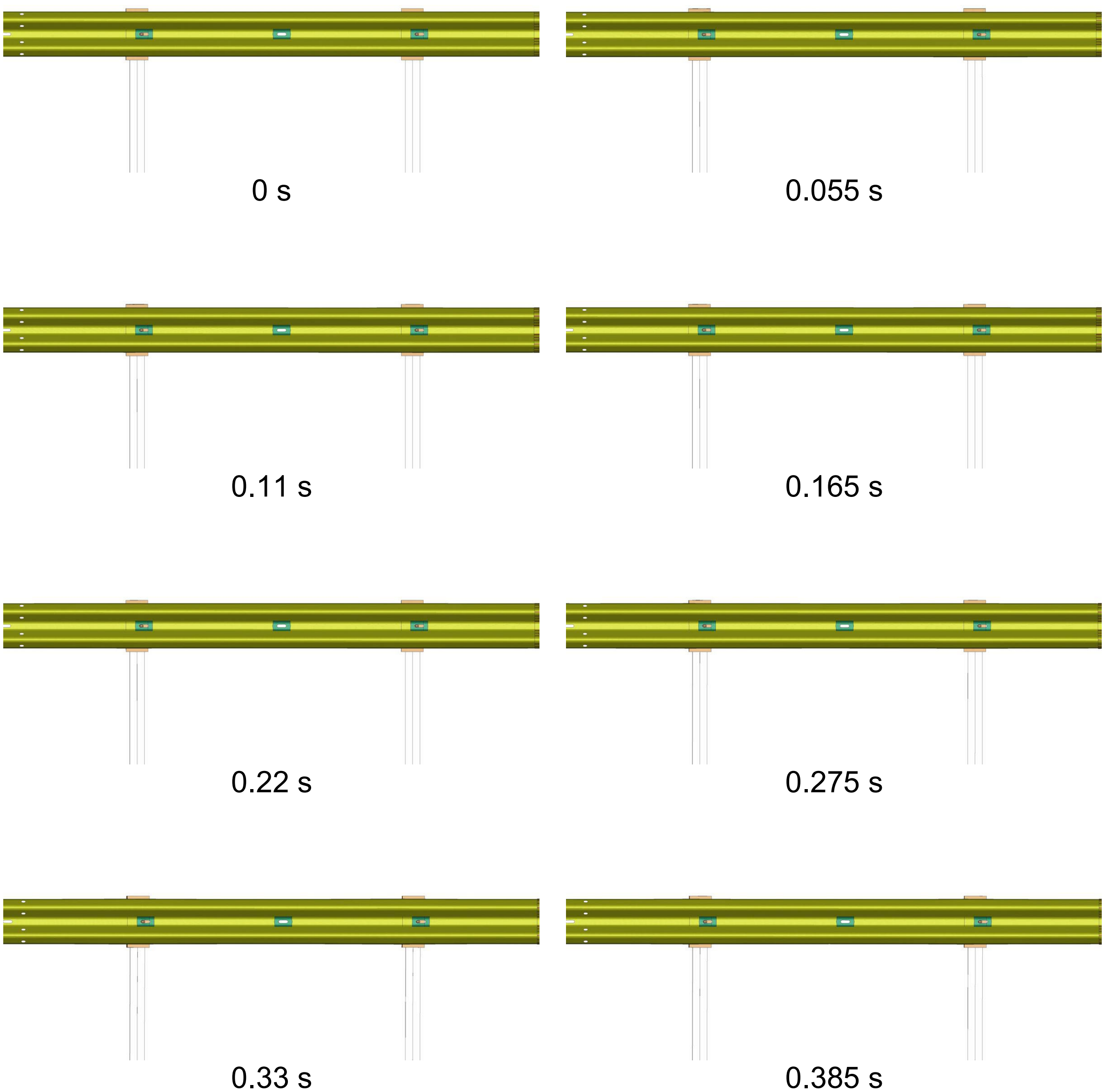


Figure 7.84. 237.5-ft Guardrail System with Refined Slot and Improved Bolt Retention – Front View of Downstream Posts During *MASH* Test 3-11

7.3.10. 250-ft Guardrail System with Refined Slot Mesh

The length of the guardrail system was increased by adding 12.5-ft to the downstream side for a total length of 250-ft. Figure 7.85 shows an overhead view of the finite element model. The system was evaluated using a computer simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 225.8-ft from the unanchored downstream end of the rail and is shown below in Figure 7.86.

Figure 7.85. Overhead View of 250-ft Long Guardrail System

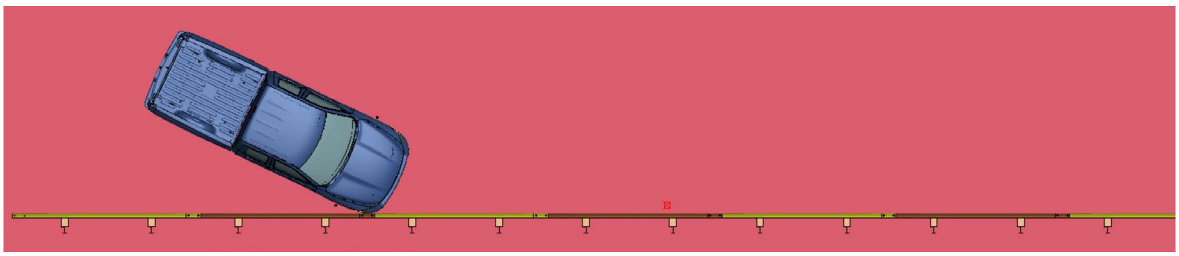


Figure 7.86. Overhead View of Impact Point for 250-ft Long Guardrail System

Figure 7.87, Figure 7.88, Figure 7.89, and Figure 7.90 show the sequential frames of *MASH* Test 3-11 on the 250-ft system with 1 mm thick refined slot element. During the impact, the w-beam rail was pulled off the posts downstream of impact and failed to meet the project objective. The researchers then increased the length of the guardrail system, and this model is discussed in the next section.

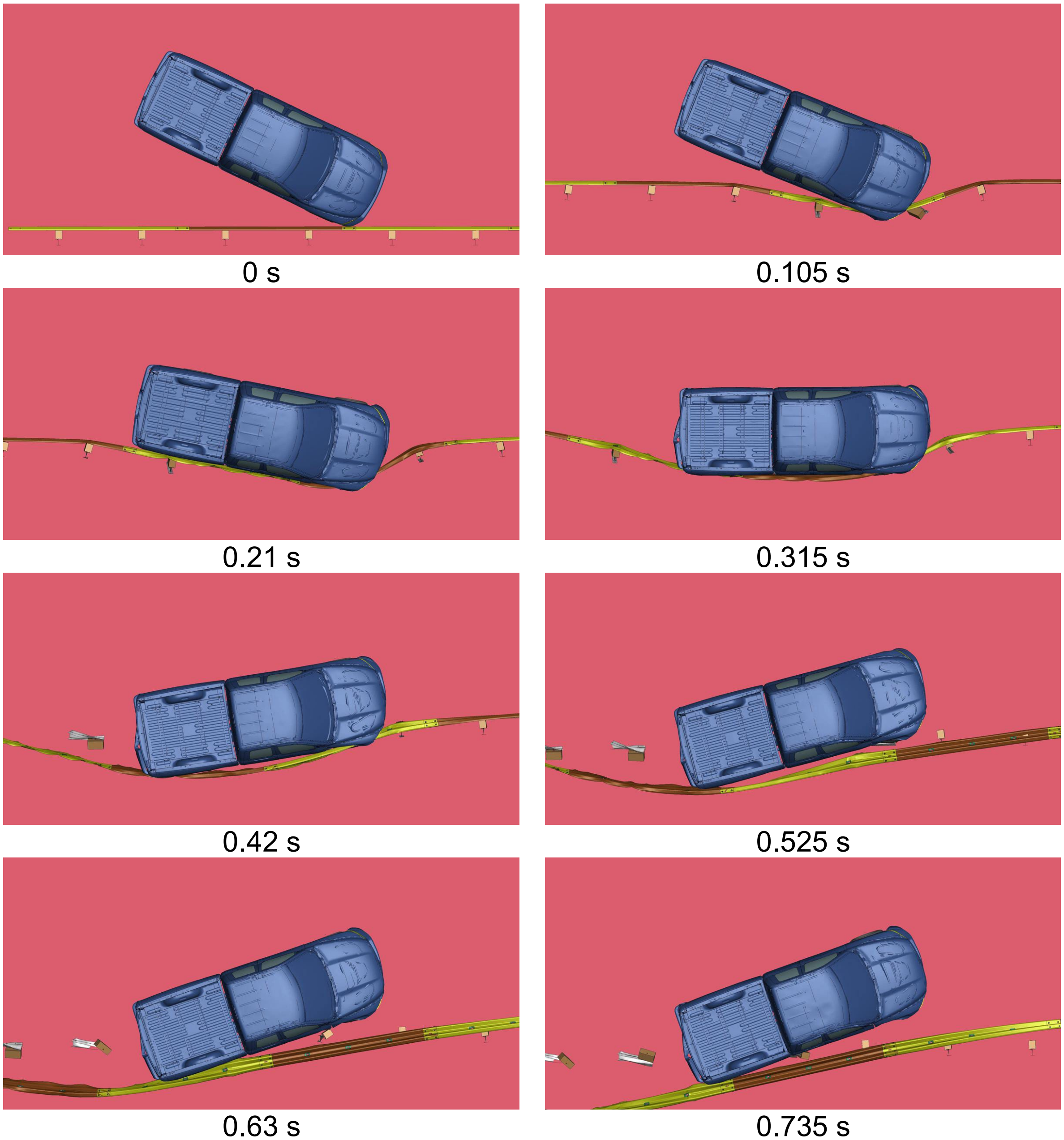


Figure 7.87. 250-ft Guardrail System with Refined Slot – Overhead View of *MASH* Test 3-11

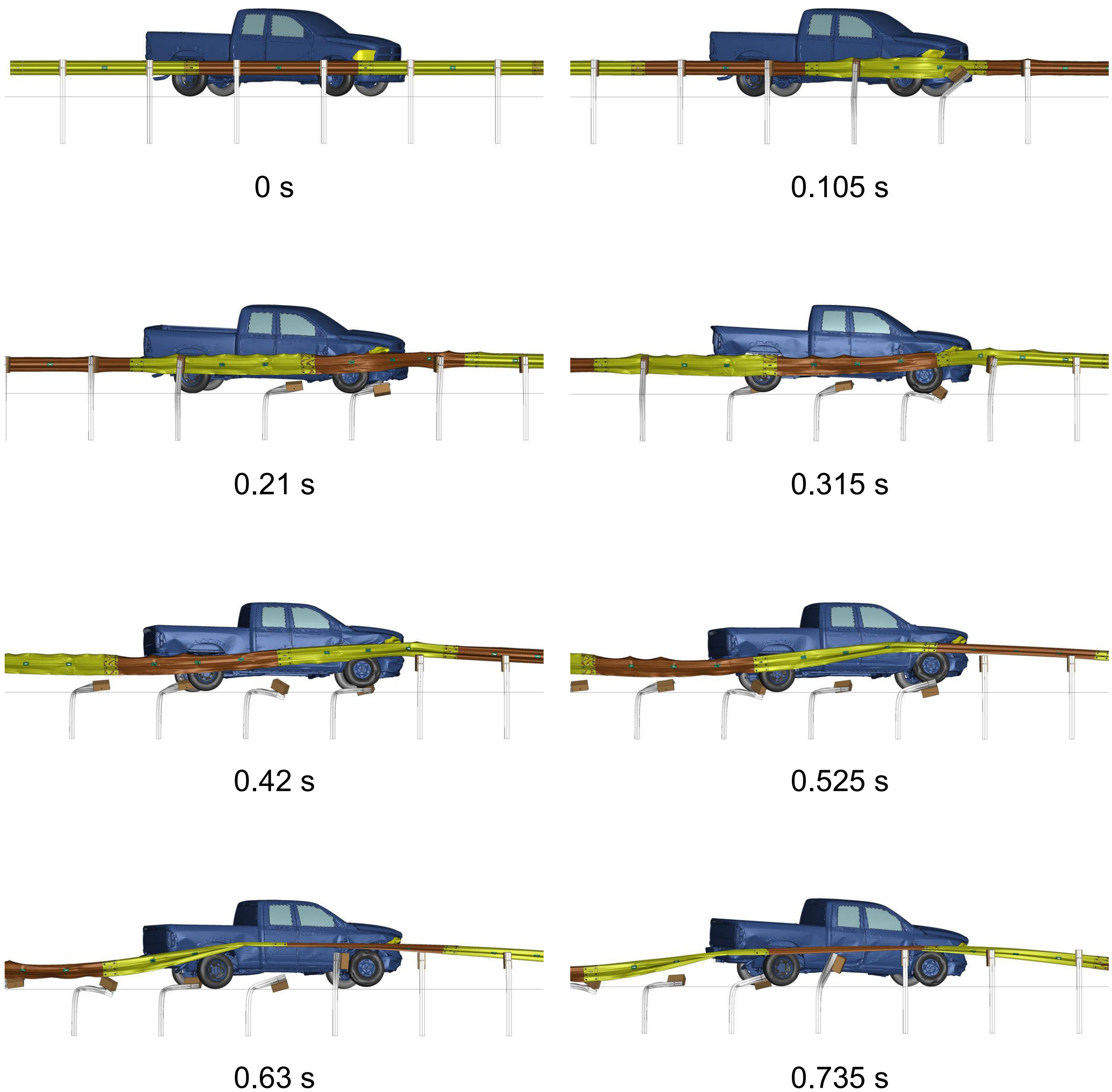


Figure 7.88. 250-ft Guardrail System with Refined Slot – Rear View of *MASH* Test 3-11

Figure 7.89. 250-ft Guardrail System with Refined Slot – Downstream View of *MASH* Test 3-11

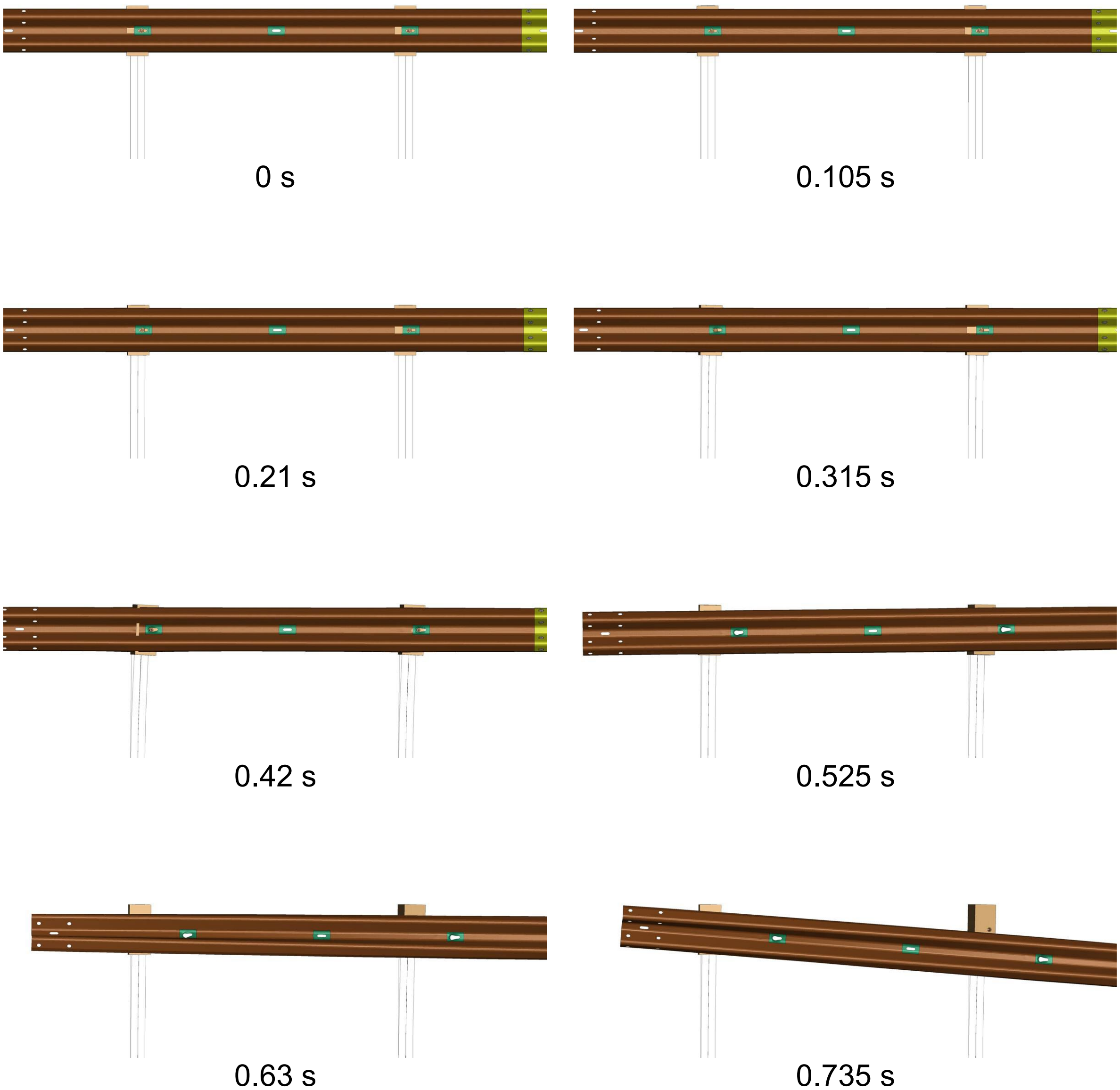


Figure 7.90. 250-ft Guardrail System with Refined Slot – Front View of Downstream Posts During *MASH* Test 3-11

7.3.11. 262.5-ft Guardrail System with Refined Slot

The length of the guardrail system was increased by adding 12.5-ft to the downstream side for a total length of 262.5-ft. This simulation was performed with the impact point 238.3-ft from the unanchored downstream end of the installation. Figure 7.91 shows an overhead view of the finite element model. The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 238.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.92.

Figure 7.91. Overhead View of 262.5-ft Long Guardrail System

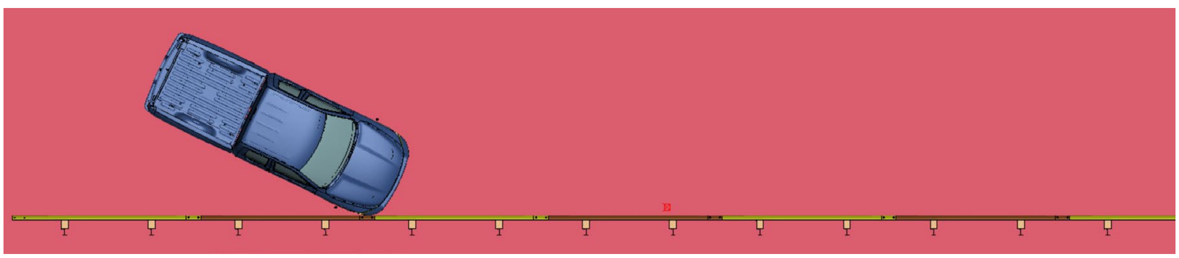


Figure 7.92. Overhead View of Impact Point for 262.5-ft Long Guardrail System

Figure 7.93, **Error! Reference source not found.**, Figure 7.95, and Figure 7.96 show the sequential frames of *MASH* Test 3-11 on the 262.5-ft system with refined slot mesh. The downstream posts maintained connectivity to the posts, and the vehicle was successfully contained and redirected. The OIV was calculated to be 5.2 m/s (preferred limit is 9.1 m/s). The RDA was calculated to be 9.4 G's (preferred limit is 15.0 G's). Based on these simulation results, the research team determined the minimum length-of-need for a guardrail system without downstream anchorage was 262.5 ft. However, this would need to be verified through full-scale testing, based upon the previous testing results.

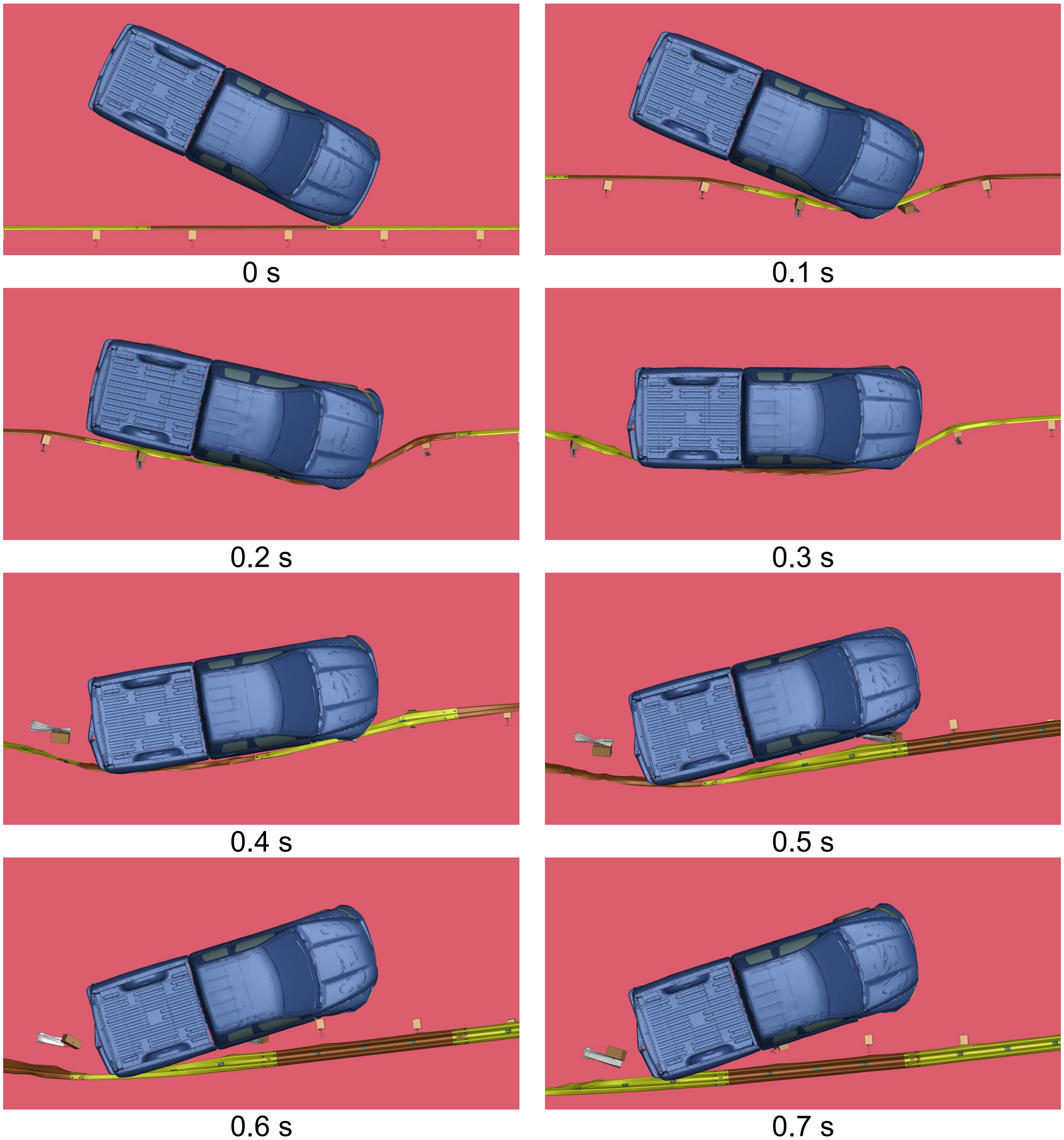
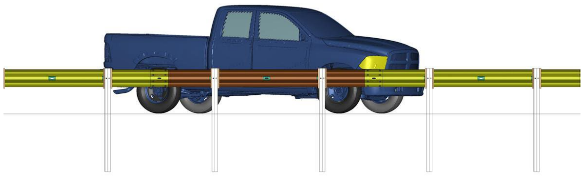
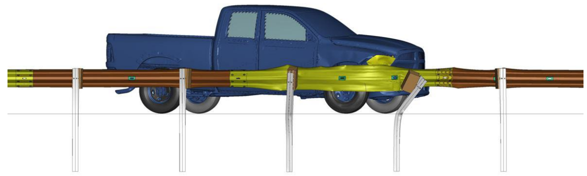


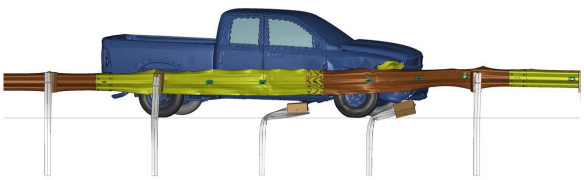
Figure 7.93. 262.5-ft Guardrail System with Refined Slot Mesh – Overhead View of *MASH* Test 3-11



0 s

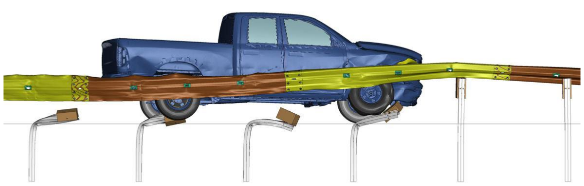


0.1 s

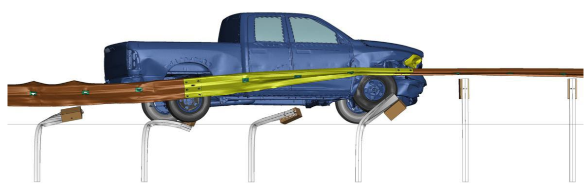


0.2 s

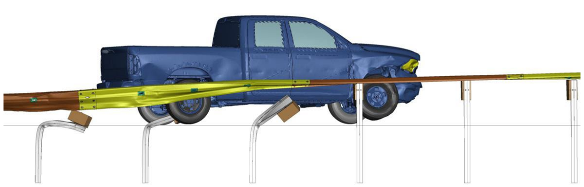
0.3 s



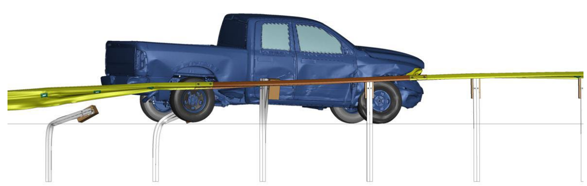
0.4 s



0.5 s



0.6 s



0.7 s

Figure 7.94. 262.5-ft Guardrail System with Refined Slot Mesh – Rear View of *MASH* Test 3-11

Figure 7.95. 262.5-ft Guardrail System with Refined Slot Mesh – Downstream View of *MASH* Test 3-11

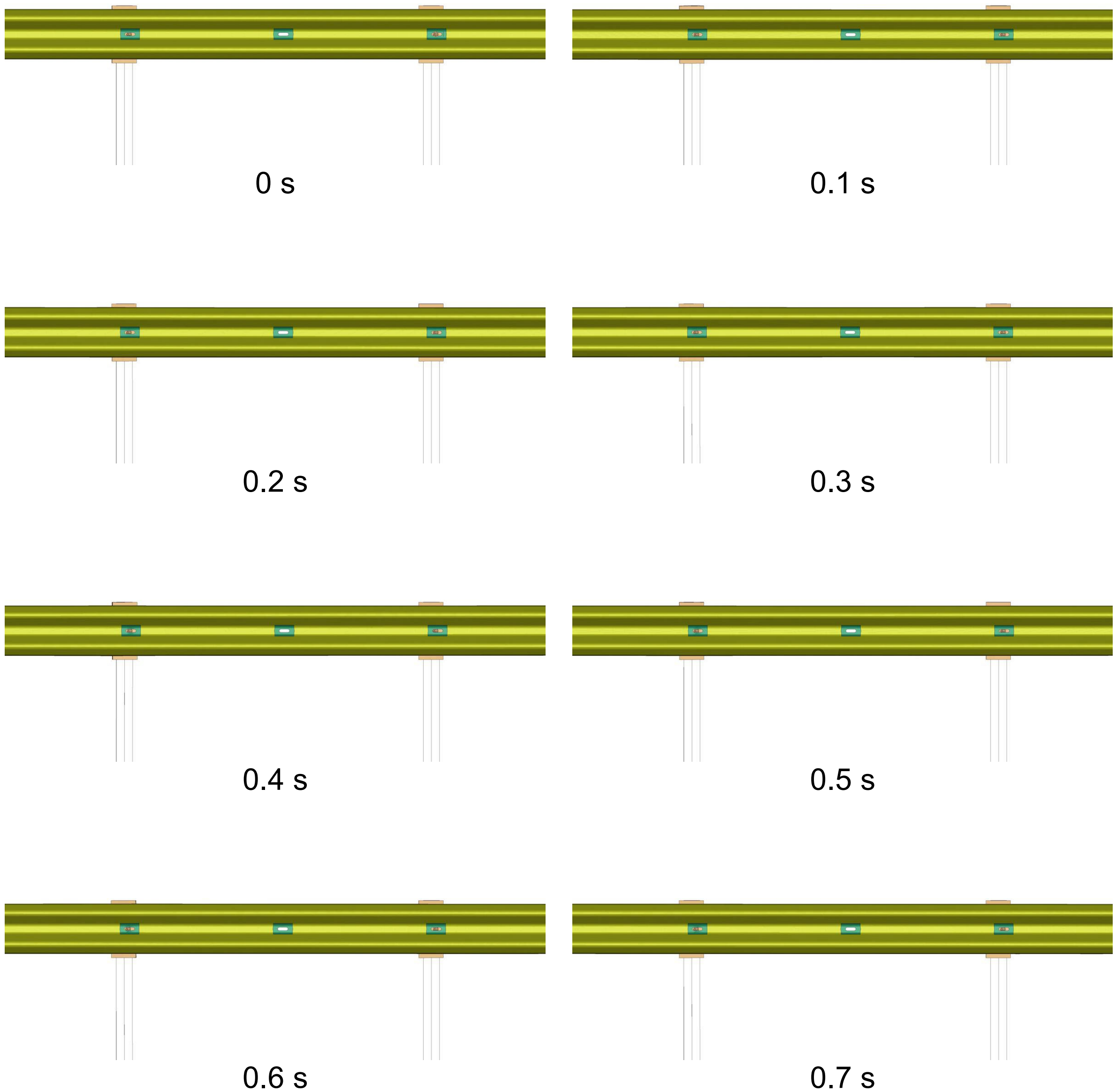


Figure 7.96. 262.5-ft Guardrail System with Refined Slot Mesh – Front View of Downstream Posts During *MASH* Test 3-11

7.4. GUARDRAIL WASHER EVALUATION

From the previous simulations, the research team determined the minimum length-of-need of w-beam guardrail required to maintain connectivity of the guardrail system and its redirective capability. This 262.5 ft length-of-need was determined by the technical representative to be impractical for field applications. Consequently, the research team in conjunction with the technical representative decided to evaluate alternative improvements for maintaining the connectivity between the rail and post members.

The most practical solution initially developed was the inclusion of industry standard guardrail washers on the downstream end posts between the w-beam rail and the bolt head, as shown in Figure 7.97. This washer is intended to be a temporary feature during guardrail construction and only located on a downstream post until a downstream terminal is installed. Consequently, the inclusion of washers at the downstream end posts was investigated through the computer simulations discussed below.

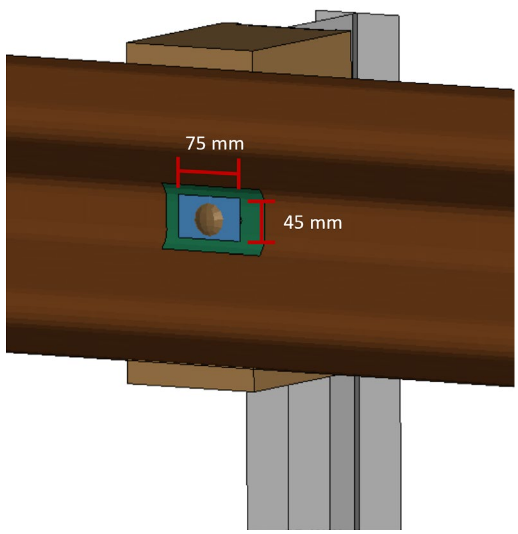


Figure 7.97. 2.2.23 – Mounted Guardrail Washer

7.4.1. 87.5-ft GUARDRAIL SYSTEM WITH REFINED SLOT MESH and One End Washer

One guardrail washer was added to the most downstream post, and the length of the guardrail system was kept at 87.5-ft. Figure 7.98 shows an overhead view of the finite element model. The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 63.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.99.

Figure 7.98. Overhead View of 87.5-ft Long Guardrail System

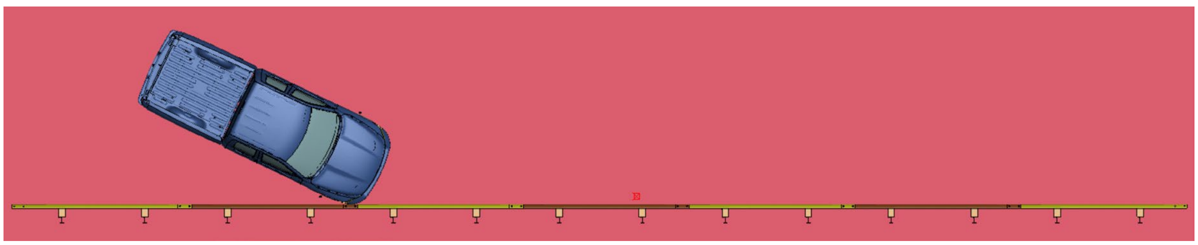


Figure 7.99. Overhead View of Impact Point for 87.5-ft Long Guardrail System

Figure 7.100, Figure 7.101, Figure 7.102, and Figure 7.103 show the sequential frames of *MASH* Test 3-11 on the 87.5-ft system with refined slot element and end washer. The OIV was calculated to be 6.0 m/s (preferred limit is 9.1 m/s). The RDA was calculated to be 9.4 G's (preferred limit is 15 G's). This configuration passed *MASH* Test 3-11 by successfully containing and redirecting the vehicle. However, the research team noticed a large amount of instability in the post-impact vehicle behavior. Therefore, the research team investigated this instability by adding tire failure into the vehicle models in the following simulations.

