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SINGLE SLOPE MEDIAN WALL FOR GRADE SEPARATIONS

by

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16. Abstract
This research explored design options of median barriers for use as grade separation on split level highways. Such type of barrier needs to provide design and construction flexibility as shoulder elevations vary along the roadway and also perform as a retaining wall. Strength and stability of the barrier were investigated to evaluate the structural ability to provide adequate stability with respect to sliding, overturning, and bearing capacity. Crashworthiness of the barrier design(s) chosen were investigated through finite element modeling analyses at *MASH* test levels 3 and 4.

An initial barrier design was proposed by Tennessee Department of Transportation (TDOT) considered the use of two independent half-size single slope barrier walls backing up to each other. The researchers proposed a slightly different design of median barrier for grade separation consisting in removing the small barrier (51-inch barrier) and maintaining only the tall barrier (112.5-inch barrier). Because of the possibility for the median vertical wall proposed design to be considered a hazard for head contact during a vehicle-barrier collision, the researchers and TDOT worked together to propose an alternative median barrier design option which should resolve the head slap concern. The median vertical wall was modified into a single slope median barrier of a total maximum height of 112.5 inches, a soil backfill height of maximum 60 inches acting on one side, and 4H:21V slope on both sides of the barrier. Stability and yield line analyses for the sloped barrier design were evaluated for the proposed designs, as well as their crashworthiness and stability through finite element analyses for *MASH* test level 3 impact conditions. These analyses resulted in acceptable barrier performance according to the criteria set forth in *MASH* for longitudinal barriers, and soil retention according to AASHTO 2007.

In a second phase of the project, researchers optimized the minimum barrier segment length needed to resist soil forces and *MASH* TL-3 and TL-4 impact conditions. The barrier segments stability and crashworthiness were evaluated according to the LRFD method and computer simulations.

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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

When widening of an existing divided highway with depressed median is proposed, adding inside lanes by using the depressed median opening is the preferred method since no additional right of way (ROW) is required. Extending the pavement at super elevations, however, requires the use of a retaining wall along with the concrete median barrier due to the grade separation that occurs.

1.2 BACKGROUND

Median barriers are typically installed to prevent errant vehicles from crossing the divided area between travel ways to prevent a collision with oncoming traffic (AASHTO, 2004). The application of median barriers depends on a multitude of factors, including median width, traffic volume, adverse geometries (split elevations), and severity of consequences due to vehicular penetration into opposing traffic lanes (AASHTO, 2004). Special considerations are taken when the travel ways are at different elevations, as shown in Figure 1.1 (AASHTO, 2004).

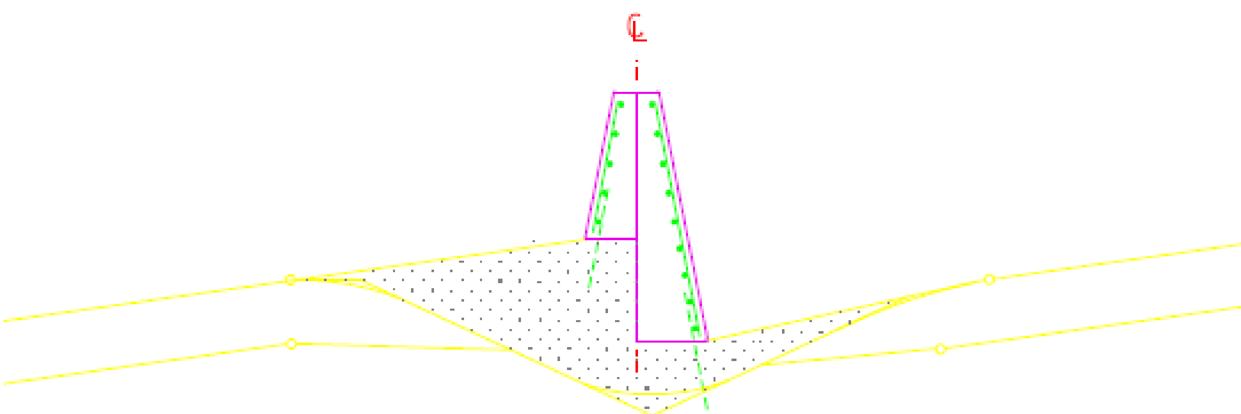


Figure 1.1. Widening of an Existing Divided Highway with Depressed Median by Adding Inside Lanes.

The correct median barrier must be selected such that the maximum dynamic deflection that occurs is less than one-half of the median width. The barrier should prevent the errant vehicle from penetrating into oncoming traffic lanes and redirect the vehicle to the correct direction of travel.

Median barriers can be categorized as flexible, semi-rigid, and rigid. Examples of typical median barriers include weak-post W-beam, three-strand cable, box beam median barrier, blocked-out W-beam strong post, blocked-out thrie beam strong post, modified thrie beam median barrier, and concrete barrier.

The use of W-beam, box beam, and cable systems are limited to flat medians and are typically not used when a split elevation between traffic ways of greater than 3:1 occur. In the case of split elevation, highways with little to no median width, such as when inside lanes are added by using the depressed median, dynamic deflection is restricted. In this situation, use of rigid barriers is most appropriate.

Concrete median barriers are the most common types of rigid barriers and include the New Jersey, F-shape, single slope barrier and vertical wall). These systems present low life cycle cost due to their effective performance and maintenance-free life. For the research conducted herein, the single slope barrier was considered exclusively.

A single slope barrier can have either a 9.1 or 10.8 degree slope and may be used as either as temporary or permanent longitudinal barrier (Beason et al., 1989). Each has been successfully tested according to criteria presented in National Cooperative Highway Research Program (NCHRP) *Report 350* (Ross et al., 1993, AASHTO, 2002). The primary advantage of the single slope barrier is that the pavement adjacent to the sloped face may be overlaid multiple times without degrading the performance of the barrier (Beason et al., 1989). These barriers are typically 42 inches tall, but may be found as short as 30 inches (AASHTO, 2002).

When a median barrier is used on highways for grade separation, the median barrier also has to perform as a retaining wall. Retaining walls can be used to support a fill along a slope or a cut into a slope, allowing for a change of grade. Conventional retaining walls are classified as rigid gravity or semi-gravity walls, as reported in Figure 1.2 (AASHTO, 2007).

Retaining walls need to be investigated for:

- Lateral earth and water pressures, including live and dead load surcharge;
- The self-weight of the wall;
- Loads applied from any bridge superstructure;
- Temperature and shrinkage deformation effects;
- Earthquake loads.

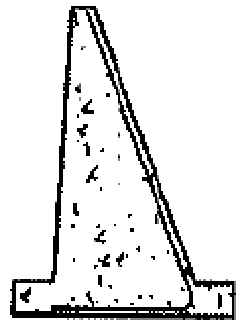
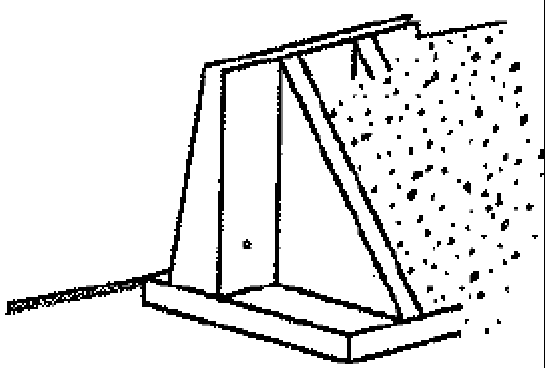
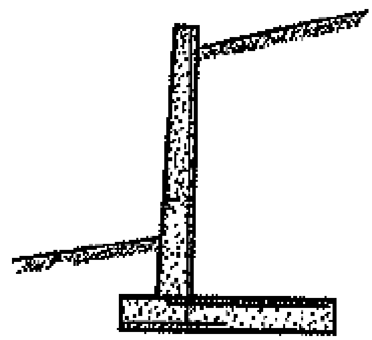
	
(a) Unreinforced Concrete Rigid-Gravity Wall	(b) Reinforced Concrete Rigid-Gravity Wall
	
(c) Reinforced Concrete Counterfort Semi-Gravity Wall	(d) Reinforced Concrete Cantilever Semi-Gravity Wall

Figure 1.2. Typical Rigid Gravity and Semi-Gravity Walls, adapted (AASHTO, 2007).

Figure 1.3 shows load combination obtained with use of principle of superimposition to evaluate external and internal wall stability.

Barrier stability should be investigated according to safety factors and American Association of State Highway and Transportation Officials (AASHTO) *Load Resistance Factor Design* (LRFD). In this study, the event of a vehicle impact is also included in the stability and strength analysis of the barrier. AASHTO *Manual for Assessing Safety Hardware* (*MASH*) Test Levels 3 and 4 (TL-3 and TL 4) are investigated (AASHTO, 2009):

- TL-3: Test Level 3, taken to be generally acceptable for a wide range of high-speed arterial highways with very low mixtures of heavy vehicles and with favorable site conditions;
- TL-4: Test Level 4, taken to be generally acceptable for the majority of applications on high speed highways, freeways, expressways, and Interstates highways with a mixture of trucks and heavy vehicles.

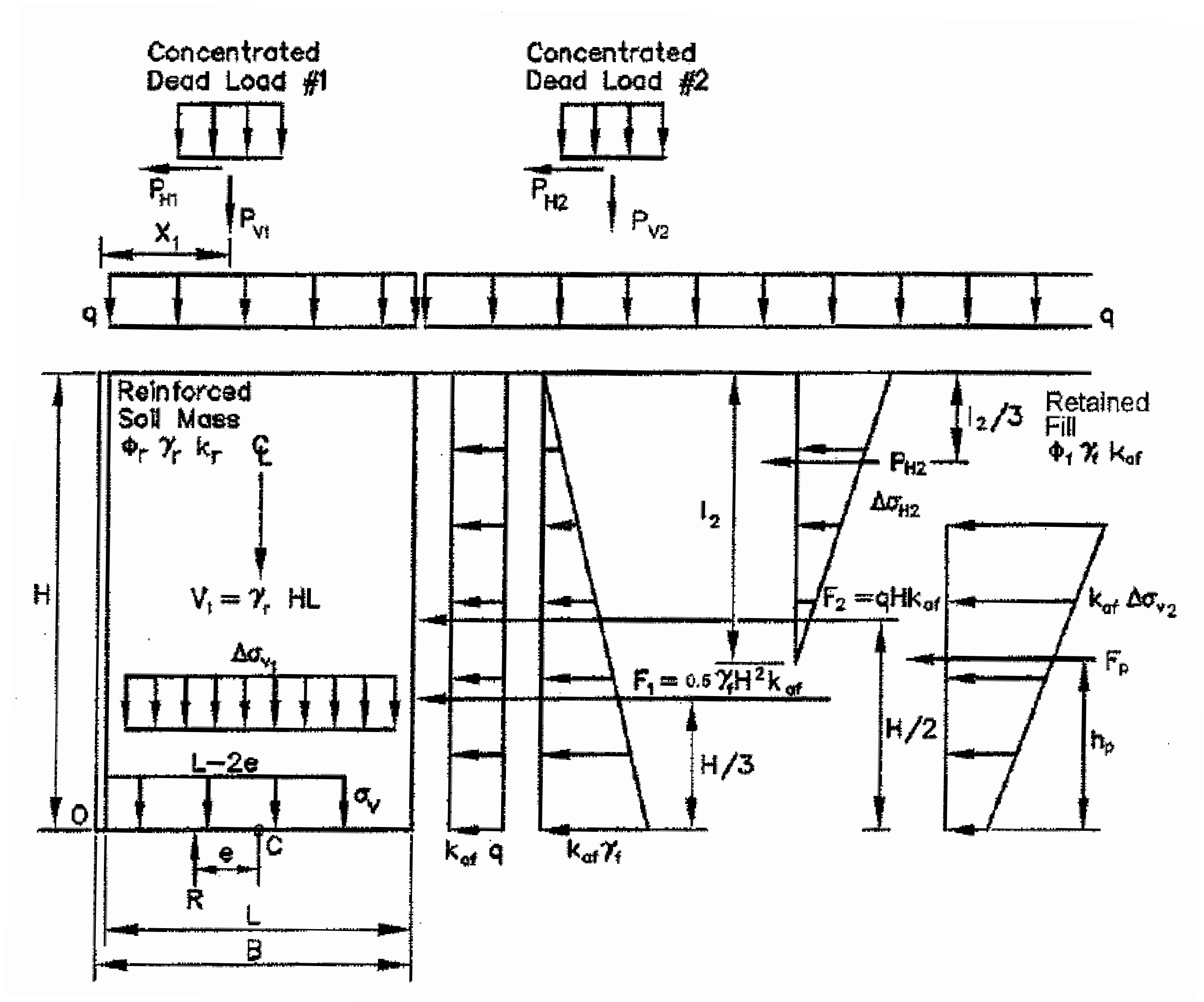


Figure 1.3. Superimposition of Concentrated Dead Loads for External and Internal Stability Evaluation (AASHTO, 2007).

1.3 OBJECTIVES AND SCOPE OF RESEARCH

The purpose of the study is to explore design options of median barriers for use as grade separation on split level highways to provide design and construction flexibility as shoulder elevations vary along the road. The median barrier also should perform as a retaining wall. Strength and stability of the barrier should be investigated to evaluate the structural ability to provide adequate stability with respect to sliding, overturning, and bearing capacity. Crashworthiness of the barrier design(s) chosen should also be investigated through finite element modeling analyses at *MASH* TL-3 and TL 4.

2. SLOPE STABILITY AND GEOTECHNICAL ANALYSIS

2.1 INTRODUCTION

Tennessee Department of Transportation (TDOT) suggested a split single slope median wall design for grade separation, consisting in two separate barriers, as represented in Figure 2.1.

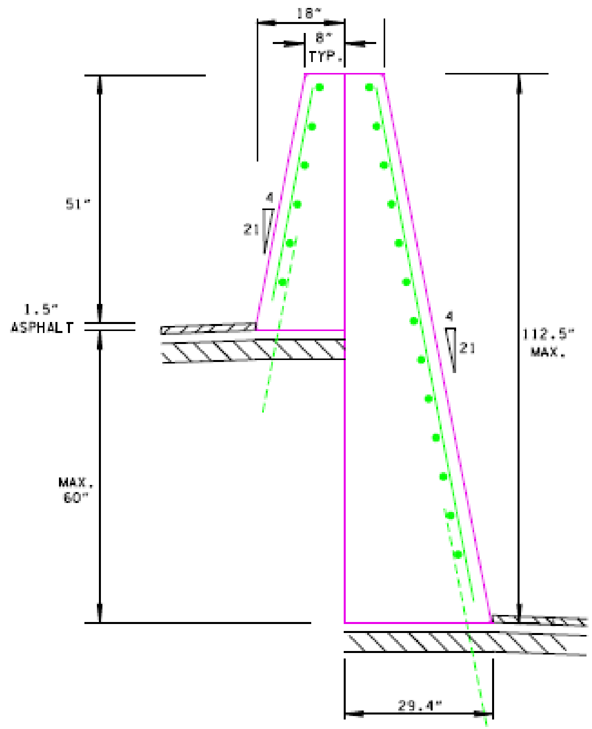
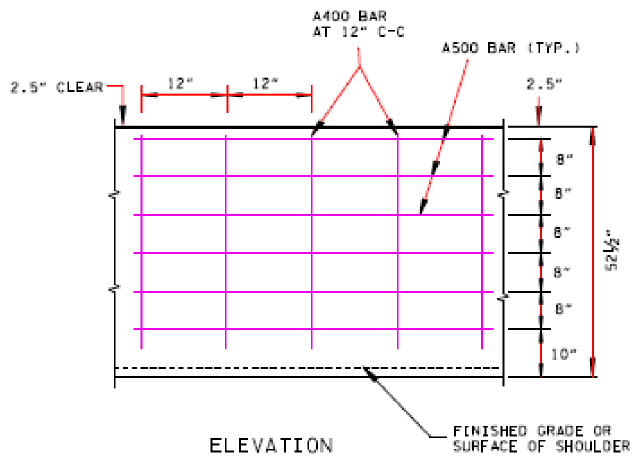


Figure 2.1. Tennessee (TN) Split Single Slope Median Wall Design for Grade Separation.

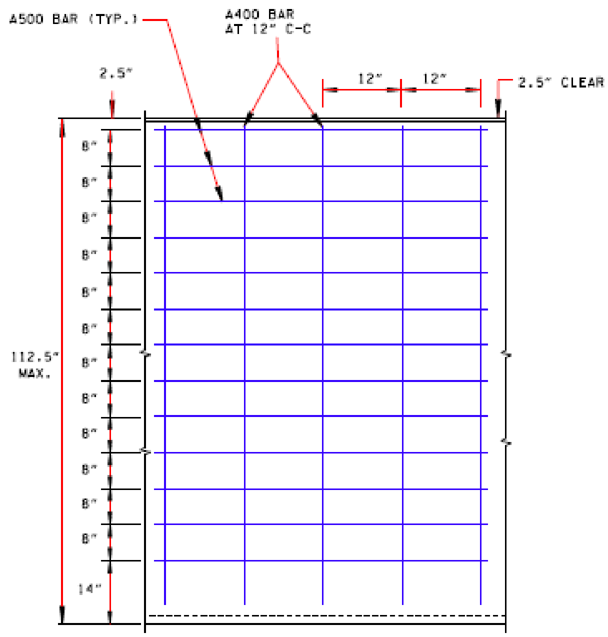
Barrier #1 is a single slope, trapezoidal barrier of 51 inches total height. The top width is 8 inches and the width at the base is 18 inches. Barrier slope of the side exposed to traffic is 4H:21V (9.1 degree). The barrier is cast in place with no use of a footing. Steel bar reinforcement is added on the traffic side of the barrier with 2 inches of concrete coverage. Both longitudinal and transverse rebar are type #4 (0.5-inch diameter) with 8-inch spacing.

Barrier #2 is a single slope, trapezoidal barrier of a maximum of 112.5 inches total height. The top width is 9 inches and the width at the base is 30.4 inches. Barrier slope of the side exposed to traffic is 4H:21V (9.1 degree). The barrier is cast in place with no use of a footing. Steel bar reinforcement is added on the traffic side of the barrier with 2 inches concrete coverage. Both longitudinal and transverse rebar are type #4 (0.5-inch diameter) with 8-inch spacing. Because the split single slope median wall is used for grade separation, the total height of barrier #2 may vary according to the grade difference. Thus, when barrier #2 used at its maximum height (112.5 inches), there would be a total of 60 inches of soil leaning to the side of the barrier.

Joints, anchor and terminal details are not included and are beyond the scope of this project. Figure 2.2 shows the steel reinforcement grid suggested for both barriers.



(a) 51-inch tall concrete barrier



(b) 112.5-inch tall concrete barrier

Figure 2.2. Original TN Split Single Slope Median Wall Reinforcement Grid for (a) 51-inch, and (b) 112.5-in Tall Concrete Barrier.

After literature review and investigation of tests conducted at Texas A&M Transportation Institute (TTI) involving impact of sloped concrete barriers and vertical walls (mechanically stabilized earth, MSE), the researchers proposed a slightly different design of median barrier for grade separation. The new design consisted in removing barrier #1 (52-inch barrier) and maintaining only barrier #2 (112.5-inch barrier) (Figure 2.3.). The geometry of barrier #2 would be the same as proposed in the original design by TDOT. The researchers suggested inclusion of a steel reinforcement grid on both sides of the barrier, maintaining the same types of bars (#4) and same bar spacing (8 inches) as proposed in the original design. The concrete coverage would still be 2 inches from the top and 2 inches from side #2. Concrete coverage of side #1, however, would be 3 inches, in accordance to the AASHTO requirements for concrete coverage for cast against earth. Inclusion of steel reinforcement on side #2 of the bar would be essential for the concrete structure to support tensile loads coming from possible impacts on that side.

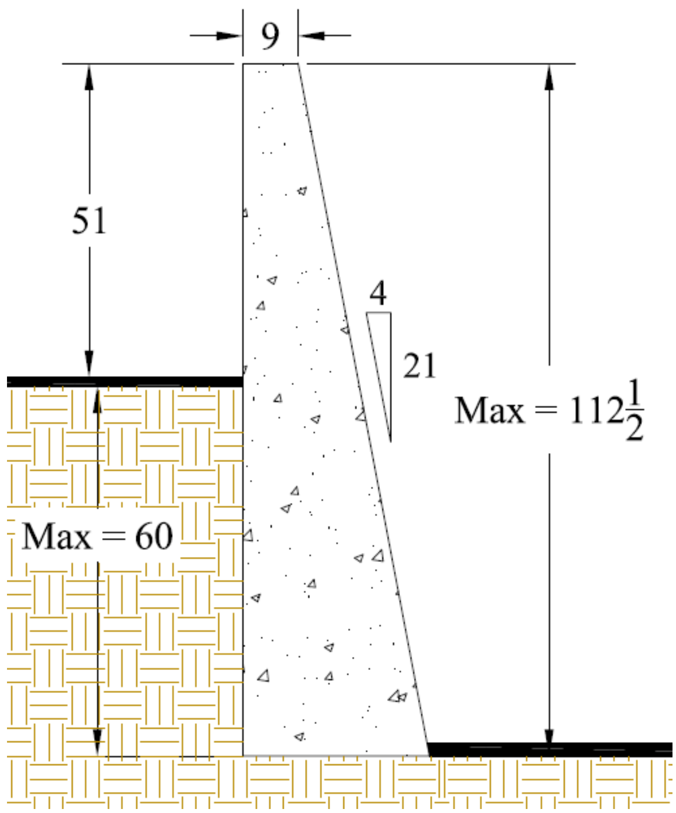


Figure 2.3. Median Vertical Wall Design for Grade Separation.

Barrier stability and strength analysis is reported in Section 2.2 and refers to this median vertical wall design option. The researchers decided to evaluate the barrier stability for the case where the wall is at its maximum height (112.5 inches), since in this case would be subjected to the highest forces coming from the soil backfill. Additional analysis, however, was carried out to evaluate the stability of the same barrier for the case where is no grade difference, when the total height of the wall would be 51 inches on both sides. Although, for this latter case, there would not be earth-active lateral forces and surcharge forces acting on the barrier side, still the barrier strength and resistance should be addressed in the event of a vehicle impact.

2.2 MEDIAN VERTICALWALL DESIGN

The stability of the median vertical wall is investigated with respect to lateral earth pressure, live (traffic) surcharge, and vehicle transverse impact loads for *MASH* TL-3.

2.2.1 Calculation of Lateral Earth Pressure (Rankine Method)

To calculate the lateral earth pressure force, there are two methods that can be used: The Rankine Earth Pressure and the Coulomb Earth Pressure. The Rankine method is used for the specific condition of a horizontal backfill surface and assumes the lateral pressure is limited to vertical walls with no adhesion or friction between the wall and the soil. There are three categories of lateral earth pressure: At rest pressure, passive pressure and active pressure. Since the active pressure is the main responsible for destabilizing earth forces behind the retaining wall, the researchers decided to investigate only this type of lateral earth pressure.

The Rankine active earth pressure coefficient for a horizontal backfill surface is calculated as follows:

$$K_a = \frac{1-\sin(\emptyset)}{1+\sin(\emptyset)} \tag{2.1}$$

where:

ø = Friction Angle of the Soil (degrees)

For this case, a soil friction angle of 32 degrees is considered. Thus,

$$K_a = \frac{1-\sin(32)}{1+\sin(32)} = 0.307 \tag{2.2}$$

2.2.2 Calculation of the Total Active Lateral Earth Pressure Force

The total active lateral earth pressure, p_a, acting along the back of the wall can be evaluated as follows:

$$p_a = K_a \cdot \gamma \cdot H \tag{2.3}$$

where:

K_a = Rankine Active Earth Pressure
γ = Soil Unit Weight (pcf)
H = Height of the Wall (ft)

For this case, a soil unit weight, γ, of 120 pcf is considered, and the height, H, of the wall on which the lateral earth pressure is acting is 5 ft. Thus,

$$p_a = K_a \cdot \gamma \cdot H = 184.36\ (pcf \cdot ft) \tag{2.4}$$

The total earth pressure force, p_a, is then evaluated as follows:

$$P_a = \frac{1}{2} \cdot K_a \cdot \gamma \cdot H^2 = 460.89\ (lbs) \tag{2.5}$$

The lateral pressure varies linearly with depth, and the resultant pressure is located at a height of H/3 above the base of the wall, where H is the length of the wall covered by soil (Figure 2.4).

