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Stacked W-Beam Transition for 31" Guardrail

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16. Abstract

A stacked W-Beam guardrail transition to a bridge rail has been successfully tested in accordance with the NCHRP Report 350 criteria with a guardrail height of 27 5/8" (FHWA Eligibility Letter B-65, 2000). This transition uses a nested w-beam to stiffen the rail and a w-beam rub rail to reduce the potential for snagging on the end of the bridge rail. Many states are raising the height of their w-beam guardrails to 31 inches to improve its performance. Several transitions have been tested for the 31 inch guardrails that use a thrie beam rail and a thrie beam to w-beam reducer section. A stacked w-beam transition is desired for the 31" guardrail systems as a simpler method of transition without unique rail elements.

Two possible 31-in stacked w-beam transition designs were investigated to evaluate the crashworthiness of the test article with respect to NCHRP Report 350 crashworthiness criteria. Finite element computer simulation investigation suggests that both designs might not meet the NCHRP Report 350 crashworthiness requirements due to severe snagging of the vehicle against the rigid parapet to which the transition is connected. Snagging occurrence is related to the relative height of the vehicle frame rail which does not allow the frame to fully engage with the top nested rail sections during the impact event. As a consequence, with both 31-in transition designs, the 2000P Report 350 pickup truck vehicle frame rail and tire snagged against the rigid parapet in between the top rail and the rubrail.

Due to the difference in frame rail height geometry, researchers suggest investigation of the 31-in stacked w-beam transition designs crashworthiness with the 2270P MASH pickup truck vehicle model. The 2270P frame rail top height is approximately three inches higher than the 2000P frame rail. That could suggest that the 2270P frame rail might be able to better engage the top nested w-beam section of the article, reducing the probability of vehicle snagging against the rigid parapet. Such investigations would have to be evaluated under a study using MASH criteria. This would have the potential to suggest a 31-in stacked w-beam transition prone to meet MASH crashworthiness 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)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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1. INTRODUCTION

1.1 PROBLEM

A stacked W-Beam guardrail transition to a bridge rail has been successfully tested in accordance with the NCHRP Report 350 criteria with a guardrail height of 27 5/8" (FHWA Eligibility Letter B-65, 2000). This transition uses a nested w-beam to stiffen the rail and a w-beam rub rail to reduce the potential for snagging on the end of the bridge rail. Many states are raising the height of their w-beam guardrails to 31 inches to improve its performance. Several transitions have been tested for the 31 inches guardrails that use a thrie beam rail and a thrie beam to w-beam reducer section. A stacked w-beam transition is desired for the 31" guardrail systems as a simpler method of transition without unique rail elements.

1.2 BACKGROUND

A stacked W-Beam guardrail transition to a bridge rail has been successfully tested in accordance with the NCHRP Report 350 criteria with a guardrail height of 27 5/8" (FHWA Eligibility Letter B-65, 2000). A standard W-beam guardrail with steel posts and wood blockouts is transitioned over a length of 3.8 m to a concrete parapet wall (Buth et al., 2000). The reinforced concrete parapet wall was 810 mm high from the roadway surface and was tapered from a vertical face at the rail transition to a NJ-shape bridge rail over 3.2 m. The center of the guardrail was mounted 550 mm above the ground. The center of the rubrail was mounted 190 mm above the ground. The end shoe was modified from its original design to be lapped under the W-beams to reduce the potential for snagging on the end of the bridge rail. The BARRIER VII program indicated the critical impact point (CIP) to be 1.5 m from the end of the vertical wall concrete parapet.

This test was a repeat of NCHRP Report 350 test 3-21 (Ross et al., 1993). The W-beam with the W-beam rub rail on steel posts transition to the vertical concrete bridge railing contained and redirected the vehicle. The vehicle did not penetrate, override, or underride the installation. No detached elements, fragments, or other debris were present to penetrate or to show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. Maximum occupant compartment deformation was 80 mm in the lateral direction near the occupant's feet. The vehicle remained upright during and after the collision event. This test passed all the safety and structural criteria requested by NCHRP Report 350 for testing of a roadside safety device.

With the raising of the w-beam guardrails height to 31", a stacked w-beam transition is desired for the 31" guardrail systems as a simpler method of transition without unique rail elements.

1.3 OBJECTIVES AND SCOPE OF RESEARCH

The objectives of this study are to identify design modifications necessary to adapt a stacked w-beam guardrail transition design for 27" (27 5/8") guardrail for use with a 31" guardrail system and to use computer simulations to determine the transition crashworthiness according to NCHRP Report 350 criteria. This project is expected to culminate with a request for an FHWA eligibility letter for this design.

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 (Hallquist, 2009). LS-DYNA is widely used to solve nonlinear, dynamic response of three-dimensional problems and is capable of capturing complex interactions and dynamic load-time history responses that occur when a vehicle impacts a barrier system.

2.2 FINITE ELEMENT MODEL DESCRIPTION

A finite element model of a vertical wall transition that was previously successfully designed and tested according to NHCRP Report 350 Test 3-21 was developed. Test 404211-12 was performed at Texas Transportation Institute (TTI) in 1998, under a Federal Highway Administration (FHWA) project with the objective to crash test and evaluate several terminals, transitions, and longitudinal barriers to NCHRP Report 350 (Buth et al., 2000). NCHRP Report 350 specifies crash tests and evaluation criteria for three performance levels for terminals and six performance levels for transitions and longitudinal barriers. Details of the vertical wall transition installation for test 404211-12 are included in Figure 2.1. This test was performed on the W-beam with W-beam rub rail and steel posts transition to the vertical concrete bridge rail.

Figure 2.2 shows details of the finite element (FE) model that was built to perform computer simulations. The reinforced concrete parapet wall was modeled as rigid with the wall being 32 inches high from the roadway surface and was constrained in all directions. It tapered from a vertical face at the rail transition to a NJ-shape bridge rail over 10.5-ft length. A 32-inch high F-shape simulated bridge rail was modeled adjacent to the parapet wall and was rigidly constrained as well. LS-DYNA soil material model *MAT_JOINTED_ROCK was used to simulate soil properties for soil-post interaction during computer simulations.

A standard W-beam guardrail with steel posts and wood blockouts is transitioned over a length of 12.5 ft to the concrete parapet wall. The center of the guardrail is mounted 21.65 inches above the ground at the rail. The two nested W-beam guardrail elements are attached to a RWE02a terminal connector with eight standard guardrail connector bolts. The terminal connector is bolted through the parapet wall with four M22x250 mm H.S. (high strength) hex bolts. Posts 1, 2, 3, 5, and 7 are not connected to the rail. Post 4 is connected to the rail. The standard guardrail section begins at post 9. A 6-in x 8-in routed wood blockout was used behind the guardrail at all posts. The center of the rub rail is mounted 7.4 inches above the ground at the rail. The W-beam rub rail is attached to a RWE02a terminal connector with eight standard guardrail connector bolts. The terminal connector is bolted through the parapet wall with four M22x250 mm H.S. hex bolts. Posts 1, 2, 3, and 5 are not connected to the rub rail. Post 4 is connected to the rub rail. The 4-in wide x 14-in long wood blockout used behind the rub rail at posts 1, 2, 3, and 4 was tapered to allow the rub rail to be flush at the parapet wall and connect behind post 6. Posts 1 and 2 are W200x19 by 2285-mm-long steel posts. Posts 3 thru 13 are standard PWE02 steel posts. The post spacing between the parapet wall, posts 1, 2, 3, and 4 is 1.6 ft. The post spacing between posts 4, 5, 6, 7, and 8 is 3.1 ft. The post spacing for the standard guardrail section is 6.25 ft. The completed installation is shown in Figure 2.2.

The tested W-Beam guardrail transition to a bridge rail was accepted with the NCHRP Report 350 criteria with a guardrail 27 and 5/8-in. Recently, many states have begun increasing the guardrail height to 31-in in order to improve its performance. When raising the guardrail to 31-in, two options for the placement of the rubrail were considered as feasible:

- The first was to increase the height of the rubrail along with the guardrail, which would lead to no difference in separation between the rubrail and the guardrail from the 27 and 5/8-in to the 31-in;
- The second option was to only increase the guardrail to 31-in and leave the rubrail in its original placement. This second option would increase the separation of the rubrail and guardrail by approximately 3 and 3/8-in.

Researchers used the National Crash Analysis Center (NCAC) detailed finite element pickup truck model to complete their simulations (NCAC, 2014). Some parts of the 2000P pickup truck model needed mesh refinement to avoid contact issues during the impact event against the finer meshed reproduction of the test article. The vehicle computer model was validated against a single slope test that was performed at TTI under an FHWA project (NCAC, 2014). The FE vehicle dynamics during the impact event was compared to the vehicle behavior witnessed during test 404211-12. Researchers used the TRAP program to evaluate occupant risk values which were also compared to the results obtained during the full-scale crash test. In addition, the Roadside Safety Verification and Validation Program (RSVVP) was used to perform validation of the vehicle model behavior according to x, y, and z local accelerations and roll, pitch, and yaw angular displacements (Ray et al., 2011). Vehicle validation results are reported in Appendix A.

Next, validation of the FE model of the test article was needed in order to verify realistic response of the stacked w-beam transition to the impact of the validated vehicle. Validation of the computer model of the test article is reported in Sub-Chapter 2.3.

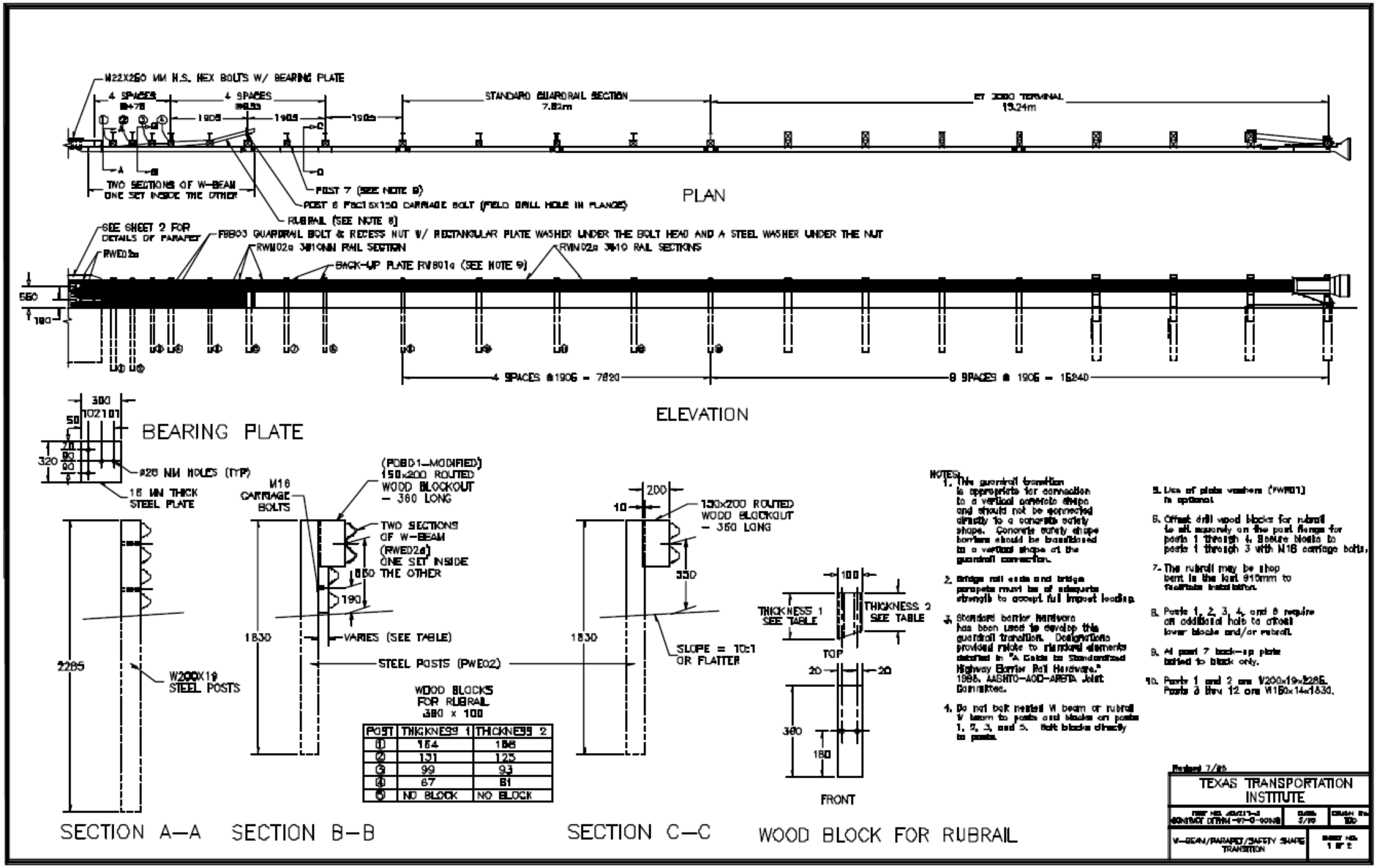


Figure 2.1. Details of the Vertical Wall Transition Installation for Test 404211-12.

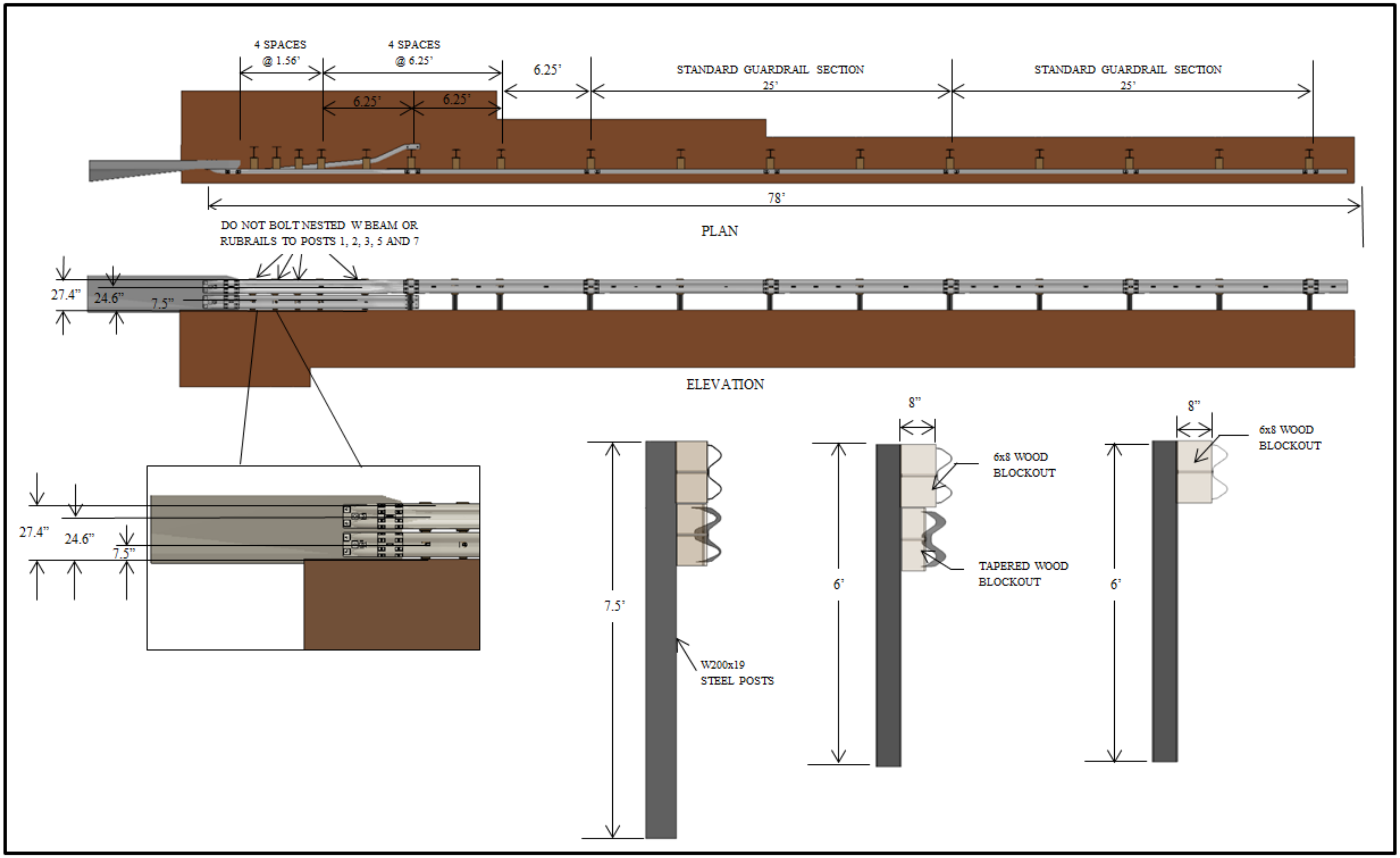


Figure 2.2. Details of the Vertical Wall Transition Installation for Finite Element Computer Model Simulations.

2.3 TRANSITION FINITE ELEMENT MODEL VALIDATION

2.3.1 Barrier Performance

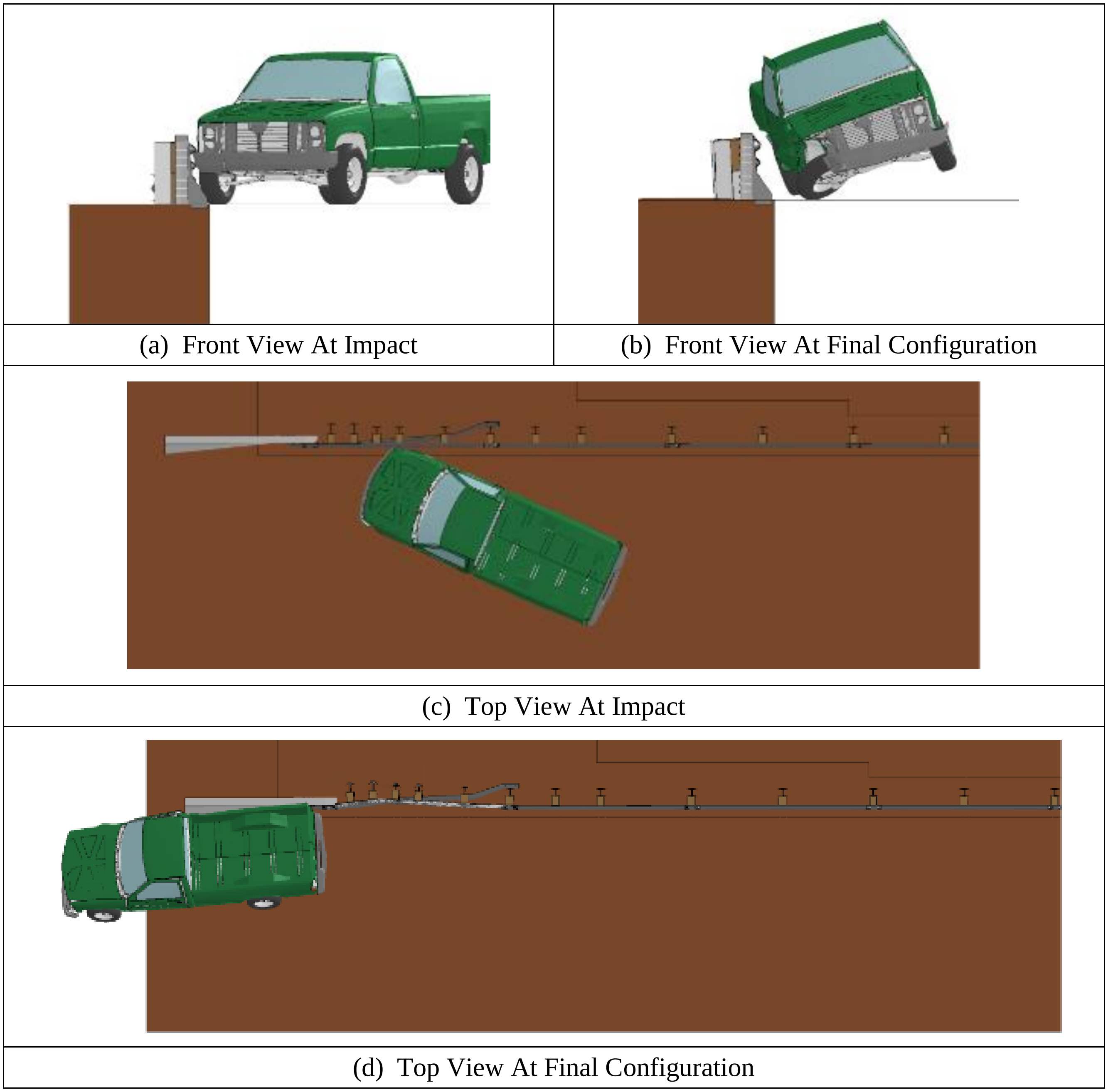
Figure 2.3 contains images of the barrier before impact and at final configuration. Figure 2.3(a) and 2.3(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 2.3(b) and 2.3(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. To replicate the impacting conditions of test 404211-12, the barrier was impacted at 5.25 ft from the end of the concrete parapet, with initial and speed and angle of 62.9 mph and 24.2 degrees, respectively.

For this FE model, soil was modeled by using LS-DYNA * MAT_JOINTED_ROCK. Thus, FE initialization was required to ensure soil and concrete barrier models would have a realistic initial geotechnical pressure at the time of vehicle impact. FE model initialization was achieved by adding gravity and a damping factor only to the barrier and soil parts. The initialized soil stresses were then applied to the soil material at the beginning of the impact event simulation.

2.3.2 Energy Values

The kinetic energy applied to the barrier by the impacting vehicle is dissipated by converting it into other forms of energy. Internal energy constitutes any energy stored in a component through plastic and elastic deformation (strains) or a change in temperature. Sliding energy represents any energy dissipated due to friction between components. Hourglass energy is an unreal numerical energy dissipated by LS-DYNA. Hourglass energy should be minimized as much as possible (less than 5 percent in any significant part and less than 10 percent 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 34 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 two percent of the initial kinetic energy is converted into hourglass energy. Approximately 19 percent of the initial kinetic energy is converted into sliding interface energy. Forty three percent of the initial kinetic energy has yet to be dissipated by the system at the time of final impact configuration, mainly due to the remaining velocity of the vehicle.



(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 (27-in Height Stacked W-Beam Transition).

2.3.3 Occupant Risk Assessment

The TRAP program was used to evaluate occupant risk factors based on the applicable *NCHRP 350* safety evaluation criteria. The modeled 2000 vehicle remained upright during and after the modeled collision event. Figure 2.5 shows vehicle roll, pitch and yaw angles throughout the impact event against 27-in high stacked w-beam transition. Maximum roll, pitch and yaw angles resulted to be 9.6, 4.3, and -29.6 degrees respectively. Occupant impact velocities were evaluated to be 30.2 ft/sec and 26.6 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were evaluated to be -10.1 g and -17.4 g in the longitudinal and lateral directions, respectively. Angular displacements obtained in the full-scale crash test and in the simulation are also reported in Figures 2.6 and 2.7, respectively.

Tables 2.1 and 2.2 compare frames from test 404211-12 and computer simulation validation at the same time after first impact occurred.

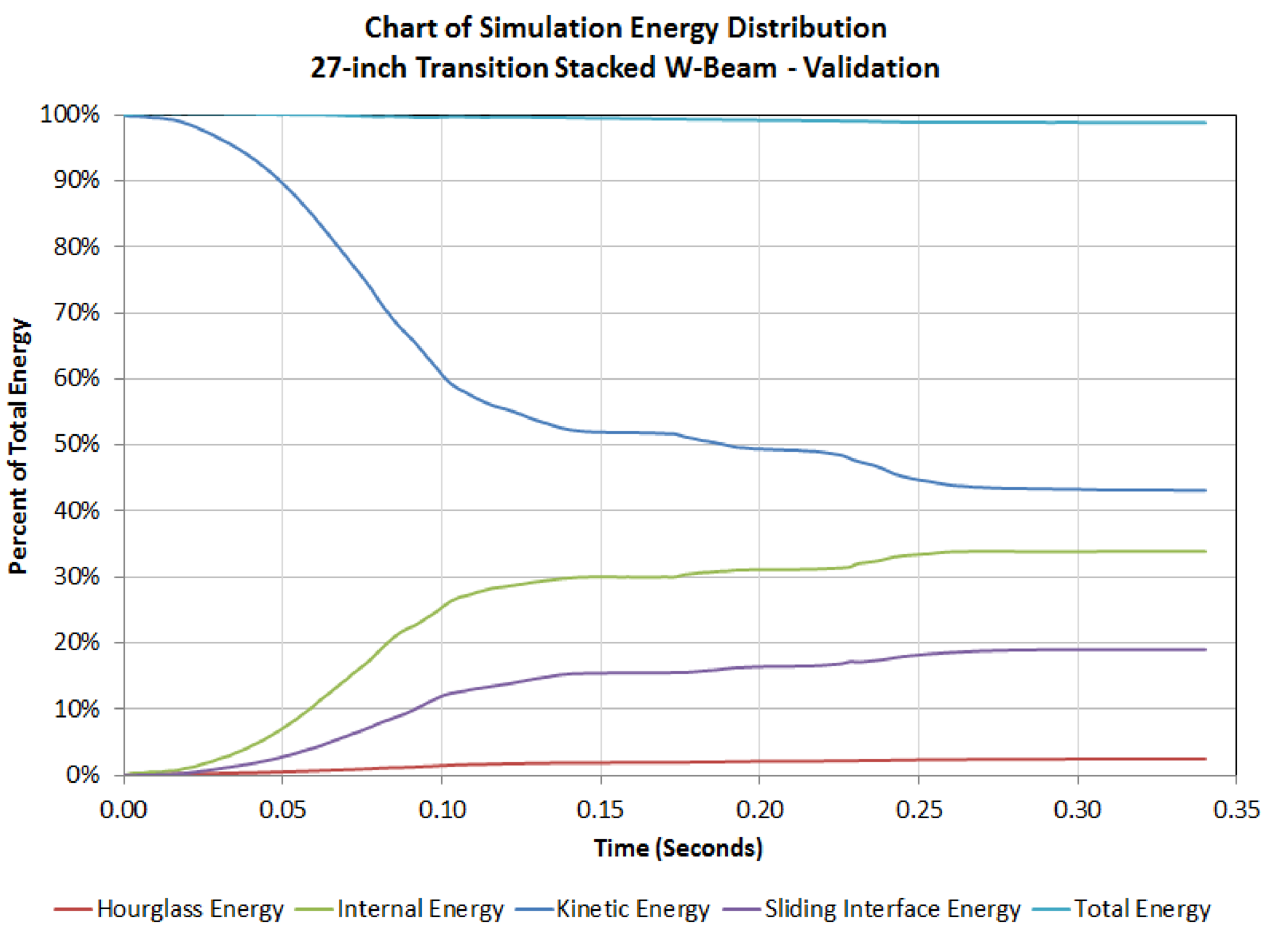


Figure 2.4. Energy Distribution Time History (27-in Height Stacked W-Beam Transition).

Occupant Risk Factors	TEST 404211-12	FE Stacked W-Beam Transition (27-in)
Impact Vel. (ft/sec)		
x-direction	24.0	30.2
y-direction	25.6	26.6
Ridedown Acc. (g's)		
x-direction	-6.7	-10.1
y-direction	-10.1	-17.4

Angles	TEST 404211-12	FE Stacked W-Beam Transition (27-in)
Roll (deg.)	25	9.6
Pitch (deg.)	8	4.3
Yaw (deg.)	-50	-29.6

Figure 2.5. Occupant Risks Values (27-in Height Stacked W-Beam Transition).

