Roadside Safety Pooled Fund

Texas A&M Transportation Institute Proving Ground

Report No. 405160-39
Report Date: April 2015

Buried Terminal Design Evaluation for Use with 31-Inch Guardrail Height through Finite Element Simulations

by

Chiara Silvestri Dobrovolny, Ph.D.
Associate Research Scientist

Dusty R. Arrington
Engineering Research Associate

and

Abhinav P. Mohanakrishnan
Graduate Student Worker

Contract No.: T4541-BM
Project No.: 405160-39

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 **Buried Terminal Design Evaluation for Use with 31-Inch Guardrail Height through Finite Element Simulations**		5. Report Date April 2015
		6. Performing Organization Code
7. Author(s) Chiara Silvestri Dobrovolny, Dusty R. Arrington, and Abhinav P. Mohanakrishnan		8. Performing Organization Report No. Report No. 405160-39
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-BM
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 March 2012 – February 2015
		14. Sponsoring Agency Code

15. Supplementary Notes
Research Study Title: Buried Terminal Design Evaluation for Use with 31 Inches Guardrail Height through Finite Element Simulations
Name of Contacting Representative: John P. Donahue, Washington State Department of Transportation

16. Abstract
Buried (in backslope) terminal designs for beam guardrail were developed under *NCHRP Report 350* criteria for 27-inch (27¾-inch) high guardrail systems. Some states have modified this design so that it could be used with 31-inch high guardrail systems. Other agencies are hesitant to use this design for 31-inch high guardrail until it has been crash tested or deemed acceptable for use by FHWA. The objective of this study was to identify design modifications necessary to adapt a buried terminal design for 27-inch (27¾-inch) guardrail for use with a 31-inch guardrail system and to determine the terminal crashworthiness according to *NHCRP Report 350* criteria. Finite element computer simulation of *NHCRP Report 350* test 3-35 according the initial impact conditions of test 404211-13 well replicated the results obtained through full-scale crash testing. Although the model did not return realistic roll rate values, other parameters compare favorably to the test outcomes. In addition, the multi-channel option evaluation through the RSVVP program without inclusion of the roll rate channel suggests that the FE model of the 27¾-inch buried-in-backslope terminal realistically replicate the results observed through the full-scale crash test. Without any additional design modifications, the researchers decided to elevate the rail height of the test article model from the original 27¾ inches to 31 inches and determine the crashworthiness of the new model according to computer simulations. Results from the computer simulation of test 3-35 against the 31-inch rail high buried-in-backslope indicate that all applicable *NHCRP Report 350* evaluation criteria were met. The vehicle was properly contained and redirected and maintained stability throughout the complete impact event. The vehicle interaction with the test article did not suggest any potential for wheel snagging. Review of the plastic strains in both rail and posts suggests that it is unlikely the rail or the posts will fail during the impact event. Occupant risk were also well below *NHCRP Report 350* limit values. Results of the FE simulations for the 27¾-inch and 31-inch rail high buried-in-backslope terminal were compared to determine the 31-inch rail performance with respect to the 27¾-inch rail height. FE computer simulations indicate that the 31-inch rail high buried-in-backslope terminal has a very similar behavior that was observed for the 27¾-inch rail high. In fact, the 31-inch rail height seems to increase the 2000P vehicle stability throughout the entire impact event, maintaining occupant risks well below the limiting values according to the *NHCRP Report 350* criteria. Based on this evaluation, the researchers suggest the proposed 31-inch rail high buried-in-backslope terminal design be accepted for FHWA eligibility.

17. Key Words		18. Distribution Statement	
Buried-in-Backslope, 31 inches, Soil, *NHCRP Report 350*, Rubrail, 4:1 slope, Steel Posts, W-Beam Guardrail		Copyrighted. Not to be copied or reprinted without consent from Washington DOT.	
19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 67	22. Price

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

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square 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

LIST OF FIGURES

LIST OF TABLES

Page

1. INTRODUCTION

1.1 PROBLEM

Buried (in backslope) terminal designs for beam guardrail were developed under National Cooperative Highway Research Program (NCHRP) *Report 350* criteria for 27-inch (27¾-inch) high guardrail systems (*1*). Some states have modified this design so that it could be used with 31-inch high guardrail systems. Other agencies are hesitant to use this design for 31-inch high guardrail until it has been crash tested or deemed acceptable for use by Federal Highway Administration (FHWA).

1.2 BACKGROUND

A W-beam guardrail can be terminated by burying the end of the rail element into a soil berm. This type of guardrail termination installation is referred to as a "buried-in-backslope end treatment." Buried-in-backslope terminal designs for beam guardrail were developed under *NHCRP Report 350* criteria for 27-inch high guardrail systems (*2*).

With the satisfactory performance of the modified G4(1S) W-beam guardrail system with timber blockouts, FHWA decided to evaluate two terminal designs of the W-beam, steel-post guardrail system with similar modification (i.e., timber blockouts). Texas A&M Transportation Institute (TTI) conducted the study with the scope of assessing the G4 guardrail system with timber blockouts as incorporated in two buried-in-backslope end treatments for W-beam guardrails (*2*). Tests were conducted in accordance with *NHCRP Report 350*, and involved a 2000P vehicle impacting the treatment conditions at nominal speed and angles of 62 mph and 20 degrees, respectively. The buried-in-backslope end treatment for the W-beam guardrail was tested under two configurations: one with a ditch and the other with a drop inlet. The top of the rail was 27 inches, measured from the shoulder grade, and the guardrail end was anchored to a concrete block buried in the backslope.

For the ditch configuration, the earth was graded away from the shoulder at a 1V:10H slope for 6 ft, followed by a 3 ft wide ditch, then by a 1V:2H backslope. For the drop inlet configuration, the earth was graded away from the shoulder at a 1V:10H slope for 9 ft, followed by a 1V:2H backslope. Both installations met evaluation criteria set forth for *NHCRP Report 350* test designation 3-35. There was minimal deformation and no intrusion into the occupant compartment. The occupant risk factors were all well within the recommended limits.

The buried terminal design was also successfully tested on installations with a 1V:6H foreslope forming a V-ditch with a 1V:4H bottom ditch and over a 1V:4H foreslope (*3*). These tests were intended primarily to evaluate the ability of the device to contain and redirect a 2000P truck (structural adequacy criteria). The tests performed were *NHCRP Report 350* test designation 3-35, with a 2000P vehicle impacting the beginning of the length of need of the terminal at a nominal speed and impact angle of 62 mph and 20 degrees, respectively.

The buried-in-backslope terminal with a 1V:6H ditch contained and redirected the vehicle. Maximum deformation of the occupant compartment was 1.77 inches and was judged to not cause serious injury. The terminal performed acceptably for *NHCRP Report 350* test designation 3-35. The buried-in-backslope terminal with a 1V:4H slope contained and redirected the vehicle. Maximum deformation of the occupant compartment was 4.9 inches and was judged to not cause serious injury. The terminal performed acceptably for *NHCRP Report 350* test designation 3-35.

The satisfactory performance of the buried-in-backslope guardrail tests in different ditch configurations culminated with an FHWA letter of acceptance # CC 53A (Acceptance Letter, 1998).

During the next few years, the existing standard guardrail heights were increased to 31 inches. Considering these standard modifications, it was advisable that the buried-in-backslope terminal design for a 27-inch high guardrail be revised to satisfy *NHCRP Report 350* criteria for a 31-inch high guardrail. A successful outcome will increase the application of this countermeasure through a higher confidence level in the acceptability of this design. It will offer a means to shield guardrail ends from direct hits, reducing potential for penetration behind the end terminal and/or for the guardrail to penetrate the vehicle.

1.3 OBJECTIVES AND SCOPE OF RESEARCH

The objective of this study is to identify design modifications necessary to adapt a buried terminal design for 27-inch (27¾-inch) guardrail for use with a 31-inch guardrail system and to determine the terminal crashworthiness according to *NHCRP Report 350* criteria. This project is expected to culminate with a request for an FHWA acceptance letter for this design.

2. FINITE ELEMENT SIMULATION – 27¾-INCH RAIL HEIGHT

2.1 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. Finite element analyses (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 (*5*). 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.

2.2 FINITE ELEMENT MODEL DESCRIPTION

A finite element model of a buried-in-backslope terminal (with 4 to 1 slope) that was previously successfully designed and tested according to *NHCRP Report 350* test 3-35 was developed. Test 404211-13 was performed at Texas Transportation Institute (TTI) in 2000, under an FHWA project with the objective to crash test and evaluate several terminals, transitions, and longitudinal barriers to *NHCRP Report 350*. *NHCRP Report 350* specifies crash tests and evaluation criteria for three performance levels for terminals and six performance levels for transitions and longitudinal barriers. Details of the buried-in-backslope end treatment for test 404211-13 are included in Figure 2.1.

The modeled guardrail installation is flared across a vee ditch with its end anchored to a post rigidly fixed to simulate being buried into the soil. The guardrail installation is the standard American Association of State Highway and Transportation Officials (AASHTO) SGR04a W-beam guardrail with wood blockouts. The guardrail is flared back in a 4:1 ratio between posts A, B, 1, and 2 (numbered sequentially from the end anchor). The guardrail between posts 2 and 4 is flared back in a 6:1 ratio; between posts 4 and 8 in an 8:1 ratio; and between posts 8 and 20 in a 13:ratio. The guardrail, beginning at post 8, is parallel to the travel way and extends for 12.5 ft beyond post 20 (length of need). The top of the rail is 27¾ inches measured from the shoulder grade.

The buried-in-backslope terminal consists of a w-beam guardrail attached to steel posts using 6-inch × 8-inch × 14-inch wood blockouts. The W-beam is connected to the end post using a special connection bracket.

A W-beam rubrail extends from post 2 to post 20. A 3-inch gap between the W-beam guardrail and the rubrail is maintained. The upstream end of the rubrail is connected to post 2 with a special connection bracket and the downstream end of the rubrail is connected to the back of post 20.

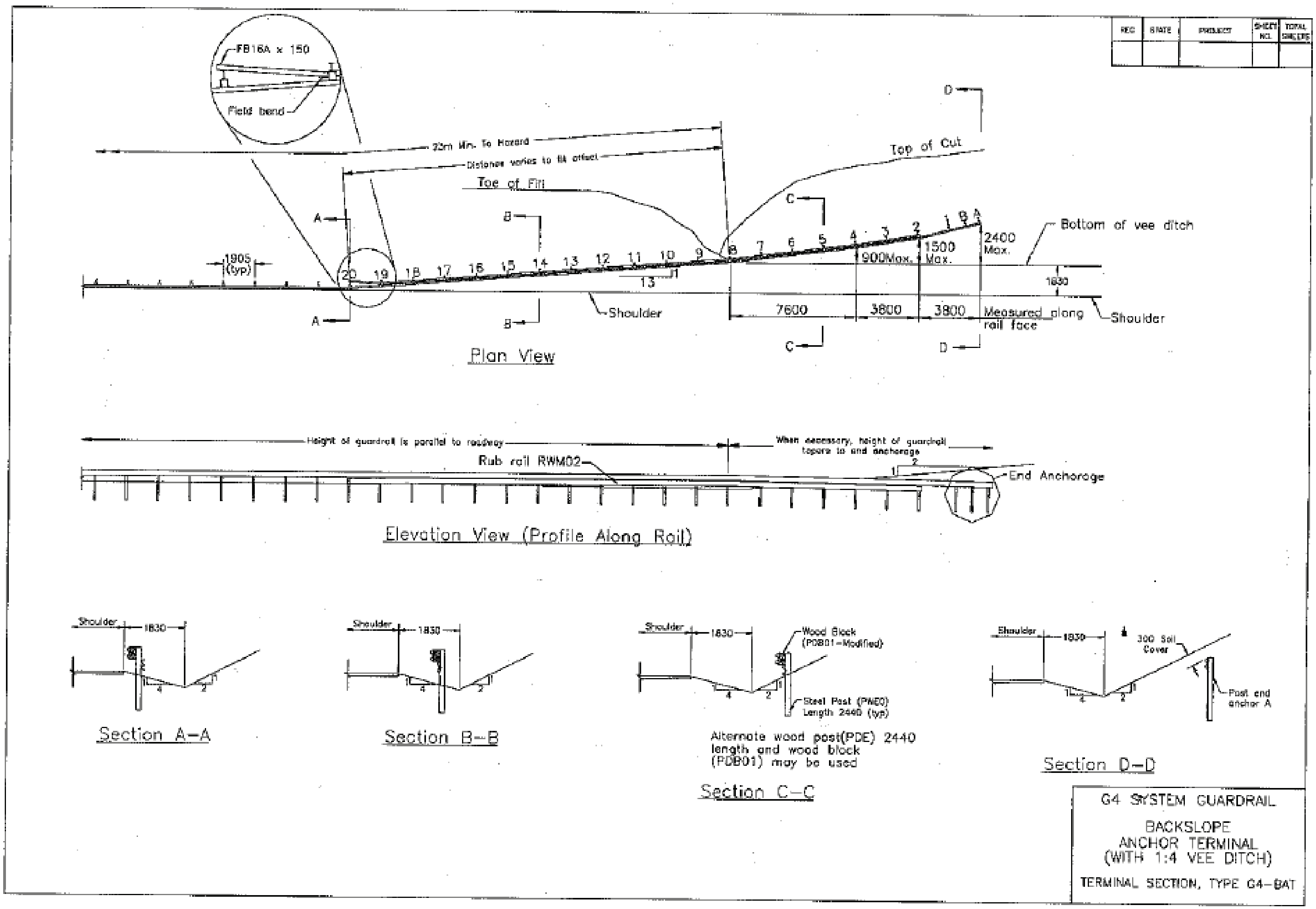


Figure 2.1. Details of the G4 W-beam Guardrail Buried-in-Backslope Installation for Test 404211-13.

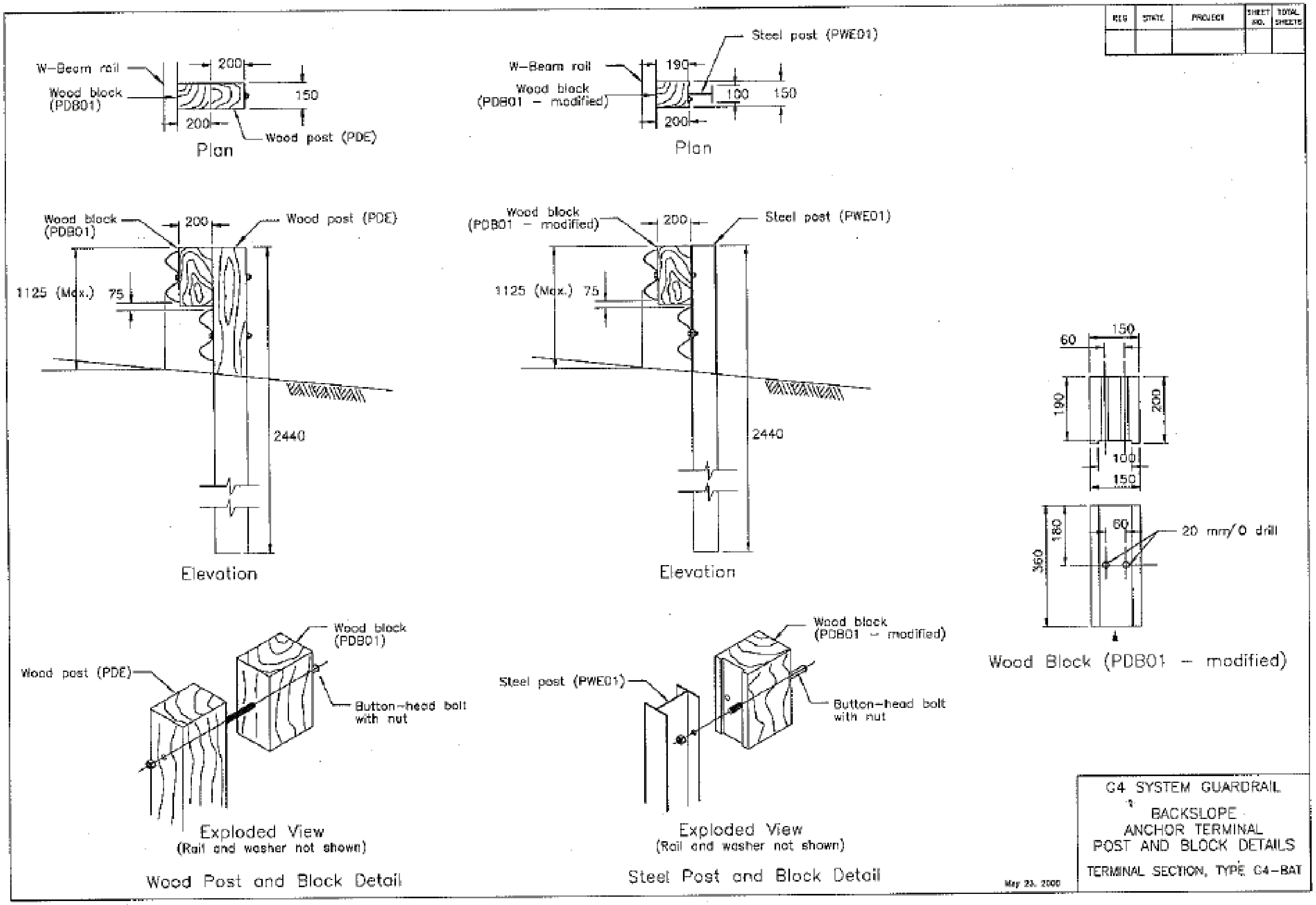


Figure 2.1. Details of the G4 W-beam Guardrail Buried-in-Backslope Installation for Test 404211-13 (Continued).

A vee ditch runs through the installation. It consists of a 4 to 1 slope from the pavement edge for 6 ft and then a 2:1 backslope continuing behind the rail. The vee ditch crosses the rail terminal at post 8.

NHCRP Report 350 test 3-35 was the only simulation performed on the transition simulations reported herein. Drawings of the 27¾-inch buried-in-backslope installation is reported in Figure 2.2.

Researchers used the National Crash Analysis Center (NCAC) detailed finite element pickup truck model to complete their simulations (*6*). Some parts of the 2000P pickup truck model needed mesh refinement to avoid contact issues during the impact event against the finer meshed reproduction of the test article.

2.3 FINITE ELEMENT MODEL VALIDATION

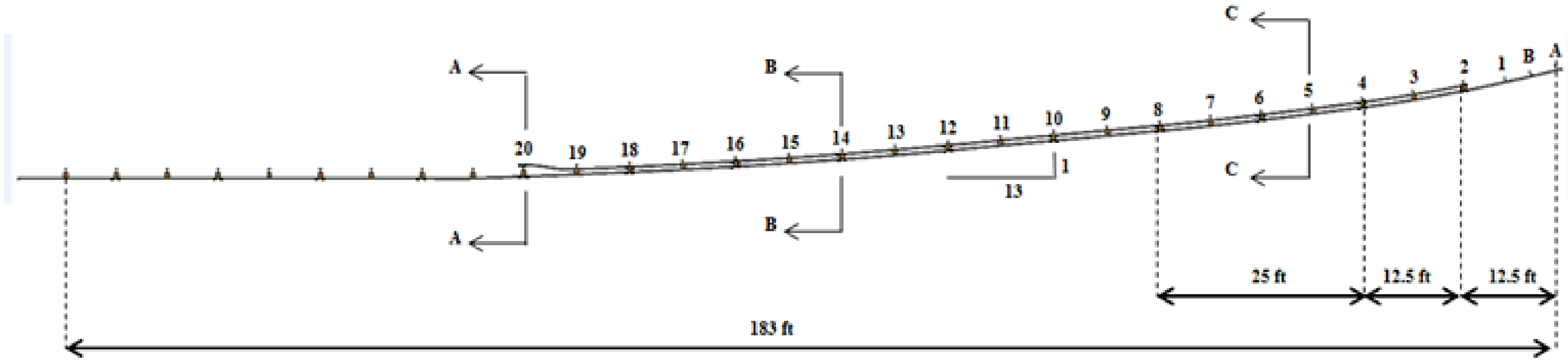
2.3.1 Barrier Performance

Table 2.1 contains images of the barrier before impact and at final configuration. Table 2.1 (a) and 2.1 (c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Table 2.1 (b) and 2.3(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. The barrier was impacted at post 8 of the buried-in-backslope terminal, with initial and speed and angle of 62.8 mph and approximately 26 degrees, respectively. The barrier successfully contained and redirected the vehicle. Barrier maximum dynamic and permanent deformations were approximately 1.7 ft and 1.44 ft, respectively.

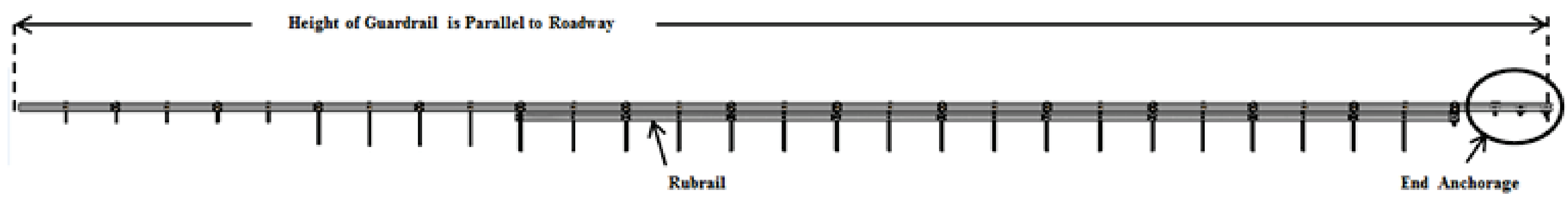
2.3.2 Energy Values

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 is 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 2.3, approximately 40 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). Five percent of the initial kinetic energy is converted into hourglass energy. Approximately 22 percent of the initial kinetic energy is converted into sliding interface energy. Twenty five 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.

