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Design and Finite Element Analysis of a *MASH* 31-inch W-Beam Guardrail System for Placement on 3H:1V Sloped Terrain Configuration (2014 WV-62)

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16. Abstract

In locations where a traversable slope is located at the edge of the shoulder, there may be a desire to offset the barrier to minimize impacts. A longitudinal system that can be placed on 3H:1V slopes would provide this flexibility. The purpose of this research was to develop a 31-inch W-beam guardrail system to be placed with a 3H:1V slope in front of the barrier. The structural capacity and the occupant risk factors of such proposed guardrail system was evaluated with respect to *MASH* TL-3 criteria. The information compiled from this research will provide the Federal Highway Administration and State Departments of Transportation with a W-beam guardrail design as a crashworthy system to be placed with a 3H:1V slope in front of a barrier. Being able to place W-beam guardrail with a 3H:1V slope in front of the barrier would reduce the number of impacts on the system and would provide flexibility in the placement of W-beam systems. Impact simulation of *MASH* test 3-11 according to the initial impact conditions of test 405160-20-1 well replicated the results obtained through full-scale crash testing. Failure properties were applied to the connection between the wheel and the vehicle to allow joint connections to fail once reached a predefined force value. The FE models of the test article and the vehicle were used as a base model to develop new guardrail designs for evaluation when placed on a 3H:1V sloped terrain configuration.

Three barrier designs for placement on a 3H:1V slope were suggested for evaluation through predictive computer simulations:

- Design 1: 31-inch W-beam rail, 7-ft steel post, wood blockouts; 3H:1V slope with posts placed 1 ft from the slope break (face of the guardrail aligned with the slope break); No rubrail (*MASH* test 3-11);
- Design 2: 31-inch W-beam rail, 8-ft steel post, wood blockouts; 3H:1V slope with posts placed 2 ft from the slope break; No rubrail (*MASH* test 3-11);
- Design 3: 31-inch W-beam rail, 8-ft steel post, wood blockouts; 3H:1V slope with posts placed 2 ft from the slope break; with rubrail (*MASH* tests 3-10 and 3-11).

All systems appear to be crashworthy and likely to pass safety evaluation criteria required for *MASH*. Depending on the desired system post distance location from the 3H:1V slope break, the researchers recommend evaluation of selected design through full-scale crash testing according to *MASH* TL-3 criteria.

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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)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		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)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		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)

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1. INTRODUCTION

1.1 PROBLEM

Testing in the 1980s showed that W-beam guardrail when placed on a 6H:1V slope had marginal performance. In this testing, the rail was positioned 27 inches above the ground and the large car vaulted over the rail when it was placed 6 ft from the slope break.

However, when a buried in backslope terminal was tested in accordance with National Cooperative Highway Research Program (NCHRP) *Report 350* Test Level 3 (TL-3), the rail was placed on a 4H:1V slope (*1, 2*). The height of the rail was maintained in relation to the shoulder elevation. Longer posts were used to maintain the height, and a rubrail was added to minimize underriding the rail.

In locations where a traversable slope is located at the edge of the shoulder, there may be a desire to offset the barrier to minimize impacts. A longitudinal system that can be placed on 3H:1V slopes would provide this flexibility.

The purpose of this research was to develop a 31-inch W-beam guardrail system to be placed with a 3H:1V slope in front of the barrier. The structural capacity and the occupant risk factors of such a proposed guardrail system would be evaluated with respect to American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware* (*MASH*) TL-3 criteria (*3*). The information compiled from this research would provide the Federal Highway Administration and State Departments of Transportation with a W-beam guardrail design as a crashworthy system to be placed with a 3H:1V slope in front of a barrier. Being able to place W-beam guardrail with a 3H:1V slope in front of the barrier would reduce the number of impacts on the system and would provide flexibility in the placement of W-beam guardrail systems.

1.2 BACKGROUND

Earliest known research about guardrail placement on slopes was conducted by ENSCO, Inc., which included a battery of pendulum tests on a single post and three full-scale crash tests *(4)*. Two tests with a large sedan impacting a G4(1S) guardrail system installed on a break point of a 2H:1V slope were considered to be successful to redirect the large sedan per *NCHRP Report 230 (5)*. One of the tests had a 6-ft post length while the other had a 7-ft post length. The 7-ft post length installation had a better performance (rail deflection and vehicle impact speed change) than the 6-ft post length installation.

With the satisfactory performance of the modified G4(1S) W-beam guardrail system with timber blockouts, Federal Highway Administration (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 *(1).* Tests were conducted in accordance with *NCHRP Report 350*, and involved a 2000P vehicle impacting the treatment conditions at nominal impact speed and angle of 62 mph (100 km/h) and 20 degrees, respectively *(2).* 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.

The guardrail was flared across a vee ditch with its end anchored to a 6-ft long steel post buried in the backslope. The guardrail installation was the standard SGRO4a W-beam guardrail with wood blockouts. A W-beam rubrail was added to minimize underriding the rail and a 3 inch between the W-beam guardrail and the rubrail was maintained, keeping the same rail height in relation to the shoulder elevation. The terminal performed acceptably for *NCHRP Report 350* test 3-35: a 2000P vehicle impacting the beginning of the length-of-need of the terminal at a nominal impact speed and angle of 62 mph and 20 degrees. 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.

Polivka et al. conducted another battery of bogie tests and a crash test of a steel post guardrail system with a 2000P test vehicle per *NCHRP Report 350* TL-3 *(6).* A region that encompassed the impact point had 7-ft long W6×8.5 steel posts placed 3 ft-1.5 inches on center. These posts were placed on the break of 2H:1V slope with 4 ft-7 inch embedment depth. The crash test was considered successful per *NCHRP Report 350* test evaluation criteria.

Abu-Odeh et al. conducted a research project with the objective to assess the performance of the modified G4(1S) guardrail system when placed on a slope equal to 2H:1V under the conditions and criteria of *NCHRP Report 350* TL-3 *(7).* The guardrail system was placed on the slope with such an offset that the face of the W-beam rail was aligned with the slope break. The first step was to evaluate the performance of the guardrail posts with various embedment lengths when impacted by a bogie vehicle. The next step was to build and calibrate finite element models of selected posts and then use them in full-scale simulations of candidate guardrail systems. Based on the results of the cases simulated, the candidate design chosen for testing was a W-beam guardrail system with 8-ft posts placed on a 2H:1V slope. The posts were placed 1 ft off the slope break and spaced at 3 ft-1½ inches (half the standard spacing for a strong-post W-Beam guardrail). In the full-scale crash test, the 2000P vehicle was contained and redirected. However, after exiting the installation, the vehicle rolled onto its left side. Due to this rollover, the guardrail on 2H:1V slope did not meet the criteria for *NCHRP Report 350* test 3-11.

Abu-Odeh et al. also conducted a study to identify an acceptable method for installing standard strong-post W-beam guardrail [Modified G4(1S)] with the face of the rail aligned with the break point of a 2H:1V slope *(8).* Following the crash test results from a previous study *(6)*, further simulation was performed to improve the performance of the guardrail on slope design. As a result, it was recommended to test a guardrail on slope system with 6 ft-3 inch spacing and 8-ft posts. *MASH* tests 3-10 and 3-11 were performed *(3).* The guardrail on slope performed acceptably according to the specifications for *MASH* TL-3.

A summary of the literature review of past guardrail testing on a slope is presented in Appendix A.

The purpose of this research was to develop a guardrail system to be placed with a 3H:1V slope in front of the barrier. The structural capacity and the occupant risk factors of such a proposed guardrail system was evaluated with respect to *MASH* TL-3 criteria. The information compiled from this research will provide FHWA and State Departments of Transportation with a W-beam guardrail design as a crashworthy system to be placed with a 3H:1V slope in front of a barrier. Being able to place W-beam guardrail with a 3H:1V slope in front of the barrier would reduce the number of impacts on the system and would provide flexibility in the placement of W-beam guardrail systems.

1.3 OBJECTIVES AND SCOPE OF RESEARCH

The purpose of this research was to develop and analyze a 31-inch W-beam guardrail system with 8-inch blockouts to be placed with a 3H:1V slope in front of the barrier. The structural capacity and the occupant risk factors of such proposed guardrail system was evaluated with respect to *MASH* TL-3 criteria with use of finite element computer simulations. No full-scale crash testing was included with this phase of the project.

2. FINITE ELEMENT MODELING

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 (*9*). 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 FULL-SCALE MODEL OF W-BEAM GUARDRAIL ON 2H:1V SLOPE WITH TIRE ROD FAILURE

2.2.1 Computer Model Description

A finite element model of the W-beam guardrail system with steel posts that was previously successfully designed and tested according to *MASH* test 3-11 was developed. Test 405160-20-1 was performed at the TTI Proving Ground in 2012 with the objective to crash test and evaluate the W-beam guardrail system on a 2H:1V slope to *MASH* (*8*). Details of the W-beam guardrail system with steel posts for test 405160-20-1 are included in Figure 2.1.

Figure 2.2 shows details of the finite element (FE) model that was built to perform computer simulations. The FE test installation consisted of 90 ft of standards 12-gauge W-beam supported by steel posts. The system was built with fourteen posts spaced at 75 inches on center. The posts were 6-inch × 8½-inch × 96-inch long posts with steel properties and a soil embedment depth of 55 inches. A 6-inch × 8-inch × 14-inch wood spacer blockout was used to block the rail away from the front face of each post. LS-DYNA soil material model *MAT_GEOLOGIC_CAP_MODEL was used to simulate soil properties for soil-post interaction during computer simulations (*9*). Standard 12 ft-6 inch long 12-gauge W-beam rails were modeled. The W-beam top rail height was 31 inches from flat level ground 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. The guardrail model was developed such that the face of the W-beam rail was aligned with the slope break of the ditch.

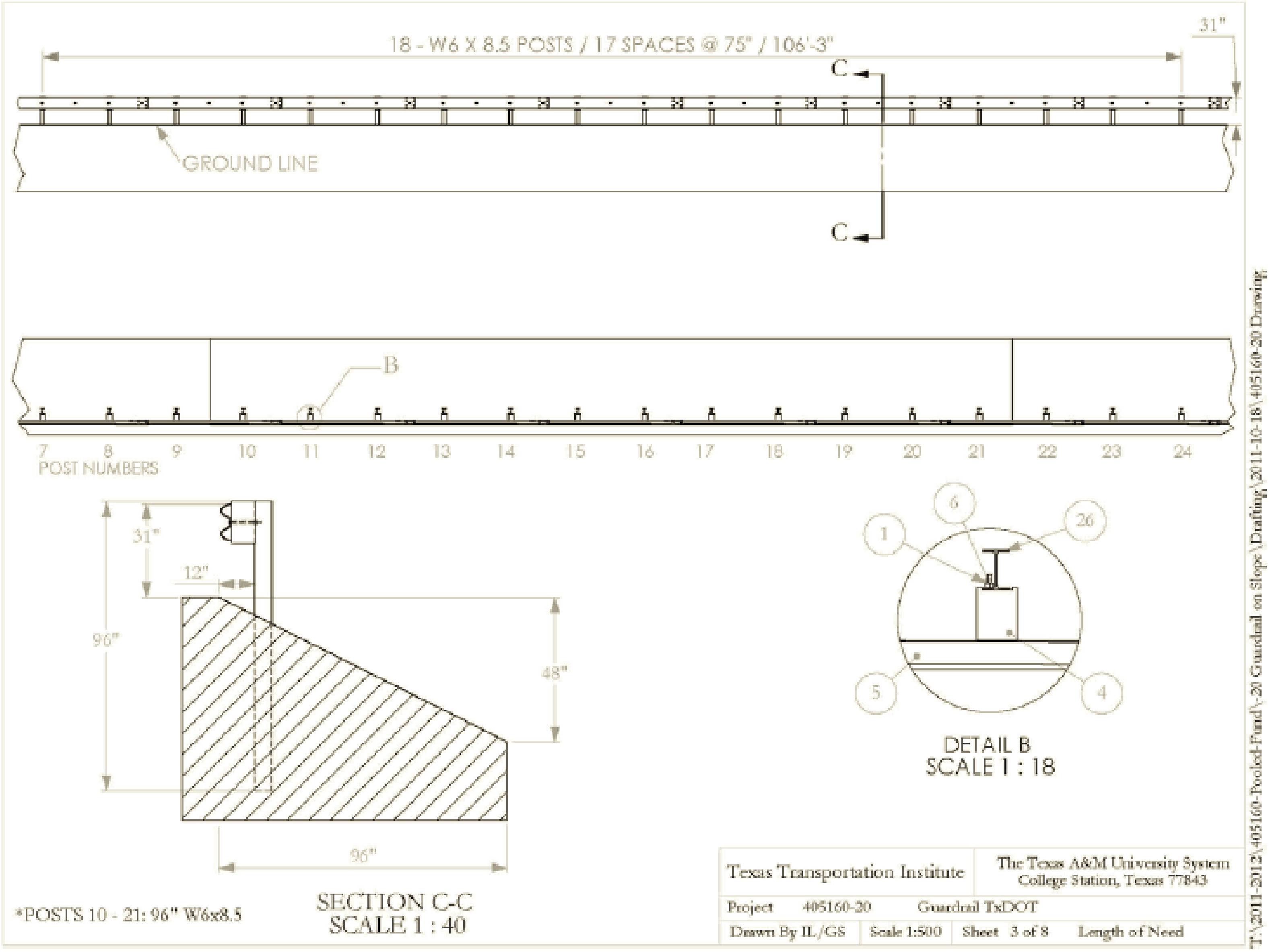


Figure 2.1. Details of the Test Article Installation for Test 405160-20-1 (*8*).

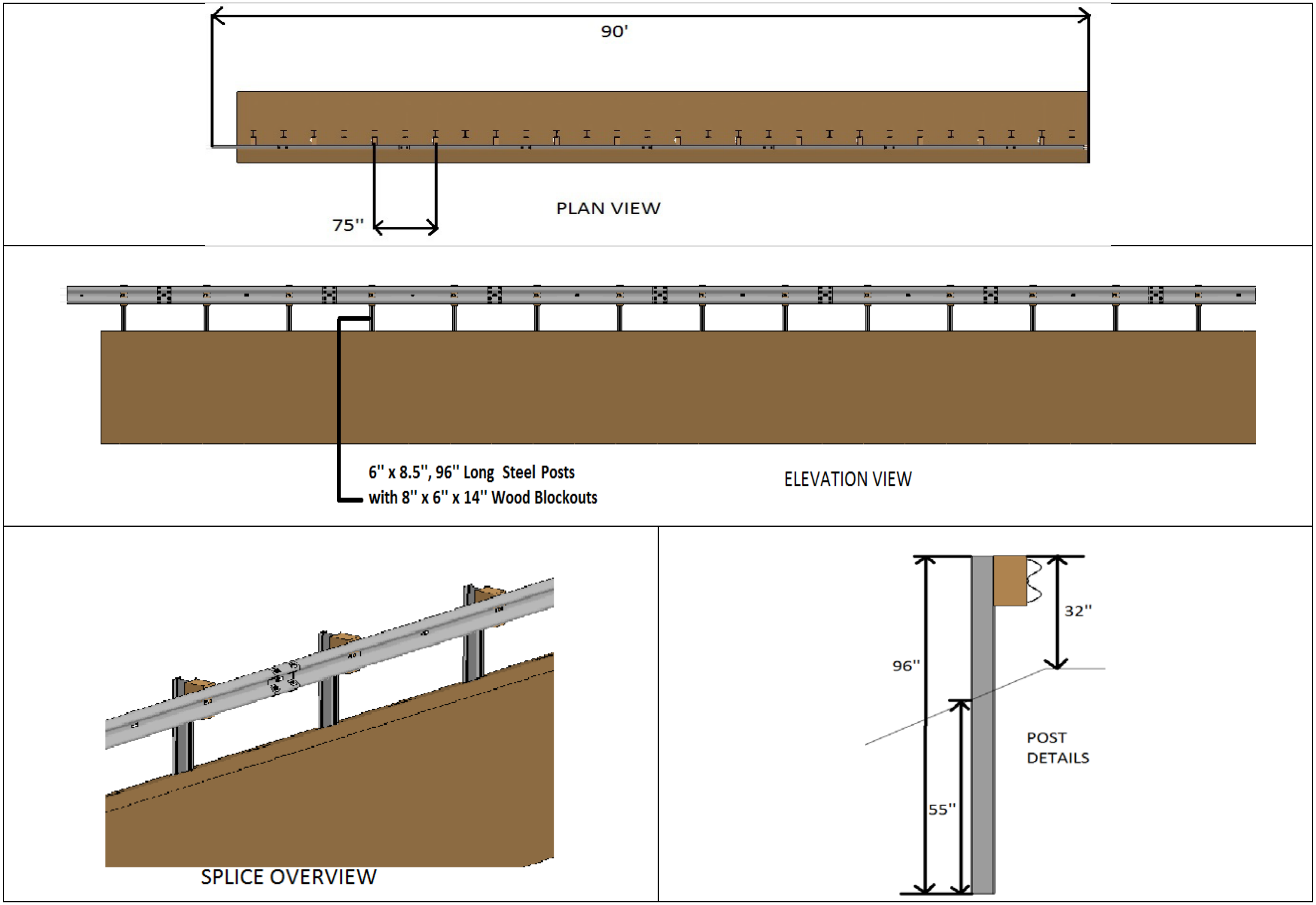


Figure 2.2. Details of the *MASH* Test Article Installation for Finite Element Computer Model Validation.

Researchers used the National Crash Analysis Center (NCAC) finite element 2270P pickup truck model to complete their simulation (*10*). The full-scale crash test impact conditions of the 2270P pickup truck against the test installation were simulated to determine if the developed FE model would replicate the behavior of the article and vehicle observed during test. This evaluation was needed in order to verify realistic response of the W-beam guardrail system to the impact of the vehicle.

2.2.2. Barrier Performance

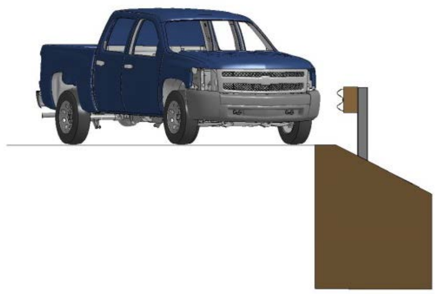
Figure 2.3 contains images of the barrier before impact and at final configuration. Figure 2.3(a) and 2.3(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 2.3(b) and 2.3(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. To replicate the impacting conditions of test 405160-20-1, the barrier was impacted at 0.9 ft upstream of a post, with impact speed and angle of 63.9 mph and 25.0 degrees, respectively.

The vehicle was contained and redirected during the impact event. Failure properties were applied to the connection between the wheel and the vehicle to allow joint connections to fail once a predefined force value was reached. The dynamic and permanent deflections of the guardrail system in the FE model were 39.1 inches and 23.8 inches, respectively (vs. 51.6 inches and 37.2 inches during the full-scale test).

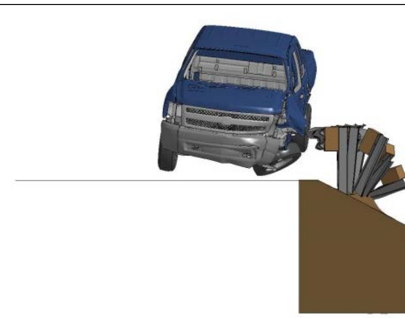
2.2.3 Energy Values

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).

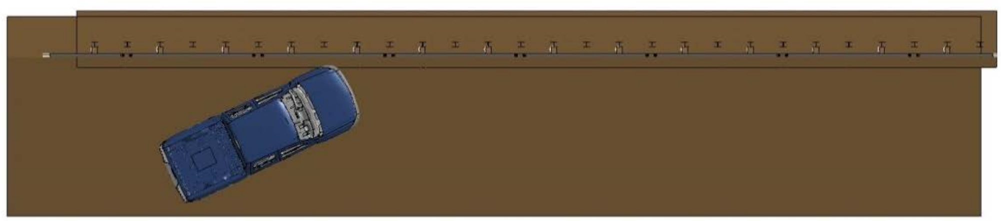
Since this is a closed system and energy is conserved, the sum of the kinetic energy, hourglass energy, sliding energy, and internal energy at any time during the simulation should equate to the initial kinetic energy of the vehicle. As shown in Figure 2.4, approximately 35 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). Approximately one 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.



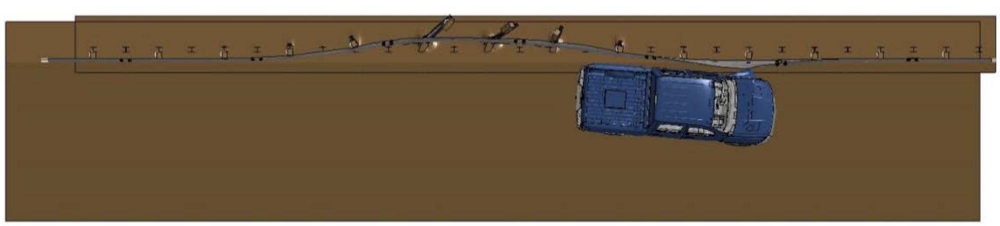
(a) Front View At Impact



(b) Front View At Final Configuration



(c) Top View At Impact



(d) Top View At Final Configuration

Figure 2.3. Initial and Deflected Shape of Barrier (W-Beam Guardrail on 2H:1V Slope with Tire Rod Failure).

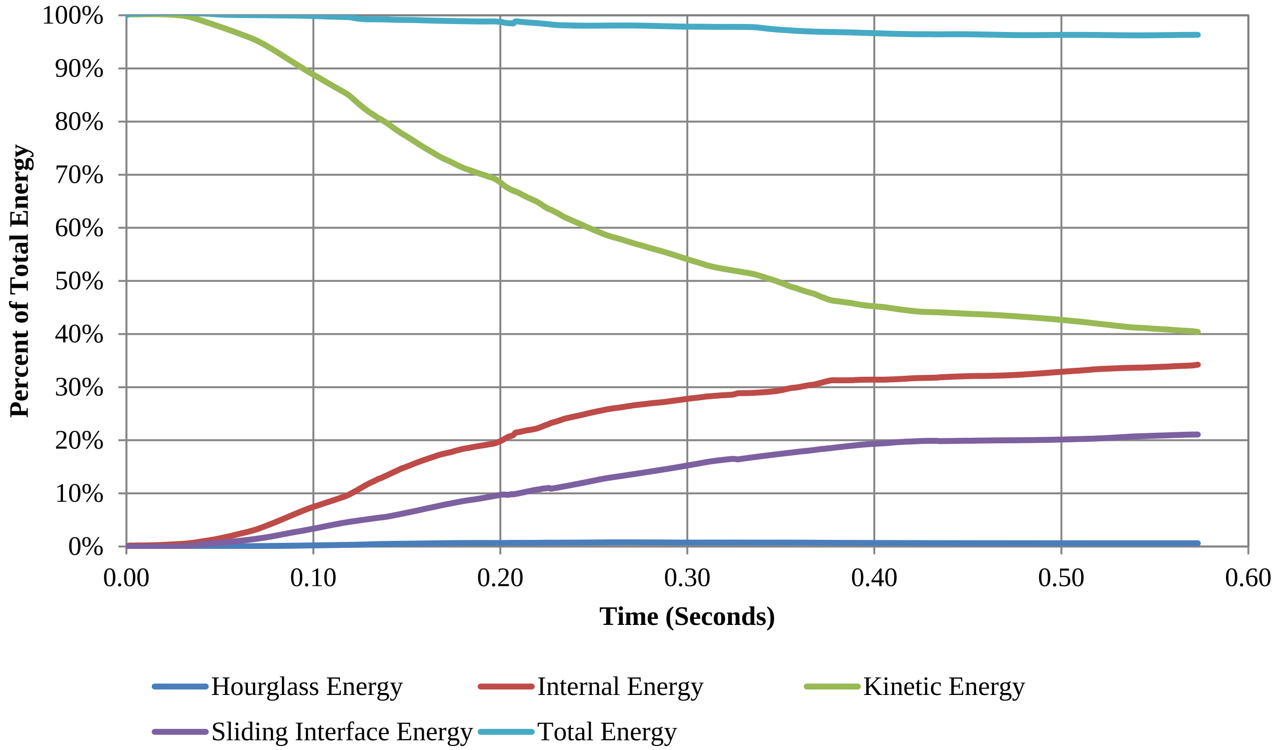


Figure 2.4. Energy Distribution Time History (W-Beam Guardrail on 2H:1V Slope with Tire Rod Failure).

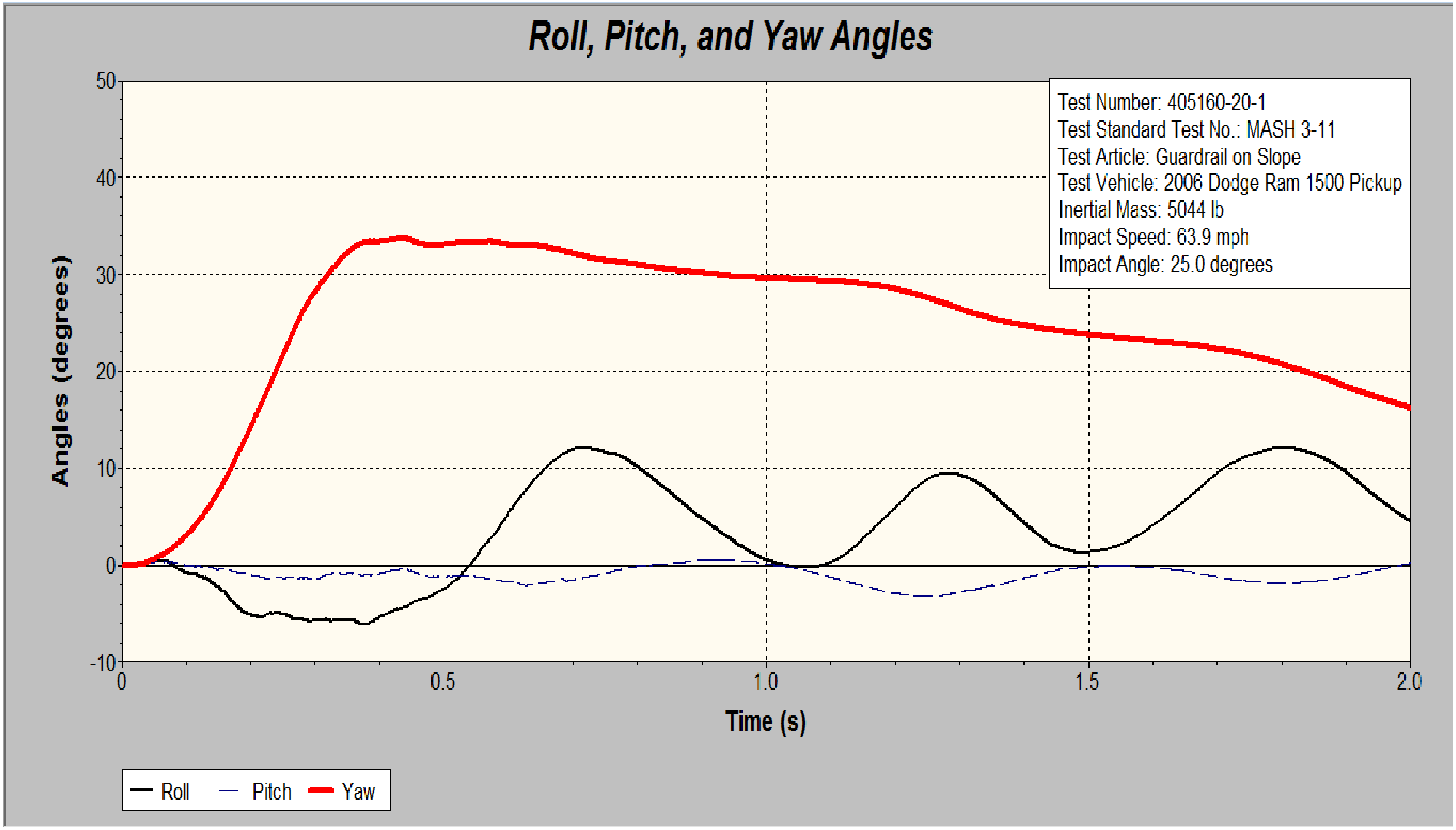
2.2.4 Occupant Risk Assessment

The Test Risk Assessment Program (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 2.1 provides a summary of results for the 31-in W-beam guardrail system with steel posts. Maximum roll, pitch and yaw angles resulted to be –13,-8.3, and 33.3 degrees, respectively. Occupant impact velocities were 16.08 ft/sec and -17.06 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were -8.3 g and 8.9 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 2.5 and 2.6, respectively.

