Report No. 12-602371-00001
Report Date: June 2015

Evaluation of the Crashworthiness Alternative of Raising Wood Blockouts on Wood Post

by

Chiara Silvestri Dobrovolny, Ph.D.
Associate Research Scientist

Nathan Schulz
Student Technician I

and

Abhinav Mohanakrishnan
Student Technician I

Contract No.: T4541-BT
Project No.: 12-602371-00001

Sponsored by
Roadside Safety Research Program Pooled Fund
Study No. TPF-5(114)

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 Riverside Campus
Building 7091
3100 State Highway 47
Bryan, TX 77807

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 Washington State Department of Transportation, the Roadside Pooled Fund Program, The Texas A&M University System, or Texas A&M Transportation Institute. This report does not constitute a standard, specification, or regulation. In addition, the above listed agencies 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.

Chiara Silvestri Dobrovolny,
Associate Research Scientist

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **Evaluation of the Crashworthiness Alternative of Raising Wood Blockouts on Wood Post**		5. Report Date June 2015 6. Performing Organization Code
7. Author(s) Chiara Silvestri Dobrovolny, Nathan Schulz, and Abhinav Mohanakrishnan		8. Performing Organization Report No. 12-602371-00001
9. Performing Organization Name and Address Texas A&M Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS) 11. Contract or Grant No. T4541-BT
12. Sponsoring Agency Name and Address Washington State Department of Transportation Transportation Building, MS 47372 Olympia, Washington 98504-7372		13. Type of Report and Period Covered Test Report August 2013 – May 2015 14. Sponsoring Agency Code

15. Supplementary Notes
Research Study Title: Evaluation of the Crashworthiness Alternative of Raising Wood Blockouts on Wood Post
Name of Contacting Representative: Christopher Lindsey, Texas Department of Transportation

16. Abstract

With recent changes/clarifications about appropriate height for beam guardrail, there are more and more existing locations identified where rail height is below the recommended heights. Pavement overlays create additional locations where this occurs. Raising blockout on the post is a cost effective means to adjust the rail height, however there is not any known analysis of how this might affects rail performance. The purpose of this research is to analyze wood posts W-beam rail performance when wood blockouts are raised on the posts as a mean for adjusting rail height. The information compiled from this research will enable the Departments of Transportation to decide whether raising wood blockouts on wood posts can be chosen as a cost effective mean to adjust rail height when below recommended value, without compromising the rail system performance. The researchers made use of the pendulum testing facility to test raised wood blockouts on wood posts. Pendulum tests were performed on wood 8-inch blockout raised on wood posts embedded in soil. Force-displacement data was recorded and evaluated to understand the strength of the raised blockout on wood post system and its capability to transmit the impact forces into the soil. Recorded data from the pendulum testing was also used to help validate the FE models of full-scale impact events.

The researchers detected real-world configurations of W-beam guardrail installations with wood blockouts on wood posts. The researchers then worked with Department of State representatives to identify those configurations for which the practice of raising wood blockouts on wood posts would need some additional investigation to assess system crashworthiness according to roadside safety standards. Three cases were identified for further evaluation through FEA analyses, and they are reported below together with test level and safety standard used for crashworthiness evaluation: 1) 31-inch MGS system with 4-inchs pavement overlay in front of post and 4-inch raised blockouts on posts (*MASH*, TL- 3-11); 2) 27¾-inch rail system with 4-inch increased post embedment due to possible rail deficiency or posts settlement, and 4-inch raised blockouts on posts (*NCHRP Report 350*, TL- 3-11); and 3) 27¾-inch rail system with 4-inch pavement overlay in front of post and 4-inch raised blockouts on posts (*NCHRP Report 350*, TL- 3-11). All cases indicate that the practice of raising wood blockouts on wood posts to maintain minimum rail height requirements appear to be crashworthy and likely to pass required roadside safety evaluation criteria.

17. Key Words	18. Distribution Statement
Raised Blockouts, Wood Blockouts, Wood Posts, W-Beam Guardrail, *MASH*, Report 350, Crashworthiness, Finite Element Analysis, Pavement Overlay, Post Settlement, Minimum Height	Copyrighted. Not to be copied or reprinted without consent from Washington DOT.

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	112	

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 yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L 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)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		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	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

ACKNOWLEDGMENTS

This research project was performed under a pooled fund program between the State of Alaska Department of Transportation and Public Facilities, California Department of Transportation (Caltrans), Florida Department of Transportation, Illinois Department of Transportation, Louisiana Department of Transportation and Development, Minnesota Department of Transportation, Pennsylvania Department of Transportation, Tennessee Department of Transportation, Texas Department of Transportation, Washington State Department of Transportation, West Virginia Department of Transportation, and the Federal Highway Administration. The authors acknowledge and appreciate their guidance and assistance.

Roadside Safety Research Pooled Fund Committee
CONTACTS

Revised February 2015

ALASKA
Jeff C. Jeffers, P.E.
Statewide Traffic & Safety Engineering
Alaska Department of Transportation and Public Facilities
3132 Channel Drive
P.O. Box 112500
Juneau, AK 99811-2500
(907) 465-8962
jeff.jeffers@alaska.gov

CALIFORNIA
John Jewell, P.E.
Caltrans
Office of Materials and Infrastructure
Division of Research and Innovation
5900 Folsom Blvd
Sacramento, CA 95819
(916) 227-5824
john_jewell@dot.ca.gov

FLORIDA
Gevin J. McDaniel, P.E.
Design Standards Administrator
FDOT Roadway Design Office
Florida Department of Transportation
605 Suwannee Street
Tallahassee, FL 32399-0450
(850) 414-4284
Gevin.McDaniel@dot.state.fl.us

ILLINOIS
Timothy J. Sheehan, P.E.
Safety Design Unit Chief
Illinois Department of Transportation
2300 Dirksen Parkway, Room 323
Springfield, IL 62764
(217) 782-8608
Tim.Sheehan@illinois.gov

LOUISIANA
Chris Guidry, P.E.
Assistant Bridge Design Administrator
Bridge and Structural Design Section
Louisiana Transportation Center
P. o. Box 94245
Baton Rouge, LA 79084-9245
(225) 379-1328
Chris.Guidry@la.gov

Kurt Brauner, P.E.
Bridge Engineer Manager
(225) 379-1933
Kurt.Brauner@la.gov

MINNESOTA
Michael Elle, P.E.
Design Standards Engineer
Minnesota Department of Transportation
395 John Ireland Blvd, MS 696
St. Paul, MN 55155-1899
(651) 366-4622
michael.elle@state.mn.us

PENNSYLVANIA
Mark R. Burkhead, P.E.
Standards & Criteria Engineer
Pennsylvania Department of Transportation
Bureau of Project Delivery
400 North Street
Harrisburg, PA 17105
(717) 783-5110
mburkhead@pa.gov

TENNESSEE
Ali Hangul, P.E.
Civil Engineering Manager
(615) 741-0840
(615) 532-7745 (fax)
Ali.Hangul@tn.gov

TEXAS
Christopher Lindsey
Transportation Engineer
Design Division
Texas Department of Transportation
118 E. Riverside Dr
Austin, TX 78704
(512) 416-2750
Christopher.Lindsey@txdot.gov

WASHINGTON
John P. Donahue, P.E.
Design Policy & Strategic Analysis
Estimating Manager
Washington State
Department of Transportation
310 Maple Park Avenue SE
Olympia, WA 98504-7329
(360)705-7952
DonahJo@wsdot.wa.gov

Jeffery K. Petterson, P.E.
Roadside Safety Engineer
(360) 705-7278
PetterJ@wsdot.wa.gov

Rhonda Brooks
Research Manager
(360) 705-7945
Brookrh@wsdot.wa.gov

WEST VIRGINIA
Donna J. Hardy, P.E.
Mobility and Safety Engineer
West Virginia Department 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

FEDERAL HIGHWAY ADMINISTRATION
Richard B. (Dick) Albin, P.E.
Safety Engineer
FHWA Resource Center Safety & Design
Technical Services Team
711 South Capitol Blvd.
Olympia, WA 98504
(303) 550-8804
Dick.Albin@dot.gov

William Longstreet
Highway Engineer
FHWA Office of Safety Design
Room E71-107
1200 New Jersey Avenue, S.E.
Washington, DC 20590
(202) 366-0087
Will.Longstreet@dot.gov

TEXAS A&M TRANSPORTATION INSTITUTE
D. Lance Bullard, Jr., P.E.
Research Engineer
Roadside Safety & Physical Security Div.
Texas A&M Transportation Institute
3135 TAMU
College Station, TX 77843-3135
(979) 845-6153
L-Bullard@tamu.edu

Roger P. Bligh, Ph.D., P.E.
Research Engineer
(979) 845-4377
RBligh@tamu.edu

TABLE OF CONTENTS

Section | Page

TABLE OF CONTENTS (CONTINUED)

Section Page

LIST OF FIGURES

Page

LIST OF FIGURES (CONTINUED)

Page

LIST OF TABLES

Page

1. INTRODUCTION

1.1 PROBLEM

With recent changes/clarifications about appropriate height for beam guardrail, there are more and more existing locations identified where rail height is below the recommended heights. Pavement overlays create additional locations where this occurs. Raising blockout on the post is a cost effective means to adjust the rail height, however there isn't any known analysis of how this might affects rail performance.

The purpose of this research is to analyze wood posts W-beam rail performance when blockouts are raised on the posts as a mean for adjusting rail height. A guideline regarding the procedure of raising wood blockouts mounting height on wood posts to achieve recommended rail height for a W-beam guardrail will be suggested for use by the Departments of Transportation (DOTs). The information compiled from this research will enable the DOTs to decide whether raising blockouts on the posts can be chosen as a cost effective mean to adjust rail height when below recommended value, without compromising the rail system performance.

1.2 BACKGROUND

On May 17, 2010, Federal Highway Administration (FHWA) issued a technical memorandum to provide guidance to State DOTs and FHWA Division Offices on height of guardrail for new installations on the National Highway System (NHS) (Nicol, 2010). The technical memorandum details the minimum mounting heights of systems successfully crash tested per the *NCHRP Report 350* "Recommended Procedures for the Safety Performance Evaluation of Highway Features" and the American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware* (*MASH*) (Ross et al., 1993; AASHTO, 2009). In regard to *MASH*, the memorandum recognized performance issues with modified G4(1S) guardrail and recommended adoption of 31-inch high guardrail designs for new installations.

The FHWA Office of Safety Design and the FHWA Resource Center gives suggestions on how to adjust rail height when pavement work is needed. In the case the barrier does not need to be moved, it is a common practice to raise the blockout on the post up to three inches, as a cost effective means to adjust rail height. This requires field drilling or punching of a new hole in the guardrail post.

There is not, however, any known analysis of how raising beam guardrail blockout might affects rail performance. In fact, a moment is also applied to the system, when subjecting the blockout-post system to an impact after the blockout is raised on the post. Tensile and compressive stresses increase proportionally with bending moment. Failure in bending might occurs when the bending moment is sufficient to induce tensile stresses greater than the yield stress of the material throughout the entire cross-section. Thus, the bending moment to which the raised blockout on post is subjected might play a significant role in the performance of the overall rail system. This research aims at analyzing wood posts W-beam rail performance when wood blockouts are raised on the posts as a mean for adjusting rail height. The information compiled from this research will enable the DOTs to decide whether raising blockouts on the posts can be chosen as a cost effective mean to adjust rail height when below recommended value, without compromising the rail system performance.

Multiple states have guidelines regarding the maintenance and updating of existing guardrails that do not comply with the current recommended mounting height. Many states recommend replacing or resetting the post to adjust rail height. A few other states including VDOT and WSDOT (and USDO Forest Services and Agriculture) have documentation on adjusting rail height by raising blockouts in certain situations. The criteria of the situations include guardrail post material and slope configuration.

In April 2009, the National Crash Analysis Center (NCAC) presented a report on "Safety Performance Evaluation of G4(2W) W-Beam Guardrail with Blockouts Raised by 3"" (Opiela et al., 2009). Computer models were created to represent the guardrail system with blockouts in the standard configuration, as well as raised three inches vertically. The simulation analysis done by NCAC was undertaken using previously developed and validated finite element models of the C2500 pick-up truck and the W-beam guardrail systems. The test used *NCHRP Report 350* involving a 2000 kg pick-up truck (2000P vehicle) at a velocity of 100 km/h (62 mi/h) at an impact angle of 25 degrees (see Figure 1.1). The following simulations were then performed to evaluate the raised blockout system (Opiela et al., 2009).

- Case 1 – Standard W-beam guardrail installation G4(2W) with the blockout in a "normal" position. This was considered to be the benchmark condition for the comparison of results.
- Case 2 – Standard W-beam guardrail installation with blockout in "normal" position, but the post at a side slope break point.
- Case 3 – Similar to Case 2, but with the blockout and rail raised 3 inches and attached to the posts with a single bolt.
- Case 4 – Similar to Case 3 but with the blockout and were attached to the posts using two bolts.

Cross-sectional rail forces were monitored at four sections on the rail. The simulations showed similar resultant rail forces in all cases with maximum forces slightly higher in case 4. The monitored maximum deflection at the four locations showed that the 2:1 backslope lead to a small increase in deflection, but "comparing cases 2, 3, and 4 indicated offsetting the blockout had minimum effect on barrier deflection" (Opiela et al., 2009). The guardrail bolt forces were the last measure taken in the guardrail behavior and were similar in all cases but slightly higher in cases 3 and 4. The researchers measured the yaw angles of the vehicle as it impacted the guardrail. "This metric provides an indication of the rate at which the vehicle is redirected by the barrier"(Opiela et al., 2009). Cases 3 and 4 have a yaw angle of almost 10 degrees less than cases 1 and 2 "showing that the vehicle is redirected at a slower rate and the barrier is absorbing more of the impact" (Opiela et al., 2009). To see if the crash showed any indication of barrier overriding, the researchers measured the bumper height throughout the duration of the crash. All 4 cases had similar bumper height tracks, but cases 2, 3, and 4 were 100 to 150 mm higher. "This result indicates that the 2:1 back slope lead may be an area of concern, but the simulations indicated that the vehicle was rebounding off the barrier in all cases by the end of the crash event and not vaulting" (Opiela et al., 2009).

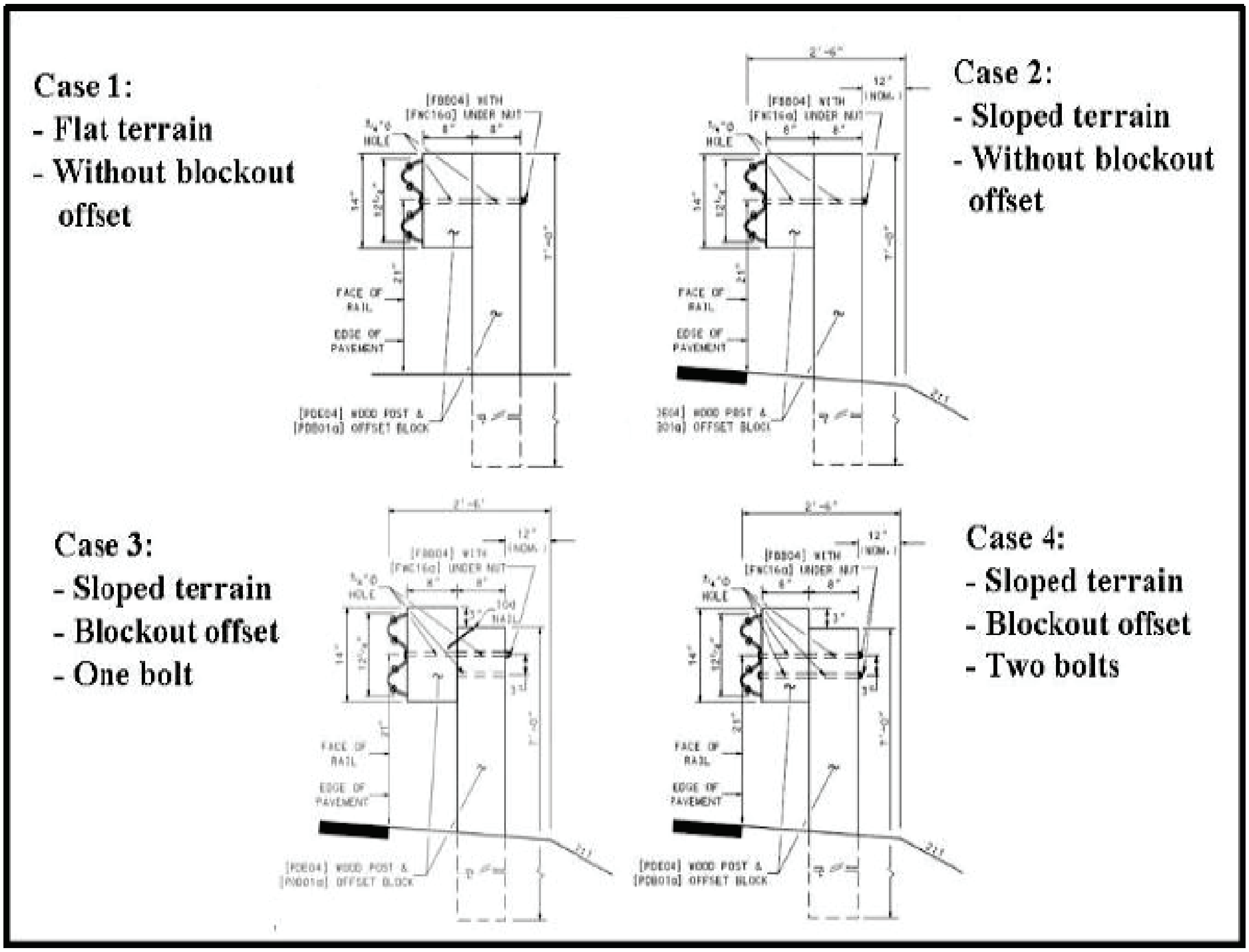


Figure 1.1. Simulated Cases (Opiela et al., 2009).

"Overall, the simulation results for the various cases are quite similar relative to forces on the guardrail system and vehicle behavior. Table 1.1 summarizes the metrics generated to evaluate occupant risk under the criteria in *NCHRP Report 350* for Test 3-11. The closeness of the data for all aspects suggests that the proposed blockout reset options are viable solutions" (Opiela et al., 2009).

The reports concludes that "From simulation data as well as visual review of the video animation, it appears that the response for the four cases were similar. This suggests that the raised blockout design is a viable option for raising the height of W-beam guardrail" (Opiela et al., 2009).

"There is no evidence from this simulation analysis that the raised blockout design would result in an increased likelihood of barrier failure or adverse effects on impacting vehicles" (Opiela et al., 2009). "Overall results suggest raising the blockouts is a viable option" (Opiela et al., 2009).

Table 1.1. Occupant Risk Results (Opiela et al., 2009).

	Case 1 Flat terrain, no offset, one bolt	**Case 2** Sloped terrain, no offset, one bolt	**Case 3** Sloped terrain, 3" offset, one bolt	**Case 4** Sloped terrain, 3"offset, two bolts
Occupant Longitudinal Ride-down Acceleration (g)	11.47	11.28	14.07	13.51
Occupant Lateral Ride-down Acceleration (g)	6.49	9.89	5.68	9.75
Occupant Longitudinal Impact Velocity (m/s)	8.08	8.67	8.60	8.12
Occupant Lateral Impact Velocity (m/s)	4.32	3.46	3.55	3.84

1.3 OBJECTIVES AND SCOPE OF RESEARCH

The purpose of this research is to analyze the rail performance when wood blockouts are raised on wood posts as a mean for adjusting rail height, and to use computer simulations to determine the articles crashworthiness according to applicable evaluation criteria. The information compiled from this research will enable the DOTs to decide whether raising blockouts on the posts can be chosen as a cost effective mean to adjust rail height when below recommended value, without compromising the rail system performance.

1.4 METHODOLOGY

The researchers followed the methodology reported below to complete this research study:

Task 1 – Literature Review

The researchers performed a literature search to collect information about existing guidelines about raising blockouts on the post as means to adjust the rail height. The literature review focused on wood-type posts.

Task 2 – Pendulum Testing

The researchers made use of the pendulum testing facility to test raised wood blockouts on wood posts. Pendulum tests were performed on wood 8-inch blockout raised on wood posts embedded in soil. Force-displacement data was recorded and evaluated to understand the strength of the raised blockout on wood post system and its capability to transmit the impact forces into the soil.

Task 3 – Finite Element Computer Analyses

The researchers performed computer finite element simulations to evaluate rail system performance with wood raised blockouts on wood posts. Specific geometrical conditions were considered and impact events were simulated with use of finite element computer program to evaluate the strength and crashworthiness of the system with raised blockouts on posts.

2. PENDULUM TESTING

Tests were conducted to determine the wooden post's dynamic performance, each test varying the direction and height of impact energy imparted by the pendulum bogie at Texas A&M Transportation Institute's (TTI) Proving Ground Pendulum Facility. The pendulum bogie, built according the specifications of the Federal Outdoor Impact Laboratory's (FOIL) pendulum, and the testing area are shown in the adjacent figure. A sweeper plate, constructed of steel angles and a steel plate, is attached to the body of the pendulum with a ground clearance of 6 inches to replicate roughly an automobile's undercarriage. The pendulum impacts the raised 8-inch wood blockout on wood posts embedded in soil at a target speed of 22 mi/h and at a height of 21-25 inches above the ground. A brief description of the procedures is presented in Appendix A.

The objective of the pendulum tests on the raised 8-inch wood blockout on wood posts embedded in soil is to evaluate the system impact response and allow understanding whether the bending moment induced by the impact is sufficient to fail the wood blockout in bending. Blockout failure mode (if any) and force-displacement data was recorded to understand the strength of the raised blockout on wood post system and its capacity to transmit the impact forces into the soil. Pendulum testing was performed September 11, 2013. Weather conditions at the time of testing were as follows: Wind speed: 3-6 mi/h; wind direction: 157-190 degrees with respect to the pendulum bogie; temperature: 84-95 ºF; relative humidity: 39-73 percent. A total of four tests were performed.

2.1 TEST P1 – PERPENDICULAR IMPACT

For Test P1, a 72-inch long modified wooden post (PDE02) with a blockout (PDB01a) was installed such that the top of the post was 28 inches above grade, and the top of the blockout was 32 inches above grade. The post was buried to a depth of 44 inches and secured with pneumatically tamped soil. A W-beam in the form of a W-beam back-up plate (RWB01a) was attached to the post and blockout with an 18-inch guardrail bolt with recessed nut and flat washer through a drilled ¾-inch diameter hole 3 inches below the top of the post (centerline at 25 inches above grade). Test P1 was designed such that the pendulum bogie impacted the face of the W-beam back-up plate at 90 degrees (normal) to what would be the direction of travel, at a target speed of 20 mi/h, and at a height of 29½ inches above grade. Detailed drawings are provided in Attachment B and photographs are shown in Figure 2.1.

The pendulum bogie impacted the raised 8-inch wood blockout mounted at 32 inches on a wood post embedded in soil at an impact speed of 19.9 mi/h. At approximately 0.038 s, the W-beam backup plate compressed and the wood post began to deflect toward the field side. By 0.143 s, the post contacted the ground, and at 0.178 s, the pendulum lost contact with the blockout and post traveling at an exit speed of 14.7 mi/h. As the pendulum bogie continued forward, the bottom of the post rotated upward and contacted the rear of the pendulum bogie.

The wood post fractured approximately 12 inches below ground level and the upper section pulled out of the ground. The blockout remained attached to the post. A ½-inch gap was measured from the lower edge of the blockout to the post, as shown in Figure 2.2.

Longitudinal occupant impact velocity was 8.5 ft/s, and longitudinal ridedown acceleration was 0.7 G. The maximum longitudinal 50-msec average acceleration was -3.7 G. Maximum 10-ms average force was 15.8 kips, and maximum kinetic energy was 12.04 ft-kips. Maximum change in velocity was 7.6 ft/s. A summary of results is provided in Table C1, and accelerometer graphs are shown in Attachment D, Figures D1 and D2.

2.2 TEST P2 – PERPENDICULAR IMPACT

Test P2 was a repeat of Test P1, with the same test installation setup and same conditions. The pendulum bogie impacted the raised 8-inch wood blockout mounted at 32 inches on a wood post embedded in soil at an impact speed of 20.0 mi/h. At approximately 0.042 s, the W-beam backup plate compressed and the wood post began to deflect toward the field side. By 0.133 s, the post contacted the ground, and at 0.184 s, the pendulum lost contact with the blockout and post traveling at an exit speed of 16.9 mi/h. As the pendulum bogie continued forward, the bottom of the post rotated upward and contacted the rear of the pendulum bogie.

The wood post fractured approximately 7 inches below ground level and the upper section pulled out of the ground. The blockout remained attached to the post and rotated slightly on the post, as shown in Figure 2.3.

Longitudinal occupant impact velocity was 6.9 ft/s, and longitudinal ridedown acceleration was 0.9 G. The maximum longitudinal 50-msec average acceleration was -3.7 G. Maximum 10-ms average force was 11.0 kips, and maximum kinetic energy was 8.26 ft-kips. Maximum change in velocity was 4.5 ft/s. A summary of results is provided in Table C2, and accelerometer graphs are shown in Attachment D, Figures D3 and D4.

Figure 2.1. Test Setup for Tests P1 and P2.

Figure 2.2. Post and Blockout after Test P1.

Figure 2.3. Post and Blockout after Test P2.

2.3 TEST P3 – LONGITUDINAL PULL

Test P3 was a pull/jerk test in the longitudinal direction (in the direction of traffic) wherein the test article was yanked by the pendulum bogie at a height of 25 inches above grade. Similar to Test P1, a 72-inch long modified wooden post (PDE02) with a blockout (PDB01a) was installed such that the top of the post was 28 inches above grade, and the top of the blockout was 32 inches above grade. The post was buried to a depth of 44 inches and secured with pneumatically tamped soil.

An 8 ft-6 inch long standard 12 gauge W-beam guardrail was attached to the wooden post and blockout with an 18-inch guardrail bolt with recessed nut and flat washer through a drilled ¾-inch diameter hole 3 inches below the top of the post (centerline at 25 inches above grade). Near the test post, the W-beam featured eight ¾-inch diameter holes through which the pendulum cable jerk bracket was attached with ⅝-inch × 2-inch bolts and recessed nuts.

The far end of the W-beam guardrail was supported by a W6×9 anchor post installed in a 6-inch × 8-inch × 6-ft deep steel tubular sleeve embedded in tamped soil. Two 3×3×½-inch angle ground struts connected (welded) the post to a steel baseplate, which was bolted to a reinforced concrete foundation. The guardrail's bolting slot on this end was cut such that it extended to the end of the rail forming a horizontal elongated "U". A standard 1¼-inch guardrail bolt and recessed nut were installed to simply support this end of the Guardrail.

Test P3 was designed such that the pendulum bogie jerked the guardrail and wooden post in a longitudinal direction and at a height of 25 inches above grade. Detailed drawings are provided in Attachment B, and photographs of the completed installation area shown Figure 2.4(a).

The pendulum bogie pulled the raised 8-inch wood blockout mounted at 31 inches on a wood post embedded in soil at a speed of 14.8 mi/h. At approximately 0.033 s, the wood post began to split and at 0.041 s, the guardrail separated from the post. The wood blockout and rail separated from the post at 0.067 s, and by 0.123 s, the wood blockout and rail contacted the ground.
The wood post split longitudinally. The blockout remained attached to the rail, as shown in Figure 2.5.

Longitudinal occupant impact velocity was 4.6 ft/s, and longitudinal ridedown acceleration was 0.4 G. The maximum longitudinal 50-msec average acceleration was -1.4 G. Maximum 10-ms average force was 8.9 kips, and maximum kinetic energy was 3.71 ft-kips. A summary of results is provided in Table C3, and accelerometer graphs are shown in Attachment D, Figures D5 and D6.

2.4 TEST P4 – LONGITUDINAL PULL

Test P4 was a pull/jerk test in the longitudinal direction (in the direction of traffic) similar to Test P3 except that the test article was yanked by the pendulum bogie at a height of 21 inches above grade (vs. 25 inches). Similar to the previous tests, a 72-inch long modified wooden post (PDE02) with a blockout (PDB01a) was installed such that the top of the post was 28 inches above grade. The post was buried to a depth of 44 inches and secured with pneumatically tamped soil. However in Test P4, the top of the blockout was also 28 inches above grade and flush with the top of the post, and the guardrail and blockout were bolted to the post with an 18-inch guardrail bolt with recessed nut and flat washer through a drilled ¾-inch diameter hole 7 inches below the top of the post (centerline at 21 inches above grade). Anchor post installation was similar to Test P3 except that the guardrail bolt was 4 inches lower to provide for a level guardrail. Detailed drawings are provided in Attachment B, and photographs are shown in Figure 2.2(b).

The pendulum bogie pulled the standard 8-inch wood blockout mounted at 27 inches on a wood post embedded in soil at a speed of 15.4 mi/h. At approximately 0.033 s, the wood post began to split where the bolt connects the guardrail, and at 0.054 s, the post split at a second location to the side of the first split. The wood blockout and bolt pulled away from the post at 0.069 , and then began to rotate toward the ground at 0.117 s. At 0.314 s, the blockout contacted the ground.

The wood post split longitudinally. The bolt pulled out of the rail, but remained attached to the blockout, as shown in Figure 2.6.

Longitudinal occupant impact velocity was 3.9 ft/s, and longitudinal ridedown acceleration was 0.4 G. The maximum longitudinal 50-msec average acceleration was -1.8 G. Maximum 10-ms average force was 8.6 kips, and maximum kinetic energy was 3.54 ft-kips. A summary of results is provided in Table C4, and accelerometer graphs are shown in Attachment D, Figures D7 and D8.

(a) Test P3

(b) Test P4

Figure 2.4. Test Setup for Longitudinal Pull Tests.

Figure 2.5. Post and Blockout after Test P3.

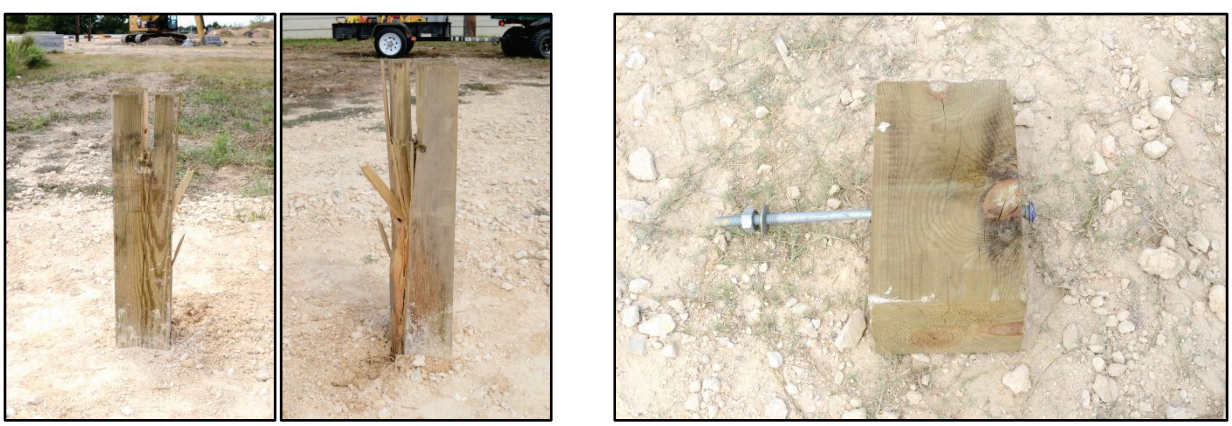


Figure 2.6. Post and Blockout after Test P4.

3. CASE INVESTIGATION

FHWA recommends a minimum height of 29 inches for newly installed W-beam guardrail systems, or where the existing W-beam system is to be removed and re-set. When following the practice of raising blockouts on posts, then a minimum rail height of 27¾ inches is acceptable.

The researchers detected real-world configurations of W-beam guardrail installations with wood blockouts on wood posts. The researchers then worked with DOT representatives to identify those configurations for which the practice of raising wood blockouts on wood posts would need some additional investigation to assess system crashworthiness according to roadside safety standards. Three cases were identified for further evaluation through finite element analyses (FEA), and they are reported below together with test level and safety standard used for crashworthiness evaluation:

1) 31-inch MGS system with 4-inch pavement overlay in front of post and 4-inch raised blockouts on posts (*MASH* criteria, TL- 3-11);
2) 27¾-inch rail system with 4-inch increased post embedment due to possible rail deficiency or posts settlement, and 4-inch raised blockouts on posts (*NCHRP Report 350* criteria, TL- 3-11);
3) 27¾-inch rail system with 4 inches pavement overlay in front of post and 4-inch raised blockouts on posts (*NCHRP Report 350* criteria, TL- 3-11).

3.1 CASE #1. PAVEMENT OVERLAY WITHOUT SOIL BACKFILL – ON AN MGS SYSTEM

Researchers considered the case of an MGS system initially installed as a 31 inches rail height with post embedment depth of 40 inches. As consequence of a pavement overlay, the height of the W-beam rail with respect to level ground has decreased to a value less than 31 inches. Post embedment has remained the same, since soil backfill was not considered given the fact that it does not seem to be a common practice for DOTs. With a 4 inches pavement overlay, for example, the height of the top of the W-beam would become 27 inches from the top of the newly added pavement overlay. The MGS system rail height would now need to be increased to comply with FHWA requirements. For this specific case, the researchers and the DOT personnel involved in this research have agreed in increasing the rail height back to the original value, which was 31 inches. This case is illustrated in Figure 3.1.

For this specific case, 72-inch long wood posts and 12-inch wood blockouts were considered for computer modeling and evaluation according to Test Level 3 of *MASH* standards.

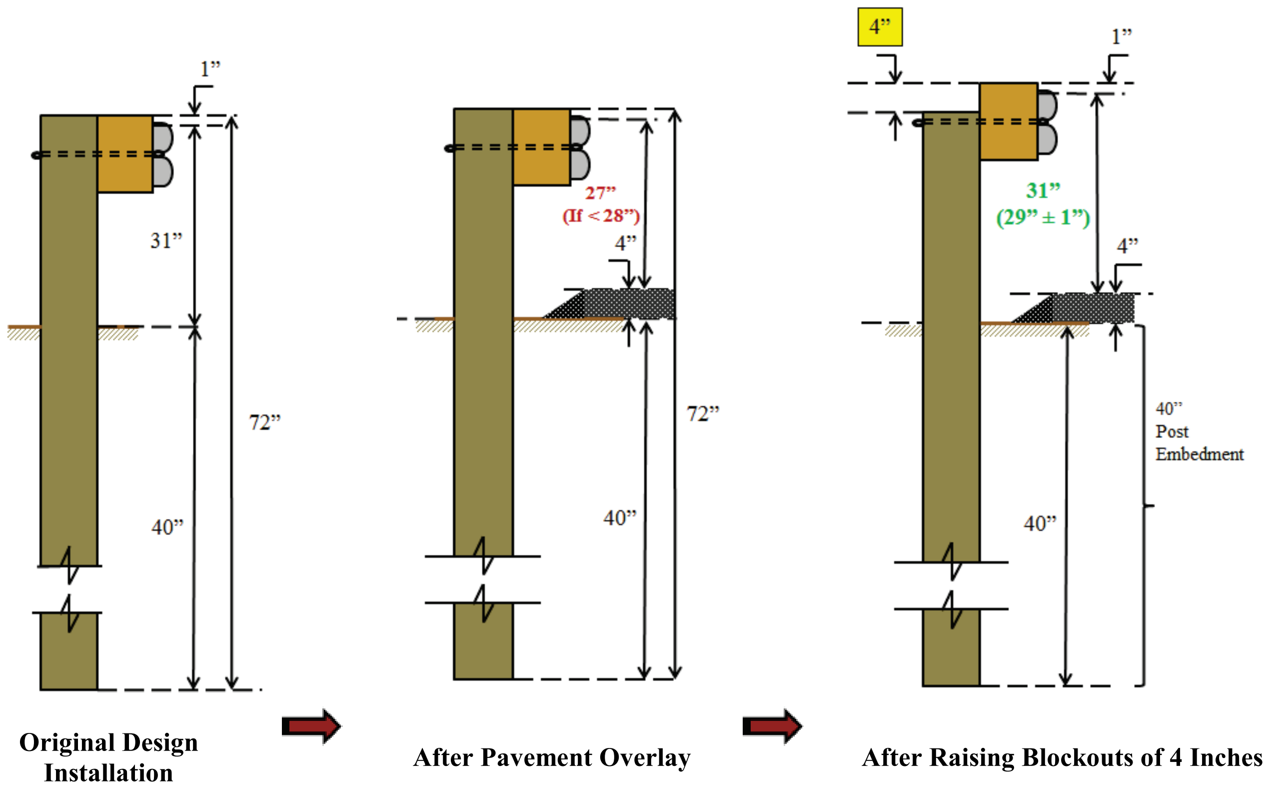


Figure 3.1. Case #1. Pavement Overlay without Soil Backfill – on an MGS System (Not to Scale).

3.2 CASE #2. DEFICIENT RAIL – ON A NOT MGS SYSTEM

The researchers refer to a “deficient rail” as a W-beam guardrail system whose rail height is less than 26½ inches from ground level.

The system was initially installed as a 27¾ inches rail height with post embedment depth of 43¾ inches. Various causes might have brought the post to settle in the ground (for example, soil material might have settled around the post with time). With post settlement, the total post embedment has increased, lowering the height of the W-beam rail with respect to level ground. When the rail height reaches a value less than 26½ inches from the ground, the rail system is considered deficient and the rail needs to be raised to a minimum value of 27¾ inches to comply with FHWA requirements. This case is illustrated in Figure 3.2.

For this specific case, 72-inch long wood posts and 8-inch wood blockouts were considered for computer modeling and evaluation according to Test Level 3 of *NCHRP Report 350* standards.

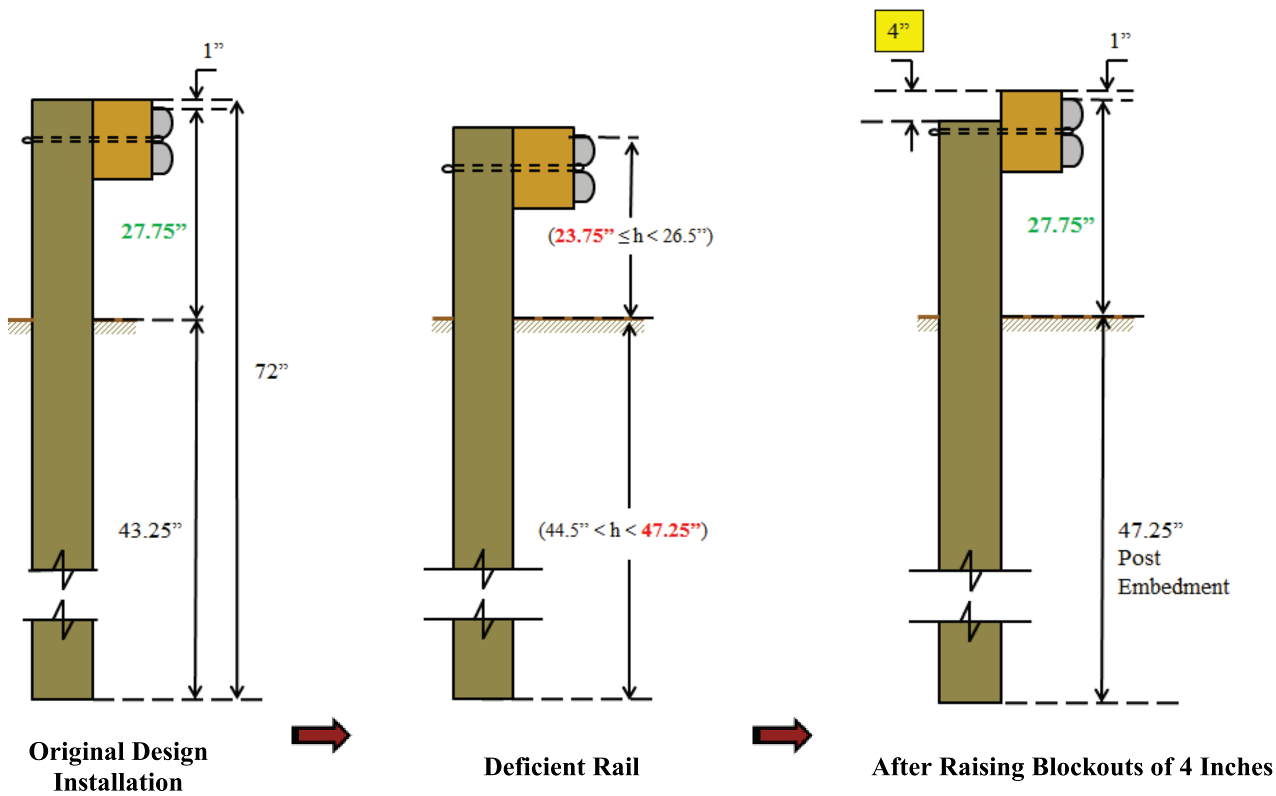


Figure 3.2. Case #2. Deficient Rail – for a Not MGS System (Not to Scale).