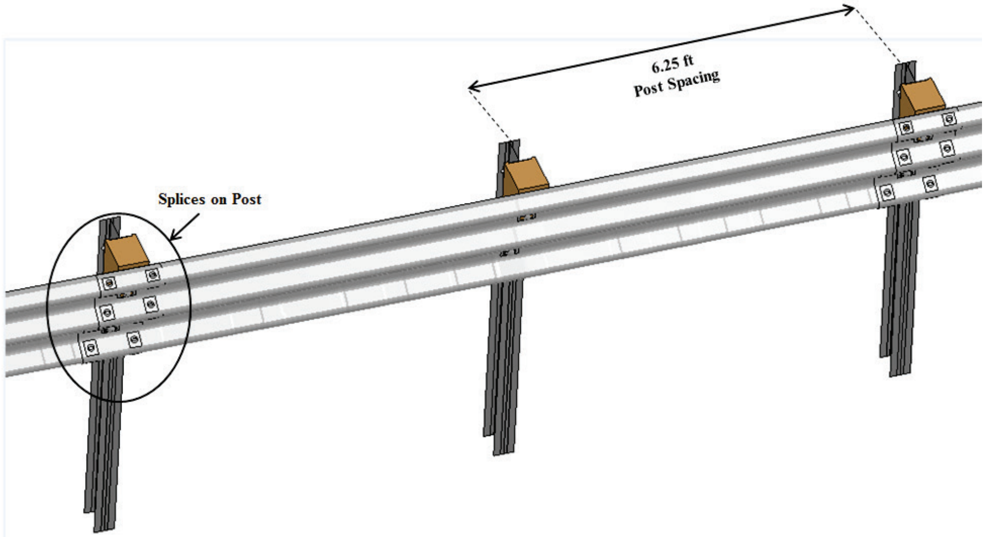


(a) Plan View

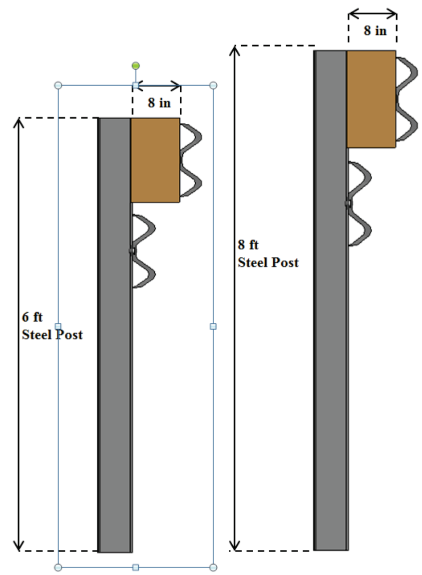


(b) Elevation View

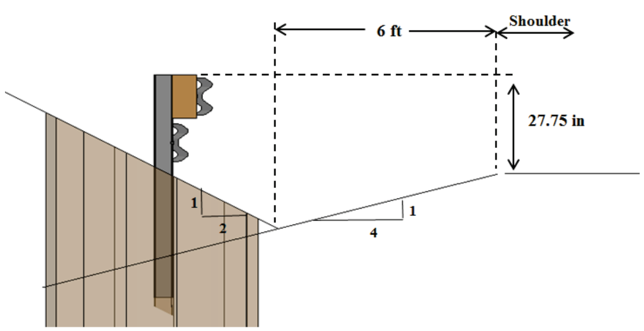
Figure 2.2. Details of the 27¾-inch High Buried-in-Backslope Terminal Installation for Finite Element Computer Model Simulation.



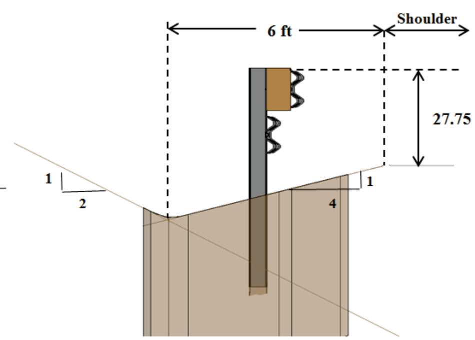
∞ (a) Post Spacing



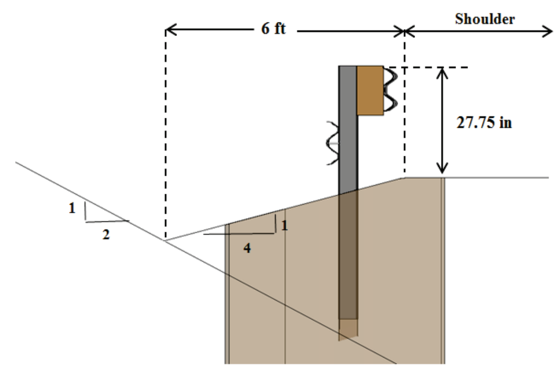
(b) Posts Profiles



(c) Section A-A



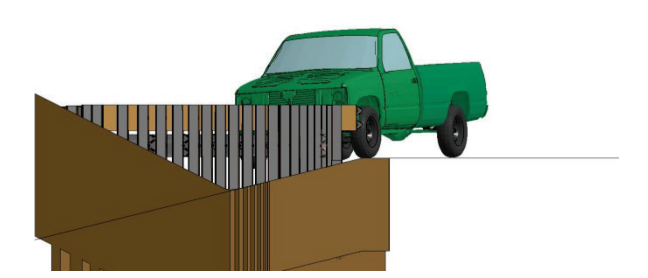
(d) Section B-B



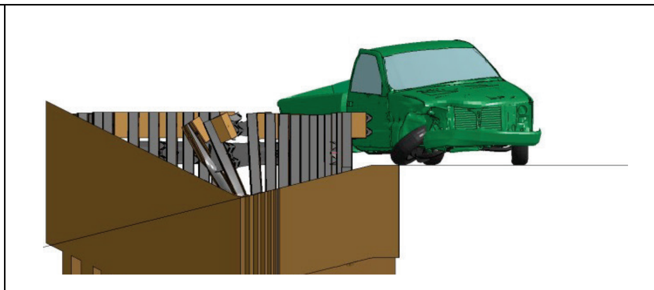
(e) Section C-C

Figure 2.2. Details of the 27¾-inch High Buried-in-Backslope Terminal Installation for Finite Element Computer Model Simulation (Continued).

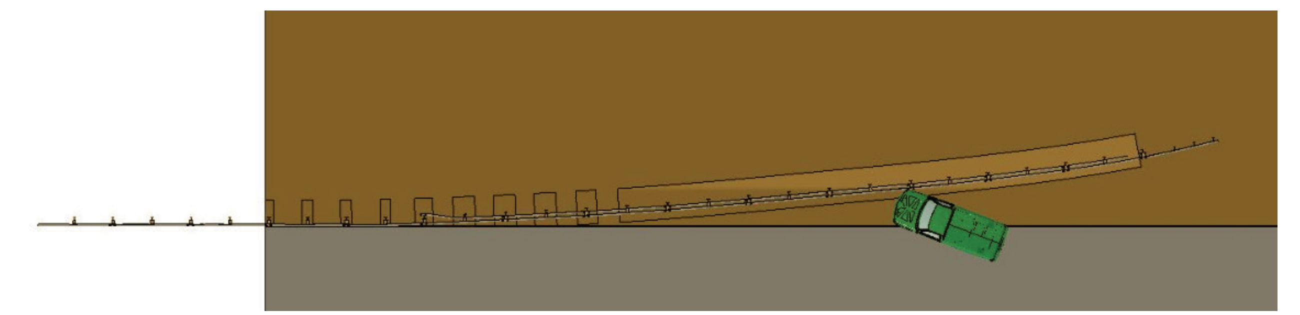
Table 2.1. Initial and Deflected Shape of Barrier (27¾-inch Height Buried-in-Backslope Terminal).



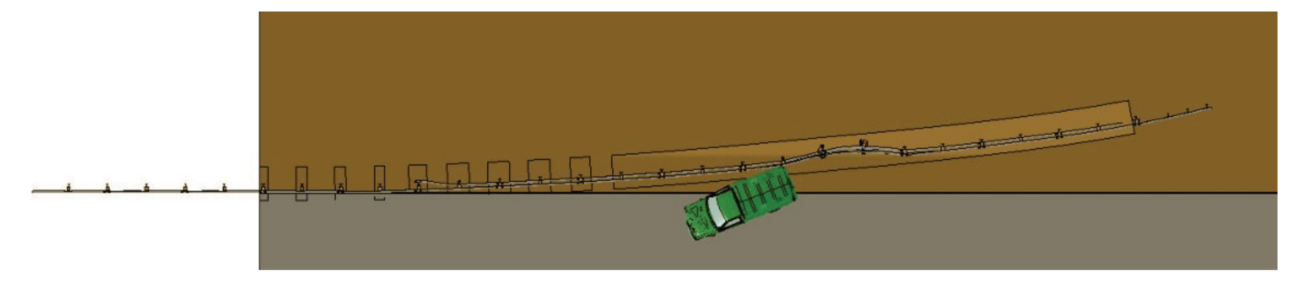
(a) Front View At Impact



(b) Front View At Final Configuration



(c) Top View At Impact



(d) Top View At Final Configuration

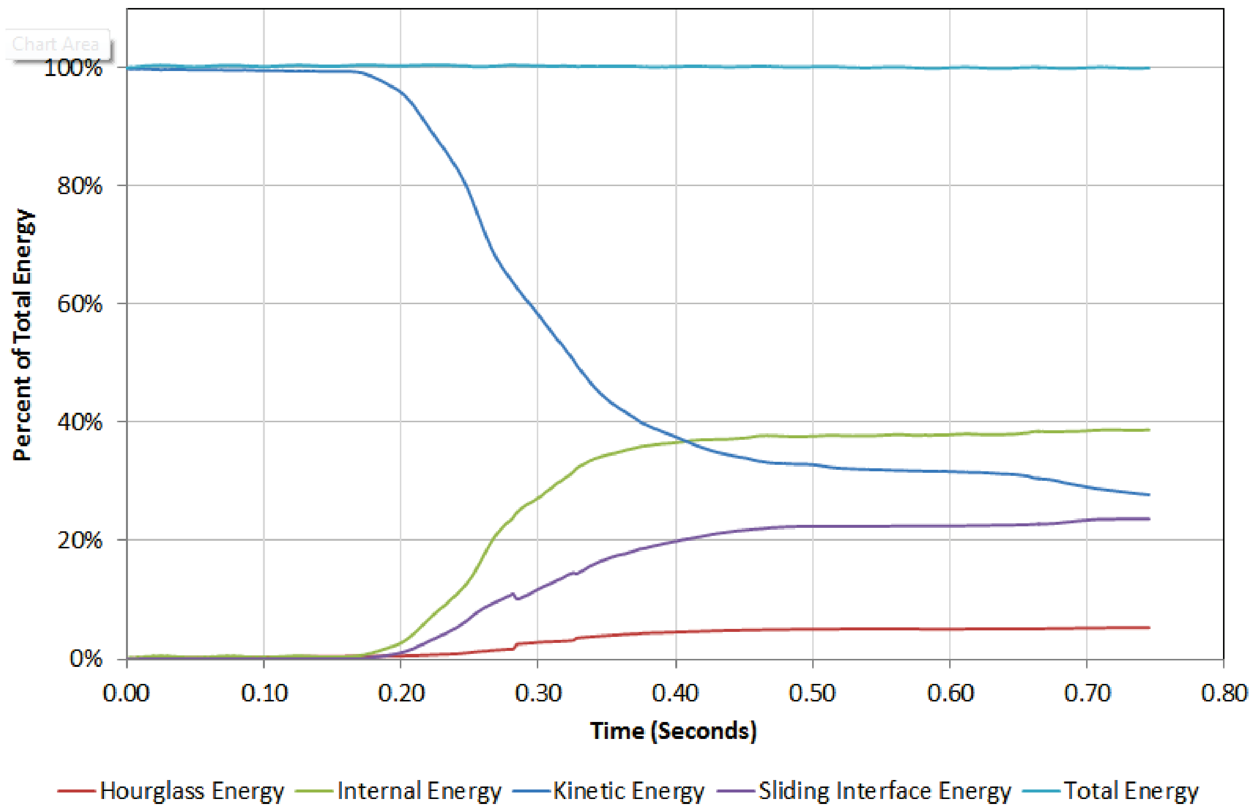


Figure 2.3. Energy Distribution Time History (27¾-inch Height Buried-in-Backslope Terminal).

2.3.3 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 2000 vehicle remained upright during and after the modeled collision event. Occupant impact velocities were evaluated to be 24.6 ft/sec and −18.7 ft/sec in the longitudinal and lateral directions, respectively (Table 2.2). Ridedown accelerations were evaluated to be -14.4 g and 11.3 g in the longitudinal and lateral directions, respectively. Figure 2.4 also shows vehicle roll, pitch and yaw angles throughout the impact event against 27-inch high buried-in-backslope terminal. Maximum roll, pitch and yaw angles resulted to be -7.3, 6.1, and 42.9 degrees, respectively. Angular displacements obtained in the full-scale crash test and in the simulation are also reported in Figures 2.4 and 2.5, respectively. Figure 2.6 reports time histories of the angular displacements curves (test and FE) and their synchronization through the Roadside Safety Verification and Validation Program (RSVVP).

Table 2.2. Occupant Risk Values (27¾-inch Height Buried-in-Backslope Terminal).

Occupant Risk Factors	Test 404211-13	Results From FE	Relative Difference
Impact Vel. -m/sec (ft/sec)			
x-direction	5.4 (17.72)	7.5 (24.61)	2.1 m/sec
y-direction	6.5 (21.33)	-5.7 (18.70)	0.8 m/sec
Ridedown Acc. (g's)			
x-direction	-8.3	-14.4	6.1
y-direction	7.9	11.3	3.4
Angles	**Test 404211-13**	**Results From FE**	**Relative Difference**
Roll (deg.)	-18	-7.3*	10.7*
Pitch (deg.)	7	6.1	0.9
Yaw (deg.)	43	42.9	0.1

* Please see researcher's comments in Sub-Chapter 2.3.4

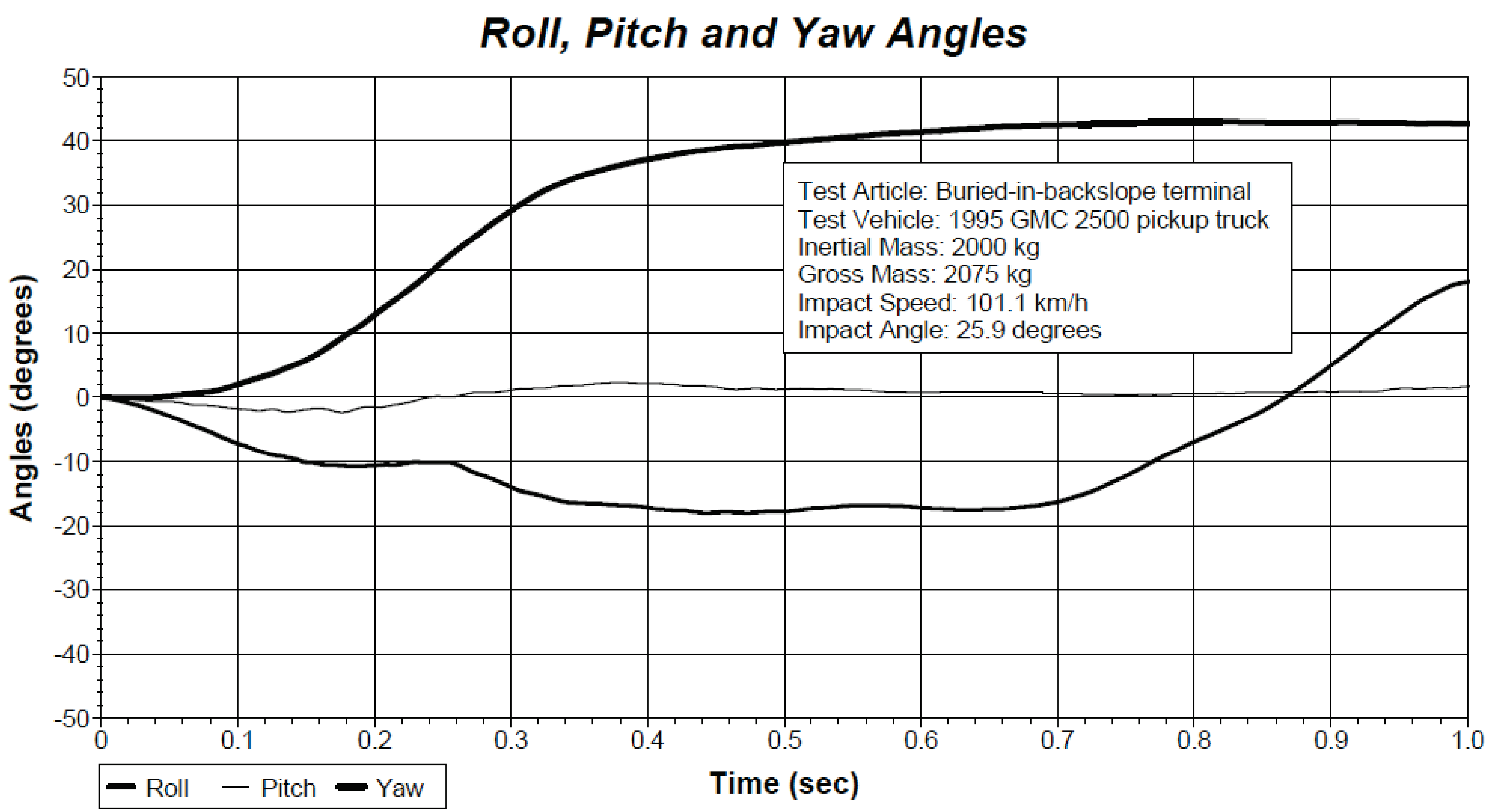


Figure 2.4. Vehicular Angular Displacements for Test 404211-13.

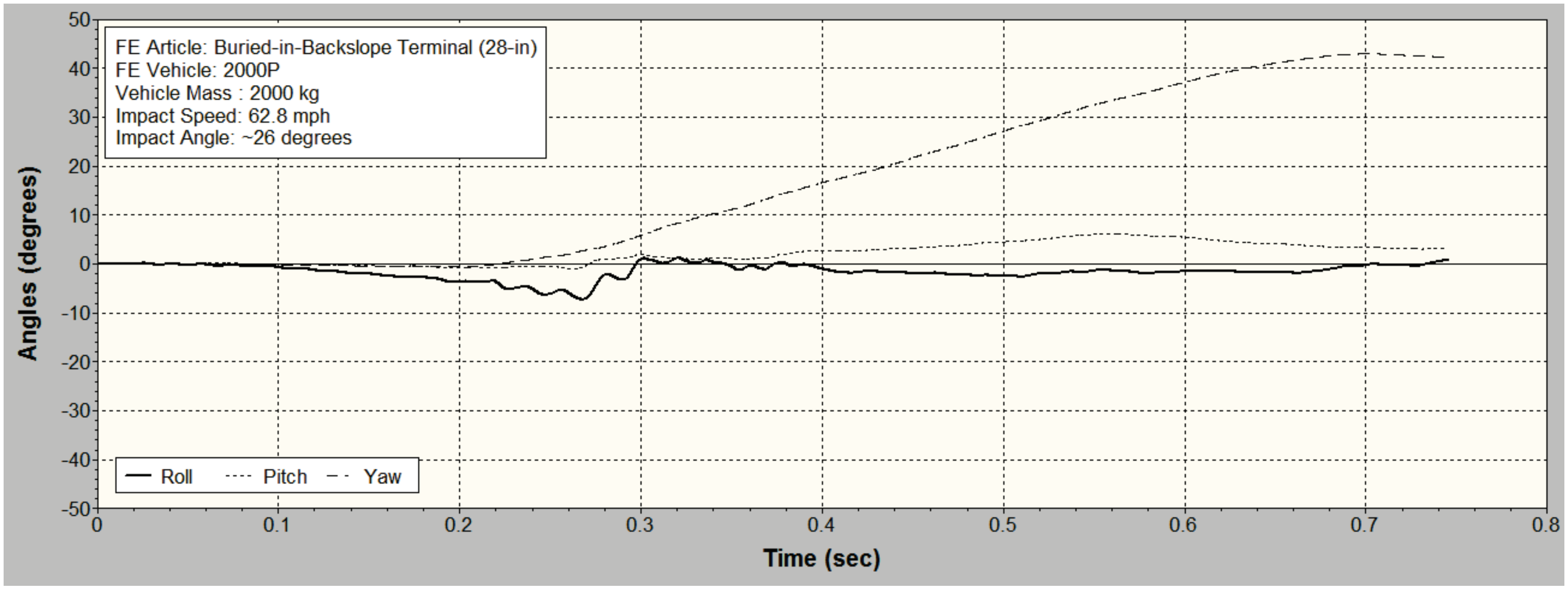
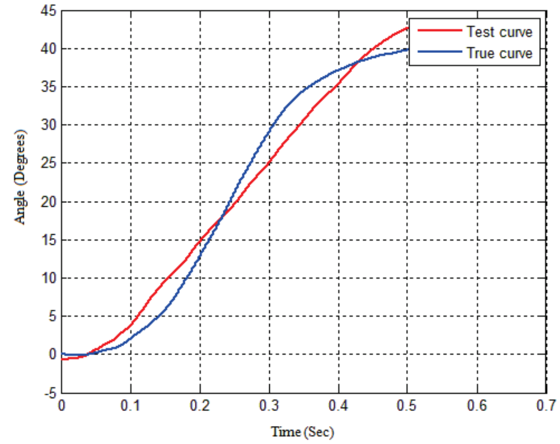
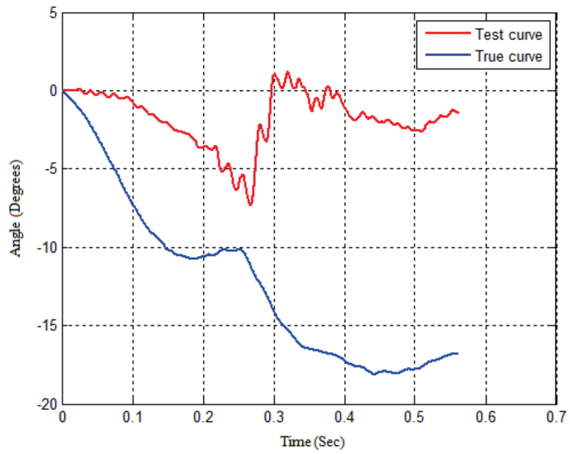


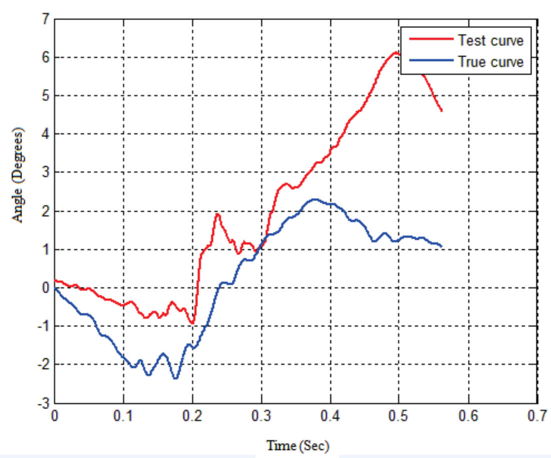
Figure 2.5. Vehicular Angular Displacements for Computer Simulation (27¾-inch Height Buried-in-Backslope Terminal).