Tables 2.2 through 2.4 compare frames from test 405160-20-1 and the computer simulation validation at the same time after first impact occurred.

Table 2.1. Occupant Risks Values (W-Beam Guardrail on 2H:1V Slope with Tire Rod Failure).

Occupant Risk Factors	TEST 405160-20-1	2270P 2H:1V Slope with Rod Failure	Relative Difference
Impact Vel. (ft/sec)			
x-direction	15.1	16.08	6.49%
y-direction	15.4	-17.06	10.8%
Ridedown Acc. (g's)			
x-direction	9	-8.3	7.78%
y-direction	6.9	8.9	29.0%
Angles	**TEST 405160-20-1**	**2270P 2H:1V Slope with Rod Failure**	**Relative Difference**
Roll (deg.)	13	-13	Absolute Difference < 5 Degrees
Pitch (deg.)	3	-8.3	Absolute Difference > 5 Degrees
Yaw (deg.)	34	33.3	Absolute Difference < 5 Degrees



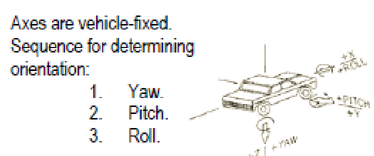


Figure 2.5. Angular Displacements for Test 405160-20-1 (*8*).

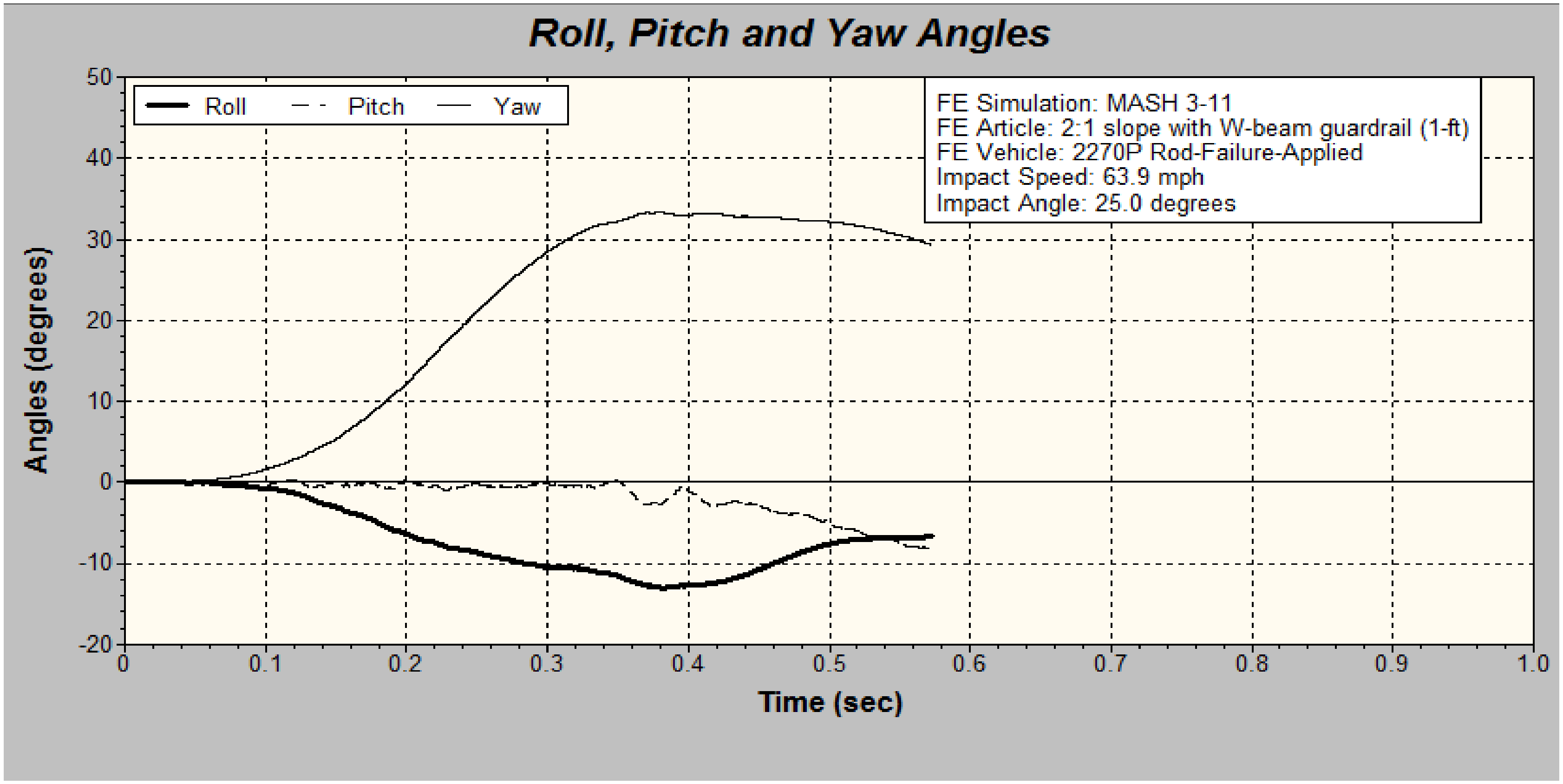


Figure 2.6. Angular Displacements for FE Simulation Validation of the W-Beam Guardrail on 2H:1V Slope with Tire Rod Failure.

Table 2.2. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Top View (W-Beam Guardrail on 2H:1V Slope with Tire Rod Failure).

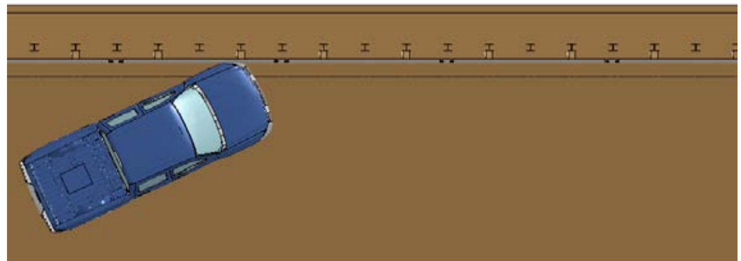
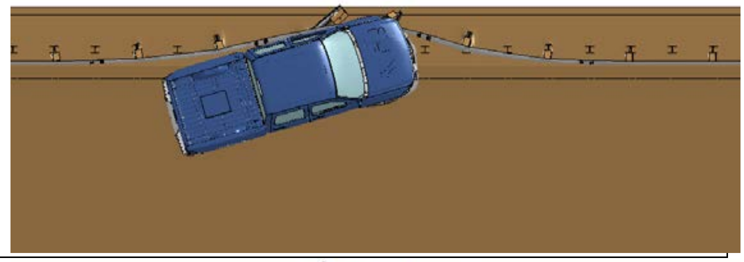
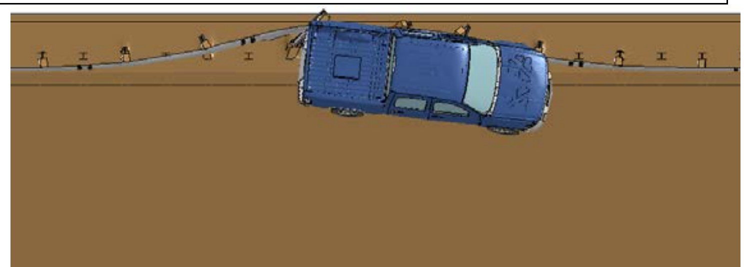
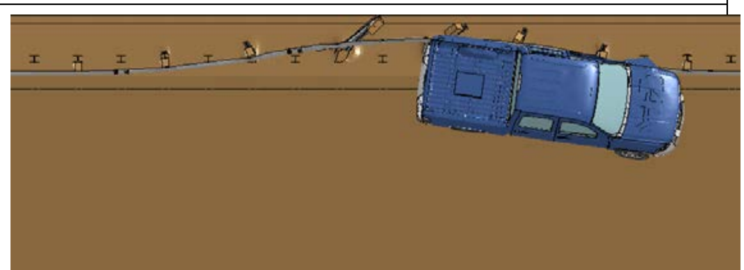
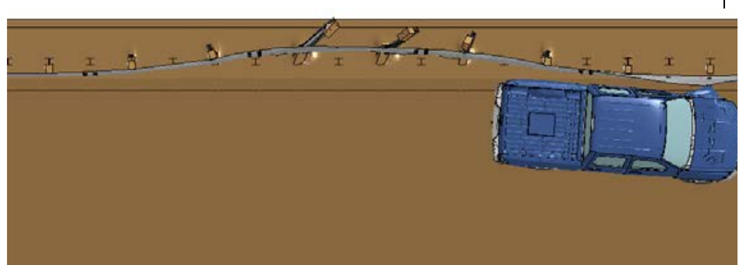
Time (sec)	TEST 405160-20-1	FE W-Beam Guardrail on 2H:1V Slope with Tire Rod Failure
0.000		
0.155		
0.310		
0.390		
0.545		

Table 2.3. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Frontal View (W-Beam Guardrail on 2H:1V Slope with Tire Rod Failure).

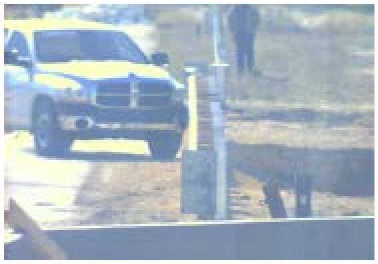
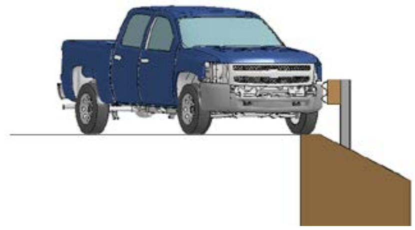
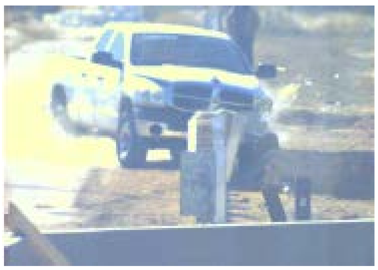
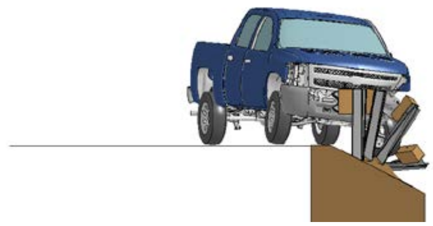
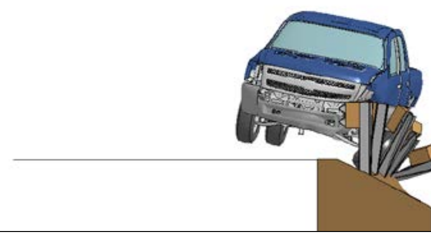
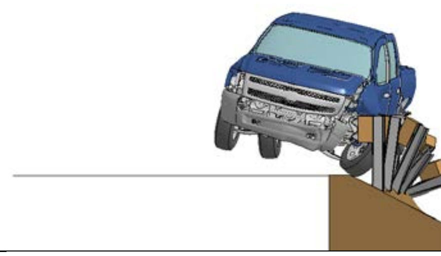
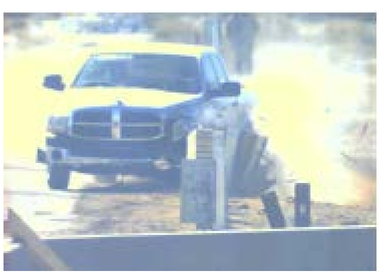
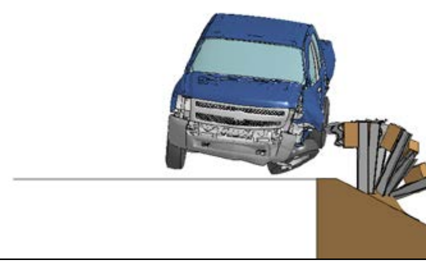
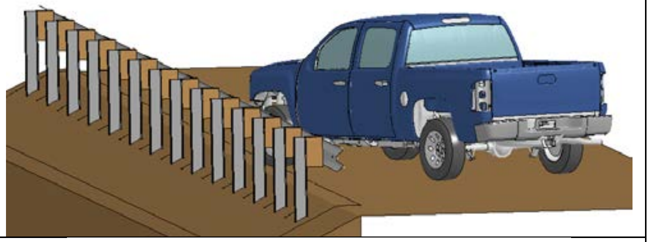
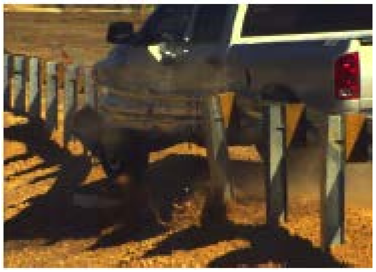
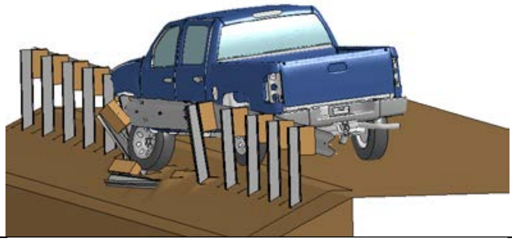
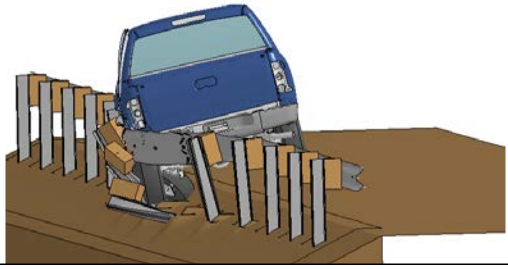
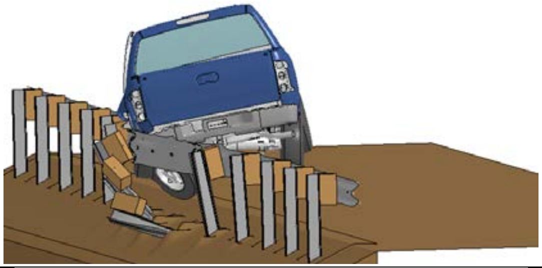
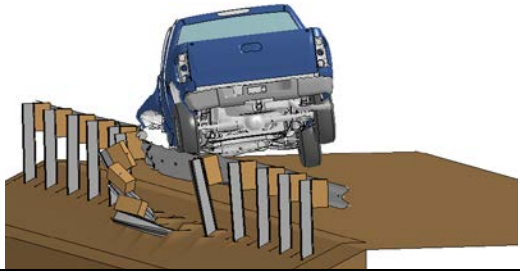
Time (sec)	TEST 405160-20-1	FE W-Beam Guardrail on 2H:1V Slope with Tire Rod Failure
0.000		
0.155		
0.310		
0.390		
0.545		

Table 2.4. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Back View (W-Beam Guardrail on 2H:1V Slope with Tire Rod Failure).

Time (sec)	TEST 405160-20-1	FE W-Beam Guardrail on 2H:1V Slope with Tire Rod Failure
0.000		
0.155		
0.310		
0.390		
0.545		

2.2.5 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 2.7 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. No regions of high plastic strains are present. After reviewing the simulation, it was concluded that rail failure is unlikely.

2.3 CONCLUSIONS

Impact simulation of *MASH* test 3-11 according to the initial impact conditions of test 405160-20-1 well replicated the results obtained through full-scale crash testing (*8*). Failure properties were applied to the connection between the wheel and the vehicle to allow joint connection failure to occur once a predefined force value was reached. Figure 2.8 summarizes results for *MASH* test 3-11 simulation with a 2270P vehicle impacting a 31-inch W-beam guardrail system with steel posts. The FE models of the test article and the vehicle with their material and failure properties were used as a base model to develop new guardrail designs for evaluation when placed on a 3H:1V sloped terrain configuration.

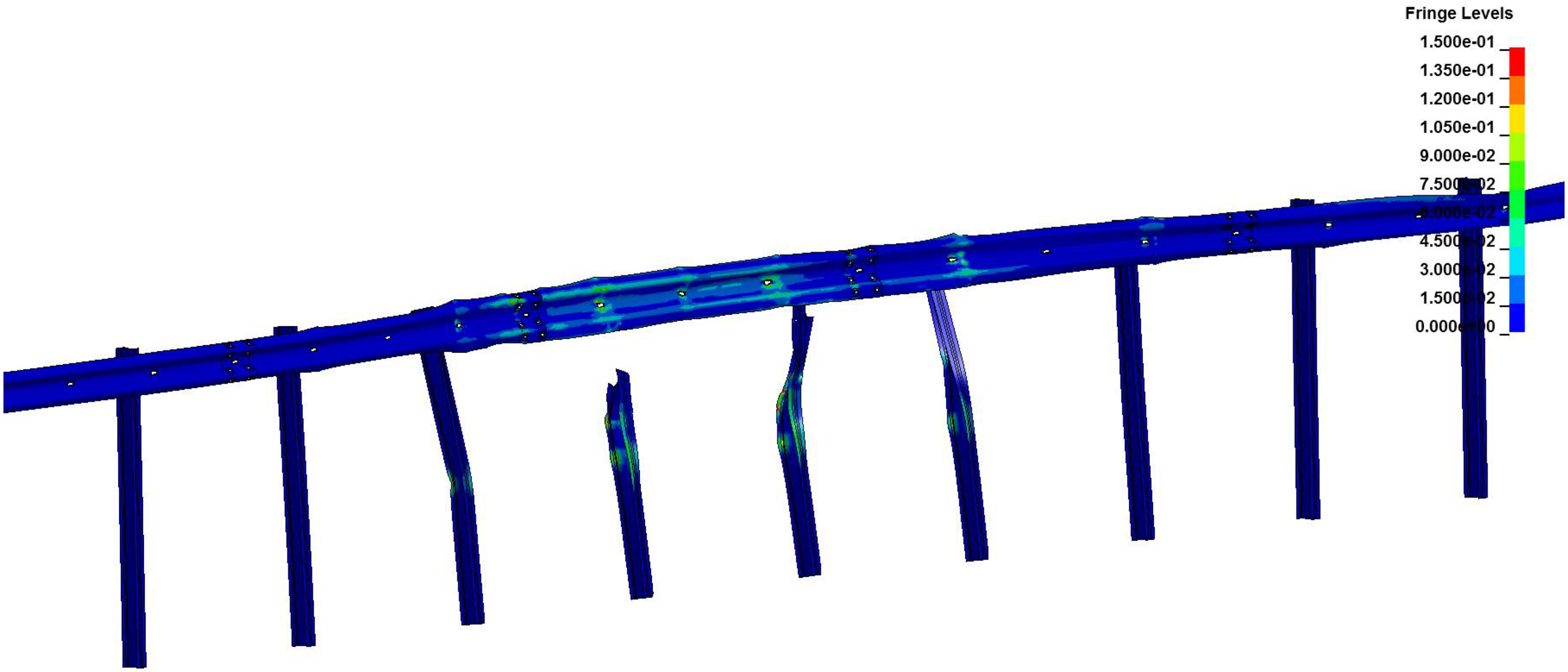
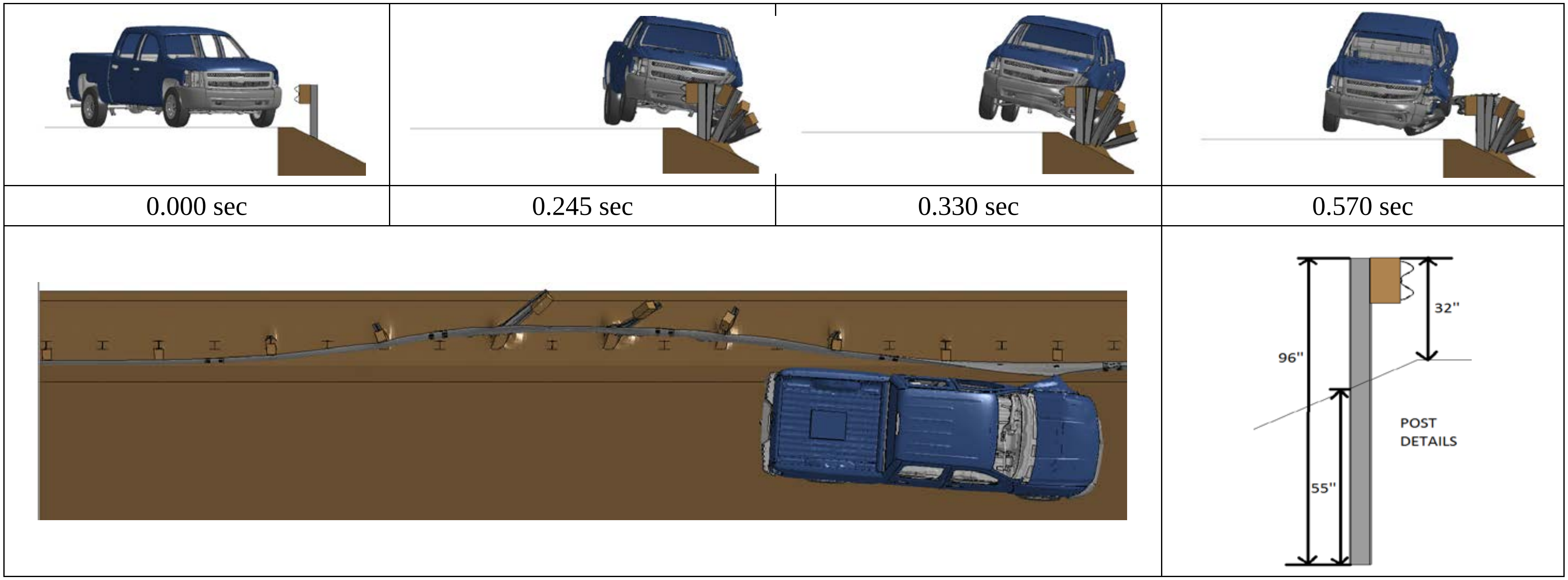


Figure 2.7. Effective Plastic Strains at the Front Face of the W-Beam Rail (On 2H:1V Slope with Tire Rod Failure Validation).



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

Test Article
Type .... 31-inch W-Beam on 2H:1V slope, 1 ft from break point
Installation Length .... 90 ft
Material or Key Elements .... W-Beam, Steel Posts, Wood Blockouts, 2H:1V Slope

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

Impact Conditions
Speed ....63.9 mph
Angle ....25 degrees
Location/Orientation ....0.9 ft upstream of post

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

Occupant Risk Values
Impact Velocity (ft/sec)
x-direction………………… 16.08
y-direction………………… -17.06
Ridedown Acceleration (g)
x-direction ....-8.3
y-direction 8.9

Vehicle Stability
Maximum Yaw Angle .... 33.3 degrees
Maximum Pitch Angle .... -8.3 degrees
Maximum Roll Angle .... -13 degrees
Vehicle Snagging .... No

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

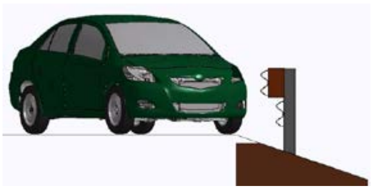
Max. Occupant Compartment Deformation ....N/A

Figure 2.8. Summary of Results for *MASH* Test 3-11 Simulation (W-Beam Guardrail on 2H:1V Slope with Tire Rod Failure).

3. FINITE ELEMENT PREDICTIVE SIMULATIONS

This chapter includes description and results of the finite element computer simulations performed to evaluate the crashworthiness of suggested barrier designs when placed on a 3H:1V slope (and when varying parameters such as posts distance from the slope break and addition of a rubrail). Table 3.1 describes the system designs suggested for further evaluation with computer modeling and simulations. More details on each of the identified cases for additional crashworthiness evaluation follow.

Table 3.1. Rail Designs and Scenarios Evaluated through Predictive Computer Simulations.

Scenario No.	Vehicle	Description	Picture
1	2270P	• 31-inch W-beam rail, 7-ft steel post, wood blockouts; • 3H:1V Slope with posts placed 1 ft from slope break (face of guardrail aligned with slope break) • NO RUBRAIL • *MASH* criteria, test 3-11	
2	2270P	• 31-inch W-beam rail, 8-ft steel post, wood blockouts; • 3H:1V Slope with posts placed 2 ft from slope break • NO RUBRAIL • *MASH* criteria, test 3-11	
3	2270P	• 31-inch W-beam rail, 8-ft steel post, wood blockouts; • 3H:1V Slope with posts placed 2 ft from slope break • YES RUBRAIL • *MASH* criteria, test 3-11	
4	1100C	• 31-inch W-beam rail, 8-ft steel post, wood blockouts; • 3H:1V Slope with posts placed 2 ft from slope break • YES RUBRAIL • *MASH* criteria, test 3-10	

3.1 W-BEAM GUARDRAIL ON 3H:1V SLOPE (1-FT) WITH NO RUBRAIL

3.1.1 Computer Model Description

The finite element model of the W-beam guardrail system with steel posts previously developed and evaluated against a full-scale crash test was modified so that the guardrail system was on a 3H:1V slope with 7-ft long posts. The face of the W-beam rail was aligned with the slope break of the ditch, and the new resulting posts embedment was 46 inches. Details of the W-beam guardrail system on a 3H:1V slope with 7-ft long posts located 1 ft away from the slope break are included in Figure 3.1.

The FE test installation consisted of 90 ft of standard 12-gauge W-beam supported by steel posts. The system was built with fourteen posts spaced at 75 inches on center. The posts were 6-inch × 8½-inch × 84-inch long posts with steel properties and a soil embedment depth of 46 inches. Failure properties were applied to the connection between the wheel and the vehicle to allow joint connection failure to occur once a predefined force value was reached. A 6-inch × 8-inch × 14-inch spacer blockout was used to block the rail away from the front face of each post. LS-DYNA soil material model *MAT_GEOLOGIC_CAP_MODEL was used to simulate soil properties for soil-post interaction during computer simulations (*9*). Standard 12 ft-6 inch long 12-gauge W-beam rails were modeled. The W-beam top rail height was 31-inch from flat level ground 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 (*10*). Evaluation of the crashworthiness of this system was evaluated according to *MASH* test 3-11 criteria.

3.1.2 Barrier Performance

Figure 3.2 contains images of the barrier before impact and at final configuration. Figure 3.2(a) and 3.2(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 3.2(b) and 3.2(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. The barrier was impacted 0.9 ft upstream of a post, with initial speed and angle of 62 mph and 25 degrees, respectively.

The vehicle was contained and redirected during the impact event. Failure properties were applied to the connection between the wheel and the vehicle to allow joint connection failure to occur once a predefined force value was reached. The dynamic and permanent deflections of the guardrail system in the FE model were 37.11 inches and 25.94 inches, respectively.