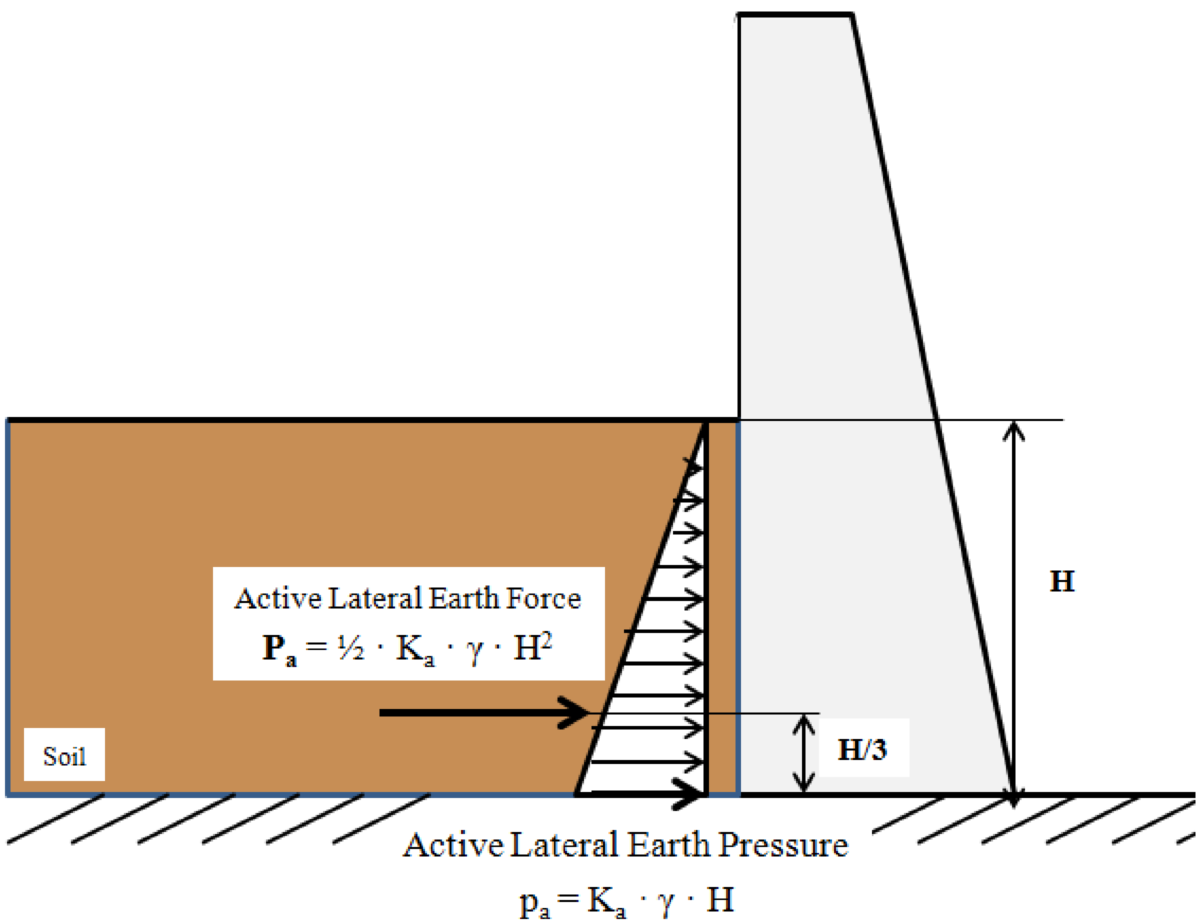


Figure 2.4. Active Lateral Earth Force Acting on the Retaining Wall.

2.2.3 Calculation of Other Forces Acting on the Wall

Generally, the earth pressure force is not the only force acting on a retaining wall. Other forces, such as surcharge load, earthquake load, and water pressure, should be considered and superimposed onto the earth pressure force to evaluate the total lateral force. In this study, the researchers included evaluation of the surcharge load. For the particular split median wall considered here, the surcharge load is due to traffic.

The surcharge pressure acting at the bottom of the wall due to traffic is evaluated as follows:

$$s = K_a \cdot q \tag{2.6}$$

where:

K_a = Rankine Active Earth Pressure
q = uniform surcharge (psf)

For this case, a uniform surcharge, q, of 250 psf is considered, thus:

$$s = 0.307 \cdot 250 = 76.81\ (psf) \tag{2.7}$$

Considering the surcharge due to traffic acts uniformly on a total height, H, of the wall of 5 ft (height of the wall in soil), the total surcharge force, P_s, due to traffic load results in:

$$P_s = s \cdot H = 76.81 \cdot 5 = 384.07\ (lb) \tag{2.8}$$

and acts at a height of H/2 from the base of the wall (Figure 2.5).

Figure 2.6 shows all the active forces acting on the barrier. The researchers determined the stability of the retaining median wall by both evaluating factors of safety (with respect to sliding, bearing capacity, and overturning) and by verifying the stability according to the LRFD (*Load Resistance Factor Design*) method suggested by AASHTO (AASHTO, 2007).

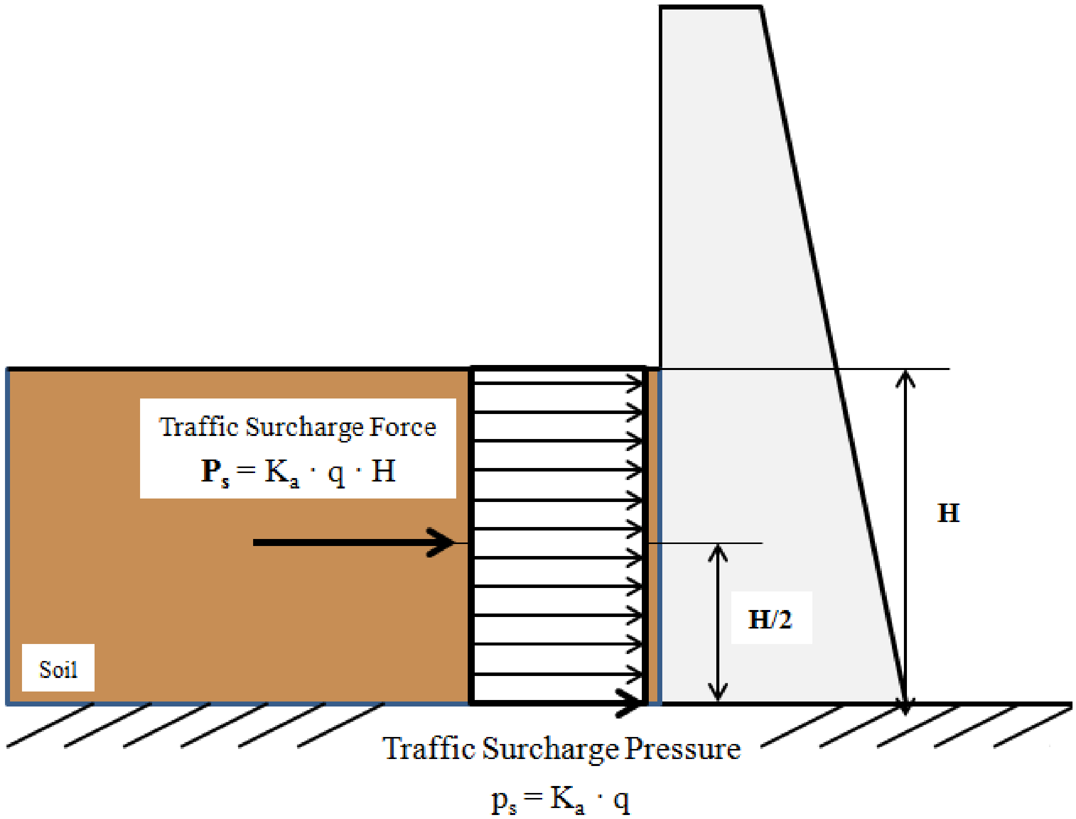


Figure 2.5. Surcharge Force Acting on the Retaining Wall.

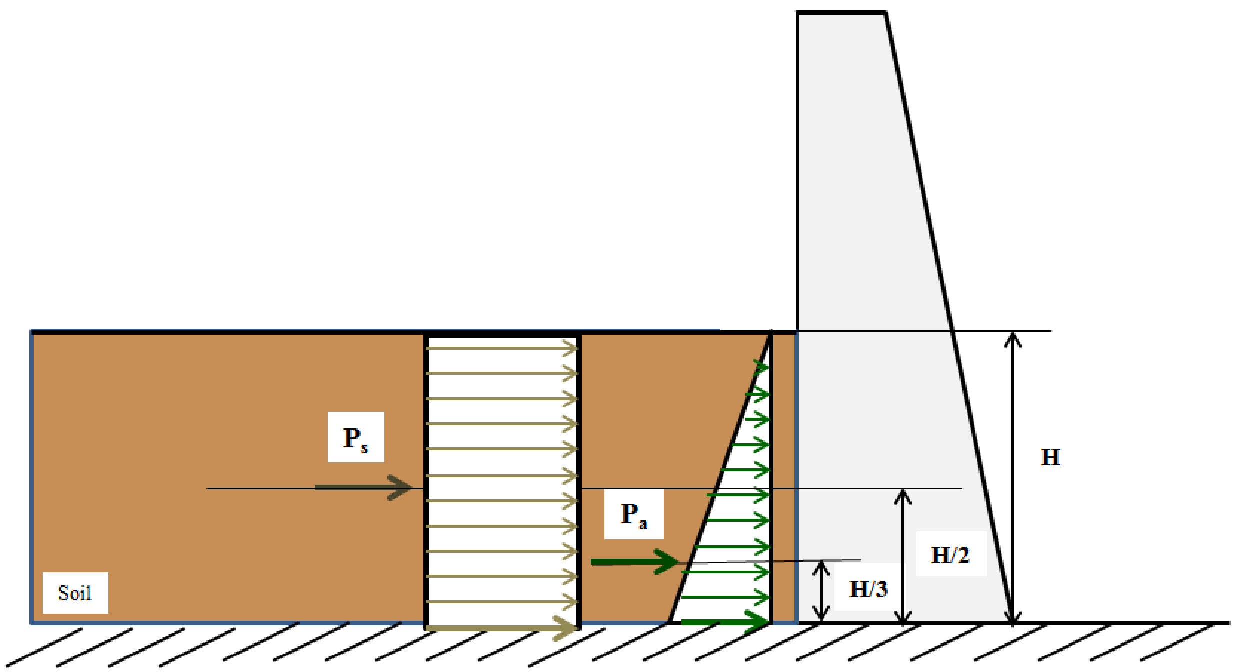


Figure 2.6. Forces Acting on the Retaining Wall.

2.2.4 Factors of Safety

The forces acting on the barrier are checked using appropriate factors of safety. The wall geometry might have to be revised until satisfactory factors of safety are reached.

2.2.4.1 Factor of Safety with Respect to Sliding

Retaining walls should provide adequate stability with respect to sliding. For the case where the bottom part of the wall is buried in the ground, the soil in the front of the wall would provide a passive-earth-pressure resistance as the wall might tend to slide into it. With front soil erosion, or excavation, or simply absence, the passive pressure component does not exist and sliding stability might occur (Bowles, 1982).

The factor of safety with respect to sliding, FS_S, is evaluated by dividing the resistance force by the driving force:

$$FS_s = \frac{\sum V \cdot \tan(k \cdot \emptyset)}{P_a} \qquad (2.9)$$

where:

ΣV = Total Vertical Force
$\emptyset$ = Friction Angle of the Soil (deg)
k = Factor ranging from 1/2 to 2/3
P_a = Total Earth Pressure Force (Horizontal Component)

This expression for the calculation of factor of safety assumes that the soil below the barrier is a cohesionless material without any cohesive strength, therefore there is no additional resistance due to cohesion. A minimum factor of safety of 1.5 is desirable to resist sliding. The total vertical forces (weights), ΣV, due to barrier #2 are calculated and results are shown below in Table 2.1.

Table 2.1. Total Vertical Forces ΣV Due to Barrier #2.

Section	Height(ft)	Width (ft)	Area (ft^2)	Unit Weight (pcf)	Weight (lb)
1	9.375	0.75	7.03	150	1054.69
2	9.375	1.783	8.36	150	1253.67
					$\boldsymbol{\Sigma V = 2308.36}$

A schematic representation of the barrier vertical forces resisting sliding is reproduced in Figure 2.7.

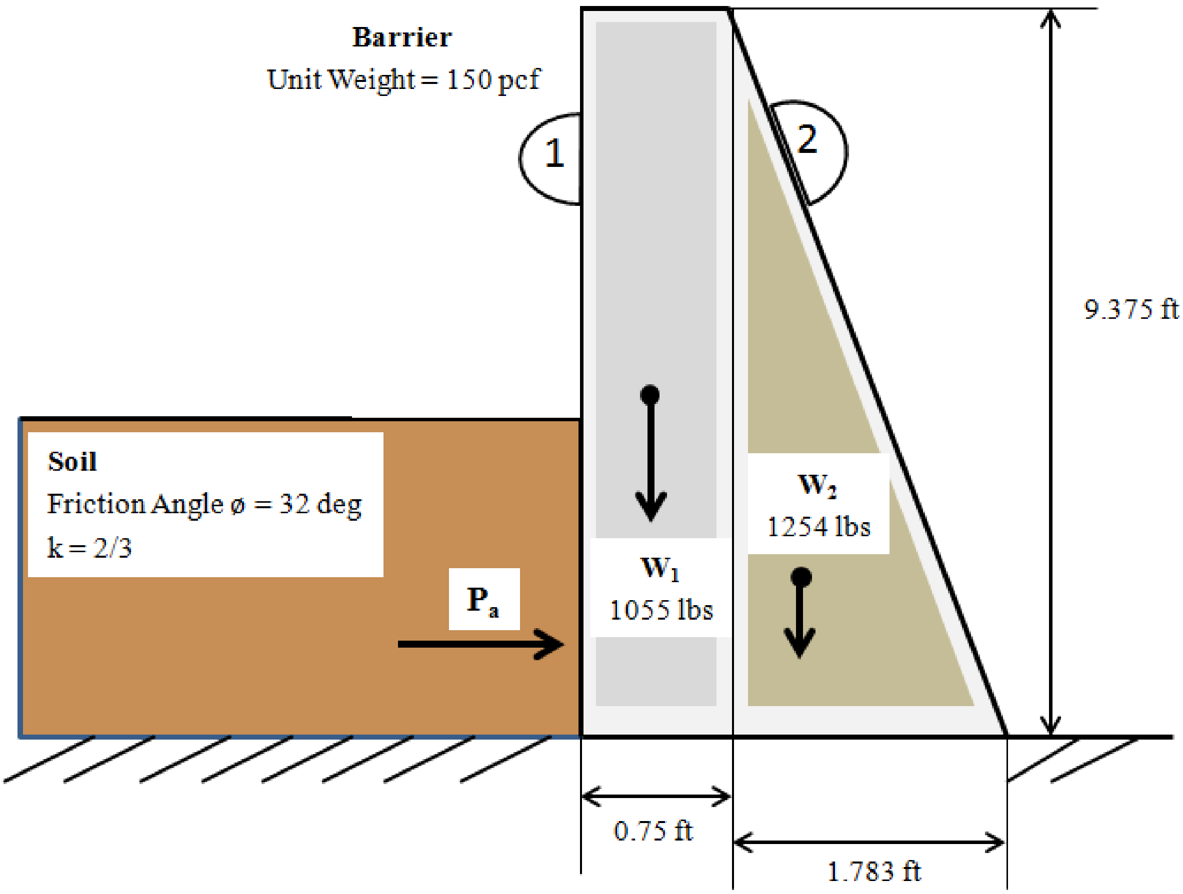


Figure 2.7. Schematic Representation of Barrier Forces Causing and Resisting Sliding.

With a k factor equal to 2/3, P_a = 460.89 lb, and a soil friction angle, ø, of 32 degrees, the factor of safety FS_S results to be:

$$FS_s = \frac{\sum V \cdot \tan(k \cdot \emptyset)}{P_a} = \frac{2308.36 \cdot \tan(0.67 \cdot 32)}{460.89} = \mathbf{2.02} > 1.5 \;\; OK \qquad (10)$$

2.2.4.2 Factor of Safety with Respect to Overturning

Retaining walls should provide adequate stability with respect to overturning. In fact, the retaining barrier would tend to rotate outward around the toe of the wall. The moment resulting from lateral forces acting on the wall (such as the horizontal component of earth pressure force and surcharge forces) must be resisted by the moments resulting from the vertical forces produced by the wall (including existing vertical component of earth pressure force).

The factor of safety with respect to overturning, FS_O, is evaluated by dividing the resisting moment by the overturning moment:

$$FS_O = \frac{\sum M_r}{\sum M_o} \tag{2.11}$$

where:

ΣM_r = Total Resisting Moments around the Toe of the Wall
ΣM_o = Total Overturning Moments around the Toe of the Wall

A minimum factor of safety of 2 to 3 is desirable to resist overturning. The total resisting moments around the toe of the wall, ΣM_r, due to barrier #2 are calculated and results are shown in Table 2.2. The total overturning moments around the toe of the wall, ΣM_o, are calculated and results are shown in Table 2.3.

Table 2.2. Total Resisting Moments ΣM_r Due to Barrier #2.

Section	Weight (lb)	Arm (ft)	Moment (ft-lb)
1	1054.69	2.16	2278.13
2	1253.67	1.19	1490.11
			$\boldsymbol{\Sigma M_r = 3768.24}$

Table 2.3. Total Overturning Moments ΣM_o Due to Barrier #2.

	Force (lb)	Arm (ft)	Moment (ft-lb)
Earth Pressure	460.89	1.67	768.15
Traffic Surcharge	384.07	2.50	960.18
			$\boldsymbol{\Sigma M_o = 1728.33}$

The factor of safety, FS_O, results to be:

$$FS_O = \frac{\sum M_r}{\sum M_o} = \frac{3722.36}{1728.33} = \mathbf{2.15} > 2 \ OK \tag{2.12}$$

A schematic representation of the forces causing and resisting overturning is reproduced in Figure 2.8.

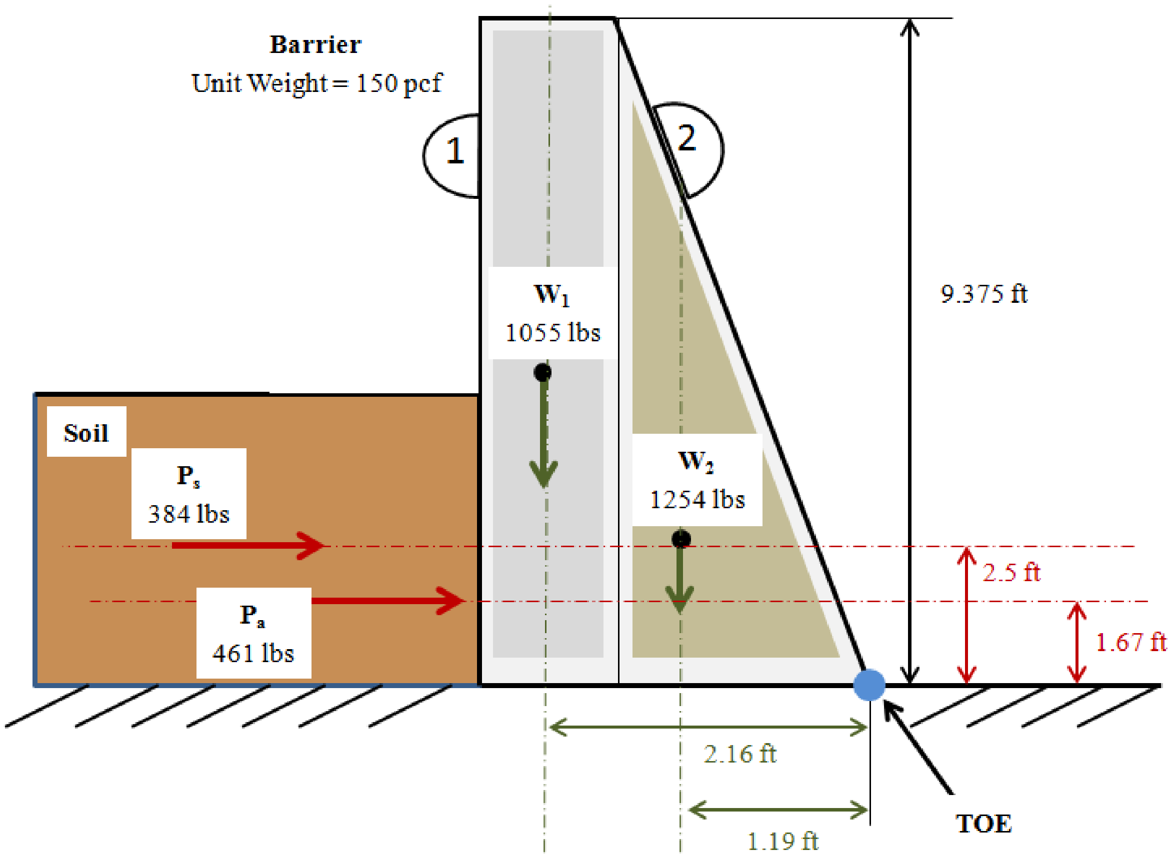


Figure 2.8. Schematic Representation of Barrier Forces Causing and Resisting Overturning.

2.2.4.3 Factor of Safety with Respect to Bearing Capacity

Retaining walls should provide adequate stability with respect to bearing capacity. Generally, the total pressure due to the earth pressure and to the weight of the retaining wall is non-uniformly distributed below the base of the wall. The greatest pressure results below the toe of the wall, while the least pressure appears to be at the heel of the base (Figure 2.9).

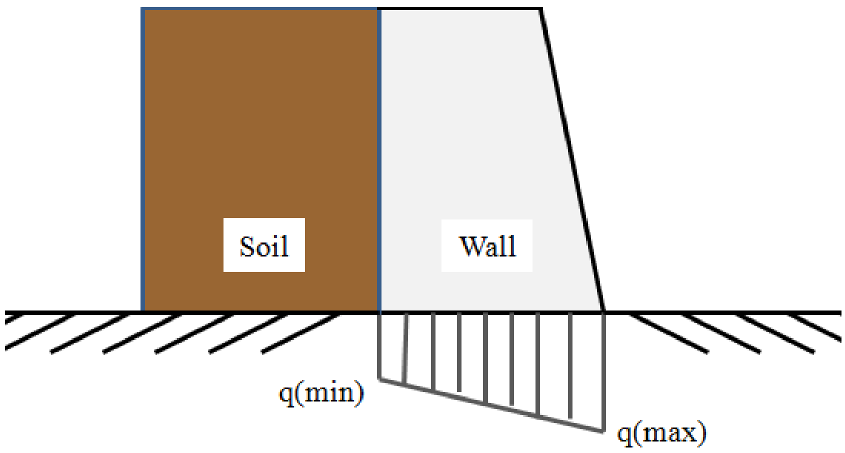


Figure 2.9. Typical Total Pressure Distribution below the Base of a Retaining Wall.

The maximum and minimum pressure below the base, B, of the wall can be evaluated as follows:

$$q_{max} = \frac{\Sigma V}{B} \cdot \left(1 + \frac{6e}{B}\right) \tag{2.13}$$

$$q_{min} = \frac{\Sigma V}{B} \cdot \left(1 - \frac{6e}{B}\right) \tag{2.14}$$

with eccentricity e being calculated as follows:

$$e = \frac{\mathrm{B}}{2} - \left(\frac{\Sigma M_r - \Sigma M_o}{\Sigma V}\right) \tag{2.15}$$

where:

B = Base of the Wall
ΣV = Total Vertical Force
ΣM_r = Total Resisting Moments around the Toe of the Wall
ΣM_o = Total Overturning Moments around the Toe of the Wall

For this case, eccentricity, maximum and minimum pressure resulted to be:

$$e = \frac{\mathrm{B}}{2} - \left(\frac{\Sigma M_r - \Sigma M_o}{\Sigma V}\right) = \frac{2.53\ \mathrm{ft}}{2} - \left(\frac{\mathbf{3722.36}\ \boldsymbol{ft \cdot lb} - \mathbf{1728.33}\ \boldsymbol{ft \cdot lb}}{\mathbf{2308.36}\ \boldsymbol{lbs}}\right) = 0.40 \tag{2.16}$$

$$q_{max} = \frac{\Sigma V}{B} \cdot \left(1 + \frac{6e}{B}\right) = \frac{2308.36\ \mathrm{lbs}}{2.53\ ft} \cdot \left(1 + \frac{6 \cdot 0.4}{2.53\ ft}\right) = 1780.44\ psf \tag{2.17}$$

$$q_{min} = \frac{\Sigma V}{B} \cdot \left(1 - \frac{6e}{B}\right) = \frac{2308.36\ \mathrm{lbs}}{2.53\ ft} \cdot \left(1 - \frac{6 \cdot 0.4}{2.53\ ft}\right) = 44.35\ psf \tag{2.18}$$

A minimum factor of safety of 3 is required to resist bearing capacity. The factor of safety, FS_{BC}, is evaluated as follows:

$$FS_{BC} = \frac{q_u}{q_{max}} \tag{2.19}$$

where q_u is the ultimate bearing capacity of the foundation soil.

Assuming an ultimate bearing capacity, q_u, of 5400 psf, the factor of safety, FS_{BC}, results to be:

$$FS_{BC} = \frac{q_u}{q_{max}} = \frac{5400\,psf}{1780.44\,psf} = \mathbf{3.03} > 3\ OK \tag{2.20}$$

Moreover, the minimum pressure, q_{min}, resulted to be a positive value. This means that the entire base lies in contact with the soil. If the minimum pressure resulted in a negative value, then it would mean that the heel of the base was tending toward lifting of the soil and would have required a revision and modification of the retaining wall dimensions and proportions.

2.2.5 LRFD Method

Barrier resistance to sliding, soil bearing capacity, and overturning can also be evaluated according to the LRFD method suggested by AASHTO (AASHTO, 2007). By using this method, a vehicle transverse impact load due to a possible impact can be incorporated in the retaining wall strength and stability evaluation.

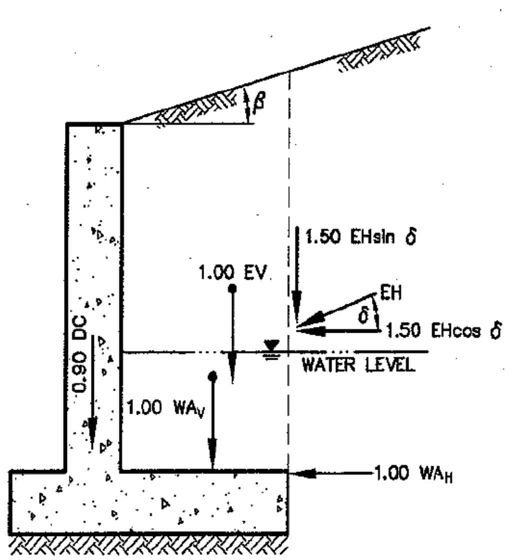
Figure 2.10 shows the typical application of load factors for evaluation of external stability of a generic retaining wall (AASHTO, 2007). The permanent and transient loads and forces include, but are not limited to:

- Permanent Loads:

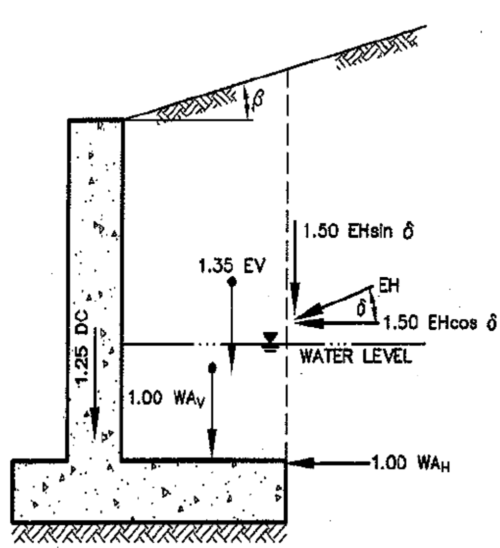
  DC = Dead Load of Structural Components
  DW = Dead Load of Wearing Surfaces and Utilities
  EH = Horizontal Earth Pressure Load
  ES = Earth Surcharge Load
  EV = Vertical Pressure from Dead Load of Earth Fill

- Transient Loads:

  LS = Live Load Surcharge
  WA = Water Load and Stream Pressure



(a) Sliding



(b) Bearing Capacity

Figure 2.10. Application of Load Factors for (a) Sliding and (b) Bearing Resistance.