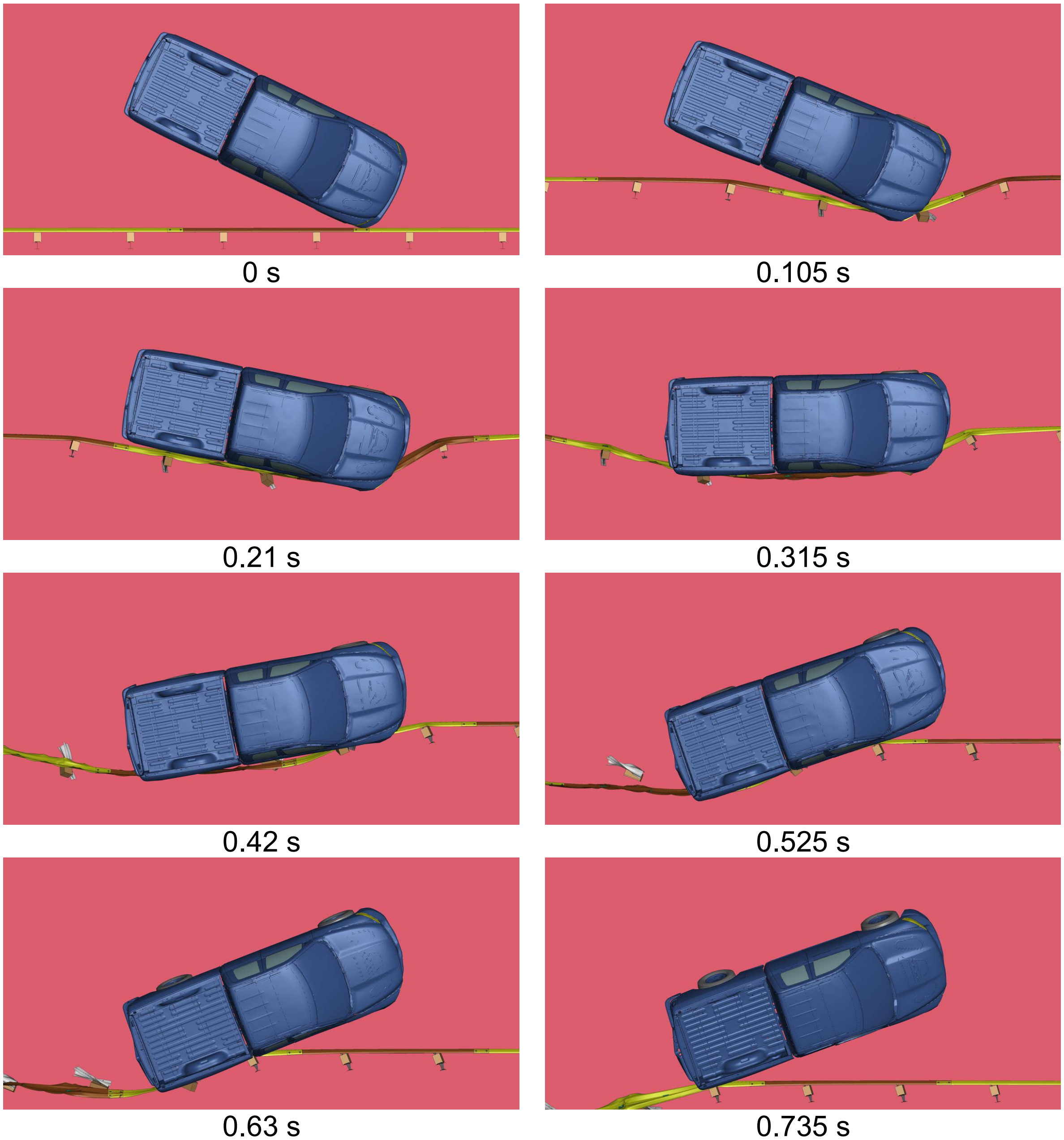


Figure 7.100. 87.5-ft Guardrail System with Refined Slot and End Washer – Overhead View of *MASH* Test 3-11

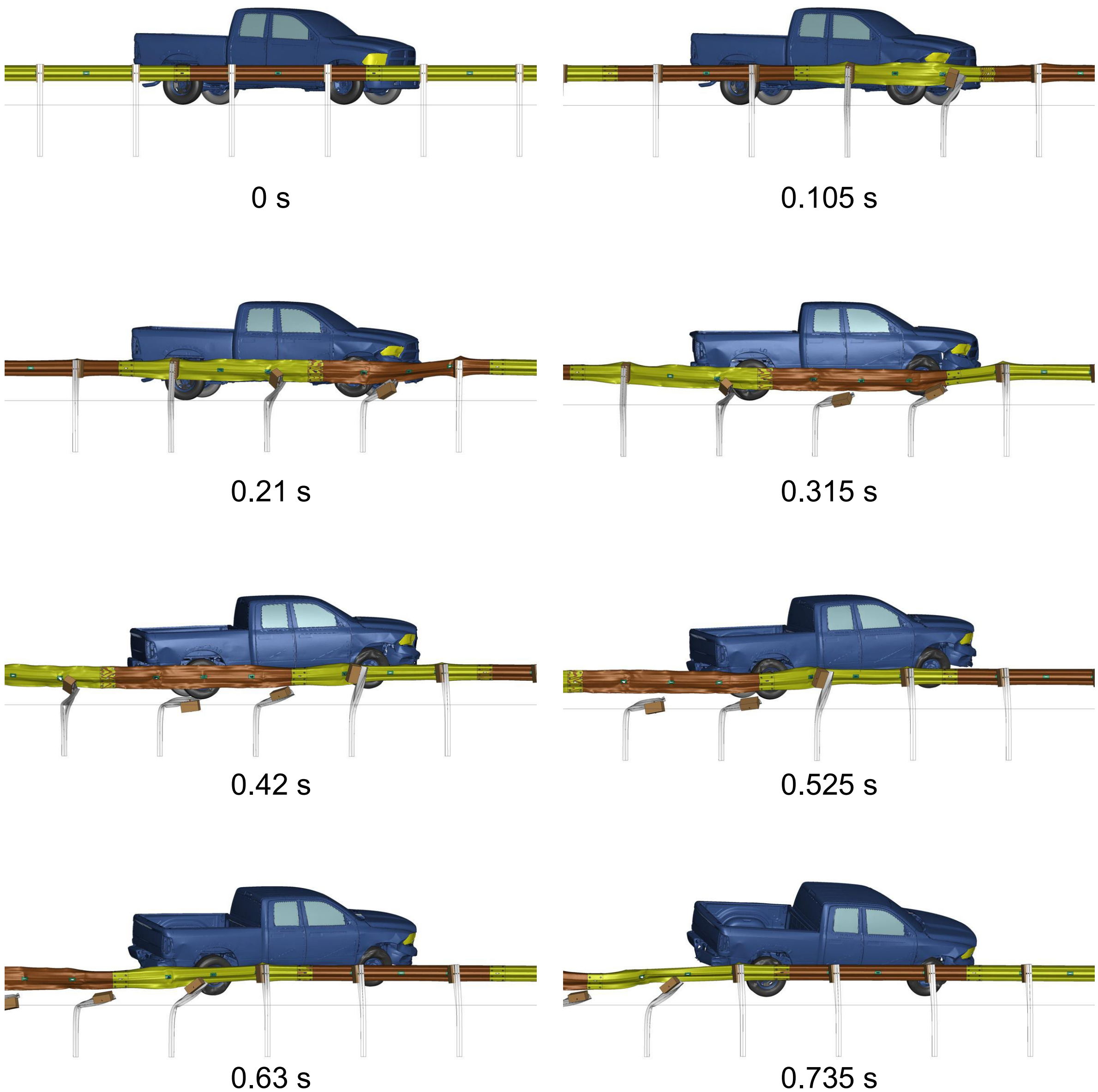


Figure 7.101. 87.5-ft Guardrail System with Refined Slot and End Washer – Rear View of *MASH* Test 3-11

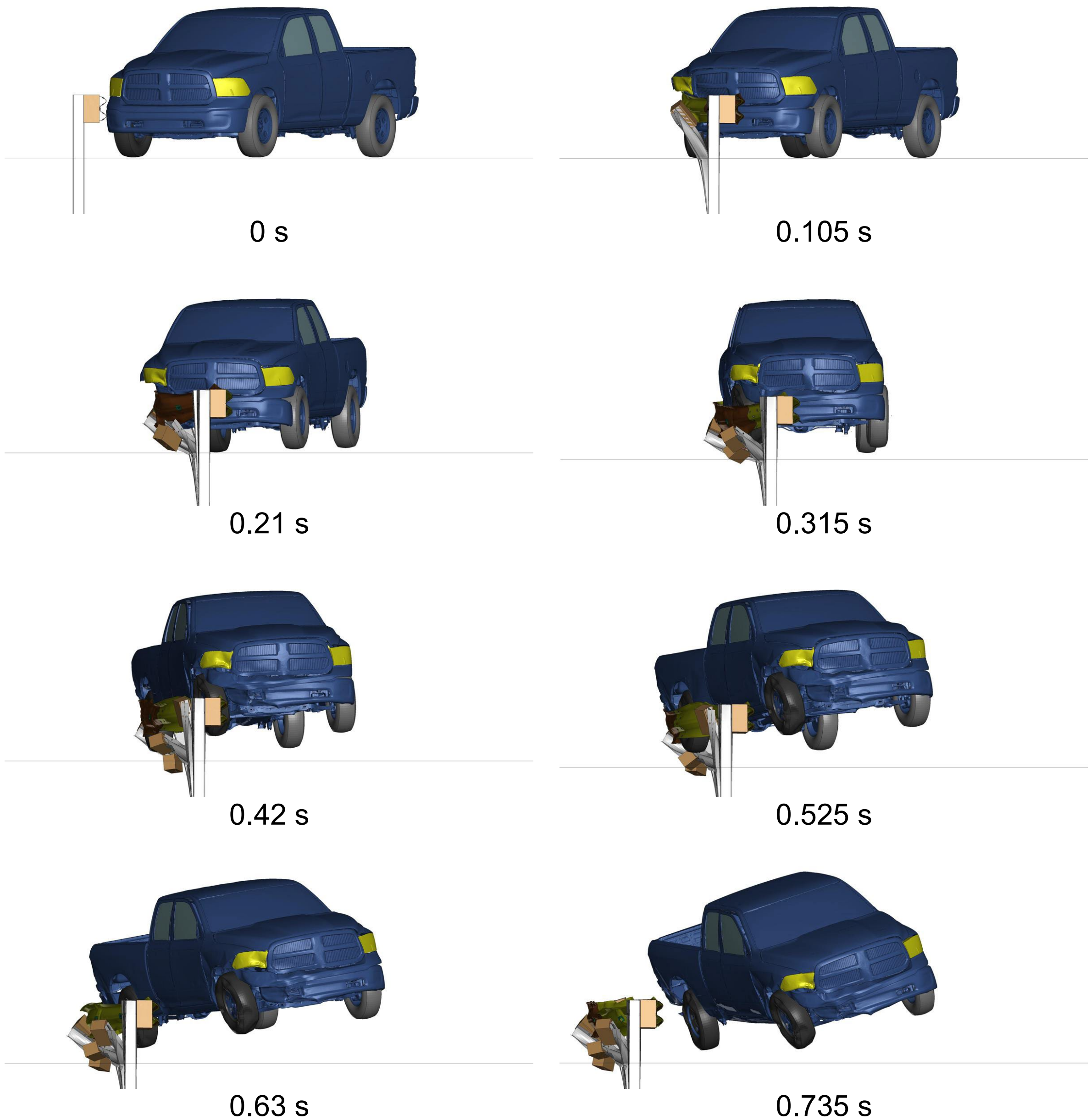


Figure 7.102. 87.5-ft Guardrail System with Refined Slot and End Washer – Downstream View of *MASH* Test 3-11

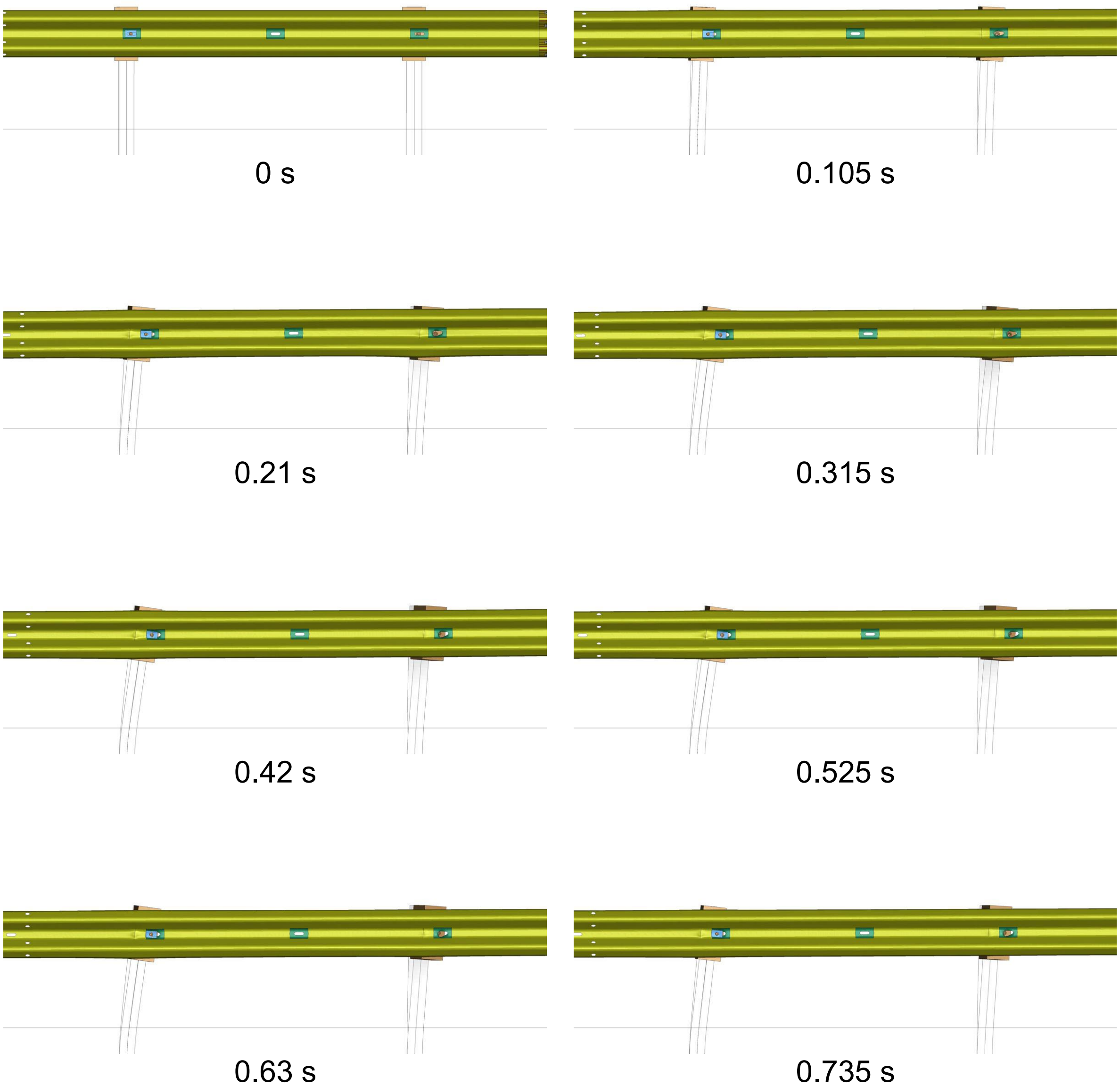


Figure 7.103. 87.5-ft Guardrail System with Refined Slot and End Washer – Front View of Downstream Posts During *MASH* Test 3-11

7.4.2. 87.5-ft GUARDRAIL SYSTEM WITH REFINED SLOT MESH and One End Washer, Improved Vehicle Model

The previous model was reused in this simulation with the addition of tire failure to the vehicle model. The vehicle model with tire failure was also utilized in subsequent simulations to mitigate numerical vehicle instability. Figure 7.104 shows an overhead view of the finite element model. The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 63.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.105.

Figure 7.104. Overhead View of 87.5-ft Long Guardrail System

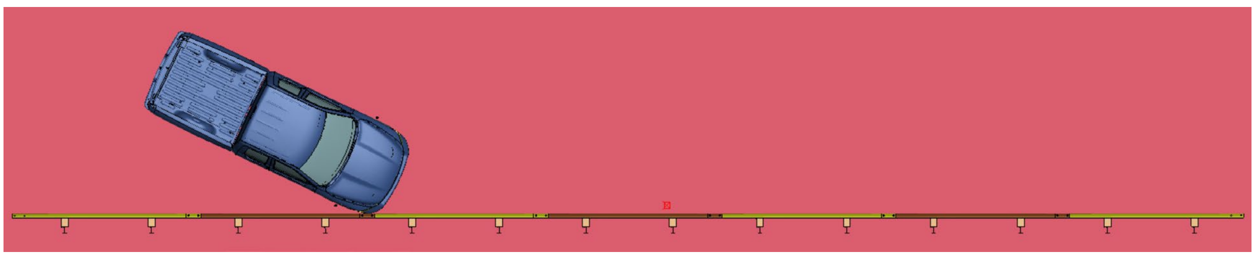


Figure 7.105. Overhead View of Impact Point for 87.5-ft Long Guardrail System

Figure 7.106, Figure 7.107, Figure 7.108, and Figure 7.109 show the sequential frames of *MASH* Test 3-11 on the 87.5-ft system with refined slot element and end washer. The OIV was calculated to be 5.9 m/s (preferred limit is 9.1 m/s). The RDA was calculated to be 8.0 G's (preferred limit is 15 G's). This configuration passed *MASH* Test 3-11 by successfully containing and redirecting the vehicle.

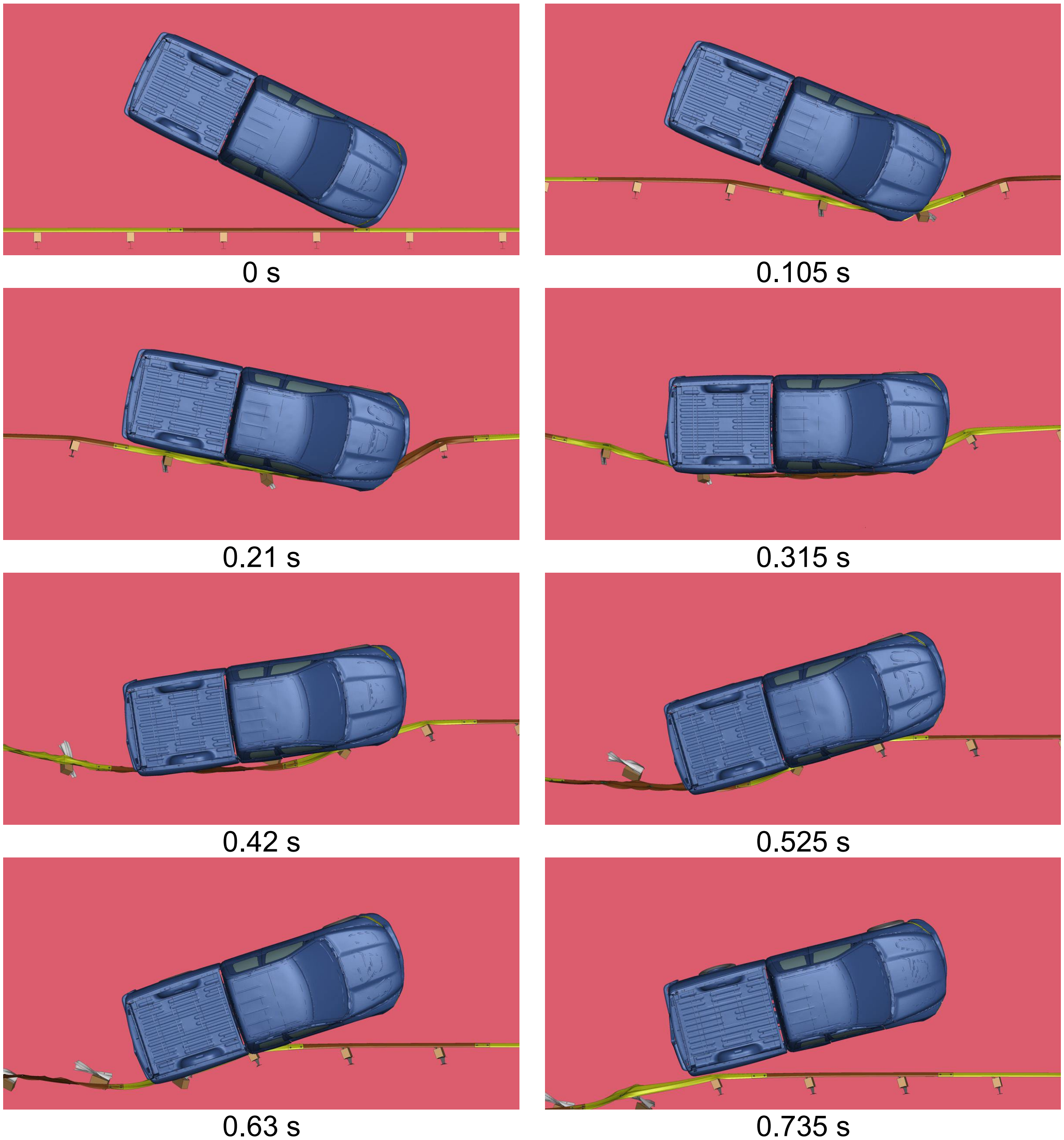


Figure 7.106. 87.5-ft Guardrail System with Refined Slot and End Washer – Overhead View of *MASH* Test 3-11

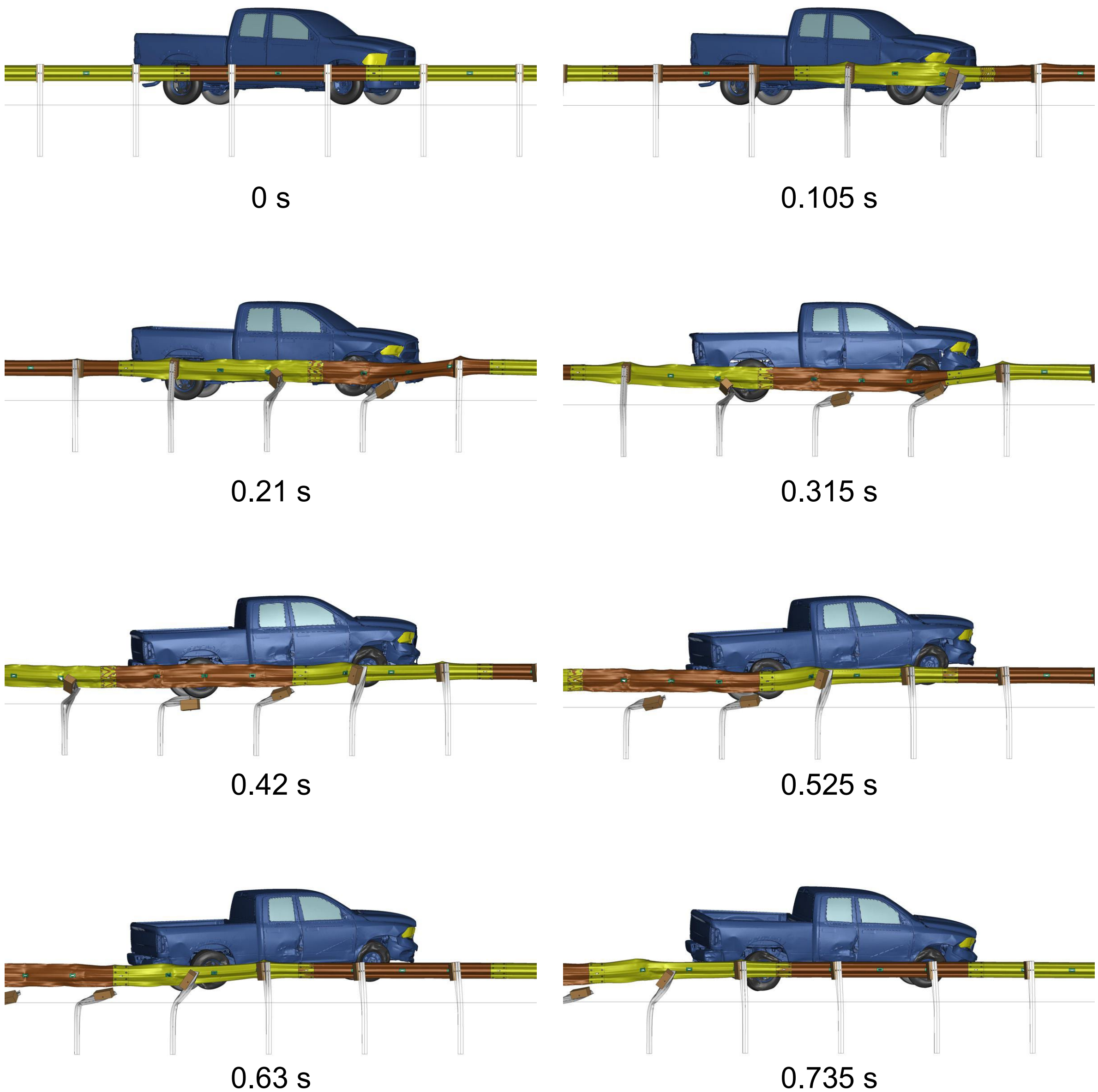


Figure 7.107. 87.5-ft Guardrail System with Refined Slot and End Washer – Rear View of *MASH* Test 3-11

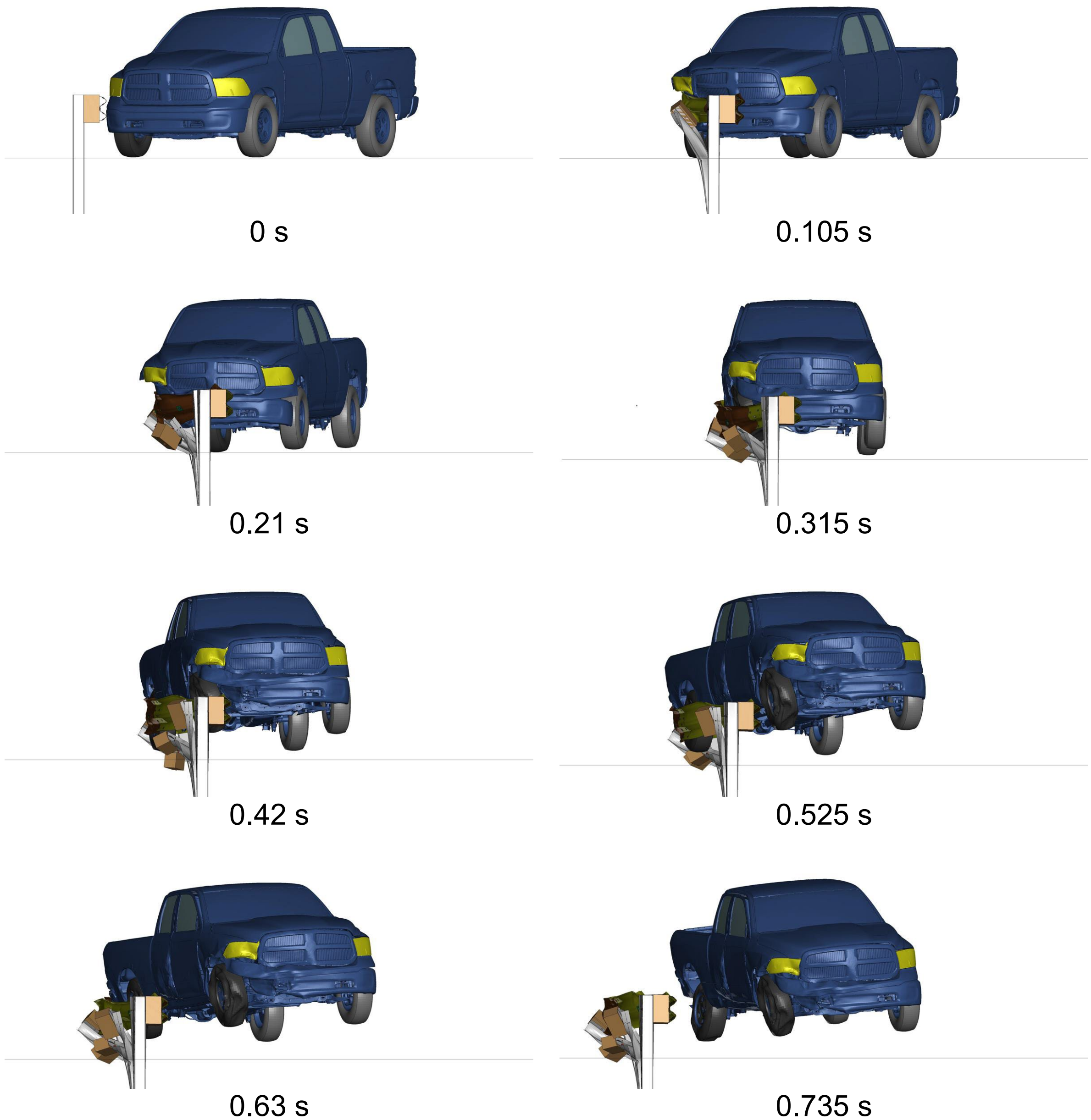


Figure 7.108. 87.5-ft Guardrail System with Refined Slot and End Washer – Downstream View of *MASH* Test 3-11

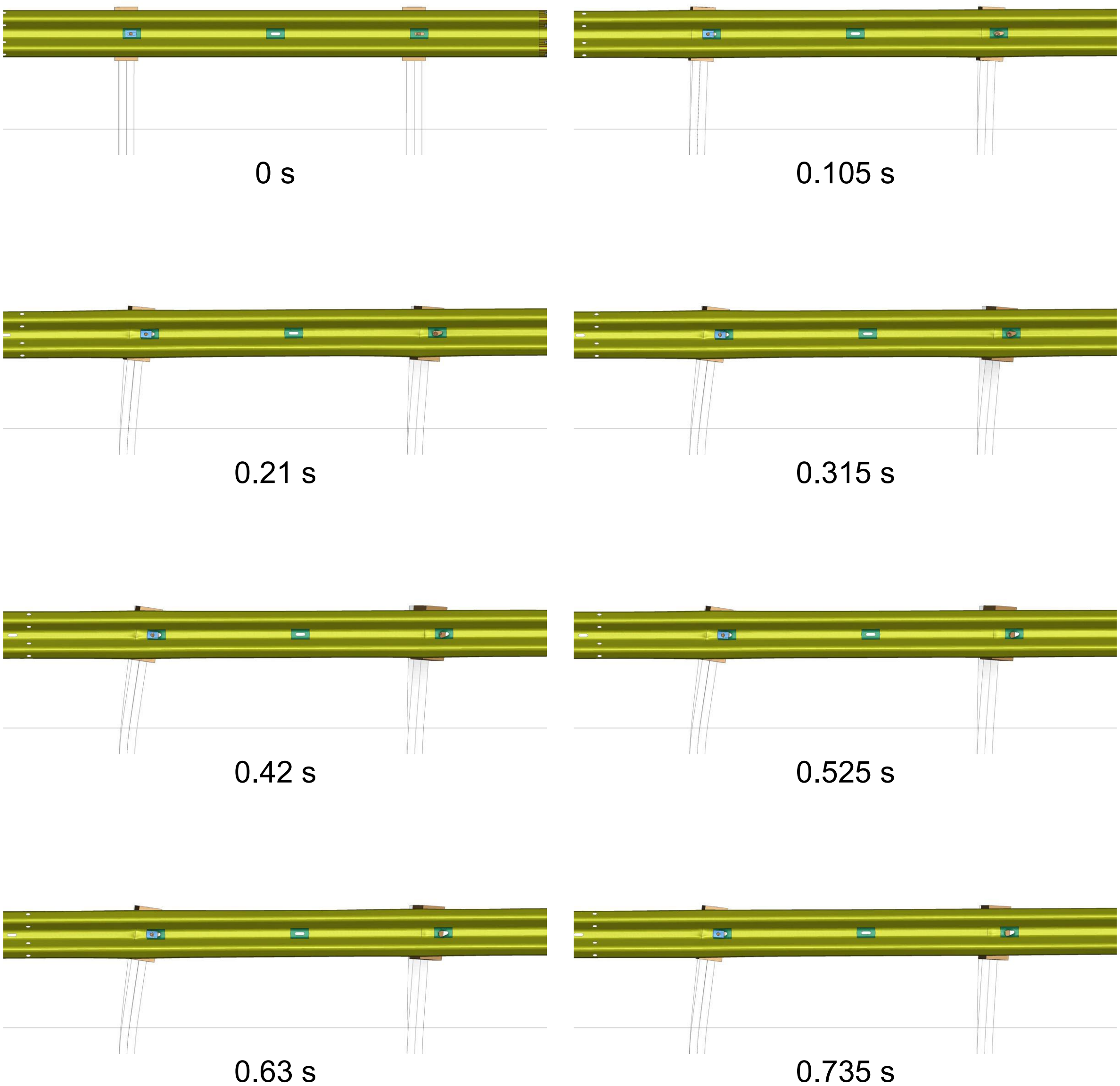


Figure 7.109. 87.5-ft Guardrail System with Refined Slot and End Washer – Front View of Downstream Posts During *MASH* Test 3-11

7.4.3. 87.5-ft GUARDRAIL SYSTEM WITH REFINED SLOT MESH and two End Washers

Compared to the previous model, an additional guardrail washer was added at the second most downstream post between the w-beam rail and the bolt head. The research team included this additional washer because the previous simulation showed the washer may pull out of the w-beam guardrail slot. Therefore, an additional washer would provide additional tensile resistance. Figure 7.110 shows an overhead view of the finite element model. The system was evaluated using a computer simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 63.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.111.

Figure 7.110. Overhead View of 87.5-ft Long Guardrail System

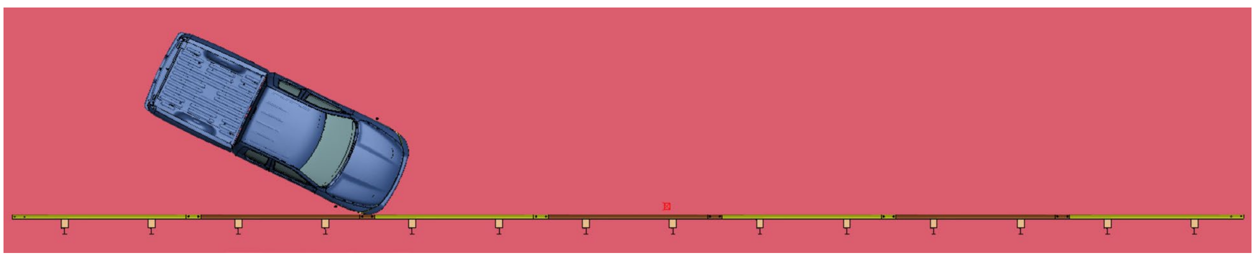


Figure 7.111. Overhead View of Impact Point for 87.5-ft Long Guardrail System

Figure 7.112, Figure 7.113, Figure 7.114, and Figure 7.115 show the sequential frames of *MASH* Test 3-11 on the 87.5-ft system with refined slot element and end washers. The OIV was calculated to be 6.1 m/s (preferred limit is 9.1 m/s). The RDA was calculated to be 7.6 G’s (preferred limit is 15 G’s). This configuration passed *MASH* Test 3-11 by successfully containing and redirecting the vehicle.