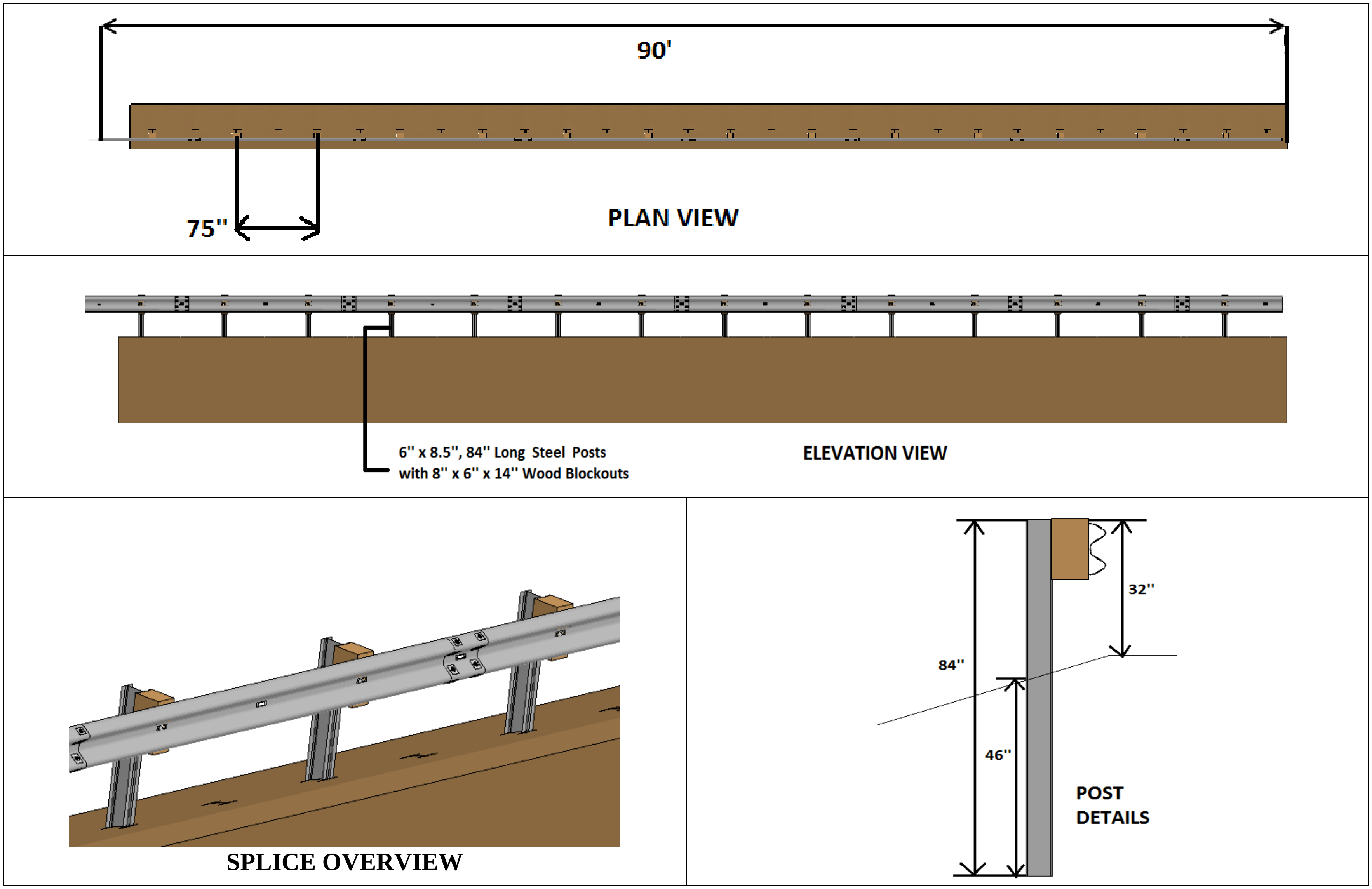
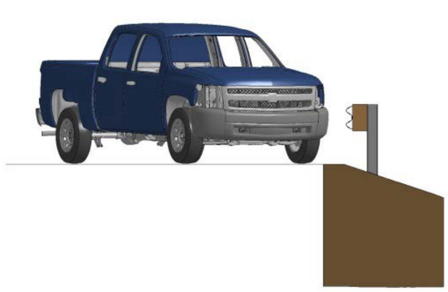
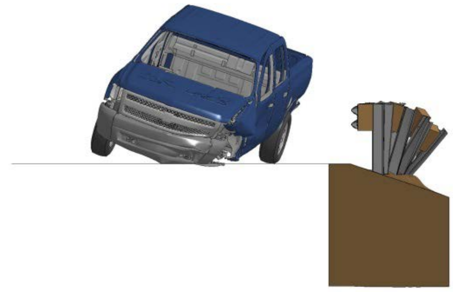


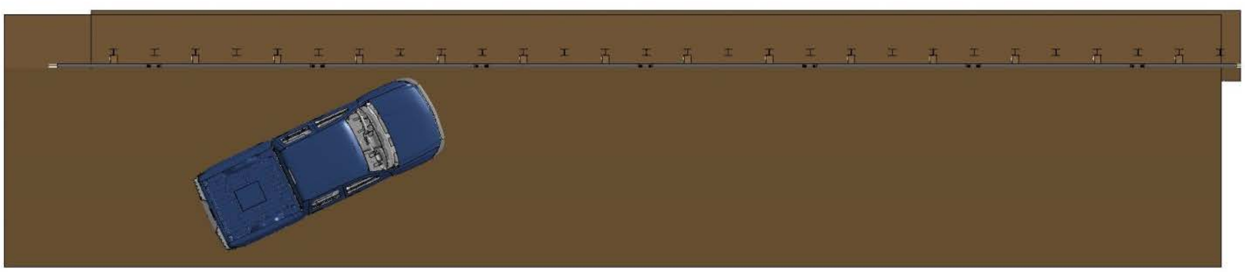
Figure 3.1. Details of the W-Beam Guardrail on 3H:1V Slope (1-ft).



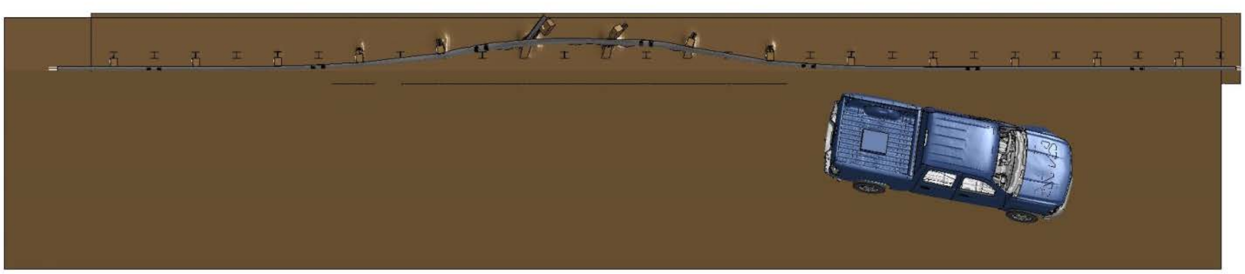
(a) Front View At Impact



(b) Front View At Final Configuration



(c) Top View At Impact



(d) Top View At Final Configuration

Figure 3.2. Initial and Deflected Shape of Barrier (W-Beam Guardrail on 3H:1V Slope (1-ft)).

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. 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 3.3, approximately 28 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). About one percent of the initial kinetic energy is converted into hourglass energy. Approximately 18 percent of the initial kinetic energy is converted into sliding interface energy. Fifty one 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.

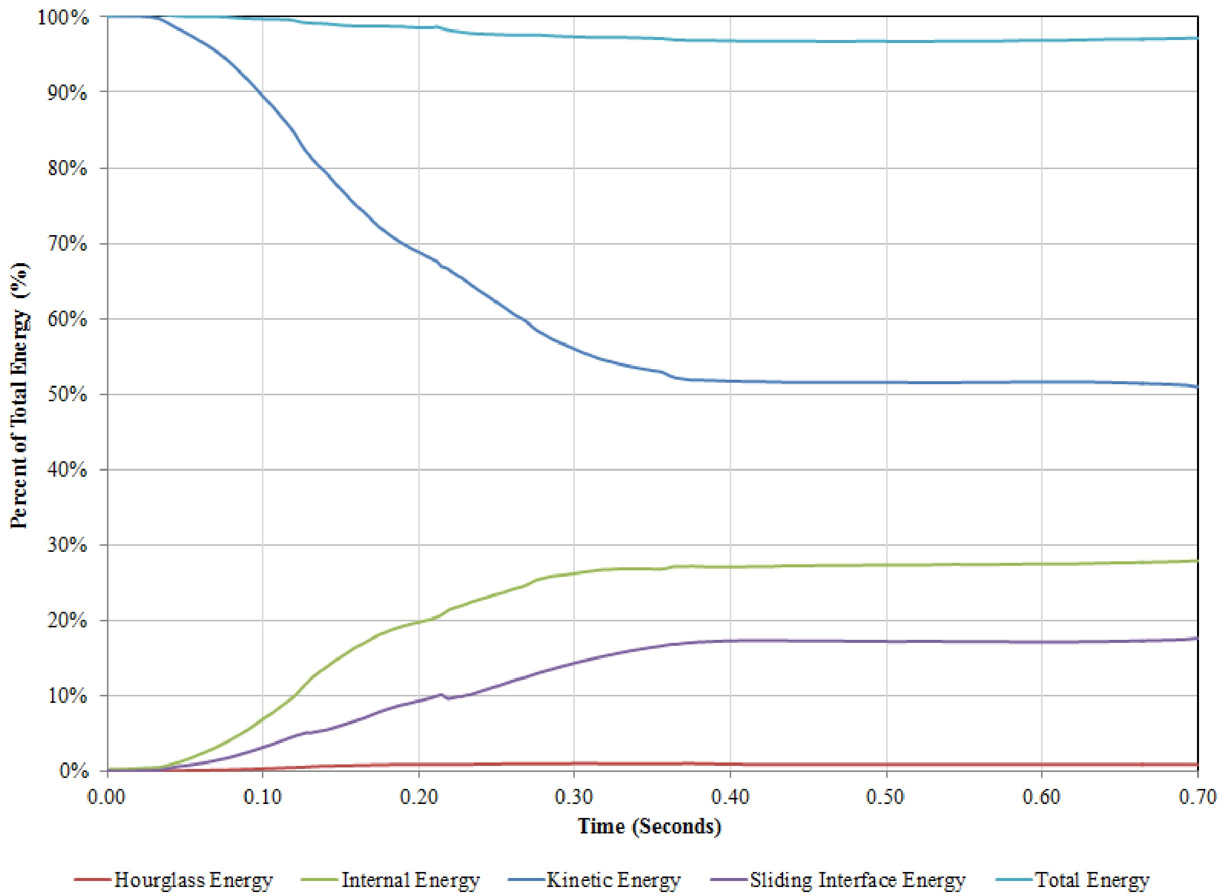


Figure 3.3. Energy Distribution Time History (W-Beam Guardrail on 3H:1V Slope (1-ft)).

Tables 3.2 through 3.4 show frames from the computer simulation impact event against the W-beam guardrail on a 3H:1V slope, with 7-ft long posts that are 1 ft away from the break point.

3.1.4 Occupant Risk Assessment

The TRAP program was used to evaluate occupant risk factors based on the applicable *MASH* safety evaluation criteria. The modeled 2270P vehicle remained upright during and after the modeled collision event. Table 3.5 provides a summary of results for the W-beam guardrail on the 3H:1V slope with 7-ft long posts located 1 foot away from the slope break. Maximum roll, pitch and yaw angles were -19.9, -7.3, and 35.6 degrees respectively. Occupant impact velocities were 15.42 ft/sec and -16.73 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were -6.5 g and 7.7 g in the longitudinal and lateral directions, respectively. Angular displacement curves are reported in Figure 3.4.

Table 3.2. Sequential Images of the 2270P Vehicle Interaction with the W-Beam Guardrail on 3H:1V Slope (1-ft) (Top View).

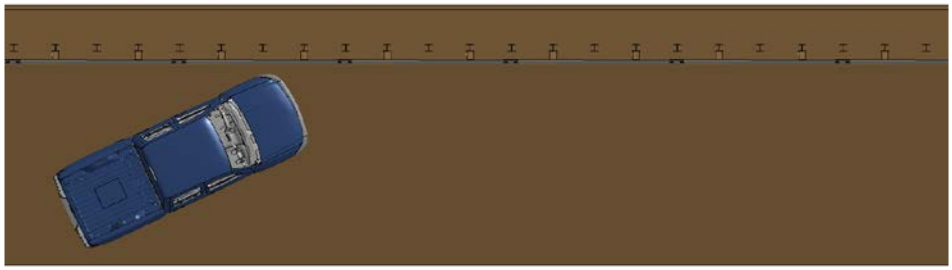
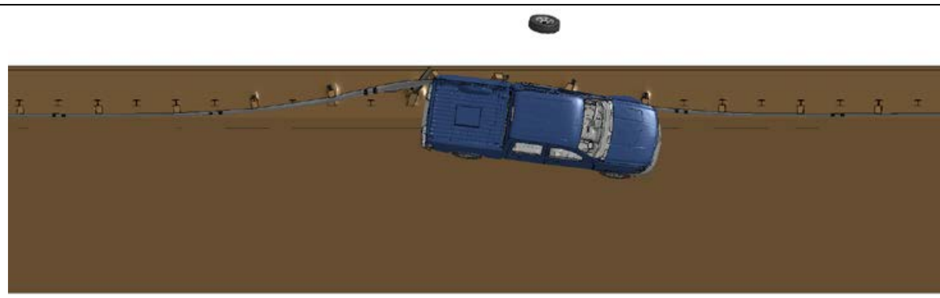
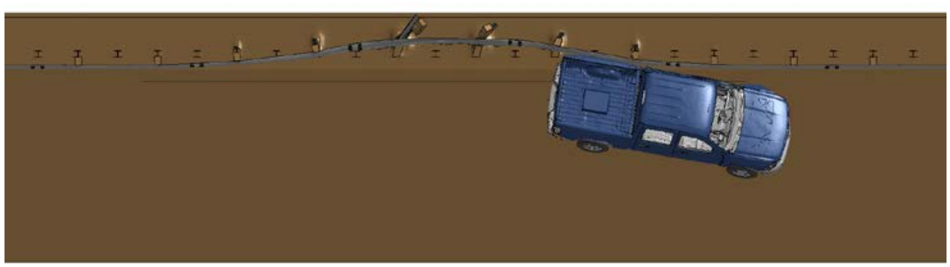
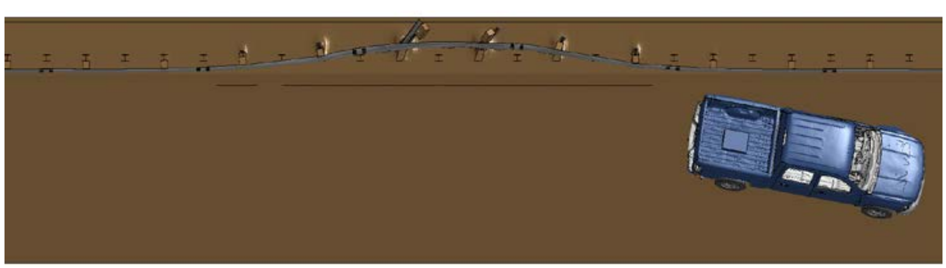
Time (sec)	FE W-Beam Guardrail on 3H:1V Slope (1-ft)
0.000	
0.175	
0.350	
0.525	
0.700	

Table 3.3. Sequential Images of the 2270P Vehicle Interaction with the W-Beam Guardrail on 3H:1V Slope (1-ft) (Front View).

Time (sec)	FE W-Beam Guardrail on 3H:1V Slope (1-ft)
0.000	
0.175	
0.350	
0.525	
0.700	

Table 3.4. Sequential Images of the 2270P Vehicle Interaction with the W-Beam Guardrail on 3H:1V Slope (1-ft) (Perspective View).

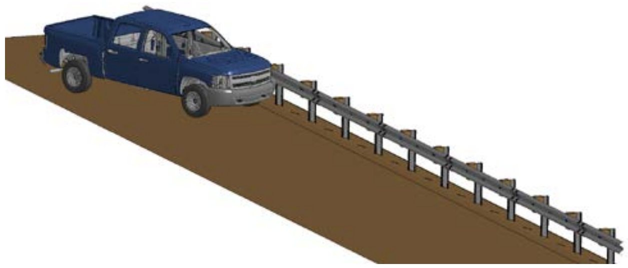
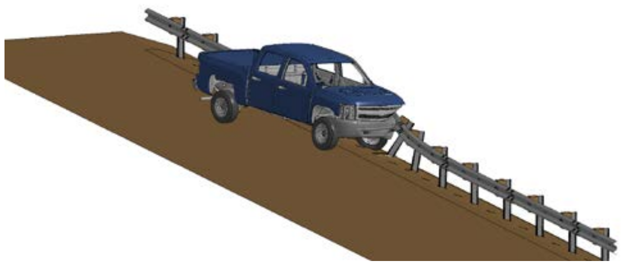
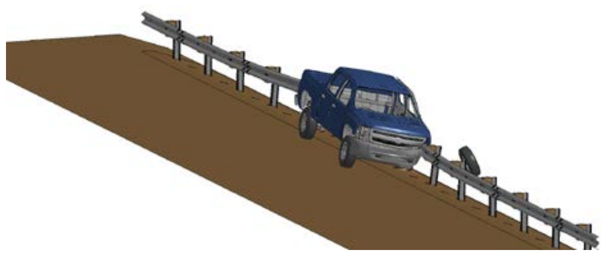
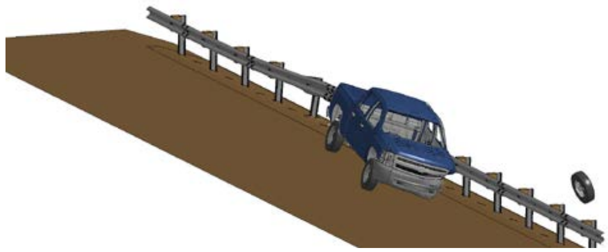
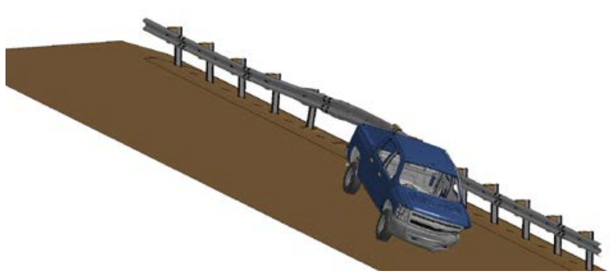
Time (sec)	FE W-Beam Guardrail on 3H:1V Slope (1-ft)
0.000	
0.175	
0.350	
0.525	
0.700	

Table 3.5. Occupant Risks Values (2270P 3H:1V Slope (1 ft), No Rubrail).

Occupant Risk Factors	**2270P 3H:1V Slope (1 ft), No Rubrail**
Impact Vel. (ft/sec)	
x-direction	15.42
y-direction	-16.73
Ridedown Acc. (g's)	
x-direction	-6.5
y-direction	7.7
Angles	**2270P 3H:1V Slope (1 ft), No Rubrail**
Roll (deg.)	-19.9
Pitch (deg.)	-7.3
Yaw (deg.)	35.6

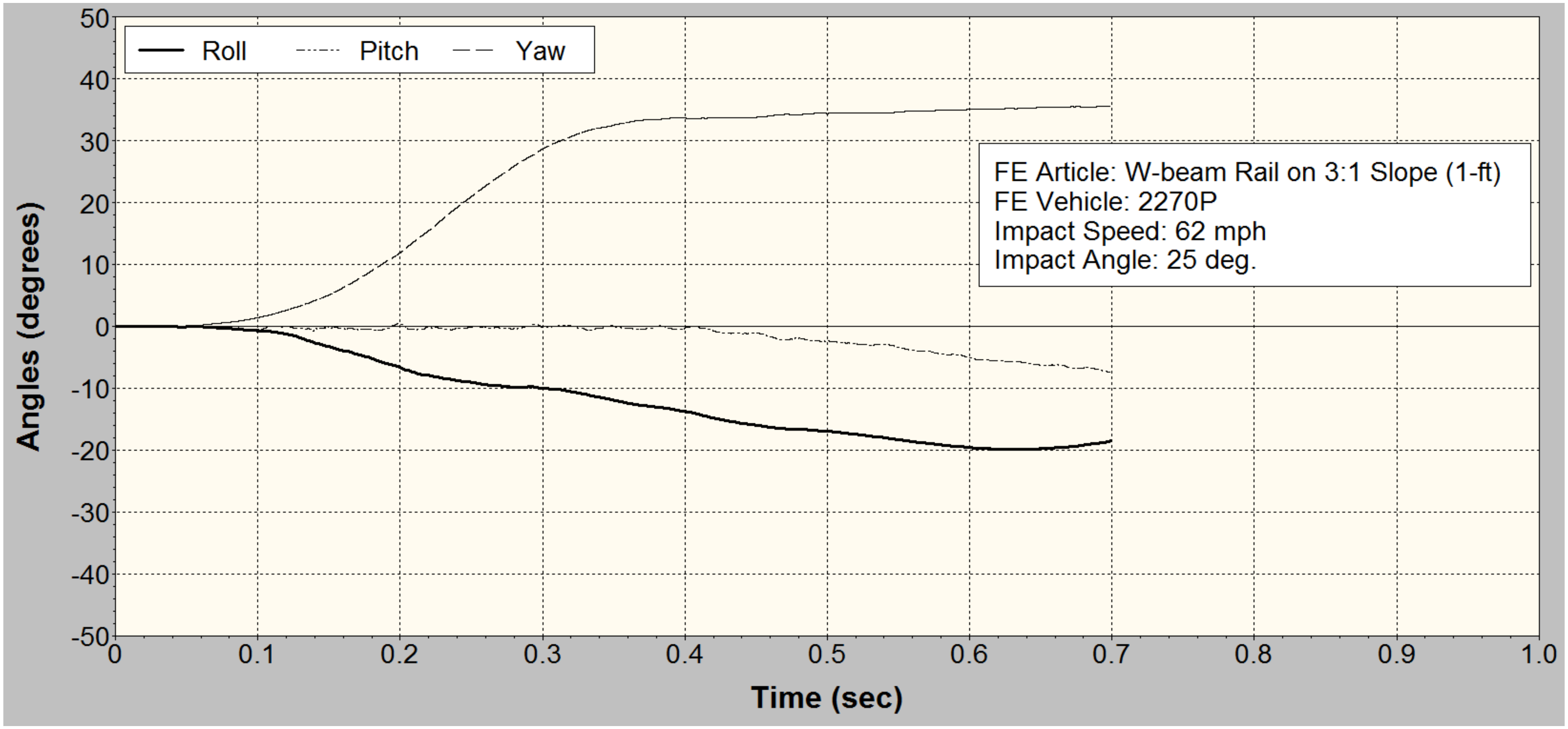


Figure 3.4. Angular Displacements for FE Simulation of W-Beam Guardrail on 3H:1V Slope (1-ft).

3.1.5 Plastic Strains

Figure 3.5 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. No regions of high plastic strains are present. After reviewing the simulation, it was concluded that rail failure is unlikely.

3.1.6 Conclusions

A predictive impact simulation was performed with a 2270P vehicle impacting a W-beam guardrail system on a 3H:1V slope, with 7-ft long posts located 1 ft from the slope break. Impact was performed according to the criteria set in *MASH* test 3-11, with initial impact conditions of 62 mph speed and 25 degrees orientation. Failure properties were applied to the connection between the wheel and the vehicle to allow joint connections to fail when a predefined force value was reached. 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*, and no pocketing occurred. The rail did not show regions of high plastic strain that might suggest failure of the steel W-beam. Results are summarized in Figure 3.6. In conclusion, results suggest that a 31-in guardrail system on a 3H:1V slope with 7-ft long posts located 1 ft from the slope break appears to be crashworthy and likely to pass safety evaluation criteria required for *MASH* test 3-11.

MASH test 3-10, which involves a small passenger car impacting the barrier at a speed of 62 mph anf at an angle of 25 degreees was not simulated. Test 405160-20-2 was performed at the TTI Proving Ground in 2012 with the objective to crash test and evaluate a 31-inch W-beam guardrail system on a 2H:1V slope to *MASH* (*8*). The guardrail on 2H:1V slope performed acceptably for *MASH* test 3-10. The proposed 31-inch W-beam guardrail design for use on a 3H:1V slope is very similar to the system evaluated under Test 405160-20-2. The differences include the slope on which the guardrail in installed and a reduction in posts length from 8 ft to 7 ft. Considering the results of test 405160-20-2 and the reduced slope severity, it is the researcher's opinion that the impact performance of the 31-inch guardrail on 3H:1V slope with 7-ft long posts located 1 ft from the slope break will be acceptable for *MASH* test 3-10. The researchers do not anticipate snagging or pocketing issues with the 1100C vehicle impacting the above proposed design on a 3H:1V slope.

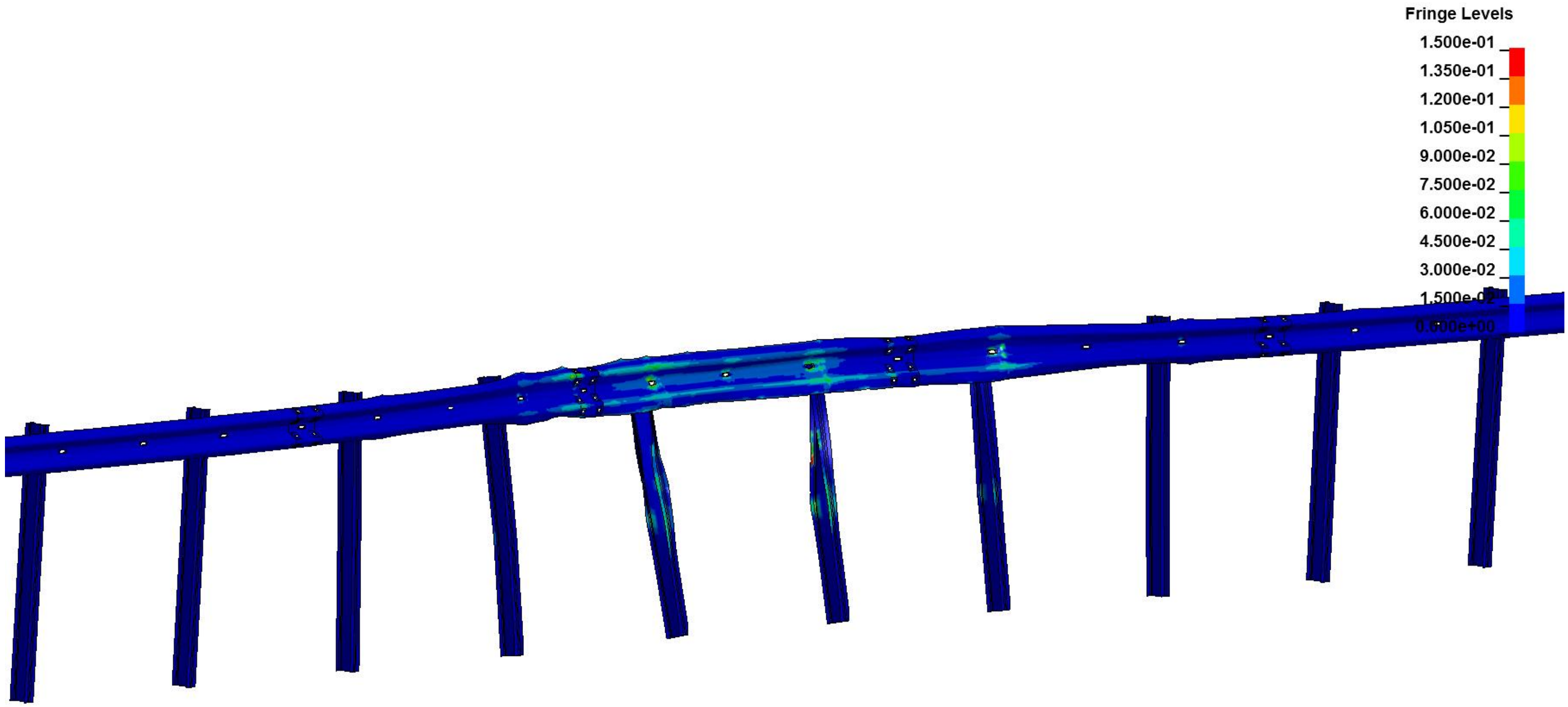
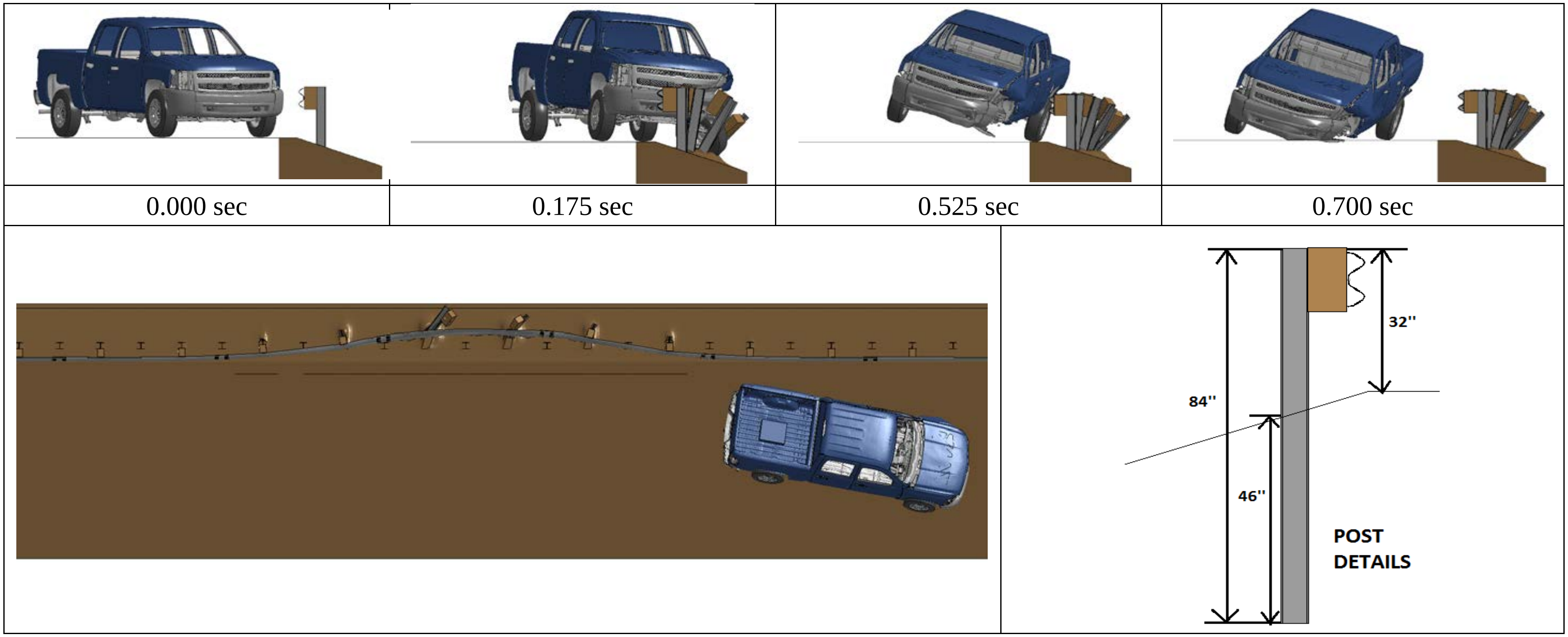


Figure 3.5. Guardrail Plastic Strain at the Front Face of the W-Beam Rail (W-Beam Guardrail on 3H:1V Slope (1-ft)).