2.2.5.1 LRFD Method to Evaluate Barrier Sliding Resistance

Barrier resistance to sliding is evaluated according the LRFD method. Figure 2.11 reports all the forces with respective load factors which are included in this analysis. Scope of this analysis is to find the minimum barrier length required for the barrier to resist the forces causing sliding. Thus, the minimum barrier length is a parameter which should be minimized. Optimization was performed using Excel, and the minimum barrier length was found when the total sliding resisting load was greater than the total sliding causing load. Table 2.4 reports the description of the loads and the load factors considered in the analysis and the minimum barrier length that resulted from the minimization procedure.

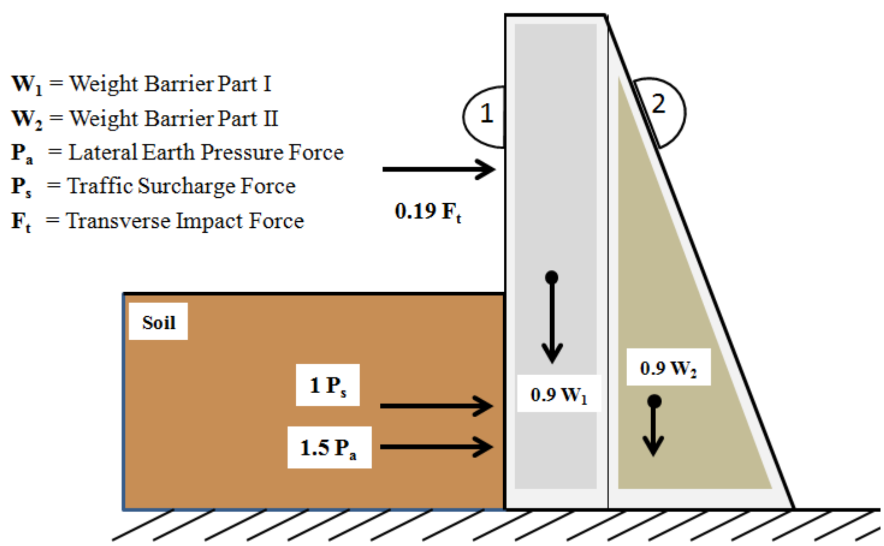


Figure 2.11. Application of Load Factors for Sliding.

Table 2.4. Evaluation of Minimum Barrier Length to Prevent Sliding for TL-3.

Force Description	Load Factor	Resistance Load (lb)	Min Barrier Length (ft)
Weight Barrier Part I	0.9	1,054.69	12
Weight Barrier Part II	0.9	1,253.67	12
		Total Sliding-Resisting Load (lb)	$\Sigma L_{SR} = 24,930.28$
Lateral Earth Pressure	1.5	460.89	12
Traffic Surcharge	1	384.07	12
Impact Load TL-3	0.19	54,000	1
		Total Sliding-Causing Load (lb)	$\Sigma L_{SC} = 22,904.86$

2.2.5.2 LRFD Method to Evaluate Barrier Bearing Capacity Resistance

Barrier resistance to bearing capacity is evaluated according the LRFD method. Figure 2.12 reports all the forces with their respective load factors which are included in this analysis. Scope of this analysis is to find the minimum barrier length required for the barrier to resist the soil bearing capacity. Thus, the minimum barrier length is a parameter which should be minimized. Optimization was performed using Excel, and the minimum barrier length was found when the total bearing capacity resisting load was greater than the total bearing capacity causing load. Table 2.5 reports the description of the loads and the load factors considered in the analysis and the minimum barrier length that resulted from the minimization procedure.

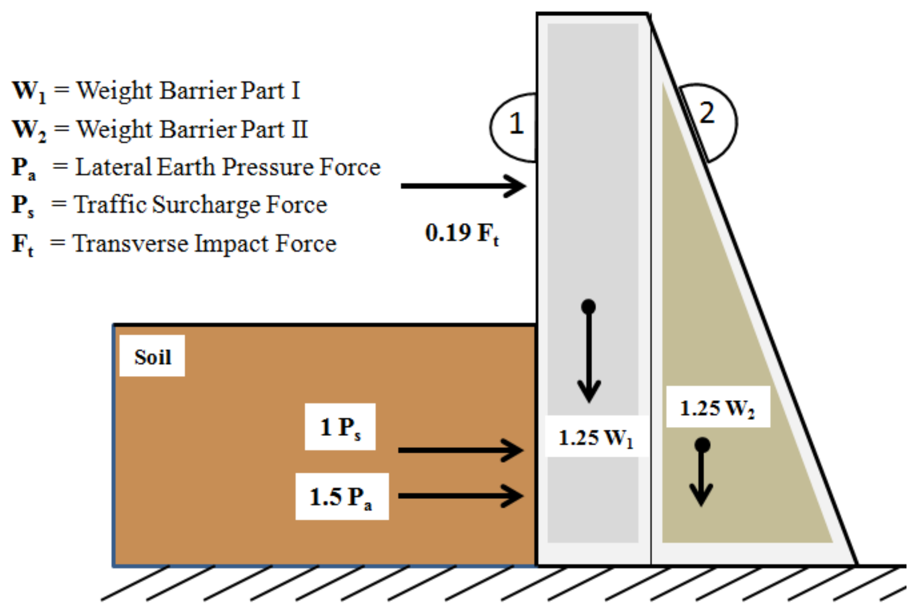


Figure 2.12. Application of Load Factors for Bearing Resistance.

Table 2.5. Evaluation of Minimum Barrier Length to Assure Bearing Resistance for TL-3.

Force Description	Load Factor	Resistance Load (lb)	Min Barrier Length (ft)
Weight Barrier Part I	1.25	1,054.69	6
Weight Barrier Part II	1.25	1,253.67	6
Total Bearing-Capacity Resisting Load (lb)			$\Sigma L_{BCR} = 17,312.70$
Lateral Earth Pressure	1.5	460.89	6
Traffic Surcharge	1	384.07	6
Impact Load TL-3	0.19	54,000	1
Total Bearing Capacity-Causing Load (lb)			$\Sigma L_{BCC} = 16,452.43$

2.2.5.3 LRFD Method to Evaluate Overturning Resistance

Barrier resistance to overturning is evaluated according the LRFD method. In this case, the transverse force, F_t, due to a vehicle impact against the barrier should be considered and included in the calculations as an overturning-causing force. AASHTO reports values of design forces that should be considered when evaluating different railing test levels (Table 2.6) (AASHTO, 2007). As indicated by AASHTO, the impact transverse force, F_t, and the height from the ground, H_e, where the force needs to be applied on the rail vary according to the railing test level considered.
Figure 2.13 illustrates the impact forces and their location on a bridge railing system, as indicated by AASHTO (AASHTO, 2007)

Table 2.6. Design Forces for Traffic Railings (AASHTO, 2007).

Design Forces and Designations	Railing Test Levels					
	TL-1	TL-2	TL-3	TL-4	TL-5	TL-6
F_t Transverse (kips)	13.5	27.0	54.0	54.0	124.0	175.0
F_L Longitudinal (kips)	4.5	9.0	18.0	18.0	41.0	58.0
F_v Vertical (kips) Down	4.5	4.5	4.5	18.0	80.0	80.0
L_t and L_L (ft.)	4.0	4.0	4.0	3.5	8.0	8.0
L_v (ft.)	18.0	18.0	18.0	18.0	40.0	40.0
H_e (min) (in.)	18.0	20.0	24.0	32.0	42.0	56.0
Minimum H Height of Rail (in.)	27.0	27.0	27.0	32.0	42.0	90.0

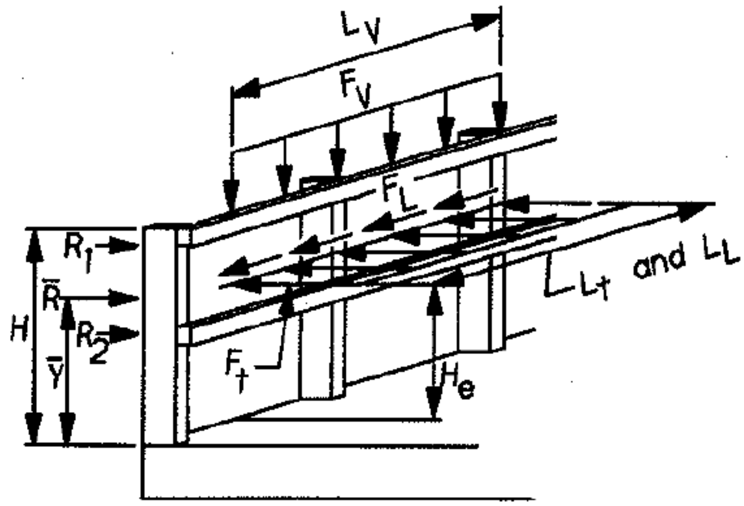


Figure 2.13. Bridge Railing Design Forces, vertical Location, and Horizontal Distribution Length (AASHTO, 2007).

For TL-3, a dynamic transverse force, F_t, of 54.0 kips (54,000 lb) should be considered. This force should be applied on the barrier at a minimum of 24 inches from the ground. AASHTO reports a dynamic value of the transverse force. This force, however, should be included in static calculations. Therefore, the corresponding static value for this 54,000-lb dynamic force was evaluated and found to be 10,000 lb. Figure 2.14 shows application of load factors and transverse impact force for overturning analysis.

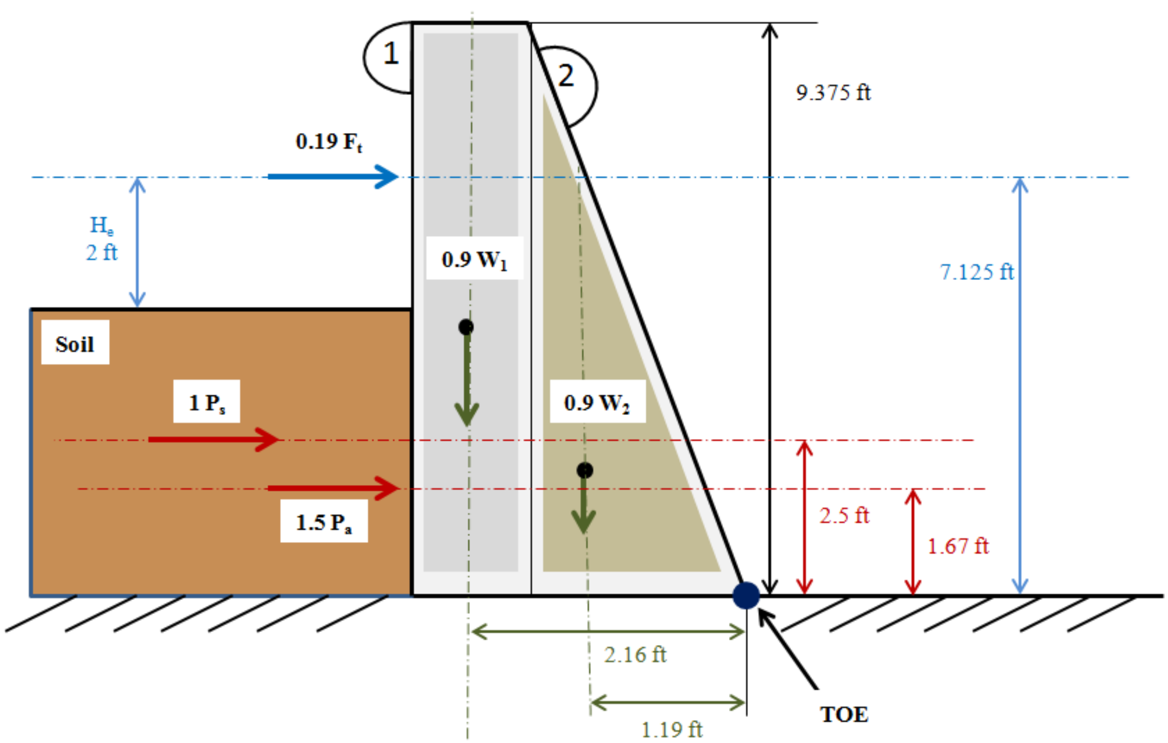


Figure 2.14. Application of Load Factors for Overturning Resistance.

An analysis was conducted to evaluate the minimum barrier length necessary to resist overturning with respect to the toe of the barrier, as indicated by Figure 2.14. The forces causing overturning are lateral earth force, P_a, traffic surcharge force, P_s, and transverse impact force, F_t. The force resisting overturning is the weight of the barrier, which was divided in two simple shapes for convenience in calculation. Each force was multiplied by a load factor. Also, each force was multiplied by the length of the barrier, which functioned as a parameter. Note that the impact load was not multiplied by the barrier length since it was only to be locally applied (on a unit barrier length). Tables 2.7 and 2.8 report all forces, load factors, and arm values used in the calculation for the cases the impact load is applied at 24 inches and 51 inches (maximum height) of the barrier. Minimum barrier lengths of 56 ft and 74 ft were required for resisting overturning with transverse impact load applied at 24 inches and 51 inches (Figure 2.15) from base of barrier, respectively.

Overturning moments:

$$\mathbf{M_O = (1.5 \cdot P_a) \cdot d_{Pa} \cdot \underline{B_L} + (1 \cdot P_s) \cdot d_{Ps} \cdot \underline{B_L} + (0.19 \cdot F_t) \cdot d_{Ft}} \tag{2.21}$$

Overturning-resisting moments:

$$\mathbf{M_R = (1.25 \cdot W_1) \cdot d_{W1} \cdot \underline{B_L} + (1.25 \cdot W_2) \cdot d_{W2} \cdot \underline{B_L}} \tag{2.22}$$

where:

$\mathbf{P_a}$	=	Lateral Earth Pressure Force (lb) - 460.89
$\mathbf{d_{Pa}}$	=	Arm for Lateral Earth Pressure Force from Toe (ft) - 1.667
$\mathbf{P_s}$	=	Traffic Surcharge Force (lb) - 384.07
$\mathbf{d_{Ps}}$	=	Arm for Traffic Surcharge Force from Toe (ft) - 2.499
$\mathbf{F_t}$	=	Transverse Impact Load TL-3 (lb) - 54,000
$\mathbf{d_{Ft}}$	=	Arm for Transverse Impact Load from Toe (ft) - 7.125
$\mathbf{W_1}$	=	Weight of Part I Barrier (lb) - 1054.69
$\mathbf{d_{W1}}$	=	Arm for Weight Part I Barrier from Toe (ft) - 2.16
$\mathbf{W_2}$	=	Weight of Part II Barrier (lb) - 1253.67
$\mathbf{d_{W2}}$	=	Arm for Weight Part II Barrier from Toe (ft) - 1.19
$\mathbf{\underline{B_L}}$	=	Minimum Barrier Length (ft) - PARAMETER to be minimized

Table 2.7. Evaluation of Minimum Barrier Length to Prevent Overturning for TL-3 with Transverse Load Applied at 24 inches from Base of Barrier.

Description	Resistance Factor	Resistance Load (lb)	Arm (ft)	Moment (lb-ft)	Min Barrier Length B_L (ft)
Weight Barrier Part I W_1	0.9	1,054.69	2.16	2,047.91	56
Weight Barrier Part II W_2	0.9	1,253.67	1.19	1,340.83	56
Total Overturning Resisting Load (lb)					$\Sigma L_{BCR} = 189,769.48$
Description	**Gamma**	**Load (lb)**	**Arm (ft)**	**Moment (lb-ft)**	**Min Barrier Length B_L (ft)**
Lateral Earth Pressure Force P_a	1.5	460.89	1.667	1,151.76	56
Traffic Surcharge Force P_s	1	384.07	2.499	959.80	56
Impact Load TL-3 F_t	0.19	54,000	7.125	71,250	1
Total Overturning-Causing Load (lb)					$\Sigma L_{BCC} = 189,497.21$

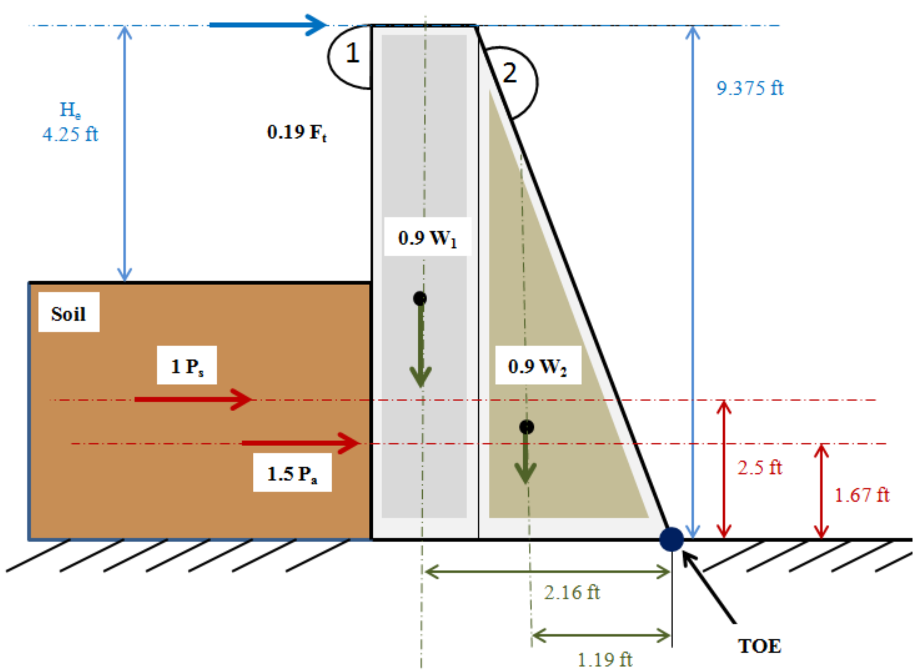


Figure 2.15. Application of Load Factors for Overturning Resistance, with Impact Force Applied at Maximum Barrier Height (51 inches).

Table 2.8. Evaluation of Minimum Barrier Length to Prevent Overturning for TL-3 with Transverse Load Applied at 51 inches from Base of Barrier.

Description	Resistance Factor	Resistance Load (lb)	Arm (ft)	Moment (lb-ft)	Min Barrier Length B_L (ft)
Weight Barrier Part I	0.9	1,054.69	2.16	2,047.91	74
Weight Barrier Part II	0.9	1,253.67	1.19	1,340.83	74
		Total Overturning Resisting Load (lb)			$\Sigma L_{BCR} = 250,766.81$
Description	**Gamma**	**Load (lb)**	**Arm (ft)**	**Moment (lb-ft)**	**Min Barrier Length B_L (ft)**
Lateral Earth Pressure Force	1.5	460.89	1.667	1,151.76	74
Traffic Surcharge Force	1	384.07	2.499	959.80	74
Impact Load TL-3	0.19	54,000	9.375	93,750	1
		Total Overturning-Causing Load (lb)			$\Sigma L_{BCC} = 250,005.25$

2.2.6 Yield Line Analysis

Researchers performed a yield line analysis to determine the nominal barrier resistance to transverse load, R_w, evaluated within a wall segment and for impacts at the end of the wall or at a joint (AASHTO, 2007).

1) For impacts within a wall segment:

$$R_w = \left(\frac{2}{2L_c - L_t}\right) \cdot \left(8M_b + 8M_w H + \frac{M_c L_c^2}{H}\right) \tag{2.23}$$

$$L_c = \left(\frac{L_t}{2}\right) + \sqrt{\left(\frac{L_t}{2}\right)^2 + \frac{8H(M_b + M_w H)}{M_c}} \tag{2.24}$$

2) For impacts at end of wall or at joint:

$$R_w = \left(\frac{2}{2L_c - L_t}\right) \cdot \left(M_b + M_w H + \frac{M_c L_c^2}{H}\right) \tag{2.25}$$

$$L_c = \left(\frac{L_t}{2}\right) + \sqrt{\left(\frac{L_t}{2}\right)^2 + H\left(\frac{M_b + M_w H}{M_c}\right)} \tag{2.26}$$

where:

F_t = Transverse Force (assumed to be acting at top of concrete wall) (kip)
H = Height of Wall (ft)
L_c = Critical Length of Yield Line failure Pattern (ft)
L_t = Longitudinal Length of Distribution of Impact Force F_t (ft)
R_w = Total Transverse Resistance of the Railing (kip)
M_b = Additional Flexural Resistance of Beam in Addition to M_w, if any, at top of wall (kft/ft)
M_w = Flexural Resistance of a Wall (kft/ft)
M_c = Flexural Resistance of Cantilevered Wall (kft/ft)

In this study, M_b is not considered. Following are graphical representations and explanation of how moments M_w and M_c were derived (Figures 2.16 to 2.19).

2.2.6.1 Calculation of moment M_w

To evaluate moment M_w, a 1-ft section (C-C) of the barrier is considered (Figure 2.16). When a beam is loaded by an external bending moment, statics show that the beam must resist the bending moment by internal stresses, indicated as a resultant tension, F_s, and a resultant compression, F_c. Without presence of an axial load, the sum of horizontal forces indicates that F_s = F_c.

Supposing the impact comes from the short side of the barrier, only the reinforcement of the tensile side of the barrier is included. The reinforcement consists in #4 (0.5-inch diameter) transverse and longitudinal rebar with 3-inch concrete coverage. Area of each bar, A_b, is 0.196 inch^2. With a transverse rebar spacing of 8 inches, the number of transverse rebar in a 1-ft wide specimen is 1.5.

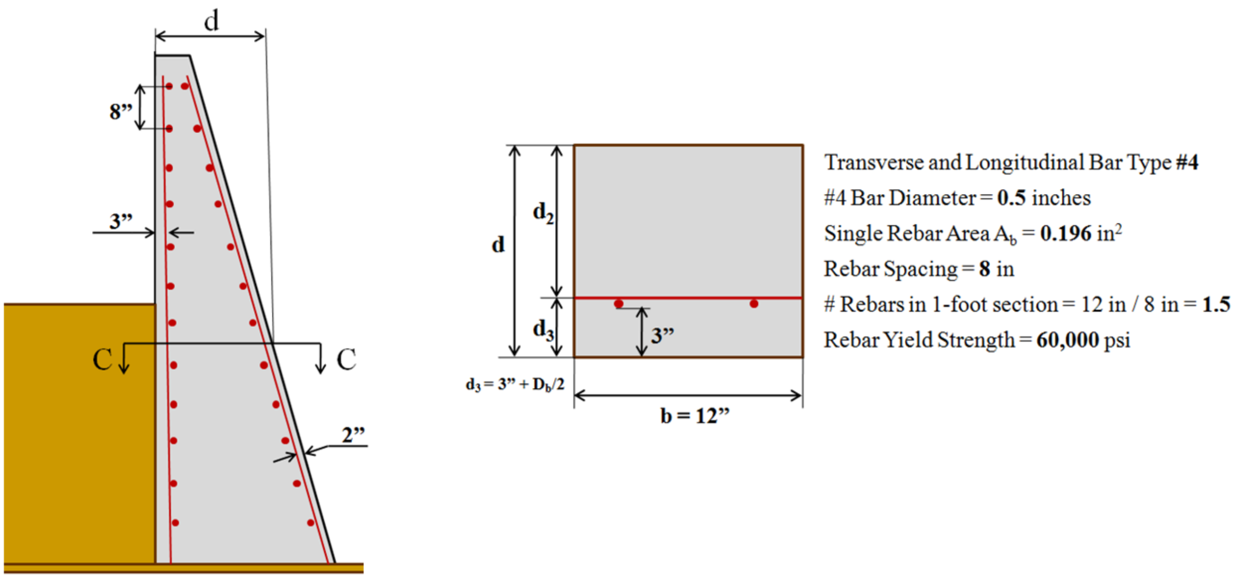


Figure 2.16. Geometrical Characteristics of 1-ft Reinforced Concrete Section C-C.

The analysis of the balanced beam starts from the strain triangles at failure, as shown in Figure 2.17. Tests observations suggest the maximum concrete strain to be 0.003 (Figure 2.17(a)). The real stress distribution can be replaced by an equivalent rectangle of stress of intensity 0.85 F_c' and depth, a (Figure 2.17(b)). For a maximum unit stress, $f_c' \leq 4{,}000$ psi, a = 0.85 c, where c is the neutral axis. Also, yield strength bar is 60 ksi.

The resultant tension force, F_s, depends on the yield strength bar (which is 60,000 psi) and on the total rebar area, A_b, in the 1-ft concrete section (Figure 2.17(c)). The reinforcing rebar of a reinforced concrete beam is assumed to carry all the tension, thus the F_s resultant is located at the level of the steel. The F_c resultant is located at a/2.