3.3 CASE #3. PAVEMENT OVERLAY WITHOUT SOIL BACKFILL – ON A NOT MGS SYSTEM

Researchers considered the case of a system initially installed as 27¾ inches rail height with post embedment depth of 43¾ inches. As consequence of a pavement overlay, the height of the W-beam rail with respect to level ground has decreased to a value less than the original one. Post embedment has remained the same, since soil backfill was not considered given the fact that it does not seem to be a common practice for DOTs. With a 4-inch pavement overlay, for example, the height of the top of the W-beam would become 23¾ inches from the top of the newly added pavement overlay. The height of the rail system would now need to be raised to a minimum value of 27¾ inches to comply with FHWA requirements. This case is illustrated in Figure 3.3.

For this specific case, 72-inch long wood posts and 8-inch wood blockouts were considered for computer modeling and evaluation according to Test Level 3 of *NCHRP Report 350* standards.

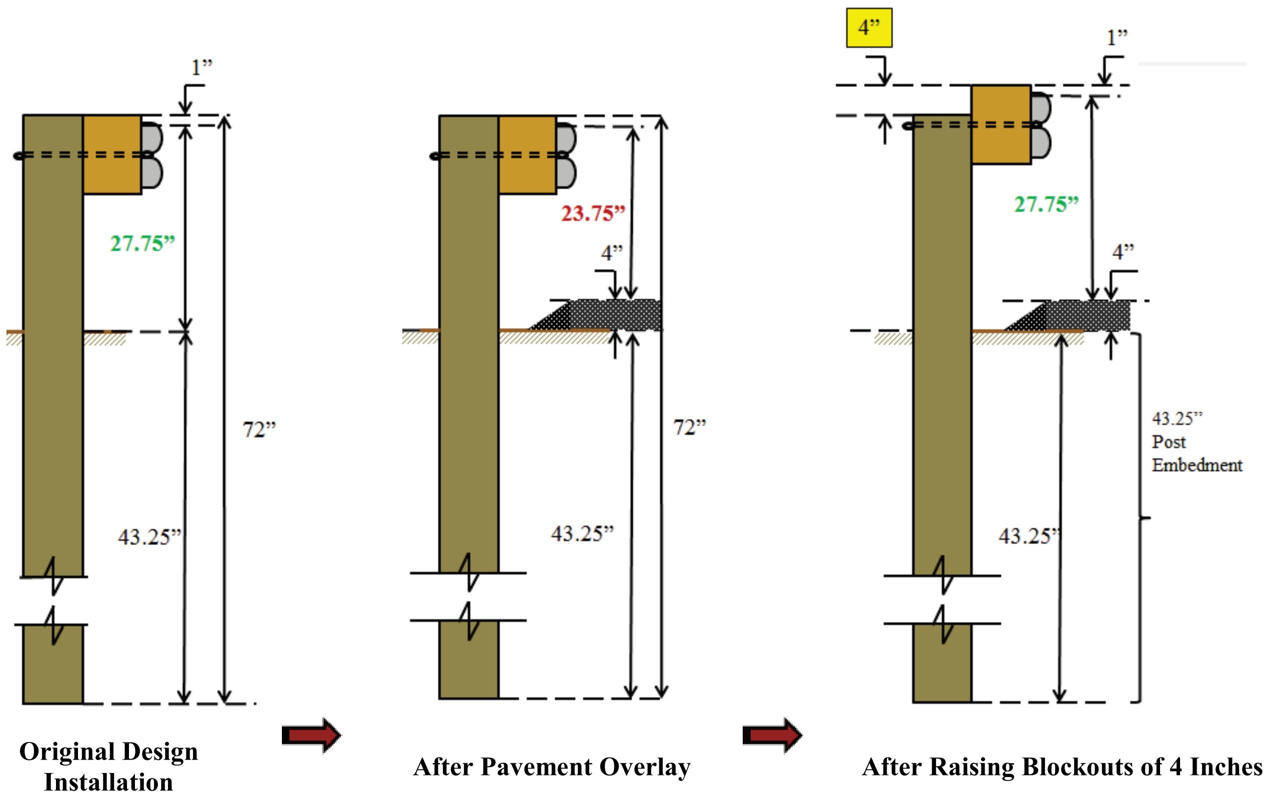


Figure 3.3. Case #3. Pavement Overlay Without Soil Backfill – on a Not MGS System (Not to Scale).

4. FINITE ELEMENT MODELING

4.1 INTRODUCTION

Recent advances in computer hardware and finite element methodologies have given researchers in the roadside safety and physical security communities the ability to investigate complex dynamic problems involving vehicular impacts into barrier systems. FEA have been used extensively to evaluate both vehicle components and crashworthiness of safety barriers and hardware.

The FEA discussed herein were performed using the LS-DYNA finite element code. LS-DYNA is a general purpose, explicit finite element code (Hallquist, 2009). LS-DYNA is widely used to solve nonlinear, dynamic response of three-dimensional problems and is capable of capturing complex interactions and dynamic load-time history responses that occur when a vehicle impacts a barrier system.

4.2 FINITE ELEMENT COMPONENT MODEL EVALUATION OF WOOD POST UNDER PENDULUM IMPACT TESTING

The first step to validate the computer model of the post and raised blockout system was to replicate with computer simulations the behavior of the above system observed during the component pendulum testing when impacting at 90-degree orientation. Researchers modeled the component system as it was for Test No. 602371-P1 (Figure 4.1). The behavior of the post in the soil was modeled using a particular type of card. This card was used to model the erosion of the wood post during impact. A MAT_ADD_EROSION_TITLE was used to cause erosion for the wood post during the finite element simulation.

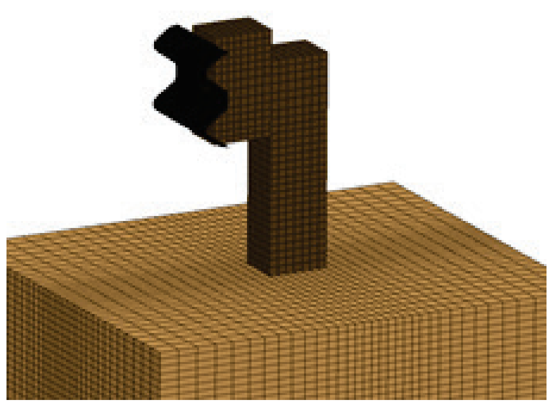
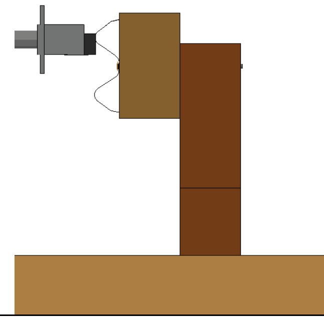
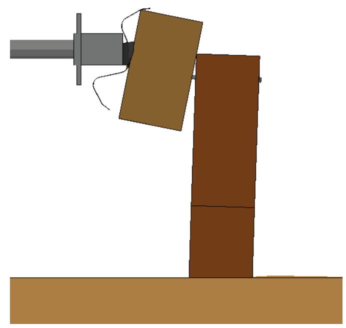
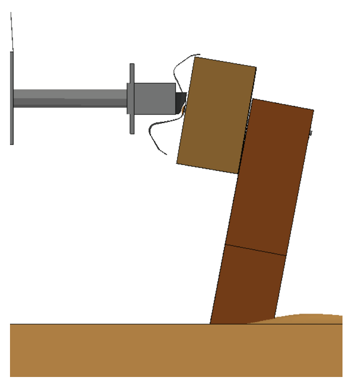
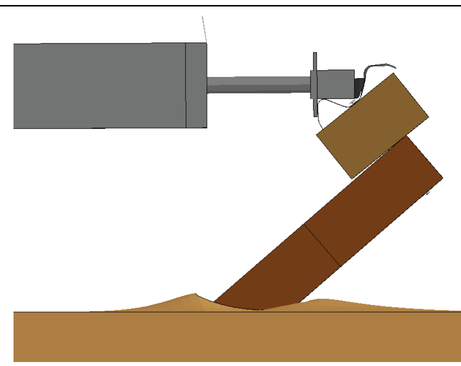


Figure 4.1. Finite Element Model of Wood Post with Wood Blockout.

Frame comparison between the component pendulum test and the FEA simulation are reported in Table 4.1. The computer model simulation replicated the relative rotation of the blockout with respect to the post and the general behavior if the component system under the pendulum loading at 90-degree orientation.

Table 4.1. Frame Comparison of Component Test and Computer Simulation – Perpendicular View (90-degree Impact).

Time After Impact (sec)	Test No. 602371-P1	FEA
0.000		
0.020		
0.045		
0.125		

Accelerometers attached to the pendulum for Test 602371-P1and P2 pendulum testing recorded x-acceleration of the pendulum. X-acceleration results from the finite element simulation were also recorded. Researchers proceeded to organize data and calculate force and kinetic energy of the pendulum for the dynamic pendulum test and computer simulation. Figure 4.2 shows the energy curve comparison between the testing and the computer simulation.

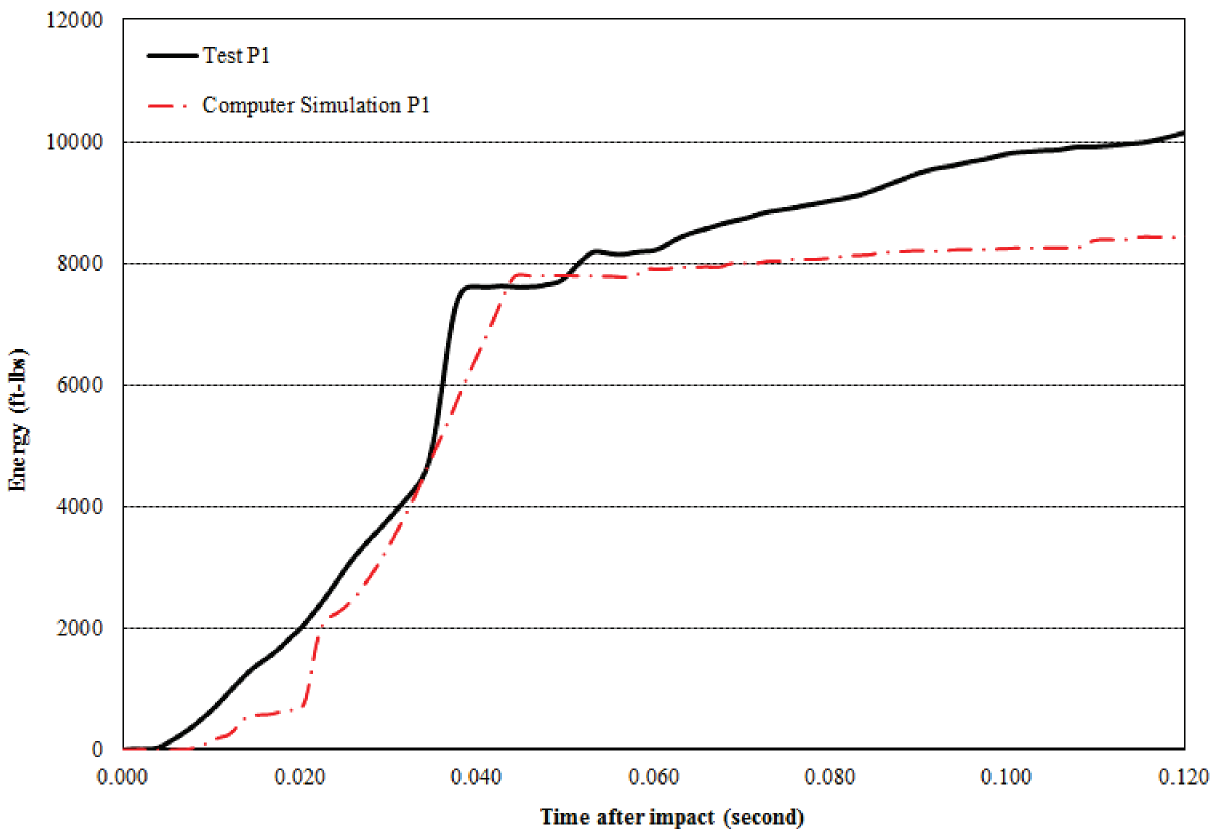


Figure 4.2. Energy Curve Comparison for Full-Scale Component Test and Computer Simulation (90-degree Impact).

Post failure was validated by comparing length of broken posts for dynamic pendulum testing and computer simulation. Film analysis was used to determine the length of the broken post for pendulum test P1. Figure 4.3 shows the length of the wood post after failure for the impact side of the post (D_1) and the back side of the post (D_2). The length of wood post after failure for finite element analysis is shown in Figure 4.4 by measuring the distance from end to end (D).

For Test P1 the length of the wood post on impact side was determined to be 42 inches and the length on the back side to be 36¾ inches. The measured length from P1 computer simulation was 36.7 inches. Results from computer simulations are very similar to actual results of failure from the dynamic pendulum tests in terms of length of post after failure.

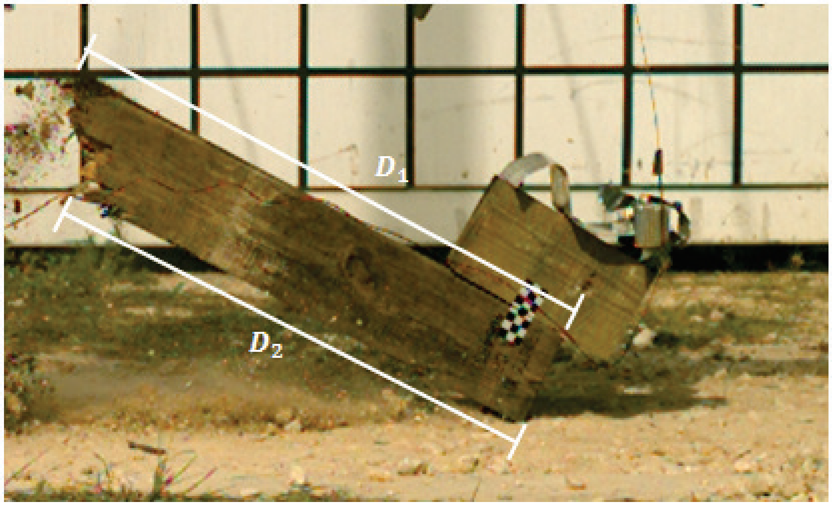


Figure 4.3. Illustrated Distances for Length of Post After Failure (Test No. 602371-P1).

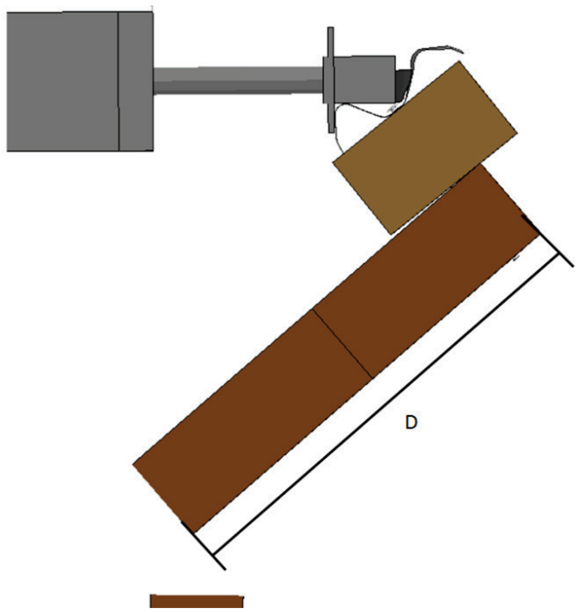


Figure 4.4. Illustrated Distances for Length of Post After Failure (Test P1 Computer Simulation).

4.3 FINITE ELEMENT FULL-SCALE MODEL VALIDATION OF MGS SYSTEM WITH WOOD POSTS

4.3.1.1 Computer Model Description

A finite element model of the MGS System with wood posts that was previously successfully designed and tested according to *MASH* Test 3-11 was developed. Test MGSSYP-1 was performed at the Midwest Roadside Safety Facility (MwRSF) in 2011 with the objective to crash test and evaluate the MGS with rectangular Southern Yellow Pine (SYP) posts to *MASH* (Gutierrez et al., 2013). Details of the MGS system with wood posts for test MGSSYP-1 are included in Figure 4.5.

Figure 4.6 shows details of the finite element (FE) model that was built to perform computer simulations. The FE test installation consisted of 150 ft of standards 12-gauge W-beam supported by wood posts. The system was built with twenty-five posts spaced at 75 inches on center. The posts were 6-inch × 8-inch × 72-inch long posts with wood properties and a soil embedment depth of 39 inches. Failure properties were given to the posts to allow elements to erode once reached a predefined principal stress value. A 6-inch × 12-inch × 14 ¼-inch spacer blockout was used to block the rail away from the front face of each post. LS-DYNA soil material model *MAT_JOINTED_ROCK was used to simulate soil properties for soil-post interaction during computer simulations. Standard 12 ft-6 inch long 12-gauge W-beam rails were modeled. The W-beam top rail height was 31 inches with a 24⅞-inch center mounting height. The rail splices were placed at midspan locations, and were configured with the upstream segment in front to minimize vehicle snag at the splice during the impact event simulation.

Researchers used the NCAC finite element 2270P pickup truck model to complete their simulations (NCAC, 2005). Validation of the FE model of the test article was needed in order to verify realistic response of the MGS system to the impact of the vehicle.

4.3.1.2 Barrier Performance

Figure 4.7 contains images of the barrier before impact and at final configuration. Figure 4.7(a) and 4.7(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 4.7(b) and 4.7(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. To replicate the impacting conditions of test MGSSYP-1, the barrier was impacted at 12 ft-6 inches upstream of a post, with initial and speed and angle of 62.2 mi/h and 24.9 degrees, respectively.

The vehicle was contained and redirected during the impact event. Failure properties were applied to the posts of the guardrail system. A total of three posts were broken as a consequence of the impact with the 2270P vehicle. During the full-scale crash test, a total of four posts were broken during impact. The dynamic and permanent deflections of the guardrail system in the FE model were 38.7 inches and 28.9 inches, respectively, which is a good agreement with 40.0 inches and 30.25 inches recorded during the full-scale test.

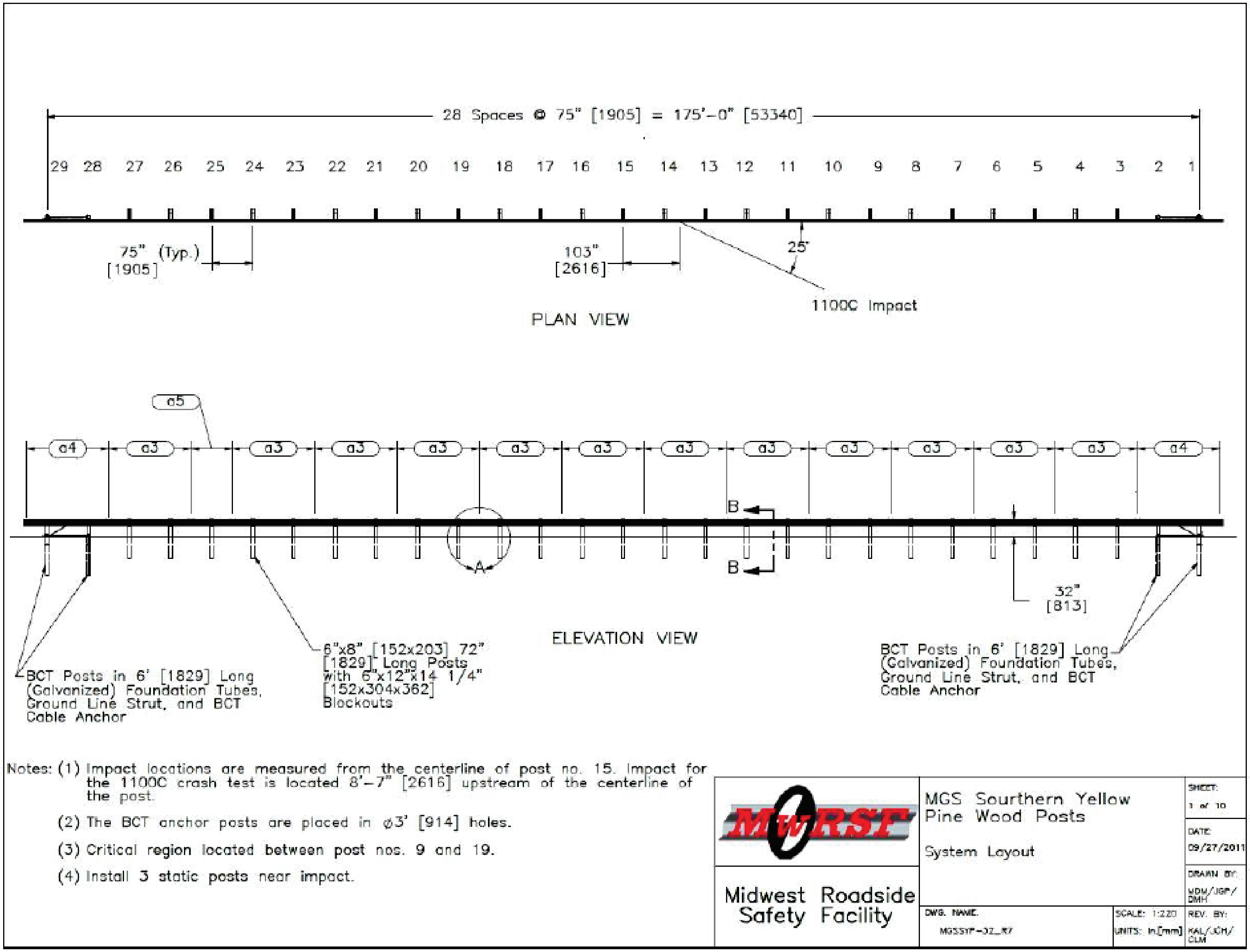


Figure 4.5. Details of the Test Article Installation for Test MGSSYP-1 (Gutierrez et al., 2013).

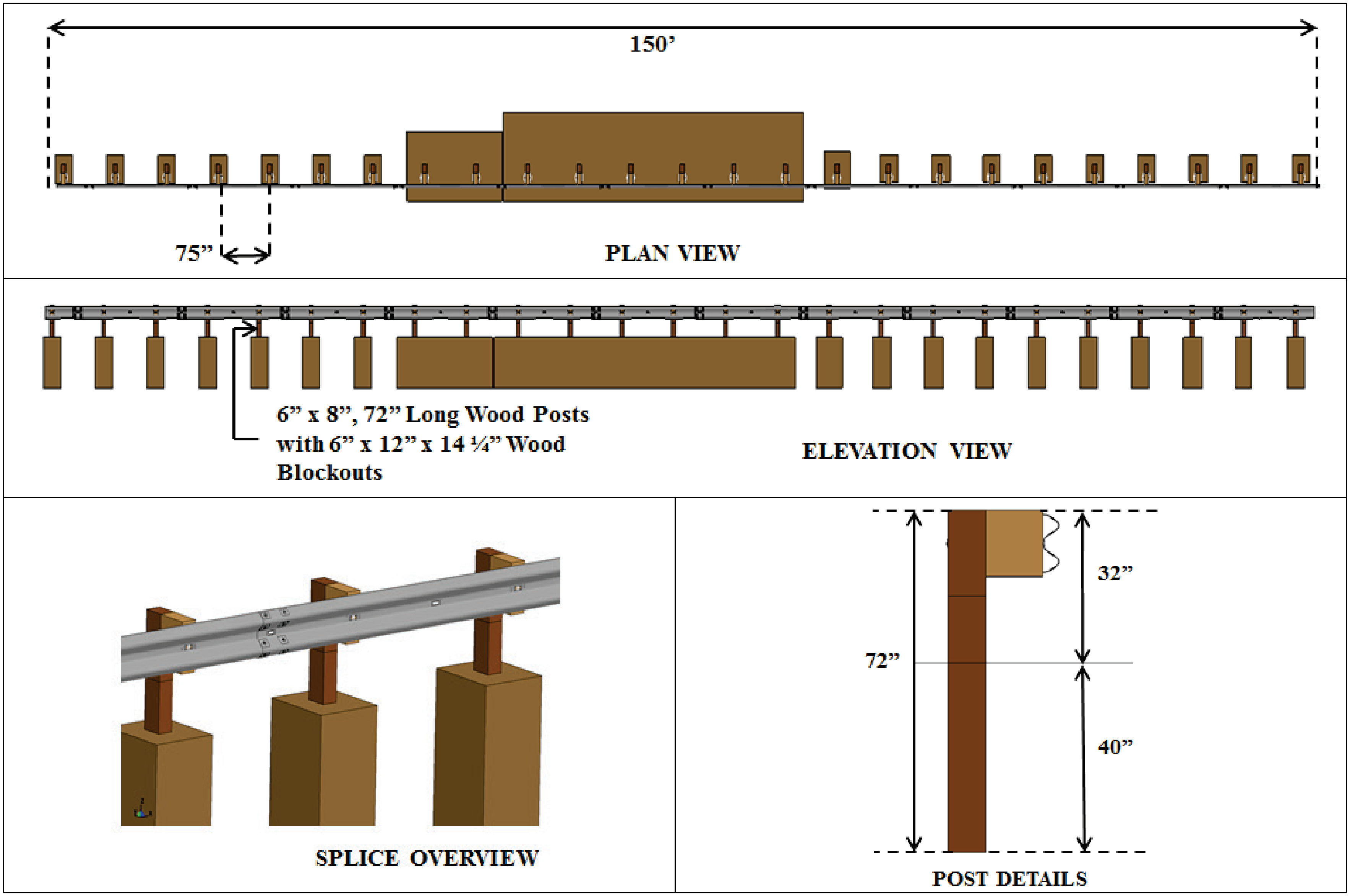
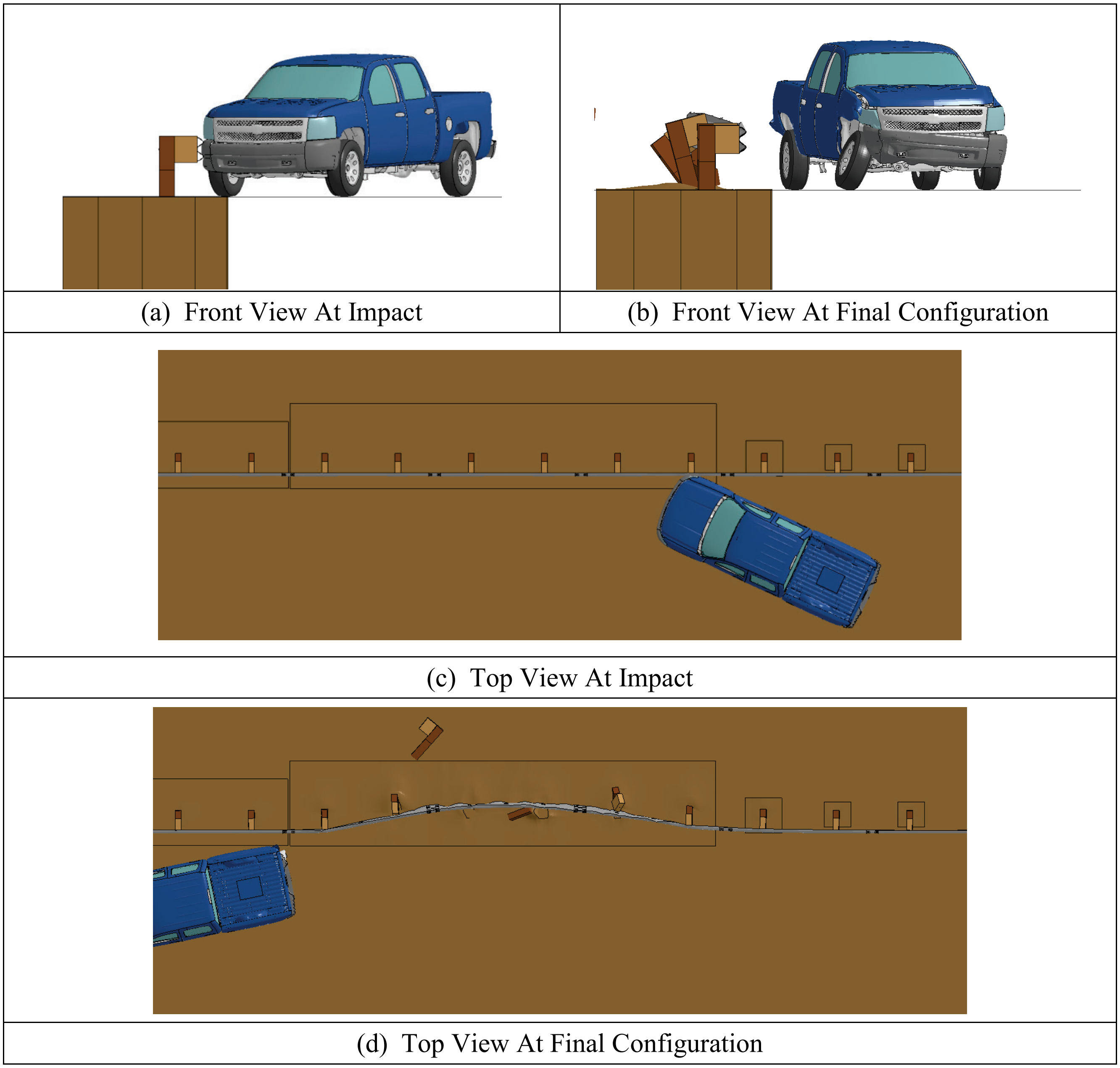


Figure 4.6. Details of the MGS Test Article Installation for Finite Element Computer Model Validation.



(a) Front View At Impact

(b) Front View At Final Configuration

(c) Top View At Impact

(d) Top View At Final Configuration

Figure 4.7. Initial and Deflected Shape of Barrier (MGS with Wood Posts Validation).

4.3.1.3 Energy Values

The kinetic energy applied to the barrier by the impacting vehicle is dissipated by converting it into other forms of energy. Internal energy constitutes any energy stored in a component through plastic and elastic deformation (strains) or a change in temperature. Sliding energy represents any energy dissipated due to friction between components. Hourglass energy is an unreal numerical energy dissipated by LS-DYNA. Hourglass energy should be minimized as much as possible (less than 5 percent in any significant part and less than 10 percent in other parts preferred).

Since this is a closed system and energy is conserved, the sum of the kinetic energy, hourglass energy, sliding energy, and internal energy at any time during the simulation should equate to the initial kinetic energy of the vehicle. As shown in Figure 4.8, approximately 35 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). Approximately four percent of the initial kinetic energy is converted into hourglass energy. Approximately 21 percent of the initial kinetic energy is converted into sliding interface energy. Twenty nine percent of the initial kinetic energy has yet to be dissipated by the system at the time of final impact configuration, mainly due to the remaining velocity of the vehicle.

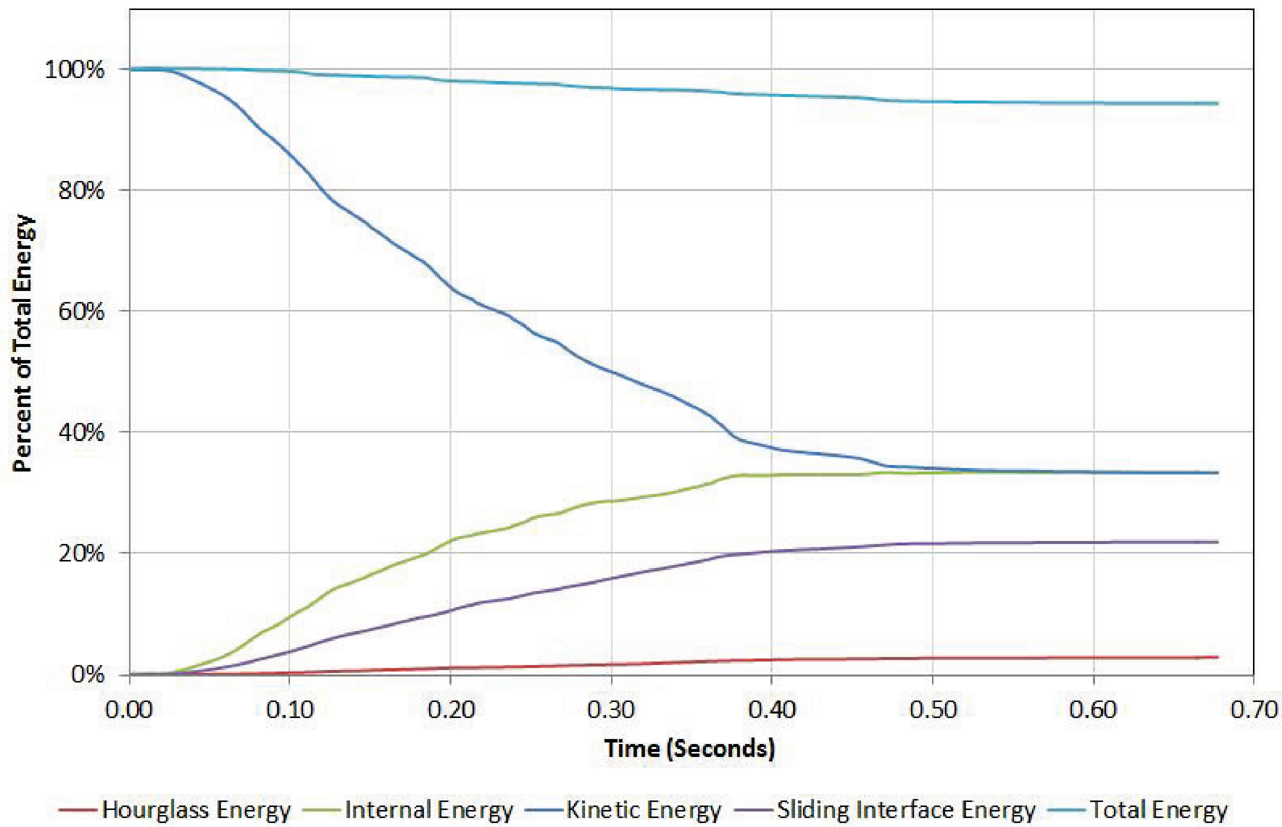


Figure 4.8. Energy Distribution Time History (MGS with Wood Posts Validation).

4.3.1.4 Occupant Risk Assessment

The TRAP program was used to evaluate occupant risk factors based on the applicable *MASH* evaluation criteria. The modeled 2270P vehicle remained upright during and after the modeled collision event. Table 4.2 provides a summary of results for the 31-inch MGS W-beam guardrail system with wood posts. Maximum roll, pitch and yaw angles resulted to be −2.8, −2.9, −36.3 degrees respectively. Occupant impact velocities were 16.73 ft/sec and 15.74 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were -9.7 g and -8.7 g in the longitudinal and lateral directions, respectively. Angular displacements obtained in the full-scale crash test and in the simulation are reported in Figures 4.9 and 4.10, respectively.

Tables 4.3 through 4.5 compare frames from test MGSSYP-1 and the computer simulation validation at the same time after first impact occurred.

Table 4.2. Occupant Risks Values (MGS with Wood Posts Validation).

Occupant Risk Factors	**TEST MGSSYP-1**	**FE MGS Wood Posts**	**Relative Difference**
Impact Vel. (ft/sec)			
x-direction	-14.20	16.73	17.8%
y-direction	-14.77	15.74	6.56%
Ridedown Acc. (g's)			
x-direction	-8.39	-9.8	16.8%
y-direction	-7.65	-8.7	13.72%
Angles	**TEST MGSSYP-1**	**FE MGS Wood Posts**	**Relative Difference**
Roll (deg.)	5.6	-2.8	Absolute Difference < 5 Degrees
Pitch (deg.)	4.4	-2.9	Absolute Difference < 5 Degrees
Yaw (deg.)	-44.1	-36.3	17.7%

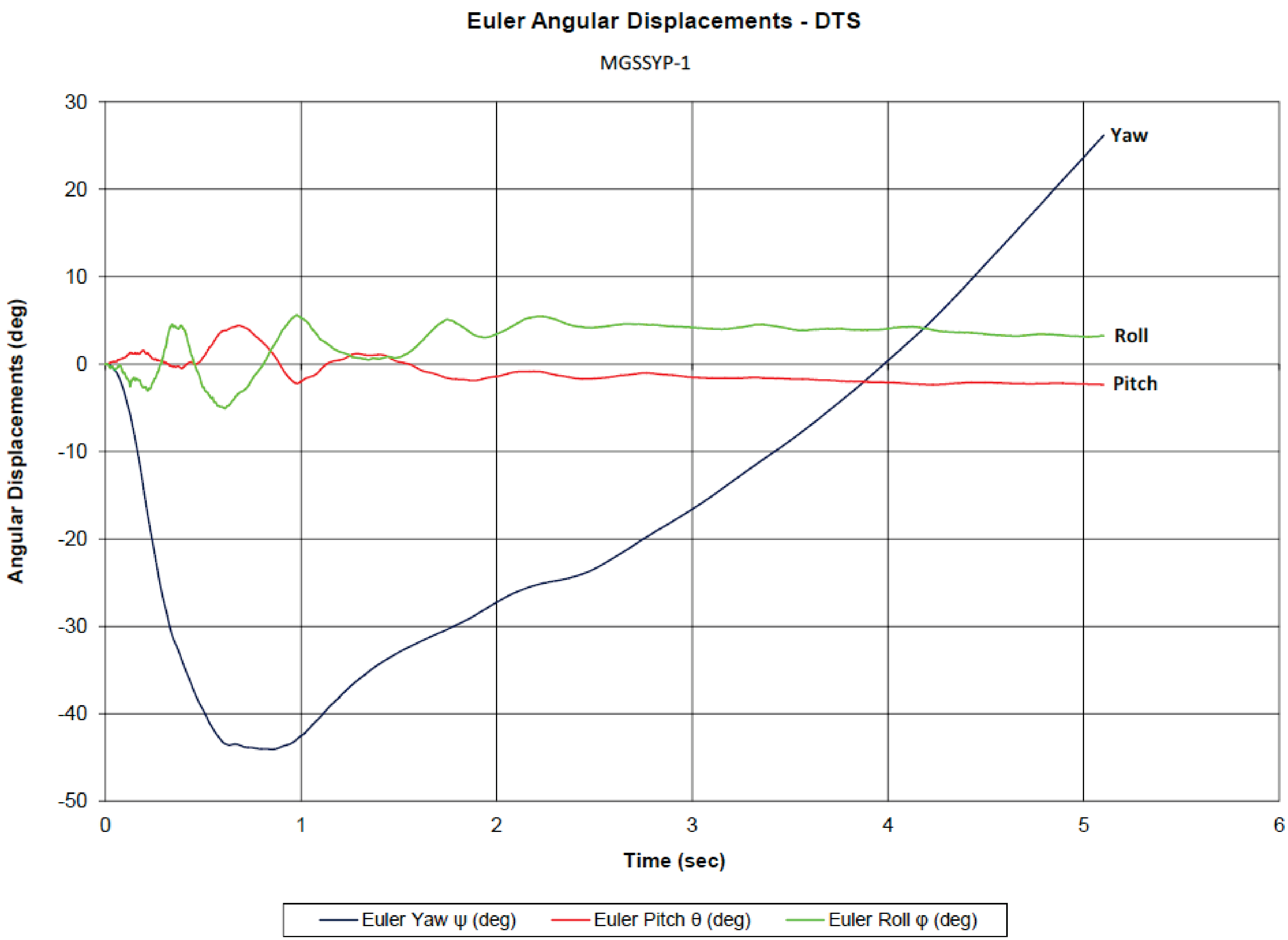


Figure 4.9. Angular Displacements for Test MGSSYP-1 (Gutierrez et al., 2013).