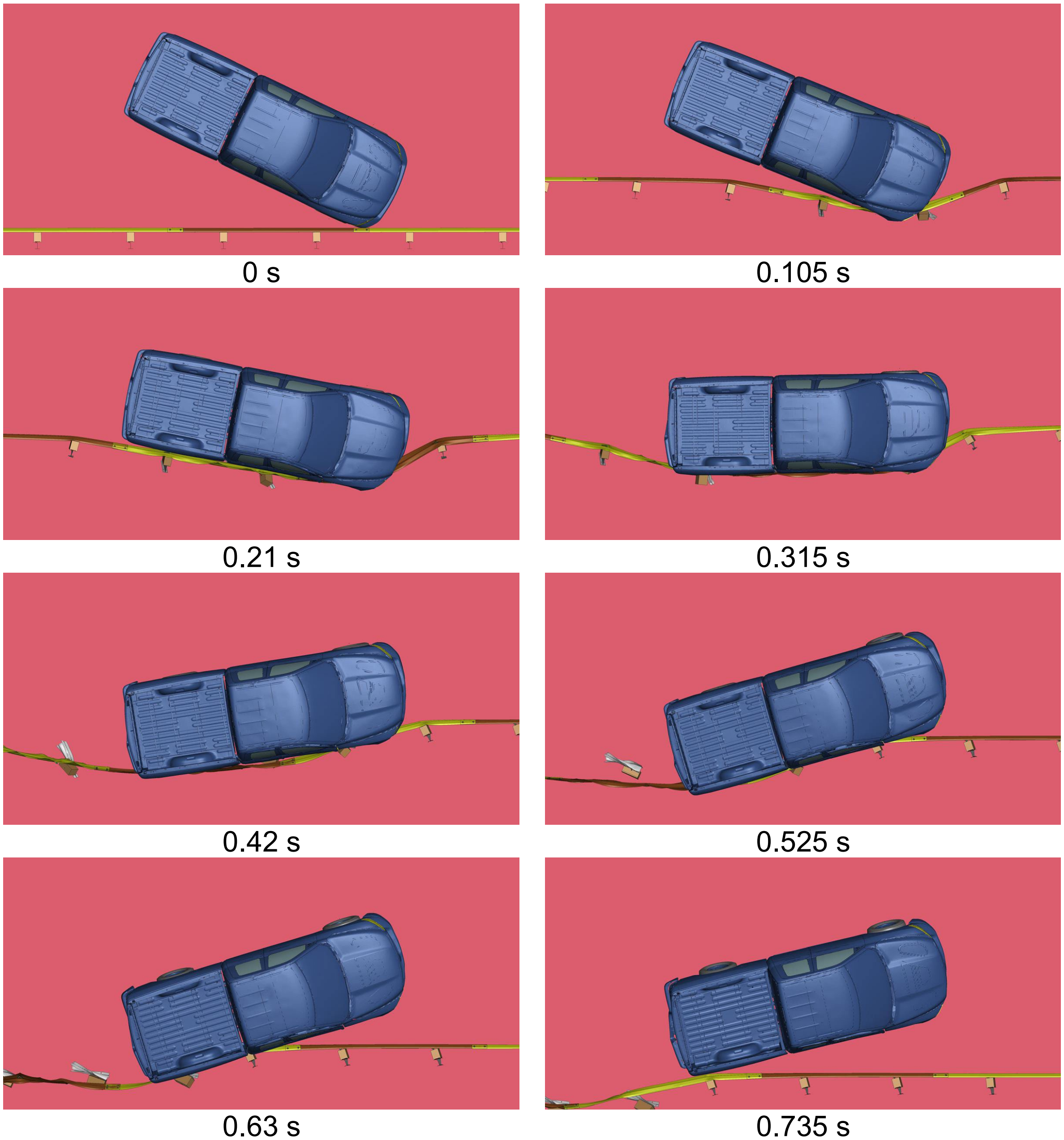


Figure 7.112. 87.5-ft Guardrail System with Refined Slot and Two End Washers – Overhead View of *MASH* Test 3-11

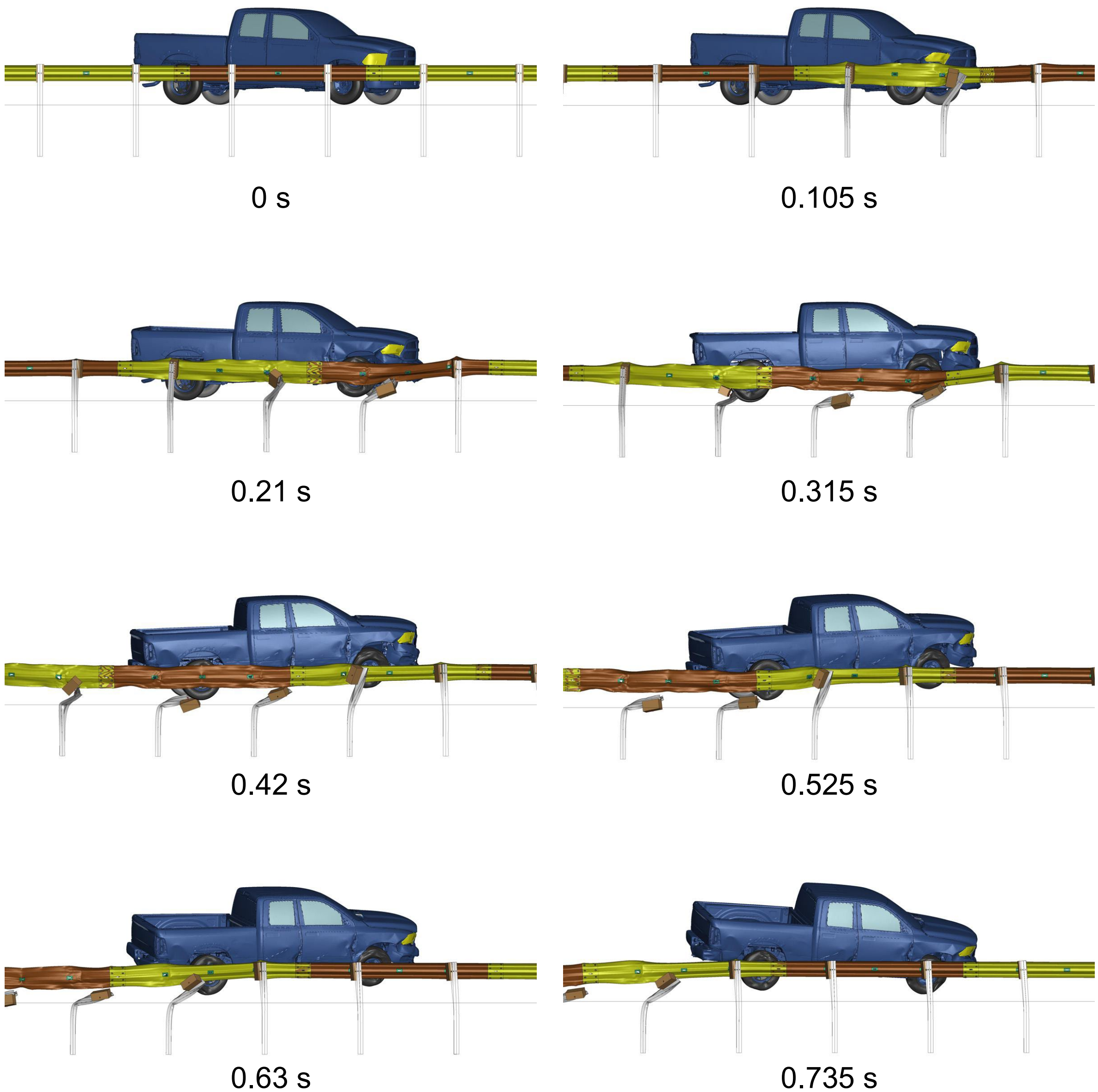


Figure 7.113. 87.5-ft Guardrail System with Refined Slot and Two End Washers – Rear View of *MASH* Test 3-11

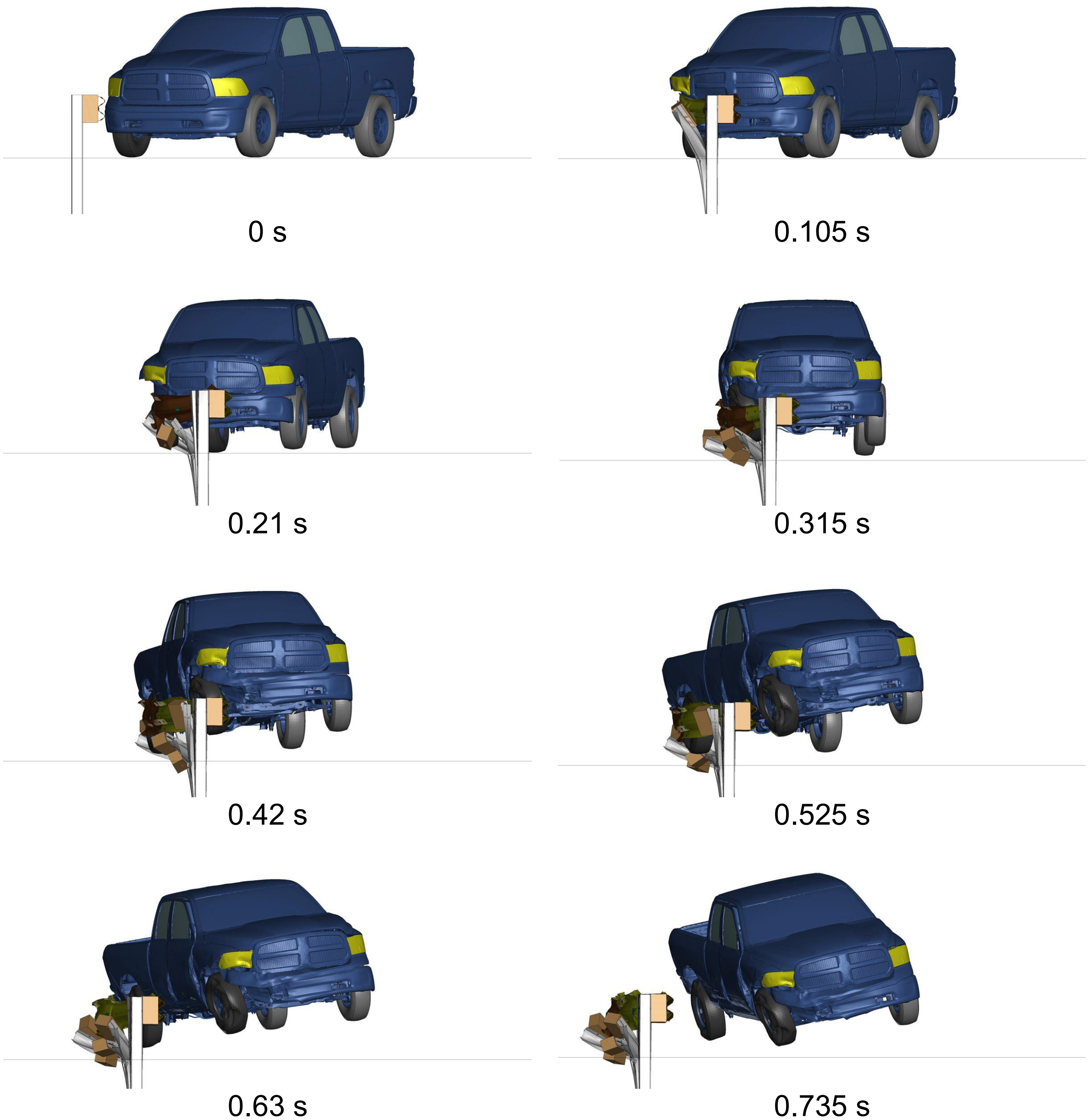


Figure 7.114. 87.5-ft Guardrail System with Refined Slot and Two End Washers – Downstream View of MASH Test 3-11

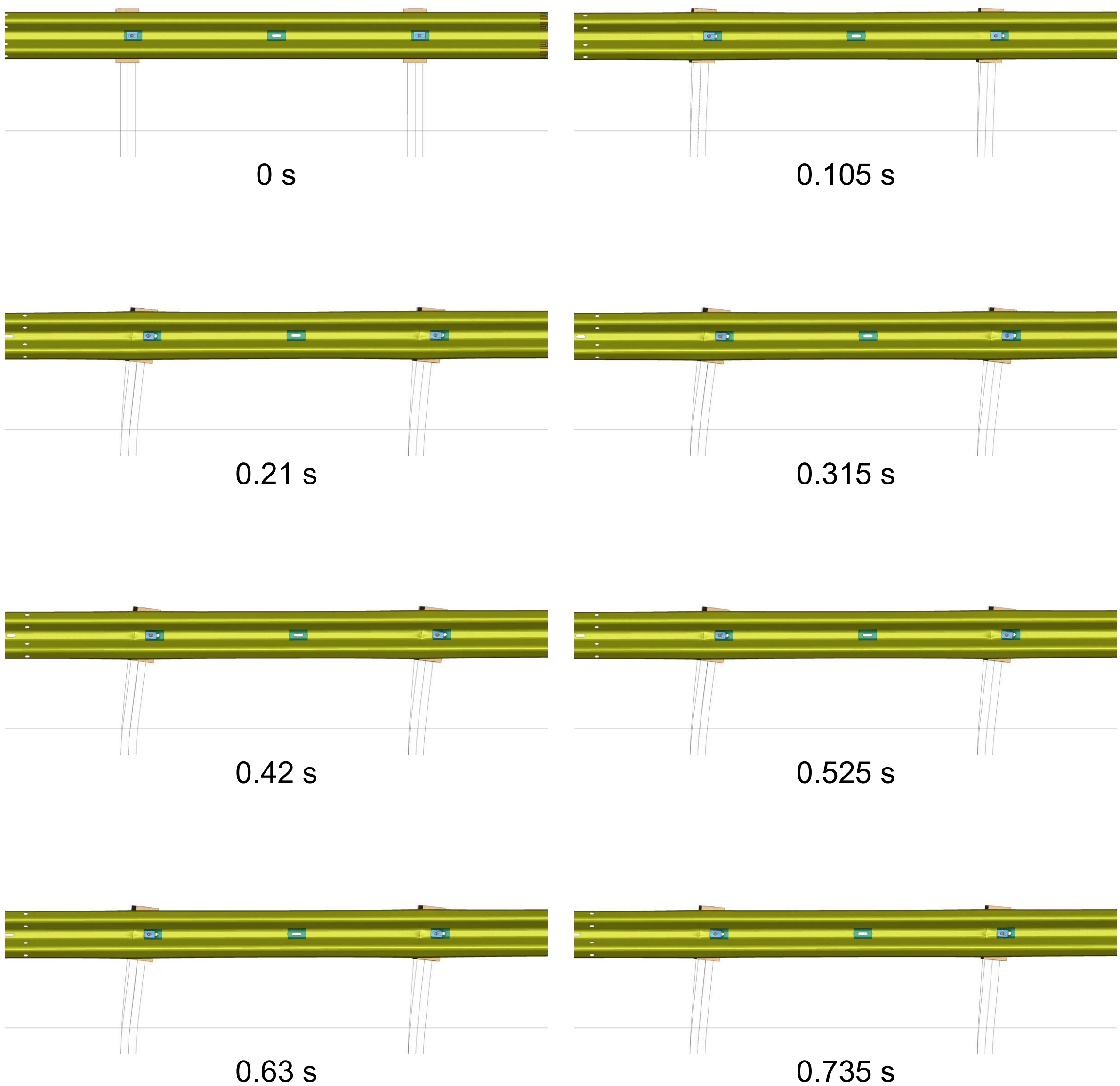


Figure 7.115. 87.5-ft Guardrail System with Refined Slot and Two End Washers – Front View of Downstream Posts During *MASH* Test 3-11

7.4.4. 75-ft GUARDRAIL SYSTEM WITH REFINED SLOT MESH and two End Washers

The length of the previous 87.5 ft guardrail system model was reduced to 75-ft, but the two downstream end posts continued to include guardrail washers. Figure 7.116 shows an overhead view of the finite element model. The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 50.8-ft from the unanchored downstream end of the rail and is shown below in Figure 7.117.

Figure 7.116. Overhead View of 75-ft Long Guardrail System

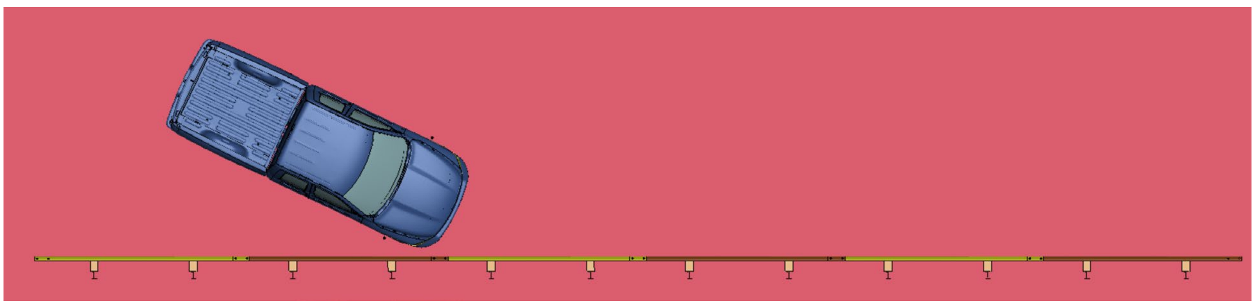


Figure 7.117. Overhead View of Impact Point for 75-ft Long Guardrail System

Figure 7.118, Figure 7.119, Figure 7.120, and Figure 7.121 show the sequential frames of *MASH* Test 3-11 on the 75-ft system with 1 mm thick refined slot element and two downstream washers. During the impact, the w-beam rail was pulled off the posts downstream of impact and failed to meet the project objective. Therefore, the 87.5 ft length-of-need with two downstream end post washers was determined to the shortest which provided redirective capability.

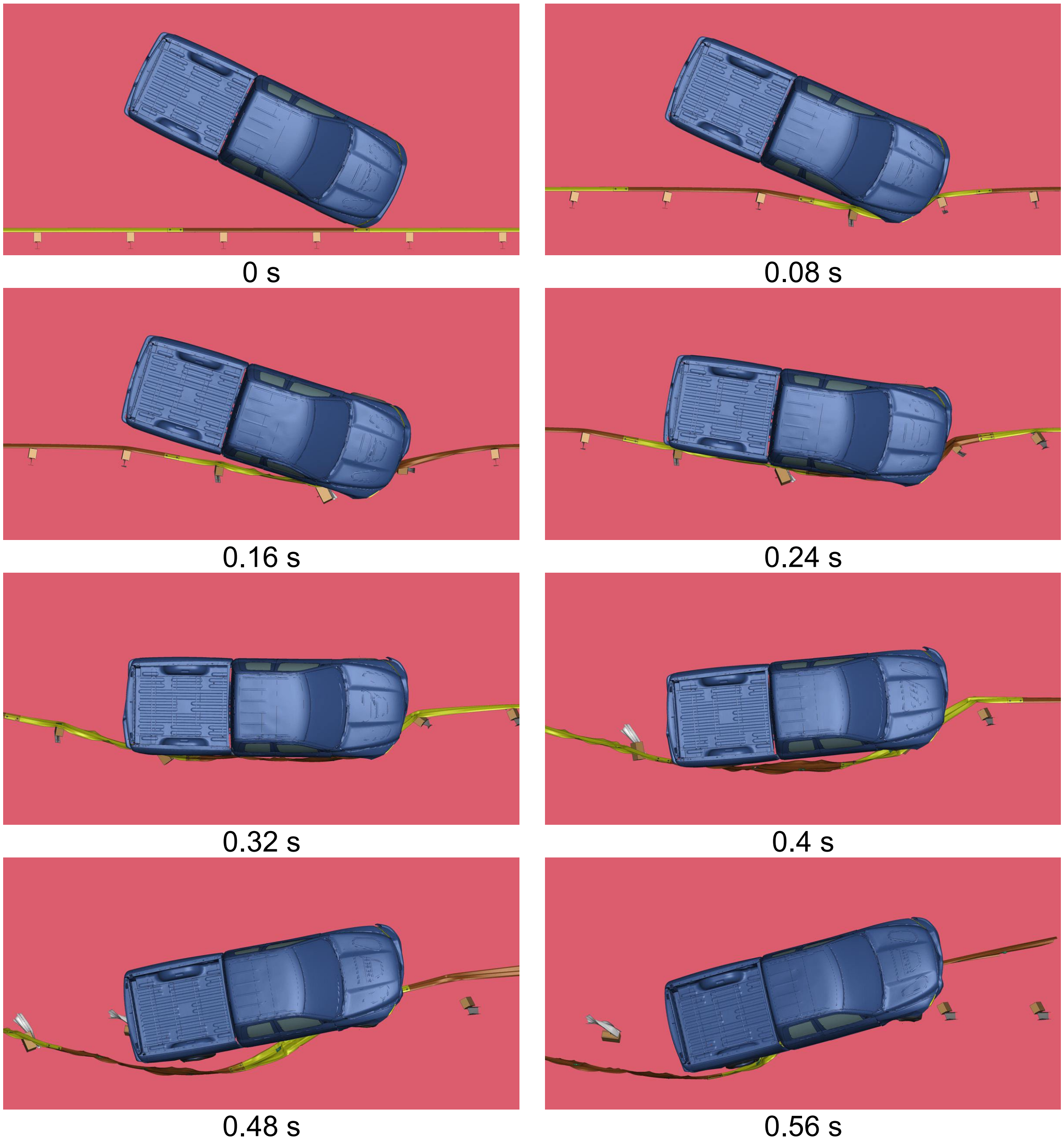


Figure 7.118. 75-ft Guardrail System with Refined Slot and Two End Washers – Overhead View of *MASH* Test 3-11

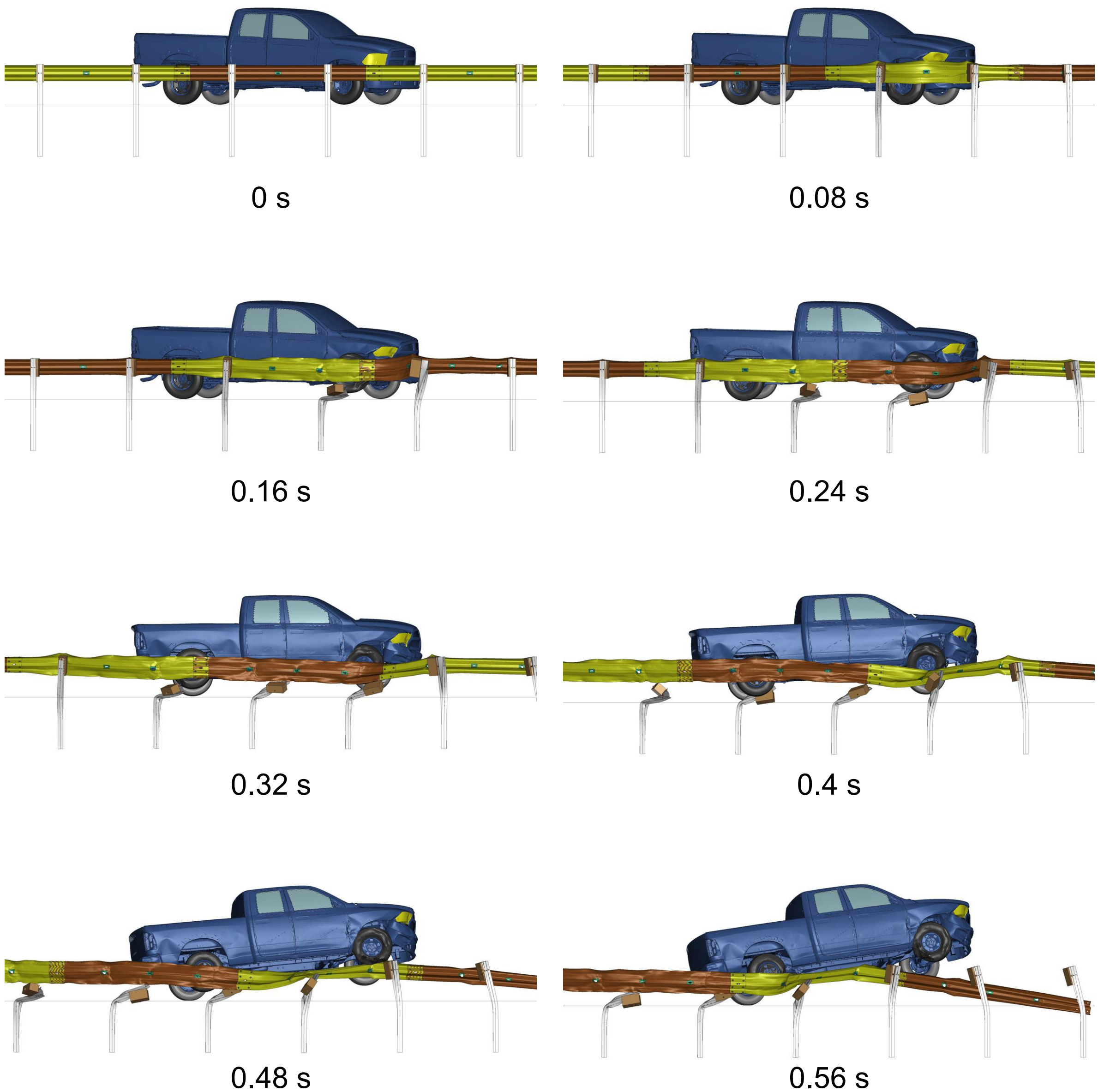


Figure 7.119. 75-ft Guardrail System with Refined Slot and Two End Washers – Rear View of *MASH* Test 3-11

Figure 7.120. 75-ft Guardrail System with Refined Slot and Two End Washers – Downstream View of *MASH* Test 3-11

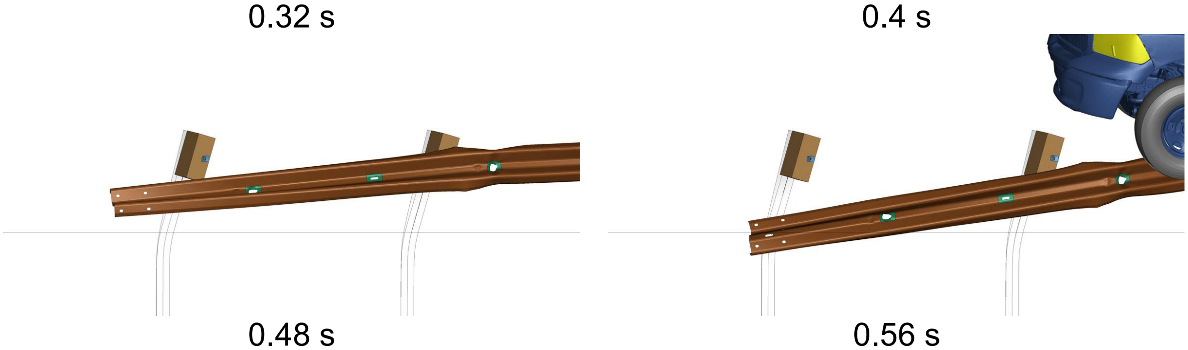


Figure 7.121. 75-ft Guardrail System with Refined Slot and Two End Washers – Front View of Downstream Posts During *MASH* Test 3-11

7.4.5. 62.5-ft GUARDRAIL SYSTEM WITH REFINED SLOT MESH and two End Washers

The length of the previous 75 ft guardrail system model was reduced to 62.5 ft, but the two downstream end posts continued to include guardrail washers. Figure 7.122 shows an overhead view of the finite element model. The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 38.3-ft from the unanchored downstream end of the rail and is shown below in Figure 7.123.

Figure 7.122. Overhead View of 62.5-ft Long Guardrail System

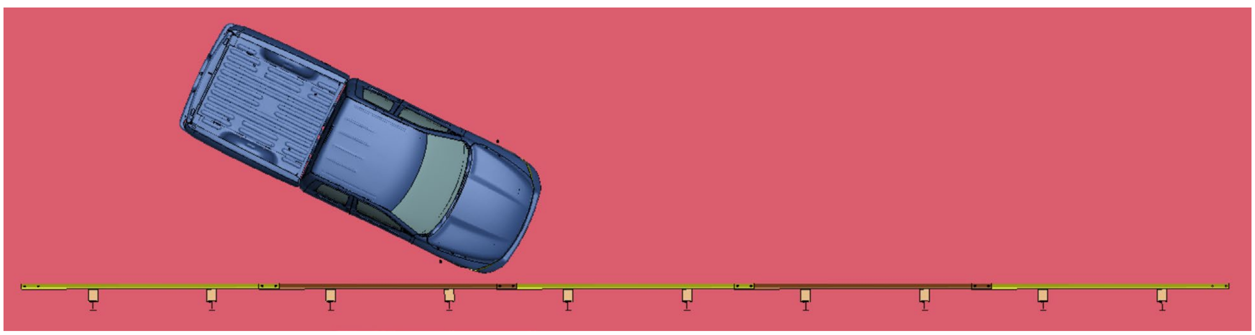
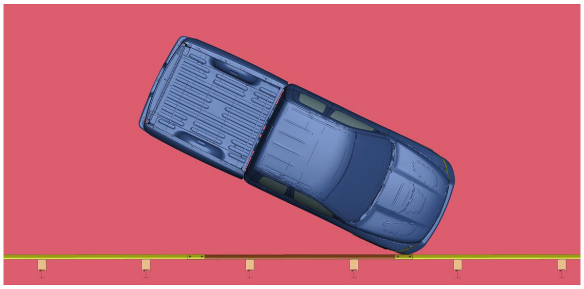
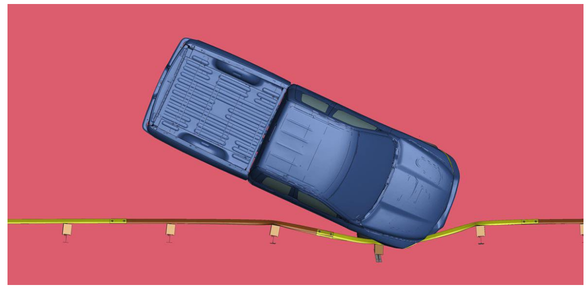
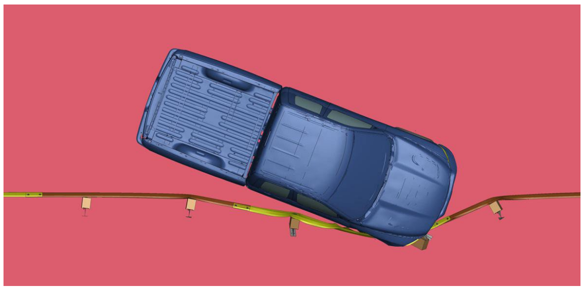


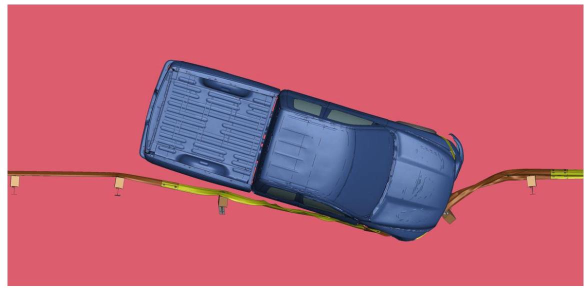
Figure 7.123. Overhead View of Impact Point for 62.5-ft Long Guardrail System

Figure 7.124, Figure 7.125, Figure 7.126, and Figure 7.127 show the sequential frames of *MASH* Test 3-11 on the 62.5-ft system with 1 mm thick refined slot element and downstream washers. During the impact, the w-beam rail was pulled off the posts downstream of impact and failed to meet the project objective.