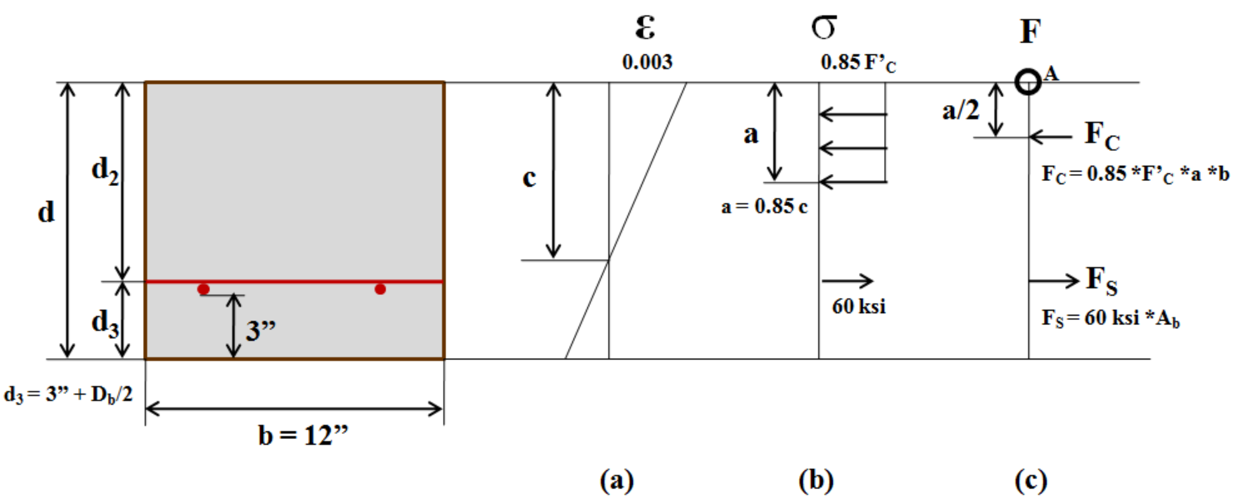


Figure 2.17. Balanced Beam. (a) Strains. (b) Equivalent Stresses. (c) Forces. Section C-C.

For equilibrium of horizontal forces:

$$\sum F_x = 0 \quad \rightarrow \quad F_c = F_s \tag{2.27}$$

with:

$$F_s = 60ksi \cdot A_b \tag{2.28}$$

$$F_c = 0.85 \cdot F_c' \cdot a \cdot b \tag{2.29}$$

$$a = 0.85 \cdot c \tag{2.30}$$

$$F_c' = 3600\,psi \tag{2.31}$$

Thus, the neutral axis c can be evaluated:

$$F_c = F_s \quad \rightarrow \quad 0.85 \cdot F_c' \cdot 0.85 \cdot c \ \cdot b = \ 60ksi \cdot A_b \tag{2.32}$$

$$c = \frac{60ksi \cdot A_b}{0.85 \cdot F_c' \cdot 0.85 \cdot b} \ = \ 0.566 \tag{2.33}$$

Finally, moment M_w can be evaluated by considering the equation of moments with respect to point A:

$$\sum M_a = 0 \quad \rightarrow \quad -M_c - F_c\left(\frac{a}{2}\right) + 60ksi \cdot A_b \cdot d_2 = 0 \tag{2.34}$$

$$M_w = -F_c\left(\frac{a}{2}\right) + 60ksi \cdot A_b \cdot d_2 \tag{2.35}$$

with:

$$d_2 = d - d_3 = d - \left(3 + \frac{D_b}{2}\right) \tag{2.36}$$

where D_b is the bar diameter. Since d varies along the height of the barrier, consequently the length d_2 varies with the height of the barrier. Thus, M_w varies also with height of the barrier.

2.2.6.2 Calculation of Moment M_c

To evaluate moment M_c, a similar procedure used for calculation of moment M_w is followed. A 1-ft (A-A) section of the barrier is considered (Figures 2.18 and 2.19).

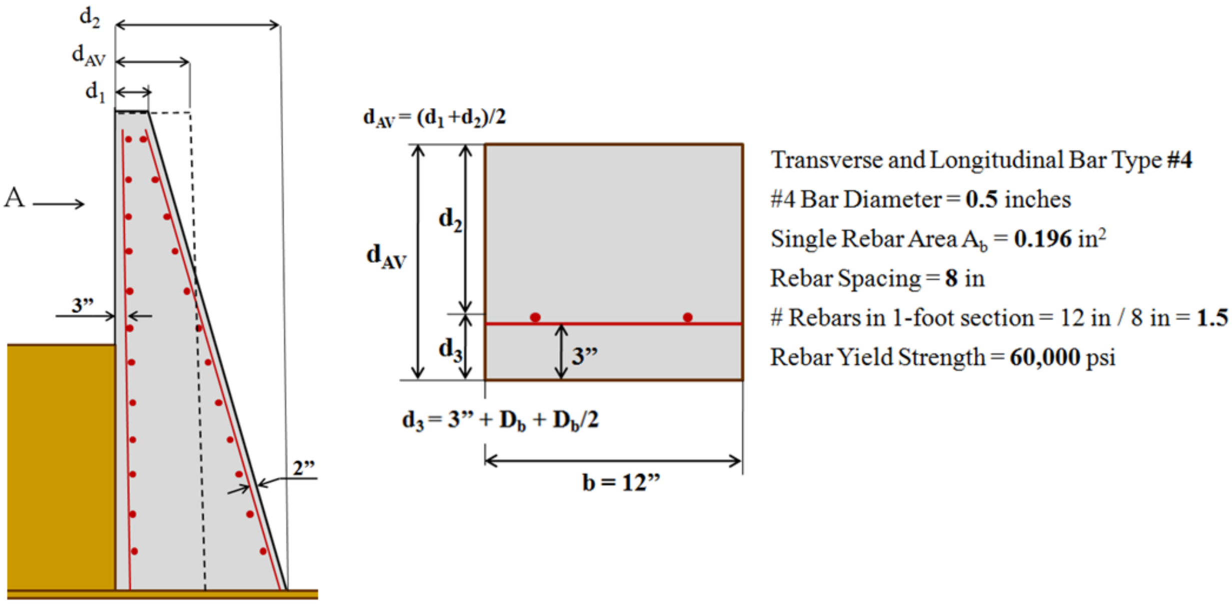


Figure 2.18. Geometrical Characteristics of 1-ft Reinforced Concrete Section A-A.

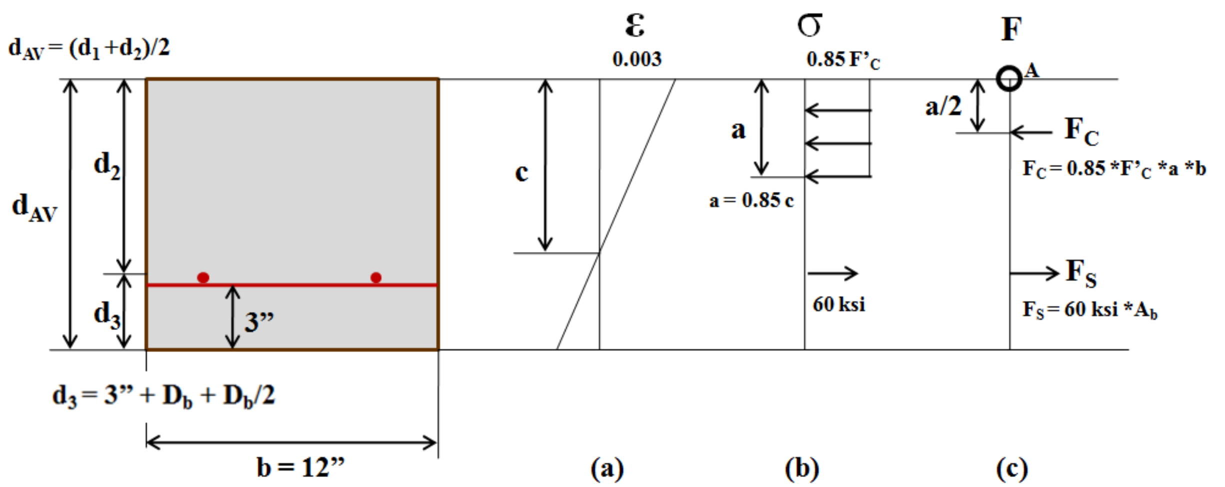


Figure 2.19. Balanced Beam. (a) Strains. (b) Equivalent Stresses. (c) Forces. Section A-A.

Supposing the impact comes from the short side of the barrier, only the reinforcement of the tensile side of the barrier is included. The reinforcement consists in #4 (0.5-inch diameter) transverse and longitudinal rebar with 3 inches of concrete coverage. Area of each bar, A_b, is 0.196 in^2. With a transverse rebar spacing of 8 inches, the number of transverse rebar in a 1-ft wide specimen is 1.5.

Moment M_c can be evaluated by considering the equation of moments with respect to point A:

$$\sum M_a = 0 \quad \rightarrow \quad -M_c - F_c\left(\frac{a}{2}\right) + 60ksi \cdot A_b \cdot d_2 = 0 \tag{2.37}$$

$$M_c = -F_c\left(\frac{a}{2}\right) + 60ksi \cdot A_b \cdot d_2 \tag{2.38}$$

with:

$$d_2 = d_{AV} - d_3 = d_{AV} - \left(3 + D_b + \frac{D_b}{2}\right) \tag{2.39}$$

where D_b is the bar diameter. Since d_{AV} varies along the height of the barrier, consequently the length d_2 varies with the height of the barrier. Thus, M_c varies also with height of the barrier.

After evaluation of both M_c and M_w, the total transverse resistance of the railing, R_w, is evaluated both within wall segments and at the end of the wall or at a joint. In both cases, the transverse resistance of the barrier, R_w, is greater than the transverse impact load, F_t, along all heights of the barrier. This means that the current barrier design is able to support a TL-3 impact.

2.2.7 Stability Analysis for the Case of Barrier at 51 inches Tall

Additional analysis was carried to evaluate the stability of the median vertical wall for the case there is no grade difference, so when the total height of the wall is 51 inches on both sides. In this case there are not earth active lateral and surcharge forces acting on the barrier side, however, still the barrier strength and resistance needs to be addressed in the event of a vehicle impact. Figure 2.20 shows the 51-inch median vertical wall geometry. Tables 2.9 to 2.10 show 51-inch median vertical wall stability results obtained with the LRFD method.

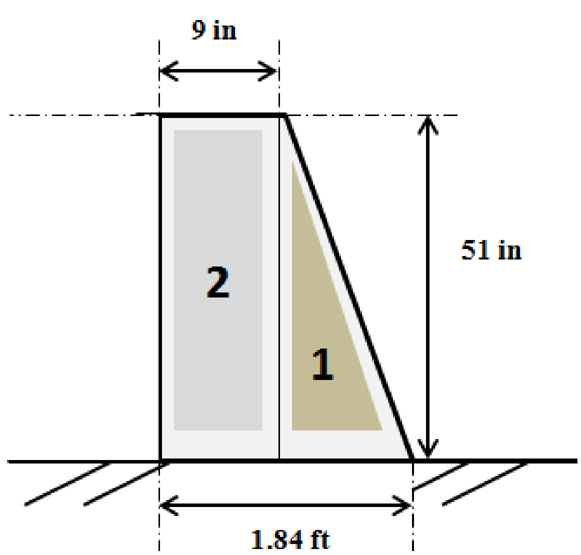


Figure 2.20. 51-inch Median Vertical Wall Geometry.

Table 2.9. Evaluation of Minimum Barrier Length for 51-inch Vertical Wall to Prevent Sliding for TL-3.

Force Description	Load Factor	Resistance Load (lb)	Min Barrier Length (ft)
Weight Barrier Part I	0.9	258.83	16
Weight Barrier Part II	0.9	478.13	16
Total Sliding-Resisting Load (lb)			$\Sigma L_{SR} = 10,612.08$
Impact Load TL-3	0.19	54,000	1
Total Sliding-Causing Load (lb)			$\Sigma L_{SC} = 10,000$

Table 2.10. Evaluation of Minimum Barrier Length for 51-inch Vertical Wall to Assure Bearing Resistance for TL-3.

Force Description	Load Factor	Resistance Load (lb)	Min Barrier Length (ft)
Weight Barrier Part I	1.25	258.83	11
Weight Barrier Part II	1.25	478.13	11
Total Bearing-Capacity Resisting Load (lb)			$\Sigma L_{BCR} = 10,133.06$
Impact Load TL-3	0.19	54,000	1
Total Bearing Capacity-Causing Load (lb)			$\Sigma L_{BCC} = 10,000$

As for overturning resistance capacity calculations, AASHTO LRFD suggests a minimum height of impact load application for TL-3 of 24 inches from the base of the barrier. Table 2.11 reports calculations for impact load applied at 24 inches from the base of the median vertical wall. With the transverse impact load applied at the top of the barrier (at 51 inches from the base), however, the overturning moment due to the impact force would be considerably higher. Table 2.12 reports calculations for impact load applied at 51 inches from the base of the median vertical wall.

Table 2.11. Evaluation of Minimum Barrier Length for 51-inch Vertical Wall to Prevent Overturning for TL-3 Applied at 24 inches from Barrier Base.

Force Description	Load Factor	Resistance Load (lb)	Arm (ft)	Moment (lb-ft)	Min Barrier Length B_L (ft)
Weight Barrier Part I	0.9	258.83	0.54	512.07	32
Weight Barrier Part II	0.9	478.13	1.19	125.79	32
Total Overturning Resisting Load (lb)					$\Sigma L_{BCR} = 20,411.55$
Description	**Gamma**	**Load (lb)**	**Arm (ft)**	**Moment (lb-ft)**	**Min Barrier Length B_L (ft)**
Impact Load TL-3	0.19	54,000	2	20,000	1
Total Overturning-Causing Load (lbs)					$\Sigma L_{BCC} = 20,000$

Table 2.12. Evaluation of Minimum Barrier Length for 51-inch Vertical Wall to Prevent Overturning for TL-3 Applied at 51 inches from Barrier Base.

Force Description	Load Factor	Resistance Load (lb)	Arm (ft)	Moment (lb-ft)	Min Barrier Length B_L (ft)
Weight Barrier Part I	0.9	258.83	0.54	512.07	67
Weight Barrier Part II	0.9	478.13	1.19	125.79	67
Total Overturning Resisting Load (lb)					$\Sigma L_{BCR} = 42,736.68$
Description	**Gamma**	**Load (lb)**	**Arm (ft)**	**Moment (lb-ft)**	**Min Barrier Length B_L (ft)**
Impact Load TL-3	0.19	54,000	4.25	42,500	1
Total Overturning-Causing Load (lbs)					$\Sigma L_{BCC} = 42,500$

2.3 CONCLUSIONS

The strength and stability analysis conducted for the 112.5-inch high median vertical wall showed that the current barrier design is capable of resisting sliding, overturning, and soil bearing capacity due to lateral earth pressure and traffic surcharge forces. Yield line analysis demonstrated the barrier capacity to resist impact transverse load for TL-3, evaluated within a wall segment and for impacts at end of the wall or at a joint. The LRFD method was also considered to determine the minimum barrier length needed to resist sliding, bearing capacity, and overturning when including impact transverse load for TL-3.

An additional analysis demonstrated the median vertical wall capacity to resist sliding, bearing capacity, and overturning for the case where there is no grade difference, when the total height of the wall is 51 inches on both sides. Table 2.12 summarizes the strength and stability findings.

According to the findings reported in Tables 2.13 and 2.14, the minimum vertical wall length required to resist sliding, bearing capacity, and overturning for TL-3 is 74 ft. The researchers suggest a median vertical wall minimum length of 80 ft to be considered for crashworthiness evaluation through finite element analyses.

Table 2.13. Strength and Stability Results for 112.5-inch Vertical Median Wall.

Evaluation	Passed	Min Barrier Length B_L (ft)
Sliding (only Lateral Earth Pressure)	✓	
Overturning (only Earth Lateral Pressure and Traffic Surcharge Force)	✓	
Bearing Capacity	✓	
Yield Analysis TL-3 (within Segment Wall)	✓	
Yield Analysis TL-3 (at End of Wall, or at Joint)	✓	
Sliding (including Transverse Impact Load TL-3)	✓	12
Bearing Capacity (including Transverse Impact Load TL-3)	✓	6
Overturning (including Transverse Impact Load TL-3 applied at 24 inches)	✓	56
Overturning (including Transverse Impact Load TL-3 applied at 51 inches)	✓	74

Table 2.14. Strength and Stability Results for 51-inch Vertical Median Wall.

Evaluation	Passed	Min Barrier Length B_L (ft)
Sliding (including Transverse Impact Load TL-3)	✓	16
Bearing Capacity (including Transverse Impact Load TL-3 applied at 24 inches)	✓	11
Overturning (including Transverse Impact Load TL-3 applied at 24 inches)	✓	32
Overturning (including Transverse Impact Load TL-3 applied at 51 inches)	✓	67

3. DESIGN MODIFICATION

3.1 INTRODUCTION

In the US, each year more than 160,000 people are involved in crashes that involve a vehicle striking a median barrier or bridge rail. Despite the use of safety belts and other occupant restraint systems, such impacts fatally injured more than 2000 people and cost society more than $3 billion every year.

One source of injuries and fatalities in these rigid barrier impacts is direct contact of the occupant's head with components of the barrier. The lateral deceleration imparted to a vehicle upon striking a rigid barrier causes the occupant to strike the door of the vehicle and their head to break out the side window. The likelihood of this head ejection resulting in contact with the barrier is a function of the barrier height and profile. Of particular concern are tall median barriers and bridge rails that are designed to accommodate a range of commercial trucks. These barriers are necessarily taller and stronger than barriers designed solely to accommodate passenger vehicles.

In recent years, this head-barrier contact problem has received considerable attention. Data analysis, full-scale tests and computer simulations are being used in Europe, Australia and Japan to understand the occupant dynamics in such types of impact scenarios, especially the interaction between the car occupant's head and the impacted barrier.

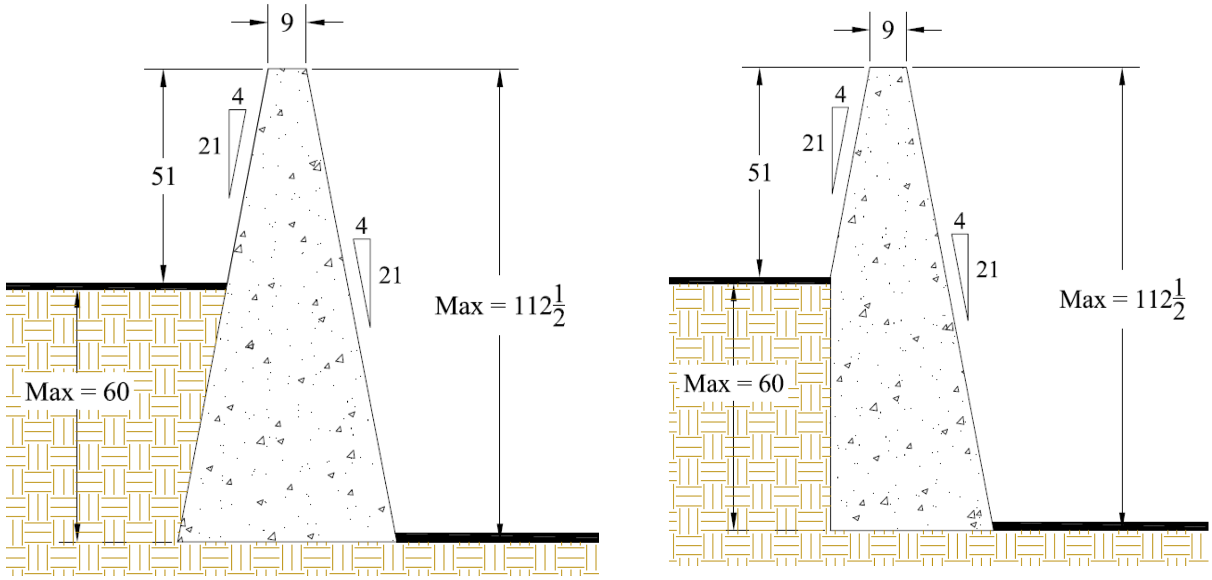
During partial ejection, the collision of the head with the barrier cannot be avoided simply through the use of seat belts and laminated window glass. Side airbags have been used to reduce the severity of injuries during impacts, but the data across the States are not totally consistent. Airbag safety research has focused primarily on severe injuries in frontal crashes, and the effectiveness of side airbags is still anecdotal.

The current median vertical wall proposed in this project might be identified as a barrier type representing a hazard for head contact during a vehicle-barrier collision. Therefore, the researchers proposed two alternative median barrier design options which should resolve the head slap concern.

3.2 DESIGN OPTIONS

Figure 3.1 illustrates two alternative median barrier designs suggested by the researchers.

Option 1 proposes the addition of a 4H:21V slope on the vertical side of the barrier (Figure 3.1(a)). The addition of the slope would help the impacting vehicle to slightly modify the dynamic through the impact process. This would help the vehicle maintain a certain distance from the barrier at the window's height, giving less chance for a head impact.



(a) Option 1: Single Slope Median Barrier (b) Option 2: Broken Back Median Barrier

Figure 3.1. Alternative Median Barrier Designs.

The top width is 9 inches and the width at the base is 51.8 inches. Barrier slope of both sides is 4H:21V (9.1 degree). The barrier would be cast in place with no use of a footing. Steel reinforcement grid is suggested on both barrier sides, with bars type #4 at spacing of 8 inches. The concrete coverage would be 2 inches from the top and 2 inches from side not covered by soil. Concrete coverage of side covered by soil would be 3 inches, in accordance to the AASHTO requirements for concrete coverage for cast against earth.

Option 2 proposes the addition of a 4H:21V slope on the vertical side of the barrier, from the top of the barrier to ground level (Figure 3.1(b)). For the portion of the barrier covered in the ground, a vertical wall design is maintained. This option would save on concrete quantity need for building the barrier, but would also lower the weight of the barrier itself, resulting in a less stable option than option #1.

The top width is 9 inches, the width at the broken back level is 28.5 inches, and the width at the base is 40.2 inches. The barrier would be cast in place with no use of a footing. Steel reinforcement grid is suggested on both barrier sides, with bars type #4 at 8-inch spacing. The concrete coverage would be 2 inches from the top and 2 inches from side not covered by soil. Concrete coverage of side covered by soil would be 3 inches, in accordance to the AASHTO requirements for concrete coverage for cast against earth.

Tennessee DOT decided to evaluate the use of median barrier option #1.

3.2.1 Calculation of Lateral Earth Pressure

Since the new design considers a sloped barrier also on the side of the soil, the backfill surface would not be horizontal. Since the lateral earth pressure would still act perpendicularly to the surface of the slope barrier, only its horizontal component would, in fact, act as a destabilizer to the barrier. For this condition, the lateral earth pressure should be evaluated with the Coulomb method, instead. The Coulomb method works under the following assumptions:

- Lateral earth pressure is evaluated for sloped walls;
- The resultant lateral earth pressure force is not necessarily parallel to the wall due to soil-wall friction δ;
- The soil-wall friction angle is commonly used as $\delta = 2\phi/3$.

For evaluation of the stability of the sloped median barrier design, the researchers decided to use the same lateral earth pressure value found with the Rankine method. Even though appropriate calculations should be performed to evaluate the lateral earth pressure force with the Coulomb method with consideration of the soil-barrier friction angle, use of the Rankine method was considered conservative. With the Rankine method, in fact, the researchers included effect of barrier destabilization from the overall lateral earth pressure force, instead of from only the horizontal component. With the Coulomb method, moreover, the vertical component of the lateral earth pressure force would help the stability of the barrier and act against the destabilizing horizontal component.

The sloped barrier design resulted to be stable with respect to sliding, overturning, and bearing capacity. Also, the sloped barrier design met the requirements according to the yield line analysis. The researchers suggest a median vertical wall minimum length of 80 ft be considered for crashworthiness evaluation through finite element analyses.

3.3 CONCLUSION

The median vertical wall proposed at the beginning of this project could represent a hazard for head contact during a vehicle-barrier collision. Therefore, the researchers proposed alternative median barrier design options to resolve the head slap concern. The barrier design chosen for consideration in this study was a single slope median barrier of a total maximum height of 112.5 inches, a soil backfill height of maximum 60 inches acting on one side, and 4H:21V slope on both sides of the barrier.

Stability and yield line analyses for the sloped barrier design were evaluated and a minimum length of 80 ft is suggested for crashworthiness evaluation through finite element analyses.

4. *MASH* TEST LEVEL 3 - FINITE ELEMENT ANALYSIS

4.1 INTRODUCTION

Recent advances in computer hardware and finite element methodologies have given researchers in the roadside safety and physical security communities the ability to investigate complex dynamic problems involving vehicular impacts into barrier systems. 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 (Hallquist, 2007). LS-DYNA is a general purpose, explicit finite element code. LS-DYNA is widely used to solve nonlinear, dynamic response of three-dimensional problems and is capable of capturing complex interactions and dynamic load-time history responses that occur when a vehicle impacts a barrier system.

4.2 SIMULATION METHODOLOGY

A matrix of FEA was performed to evaluate the crashworthiness of the proposed median barrier system. These computer simulations were performed in accordance with the AASHTO *Manual for Assessing Safety Hardware* (*MASH*) for TL-3 using a finite element model of a 2270 kg Silverado pickup truck developed by National Crash Analysis Center (NCAC). This model meets the specification criteria for *MASH* TL-3 design truck. The researchers opted not to evaluate a small car impact. The *MASH* pickup truck provided the maximum impact load required to evaluate the median barrier system.

The simulations reported herein were performed according to *MASH* TL-3 involving the design truck impacting the median barrier system at 25 degrees and 62 mph. The target impact point was at the third point of the barrier, such that redirection would occur within the remaining length of the median barrier. This minimizes issues that occur when impacting near the barrier's end locations.