(a) Yaw



(b) Roll



(c) Pitch

*The true curve refers to the curve from the test and the test curve refers to the curves from the FE simulation

Figure 2.6. Vehicular Angular Displacements for Computer Simulation (27¾-inch Height Buried-in-Backslope Terminal).

Tables 2.3 and 2.4 show frames from computer simulation of the impact event and from the actual full-scale crash test against the 27¾-inch high buried-in-backslope terminal. Generally, there is a good agreement between the vehicle stability and relative position between the vehicle and the test article between computer simulations and full-scale test. It appears, however, that at first contact with the test article, the 2000P FE vehicle is presenting itself with a smaller roll inclination than the one observed from the frame of the full-scale test. Researchers attributed this position variation as a result of the actual FE vehicle suspension model limitation.

2.3.4 Roll Angle Measurement from FE Computer Simulation

Vehicle stability results obtained with the TRAP program indicated that after the moment of first impact with the test article, the vehicle underwent a negative roll. According to the TRAP data, the vehicle roll values decreased and soon oscillated around the zero value throughout the rest of the impact event. These results were not completely in agreement with the data from the 404211-13 full-scale test, where the vehicle maintained a negative roll during the complete impact event. Images from the finite element computer simulations, however, clearly showed that the vehicle maintained a negative roll throughout the impact event. As a result, the researchers investigated the stability of the vehicle within the FE computer simulation more closely.

Specifically, the behavior of the vehicle simulated transducer was examined, since the vehicle stability is determined by analyzing the yaw, pitch and roll rate data obtained from the sensor with respect to a local coordinate system. Frames of the simulations were reviewed with respect to the vehicle accelerometer behavior (Figure 2.7 and Tables 2.5 and 2.6). It was noted that although the vehicle was rolling at a certain degree, the accelerometer did not appear to roll of the same amount (Table 2.5). In fact, at certain times of the impact event, the accelerometer was experiencing an opposite inclination with respect to the vehicle's body (Table 2.6). When this behavior was reviewed more closely, the researchers noted that the floorboard of the vehicle experienced local deformation at the mounting location of the sensor. The researchers concluded that as consequence of this local deformation, the accelerometer experienced a local roll angle that was significantly less than that of the vehicle. For this reason, the researchers suggest not to direct compare roll rate and angle data between the computer simulation and the test.

Table 2.3. Sequential Images of the 2000P Vehicle Interaction with the 27¾-inch High Buried-in-Backslope Terminal (Top View).

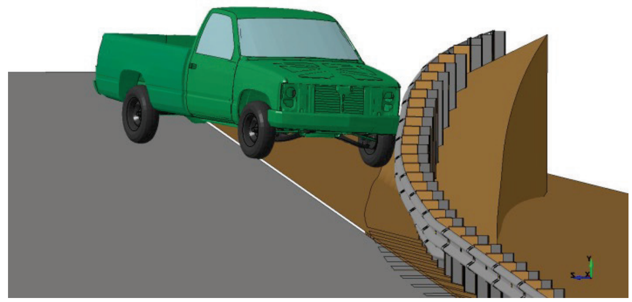
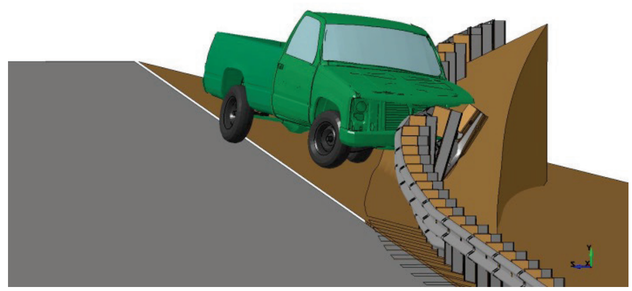
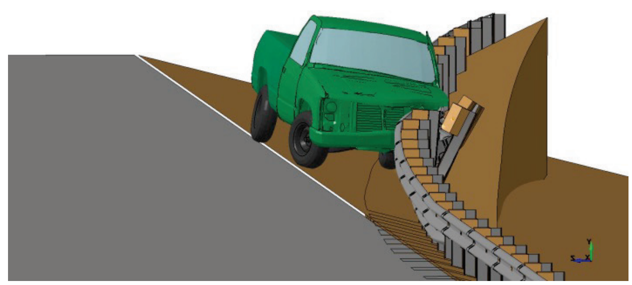
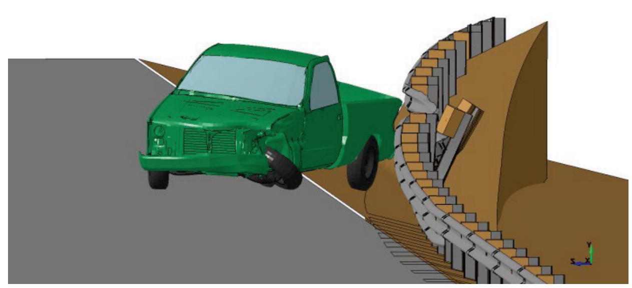
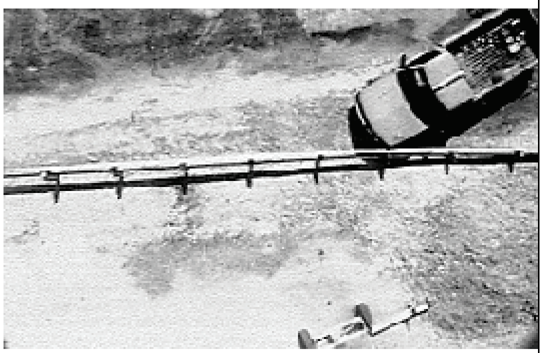
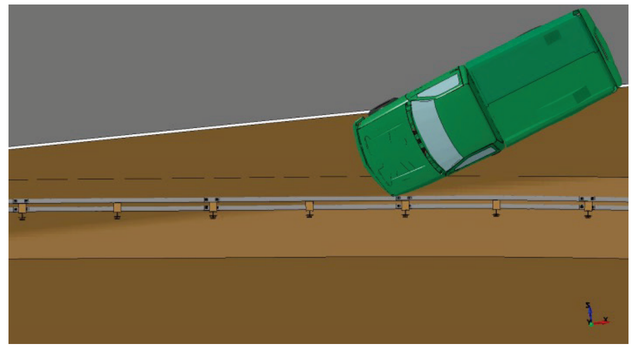
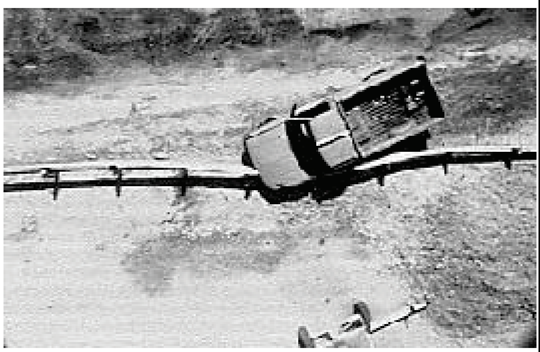
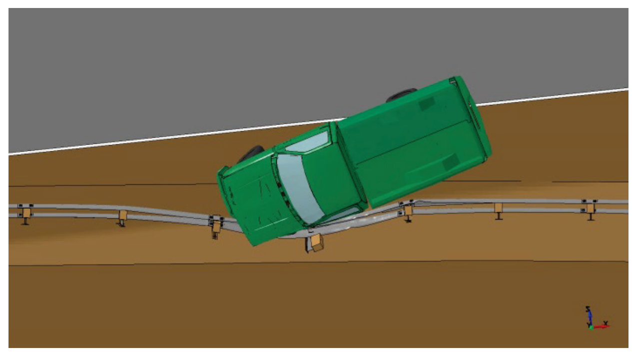
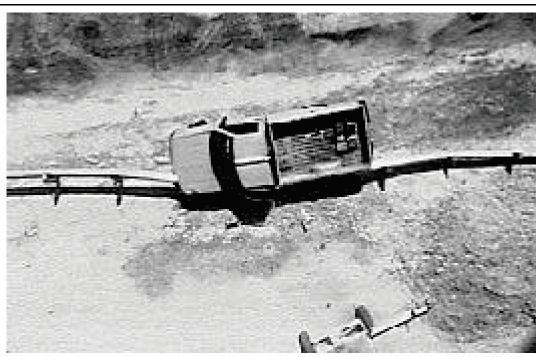
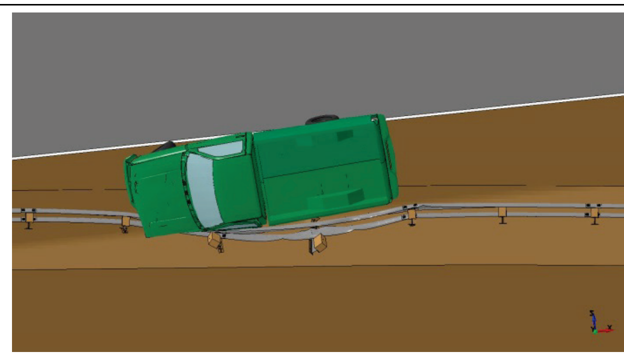
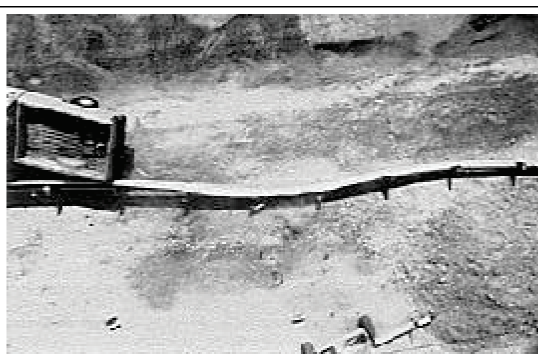
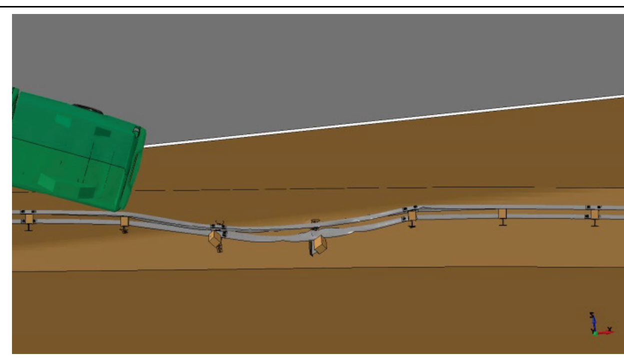
Time (sec)	TEST 404211-13	FE-Validation
0.000s		
0.128		
0.230 s		
0.587 s		

Table 2.4. Sequential Images of the 2000P Vehicle Interaction with the 31-inch High Buried-in-Backslope Terminal (Front View).

Time (sec)	TEST 404211-13	FE-Validation
0.000s		
0.128		
0.230 s		
0.587 s		

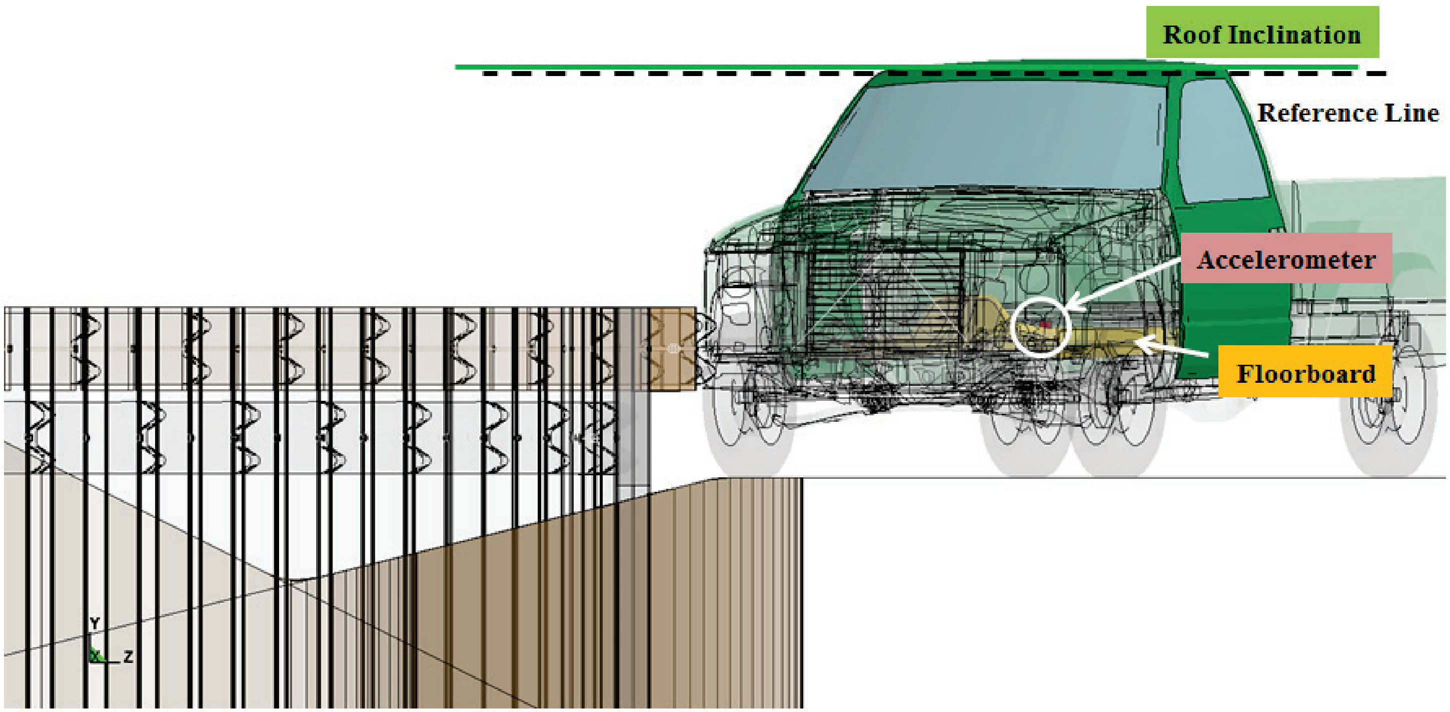


Figure 2.7. Reference Picture for Identification of the Roof, Accelerometer, and Floorboard of the 2000P Vehicle in the Computer Simulation.

Table 2.5. Accelerometer and Vehicle Inclinations in the Computer Simulation.

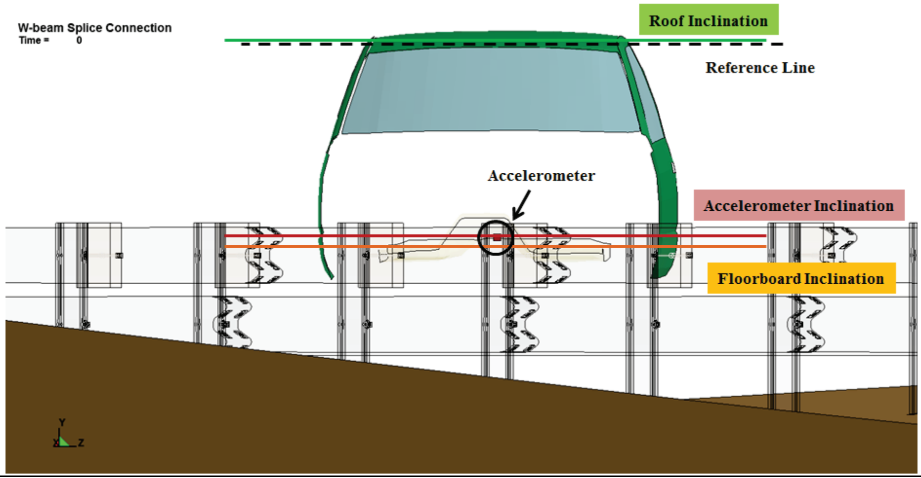
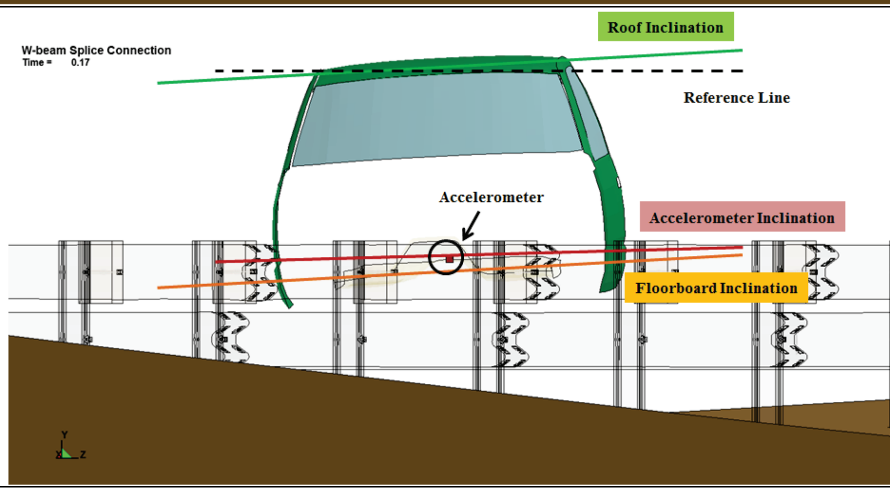
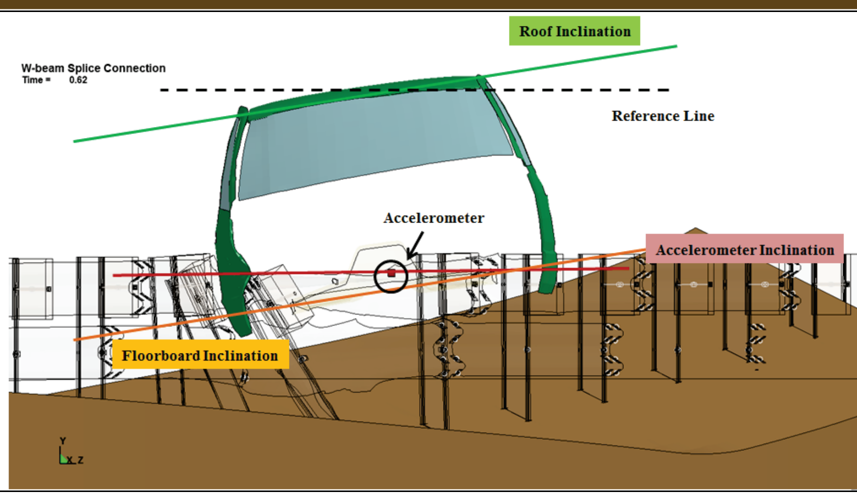
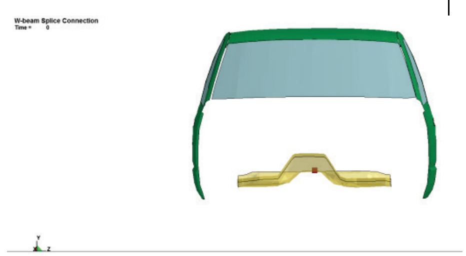
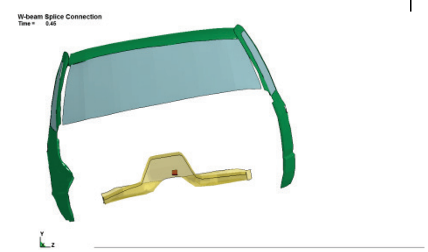
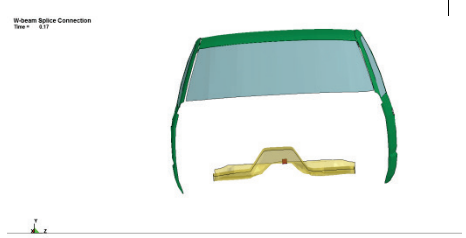
Simulation Time (sec)	FE Simulation Frame
0.000	
0.170 (First Impact with the Test Article)	
0.620	

Table 2.6. Sequential Images of the Accelerometer and Vehicle Inclinations Throughout the Simulated Impact Event.