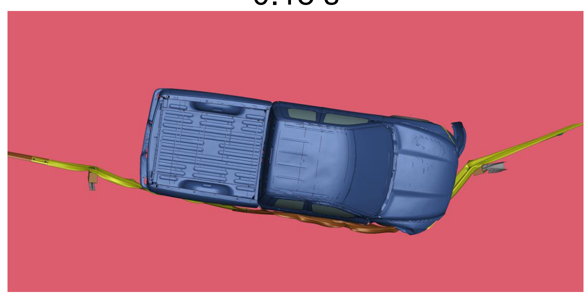

0 s

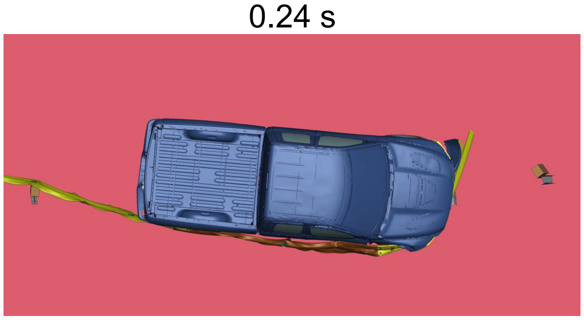

0.06 s


0.12 s


0.18 s


0.24 s


0.3 s


0.36 s

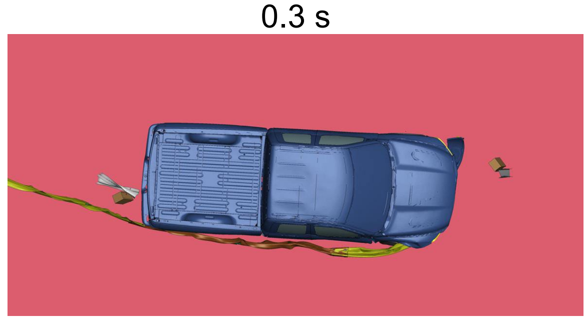

0.42 s

Figure 7.124. 62.5-ft Guardrail System with Refined Slot and Two End Washers – Overhead View of *MASH* Test 3-11

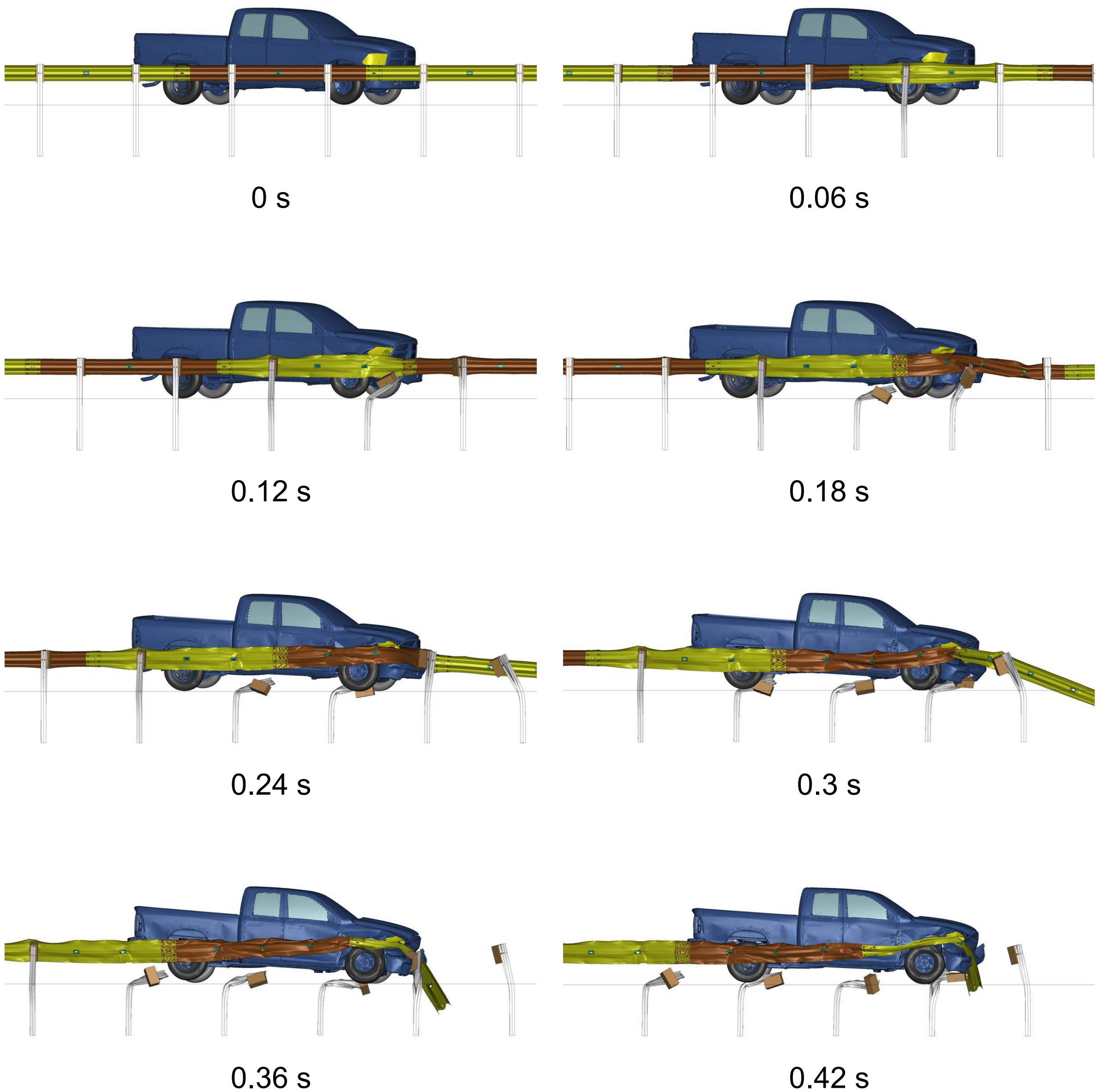


Figure 7.125. 62.5-ft Guardrail System with Refined Slot and Two End Washers – Rear View of *MASH* Test 3-11

Figure 7.126. 62.5-ft Guardrail System with Refined Slot and Two End Washers – Downstream View of *MASH* Test 3-11

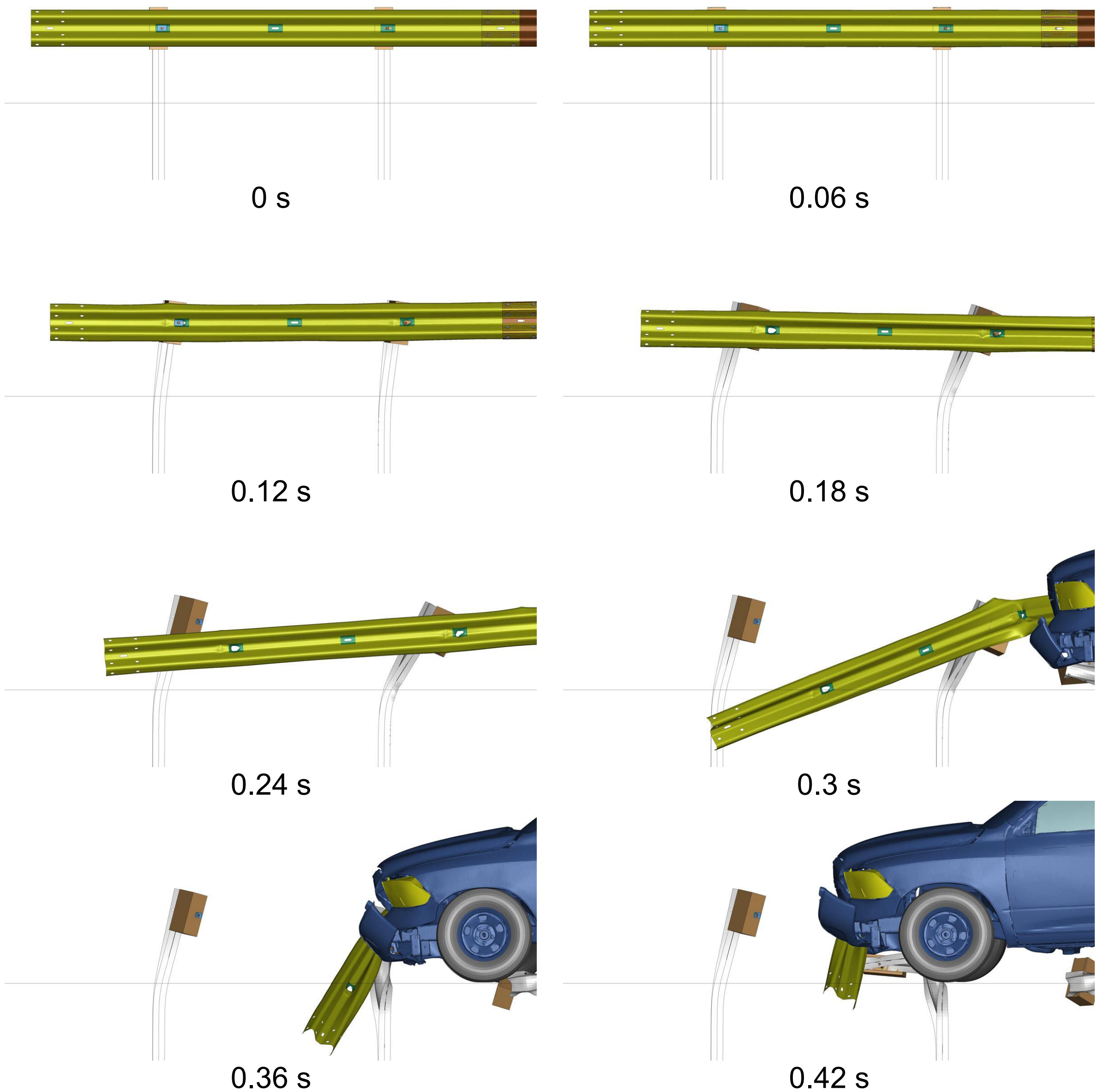


Figure 7.127. 62.5-ft Guardrail System with Refined Slot and Two End Washers – Front View of Downstream Posts During *MASH* Test 3-11

7.4.6. 50-ft GUARDRAIL SYSTEM WITH REFINED SLOT MESH and two End Washers

The length of the previous 62.5 ft guardrail system model was reduced to 50 ft, but the two downstream end posts continued to included guardrail washers. Figure 7.128 shows an overhead view of the finite element model. The system was evaluated using a simulated *MASH* Test 3-11. The 2270P *MASH* pickup truck impacted the guardrail system at 62 mi/h with an impact angle of 25˚. The impact point was 25.8-ft from the unanchored downstream end of the rail and is shown below in Figure 7.129.

Figure 7.128. Overhead View of 50-ft Long Guardrail System

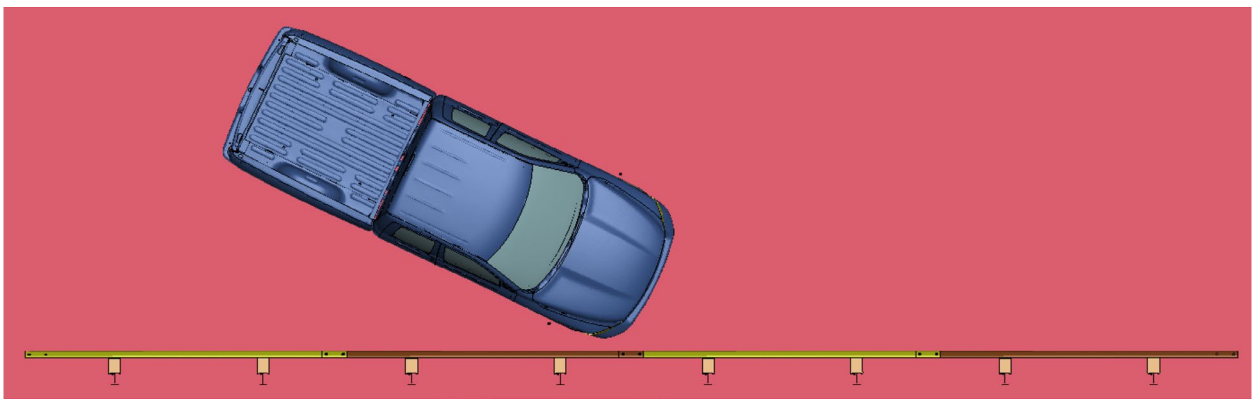
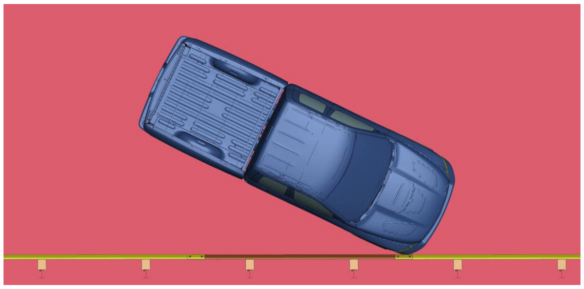
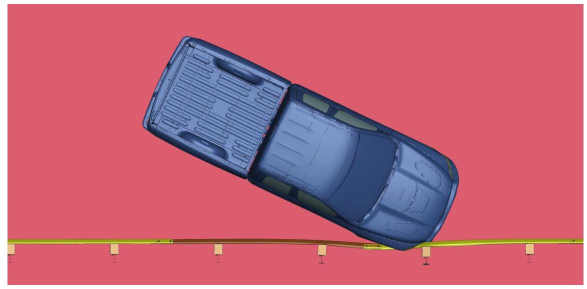
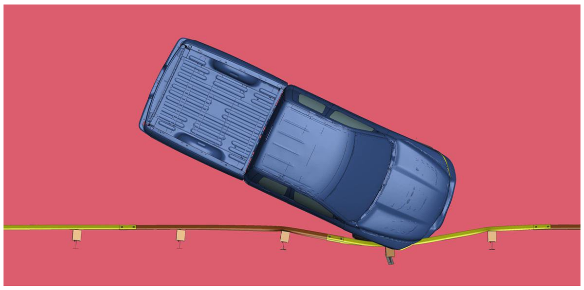
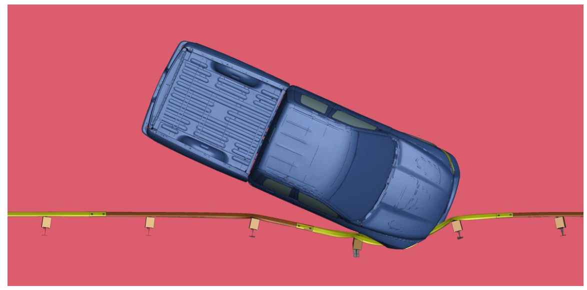


Figure 7.129. Overhead View of Impact Point for 50-ft Long Guardrail System

Figure 7.130, Figure 7.131, Figure 7.132, and Figure 7.133 show the sequential frames of *MASH* Test 3-11 on the 50-ft system with 1 mm thick refined slot element and downstream washers. During the impact, the w-beam rail was pulled off the posts downstream of impact and failed to meet the project objective.


0 s

0.025 s

0.05 s

0.075 s

0.1 s

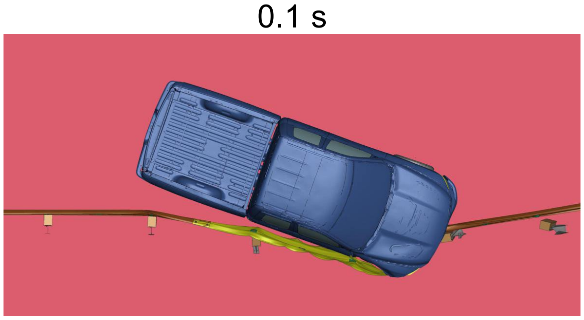
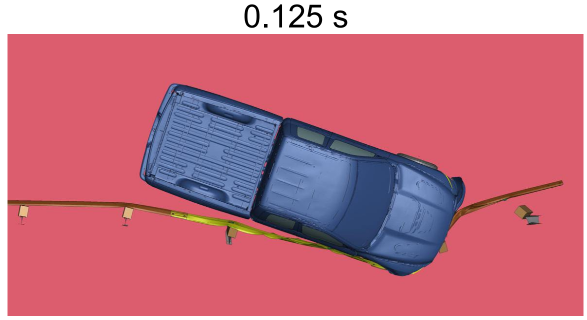
0.125 s

0.15 s

0.175 s

Figure 7.130. 50-ft Guardrail System with Refined Slot and Two End Washers – Overhead View of *MASH* Test 3-11

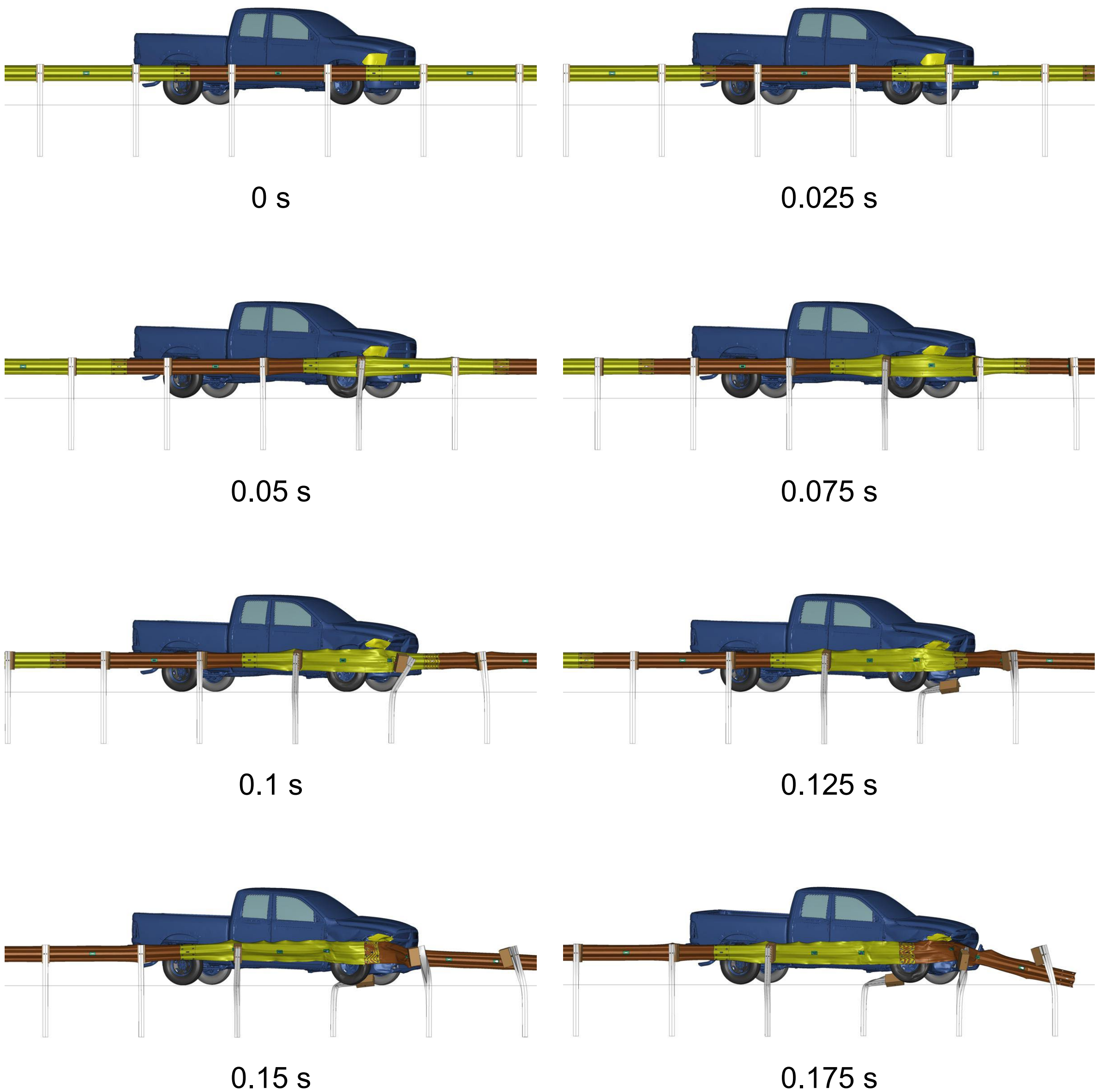


Figure 7.131. 50-ft Guardrail System with Refined Slot and Two End Washers – Rear View of *MASH* Test 3-11

Figure 7.132. 50-ft Guardrail System with Refined Slot and Two End Washers – Downstream View of *MASH* Test 3-11

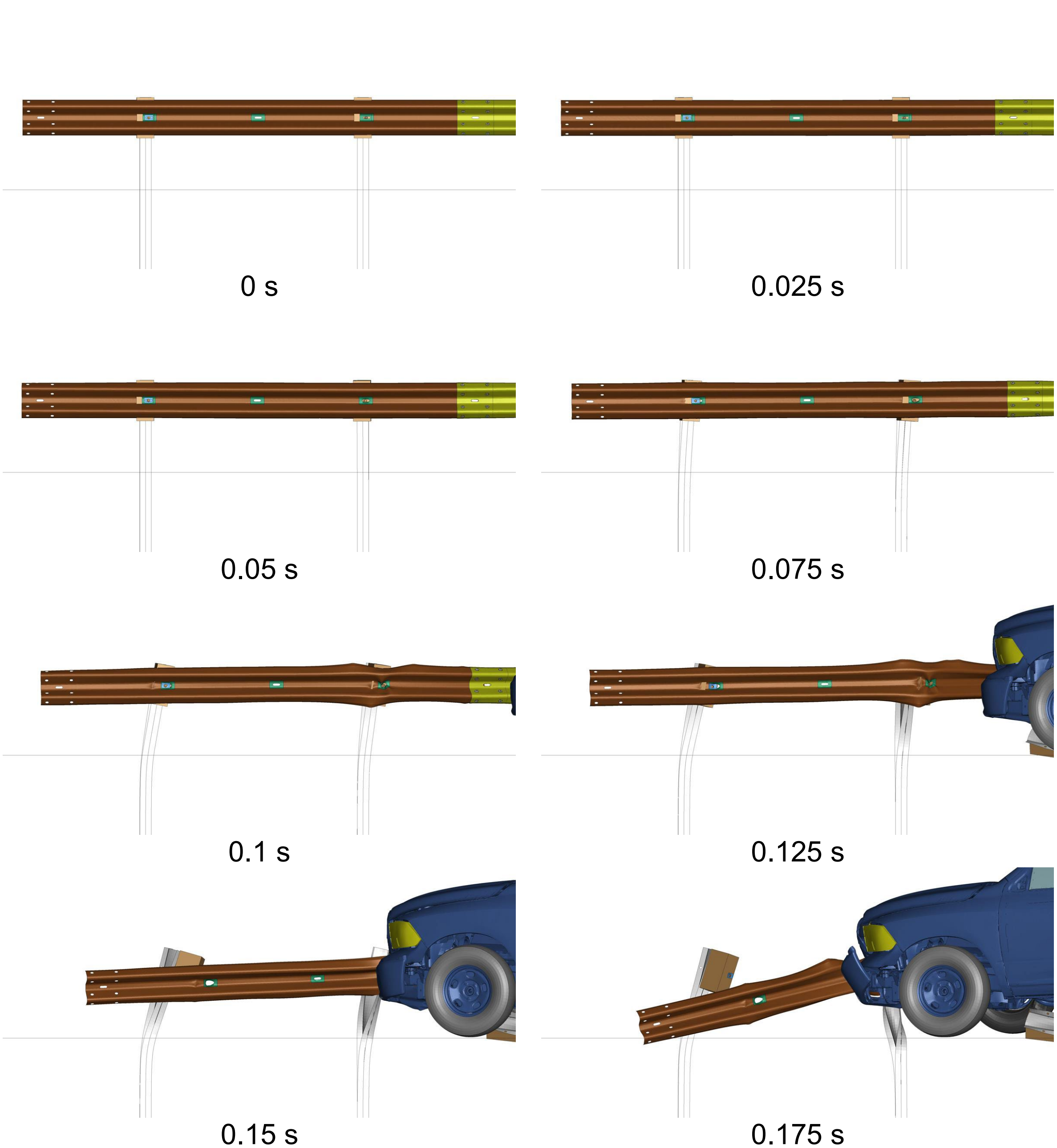


Figure 7.133. 50-ft Guardrail System with Refined Slot and Two End Washers – Front View of Downstream Posts During *MASH* Test 3-11

7.5. COMPUTER SIMULATION CONCLUSIONS

Following the failed crash test, the researchers investigated the computer simulations and developed improvements to the models for increasing the simulations' predictive capabilities. After the models were improved, the researchers parametrically studied the redirective capability of various lengths-of-needs without downstream anchorage. This minimum length-of-need was determined to be 262.5 ft. Upon discussions with the technical representative, this length was determined to be impractical for field use. Consequently, the research team investigated other hardware improvements to maintain connectivity between the posts and rails. Through this effort, the research team evaluated the addition of guardrail washers to the downstream end posts, which would be utilized in a temporary capacity until full termination could be installed. With the inclusion of washers in the models, the research team determined the original physically tested length of 75 ft, but with the additional of guardrail washers to the two most downstream posts, to be the minimum required installation to provide redirective capability. This is assuming 12.5 ft of additional length is accounted for in a *MASH* compliant terminal, similar to what is discussed earlier in the previous simulation effort. This installation would be further evaluated through full-scale crash testing, which is described in the following chapter.

CHAPTER 8. *MASH* TEST 3-11 (CRASH TEST NO. 614721-01-1)

8.1. TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

MASH Test 3-11 involves a 2270P vehicle weighing 5000 lb ± 110 lb impacting the CIP of the longitudinal barrier at an impact speed of 62 mi/h ± 2.5 mi/h and an angle of 25 degrees ± 1.5 degrees. The CIP for *MASH* Test 3-11 on the Guardrail without downstream anchorage was 42 inches ± 12 inches upstream of the centerline of post 11. Figure 4.1 and Figure 8.1 depict the target impact setup.

Figure 8.1. Guardrail without downstream anchorage/Test Vehicle Geometrics for Test No. 614721-01-1.

The 2270P vehicle weighed 5041 lb, and the actual impact speed and angle were 62.1 mi/h and 25.1 degrees. The actual impact point was 42.9 inches upstream from centerline of post 11. Minimum target impact severity (IS) was 106 kip-ft, and actual IS was 116.9 kip-ft.

8.2. WEATHER CONDITIONS

The test was performed on the morning of October 26, 2022. Weather conditions at the time of testing were as follows: wind speed: 2 mi/h; wind direction: 97 degrees (vehicle was traveling at a heading of 195 degrees); temperature: 68°F; relative humidity: 47 percent.

8.3. TEST VEHICLE

Figure 8.2 shows the 2016 RAM 1500 used for the crash test. The vehicle's test inertia weight was 5041 lb, and its gross static weight was 5041 lb. The height to the lower edge of the vehicle bumper was 11.75 inches, and the height to the upper edge of the bumper was 27 inches. Table D.1 in Appendix D.1 gives additional dimensions and information on the vehicle. The vehicle was directed into the installation using a cable reverse tow and guidance system and was released to be freewheeling and unrestrained just prior to impact.

Figure 8.2. Test Vehicle before Test No. 614721-01-1.

8.4. TEST DESCRIPTION

Table 8.1 lists events that occurred during Test No. 614721-01-1. Figures D.1 and D.2 in Appendix D.2 present sequential photographs during the test.

Table 8.1. Events during Test No. 614721-01-1.

Time (s)	Events
0.0000	Vehicle impacted the installation
0.0190	Posts 10 and 11 began to move toward field side
0.0330	Vehicle began to redirect
0.0330	Post 12 began to move toward field side
0.0470	Post 9 began to rotate clockwise
0.0660	Post 13 began to rotate counterclockwise and lean toward field side
0.0740	Posts 14 and 15 began to rotate counterclockwise
0.0870	Rail released from posts 14 and 15
0.5080	Vehicle began to rotate clockwise behind the rail

For longitudinal barriers, it is desirable for the vehicle to redirect and exit the barrier within the exit box criteria (not less than 32.8 ft downstream from loss of contact for cars and pickups). The test vehicle did not exit within the exit box criteria defined in *MASH*. Brakes on the vehicle were not applied after impact. After loss of contact with the barrier, the vehicle came to rest 51 ft downstream of the point of impact and 28 ft toward the field side of the installation.

8.5. DAMAGE TO TEST INSTALLATION

The rail released from posts 11-20 and the blockouts also released from posts 12-15.

Table 8.2 shows the post deflections after the crash test. Figure 8.3 shows the damage to the Guardrail without downstream anchorage. Working width, working width height, maximum dynamic deflection, and maximum permanent deformation were unable to be measured as the rail broke free from the end of the installation.

Table 8.2. Post Deflections after Test 614721-01-1

Post	Post Lean	Soil Gap
Anchor	-	¼-inch u/s
9	-	¼-inch t/s
10	5° f/s	1½-inch t/s; 1¼-inch f/s
11	18° f/s	2-inch f/s
12-17	69° d/s	-
18	9° f/s	-
19	36° u/s	-
20	26° u/s	-

t/s=traffic side; f/s=field side; u/s=upstream; d/s=downstream

Figure 8.3. Guardrail without downstream anchorage after Test No. 614721-01-1.

8.6. DAMAGE TO TEST VEHICLE

The front bumper, hood, grill, radiator and support, right front tire and rim, right front quarter fender, right front door, right rear door, right cab corner, right rear quarter fender, right rear tire and rim, right tail light, rear bumper, left front quarter fender, left front door glass, left rear door, left rear quarter fender, left rear rim, left A-pillar, and left front and rear door frame were damaged.

Figure 8.4 shows the damage sustained by the vehicle. No fuel tank damage was observed. Maximum exterior crush to the vehicle was 10 inches in the front plane at the right front corner at bumper height. There was a 3 inch wide by 14 inch long laceration in the left rear door skin. There was no occupant compartment deformation. Figure 8.5 shows the interior of the vehicle. Tables D.2 and D.3 in Appendix D.1 provide exterior crush and occupant compartment measurements.

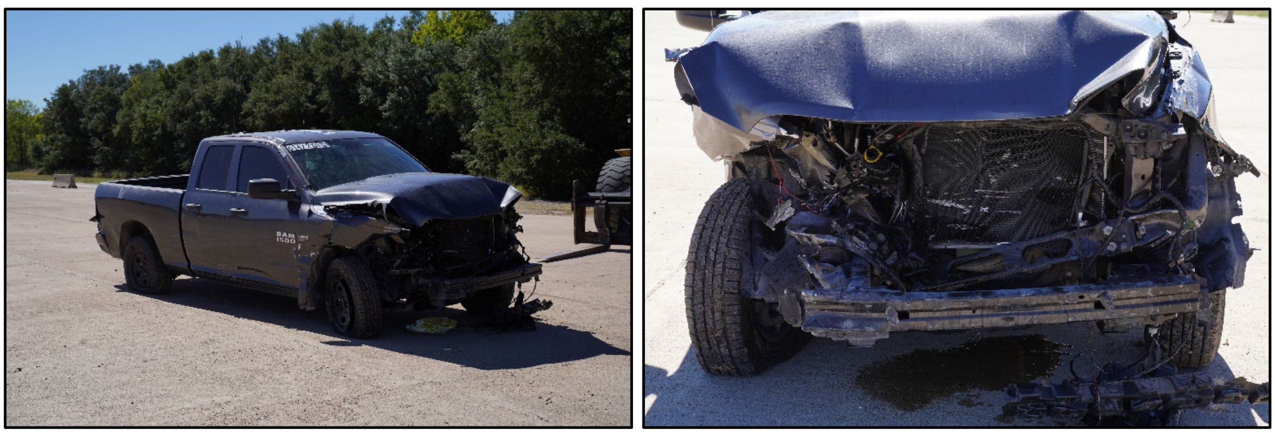


Figure 8.4. Test Vehicle after Test No. 614721-01-1.

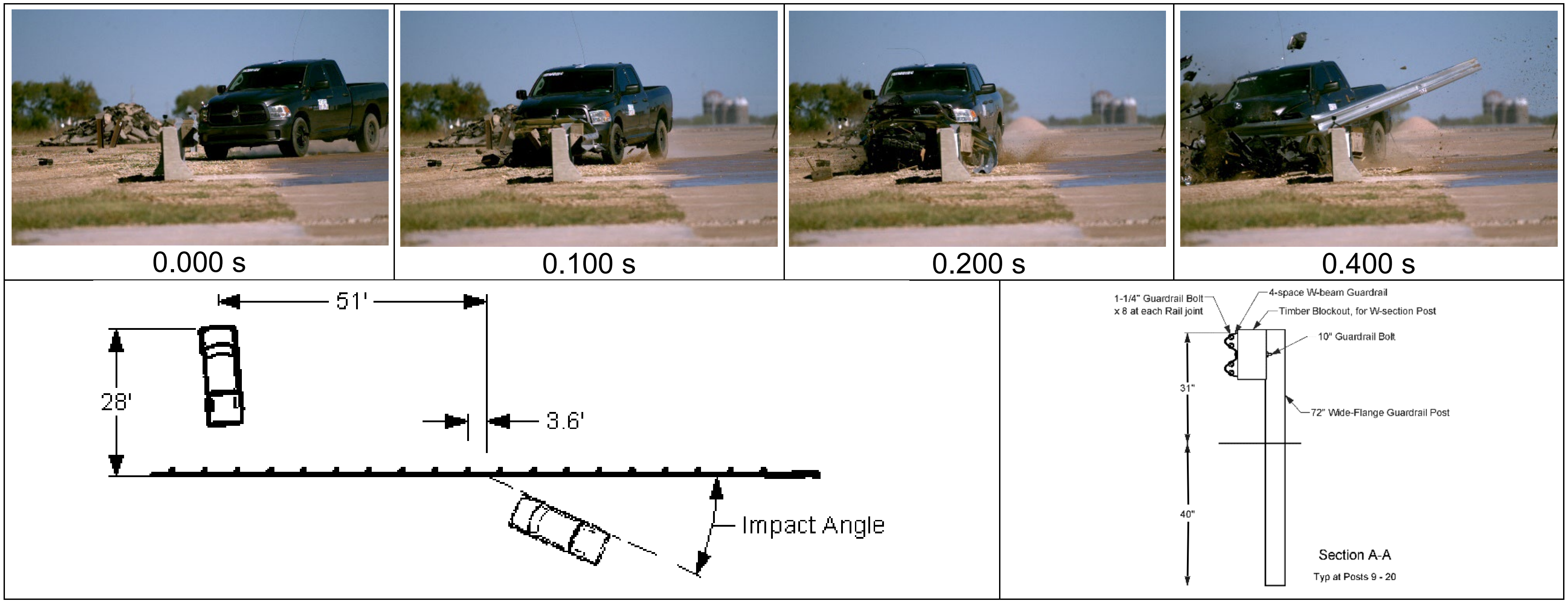
Figure 8.5. Interior of Test Vehicle after Test No. 614721-01-1.

8.7. OCCUPANT RISK FACTORS

Data from the accelerometers were digitized for evaluation of occupant risk, and the results are shown in Table 8.3. Figure D.3 in Appendix D.3 shows the vehicle angular displacements, and Figures D.4 through D.6 in Appendix D.4 show acceleration versus time traces. Figure 8.6 summarizes pertinent information from the test.

Table 8.3. Occupant Risk Factors for Test No. 614721-01-1.

Occupant Risk Factor	Value	Time
Occupant Impact Velocity (OIV)		
Longitudinal	15.1 ft/s	0.1714 seconds on right side of interior
Lateral	10.7 ft/s	
Occupant Ridedown Accelerations		
Longitudinal	8.1 g	0.5335 - 0.5435 seconds
Lateral	5.4 g	0.2190 - 0.2290 seconds
Theoretical Head Impact Velocity (THIV)	5.4 m/s	0.1624 seconds on right side of interior
Acceleration Severity Index (ASI)	0.5	0.0667 - 0.1167 seconds
Maximum 50-ms Moving Average		
Longitudinal	-5.9 g	0.4993 - 0.5493 seconds
Lateral	-3.5 g	0.0381 - 0.0881 seconds
Vertical	1.9 g	0.3279 - 0.3779 seconds
Maximum Yaw, Pitch, and Roll Angles		
Roll	12°	0.6911 seconds
Pitch	3°	1.0549 seconds
Yaw	36°	2.0000 seconds



General Information	
Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard Test No.	*MASH* Test 3-11
TTI Test No.	614721-01-1
Test Date	2022-10-26
Test Article	
Type	Longitudinal Barrier—Guardrail
Name	Guardrail without downstream anchorage
Installation Length	125 ft-9½ inches
Material or Key Elements	W-beam rail element mounted at 31 inches on 72-inch long wide flange steel guardrail posts without downstream anchoragel
Soil Type and Condition	Crushed concrete, dry
Test Vehicle	
Type/Designation	2270P
Make and Model	2016 RAM 1500
Curb	4947 lb
Test Inertial	5041 lb
Dummy	N/A
Gross Static	5041 lb

Impact Conditions	
Speed	62.1 mi/h
Angle	25.1°
Location/Orientation	42.9 inches upstream from the centerline of post 11
Impact Severity	116.9 kip-ft
Exit Conditions	
Speed	Not measurable
Trajectory/Heading Angle	Not measurable
Occupant Risk Values	
Longitudinal OIV	15.1 ft/s
Lateral OIV	10.7 ft/s
Longitudinal Ridedown	8.1 g
Lateral Ridedown	5.4 g
THIV	5.4 m/s
ASI	0.5
Max. 0.050-s Average	
Longitudinal	-5.9 g
Lateral	-3.5 g
Vertical	1.9 g

Post-Impact Trajectory	
Stopping Distance	51 ft downstream 28 ft to field side
Vehicle Stability	
Maximum Roll Angle	12°
Maximum Pitch Angle	3°
Maximum Yaw Angle	36°
Vehicle Snagging	No
Vehicle Pocketing	No
Test Article Deflections	
Dynamic	Not measurable
Permanent	Not measurable
Working Width	Not measurable
Height of Working Width	Not measurable
Vehicle Damage	
VDS	01RFQ4
CDC	01FREW3
Max. Exterior Deformation	10 inches
Max. Occupant Compartment Deformation	None

Figure 8.6. Summary of Results for *MASH* Test 3-11 on Guardrail without downstream anchorage.

CHAPTER 9. SUMMARY AND CONCLUSIONS

9.1. ASSESSMENT OF TEST RESULTS

The crash tests reported herein were performed in accordance with *MASH* 3-11 criteria on the Guardrail without downstream anchorage. Table 9.1 provides an assessment of each test based on the applicable 3-11 safety evaluation criteria for *MASH* TL-3 longitudinal barriers.

Table 9.1. Assessment Summary for *MASH* TL-3 Tests on the Guardrail without downstream anchorage.

Evaluation Criteria	Description	Test No. 614721-01-1	Test No. 614721-01-2
A	Contain, Redirect, or Controlled Stop	Fail	Fail
D	No Penetration into Occupant Compartment	S	S
F	Roll and Pitch Limit	S	S
H	OIV Threshold	S	S
I	Ridedown Threshold	S	S
Overall		Fail	Fail

Note: S = Satisfactory; N/A = Not Applicable.
[1] See Table 4.2 for details

9.2. CONCLUSIONS

The research team performed numerous computer simulations to determine the minimum required length-of-need for MGS without downstream anchorage. Despite promising computer simulations, the physical crash testing did not exhibit the desired redirective capability with The system failing to meet the *MASH* test 3-11 performance criteria. Therefore, additional research is need to provide a redirective solution for state DOT implementation.