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

Test Article
Type .... 31-inch W-Beam on 3H:1V slope, 1 ft from break point
Installation Length .... 90 ft
Material or Key Elements .... W-Beam, Steel Posts, Wood Blockouts, 3H:1V Slope

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

Impact Conditions
Speed .... 62.0 mph
Angle .... 25 degrees
Location/Orientation .... 0.9 ft upstream of post

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

Occupant Risk Values
Impact Velocity (ft/sec)
x-direction..................... 15.42
y-direction..................... -16.73
Ridedown Acceleration (g)
x-direction .... -6.5
y-direction 7.7

Vehicle Stability
Maximum Yaw Angle..................... 35.6 degree
Maximum Pitch Angle .... -7.3 degree
Maximum Roll Angle .... -19.9 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 3.6. Summary of Results for *MASH* Test 3-11 Simulation (W-Beam Guardrail on 3H:1V Slope (1-ft)).

3.2 W-BEAM GUARDRAIL ON 3H:1V SLOPE (2-FT) WITH NO RUBRAIL

3.2.1 Computer Model Description

The finite element model of the W-beam guardrail system with steel posts previously developed and evaluated against a full-scale crash test was modified so that the guardrail system was on a 3H:1V slope with 8-ft long posts located 2 ft away from the slope break. Post embedment resulted in 54 inches. Details of the W-beam guardrail system on a 3H:1V slope with 8-ft long posts located 2 ft away from the slope break are included in Figure 3.7.

The FE test installation consisted of 90 ft of standards 12-gauge W-beam supported by steel posts. The system was built with fourteen posts spaced at 75 inches on center. The posts were 6-inch × 8½-inch × 96-inch long posts with steel properties and a soil embedment depth of 54 inches. Failure properties were applied to the connection between the wheel and the vehicle to allow joint connections to fail once a predefined force value was reached. A 6-inch × 8-inch × 14-inch spacer blockout was used to block the rail away from the front face of each post. LS-DYNA soil material model *MAT_GEOLOGIC_CAP_MODEL was used to simulate soil properties for soil-post interaction during computer simulations (*9*). Standard 12 ft-6 inch long 12-gauge W-beam rails were modeled. The W-beam top rail height was 31 inches from flat level ground 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 (*10*). Evaluation of the crashworthiness of this system was evaluated according to *MASH* test 3-11 criteria.

3.2.2 Barrier Performance

Figure 3.8 contains images of the barrier before impact and at final configuration. Figure 3.9(a) and 3.9(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 3.9(b) and 3.9(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. The barrier was impacted 0.9 ft upstream of a post, with initial speed and angle of 62 mph and 25 degrees, respectively.

The vehicle was contained and redirected during the impact event. Failure properties were applied to the connection between the wheel and the vehicle to allow joint connection failure to occur once a predefined force value was reached. The dynamic and permanent deflections of the guardrail system in the FE model were 35.8 inches and 24.44 inches, respectively.

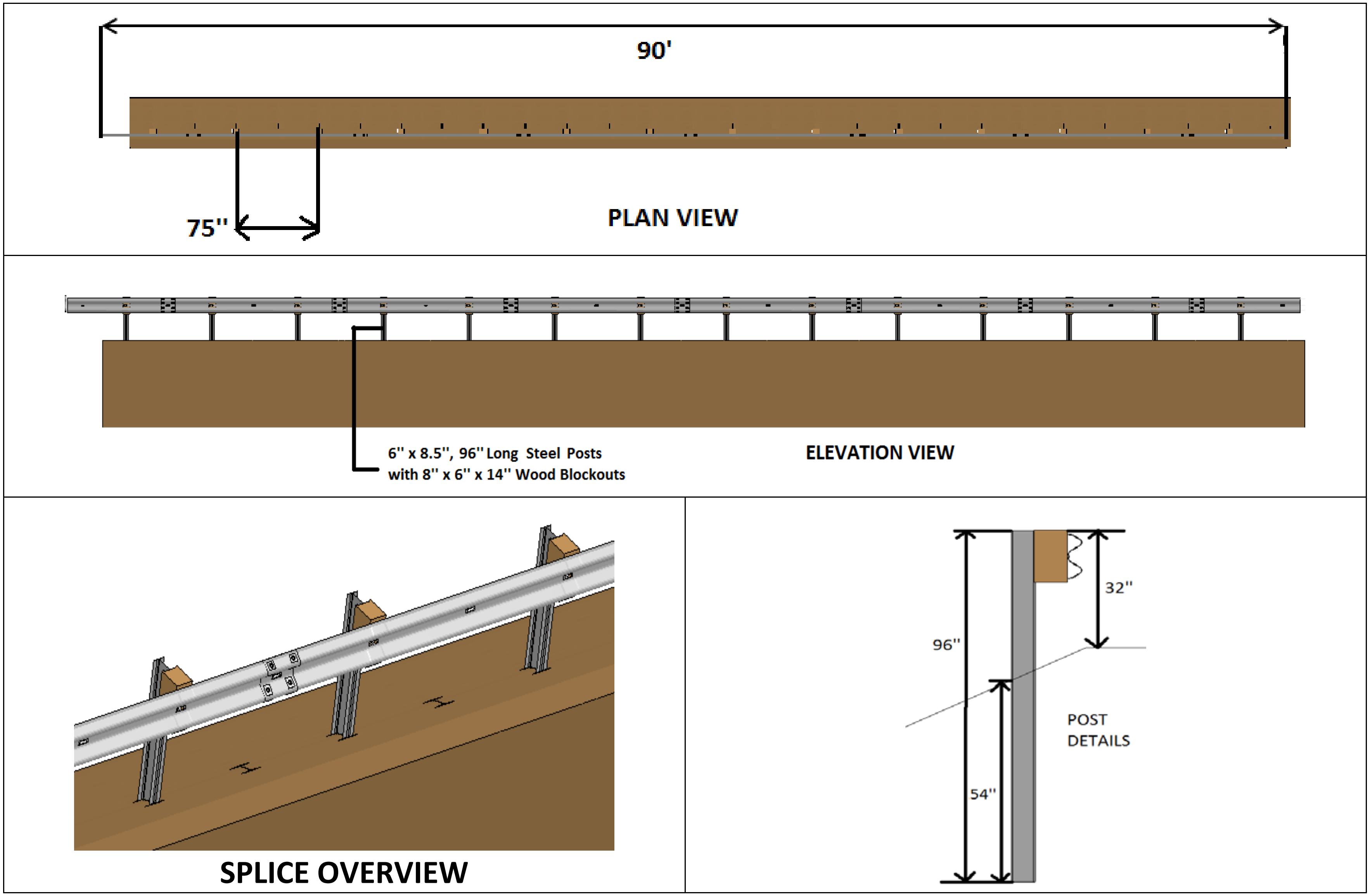
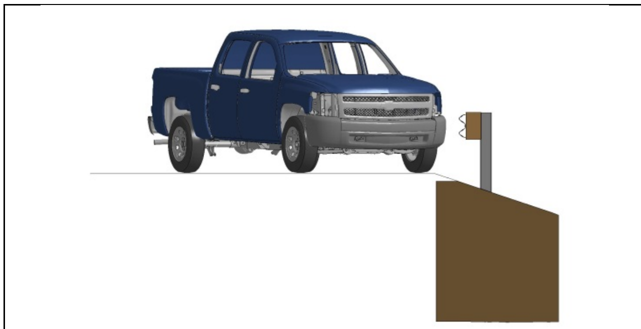
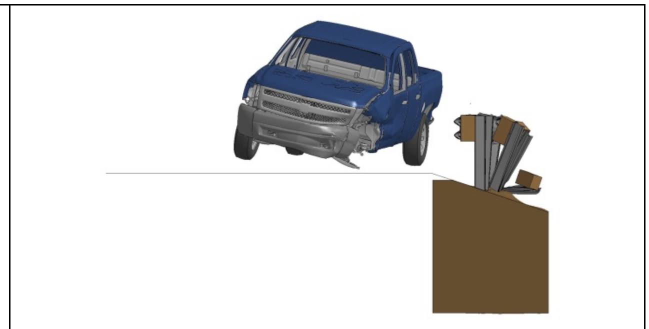


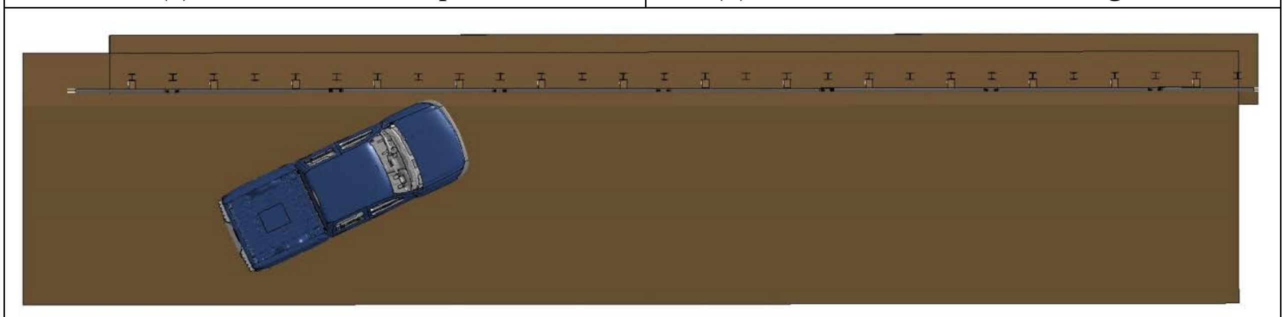
Figure 3.7. Details of the W-Beam Guardrail on 3H:1V Slope (2-ft).



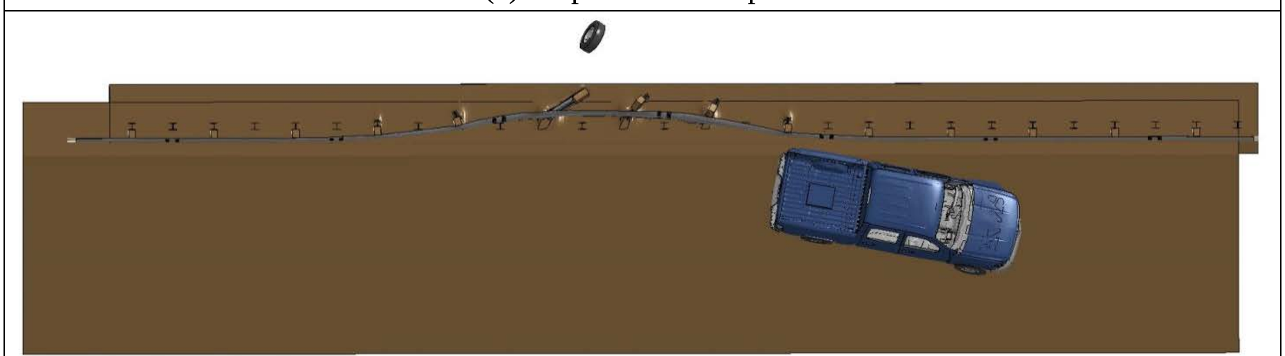
(a) Front View At Impact



(b) Front View At Final Configuration



(c) Top View At Impact



(d) Top View At Final Configuration

Figure 3.8. Initial and Deflected Shape of Barrier (W-Beam Guardrail on 3H:1V Slope (2-ft)).

3.2.3 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 3.9, approximately 31 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). About one percent of the initial kinetic energy is converted into hourglass energy. Approximately 18 percent of the initial kinetic energy is converted into sliding interface energy.

Forty 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.

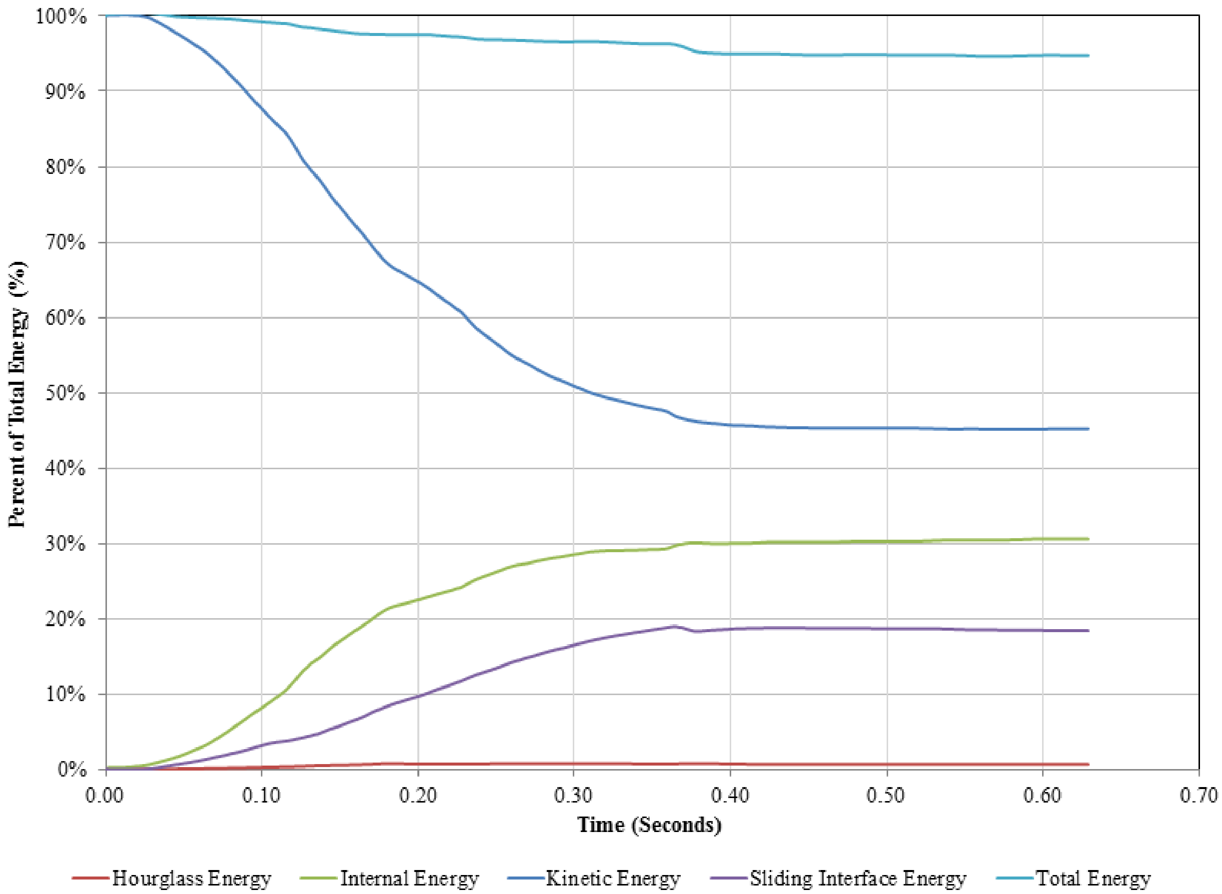


Figure 3.9. Energy Distribution Time History (W-Beam Guardrail on 3H:1V Slope (2-ft)).

Tables 3.6 through 3.8 show frames from the computer simulation impact event against the W-beam guardrail on a 3H:1V slope, with 8-ft long posts placed at two feet from the break point.

3.2.4 Occupant Risk Assessment

The TRAP program was used to evaluate occupant risk factors based on the applicable *MASH* safety evaluation criteria. The modeled 2270P vehicle remained upright during and after the modeled collision event. Table 3.9 provides a summary of results for the W-beam guardrail on the 3H:1V slope with 8-ft long posts located 2 ft away from the break point. Maximum roll, pitch and yaw angles were -14.1, -2.6, and 35.4 degrees respectively. Occupant impact velocities were 17.72 ft/sec and -16.73 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were -7.4 g and 8.2 g in the longitudinal and lateral directions, respectively. Angular displacement curves are reported in Figure 3.10.

Table 3.6. Sequential Images of the 2270P Vehicle Interaction with the W-Beam Guardrail on 3H:1V Slope (2-ft) (Top View).

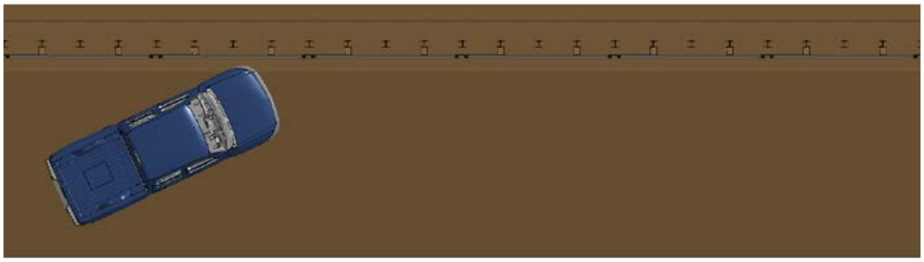
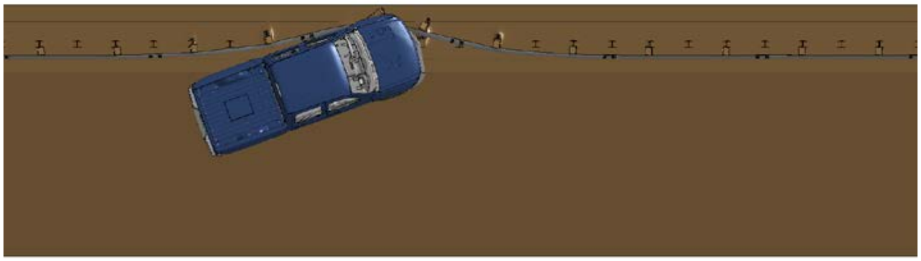
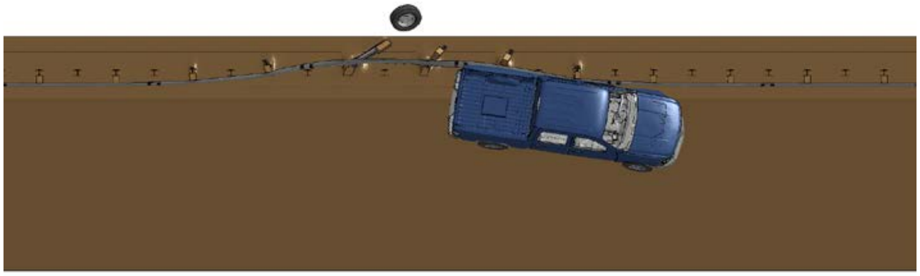
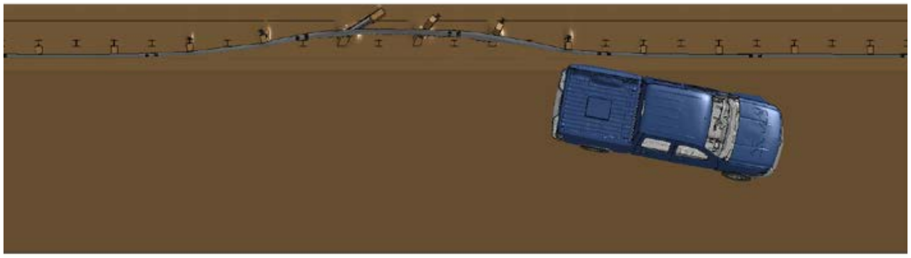
Time (sec)	FE W-Beam Guardrail on 3H:1V Slope (2-ft)
0.000	
0.150	
0.315	
0.475	
0.630	

Table 3.7. Sequential Images of the 2270P Vehicle Interaction with the W-Beam Guardrail on 3H:1V Slope (2-ft) (Front View).

Time (sec)	FE W-Beam Guardrail on 3H:1V Slope (2-ft)
0.000	
0.150	
0.315	
0.475	
0.630	

Table 3.8. Sequential Images of the 2270P Vehicle Interaction with the W-Beam Guardrail on 3H:1V Slope (2-ft) (Perspective View).

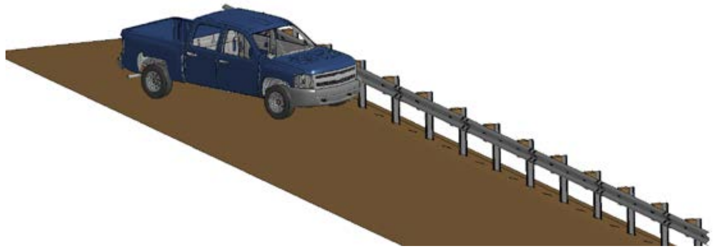
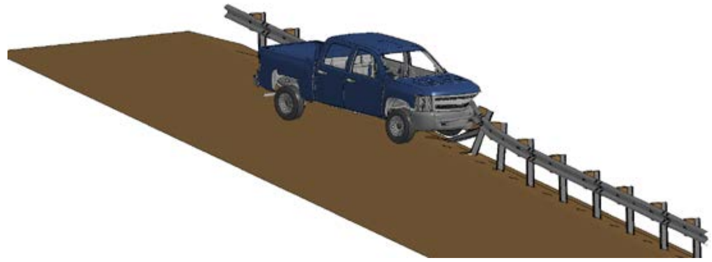
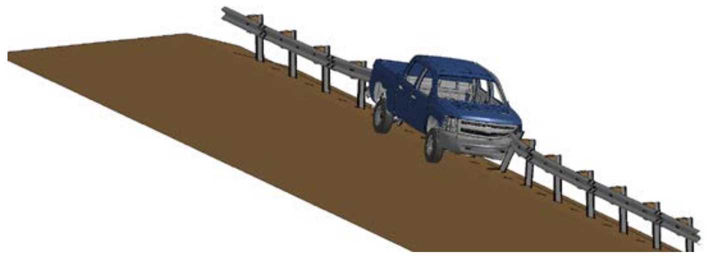
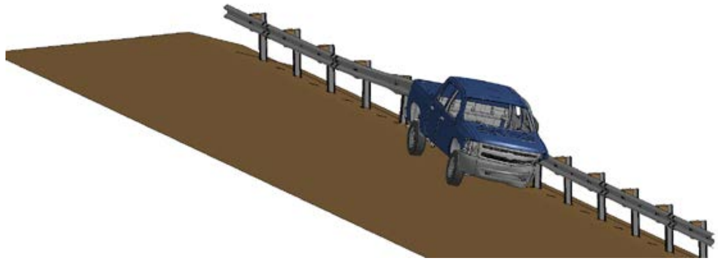
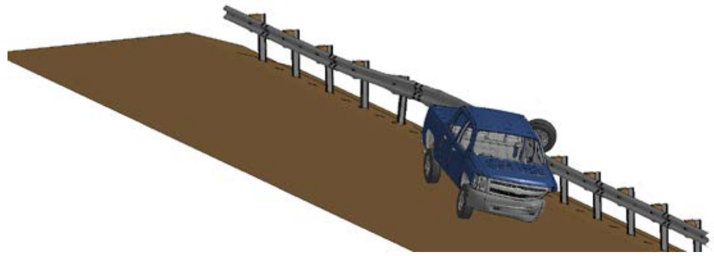
Time (sec)	FE W-Beam Guardrail on 3H:1V Slope (2-ft)
0.000	
0.150	
0.315	
0.475	
0.630	

Table 3.9. Occupant Risks Values (2270P 3H:1V Slope (2 ft), No Rubrail).

Occupant Risk Factors	2270P 3H:1V Slope (2 ft), No Rubrail
Impact Vel. (ft/sec)	
x-direction	17.72
y-direction	-16.73
Ridedown Acc. (g's)	
x-direction	-7.4
y-direction	8.2
Angles	**2270P 3H:1V Slope (2 ft), No Rubrail**
Roll (deg.)	-14.1
Pitch (deg.)	-2.6
Yaw (deg.)	35.4

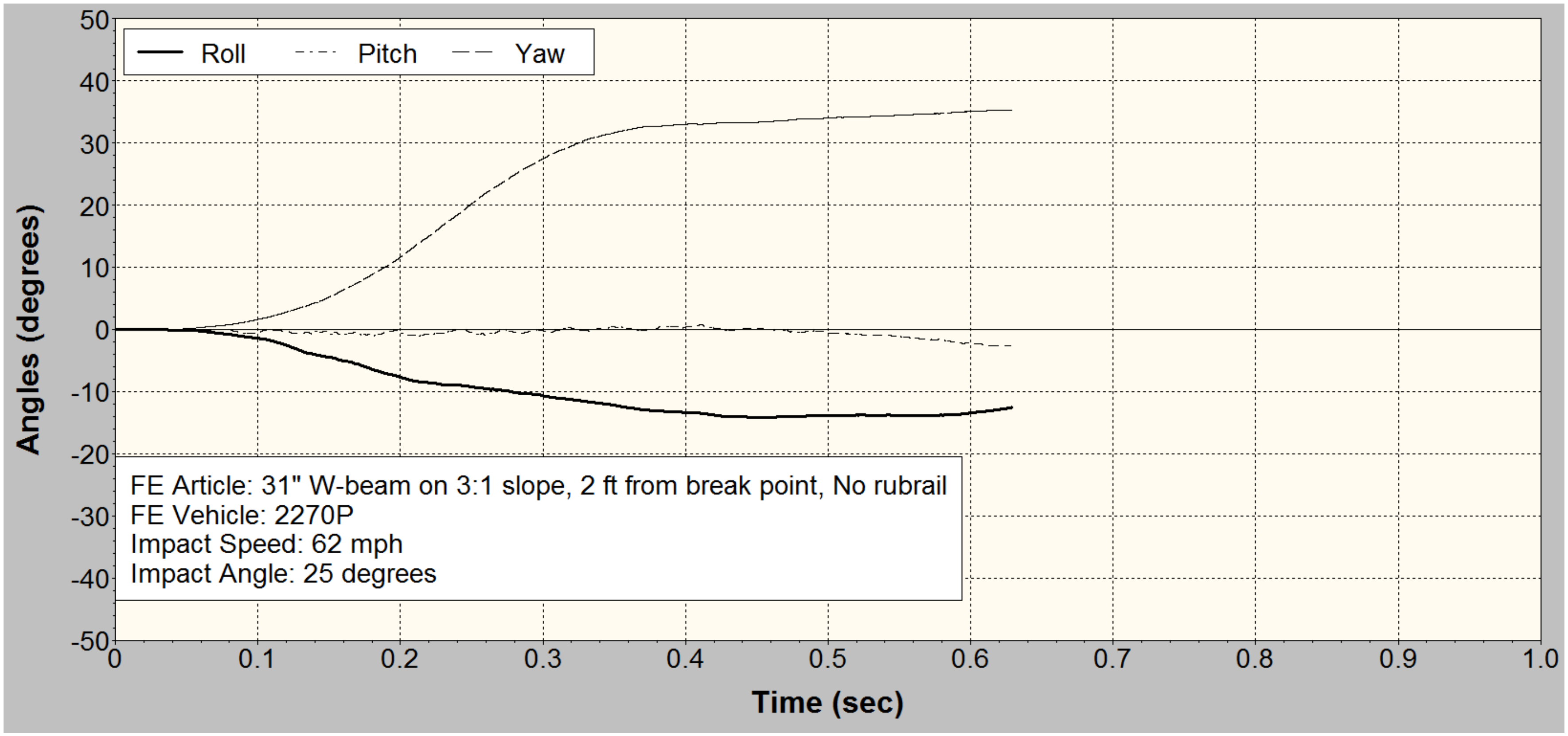


Figure 3.10. Angular Displacements for FE Simulation of W-Beam Guardrail on 3H:1V Slope (2-ft).

3.2.5 Plastic Strains

Figure 3.11 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. No regions of high plastic strains are present. After reviewing the simulation, it was concluded that rail failure is unlikely.