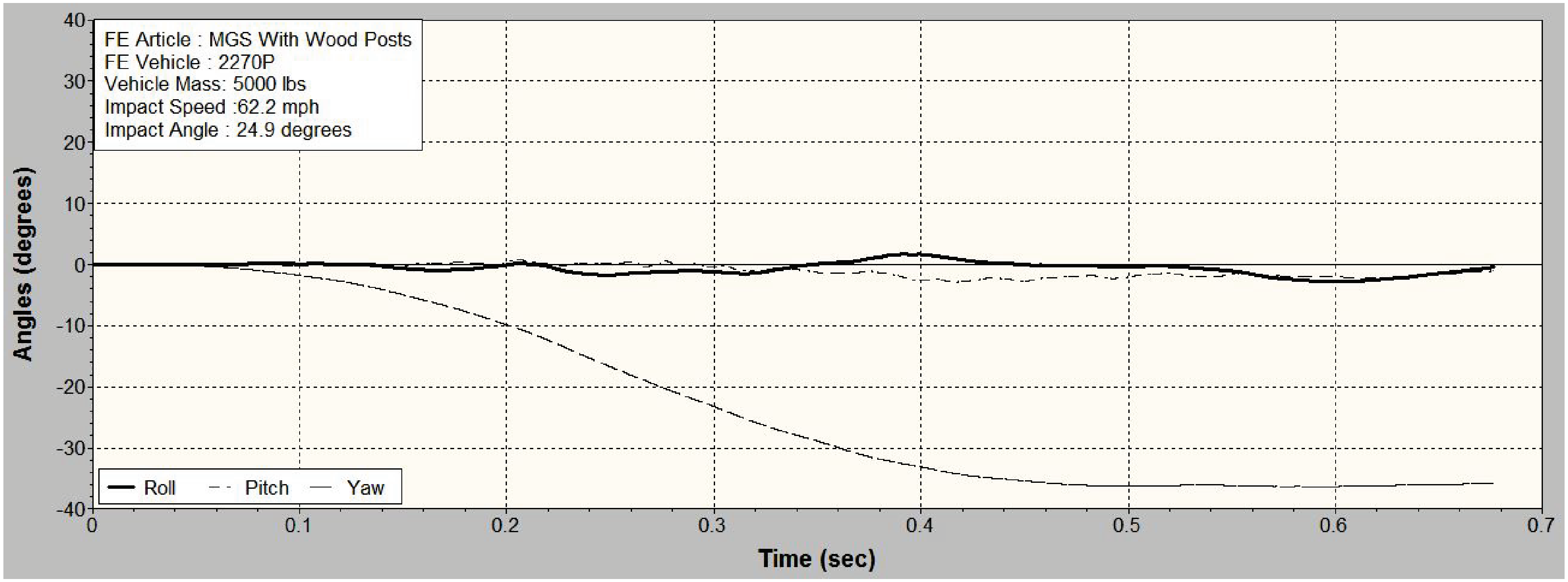


Figure 4.10. Angular Displacements for FE Simulation Validation of the MGS with Wood Posts.

Table 4.3. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Top View (MGS with Wood Posts Validation).

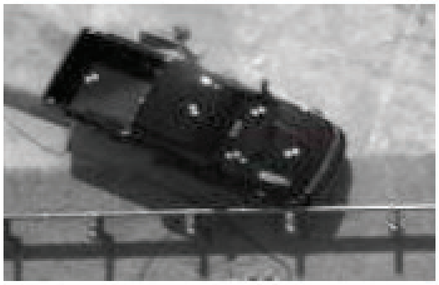
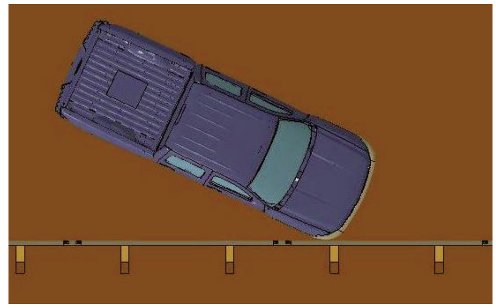
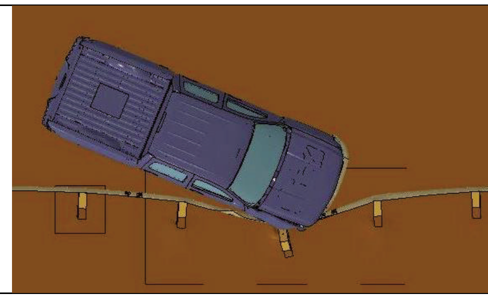
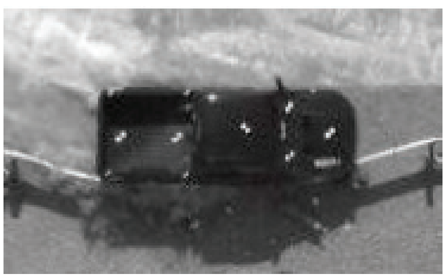
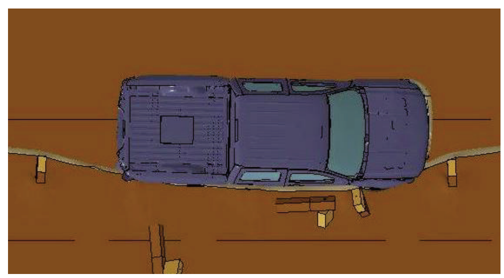
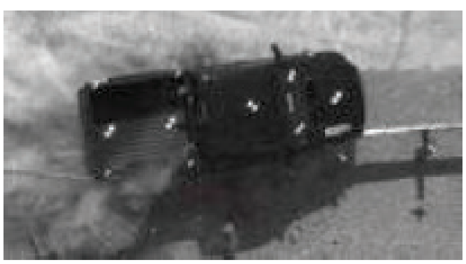
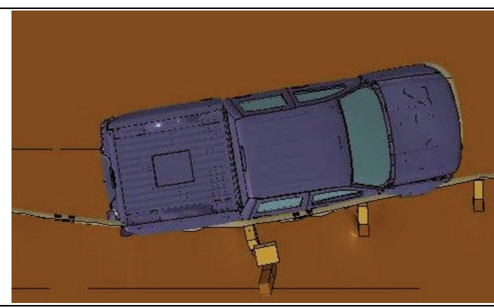
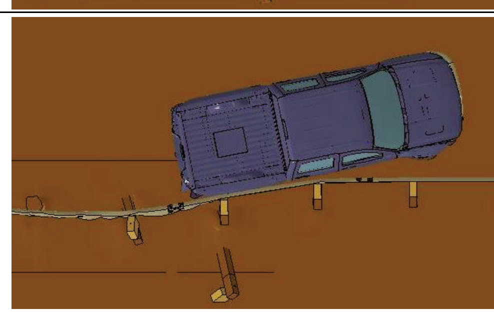
Time (sec)	TEST MGSSYP-1	MGS with Wood Posts
0.000		
0.096		
0.290		
0.402		
0.602		

Table 4.4. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Frontal View (MGS with Wood Posts Validation).

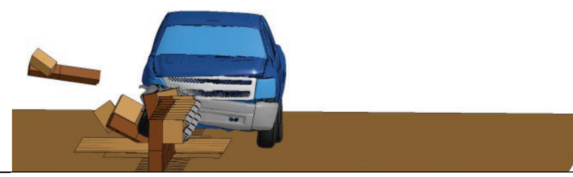
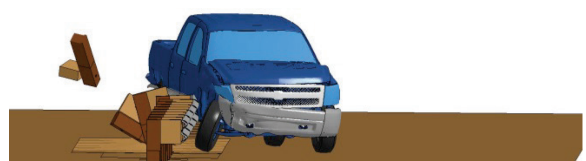
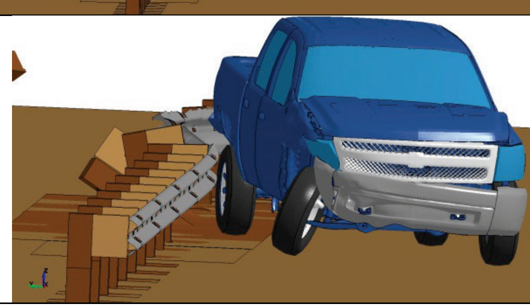
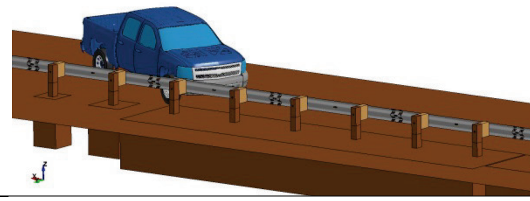
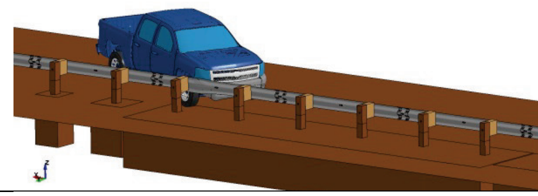
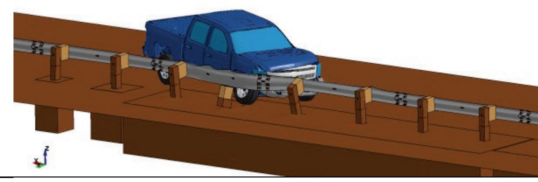
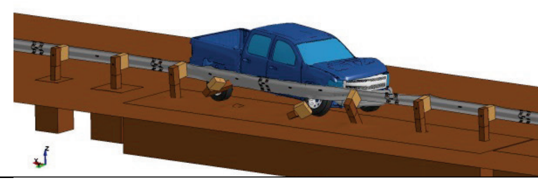
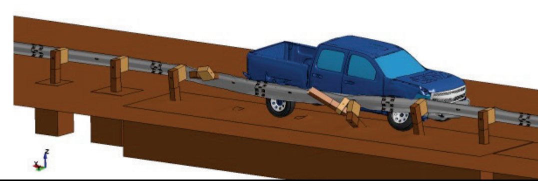
Time (sec)	TEST MGSSYP-1	MGS with Wood Posts
0.000		
0.138		
0.290		
0.490		
0.790		

Table 4.5. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Back View (MGS with Wood Posts Validation).

Time (sec)	TEST MGSSYP-1	MGS with Wood Posts
0.000		
0.022		
0.118		
0.218		
0.338		

4.3.1.5 RSVVP Validation

A program called the Roadside Safety Verification and Validation Program (RSVVP) was developed for validation of numerical models in roadside safety (Ray et al., 2011). This program was used to compute the comparison metrics for a quantitative validation of the pickup truck FE impact model. This quantitative verification approach is based on the comparison of acceleration and angle curves from both simulation and test data according to Sprague and Geers (S&G) MPC and variance (ANOVA) metrics. Acceleration and angle rates histories of the vehicle are collected in LS-DYNA with use of a rigid brick element defined by the card *ELEMENT_SEATBELT_ACCELEROMETER and rigidly linked to the vehicle at its center of gravity (Hallquist, 2009). Before computing the metrics with the RSVVP program, each curve was filtered and synchronized by minimizing the absolute area of the residuals.

The results of the evaluation for the individual channels are shown in Table 4.6. Based on both the Sprague & Geers and the ANOVA metrics, the y- and yaw-channels indicated that the numerical analysis was in agreement with the test, and that the x-, z-, roll- and pitch-channels were not. Since the metrics computed for the individual data channels did not all satisfy the acceptance criteria, the multi-channel option in RSVVP was used to calculate the weighted Sprague-Geer and ANOVA metrics for the six channels of data. The resulting weight factors computed for each channel are shown in both tabular form and graphical form in Table 4.7. The results indicate that the x-, y-, and yaw rate-channels dominate the kinematics of the impact event. The weighted metrics computed in RSVVP using the Area II method in the multi-channel mode all satisfy the acceptance criteria, and therefore the time history comparison can be considered acceptable.

4.3.1.6 Plastic Strains

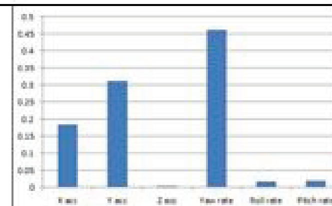
Plastic strains contours are used to visualize possible barrier component failure locations. A blue region represents regions with little to no plastic strain. Red regions represent regions with plastic strains equal to or greater than 15 percent. Plastic strains greater than 15 percent for steel material indicate regions where local steel failure is likely to occur. In tension regions, high plastic strains indicate a high likelihood of material failure by rupture. It should be noted that very small localized high plastic strains are common and can be a result of element size and formulation in the finite element model. These small areas of high plastic strain generally are not a concern. When looking for regions of interest (areas of high plastic strains) analysts should observe how much of the cross section has developed high plastic strains.

Figure 4.11 shows the plastic strains on the traffic side of the W-beam rail, in the region of contact with the vehicle during the impact event. Only small regions of high plastic strains are present. These regions of high plastic strains are localized. After reviewing the simulation, it was concluded that rail failure is unlikely.

Table 4.6. Roadside Safety Validation Metrics Rating Table for MGS with Wood Posts Validation (Single Channel Option).

<table>
<tr><td colspan="9">Evaluation Criteria</td><td colspan="3" rowspan="2">Time interval [0 sec; 0.2399 sec]</td></tr>
<tr><td>O</td><td colspan="8">Sprague-Geer Metrics
List all the data channels being compared. Calculate the M and P metrics using RSVVP and enter the results. Values less than or equal to 40 are acceptable.</td></tr>
<tr><td rowspan="9"></td><td rowspan="3"></td><td colspan="6">RSVVP Curve Preprocessing Options</td><td rowspan="3">M [%]</td><td rowspan="3">P [%]</td><td rowspan="3">Pass?</td></tr>
<tr><td rowspan="2">Filter Option</td><td rowspan="2">Sync. Option</td><td colspan="2">Shift</td><td colspan="2">Drift</td></tr>
<tr><td>True Curve</td><td>Test Curve</td><td>True Curve</td><td>Test Curve</td></tr>
<tr><td>X acceleration</td><td>CFC 180</td><td>Min. area of Residuals</td><td>N</td><td>N</td><td>N</td><td>N</td><td>16.1</td><td>44.1</td><td>N</td></tr>
<tr><td>Y acceleration</td><td>CFC 180</td><td>Min. area of Residuals</td><td>N</td><td>N</td><td>N</td><td>N</td><td>17.5</td><td>35.2</td><td>Y</td></tr>
<tr><td>Z acceleration</td><td>CFC 180</td><td>Min. area of Residuals</td><td>N</td><td>N</td><td>N</td><td>N</td><td>103.4</td><td>52.6</td><td>N</td></tr>
<tr><td>Yaw</td><td>CFC 180</td><td>Min. area of Residuals</td><td>N</td><td>N</td><td>N</td><td>N</td><td>10.7</td><td>2.1</td><td>Y</td></tr>
<tr><td>Roll</td><td>CFC 180</td><td>Min. area of Residuals</td><td>N</td><td>N</td><td>N</td><td>N</td><td>49.3</td><td>27.3</td><td>N</td></tr>
<tr><td>Pitch</td><td>CFC 180</td><td>Min. area of Residuals</td><td>N</td><td>N</td><td>N</td><td>N</td><td>15.6</td><td>58</td><td>N</td></tr>
<tr><td rowspan="7">P</td><td colspan="8">ANOVA Metrics
List all the data channels being compared. Calculate the ANOVA metrics using RSVVP and enter the results. Both of the following criteria must be met:
• The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \leq 0.05 \cdot a_{Peak}$) and
• The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)</td><td>Mean Residual [%]</td><td>Standard Deviation of Residuals [%]</td><td>Pass?</td></tr>
<tr><td colspan="8">X acceleration/Peak</td><td>-2.32</td><td>33.24</td><td>Y</td></tr>
<tr><td colspan="8">Y acceleration/Peak</td><td>2.56</td><td>25.73</td><td>Y</td></tr>
<tr><td colspan="8">Z acceleration/Peak</td><td>0.82</td><td>54.89</td><td>N</td></tr>
<tr><td colspan="8">Yaw</td><td>6.83</td><td>5.04</td><td>Y</td></tr>
<tr><td colspan="8">Roll</td><td>-0.8</td><td>44.7</td><td>N</td></tr>
<tr><td colspan="8">Pitch</td><td>-46.44</td><td>36.03</td><td>N</td></tr>
</table>

Table 4.7. Roadside Safety Validation Metrics Rating Table for MGS with Wood Posts Validation (Multi-Channel Option Using Area II Method).

<table>
<tr><td colspan="6">Evaluation Criteria (time interval [0 sec; 0.7 sec])</td></td></tr>
<tr><td colspan="6">Channels (Select which were used)</td></tr>
<tr><td colspan="2">☒ X Acceleration</td><td colspan="2">☒ Y Acceleration</td><td colspan="2">☒ Z Acceleration</td></tr>
<tr><td colspan="2">☒ Roll rate</td><td colspan="2">☒ Pitch rate</td><td colspan="2">☒ Yaw rate</td></tr>
<tr><td colspan="2">Multi-Channel Weights
-Area (II) Method-</td><td colspan="2">X Channel – 0.18633878
Y Channel – 0.3119941
Z Channel – 0.00166705
Yaw Channel – 0.45624038
Roll Channel – 0.01947689
Pitch Channel – 0.0242827</td><td colspan="2"></td></tr>
<tr><td rowspan="2">O</td><td rowspan="2">Sprague-Geer Metrics
Values less or equal to 40 are acceptable.</td><td>M</td><td>P</td><td colspan="2">Pass?</td></tr>
<tr><td>14.8</td><td>21.9</td><td colspan="2">Y</td></tr>
<tr><td rowspan="2">P</td><td rowspan="2">ANOVA Metrics
Both of the following criteria must be met:
• The mean residual error must be less than five percent of the peak acceleration ($e \leq 0.05 \cdot a_{Peak}$)
• The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)</td><td>Mean Residual</td><td>Standard Deviation of Residuals</td><td colspan="2">Pass?</td></tr>
<tr><td>2.6</td><td>18.2</td><td colspan="2">Y</td></tr>
</table>

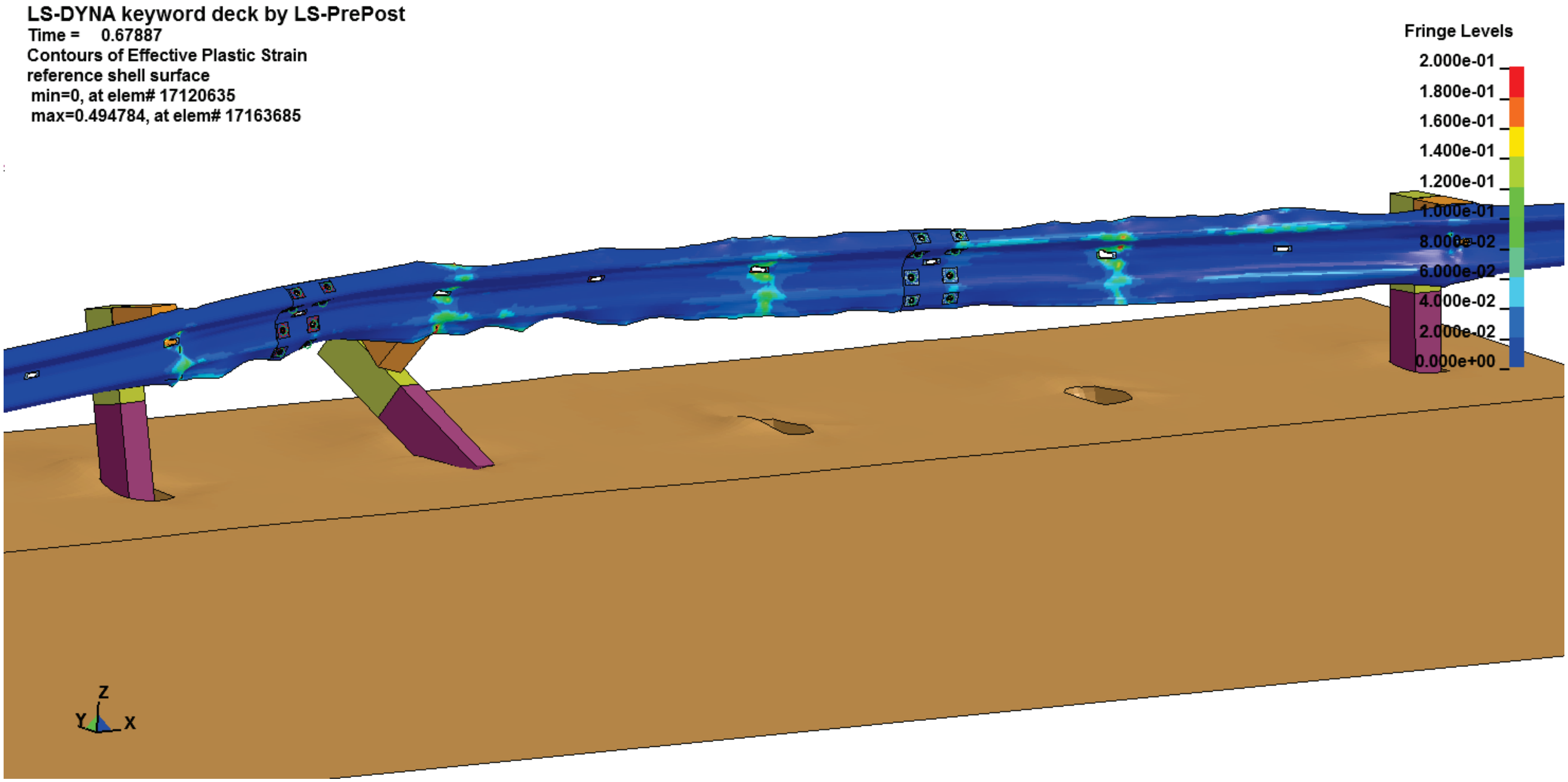
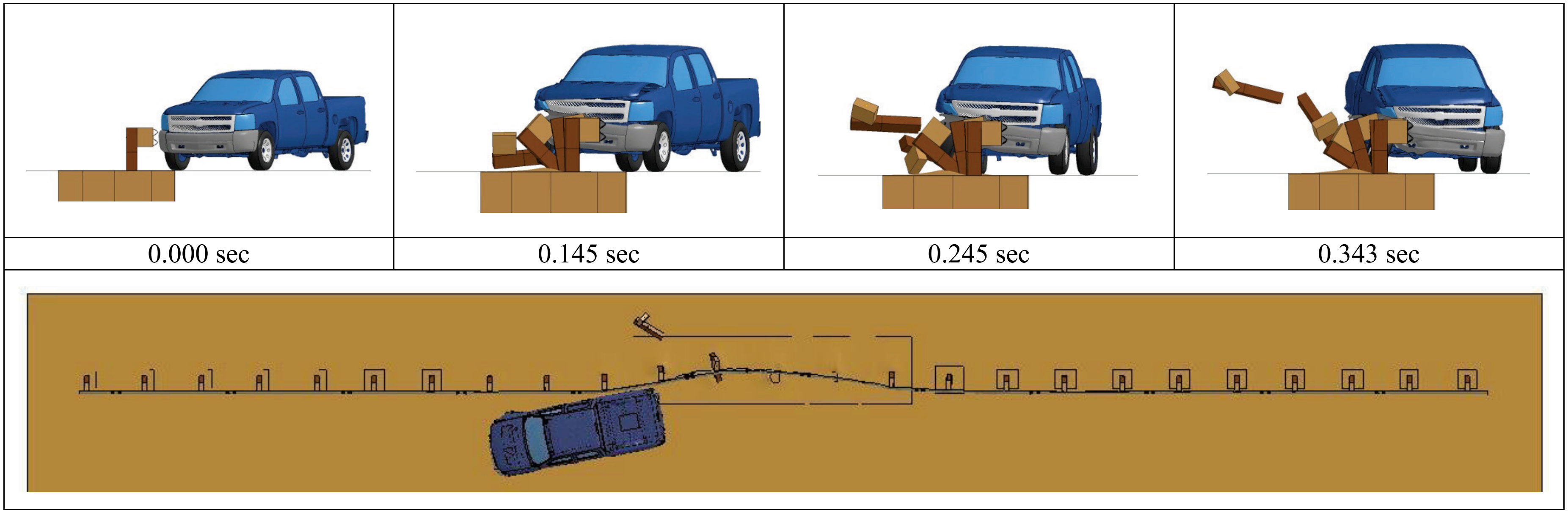


Figure 4.11. Effective Plastic Strains at the Front Face of the W-Beam Rail (MGS with Wood Posts Validation).

4.3.1.7 Conclusions

Impact simulation of *MASH* Test 3-11 according the initial impact conditions of test MGSSYP-1 well replicated the results obtained through full-scale crash testing. The multi-channel option evaluation through the RSVVP program suggests that the FE model of the 31-inch MGS W-beam guardrail system with wood posts can be considered validated. Figure 4.12 summarizes results for *MASH* Test 3-11 simulation with a 2270P vehicle impacting a 31-inch MGS W-beam guardrail system with wood posts.



General Information
Test Agency .... Texas A&M Transportation Institute (TTI)
Test Standard Test No. .... *MASH* Test 3-11
Date .... N/A

Test Article
Type .... MGS with Wood Posts

Installation Length .... 150 ft
Material or Key Elements .. MGS, 31-inch W-Beam, Wood Posts

Test Vehicle
Type/Designation 2270P
Weight .... 5000 lbs
Dummy .... No Dummy

Impact Conditions
Speed .... 62.2 mi/h
Angle .... 24.9 degrees
Location/Orientation .... 12 ft - 6 in Upstream of Post

Post-Impact Trajectory
Stopping Distance............ N/A

Occupant Risk Values
Impact Velocity (ft/sec)
x-direction…………………. 16.73
y-direction…………………. 15.74
Ridedown Acceleration (g)
x-direction ....-9.8
y-direction ....-8.7

Vehicle Stability
Maximum Yaw Angle............. -36.3 degree
Maximum Pitch Angle .... -2.9 degree
Maximum Roll Angle .... -2.8 degree
Vehicle Snagging .... No

Vehicle Damage
VDS .... N/A
CDC .... N/A
Max. Exterior Deformation ...... N/A
OCD. .... N/A

Max. Occupant Compartment Deformation .... N/A

Figure 4.12. Summary of Results for *MASH* Test 3-11 Simulation (MGS with Wood Posts Validation).

5. FINITE ELEMENT PREDICTIVE SIMULATIONS

This Chapter includes description and results of the finite element computer simulations performed to evaluate the crashworthiness of the common practice of raising blockouts with respect to the posts when using wood posts and wood blockout material.

As explained in details in Chapter 3, three cases were considered for replication with computer modeling and simulations:

1) 31-inch MGS system with 4-inch pavement overlay in front of post and 4-inch raised blockouts on posts (*MASH* criteria, TL- 3-11);
2) 27¾-inch rail system with 4-inch increased post embedment due to possible rail deficiency or posts settlement, and 4-inch raised blockouts on posts (*NCHRP Report 350* criteria, TL- 3-11).
3) 27¾-inch rail system with 4-inch pavement overlay in front of post and 4-inch raised blockouts on posts (*NCHRP Report 350* criteria, TL- 3-11);

For each one of the considered cases, FE simulations were run to determine how the test article would perform after raising the blockouts on the posts to obtain the desired rail height with respect to ground/pavement overlay.

For those cases which included pavement overlay, tapered edge details from Texas Department of Transportation standards were considered for implementation within the computer models (Figure 5.1) (TxDOT, 2011). According to such standards, the pavement overlay should have a tapered edge length of 1.75 * T, where "T" is the total thickness of all overlay layer. It was also assumed that the tapered edge would start at the height of the face of the guardrail, following Washington State Department of transportation standard (Figure 5.2) (WSDOT, 2011).

More details on each of the identified cases for additional crashworthiness evaluation are explained next.

5.1 MGS System with 4-inch Pavement Overlay and 4-inch Raised Blockouts

5.1.1 Computer Model Description

The finite element model of the MGS system with wood posts previously developed and validated was modified so that a 4-inch overlay was added in front of the post. The 4-inch overlay was terminated following the TxDOT guidelines reported in their standards. To maintain the original rail height of the MGS system after the overlay, the wood blockouts were raised 4 inches with respect to the posts. Post embedment remains 40 inches, as in the original MGS system installation. Details of the MGS system with 4-inch pavement overlay and 4-inch raised blockouts are included in Figure 5.3.

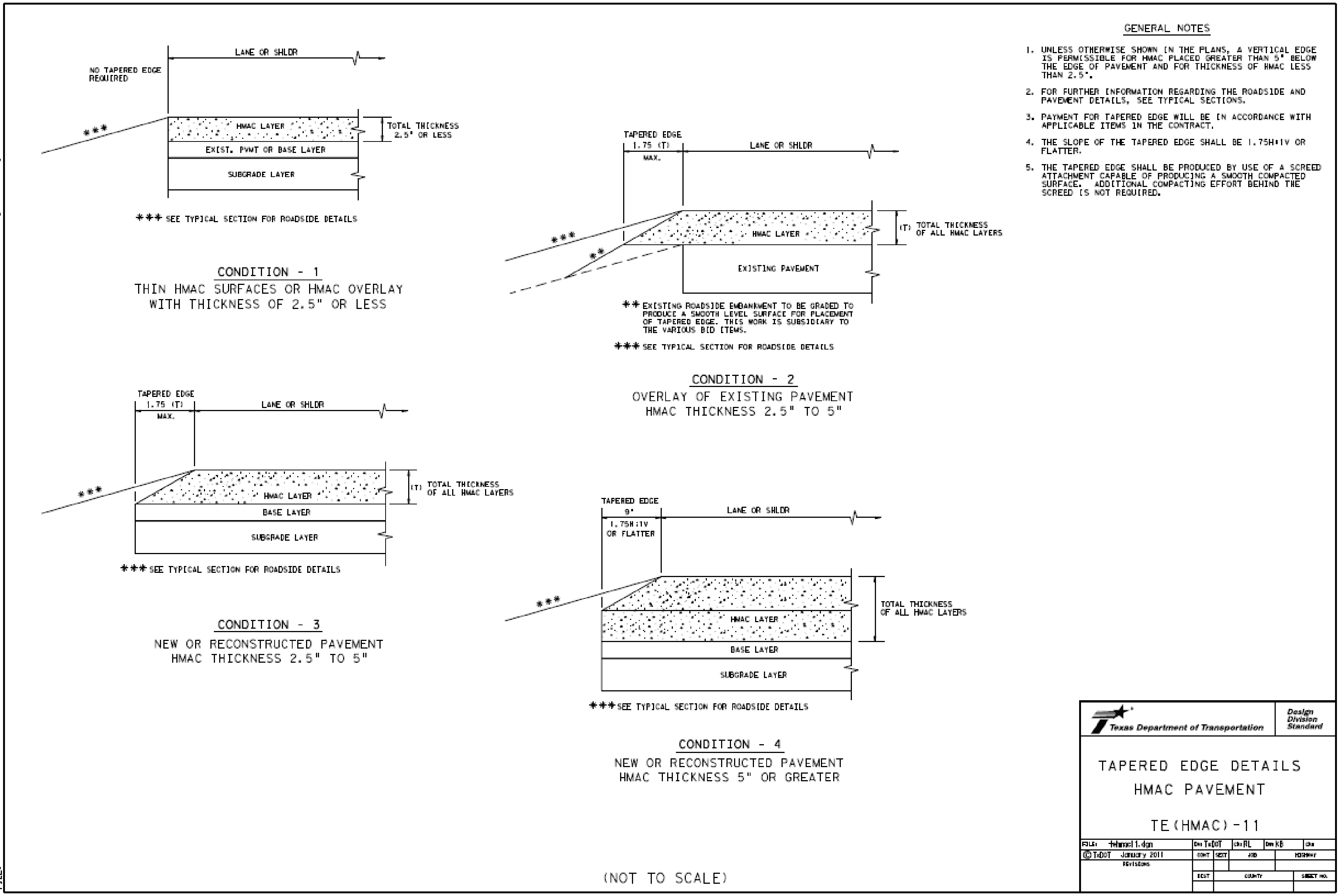


Figure 5.1. Tapered Edge Details – HMAC Pavement – TE (HMAC)-11 (TxDOT, 2011).

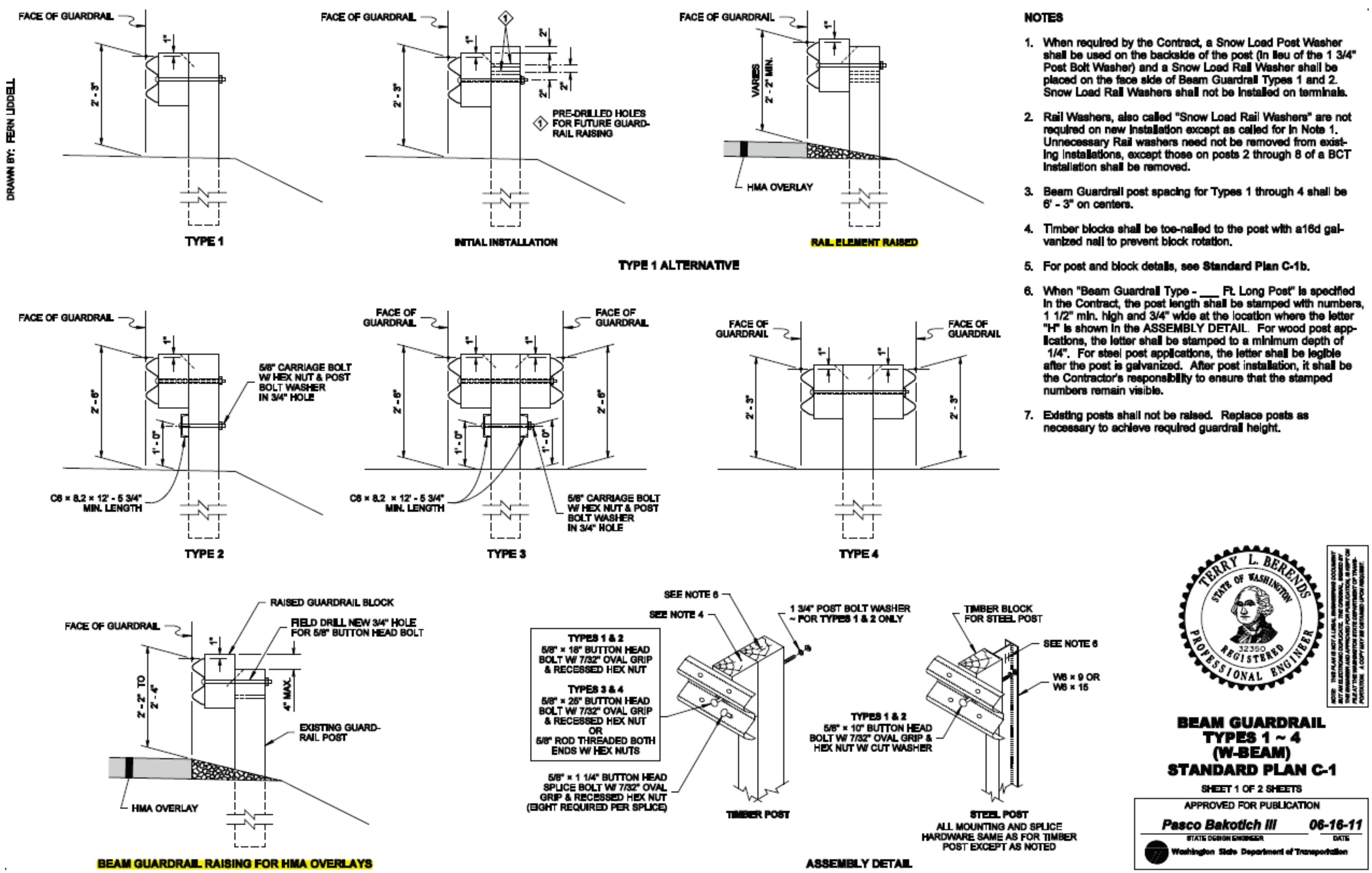


Figure 5.2. Beam Guardrail Types 1 ~4 (W-Beam) Standard Plan C-1 (WSDOT, 2011).

The FE test installation consisted of 150 ft of standards 12-gauge W-beam supported by wood posts. The system was built with twenty-five posts spaced at 75 inches on center. The posts were 6-inch × 8-inch × 72-inch long posts with wood properties and a soil embedment depth of 40 inches. Failure properties were given to the posts to allow elements to erode once reached a predefined principal stress value. A 6-inch × 12-inch × 14¼-inch spacer blockout was used to block the rail away from the front face of each post. LS-DYNA soil material model *MAT_JOINTED_ROCK was used to simulate soil properties for soil-post interaction during computer simulations. Standard 12 ft-6 inch long 12-gauge W-beam rails were modeled. The W-beam top rail height was 31-inch with a 24⅞-inch center mounting height. The rail splices were placed at midspan locations, and were configured with the upstream segment in front to minimize vehicle snag at the splice during the impact event simulation.

Researchers used the NCAC finite element 2270P pickup truck model to complete their simulations (NCAC, 2005). Validation of the FE model of the test article was needed in order to verify realistic response of the MGS system to the impact of the vehicle.

Evaluation of the crashworthiness of this system was evaluated according to *MASH* Test Level 3-11 criteria.

5.1.2 Barrier Performance

Figure 5.4 contains images of the barrier before impact and at final configuration. Figure 5.4(a) and 5.4(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 5.4(b) and 5.4(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. The barrier was impacted 12 ft upstream of a post, with initial speed and angle of 62 mi/h and 25 degrees, respectively.

The vehicle was contained and redirected during the impact event. Failure properties were applied to the posts of the guardrail system. A total of four posts were broken as a consequence of the impact with the 2270P vehicle. The dynamic and permanent deflections of the guardrail system in the FE model were 40.67 inches and 27.3 inches, respectively.

5.1.3 Energy Values

The kinetic energy applied to the barrier by the impacting vehicle is dissipated by converting it into other forms of energy. Since this is a closed system and energy is conserved, the sum of the kinetic energy, hourglass energy, sliding energy, and internal energy at any time during the simulation should equate to the initial kinetic energy of the vehicle. As shown in Figure 5.5, approximately 30 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). Less than four percent of the initial kinetic energy is converted into hourglass energy. Approximately 21 percent of the initial kinetic energy is converted into sliding interface energy. Forty percent of the initial kinetic energy has yet to be dissipated by the system at the time of final impact configuration, mainly due to the remaining velocity of the vehicle.