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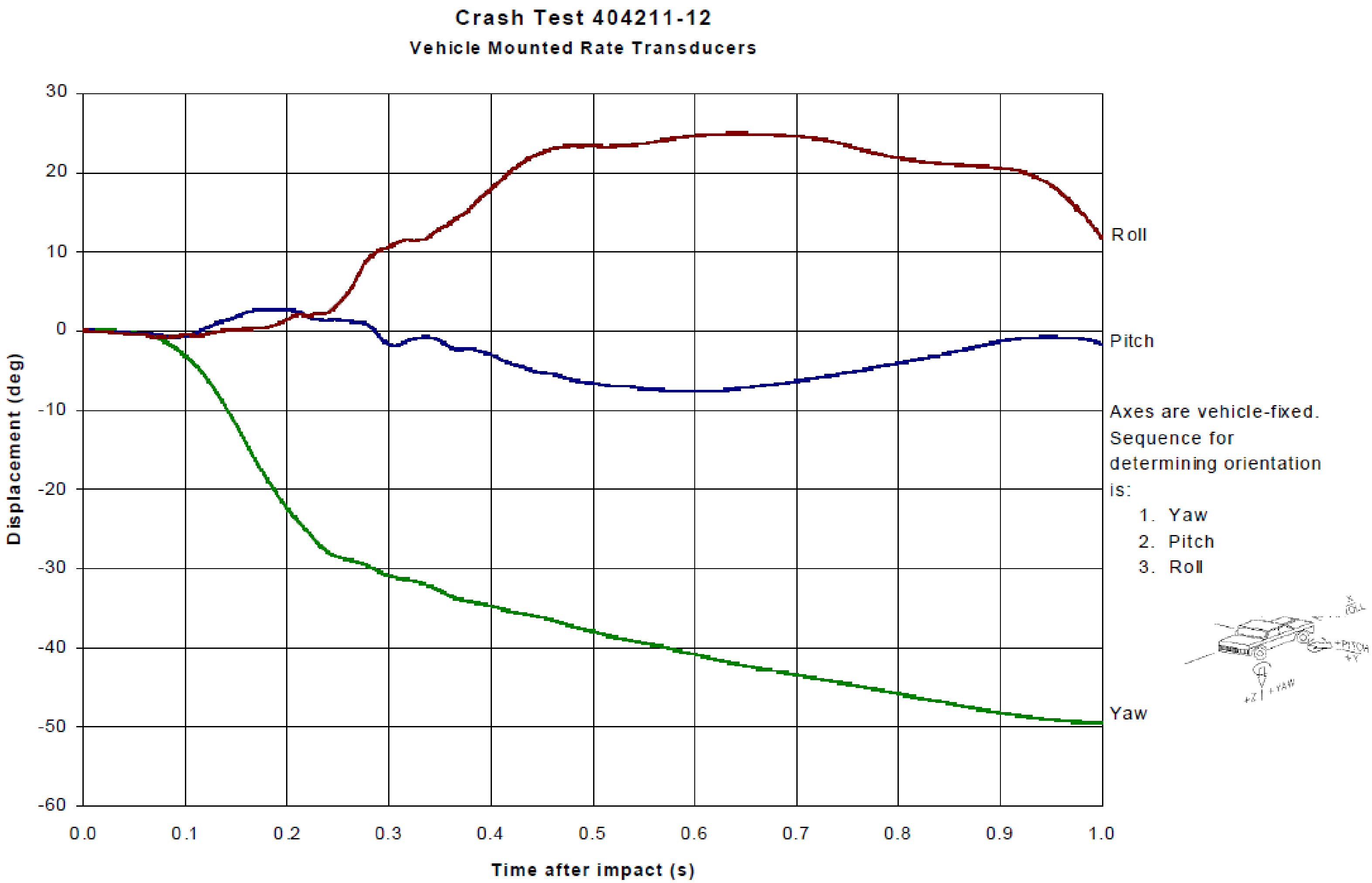


Figure 2.6. Angular Displacements for Test 404211-12.

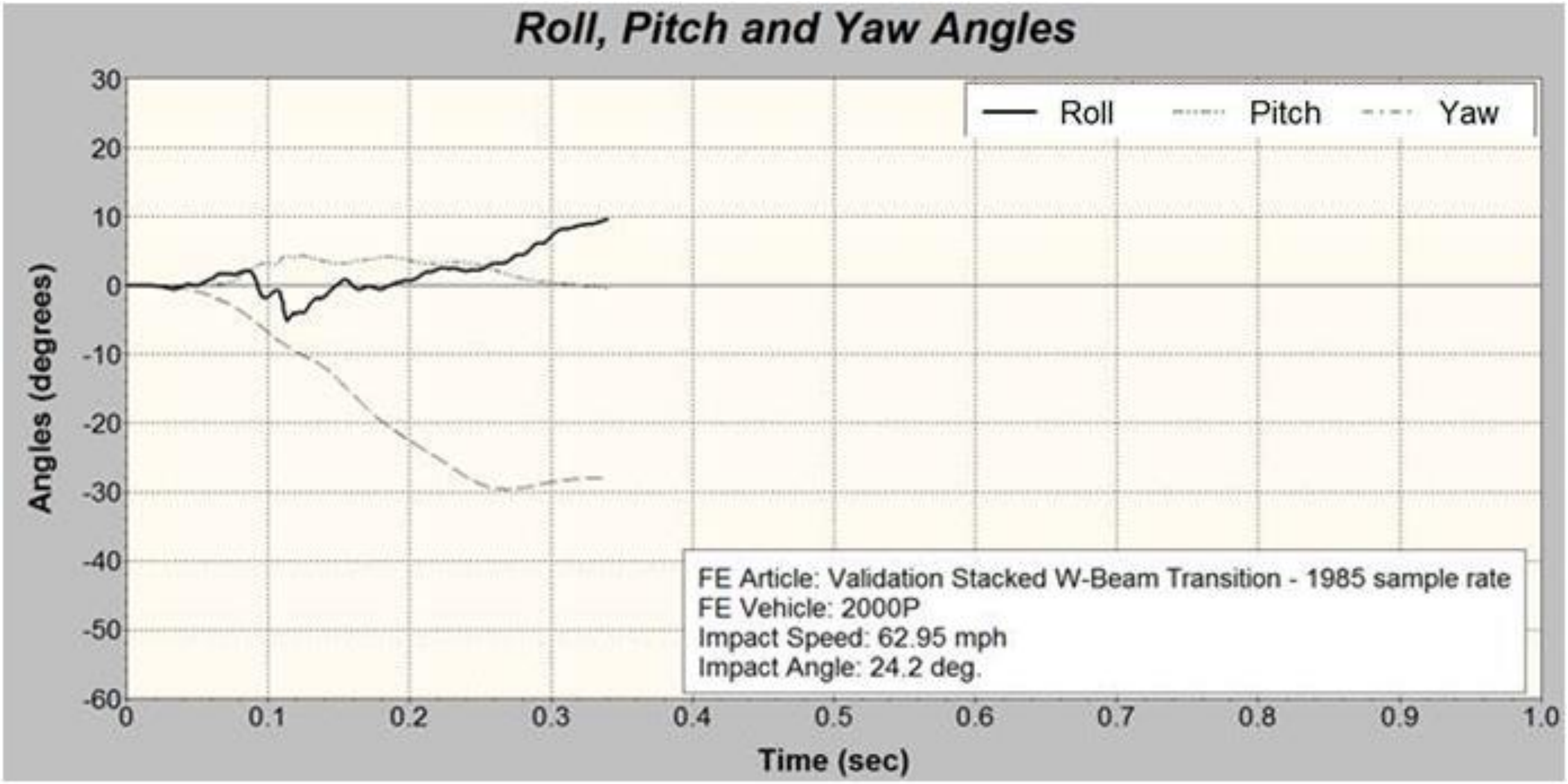


Figure 2.7. Angular Displacements for FE Simulation Validation of the 27-in High Stacked W-Beam Transition.

Table 2.1. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Top View (27-in Height Stacked W-Beam Transition).

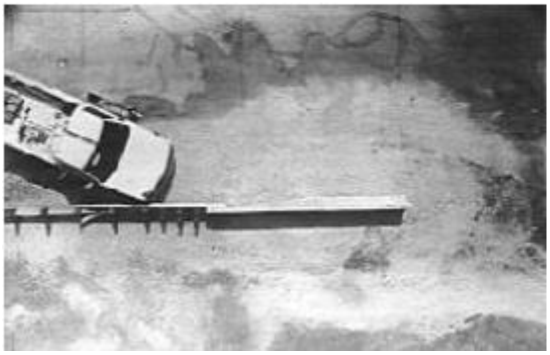
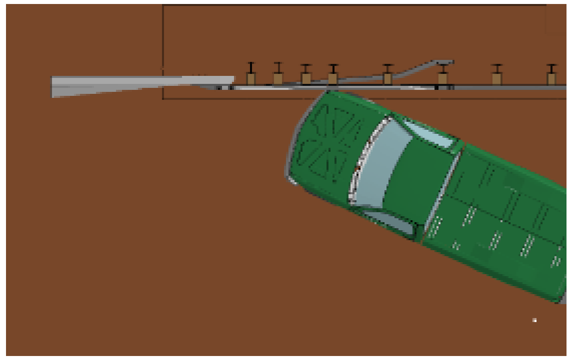
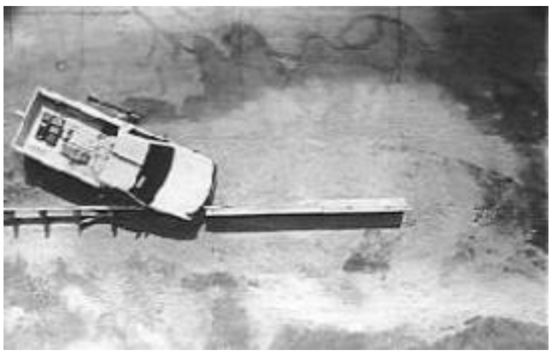
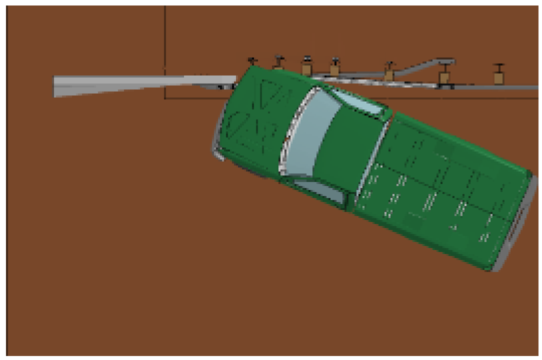
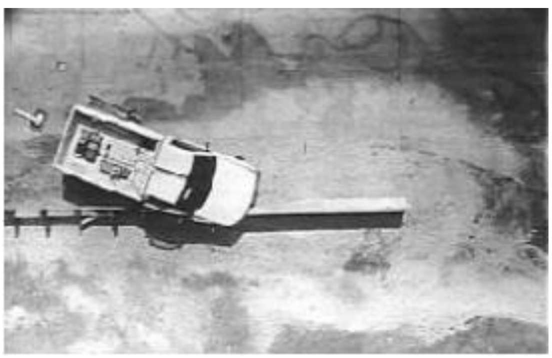
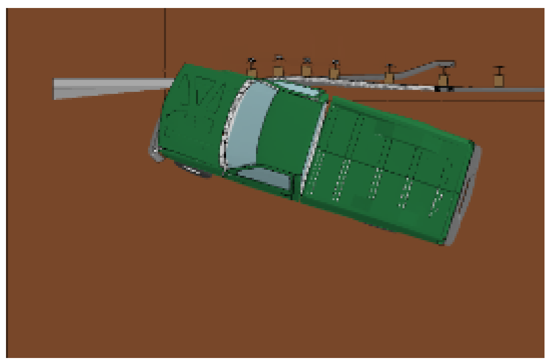
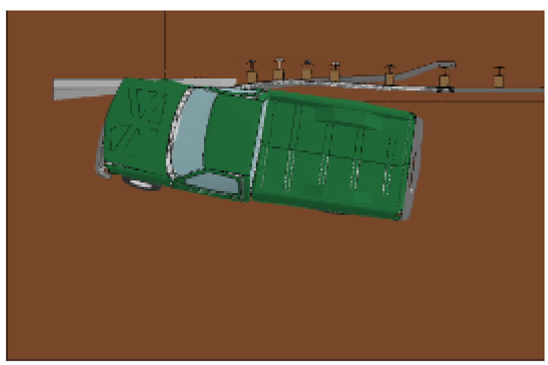
Time (sec)	TEST 404211-12	FE Stacked W-Beam Transition (27-in)
0.000		
0.049		
0.098		
0.145		

Table 2.1. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Top View (27-in Height Stacked W-Beam Transition) (Continued).

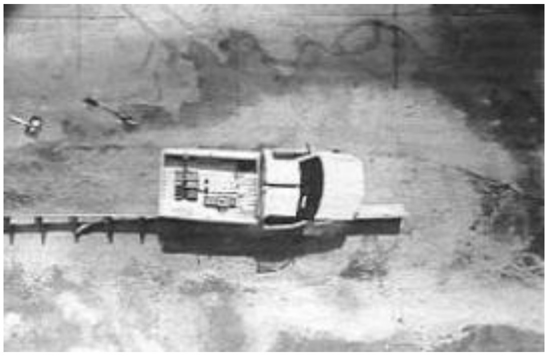
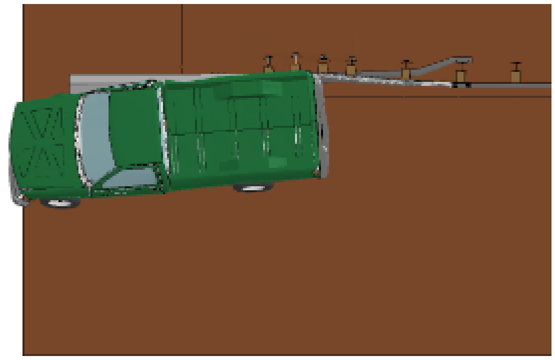
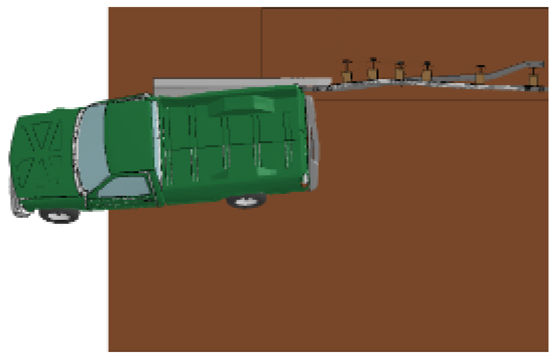
Time (sec)	TEST 404211-12	FE Stacked W-Beam Transition (27-in)
0.245		
0.343		

Table 2.2. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Frontal View (27-in Height Stacked W-Beam Transition).

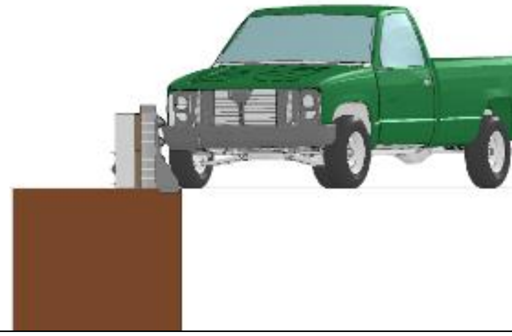
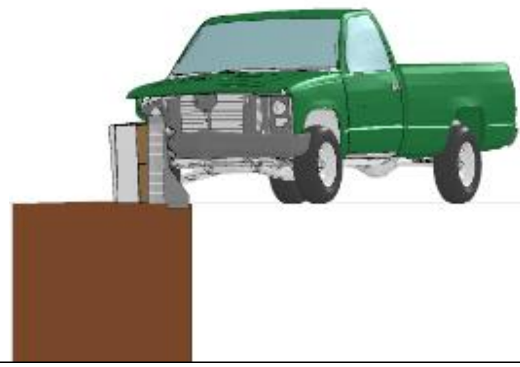
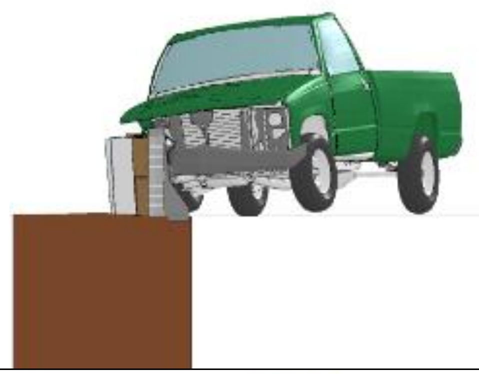
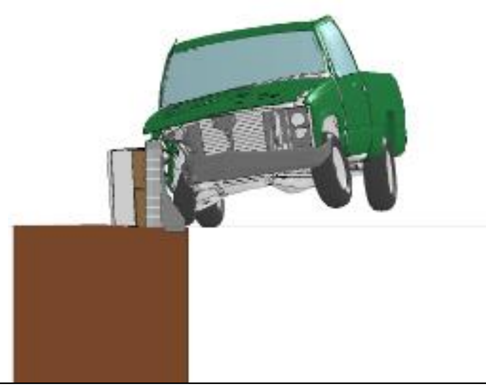
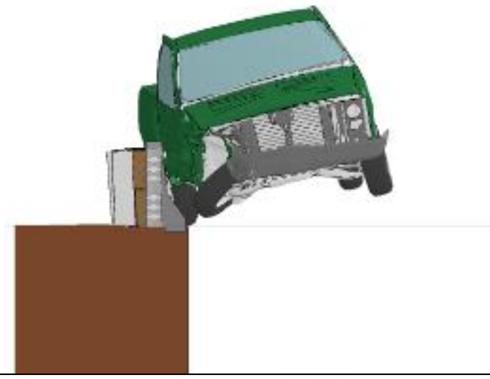
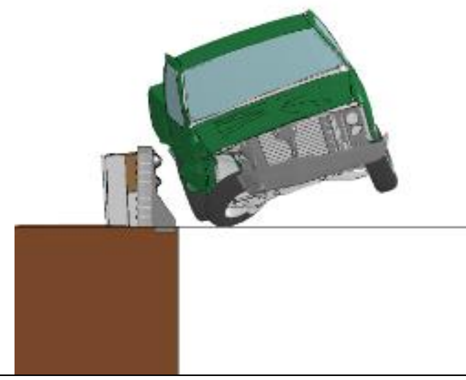
Time (sec)	TEST 404211-12	FE Stacked W-Beam Transition (27-in)
0.000		
0.049		
0.098		
0.145		

Table 2.2. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Frontal View (27-in Height Stacked W-Beam Transition) (Conitnued).

Time (sec)	TEST 404211-12	FE Stacked W-Beam Transition (27-in)
0.245		
0.343		

2.3.4 RSVVP Validation

A program called the Roadside Safety Verification and Validation Program (RSVVP) was developed for validation of numerical models in roadside safety (9). This program was used to compute the comparison metrics for a quantitative validation of the pickup truck FE impact model. This quantitative verification approach is based on the comparison of acceleration and angle curves from both simulation and test data according to Sprague and Geers (S&G) MPC and variance (ANOVA) metrics. Acceleration and angle rates histories of the vehicle are collected in LS-DYNA with use of a rigid brick element defined by the card *ELEMENT_SEATBELT_ACCELEROMETER and rigidly linked to the vehicle at its center of gravity (ref LS-DYNA). Before computing the metrics with the RSVVP program, each curve was filtered and synchronized by minimizing the absolute area of the residuals.

The results of the evaluation for the individual channels are shown in Table 2.3. Based on the Sprague & Geers metrics, the x-, roll- and yaw-channels indicated that the numerical analysis was in agreement with the test, and that the y-, z-, and pitch-channels were not. The ANOVA metrics indicated that the simulation was in good agreement with the test for all channels except the pitch-channel. Since the metrics computed for the individual data channels did not all satisfy the acceptance criteria, the multi-channel option in RSVVP was used to calculate the weighted Sprague-Geer and ANOVA metrics for the six channels of data. The resulting weight factors computed for each channel are shown in both tabular form and graphical form in Table 2.4. The results indicate that the x-, y-, and yaw rate-channels dominate the kinematics of the impact event. The weighted metrics computed in RSVVP using the Area II method in the multi-channel mode all satisfy the acceptance criteria, and therefore the time history comparison can be considered acceptable.

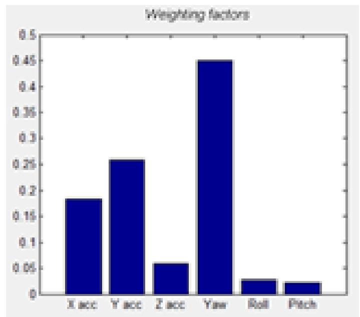
2.3.5 Conclusions

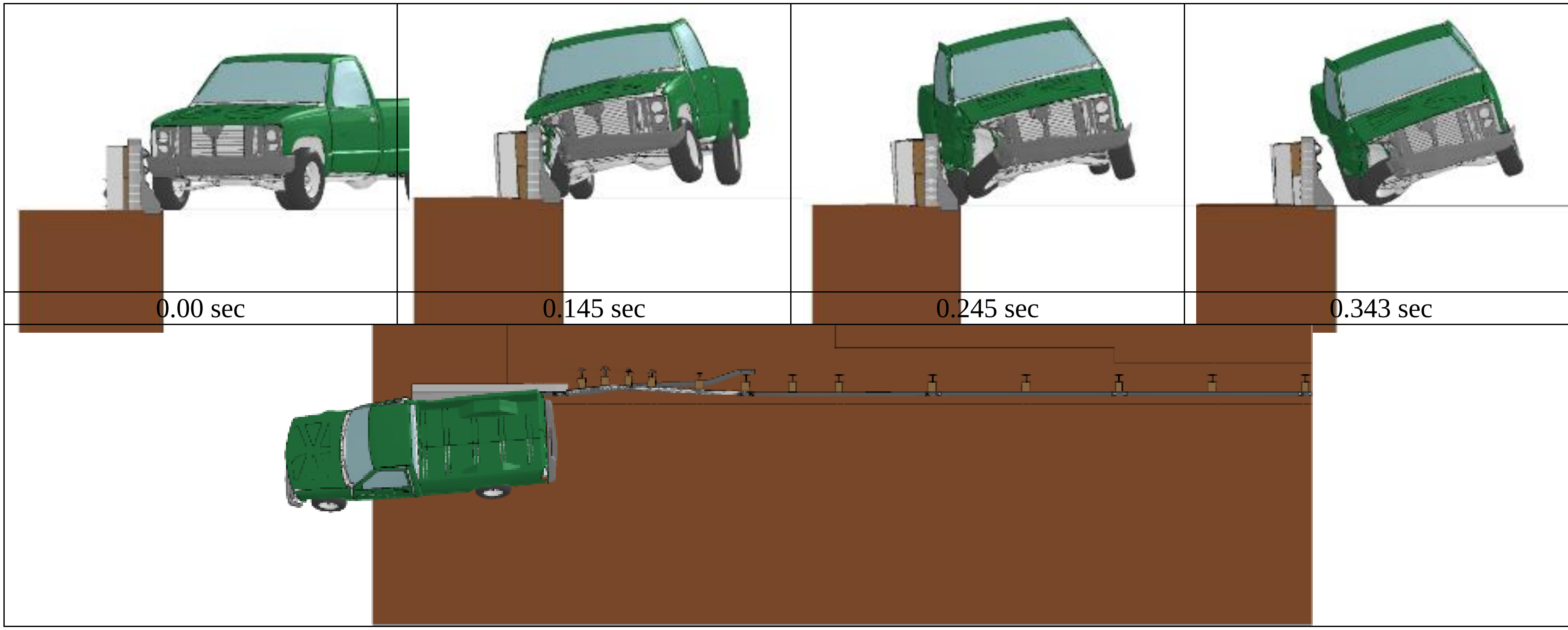
Computer simulation of NCHRP 350 Test 3-21 according the initial impact conditions of test 404211-12 well replicate the results obtained through full-scale crash testing. Although the model seems to underpredict roll vehicle displacement, other parameters compare favorably to the test outcomes. In addition, the multi-channel option evaluation through the RSVVP program suggests that the FE model of the 27-in stacked W-beam transition can be considered validated. Figure 2.8 summarizes results for NCHRP 350 Test 3-21 simulation with a 2000P vehicle impacting a 27-in high stacked W-beam transition.

Table 2.3. Roadside Safety Validation Metrics Rating Table for 27-in Stacked W-Beam Transition (Single Channel Option).

	Evaluation Criteria							Time Interval [0 sec; 0.274 sec]		
O	***Sprague-Geers Metrics*** List all the data channels being compared. Calculate the M and P metrics using RSVVP and enter the results. Values less than or equal to 40 are acceptable.							Simulation vs. Test 1		
		RSVVP Curve Preprocessing Options						M [%]	P [%]	Pass?
		Filter Options	Sync. Options	Shift		Drift				
				Test Curve	Test Curve	Test Curve	Test Curve			
	X Acceleration	CFC 180	Min. area of Residuals	N	N	N	N	2.7	37.5	Y
	Y Acceleration	CFC 180	Min. area of Residuals	N	N	N	N	9.3	40.7	N
	Z Acceleration	CFC 180	Min. area of Residuals	N	N	N	N	2.1	51.1	N
	Yaw Angle	CFC 180	Min. area of Residuals	N	N	N	N	1	2	Y
	Roll Angle	CFC 180	Min. area of Residuals	N	N	N	N	24.1	16.9	Y
	Pitch Angle	CFC 180	Min. area of Residuals	N	N	N	N	65.3	17.4	N
P	***ANOVA Metrics*** List all the data channels being compared. Calculate the ANOVA metrics using RSVVP and enter the results. Both of the following criteria must be met: • The mean residual error must be less than 5 percent of the peak acceleration ($\bar{e} \leq 0.05*a_{peak}$) and • The standard deviation of the residuals must be less than 35% of the peak acceleration ($\sigma \leq 0.35*a_{peak}$)							Mean Residual [%]	Standard Deviation of Residuals [%]	Pass?
	X Acceleration/Peak							-0.81	19.73	Y
	Y Acceleration/Peak							0.21	33.24	Y
	Z Acceleration/Peak							1.22	30.4	Y
	Yaw Angle							-0.96	3.7	Y
	Roll Angle							4.33	14.92	Y
	Pitch Angle							44.17	32.91	N

Table 2.4. Roadside Safety Validation Metrics Rating Table for 27-in Stacked W-Beam Transition (Multi-Channel Option Using Area II Method).

Evaluation Criteria (time interval [0 sec; 0.274 sec])				
Channels (select which used)				
✓ X Acceleration	**✓ Y Acceleration**		**✓ Z Acceleration**	
✓ Roll rate	**✓ Pitch rate**		**✓ Yaw rate**	
Multi-Channel Weights-Area (II) Method	X Channel- 0.183162882 Y Channel- 0.258832272 Z Channel- 0.058004846 Roll Channel- 0.026509263 Pitch Channel- 0.022771179 Yaw Channel- 0.450719558			
O	***Sprague-Geer Metrics*** Values less or equal to 40 are acceptalbe	**M**	**P**	**Pass?**
		5.6	22.1	Y
P	***ANOVA Metrics*** Both of the following criteria must be met: • The mean residual error must be less than 5 percent of the peak acceleration ($\bar{e} \leq 0.05 * a_{peak}$) • The standard deviation of the residuals must be less than 35% of the peak acceleration ($\sigma \leq 0.35 * a_{peak}$)	**Mean Residual**	**Standard Deviation of Residuals**	**Pass?**
		0.7	16.8	Y



General Information
Test Agency.................... Texas A&M Transportation Institute (TTI)
Test Standard Test No..... *NCHRP Report 350* Test 3-21
Date................................ N/A

Test Article
Type .... 27-in Stacked W-Beam Transition

Installation Length............ 78 ft
Material or Key Elements. Stacked W-Beam, 27-in Rail, Rigid Parapet

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

Impact Conditions
Speed ....62.9 mi/h
Angle ....24.2 degrees
Location/Orientation............5.25 ft from End of Rigid Parapet

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

Occupant Risk Values
Impact Velocity (ft/sec)
x-direction…………………. 30.2
y-direction…………………. 26.6
Ridedown Acceleration (g)
x-direction ....-10.1
y-direction ....-17.4

Vehicle Stability
Maximum Yaw Angle .... -29.6 degree
Maximum Pitch Angle .... 4.3 degree
Maximum Roll Angle .... 9.6 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 2.8. Summary of Results for *NCHRP 350* Test 3-21 simulation (27” Height Stacked W-Beam Transition).

3. FINITE ELEMENT SIMULATIONS FOR 31-IN RAIL HEIGHT

The tested W-Beam guardrail transition to a bridge rail was accepted with the NCHRP Report 350 criteria with a guardrail 27 and 5/8-in. As reported above, recently many states have begun increasing the guardrail height to 31-in in order to improve its performance. When raising the guardrail to 31-in, two options for the placement of the rubrail were considered as feasible.

Researchers modeled and evaluated impact performance results related to a 31-in rail transition, with both top rail and rubrail increased in height. Due to the results of these simulations, researchers did not perform simulations of the test article new height with increasing only the top rail height and leaving the rubrail in its original placement.

According to NCHRP Report 350, two tests are required to evaluate transitions to test level three (TL-3), as described below.