3.2.6 Conclusions

A predictive impact simulation was performed with a 2270P vehicle at 62 mph and 25 degrees orientation against a W-beam guardrail system on a 3H:1V slope with 8-ft long posts located 2 ft from the slope break according to the criteria set in *MASH*. Failure properties were applied to the connection between the wheel and the vehicle to allow joint connection failure to occur when a predefined force value was reached. 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 pocketing occurred. The rail did not show regions of high plastic strain that might suggest failure of the steel W-beam. Results are summarized in Figure 3.12. In conclusion, results suggest that a 31-inch guardrail system on a 3H:1V slope with 8-ft long posts located 2 ft from the slope break appears to be crashworthy and likely to pass safety evaluation criteria required for *MASH* test 3-11.

Efforts were made to simulate impact performance of the small passenger car impacting the barrier at a speed of 62 mph and at an angle of 25 degrees. Since various numerical issues related to the vehicle model arose and considering the limited project funding, the researchers decided to abandon the use of computer simulations to predict the behavior and the crashworthyness of the barrier under *MASH* test 3-10 conditions. The researchers, instead, used previous testing experience and engineering analysis to determine the crashworthiness of the proposed system. When test 405160-20-2 was performed at the TTI Proving Ground in 2012 with the objective to crash test and evaluate a W-beam guardrail system on a 2H:1V slope to *MASH, t*he guardrail on slope performed acceptably for *MASH* test 3-10. The proposed 31-inch W-beam guardrail design for use on a 3H:1V slope is very similar to the system evaluated under Test 405160-20-2. The differences include the slope on which the guardrail is installed and relocation of the 8-ft long posts at 2 ft (instead of only 1 ft) from the slope break. The researchers developed trajectory analysis of a small passenger car impacting the proposed system at the conditions required by *MASH* test 3-10. After review of the trajectory results, it is the researchers' opinion that the vehicle will interact with the W-beam guardrail prior to have any influence or interaction with the slope. The stiffness of a 31-inch guardrail system installed at 1 ft from the slope break of a 3H:1V slope is not significantly different from a 31-inch guardrail located at 2 ft from the slope break of a 2H:1V slope, with same post length. The local embedment depth of the posts differs for only 2 inches and the terrain drop off behind the posts is less severe for the 3H:1V slope than for the 2H:1V slope. Considering the results of test 405160-20-2 and the reduced slope severity, it is the researcher's opinion that the impact performance of the 31-inch guardrail on 3H:1V slope with 8-ft long posts located 2 ft from the slope break will be acceptable for *MASH* test 3-10. The researchers do not anticipate snagging or pocketing issues with the 1100C vehicle impacting the above proposed design on a 3H:1V slope.

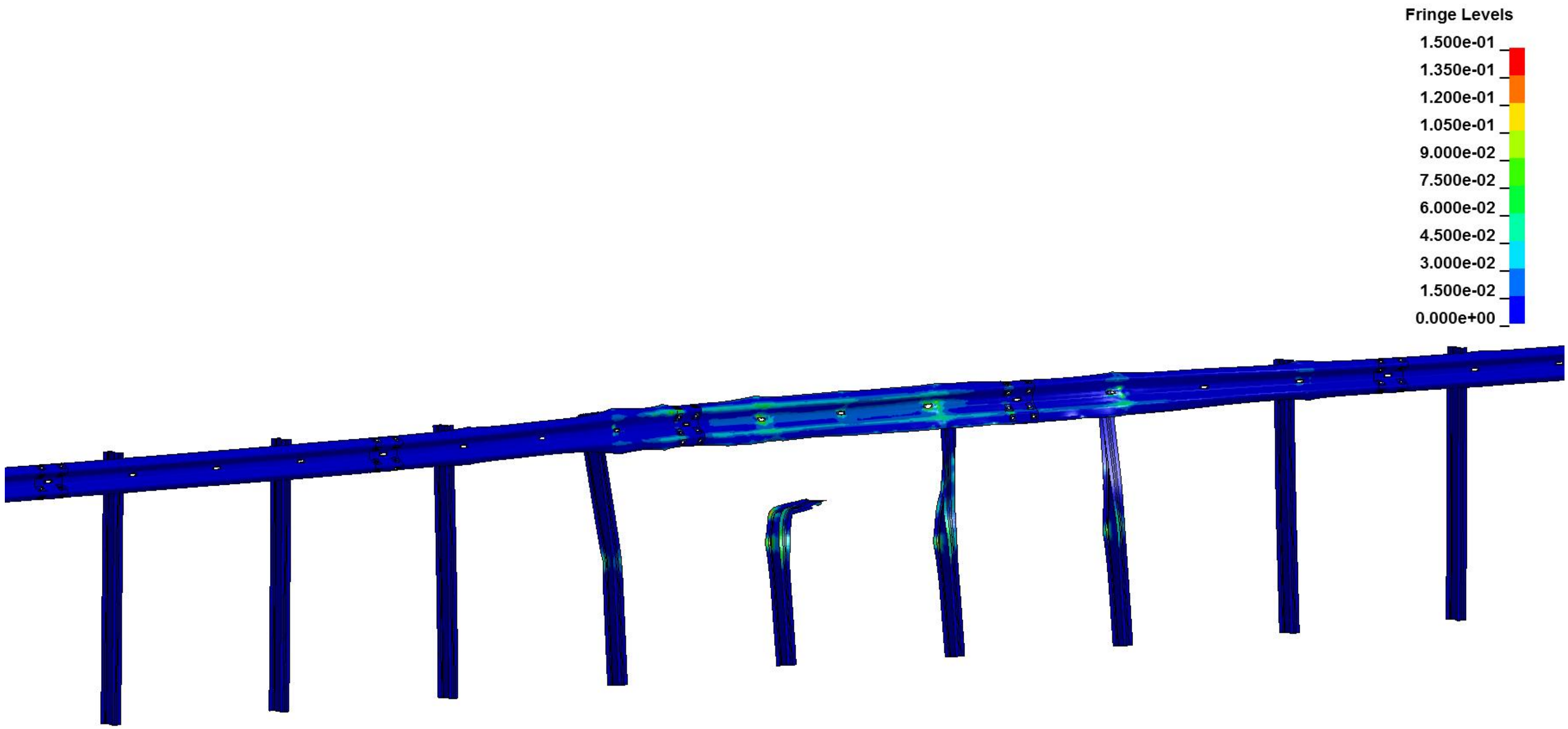
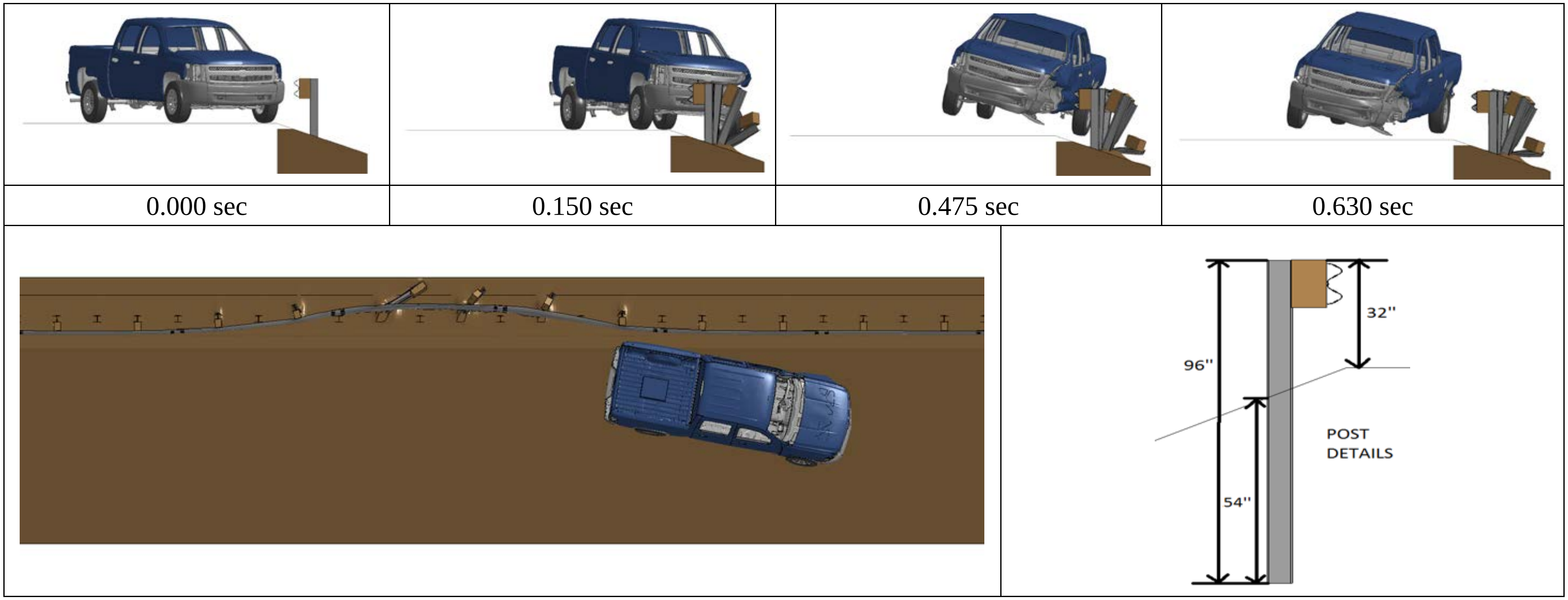


Figure 3.11. Guardrail Plastic Strain at the Front Face of the W-Beam Rail (W-Beam Guardrail on 3H:1V Slope (2-ft)).



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

Test Article
- Type .... 31-inch W-Beam on 3H:1V slope, 2 ft from break point
- Installation Length .... 90 ft
- Material or Key Elements .... W-Beam, Steel Posts, Wood Blockouts, 3H:1V Slope

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

Impact Conditions
- Speed ....62.0 mph
- Angle ....25 degrees
- Location/Orientation ....0.9 ft upstream of post

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

Occupant Risk Values

Impact Velocity (ft/sec)
- x-direction………………… 17.72
- y-direction………………… -16.73

Ridedown Acceleration (g)
- x-direction ....-7.4
- y-direction 8.2

Vehicle Stability
- Maximum Yaw Angle .... 35.4 degree
- Maximum Pitch Angle .... -2.6 degree
- Maximum Roll Angle .... -14.1 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 3.12. Summary of Results for *MASH* Test 3-11 Simulation (W-Beam Guardrail on 3H:1V Slope (2-ft)).

3.3 W-BEAM GUARDRAIL ON 3H:1V SLOPE (2-FT) WITH RUBRAIL—2270P

3.3.1 Computer Model Description

The finite element model of the W-beam guardrail system with steel posts previously developed and evaluated against a full-scale crash test was modified so that the guardrail system was on a 3H:1V slope with 8-ft long posts located 2 ft from the slope break and included a rubrail. The new post embedment was 54 inches. Details of the W-beam guardrail system with rubrail on a 3H:1V slope with 8-ft long posts located 2 ft away from the slope break are included in Figure 3.13.

The FE test installation consisted of 90 ft of standards 12-gauge W-beam supported by steel posts. The system was built with fourteen posts spaced at 75 inches on center. The posts were 6-inch × 8½-inch × 96-inch long posts with steel properties and a soil embedment depth of 54 inches. Failure properties were applied to the connection between the wheel and the vehicle to allow joint connections to fail once predefined force value was reached. A 6-inch × 8-inch × 14-inch spacer blockout was used to block the rail away from the front face of each post. No spacer blockouts were used to block the rubrail away from the front face of each post. LS-DYNA soil material model *MAT_GEOLOGIC_CAP_MODEL was used to simulate soil properties for soil-post interaction during computer simulations (*9*). Standard 12 ft-6 inch long 12-gauge W-beam rails were modeled. The W-beam top rail height was 31 inches from flat level ground 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 (*10*). Evaluation of the crashworthiness of this system was evaluated according to *MASH* test 3-11 criteria.

3.3.2 Barrier Performance

Figure 3.14 contains images of the barrier before impact and at final configuration. Figure 3.14(a) and 3.14(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 3.14(b) and 3.14(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. The barrier was impacted 0.9 ft upstream of a post, with initial speed and angle of 62 mph and 25 degrees, respectively.

The vehicle was contained and redirected during the impact event. Failure properties were applied to the connection between the wheel and the vehicle to allow joint connection failure to occur once a predefined force value was reached. The dynamic and permanent deflections of the guardrail system in the FE model were 25.32 inches and 21.61 inches, respectively.

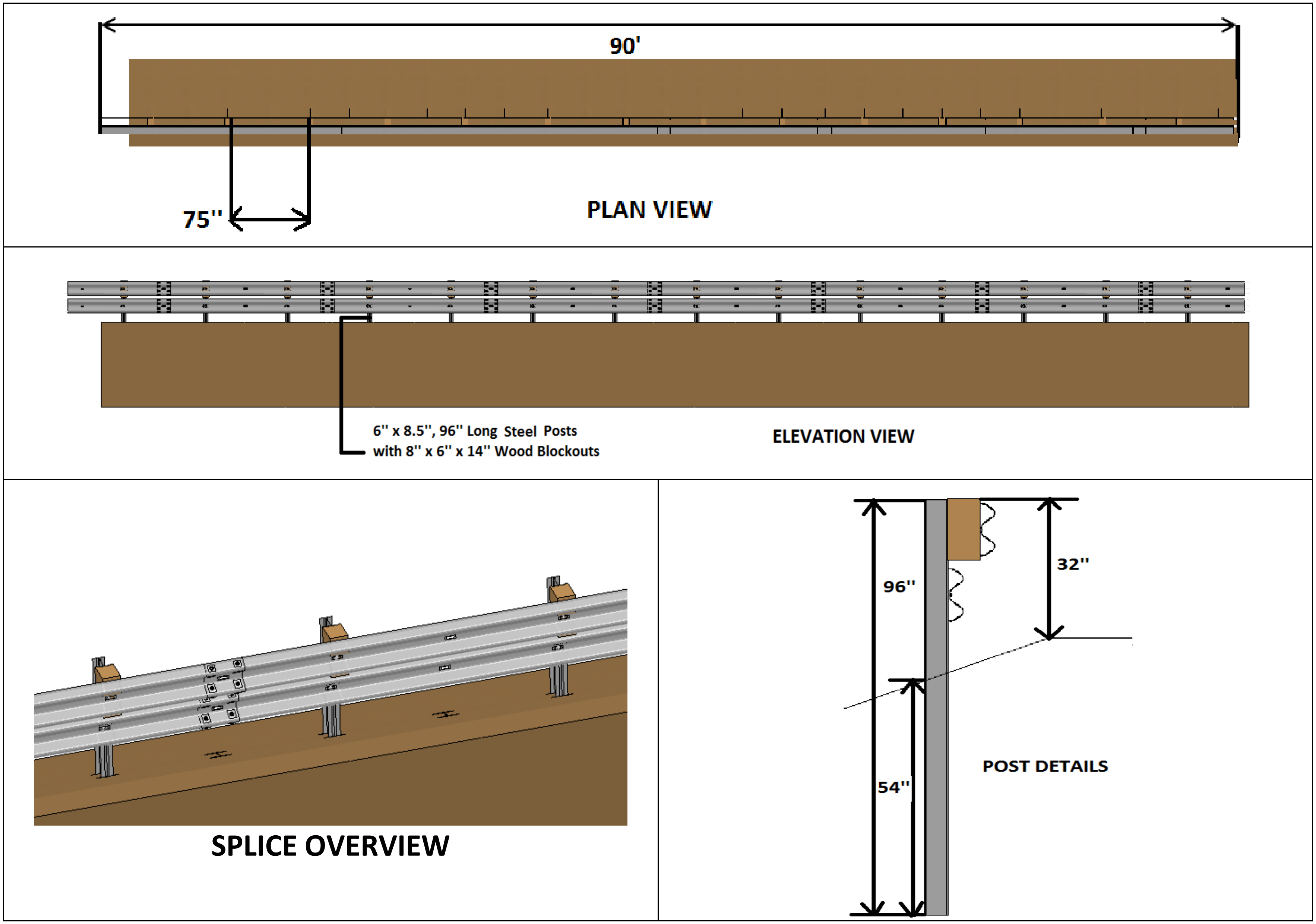
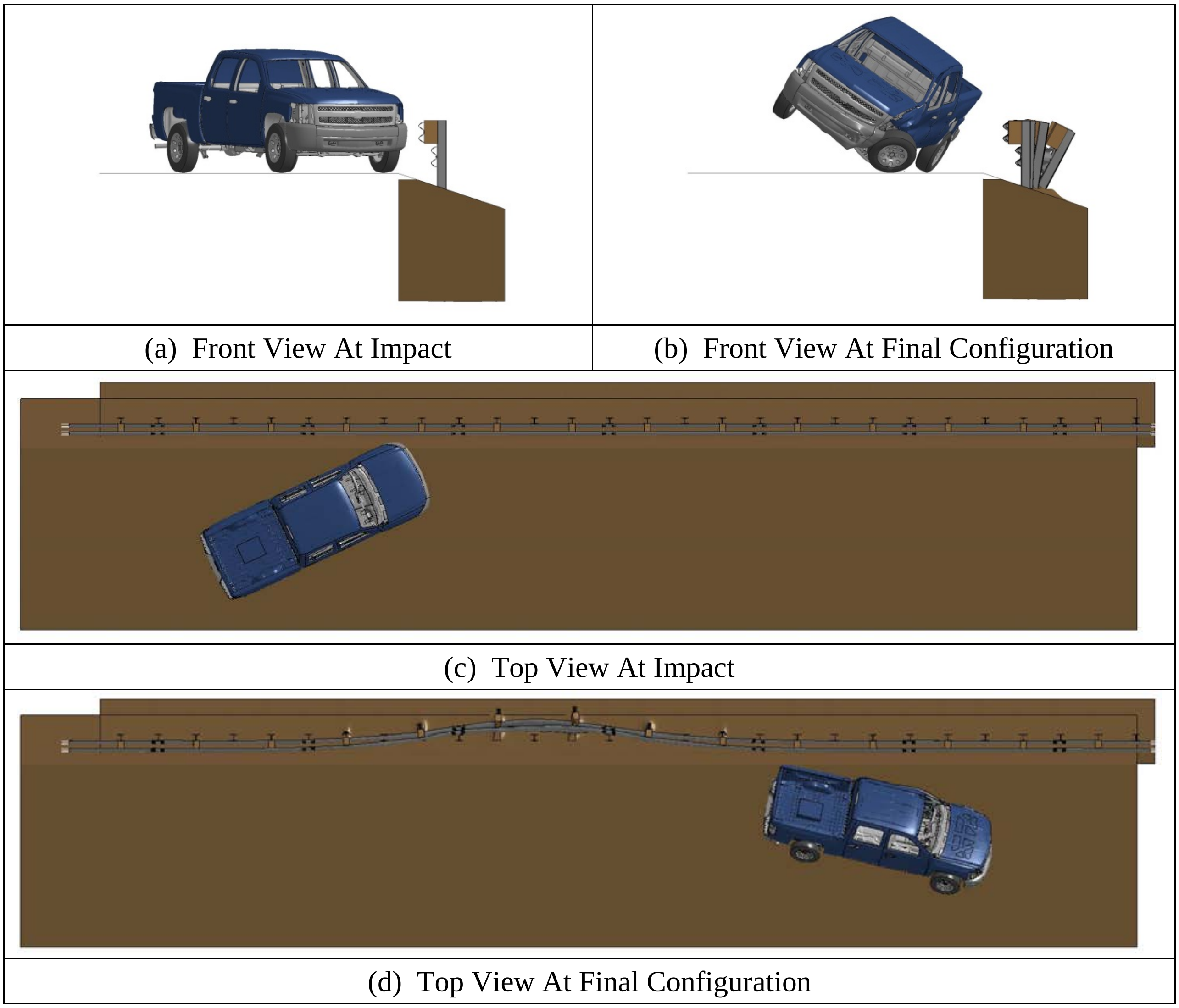


Figure 3.13. Details of the W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail.



(a) Front View At Impact

(b) Front View At Final Configuration

(c) Top View At Impact

(d) Top View At Final Configuration

Figure 3.14. Initial and Deflected Shape of Barrier (W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail).

3.3.3 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 3.15, approximately 28 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). About one percent of the initial kinetic energy is converted into hourglass energy. Approximately 17 percent of the initial kinetic energy is converted into sliding interface energy. Forty eight 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.

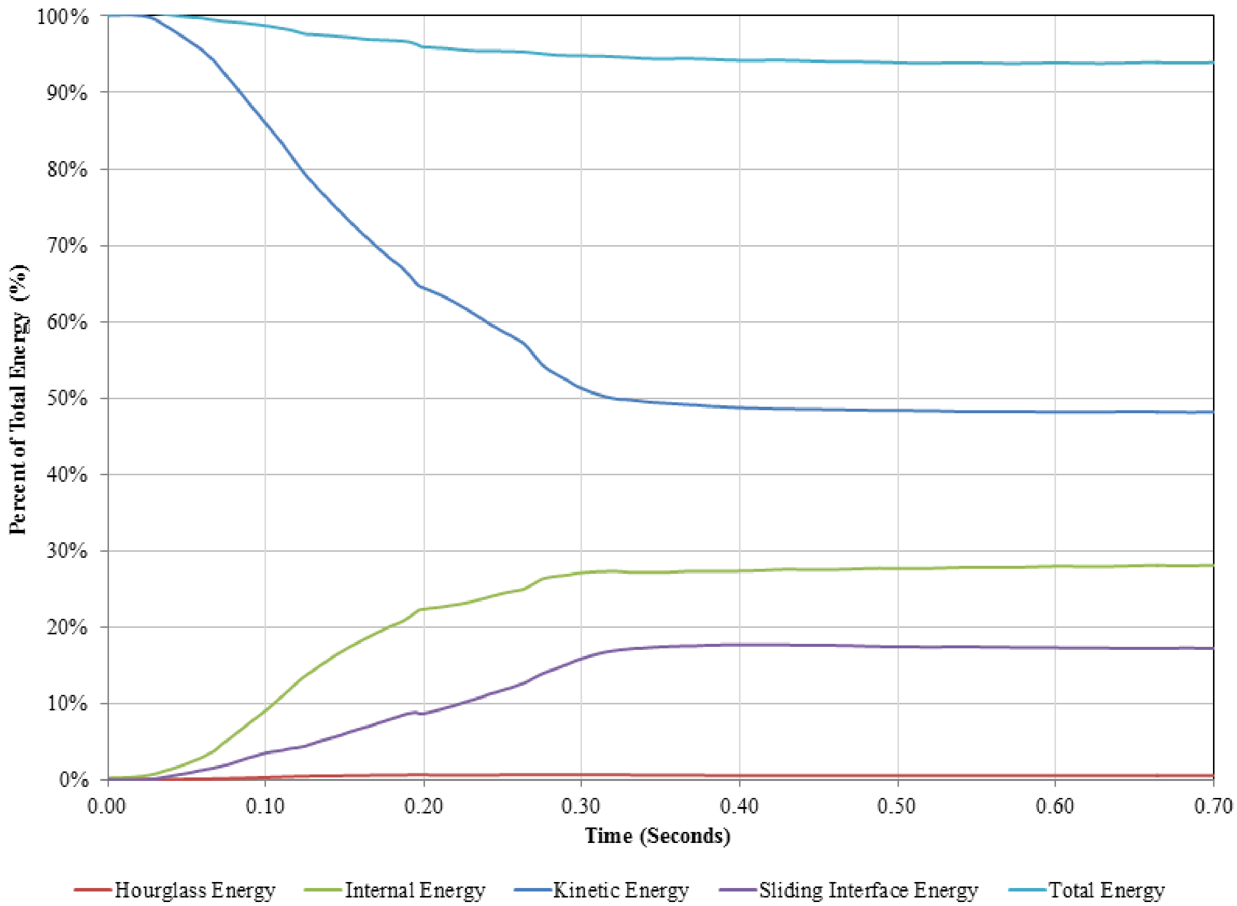


Figure 3.15. Energy Distribution Time History (W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail).

Tables 3.10 through 3.12 show frames from the computer simulation impact event against the W-beam guardrail with rubrail on a 3H:1V slope and 8-ft long posts placed 2 ft from the break point.

3.3.4 Occupant Risk Assessment

The TRAP program was used to evaluate occupant risk factors based on the applicable *MASH* safety evaluation criteria. Table 3.13 provides a summary of results for the W-beam guardrail with rubrail on the 3H:1V slope with 8-ft long posts located 2 ft away from the break point. Maximum roll, pitch and yaw angles were -34.6, 2.6, and 37.8 degrees respectively. Occupant impact velocities were 16.40 ft/sec and -16.73 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were -11.3 g and 8.7 g in the longitudinal and lateral directions, respectively. Angular displacement curves are reported in Figure 3.16. Although the roll angle increased from approximately 14 degrees (recorded during impact against the system with no addition of rubrail) to more than 34 degrees (with inclusion of rubrail), the modeled 2270P vehicle remained upright during and after the modeled collision event.

Table 3.10. Sequential Images of the 2270P Vehicle Interaction with the W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail (Top View).

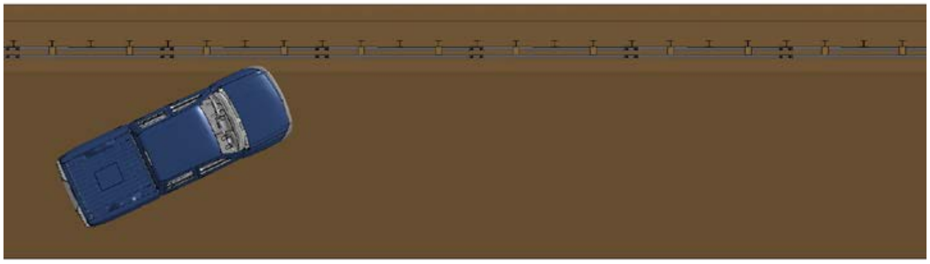
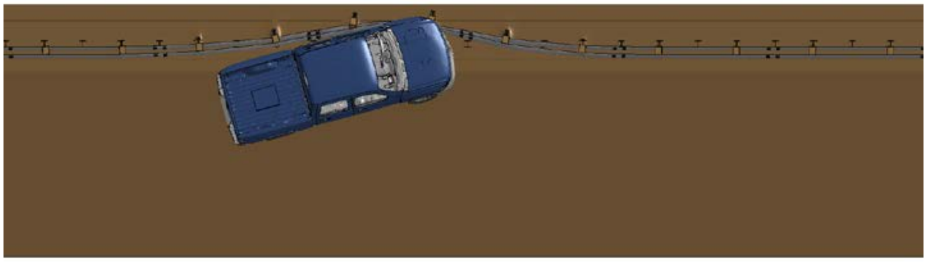
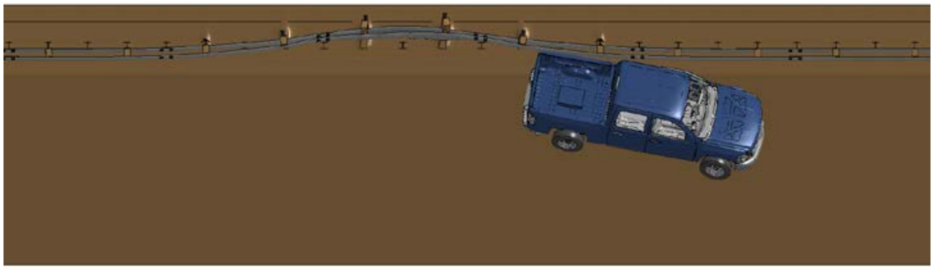
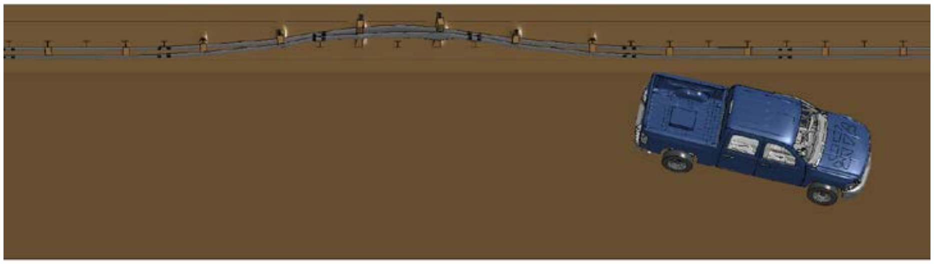
Time (sec)	FE W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail
0.000	
0.175	
0.350	
0.545	
0.700	

Table 3.11. Sequential Images of the 2270P Vehicle Interaction with the W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail (Front View).

Time (sec)	FE W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail
0.000	
0.175	
0.350	
0.545	
0.700	

Table 3.12. Sequential Images of the 2270P Vehicle Interaction with the W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail (Perspective View).