FE Simulation Time (sec)	Test Frames	FE Simulation Time (sec)	Test Frames
0.00		0.45	
0.17		0.60	
0.30		0.745	

2.3.5 RSVVP Validation

A program called the Roadside Safety Verification and Validation Program (RSVVP) was developed for validation of numerical models in roadside safety (*7*). 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 (ref LS-DYNA). 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 2.7. Based on the Sprague & Geers metrics, the x-, y- and yaw-channels indicated that the numerical analysis was in agreement with the test, and that the z-, roll and pitch-channels were not. The ANOVA metrics indicated that the simulation was in good agreement with the test for all channels except the roll and pitch channels. 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 2.8. The results indicate that the x-, y-, yaw and roll 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 did not satisfy the acceptance criteria.

Considering the fact that non-realistic vehicle roll results were extrapolated from the computer simulation, the researchers decided to compute the comparison metrics for a quantitative validation of the pickup truck FE impact model without inclusion of the roll rate curve comparison. The results of the evaluation for the individual channels are shown in Table 2.9. Based on the Sprague & Geers metrics, the x-, y- and yaw-channels indicated that the numerical analysis was in agreement with the test, and that the z- and pitch-channels were not. The ANOVA metrics indicated that the simulation was in good agreement with the test for all channels except the pitch channel. 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 five channels of data. The resulting weight factors computed for each channel are shown in both tabular form and graphical form in Table 2.10. 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 did satisfy the acceptance criteria. The time history comparison (with exclusion of the roll rate channel) can be considered acceptable.

Table 2.7. Roadside Safety Validation Metrics Rating Table (Single Channel Option).

<table>
<tr><td colspan="8">Evaluation</td><td colspan="3" rowspan="2">Time interval [0 sec; 0.5629 sec]</td></tr>
<tr><td rowspan="8">O</td><td colspan="7">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="2"></td><td colspan="6">RSVVP Curve Preprocessing Options</td><td rowspan="2">M [%]</td><td rowspan="2">P [%]</td><td rowspan="2">Pass?</td></tr>
<tr><td>Filter Option</td><td>Sync. Option</td><td>Shift True Curve</td><td>Shift Test Curve</td><td>Drift True Curve</td><td>Drift 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>3.6</td><td>47.1</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>12.5</td><td>41</td><td>N</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>27.3</td><td>49.9</td><td>N</td></tr>
<tr><td>Yaw rate</td><td>CFC 180</td><td>Min. area of Residuals</td><td>N</td><td>N</td><td>N</td><td>N</td><td>0.5</td><td>2.9</td><td>Y</td></tr>
<tr><td>Roll rate</td><td>CFC 180</td><td>Min. area of Residuals</td><td>N</td><td>N</td><td>N</td><td>N</td><td>81.5</td><td>26.1</td><td>N</td></tr>
<tr><td></td><td>Pitch rate</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</td><td>24.7</td><td>N</td></tr>
<tr><td rowspan="7">P</td><td colspan="7">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 ($e \leq 0.05 \cdot a_{Peak}$) 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</td><td>Pass?</td></tr>
<tr><td colspan="7">X acceleration/Peak</td><td>-2.8</td><td>21.84</td><td>Y</td></tr>
<tr><td colspan="7">Y acceleration/Peak</td><td>-1.57</td><td>17.69</td><td>Y</td></tr>
<tr><td colspan="7">Z acceleration/Peak</td><td>0.95</td><td>30.46</td><td>Y</td></tr>
<tr><td colspan="7">Yaw rate</td><td>0.44</td><td>5.97</td><td>Y</td></tr>
<tr><td colspan="7">Roll rate</td><td>57.7</td><td>30.06</td><td>N</td></tr>
<tr><td colspan="7">Pitch rate</td><td>74.28</td><td>58.93</td><td>N</td></tr>
</table>

Table 2.8. Roadside Safety Validation Metrics Rating Table for Validation (Multi-Channel Option Using Area II Method).

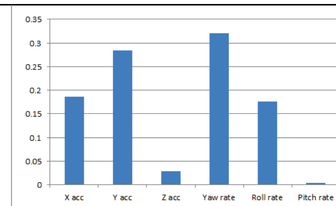
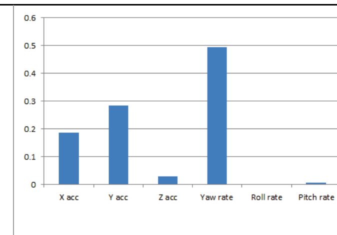
<table>
<tr><td colspan="5">Evaluation Criteria (time interval [0 sec; 0.5629 sec])</td></tr>
<tr><td colspan="5">Channels (Select which were used)</td></tr>
<tr><td colspan="2">☒ X Acceleration</td><td>☒ Y Acceleration</td><td colspan="2">☒ Z Acceleration</td></tr>
<tr><td colspan="2">☒ Roll rate</td><td>☒ Pitch rate</td><td colspan="2">☒ Yaw rate</td></tr>
<tr><td colspan="2">Multi-Channel Weights
-Area (II) Method-</td><td>X Channel – 0.186163
Y Channel – 0.284737
Z Channel – 0.029101
Yaw Channel – 0.321161
Roll Channel – 0.175429
Pitch Channel- 0.00341</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>Pass?</td></tr>
<tr><td>19.8</td><td>27.5</td><td>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 ($e \le 0.05 \cdot a_{Peak}$)
• The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \le 0.35 \cdot a_{Peak}$)</td><td>Mean Residual</td><td>Standard Deviation of Residuals</td><td>Pass?</td></tr>
<tr><td>9.6</td><td>17.4</td><td>N</td></tr>
</table>

Table 2.9. Roadside Safety Validation Metrics Rating Table (Single Channel Option without Roll Channel).

<table>
<tr><th colspan="9">Evaluation</th><th colspan="3" rowspan="2">Time interval [0 sec; 0.5629 sec]</th></tr>
<tr><td rowspan="10">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="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>3.6</td><td>47.1</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>12.5</td><td>41</td><td>N</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>27.3</td><td>49.9</td><td>N</td></tr>
<tr><td>Yaw rate</td><td>CFC 180</td><td>Min. area of Residuals</td><td>N</td><td>N</td><td>N</td><td>N</td><td>0.5</td><td>2.9</td><td>Y</td></tr>
<tr><td>Roll rate</td><td>CFC 180</td><td>Min. area of Residuals</td><td>N</td><td>N</td><td>N</td><td>N</td><td>N/A</td><td>N/A</td><td></td></tr>
<tr><td>Pitch rate</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</td><td>24.7</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 ($\bar{e} \le 0.05 \cdot a_{Peak}$) and
• The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \le 0.35 \cdot a_{Peak}$)</td><td>Mean Residual [%]</td><td>Standard Deviation of</td><td>Pass?</td></tr>
<tr><td colspan="8">X acceleration/Peak</td><td>-2.8</td><td>21.84</td><td>Y</td></tr>
<tr><td colspan="8">Y acceleration/Peak</td><td>-1.57</td><td>17.69</td><td>Y</td></tr>
<tr><td colspan="8">Z acceleration/Peak</td><td>0.95</td><td>30.46</td><td>Y</td></tr>
<tr><td colspan="8">Yaw rate</td><td>0.44</td><td>5.97</td><td>Y</td></tr>
<tr><td colspan="8">Roll rate</td><td>N/A</td><td>N/A</td><td></td></tr>
<tr><td colspan="8">Pitch rate</td><td>74.28</td><td>58.93</td><td>N</td></tr>
</table>

Table 2.10. Roadside Safety Validation Metrics Rating Table for Validation (Multi-Channel Option Using Area II Method Without Roll Channel).

<table>
<tr><th colspan="6">Evaluation Criteria (time interval [0 sec; 0.5629 sec])</th></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 – 0.186163
Y Channel – 0.284737
Z Channel – 0.029101
Yaw Channel – 0.494746
Roll Channel – 0
Pitch Channel- 0.005254</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>5.8</td><td>23.5</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>-0.3</td><td>13.3</td><td colspan="2">Y</td></tr>
</table>

2.3.6 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.

Figures 2.8 and 2.9 show the plastic strains in the front and field sides of the w-beam rail, respectively, at 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. Considering the number and size of plastic strain areas identified in the model are insignificant, the failure of the rail or post in the modeled scenario is unlikely.

2.3.7 Surrogate Measure of OCD

A common cause of barrier failure in a crash test is excessive occupant compartment deformation (OCD). Bullard et al. (2006) determined a measure that would demonstrate the best correlation with the maximum OCD reported in the crash tests. In their study, the internal energy of the floorboard of the pickup truck finite element model was selected as the most appropriate surrogate measure for evaluating OCD. Using the internal energy from FE simulations and the reported OCD values from crash tests, thresholds for the surrogate measure were established. As shown in Figure 2.10, the passing limit was selected as 2200 N-m and the failure limit was tentatively set at 10,700 N-m of internal energy in the floorboard of the pickup truck. The outcome of impacts with solid barriers in which the internal energy of the floorboard is between 2200 N-m and 10,700 N-m is largely unknown due to lack of crash test data with a sufficient range of OCD values. That means, for those simulations where the floorboard has an internal energy value between 2200 N-m and 10,700 N-m, there is the chance that vehicle OCD would not meet *NHCRP Report 350* test passing requirements (Figure 2.10).

Figure 2.11 summarizes measured internal energy of the of the pickup truck floorboard when impacting the 27¾-inch buried-in-backslope terminal during simulation of *NCHRP Report 350* test 3-35. The internal energy of the floorboard is never greater than values of 330 N-m, remaining well below the 2200 N-m passing threshold suggested by Bullard et al. The resulting OCD, therefore, would be passing *NCHRP Report 350* requirements.

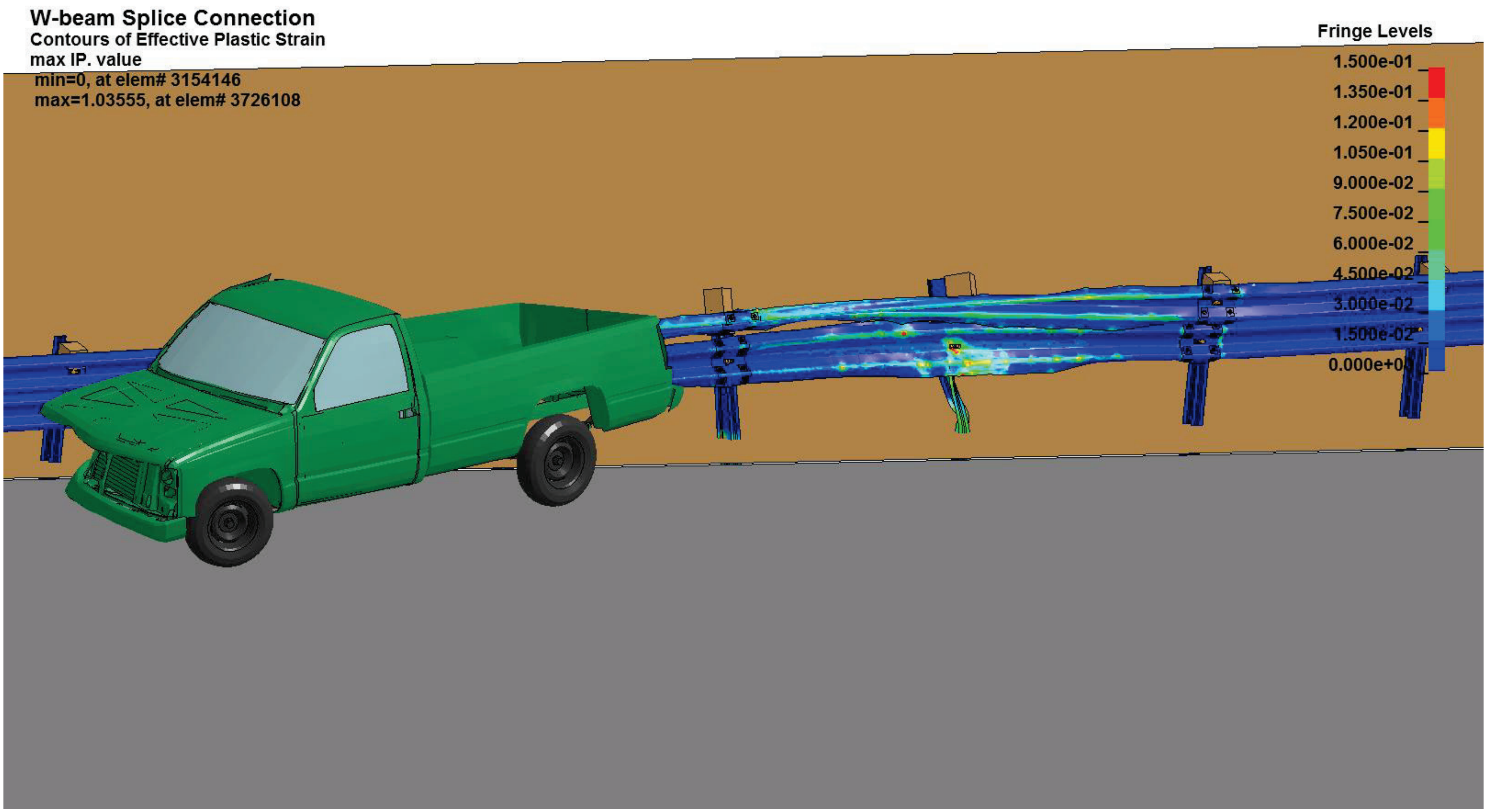


Figure 2.8. Effective Plastic Strains at the Front Face of the W-Beam Rail (27¾-inch High Buried-in-Backslope Terminal).

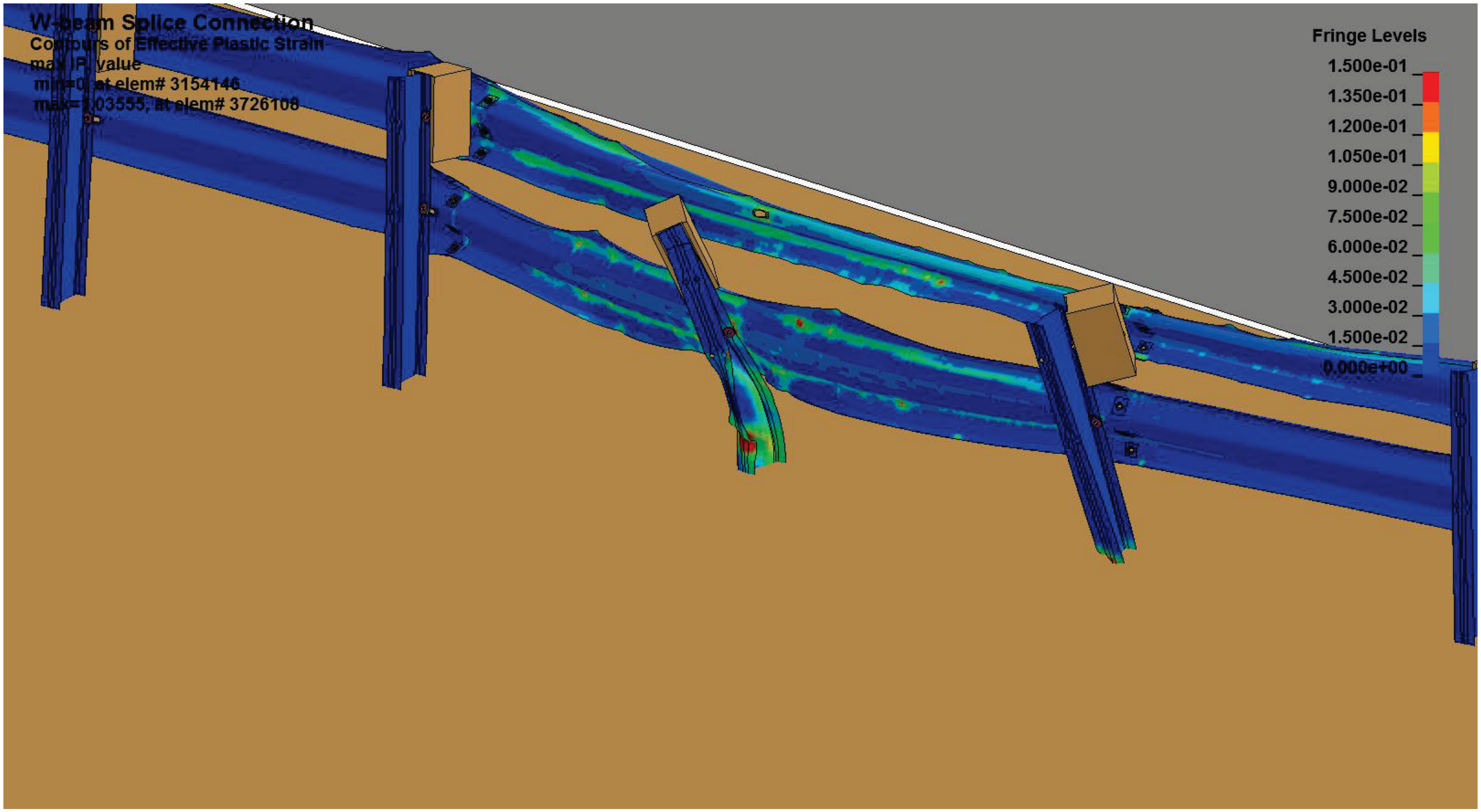


Figure 2.9. Effective Plastic Strains at the Field Face of the W-Beam Rail (27¾-inch High Buried-in-Backslope Terminal).

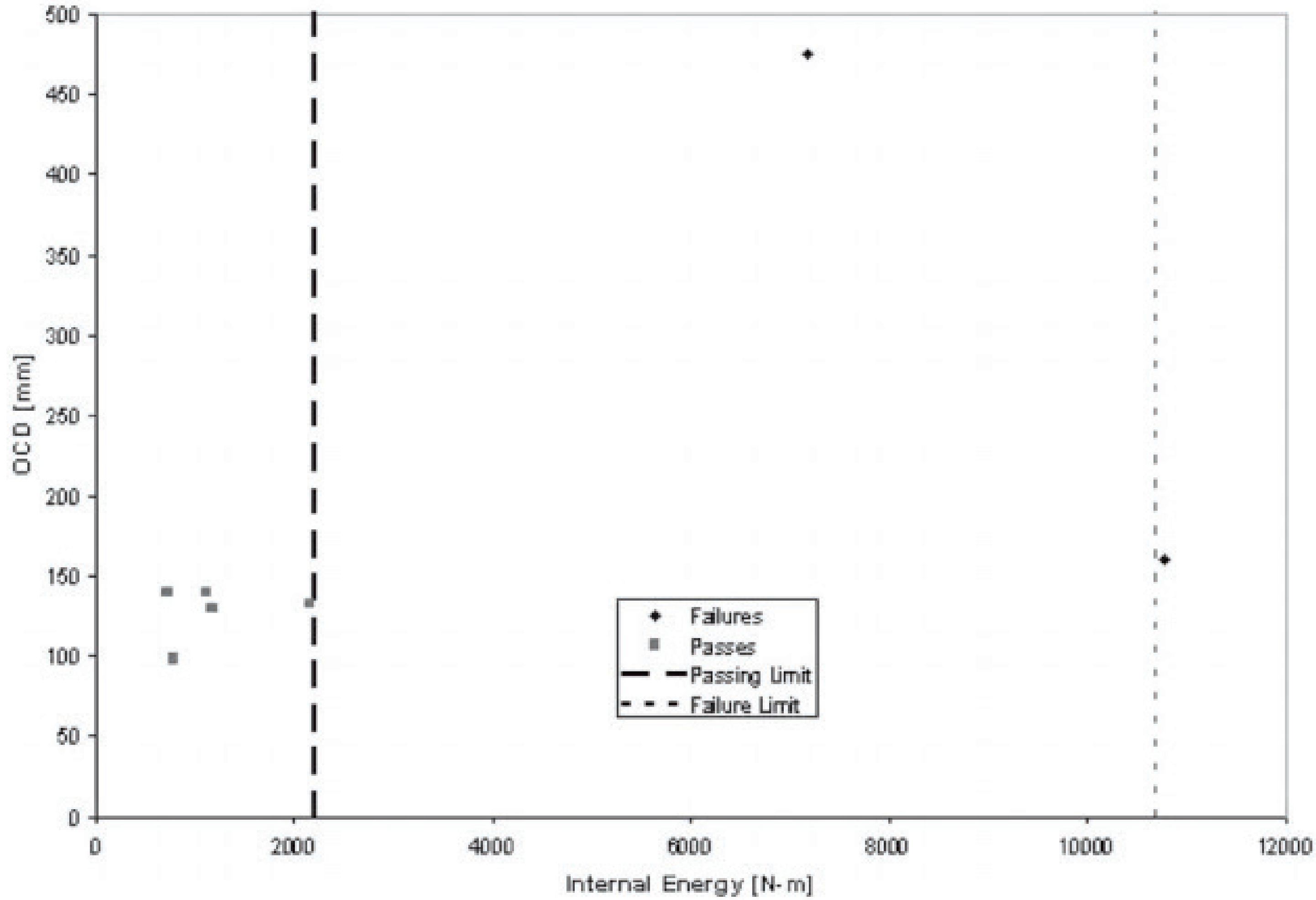


Figure 2.10. Passing and Failing Crash Tests OCD Versus Internal Energies of Floorboard (Bullard et al., 2006).