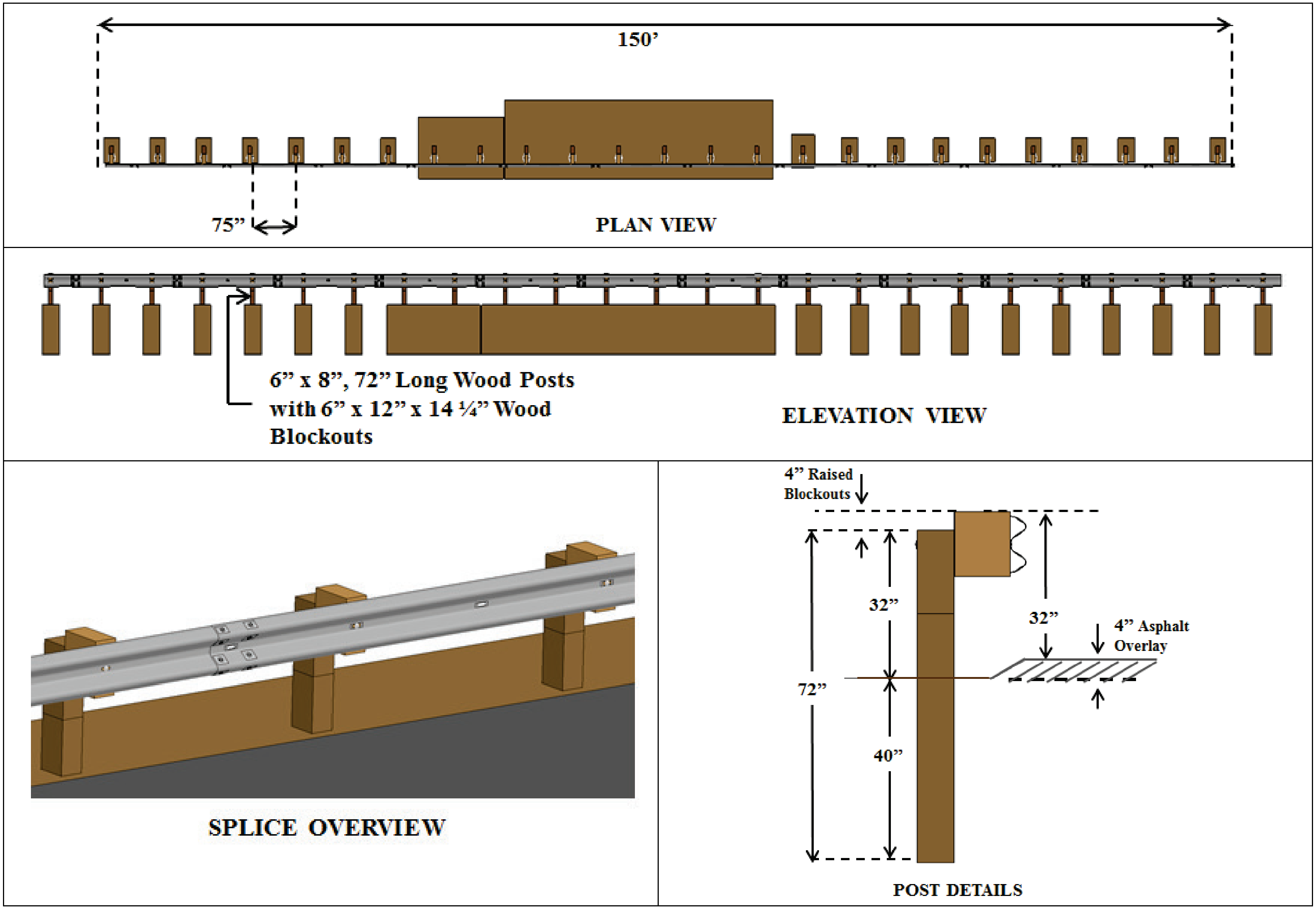
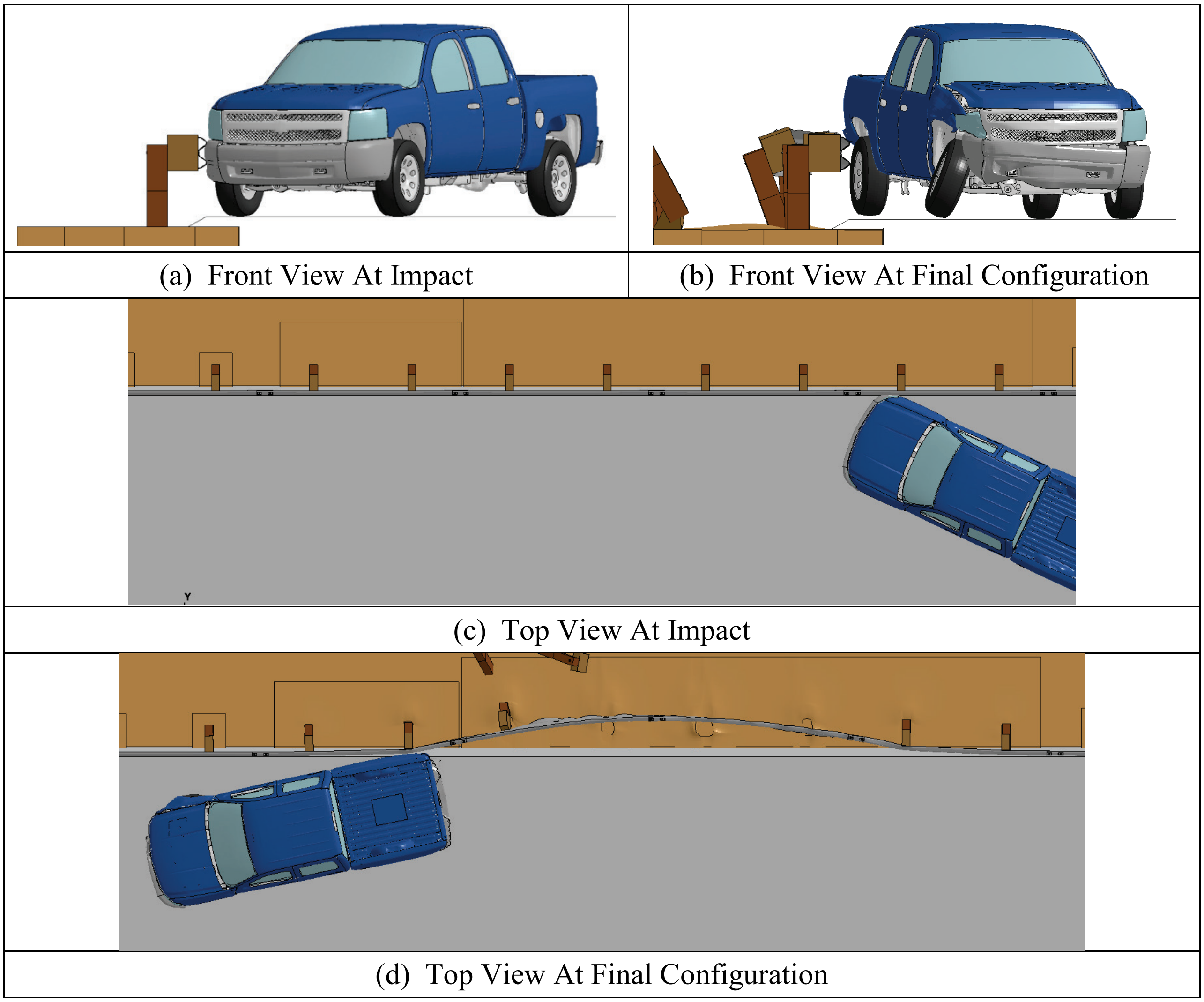


Figure 5.3. Details of the MGS Test Article Installation with 4-inch Pavement Overlay and 4-inch Raised Blockouts.



(a) Front View At Impact

(b) Front View At Final Configuration

(c) Top View At Impact

(d) Top View At Final Configuration

Figure 5.4. Initial and Deflected Shape of Barrier (MGS with Wood Posts, 4-inch Pavement Overlay, and 4-inch Raised Blockouts).

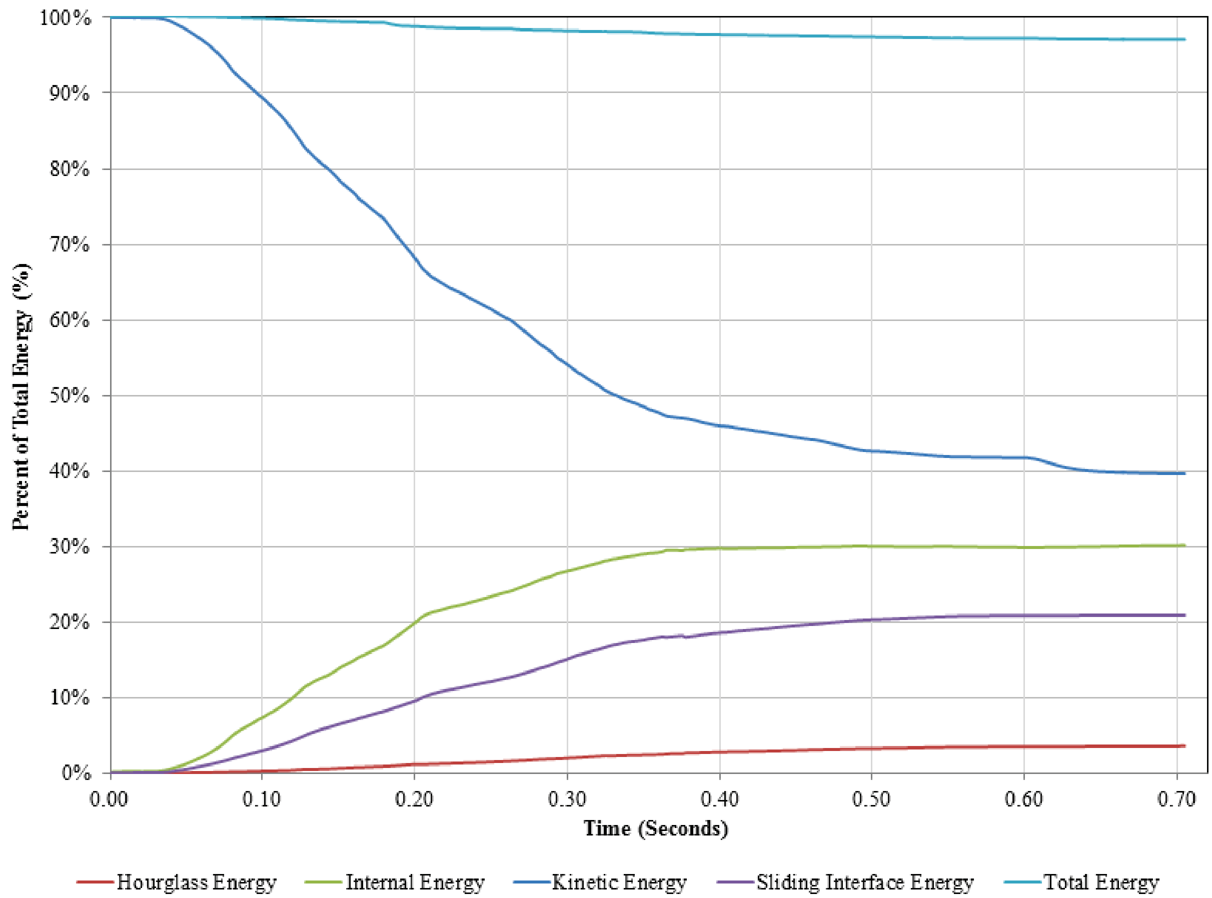


Figure 5.5. Energy Distribution Time History (MGS with Wood Posts, 4-inch Pavement Overlay, and 4-inch Raised Blockouts).

Tables 5.1 through 5.3 show frames from the computer simulation impact event against the MGS guardrail system with wood posts, 4-inch pavement overlay, and 4-inch raised blockouts.

5.1.4 Occupant Risk Assessment

The TRAP program was used to evaluate occupant risk factors based on the applicable *MASH* safety evaluation criteria. The modeled 2700P vehicle remained upright during and after the modeled collision event. Table 5.4 provides a summary of results for the MGS system with 4-inch pavement overlay in front of the post and 4-inch raised blockouts. Maximum roll, pitch and yaw angles were 2.9, -2.1, and -37.3 degrees respectively. Occupant impact velocities were 15.09 ft/sec and 15.42 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were -7.7 g and -7.2 g in the longitudinal and lateral directions, respectively. Angular displacement curves are reported in Figure 5.6.

Table 5.1. Sequential Images of the 2700P Vehicle Interaction with the MGS with Wood Posts, 4-inch Pavement Overlay, and 4-inch Raised Blockouts (Top View).

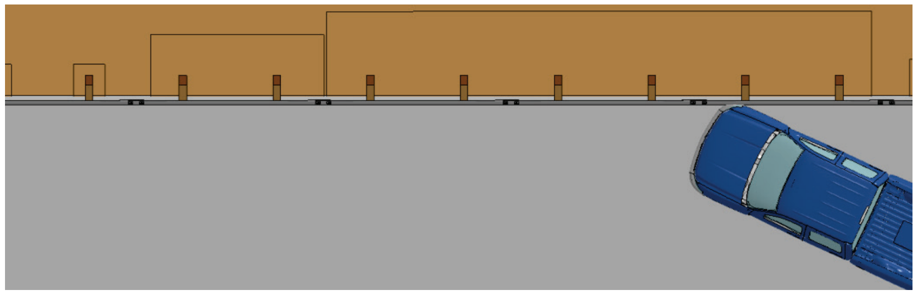
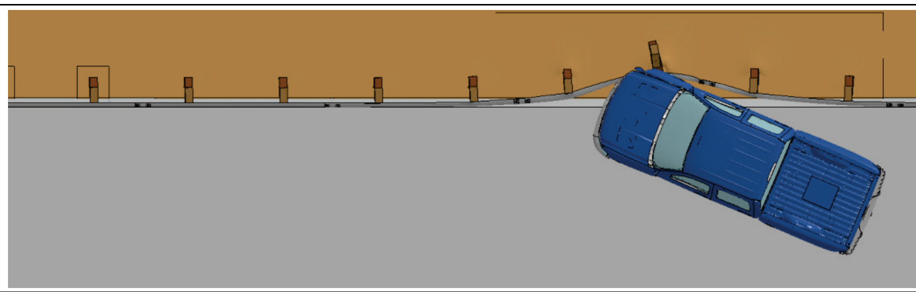
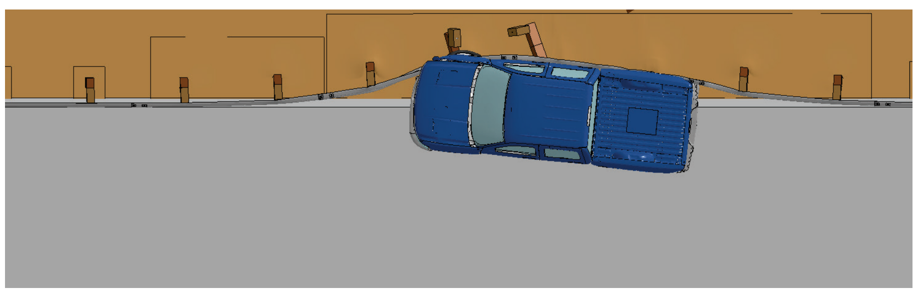
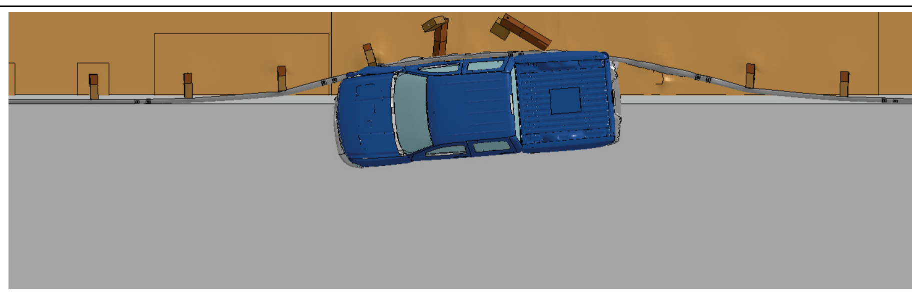
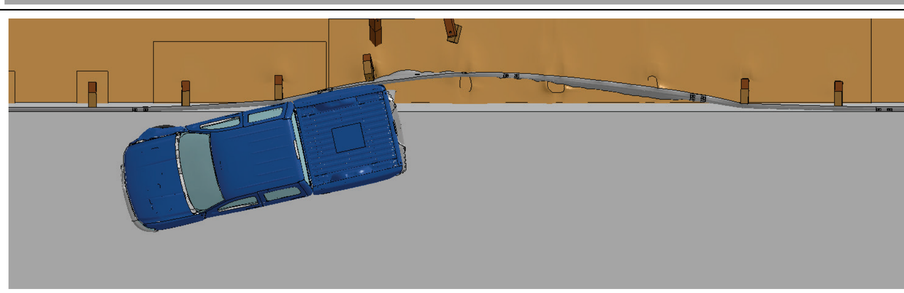
Time (sec)	FE MGS with 4-inch Pavement Overlay and 4-inch Raised Blockouts
0.000	
0.085	
0.245	
0.330	
0.570	

Table 5.2. Sequential Images of the 2700P Vehicle Interaction with the MGS with Wood Posts, 4-inch Pavement Overlay, and 4-inch Raised Blockouts (Front View).

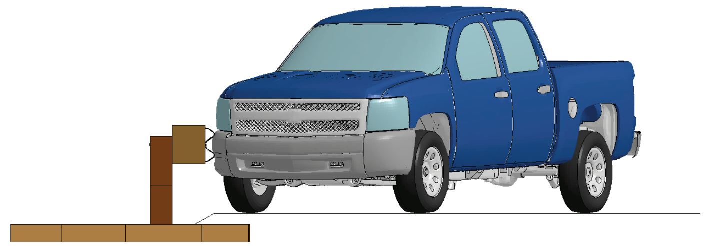
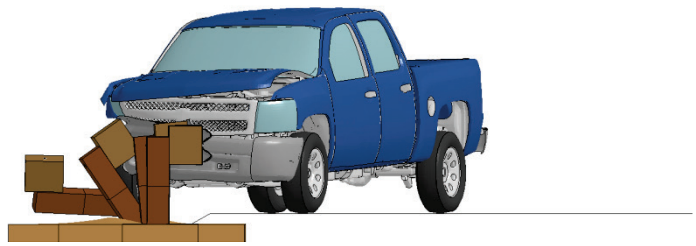
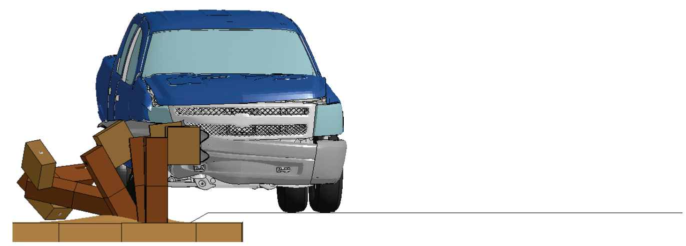
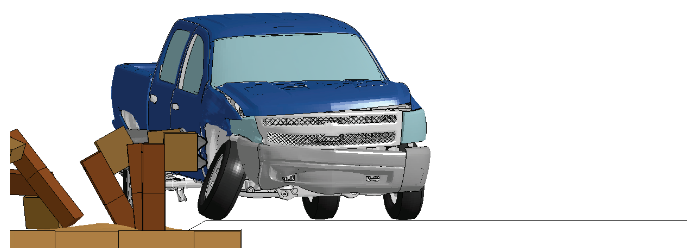
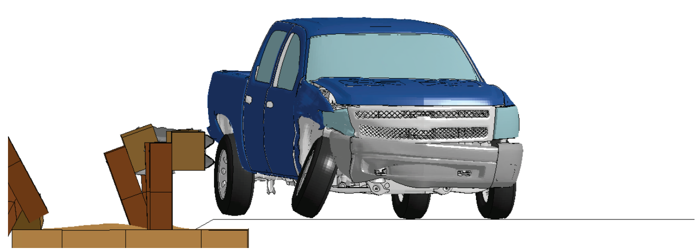
Time (sec)	FE MGS with 4-inch Pavement Overlay and 4-inch Raised Blockouts
0.000	
0.120	
0.330	
0.490	
0.675	

Table 5.3. Sequential Images of the 2700P Vehicle Interaction with the MGS with Wood Posts, 4-inch Pavement Overlay, and 4-inch Raised Blockouts (Perspective View).

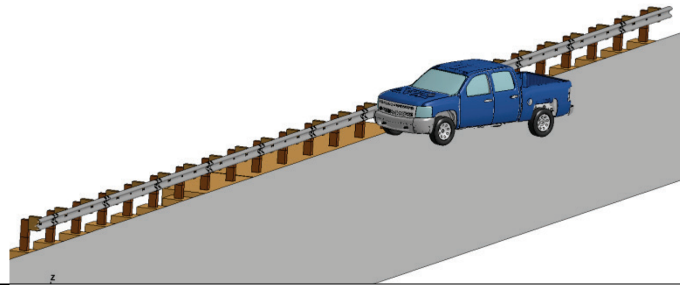
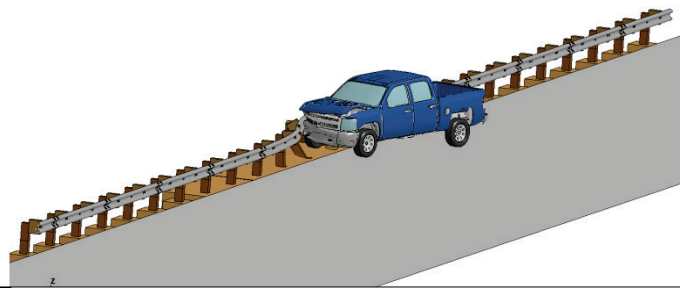
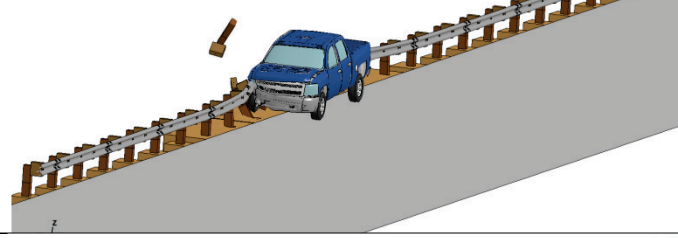
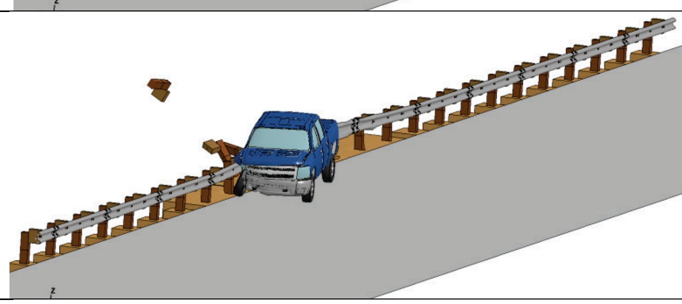
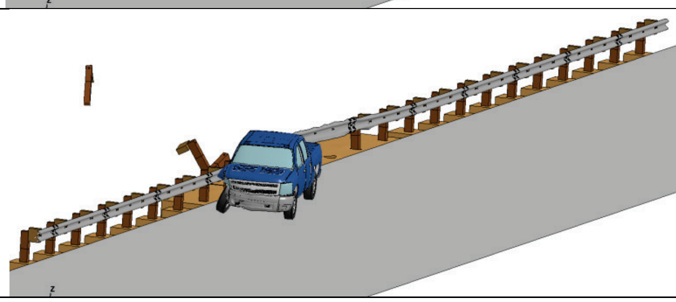
Time (sec)	FE MGS with 4-inch Pavement Overlay and 4-inch Raised Blockouts
0.000	
0.120	
0.330	
0.490	
0.675	

Table 5.4. Occupant Risks Values (MGS with Wood Posts, 4-inch Pavement Overlay, and 4-inch Raised Blockouts).

Occupant Risk Factors	FE MGS with 4-inch Pavement Overlay and 4-inch Raised Blockouts
Impact Vel. (ft/sec)	
x-direction	15.09
y-direction	15.42
Ridedown Acc. (g's)	
x-direction	-7.7
y-direction	-7.2
Angles	**FE MGS with 4-inch Pavement Overlay and 4-inch Raised Blockouts**
Roll (deg.)	2.9
Pitch (deg.)	-2.1
Yaw (deg.)	-37.3

5.1.5 Plastic Strains

Figure 5.7 shows the plastic strains on the traffic side of the W-beam rail, in the region of contact with the vehicle during the impact event. Only small regions of high plastic strains are present. These regions of high plastic strains are localized. After reviewing the simulation, it was concluded that rail failure is unlikely.

5.1.6 Conclusions

A predictive impact simulation was performed with a 2270P vehicle at 62 mi/h and 25 degrees orientation against an MGS system with 4-inch pavement overlay in front of the post and 4-inch raised blockouts on posts according to the criteria set in *MASH*. The vehicle was contained and redirected, and maintained its stability throughout the impact event. Occupant risks values were all below the limits required by *MASH* criteria, and no phenomenon of snagging or pocketing seemed to occur. The rail did not show regions of high plastic strain that might suggest failure of the steel W-beam. Results are summarized in Figure 5.8. In conclusion, results suggest that the practice of raising wood blockouts on wood posts for an MGS system to maintain a rail height at 31 inches from the pavement overlay appear to be crashworthy and likely to pass safety evaluation criteria required by *MASH*.

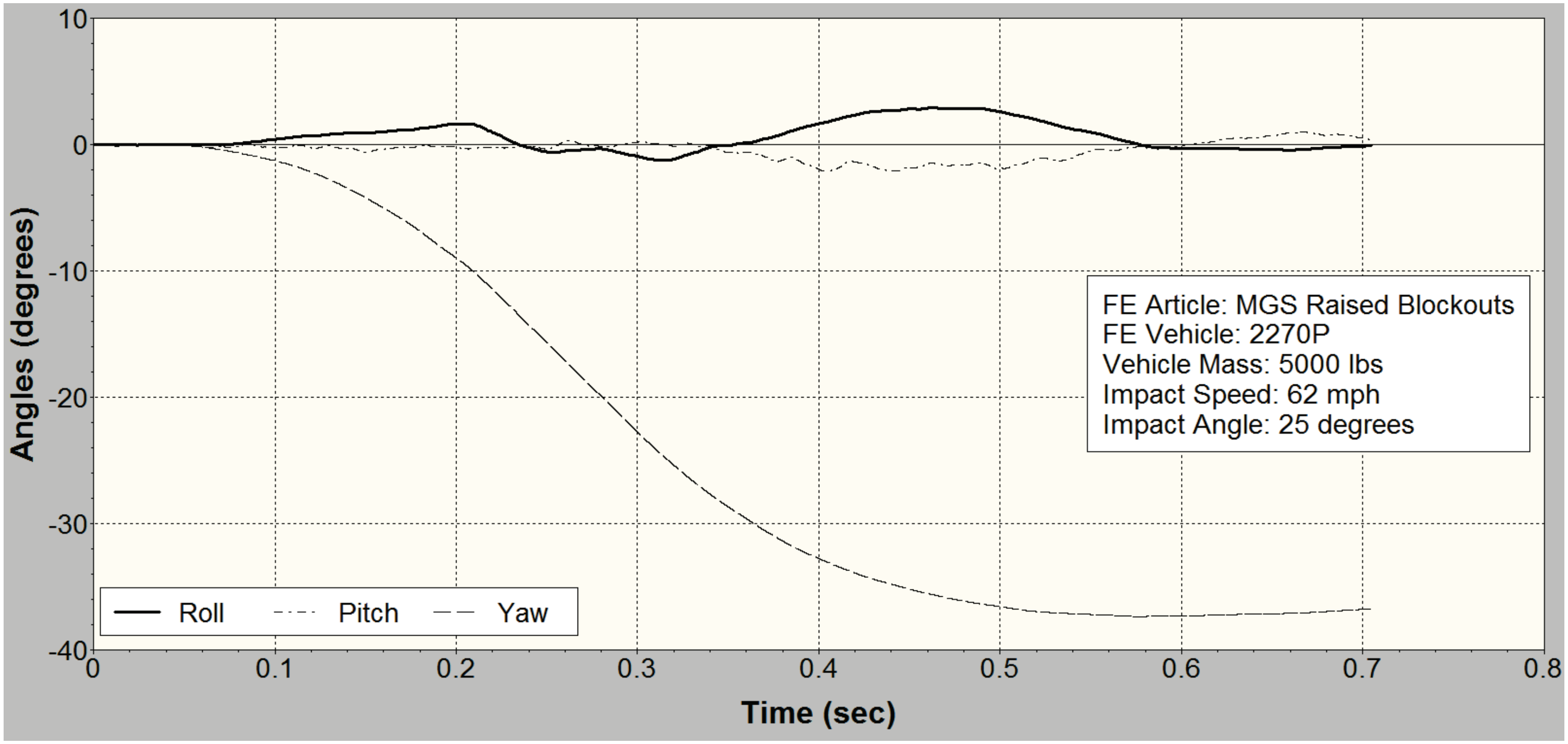
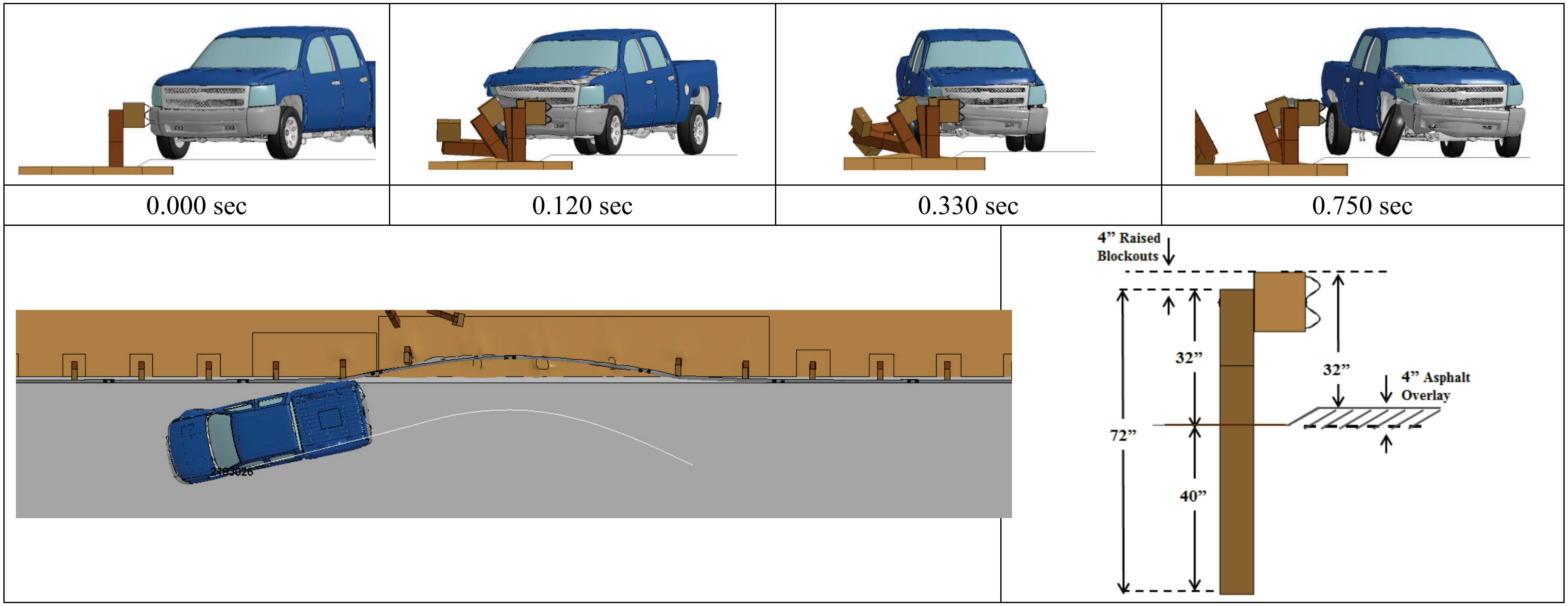


Figure 5.6. Angular Displacements for FE Simulation of MGS with Wood Posts, 4-inch Pavement Overlay, and 4-inch Raised Blockouts.

Figure 5.7. Guardrail Plastic Strain Along Impact of Vehicle and Rail (MGS with Wood Posts, 4-inch Pavement Overlay, and 4-inch Raised Blockouts).



General Information
Test Agency.......................... Texas A&M Transportation Institute (TTI)
Test Standard Test No. .... *MASH* Test 3-11
Date .... N/A

Test Article
Type .... MGS with Wood Posts, 4-inch Pavement Overlay, 4-inch Raised Blockouts
Installation Length .... 150 ft
Material or Key Elements..... W-Beam, MGS, Wood Posts, Wood Blockouts, Pavement Overlay, Raised Blockouts

Test Vehicle
Type/Designation 2270P
Weight................................. 5000 lbs
Dummy................................. No Dummy

Impact Conditions
Speed ....62.0 mi/h
Angle ....25 degrees
Location/Orientation ....12 ft upstream of post

Post-Impact Trajectory
Stopping Distance............ N/A

Occupant Risk Values
Impact Velocity (ft/sec)
x-direction…………………. 15.09
y-direction…………………. 15.42
Ridedown Acceleration (g)
x-direction..............................-7.7
y-direction..............................-7.2

Vehicle Stability
Maximum Yaw Angle................... -37.3 degree
Maximum Pitch Angle .... -2.1 degree
Maximum Roll Angle .... 2.9 degree
Vehicle Snagging.......................... No

Vehicle Damage
VDS ....N/A
CDC ....N/A
Max. Exterior Deformation ....N/A
OCD...N/A

Max. Occupant Compartment Deformation.............................N/A

Figure 5.8. Summary of Results for *MASH* Test 3-11 simulation (MGS with Wood Posts, 4-inch Pavement Overlay, and 4-inch Raised Blockouts).

5.2 27¾-inch Rail System with Height Deficiency and 4-inch Raised Blockouts

5.2.1 Computer Model Description

An FE model of 27¾-inch high W-beam guardrail system with wood posts and wood blockouts was developed. The system was modified to include 4 inches of additional post embedment. In real life, this additional soil embedment could be the result of post settlement, or accumulation of soil and/or debris around the post installation, which ultimately would lead to a rail height which is considered deficient for the impact conditions considered. To maintain the original height of the rail after the additional soil embedment, the wood blockouts were raised 4 inches with respect to the posts. The resulting post embedment was 47¼ inches. Details of the rail system with rail height deficiency and 4-inch raised blockouts are included in Figure 5.9.

The FE test installation consisted of 150 ft of standard 12-gauge W-beam supported by wood posts. The system was built with twenty-five posts spaced at 75 inches on center. The posts were 6-inch × 8-inch × 72-inch long with wood properties and a soil embedment depth of 47¼ inches. Failure properties were given to the posts to allow elements to erode after reaching a predefined principal stress value. A 6-inch × 8-inch × 14¼-inch spacer blockout was used to block the rail away from the front face of each post. LS-DYNA soil material model *MAT_JOINTED_ROCK was used to simulate soil properties for soil-post interaction. Standard 12 ft-6 inch long 12-gauge W-beam rails were modeled. The W-beam top rail height was 27¾ inches with a 21⅞-inch center mounting height. The rail splices were placed at post locations, and were configured with the upstream segment in front to minimize vehicle snag at the splice during the impact event simulation.

Researchers used the NCAC finite element 2000P pickup truck model in the impact simulation (NCAC, 2005). Some parts of the 2000P pickup truck model needed mesh refinement to avoid contact issues during the impact event against the finer meshed guardrail model.

This system was evaluated according to *NCHRP Report 350* Test 3-11 impact conditions and evaluation criteria.

5.2.2 Barrier Performance

Figure 5.10 contains images of the barrier before impact and at final configuration. Figure 5.10(a) and 5.10(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 5.10(b) and 5.10(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. The barrier was impacted 12.3 ft upstream of a post, with initial speed and angle of 62 mi/h and 25 degrees, respectively.

The vehicle was contained and redirected during the impact event. Failure properties were applied to the posts of the guardrail system. A total of three posts were broken as a consequence of the impact with the 2000P vehicle. The dynamic and permanent deflections of the guardrail system in the FE model were 3.0 ft and 1.87 ft, respectively.

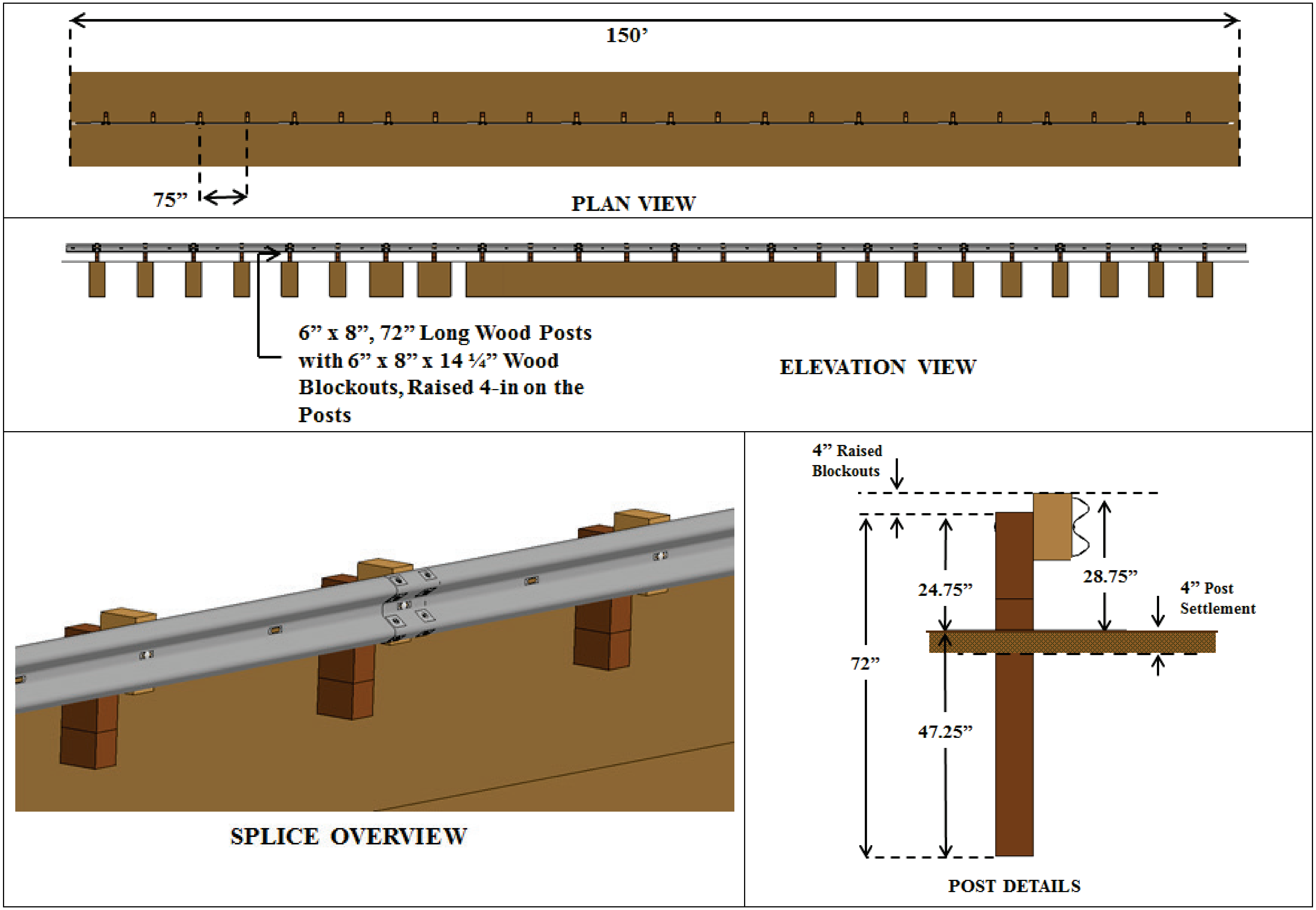
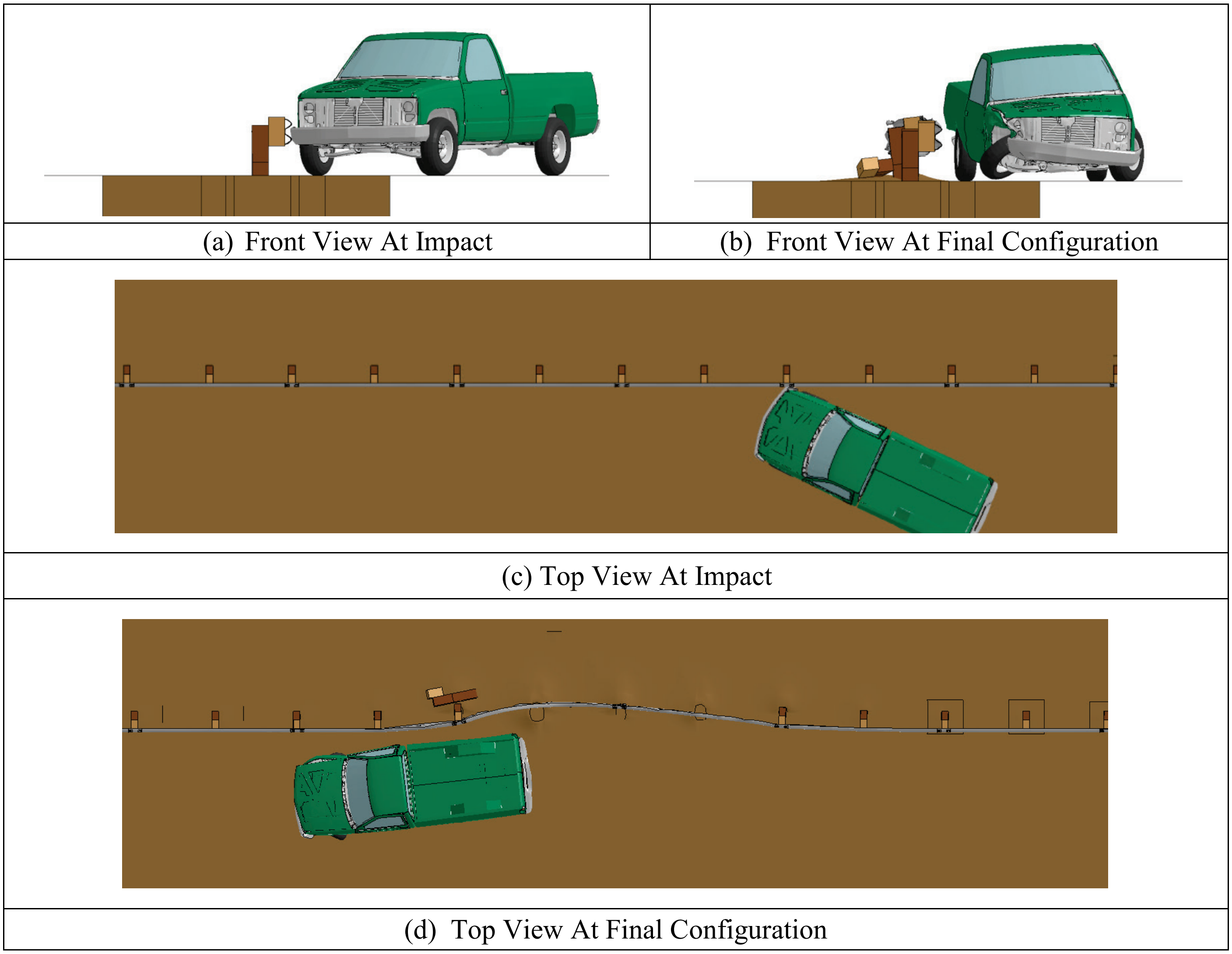


Figure 5.9. Details of the 27¾-inch Rail System Installation with Height Deficiency and 4-inch Raised Blockouts.