4.2.1 Vehicle Model and Validation

There are currently two versions of the *MASH* pickup truck vehicle model available in the public domain, both developed by NCAC under funding from Federal Highway Administration (FHWA). One is a detailed version and contains 930,000 elements, while the other is a reduced version containing 250,000 elements. Initially, only the detailed model was developed and released. The researchers have used the detailed version and performed various validation simulations to gain more confidence in its use. Several changes were also made to this model over the course of its use to improve accuracy and robustness. Recently, however, the reduced version of the vehicle model was developed and released. Due to a very significant reduction in model size, and the number of simulations to be performed under this project using a *MASH* pickup, the researchers believed that significant savings in CPU usage and run times could be achieved by using the reduced model. However, since no validation runs were performed in the past, the researchers used one of the previous *MASH* TL-3 tests for validation purposes. The test was performed with rigid New Jersey (NJ) concrete barrier. The researchers modeled the rigid NJ barrier and performed the impact simulations. Several changes were made to the reduced pickup truck model to improve correlation between test and simulation results. Figure 4.1 shows comparison of the final simulation results. Figure 4.2 shows comparison of the vehicle kinematics between simulation and test.

0.23 sec

0.46 sec

Figure 4.1. Comparison of FE Simulation and Crash Test Results with Rigid NJ Barrier.

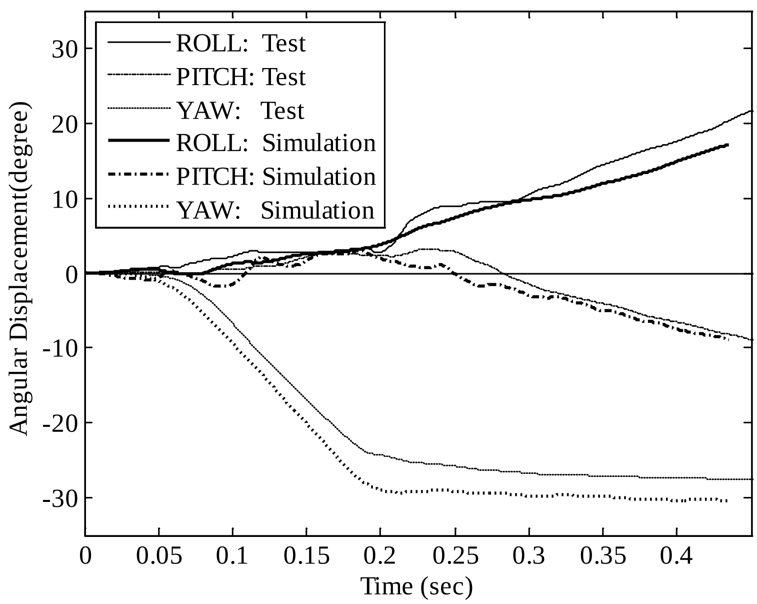


Figure 4.2. Vehicle Kinematics Comparison between FE Simulation and Crash Test Results with Rigid NJ Barrier.

Having significantly validated the reduced vehicle model, the researchers feel confident in its use for the rest of the project.

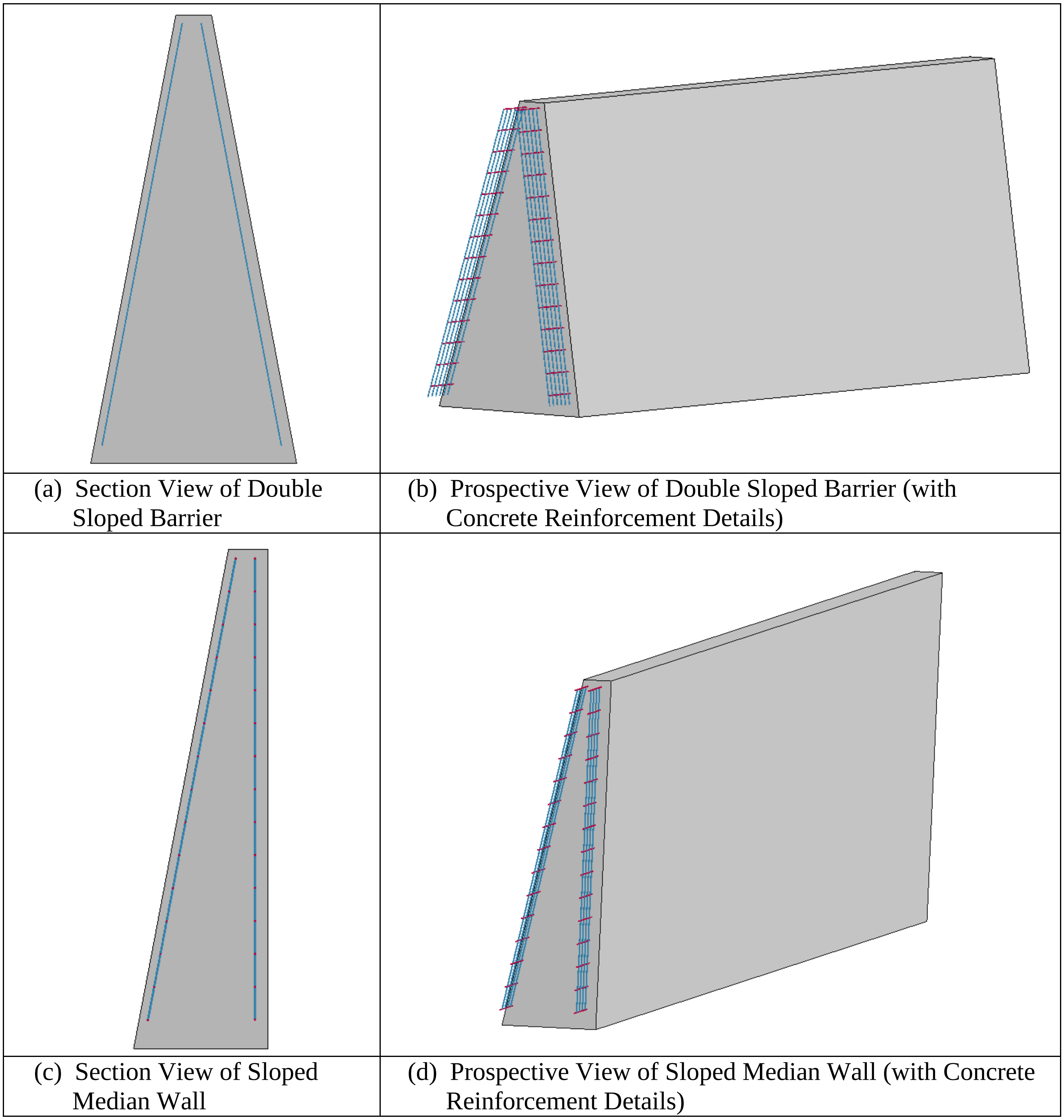
4.2.2 Vertical and Single Slope Median Wall Barrier Models

The crashworthiness of a vertical median wall and a single slope median wall were evaluated using finite element simulations. Different models were developed and impact simulations performed to capture the range of geometries (i.e. grade separation, height) that the barrier system would be installed. These models were used to evaluate the barriers ability to retain soil according to AASHTO and as a longitudinal barrier according to *MASH* (AASHTO, 2007). The first of these models consisted of a 51-inch single slope on the impact side and a 112.5-inch single slope face opposite to impact. The second model consisted of a 51-inch vertical wall on the impact side and a 112.5-inch single slope face opposite to impact. Both systems were also evaluated in the case grade separation does not occur, thus when both sides of the barriers are 51 inches tall.

It is reasonable to assume that the crashworthiness of a median barrier between either of these geometries, 112.5-inch and 51-inch, will meet the requirements of *MASH* for crashworthiness and AASHTO for soil retention.

The first simulation model was developed using the geometry of the proposed double sloped barrier. A single 80-ft section of the median barrier was modeled for the impact simulation. The top width of the barrier is 9 inches and the width at the base is 51.8 inches. Both sides of the barrier are 4H:21V (9.1 degree) sloped. The overall height of the barrier is 112.5 inches. The barrier's reinforcement was modeled using #4 reinforcing bars spaced 8 inches on center, each direction. The reinforcing bars had 2 inches of clear cover from both the top of the barrier and the sloped face. A clear cover of 3 inches was modeled on the side nearest the earth backfill. The same model was then modified so that the overall height of the barrier would be 51 inches. This model had level grades on either side of the barrier. In this instance, the barrier is not used to retain soil. The finite element model of this barrier is shown in Figure 4.3(a) and (b).

The second simulation model was developed using the geometry of the tall barrier proposed by TDOT. A single 80-ft section of the median barrier was modeled for the impact simulation. The top width of the barrier is 9 inches and the width at the base is 30.4 inches. The impact side of the barrier is a vertical wall. The slope of the barrier opposite of impact is 4H:21V (9.1 degree). The overall height of the barrier is 112.5 inches. The barrier's reinforcement was modeled using #4 reinforcing bars spaced 8 inches on center, each direction. The reinforcing bars had 2 inches of clear cover from both the top of the barrier and the sloped face. A clear cover of 3 inches was modeled on the side nearest the earth backfill. The same model was then modified so that the overall height of the barrier would be 51 inches. This model had level grades on either side of the barrier. In this instance, the barrier is not used to retain soil. The finite element model of this barrier is shown in Figure 4.3(c) and (d).



(a) Section View of Double Sloped Barrier

(b) Prospective View of Double Sloped Barrier (with Concrete Reinforcement Details)

(c) Section View of Sloped Median Wall

(d) Prospective View of Sloped Median Wall (with Concrete Reinforcement Details)

Figure 4.3. Double Sloped Barrier and Sloped Median Wall Finite Element Models Geometry.

The soil was modeled using eight-node brick elements. A single surface contact between the interface of the soil and the barrier were used to capture the soil interaction. Ample time was allowed for the soil to reach an initialized state, in which the soil's pressure distribution was stable and all settlement had occurred, prior to the vehicle impacting the barrier. This was accomplished by offsetting the vehicle a distance from the barrier to allow time for initialization. Movement of the soil mass was only allowed at the interface with the barrier. The sides, rear, and bottom boundaries of the soil mass were confined from movement.

The barrier's concrete section was modeled using eight-node solid brick elements and reinforcing bars using beam elements. Typically, the reinforcing bars are coupled inside the solid brick elements using a constrained Lagrange in solid command. The constrained Lagrange command required large amounts of physical memory, thus could not be used for this larger models which include high numbers of elements and nodes. To circumvent the use of a constrained Lagrange command, the researchers opted to build the model such that the beams used to model the reinforcing bars were directly merged with the nodes of the solid brick elements comprising the concrete section. This behavior is based on the assumption that a perfect bond exists between the reinforcing bars and concrete.

LS-DYNA material card #159 *MAT_CSCM_CONCRETE was used to model the material behavior of the concrete barrier. Concrete compression strength was considered to be 4000 psi (27.58 MPa), and aggregate size was supposed to be 3/4 inches (19 mm). Reinforced bars were modeled with LS-DYNA material type #24 *MAT_PIECEWISE_LINEAR_PLASTICITY, with a yield stress value of 414 MPa. The soil material was modeled using LS-DYNA material card #25 *MAT_GEOLOGIC_CAP_MODEL.

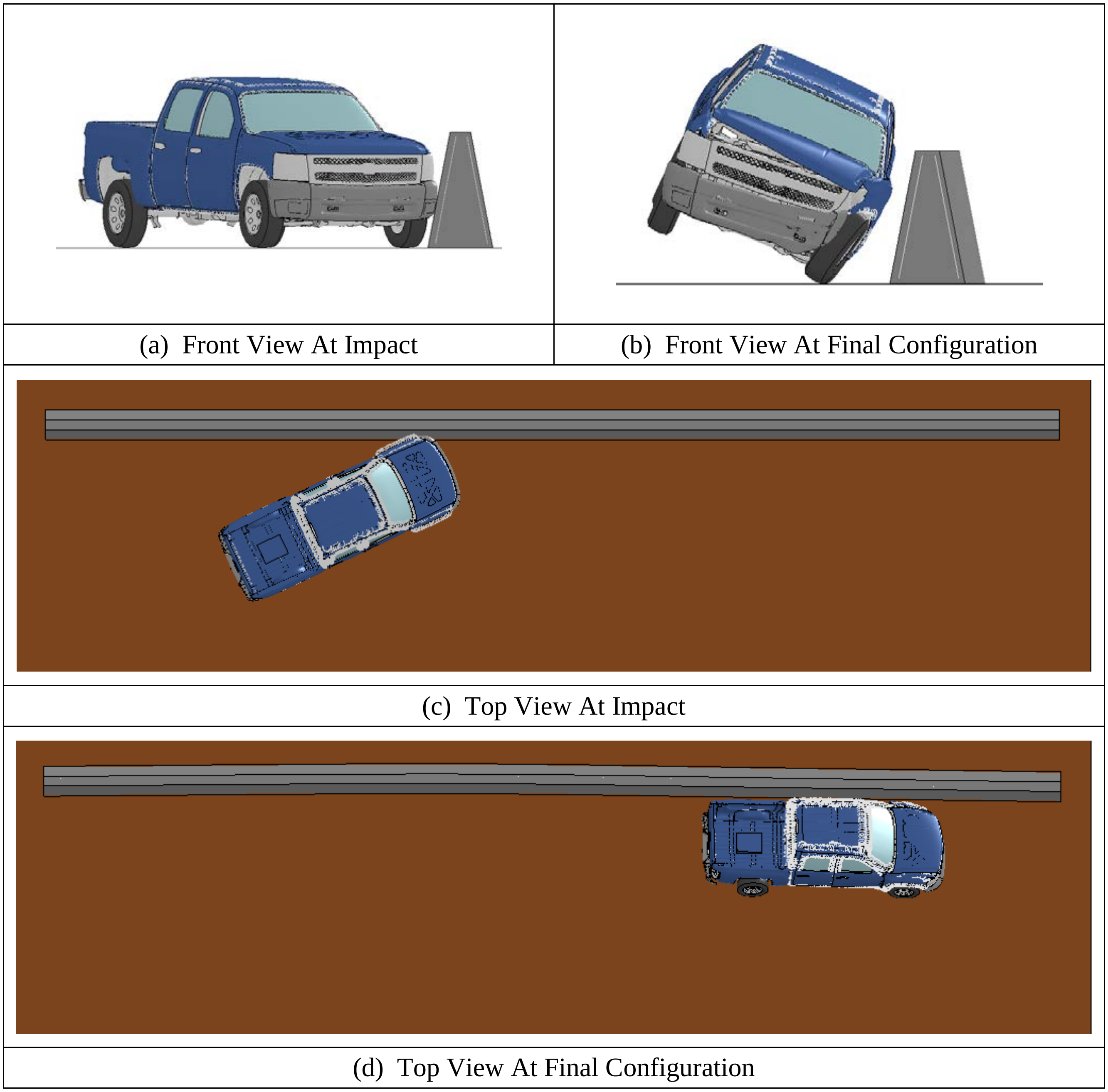
4.3 FINITE ELEMENT RESULTS

4.3.1 *MASH* TL 3-11: 80-ft Single Sloped Median Wall 51 inches Tall

This section contains results from a simulated *MASH* TL 3-11 impact into an 80-ft long, 51-inch tall sloped median wall segment. The authors decided to use FE simulations to evaluate the 51 inches free standing median wall structural capacity and the vehicle stability during the *MASH* TL 3-11 impact event.

4.3.1.1 Barrier Performance

Figure 4.4 contains images of the barrier before impact and at final configuration. A maximum barrier deformation of 0.5 ft (6.3 inches) was reached at approximately 0.49 seconds after impact. Figure 4.4(a) and 4.4(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 4.4(b) and 4.4(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. The barrier was impacted at the one-third point of the installation.



(a) Front View At Impact

(b) Front View At Final Configuration

(c) Top View At Impact

(d) Top View At Final Configuration

Figure 4.4. Initial and Deflected Shape of Barrier for *MASH* TL 3-11 Impact (Sloped Median Wall – 51-inch).

4.3.1.2 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 in other parts preferred).

Since this is a closed system and energy is conserved, the sum of the kinetic energy, hourglass energy, sliding energy, and internal energy at any time during the simulation should equate to the initial kinetic energy of the vehicle. As shown in Figure 4.5, approximately 12 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 1 percent of the initial kinetic energy is converted into hourglass energy. Approximately 12 percent of the initial kinetic energy is converted into sliding interface energy. Seventy three percent of the initial kinetic energy has yet to be dissipated by the system at the time of final impact configuration, mainly due to the remaining velocity of the vehicle.

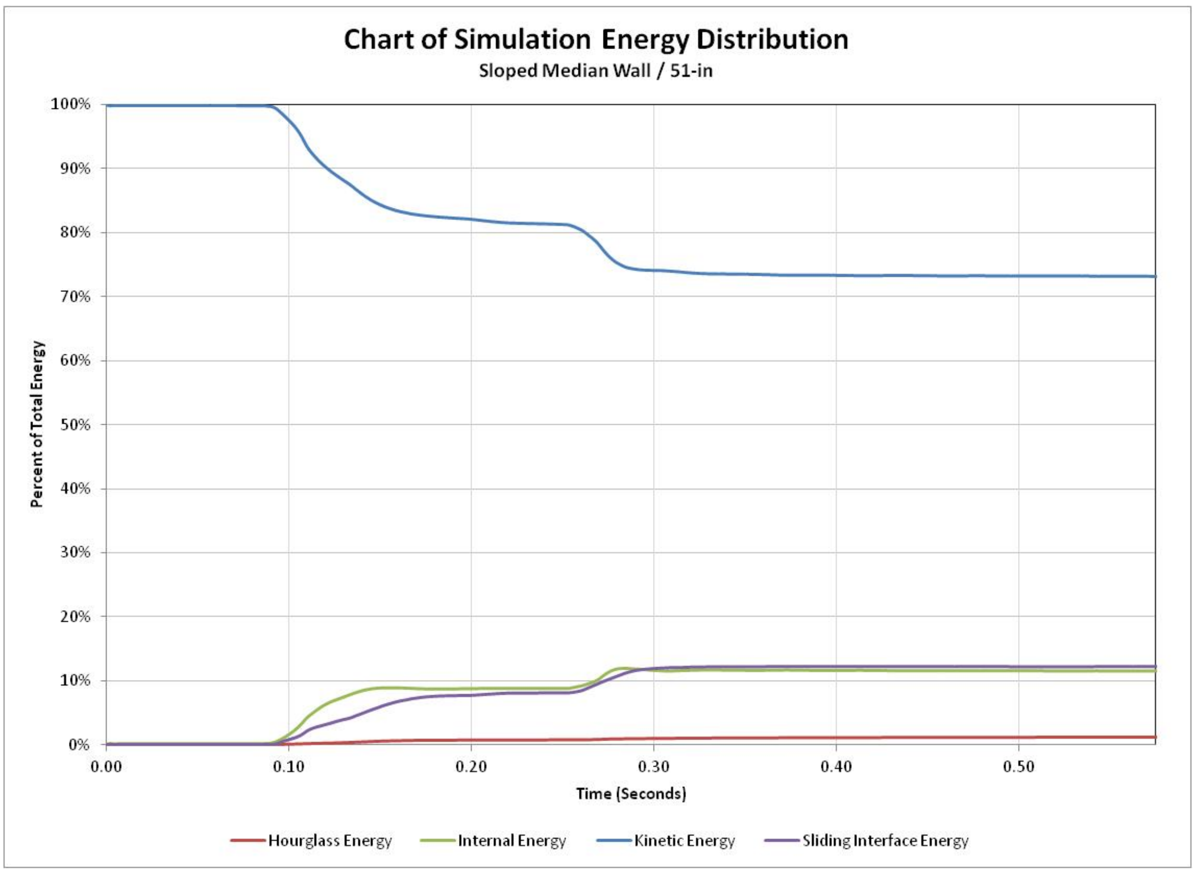
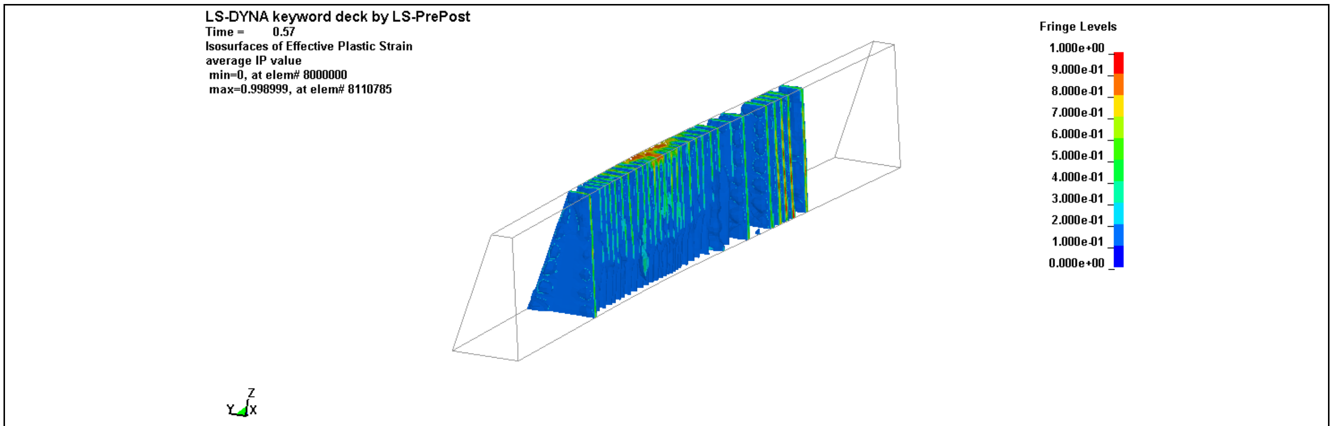


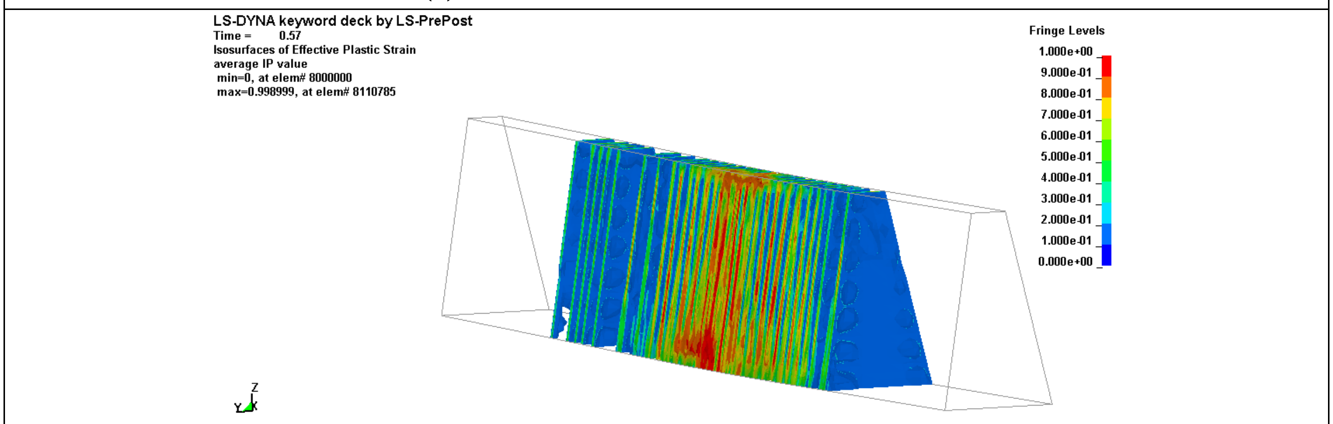
Figure 4.5. Energy Distribution Time History for *MASH* TL 3-11 Impact (Sloped Median Wall – 51-inch).

4.3.1.3 Plastic Strain

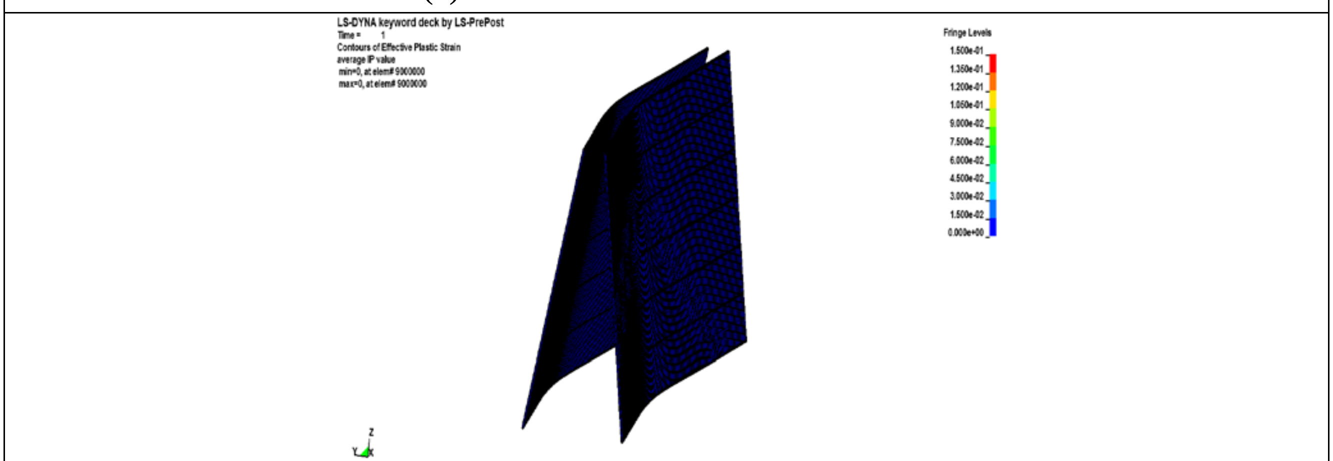
Plastic strain contours shown in Figure 4.6 are used to visualize possible barrier failure locations. Blue color represents regions with little to no plastic strain. Red color represents regions with plastic strains equal to or greater than 15 percent. Plastic strains greater than 15 percent for steel material indicate regions where local steel failure is likely to occur.



(a) Front Side of the Concrete Barrier



(b) Back Side of the Concrete Barrier



(c) Barrier Steel Reinforcement

Figure 4.6. Concrete Stresses for *MASH* TL 3-11 Impact (Sloped Median Wall – 51-inch).