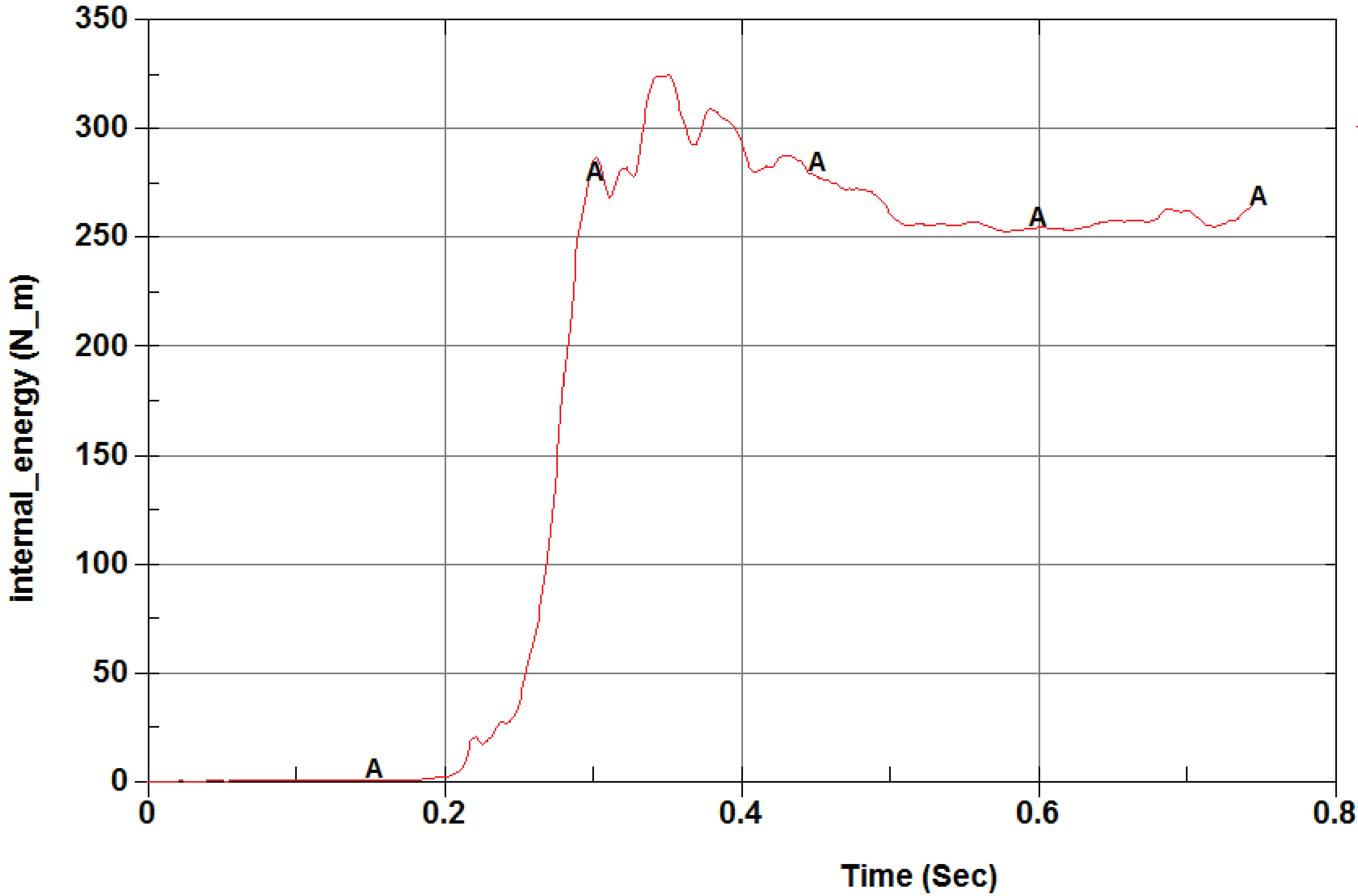
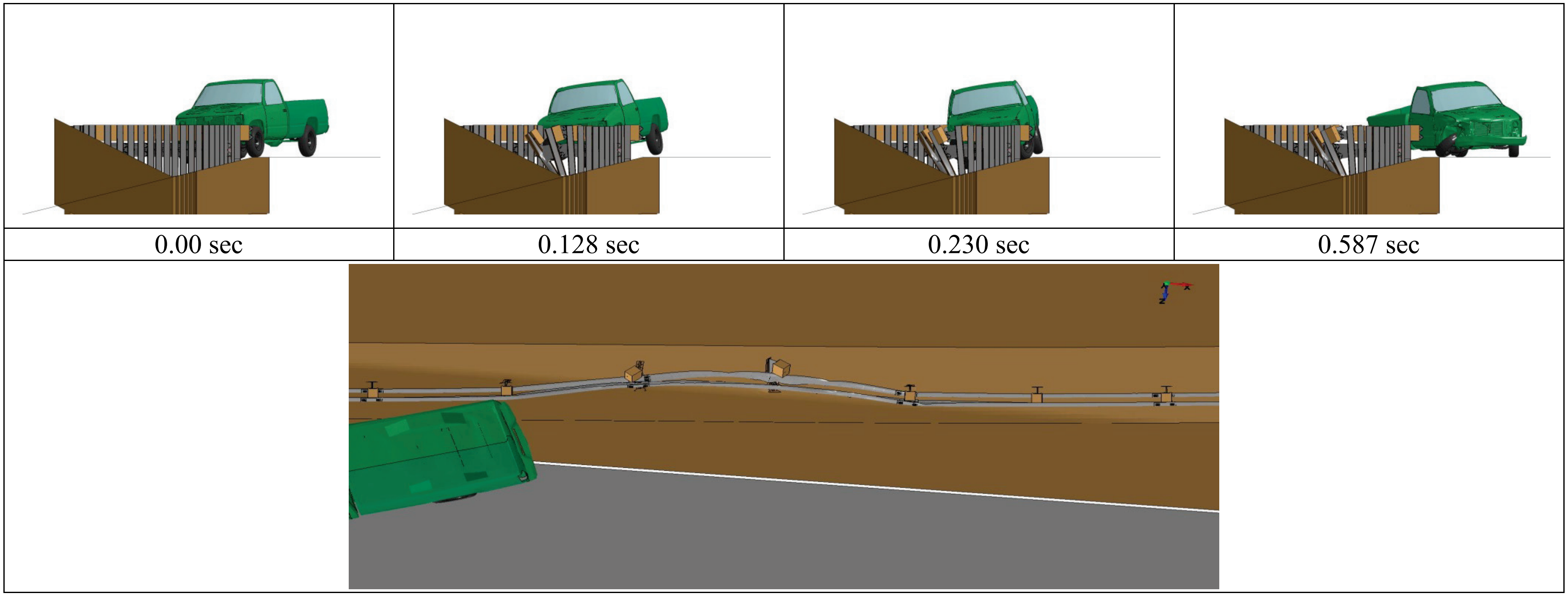


Figure 2.11. Floorboard Internal Energy for *NCHRP Report 350* Test 3-35 with 27¾-inch High Buried-in-Backslope Terminal.

2.3.8 Conclusion

Figure 2.12 summarizes results for *NCHRP Report 350* Test 3-35 simulation with a 2000P vehicle impacting the 27¾-inch high buried-in-backslope terminal. Computer simulation of *NCHRP Report 350* test 3-35 according the initial impact conditions of test 404211-13 well replicated the results obtained through full-scale crash testing. Although the model did not return matching roll rate values, other parameters compare favorably to those measured in the full scale test. In addition, the multi-channel option evaluation through the RSVVP program without inclusion of the roll rate channel suggests that the FE model of the 27¾-inch buried-in-backslope terminal realistically replicate the results observed through the full-scale crash test.



General Information
Test Agency .... Texas A&M Transportation Institute (TTI)
Test Standard Test No..... *NHCRP Report 350* Test 3-35
Date................................ N/A

Test Article
Type .... 27¾-inch Buried-in-Backslope Terminal

Installation Length............ 183 ft
Material or Key Elements. W-Beam Guardrail, 27.75-in Rail, Steel Posts with Wood Blockouts, Rubrail, 4:1 Slope

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

Impact Conditions
Speed................................62.8 mi/h
Angle ....26 degrees
Location/Orientation............At Post 8

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

Occupant Risk Values
Impact Velocity (ft/sec)
x-direction…………………. 24.61
y-direction…………………. -18.70
Ridedown Acceleration (g)
x-direction..........................-14.4
y-direction.......................... 11.3

Vehicle Stability
Maximum Yaw Angle .... 42.9 degree
Maximum Pitch Angle .... 6.1 degree
Maximum Roll Angle .... -7.3 degree
Vehicle Snagging......................No

Vehicle Damage
VDS..N/A
CDC..N/A
Max. Exterior Deformation ....N/A
OCD. ....< 2,200 N/m Floorboard Internal Energy
Max. Occupant Compartment Deformation........................N/A

Figure 2.12. Summary of Results for *NCHRP Report 350* Test 3-35 Simulation (27¾-inch High Buried-in-Backslope Terminal).

3. FINITE ELEMENT SIMULATION – 31-INCH RAIL HEIGHT

3.1 INTRODUCTION

The objective of this study is to identify design modifications necessary to adapt the buried terminal design for 27-inch (27¾-inch) guardrail for use with a 31-inch guardrail system and to determine the terminal crashworthiness according to *NHCRP Report 350* criteria. Without any additional design modifications, the researchers decided to elevate the rail height of the test article model from the original 27¾ inches to 31 inches and determine the crashworthiness of the new model according to computer simulations.

3.2 FINITE ELEMENT MODEL DESCRIPTION

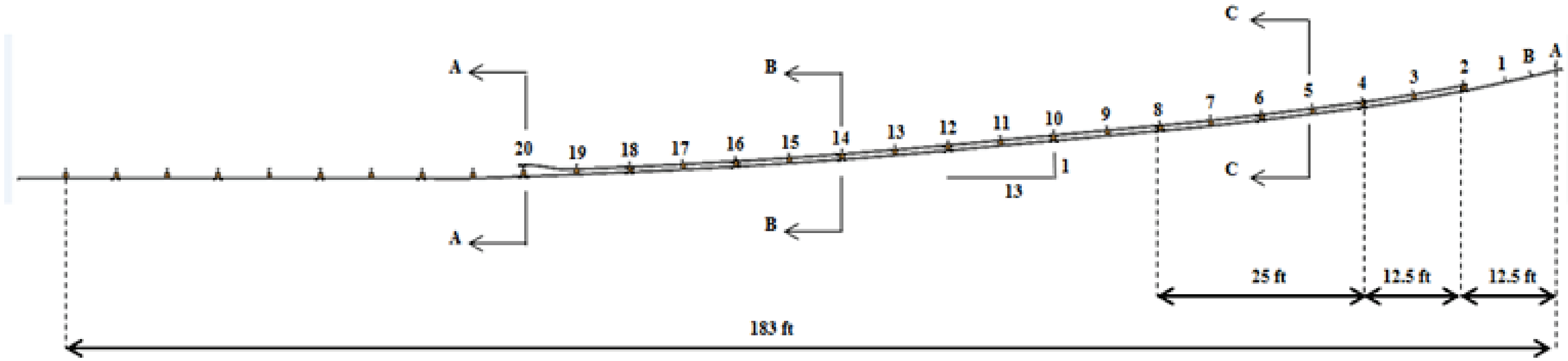
The modeled guardrail installation is flared across a vee ditch with its end anchored to a post rigidly fixed to simulate being buried into the soil. The guardrail installation is the standards SGR04a W-beam guardrail with wood blockouts. The guardrail is flared back in a 4 to 1 ratio between posts A, B, 1, and 2 (numbered sequentially from the end anchor). The guardrail between posts 2 and 4 is flared back in a 6:1 ratio; between posts 4 and 8 in an 8:1 ratio; and between posts 8 and 20 in a 13:1 ratio. The guardrail, beginning at post 8, is parallel to the travel way and extends for 12.5 ft beyond post 20 (length of need). The top of the rail is 31 inches measured from the shoulder grade.

The buried-in-backslope terminal consists of a w-beam guardrail attached to steel posts using 6-inch × 8-inch × 14-inch wood blockouts. The W-beam is connected to the end post using a special connection bracket.

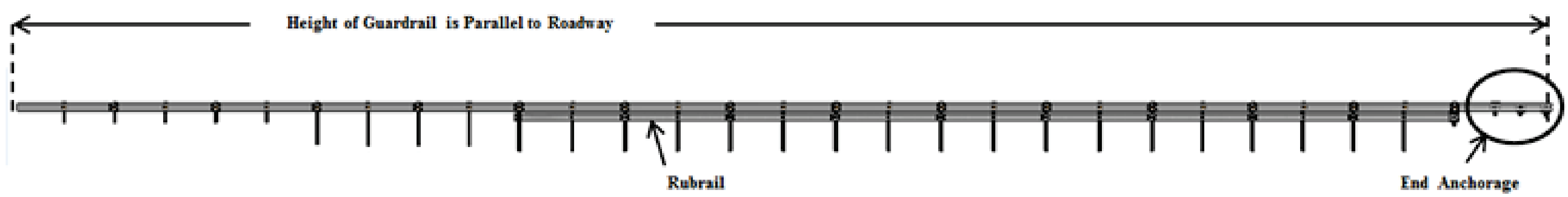
A W-beam rubrail extends from post 2 to post 20. A 3-inch gap between the w-beam guardrail and the rubrail is maintained. The upstream end of the rubrail is connected to post 2 with a special connection bracket and the downstream end of the rubrail is connected to the back of post 20.

A vee ditch runs through the installation. It consists of a 4:1 slope from the pavement edge for 6 ft and then a 2:1 backslope continuing behind the rail. The vee ditch crosses the rail terminal at post 8.

NHCRP Report 350 test 3-35 was the only simulation performed on the transition simulation reported herein. Drawing of the 31-inch buried-in-backslope installation is reported in Figure 3.1.

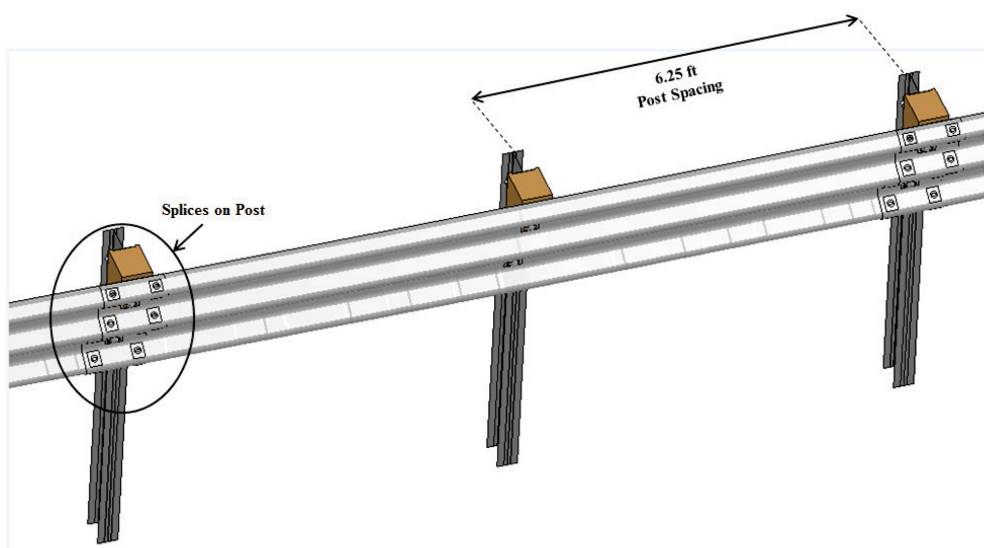


(a) Plan View

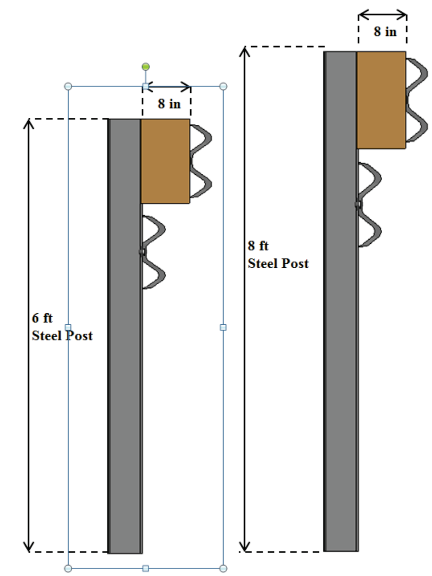


(b) Elevation View

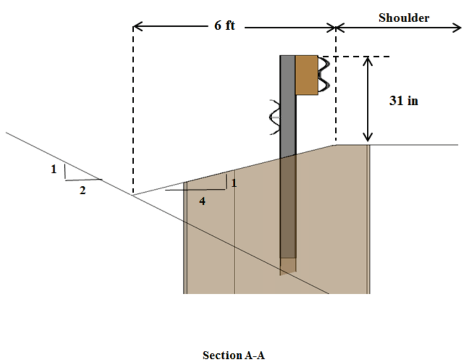
Figure 3.1. Details of the 31-inch High Buried-in-Backslope Terminal Installation for Finite Element Computer Model Simulation.



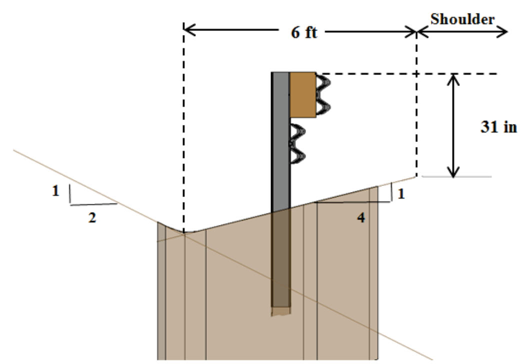
(a) Post Spacing



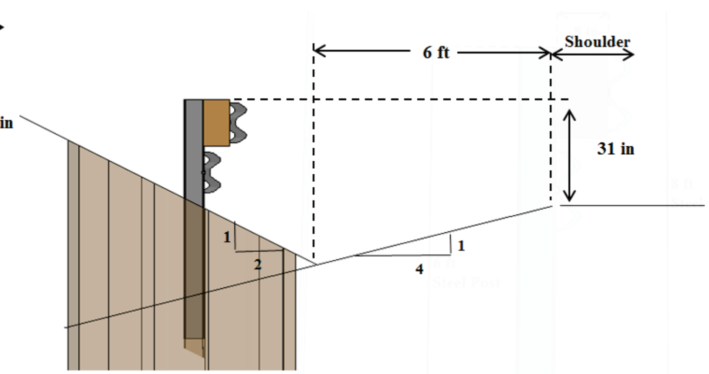
(b) Posts Profiles



(c) Section A-A



(d) Section B-B



(e) Section C-C

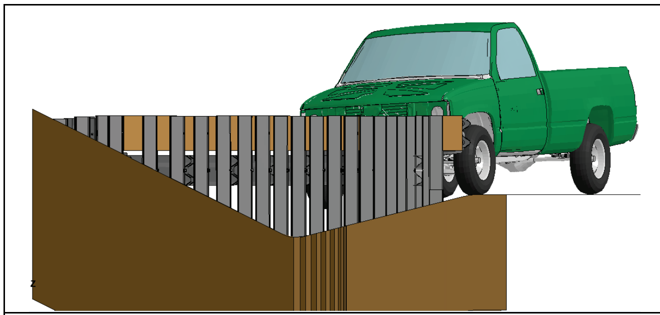
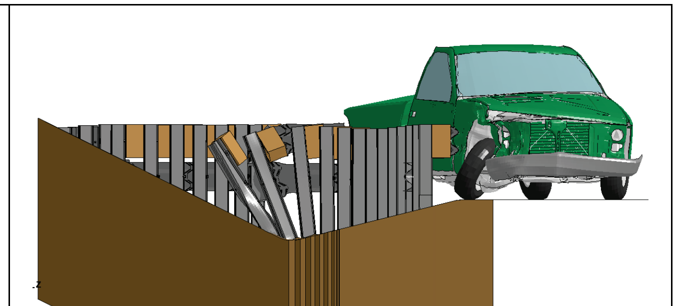
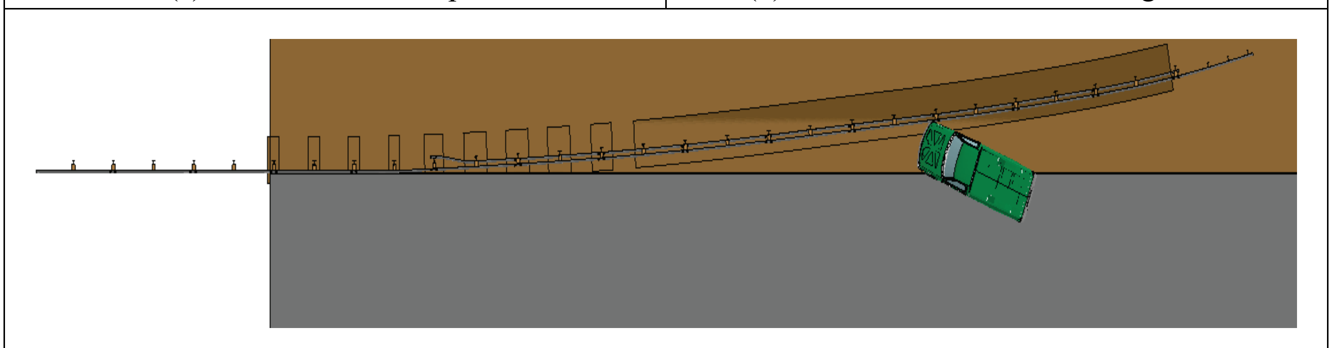
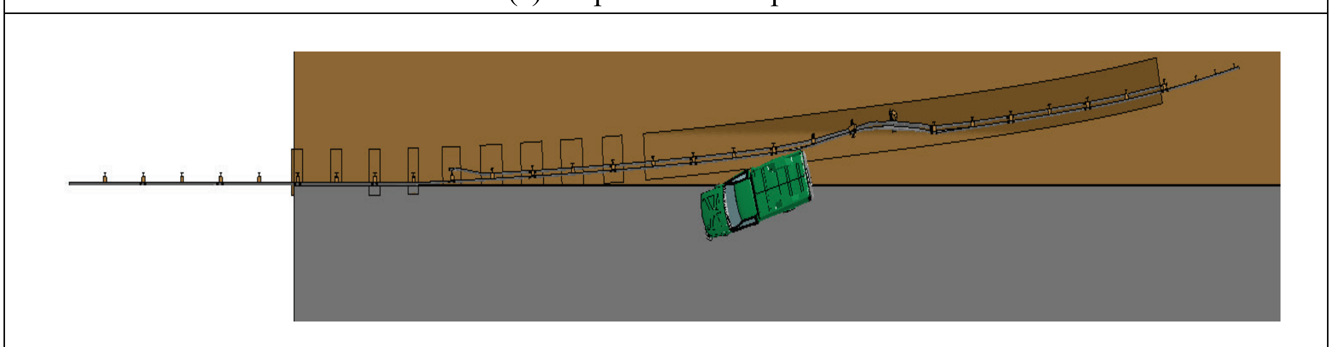
Figure 3.1. Details of the 31-inch High Buried-in-Backslope Terminal Installation for Finite Element Computer Model Simulation (Continued).