(a) Front View At Impact

(b) Front View At Final Configuration

(c) Top View At Impact

(d) Top View At Final Configuration

Figure 5.10. Initial and Deflected Shape of Barrier (27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts).

5.2.3 Energy Values

Since this is a closed system and energy is conserved, the sum of the kinetic energy, hourglass energy, sliding energy, and internal energy at any time during the simulation should equate to the initial kinetic energy of the vehicle. As shown in Figure 5.11, approximately 43 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). Four percent of the initial kinetic energy is converted into hourglass energy. Approximately 24 percent of the initial kinetic energy is converted into sliding interface energy. Twenty three percent of the initial kinetic energy has yet to be dissipated by the system at the time of final impact configuration, mainly due to the remaining velocity of the vehicle.

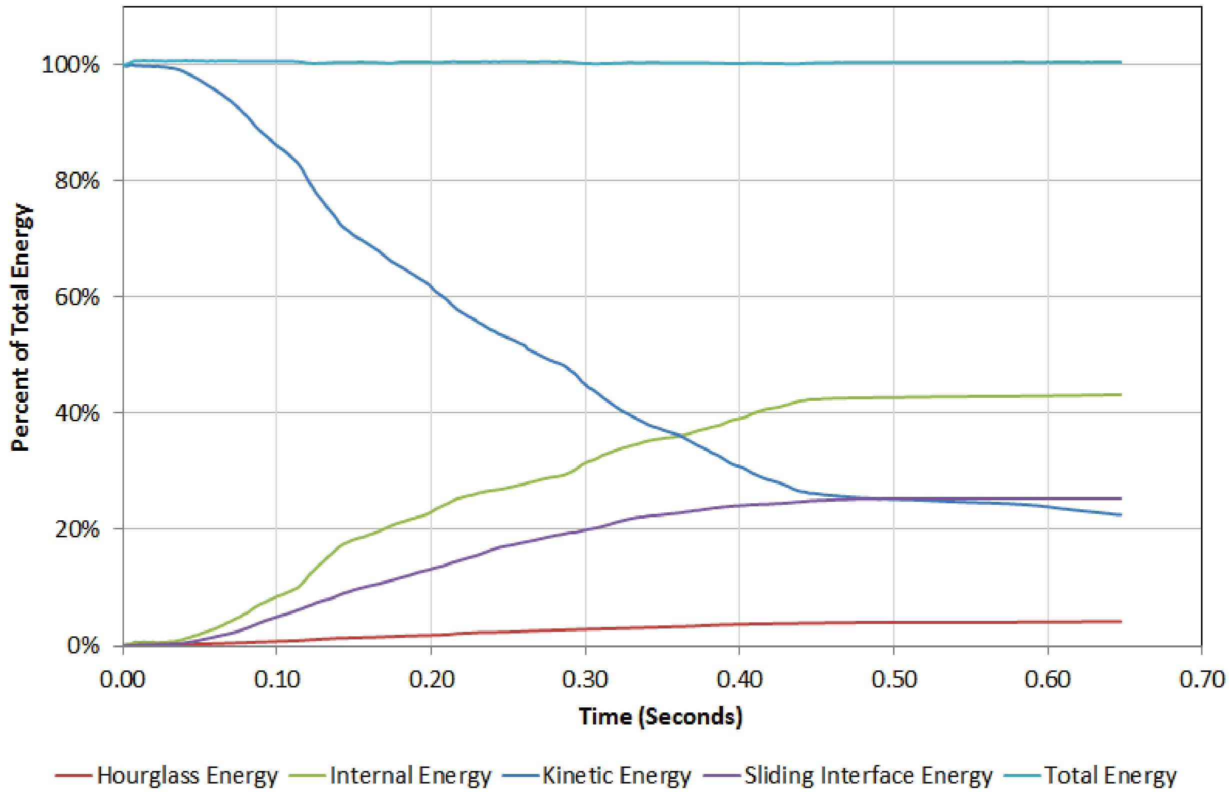


Figure 5.11. Energy Distribution Time History (27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts).

Tables 5.5 through 5.7 show frames from the computer simulation impact event against the 27¾-inch high W-beam guardrail with raised blockouts.

5.2.4 Occupant Risk Assessment

The TRAP program was used to evaluate occupant risk factors based on the applicable *NCHRP Report 350* safety evaluation criteria. The modeled 2000P vehicle remained upright during and after the modeled collision event. Table 5.8 provides a summary of results for the 27¾-inch W-beam guardrail with raised blockouts. Maximum roll, pitch and yaw angles were 3.8, 1.8, and 32.0 degrees respectively. Occupant impact velocities were 18.37 ft/sec and −17.72 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were −10.6 g and 10.2 g in the longitudinal and lateral directions, respectively. Angular displacement curves are reported in Figure 5.12.

Table 5.5. Sequential Images of the 2000P Vehicle Interaction with the 27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts (Top View).

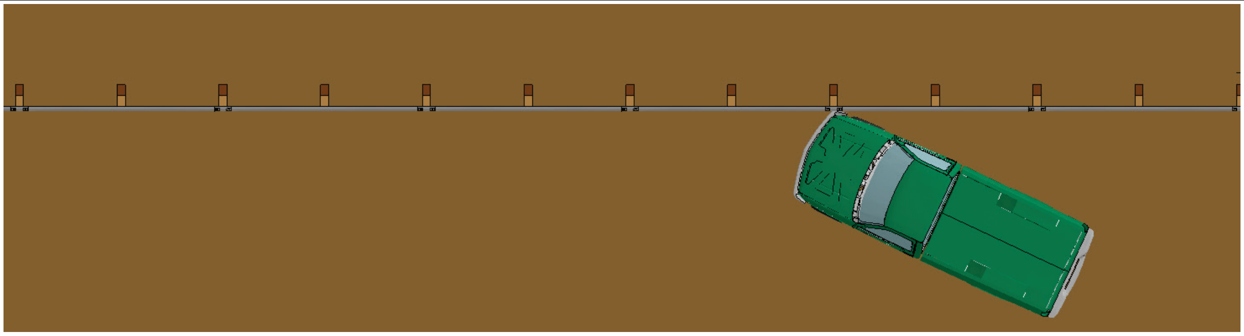
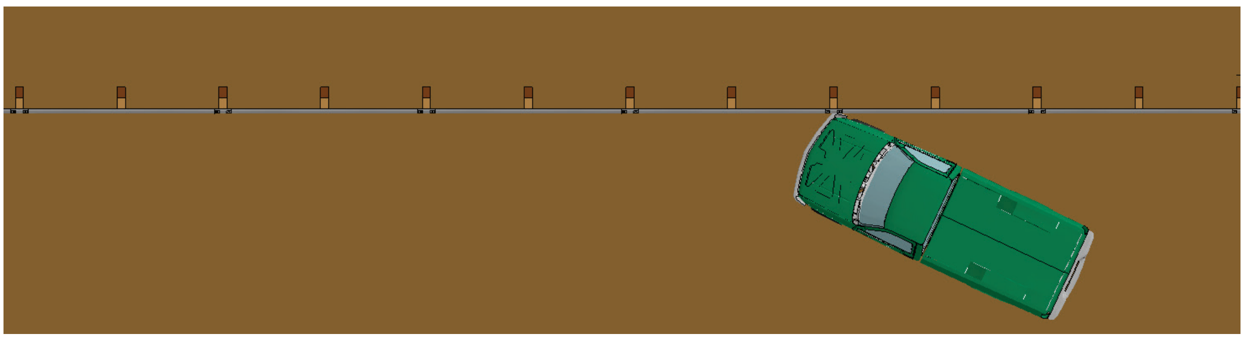
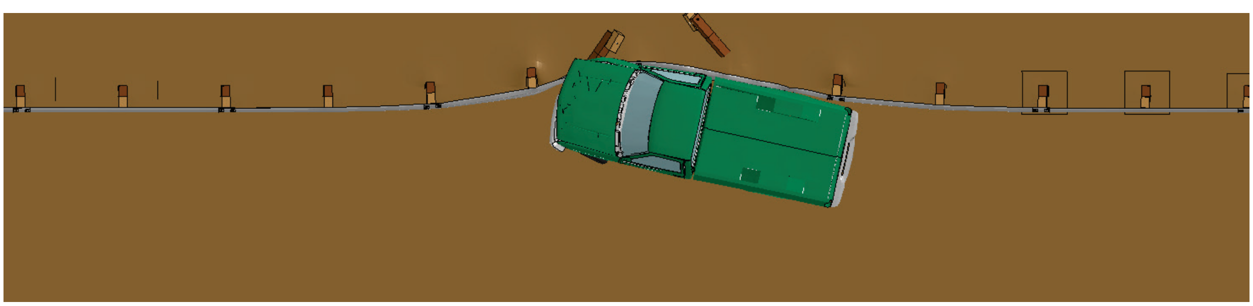
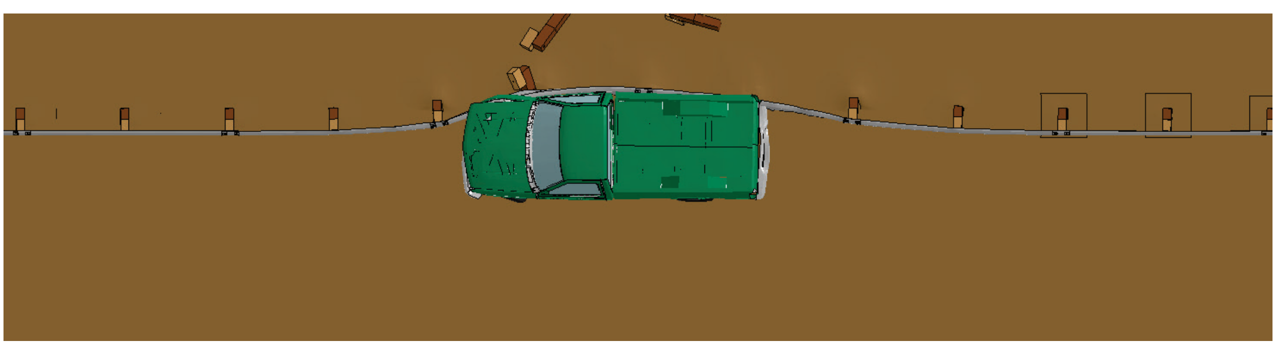
Time (sec)	FE 27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts
0.0	
0.1	
0.2	
0.3	

Table 5.5. Sequential Images of the 2000P Vehicle Interaction with the 27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts (Top View) (Continued).

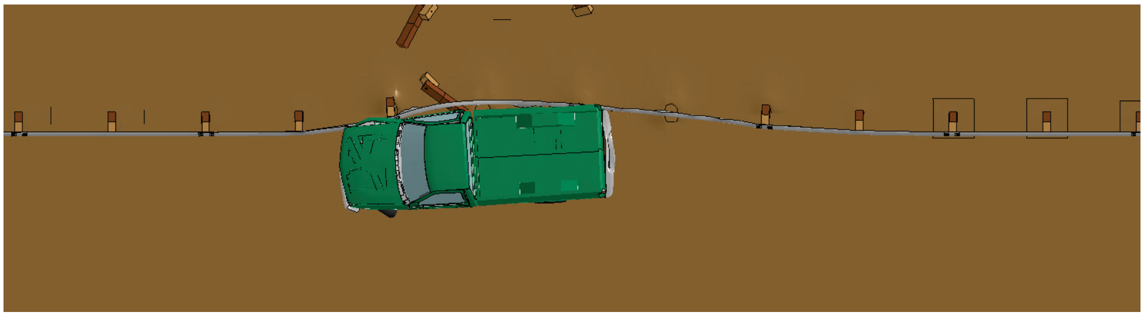
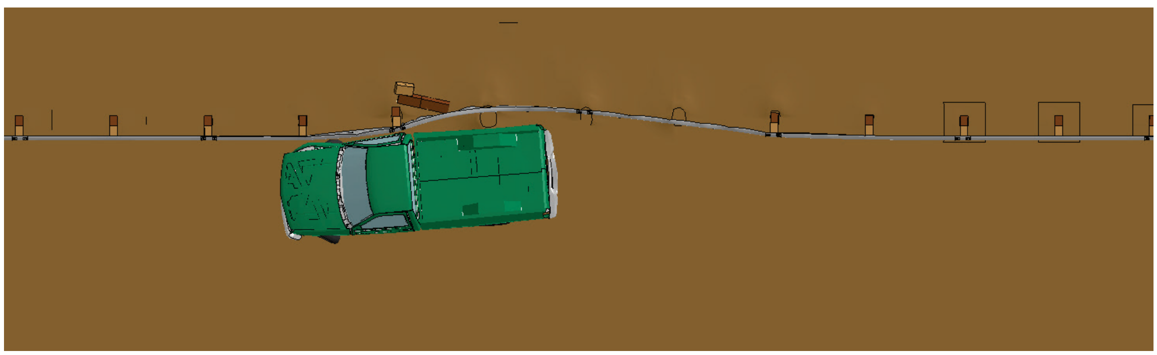
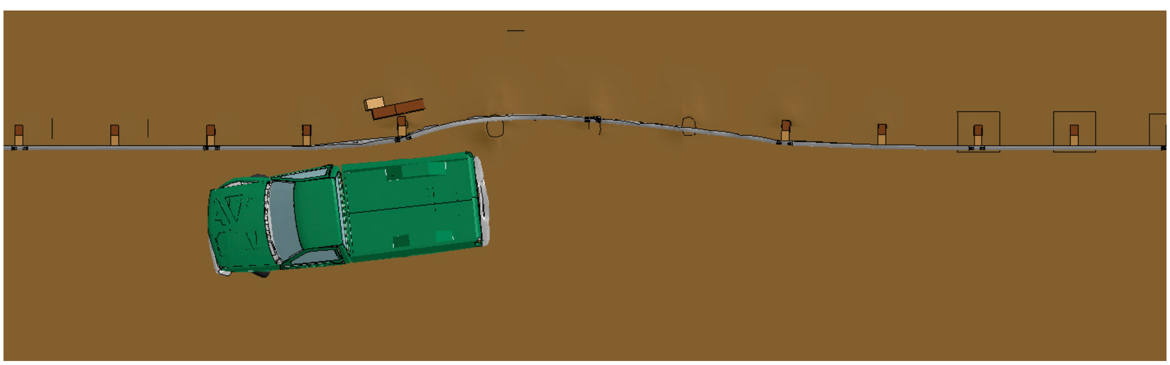
Time (sec)	FE 27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts
0.4	
0.5	
0.62	

Table 5.6. Sequential Images of the 2000P Vehicle Interaction with the 27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts (Front View).

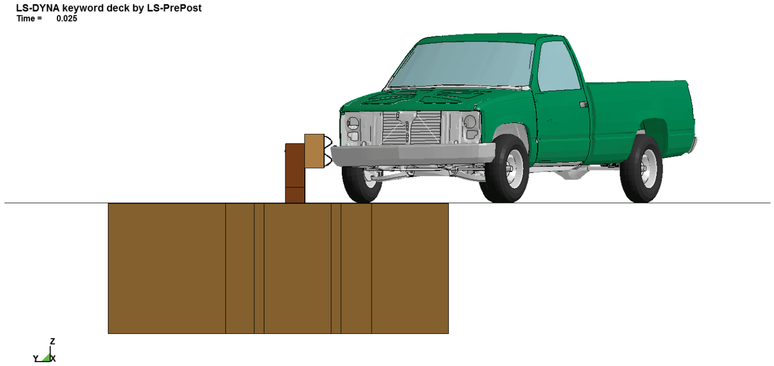
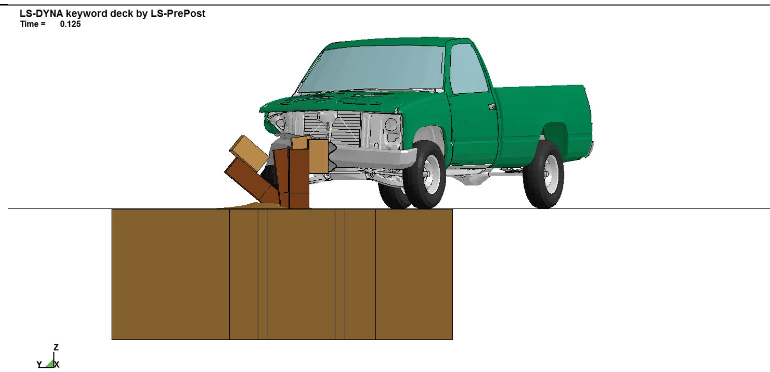
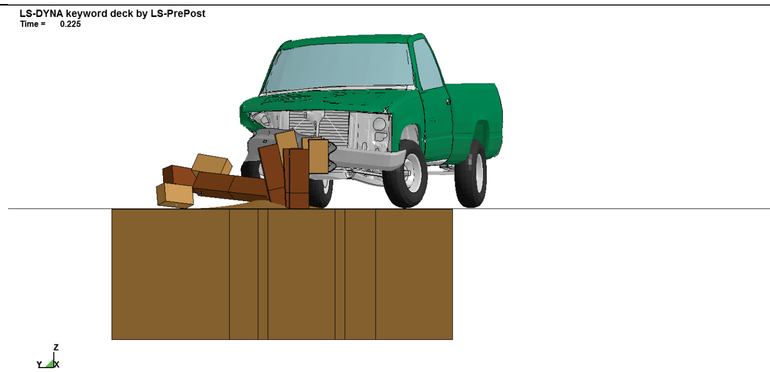
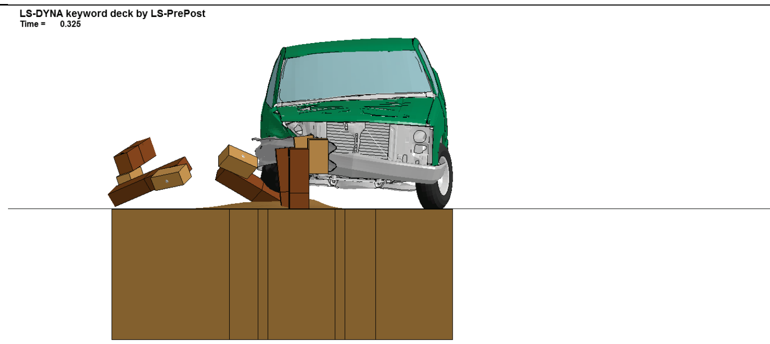
Time (sec)	FE 27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts
0.0	
0.1	
0.2	
0.3	

Table 5.6. Sequential Images of the 2000P Vehicle Interaction with the 27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts (Front View) (Continued).

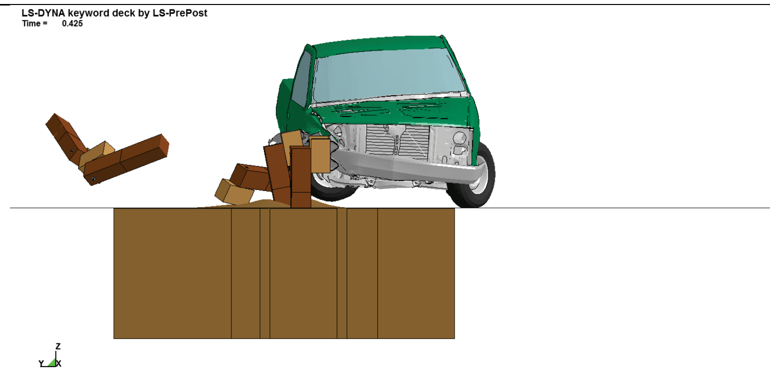
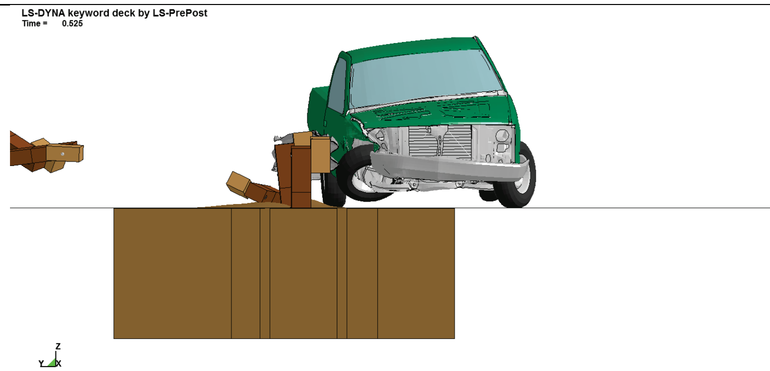
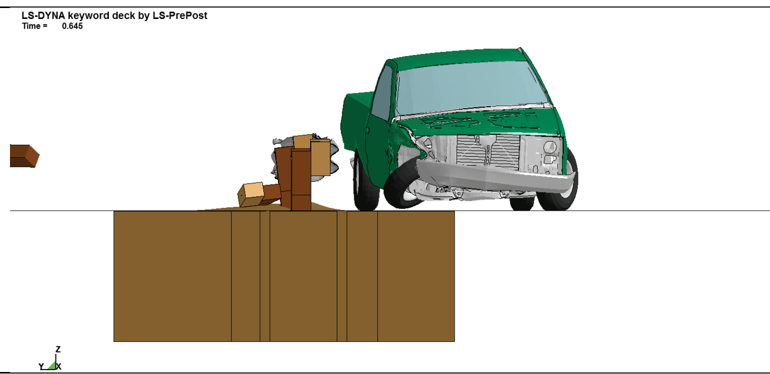
Time (sec)	FE 27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts
0.4	
0.5	
0.62	

Table 5.7. Sequential Images of the 2000P Vehicle Interaction with the 27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts (Perspective View).

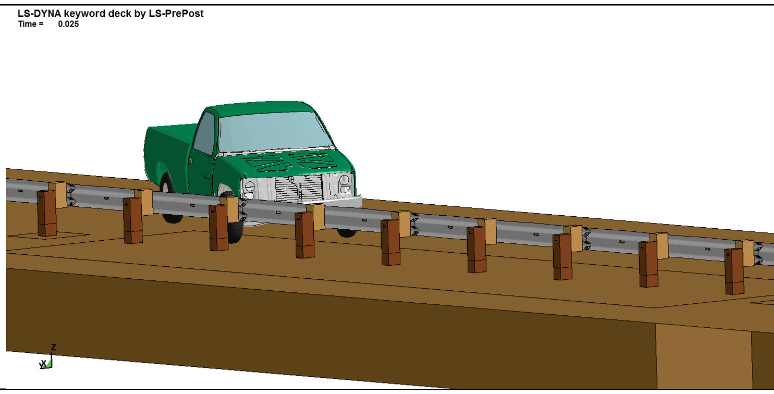
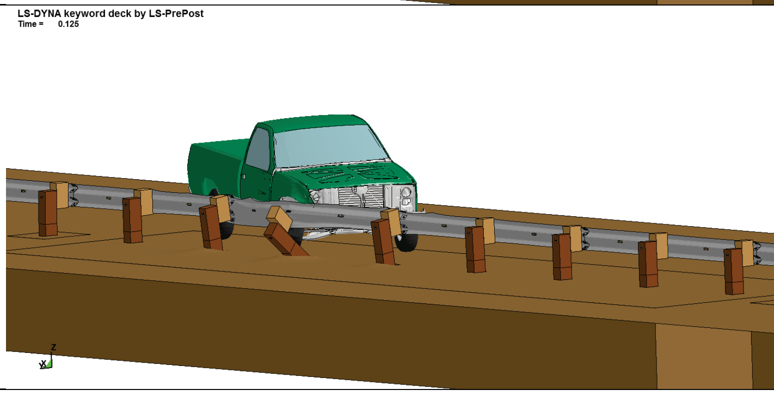
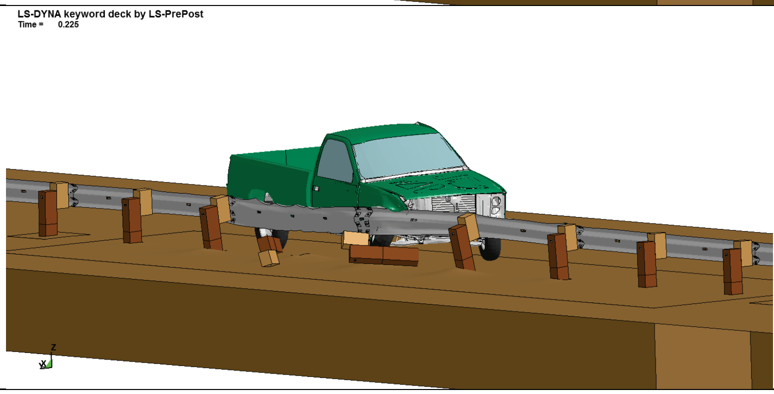
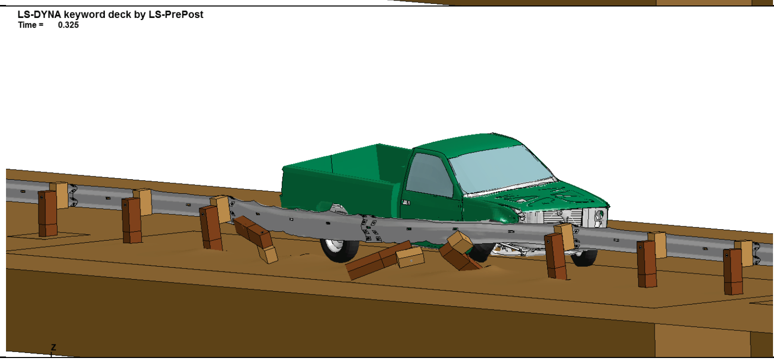
Time (sec)	FE 27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts
0.0	
0.1	
0.2	
0.3	

Table 5.7. Sequential Images of the 2000P Vehicle Interaction with the 27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts (Perspective View) (Continued).

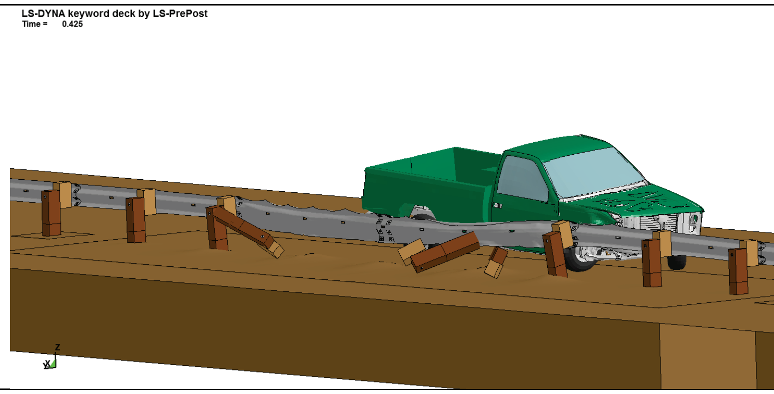
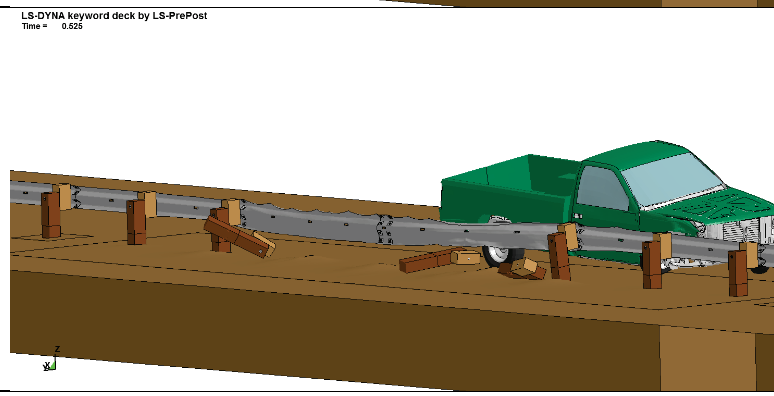
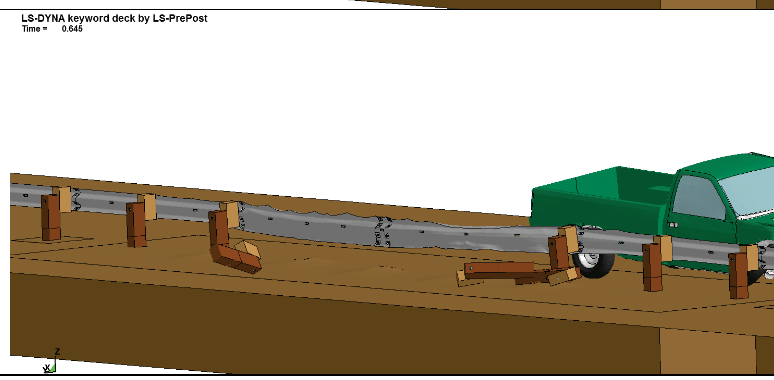
Time (sec)	FE 27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts
0.4	
0.5	
0.62	

Table 5.8. Occupant Risks Values (27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts).

Occupant Risk Factors	FE 27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts
Impact Vel. (ft/sec)	
x-direction	18.37
y-direction	-17.72
Ridedown Acc. (g's)	
x-direction	-10.6
y-direction	10.2
Angles	**FE 27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts**
Roll (deg.)	3.8
Pitch (deg.)	1.8
Yaw (deg.)	32.0

5.3.5 Plastic Strains

Figures 5.15 and 5.16 show plastic strains on the traffic and field sides of the W-beam rail, for the region of vehicle contact during the impact event. Only limited regions of high plastic strains are present. These regions of high plastic strains are localized. After reviewing the simulation, it was concluded that rail failure is unlikely.

5.3.6 Conclusions

A predictive impact simulation was performed with a 2000P vehicle at 62 mi/h and 25 degrees orientation against a 27¾-inch high rail system with 4-inch additional post embedment and 4-inch raised blockouts on posts according to the criteria set in *NCHRP Report 350*. The vehicle was contained and redirected, and maintained its stability throughout the impact event. Occupant risk values were all below the limits required by *NCHRP Report 350* criteria. The rail did not show extended regions of high plastic strain that might suggest failure of the steel W-beam. Results are summarized in Figure 5.17. In conclusion, results suggest that the practice of raising wood blockouts on wood posts for a 27¾-inch high rail system to maintain a rail height at 27¾-inch from ground appears to be crashworthy and likely to pass safety evaluation criteria required by *NCHRP Report 350*.

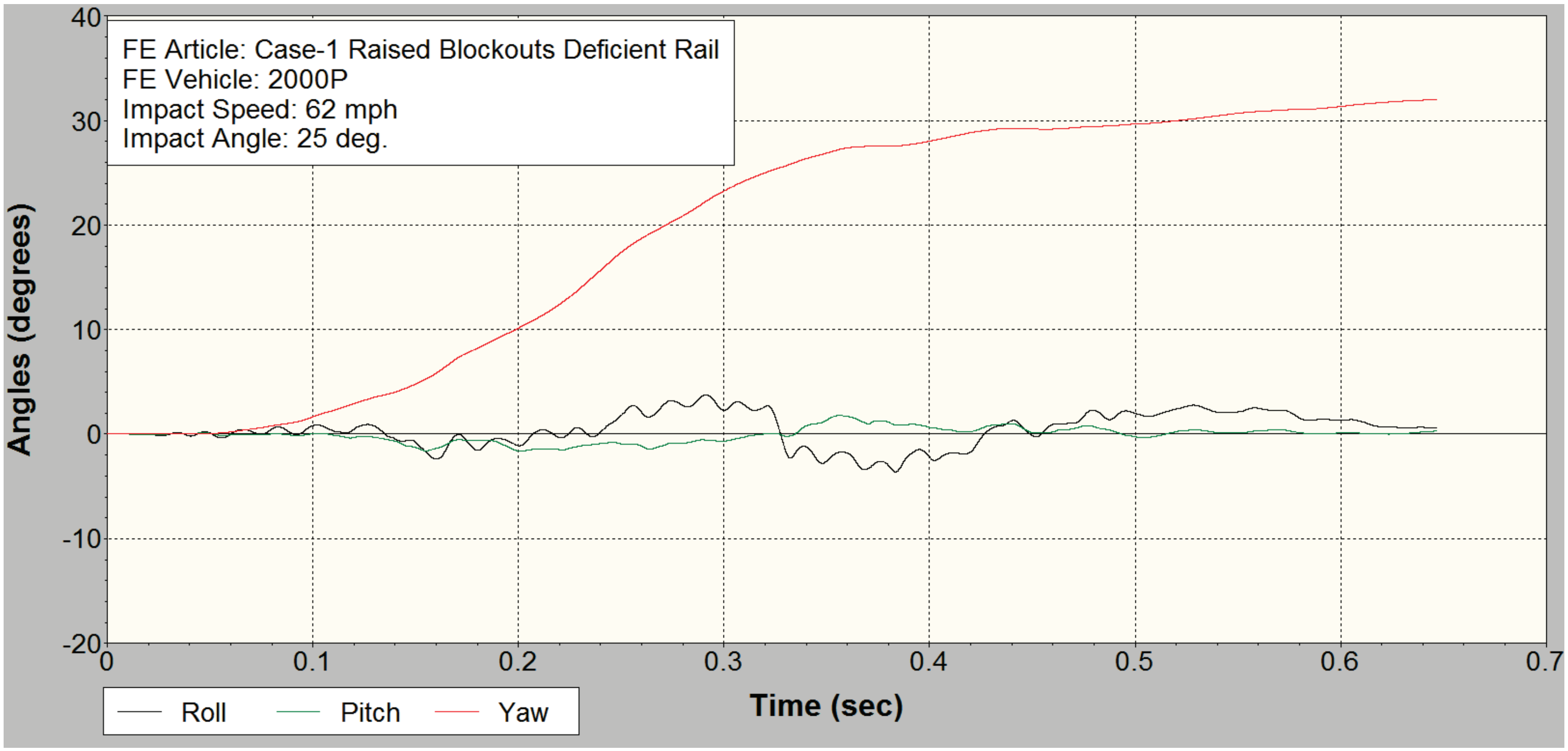


Figure 5.12. Angular Displacements for FE Simulation of the 27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts.

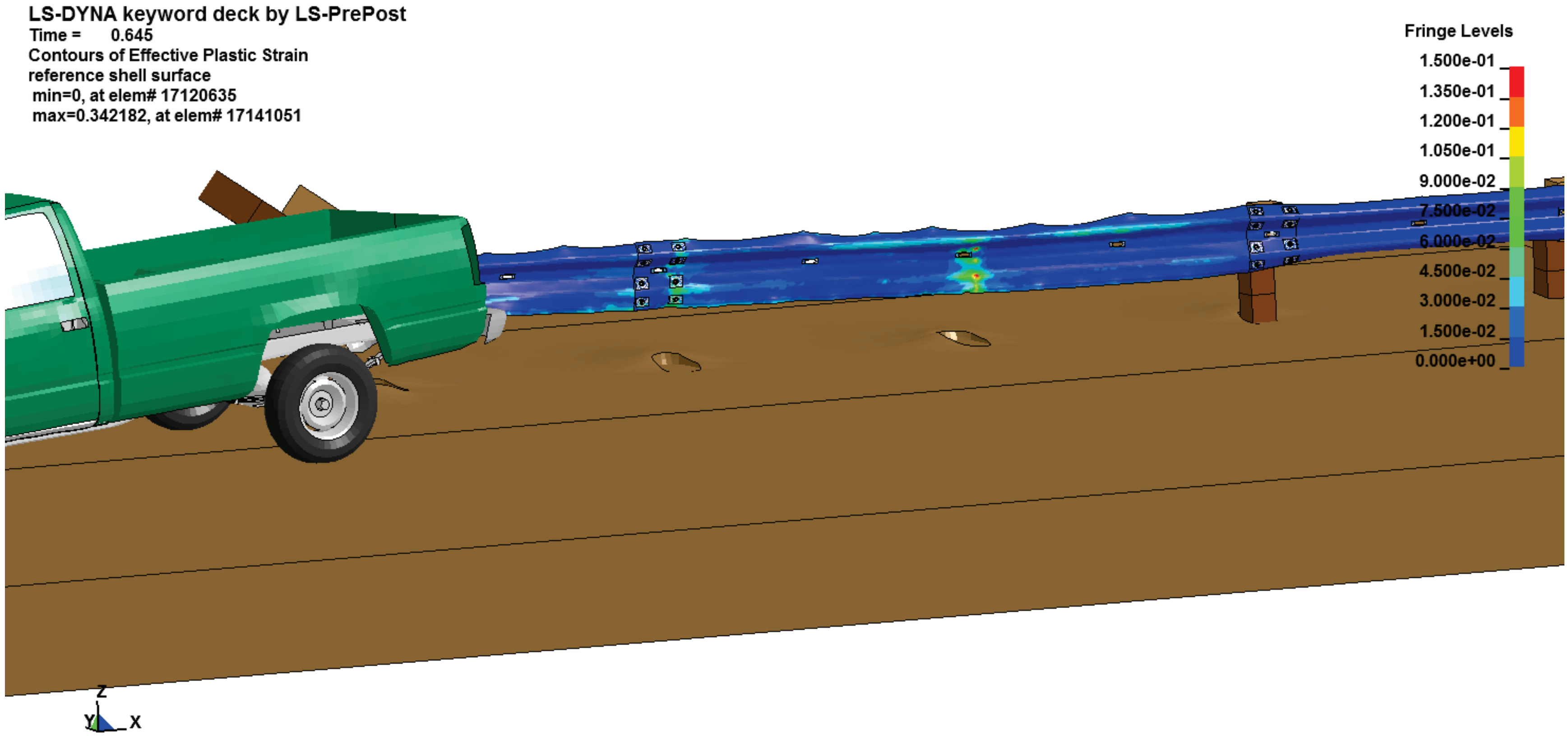


Figure 5.13. Guardrail Plastic Strains – Front View (27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts).