- NCHRP Report 350 test designation 3-20: An 820-kg passenger car impacting the transition at the critical impact point (CIP) of the transition at a nominal speed and angle of 100 km/h and 20 degrees. The test is intended to evaluate occupant risk and post-impact trajectory;
- NCHRP Report 350 test designation 3-21: A 2000-kg pickup truck impacting the transition at the CIP of the transition at a nominal speed and angle of 100 km/h and 25 degrees. The test is intended to evaluate strength of the section in containing and redirecting the 2000-kg vehicle.

NCHRP Report 350 test 3-21 was the only simulation performed on the transition simulations reported herein.

3.1.1 Stacked W-Beam Transition for 31-in Guardrail (without bolts)

Drawing of the 31-in stacked w-beam transition installation with rubrail height increased is reported in Figure 3.1. No additional modifications were made to the initial design of the 27-in transition article. The designation “without bolts” will be used from now on in the report to indicate that posts 1, 2, 3, 5, and 7 were left not bolted to the rail and rubrail sections, as in the original 27-in test article design.

3.1.1.1 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 5.25 ft from the end of the concrete parapet, with initial and speed and angle of 62 mph and 25 degrees, respectively.

3.1.1.2 Energy Values

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

Since this is a closed system and energy is conserved, the sum of the kinetic energy, hourglass energy, sliding energy, and internal energy at any time during the simulation should equate to the initial kinetic energy of the vehicle. As shown in Figure 3.3, approximately 43 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). Less than three 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. Thirty seven 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.

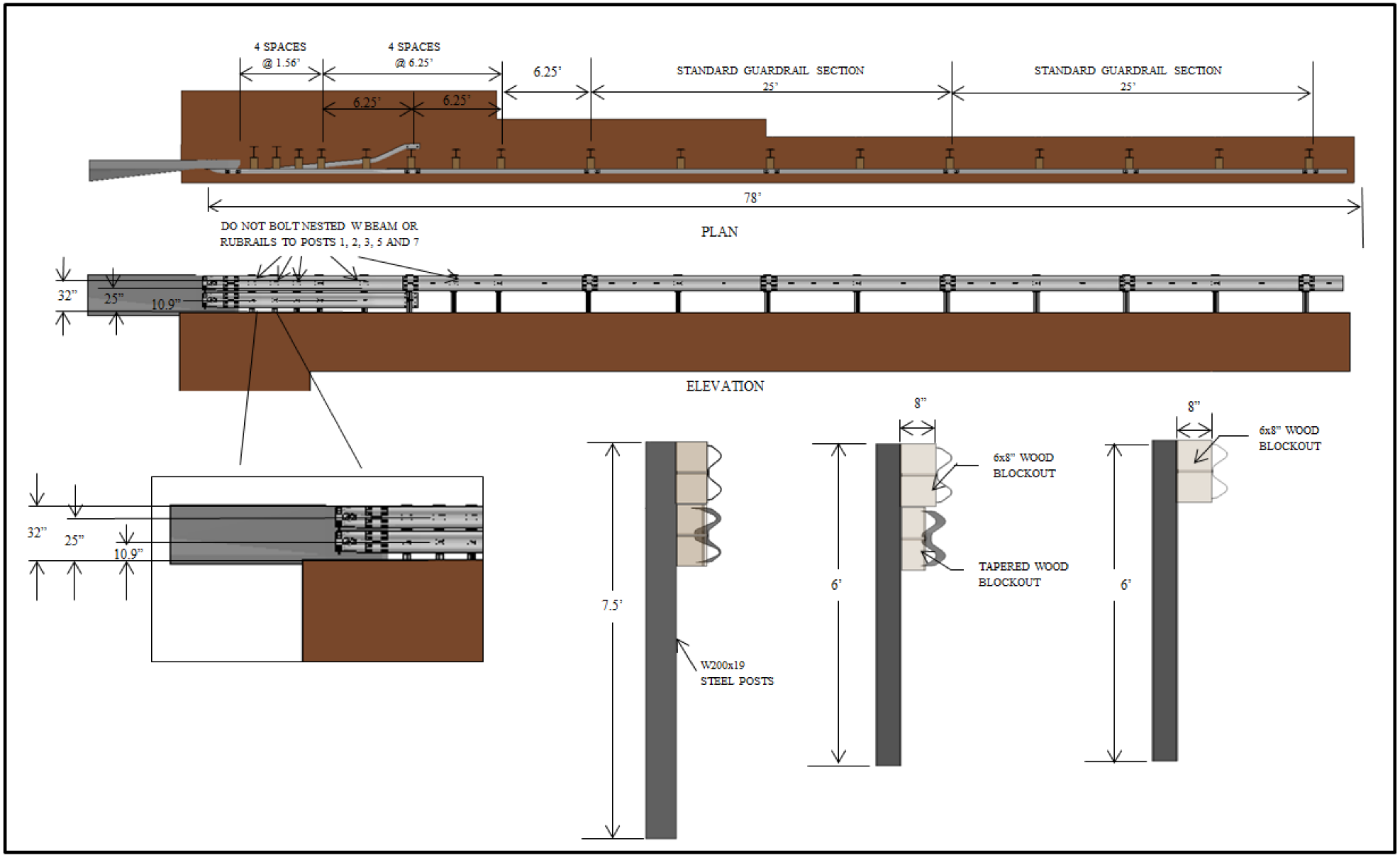
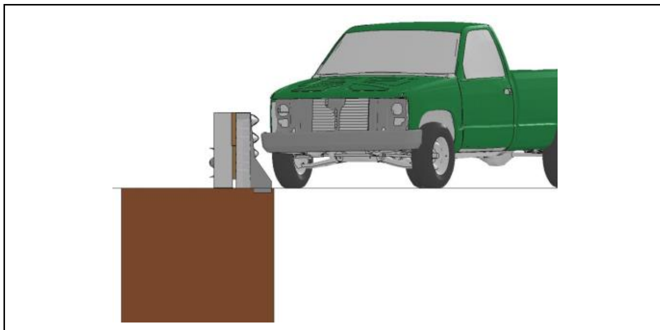
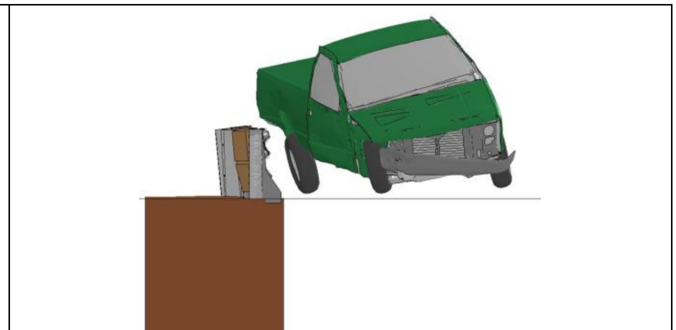


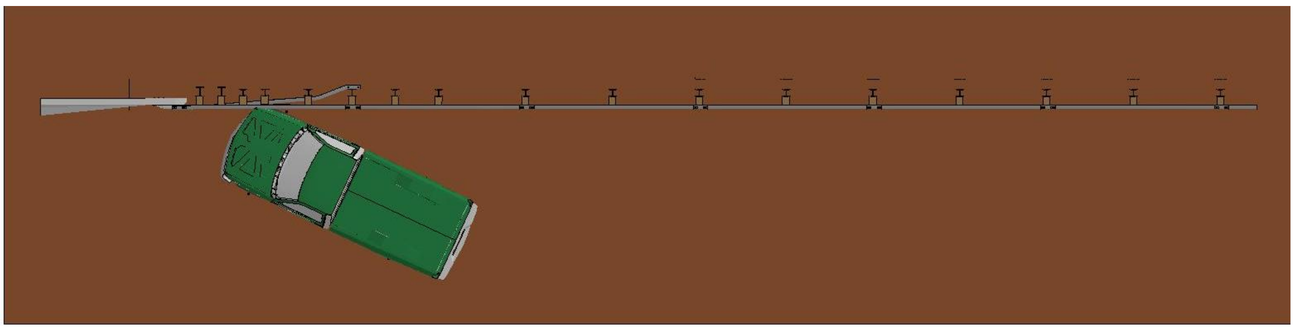
Figure 3.1. Details of the Vertical Wall Transition Installation for Finite Element Computer Model Simulations (31-in, no bolts).



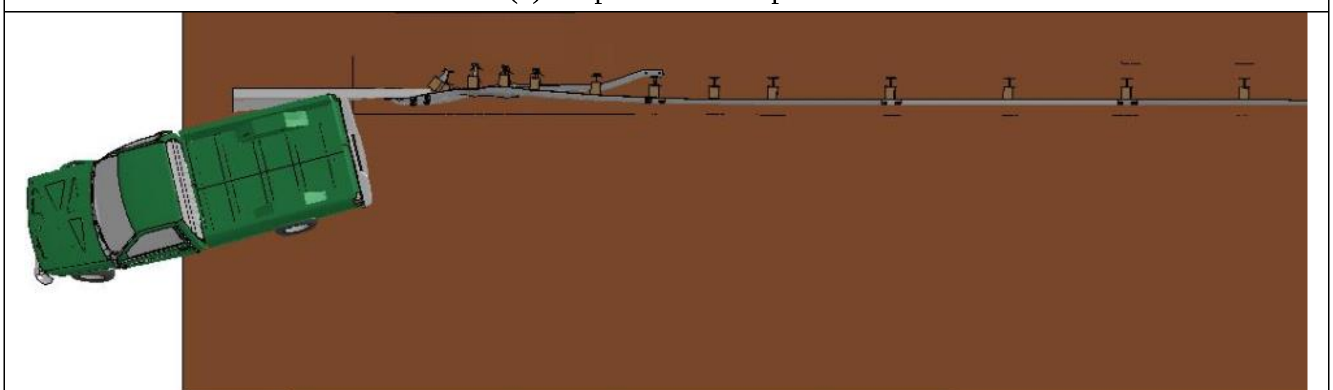
(a) Front View At Impact



(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 (31” Height Stacked W-Beam Transition, without Bolts).

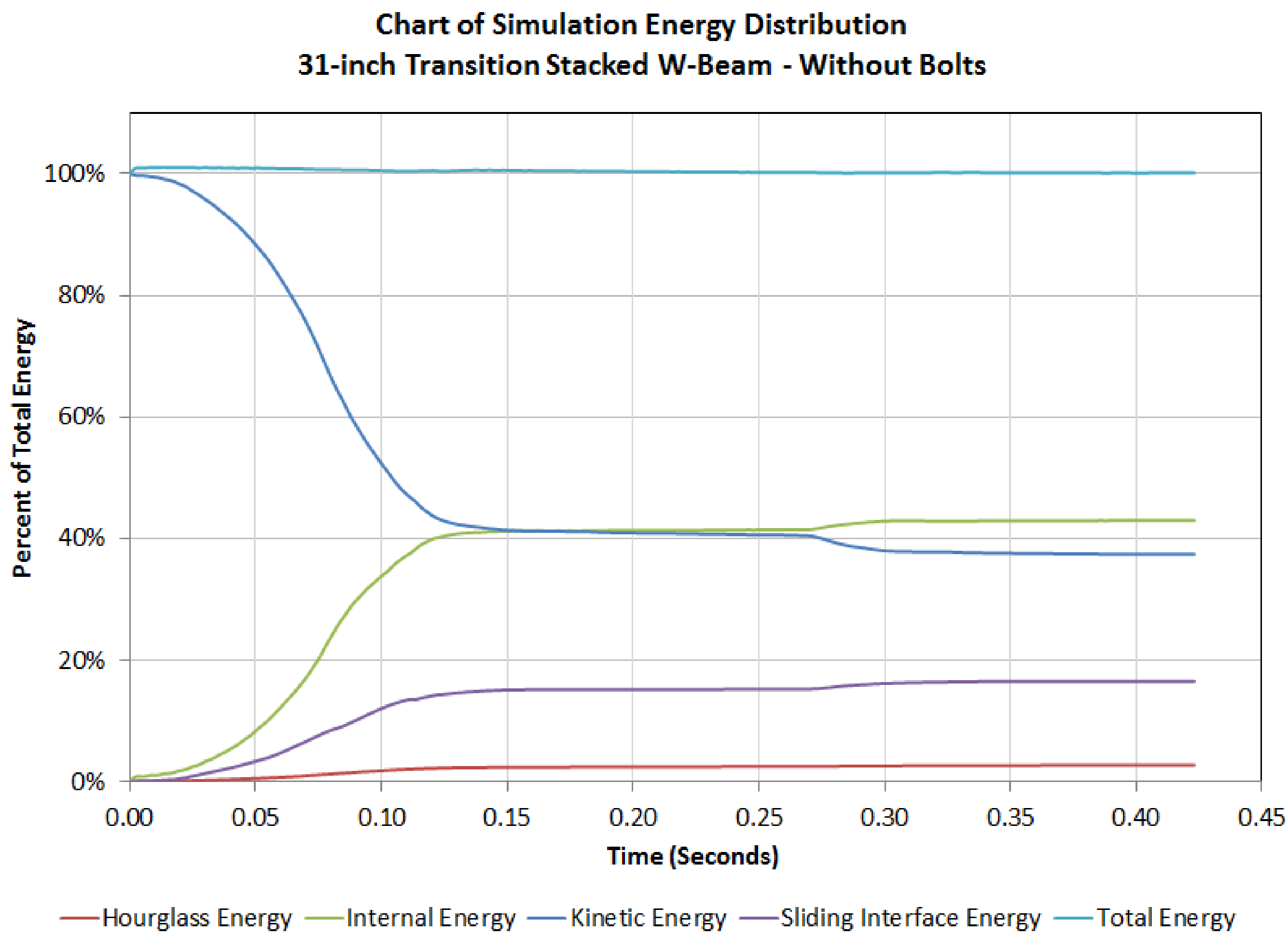


Figure 3.3. Energy Distribution Time History (31-in Height Stacked W-Beam Transition without Bolts).

Tables 3.1 and 3.2 show frames from computer simulation of the impact event against the 31-in high stacked W-beam transition, with raised rubrail and original design details (no bolts).

Table 3.1. Sequential Images of the 2000P Vehicle Interaction with the 31” Height Stacked W-Beam Transition, without Bolts (Top View).

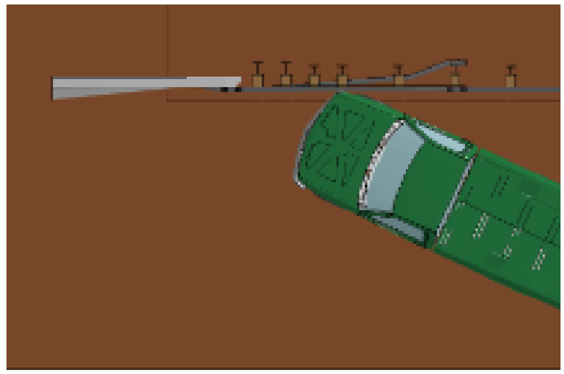
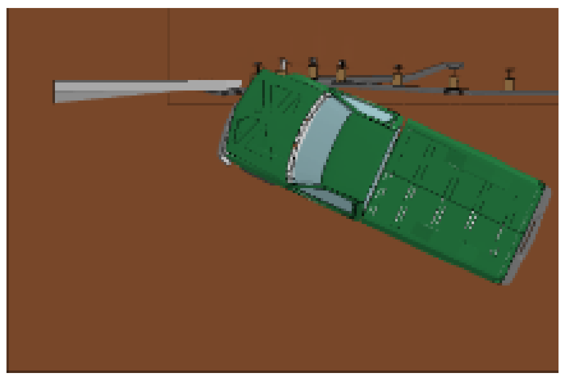
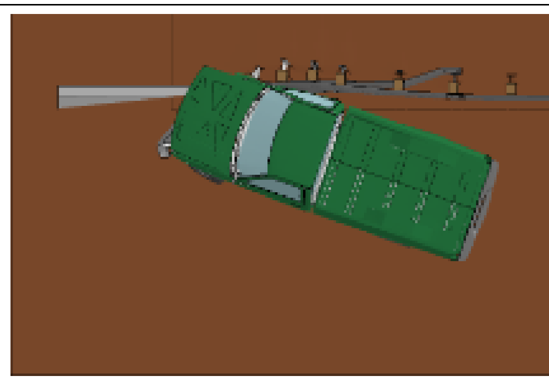
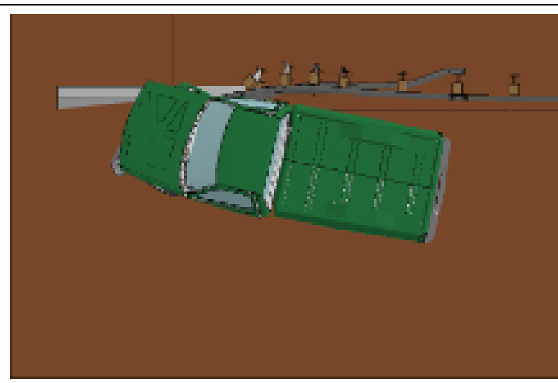
Time (sec)	FE 31” Transition without Bolts
0.000	
0.049	
0.098	
0.145	

Table 3.1. Sequential Images of the 2000P Vehicle Interaction with the 31" Height Stacked W-Beam Transition, without Bolts (Top View) (Continued).

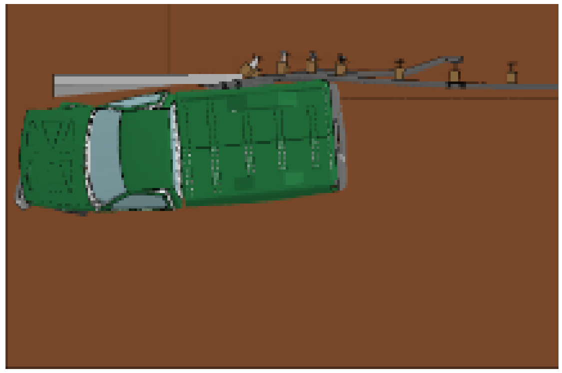
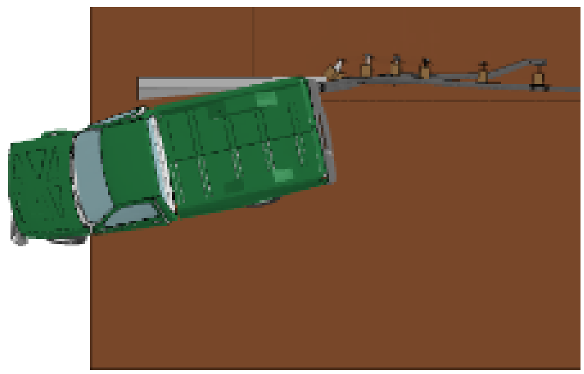
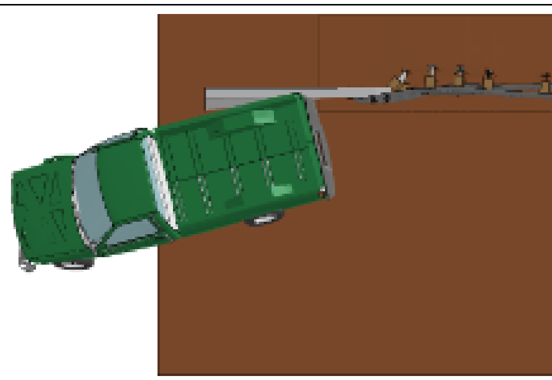
Time (sec)	FE 31" Transition without Bolts
0.245	
~0.343	
0.415	

Table 3.2. Sequential Images of the 2000P Vehicle Interaction with the 31" Height Stacked W-Beam Transition, without Bolts (Front View).

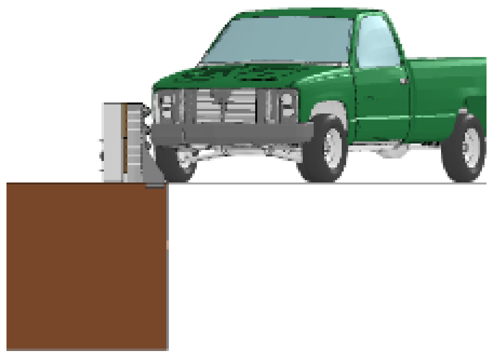
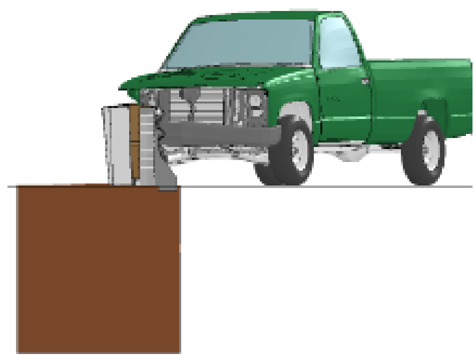
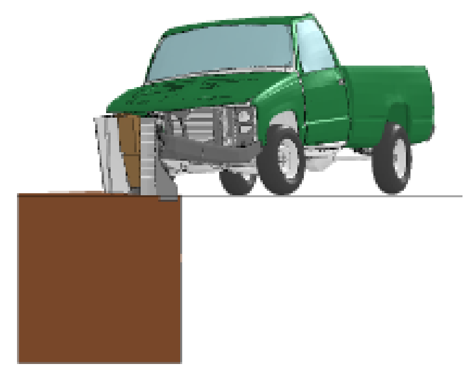
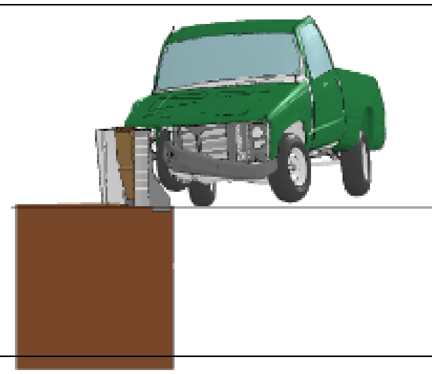
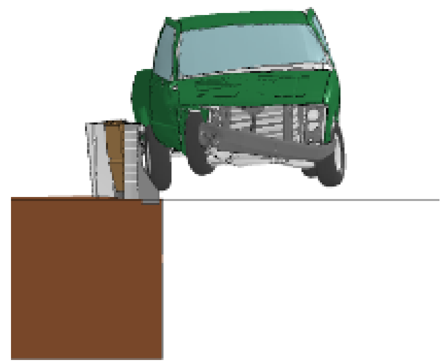
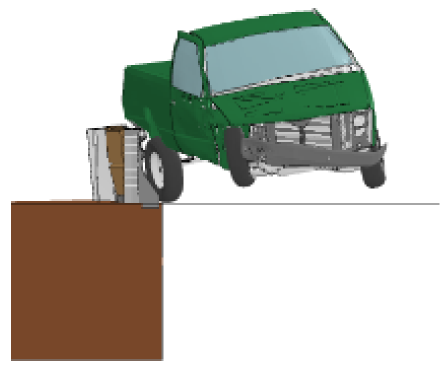
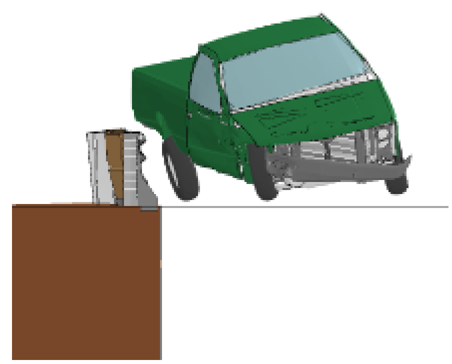
Time (sec)	FE 31" Transition without Bolts
0.000	
0.049	
0.098	
0.145	

Table 3.2. Sequential Images of the 2000P Vehicle Interaction with the 31" Height Stacked W-Beam Transition, without Bolts (Front View) (Continued).

Time (sec)	FE 31" Transition without Bolts
0.245	
0.343	
0.415	

4.4.2.5 Occupant Risk Assessment

The TRAP program was used to evaluate occupant risk factors based on the applicable *NCHRP Report 350* safety evaluation criteria. The modeled 2000P vehicle remained upright during and after the modeled collision event. Figure 3.4 shows vehicle roll, pitch and yaw angles throughout the impact event against the 31-in stacked W-beam transition with rubrail up and no bolts. Maximum roll, pitch and yaw angles resulted to be -15.9, 6.8, and -39.3 degrees respectively. Occupant impact velocities were evaluated to be 37.73 ft/sec and 29.53 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were evaluated to be –9.9 g and -9.8 g in the longitudinal and lateral directions, respectively. Angular displacement curves are also reported in Figure 3.5.

Occupant Risk Factors	FE Stacked W-Beam Transition (31-in) – without Bolts
Impact Vel. (ft/sec)	
x-direction	37.73
y-direction	29.53
Ridedown Acc. (g's)	
x-direction	-9.9
y-direction	-9.8

Angles	FE Stacked W-Beam Transition (31-in) – without Bolts
Roll (deg.)	-15.9
Pitch (deg.)	6.8
Yaw (deg.)	-39.3

Figure 3.4. Occupant Risks Values (31-in Height Stacked W-Beam Transition, without Bolts).

4.4.2.6 Surrogate Measure of OCD

A common cause of barrier failure in a crash test is excessive occupant compartment deformation (OCD). Bullard et al. (ref) determined a measure that would demonstrate the best correlation with the maximum OCD reported in the crash tests. In their study, the internal energy of the floorboard of the pickup truck finite element model was selected as the most appropriate surrogate measure for evaluating OCD. Using the internal energy from FE simulations and the reported OCD values from crash tests, thresholds for the surrogate measure were established. As shown in Figure 3.6, the passing limit was selected as 2,200 N-m and the failure limit was tentatively set at 10,700 N-m of internal energy in the floorboard of the pickup truck. The outcome of impacts with solid barriers in which the internal energy of the floorboard is between 2,200 N-m and 10,700 N-m is largely unknown due to lack of crash test data with a sufficient range of OCD values. That means, for those simulations where the floorboard has an internal energy value between 2,200 N-m and 10,700 N-m, there is the chance that vehicle OCD would not meet NCHRP Report 350 test passing requirements (Figure 3.7).

Figure x.x summarizes measured internal energy of the of the pickup truck floorboard when impacting the 31-in stacked W-beam transition (with no bolts) during simulation of NCHRP 350 test 3-21. The internal energy of the floorboard reaches values that are above the 2,200 N-m passing threshold suggested by Bullard et al. (ref.). Although the internal energy value is very close to the passing limit threshold of 2,200 N-m, it would still be unknown if a realistic resulting OCD would be passing NCHRP 350 requirements.

4.4.2.7 Conclusions

Figure 3.8 summarizes results for NCHRP 350 Test 3-21 simulation with a 2000P vehicle impacting the 31-in high stacked W-beam transition, with raised rubrail and original design details of the 27-in high transition rail (no rail and rubrail sections bolted to posts 1, 2, 3, 5, and 7). Although the vehicle was contained, redirected, and maintained stability during the impact event, it appeared cleared that vehicle snagging occurred against the rigid parapet. Simulation frame results suggest that the vehicle frame rail did not fully engage the top rail when impacting the test article, due to the fact that the test installation (including the top rail) was raised to 31 inches of height. Although the rubrail was as well increased in height in order to maintain same relative distance from the top rail as in its original design, the rubrail location was still too low to allow vehicle frame rail to engage the rubrail instead.

Thus, with the article installation increased to 31 inches, the vehicle frame rail impacted right in between the top nested rail and the rubrail (Figure 3.9). The vehicle frame rail and tire started compressing the rubrail, “opening” an unprotected empty space in the test article through the impact event, until they both impacted the rigid parapet. Snagging was visually evident during the simulation and affected occupant risk values.

Although still occupant impact velocities and ridedown accelerations were contained within NCHRP Report 350 limit criteria, researchers decided to investigate OCD through evaluation of the internal energy level measured in the vehicle floorboard. When vehicle snagging occurs, vehicle OCD might increase over the maximum passing limits criteria. In a previous effort, the floorboard internal energy was found to be a good indicator of OCD during impact with rigid barriers. The floorboard internal energy experienced by the 350 pickup truck in the simulation with 31-in stacked w-beam transition was just over the suggested passing limit, giving indication that OCD might not meet acceptable NCHRP 350 deformation requirements.

Snagging did not occur when the test article total height was 27 inches, because the vehicle frame rail did impact the nested top rail and was fully contained and protected by it when approaching the rigid parapet.