3.3 FINITE ELEMENT SIMULATION FOR 31-IN RAIL HEIGHT

3.3.1 Barrier Performance

Table 3.1 contains images of the barrier before impact and at final configuration. Table 3.1(a) and 3.1(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Table 3.1(b) and 3.1(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. The barrier was impacted at post 8 of the buried-in-backslope terminal, with initial and speed and angle of 62.8 mph and approximately 26 degrees, respectively. The barrier successfully contained and redirected the vehicle. Barrier maximum dynamic and permanent deformations were approximately 1.91 and 1.45 ft, respectively.

Table 3.1. Initial and Deflected Shape of Barrier (31-inch High Buried-in-Backslope Terminal).

	
(a) Front View At Impact	(b) Front View At Final Configuration
	
(c) Top View At Impact	
	
(d) Top View At Final Configuration	

3.3.2 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 is 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 3.2, approximately 40 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). Five 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 two 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.

Tables 3.2 through 3.4 show frames from computer simulation of the impact event against the 31-inch high buried-in-backslope terminal.

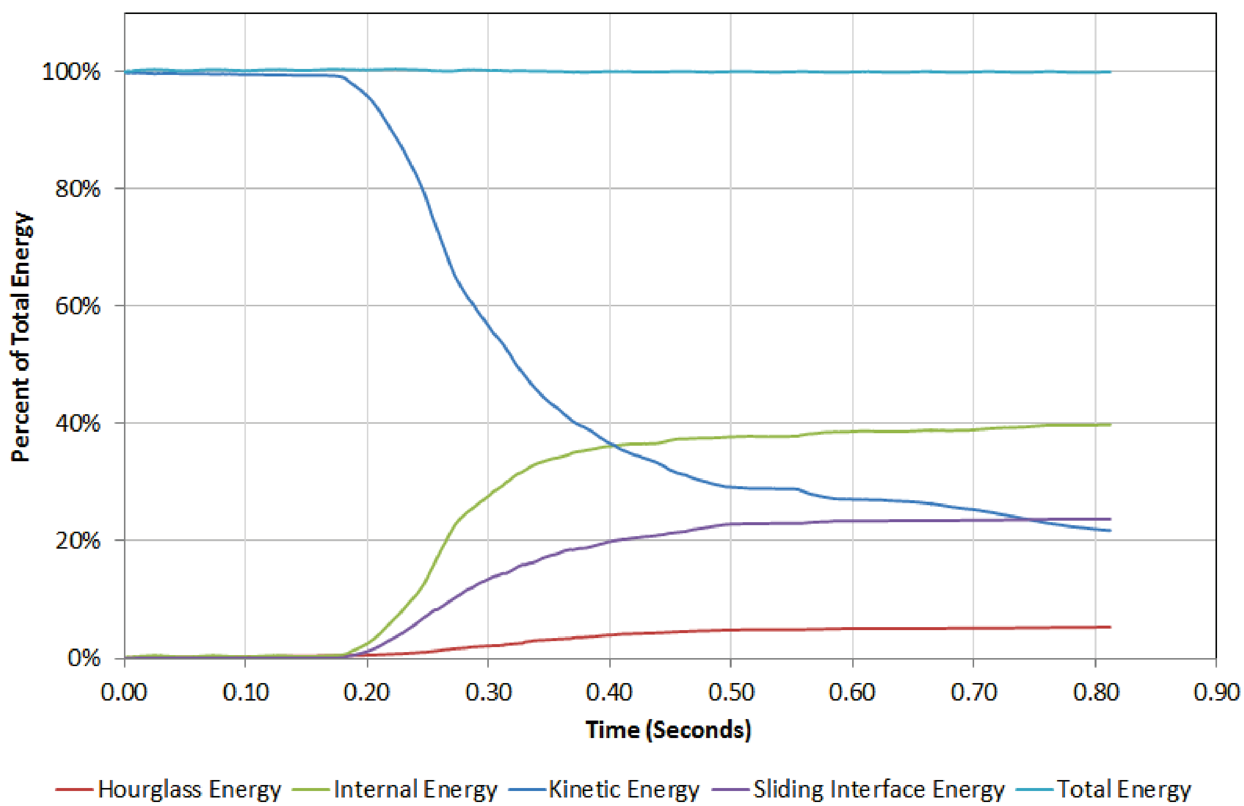


Figure 3.2. Energy Distribution Time History (31-inch Height Buried-in-Backslope Terminal).

Table 3.2. Sequential Images of the 2000P Vehicle Interaction with the 31-inch High Buried-in-Backslope Terminal (Top View).

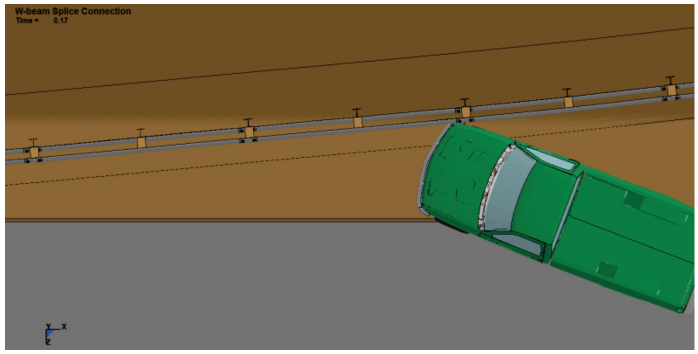
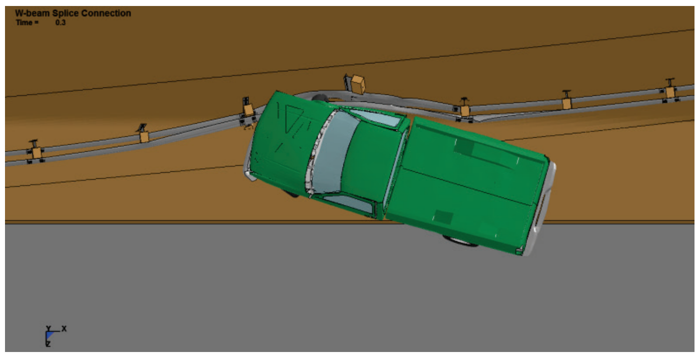
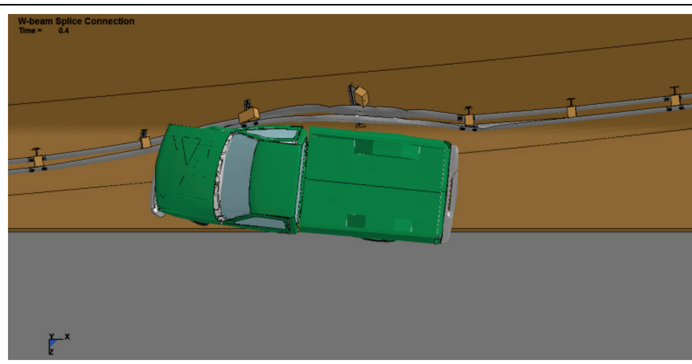
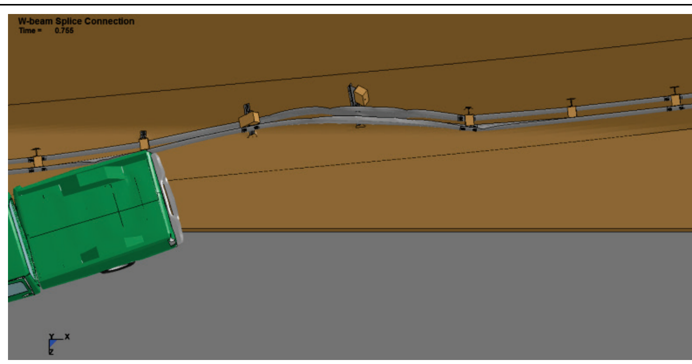
Time (sec)	Simulation Frames
0.000	
0.128	
0.230	
0.587	

Table 3.3. Sequential Images of the 2000P Vehicle Interaction with the 31-inch High Buried-in-Backslope Terminal (Front View).

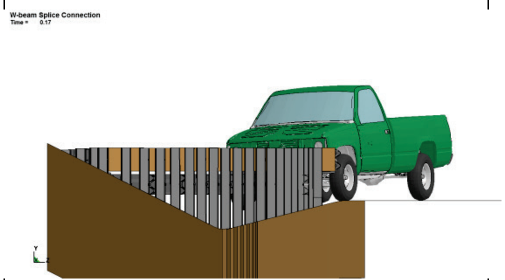
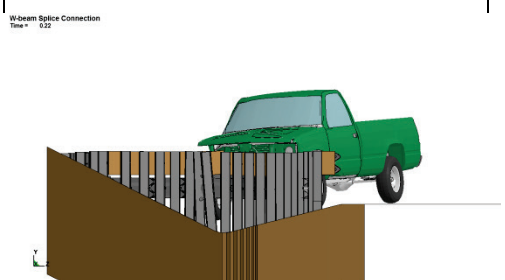
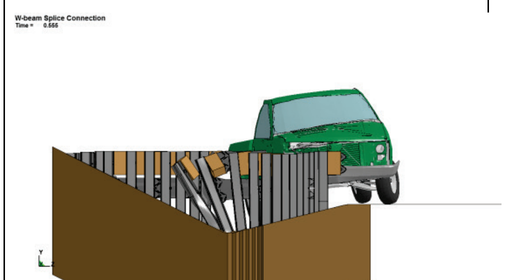
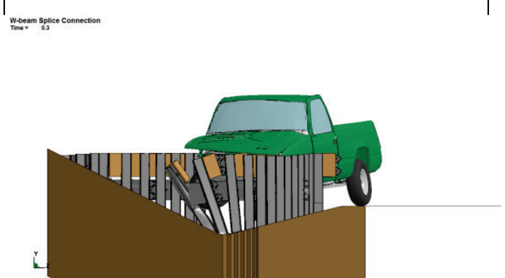
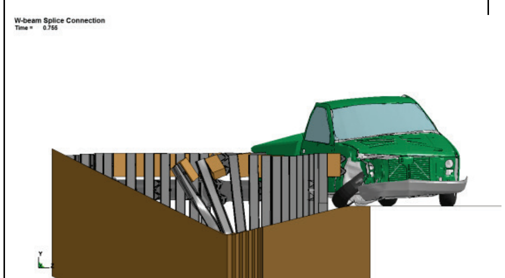
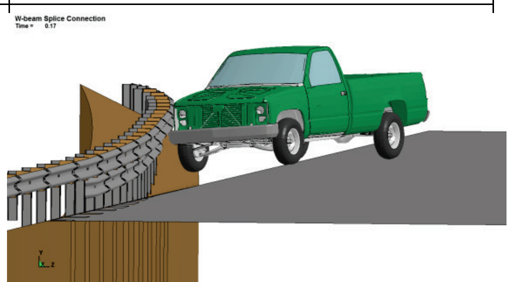
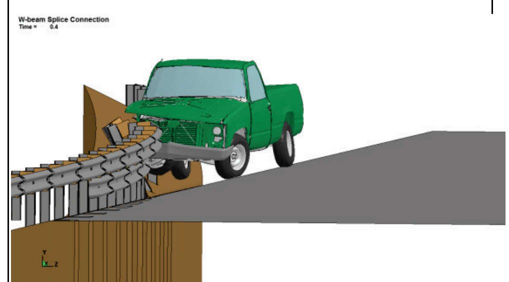
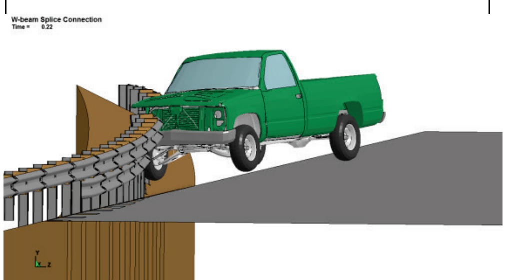
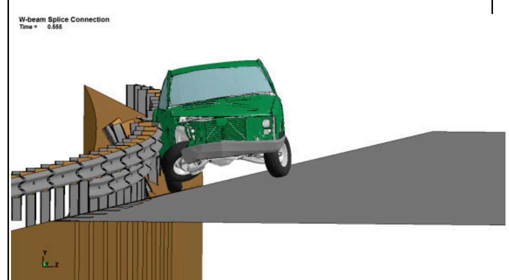
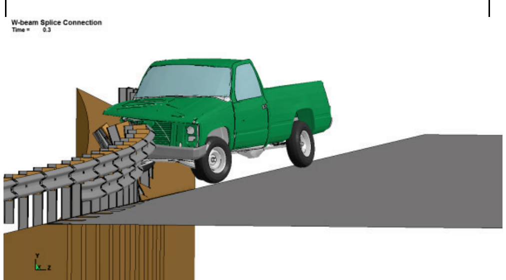
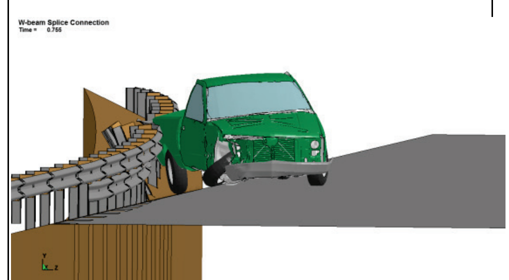
Time (sec)	Test Frames	Time (sec)	Test Frames
0.000		0.230	
0.051		0.383	
0.128		0.587	

Table 3.4. Sequential Images of the 2000P Vehicle Interaction with the 31-inch High Buried-in-Backslope Terminal (Perspective View).

Time (sec)	Test Frames	Time (sec)	Test Frames
0.000		0.230	
0.051		0.383	
0.128		0.587	

3.3.3 Occupant Risk Assessment

The TRAP program was used to evaluate occupant risk factors based on the applicable *NHCRP Report 350* safety evaluation criteria. The modeled 2000P vehicle remained upright during and after the modeled collision event. Table 3.5 shows vehicle roll, pitch and yaw angles throughout the impact event against the 31-inch buried-in-backslope terminal. Maximum roll, pitch and yaw angles resulted to be 9.9, 5.6, and 37.6 degrees, respectively. Occupant impact velocities were evaluated to be 26.57 ft/sec and -20.01 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were evaluated to be –10.0 g and 9.9 g in the longitudinal and lateral directions, respectively. Angular displacement curves are also reported in Figure 3.3.

Table 3.5. Occupant Risks Values (31-inch High Buried-in-Backslope Terminal).

Occupant Risk Factors	FE Buried-in-backslope Terminal (31-inch)
Impact Vel. (ft/sec)	
x-direction	26.57
y-direction	-20.01
Ridedown Acc. (g's)	
x-direction	-10.0
y-direction	9.9

Angles	FE Buried-in-backslope Terminal (31-inch)
Roll (deg.)*	9.9
Pitch (deg.)	5.6
Yaw (deg.)	37.6

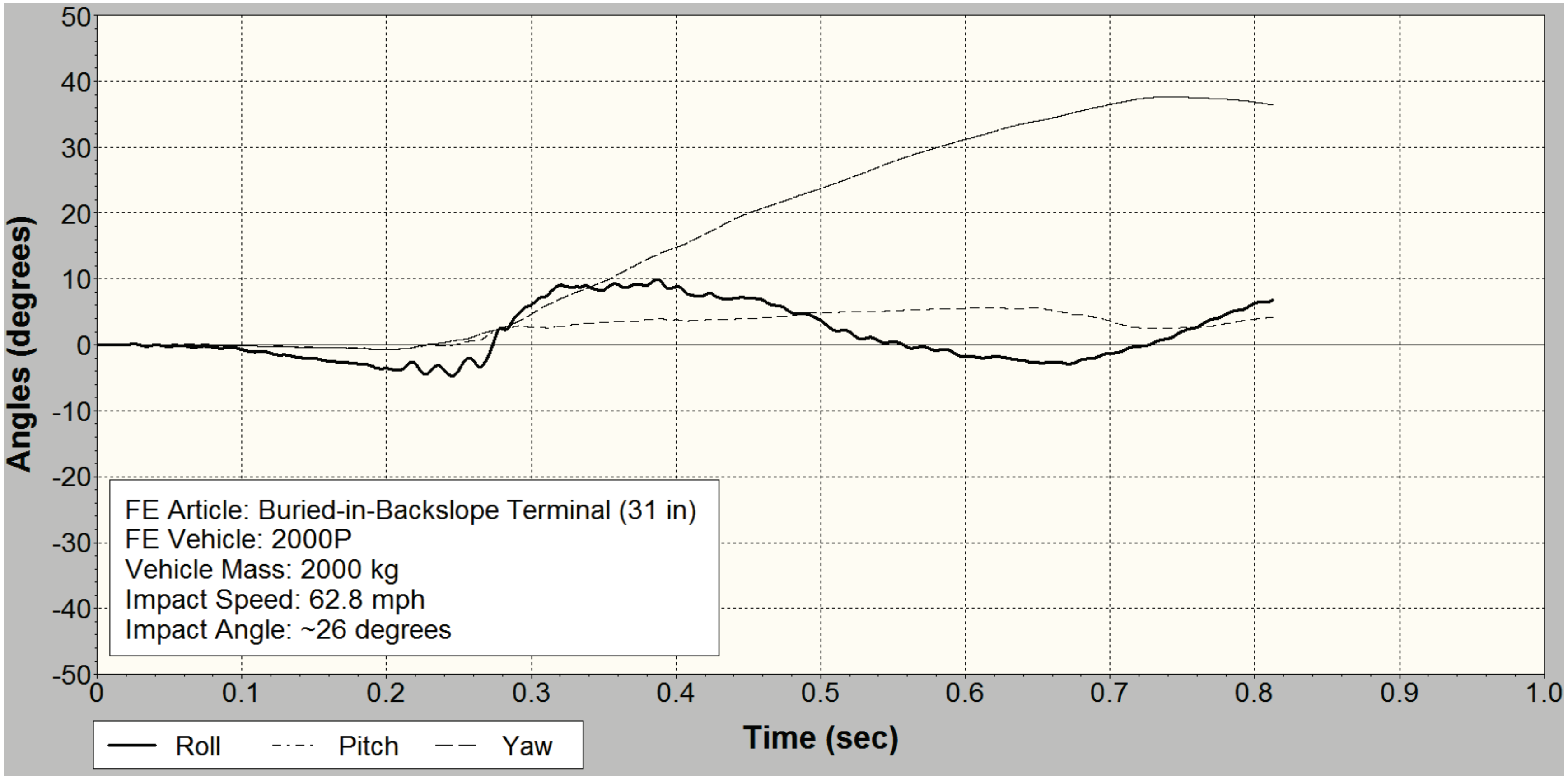


Figure 3.3. Angular Displacements for FE Simulation Validation of the 31-inch High Buried-in-Backslope Terminal.

3.3.4 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.