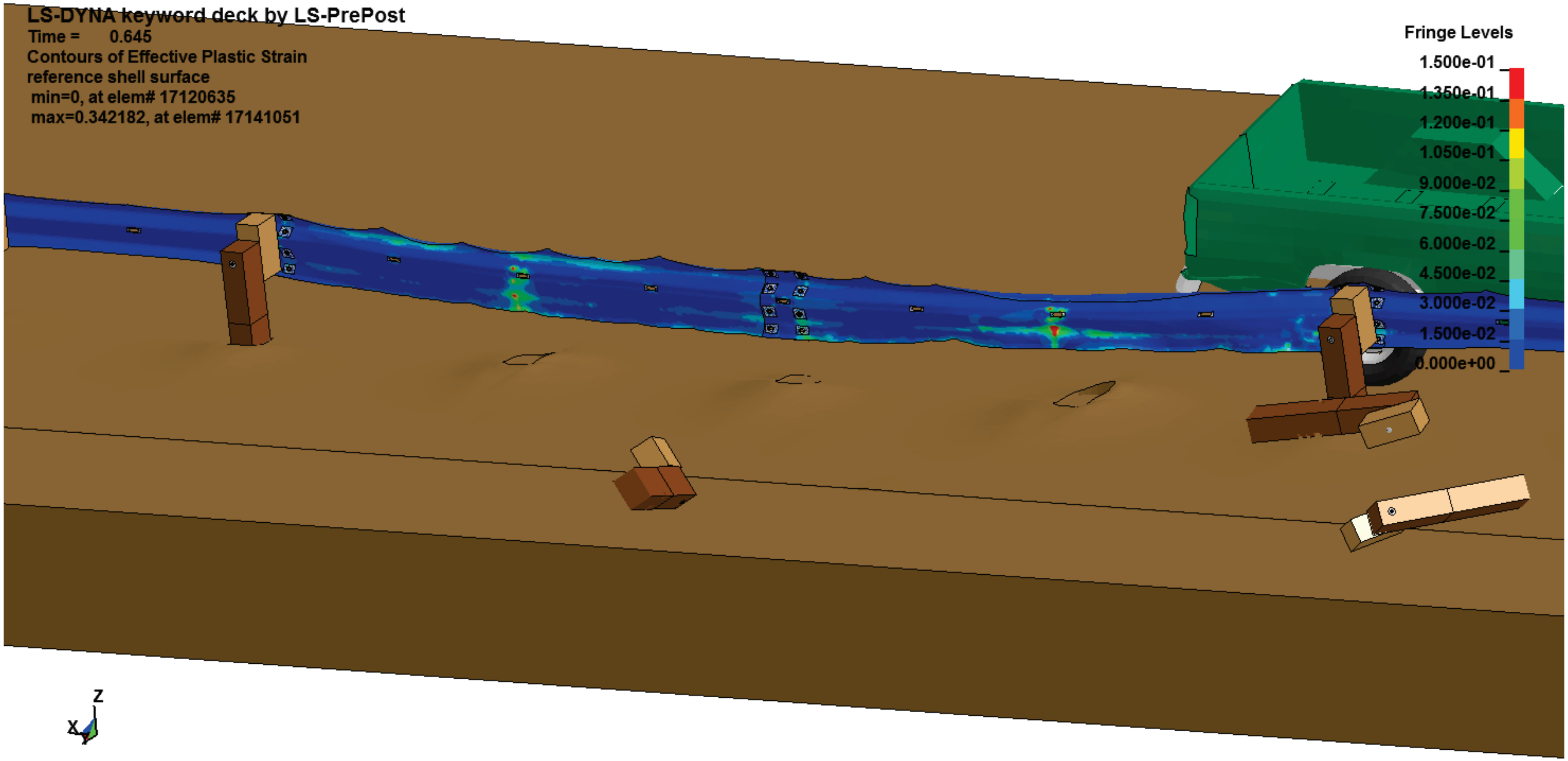
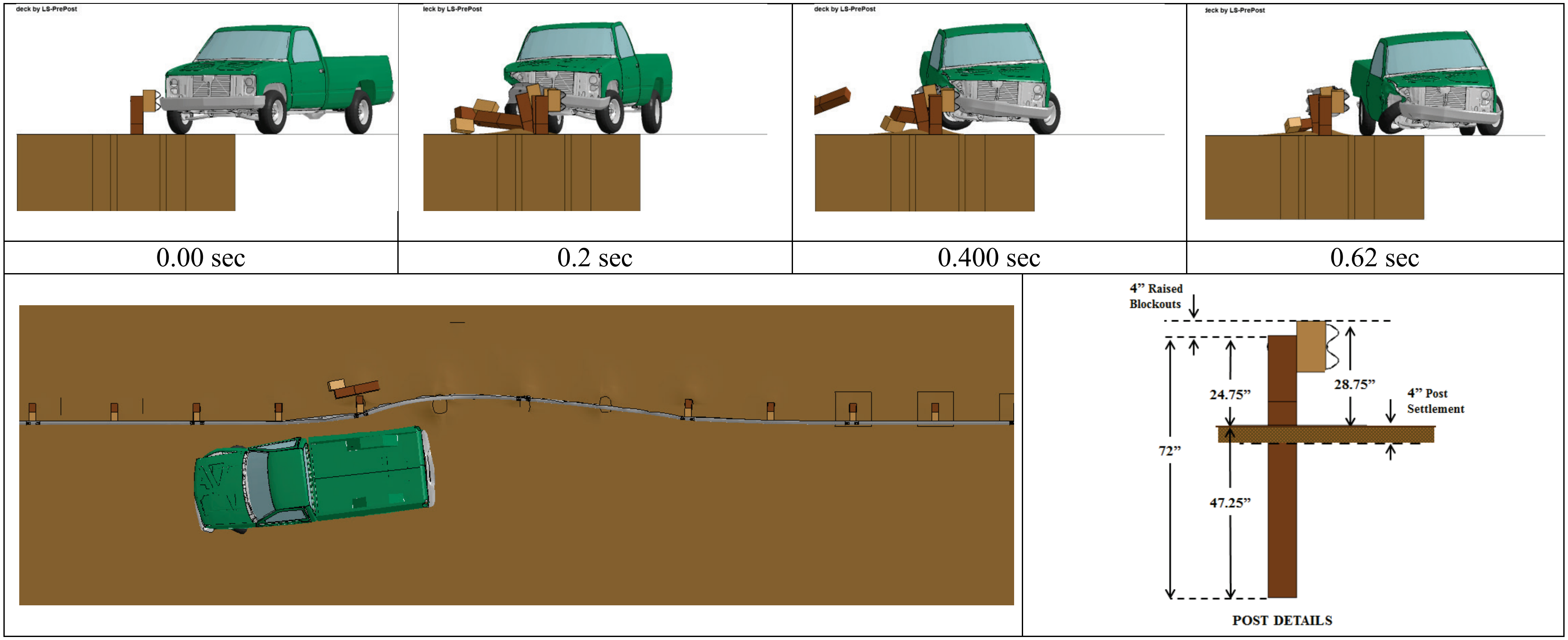


Figure 5.14. Guardrail Plastic Strains – Filed View (27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts).



General Information
Test Agency........................ Texas A&M Transportation Institute (TTI)
Test Standard Test No. .... *NCHRP Report 350* Test 3-11
Date .... N/A

Test Article
Type .... , 27¾-inch W-Beam Guardrail, 4-inch Additional Post Embedment, 4-inch Raised Blockouts
Installation Length .... 150 ft
Material or Key Elements.... W-Beam, 27¾-inch Rail Height, Wood Blockout, Wood Post, Raised Blockouts

Test Vehicle
Type/Designation 2000P
Weight................................ 2000 lbs
Dummy............................... No Dummy

Impact Conditions
Speed......................................62.0 mi/h
Angle......................................25 degrees
Location/Orientation ....12.3 ft Upstream of Post

Post-Impact Trajectory
Stopping Distance............ N/A

Occupant Risk Values
Impact Velocity (ft/sec)
x-direction…………………. 18.37
y-direction…………………. -17.72
Ridedown Acceleration (g)
x-direction ....-10.6
y-direction 10.2

Vehicle Stability
Maximum Yaw Angle .... 32.0 degrees
Maximum Pitch Angle .... 1.8 degrees
Maximum Roll Angle.................... 3.8degrees
Vehicle Snagging .... No

Vehicle Damage
VDS ....N/A
CDC ....N/A
Max. Exterior Deformation ....N/A
OCD..< 150.8 N/m Floorboard Internal Energy

Max. Occupant Compartment Deformation.............................N/A

Figure 5.15. Summary of Results for *NCHRP 350* Test 3-11 simulation (27¾-inch Rail Height with Height Deficiency and 4-inch Raised Blockouts).

5.3 27¾-inch Rail Height with 4-inch Pavement Overlay and 4-inch Raised Blockouts

5.3.1 Computer Model Description

An FE model of 27¾-inch high W-beam guardrail system with wood posts and wood blockouts was developed. The system was modified to include 4 inches of overlay in front of the post. The 4-inch overlay was terminated in front of the guardrail following TxDOT guidelines. To maintain the original height of the rail after overlay, the wood blockouts were raised 4 inches with respect to the posts. Post embedment remained 43¼ inches, as in the original rail system installation. Details of the rail system with 4-inch pavement overlay and 4-inch raised blockouts are included in Figure 5.16.

The FE test installation consisted of 150 ft of standard 12-gauge W-beam supported by wood posts. The system was built with twenty-five posts spaced at 75 inches on center. The posts were 6-inch × 8-inch × 72-inch long with wood properties and a soil embedment depth of 43¼ inches. Failure properties were given to the posts to allow elements to erode after reaching a predefined principal stress value. A 6-inch × 8-inch × 14¼-inch spacer blockout was used to block the rail away from the front face of each post. LS-DYNA soil material model *MAT_JOINTED_ROCK was used to simulate soil properties for soil-post interaction. Standard 12 ft-6 in long 12-gauge W-beam rails were modeled. The W-beam top rail height was 27¾ inches with a 21⅞-inch center mounting height. The rail splices were placed at post locations, and were configured with the upstream segment in front to minimize vehicle snag at the splice during the impact event simulation.

Researchers used the NCAC finite element 2000P pickup truck model in the impact simulation (NCAC, 2005). Some parts of the 2000P pickup truck model needed mesh refinement to avoid contact issues during the impact event against the finer meshed guardrail model.

This system was evaluated according to *NCHRP Report 350* Test 3-11 impact conditions and evaluation criteria.

5.3.2 Barrier Performance (All Contacts)

Figure 5.17 contains images of the barrier before impact and at final configuration. Figure 5.17(a) and 5.17(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 5.17(b) and 5.17(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. The barrier was impacted 13.3 ft from the beginning of the guardrail system, with initial speed and angle of 62 mi/h and 25 degrees, respectively.

The vehicle was contained and redirected during the impact event. Failure properties were applied to the posts of the guardrail system. A total of three posts were broken as a consequence of the impact with the 2000P vehicle. The dynamic and permanent deflections of the guardrail system in the FE model were 2.89 ft and 1.72 ft, respectively.

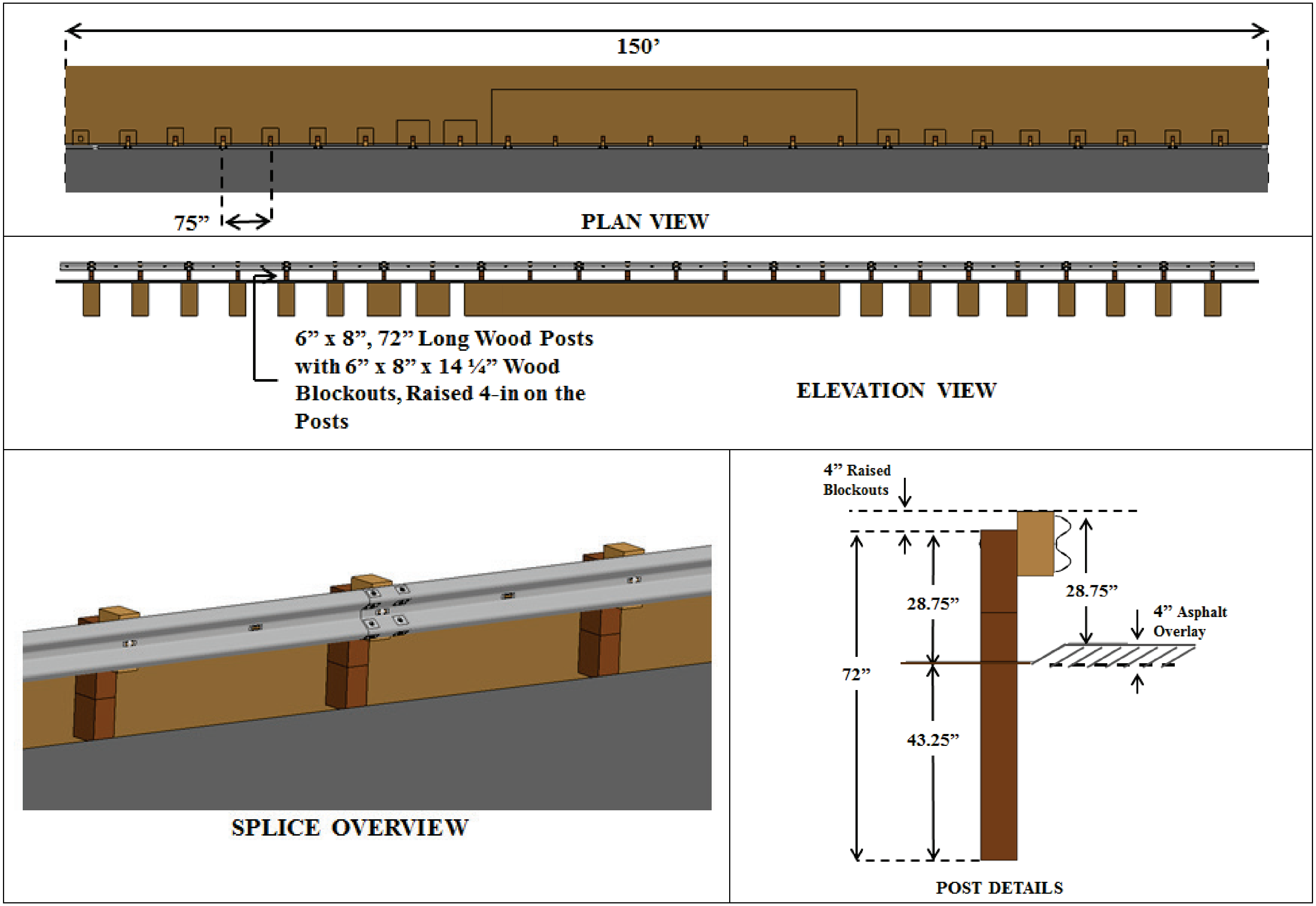
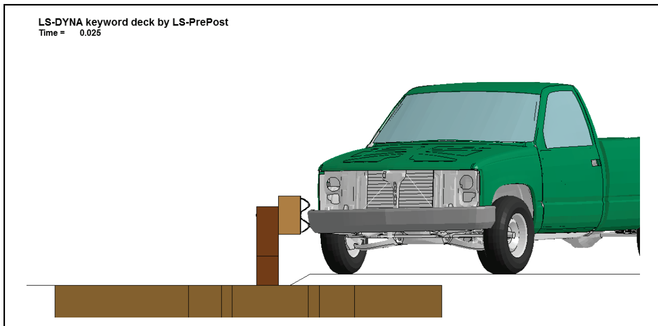
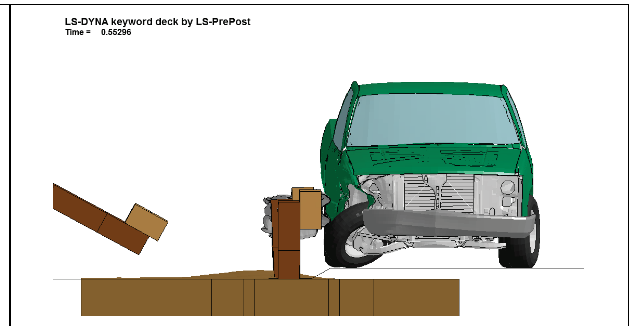


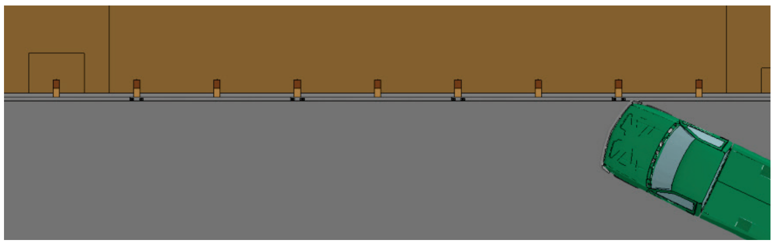
Figure 5.16. Details of the 27¾-inch Guardrail Height Installation with 4-inch Pavement Overlay and 4-inch Raised Blockouts.



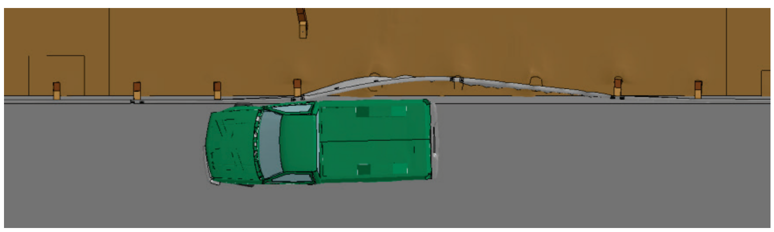
(a) Front View At Impact



(b) Front View At Final Configuration



(c) Top View At Impact



(d) Top View At Final Configuration

Figure 5.17. Initial and Deflected Shape of Barrier (27¾-inch Rail Height with 4-inch Pavement Overlay and 4-inch Raised Blockouts).

5.3.3 Energy Values

Since this is a closed system and energy is conserved, the sum of the kinetic energy, hourglass energy, sliding energy, and internal energy at any time during the simulation should equate to the initial kinetic energy of the vehicle. As shown in Figure 5.18, approximately 35 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). Less than four percent of the initial kinetic energy is converted into hourglass energy. Approximately 34 percent of the initial kinetic energy is converted into sliding interface energy. Twenty three percent of the initial kinetic energy has yet to be dissipated by the system at the time of final impact configuration, mainly due to the remaining velocity of the vehicle.

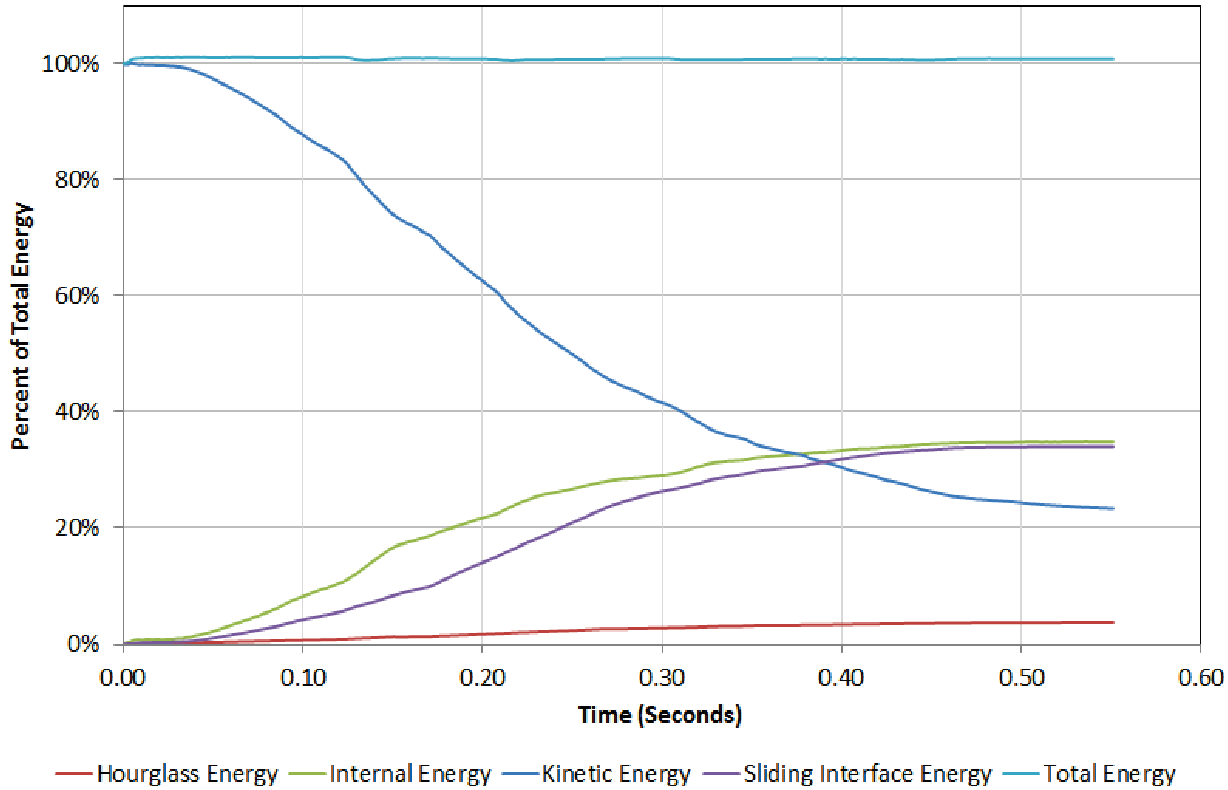


Figure 5.18. Energy Distribution Time History (27¾-inch Rail Height with 4-inch Pavement Overlay and 4-inch Raised Blockouts).

Tables 5.9 and 5.10 show frames from the computer simulation impact event against the 27¾-inch high W-beam guardrail with 4-inch pavement overlay and 4-inch raised blockouts.

5.3.4 Occupant Risk Assessment

The TRAP program was used to evaluate occupant risk factors based on the applicable *NCHRP Report 350* safety evaluation criteria. The modeled 2000P vehicle remained upright during and after the modeled collision event. Table 5.11 provides a summary of results for the 27¾-inch W-beam guardrail with 4-inch raised blockouts and 4-inch asphalt overlay. Maximum roll, pitch and yaw angles were 6.4, 3.0, and 26.8 degrees respectively. Occupant impact velocities were 17.06 ft/sec and -16.4 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were –15.4 g and 10.9 g in the longitudinal and lateral directions, respectively. Angular displacement curves are reported in Figure 5.19.

Table 5.9. Sequential Images of the 2000P Vehicle Interaction with the 27¾-inch Guardrail Height with 4-inch Pavement Overlay and 4-inch Raised Blockouts (Top View).

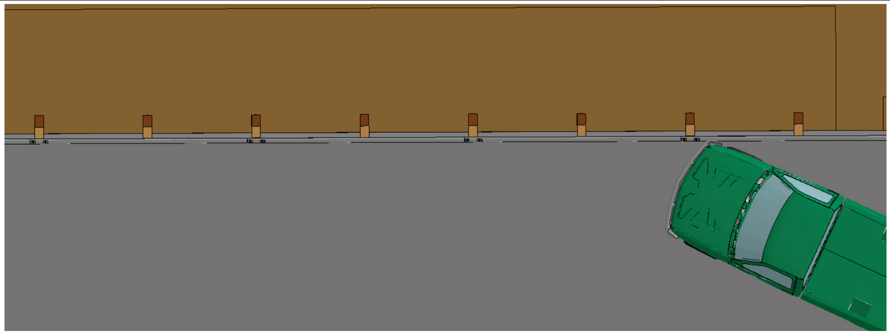
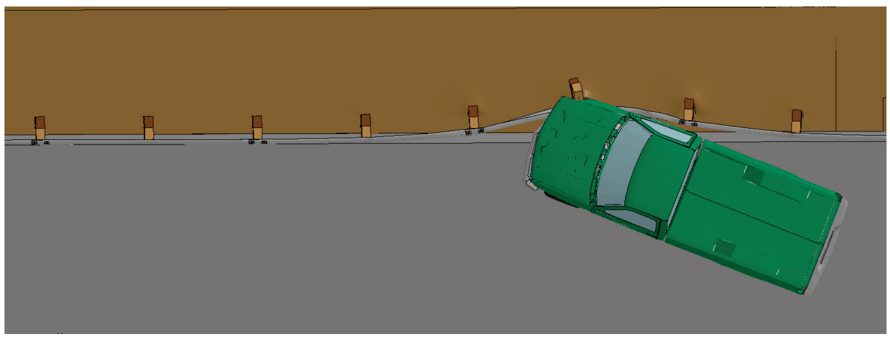
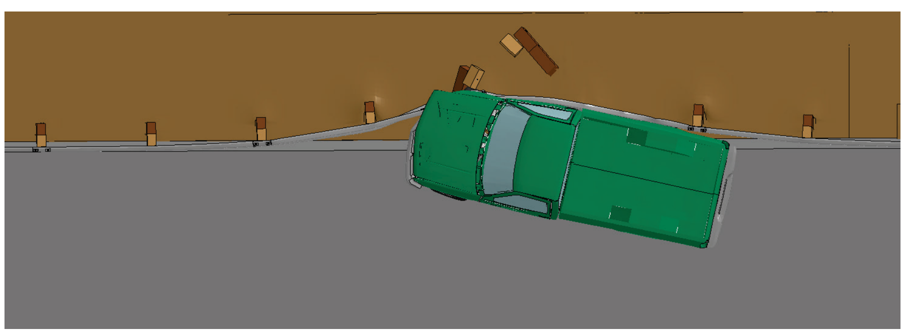
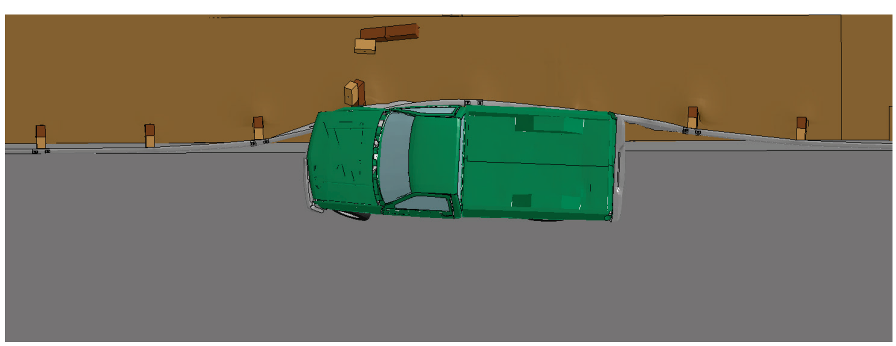
Time (sec)	FE 27¾-inch Rail System with 4-inch Pavement Overlay and 4-inch Raised Blockouts
0.000	
0.100	
0.200	
0.300	

Table 5.9. Sequential Images of the 2000P Vehicle Interaction with 27¾ inch Guardrail Height with 4-inch Pavement Overlay and 4-inch Raised Blockouts (Top View) (Continued).

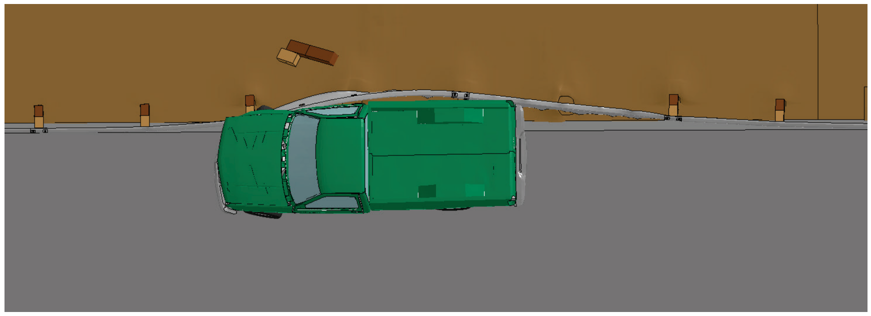
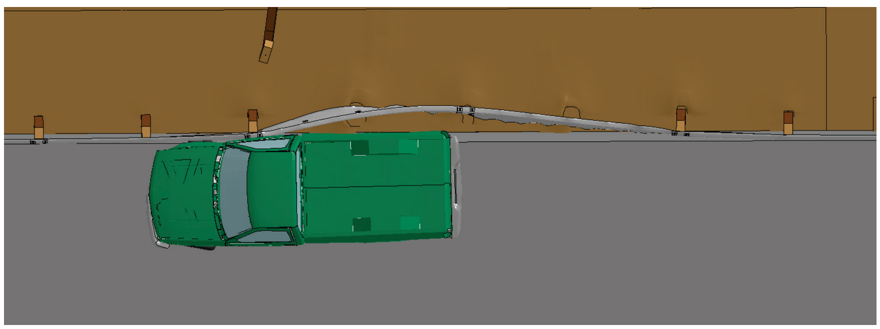
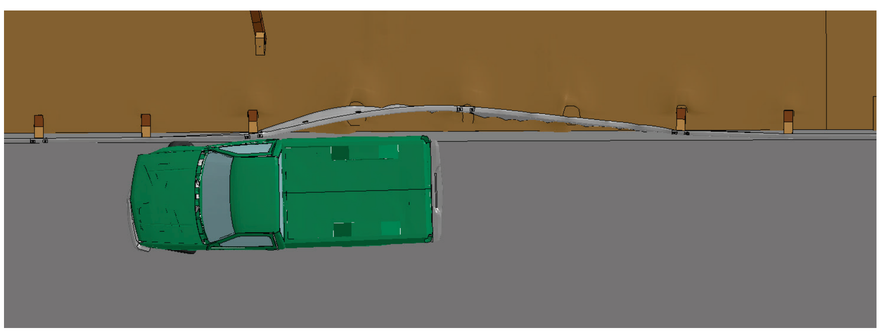
Time (sec)	FE 27¾-inch Rail System with 4-inch Pavement Overlay and 4-inch Raised Blockouts
0.400	
0.500	
0.528	

Table 5.10. Sequential Images of the 2000P Vehicle Interaction with the 27¾-inch Guardrail Height with 4-inch Pavement Overlay and 4-inch Raised Blockouts (Front View).

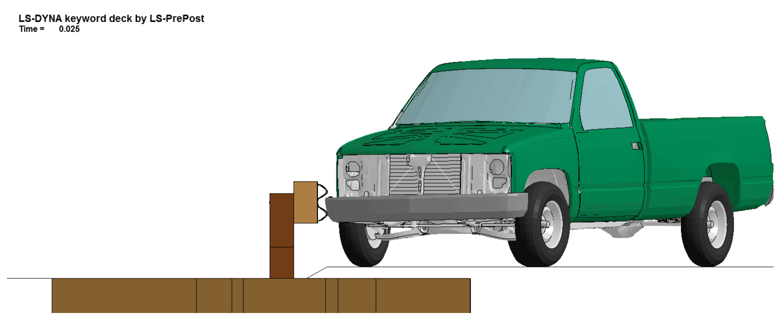
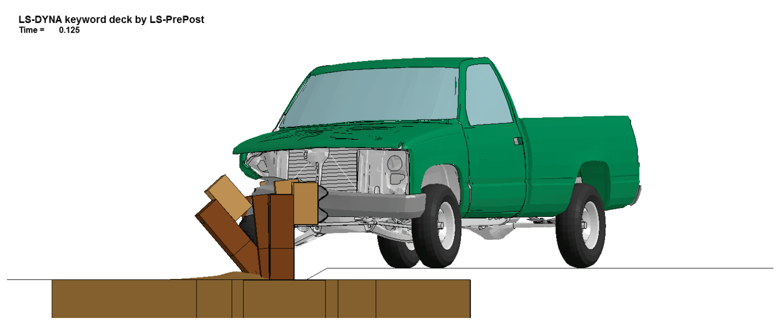
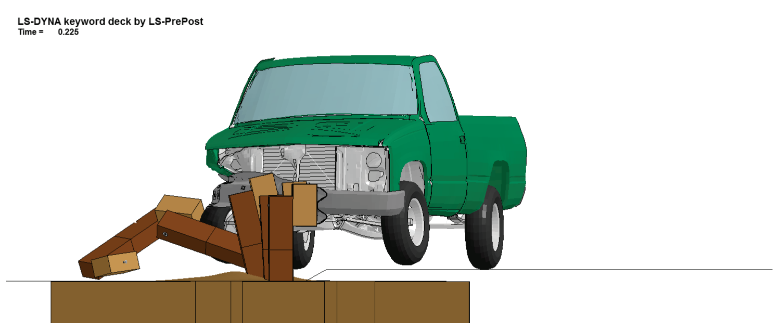
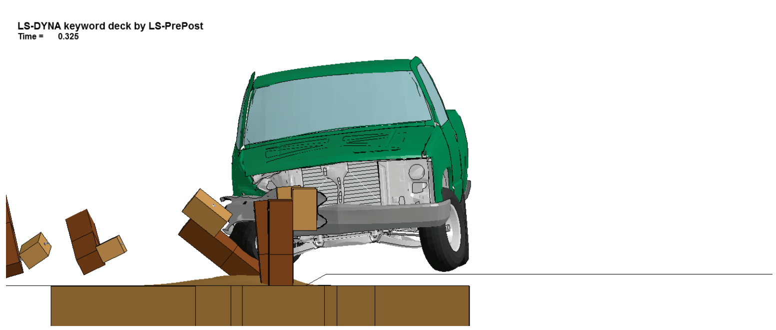
Time (sec)	FE 27¾-inch Rail System with 4-inch Pavement Overlay and 4-inch Raised Blockouts
0.000	
0.100	
0.200	
0.300	

Table 5.10. Sequential Images of the 2000P Vehicle Interaction with the 27¾-inch Guardrail Height with 4-inch Pavement Overlay and 4-inch Raised Blockouts (Front View) (Continued).

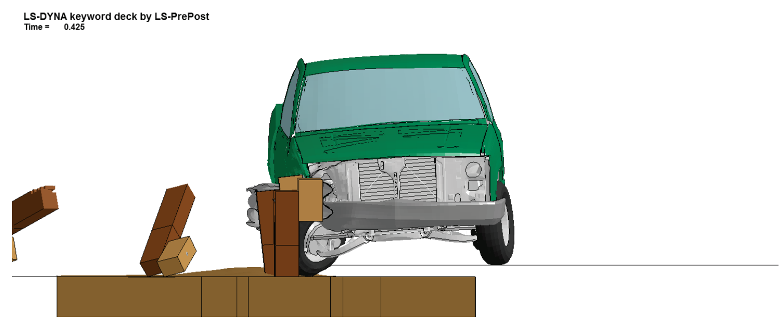
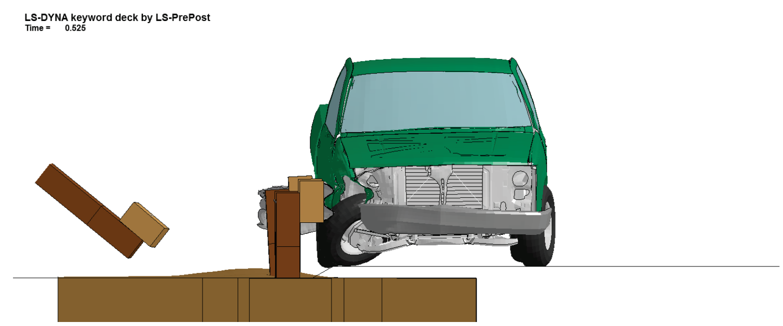
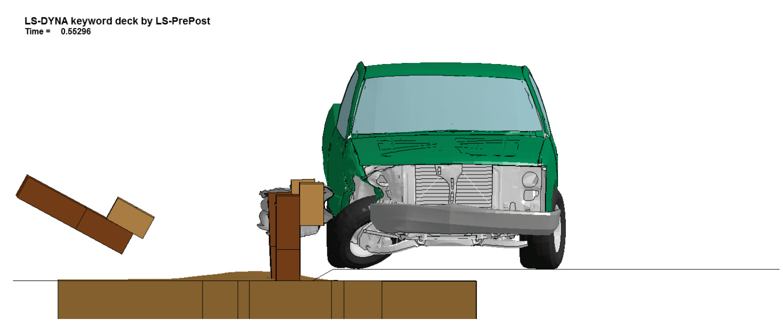
Time (sec)	FE 27 ¾-inch Rail System with 4-inch Pavement Overlay and 4-inch Raised Blockouts
0.400	
0.500	
0.528	

Table 5.11. Occupant Risks Values (27¾-inch Rail Height with 4-inch Pavement Overlay and 4-inch Raised Blockouts).

Occupant Risk Factors	**FE 27¾-inch Rail System with 4-inch Pavement Overlay and 4-inch Raised Blockouts**
Impact Vel. (ft/sec)	
x-direction	17.06
y-direction	-16.4
Ridedown Acc. (g's)	
x-direction	-15.4
y-direction	10.9
Angles	**FE 27¾-inch Rail System with 4-inch Pavement Overlay and 4-inch Raised Blockouts**
Roll (deg.)	6.4
Pitch (deg.)	3.0
Yaw (deg.)	26.8

5.3.5 Plastic Strains

Figures 5.20 and 5.21 show the plastic strains on the traffic and field sides of the W-beam rail, respectively, along the region of contact with the vehicle during the impact event. Only limited regions of high plastic strains are present. These regions of high plastic strains are localized. After reviewing the simulation, it was concluded that rail failure is unlikely.

5.3.6 Conclusions

A predictive impact simulation was performed with a 2000P vehicle at 62 mi/h and 25 degrees orientation against a 27¾-inch high rail system with 4-inch pavement overlay in front of the post and 4-inch raised blockouts on posts according to the criteria set in *NCHRP Report 350*. The vehicle was contained and redirected, and maintained its stability throughout the impact event. Occupant risk values were all below the limits required by *NCHRP Report 350* criteria. The rail did not show extended regions of high plastic strain that might suggest failure of the steel W-beam. Results are summarized in Figure 5.22. In conclusion, results suggest that the practice of raising wood blockouts on wood posts for a 27¾-inch high rail system to maintain the rail height at 27¾ inches from the pavement overlay appears to be crashworthy and likely to pass safety evaluation criteria required by *NCHRP Report 350*.

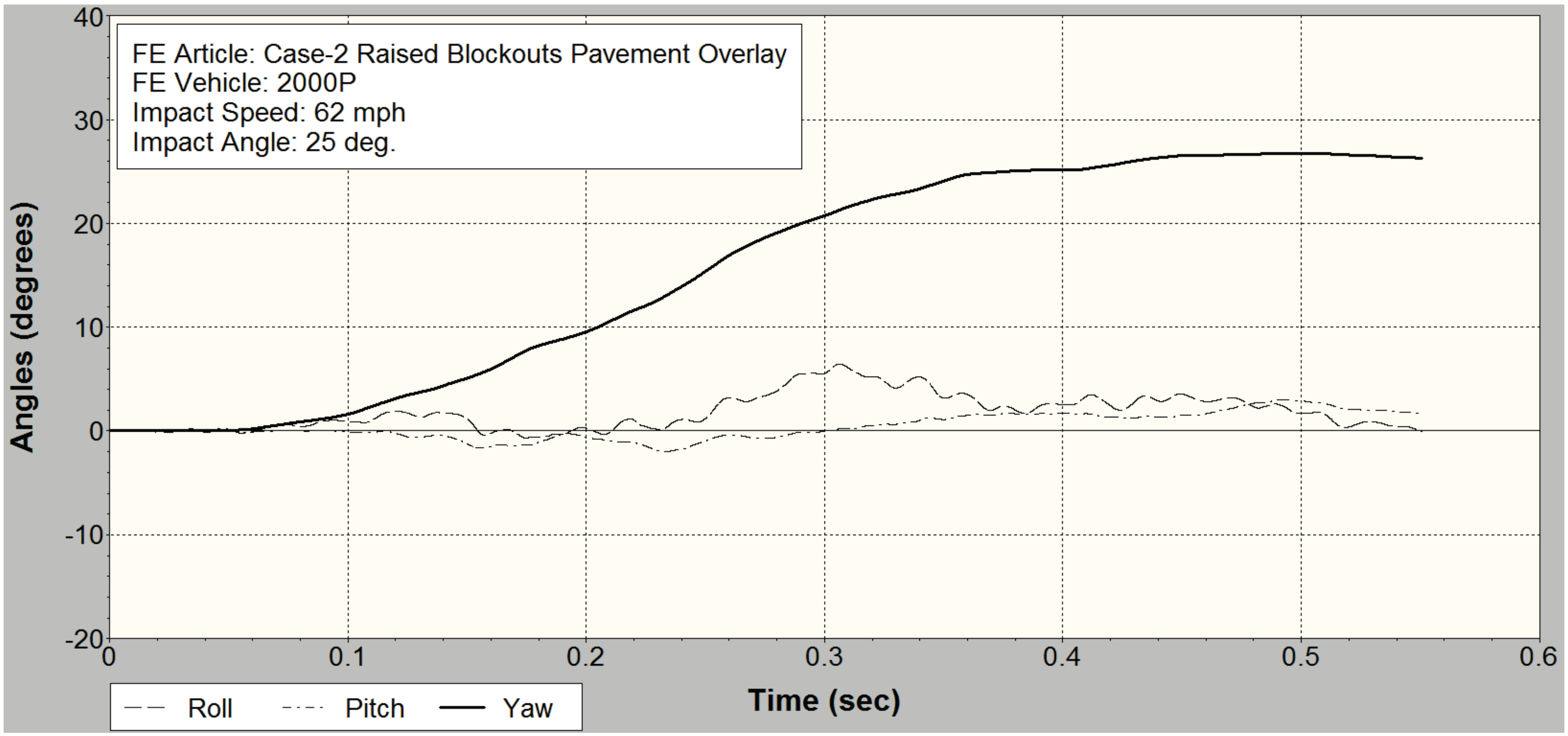


Figure 5.19. Angular Displacements for FE Simulation 27¾-inch Guardrail Height with 4-inch Pavement Overlay and 4-inch Raised Blockouts.