Regions in compression with high plastic strains are of less concern unless the region is acting as a column. In compression zones, high plastic strains usually occur as the result of buckling as opposed to rupture. Buckling regions that form usually do not signify failure of a component. In most cases a buckled region can still resist a significant portion of the unbuckled sections load capacity.

4.3.1.4 Concrete Foundation Stresses

Figure 4.6 shows the plastic strains in (a) the front and (b) the back side of the barrier. Areas shown in Figure 4.6(b) are areas where damage to the concrete barrier is likely to occur. It is likely that cracks will form in these locations at the back side of the barrier; it is unlikely, however, that a catastrophic failure of the concrete barrier will occur.

Figure 4.6(c) shows the plastic strains in the rebar structure of the barrier. Blue regions represent regions with little to no plastic strain. Red regions represent regions with plastic strains equal to or greater than 15 percent. As shown in Figure 4.6(c), there are no high plastic strain regions in the rebar cage.

Tables 4.1 and 4.2 show frames from FE simulation of impact against the modeled 51-inch tall sloped median wall.

4.3.1.5 Occupant Risk Assessment

A program called TRAP was used to evaluate occupant risk factors based on the applicable *MASH* safety evaluation criteria (TRAP, 2011). The modeled 2270P vehicle remained upright during and after the modeled collision event. Figure 4.7 shows vehicle roll, pitch, and yaw angles throughout the impact event against the 51-inch high sloped median wall. Maximum roll, pitch, and yaw angles resulted in -24.6, -4.1, and 27.8 degrees, respectively. Previous multiple test experience showed that occupant risk results are not a concern for impact of vehicle against single sloped concrete barrier, since they all remained in the range required by *MASH* criteria. As consequence, occupant risk values were not evaluated for this finite element simulation.

4.3.1.6 Results

Figure 4.8 summarizes results for *MASH* Test 3-11 simulation with a 2270P vehicle impacting a 51-inch high sloped median wall. Results showed that the 51-inch tall single sloped median wall performed adequately by containing and redirecting the impacting 2270P vehicle. The free standing barrier slid a little over 6 inches from its initial position during the impact event. However, the barrier did not show any potential for tipping over and allowing the impacting vehicle for intrusion in the opposing lane. Also, simulations indicate the 2270P vehicle maintaining stability during the *MASH* TL 3-11 impact conditions event.

Table 4.1. Sequential Images of the 2270P Vehicle Interaction with the 51-inch Tall Sloped Median Wall Model for *MASH* TL 3-11 Impact (Perpendicular and Oblique Views).

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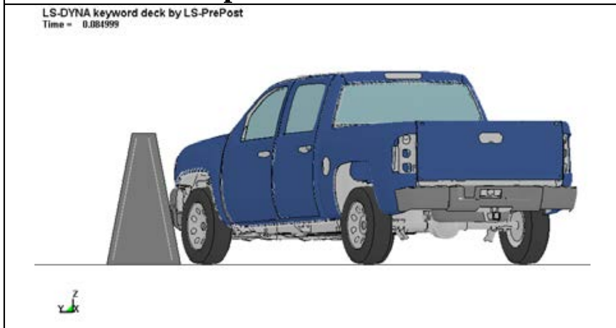
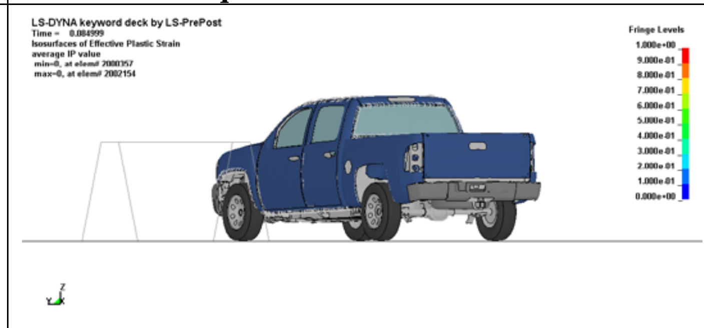
<tr><th>Perpendicular View</th><th>Oblique View - Barrier Strains</th></tr>
<tr><td>
</td><td>
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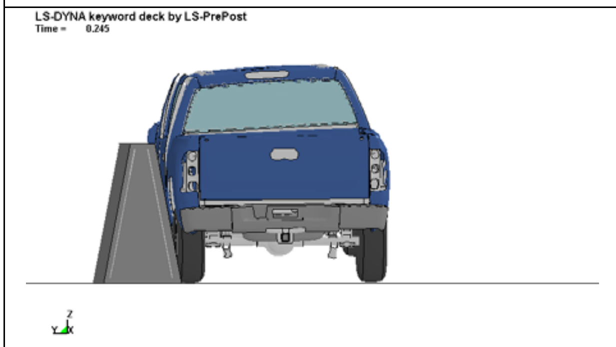
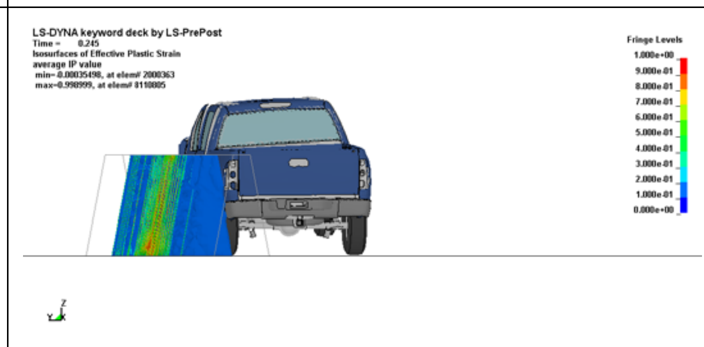
<tr><td>
</td><td>
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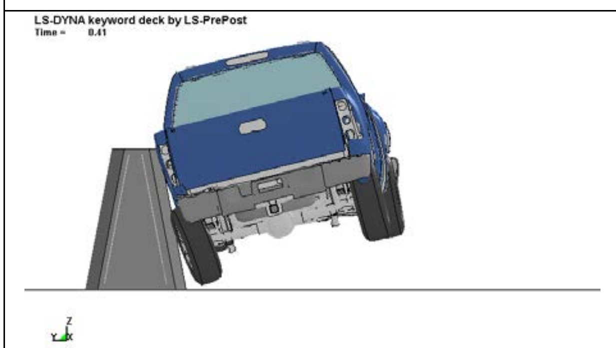
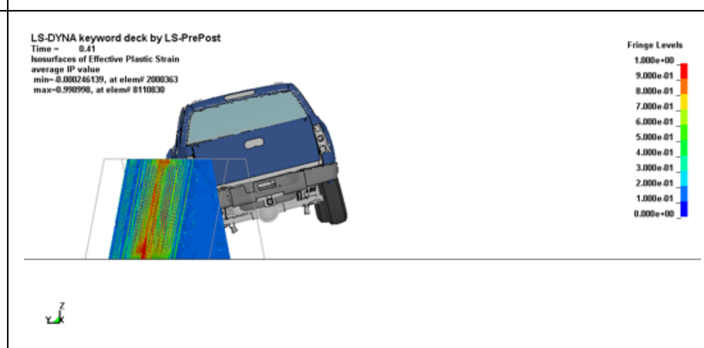
<tr><td>
</td><td>
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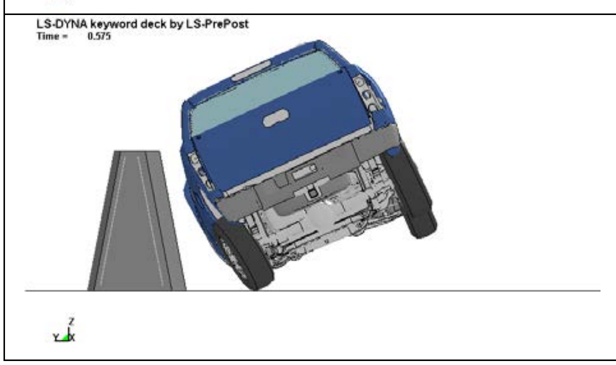
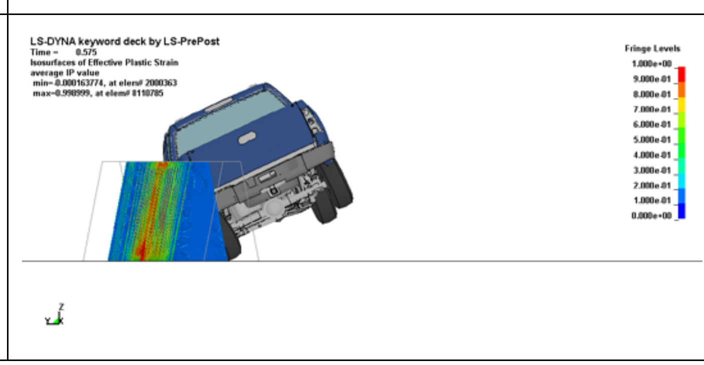
<tr><td>
</td><td>
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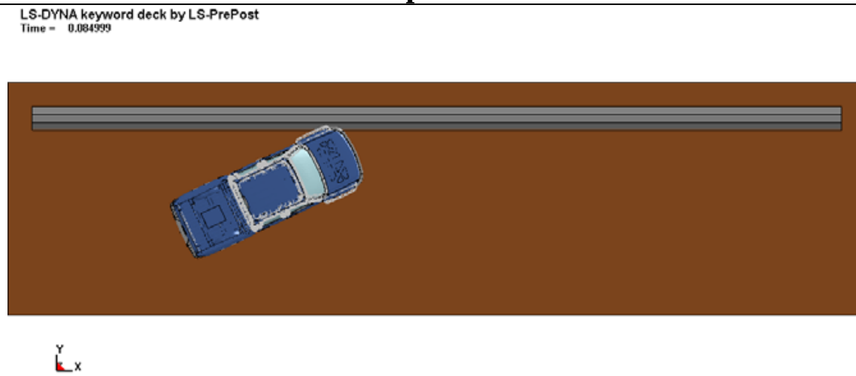
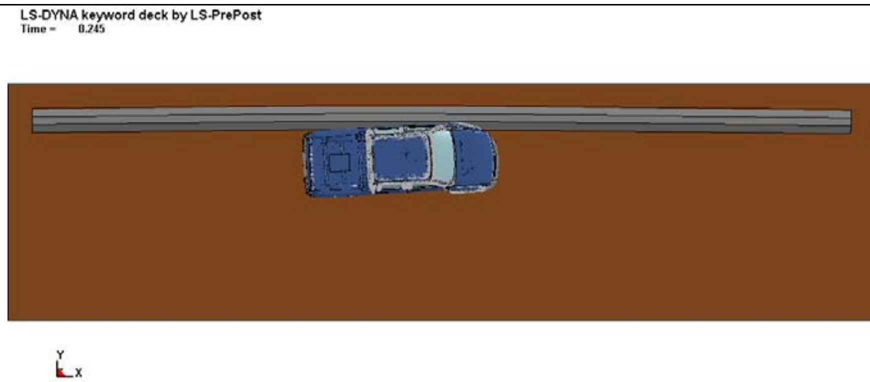
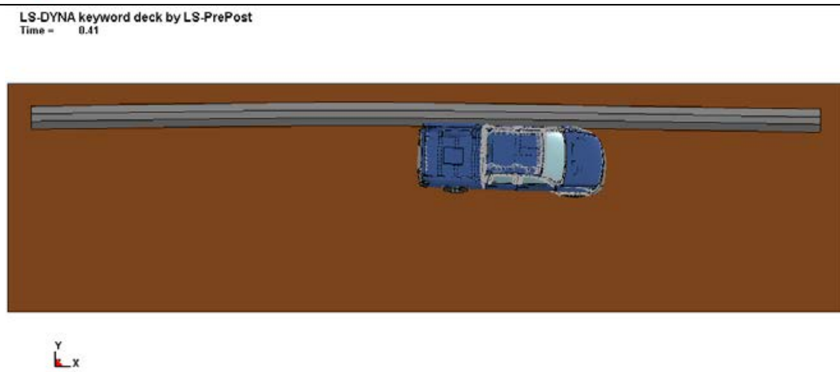
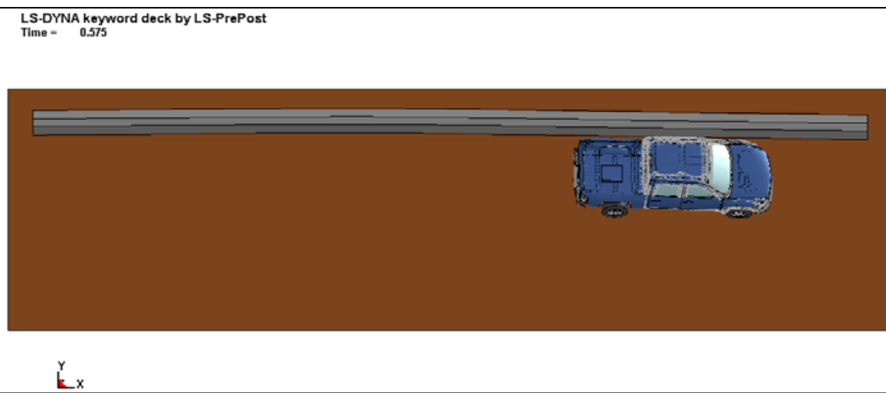
Table 4.2. Sequential Images of the 2270P Vehicle Interaction with the 51-inch Tall Sloped Median Wall Model for *MASH* TL 3-11 Impact (Top View).

Top View





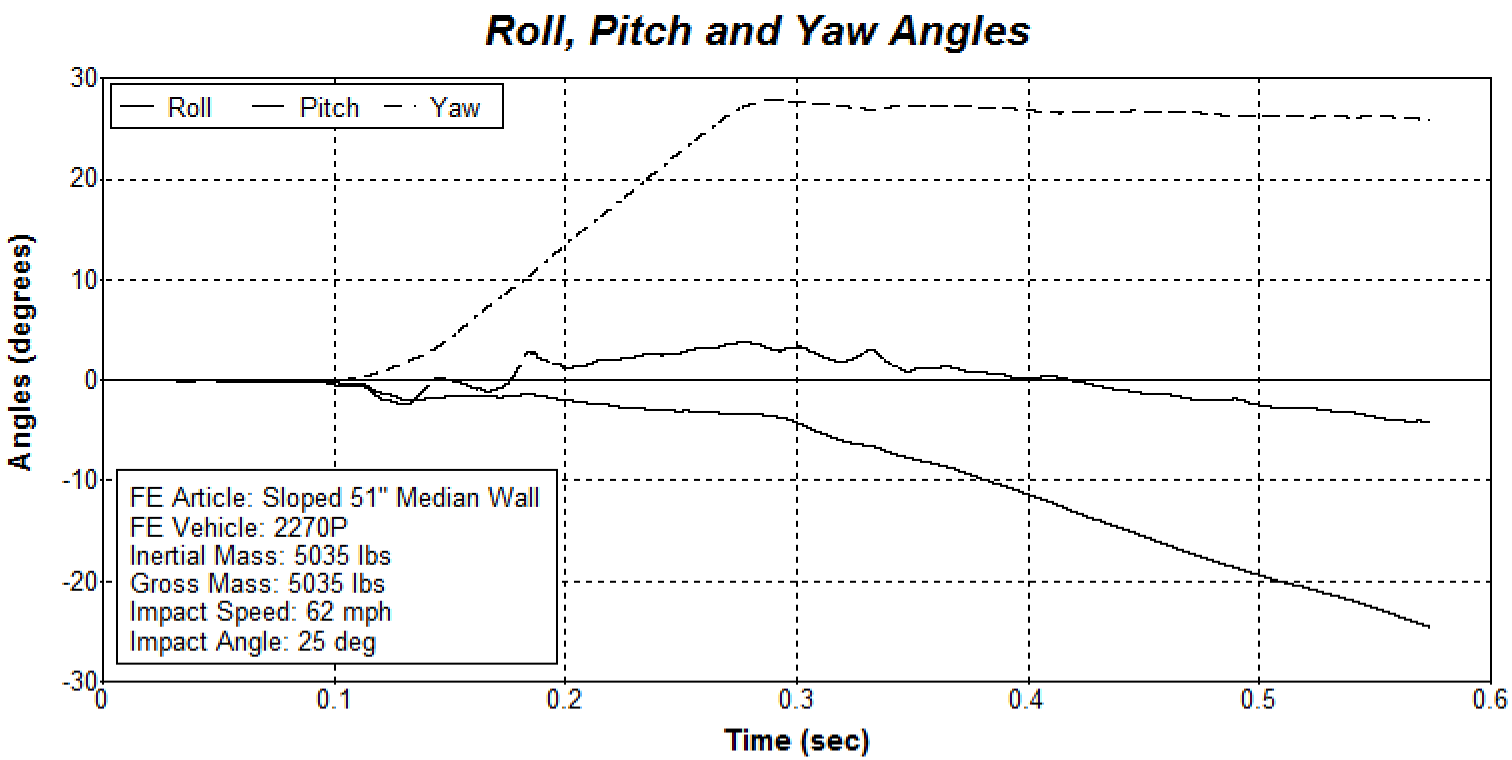
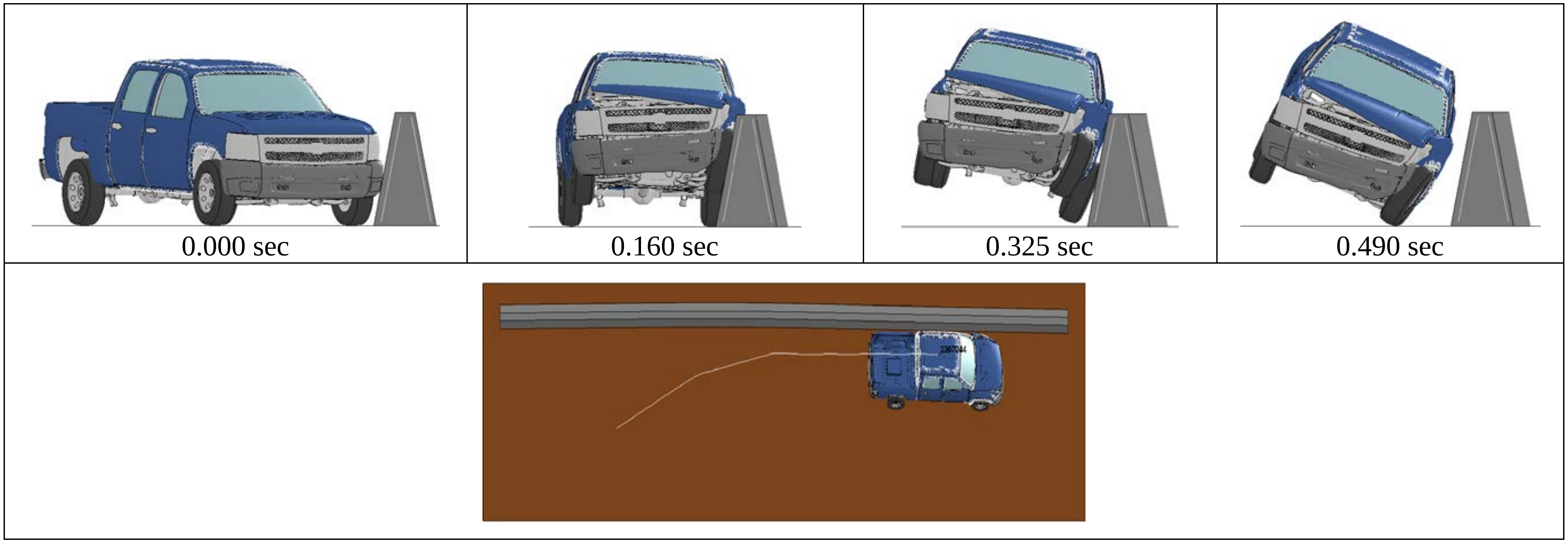


Figure 4.7. Roll, Pitch and Yaw Angles for *MASH* TL 3-11 Impact (Sloped Median Wall – 51-inch).



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

Test Article
Type................................ Median Barrier for Grade Separation
Name .... 51" Concrete Single Sloped Median Wall
Installation Length .... 80 ft
Material or Key Elements Steel Reinforced Concrete Barrier

Test Vehicle
Type/Designation 2270P
Make and Model.............. Finite Element Silverado Pickup
Curb .... 5035 lb
Test Inertial .... 5035 lb
Dummy............................ No Dummy
Gross Static..................... 5035 lb

Impact Conditions
Speed.................................62.0 mi/h
Angle..................................25 degrees
Location/Orientation ....One Third of Barrier Length

Exit Conditions
Speed.................................53.0 mi/h
Angle..................................0.8 degrees

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

Vehicle Stability
Maximum Yaw Angle................ 27.8 degree
Maximum Pitch Angle............... -4.1 degree
Maximum Roll Angle................ -24.6 degree
Vehicle Snagging...................... No
Vehicle Pocketing..................... No

Test Article Deflections
Dynamic .... 6.3 inches
Permanent................................ 6.3 inches
Working Width .... N/A

Vehicle Damage
VDS.. N/A
CDC .... N/A
Max. Exterior Deformation .... N/A
OCDI .... N/A
Max. Occupant Compartment Deformation........................ N/A

Figure 4.8. Summary of Results for *MASH* Test 3-11 Simulation (Sloped Median Wall – 51-inch).

4.3.2 *MASH* TL 3-11: 80-ft Single Sloped Median Wall 112.5 inches Tall

This section contains results from a simulated *MASH* TL 3-11 impact into an 80-ft long, 112.5-inch tall sloped median wall segment. The authors decided to use FE simulations to evaluate the 112.5-inch free standing median wall structural capacity and the vehicle stability during the *MASH* TL 3-11 impact event.

4.3.2.1 Barrier Performance

Figure 4.9 contains images of the barrier before impact and at final configuration. After impact, the barrier deformation was negligible. Figure 4.9(a) and 4.9(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 4.9(b) and 4.9(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. The barrier was impacted at the one-third point of the installation.

For this FE model, soil was modeled by using LS-DYNA *MAT_GEOLOGIC_CAP_MODEL. 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 to the whole model and a damping factor only to the barrier and soil parts. The impact time was delayed accordingly to ensure initialization was completed before the vehicle would impact the barrier.

4.3.2.2 Energy Values

Since this is a closed system and energy is conserved, the sum of the kinetic energy, hourglass energy, sliding energy, and internal energy at any time during the simulation should equate to the initial kinetic energy of the vehicle. As shown in Figure 4.10, approximately 13 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 1 percent of the initial kinetic energy is converted into hourglass energy. Approximately 13 percent of the initial kinetic energy is converted into sliding interface energy. Seventy two percent of the initial kinetic energy has yet to be dissipated by the system at the time of final impact configuration, mainly due to the remaining velocity of the vehicle.

4.3.2.3 Plastic Strain

Plastic strain contours shown in Figure 4.11 are used to visualize possible barrier failure locations. Blue color represents regions with little to no plastic strain. Red color represents regions with plastic strains equal to or greater than 15 percent. Plastic strains greater than 15 percent for steel material indicate regions where local steel failure is likely to occur.

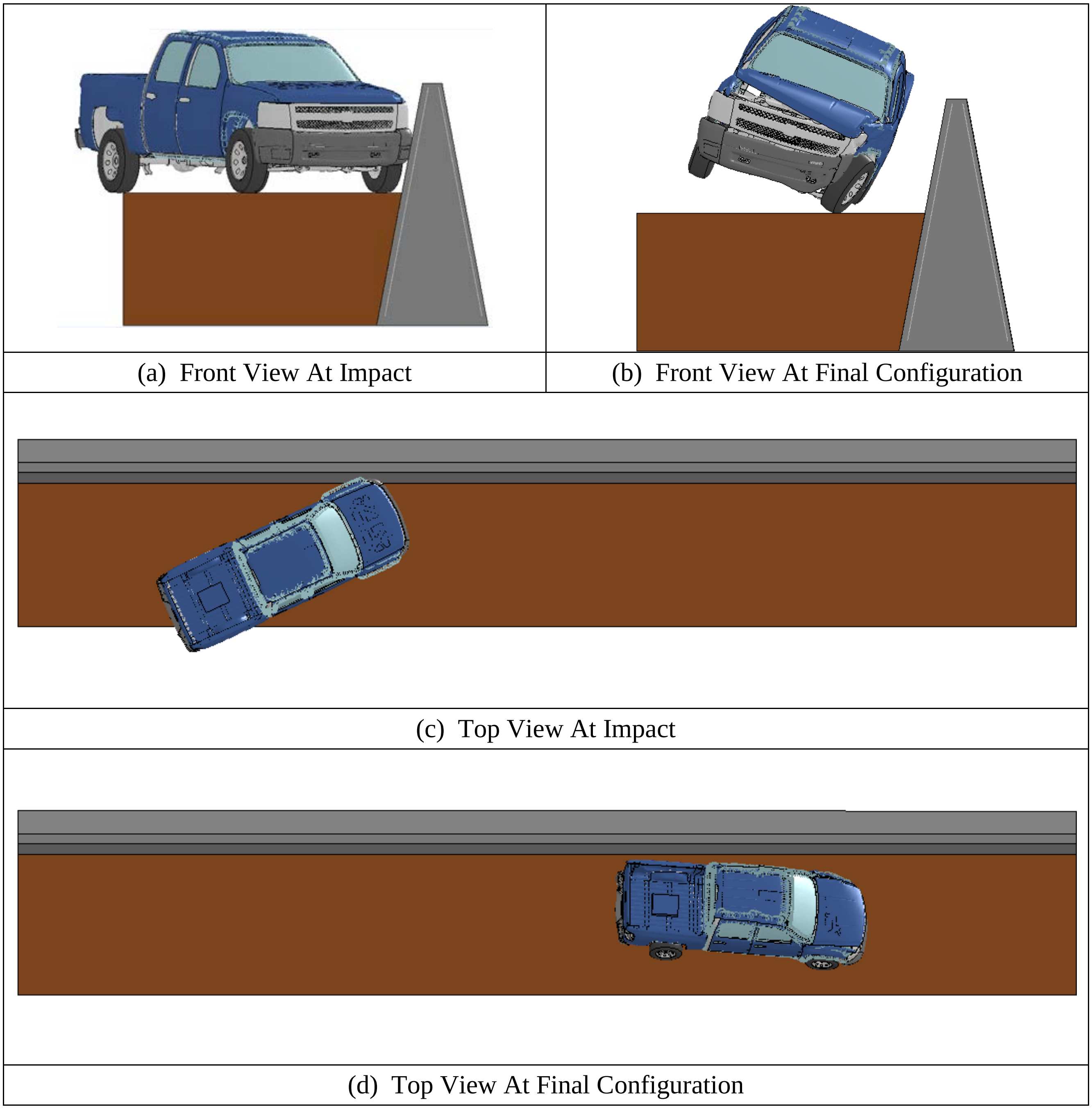

(a) Front View At Impact
(b) Front View At Final Configuration
(c) Top View At Impact
(d) Top View At Final Configuration

Figure 4.9. Initial and Deflected Shape of Barrier for *MASH* TL 3-11 Impact (Sloped Median Wall - 112.5-inch).