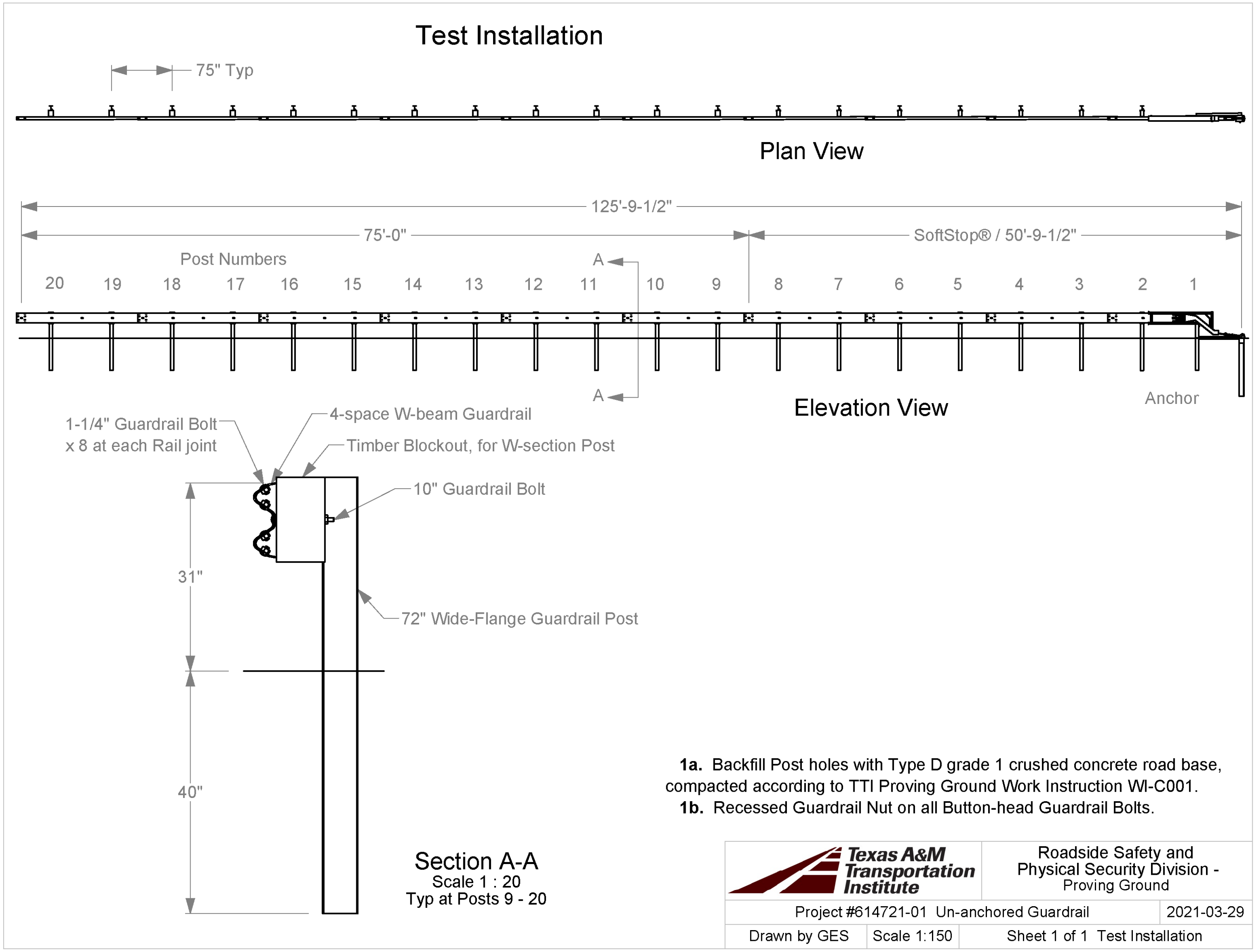
The researchers have recommend additional calibration of the simulation models in order to better predict the interaction of the guardrail bolt and the w-beam rail. This may include component testing, such as pendulum or surrogate vehicle dynamic evaluation efforts. Following the calibration effort, researchers would complete a parametric study to determine the minimum length-of-need for guardrail without anchorage. This may involve the inclusion of additional hardware, such as guardrail washers, to improve connectivity between the downstream posts and the w-beam rails. Lastly, *MASH* TL-3 physical crash testing will be required.

REFERENCES

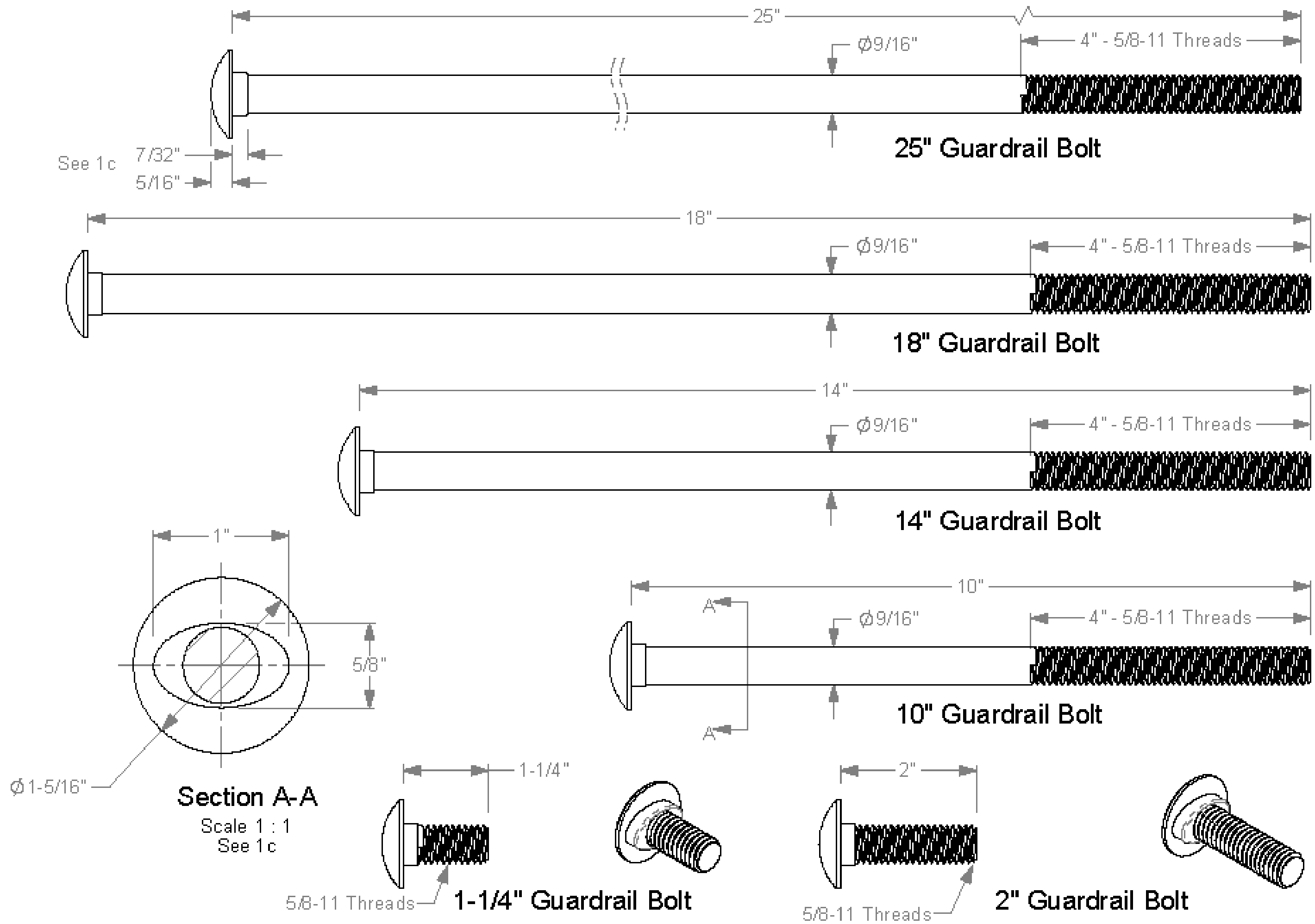
1. AASHTO. *Manual for Assessing Roadside Safety Hardware, Second Edition.* American Association of State Highway and Transportation Officials: Washington, DC, 2016.

APPENDIX A. DETAILS OF THE GUARDRAIL WITHOUT DOWNSTREAM ANCHORAGE

A.1. DETAILS OF THE GUARDRAIL WITHOUT DOWNSTREAM ANCHORAGE FOR TEST 614721-01-2



Q:\Accreditation-17025-2017\EIR-000 Project Files\614721-01 - Un-anchored Guardrail - Kovar\Drafting, 614721-01\614721-01 Drawing sa

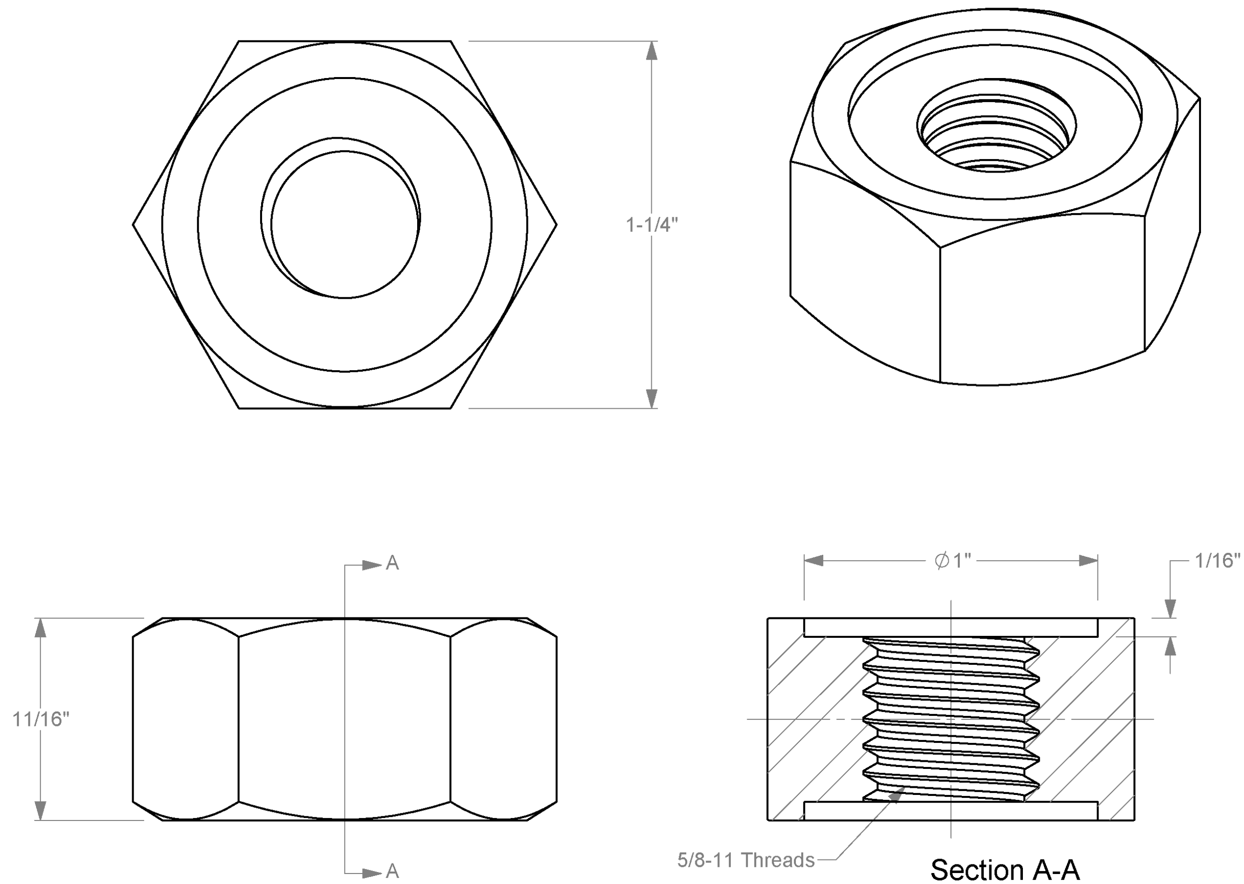


1a. Material is ASTM A307.
1b. All bolt sizes not used in all projects. See system drawing.
1c. Head and shoulder dimensions typical all sizes.

Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground	
Guardrail Bolt		2020-04-22
Drawn by GES/WS	Scale 1:2	Sheet 1 of 1

T:\Drafting Department\Solidworks\Standard Parts\Guardrail Parts and Subs\Guardrail Drawings\Guardrail Bolt

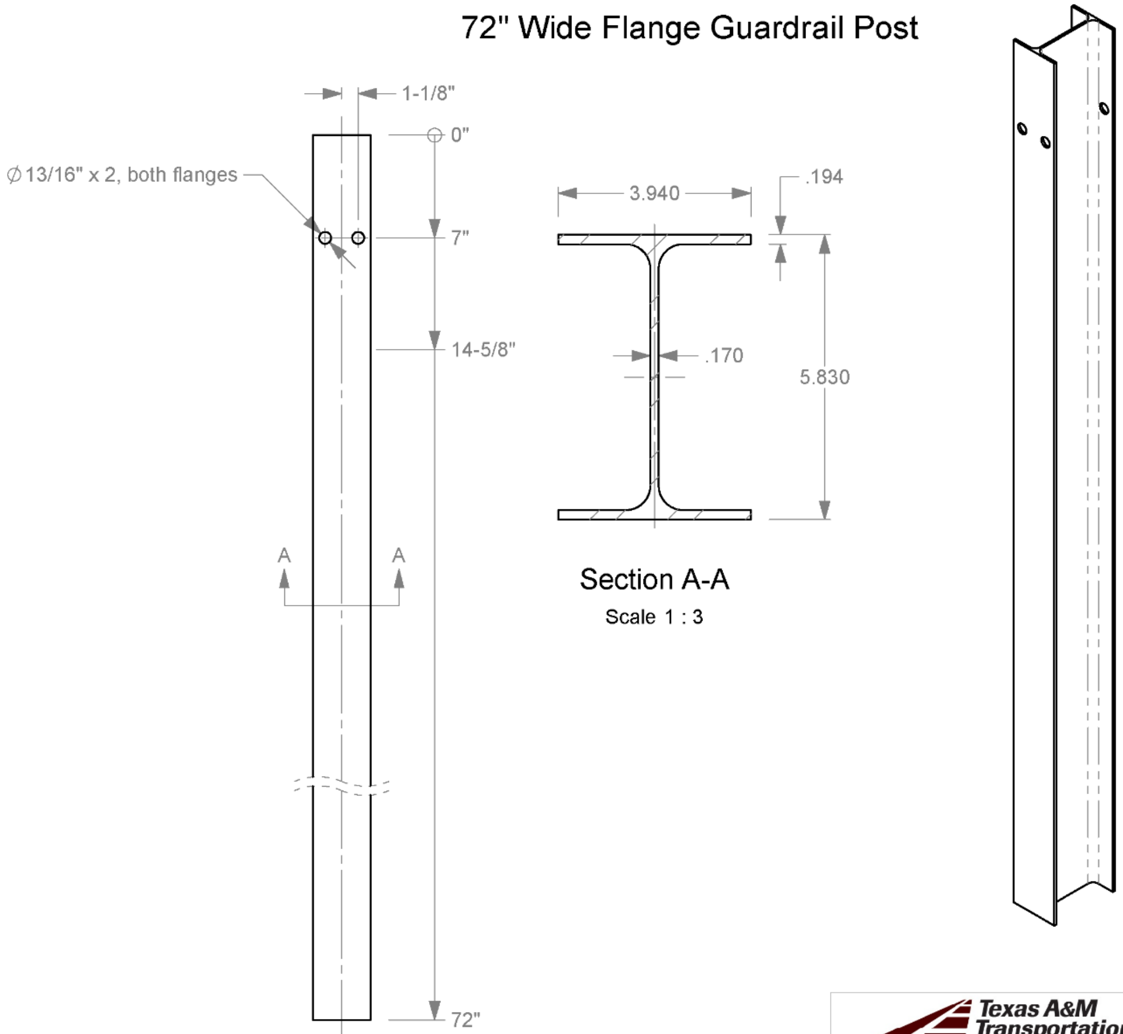
Recessed Guardrail Nut



1a. Material is ASTM A 563 Grade A.

Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground		
Recessed Guardrail Nut			2019-06-27
Drawn by GES	Scale 2:1	Sheet 1 of 1	

72" Wide Flange Guardrail Post



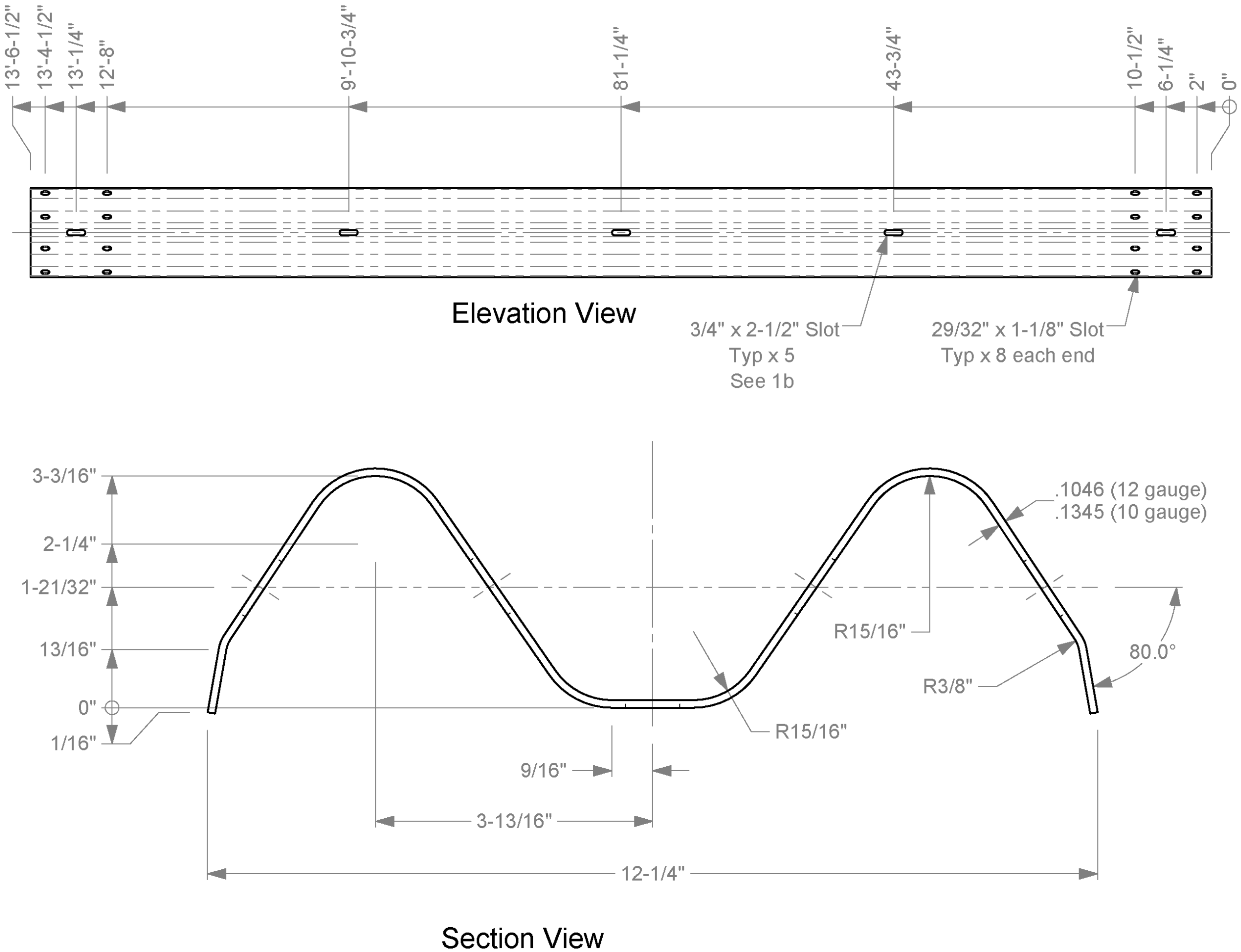
Elevation View

Section A-A
Scale 1 : 3

Isometric View

Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground	
72" Wide-Flange Guardrail Post for Thrie-beam		2020-11-10
Drawn by GES	Scale 1:10	Sheet 1 of 1

T:\Drafting Department\Solidworks\Standard Parts\Guardrail Parts and Subs\Guardrail Drawings\Post, 72" Wide Flange for W-beam



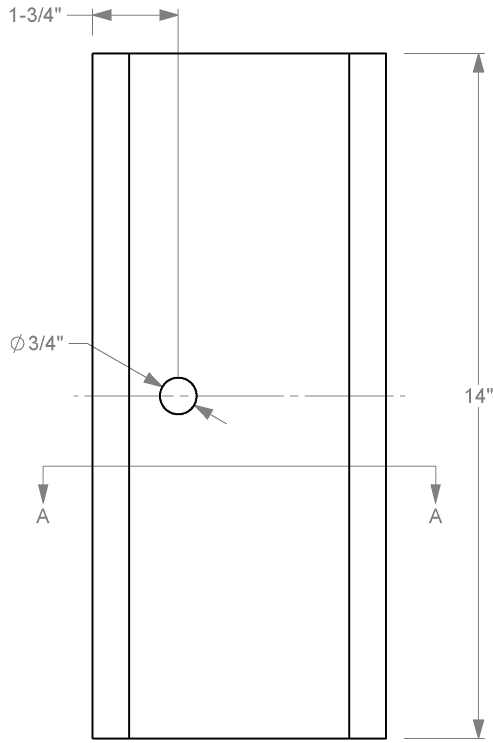
1a. Manufacture per AASHTO M180 specifications.

1b. 4-space Guardrail is shown. Slots typical x 3 for 2-space W-beam spaced at 75", and typical x 9 for 8-space W-beam spaced at 18-3/4". Slots are typical x 4 at 37-1/2" for 9'-4-1/2" span W-beam.

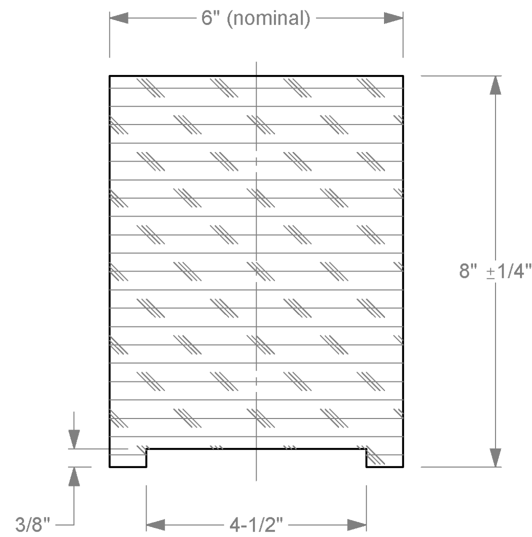
Texas A&M Transportation Institute		Roadside Safety and Physical Security Division - Proving Ground	
4-space W-beam Guardrail			2020-06-05
Drawn by GES	Scale 1:20	Sheet 1 of 1	

T:\Drafting Department\Solidworks\Standard Parts\Guardrail Parts and Subs\Guardrail Drawings\W-Beam Guardrail

Timber Blockout for W-section Post



Elevation View



Section A-A

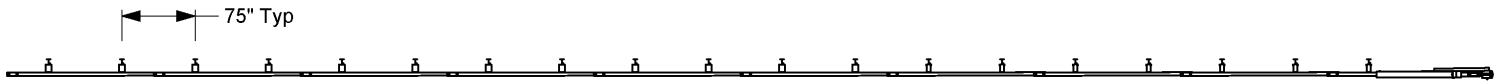
1a. Timber blockouts are treated with a preservative in accordance with AASHTO M 133 after all cutting and drilling.

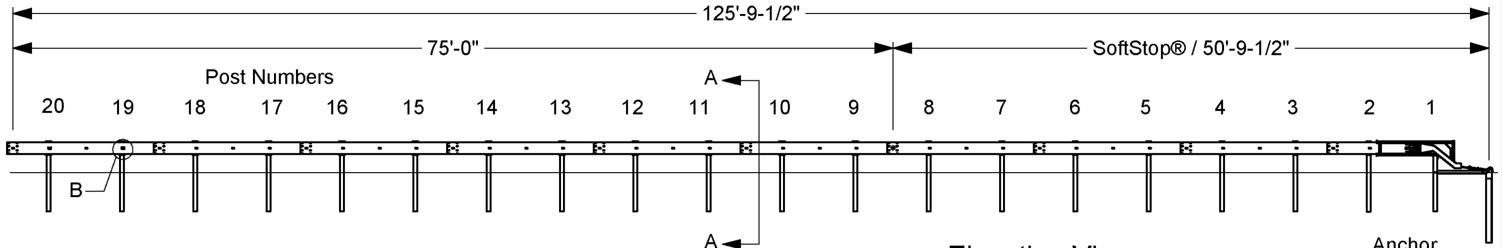
Texas A&M Transportation Institute		Roadside Safety and Physical Security Division - Proving Ground	
Timber Blockout, for W-section Post			2019-07-03
Drawn by GES	Scale 1:3	Sheet 1 of 1	

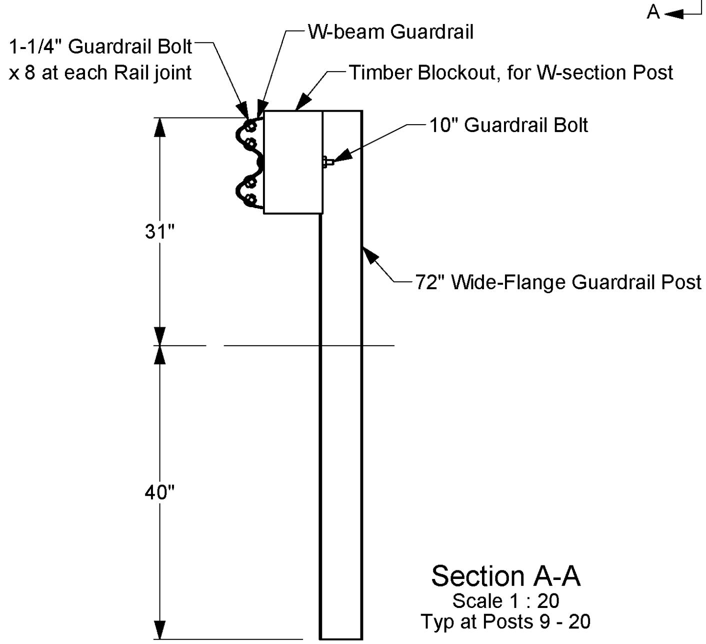
T:\Drafting Department\Solidworks\Standard Parts\Guardrail Parts and Subs\Guardrail Drawings\Timber Blockout for W-section Post

A.2. DETAILS OF THE GUARDRAIL WITHOUT DOWNSTREAM ANCHORAGE FOR TEST 614721-01-1

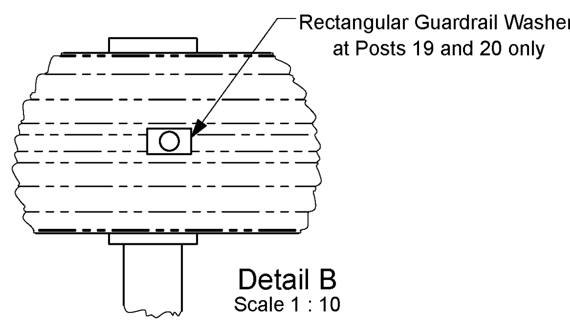
Test Installation







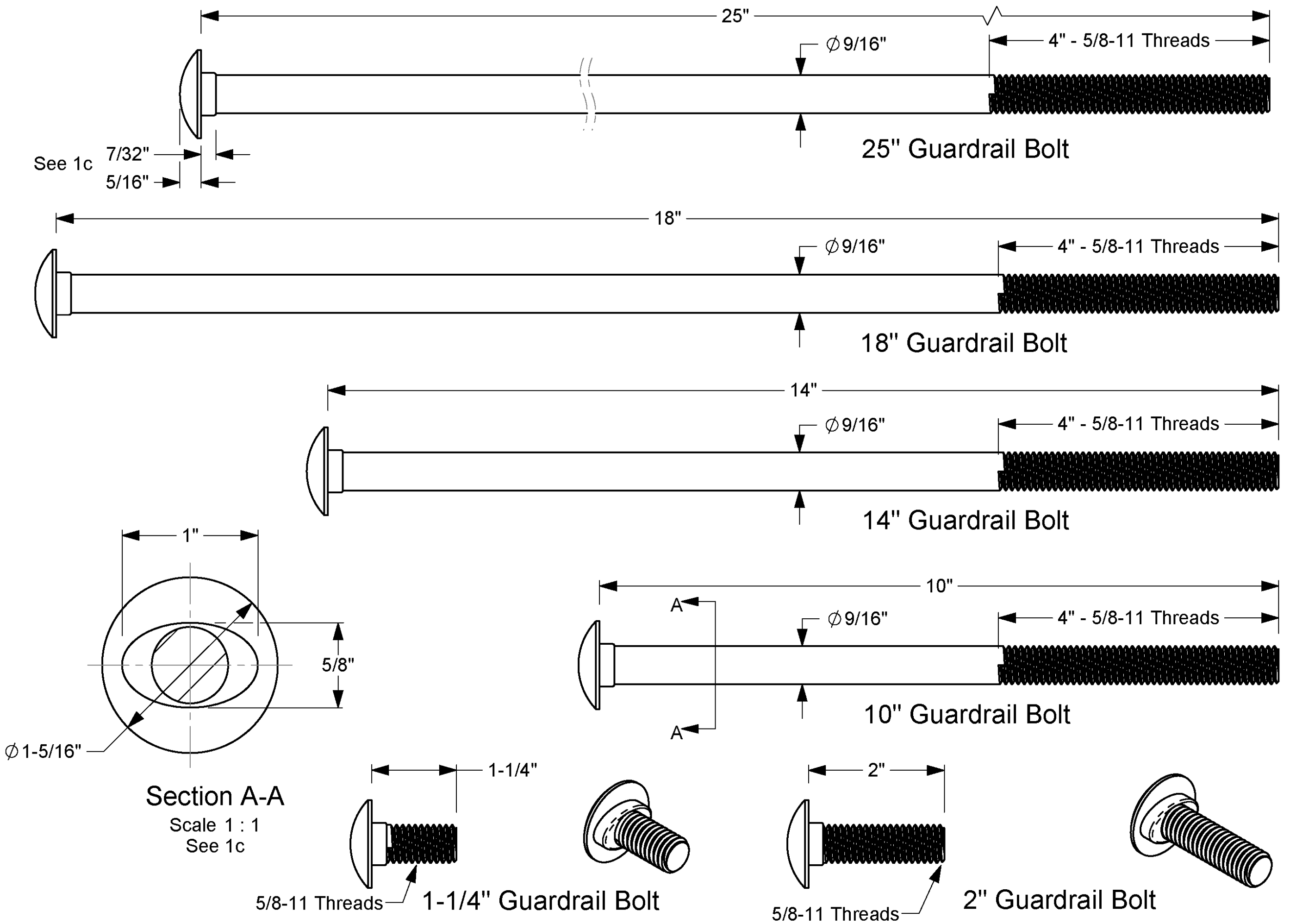
Section A-A
Scale 1 : 20
Typ at Posts 9 - 20



Detail B
Scale 1 : 10

1a. Backfill Post holes with Type D grade 1 crushed concrete road base, compacted according to TTI Proving Ground Work Instruction WI-C001.
1b. Recessed Guardrail Nut on all Button-head Guardrail Bolts.

Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground	
Project #614721-01 Un-anchored Guardrail		2022-07-21
Drawn by GES	Scale 1:150	Sheet 1 of 1 Test Installation



Section A-A
Scale 1 : 1
See 1c

1-1/4" Guardrail Bolt

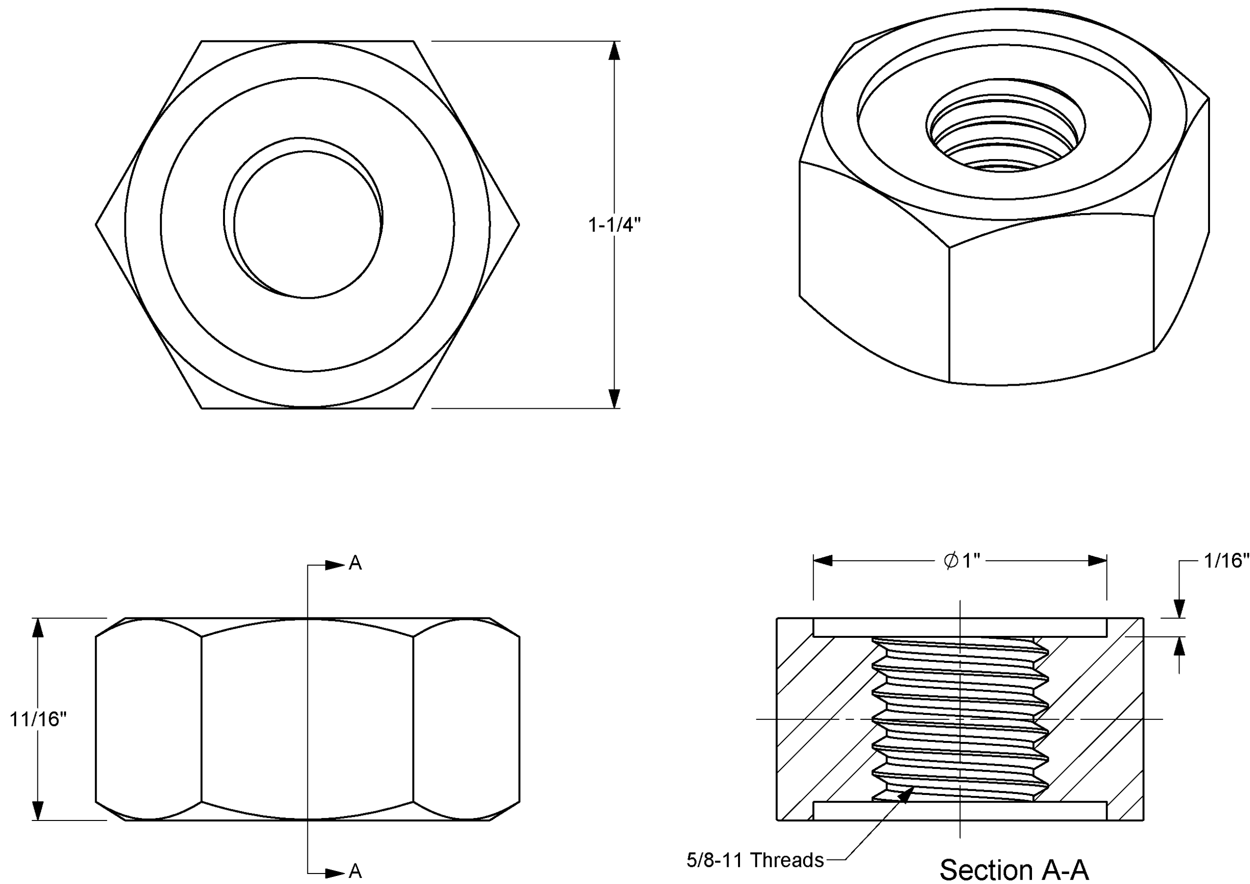
2" Guardrail Bolt

1a. Material is ASTM A307.
1b. All bolt sizes not used in all projects. See system drawing.
1c. Head and shoulder dimensions typical all lengths.