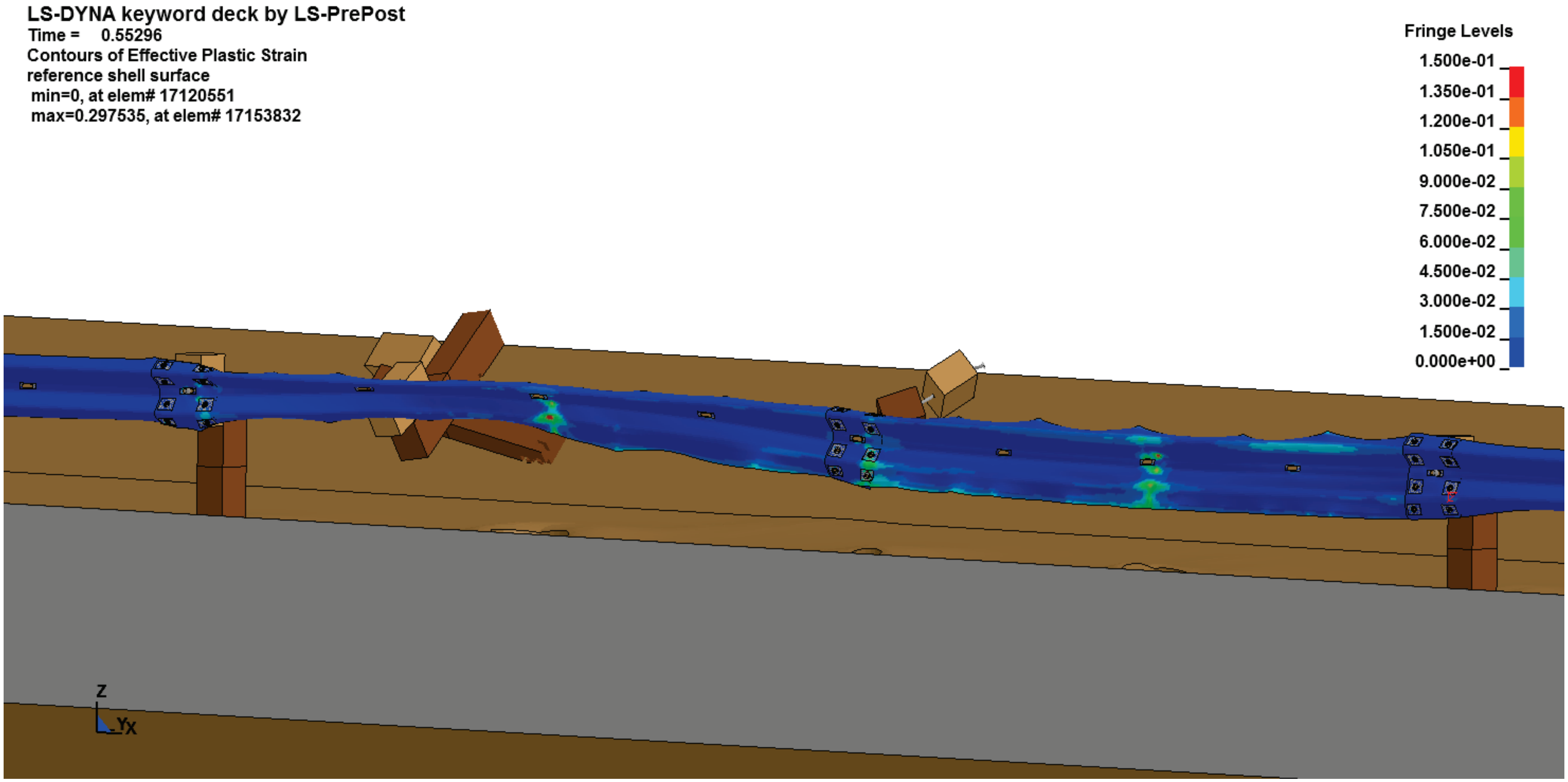


Figure 5.20. Guardrail Plastic Strains – Front View (27¾-inch Rail Height with 4-inch Pavement Overlay and 4-inch Raised Blockouts).

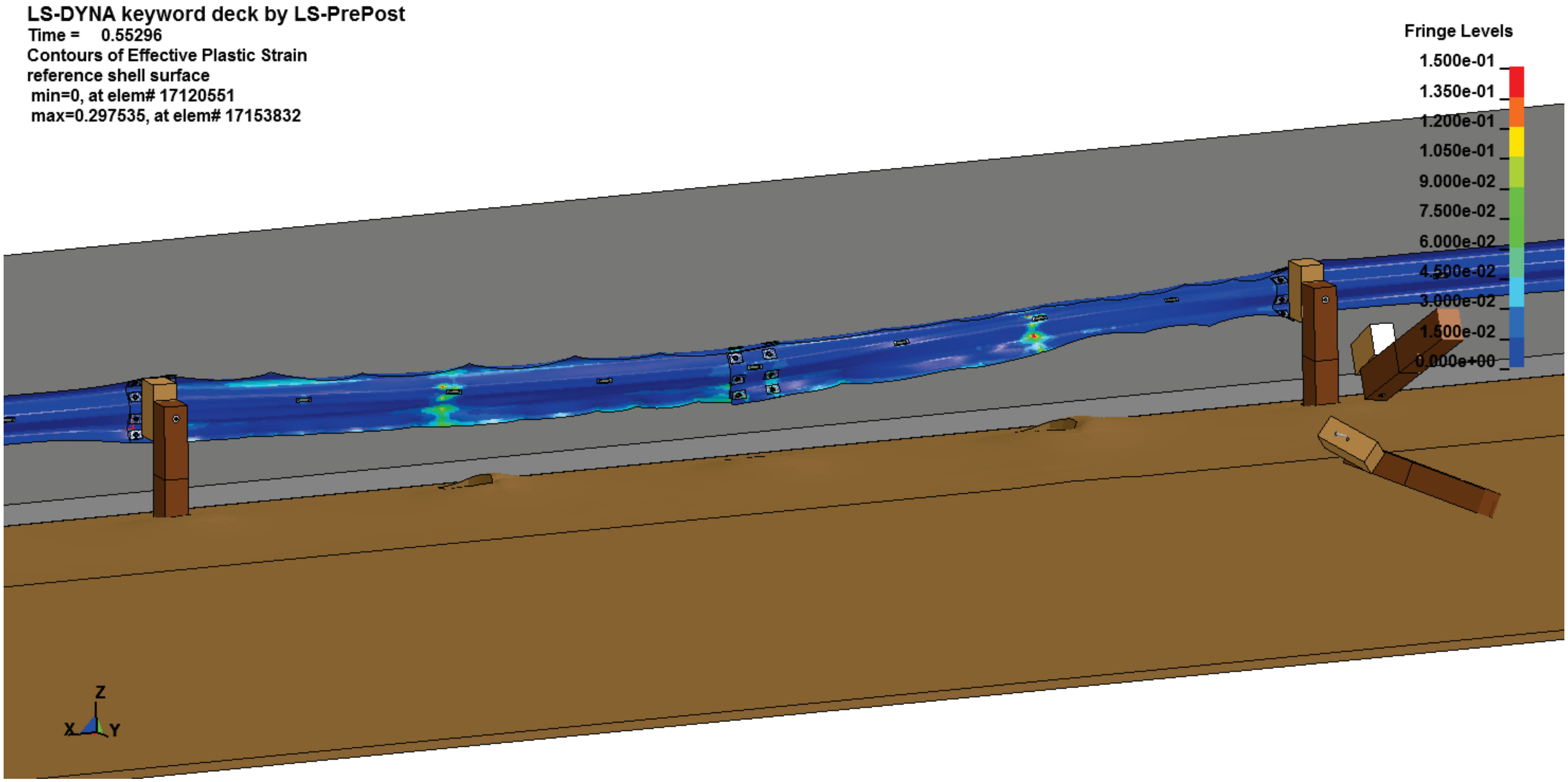
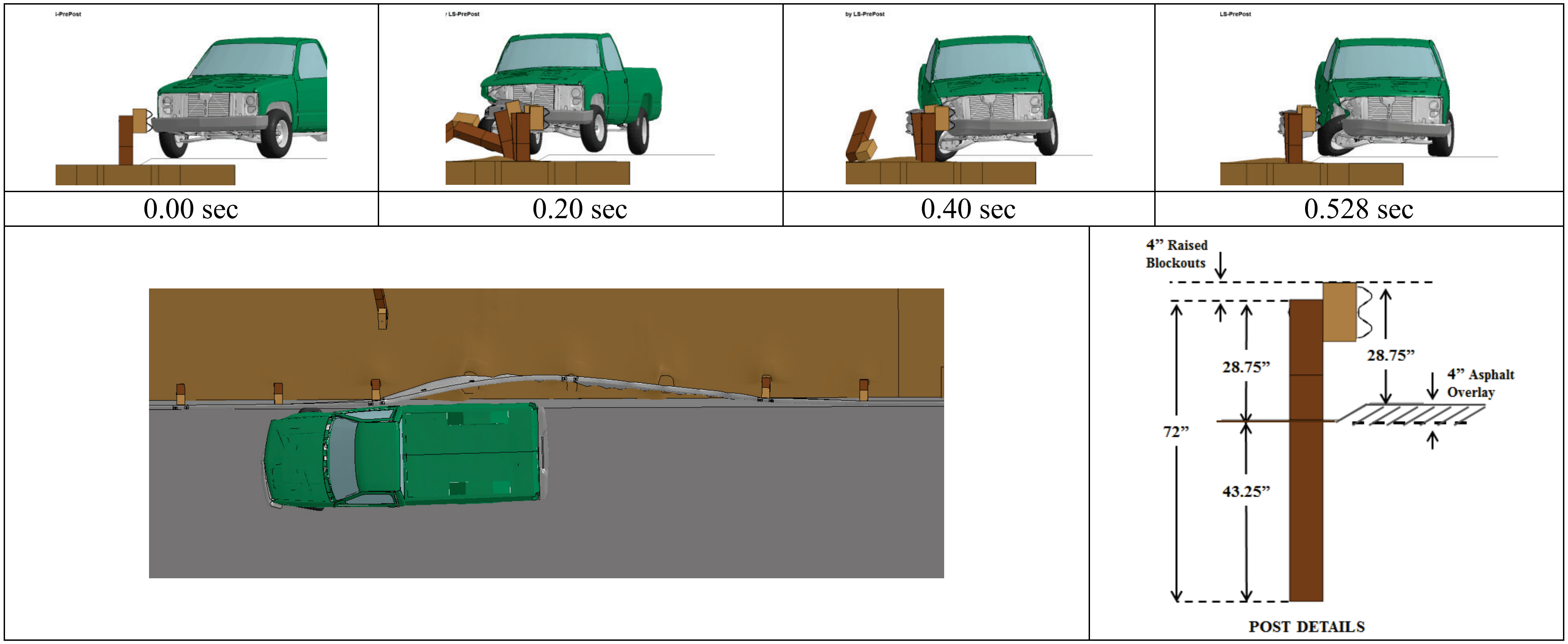


Figure 5.21. Guardrail Plastic Strains – Field View (27¾-inch Rail Height with 4-inch Pavement Overlay and 4-inch Raised Blockouts).



General Information
Test Agency.......................... Texas A&M Transportation Institute (TTI)
Test Standard Test No. .... *NCHRP Report 350* Test 3-11
Date .... N/A

Test Article
Type .... 27¾-in W-Beam Rail, 4-inch Raised Blockouts, 4-inch Pavement Overlay
Installation Length .... 150 ft
Material or Key Elements..... W-Beam, 27¾-in Rail, Wood Blockout, Raised Blockouts, Pavement Overlay

Test Vehicle
Type/Designation 2000P
Weight................................. 2000 lbs
Dummy................................ No Dummy

Impact Conditions
Speed .... 62.0 mi/h
Angle .... 25 degrees
Location/Orientation .... 13.3 ft from Upstream of Post

Post-Impact Trajectory
Stopping Distance............ N/A

Occupant Risk Values
Impact Velocity (ft/sec)
x-direction…………………. 17.06
y-direction…………………. -16.4
Ridedown Acceleration (g)
x-direction.............................. -15.4
y-direction.............................. 10.9

Vehicle Stability
Maximum Yaw Angle .... 26.8 degrees
Maximum Pitch Angle .... 3.0 degrees
Maximum Roll Angle .... 6.4 degrees
Vehicle Snagging .... No

Vehicle Damage
VDS .... N/A
CDC .... N/A
Max. Exterior Deformation .... N/A
OCD. .... N/A

Max. Occupant Compartment Deformation............................ N/A

Figure 5.22. Summary of Results for *NCHRP 350* Test 3-21 simulation (27¾-inch Rail Height with 4-inch Pavement Overlay and 4-inch Raised Blockouts).

6. SUMMARY AND CONCLUSIONS

6.1 SUMMARY

With recent changes/clarifications about appropriate height for W-beam guardrail, there are more and more existing locations identified where rail height is below the recommended heights. Pavement overlays create additional locations where this occurs. Raising blockouts on the posts is a cost effective means to adjust the rail height; however, there was not any known analysis of how this practice might affect rail performance.

The purpose of this research was to analyze wood post W-beam guardrail performance when wood blockouts are raised on the posts to adjust rail height. The information compiled from this research will enable Departments of Transportation to decide whether raising wood blockouts on wood posts can be used as a cost effective means to adjust rail heights that are below recommended values, without compromising the rail impact performance.

The researchers made use of pendulum testing to evaluate raised wood blockouts on wood posts. Pendulum tests were performed on 6-inch × 8-inch wood blockouts raised on 6-inch × 8-inch wood posts embedded in soil. Force-displacement data was recorded and evaluated to understand the strength of the raised blockout on wood post system. Recorded data from the pendulum testing was also used to help validate FE models for use in full-scale impact simulations.

The researchers identified real-world configurations of W-beam guardrail installations with wood blockouts on wood posts. The researchers worked with State DOT representatives to identify those configurations for which the practice of raising wood blockouts on wood posts would need some additional investigation to assess system crashworthiness according to applicable performance guidelines. Three cases were identified for further evaluation through FEA analyses:

1) 31-inch MGS system with 4-inches pavement overlay in front of post and 4-inch raised blockouts on posts (*MASH*, Test 3-11);
2) 27¾-inch rail system with 4-inch increased post embedment due to possible rail deficiency or post settlement, and 4-inch raised blockouts on posts (*NCHRP Report 350*, Test 3-11);
3) 27¾-inch rail system with 4-inch pavement overlay in front of post and 4-inch raised blockouts on posts (*NCHRP Report 350*, Test 3-11).

For those cases which included pavement overlay, tapered edge details from Texas Department of Transportation standards were implemented within the computer models. According to such standards, the pavement overlay should have a tapered edge length of 1.75 * T, where "T" is the total thickness of all overlay layer. It was also assumed that the tapered edge would start at the height of the face of the guardrail following Washington State Department of Transportation standard.

6.2 MGS SYSTEM WITH 4-INCH PAVEMENT OVERLAY AND 4-INCH RAISED BLOCKOUTS

A finite element model of the MGS with wood posts was developed with a 4-inch overlay added in front of the post. The 4-inch overlay was terminated in front of the guardrail following TxDOT guidelines. To maintain the original rail height of the MGS system after the overlay, the wood blockouts were raised 4 inches with respect to the posts. Post embedment remained 40 inches, as in the original MGS installation.

The FE test installation consisted of 150 ft of standard 12-gauge W-beam supported by wood posts. The system included twenty-five posts spaced at 75 inches on center. The posts were 6-inch × 8-inch × 72-inch long with wood properties and a soil embedment depth of 40 inches. Failure properties were given to the posts to allow elements to erode after reaching a predefined principal stress value. A 6-inch × 12-inch × 14¼-inch spacer blockout was used to block the rail away from the front face of each post. LS-DYNA soil material model *MAT_JOINTED_ROCK was used to simulate soil properties for soil-post interaction. Standard 12-ft 6-in long 12-gauge W-beam rails were modeled. The W-beam top rail height was 31 inches with a 24⅞-inch center mounting height. The rail splices were placed at midspan locations, and were configured with the upstream segment in front to minimize vehicle snag at the splice during the impact simulation. Evaluation of the crashworthiness of this system followed *MASH* Test 3-11 impact conditions and evaluations criteria.

A predictive computer simulation was performed to evaluate a 2270P vehicle impacting at 62 mi/h and 25 degrees orientation against an MGS system with 4-inch pavement overlay in front of the post and 4-inch raised blockouts on posts, according to the criteria set in *MASH*. The vehicle was contained and redirected, and maintained its stability throughout the impact event. Occupant risk values were all below the limits required by *MASH* criteria, and there was no observed snagging or pocketing. The rail did not show regions of high plastic strains that might suggest failure of the steel W-beam. In conclusion, results suggest that the practice of raising wood blockouts on wood posts for an MGS system to maintain the rail height at 31-inch behind a pavement overlay appears to be crashworthy and likely to pass safety evaluation criteria required by *MASH*.

6.3 27¾-INCH RAIL SYSTEM WITH HEIGHT DEFICIENCY AND 4-INCH RAISED BLOCKOUTS

An FE model of a 27¾-inch high W-beam guardrail system with wood posts and wood blockouts was developed. The system was modified to include 4 inches additional post embedment. In real life, this additional soil embedment could be the result of post settlement, or accumulation of soil and/or debris around the posts, which ultimately would lead to a rail height which is considered deficient for the impact conditions considered. To maintain the original height of the rail after the additional soil embedment, the wood blockouts were raised 4 inches with respect to the posts. Post embedment results being 47¼ inches.

The FE test installation consisted of 150 ft of standards 12-gauge W-beam supported by wood posts. The system included twenty-five posts spaced at 75 inches on center. The posts were 6-inch × 8-inch × 72-inch long with wood properties and a soil embedment depth of 47¼ inches.

Failure properties were given to the posts to allow elements to erode after reaching a predefined principal stress value. A 6-inch × 8-inch × 14¼-inch spacer blockout was used to block the rail away from the front face of each post. LS-DYNA soil material model *MAT_JOINTED_ROCK was used to simulate soil properties for soil-post interaction. Standard 12 ft-6 in long 12-gauge W-beam rails were modeled. The W-beam top rail height was 27¾-inch with a 21⅞-inch center mounting height. The rail splices were placed at post locations, and were configured with the upstream segment in front to minimize vehicle snag at the splice during the impact simulation. The crashworthiness of this system was evaluated according to *NCHRP Report 350* Test 3-11 impact conditions and evaluations criteria.

A predictive computer simulation was performed to evaluate a 2000P vehicle impacting at 62 mi/h and 25 degrees orientation against a 27¾-inch high rail system with 4-inch additional post embedment and 4-inch raised blockouts on posts, according to the criteria set in *NCHRP Report 350*. The vehicle was contained and redirected, and maintained its stability throughout the impact event. Occupant risk values were all below the limits required by *NCHRP Report 350* criteria. The rail did not show extended regions of high plastic strain that might suggest failure of the steel W-beam. In conclusion, results suggest that the practice of raising wood blockouts on wood posts for a 27¾-inch high rail system to maintain the rail height at 27¾ inches from ground appears to be crashworthy and likely to pass safety evaluation criteria required by *NCHRP Report 350*.

6.4 27¾-INCH RAIL SYSTEM WITH 4-INCH PAVEMENT OVERLAY AND 4-INCH RAISED BLOCKOUTS

An FE model of a 27¾-inch high W-beam guardrail system with wood posts and wood blockouts was developed. The system was modified to include a 4-inch overlay in front of the posts. The 4-inch overlay was terminated in front of the guardrail following TxDOT guidelines. To maintain the original height of the rail after the overlay, the wood blockouts were raised 4 inches with respect to the posts. Post embedment remained 43¼ inches, as in the original rail system installation.

The FE test installation consisted of 150 ft of standards 12-gauge W-beam supported by wood posts. The system included twenty-five posts spaced at 75 inches on center. The posts were 6-inch × 8-inch × 72-inch long with wood properties and a soil embedment depth of 43¼ inches. Failure properties were given to the posts to allow elements to erode once reached a predefined principal stress value. A 6-inch × 8-inch × 14¼-inch spacer blockout was used to block the rail away from the front face of each post. LS-DYNA soil material model *MAT_JOINTED_ROCK was used to simulate soil properties for soil-post interaction during the computer simulation. Standard 12 ft-6 inch long 12-gauge W-beam rails were modeled. The W-beam top rail height was 27¾ inches with a 21⅞-inch center mounting height. The rail splices were placed at post locations, and were configured with the upstream segment in front to minimize vehicle snag at the splice during the impact event simulation. This system was evaluated according to *NCHRP Report 350* Test 3-11 impact conditions and evaluations criteria.

A predictive computer simulation was developed to evaluate a 2000P vehicle impacting at 62 mi/h and 25 degrees orientation against a 27¾-inch high rail system with 4-inch pavement overlay in front of the post and 4-inch raised blockouts on posts, according to the criteria set in *NCHRP Report 350*. The vehicle was contained and redirected, and maintained its stability throughout the impact event. Occupant risk values were all below the limits required by *NCHRP Report 350* criteria. The rail did not show extended regions of high plastic strain that might suggest failure of the steel W-beam. In conclusion, results suggest that the practice of raising wood blockouts on wood posts for a 27¾-inch high rail system to maintain the rail height at 27¾ inches after a pavement overlay appears to be crashworthy and likely to pass safety evaluation criteria required by *NCHRP Report 350*.

6.5 CONCLUSIONS

Dynamic pendulum impact testing was performed on wood posts with standard and raised blockouts. Results of the testing suggested that strength of the raised wood blockout on wood post system and its capability to transmit the impact forces into the soil was very similar to the wood post system with standard blockout configuration.

Three cases were identified for further evaluation through FEA analyses, according to Test Level 3 impact conditions. All three investigated cases indicate that the practice of raising wood blockouts on wood posts to maintain minimum rail height requirements appear to be crashworthy and likely to meet applicable *NCHRP Report 350* or *MASH* evaluation criteria.

7. REFERENCES

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

2. Gutierrez, D.A., Bielenberg, R.W., Reid, J.D., Lechtenberg, K.A., Faller, R.K., and Sicking, D.L., "Midwest Guardrail System (MGS) with Southern Yellow Pine Posts," Midwest Roadside Safety Facility, MwRSF Research Report No. TRP-03-272-13, Lincoln, Nebraska, 2013.

3. Hallquist J. O., "*LS-DYNA Keyword User's Manual, Version 971*," Livermore Software Technology Corporation, Livermore, California, 2009.

4. National Crash Analysis Center (NCAC), "*Finite Element Model Archive*," Accessed November, 2005 http://www.ncac.gwu.edu/.

5. Nicol D.A. *"Memorandum. Roadside Design: Steel Strong Post W-Beam Guardrail."* Federal Highway Administration, Washington D.C., May 17th, 2010, http://safety.fhwa.dot.gov/roadway_dept/policy_guide/road_hardware/policy_memo/memo051710/, retrieved May 2015.

6. Opiela, K., Kan, S., and Marzougui, D., "*Safety Performance Evaluation of G4(2W) W-Beam Guardrail with Blockouts Raised by 3"*," NCAC 2009-T-002, Washington, D.C., 2009.

7. Ray, M.H., Plaxico, C., Anghileri, M., Mongiardini, M., "*Development of Verification and Validation Procedures for Computer Simulation Use in Roadside Safety Applications*," National Cooperative Highway Research Program Report 22-24, Transportation Research Board, National Research Council, Washington, D.C., 2011.

8. Ross H.E., Sicking D.L., Zimmer R.A., and Michie J.D., "*Recommended Procedures for the Safety Performance Evaluation*," *NCHRP Report 350*, National Academy Press, National Cooperative Highway Research Program, Washington, D.C. 1993.

9. TxDOT, "*Tapered Edge Details HMAC Pavement TE (HMAC) -11*," 2011.

10. WSDOT, "*Beam Guardrail Types 1 ~ 4 (W-Beam) Standard Plan C-1*," 2011.

ATTACHMENT A. PENDULUM TEST PROCEDURES AND DATA ANALYSIS

The pendulum test and data analysis procedures were in accordance with guidelines presented in *NCHRP Report 350*. Brief descriptions of these procedures are presented as follows.

ELECTRONIC INSTRUMENTATION AND DATA PROCESSING

The bogie was instrumented with two accelerometers mounted at the rear of the bogie to measure longitudinal acceleration levels. The accelerometers were strain gage type with a linear millivolt output proportional to acceleration.

The electronic signals from the accelerometers were amplified and transmitted to a base station by means of constant bandwidth FM/FM telemetry link for recording on magnetic tape and for display on a real-time strip chart. Calibration signals were recorded before and after the test and an accurate time reference signal was simultaneously recorded with the data. Pressure sensitive switches on the nose of the bogie were actuated by wooden dowel rods and initial contact to produce speed trap and "event" marks on the data record to establish the exact instant of contact with the installation, as well as impact velocity.

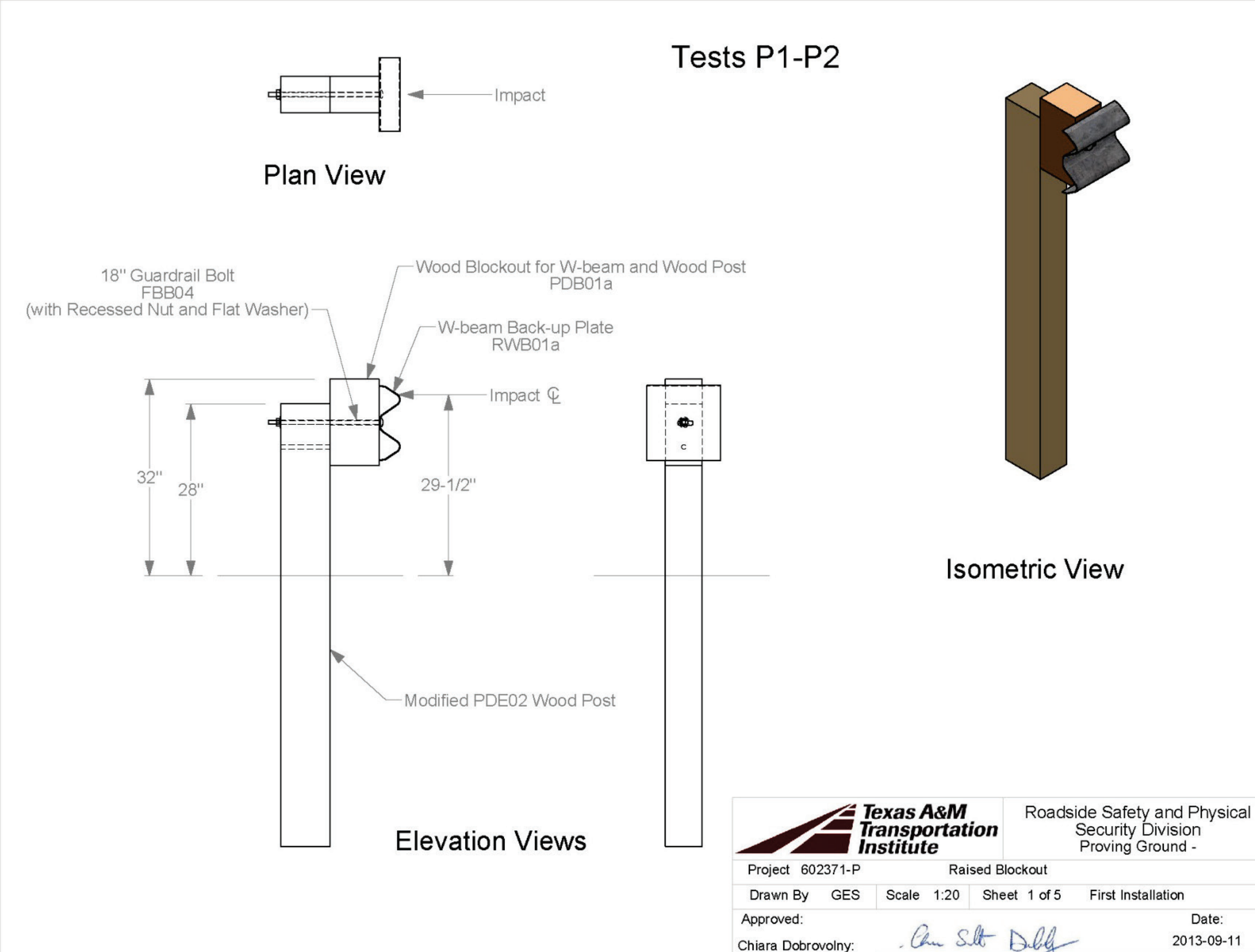
The multiplex of data channels, transmitted on one radio frequency, is received and demultiplexed onto TEAC® instrumentation data recorder. After the test, the data are played back from the TEAC® recorder and digitized. A proprietary software program (WinDigit) converts the analog data from each transducer into engineering units using the R-cal and pre-zero values at 10,000 samples per second, per channel. WinDigit also provides Society of Automotive Engineers (SAE) J211 class 180 phaseless digital filtering and bogie impact velocity.

The Test Risk Assessment Program (TRAP) uses the data from WinDigit to compute occupant/compartment impact velocities, time of occupant/compartment impact after bogie impact, and the highest 10-ms average ridedown acceleration. WinDigit calculates change in bogie velocity at the end of a given impulse period. In addition, maximum average accelerations over 50-ms are computed. For reporting purposes, the data from the bogie-mounted accelerometers were then filtered with a 180 Hz digital filter and plotted using a commercially available software package (Microsoft EXCEL).

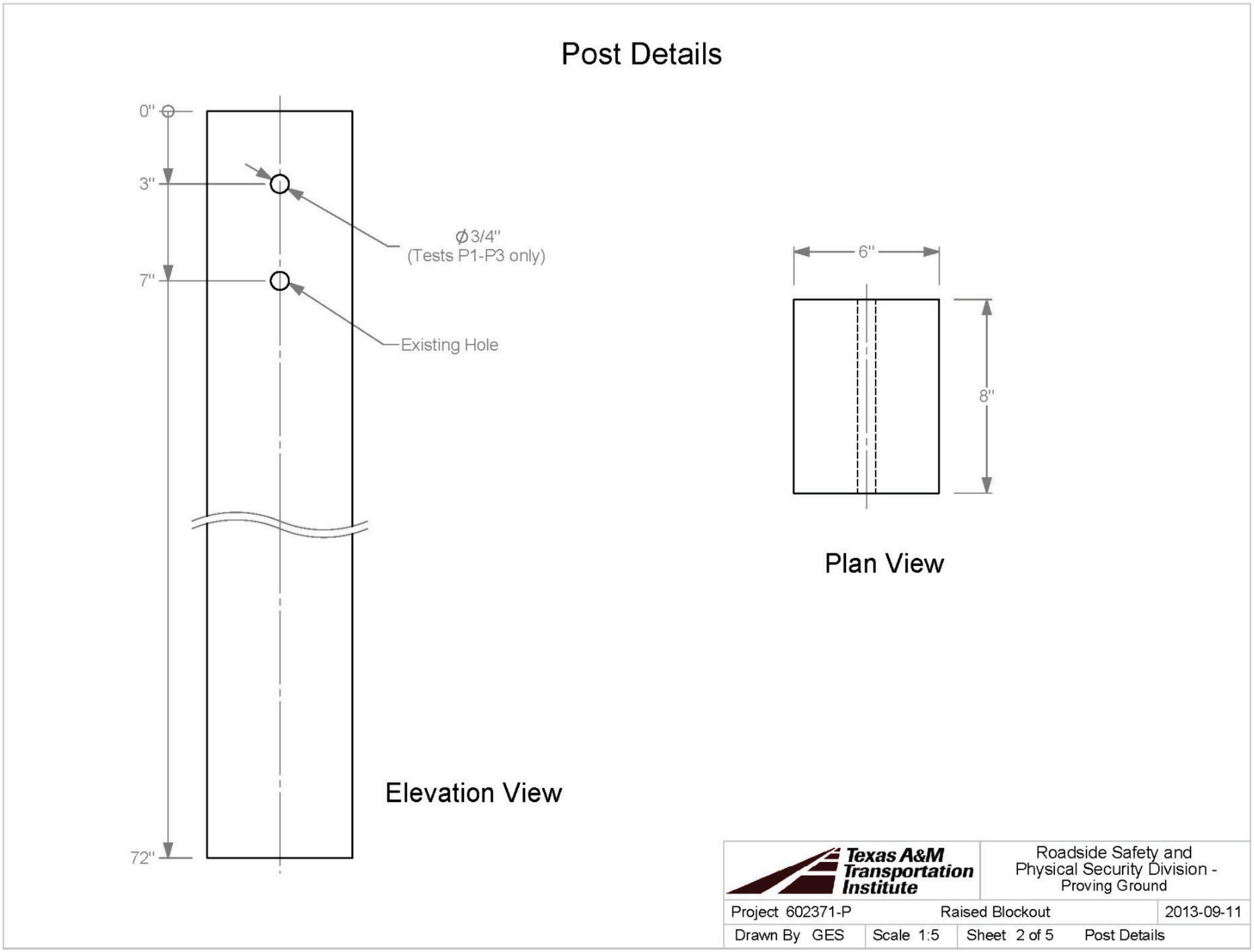
PHOTOGRAPHIC INSTRUMENTATION

A high-speed digital camera, positioned perpendicular to the path of the bogie and the test article, was used to record the collision period. The film from this high-speed camera was analyzed on a computer to observe phenomena occurring during the collision and to obtain time-event, displacement, and angular data. A mini-DV camera and still cameras were used to document the bogie nose and the test article before and after the test.