Figures 3.4 and 3.5 show the plastic strains in the front and field sides of the w-beam rail, respectively, at 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 is unlikely that the rail or the posts will fail during the impact event.

3.3.5 Surrogate Measure of OCD

Figure 3.6 summarizes measured internal energy of the of the pickup truck floorboard when impacting the 31-inch buried-in-backslope terminal during simulation of *NCHRP Report 350* test 3-35. The internal energy of the floorboard is never greater than values of 350 N-m, remaining well below the 2200 M-m passing threshold suggested by Bullard et al. The resulting OCD, therefore, would be passing *NCHRP Report 350* requirements.

3.3.6 Conclusions

Figure 3.7 summarizes results for *NCHRP Report 350* test 3-35 simulation with a 2000P vehicle impacting the 31-in high buried-in-backslope terminal. Without any additional design modifications, the researchers decided to elevate the rail height of the test article model from the original 27¾ inches to 31 inches. The crashworthiness of the new model was investigated through finite element computer simulation replicating the same initial impact conditions of the previously completed full-scale crash Test 404211-13 with 27¾-inch rail height. Results from the computer simulation of test 3-35 against the 31-in rail high buried-in-backslope indicate that all applicable *NHCRP Report 350* evaluation criteria were met. The vehicle was properly contained and redirected and maintained stability throughout the complete impact event. The vehicle interaction with the test article did not suggest any potential for wheel snagging. Review of the plastic strains in both rail and posts suggests that it is unlikely the rail or the posts will fail during the impact event. Occupant risk were also well below *NHCRP Report 350* limit values.

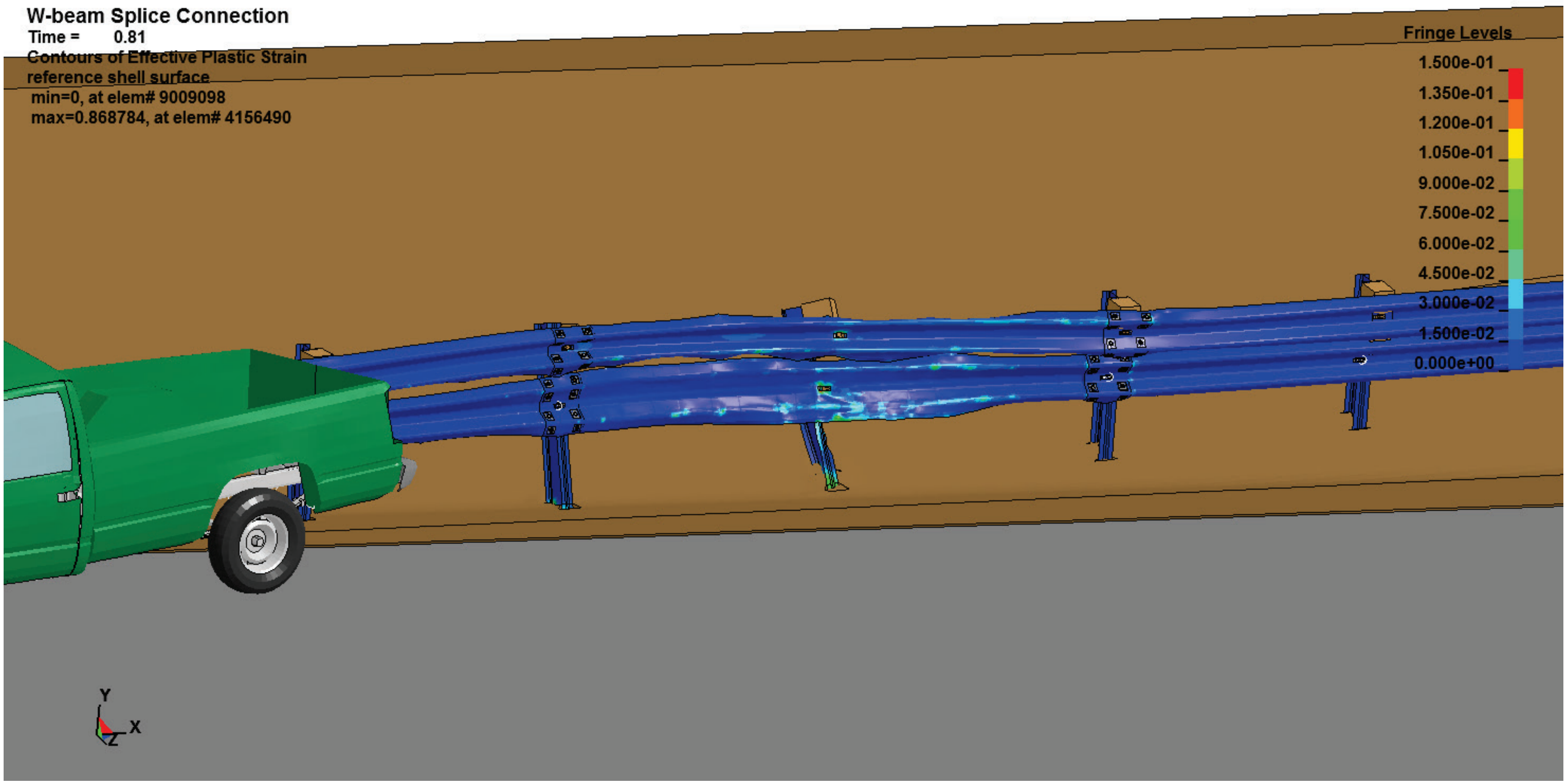


Figure 3.4. Effective Plastic Strains at the Front Face of the W-Beam Rail (31-inch High Buried-in-Backslope Terminal).

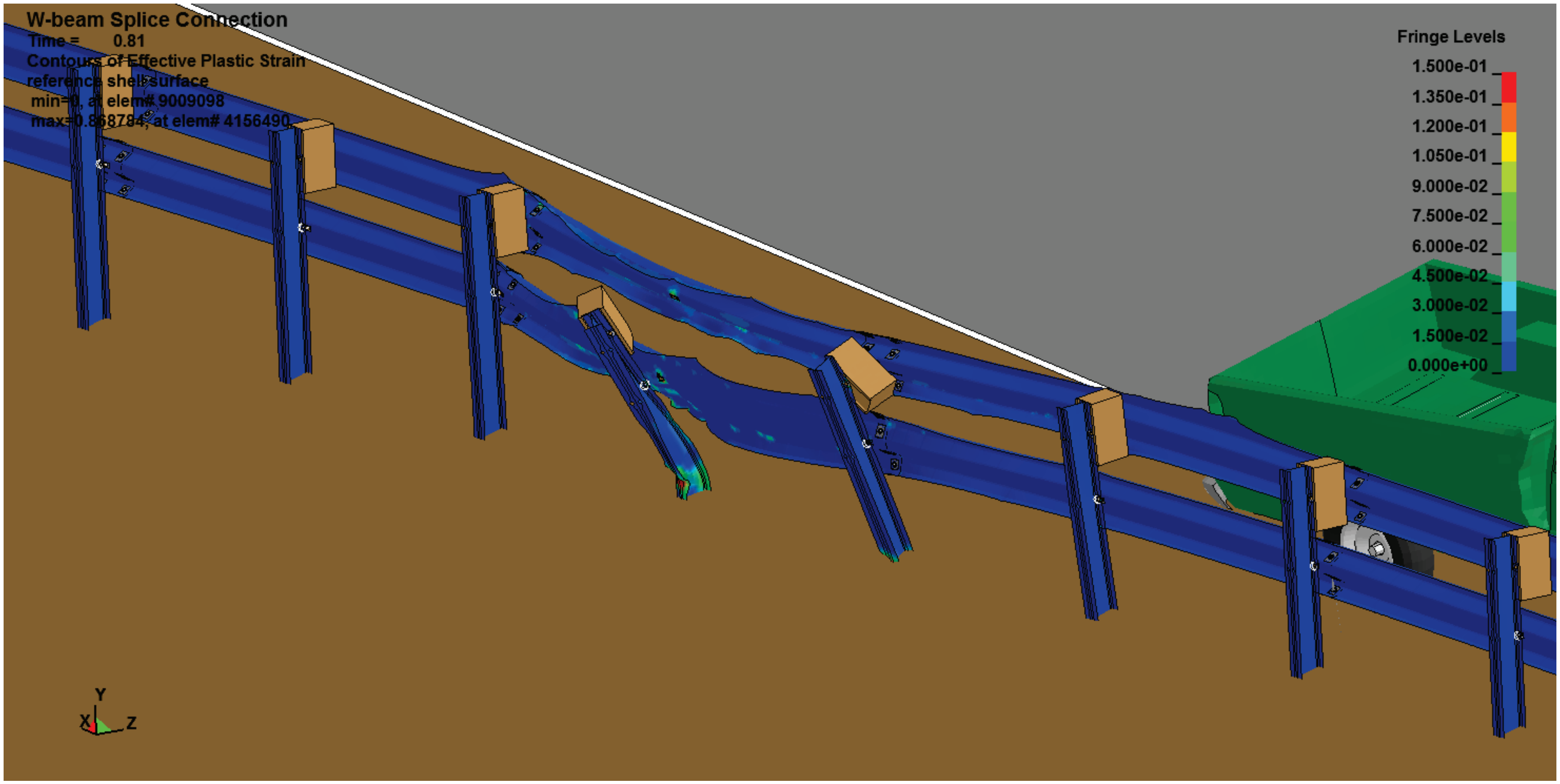


Figure 3.5. Effective Plastic Strains at the Field Face of the W-Beam Rail (31-inch High Buried-in-Backslope Terminal).

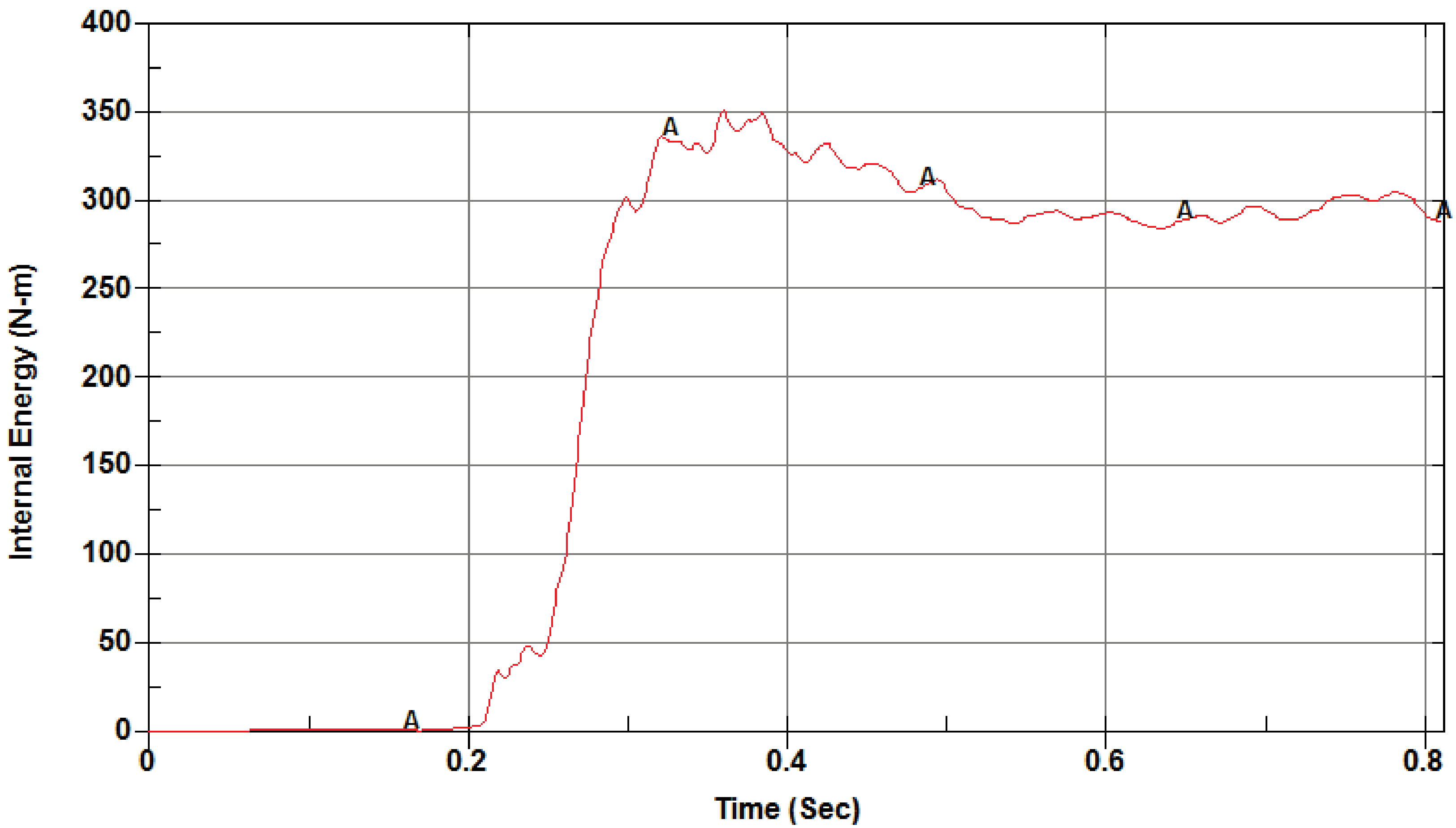
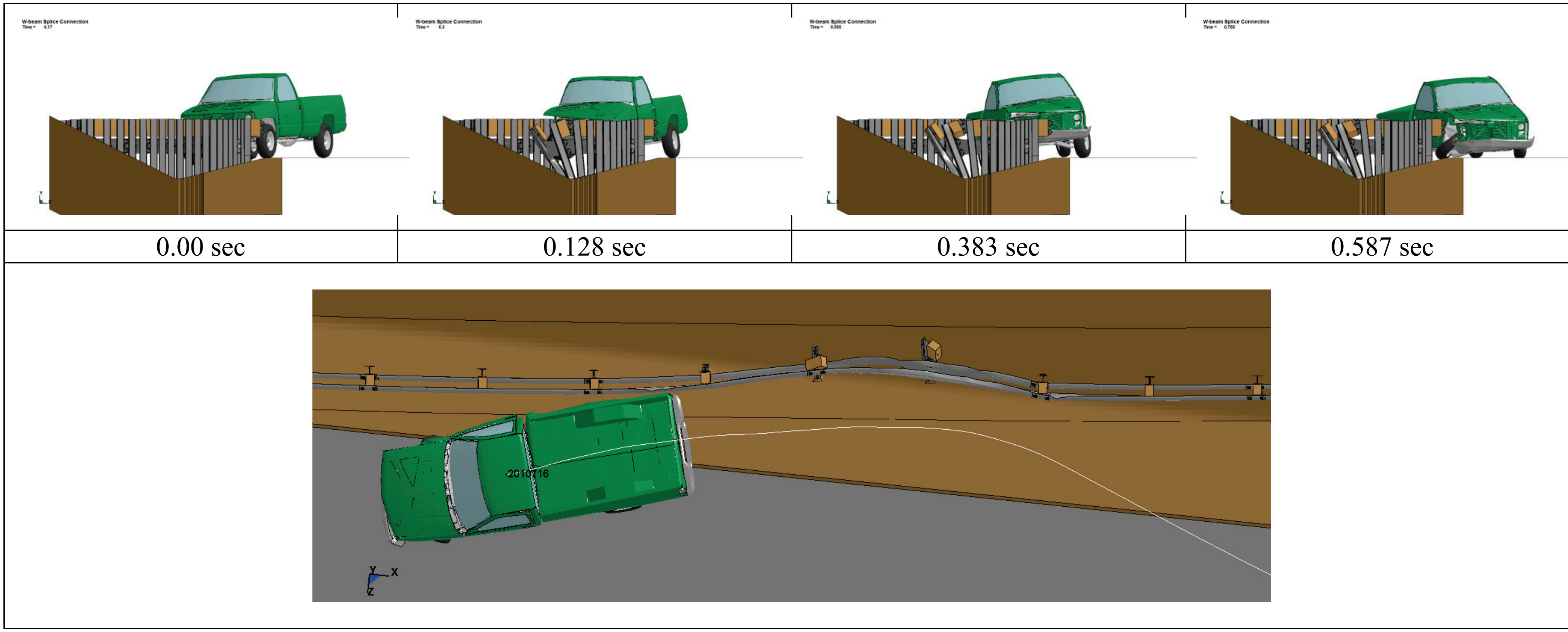


Figure 3.6. Floorboard Internal Energy for *NCHRP Report 350* Test 3-35 with 31-inch High Buried-in-Backslope Terminal.



General Information
Test Agency .... Texas A&M Transportation Institute (TTI)
Test Standard Test No..... *NHCRP Report 350* Test 3-35
Date................................ N/A

Test Article
Type .... 31-inch Buried-in-Backslope Terminal
Installation Length............ 183 ft
Material or Key Elements. W-Beam Guardrail, 31-in Rail, Steel Posts with Wood Blockouts, Rubrail, 4:1 Slope

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

Impact Conditions
Speed ....62.8 mi/h
Angle ....26 degrees
Location/Orientation...........At Post 8

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

Occupant Risk Values
Impact Velocity (ft/sec)
x-direction...................... 26.57
y-direction...................... -20.01
Ridedown Acceleration (g)
x-direction..........................-10.0
y-direction.......................... 9.9

Vehicle Stability
Maximum Yaw Angle .... 37.6 degree
Maximum Pitch Angle .... 5.6 degree
Maximum Roll Angle .... 9.9 degree
Vehicle Snagging.....................No

Vehicle Damage
VDS ....N/A
CDC...N/A
Max. Exterior Deformation ....N/A
OCD. ....< 2200 N/m Floorboard Internal Energy
Max. Occupant Compartment Deformation ....N/A

Figure 3.7. Summary of Results for *NCHRP Report 350* Test 3-35 Simulation (31-inch High Buried-in-Backslope Terminal).

3.4 COMPARISON OF FINITE ELEMENT SIMULATIONS FOR 27¾-INCH AND 31-INCH RAIL HEIGHT

Results of the FE simulations for the 27¾-inch and 31-inch high buried-in-backslope terminal were compared to determine the 31-inch rail relative performance with respect to the 27¾-inch rail height. Tables 3.6 through 3.8 show the impact events for both 27¾-inch and 31-inch rail height simulations. Images of the simulations support results obtained through accelerometer data that indicate the vehicle behavior and stability is comparable in both simulations (Tables 3.9 and 3.10). Since it is not possible to make an assessment for the vehicle roll angle through the vehicle accelerometer data, images of Table 3.6 show that the 2000P vehicle undergoes a smaller roll angle throughout the impact event with the 31-inch high buried-in-backslope terminal.

Occupant risk values are very similar between the two simulations. The impact velocity slightly increases in both longitudinal and lateral direction for the 31-inch rail high case (+1.96 ft/sec and +1.31 ft/sec, respectively). The predicted ridedown acceleration, however, is noticeably reduced for the 31-inch rail height article (there is a decrease of 4.4 g's and 1.4 g's in longitudinal and lateral direction, respectively).

The test article dynamic deflection slightly increases for the 31-inch rail height case (+12%), however, the permanent deflection remains the same. Post-impact simulations analysis reveals that rail and posts plastic strains for the 31-inch rail are lower than those calculated for the 27¾-inch rail height (Table 3.11).

Additionally, careful review of the simulation for impact with the 31-inch rail height does not reveal or indicate any potential vehicle wheel snagging against article posts (Table 3.12). This statement is supported by the analytical evaluation of the vehicle floorboard internal energy, which is never greater than values of 350 N-m, remaining well below the 2200 N-m passing threshold suggested as a surrogate measure for occupant compartment deformation for the FE *NHCRP Report 350* truck model (Bullard et al., 2006).

To summarize, FE computer simulations indicate that the 31-inch high buried-in-backslope terminal has a very similar observed behavior to that of the 27¾-inch rail height. In fact, the 31-inch rail height seems to increase the 2000P vehicle stability throughout the entire impact event (a visual assessment shows a smaller roll angle with respect to the one with the 27¾-inch rail height), maintaining occupant risks well below the limiting values according to the *NHCRP Report 350* criteria.

Table 3.6. Comparison of the 2000P Vehicle Interaction with the 27¾-inch and 31-inch High Buried-in-Backslope Terminals (Front View).