Texas A&M Transportation Institute		Roadside Safety and Physical Security Division - Proving Ground	
Guardrail Bolt			2020-07-08
Drawn by GES/WS	Scale 1:2	Sheet 1 of 1	

T:\Drafting Department\Solidworks\Standard Parts\Guardrail Parts and Subs\Guardrail Drawings\Guardrail Bolt

Recessed Guardrail Nut



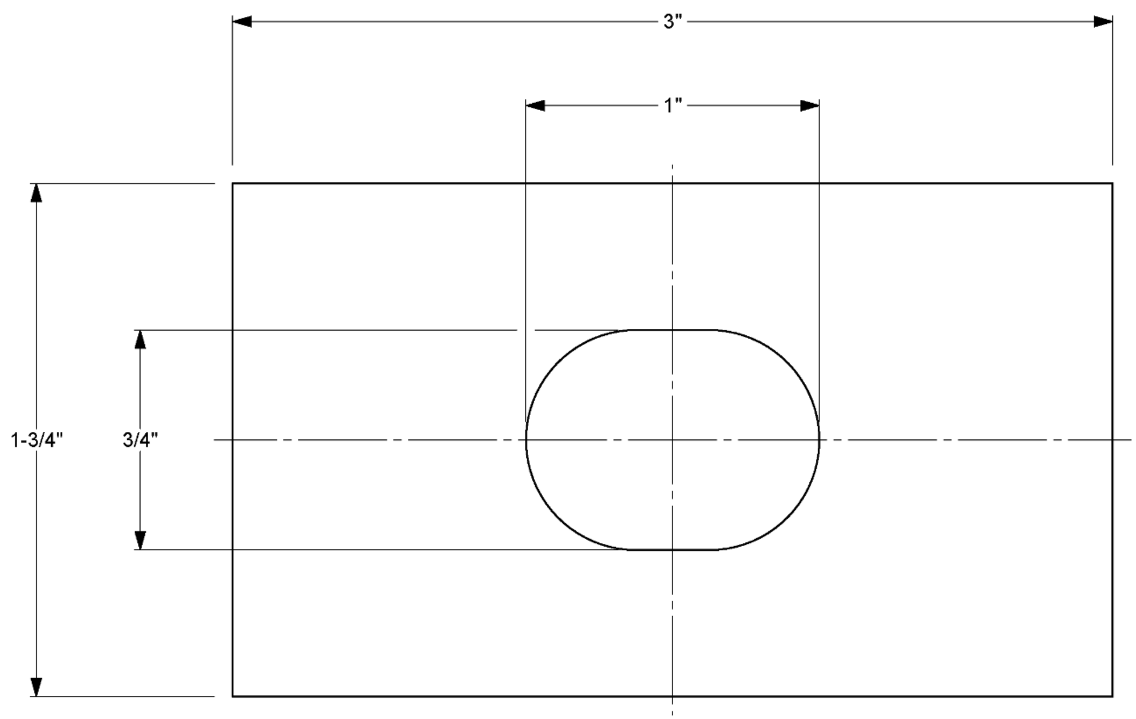
1a. Material is ASTM A 563 Grade A.

Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground		
Recessed Guardrail Nut		2022-07-18	
Drawn by GES	Scale 2:1	Sheet 1 of 1	

T:\Drafting Department\Solidworks\Standard Parts\Guardrail Parts and Subs\Guardrail Drawings\Nut, Recessed Guardrail

Rectangular Guardrail Washer

0.20" thick

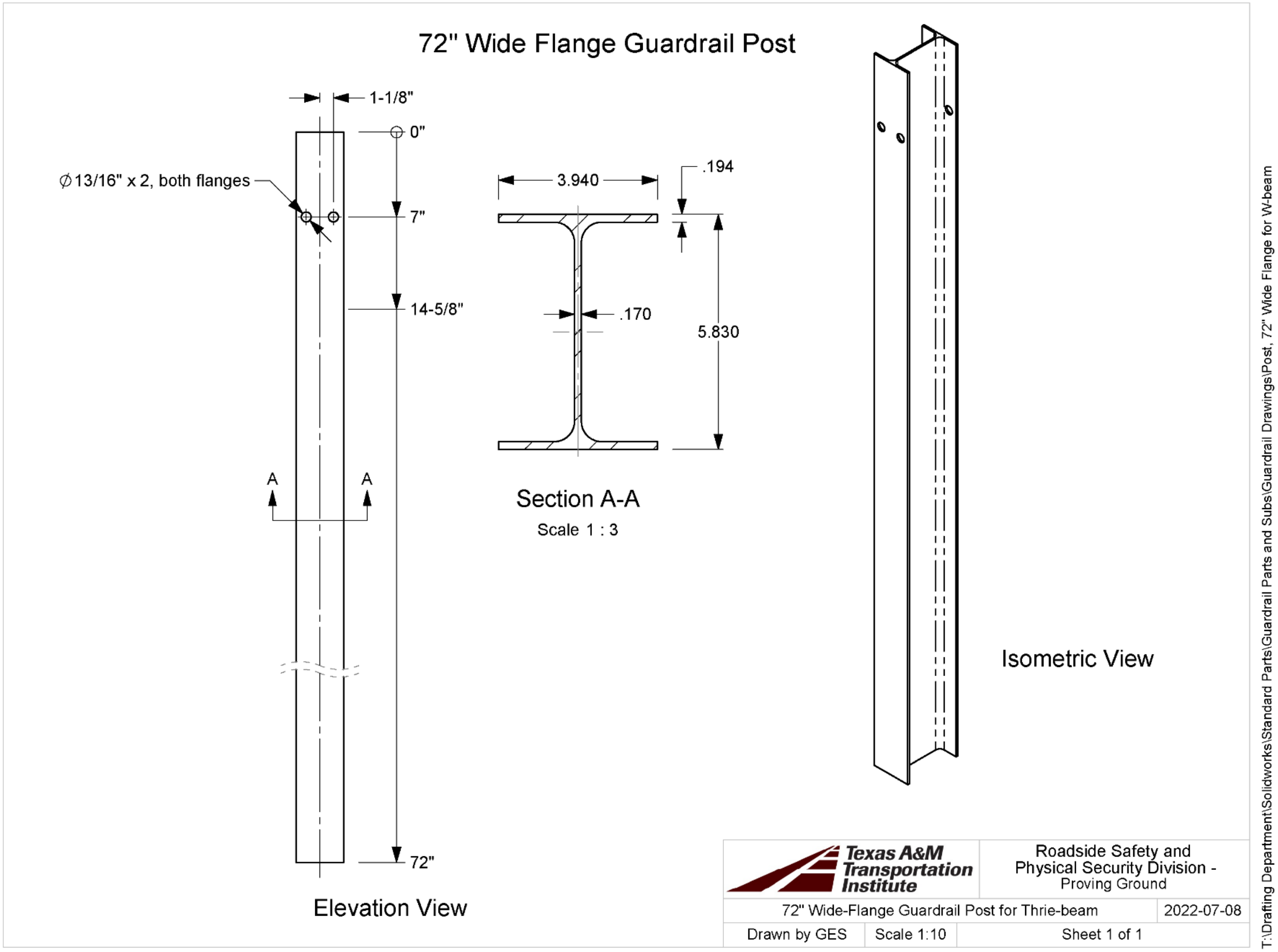


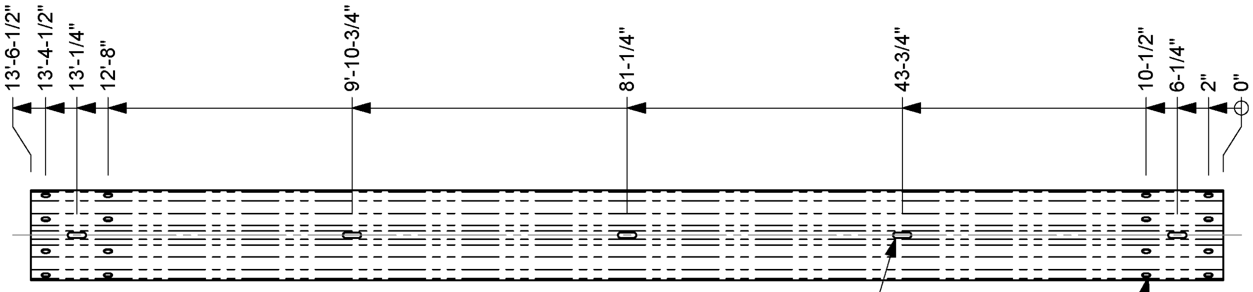
Texas A&M Transportation Institute

Roadside Safety and Physical Security Division - Proving Ground

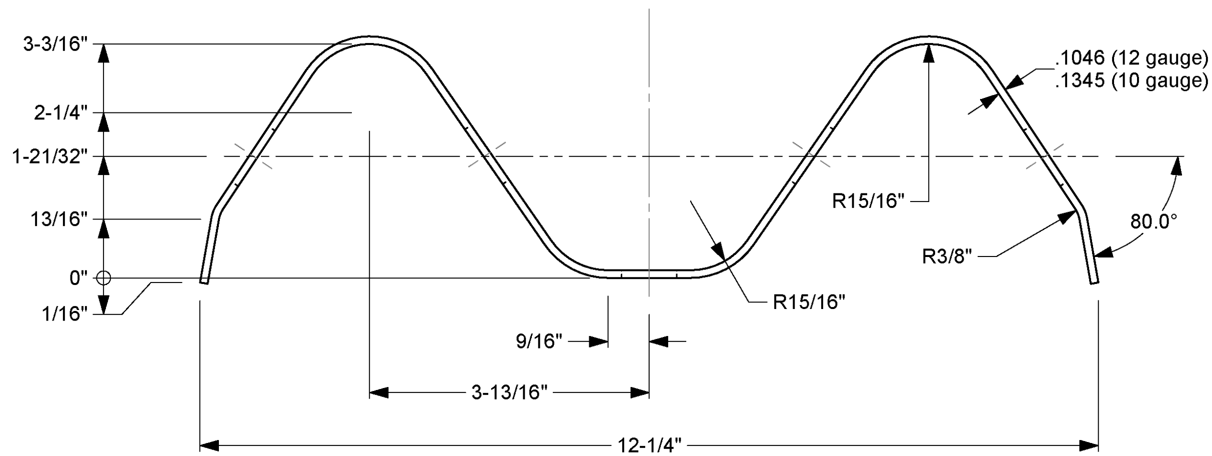
Rectangular Guardrail Washer	2022-07-08
Drawn by GES	Scale 2:1
Sheet 1 of 1	

T:\Drafting Department\Solidworks\Standard Parts\Guardrail Parts and Subs\Guardrail Drawings\Washer, rect.


72" Wide Flange Guardrail Post
1-1/8"
0"
∅13/16" x 2, both flanges
7"
14-5/8"
72"
A
A
Elevation View
3.940
.194
.170
5.830
Section A-A
Scale 1 : 3
Isometric View
Texas A&M Transportation Institute
Roadside Safety and Physical Security Division - Proving Ground
72" Wide-Flange Guardrail Post for Thrie-beam
2022-07-08
Drawn by GES
Scale 1:10
Sheet 1 of 1
T:\Drafting Department\Solidworks\Standard Parts\Guardrail Parts and Subs\Guardrail Drawings\Post, 72" Wide Flange for W-beam



Elevation View



Section View

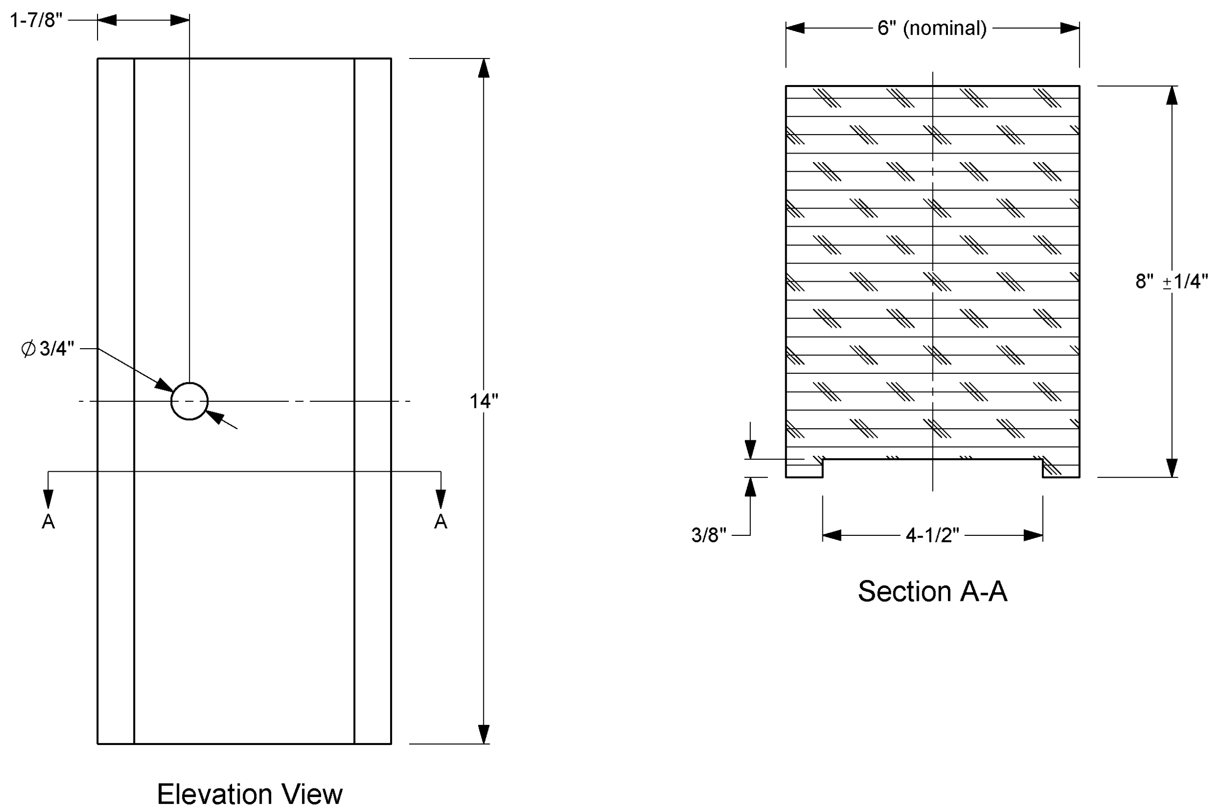
1a. Manufacture per AASHTO M180 specifications.

1b. 4-space Guardrail is shown. Slots typical x 3 for 2-space W-beam spaced at 75", and typical x 9 for 8-space W-beam spaced at 18-3/4". Slots are typical x 4 at 37-1/2" for 9'-4-1/2" span W-beam.

Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground	
W-beam Guardrail		2022-07-13
Drawn by GES	Scale 1:20	Sheet 1 of 1

T:\Drafting Department\Solidworks\Standard Parts\Guardrail Parts and Subs\Guardrail Drawings\W-Beam Guardrail

Timber Blockout for W-section Post



1a. Timber blockouts are treated with a preservative in accordance with AASHTO M 133 after all cutting and drilling.

Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground	
Timber Blockout, for W-section Post		2022-07-08
Drawn by GES	Scale 1:3	Sheet 1 of 1

T:\Drafting Department\Solidworks\Standard Parts\Guardrail Parts and Subs\Guardrail Drawings\Timber Blockout for W-section Post

APPENDIX B. SUPPORTING CERTIFICATION DOCUMENTS

Certified Analysis

Trinity Highway Products LLC
2548 N.E. 28th St.
Ft Worth (THP), TX 76111 Phn:(817) 665-1499

Customer: SAMPLES, TESTING MATERIALS
15601 Dallas Pkwy
Suite 525

ADDISON, TX 75001

Order Number: 1343950 Prod Ln Grp: 19-CASS
Customer PO: 614031
BOL Number: 85823 Ship Date:
Document #: 1
Shipped To: TX
Use State: TX

As of: 11/2/21

Project: TTI TESTING THRIE BEAM AT FIXED OBJECT

Qty	Part #	Description	Spec	CL	TY	Heat Code/ Heat	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
24	11G	12/12'6/3'1.5/S			2	F12721													
			M-180	A	2	2113321	52,900	80,800	27.0	0.240	1.000	0.011	0.001	0.020	0.150	0.002	0.060	0.004	4
			M-180	A	2	2113322	56,700	80,500	26.0	0.230	1.000	0.010	0.002	0.030	0.140	0.002	0.060	0.004	4
			M-180	A	2	2213517	55,100	79,900	26.0	0.230	0.980	0.010	0.001	0.030	0.120	0.002	0.060	0.005	4
			M-180	A	2	2213518	57,000	84,200	26.0	0.230	0.980	0.011	0.001	0.020	0.120	0.001	0.070	0.004	4
	11G				2	F13521													
			M-180	A	2	2112289	58,300	82,800	21.0	0.220	0.810	0.010	0.003	0.030	0.150	0.001	0.050	0.002	4
			M-180	A	2	2112291	59,700	81,900	22.0	0.220	0.810	0.011	0.003	0.020	0.150	0.001	0.050	0.002	4
	11G				2	F13621													
			M-180	A	2	2112291	59,700	81,900	22.0	0.220	0.810	0.011	0.003	0.020	0.150	0.001	0.050	0.002	4
			M-180	A	2	2112293	61,700	85,500	20.0	0.220	0.810	0.011	0.003	0.020	0.140	0.002	0.050	0.002	4
			M-180	A	2	2112297	62,000	83,600	24.0	0.210	0.810	0.012	0.002	0.030	0.140	0.000	0.050	0.002	4
50	533G	6'0 POST/8.5/DDR/7	A-36			1111517	54,400	67,300	28.0	0.070	0.800	0.008	0.019	0.200	0.090	0.014	0.040	0.002	4
	533G		A-36			1114803	54,500	67,500	28.3	0.070	0.840	0.007	0.022	0.230	0.130	0.015	0.040	0.002	4
	533G		A-36			2104723	54,000	66,200	26.0	0.070	80.000	0.013	0.020	0.200	0.100	0.014	0.040	0.002	4
2	700A	3/16X12.5X16 CAB ANC BRKT	WIRE			17044592													4
	700A		A-36			821P12700	45,600	67,500	31.0	0.160	0.830	0.010	0.005	0.007	0.025	0.002	0.025	0.001	4
4	3000G	CBL 3/4X6'6/DBL SWG/NOHWD	WIRE			SO03-005338													4
450	3340G	5/8" GR HEX NUT	FAST			21-38-003													4
400	3360G	5/8"X1.25" GR BOLT	A307-3360G			968936-5													4

TR No. 614721-01-1&2

191

2023-08-08

Certified Analysis

Trinity Highway Products LLC
2548 N.E. 28th St.
Ft Worth (THP), TX 76111 Phn:(817) 665-1499

Customer: SAMPLES, TESTING MATERIALS
15601 Dallas Pkwy
Suite 525
ADDISON, TX 75001

Order Number: 1343950   Prod Ln Grp: 19-CASS
Customer PO: 614031
BOL Number: 85823   Ship Date:
Document #: 1
Shipped To: TX
Use State: TX

As of: 11/2/21

Project: TTI TESTING THRIE BEAM AT FIXED OBJECT

Qty	Part #	Description	Spec	CL	TY	Heat Code/ Heat	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
50	3500G	5/8"X10" GR BOLT A307	A307-3500G			958524-6													4
8	3900G	1" ROUND WASHER F844	F844-3900			5053124													4
8	3910G	1" HEX NUT A563	A563-3910			P39590 R75013													4
50	4076B	WD BLK RTD 6X8X14	WOOD			4850													
4	12227G	T12/12'6/3'1.5:6@1'6.75/S				F10621													
			M-180	A		2106282	64,100	86,000	23.0	0.210	0.760	0.008	0.001	0.030	0.080	0.002	0.040	0.003	4
4	20207G	12/9'4.5/8-HOLE ANCH/S			2	F12821													
			M-180	A	2	2113322	56,700	80,500	26.0	0.230	1.000	0.010	0.002	0.030	0.140	0.002	0.060	0.004	4
			M-180	A	2	2113955	55,900	82,400	25.0	0.230	0.970	0.010	0.001	0.030	0.110	0.002	0.050	0.004	4
			M-180	A	2	2213518	57,000	84,200	26.0	0.230	0.980	0.011	0.001	0.020	0.120	0.001	0.070	0.004	4
			M-180	A	2	2215927	57,100	80,900	28.0	0.210	0.790	0.010	0.002	0.020	0.070	0.001	0.040	0.004	4
			M-180	A	2	2215929	58,600	80,900	27.0	0.200	0.780	0.009	0.003	0.020	0.070	0.001	0.010	0.004	4
			M-180	A	2	264922	60,406	79,043	24.0	0.200	0.730	0.008	0.002	0.020	0.100	0.000	0.060	0.001	4
			M-180	A	2	267328	62,895	81,187	25.1	0.190	0.720	0.006	0.002	0.020	0.110	0.001	0.060	0.002	4
2	32218G	T10/TRAN/TB:WB/ASYM/RT	M-180	B	2	C89858	59,300	81,600	24.2	0.200	0.490	0.014	0.002	0.030	0.090	0.000	0.060	0.001	4
	32218G		M-180	B	2	C89858	59,300	81,600	24.2	0.200	0.490	0.014	0.002	0.030	0.090	0.000	0.060	0.001	4
2	32219G	T10/TRAN/TB:WB/ASYM/LT	M-180	B	2	248834	59,940	78,890	27.2	0.210	0.720	0.013	0.003	0.020	0.100	0.000	0.050	0.000	4
	32219G		M-180	B	2	267473	59,260	78,979	25.5	0.190	0.710	0.014	0.002	0.020	0.100	0.000	0.080	0.001	4

Certified Analysis

Trinity Highway Products LLC
2548 N.E. 28th St.
Ft Worth (THP), TX 76111 Phn:(817) 665-1499

Customer: SAMPLES, TESTING MATERIALS
15601 Dallas Pkwy
Suite 525

ADDISON, TX 75001

Project: TTI TESTING UNANCHORED RAIL

Order Number: 1343952 Prod Ln Grp: 19-CASS
Customer PO: 614721
BOL Number: 85824 Ship Date:
Document #: 1
Shipped To: TX
Use State: TX

As of: 11/2/21

Qty	Part #	Description	Spec	CL	TY	Heat Code/ Heat	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
18	11G	12/12'6/3'1.5/S			2	F12721													
			M-180	A	2	2113321	52,900	80,800	27.0	0.240	1.000	0.011	0.001	0.020	0.150	0.002	0.060	0.004	4
			M-180	A	2	2113322	56,700	80,500	26.0	0.230	1.000	0.010	0.002	0.030	0.140	0.002	0.060	0.004	4
			M-180	A	2	2213517	55,100	79,900	26.0	0.230	0.980	0.010	0.001	0.030	0.120	0.002	0.060	0.005	4
			M-180	A	2	2213518	57,000	84,200	26.0	0.230	0.980	0.011	0.001	0.020	0.120	0.001	0.070	0.004	4
	11G				2	F13521													
			M-180	A	2	2112289	58,300	82,800	21.0	0.220	0.810	0.010	0.003	0.030	0.150	0.001	0.050	0.002	4
			M-180	A	2	2112291	59,700	81,900	22.0	0.220	0.810	0.011	0.003	0.020	0.150	0.001	0.050	0.002	4
	11G				2	F13621													
			M-180	A	2	2112291	59,700	81,900	22.0	0.220	0.810	0.011	0.003	0.020	0.150	0.001	0.050	0.002	4
			M-180	A	2	2112293	61,700	85,500	20.0	0.220	0.810	0.011	0.003	0.020	0.140	0.002	0.050	0.002	4
			M-180	A	2	2112297	62,000	83,600	24.0	0.210	0.810	0.012	0.002	0.030	0.140	0.000	0.050	0.002	4
36	533G	6'0 POST/8.5/DDR/7	A-36			1111517	54,400	67,300	28.0	0.070	0.800	0.008	0.019	0.200	0.090	0.014	0.040	0.002	4
	533G		A-36			1114803	54,500	67,500	28.3	0.070	0.840	0.007	0.022	0.230	0.130	0.015	0.040	0.002	4
	533G		A-36			2104723	54,000	66,200	26.0	0.070	80.000	0.013	0.020	0.200	0.100	0.014	0.040	0.002	4
180	3340G	5/8" GR HEX NUT	FAST			21-38-003													4
144	3360G	5/8"X1.25" GR BOLT	A307-3360G			968936-5													4
36	3500G	5/8"X10" GR BOLT A307	A307-3500G			958524-6													4
36	4076B	WD BLK RTD 6X8X14	WOOD			4850													

Certified Analysis

Trinity Highway Products LLC
2548 N.E. 28th St.
Ft Worth (THP), TX 76111 Phn:(817) 665-1499

Customer: SAMPLES, TESTING MATERIALS
15601 Dallas Pkwy
Suite 525

ADDISON, TX 75001

Project: TTI TESTING UNANCHORED RAIL

Order Number: 1343952 Prod Ln Grp: 19-CASS
Customer PO: 614721
BOL Number: 85824 Ship Date:
Document #: 1
Shipped To: TX
Use State: TX

As of: 11/2/21

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.
ALL COATINGS PROCESSES OF THE STEEL OR IRON ARE PERFORMED IN USA AND COMPLIES WITH THE "BUY AMERICA ACT", 23 CFR 635.410.
ALL GALVANIZED MATERIAL CONFORMS WITH ASTM A-123 (US DOMESTIC SHIPMENTS)
ALL GALVANIZED MATERIAL CONFORMS WITH ASTM A-123 & 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, UNLESS OTHERWISE STATED.
3/4" DIA CABLE 6X19 ZINC COATED SWAGED END AISI C-1035 STEEL ANNEALED STUD 1" DIA ASTM449 AASHTO M30, TYPE II BREAKING STRENGTH – 46000 LB

State of Texas, County of Tarrant. Sworn and subscribed before me this 2nd day of November, 2021 .

Notary Public:
Commission Expires: /

NOTARY PUBLIC STATE OF TEXAS
Miguel Jimenez Jr
My Commission Expires
9/21/2025
Notary ID
133343176

Trinity Highway Products, LLC
Certified By:
Quality Assurance

TR No. 614721-01-1&2

194

2023-08-08

Certified Analysis

Trinity Highway Products LLC
2548 N.E. 28th St.
Ft Worth (THP), TX 76111 Phn:(817) 665-1499

Customer: SAMPLES, TESTING MATERIALS
15601 Dallas Pkwy
Suite 525

ADDISON, TX 75001

Project: TTI TESTING NCHRP PROJECT

Order Number: 1343951 Prod Ln Grp: 19-CASS
Customer PO: NCHRP 350
BOL Number: 85825 Ship Date:
Document #: 1
Shipped To: TX
Use State: TX

As of: 11/2/21

Qty	Part #	Description	Spec	CL	TY	Heat Code/ Heat	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
28	11G	12/12'6/3'1.5/S			2	F12721													
			M-180	A	2	2113321	52,900	80,800	27.0	0.240	1.000	0.011	0.001	0.020	0.150	0.002	0.060	0.004	4
			M-180	A	2	2113322	56,700	80,500	26.0	0.230	1.000	0.010	0.002	0.030	0.140	0.002	0.060	0.004	4
			M-180	A	2	2213517	55,100	79,900	26.0	0.230	0.980	0.010	0.001	0.030	0.120	0.002	0.060	0.005	4
			M-180	A	2	2213518	57,000	84,200	26.0	0.230	0.980	0.011	0.001	0.020	0.120	0.001	0.070	0.004	4
	11G				2	F13521													
			M-180	A	2	2112289	58,300	82,800	21.0	0.220	0.810	0.010	0.003	0.030	0.150	0.001	0.050	0.002	4
			M-180	A	2	2112291	59,700	81,900	22.0	0.220	0.810	0.011	0.003	0.020	0.150	0.001	0.050	0.002	4
	11G				2	F13621													
			M-180	A	2	2112291	59,700	81,900	22.0	0.220	0.810	0.011	0.003	0.020	0.150	0.001	0.050	0.002	4
			M-180	A	2	2112293	61,700	85,500	20.0	0.220	0.810	0.011	0.003	0.020	0.140	0.002	0.050	0.002	4
			M-180	A	2	2112297	62,000	83,600	24.0	0.210	0.810	0.012	0.002	0.030	0.140	0.000	0.050	0.002	4
50	533G	6'0 POST/8.5/DDR/7	A-36			1111517	54,400	67,300	28.0	0.070	0.800	0.008	0.019	0.200	0.090	0.014	0.040	0.002	4
	533G		A-36			1114803	54,500	67,500	28.3	0.070	0.840	0.007	0.022	0.230	0.130	0.015	0.040	0.002	4
	533G		A-36			2104723	54,000	66,200	26.0	0.070	80.000	0.013	0.020	0.200	0.100	0.014	0.040	0.002	4
2	700A	3/16X12.5X16 CAB ANC BRKT	WIRE			17044592													4
	700A		A-36			821P12700	45,600	67,500	31.0	0.160	0.830	0.010	0.005	0.007	0.025	0.002	0.025	0.001	4
4	3000G	CBL 3/4X6'6/DBL SWG/NOHWD	WIRE			SO03-005338													4
224	3360G	5/8"X1.25" GR BOLT	A307-3360G			968936-5													4
50	3500G	5/8"X10" GR BOLT A307	A307-3500G			958524-6													4

Certified Analysis

Trinity Highway Products LLC
2548 N.E. 28th St.
Ft Worth (THP), TX 76111 Phn:(817) 665-1499

Customer: SAMPLES, TESTING MATERIALS
15601 Dallas Pkwy
Suite 525

ADDISON, TX 75001

Project: TTI TESTING NCHRP PROJECT

Order Number: 1343951 Prod Ln Grp: 19-CASS
Customer PO: NCHRP 350
BOL Number: 85825 Ship Date:
Document #: 1
Shipped To: TX
Use State: TX

As of: 11/2/21

Qty	Part #	Description	Spec	CL	TY	Heat Code/ Heat	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
8	3900G	1" ROUND WASHER F844	F844-3900			5053124													4
8	3910G	1" HEX NUT A563	A563-3910			P39590 R75013													4
50	4076B	WD BLK RTD 6X8X14	WOOD			4850													
4	20207G	12/9'4.5/8-HOLE ANCH/S			2	F12821													
			M-180	A	2	2113322	56,700	80,500	26.0	0.230	1.000	0.010	0.002	0.030	0.140	0.002	0.060	0.004	4
			M-180	A	2	2113955	55,900	82,400	25.0	0.230	0.970	0.010	0.001	0.030	0.110	0.002	0.050	0.004	4
			M-180	A	2	2213518	57,000	84,200	26.0	0.230	0.980	0.011	0.001	0.020	0.120	0.001	0.070	0.004	4
			M-180	A	2	2215927	57,100	80,900	28.0	0.210	0.790	0.010	0.002	0.020	0.070	0.001	0.040	0.004	4
			M-180	A	2	2215929	58,600	80,900	27.0	0.200	0.780	0.009	0.003	0.020	0.070	0.001	0.010	0.004	4
			M-180	A	2	264922	60,406	79,043	24.0	0.200	0.730	0.008	0.002	0.020	0.100	0.000	0.060	0.001	4
			M-180	A	2	267328	62,895	81,187	25.1	0.190	0.720	0.006	0.002	0.020	0.110	0.001	0.060	0.002	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.

ALL COATINGS PROCESSES OF THE STEEL OR IRON ARE PERFORMED IN USA AND COMPLIES WITH THE "BUY AMERICA ACT", 23 CFR 635.410.
ALL GALVANIZED MATERIAL CONFORMS WITH ASTM A-123 (US DOMESTIC SHIPMENTS)
ALL GALVANIZED MATERIAL CONFORMS WITH ASTM A-123 & ISO 1461 (INTERNATIONAL SHIPMENTS)

FINISHED GOOD PART NUMBERS ENDING IN SUFFIX B,P, OR S, ARE UNCOATED

Certified Analysis

Trinity Highway Products LLC
2548 N.E. 28th St.
Ft Worth (THP), TX 76111 Phn:(817) 665-1499
Customer: SAMPLES, TESTING MATERIALS
15601 Dallas Pkwy
Suite 525
ADDISON, TX 75001
Project: TTI TESTING NCHRP PROJECT

Order Number: 1343951 Prod Ln Grp: 19-CASS
Customer PO: NCHRP 350
BOL Number: 85825 Ship Date:
Document #: 1
Shipped To: TX
Use State: TX

As of: 11/2/21

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, 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 – 46000 LB

State of Texas, County of Tarrant. Sworn and subscribed before me this 2nd day of November, 2021 .

Notary Public:
Commission Expires: /

NOTARY PUBLIC STATE OF TEXAS
Miguel Jimenez Jr
My Commission Expires
9/21/2025
Notary ID
133343176

Certified By: Trinity Highway Products LLC
Quality Assurance

B.1. SOIL PROPERTIES

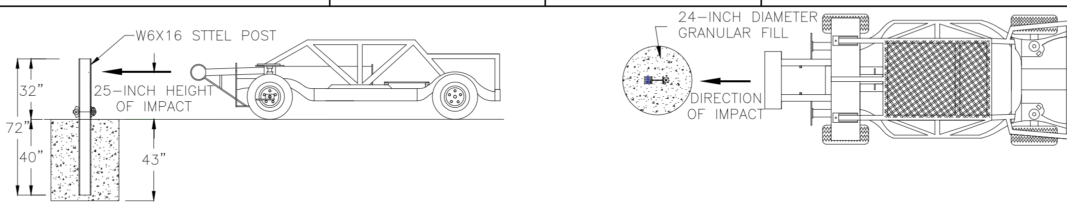
Table B.1. Summary of Strong Soil Test Results for Establishing Installation Procedure.


Dynamic Test Setup

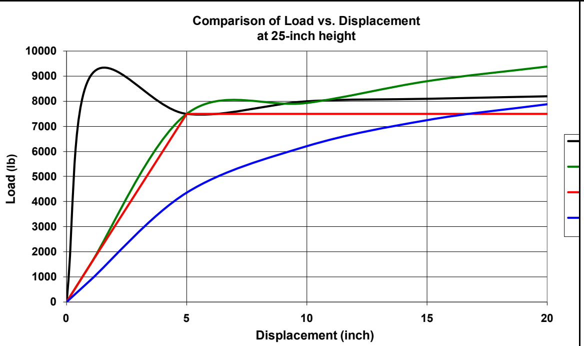

Post-Test Photo of post


Static Load Test

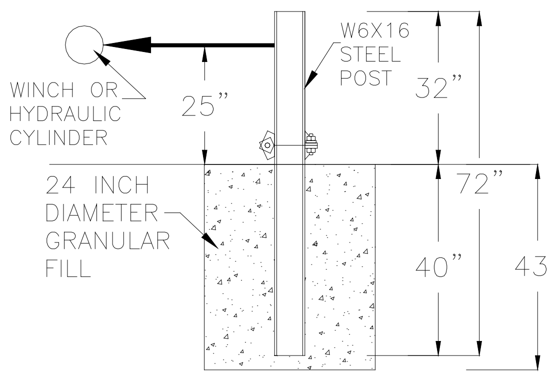

Post-Test Photo



Dynamic Test Installation Details



Comparison of Load vs. Displacement



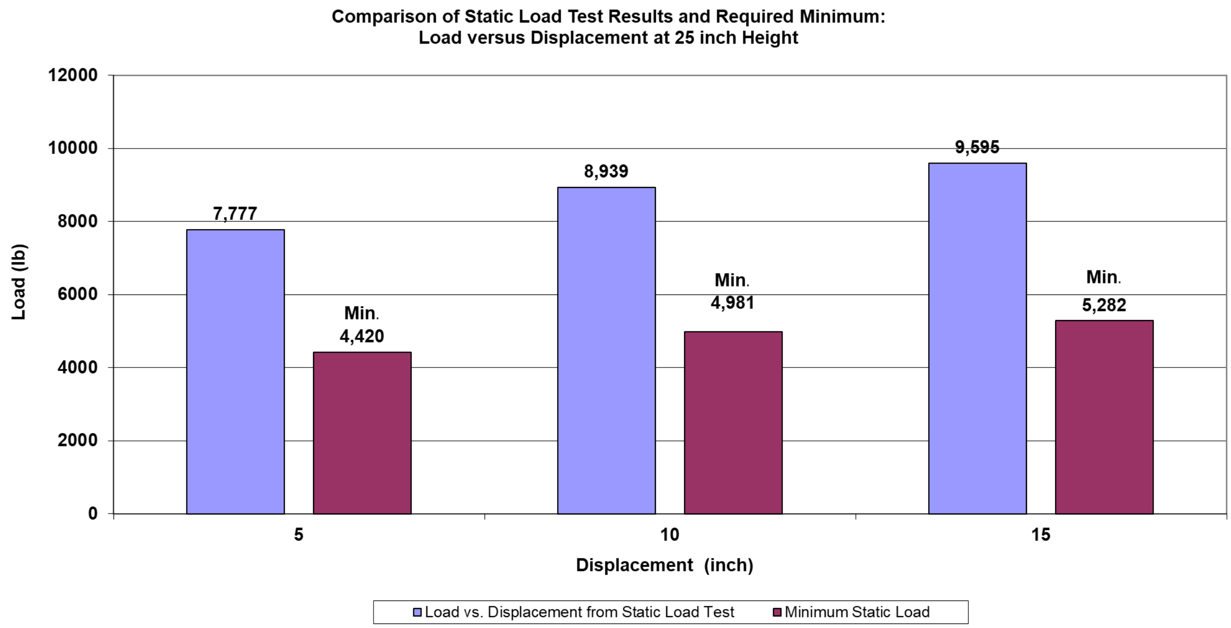
Static Load Test Installation Details

Date	2020-02-02
Test Facility and Site Location	TTI Proving Ground, 3100 SH 47, Bryan, TX 77807
In Situ Soil Description (ASTM D2487)	Sandy gravel with silty fines
Fill Material Description (ASTM D2487) and sieve analysis	AASHTO M147 Grade D or Type D Crushed Concrete Road Base
Description of Fill Placement Procedure	12-inch lifts tamped with a pneumatic compactor for 20 sec
Bogie Weight	2020 lb
Impact Velocity	19.2 mph

TR No. 614721-01-1&2 197 2023-08-08

Table B.2. Test Day Static Soil Strength Documentation for Test No. 614721-01-2.