ATTACHMENT B. DETAILS OF TEST ARTICLES

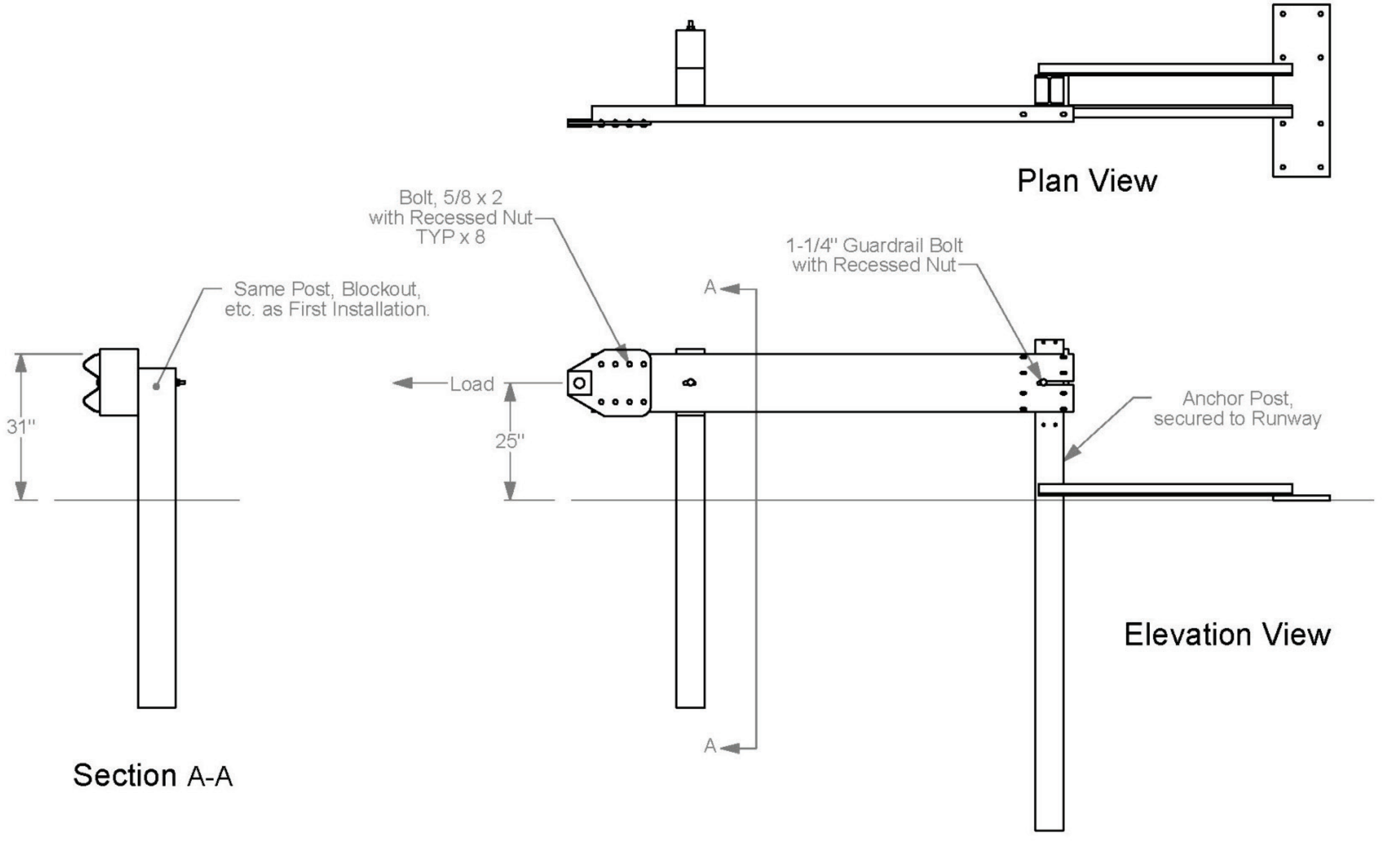


T:\2013-2014\602371-Raised Blockout\Drafting\602371-P Drawing , as tested



T:\2013-2014\602371-Raised Blockout\Drafting\602371-P Drawing , as tested

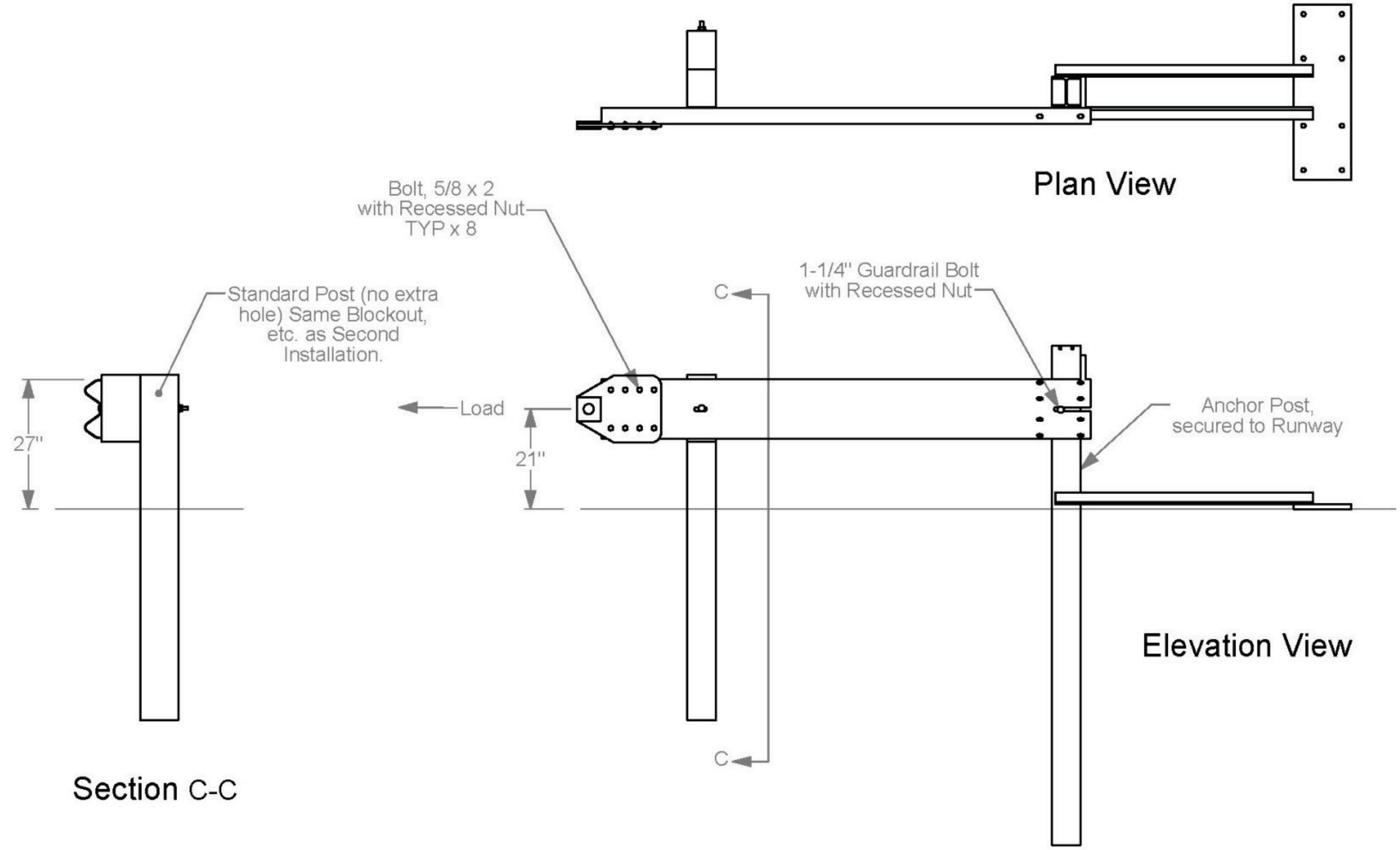
Test P3
Pull Test



Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground	
Project 602371-P	Raised Blockout	2013-09-11
Drawn By GES	Scale 1:30	Sheet 3 of 5	Second Installation

T:\2013-2014\602371-Raised Blockout\Drafting\602371-P Drawing , as tested

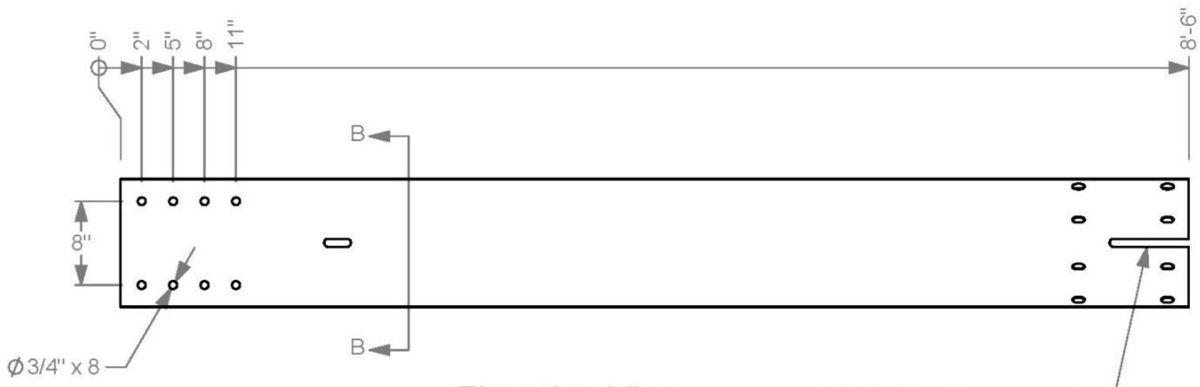
Test P4
Pull Test



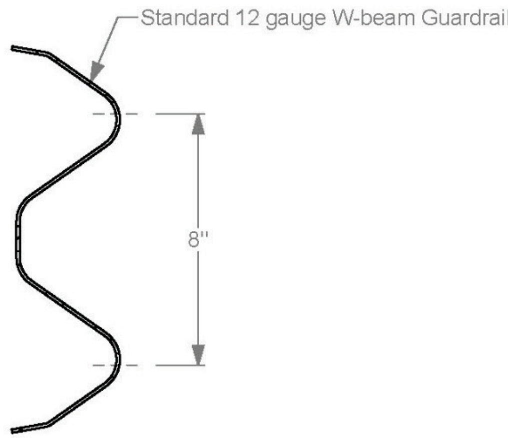
Texas A&M Transportation Institute		Roadside Safety and Physical Security Division - Proving Ground
Project 602371-P	Raised Blockout	2013-09-11
Drawn By GES	Scale 1:30	Sheet 4 of 5 Third Installation

T:\2013-2014\602371-Raised Blockout\Drafting\602371-P Drawing , as tested

Rail Details
Pull Test



Elevation View



Section B-B
Scale 1 : 5

Texas A&M Transportation Institute		Roadside Safety and Physical Security Division - Proving Ground	
Project 602371-P		Raised Blockout	2013-09-11
Drawn By GES	Scale 1:15	Sheet 5 of 5	Rail Details

T:\2013-2014\602371-Raised Blockout\Drafting\602371-P Drawing , as tested

ATTACHMENT C. TESTING SUMMARIES

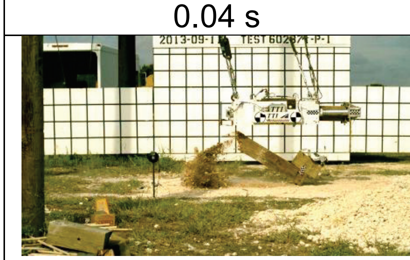
Table C1. Summary of Results for Pendulum Test 602371- P1.

0.000 s

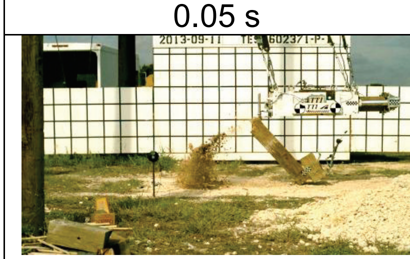
0.02 s

0.03 s

0.04 s



0.05 s



0.06 s

General Information

Test Agency	Texas A&M Transportation Institute
Test No.	602371- P1
Date	2013-09-11

Test Article

Type	Wood Blockout
Name	Raised 8-inch Wood Blockout
Installation Height	32 inches
Material of Key Element	8-inch Wood Blockout on Wood Post embedded in Soil

Soil Type	Standard Soil

Test Vehicle

Type	Bogie
Designation	Pendulum
Test Inertia Mass	1750 lb

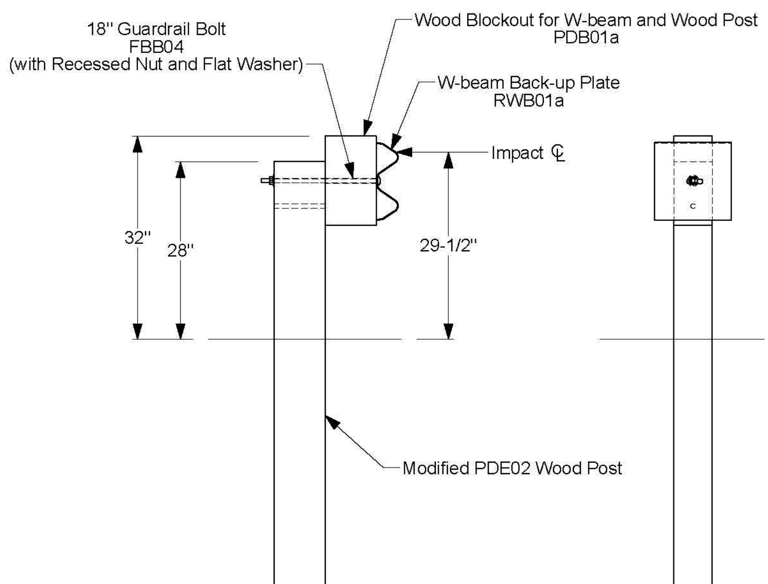
Impact Conditions

Speed	19.9 mi/h
Angle	90 deg

Occupant Risk Values

Longitudinal Occupant Impact Velocity	8.5 ft/s
Longitudinal Ridedown Acceleration	0.7 G

Maximum Change in Velocity	7.6 ft/s
Maximum 10-ms Force	15.8 kips
Maximum Kinetic Energy	12.04 ft-kips



Elevation Views

Table C2. Summary of Results for Pendulum Test 602371- P2.

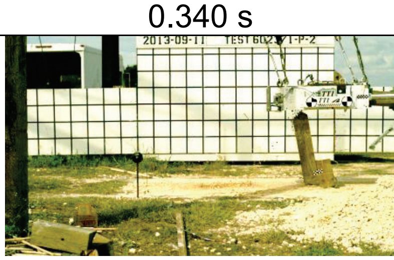
0.000 s

0.085 s

0.170 s

0.255 s

0.340 s



0.425 s

General Information
- Test Agency .... Texas A&M Transportation Institute
- Test No. 602371- P2
- Date 2013-09-11

Test Article
- Type .... Wood Blockout
- Name .... Raised 8-inch Wood Blockout
- Installation Height .... 32 inches
- Material of Key Element .... 8-inch Wood Blockout on Wood Post embedded in Soil

Soil Type .... Standard Soil

Test Vehicle
- Type .... Bogie
- Designation .... Pendulum
- Test Inertia Mass .... 1750 lb

Impact Conditions
- Speed .... 20.0 mi/h
- Angle .... 90 deg

Occupant Risk Values
- Longitudinal Occupant Impact Velocity .... 6.9 ft/s
- Longitudinal Ridedown Acceleration .... 0.9 G

Maximum Change in Velocity .... 4.5 ft/s

Maximum 10-ms Force .... 11.0 kips

Maximum Kinetic Energy .... 8.26 ft-kips

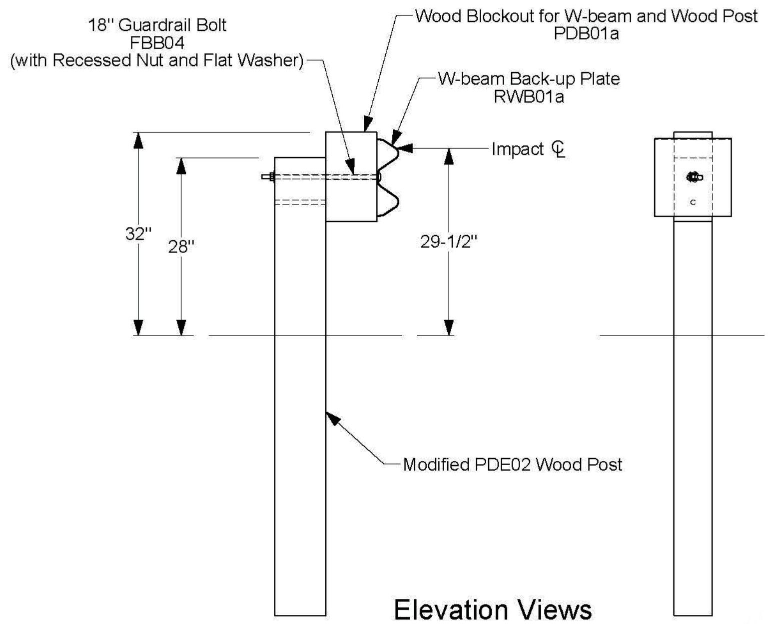
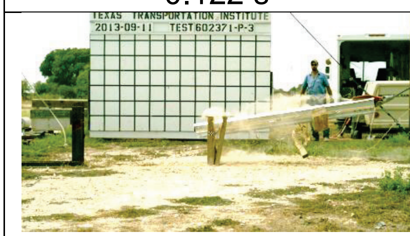


Table C3. Summary of Results for Pendulum Test 602371- P3.

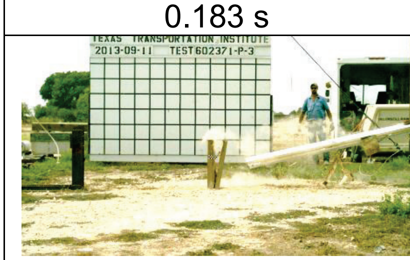
0.000 s

0.061 s

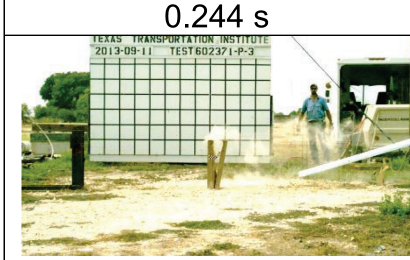
0.122 s



0.183 s



0.244 s



0.305 s

General Information
- Test Agency .... Texas A&M Transportation Institute
- Test No. 602371- P3
- Date 2013-09-11

Test Article
- Type .... Wood Blockout
- Name .... Raised 8-inch Wood Blockout
- Installation Height .... 31 inches
- Material of Key Element .... 8-inch Wood Blockout on Wood Post embedded in Soil

Soil Type .... Standard Soil

Test Vehicle
- Type .... Bogie
- Designation .... Pendulum
- Test Inertia Mass .... 2062 lb

Impact Conditions
- Speed (pull) .... 14.8 mi/h
- Angle .... 90 deg

Occupant Risk Values
- Longitudinal Occupant Impact Velocity .... 4.6 ft/s
- Longitudinal Ridedown Acceleration .... 0.4 G

Maximum 10-ms Force .... 8.9 kips

Maximum Kinetic Energy .... 3.71 ft-kips

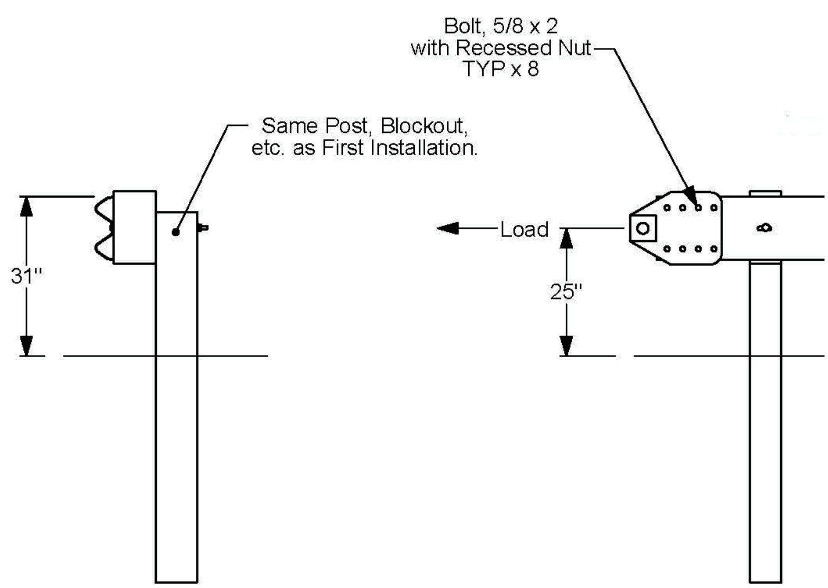
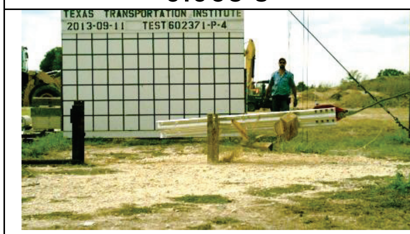


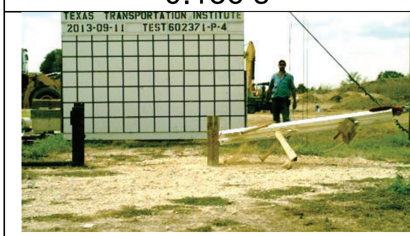
Table C4. Summary of Results for Pendulum Test 602371- P4.

0.000 s

0.068 s

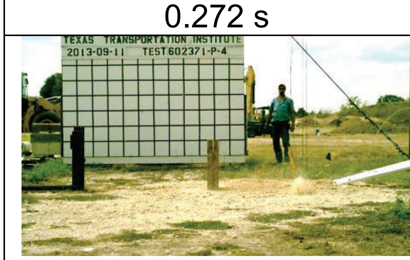


0.136 s



0.204 s

0.272 s



0.340 s

General Information
- Test Agency .... Texas A&M Transportation Institute
- Test No. 602371- P4
- Date 2013-09-11

Test Article
- Type .... Wood Blockout
- Name .... 8-inch Wood Blockout
- Installation Height .... 27 inches
- Material of Key Element .... 8-inch Wood Blockout on Wood Post embedded in Soil

Soil Type .... Standard Soil

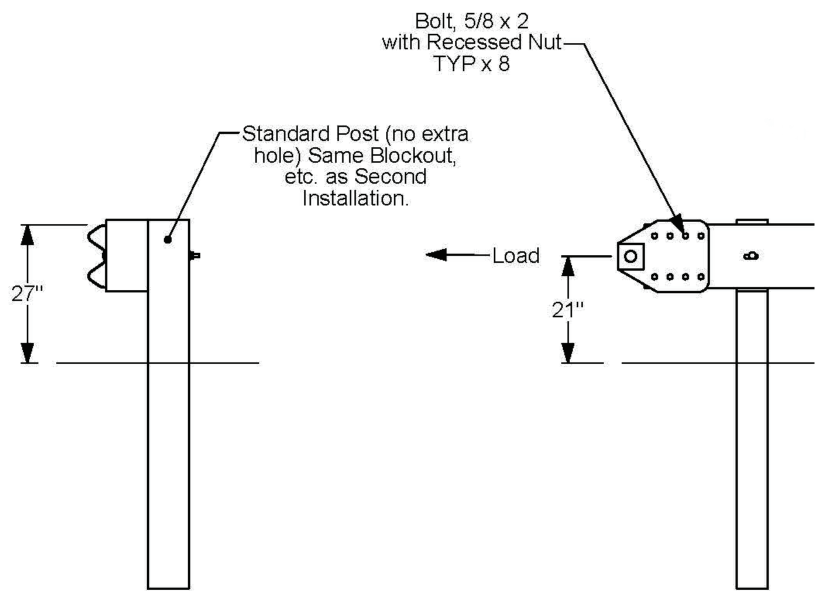
Test Vehicle
- Type .... Bogie
- Designation .... Pendulum
- Test Inertia Mass .... 2062 lb

Impact Conditions
- Speed (pull) .... 15.4 mi/h
- Angle .... 90 deg

Occupant Risk Values
- Longitudinal Occupant Impact Velocity .... 3.9 ft/s
- Longitudinal Ridedown Acceleration .... 0.4 G

Maximum 10-ms Force .... 8.6 kips

Maximum Kinetic Energy .... 3.54 ft-kips



ATTACHMENT D. ACCELERATION AND FORCE TRACES

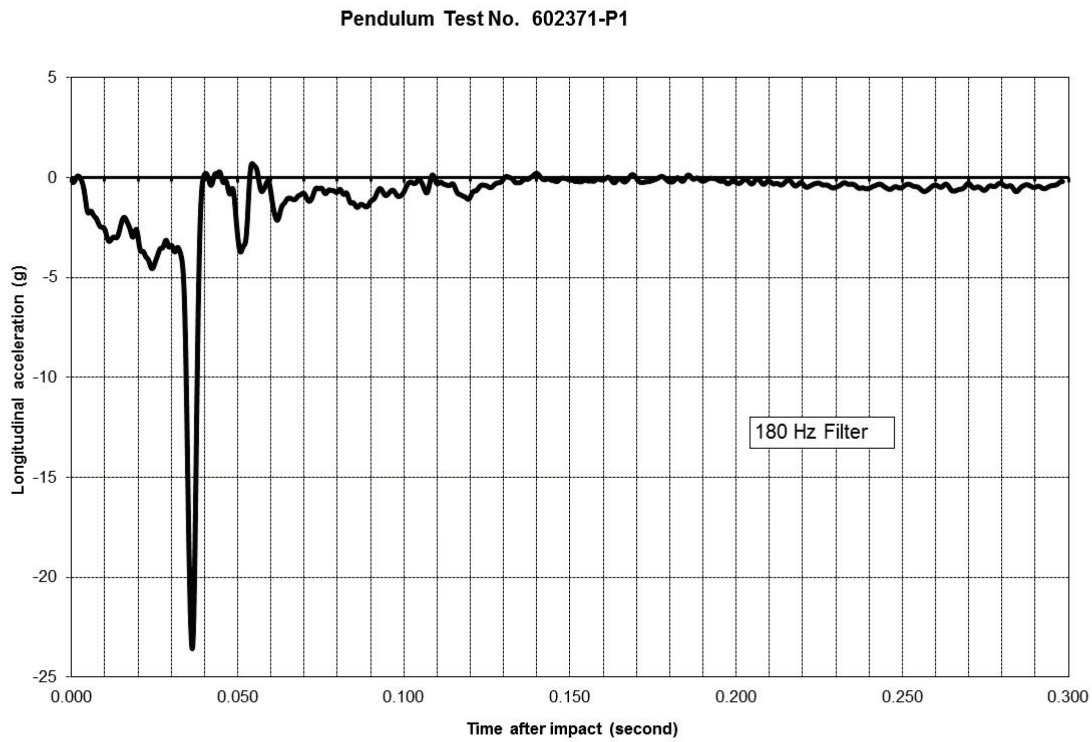


Figure D1. Accelerometer Trace for Test 602371-P1.

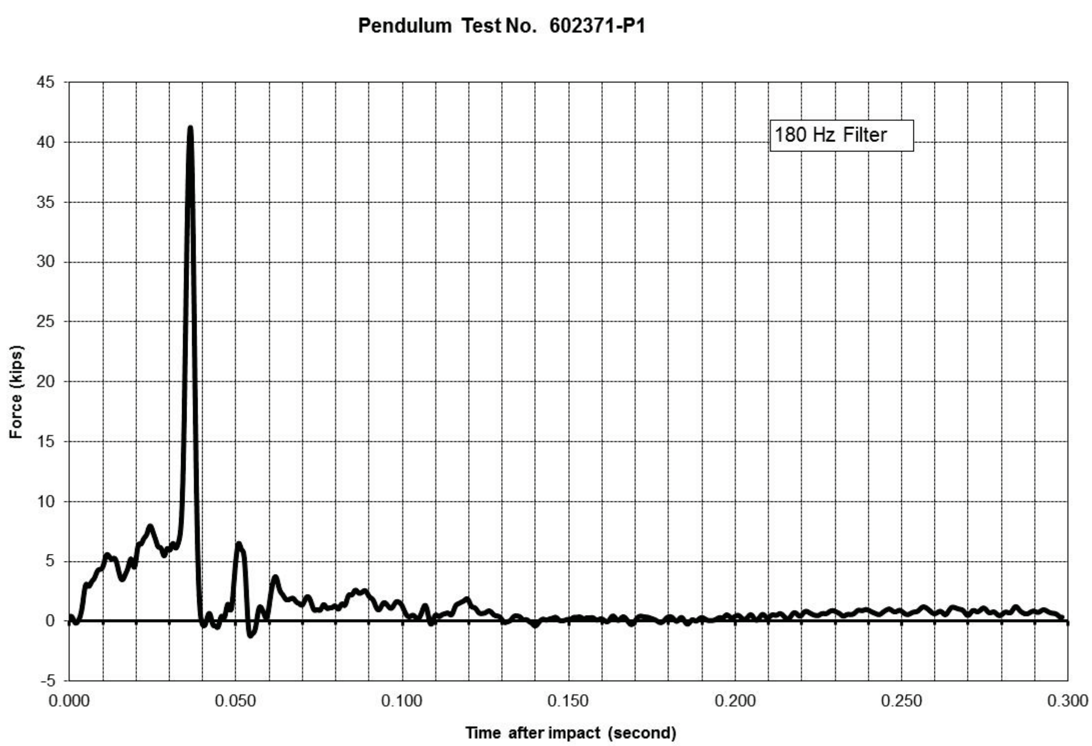


Figure D2. Force Trace for Test 602371-P1.

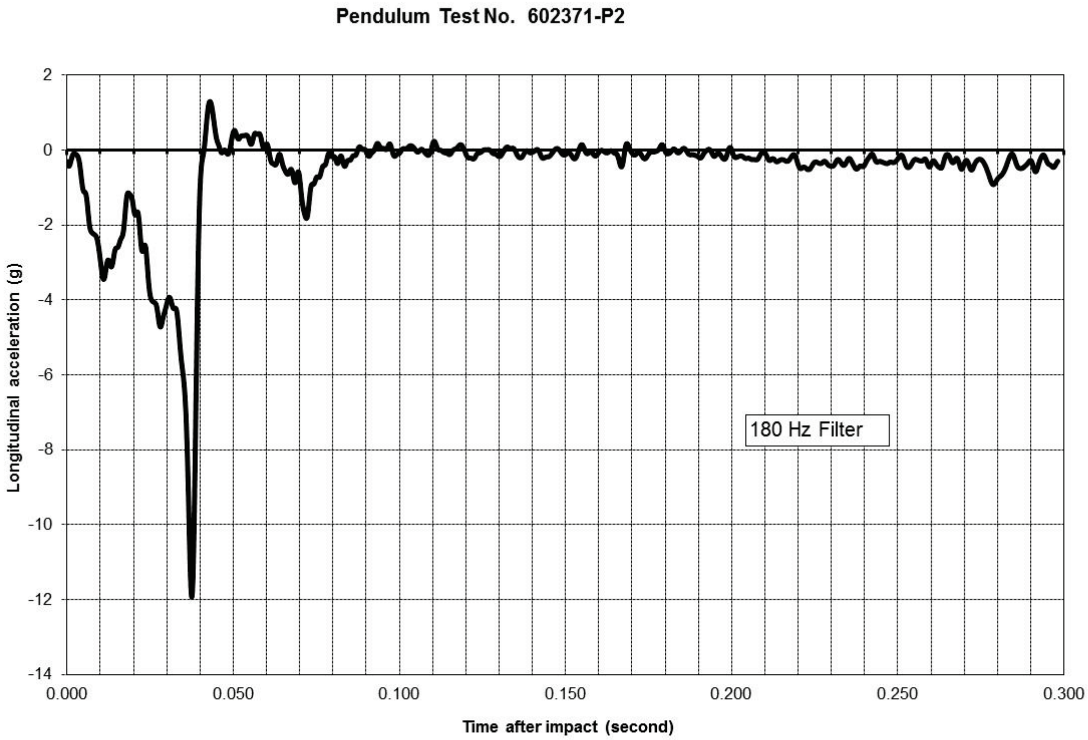


Figure D3. Accelerometer Trace for Test 602371-P2.

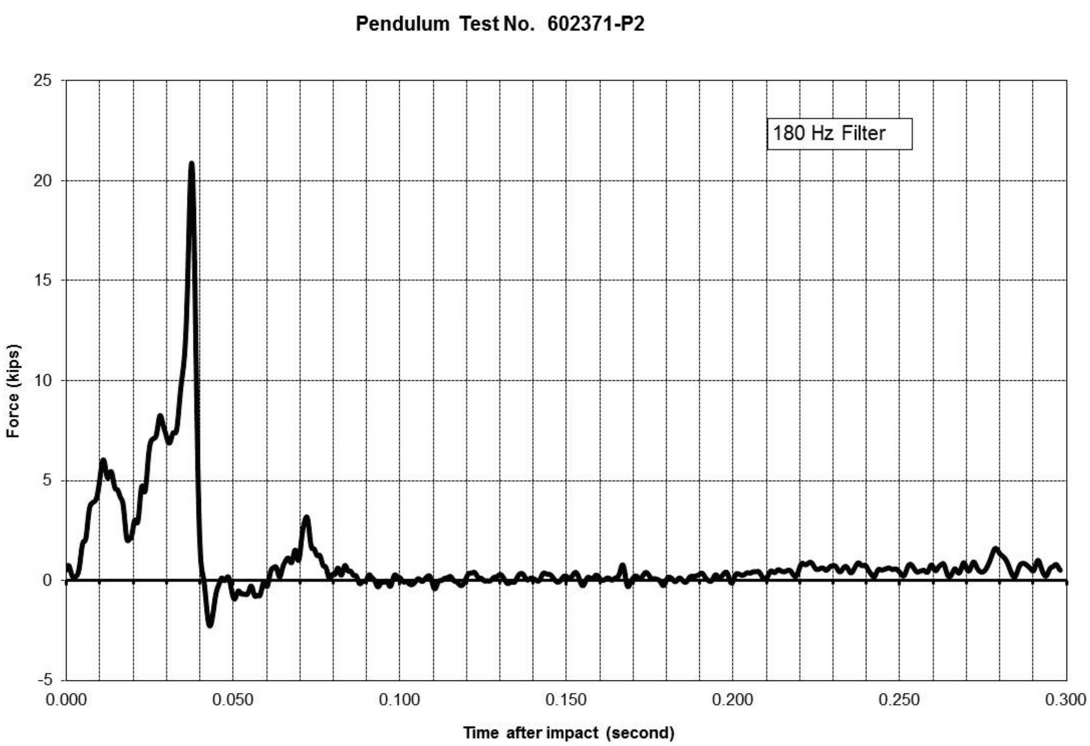


Figure D4. Force Trace for Test 602371-P2.

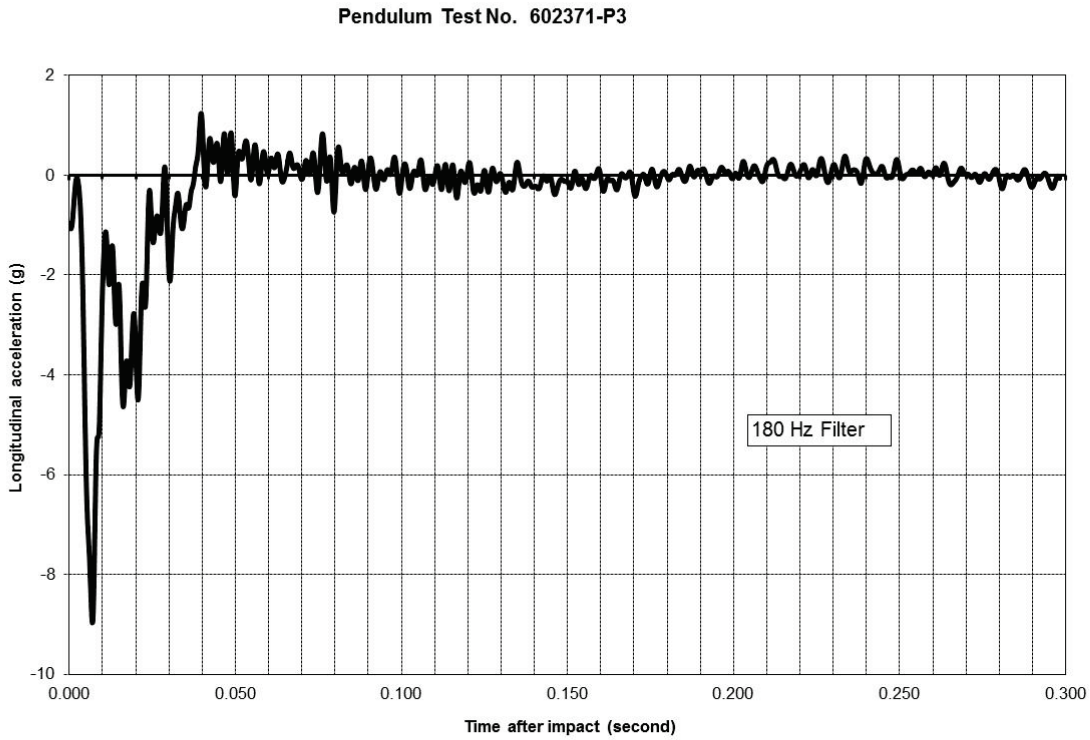


Figure D5. Accelerometer Trace for Test 602371-P3.

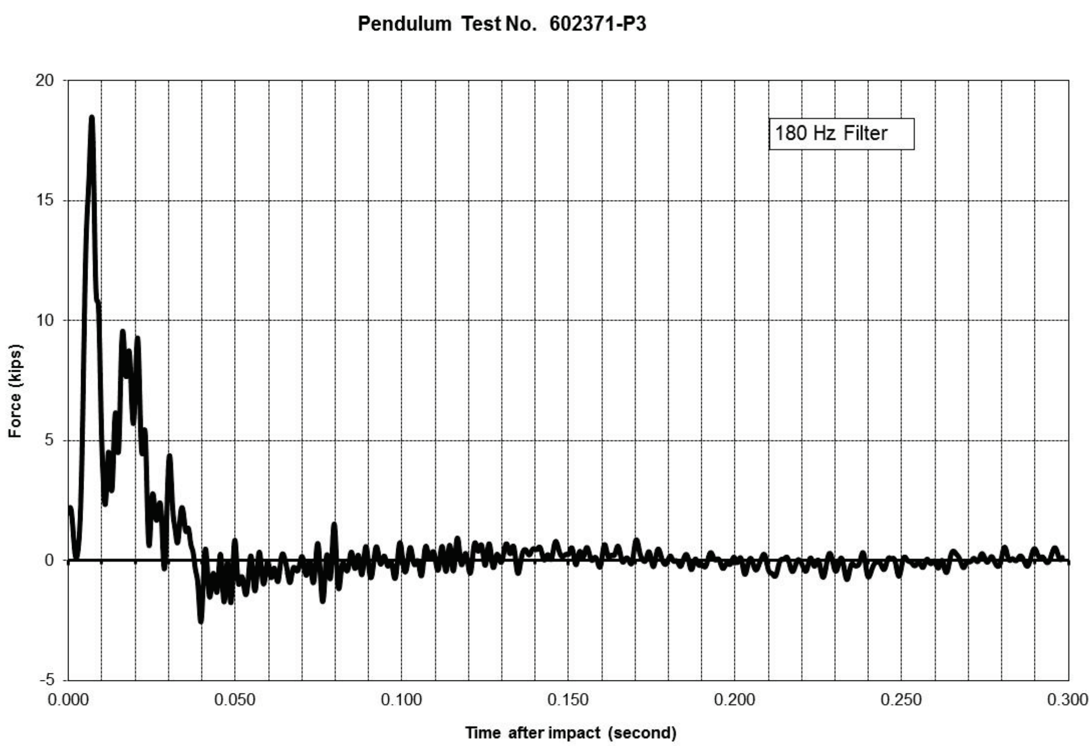


Figure D6. Force Trace for Test 602371-P3.

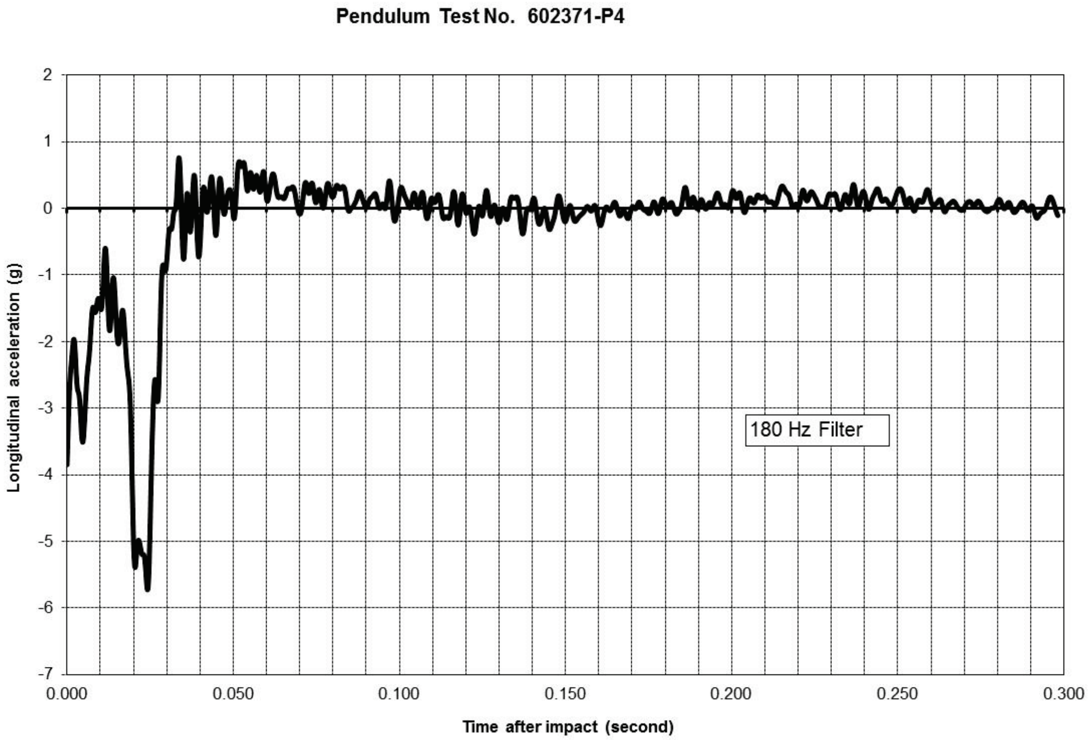


Figure D7. Accelerometer Trace for Test 602371-P4.

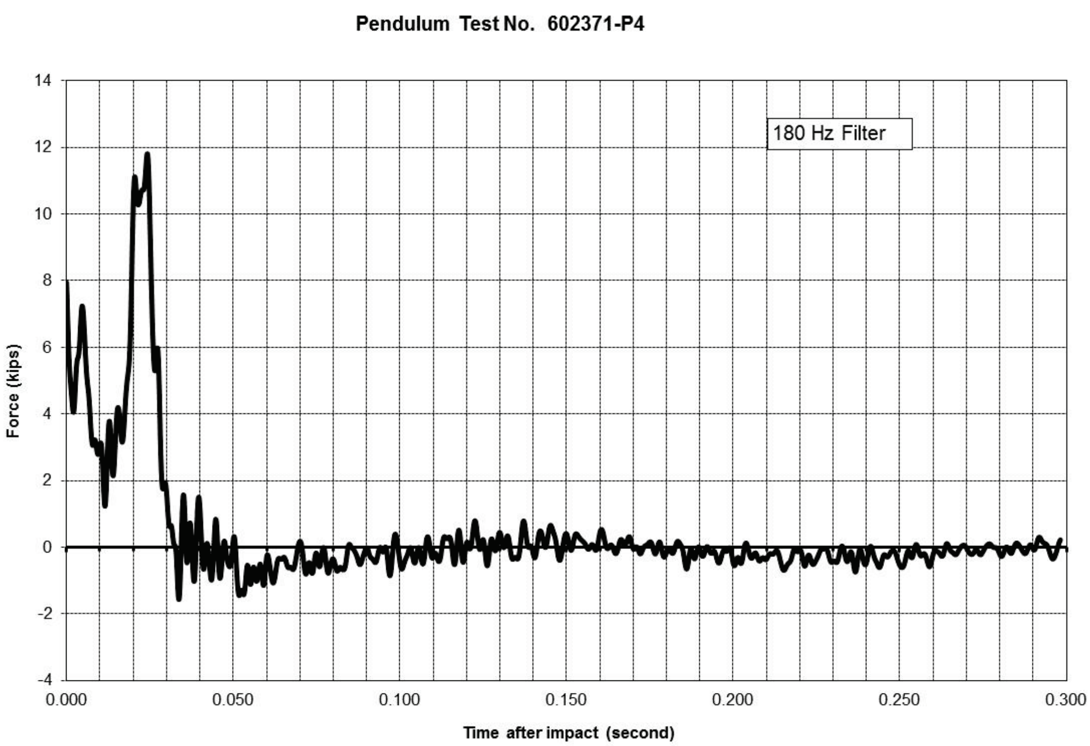


Figure D8. Force Trace for Test 602371-P4.