Due to visual evidence of vehicle snagging against the rigid parapet of the test article, high values (next to the allowable limit) of occupant risk and high internal energy in the vehicle floorboard (indication of too high OCD), the researchers believe that the simulation results indicate the 31-in stacked w-beam transition without bolts might not meet the crashworthiness NCHRP Report 350 requirements. This evaluation was made for the 31-in article model with both top rail and rubrail elevated of the same distance. Researchers did not evaluate the case of the 31-in article height with leaving the rubrail at its original location because that would not prevent the vehicle from snagging on the rigid parapet. A lower rubrail might actually increase the vehicle snagging force, since the vehicle frame rail would not dissipate energy trying to compress the rubrail before the snagging point.

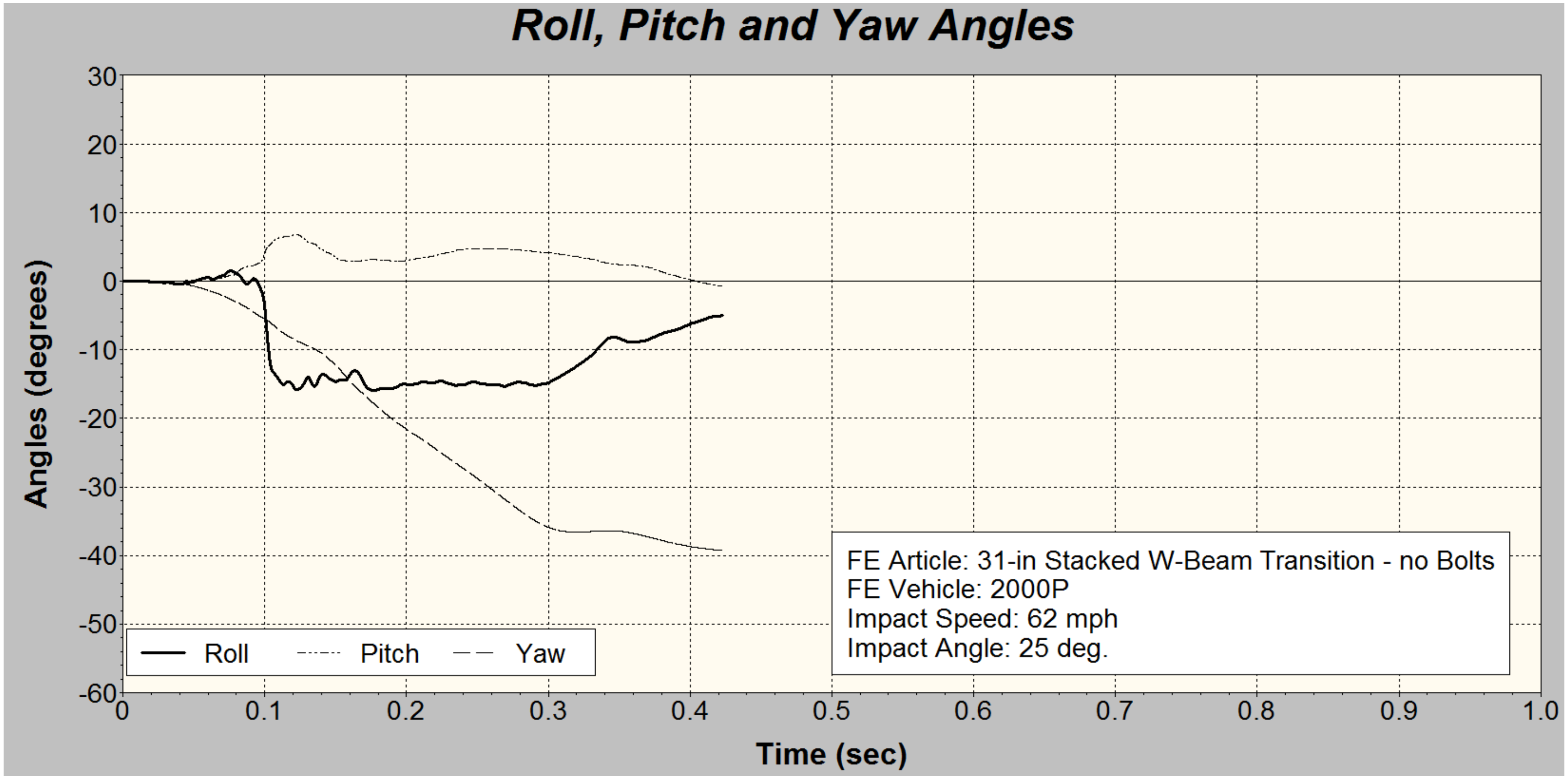


Figure 3.5. Angular Displacements for FE Simulation Validation of the 31-in High Stacked W-Beam Transition, no Bolts.

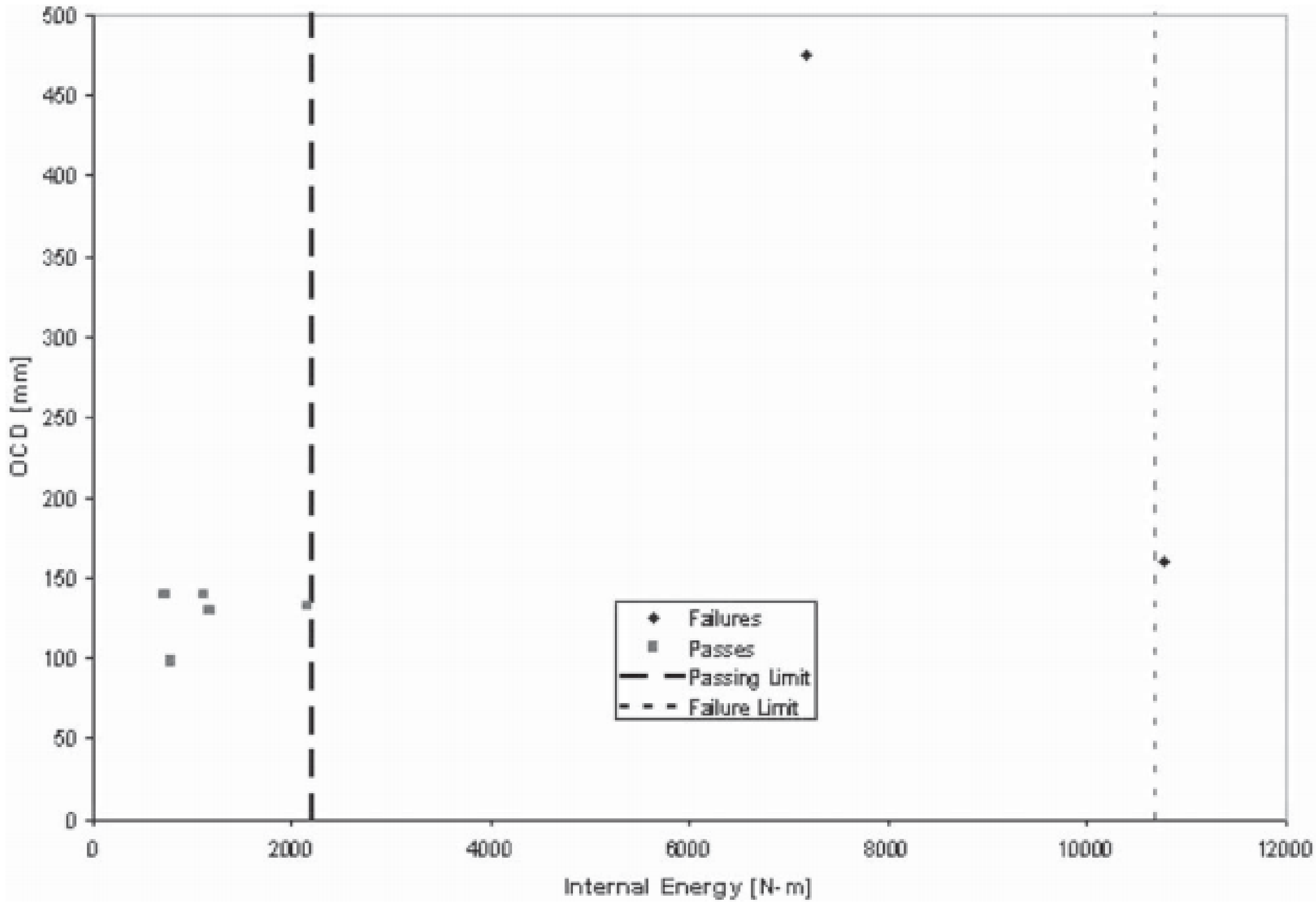


Figure 3.6. Passing and Failing Crash Tests OCD Versus Internal Energies of Floorboard (ref.).

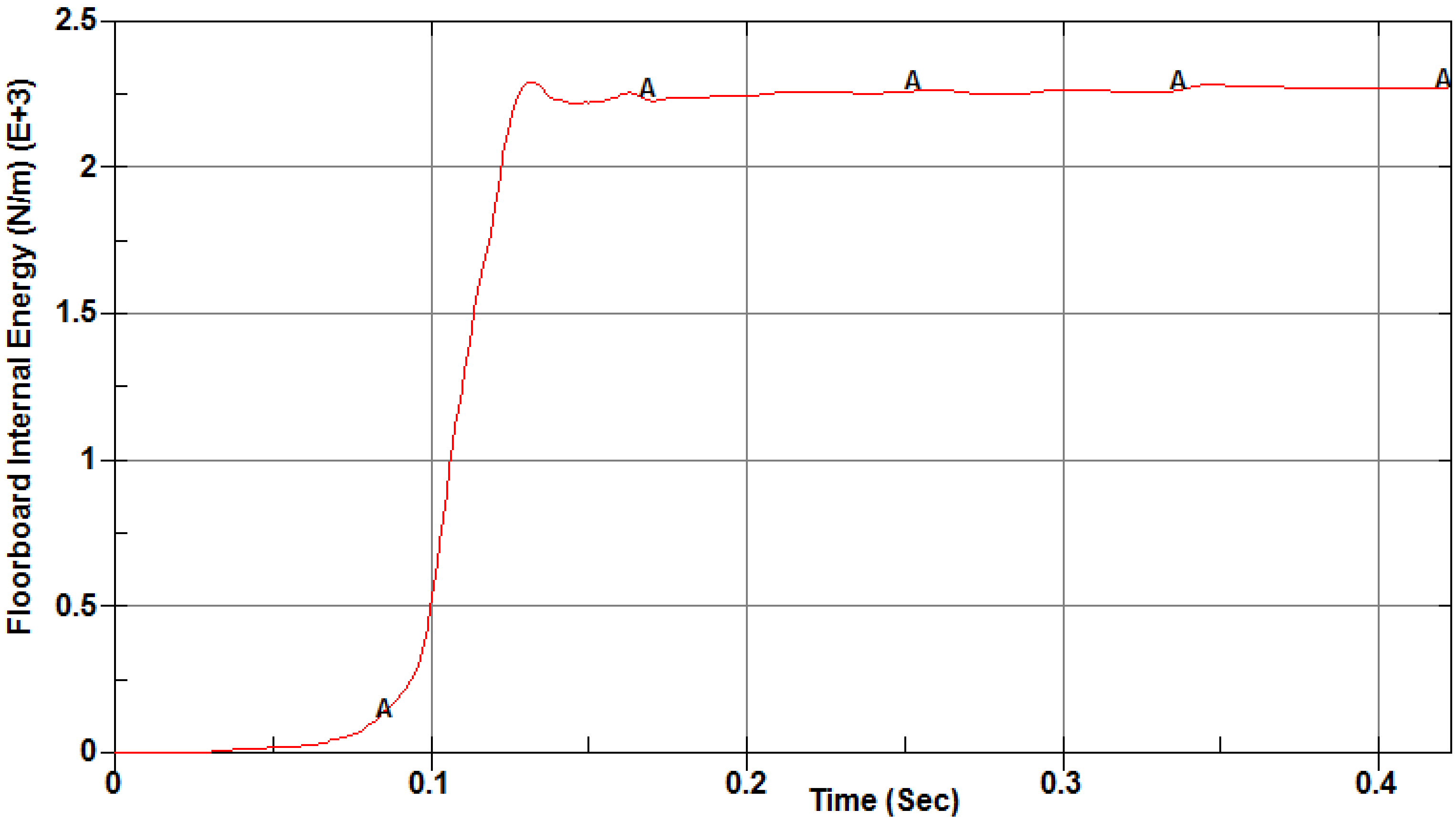
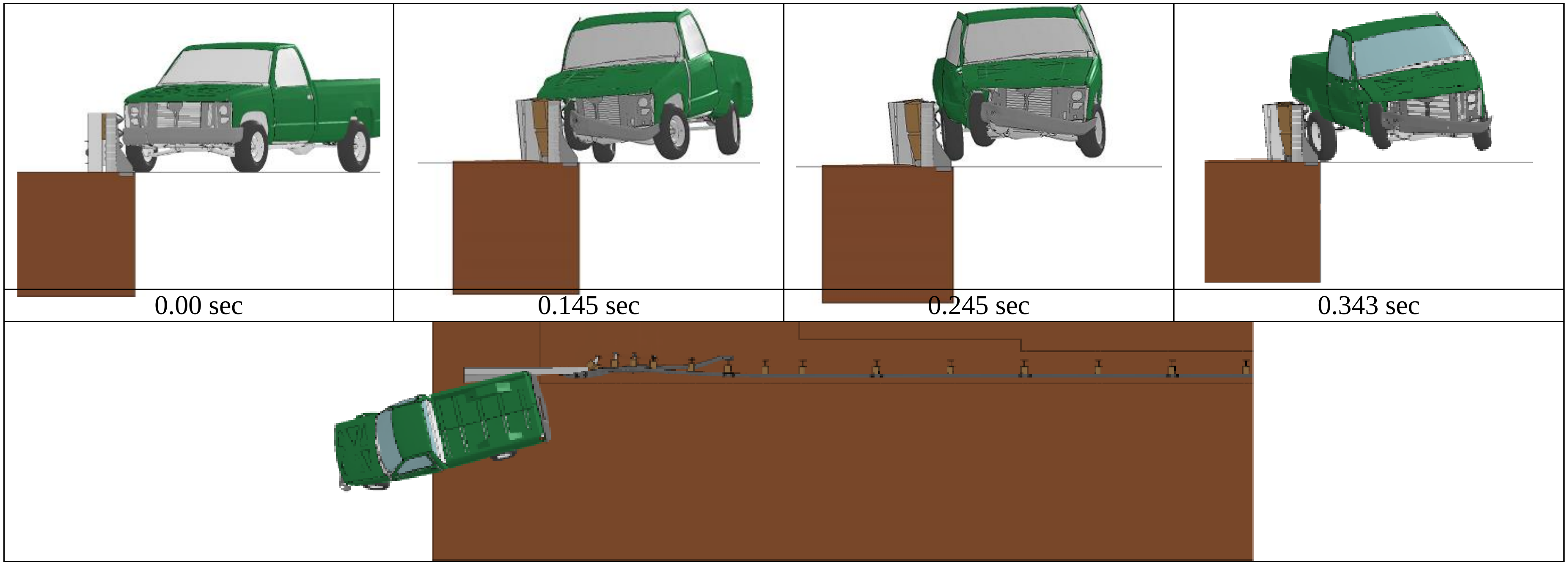


Figure 3.7. Floorboard Internal Energy for NCHRP 350 Test 3-21 with 31-in Stacked W-Beam Transition (without Bolts).



General Information
- Test Agency: Texas A&M Transportation Institute (TTI)
- Test Standard Test No.: *NCHRP Report 350* Test 3-21
- Date: N/A

Test Article
- Type: 31-in Stacked W-Beam Transition , no Bolts
- Installation Length: 78 ft
- Material or Key Elements: Stacked W-Beam, 31-in Rail, Rigid Parapet

Test Vehicle
- Type/Designation: 2000P
- Weight: 2000 lbs
- Dummy: No Dummy

Impact Conditions
- Speed: 62.0 mi/h
- Angle: 25 degrees
- Location/Orientation: 5.25 ft from End of Rigid Parapet

Post-Impact Trajectory
- Stopping Distance: N/A

Occupant Risk Values

Impact Velocity (ft/sec)
- x-direction: 37.73
- y-direction: 29.53

Ridedown Acceleration (g)
- x-direction: -9.9
- y-direction: -9.8

Vehicle Stability
- Maximum Yaw Angle: -15.9 degree
- Maximum Pitch Angle: 6.8 degree
- Maximum Roll Angle: -36.6 degree
- Vehicle Snagging: Yes

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

Figure 3.8. Summary of Results for *NCHRP 350* Test 3-21 simulation (31-in Height Stacked W-Beam Transition, without Bolts).

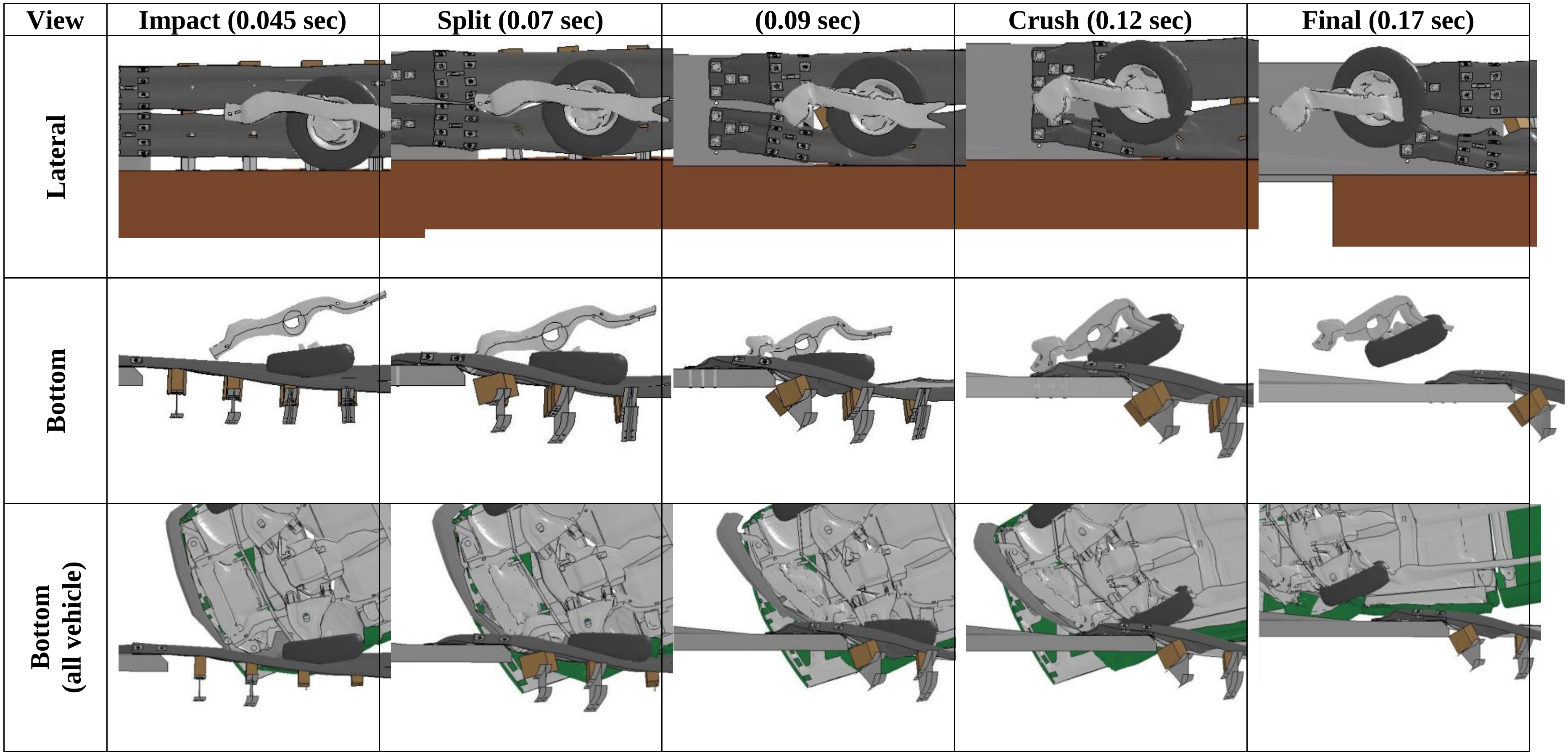


Figure 3.9. Vehicle Snagging Behavior Against Parapet from FE Simulation of 31-in High Stacked W-Beam Transition (without Bolts).

Researchers decided to apply minor modifications to the test article model with the intent to limit the relative displacement of the two rail sections (top rail and rubrail) during the impact event. Rail and rubrail were bolted to the posts in all locations. The hope was that by bolting the rail sections to the posts, the rails were stiffened and were able to contain the impacting vehicle so that no snagging would occur on the concrete parapet. The designation "with bolts" will be used from now on in the report to indicate all rail sections being bolted to posts.

3.1.2 Stacked W-Beam Transition for 31-in Guardrail (with bolts)

Drawing of the 31-in stacked w-beam transition installation with rubrail height increased and with bolted rail in all locations is reported in Figure 3.10.

3.1.2.1 Barrier Performance

Figure 3.11 contains images of the barrier before impact and at final configuration. Figure 3.11(a) and 3.11(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 3.11(b) and 3.11(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. The barrier was impacted 5.25 ft from the end of the concrete parapet, with initial and speed and angle of 62 mph and 25 degrees, respectively.

3.1.2.2 Energy Values

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

Since this is a closed system and energy is conserved, the sum of the kinetic energy, hourglass energy, sliding energy, and internal energy at any time during the simulation should equate to the initial kinetic energy of the vehicle. As shown in Figure 3.12, approximately 48 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). Approximately four percent of the initial kinetic energy is converted into hourglass energy. Approximately 16 percent of the initial kinetic energy is converted into sliding interface energy. Thirty percent of the initial kinetic energy has yet to be dissipated by the system at the time of final impact configuration, mainly due to the remaining velocity of the vehicle.

Tables 3.3 and 3.4 show frames of the computer simulation impact event against the 31-in stacked w-beam transition with respect to different views.

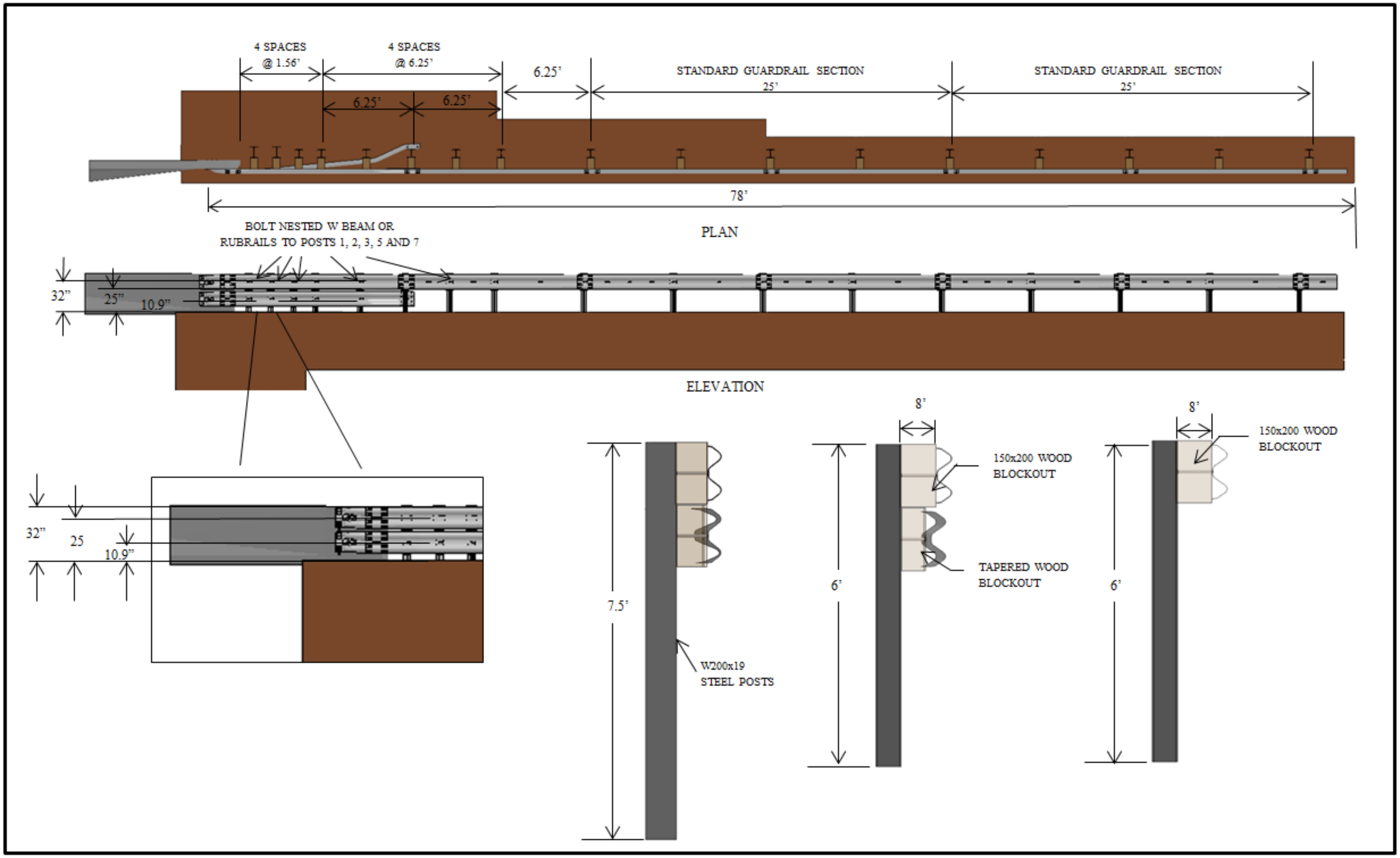
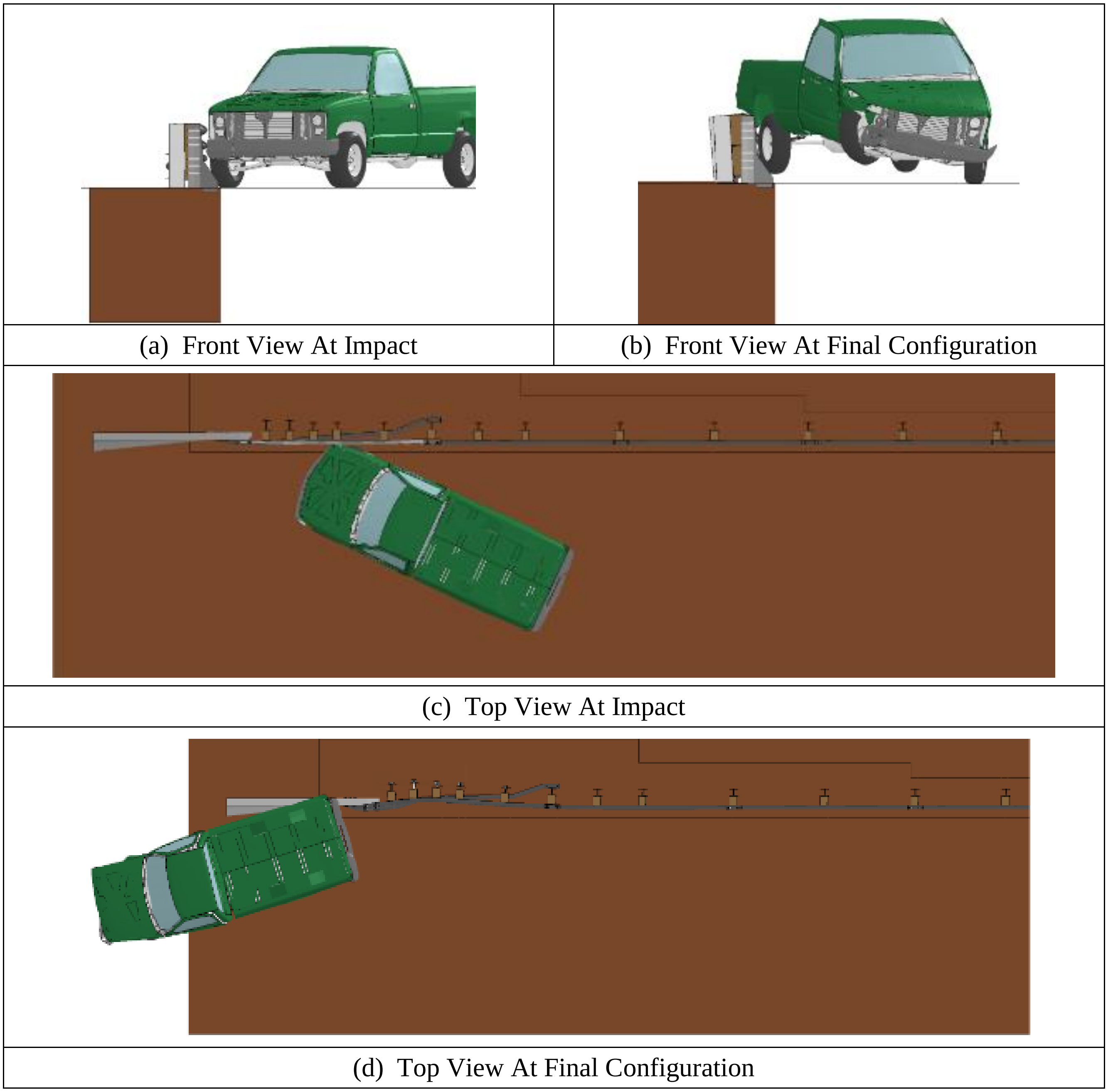


Figure 3.10. Details of the Vertical Wall Transition Installation for Finite Element Computer Model Simulations (31-in, with Bolts).