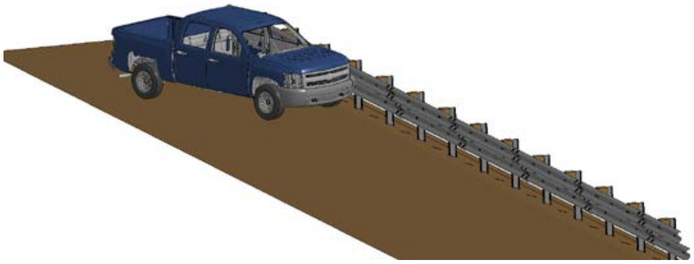
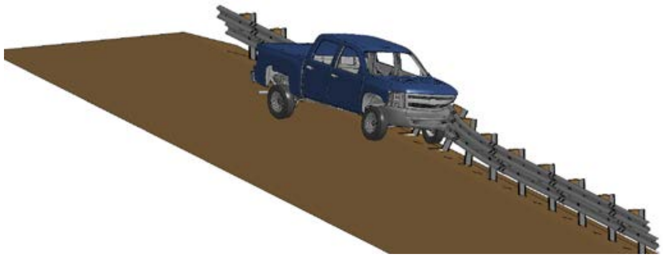
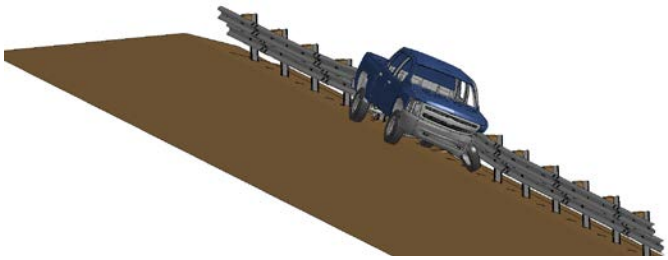
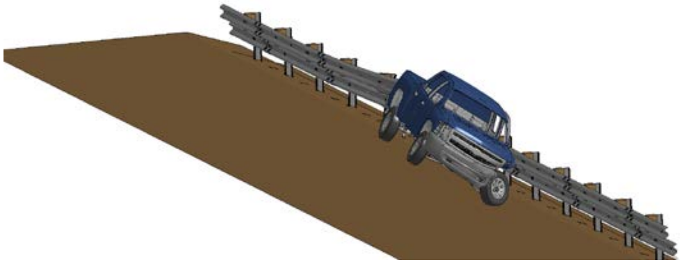
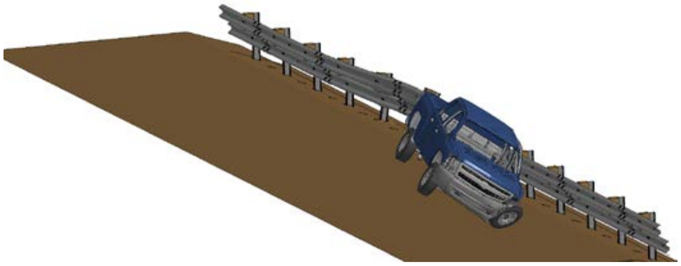
Time (sec)	FE W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail
0.000	
0.175	
0.350	
0.545	
0.700	

Table 3.13. Occupant Risks Values (2270P 3H:1V Slope (2 ft), with Rubrail).

Occupant Risk Factors	**2270P 3H:1V slope (2 ft), with Rubrail**
Impact Vel. (ft/sec)	
x-direction	16.40
y-direction	-16.73
Ridedown Acc. (g's)	
x-direction	-11.3
y-direction	8.7
Angles	**2270P 3H:1V slope (2 ft), with Rubrail**
Roll (deg.)	-34.6
Pitch (deg.)	2.6
Yaw (deg.)	37.8

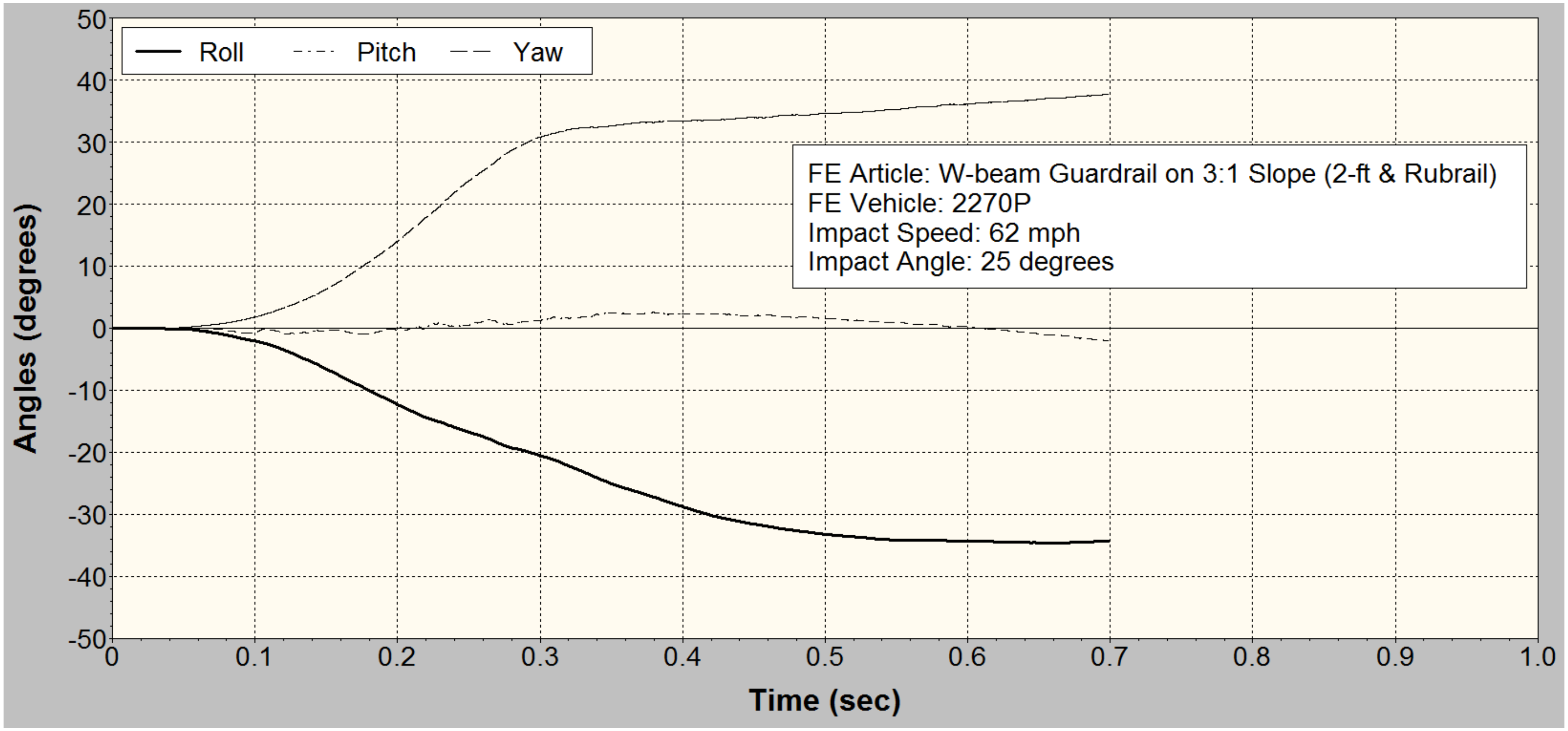


Figure 3.16. Angular Displacements for FE Simulation of W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail.

3.3.5 Plastic Strains

Figure 3.17 shows the plastic strains on the traffic side of the W-beam rail and the rubrail, in the region of contact with the vehicle during the impact event. No regions of high plastic strains are present. After reviewing the simulation, it was concluded that rail failure is unlikely.

3.3.6 Conclusions

A predictive impact simulation was performed with a 2270P vehicle at 62 mph and 25 degrees orientation against a W-beam guardrail system with rubrail on a 3H:1V slope with 8-ft long posts located 2 ft away from the slope break according to the criteria set in *MASH*. Failure properties were applied to the connection between the wheel and the vehicle to allow joint connection failure to occur once a predefined force value was reached. 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 pocketing occurred. Neither the W-beam rail nor the rubrail showed regions of high plastic strain that might suggest failure of the steel. Results are summarized in Figure 3.18. In conclusion, results suggest that a 31-inch guardrail system with rubrail on a 3H:1V slope with 8-ft long posts located 2 ft from the slope break appears to be crashworthy and likely to pass safety evaluation criteria required for *MASH* test 3-11.

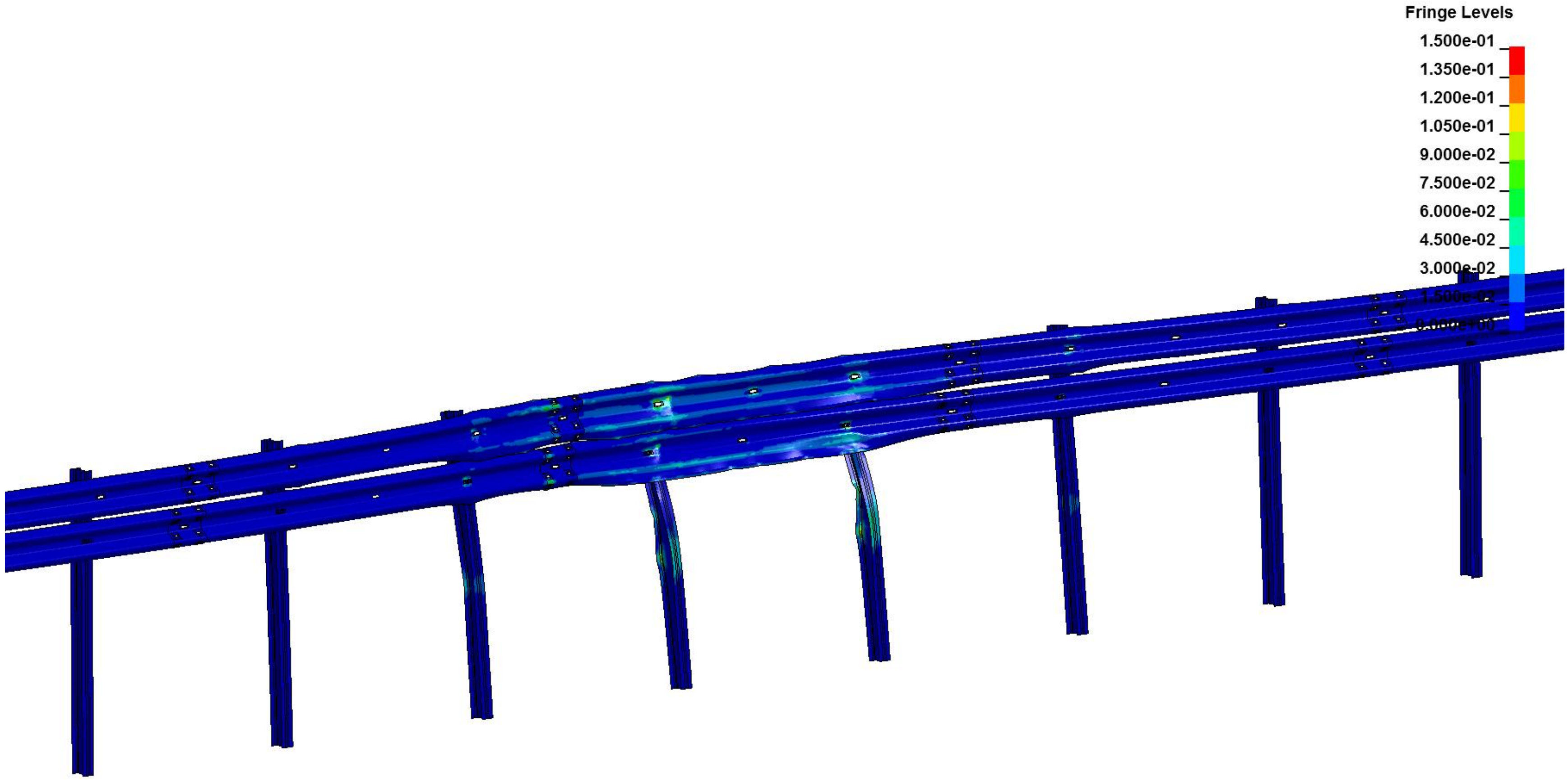
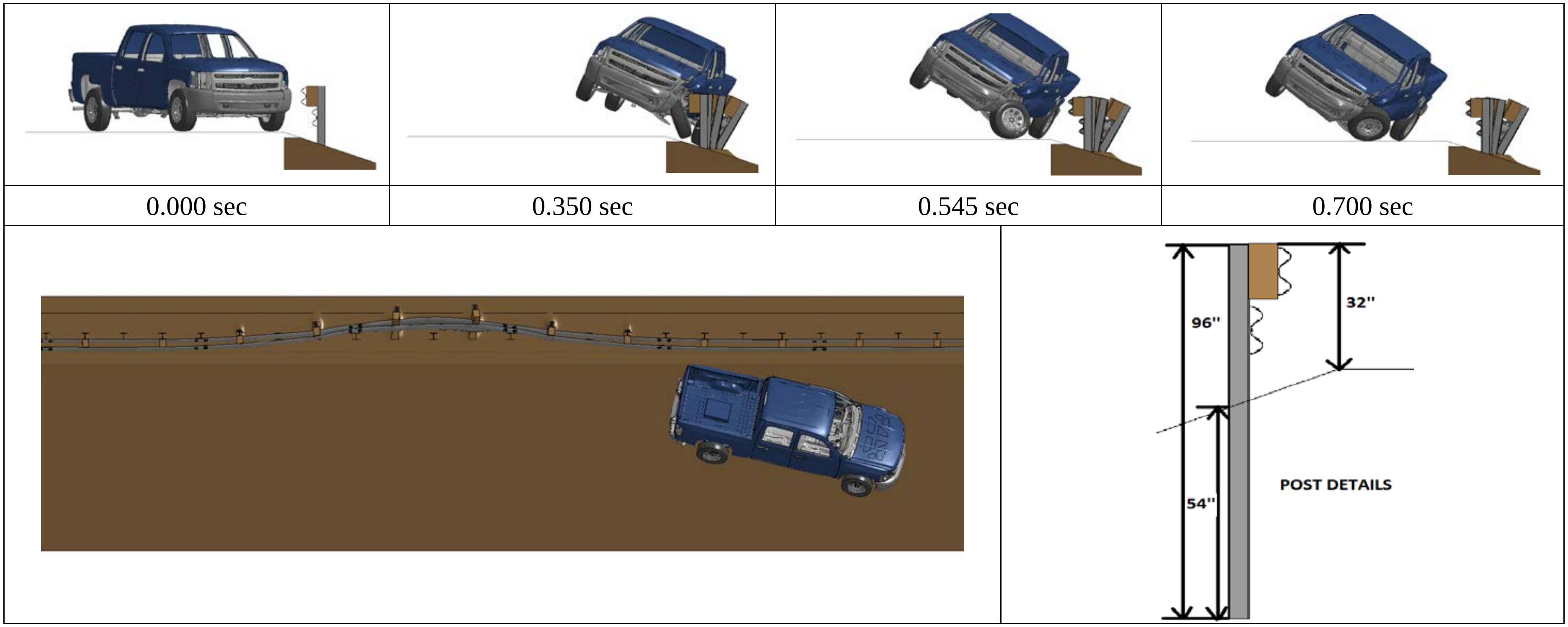


Figure 3.17. Guardrail Plastic Strain at the Front Face of the W-Beam Rail (W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail).



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

Test Article
Type .... 31-inch W-Beam with rubrail on 3H:1V slope, 2 ft from break point
Installation Length .... 90 ft
Material or Key Elements .... W-Beam, Steel Posts, Wood Blockouts, 3H:1V Slope, Rubrail

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

Impact Conditions
Speed ....62.0 mph
Angle ....25 degrees
Location/Orientation ....0.9 ft upstream of post

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

Occupant Risk Values
Impact Velocity (ft/sec)
x-direction………………… 16.40
y-direction………………… -16.73
Ridedown Acceleration (g)
x-direction ....-11.3
y-direction 8.7

Vehicle Stability
Maximum Yaw Angle..................... 37.8 degree
Maximum Pitch Angle .... 2.6 degree
Maximum Roll Angle .... -34.6 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 3.18. Summary of Results for *MASH* Test 3-11 Simulation (W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail).

3.4 W-BEAM GUARDRAIL ON 3H:1V SLOPE (2-FT) WITH RUBRAIL—1100C

3.4.1 Computer Model Description

The finite element model of the W-beam guardrail system with steel posts previously developed and evaluated against a full-scale crash test was modified so that the guardrail system was on a 3H:1V slope with 8-ft long posts located 2 ft from the slope break and included rubrail. The new post embedment was 54 inches. Details of the W-beam guardrail system with rubrail on a 3H:1V slope with 8-ft long posts located 2 ft away from the slope break are included in Figure 3.13.

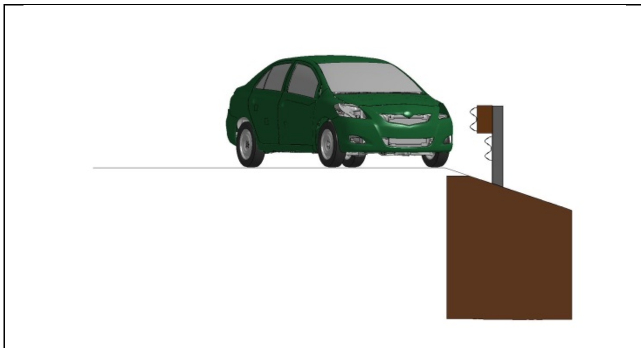
The FE test installation consisted of 90 ft of standards 12-gauge W-beam supported by steel posts. The system was built with fourteen posts spaced at 75 inches on center. The posts were 6-inch × 8½-inch × 96-inch long posts with steel properties and a soil embedment depth of 54 inches. Failure properties were applied to the connection between the wheel and the vehicle to allow joint connection failure to occur once a predefined force value was reached. A 6-inch × 8-inch × 14-inch spacer blockout was used to block the rail away from the front face of each post. LS-DYNA soil material model *MAT_GEOLOGIC_CAP_MODEL was used to simulate soil properties for soil-post interaction during computer simulations (*9*). Standard 12 ft-6 inch long 12-gauge W-beam rails were modeled. The W-beam top rail height was 31 inches from flat level ground 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 1100C passenger car model to complete their simulations (*10*). Evaluation of the crashworthiness of this system was evaluated according to *MASH* test 3-10 criteria.

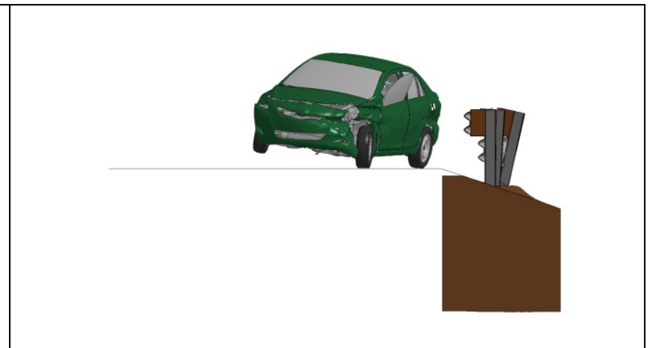
3.4.2 Barrier Performance

Figure 3.19 contains images of the barrier before impact and at final configuration. Figure 3.19(a) and 3.19(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 3.19(b) and 3.19(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. The barrier was impacted 0.9 ft upstream of a post, with initial speed and angle of 62 mph and 25 degrees, respectively.

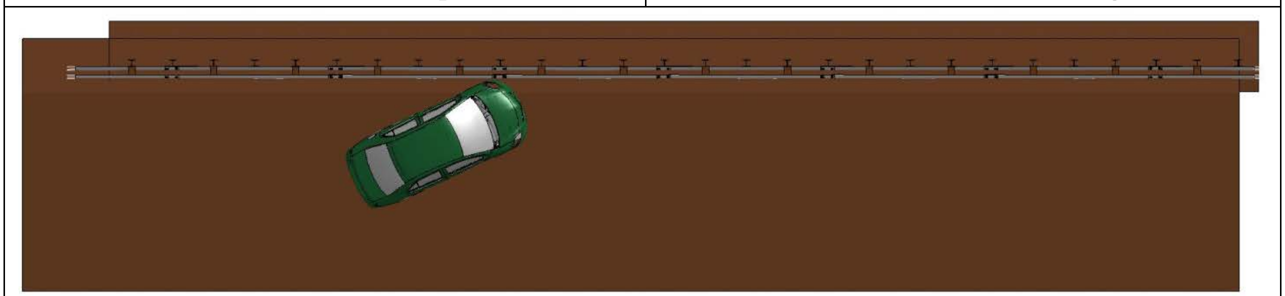
The vehicle was contained and redirected during the impact event. The dynamic and permanent deflections of the guardrail system in the FE model were 20.50 inches and 15.46 inches, respectively.



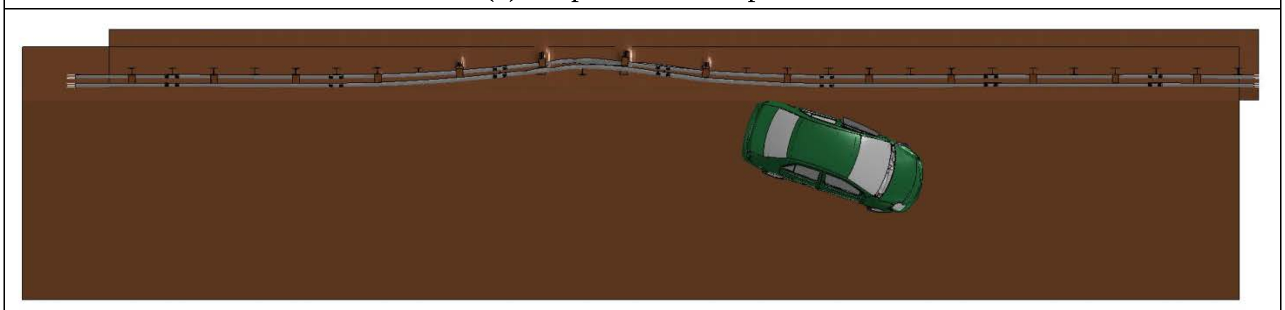
(a) Front View At Impact



(b) Front View At Final Configuration



(c) Top View At Impact



(d) Top View At Final Configuration

Figure 3.19. Initial and Deflected Shape of Barrier (W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail—1100C).

3.4.3 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 3.20, approximately 33 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). About two percent of the initial kinetic energy is converted into hourglass energy. Approximately 23 percent of the initial kinetic energy is converted into sliding interface energy. Forty-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.

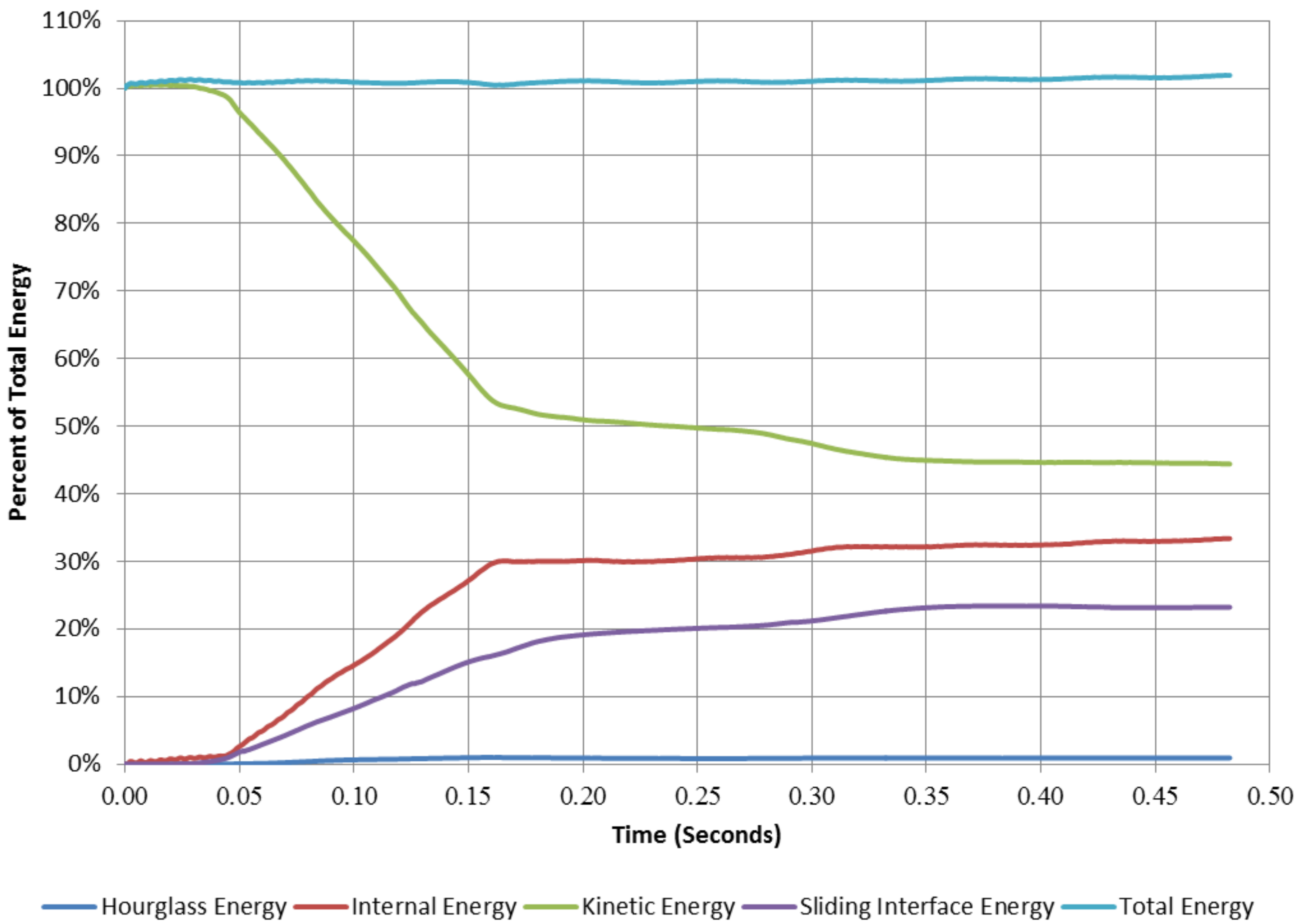


Figure 3.20. Energy Distribution Time History (W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail—1100C).

Tables 3.14 through 3.16 show frames from the computer simulation impact event against the W-beam guardrail with rubrail on a 3H:1V slope and 8-ft long posts that are 2 ft away from the break point.

3.4.4 Occupant Risk Assessment

The TRAP program was used to evaluate occupant risk factors based on the applicable *MASH* safety evaluation criteria. The modeled 1100C vehicle remained upright during and after the modeled collision event. Table 3.17 provides a summary of results for the W-beam guardrail with rubrail on the 3H:1V slope with 8 ft long posts located 2 ft away from the break point. Maximum roll, pitch and yaw angles were -9.9, -3.8, and 43.1 degrees respectively. Occupant impact velocities were 21.65 ft/sec and -22.64 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were -14.0 g and 11.0 g in the longitudinal and lateral directions, respectively. Angular displacement curves are reported in Figure 3.21.

Table 3.14. Sequential Images of the 1100C Vehicle Interaction with the W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail (Top View).