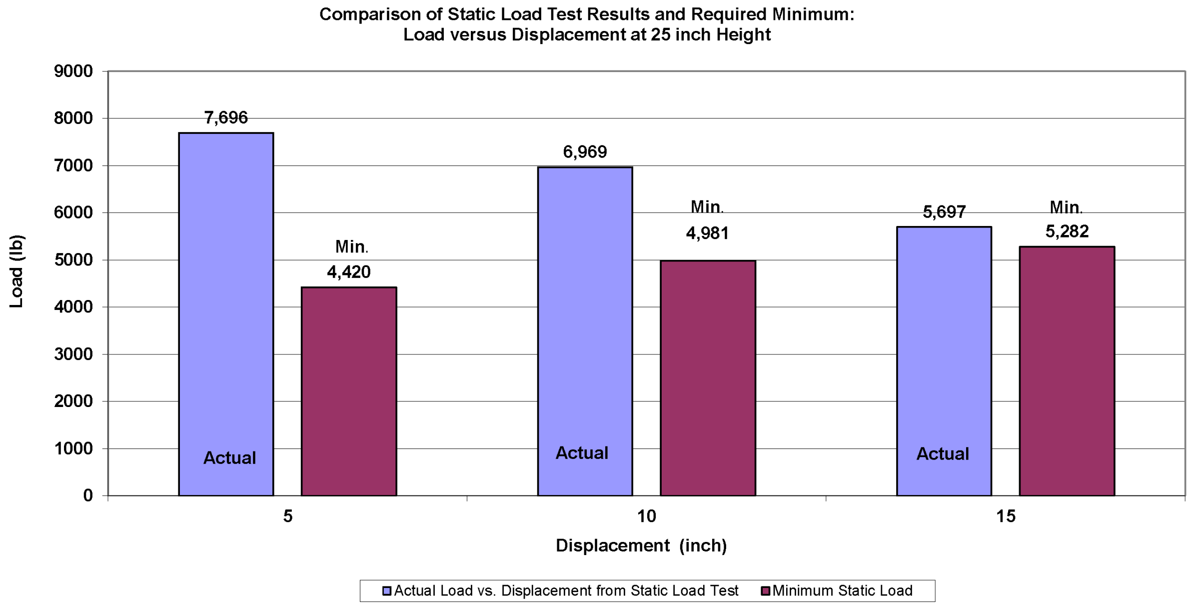
C



Date	2021-04-06
	Test No. 614721-01-2
Test Facility and Site Location	TTI Proving Ground – 3100 SH 47, Bryan, Tx
In Situ Soil Description (ASTM D2487)	Crushed Concrete
Fill Material Description (ASTM D2487) and sieve analysis	AASHTO M147 Grade D or Type D Crushed Concrete Road Base
Description of Fill Placement Procedure	6-inch lifts tamped with a pneumatic compactor

TR No. 614721-01-1&2 199 2023-08-08

Table B.3. Test Day Static Soil Strength Documentation for Test No. 614721-01-1.



Date	2022-10-26
	Test No. 614721-01-1
Test Facility and Site Location	TTI Proving Ground – 3100 SH 47, Bryan, Tx
In Situ Soil Description (ASTM D2487)	Crushed Concrete
Fill Material Description (ASTM D2487) and sieve analysis	AASHTO M147 Grade D or Type D Crushed Concrete Road Base
Description of Fill Placement Procedure	6-inch lifts tamped with a pneumatic compactor

APPENDIX C. *MASH* TEST 3-11 (CRASH TEST NO. 614721-01-2)

C.1. VEHICLE PROPERTIES AND INFORMATION

Table C.1. Vehicle Properties for Test No. 614721-01-2.

Date: 2021-4-6 Test No.: 614721-01-2 VIN No.: 1C6RR6FT8HS695546

Year: 2017 Make: RAM Model: 1500

Tire Size: 265/70 R 17 Tire Inflation Pressure: 35 psi

Tread Type: Highway Odometer: 131685

Note any damage to the vehicle prior to test: None

● Denotes accelerometer location.

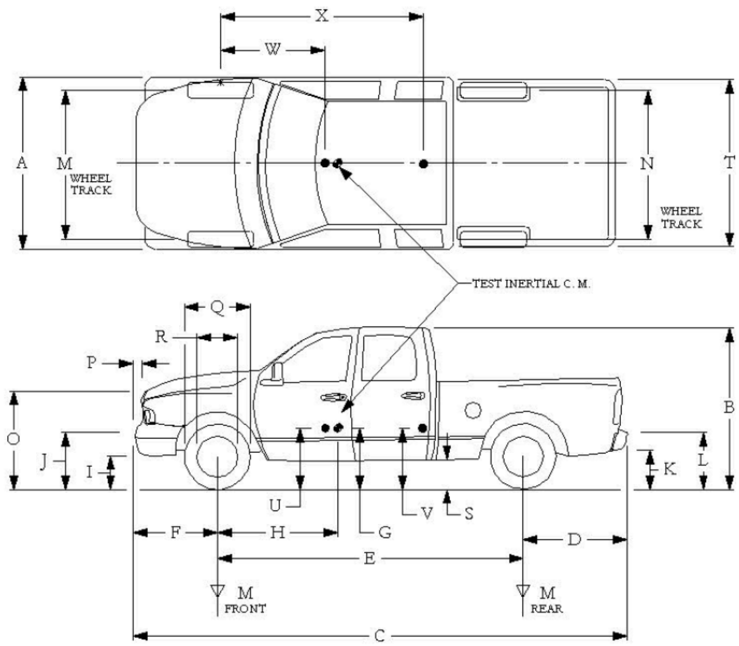
NOTES: None

Engine Type: V-8
Engine CID: 5.7

Transmission Type:
☑ Auto or ☐ Manual
☐ FWD ☑ RWD ☐ 4WD

Optional Equipment:
None

Dummy Data:
Type: NONE
Mass: 0 lb
Seat Position:



Geometry: inches

A	78.50	F	40.00	K	20.00	P	3.00	U	26.75
B	74.00	G	28.25	L	30.00	Q	30.50	V	30.25
C	227.50	H	61.55	M	68.50	R	18.00	W	61.50
D	44.00	I	11.75	N	68.00	S	13.00	X	79.00
E	140.50	J	27.00	O	46.00	T	77.00		

Wheel Center Height Front	14.75	Wheel Well Clearance (Front)	6.00	Bottom Frame Height - Front	12.50
Wheel Center Height Rear	14.75	Wheel Well Clearance (Rear)	9.25	Bottom Frame Height - Rear	22.50

RANGE LIMIT: A=78 ±2 inches; C=237 ±13 inches; E=148 ±12 inches; F=39 ±3 inches; G = > 28 inches; H = 63 ±4 inches; O=43 ±4 inches; (M+N)/2=67 ±1.5 inches

GVWR Ratings:		**Mass:** lb	Curb	Test Inertial	Gross Static
Front	3700	M_{front}	2969	2829	2829
Back	3900	M_{rear}	2148	2206	2206
Total	6700	M_{Total}	5117	5035	5035

(Allowable Range for TIM and GSM = 5000 lb ±110 lb)

Mass Distribution:
lb LF: 1436 RF: 1393 LR: 1118 RR: 1088

Table C.2. Exterior Crush Measurements for Test No. 614721-01-2.

Date:	2021-4-6	Test No.:	614721-01-2	VIN No.:	1C6RR6FT8HS695546
Year:	2017	Make:	RAM	Model:	1500

VEHICLE CRUSH MEASUREMENT SHEET[1]

Complete When Applicable	
End Damage	Side Damage
Undeformed end width ________	Bowing: B1 _____ X1 _____
Corner shift: A1 ________	B2 _____ X2 _____
A2 ________	
End shift at frame (CDC)	Bowing constant
(check one)	$\frac{X1+X2}{2}$ = _______
< 4 inches ________	
≥ 4 inches ________	

Note: Measure C_1 to C_6 from Driver to Passenger Side in Front or Rear Impacts – Rear to Front in Side Impacts.

Specific Impact Number	Plane* of C-Measurements	Direct Damage Width** (CDC)	Direct Damage Max*** Crush	Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
1	Front plane at bmp ht	72	11	72	-	-	-	-	-	-	0
	Measurements recorded										
	☑ **inches or** ☐ **mm**										

[1]Table taken from National Accident Sampling System (NASS).

*Identify the plane at which the C-measurements are taken (e.g., at bumper, above bumper, at sill, above sill, at beltline, etc.) or label adjustments (e.g., free space).

Free space value is defined as the distance between the baseline and the original body contour taken at the individual C locations. This may include the following: bumper lead, bumper taper, side protrusion, side taper, etc. Record the value for each C-measurement and maximum crush.

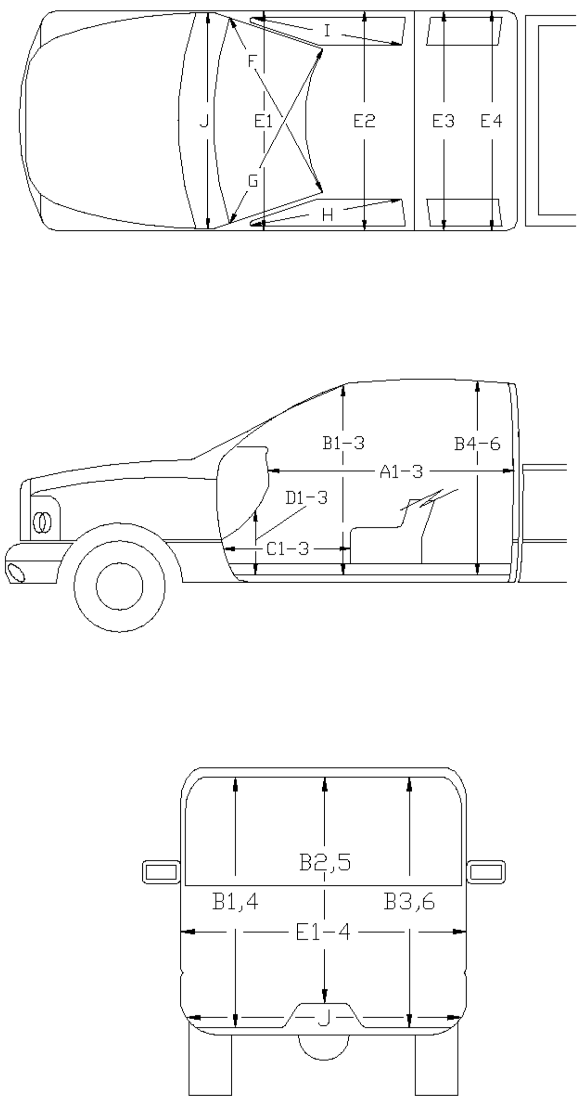
**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

***Measure and document on the vehicle diagram the location of the maximum crush.

Note: Use as many lines/columns as necessary to describe each damage profile.

Table C.3. Occupant Compartment Measurements for Test No. 614721-01-2.

Date:	2021-4-6	Test No.:	614721-01-2	VIN No.:	1C6RR6FT8HS695546
Year:	2017	Make:	RAM	Model:	1500



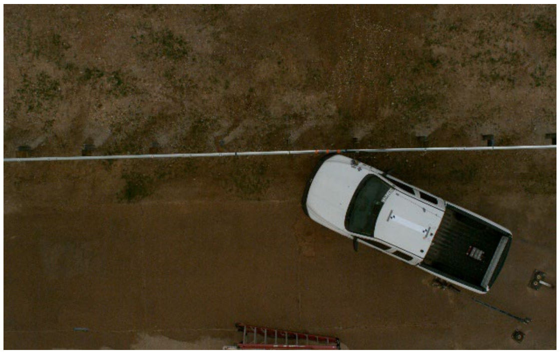
*Lateral area across the cab from driver's side kickpanel to passenger's side kickpanel.

OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

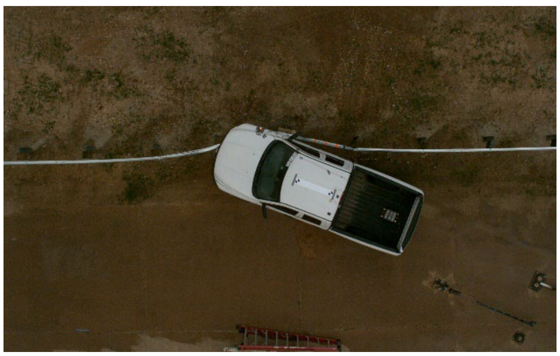
	Before	After (inches)	Differ.
A1	65.00	65.00	0.00
A2	63.00	63.00	0.00
A3	65.50	65.50	0.00
B1	45.00	45.00	0.00
B2	38.00	38.00	0.00
B3	45.00	45.00	0.00
B4	39.50	39.50	0.00
B5	43.00	43.00	0.00
B6	39.50	39.50	0.00
C1	26.00	26.00	0.00
C2	0.00	0.00	0.00
C3	26.00	26.00	0.00
D1	11.00	11.00	0.00
D2	0.00	0.00	0.00
D3	11.50	11.50	0.00
E1	58.50	58.50	0.00
E2	63.50	63.50	0.00
E3	63.50	63.50	0.00
E4	63.50	63.50	0.00
F	59.00	59.00	0.00
G	59.00	59.00	0.00
H	37.50	37.50	0.00
I	37.50	37.50	0.00
J*	25.00	25.00	0.00

TR No. 614721-01-1&2 204 2023-08-08

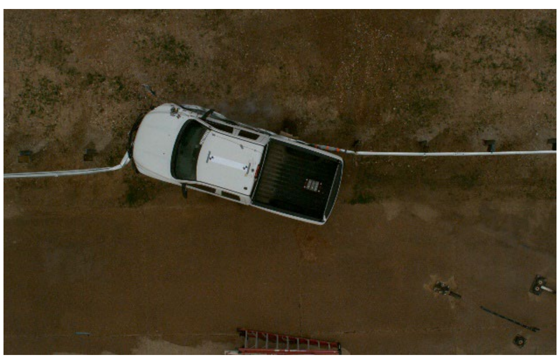
C.2. SEQUENTIAL PHOTOGRAPHS



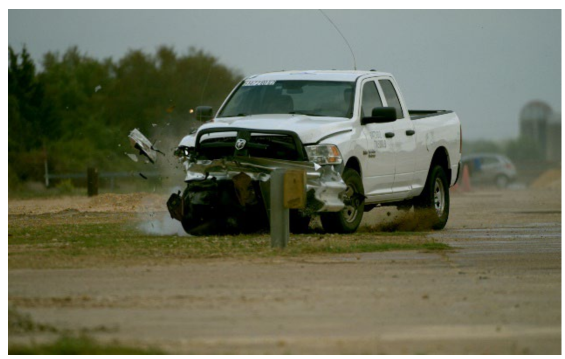
0.000 s

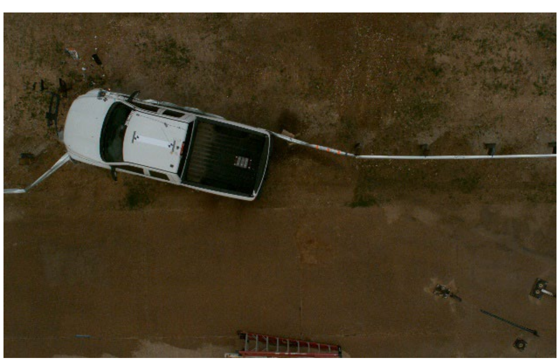


0.100 s



0.200 s





0.300 s

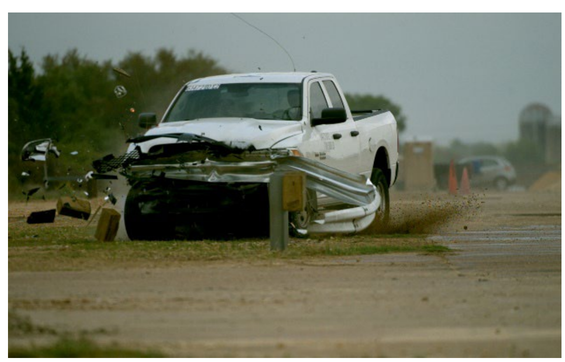


Figure C.1. Sequential Photographs for Test No. 614721-01-2 (Overhead and Frontal Views).

TR No. 614721-01-1&2
205
2023-08-08


0.400 s



0.500 s



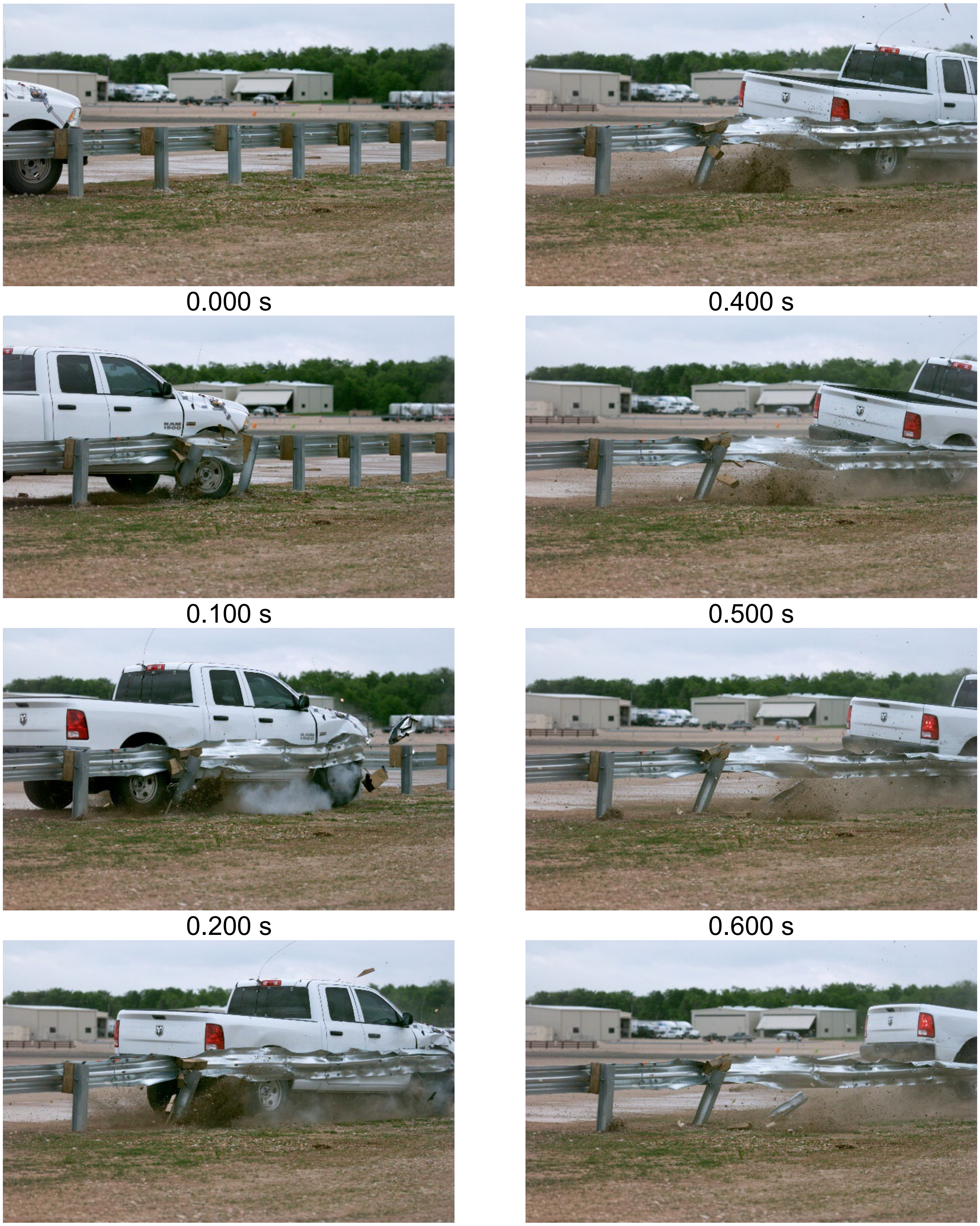
0.600 s



0.700 s

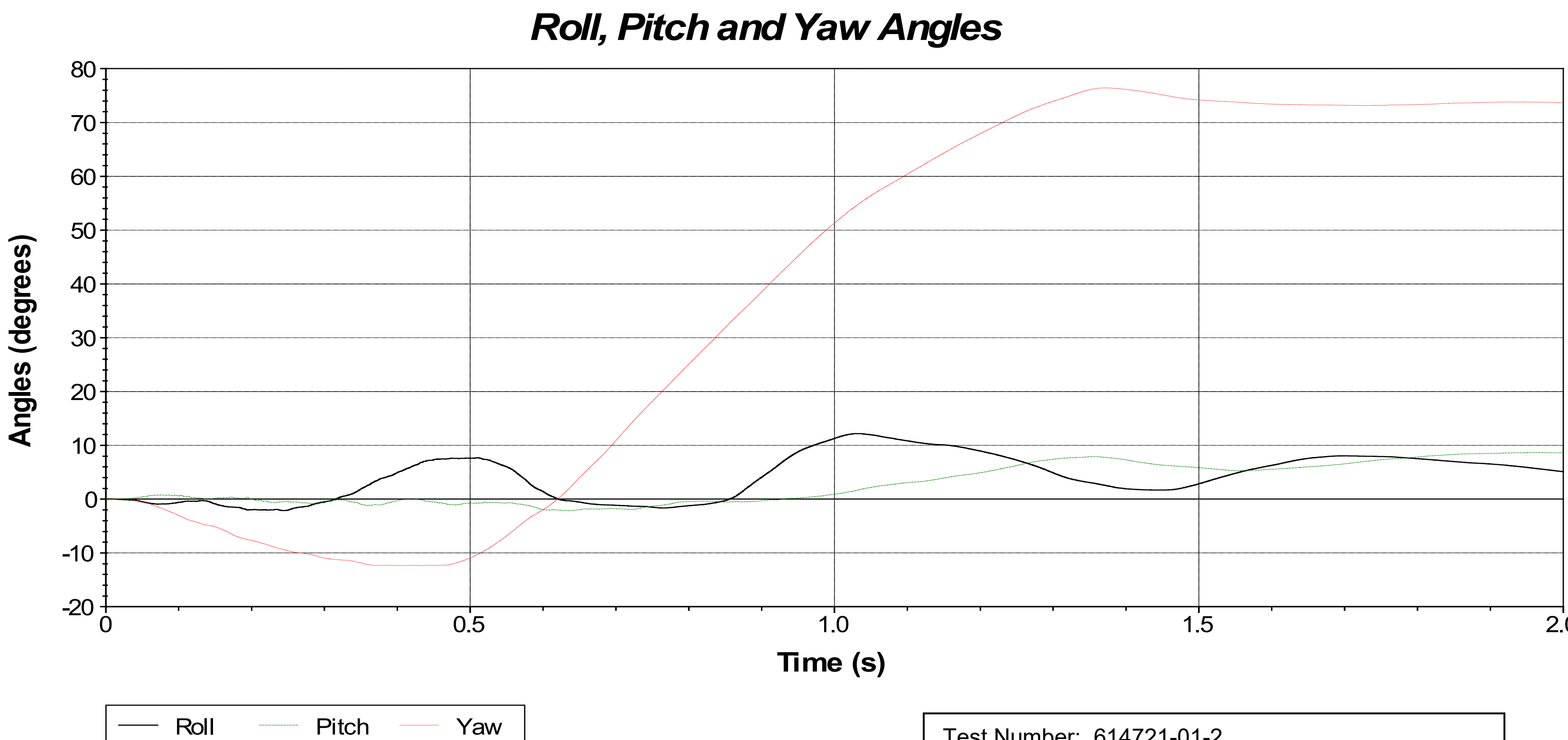

Figure C.1. Sequential Photographs for Test No. 614721-01-2 (Overhead and Frontal Views) (Continued).

TR No. 614721-01-1&2
206
2023-08-08



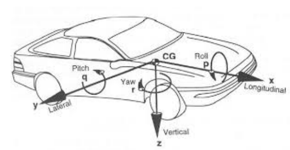
0.000 s
0.100 s
0.200 s
0.300 s
0.400 s
0.500 s
0.600 s
0.700 s

Figure C.2. Sequential Photographs for Test No. 614721-01-2 (Rear View).



Axes are vehicle-fixed.
Sequence for
determining orientation:

1. Yaw.
2. Pitch.
3. Roll.



Test Number: 614721-01-2
Test Standard Test Number: *MASH* Test 3-11
Test Article: Guardrail without downstream anchorage
Test Vehicle: 2017 RAM 1500 Pickup
Inertial Mass: 5035 lb
Gross Mass: 5035 lb
Impact Speed: 62.8 mi/h

Figure C.3. Vehicle Angular Displacements for Test No. 614721-01-2.

C.4. VEHICLE ACCELERATIONS

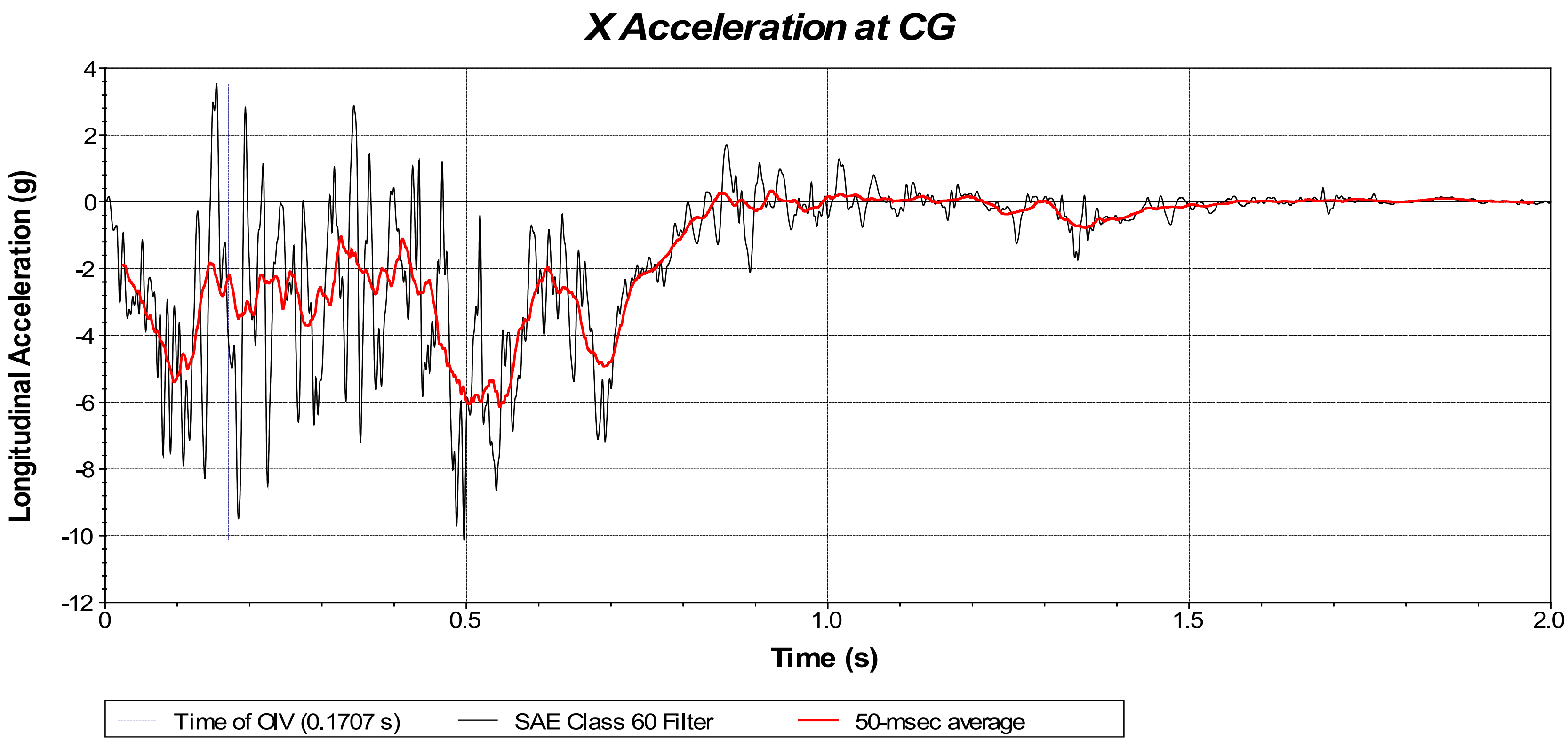


Figure C.4. Vehicle Longitudinal Accelerometer Trace for Test No. 614721-01-2 (Accelerometer Located at Center of Gravity).

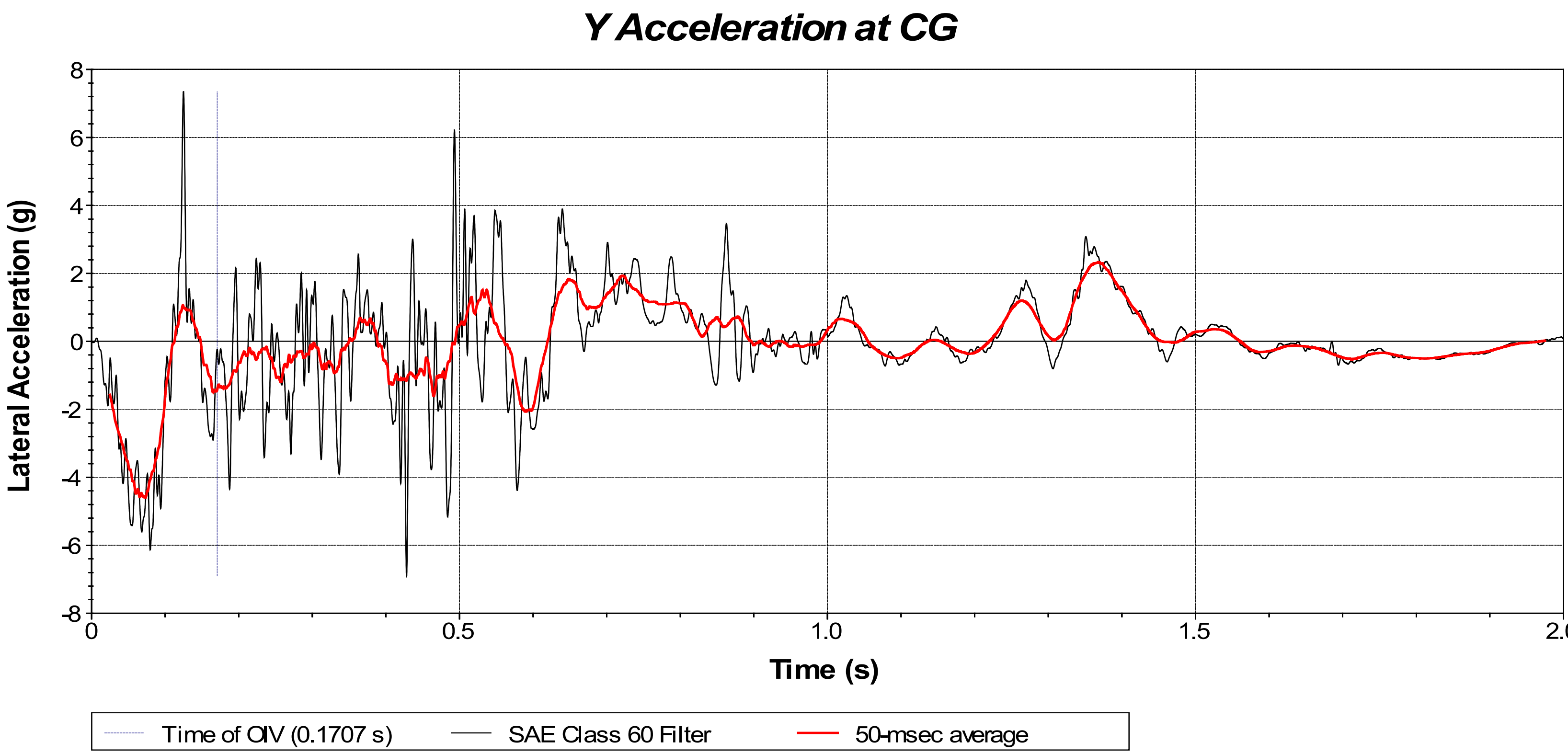


Figure C.5. Vehicle Lateral Accelerometer Trace for Test No. 614721-01-2 (Accelerometer Located at Center of Gravity).