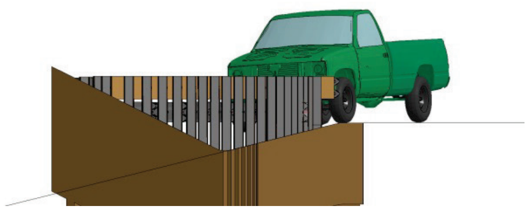
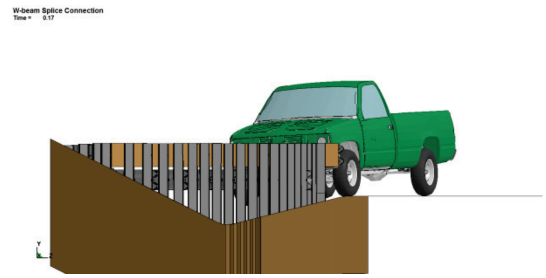
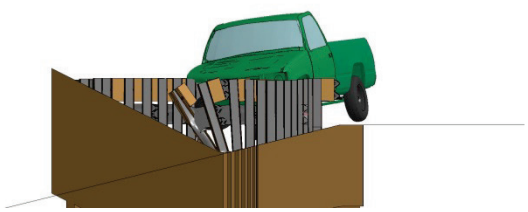
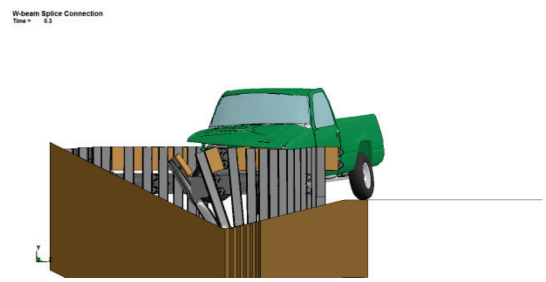
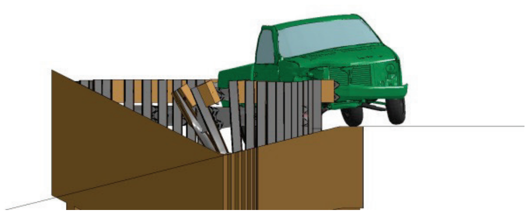
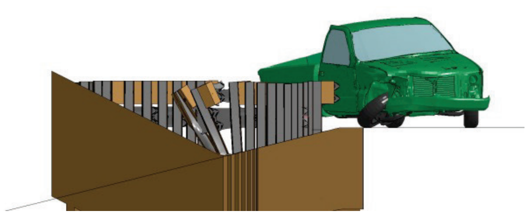
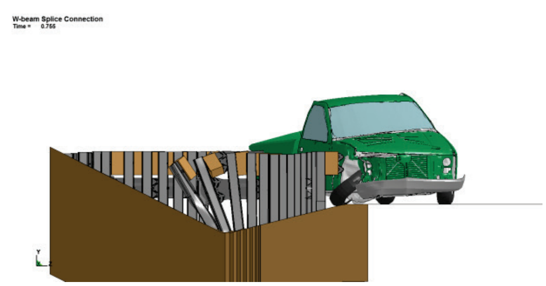
Time (sec)	FE- 27¾-inch Posts	FE-31-inch Posts
0.000		
0.128		
0.383		
0.587		

Table 3.7. Comparison of the 2000P Vehicle Interaction with the 27¾-inch and 31-inch High Buried-in-Backslope Terminals (Top View).

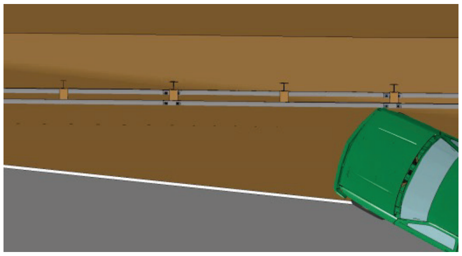
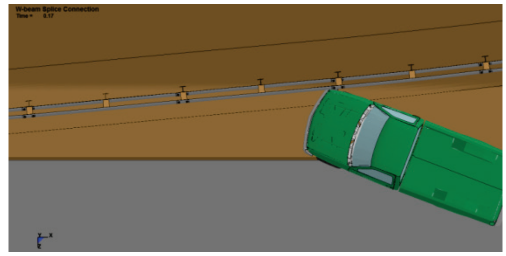
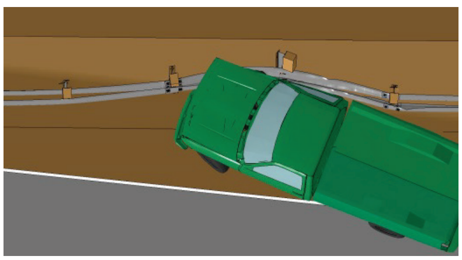
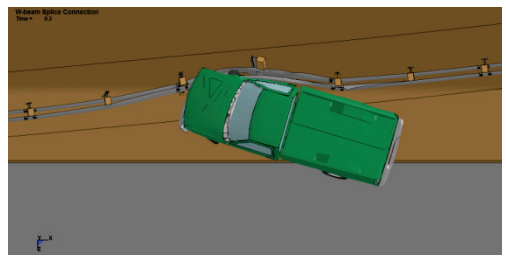
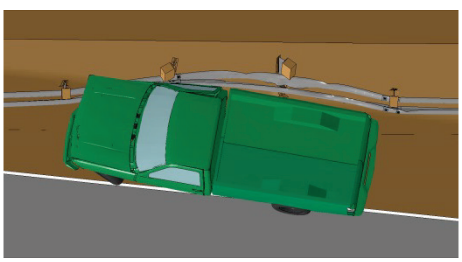
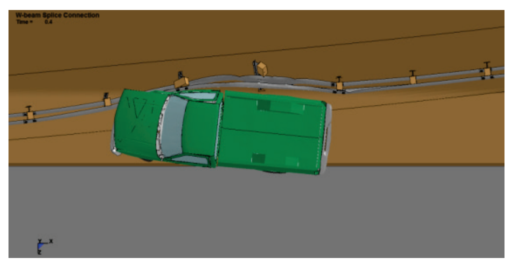
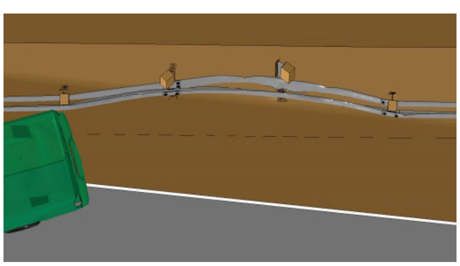
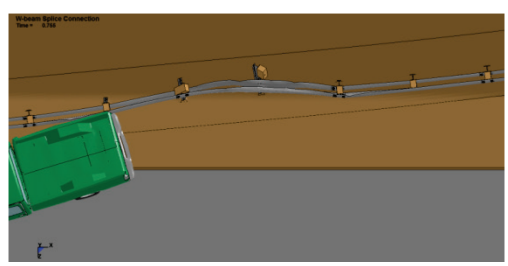
Time (sec)	FE- 27¾-inch Posts	FE-31-inch Posts
0.000		
0.128		
0.230		
0.587		

Table 3.8. Comparison of the 2000P Vehicle Interaction with the 27¾-inch and 31-inch High Buried-in-Backslope Terminals (Perspective View).

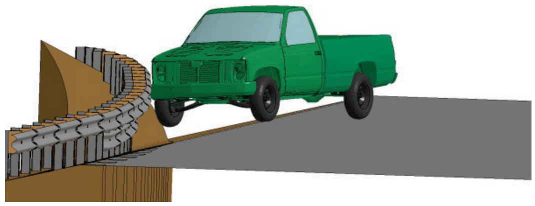
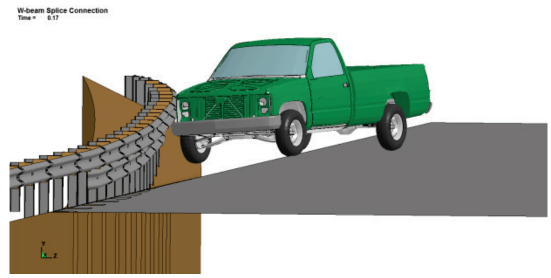
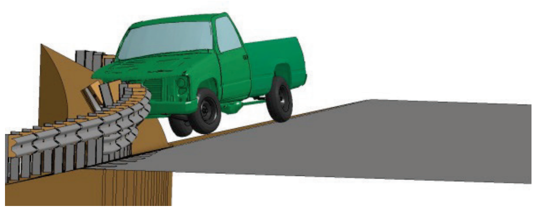
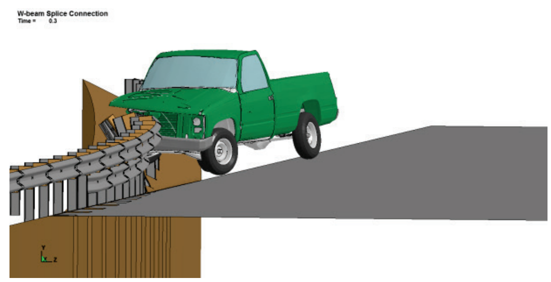
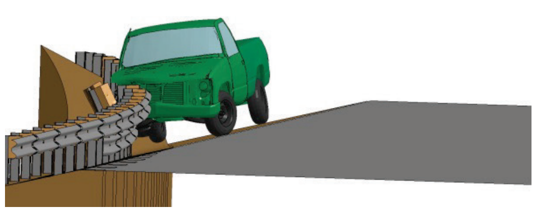
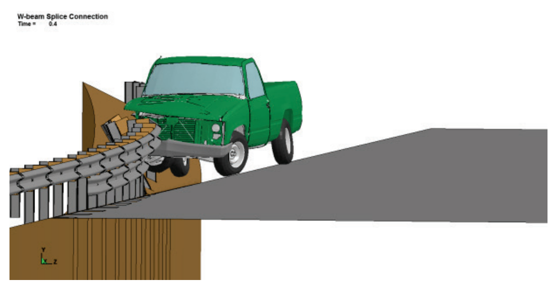
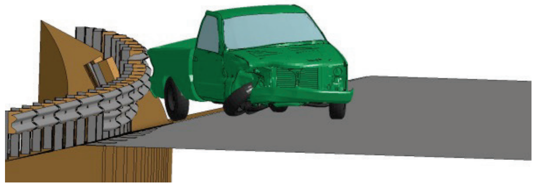
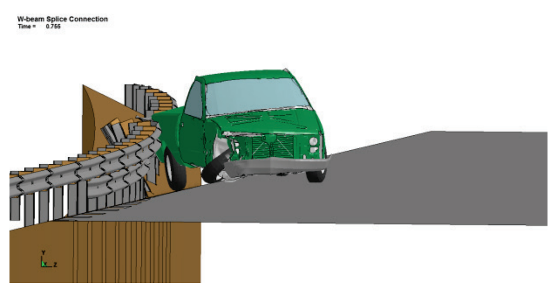
Time (sec)	FE- 27¾-inch Posts	FE-31-inch Posts
0.000		
0.128		
0.230		
0.587		

Table 3.9. Occupant Risk Value Comparison.

	Test	FE 27¾"	FE 31"	Absolute Difference (Between 27- and 31-inch Rail Height Simulations)
Impact Velocity m/sec (ft/sec)				
x-direction	5.4 (17.72)	7.5 (24.61)	8.07 (26.57)	0.57
y-direction	6.5 (21.33)	-5.7(18.7)	-6.1 (20.01)	4.1
Ridedown Accelerations (g's)				
x-direction	-8.3	-14.4	-10	4.4
y-direction	7.9	11.3	9.9	1.4
Angles (deg)				
Roll*	-18	-7.3	9.9	2.6
Pitch	7	6.1	5.6	0.5
Yaw	43	42.9	37.6	5.3

* Please see researcher's comments in Sub-Chapter 2.3.4

Table 3.10. Deflections Value Comparison.

	FE 27¾"	FE 31"
Dynamic Deflection (ft)	1.7	1.91
Permanent Deflection (ft)	1.44	1.45

Table 3.11. Comparison of Rail and Posts Plastic Strains for the 27¾-inch and 31-inch High Buried-in-Backslope Terminals.

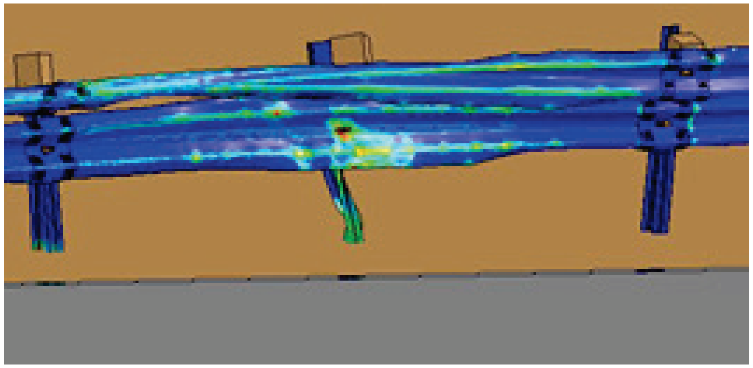
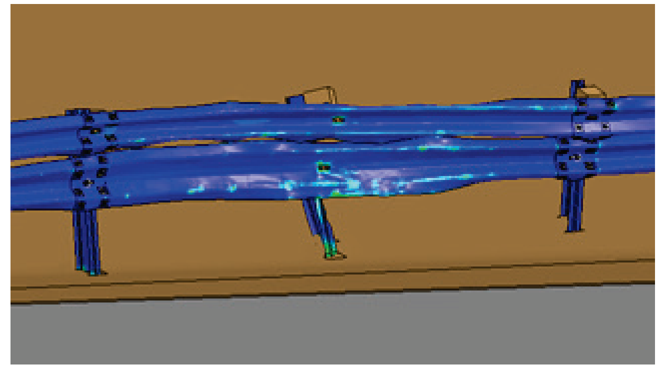
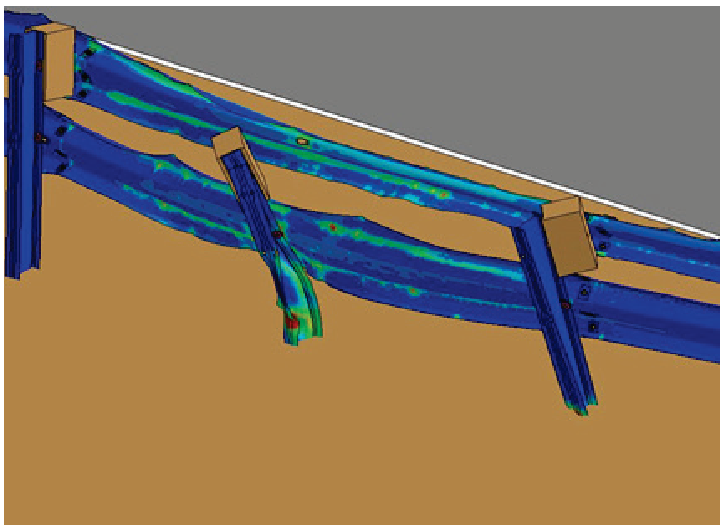
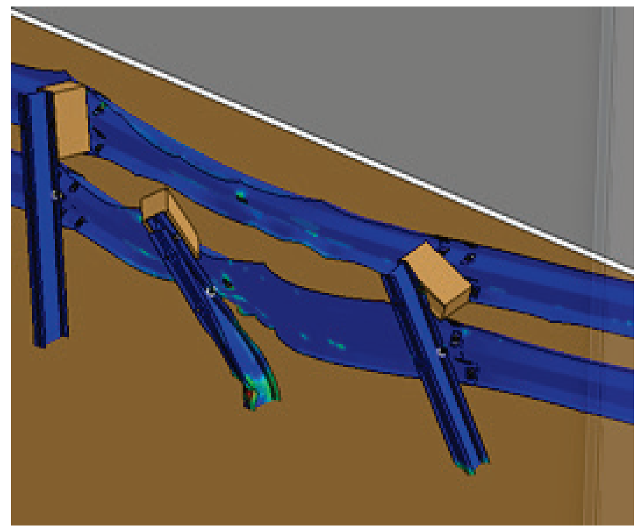
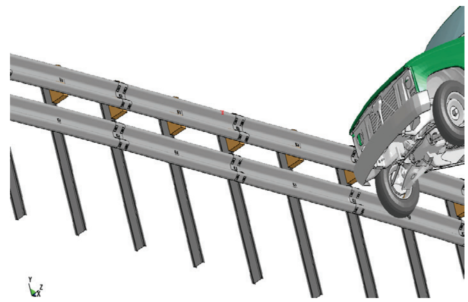
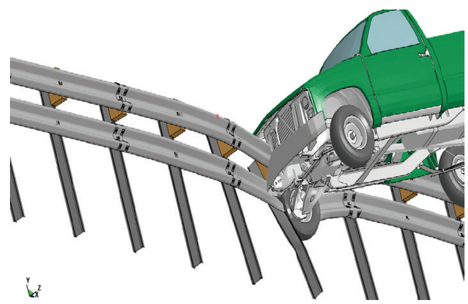
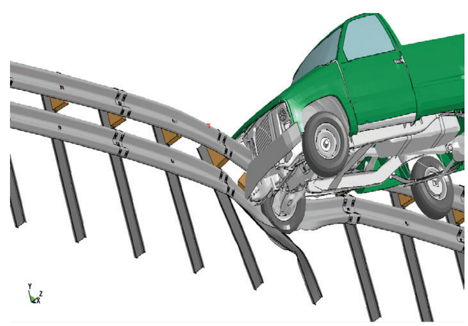
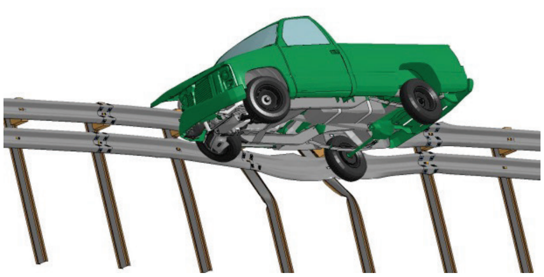
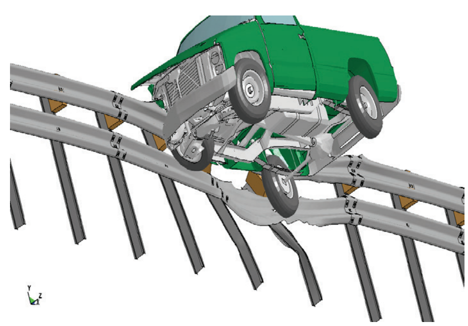
FE- 27¾-inch	FE-31-inch
	
	

Table 3.12. Comparison of the 2000P Vehicle Interaction with the 27¾-inch and 31-inch High Buried-in-Backslope Terminals (Bottom View).

Time (sec)	FE- 27¾-inch Posts	FE-31-inch Posts
0.000		
0.08		
0.105		
0.31		

4. SUMMARY AND CONCLUSIONS

4.1 SUMMARY

Buried (in backslope) terminal designs for beam guardrail were developed under *NCHRP Report 350* criteria for 27-inch (27¾-inch) high guardrail systems. Some states have modified this design so that it could be used with 31-inch high guardrail systems. Other agencies are hesitant to use this design for 31-inch high guardrail until it has been crash tested or deemed acceptable for use by FHWA.

The objective of this study was to identify design modifications necessary to adapt a buried terminal design for 27-inch (27¾-inch) guardrail for use with a 31-inch guardrail system and to determine the terminal crashworthiness according to *NHCRP Report 350* criteria.

Finite element computer simulation of *NCHRP Report 350* Test 3-35 according the initial impact conditions of test 404211-13 well replicated the results obtained through full-scale crash testing. Although the model did not return realistic roll rate values, other parameters compare favorably to the test outcomes. In addition, the multi-channel option evaluation through the RSVVP program without inclusion of the roll rate channel suggests that the FE model of the 27¾-inch buried-in-backslope terminal realistically replicate the results observed through the full-scale crash test.

Without any additional design modifications, the researchers decided to elevate the rail height of the test article model from the original 27¾ inches to 31 inches and determine the crashworthiness of the new model according to computer simulations. Results from the computer simulation of Test 3-35 against the 31-inch rail high buried-in-backslope indicate that all applicable *NHCRP Report 350* evaluation criteria were met. The vehicle was properly contained and redirected and maintained stability throughout the complete impact event. The vehicle interaction with the test article did not suggest any potential for wheel snagging. Review of the plastic strains in both rail and posts suggests that it is unlikely the rail or the posts will fail during the impact event. Occupant risk were also well below *NHCRP Report 350* limit values.

4.2 CONCLUSIONS

Results of the FE simulations for the 27¾-inch and 31-inch rail high buried-in-backslope terminal were compared to determine the 31-inch rail relative performance with respect to the 27¾-inch rail height. FE computer simulations indicate that the 31-inch high buried-in-backslope terminal has a very similar observed behavior when compared to the 27¾-inch rail height. In fact, the 31-inch rail height seems to increase the 2000P vehicle stability throughout the entire impact event, maintaining occupant risks well below the limiting values according to the *NHCRP Report 350* criteria. Based on this evaluation, the researchers suggest the proposed 31-inch high buried-in-backslope terminal design should meet FHWA requirements.

5. REFERENCES

1. Ross, Jr., H.E., Sicking, D.L., Zimmer, R.A. and Michie, J.D., "Recommended Procedures for the Safety Performance Evaluation of Highway Features," National Cooperative Highway Research Program *Report 350*, Transportation Research Board, National Research Council, Washington, D.C., 1993.
2. Arnold, A.G., Buth, C.E., and Menges, W.L., Testing and Evaluation of W-Beam Guardrails Buried-in-Backslope, Texas A&M Transportation Institute, College Station, TX, January 1999.
3. Buth, C.E., Menges, W.L., and Schoeneman, S.K., *NHCRP Report 350 Assessment of Existing Roadside Safety Hardware*, Texas A&M Transportation Institute, College Station, TX, November 2000.
4. Federal Highway Administration, Acceptance Letter CC-53 entitled "INFORMATION: Buried-in-backslope Guardrail Anchor," July 10,1998.
5. Hallquist J. O. *LS-DYNA Keyword User's Manual, Version 971*. Livermore Software Technology Corporation, Livermore, California, 2009.
6. National Crash Analysis Center. *Finite Element Model Archive*. Accessed November, 2005 http://www.ncac.gwu.edu/.
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. Bullard, D. L., Sheikh, N. M., Bligh, R. P., Haug, R. R., Schutt, J. R., and Storey, B.J., "Aesthetic 27 Concrete Barrier Design," National Cooperative Highway Research Program Report 554, 28 Transportation Research Board, National Research Council, Washington, D.C., 2006.