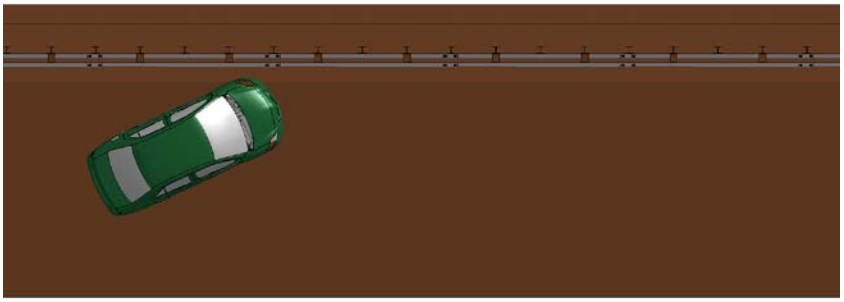
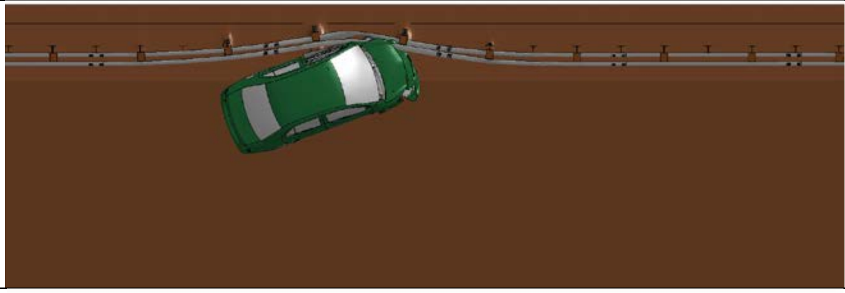
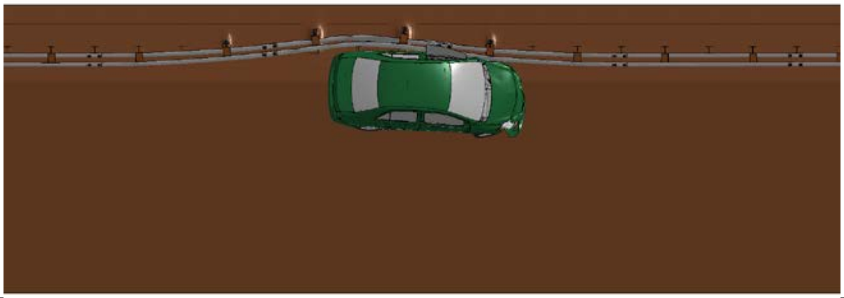
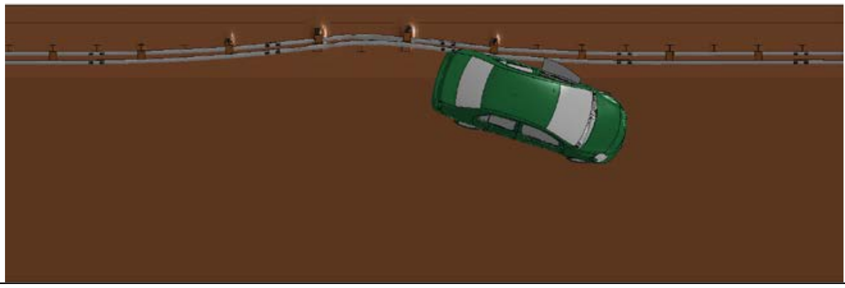
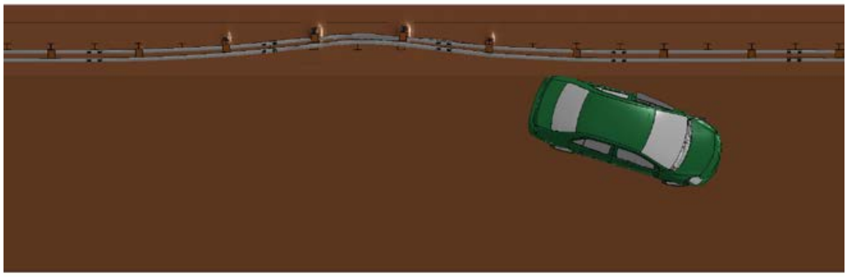
Time (sec)	FE W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail
0.000	
0.120	
0.240	
0.360	
0.484	

Table 3.15. Sequential Images of the 1100C Vehicle Interaction with the W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail (Front View).

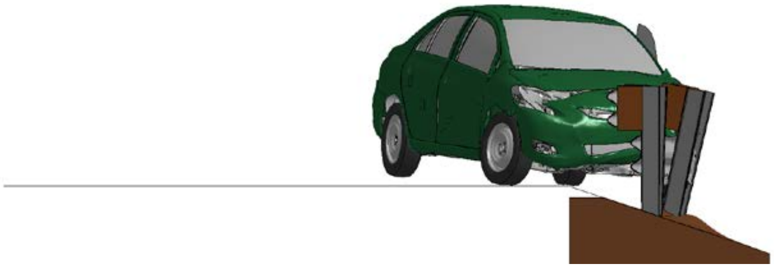
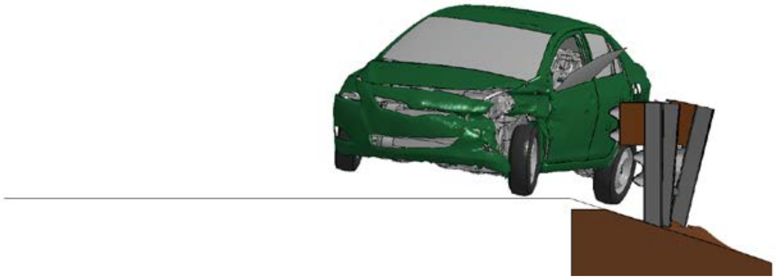
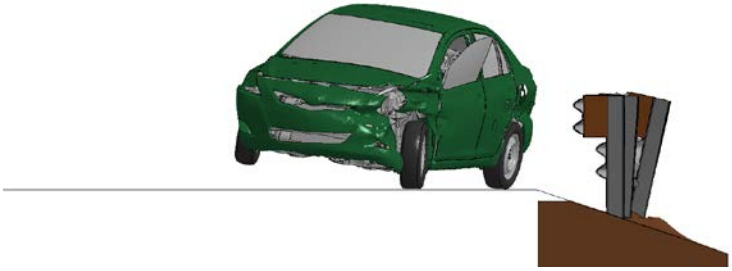
Time (sec)	FE W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail
0.000	
0.120	
0.240	
0.360	
0.484	

Table 3.16. Sequential Images of the 1100C Vehicle Interaction with the W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail (Front View).

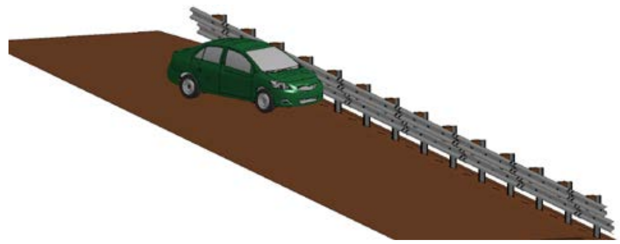
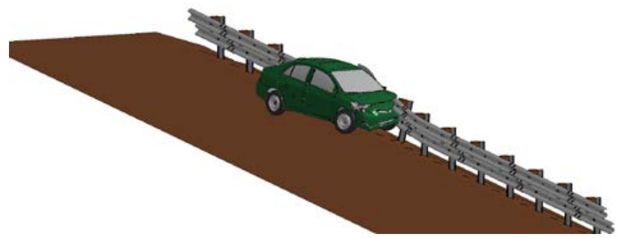
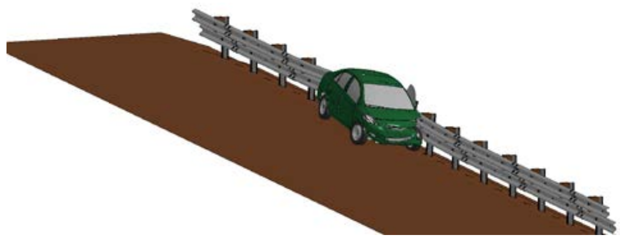
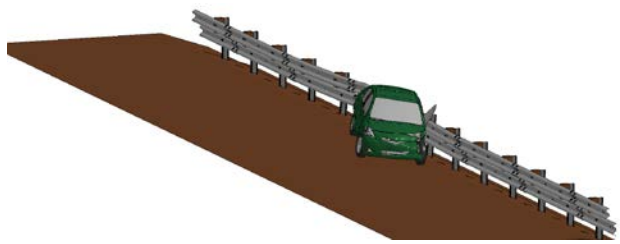
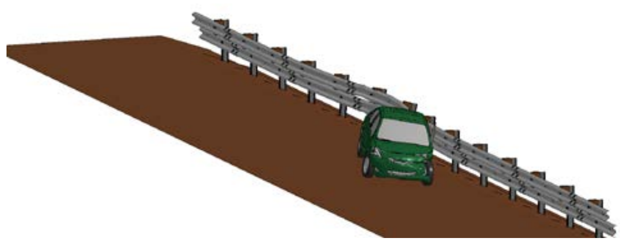
Time (sec)	FE W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail
0.000	
0.120	
0.240	
0.360	
0.484	

Table 3.17. Occupant Risks Values (1100C 3H:1V Slope (2 ft), with Rubrail).

Occupant Risk Factors	**1100C 3H:1V slope (2 ft), with Rubrail**
Impact Vel. (ft/sec)	
x-direction	21.65
y-direction	-22.64
Ridedown Acc. (g's)	
x-direction	-14.0
y-direction	11.0
Angles	**1100C 3H:1V slope (2 ft), with Rubrail**
Roll (deg.)	-9.9
Pitch (deg.)	-3.8
Yaw (deg.)	43.1

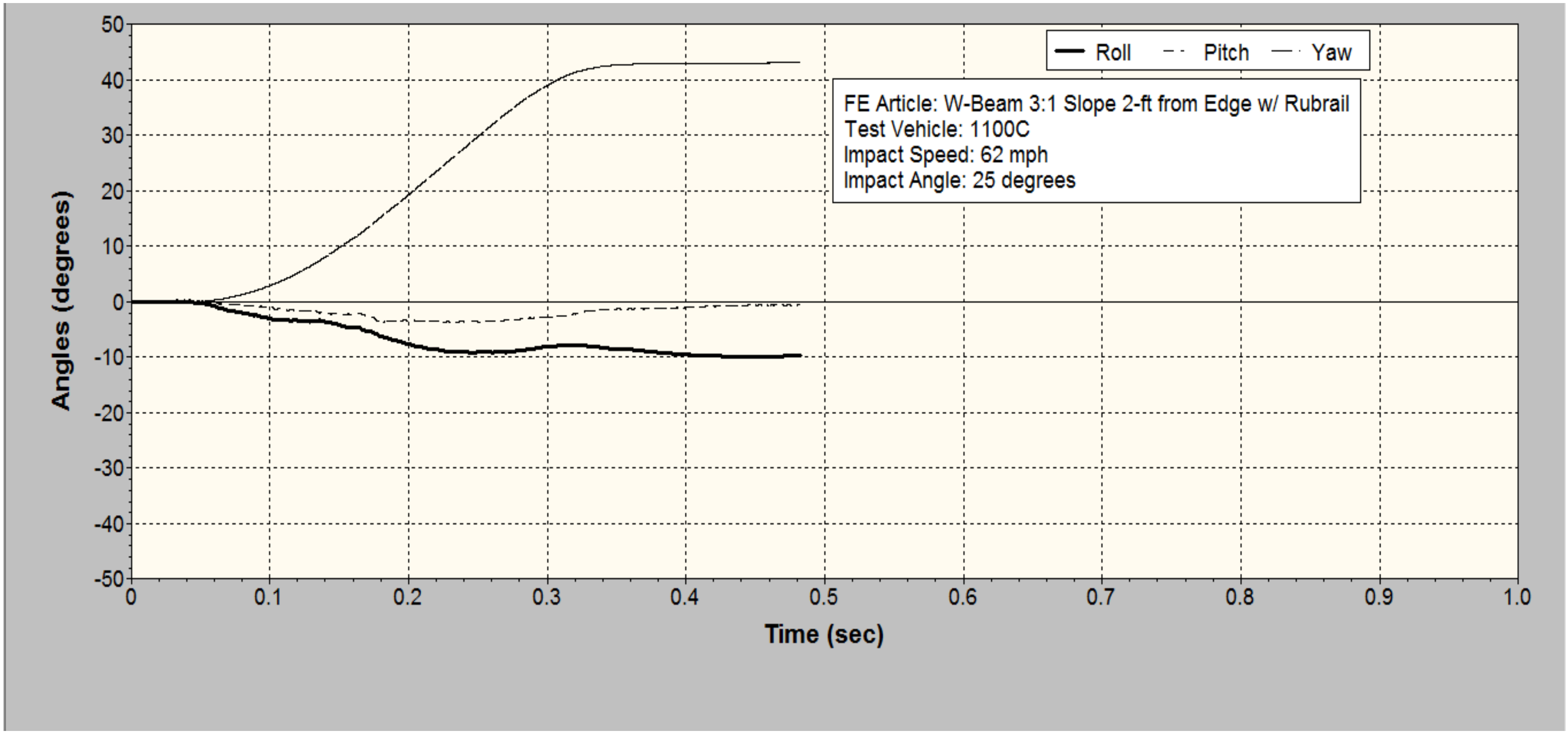


Figure 3.21. Angular Displacements for FE Simulation of W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail—1100C.

3.4.5 Plastic Strains

Figure 3.22 shows the plastic strains on the traffic side of the W-beam rail and rubrail, in the region of contact with the vehicle during the impact event. No regions of high plastic strains are present. After reviewing the simulation, it was concluded that rail failure is unlikely.

3.4.6 Conclusions

A predictive impact simulation was performed with a 1100C vehicle at 62 mph and 25 degrees orientation against a W-beam guardrail system with rubrail on a 3H:1V slope with 8-ft long posts located 2 ft away from the slope break 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 snagging or pocketing occurred. Neither the W-beam rail nor the rubrail showed regions of high plastic strain that might suggest failure of the steel. Results are summarized in Figure 3.23. In conclusion, results suggest that a 31-inch guardrail system with rubrail on a 3H:1V slope with 8-ft long posts located 2 ft from the slope break appears to be crashworthy and likely to pass safety evaluation criteria required for *MASH* test 3-10.

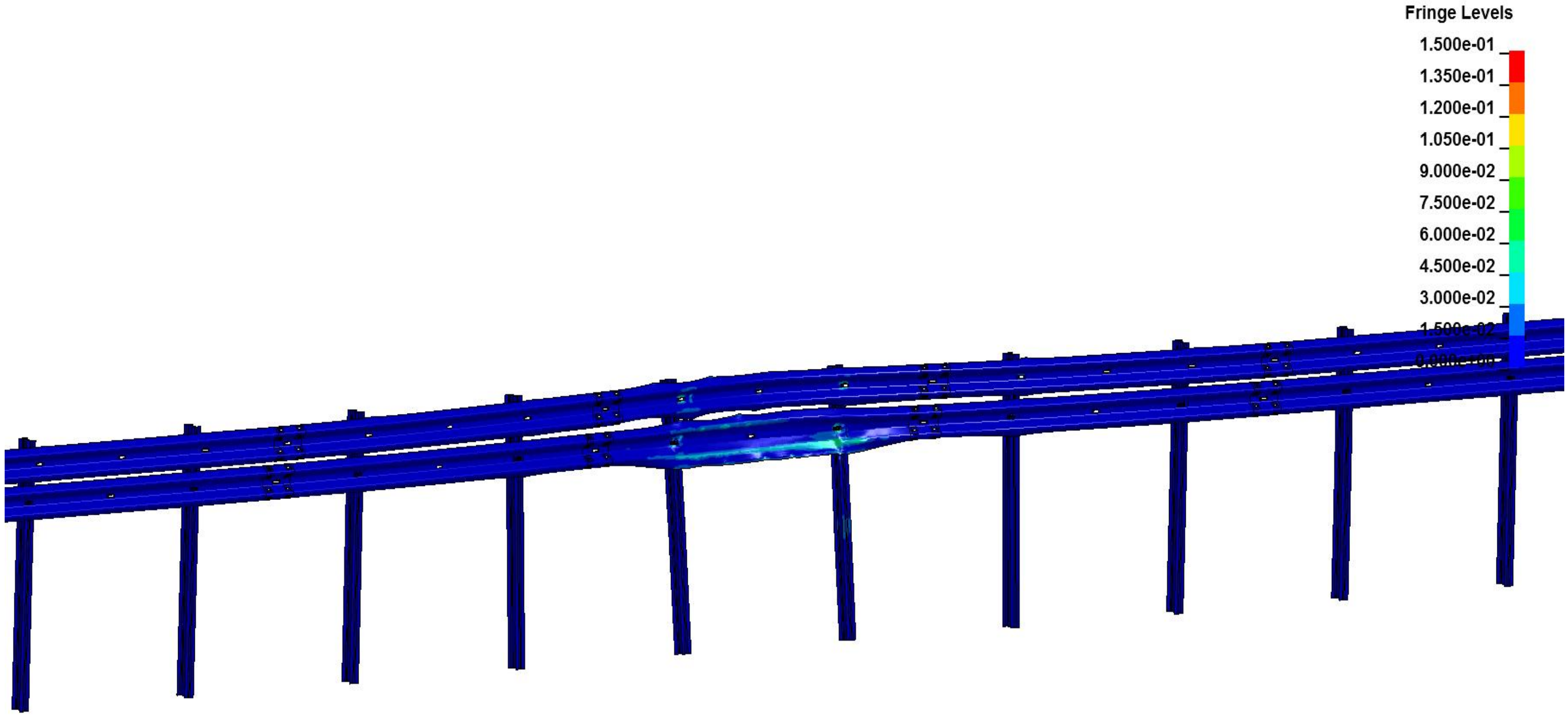
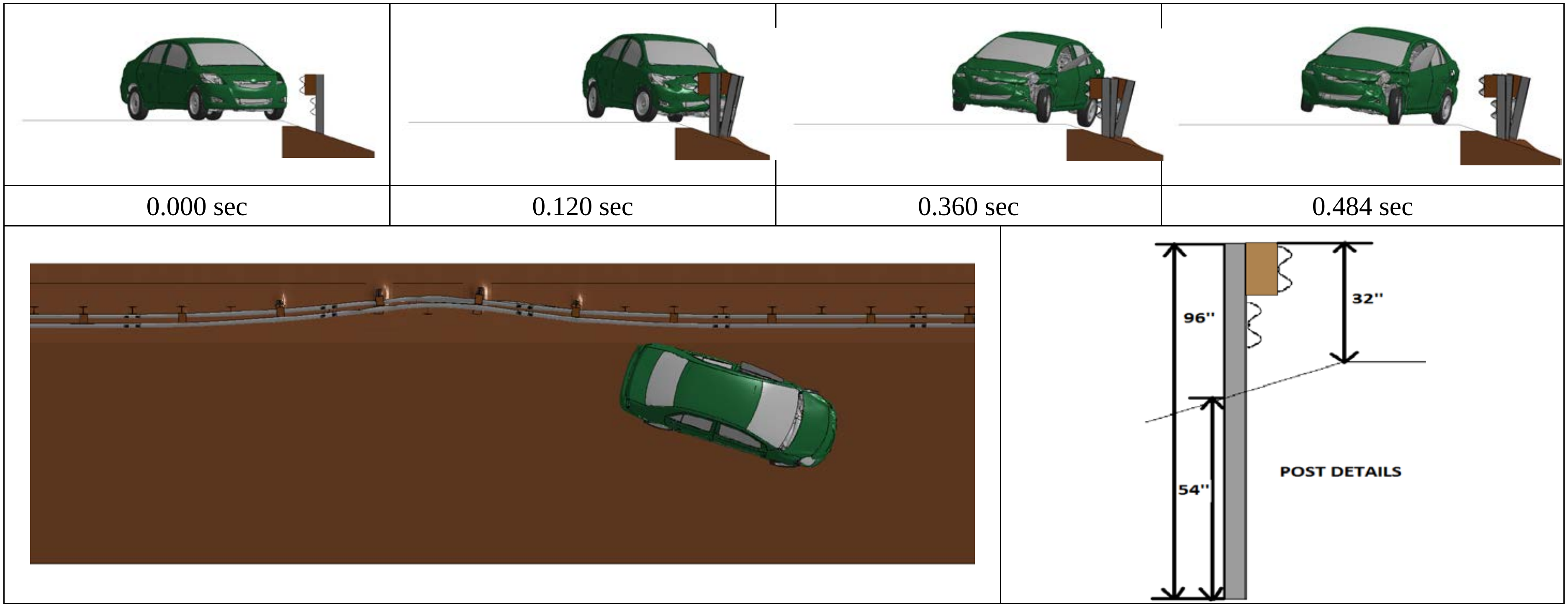


Figure 3.22. Guardrail Plastic Strain at the Front Face of the W-Beam Rail (W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail).



General Information
- Test Agency .... Texas A&M Transportation Institute (TTI)
- Test Standard Test No. .... *MASH* Test 3-10
- Date .... N/A

Test Article
- Type...................................... 31-inch W-Beam with rubrail on 3H:1V slope, 2 ft from break point
- Installation Length .... 90 ft
- Material or Key Elements ..... W-Beam, Steel Posts, Wood Blockouts, 3H:1V Slope, Rubrail

Test Vehicle
- Type/Designation 1100C
- Weight .... 2500 lbs
- Dummy.................................. No Dummy

Impact Conditions
- Speed....................................... 62.0 mph
- Angle....................................... 25 degrees
- Location/Orientation................ 0.9 ft upstream of post

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

Occupant Risk Values

Impact Velocity (ft/sec)
- x-direction………………… 21.65
- y-direction………………… -22.64

Ridedown Acceleration (g)
- x-direction............................... -14.0
- y-direction............................... 11.0

Vehicle Stability
- Maximum Yaw Angle .... 43.1 degree
- Maximum Pitch Angle.................... -3.8 degree
- Maximum Roll Angle .... -9.9 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 3.23. Summary of Results for *MASH* Test 3-10 Simulation (W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail—1100C).

4. SUMMARY AND CONCLUSIONS

4.1 SUMMARY

In locations where a traversable slope is located at the edge of the shoulder, there may be a desire to offset the barrier to minimize impacts. A longitudinal system that can be placed on 3H:1V slopes would provide this flexibility.

The purpose of this research was to develop a 31-inch W-beam guardrail system to be placed with a 3H:1V slope in front of the barrier. The structural capacity and the occupant risk factors of such proposed guardrail system were evaluated with respect to *MASH* TL-3 criteria. The information compiled from this research will provide the FHWA and State Departments of Transportation with a W-beam guardrail design as a crashworthy system to be placed with a 3H:1V slope in front of a barrier. Being able to place W-beam guardrail with a 3H:1V slope in front of the barrier would reduce the number of impacts on the system and would provide flexibility in the placement of W-beam systems.

Impact simulation of *MASH* test 3-11 according to the initial impact conditions of test 405160-20-1 well replicated the results obtained through full-scale crash testing (*8*). Failure properties were applied to the connection between the wheel and the vehicle to allow joint connection failure to occur once a predefined force value was reached. The FE models of the test article and the vehicle with their material and failure properties were used as a base model to develop new guardrail designs for evaluation when placed on a 3H:1V sloped terrain configuration.

Three barrier designs for placement on a 3H:1V slope were suggested for evaluation through predictive computer simulations:

- Design 1: 31-inch W-beam rail, 7-ft steel post, wood blockouts on a 3H:1V Slope with posts placed 1 ft from the slope break (face of the guardrail aligned with the slope break); No rubrail (*MASH* test 3-11);
- Design 2: 31-inch W-beam rail, 8-ft steel post, wood blockouts on a 3H:1V Slope with posts placed 2 ft from the slope break; No rubrail (*MASH* test 3-11);
- Design 3: 31-inch W-beam rail, 8-ft steel post, wood blockouts; 3H:1V Slope with posts placed 2 ft from the slope break; with rubrail (*MASH* tests 3-10 and 3-11).

4.2 DESIGN #1. W-BEAM GUARDRAIL ON 3H:1V SLOPE (1-FT) WITH NO RUBRAIL

An FE model of a 31-inch W-beam guardrail system with steel posts and wood blockouts was developed. The system was modified to be located on a 3H:1V slope and to include 7-ft long posts located 1 ft away from the slope break. The posts had a soil embedment depth of 46 inches. An 8-inch spacer blockout was used to block the rail away from the front face of each post. The W-beam top rail height was 31-inch with a 24⅞-inch center mounting height.

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 mph and 25 degrees orientation against a W-beam guardrail system on a 3H:1V slope with 7-ft long posts located 1 ft away from the slope break, 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 using a 31-inch guardrail system on a 3H:1V slope with 7-ft long posts placed 1 ft from the slope break appears to be crashworthy and likely to pass safety evaluation criteria required by *MASH* test 3-11. Table 4.1 provides a summary of the results of the test.

The guardrail on 2H:1V slope performed acceptably for *MASH* test 3-10. The proposed 31-inch W-beam guardrail design for use on a 3H:1V slope is very similar to the system evaluated under Test 405160-20-2. The differences include the slope on which the guardrail in installed and a reduction in post length from 8 ft to 7 ft. Considering the results of test 405160-20-2 and the reduced slope severity, it is the researcher's opinion that the impact performance of the 31-inch guardrail on 3H:1V slope with 7-ft long posts located 1 ft from the slope break will be acceptable for *MASH* test 3-10. The researchers do not anticipate snagging or pocketing issues with the 1100C vehicle impacting the above proposed design on a 3H:1V slope.

4.3 DESIGN #2. W-BEAM GUARDRAIL ON 3H:1V SLOPE (2-FT) WITH NO RUBRAIL

An FE model of a 31-inch W-beam guardrail system with no rubrail, steel posts and wood blockouts was developed. The system was modified to be located on a 3H:1V slope and to include 8-ft long posts located 2 ft away from the slope break. The posts had a soil embedment depth of 54 inches. An 8-inch spacer blockout was used to block the rail away from the front face of each post. The W-beam top rail height was 31 inches with a 24⅞-inch center mounting height. Evaluation of the crashworthiness of this system followed *MASH* test 3-11 impact conditions and evaluations criteria.

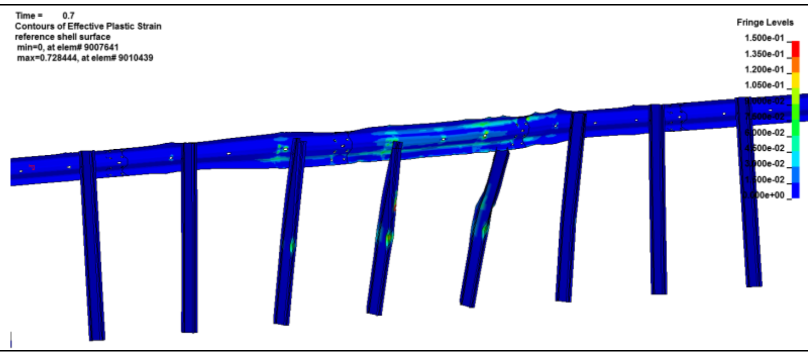
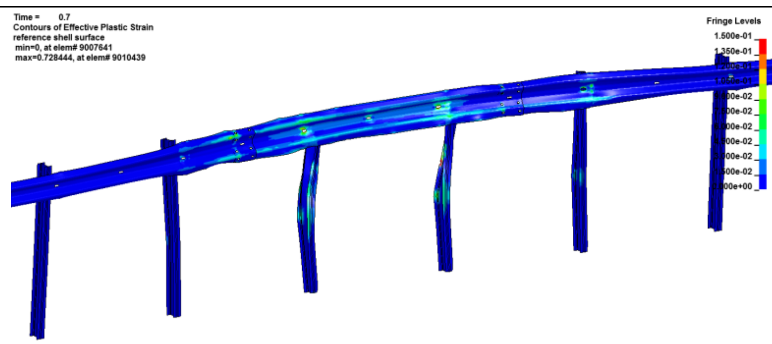
A predictive computer simulation was performed to evaluate a 2270P vehicle impacting at 62 mph and 25 degrees orientation against a W-beam guardrail system on a 3H:1V slope with 8-ft long posts located 2 ft away from the slope break, according to the criteria set in *MASH*. The vehicle was contained 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 using a 31-inch guardrail system on a 3H:1V slope with 8-ft long posts placed 2 ft from the slope break appears to be crashworthy and likely to pass safety evaluation criteria required by *MASH* test 3-11. Table 4.2 provides a summary of the results of the test.

Table 4.1. Summary of Results of 31-inch W-Beam Guardrail on 3H:1V Slope (1-ft) with No Rubrail.