(a) Front View At Impact

(b) Front View At Final Configuration

(c) Top View At Impact

(d) Top View At Final Configuration

Figure 3.11. Initial and Deflected Shape of Barrier (31-in Height Stacked W-Beam Transition with Bolts).

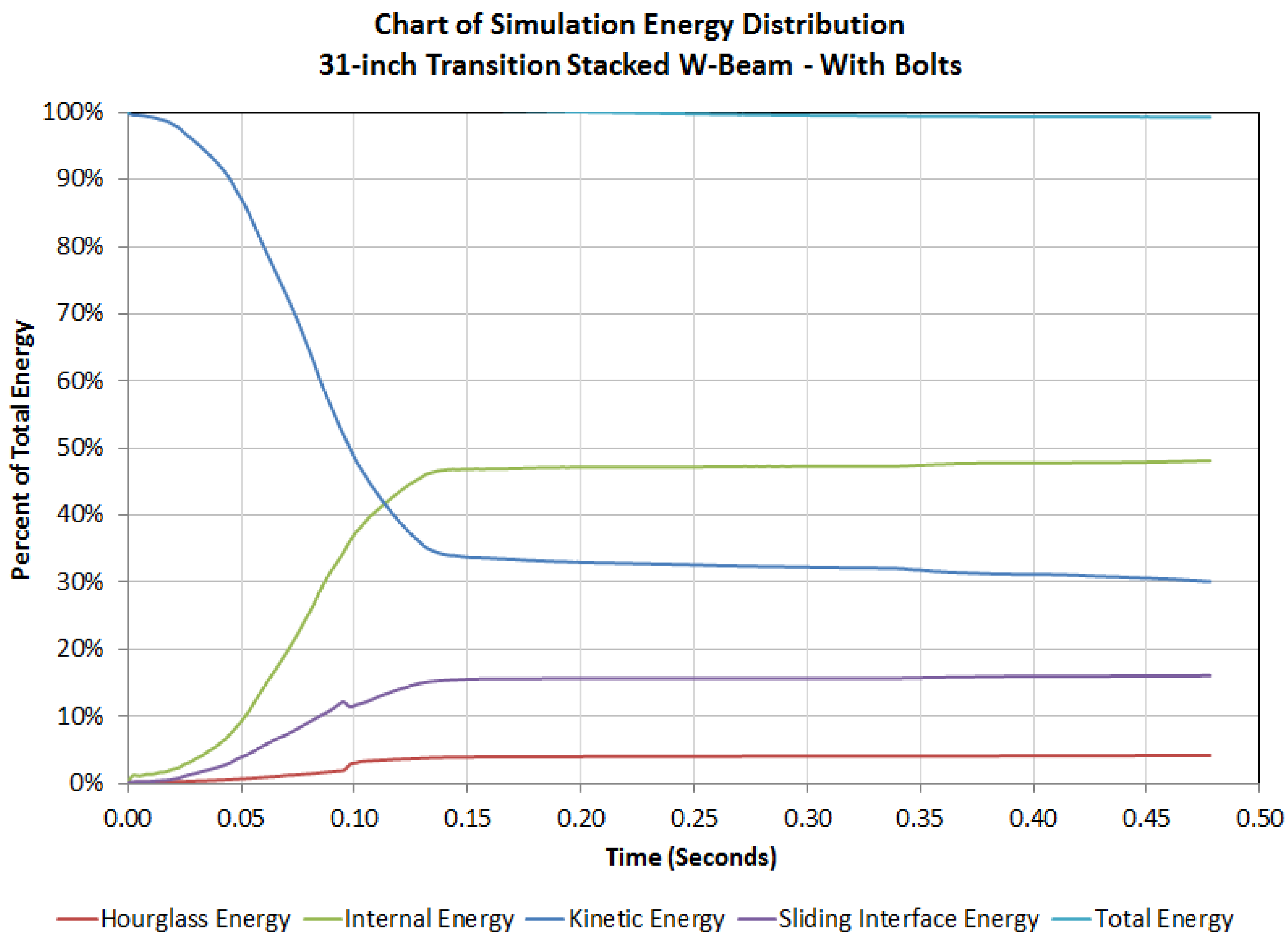


Figure 3.12. Energy Distribution Time History (31-in Height Stacked W-Beam Transition with Bolts).

Table 3.3. Sequential Images of the 2270P Vehicle Interaction with the 31-in Height Stacked W-Beam Transition with Bolts (Top View).

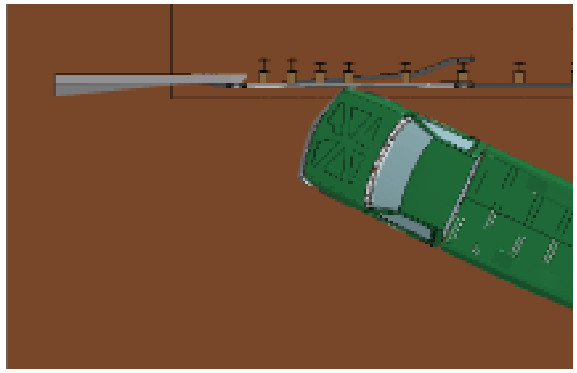
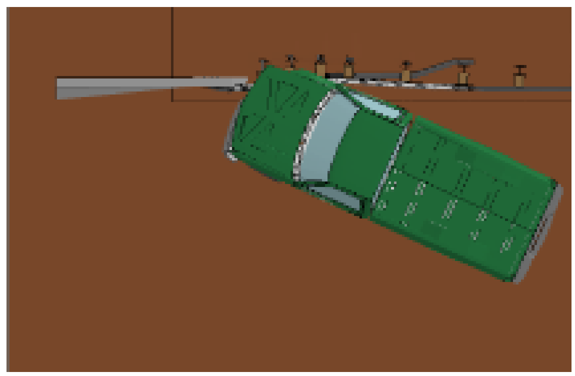
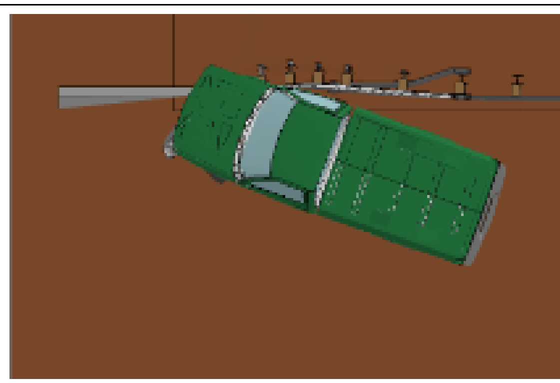
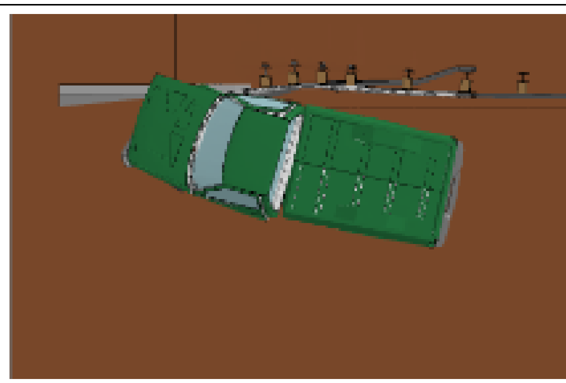
Time (sec)	FE 31-in Rubrail with Bolts
0.000	
0.049	
0.098	
0.145	

Table 3.3. Sequential Images of the 2270P Vehicle Interaction with the 31-in Height Stacked W-Beam Transition with Bolts (Top View) (Continued).

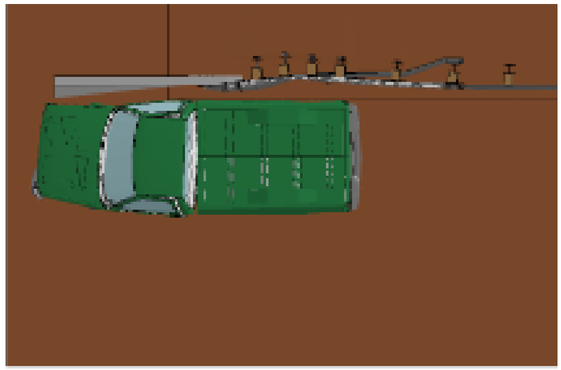
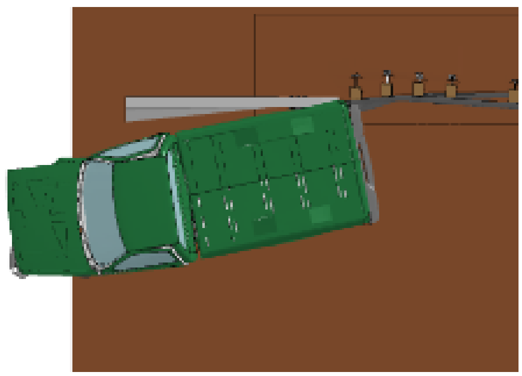
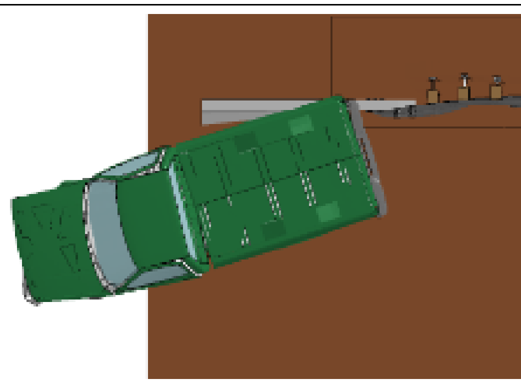
Time (sec)	FE 31-in Rubrail with Bolts
0.245	
0.343	
0.415	

Table 3.4. Sequential Images of the 2000P Vehicle Interaction with the 31-in Height Stacked W-Beam Transition with Bolts (Front View).

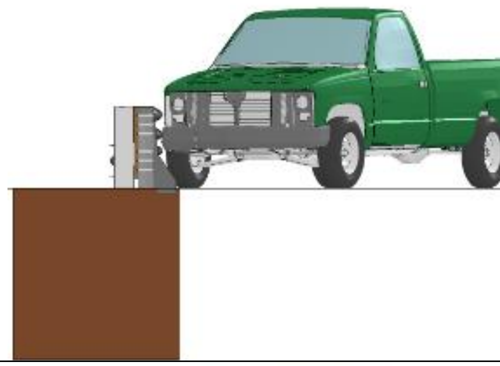
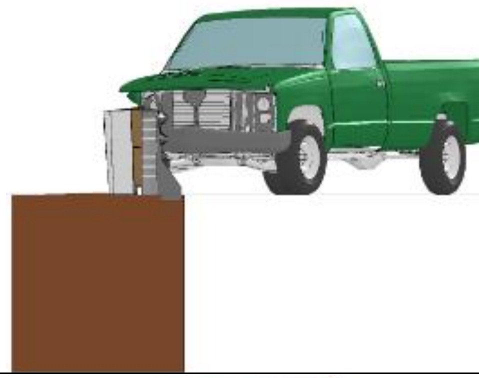
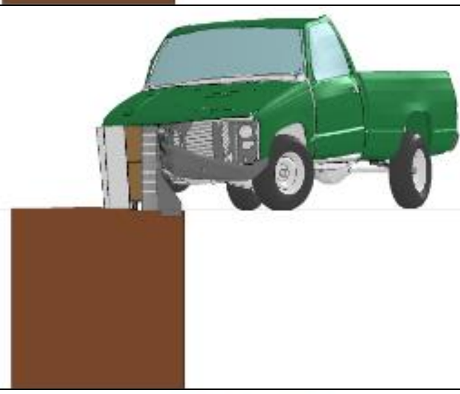
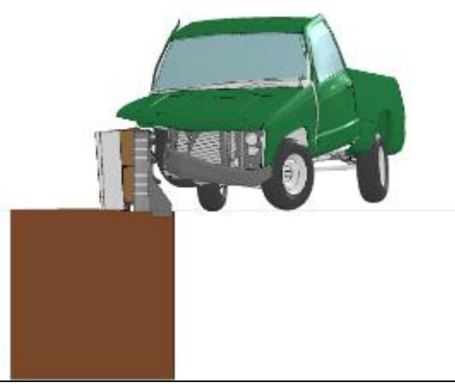
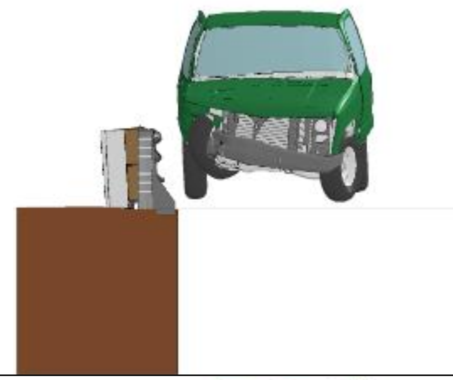
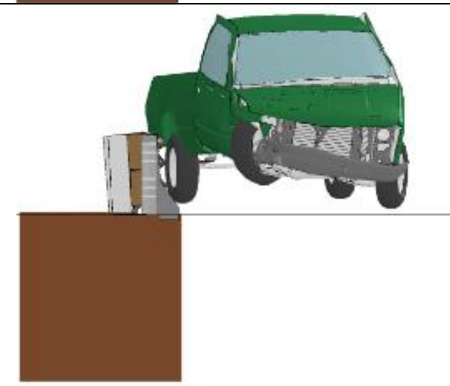
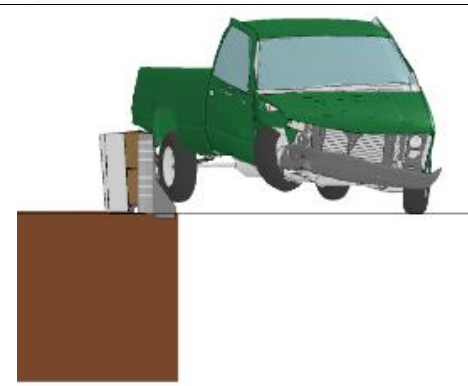
Time (sec)	FE 31-in Rubrail with Bolts
0.000	
0.049	
0.098	
0.145	

Table 3.4. Sequential Images of the 2000P Vehicle Interaction with the 31-in Height Stacked W-Beam Transition with Bolts (Front View) (Continued).

Time (sec)	FE 31-in Rubrail with Bolts
0.245	
0.343	
0.415	

3.1.2.3 Occupant Risk Assessment

The TRAP program was used to evaluate occupant risk factors based on the applicable *MASH* safety evaluation criteria. The modeled 2000 vehicle remained upright during and after the modeled collision event. Figure 3.13 shows vehicle roll, pitch and yaw angles throughout the impact event against 27-in high stacked w-beam transition. Maximum roll, pitch and yaw angles resulted to be -22.4, 6.4, and -44.9 degrees respectively. Occupant impact velocities were evaluated to be 41.34 ft/sec and 28.54 ft/sec in the longitudinal and lateral directions, respectively. Ridedown accelerations were evaluated to be -10.6 g and -10.2 g in the longitudinal and lateral directions, respectively. Angular displacement curves are also reported in Figure 3.14.

Occupant Risk Factors	FE Stacked W-Beam Transition (31-in) – with Bolts
Impact Vel. (ft/sec)	
x-direction	41.34
y-direction	28.54
Ridedown Acc. (g's)	
x-direction	-10.6
y-direction	-10.2

Angles	FE Stacked W-Beam Transition (31-in) – with Bolts
Roll (deg.)	-22.4
Pitch (deg.)	6.4
Yaw (deg.)	-44.9

Figure 3.13. Occupant Risks Values (31-in Height Stacked W-Beam Transition, with Bolts).

3.1.2.4 Surrogate Measure of OCD

Figure 3.15 summarizes measured internal energy of the of the pickup truck floorboard when impacting the 31-in stacked W-beam transition during simulation of NCHRP 350 test 3-21. The internal energy of the floorboard reaches values that are well above the 2,200 N-m passing threshold suggested by Bullard et al. (ref.). Although the internal energy value is lower than the failure limit threshold of 10,700 N-m, it would still be unknown if a realistic resulting OCD would be passing NCHRP 350 requirements.

3.1.2.5 Conclusions

Figure 3.16 summarizes results for NCHRP 350 Test 3-21 simulation with a 2000P vehicle impacting the 31-in high stacked W-beam transition, with raised rubrail and bolted rail sections to posts in all locations. Although the vehicle was contained, redirected, and maintained stability during the impact event, it appeared cleared that vehicle snagging occurred against the rigid parapet. Simulation frame results suggest that the vehicle frame rail did not fully engage the top rail when impacting the test article, due to the fact that the test installation (including the top rail) was raised to 31 inches of height. Although the rubrail was as well increased in height in order to maintain same relative distance from the top rail as in its original design, the rubrail location was still too low to allow vehicle frame rail to engage the rubrail instead. Also, although the rail sections were bolted to posts in all locations to limit relative displacement and maintain limited gap between top nested rail and rubrail, the frame rail still engages the rigid parapet.

Even with the additions of bolts between rail and posts for the article installation increased to 31 inches, the vehicle frame rail impacted the rigid parapet right in between the top nested rail and the rubrail (Figure 3.17). The vehicle frame rail and tire started compressing the rubrail, “opening” an unprotected empty space in the test article through the impact event, until they both impacted the rigid parapet. Snagging was visually evident during the simulation and affected occupant risk values.

Longitudinal occupant impact velocity resulted to be higher than the limit allowed from NCHRP Report 350. In a previous effort, the floorboard internal energy was found to be a good indicator of OCD during impact with rigid barriers. The floorboard internal energy experienced by the 350 pickup truck in the simulation with 31-in stacked w-beam transition with additions of bolts was over the suggested passing limit, giving indication that OCD might not meet acceptable NCHRP 350 deformation requirements.

Due to visual evidence of vehicle snagging against the rigid parapet of the test article, high values (over the allowable limit) of occupant impact velocity and high internal energy in the vehicle floorboard (indication of too high OCD), the researchers believe that the simulation results indicate the 31-in stacked w-beam transition with bolts might not meet the NCHRP Report 350 crashworthiness requirements. This evaluation was made for the 31-in article model with both top rail and rubrail elevated of the same distance and with rail and rubrail sections bolted to posts in all locations. Researchers did not evaluate the case of the 31-in article height with leaving the rubrail at its original location because that would not prevent the vehicle from snagging on the rigid parapet.

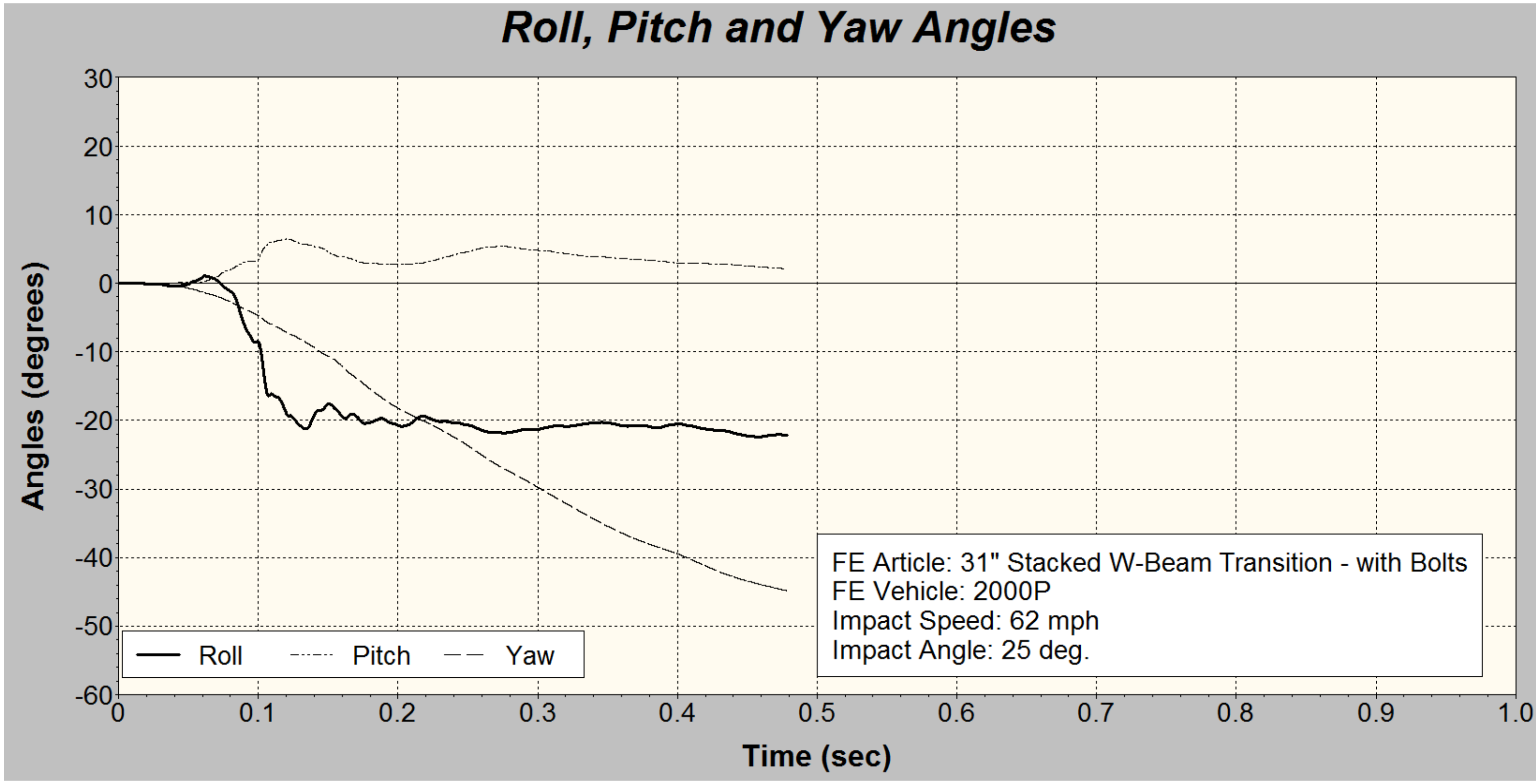


Figure 3.14. Angular Displacements for FE Simulation of the 31-in High Stacked W-Beam Transition (with Bolts).

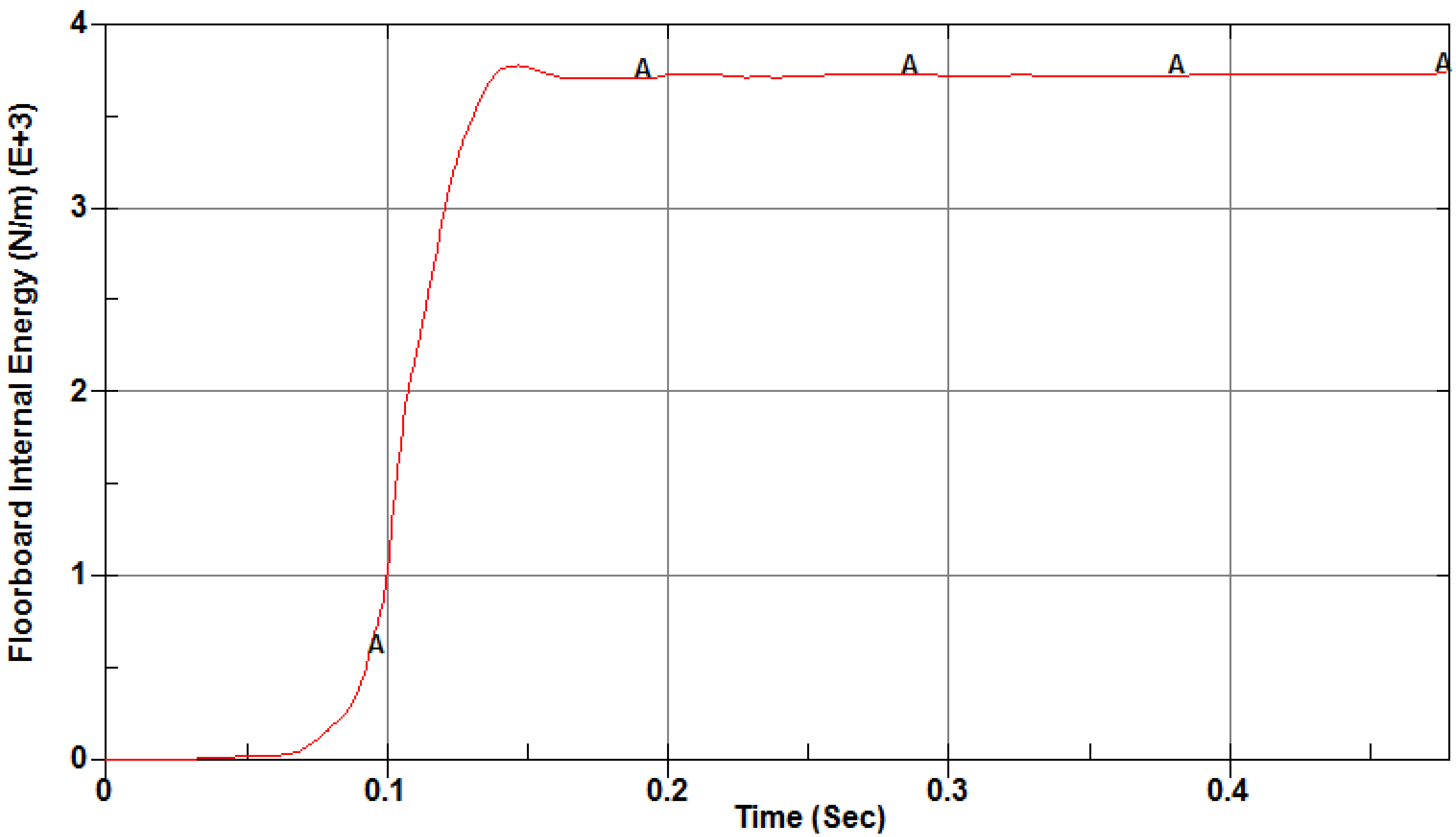
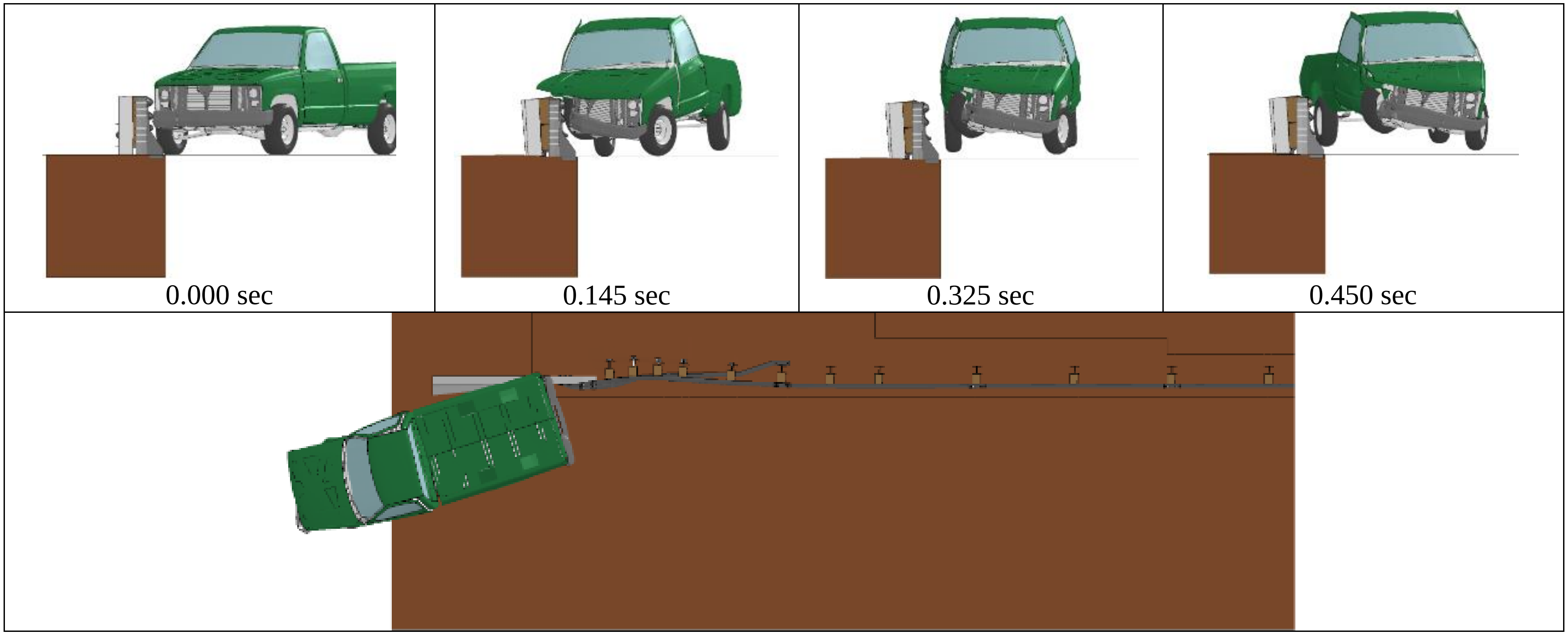


Figure 3.15. Floorboard Internal Energy for NCHRP 350 Test 3-21 with 31-in Stacked W-Beam Transition (with Bolts).