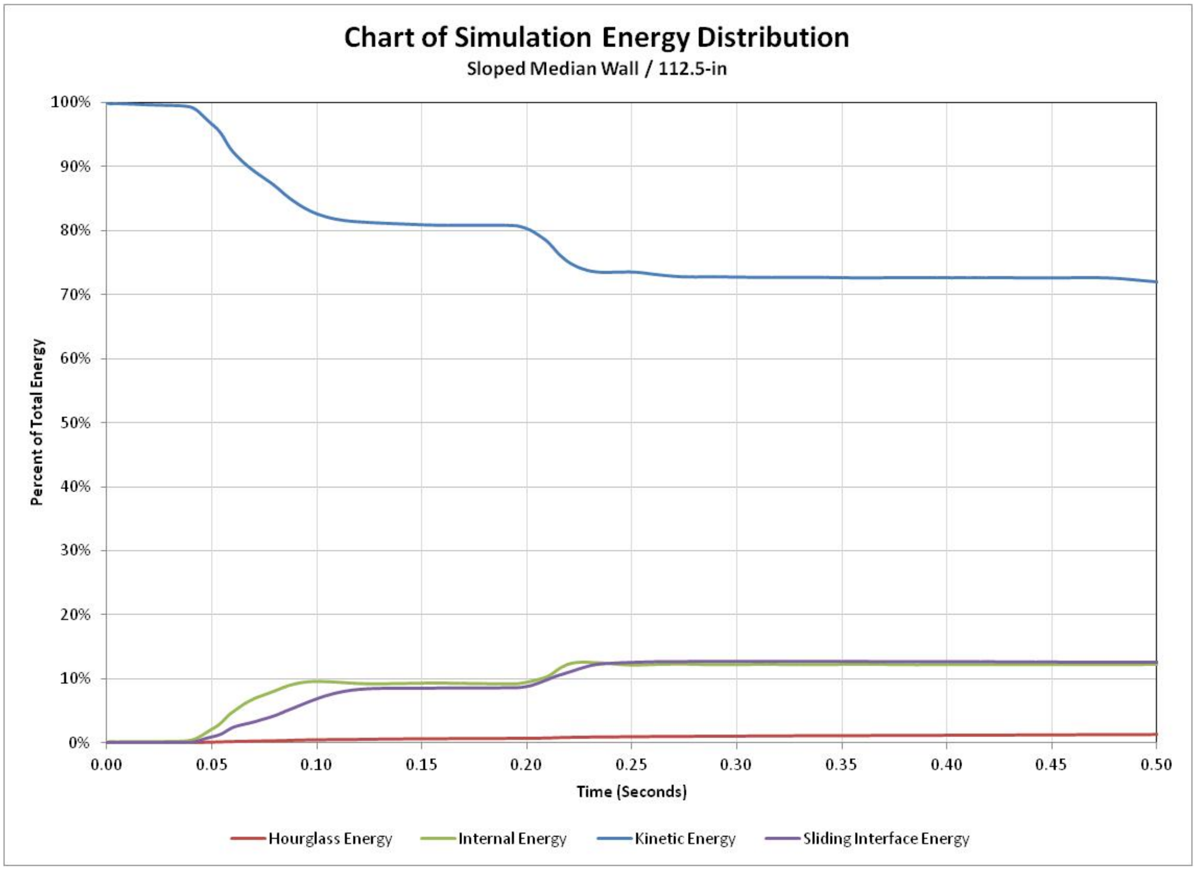


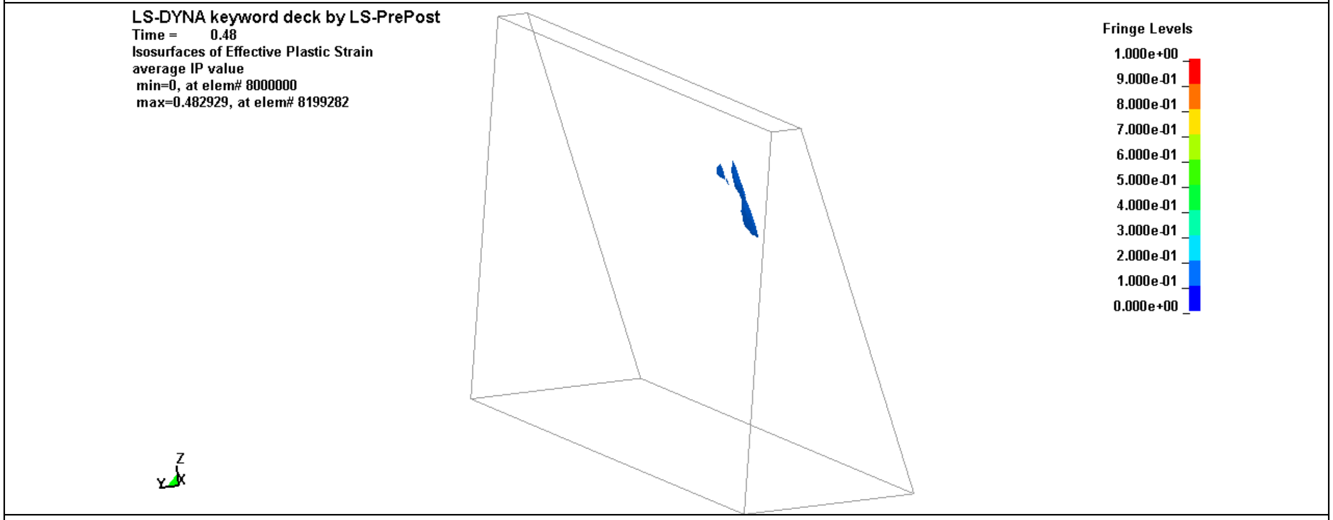
Figure 4.10. Energy Distribution Time History for *MASH* TL 3-11 Impact (Sloped Median Wall - 112.5-inch).

4.3.2.4 Concrete Foundation Stresses

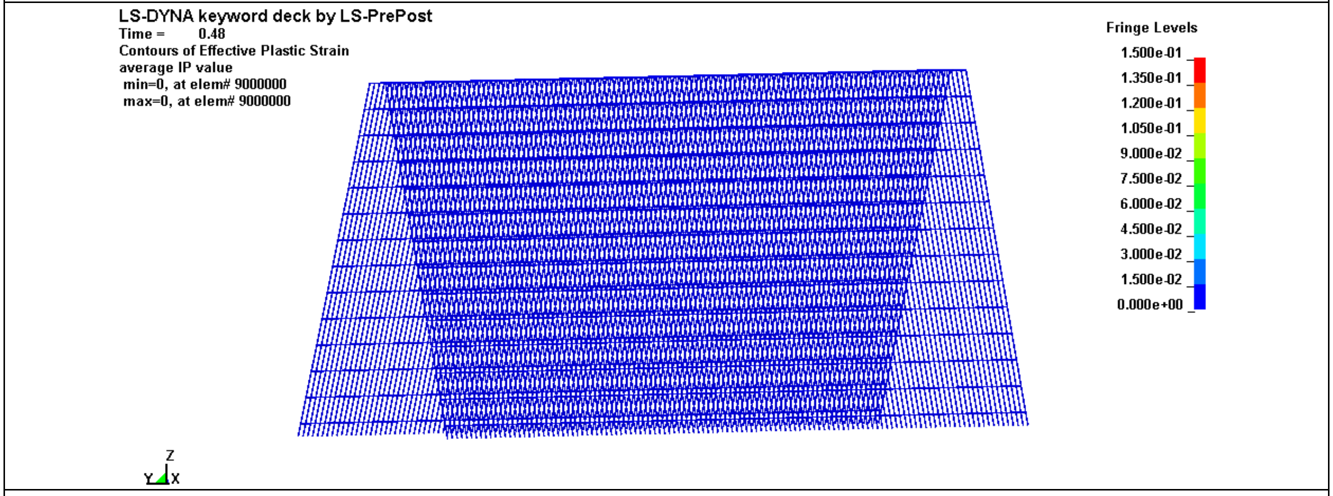
Figure 4.11 shows the plastic strains in (a) the front and (b) the back side of the barrier. As shown in Figures 4.11(a) and (b), there are no high plastic strain regions in the concrete barrier. It is unlikely that cracks of the concrete barrier will occur.

Figure 4.11(c) shows the plastic strains in the rebar structure of the barrier. Blue regions represent regions with little to no plastic strain. Red regions represent regions with plastic strains equal to or greater than 15 percent. As shown in Figure 4.11(c), there are no high plastic strain regions in the rebar cage.

(a) Front Side of the Concrete Barrier



(b) Back Side of the Concrete Barrier



(c) Barrier Steel Reinforcement

Figure 4.11. Concrete Stresses for *MASH* TL 3-11 Impact (Sloped Median Wall – 112.5-inch).

Tables 4.3 and 4.4 show frames from FE simulation of impact against the modeled 112.5-inch tall sloped median wall.

Table 4.3. Sequential Images of the 2270P Vehicle Interaction with the 112.5-inch Tall Sloped Median Wall Model for *MASH* TL 3-11 Impact (Perpendicular and Oblique Views).

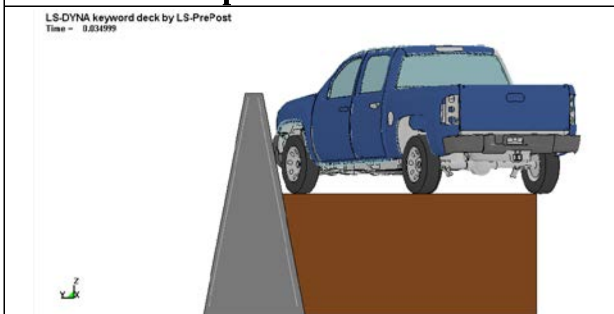
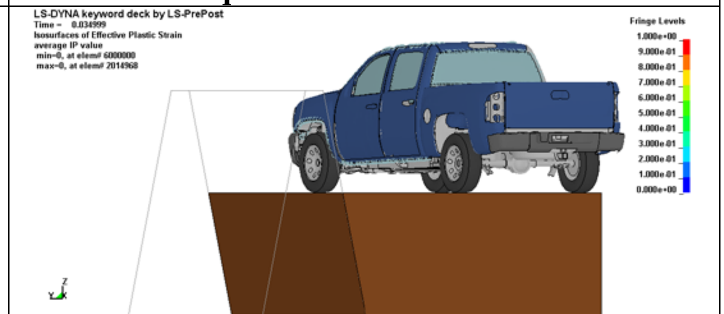
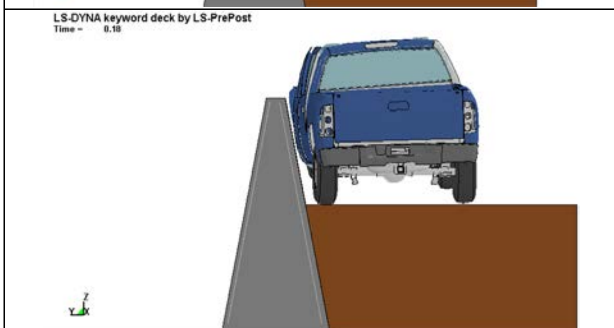
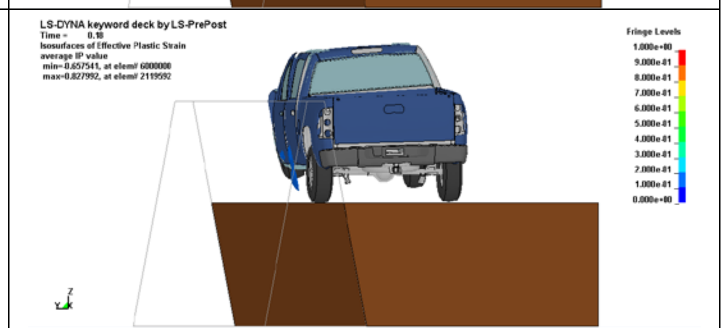
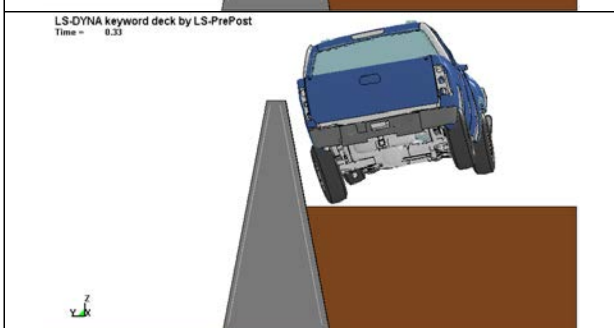
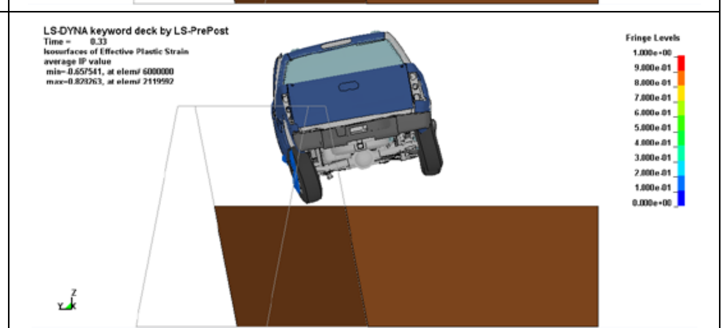
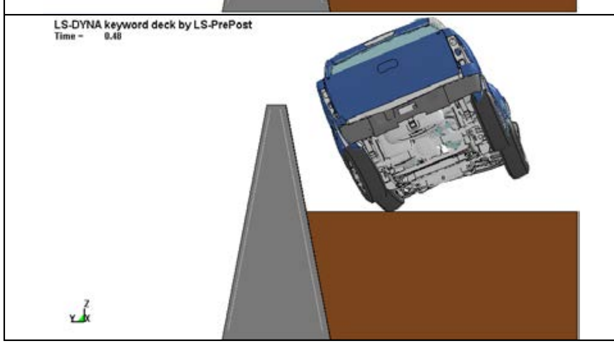
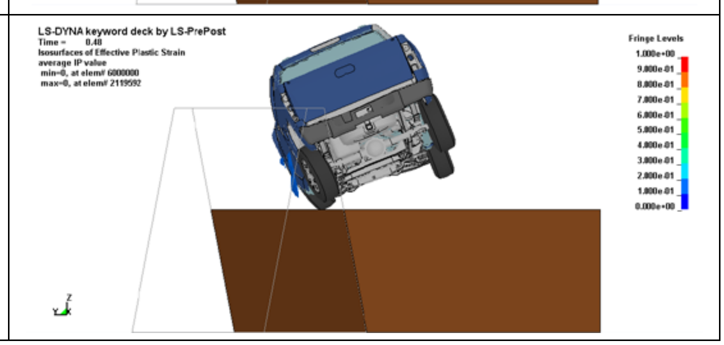
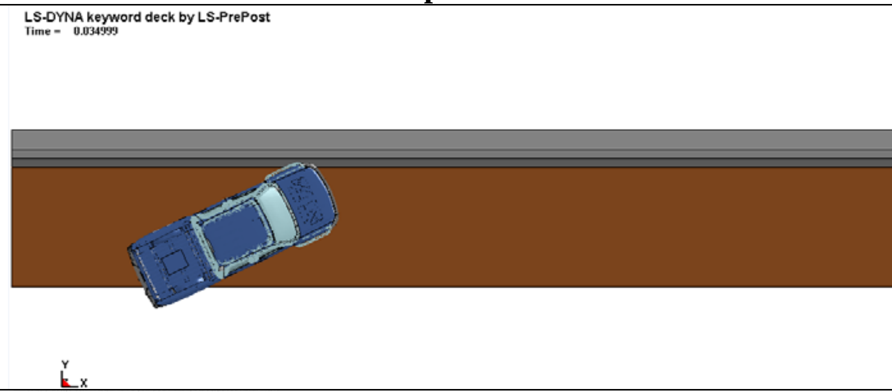
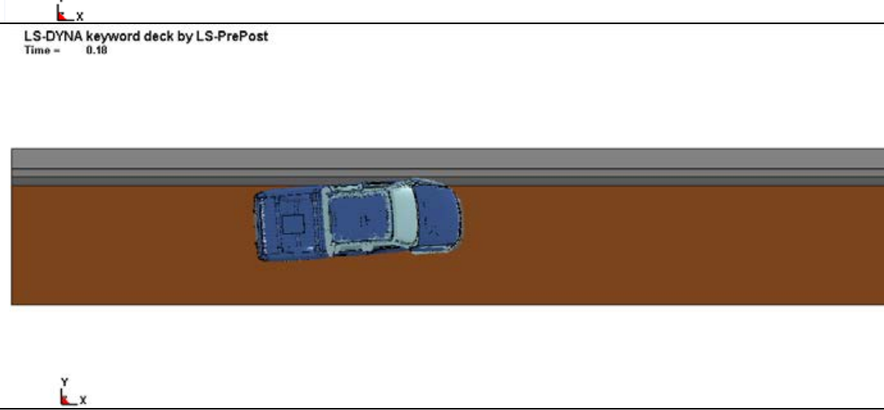
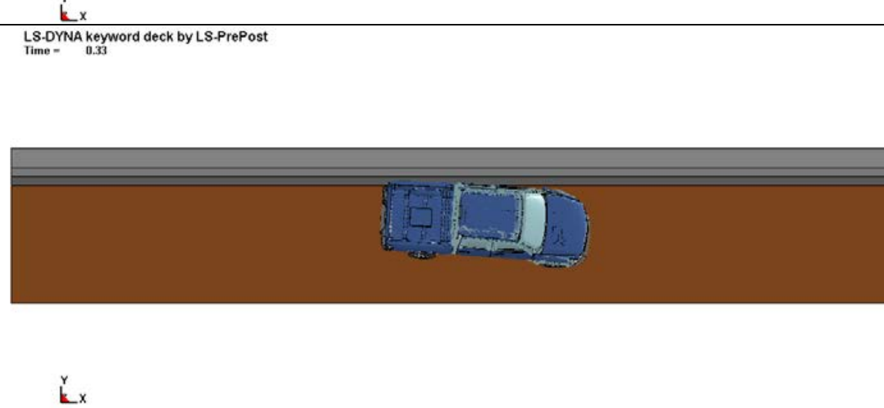
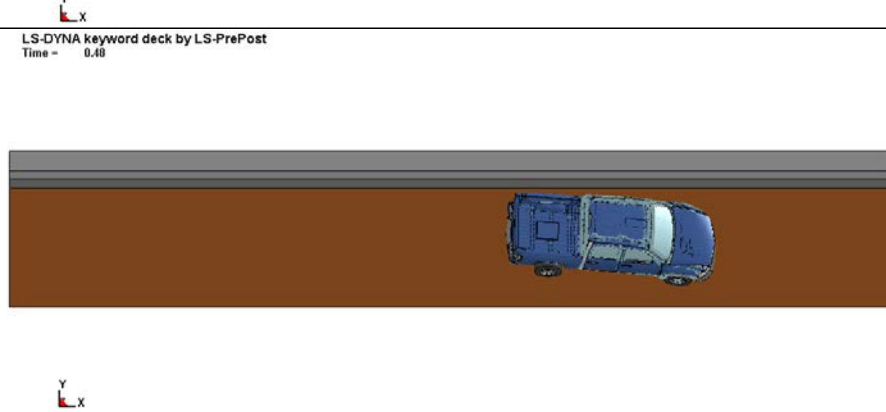
Perpendicular View	Oblique View - Barrier Strains
	
	
	
	

Table 4.4. Sequential Images of the 2270P Vehicle Interaction with the 112.5-inch Tall Sloped Median Wall Model for *MASH* TL 3-11 Impact (Top View).

Top View





4.3.2.5 Occupant Risk Assessment

The TRAP program was used to evaluate occupant risk factors based on the applicable *MASH* safety evaluation criteria. The modeled 2270P vehicle remained upright during and after the modeled collision event. Figure 4.12 shows vehicle roll, pitch and yaw angles throughout the impact event against the 112.5-inch high sloped median wall. Maximum roll, pitch, and yaw angles resulted to be -22.7, -6.2, and 29.4 degrees respectively. Previous multiple test experience showed that occupant risk results are not a concern for impact of vehicle against single sloped concrete barrier, since they all remained in the range required by *MASH* criteria. As consequence, occupant risk values were not evaluated for this finite element simulation.

4.3.2.6 Results

Figure 4.13 summarizes results for *MASH* Test 3-11 simulation with a 2270P vehicle impacting a 112.5-inch high sloped median wall. Results showed that the 112.5-inch tall single sloped median wall performed adequately by containing and redirecting the impacting 2270P vehicle. Sliding of the free standing barrier from its initial position during the impact event was negligible. The barrier did not show any potential for tipping over and allowing the impacting vehicle for intrusion in the opposing lane. Also, simulations indicate the 2270P vehicle maintaining stability during the *MASH* TL 3-11 impact conditions event.

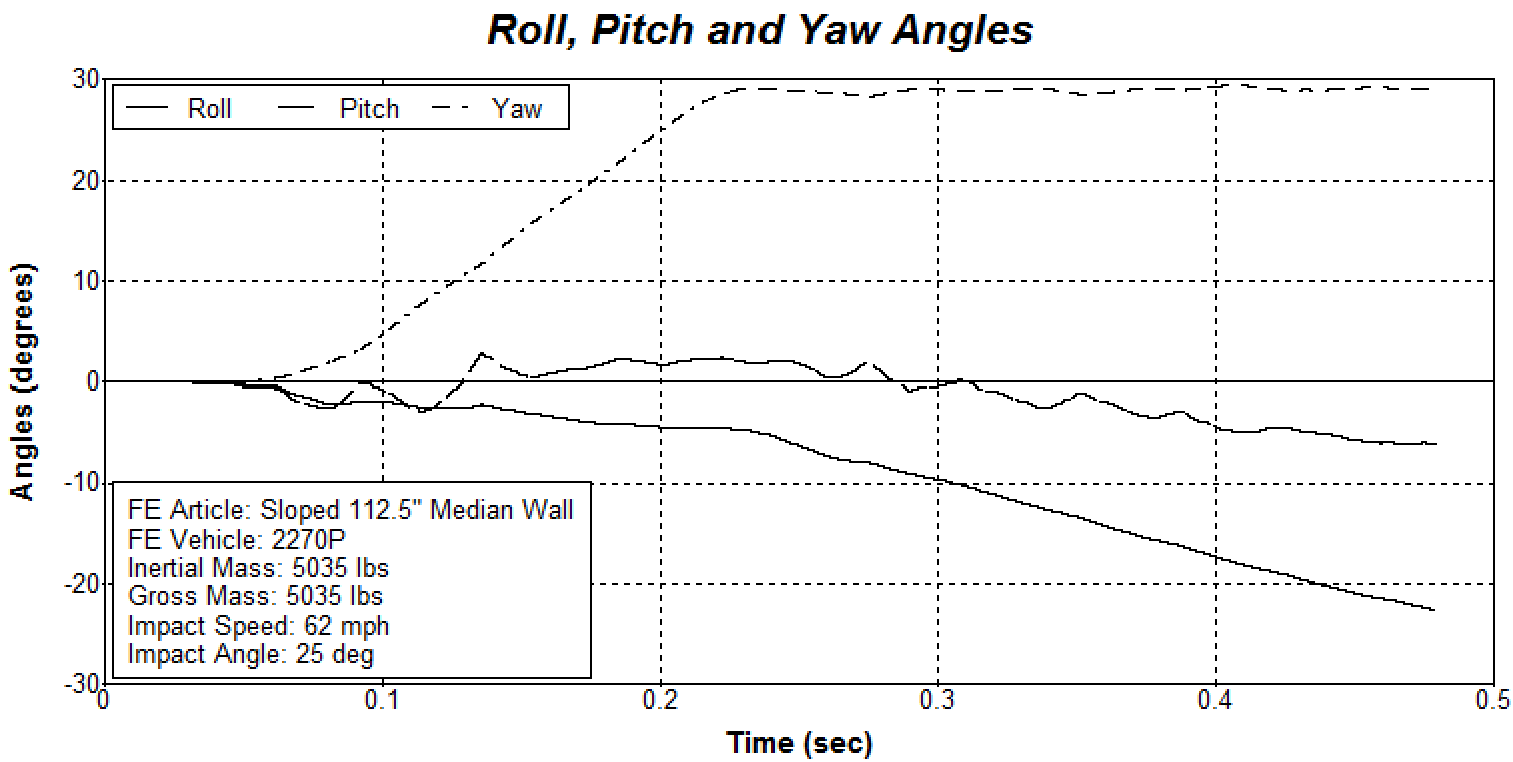
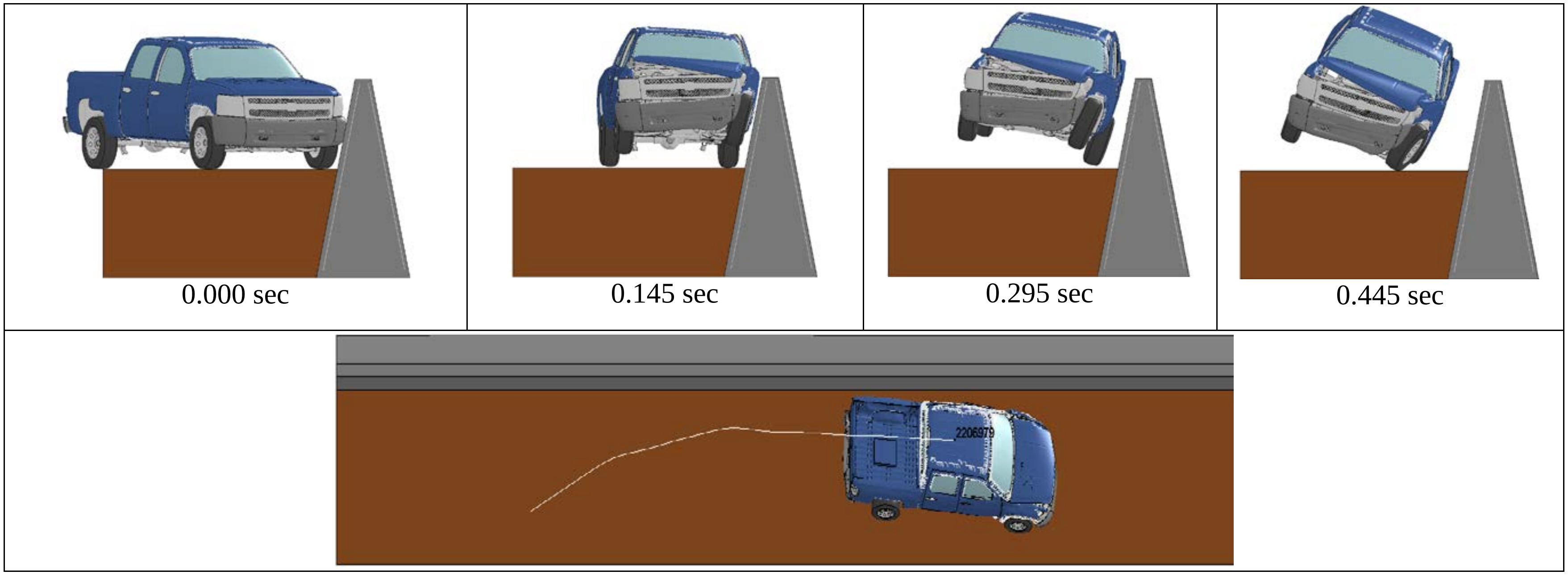


Figure 4.12. Roll and Pitch Angles for *MASH* TL 3-11 Impact (Sloped Median Wall - 112.5-inch).