MASH Occupant Risk Values

W-beam Guardrail on 3H:1V Slope (1-ft), No Rubrail, 2270P		*MASH* Values	
Impact Velocity (ft/sec)		**Preferred**	**Max**
x-direction	**5.42**	30	40
y-direction	**6.73**	30	40
Ridedown Accelerations (g's)			
x-direction	**-6.5**	15	20.49
y-direction	**7.7**	15	20.49

Plastic Strains

Back View	
Front View	

Angle Displacements

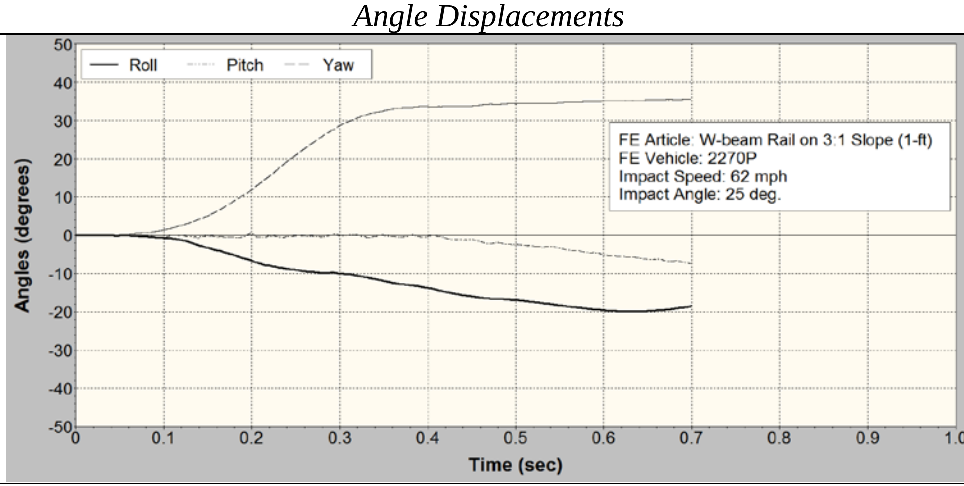
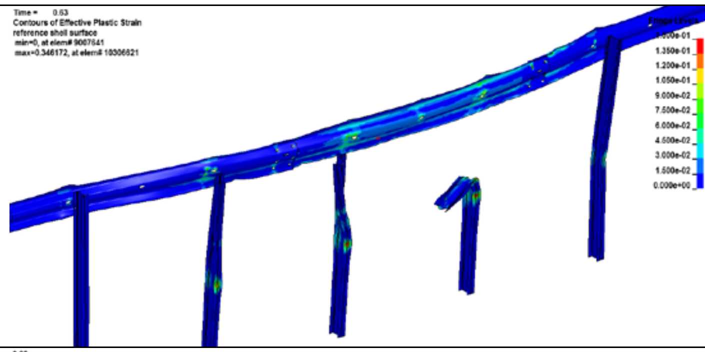
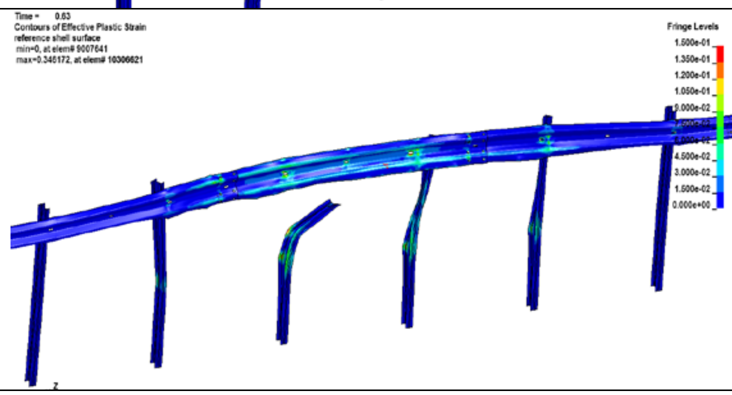
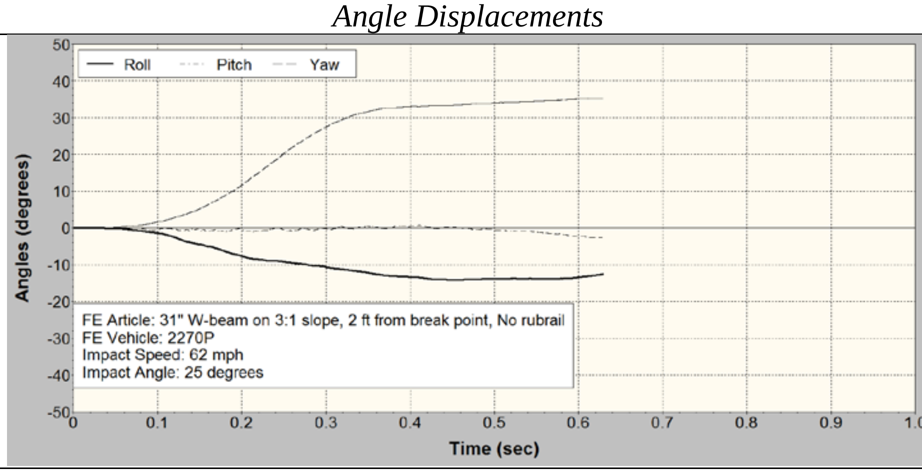


Table 4.2. Summary of Results of 31-inch W-Beam Guardrail on 3H:1V Slope (2-ft) with No Rubrail.

MASH Occupant Risk Values				
	**W-beam Guardrail on 3H:1V Slope (2-ft, No Rubrail) – 2270P**		***MASH* Values**	
	Impact Velocity (ft/sec)		**Preferred**	**Max**
	x-direction	**7.72**	30	40
	y-direction	**6.73**	30	40
	Ridedown Accelerations (g's)			
	x-direction	**-7.4**	15	20.49
	y-direction	**8.2**	15	20.49

Plastic Strains	
Back View	
Front View	

Angle Displacements


The researchers used previous testing experience and engineering analysis to determine the crashworthiness of the proposed system under *MASH* test 3-10 conditions. The proposed 31-inch W-beam guardrail design for use on a 3H:1V slope is very similar to the system evaluated under Test 405160-20-2. The differences include the slope on which the guardrail is installed and relocation of the 8-ft long posts at two feet (instead of only 1 ft) from the slope break. The researchers developed trajectory analysis of a small passenger car impacting the proposed system at the conditions required by *MASH* test 3-10. After review of the trajectory results, it is the researchers' opinion that the vehicle will interact with the W-beam guardrail prior to have any influence or interaction with the slope. The stiffness of a 31-inch guardrail system installed at 1 ft from the slope break of a 3H:1V slope is not significantly different from a 31-inch guardrail located at 2 feet from the slope break of a 2H:1V slope, with same post length. The local embedment depth of the posts differs for only 2 inches and the terrain drop off behind the posts is less severe for the 3H:1V slope than for the 2H:1V slope. Considering the results of test 405160-20-2 and the reduced slope severity, it is the researcher's opinion that the impact performance of the 31-inch guardrail on 3H:1V slope with 8-ft long posts located 2 ft from the slope break will be acceptable for *MASH* test 3-10. The researchers do not anticipate snagging or pocketing issues with the 1100C vehicle impacting the above proposed design on a 3H:1V slope.

4.4 DESIGN #3. W-BEAM GUARDRAIL ON 3H:1V SLOPE (2-FT) WITH RUBRAIL - 2270P

An FE model of a 31-inch W-beam guardrail system with steel posts and wood blockouts was developed. The system was modified to be located on a 3H:1V slope, include 8-ft long posts located 2 ft away from the slope break, and include rubrail. The posts had a soil embedment depth of 54 inches. An 8-inch spacer blockout was used to block the rail away from the front face of each post. The W-beam top rail height was 31 inches with a 24⅞-inch center mounting height. 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 mph and 25 degrees orientation against a W-beam guardrail system with rubrail on a 3H:1V slope with 8-ft long posts located 2 ft away from the slope break, 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 using a 31-inch guardrail system on a 3H:1V slope with 8-ft long posts placed 2 ft from the slope break and with inclusion of a rubrail appears to be crashworthy and likely to pass safety evaluation criteria required by *MASH* test 3-11. Table 4.3 provides a summary of the results of the test.

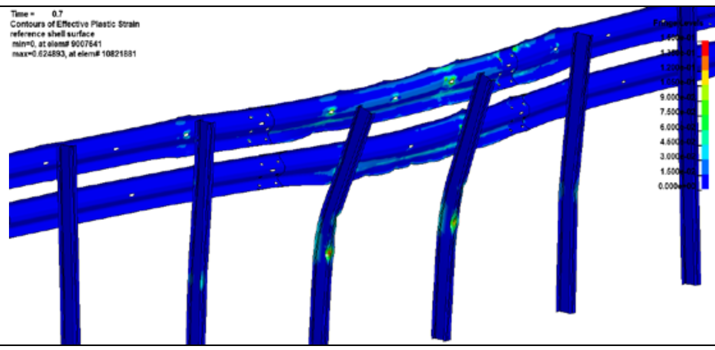
Table 4.3. Summary of Results of 31-inch W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail--2270P.

MASH Occupant Risk Values

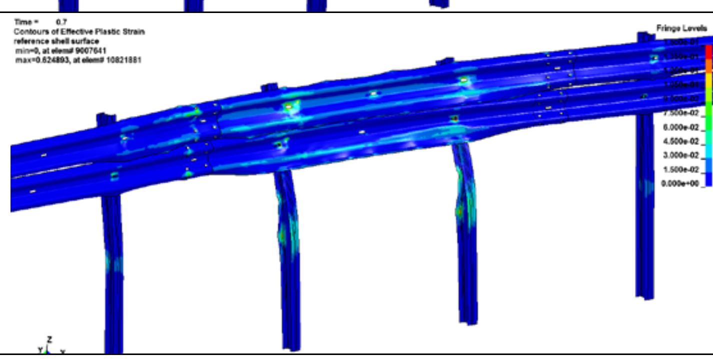
W-beam Guardrail on 3H:1V Slope (2-ft, Rubrail) – 2270P		*MASH* Values	
Impact Velocity (ft/sec)		**Preferred**	**Max**
x-direction	**16.40**	30	40
y-direction	**16.73**	30	40
Ridedown Accelerations (g's)			
x-direction	**-11.3**	15	20.49
y-direction	**8.7**	15	20.49

Plastic Strains

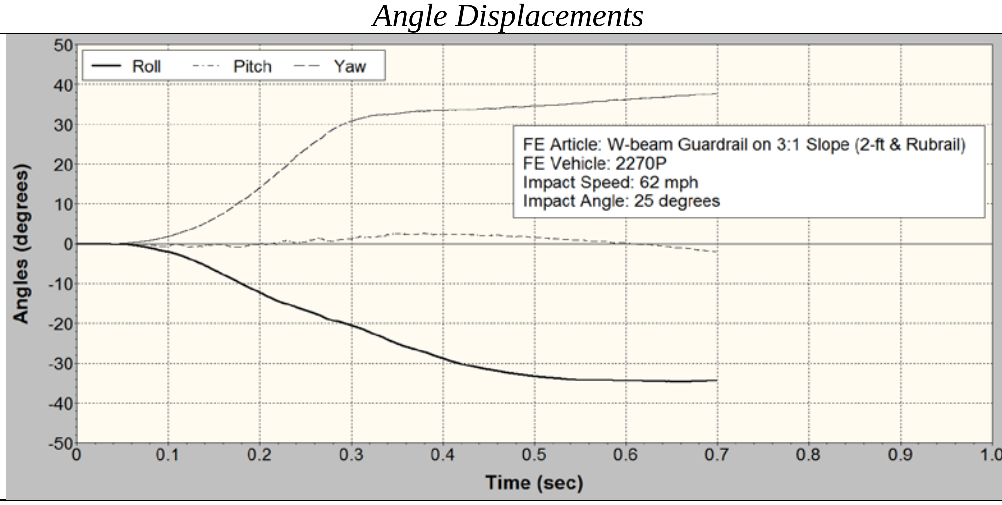
Back View



Front View



Angle Displacements



4.5 DESIGN #3. W-BEAM GUARDRAIL ON 3H:1V SLOPE (2-FT) WITH RUBRAIL - 1100C

An FE model of a 31-inch W-beam guardrail system with steel posts and wood blockouts was developed. The system was modified to be located on a 3H:1V slope, include 8-ft long posts located 2 ft away from the slope break, and include rubrail. The posts had a soil embedment depth of 54 inches. A 8-inch wood blockout was used to block the rail away from the front face of each post. The W-beam top rail height was 31 inches with a 24⅞-inch center mounting height. Evaluation of the crashworthiness of this system followed *MASH* test 3-10 impact conditions and evaluations criteria.

A predictive computer simulation was performed to evaluate a 2270P vehicle impacting at 62 mph and 25 degrees orientation against a W-beam guardrail system with rubrail on a 3H:1V slope with 8-ft long posts located 2 ft away from the slope break, 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 using a 31-inch guardrail system on a 3H:1V slope with 8-ft long posts placed 2 ft from the slope break and with inclusion of a rubrail appears to be crashworthy and likely to pass safety evaluation criteria required by *MASH* test 3-10. Table 4.4 provides a summary of the results of the test.

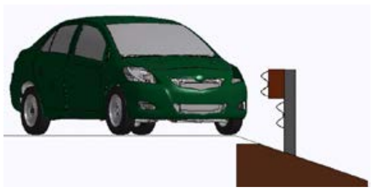
4.6 CONCLUSIONS

Three barrier designs proposed for placement on a 3H:1V slope were evaluated through predictive computer simulations. The designs were evaluated according to *MASH* TL-3 impact conditions. All three designs appear to meet applicable *MASH* evaluation criteria for *MASH* test 3-11 with the pickup truck. However, the roll angle was significantly higher for the 31-inch guardrail with rubrail than for the other two designs.

Simulations were not conducted with use of passenger car for barrier designs #1 and #2. Instead, engineering analysis and previous testing experience was employed to determine crashworthiness of barrier designs #1 and #2 when impacted by a small passenger car. FE analysis was conducted to evaluate crashworthiness of barrier design #3 under *MASH* test 3-10 conditions (passenger car). Computer simulations results suggest that barrier design #3 (inclusion of rubrail) appear to meet *MASH* requirements for both passenger car and pickup truck. Based on FE simulation results and previous testing results, the researchers have high confidence in the crashworthy behavior of barrier design #1 (1 ft offset) when impacted under *MASH* TL-3 impact conditions. Based on FE simulation results and engineering analysis, barrier design #2 (2 ft offset) seem to show more critical crashworthy behavior when impacted under *MASH* TL-3 impact conditions. Barrier design #2, still, demonstrates a reasonable chance to meet *MASH* criteria. The local embedment depth of the posts differs for only 2 inches and the terrain drop off behind the posts is less severe for the 3H:1V slope than for the 2H:1V slope.

Table 4.4. Summary of Results of 31-inch W-Beam Guardrail on 3H:1V Slope (2-ft) with Rubrail—1100C.

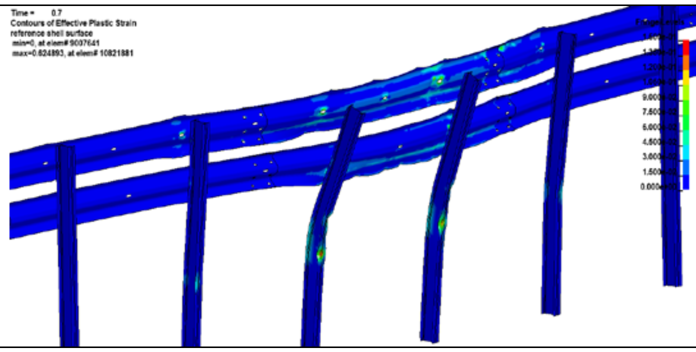
MASH Occupant Risk Values



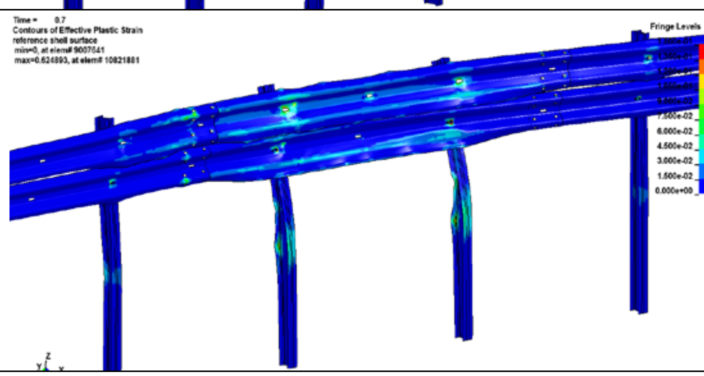
W-beam Guardrail on 3H:1V Slope (2-ft, Rubrail) – 1100C		*MASH* Values	
Impact Velocity (ft/sec)		**Preferred**	**Max**
x-direction	**21.65**	30	40
y-direction	**22.64**	30	40
Ridedown Accelerations (g's)			
x-direction	**-14**	15	20.49
y-direction	**11**	15	20.49

Plastic Strains

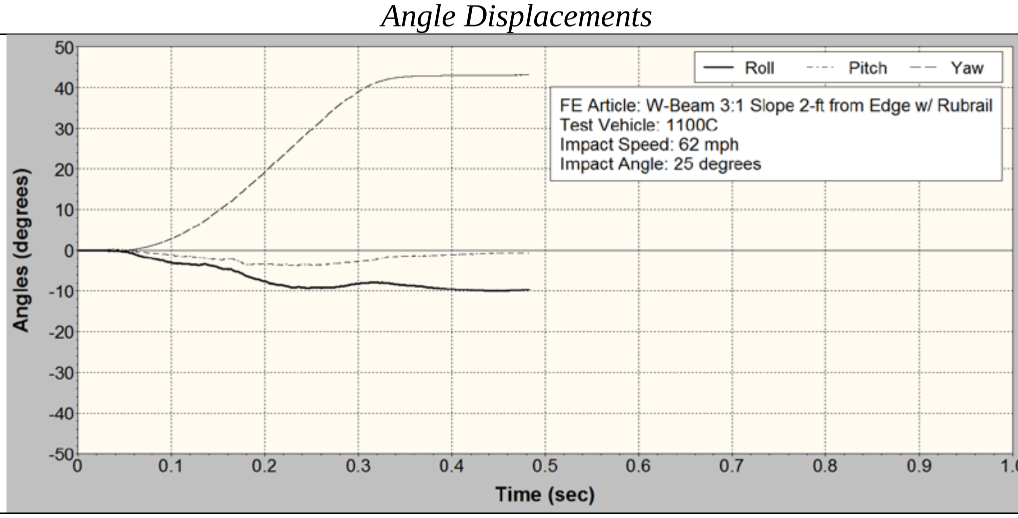
Back View



Front View



Angle Displacements



All systems appear to be crashworthy and likely to pass safety evaluation criteria required for *MASH*. Depending on the desired system post distance location from the 3H:1V slope break, the researchers recommend evaluation of selected design through full-scale crash testing according to *MASH* TL-3 criteria.

5. REFERENCES

1. Arnold, G.A., Buth, C.E., and Menges, W.L. (1999). *Testing and Evaluation of W-Beam Guardrails Buried-in-Backslope*. FHWA-RD-99-055.

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7. Abu-Odeh, A.Y., et al. *Crash Testing and Evaluation of the Modified G4(1S) W-Beam Guardrail on 2H:1V Slope.* Report No. 405160-4-1, Roadside Safety Pooled Fund Study, Washington State Department of Transportation, Texas Transportation Institute, 2008.

8. Abu-Odeh, A.Y., et al. *MASH TL-3 Testing and Evaluation of the W-Beam Guardrail on Slope.* Report No. 405160-20, Roadside Safety Pooled Fund Study, Washington State Department of Transportation, Texas Transportation Institute, 2013.

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

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A literature review of past guardrail testing on a slope was conducted. Brief descriptions of the most relevant tests are presented in the following tables.

Table A1. Summary of test characteristics and impaction conditions of past testing performed on a slope.

Test No.	Test No.	Test Characteristics					Impact Conditions	
		Name & Description	Year	Type of Test	Test Level	Vehicle Type	Speed (km/h)	Angle
FHWA-RD-99-055 Testing and Evaluation of W-Beam Guardrails Buried in Backslope	405521-1	(1) W-Beam with a rubrail buried in backslope with a ditch	1996	*NCHRP Report 350*	TL 3-35	2000P	98.12	21.25
	405521-2	(2) W-Beam with a rubrail buried in backslope with a drop inlet					97	21.97
TRP-03-185-10 Development of the MGS Placed Adjacent to a 2H:1V Slope	MGS221-1	(1) 27" Midwest Guardrail System	2006	*MASH*	TL 3-11	2270P	101.5	27.1
	MGS221-2	(2) 31" Midwest Guardrail System					101.5	25.5
Approach Slope for MGS	MGSAS-1	(1) Guardrail on Slope with Pickup	2006	*NCHRP Report 350*	TL 3-11	2000P	62.4mph	25.9
	MGSAS-2	(2) Guardrail on Slope with Car			TL 3-10	820C	61.9	21.6
405160-4-1 Crash Testing and Evaluation of the Modified W-Beam Guardrail on 2H:1V Slope	405160-4-1	Guardrail on Slope	2008	*NCHRP Report 350*	TL 3-11	2000P	62.3 mph	25.1
405160-20 Testing and Evaluation of the W-Bean Guardrail on Slope	405160-20-1	(1) Guardrail on Slope with Pickup	2012	*MASH*	TL 3-11	2270P	63.9 mph	25
	405160-20-2	(2) Guardrail on Slope with Car			TL 3-10	1100C	60.3	25.9

Table A2. Summary of system characteristics of past testing performed on a slope.

Test No.	Test No.	System Characteristics										
		Slope	Installation Length (ft)	Whole system in Slope?	Height of System (in)	Rubrail?	Type of Post	Post Length (ft)	Post Spacing (in)	Blockouts	Height of System (in)	Position of Rail (from Slope)
FHWA-RD-99-055 Testing and Evaluation of W-Beam Guardrails Buried in Backslope	405521-1	1 to 2	114.3	No	27	Yes	Steel	9	75	150x200 Timber	27.8 from shoulder grade	
	405521-2	1 to 2	114.3	No	27	Yes	Steel	9	75	150x200 Timber		
TRP-03-185-10 Development of the MGS Placed Adjacent to a 2H:1V Slope	MGS221-1	1 to 2	175		27 3/4	No	W6x9	Steel Posts 3-8, 21-27 (6 ft), 9-20 (9 ft) Wood Posts 1-2,28-29 (3.5 ft)	75	152x300 Wood	27.8	
	MGS221-2	1 to 2	175		31	No			75	152x300 Wood	31	
Approach Slope for MGS	MGSAS-1	8H:1V	175	Yes	31	No	W6x9	Steel Posts 3-27 (6 ft), Wood Posts 1-2, 29-29 (3.5 ft)	75	6x12x14.25	31	
	MGSAS-2	8H:1V	175	Yes	31	No	W6x10		75	6x12x14.26	31	
405160-4-1 Crash Testing and Evaluation of the Modified W-Beam Guardrail on 2H:1V Slope	405160-4-1	2H:1:V	175	No	28	No	Steel W6x8½	Steel Posts 7, 8, 9, 31,32,33 (6 ft) Posts 10-30 (8 ft)	Posts 1-10, 30-39 @ 75, Posts 11-30 @ 62.5	152x200	28 from shoulder grade	12"
405160-20 Testing and Evaluation of the W-Bean Guardrail on Slope	405160-20-1	2H:1V	181	Yes	31	No	W5x8½	8	Posts 1-10, 30-39 @ 75, Posts 11-30 @ 62.5		31" from Shoulder grade	12"
	405160-20-2	2H:1V	182	Yes	31	No	W5x8½	8			31" from Shoulder grade	12"

Table A3. Summary of the results of past testing performed on a slope.

Test No.	Occupant Impact Velocity (ft/s)			Occupant Ridedown Deceleration (g's)			Test Article Deflections (in)			Angular Displacements			Pass/Fail	Reason
	Long.	Lat.	Max	Longitudinal	Lateral	Max	Permanent	Dynamic	Working Width	Roll	Pitch	Yaw		
405521-1	24.3	19.2	39.4	5.59	8.92	20	9.25	29.65	N/A	-29.44	-5.94	-35.11	Pass	
405521-2	25.4	19.2	39.4	7.56	7.27	20	19.69	31.57	N/A	41.3	-4.68	36.74	Pass	
MGS221-1	-16.2	3.9	40	-11.66	5.38	20.49	42.76	44.33	N/A	-32.2	-23.7	-34.3	FAIL	Vehicle overrode system
MGS221-2	-13.9	4.15	40	-5.36	5.28	20.49	42	57.60	64.21	6	5	45	Pass	
405160-4-1	19	16.1	40	-10.2	8.4		22.8	32.52	48.12	-117	-22	137	FAIL	Vehicle rollover
405160-20-1	15.1	15.4	40	9	6	20.49	37.2	51.6	55.2	13	4	34	Pass	
405160-20-2	17.4	16.1	40	7.3	6.8		22.8	32.4	37.2	7	5	38	Pass	
MGSAS-1	-20.2	-11.3	39.4	-9.49	-6.43	20	34.25	57.6	82.8				Pass	
MGSAS-2	-12.3	-17.4	39.4	-4.03	-9.65	20	14.63	25	46.3				Pass	

Table A4. Pictures from past testing performed on a slope.

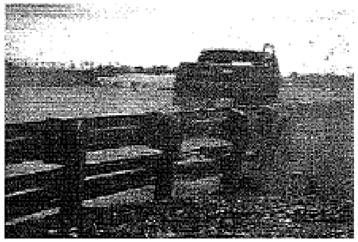
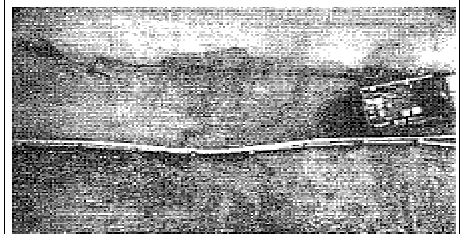
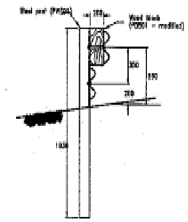
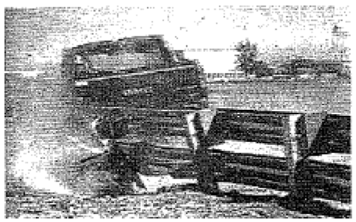
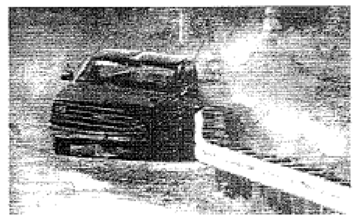
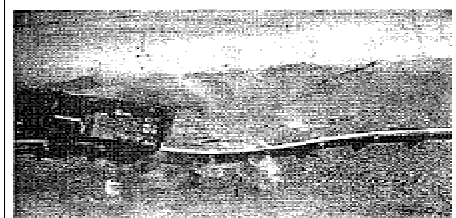
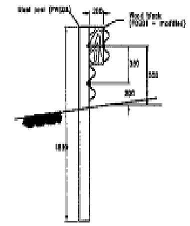
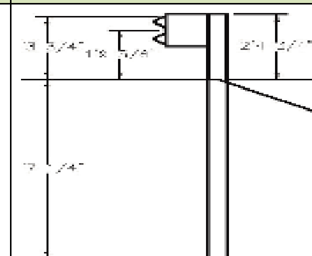
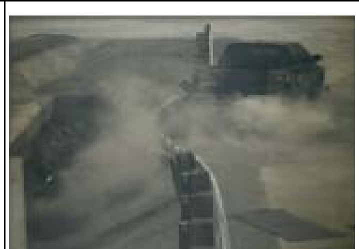
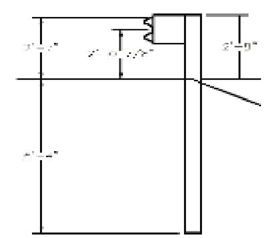
Test No.	Description	Rear View	Front View	Overhead View	Test Article
405521-1	With ditch				
405521-2	With droplet				
MGS221-1	27-in				
MGS221-2	31-in				

Table A4. Pictures from past testing performed on a slope (Continued).

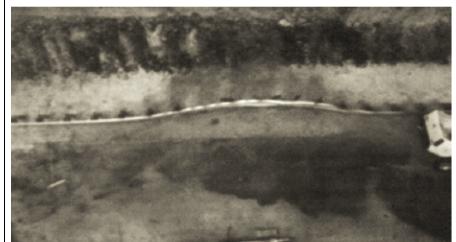
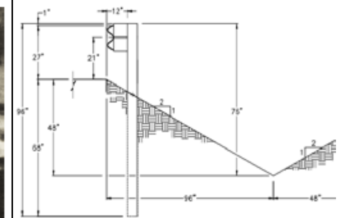
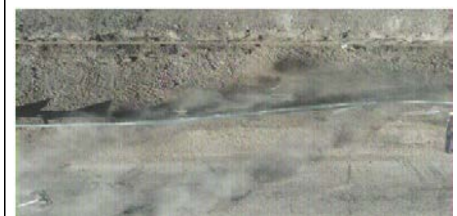
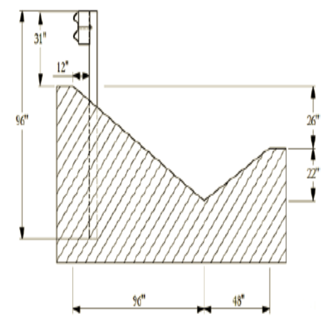
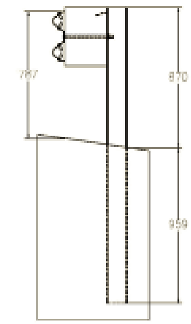
Test No.	Description	Rear View	Front View	Overhead View	Test Article
405160-4-1					
405160-20-1	2270P				
405160-20-2	1100C				

Table A4. Pictures from past testing performed on a slope (Continued).

Test No.	Description	Rear View	Front View	Overhead View	Test Article
MGSAS-1	200P				
MGSAS-2	810C