General Information
Test Agency .... Texas A&M Transportation Institute (TTI)
Test Standard Test No..... *NCHRP Report 350* Test 3-21
Date................................ N/A

Test Article
Type .... 31-in Stacked W-Beam Transition , with Bolts
Installation Length............ 78 ft
Material or Key Elements. Stacked W-Beam, 31-in Rail, Rigid Parapet

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

Impact Conditions
Speed................................62.0 mi/h
Angle ....25 degrees
Location/Orientation............5.25 ft from End of Rigid Parapet

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

Occupant Risk Values
Impact Velocity (ft/sec)
x-direction…………………. 41.3
y-direction…………………. 28.5
Ridedown Acceleration (g)
x-direction..........................-10.6
y-direction..........................-10.2

Vehicle Stability
Maximum Yaw Angle .... -44.9degree
Maximum Pitch Angle .... 6.4 degree
Maximum Roll Angle .... -22.4 degree
Vehicle Snagging...................... Yes

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

Figure 3.16. Summary of Results for *MASH* Test 3-11simulation (31" Height Stacked W-Beam Transition with bolts).

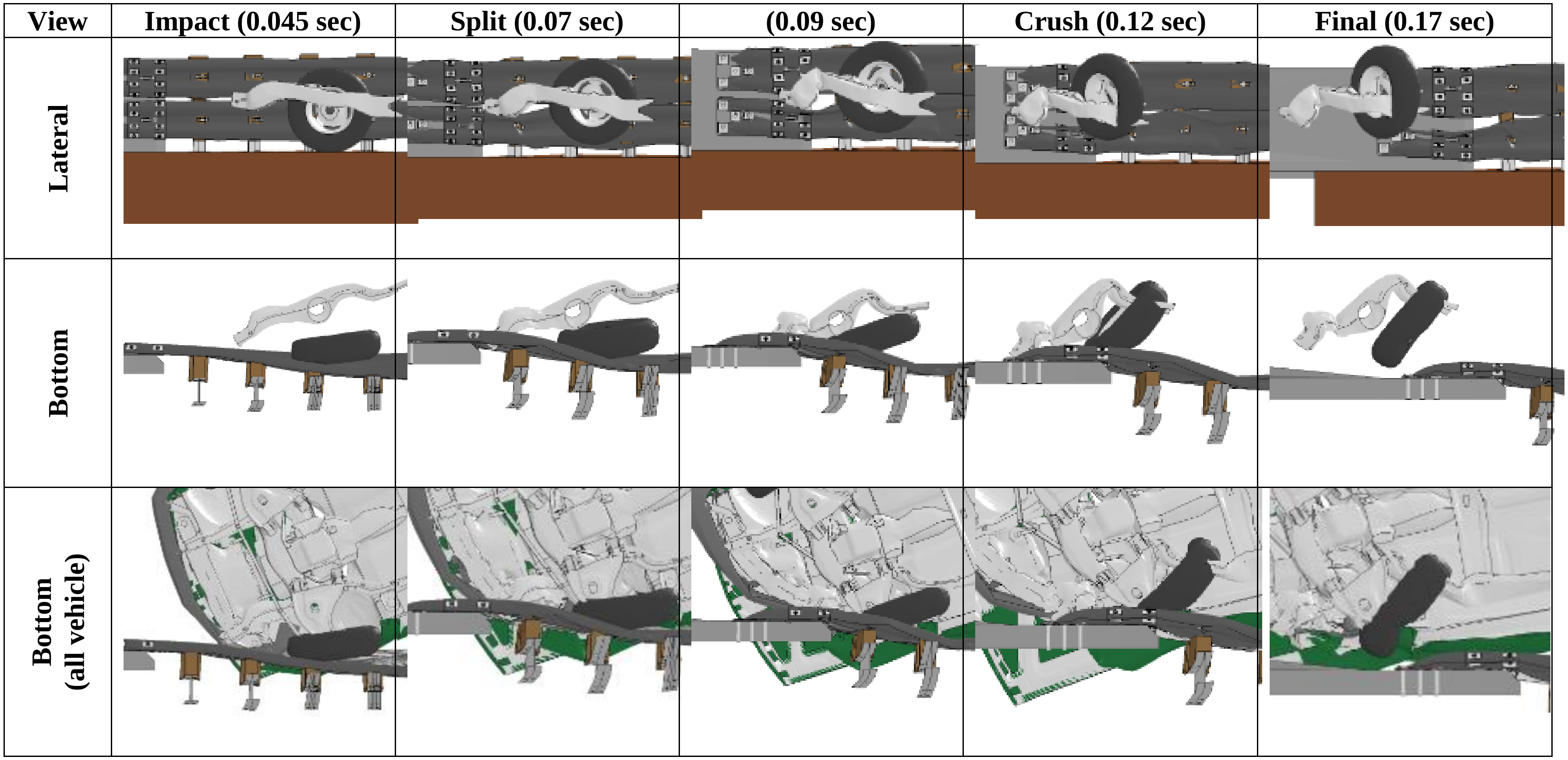


Figure 3.17. Vehicle Snagging Behavior Against Parapet from FE Simulation of 31-in High Stacked W-Beam Transition (with Bolts).

3.1.3 Comparison of Vehicle Interaction with the 31-in Stacked W-Beam Transition Designs

Tables 3.5 and 3.6 offer a direct comparison of sequential images extracted from simulations of the 2000P vehicle impacting the 31-in stacked w-beam transition designs (without and with rail sections bolted to posts). Tables 3.7 and 3.8 show the vehicle frame rail and tire impact dynamics and interaction with the rail and rubrail sections that ultimately lead to snagging of the vehicle against the rigid parapet.

Table 3.5. Sequential Images Comparison of 2000P Vehicle Interaction with the 31-in Height Stacked W-Beam Transition Designs with and Without Bolts (Top View).

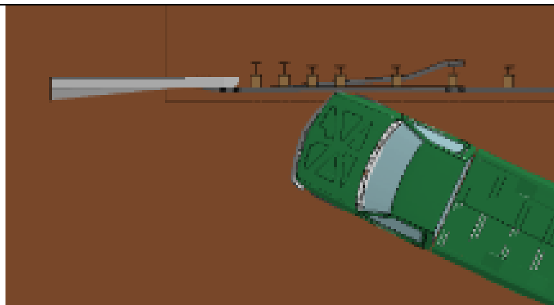
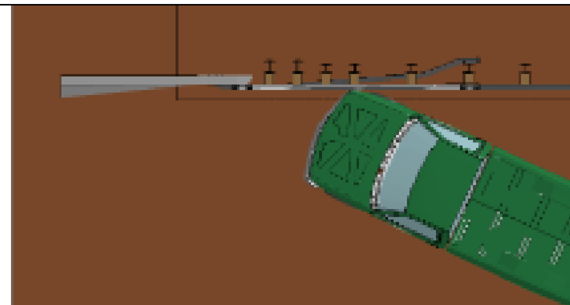
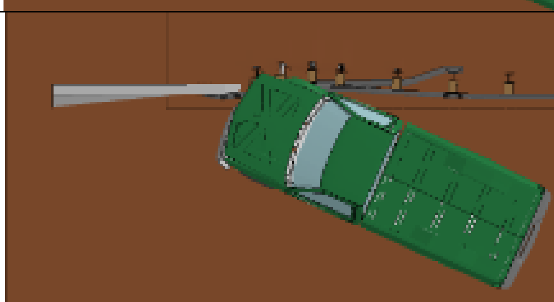
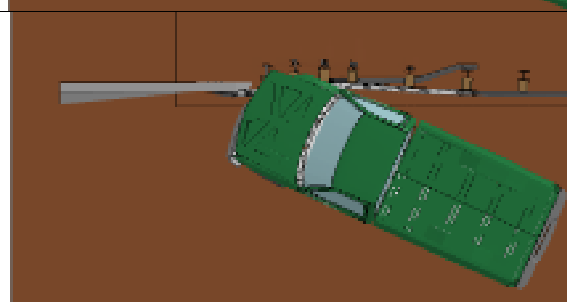
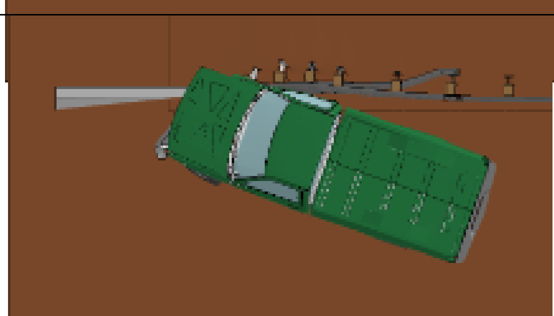
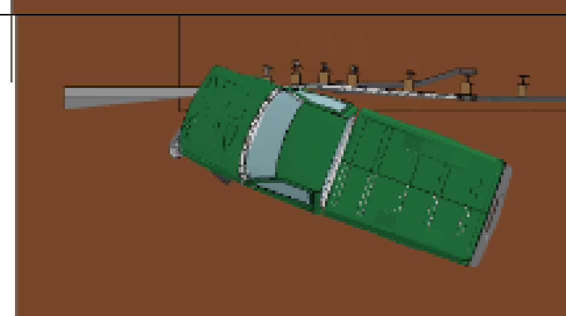
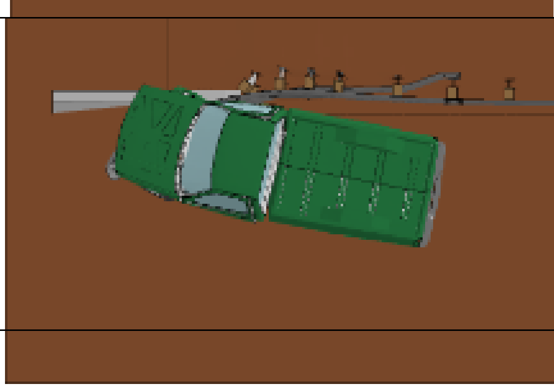
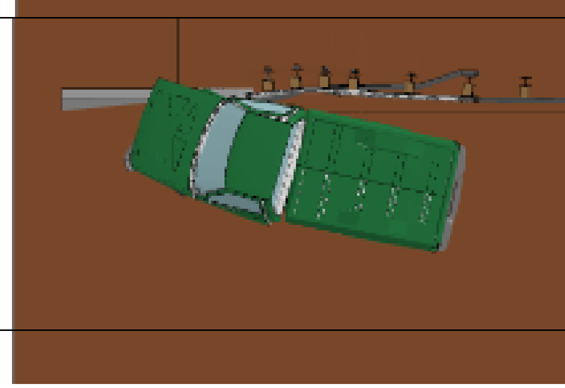
Time (sec)	FE 31-in Height Stacked W-Beam Transition NCHRP Report 350 (2000P) Without Bolts	FE 31-in Height Stacked W-Beam Transition NCHRP Report 350 (2000P) With Bolts
0.000		
0.049		
0.098		
0.145		

Table 3.5. Sequential Images Comparison of 2000P Vehicle Interaction with the 31-in Height Stacked W-Beam Transition Designs with and Without Bolts (Top View) (Continued).

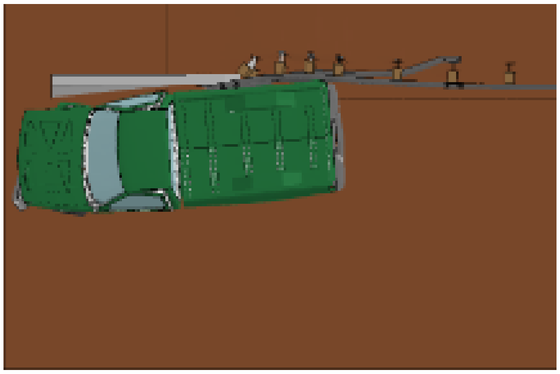
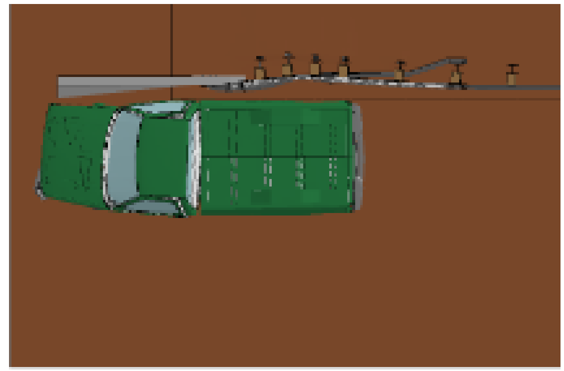
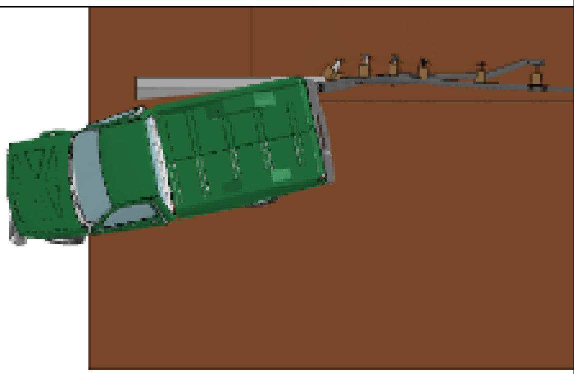
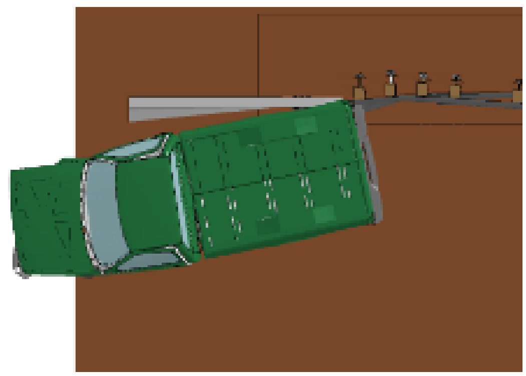
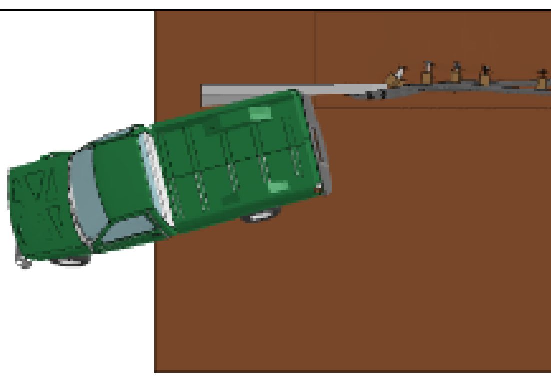
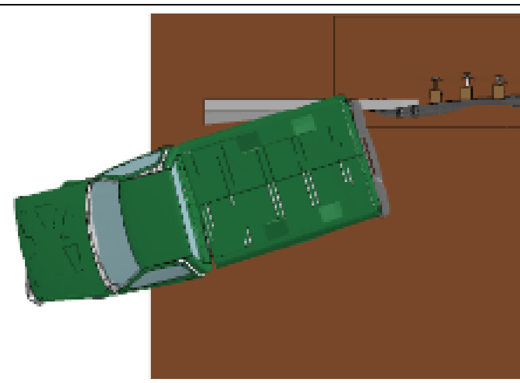
Time (sec)	FE 31-in Height Stacked W-Beam Transition NCHRP Report 350 (2000P) Without Bolts	FE 31-in Height Stacked W-Beam Transition NCHRP Report 350 (2000P) With Bolts
0.245		
0.343		
0.415		

Table 3.6. Sequential Images Comparison of 2000P Vehicle Interaction with the 31-in Height Stacked W-Beam Transition Designs with and Without Bolts (Front View).

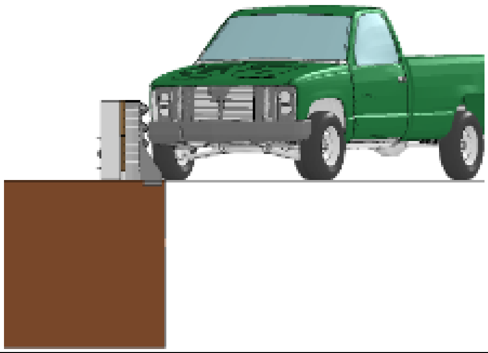
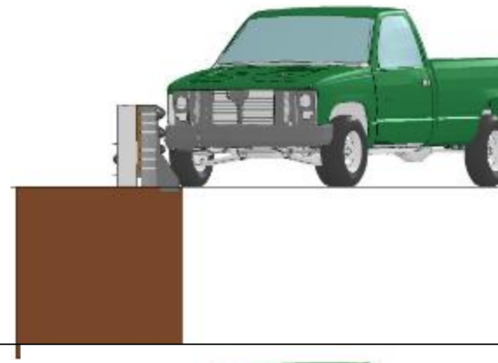
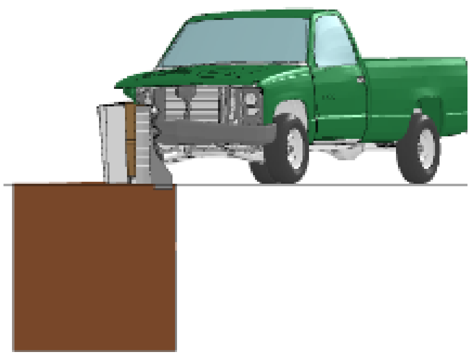
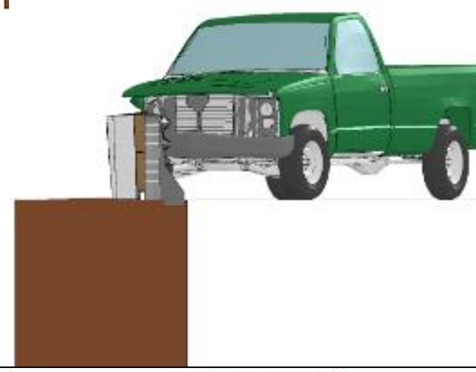
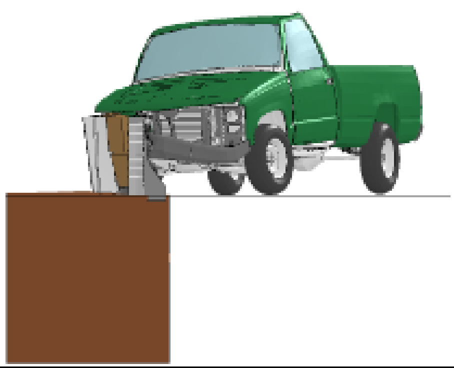
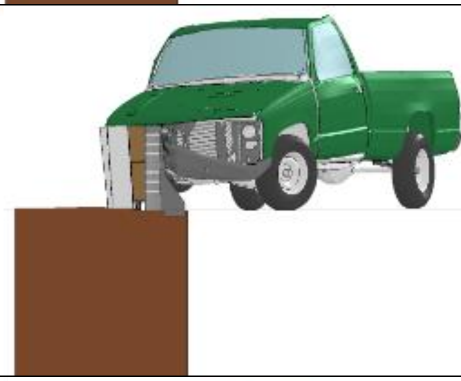
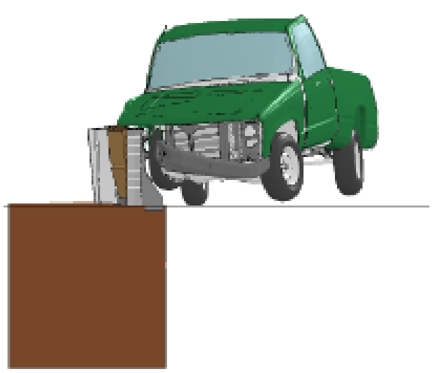
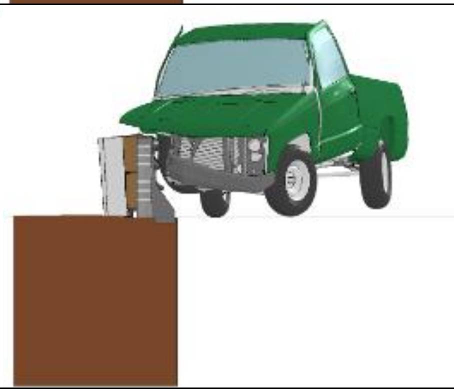
Time (sec)	FE 31-in Height Stacked W-Beam Transition NCHRP Report 350 (2000P) Without Bolts	FE 31-in Height Stacked W-Beam Transition NCHRP Report 350 (2000P) With Bolts
0.000		
0.049		
0.098		
0.145		

Table 3.6. Sequential Images Comparison of 2000P Vehicle Interaction with the 31-in Height Stacked W-Beam Transition Designs with and Without Bolts (Front View) (Continued).

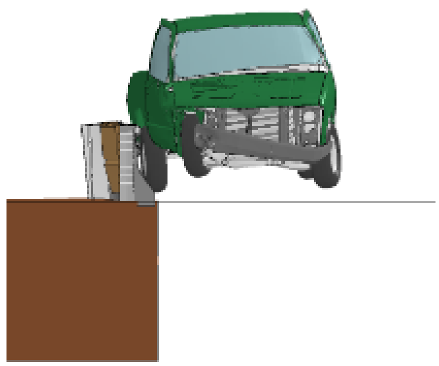
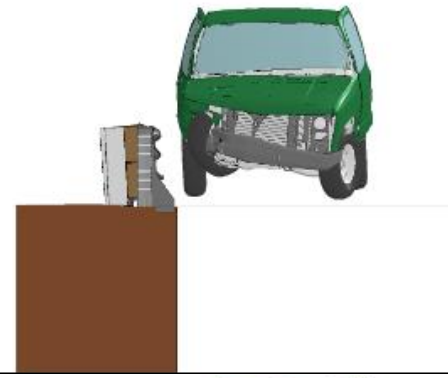
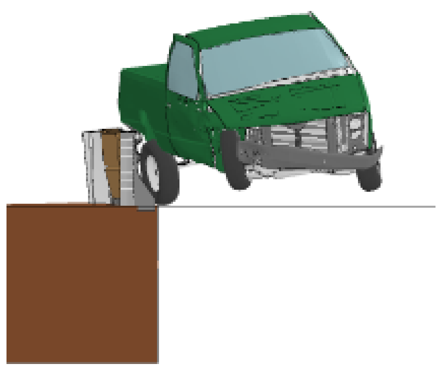
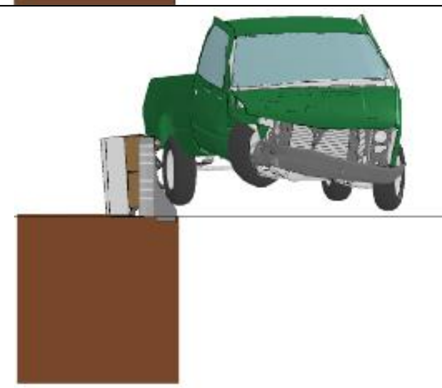
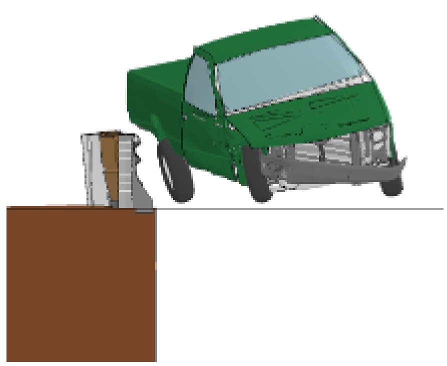
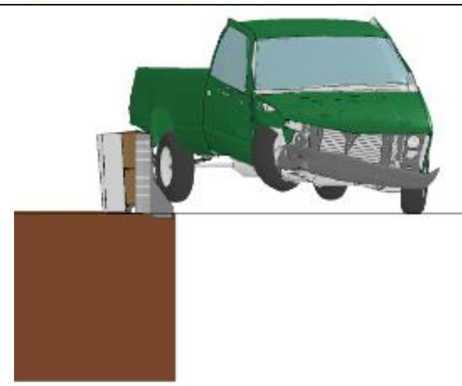
Time (sec)	FE 31-in Height Stacked W-Beam Transition NCHRP Report 350 (2000P) Without Bolts	FE 31-in Height Stacked W-Beam Transition NCHRP Report 350 (2000P) With Bolts
0.245		
0.343		
0.415		

Table 3.7. Sequential Images Comparison of 2000P Vehicle Interaction with the Rail Sections and the Rigid Parapet for the Stacked W-Beam Transition Designs (Lateral View).