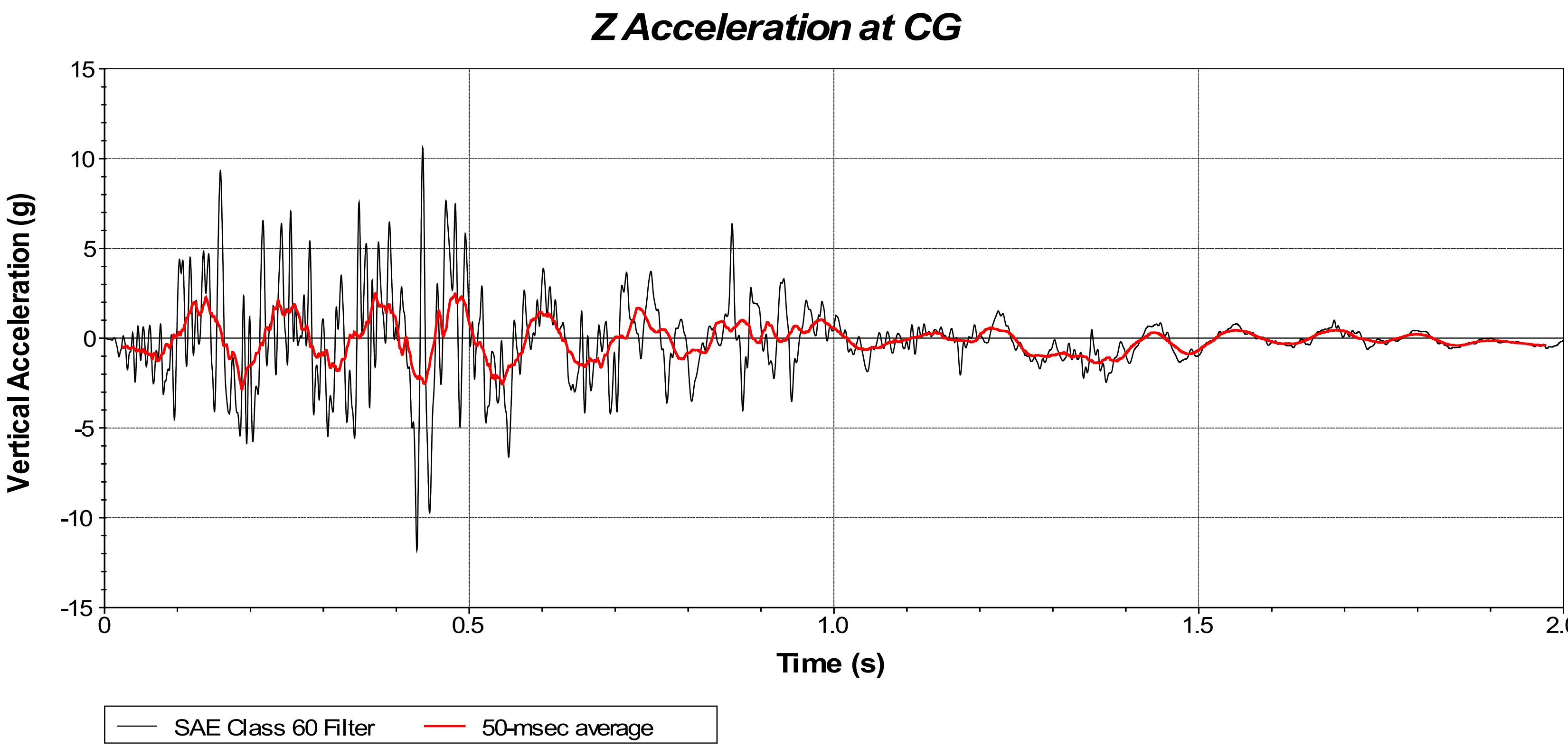


Figure C.6. Vehicle Vertical Accelerometer Trace for Test No. 614721-01-2 (Accelerometer Located at Center of Gravity).

APPENDIX D. *MASH* TEST 3-11 (CRASH TEST NO. 614721-01-1)

D.1. VEHICLE PROPERTIES AND INFORMATION

Table D.1. Vehicle Properties for Test No. 614721-01-1.

Date:	2022-10-26	Test No.:	614721-01-1	VIN No.:	1C6RR6FT1GS405436
Year:	2016	Make:	RAM	Model:	1500

Tire Size: 265/70 R 17 | Tire Inflation Pressure: 35 psi

Tread Type: Highway | Odometer: 132772

Note any damage to the vehicle prior to test: None

● Denotes accelerometer location.

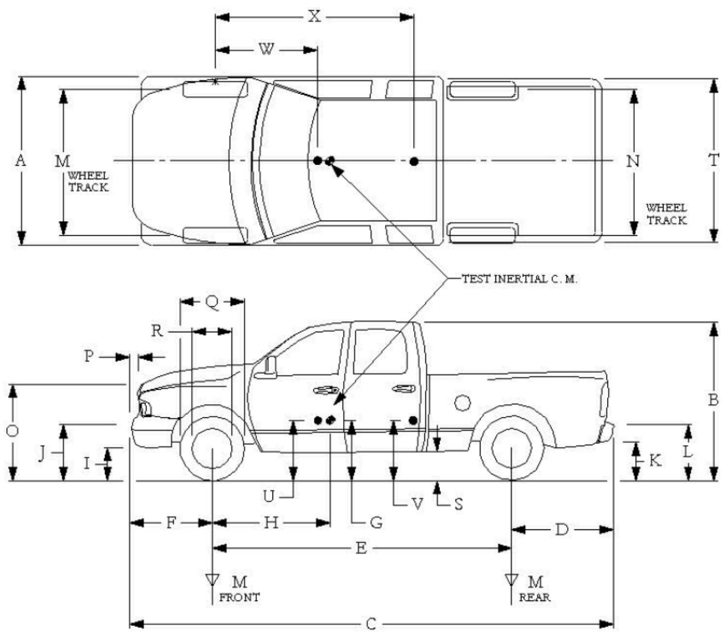
NOTES: None

Engine Type: V-8
Engine CID: 5.7 liter

Transmission Type:
☑ Auto or ☐ Manual
☐ FWD ☑ RWD ☐ 4WD

Optional Equipment:
None

Dummy Data:
Type: NONE
Mass: lb
Seat Position:



Geometry: inches

A	78.50	F	40.00	K	20.00	P	3.00	U	26.75
B	74.00	G	28.40	L	30.00	Q	30.50	V	30.25
C	227.50	H	61.54	M	68.50	R	18.00	W	61.50
D	44.00	I	11.75	N	68.00	S	13.00	X	79.00
E	140.50	J	27.00	O	46.00	T	77.00		

Wheel Center Height Front	14.75	Wheel Well Clearance (Front)	6.00	Bottom Frame Height - Front	12.50
Wheel Center Height Rear	14.75	Wheel Well Clearance (Rear)	9.25	Bottom Frame Height - Rear	22.50

RANGE LIMIT: A=78 ±2 inches; C=237 ±13 inches; E=148 ±12 inches; F=39 ±3 inches; G = > 28 inches; H = 63 ±4 inches; O=43 ±4 inches; (M+N)/2=67 ±1.5 inches

GVWR Ratings:		**Mass:** lb	Curb	Test Inertial	Gross Static
Front	3700	M_{front}	2927	2833	2833
Back	3900	M_{rear}	2020	2208	2208
Total	6700	M_{Total}	4947	5041	5041

(Allowable Range for TIM and GSM = 5000 lb ±110 lb)

Mass Distribution:
lb LF: 1409 RF: 1424 LR: 1139 RR: 1069

Table D.2. Exterior Crush Measurements for Test No. 614721-01-1.

Date:	2022-10-26	Test No.:	614721-01-1	VIN No.:	1C6RR6FT1GS405436
Year:	2016	Make:	RAM	Model:	1500

VEHICLE CRUSH MEASUREMENT SHEET[1]

<table>
<tr><th colspan="2">Complete When Applicable</th></tr>
<tr><th>End Damage</th><th>Side Damage</th></tr>
<tr><td>Undeformed end width ________
Corner shift: A1 ________
A2 ________
End shift at frame (CDC)
(check one)
< 4 inches ________
≥ 4 inches ________</td><td>Bowing: B1 _____ X1 _____
B2 _____ X2 _____
Bowing constant
$\frac{X1+X2}{2}$ = _______</td></tr>
</table>

Note: Measure C_1 to C_6 from Driver to Passenger Side in Front or Rear Impacts – Rear to Front in Side Impacts.

Specific Impact Number	Plane* of C-Measurements	Direct Damage Width** (CDC)	Max*** Crush	Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
1	ABOVE FT BUMPER	14	10	72							0
	Measurements recorded										
	☑ inches or ☐ mm										

[1]Table taken from National Accident Sampling System (NASS).

*Identify the plane at which the C-measurements are taken (e.g., at bumper, above bumper, at sill, above sill, at beltline, etc.) or label adjustments (e.g., free space).

Free space value is defined as the distance between the baseline and the original body contour taken at the individual C locations. This may include the following: bumper lead, bumper taper, side protrusion, side taper, etc. Record the value for each C-measurement and maximum crush.

**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

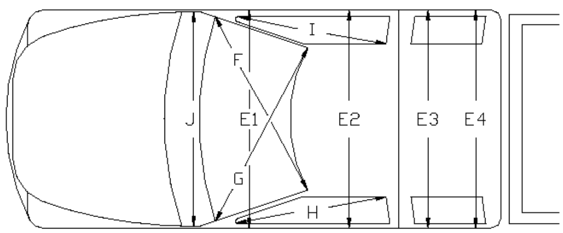
***Measure and document on the vehicle diagram the location of the maximum crush.

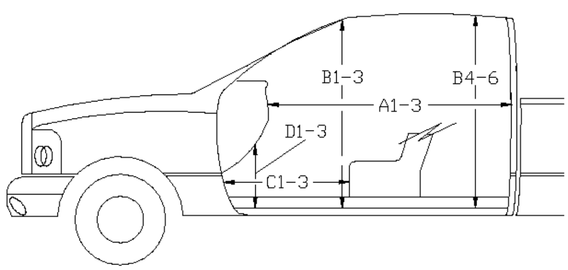
Note: Use as many lines/columns as necessary to describe each damage profile.

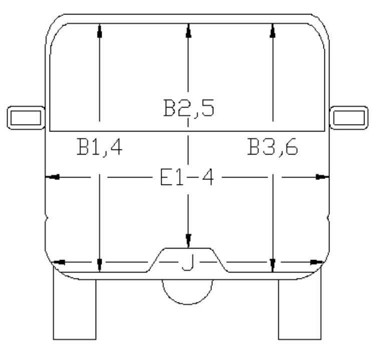
TR No. 614721-01-1&2 213 2023-08-08

Table D.3. Occupant Compartment Measurements for Test No. 614721-01-1.

Date:	2022-10-26	Test No.:	614721-01-1	VIN No.:	1C6RR6FT1GS405436
Year:	2016	Make:	RAM	Model:	1500







*Lateral area across the cab from driver's side kickpanel to passenger's side kickpanel.

OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

	Before	After (inches)	Differ.
A1	65.00	65.00	0.00
A2	63.00	63.00	0.00
A3	65.50	65.50	0.00
B1	45.00	45.00	0.00
B2	38.00	38.00	0.00
B3	45.00	45.00	0.00
B4	39.50	39.50	0.00
B5	43.00	43.00	0.00
B6	39.50	39.50	0.00
C1	26.00	26.00	0.00
C2	0.00	0.00	0.00
C3	26.00	26.00	0.00
D1	11.00	11.00	0.00
D2	0.00	0.00	0.00
D3	11.50	11.50	0.00
E1	58.50	58.50	0.00
E2	63.50	63.50	0.00
E3	63.50	63.50	0.00
E4	63.50	63.50	0.00
F	59.00	59.00	0.00
G	59.00	59.00	0.00
H	37.50	37.50	0.00
I	37.50	37.50	0.00
J*	25.00	25.00	0.00

TR No. 614721-01-1&2 214 2023-08-08

D.2. SEQUENTIAL PHOTOGRAPHS

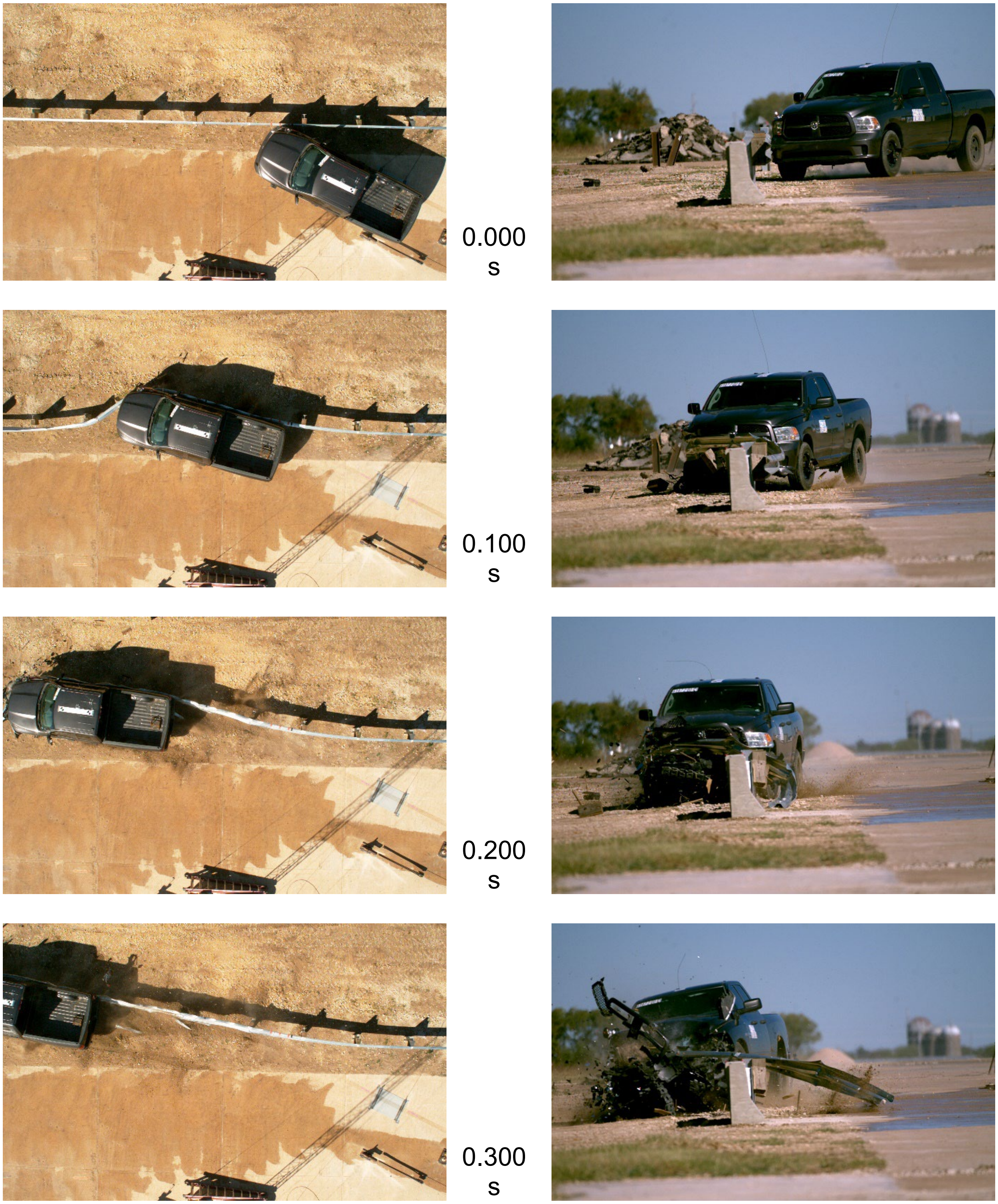


Figure D.1. Sequential Photographs for Test No. 614721-01-1 (Overhead and Frontal Views).

TR No. 614721-01-1&2
215
2023-08-08

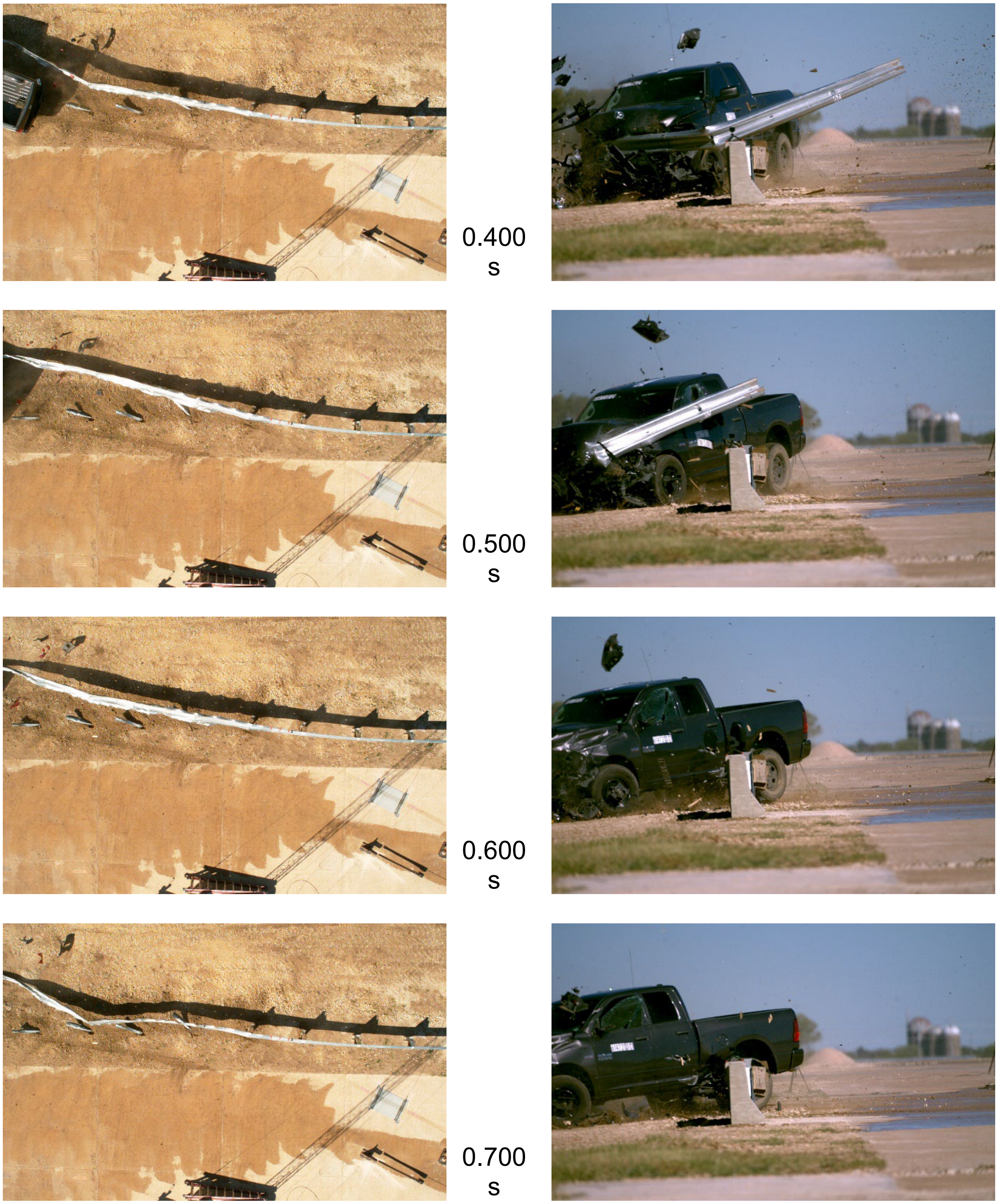
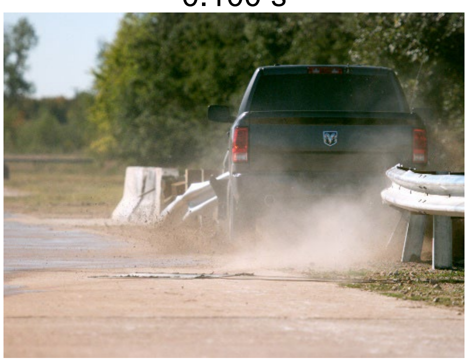


Figure D.1. Sequential Photographs for Test No. 614721-01-1 (Overhead and Frontal Views) (Continued).

0.000 s

0.100 s

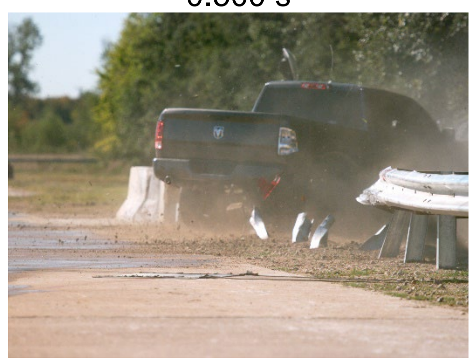


0.200 s

0.300 s

0.400 s

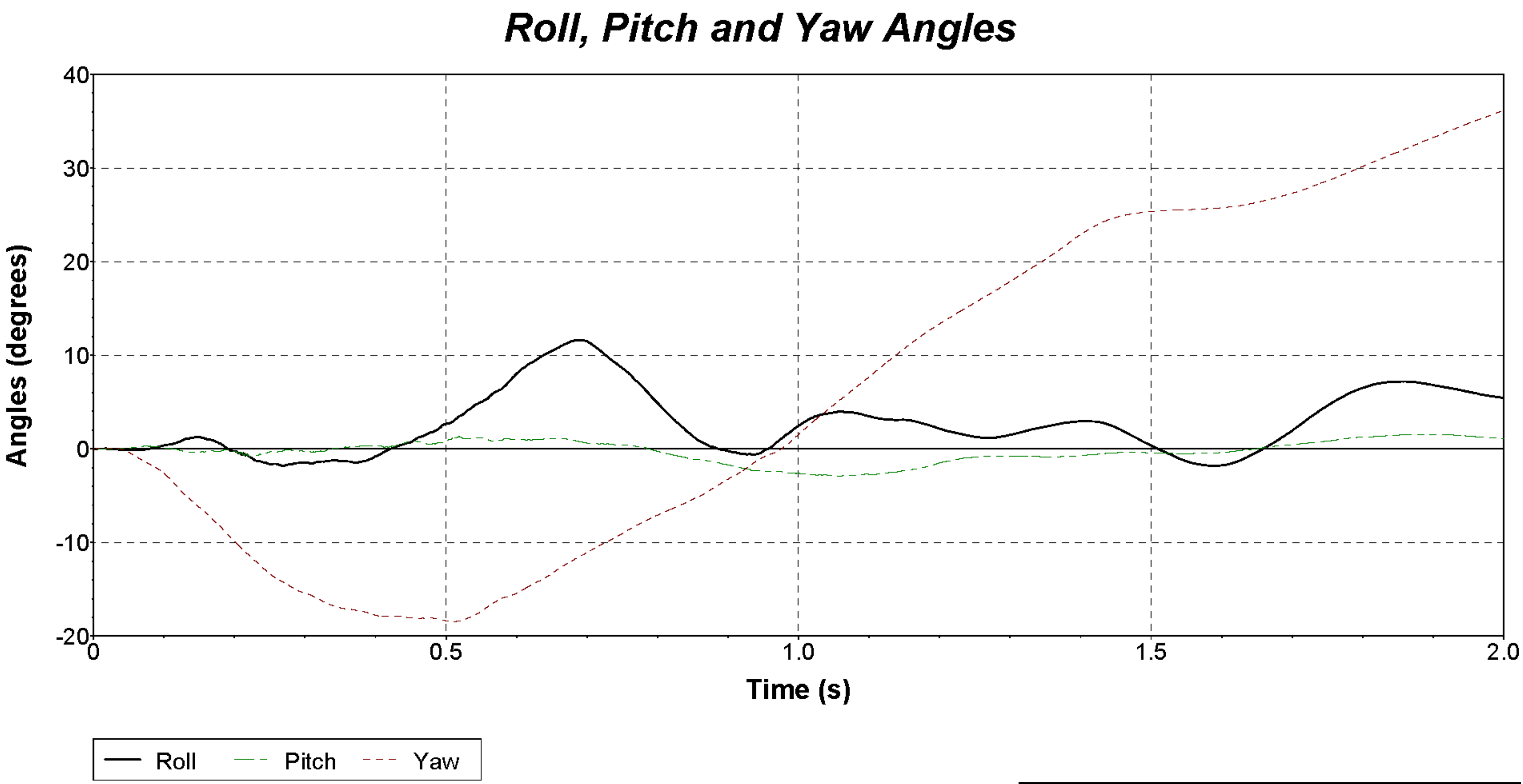
0.500 s



0.600 s

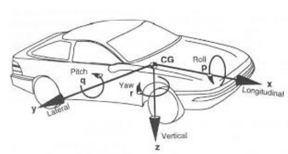
0.700 s

Figure D.2. Sequential Photographs for Test No. 614721-01-1 (Rear View).



Axes are vehicle-fixed.
Sequence for
determining orientation:

1. Yaw.
2. Pitch.
3. Roll.



Test Number: 614721-01-1
Test Standard Test Number: *MASH* Test 3-11
Test Article: Guardrail without downstream anchorage
Test Vehicle: 2016 RAM 1500
Inertial Mass: 5041 lb
Gross Mass: 5041 lb
Impact Speed: 62.1 mi/h

Figure D.3. Vehicle Angular Displacements for Test No. 614721-01-1.

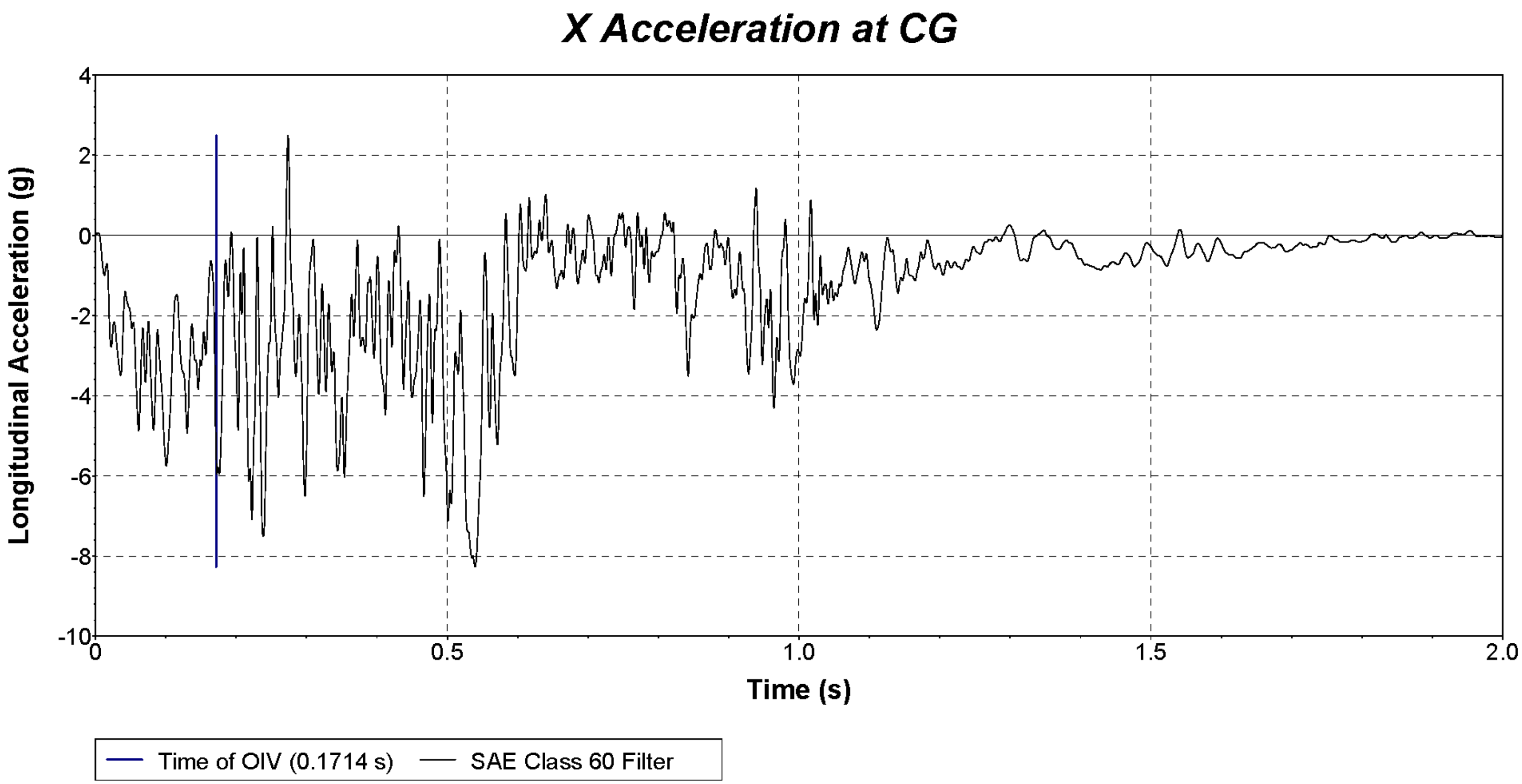


Figure D.4. Vehicle Longitudinal Accelerometer Trace for Test No. 614721-01-1 (Accelerometer Located at Center of Gravity).

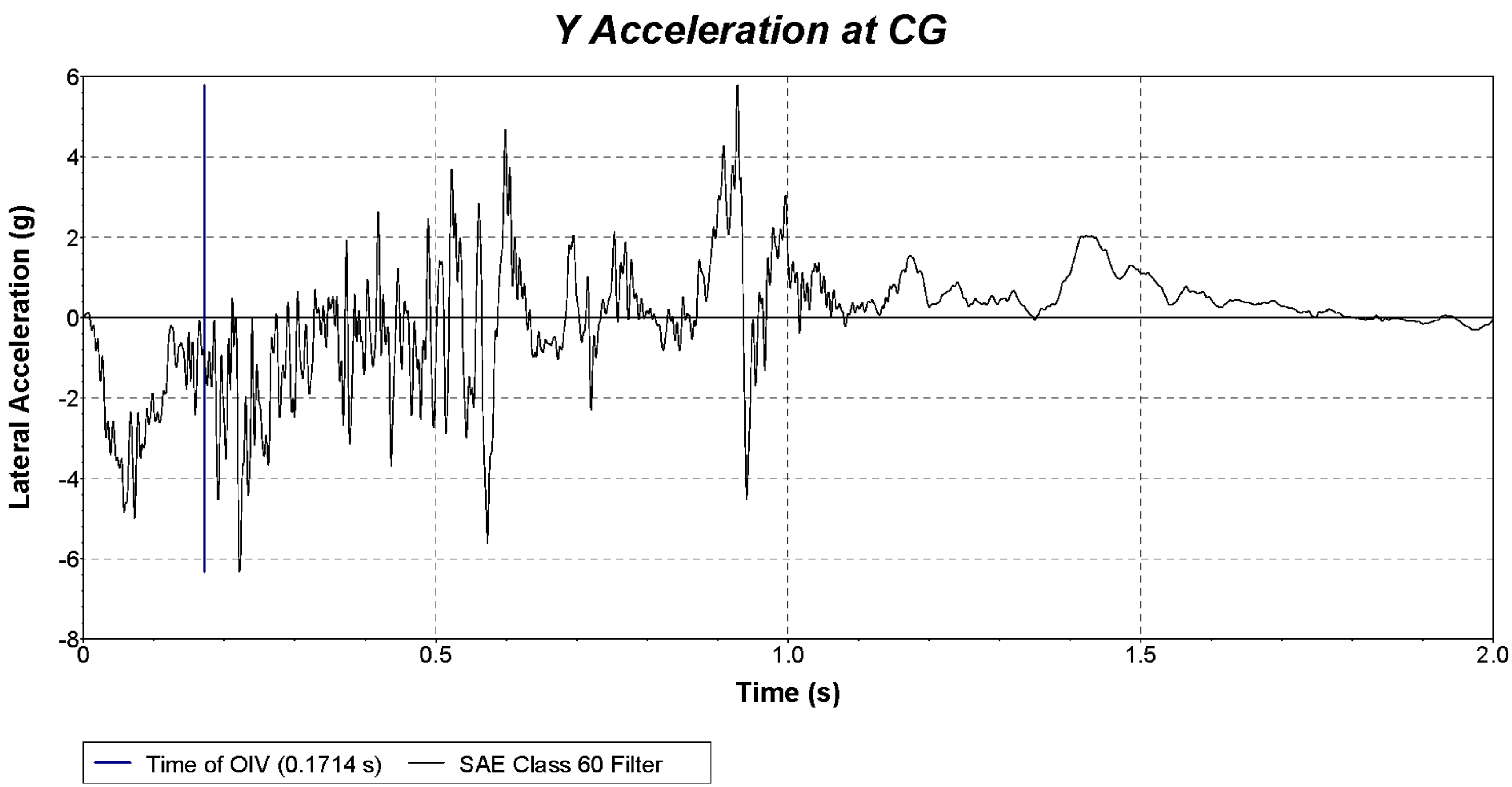


Figure D.5. Vehicle Lateral Accelerometer Trace for Test No. 614721-01-1 (Accelerometer Located at Center of Gravity).

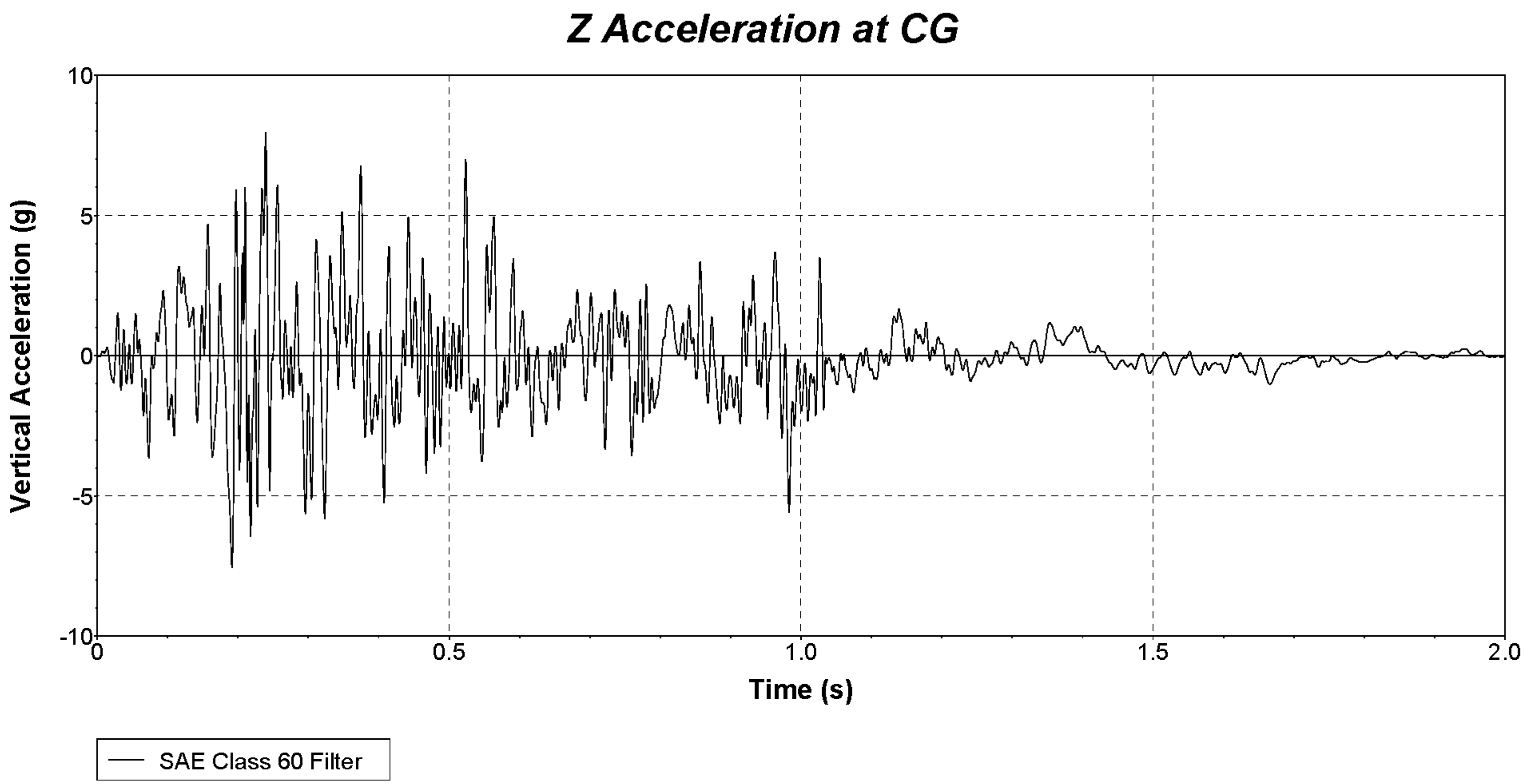


Figure D.6. Vehicle Vertical Accelerometer Trace for Test No. 614721-01-1 (Accelerometer Located at Center of Gravity).