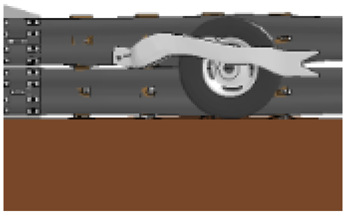
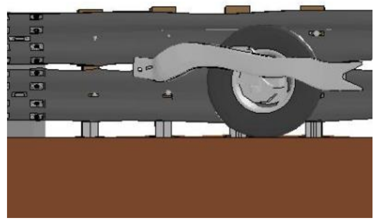
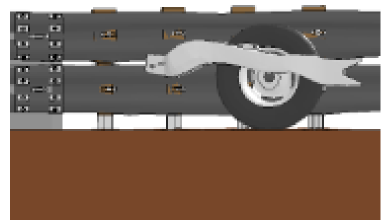
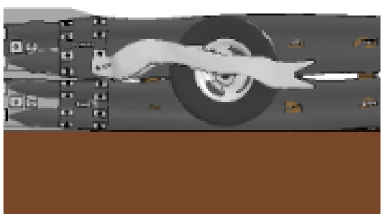
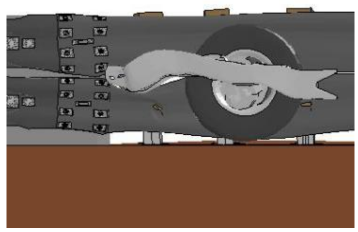
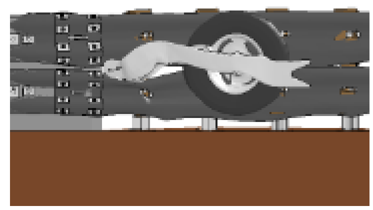
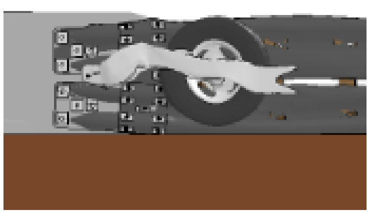
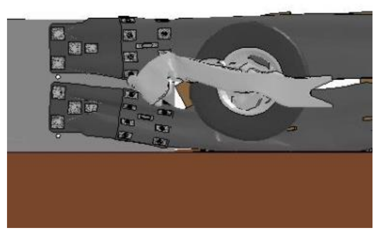
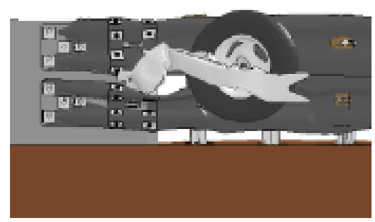
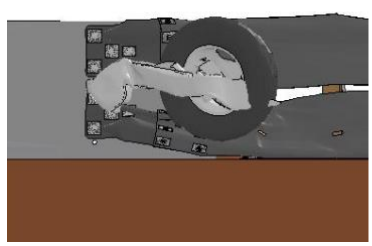
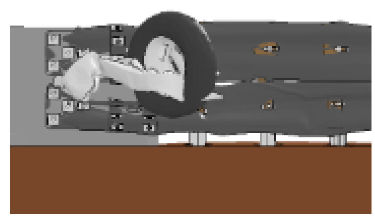
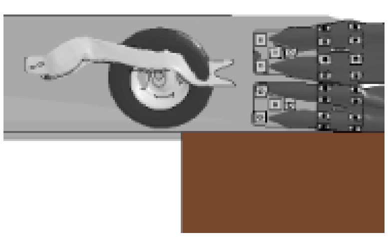
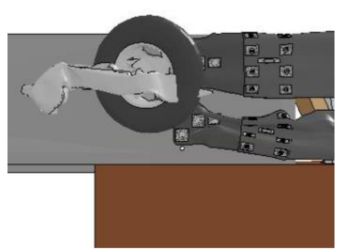
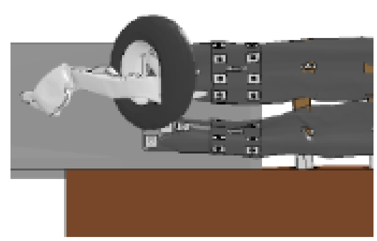
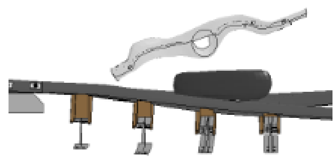
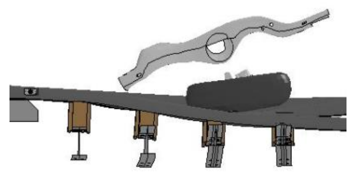
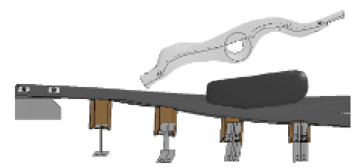
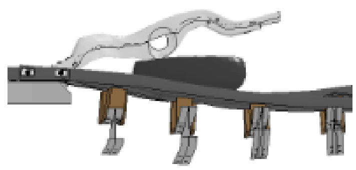
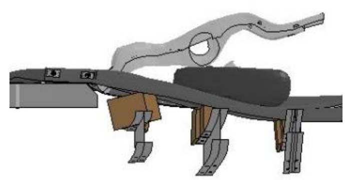
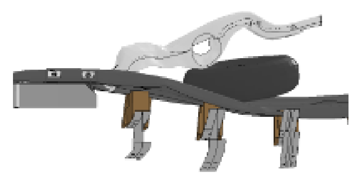
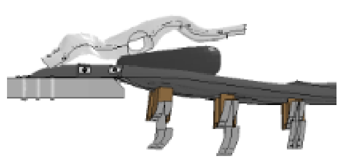
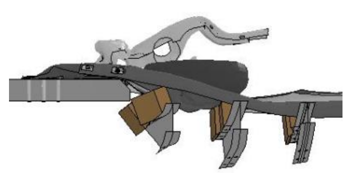
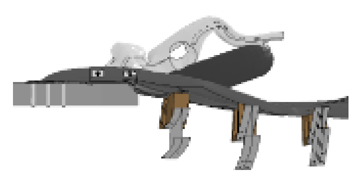
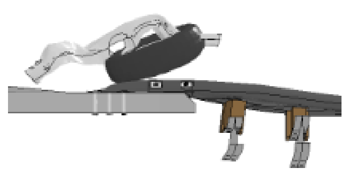
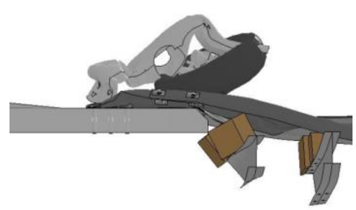
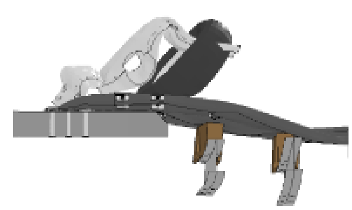
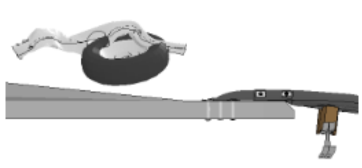
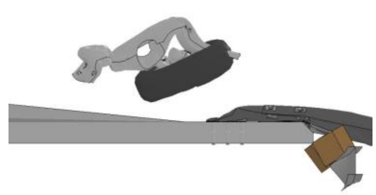
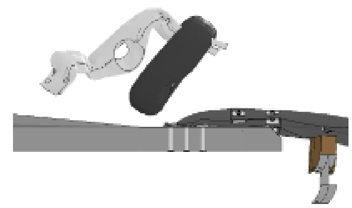
Time (sec)	FE 27-in Height Stacked W-Beam Transition NCHRP Report 350 Validation (20000P)	FE 31-in Height Stacked W-Beam Transition NCHRP Report 350, without Bolts (20000P)	FE 31-in Height Stacked W-Beam Transition NCHRP Report 350, with Bolts (20000P)
0.045			
0.07			
0.09			
0.12			
0.17			

Table 3.8. Sequential Images Comparison of 2000P Vehicle Interaction with the Rail Sections and the Rigid Parapet for the Stacked W-Beam Transition Designs (Bottom View).

Time (sec)	FE 27-in Height Stacked W-Beam Transition NCHRP Report 350 Validation (20000P)	FE 31-in Height Stacked W-Beam Transition NCHRP Report 350, without Bolts (20000P)	FE 31-in Height Stacked W-Beam Transition NCHRP Report 350, with Bolts (20000P)
0.045			
0.07			
0.09			
0.12			
0.17			

4. SUMMARY AND CONCLUSIONS

4.1 SUMMARY

A stacked W-Beam guardrail transition to a bridge rail has been successfully tested in accordance with the NCHRP Report 350 criteria with a guardrail height of 27 5/8" (FHWA Eligibility Letter B-65, 2000). This transition uses a nested w-beam to stiffen the rail and a w-beam rub rail to reduce the potential for snagging on the end of the bridge rail. With many states raising the height of their w-beam guardrails to 31 inches to improve its performance, a stacked w-beam transition is desired for the 31 inches guardrail systems as a simpler method of transition without unique rail elements.

The objectives of this study were to identify design modifications necessary to adapt a stacked w-beam guardrail transition design for 27 inches (27 and 5/8 inches) guardrail for use with a 31-in guardrail system and to use computer simulations to determine the transition crashworthiness according to NCHRP Report 350 criteria. This project was expected to culminate with a request for an FHWA eligibility letter for this design.

When raising the guardrail to 31-in, two options for the placement of the rubrail were considered as feasible:

- The first was to increase the height of the rubrail along with the guardrail, which would lead to no difference in separation between the rubrail and the guardrail from the 27 and 5/8-in to the 31-in;
- The second option was to only increase the guardrail to 31-in and leave the rubrail in its original placement. This second option would increase the separation of the rubrail and guardrail by approximately 3 and 3/8-in.

Researchers have developed a finite element computer model of the existing 27-in high stacked w-beam transition and have successfully validated it against NCHRP Test 3-21 404211-12 performed previously at TTI. Next, the FE model was raised so that the top rail would be at 31 inches from ground and the rubrail section was also moved up in height to maintain the original relative distance from the top nested rail section.

4.2 31-IN TRANSITION WITHOUT BOLTS

Initially, no modifications were made with respect to the original design of the 27-in article, besides raising the rail and rubrail height. This model was referred to as the 31-in without bolts throughout the all report. This refers to the fact that posts 1, 2, 3, 5, and 7 were not bolted to the top rail sections and that posts 1, 2, 3 ad 5 were not bolted to the rubrail section. When evaluated the crashworthiness of the 31-in stacked w-beam transition without bolts with respect to NCHRP Report 350 Test 3-21, it was evident that vehicle snagging occurred at the rigid parapet.

Although the vehicle was contained, redirected, and maintained stability during the impact event, simulation suggested that the vehicle frame rail did not fully engage the top rail when impacting the test article, due to the fact that the test installation (including the top rail) was raised to 31 inches of height. Although the rubrail was as well increased in height in order to maintain same relative distance from the top rail as in its original design, the rubrail location was still too low to allow vehicle frame rail to engage the rubrail instead.

Although still occupant impact velocities and ridedown accelerations were contained within NCHRP Report 350 limit criteria, researchers decided to investigate OCD through evaluation of the internal energy level measured in the vehicle floorboard. The floorboard internal energy experienced by the 350 pickup truck in the simulation with 31-in stacked w-beam transition without bolts was just over the suggested passing limit of 2,200 N/m, giving indication that OCD might not meet acceptable NCHRP 350 deformation requirements. Due to visual evidence of vehicle snagging against the rigid parapet of the test article, high values (next to the allowable limit) of occupant risks and high internal energy in the vehicle floorboard (indication of too high OCD), the researchers believe that the simulation results indicate the 31-in stacked w-beam transition without bolts might not pass the NCHRP Report 350 crashworthiness requirements.

Snagging did not occur when the test article total height was 27 inches, because the vehicle frame rail did impact the nested top rail and was fully contained and protected by it when approaching the rigid parapet.

Due to visual evidence of vehicle snagging against the rigid parapet of the test article, high values (next to the allowable limit) of occupant risks and high internal energy in the vehicle floorboard (indication of too high OCD), the researchers believe that the simulation results indicate the 31-in stacked w-beam transition without bolts might not pass the NCHRP Report 350 crashworthiness requirements. Researchers did not evaluate the case of the 31-in article height with leaving the rubrail at its original location because that would not prevent the vehicle from snagging on the rigid parapet.

4.3 31-IN TRANSITION WITH BOLTS

Researchers decided to apply minor modifications to the test article model with the intent to limit the relative displacement of the two rail sections (top rail and rubrail) during the impact event. Rail and rubrail were bolted to the posts in all locations. The hope was that by bolting the rail sections to the posts, the rails were stiffened and were able to contain the impacting vehicle so that no snagging would occur on the concrete parapet.

This model was referred to as the 31-in with bolts throughout the all report. This refers to the fact that posts 1, 2, 3, 5, and 7 were now bolted to the top rail sections and that posts 1, 2, 3 ad 5 were now bolted to the rubrail section. When evaluated the crashworthiness of the 31-in stacked w-beam transition with bolts with respect to NCHRP Report 350 Test 3-21, it was evident that still vehicle snagging occurred at the rigid parapet.

Although the vehicle was contained, redirected, and maintained stability during the impact event, it appeared cleared that vehicle snagging occurred against the rigid parapet. Simulation frame results suggest that the vehicle frame rail still did not fully engage the top rail when impacting the test article, due to the fact that the test installation (including the top rail) was raised to 31 inches of height and rail sections were bolted to posts in all locations. Although the rubrail was as well increased in height in order to maintain same relative distance from the top rail as in its original design, the rubrail location was still too low to allow vehicle frame rail to engage the rubrail instead. Also, although the rail sections were bolted to posts in all locations to limit relative displacement and maintain limited gap between top nested rail and rubrail

Even with the additions of bolts between rail and posts for the article installation increased to 31 inches, the vehicle frame rail impacted the rigid parapet right in between the top nested rail and the rubrail. The vehicle frame rail and tire started compressing the rubrail, "opening" an unprotected empty space in the test article through the impact event, until they both impacted the rigid parapet. Snagging was visually evident during the simulation and affected occupant risks values.

Longitudinal occupant impact velocity resulted to be higher than the limit allowed from NCHRP Report 350. The floorboard internal energy experienced by the 350 pickup truck in the simulation with 31-in stacked w-beam transition with additions of bolts was over the suggested passing limit, giving indication that OCD might not meet acceptable NCHRP 350 deformation requirements.

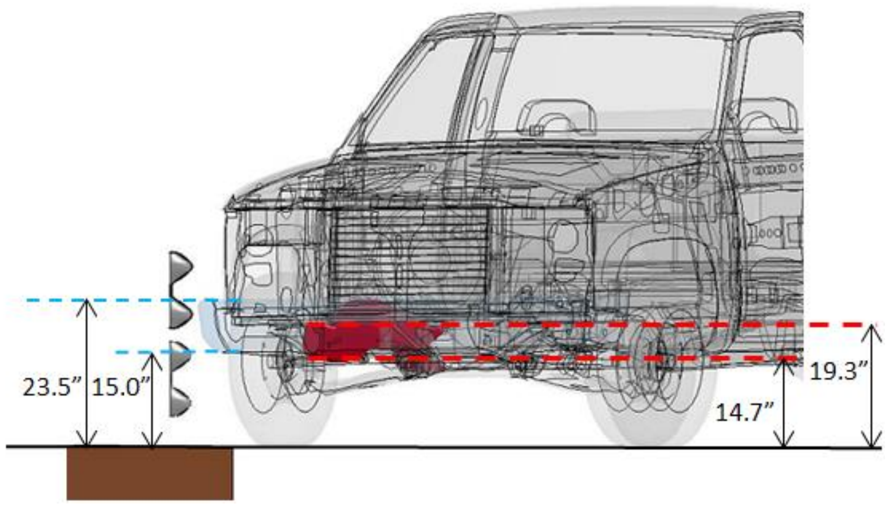
Due to visual evidence of vehicle snagging against the rigid parapet of the test article, high values (over the allowable limit) of occupant impact velocity and high internal energy in the vehicle floorboard (indication of too high OCD), the researchers believe that the simulation results indicate the 31-in stacked w-beam transition with bolts might not pass the NCHRP Report 350 crashworthiness requirements. This evaluation was made for the 31-in article model with both top rail and rubrail elevated of the same distance and with rail and rubrail sections bolted to posts in all locations. Researchers did not evaluate the case of the 31-in article height with leaving the rubrail at its original location because that would not prevent the vehicle from snagging on the rigid parapet.

4.4 CONCLUSIONS

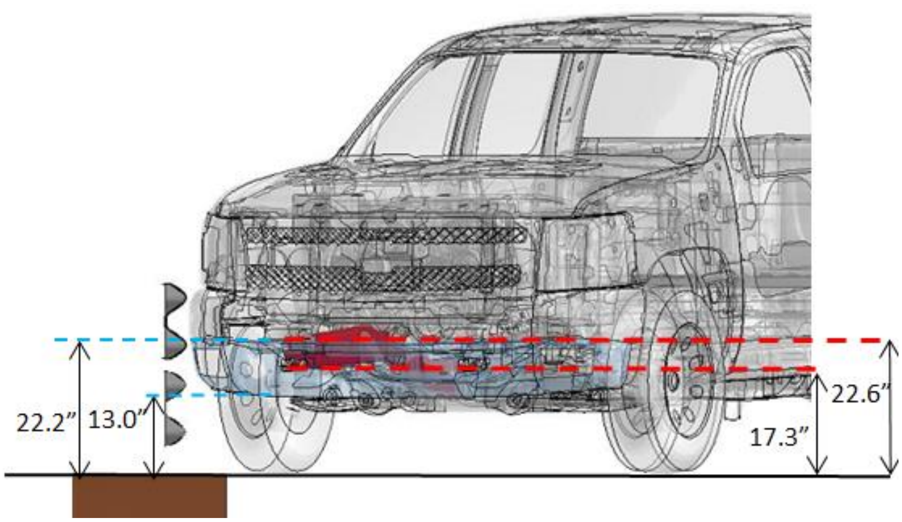
Two possible 31-in stacked w-beam transition designs were investigated to evaluate the crashworthiness of the test article with respect to NCHRP Report 350 crashworthiness criteria. Finite element computer simulation investigation suggests that both designs might not meet the NCHRP Report 350 crashworthiness requirements due to severe snagging of the vehicle against the rigid parapet to which the transition is connected. Snagging occurrence is related to the relative height of the vehicle frame rail which does not allow the frame to fully engage with the top nested rail sections during the impact event (Figure 4.1 (a)). As a consequence, with both 31-in transition designs, the 2000P Report 350 pickup truck vehicle frame rail and tire snagged against the rigid parapet in between the top rail and the rubrail. Due to these conclusions, it is

TTI recommendation not to pursue request for an FHWA eligibility letter for these designs, through computer simulations.

Due to the difference in frame rail height geometry, researchers suggest investigation of the 31-in stacked w-beam transition designs crashworthiness with the 2270P MASH pickup truck vehicle model. As shown in Figure 4.1 (b), the 2270P frame rail top height is approximately three inches higher than the 2000P frame rail. That could suggest that the 2270P frame rail might be able to better engage the top nested w-beam section of the article, reducing the probability of vehicle snagging against the rigid parapet. Such investigations would have to be evaluated under a study using MASH criteria. Researchers also suggest including evaluation MASH Test 3-20 (1100C, 62mph, and 25 deg.) to account for increased impact angle and impact severity. This would have the potential to suggest a 31-in stacked w-beam transition prone to meet MASH crashworthiness criteria.



(a) Report 350 Pickup Truck Model (2000P)



(b) MASH Pickup Truck Model (2270P)

Figure 4.1. Vehicle Frame Rail and Bumper Relative Position with respect to the 31-in High Stacked W-Beam Transition Design with Rubrail Up.

7. REFERENCES

1. Buth, C.E., Menges, W.L., and Schoeneman, S.K. (2000), *NCHRP Report 350 Assessment of Existing Roadside Safety Hardware*, FHWA-RD-01-042, Texas Transportation Institute, College Station, TX.

2. FHWA Acceptance Letter B-65 (2000), *Report 350 Acceptance of W-Beam Transition to a Vertical Concrete Parapet*, http://safety.fhwa.dot.gov/roadway_dept/policy_guide/road_hardware/listing.cfm?code=long, last retrieved January 22nd 2013.

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4. National Crash Analysis Center. *Finite Element Model Archive*. Accessed April, 2014 http://www.ncac.gwu.edu/

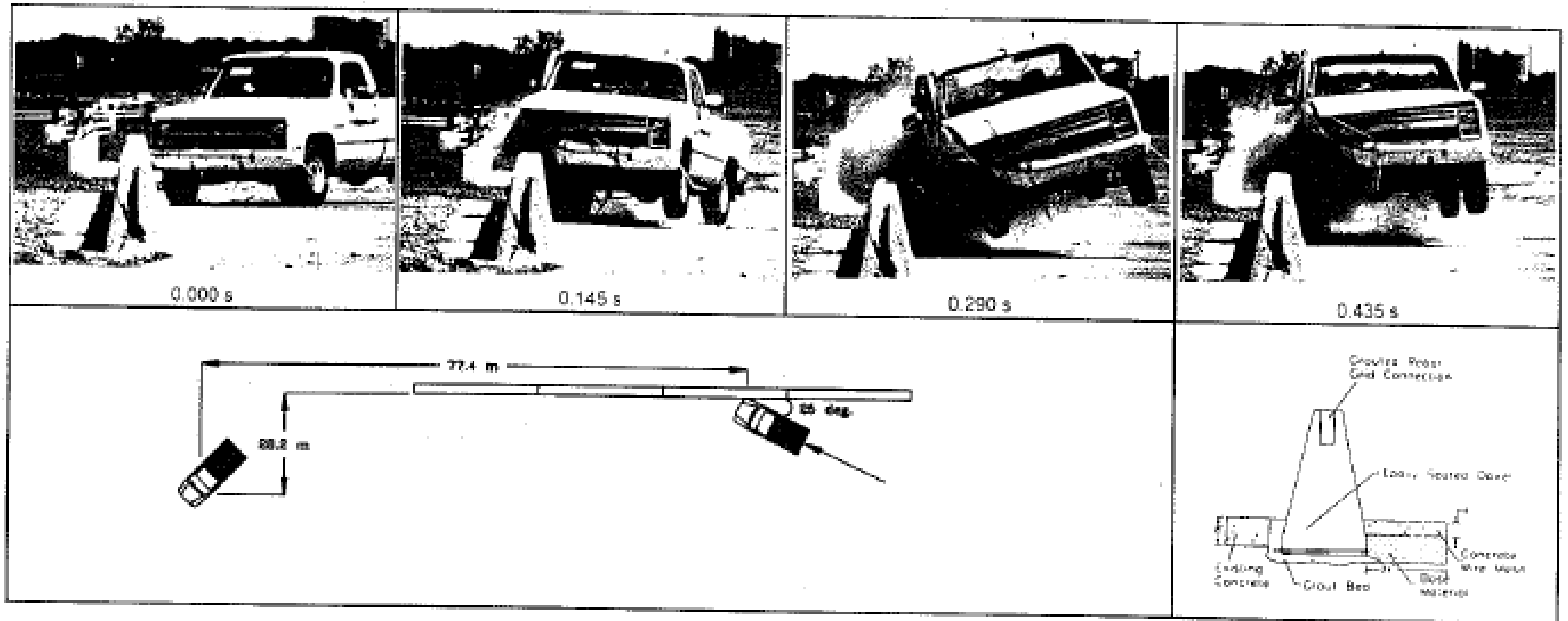
5. Ray, M.H., Plaxico, C., Anghileri, M., Mongiardini, M. Development of Verification and Validation Procedures for Computer Simulation Use in Roadside Safety Applications. National Cooperative Highway Research Program Report 22-24, *Transportation Research Board*, National Research Council, Washington,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

APPENDIX A: VALIDATION OF THE COMPUTER MODEL OF THE 350 PICKUP TRUCK VEHICLE

This Appendix contains computer simulation results that support validation of the FE model of the Report 350 pickup truck (2000P). Impact event of a 2000P vehicle against a single slope barrier was replicated with computer simulations and results were compared to test outcomes to determine validation of the FE model. Validation investigation was developed with respect to the following:

- Vehicle containment and redirection after the impact event;
- Vehicle stability and angular displacements throughout the impact event (roll, pitch, and yaw);
- Occupant risk values;
- RSVVP evaluation (single and multichannel comparison of acceleration and angle rate curves)

Computer FE results compare favorably to the outcomes of the full-scale crash test. The FE model of the Report 350 pickup truck (2000P) can be considered validated and ready for use in predictive simulations.



21

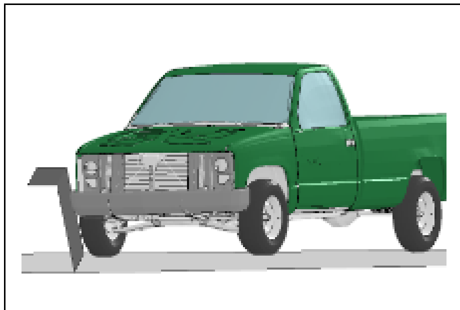
General Information	
Test Agency	Texas Transportation Institute
Test No.	7147-15
Date	05/03/93
Test Article	
Type	Bridge Rail
	Single Slope Concrete
Installation Length (m)	36.6 (120 ft)
Size and/or Dimension and Material of Key Elements	813-mm- (32-in-) High Concrete
Soil Type and Condition	N/A
Test Vehicle	
Type	Production Model
Designation	2000 P
Model	1985 Chevrolet Custom
Mass (kg) Curb	1993 (4390 lb)
Test Inertial	2000 (4405 lb)
Dummy	76 (167 lb)
Gross Static	2076 (4573 lb)

Impact Conditions	
Speed (km/h)	97.2 (60.4 mi/h)
Angle (deg)	25.5
Exit Conditions	
Speed (km/h)	76.6 (47.6 mi/h)
Angle (deg)	3.3
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	5.4 (17.7 ft/s)
y-direction	7.8 (25.6 ft/s)
THIV (optional)	
Ridedown Accelerations (g's)	
x-direction	-6.1
y-direction	-12.6
PHD (optional)	
ASI (optional)	
Max. 0.050-s Averages (g's)	
x-direction	-7.3
y-direction	-13.3
z-direction	-5.6

Test Article Deflections (mm)	
Dynamic	N/A
Permanent	6 (0.3 in)
Vehicle Damage	
Exterior	
VDS	01RD5
CDC	01FREK2 & 01RDEW2
Interior	
OCDI	RF0020000
Maximum Exterior Vehicle Crush (mm)	409 (16.1 in)
Max. Occ. Compart. Deformation (mm)	140 (5.5 in)
Post-Impact Behavior	
Max. Roll Angle (deg)	30
Max. Pitch Angle (deg)	7
Max. Yaw Angle (deg)	40

Figure 11. Summary of results for test 7147-15.

Figure A.1. Summary of Results for Test 471470 (Single Slope Barrier).



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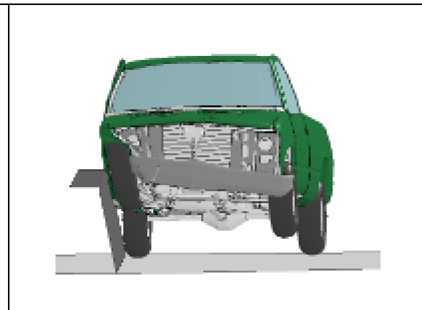

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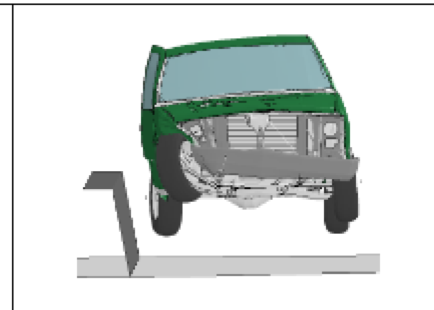

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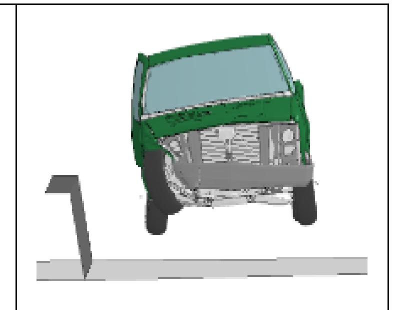

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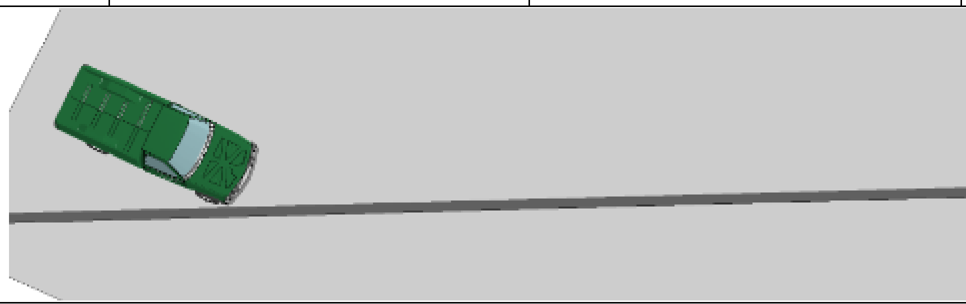


General Information
- Test Agency .... Texas Transportation Institute (TTI)
- Test Standard Test No. ... *4147-15*
- Date 05/03/1993

Test Article
- Type............................... Bridge Rail
- Name .... Single Slope Concrete
- Installation Length .... 120 ft
- Material or Key Elements 32" High Concrete

Test Vehicle
- Type/Designation 2000P
- Make and Model.............. Finite Element
- Dummy .... No Dummy
- Gross Static..................... ~2000 kg

Impact Conditions
- Speed.................................60.4 mi/h
- Angle..................................25.5 degrees

Exit Conditions
- Speed.................................N/A
- Angle..................................N/A

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

Vehicle Stability
- Maximum Yaw Angle................ -42.3 degree
- Maximum Pitch Angle............... --3.3 degree
- Maximum Roll Angle................. 4.1 degree

Occupant Risk Values

Impact Velocity
- x-direction................................. N/A
- y-direction………………………. N/A

Ridedown Acceleration
- x-direction................................. N/A
- y-direction................................. N/A

Figure A.2. Summary of Results for *NCHRP 350* Test 3-21 simulation (Single Slope Barrier).

Table A.1. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Top View (Single Slope Barrier).

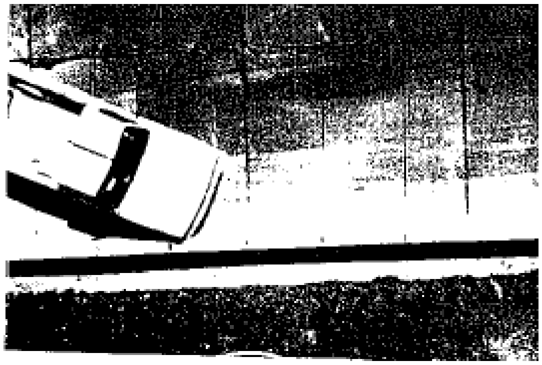
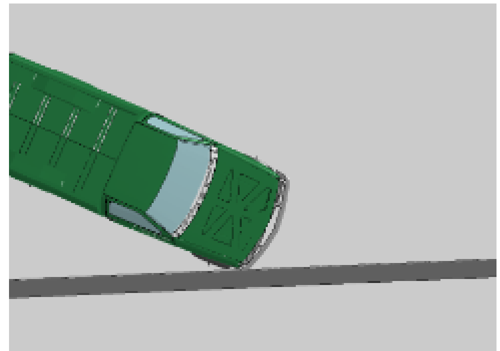
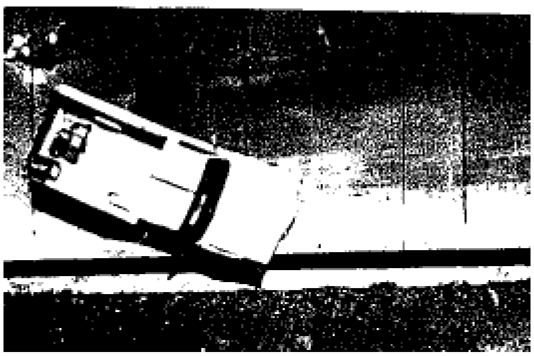
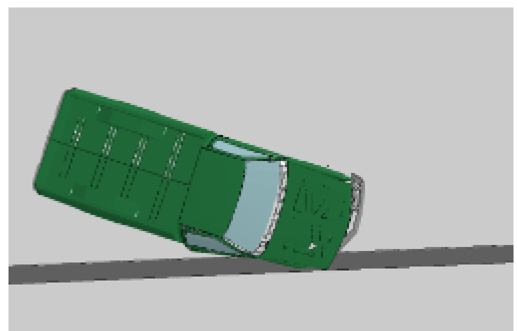
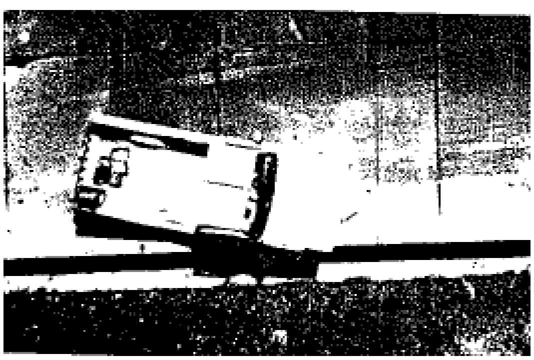
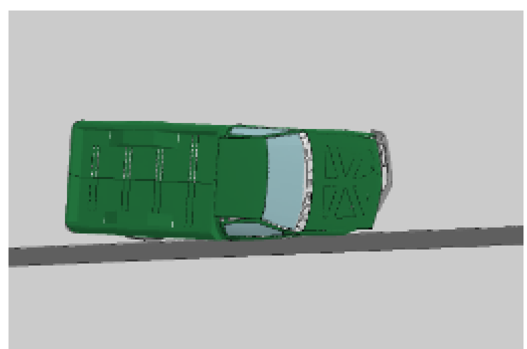
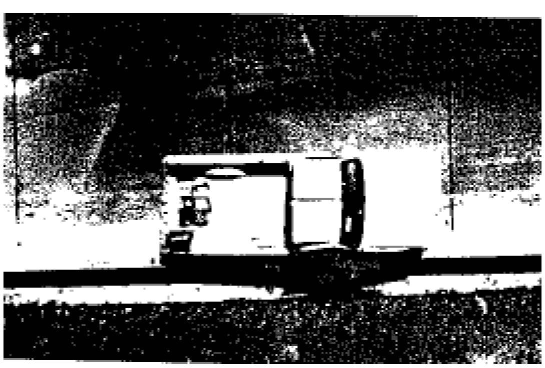
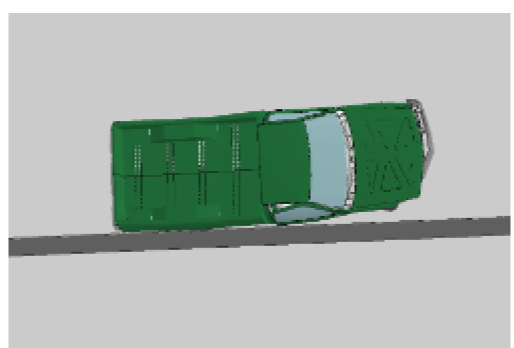
Time (sec)	TEST 471470	FE Single Slope Bridge Rail NCHRP Report 350 (2000P)
0.000		
0.073		
0.145		
0.218		

Table A.1. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Top View (Single Slope Barrier). (Continued)

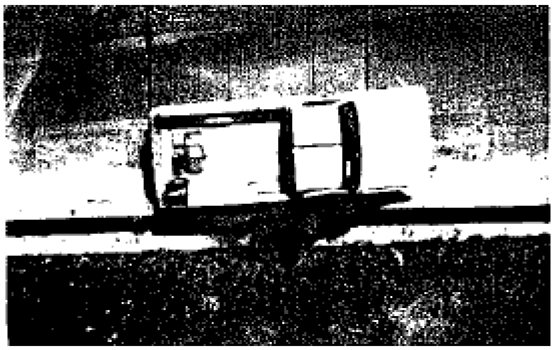
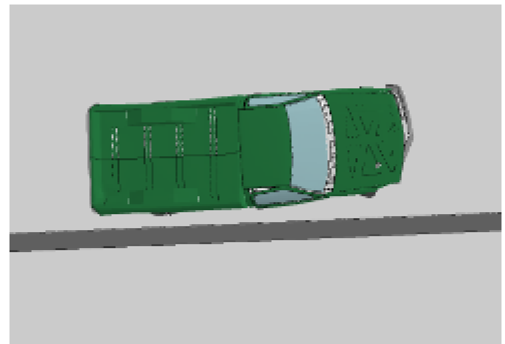
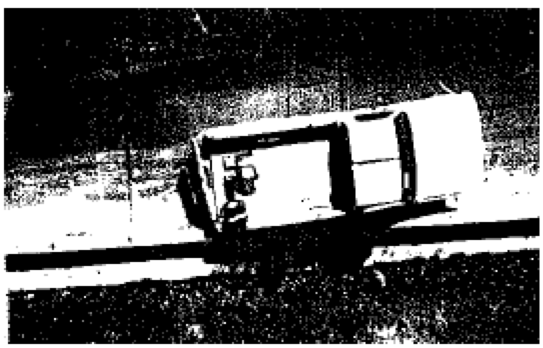
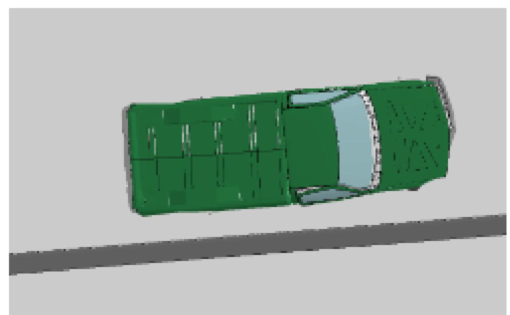
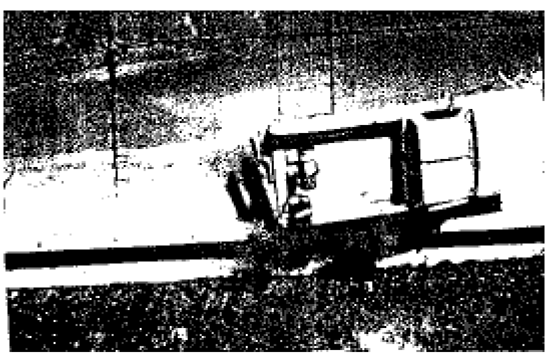
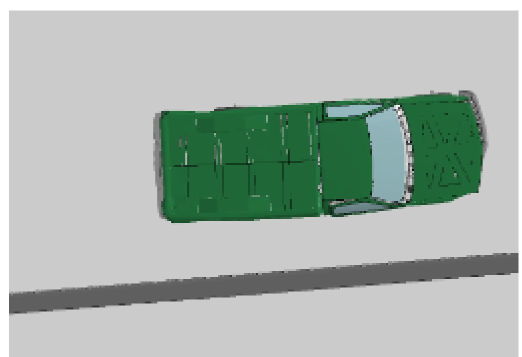
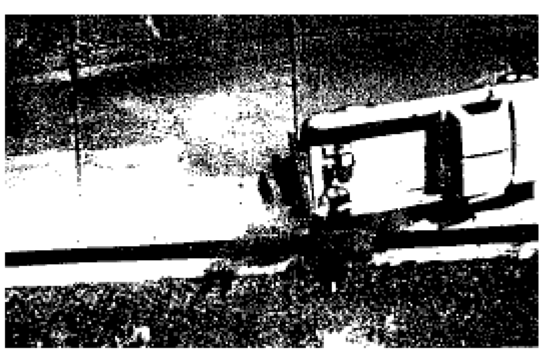
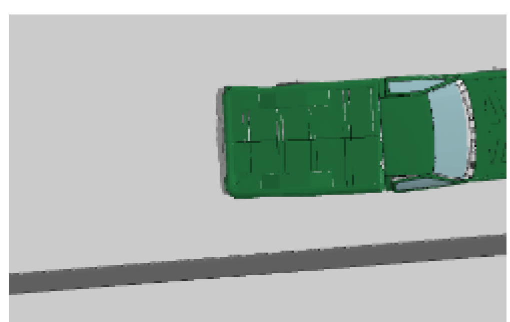
Time (sec)	TEST 471470	FE Single Slope Bridge Rail NCHRP Report 350 (2000P)
0.290		
0.363		
0.435		
0.508		

Table A.2. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Front View (Single Slope Barrier).

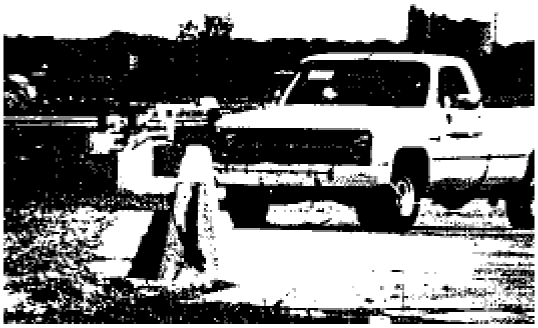
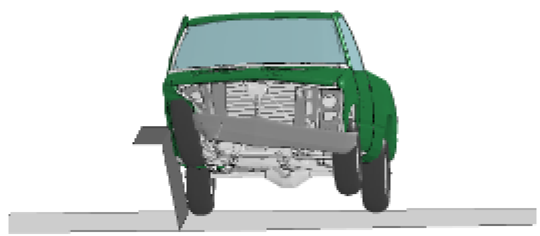
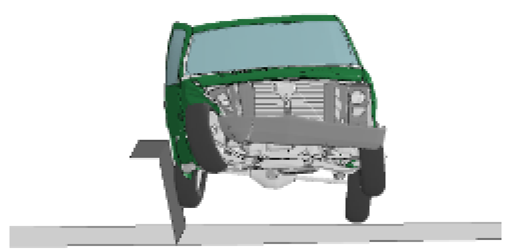
Time (sec)	TEST 471470	FE Single Slope Bridge Rail NCHRP Report 350 (2000P)
0.000		
0.073		
0.145		
0.218		

Table A.2. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Front View (Single Slope Barrier). (Continued)

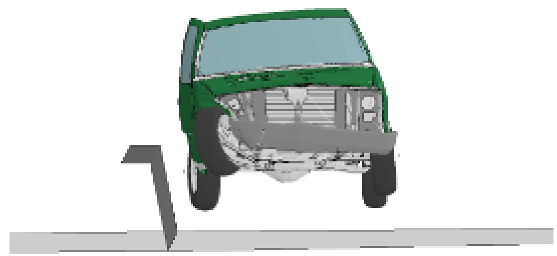
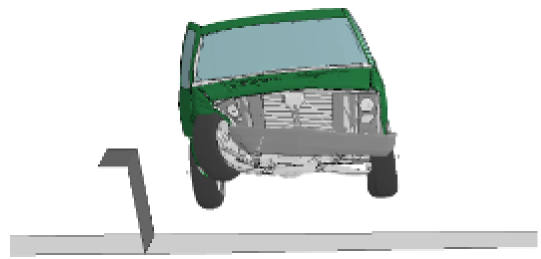
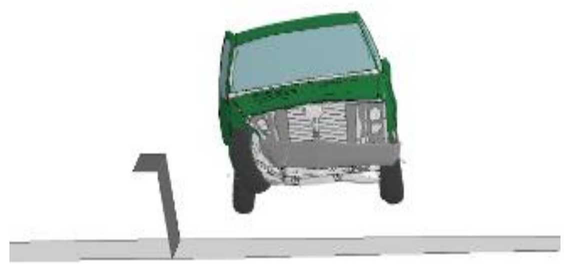
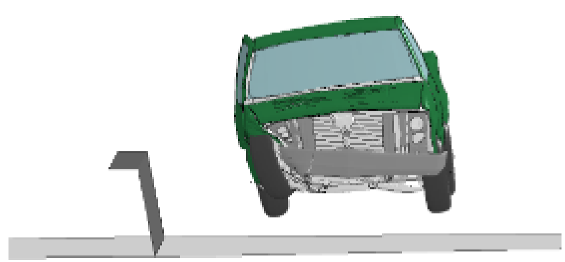
Time (sec)	TEST 471470	FE Single Slope Bridge Rail NCHRP Report 350 (2000P)
0.290		
0.363		
0.435		
0.508		

Table A.3. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Perspective View (Single Slope Barrier).

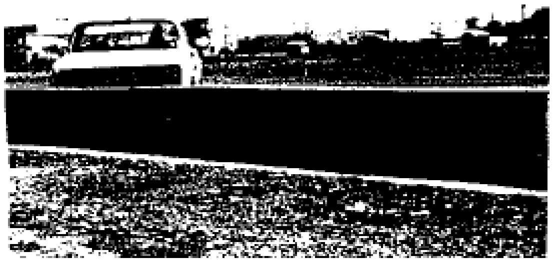
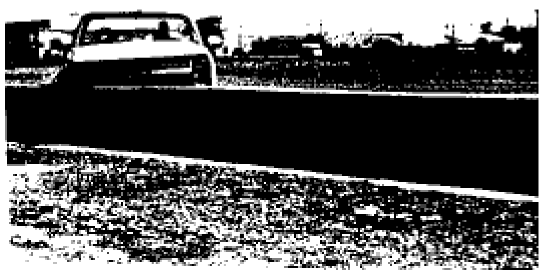
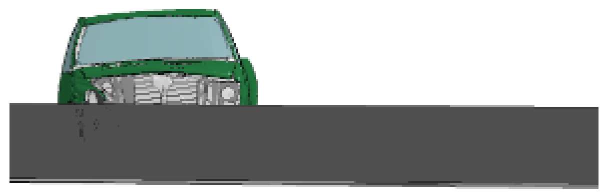
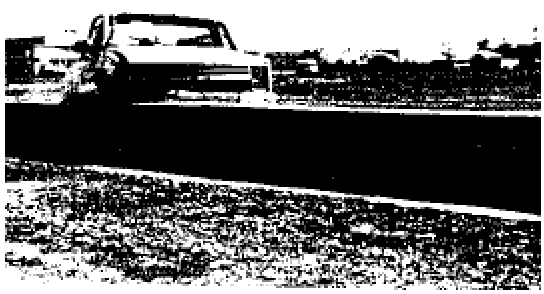
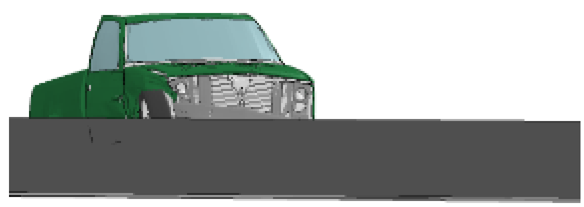
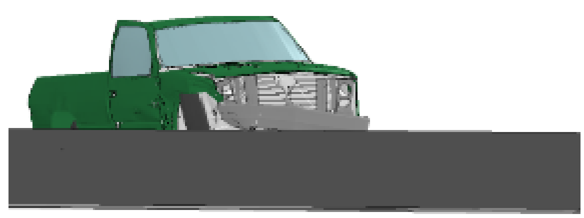
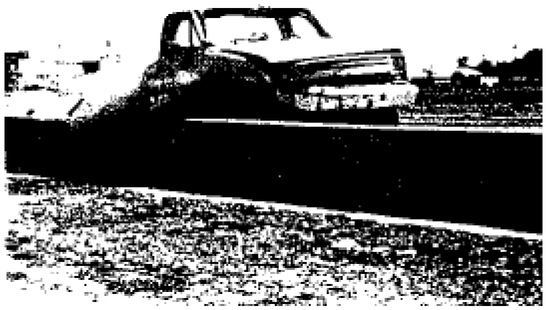
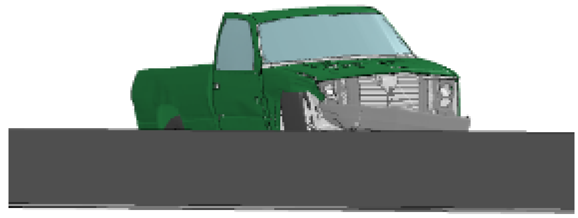
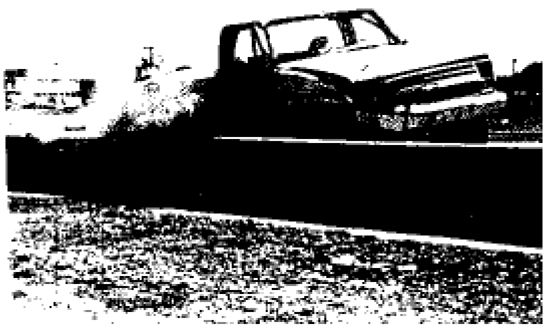
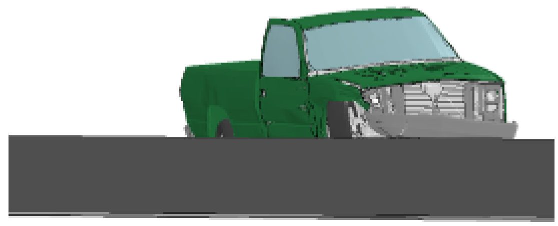
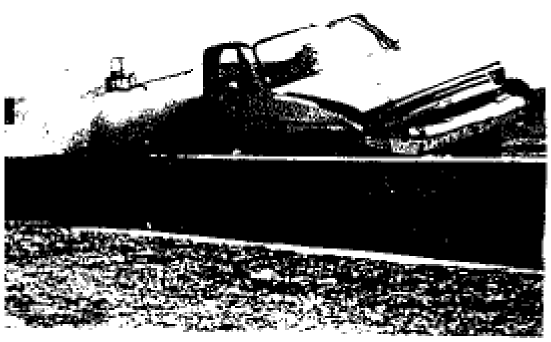
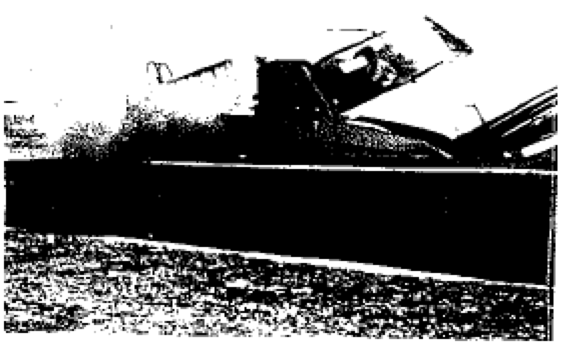
Time (sec)	TEST 471470	FE Single Slope Bridge Rail NCHRP Report 350 (2000P)
0.000		
0.073		
0.145		
0.218		

Table A.3. Frame Comparison of Full-Scale Crash Test and Computer Simulation – Perspective View (Single Slope Barrier). (Continued)

Time (sec)	TEST 471470	FE Single Slope Bridge Rail NCHRP Report 350 (2000P)
0.290		
0.363		
0.435		
0.508		

Occupant Risk Factors	**TEST 471470**	**FE Single Slope Bridge Rail NCHRP Report 350 (2000P)**
Impact Vel. (ft/sec)		
x-direction	17.7	12.8
y-direction	25.6	28.9
Ridedown Acc. (g's)		
x-direction	-6.1	-5.7
y-direction	-12.6	10.6

Angles	**TEST 471470**	**FE Single Slope Bridge Rail NCHRP Report 350 (2000P)**
Roll (deg.)	30	-4.6
Pitch (deg.)	7	5.3
Yaw (deg.)	40	-27.4

Figure A.4. Occupant Risk Values (Single Slope Barrier).

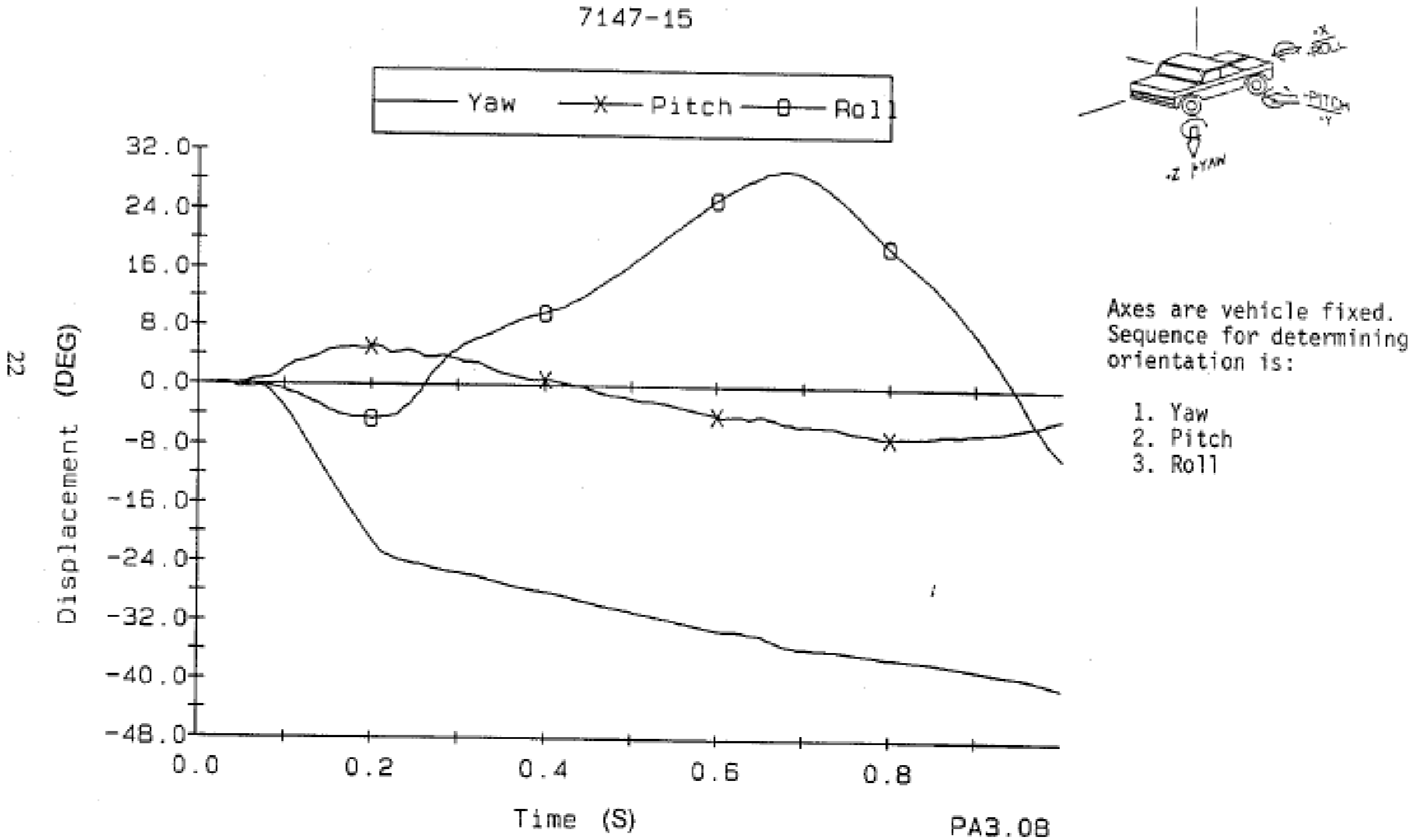


Figure 12. Vehicle angular displacements for test 7147-15.

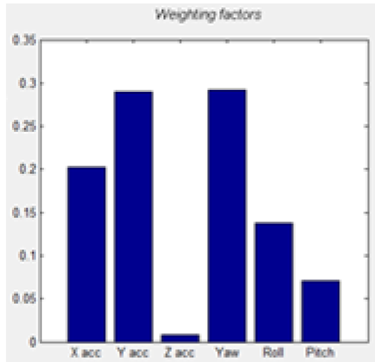
Figure A.5. Angular Displacements for Test 471470.

Figure A.6. Angular Displacements for FE Simulation Validation of the Single Slope Barrier.

Table A.4. Roadside Safety Validation Metrics Rating Table for Single Slope Barrier (Single Channel Option).

	Evaluation Criteria								Time Interval [0 sec; 0.8438 sec]		
O	***Sprague-Geers Metrics*** List all the data channels being compared. Calculate the M and P metrics using RSVVP and enter the results. Values less than or equal to 40 are acceptable.								**Simulation vs. Test 1**		
		RSVVP Curve Preprocessing Options							**M [%]**	**P [%]**	**Pass?**
		Filter Options	**Sync. Options**	**Shift**		**Drift**					
				Test Curve	**Test Curve**	**Test Curve**	**Test Curve**				
	X Acceleration	CFC 180	Min. area of Residuals	N	N	N	N		56	46.2	N
	Y Acceleration	CFC 180	Min. area of Residuals	N	N	N	N		1.4	32	Y
	Z Acceleration	CFC 180	Min. area of Residuals	N	N	N	N		23.8	46.7	N
	Yaw Rate	CFC 180	Min. area of Residuals	N	N	N	N		13.9	15.2	Y
	Roll Rate	CFC 180	Min. area of Residuals	N	N	N	N		11.5	46.7	N
	Pitch Rate	CFC 180	Min. area of Residuals	N	N	N	N		17.1	35.9	Y
P	***ANOVA Metrics*** List all the data channels being compared. Calculate the ANOVA metrics using RSVVP and enter the results. Both of the following criteria must be met: • The mean residual error must be less than 5 percent of the peak acceleration ($\bar{e} \leq 0.05 * a_{peak}$) and • The standard deviation of the residuals must be less than 35% of the peak acceleration ($\sigma \leq 0.35 * a_{peak}$)								**Mean Residual [%]**	**Standard Deviation of Residuals [%]**	**Pass?**
	X Acceleration/Peak								0.83	22.45	Y
	Y Acceleration/Peak								1.09	16.84	Y
	Z Acceleration/Peak								-0.63	24.19	Y
	Yaw Rate								11.62	14.68	N
	Roll Rate								-7.31	46.23	N
	Pitch Rate								7.58	36.04	N

Table A.5. Roadside Safety Validation Metrics Rating Table for Single Slope Barrier (Multi-Channel Option Using Area II Method).

<table>
<tr><th colspan="5">Evaluation Criteria (time interval [0 sec; 0.8438 sec])</th></tr>
<tr><th colspan="5">Channels (select which used)</th></tr>
<tr><td colspan="2">✓ X Acceleration</td><td colspan="2">✓ Y Acceleration</td><td>✓ Z Acceleration</td></tr>
<tr><td colspan="2">✓ Roll rate</td><td colspan="2">✓ Pitch rate</td><td>✓ Yaw rate</td></tr>
<tr><td colspan="2">Multi-Channel Weights-Area (II) Method</td><td colspan="3">
</td></tr>
<tr><td rowspan="2">O</td><td>Sprague-Geer Metrics</td><td>M</td><td>P</td><td>Pass?</td></tr>
<tr><td>Values less or equal to 40 are acceptalbe</td><td>18.8</td><td>32.4</td><td>Y</td></tr>
<tr><td rowspan="2">P</td><td rowspan="2">ANOVA Metrics
Both of the following criteria must be met:
• The mean residual error must be less than 5 percent of the peak acceleration ($\bar{e} \le 0.05*a_{peak}$)
• The standard deviation of the residuals must be less than 35% of the peak acceleration ($\sigma \le 0.35*a_{peak}$)</td><td>Mean Residual</td><td>Standard Deviation of Residuals</td><td>Pass?</td></tr>
<tr><td>3.4</td><td>22.8</td><td>Y</td></tr>
</table>