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

Test Article
- Type .... Median Barrier for Grade Separation
- Name.............................. 112.5" Concrete Single Sloped Median Wall
- Installation Length............ 80 ft
- Material or Key Elements. Steel Reinforced Concrete Barrier

Test Vehicle
- Type/Designation............. 2270P
- Make and Model .... Finite Element Silverado Pickup
- Curb .... 5035 lb
- Test Inertial..................... 5035 lb
- Dummy........................... No Dummy
- Gross Static..................... 5035 lb

Impact Conditions
- Speed ....62.0 mi/h
- Angle ....25 degrees
- Location/Orientation...........One Third of Barrier Length

Exit Conditions
- Speed ....52.6 mi/h
- Angle ....3.9 degrees

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

Vehicle Stability
- Maximum Yaw Angle .... 29.4 degree
- Maximum Pitch Angle ....-6.2 degree
- Maximum Roll Angle ....-22.7 degree
- Vehicle Snagging......................No
- Vehicle Pocketing ....No

Test Article Deflections
- Dynamic...................................Negligible
- Permanent ....Negligible
- Working Width ....N/A

Vehicle Damage
- VDS...N/A
- CDC...N/A
- Max. Exterior Deformation ....N/A
- OCDI ....N/A
- Max. Occupant Compartment Deformation.......................N/A

Figure 4.13. Summary of Results for *MASH* Test 3-11 Simulation (Sloped Median Wall - 112.5-inch).

4.3.3 *MASH* TL 3-11: 80-ft Vertical Median Wall 51-inches Tall

This section contains results from a simulated *MASH* TL 3-11 impact into an 80-ft long, 51-inch tall vertical median wall segment. The authors decided to use FE simulations to evaluate the 51-inch free standing median wall structural capacity and the vehicle stability during the *MASH* TL 3-11 impact event.

4.3.3.1 Barrier Performance

Figure 4.14 contains images of the barrier before impact and at final configuration. A maximum barrier deformation of 1.1 ft (13 inches) was reached at approximately 0.65 seconds after impact. Figure 4.14(a) and 4.14(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 4.14(b) and 4.14(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. The barrier was impacted at the one-third point of the installation.

4.3.3.2 Energy Values

Since this is a closed system and energy is conserved, the sum of the kinetic energy, hourglass energy, sliding energy, and internal energy at any time during the simulation should equate to the initial kinetic energy of the vehicle. As shown in Figure 4.15, approximately 13 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 1 percent of the initial kinetic energy is converted into hourglass energy. Approximately 11 percent of the initial kinetic energy is converted into sliding interface energy. Sixty nine percent of the initial kinetic energy has yet to be dissipated by the system at the time of final impact configuration, mainly due to the remaining velocity of the vehicle.

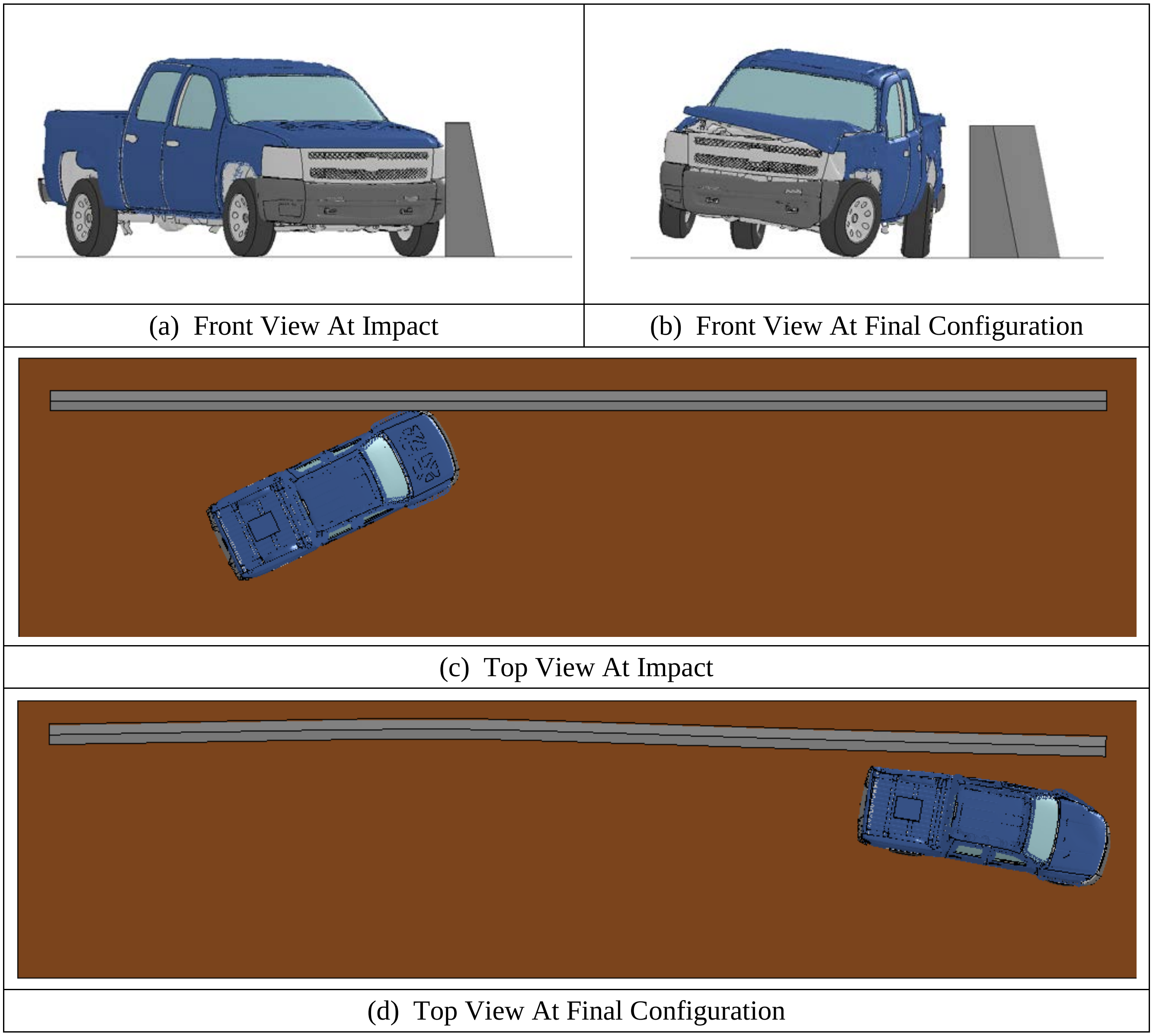
4.3.3.3 Plastic Strain

Plastic strain contours shown in Figure 4.16 are used to visualize possible barrier failure locations. Blue color represents regions with little to no plastic strain. Red color represents regions with plastic strains equal to or greater than 15 percent. Plastic strains greater than 15 percent for steel material indicate regions where local steel failure is likely to occur.

4.3.3.4 Concrete Foundation Stresses

Figure 4.16 shows the plastic strains in (a) the front and (b) the back side of the barrier. Areas shown in Figure 4.16(b) are areas where damage to the concrete barrier is likely to occur. It is likely that cracks will form in these locations at the back side of the barrier; it is unlikely, however, that a catastrophic failure of the concrete barrier will occur.

Figure 4.16(c) shows the plastic strains in the rebar structure of the barrier. Blue regions represent regions with little to no plastic strain. Red regions represent regions with plastic strains equal to or greater than 15 percent. As shown in Figure 4.16(c), there are no high plastic strain regions in the rebar cage.



(a) Front View At Impact

(b) Front View At Final Configuration

(c) Top View At Impact

(d) Top View At Final Configuration

Figure 4.14. Initial and Deflected Shape of Barrier for *MASH* TL 3-11 Impact (Vertical Median Wall – 51-inch).

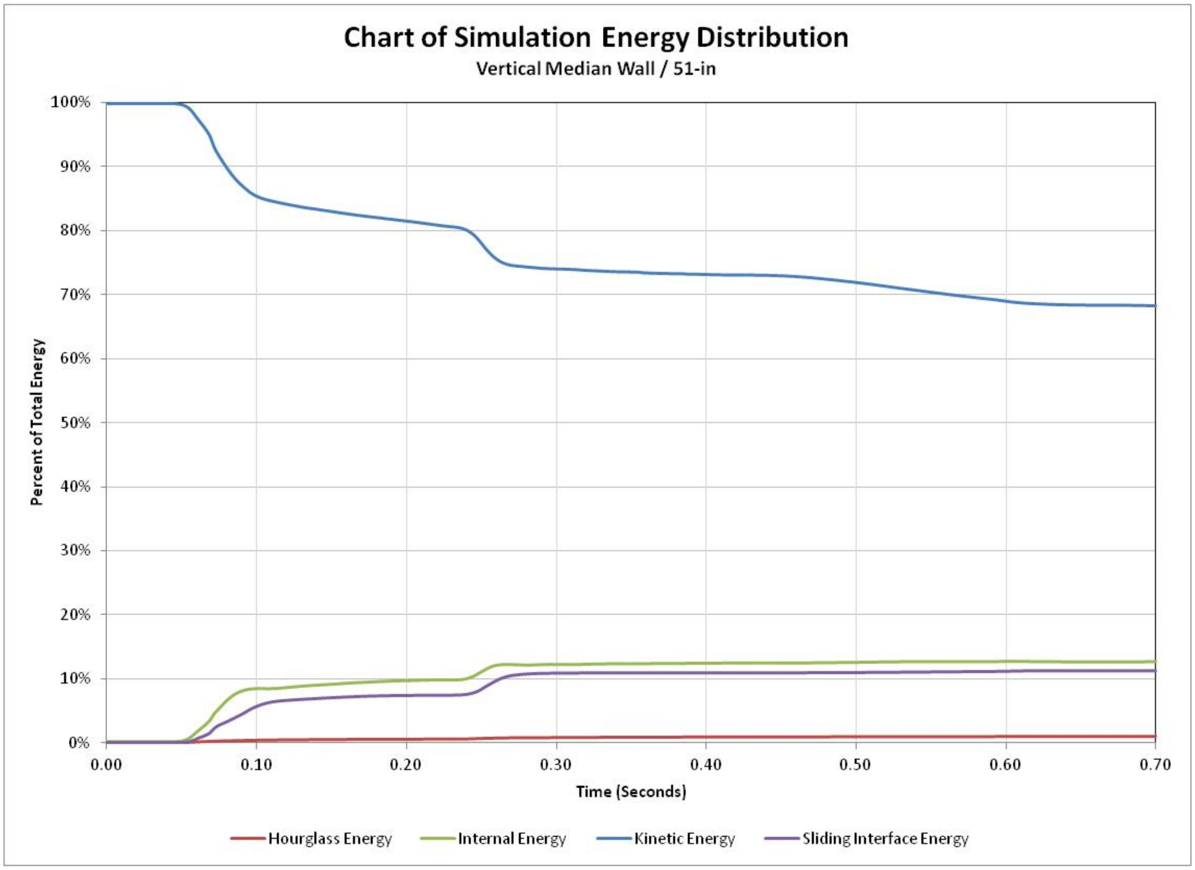
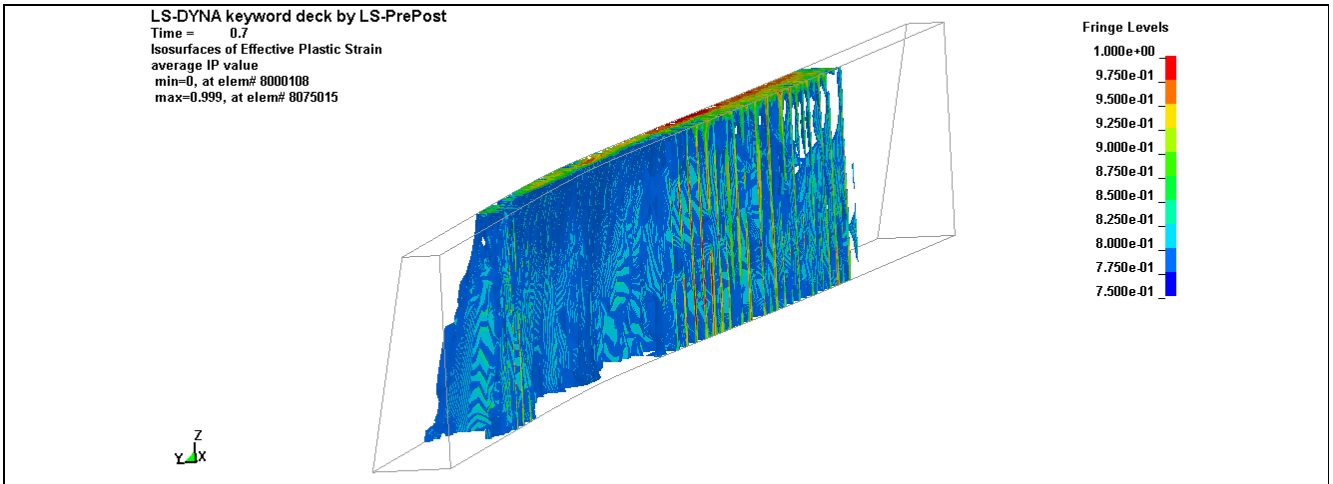
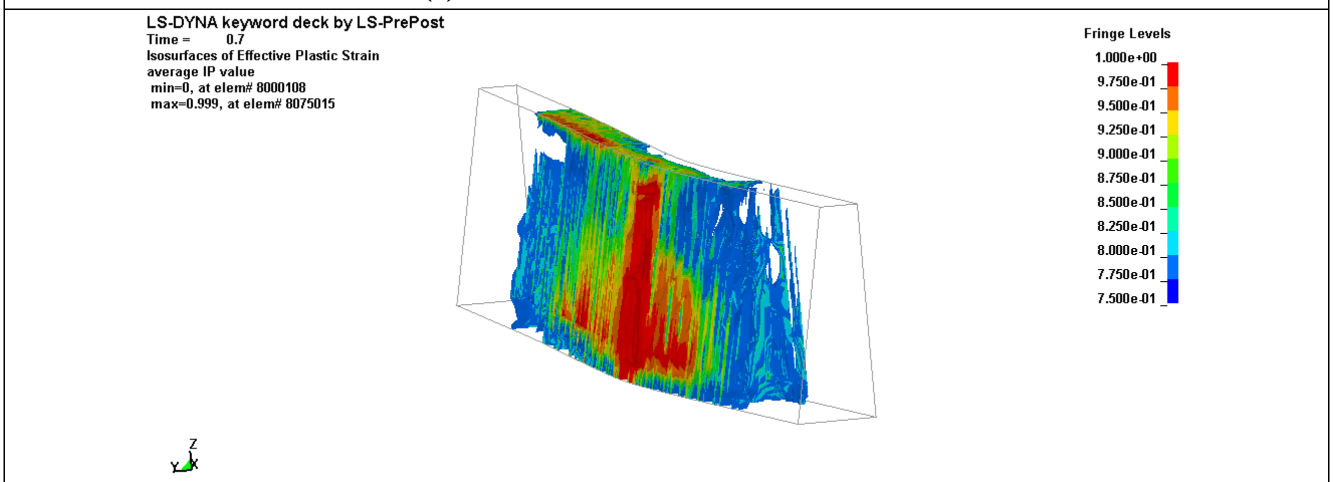


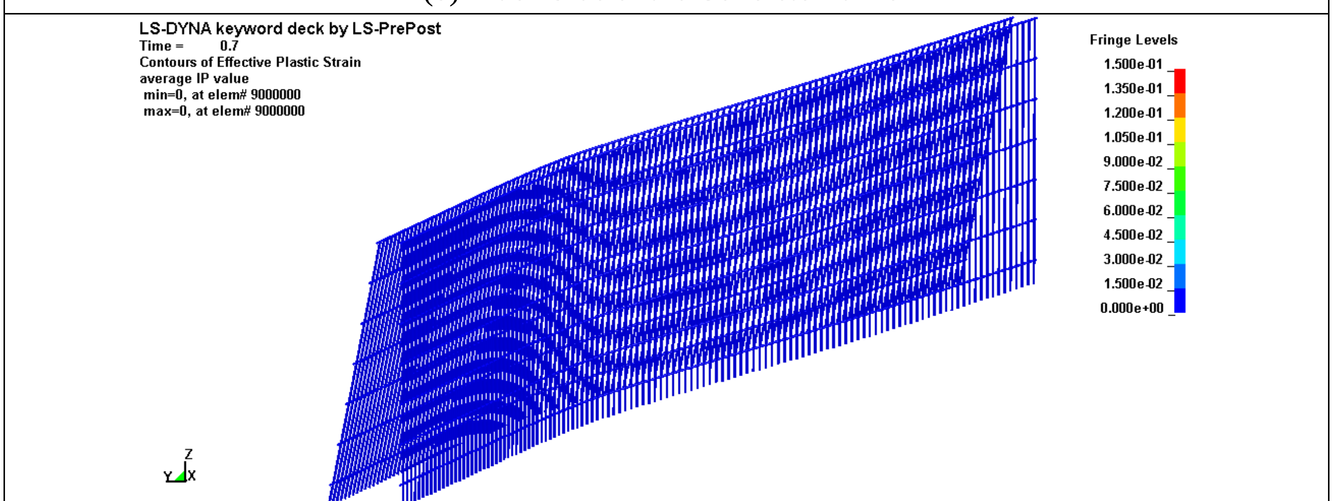
Figure 4.15. Energy Distribution Time History for *MASH* TL 3-11 Impact (Vertical Median Wall – 51-inch).



(a) Front Side of the Concrete Barrier



(b) Back Side of the Concrete Barrier



(c) Barrier Steel Reinforcement

Figure 4.16. Concrete Stresses for *MASH* TL 3-11 Impact (Vertical Median Wall – 51-inch).

Tables 4.5 and 4.6 show frames from FE simulation of impact against the modeled 51-inch tall vertical median wall.

Table 4.5. Sequential Images of the 2270P Vehicle Interaction with the 51-inch Tall Vertical Median Wall Model for *MASH* TL 3-11 Impact (Perpendicular and Oblique Views).

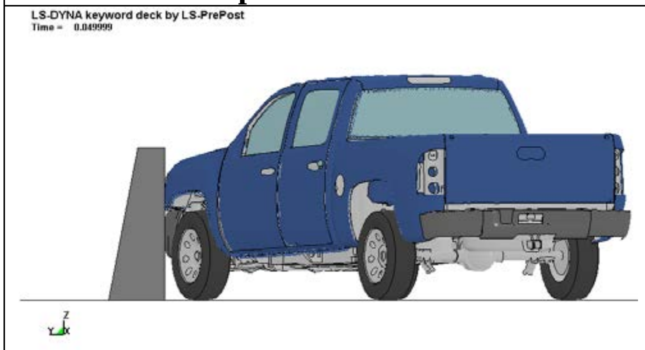
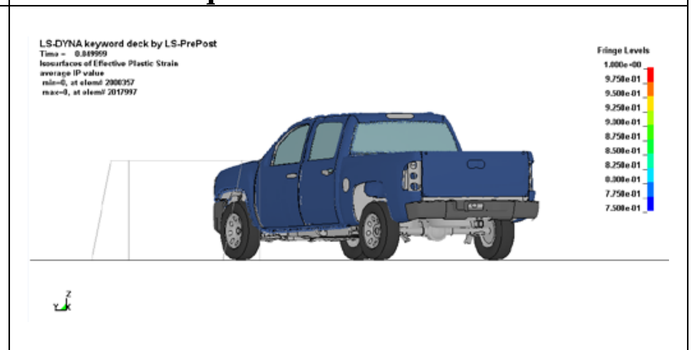
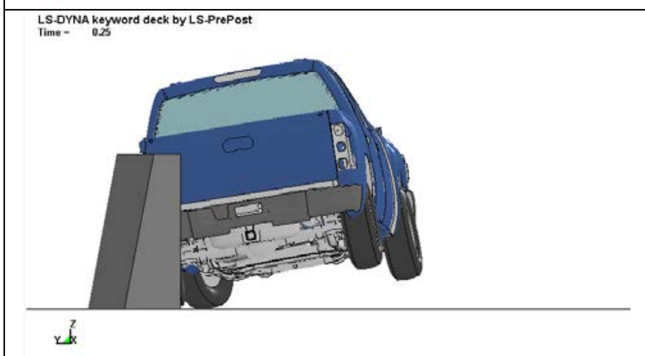
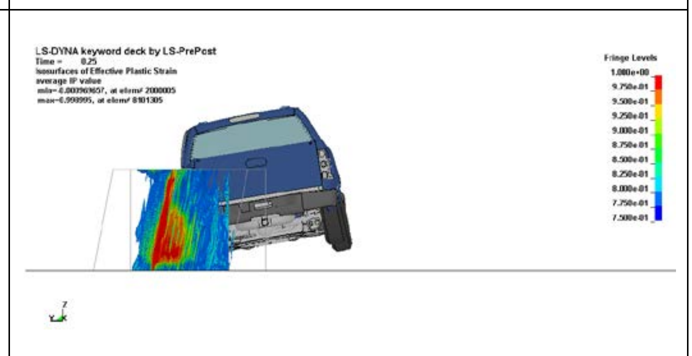
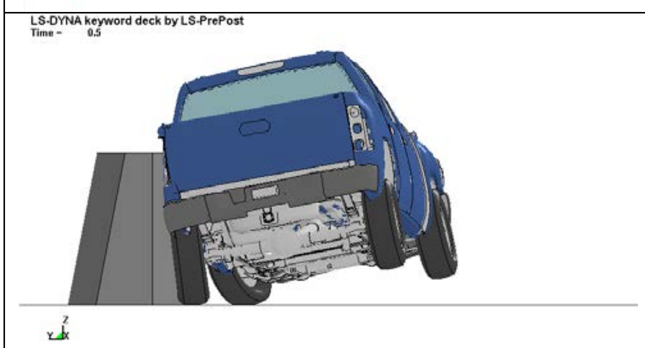
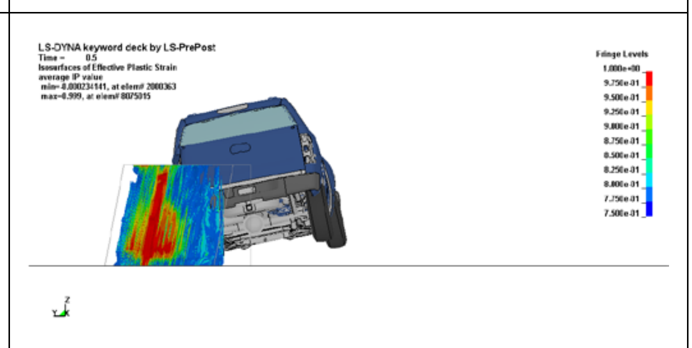
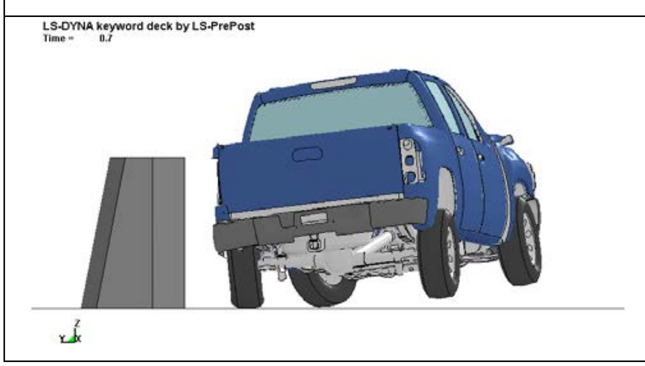
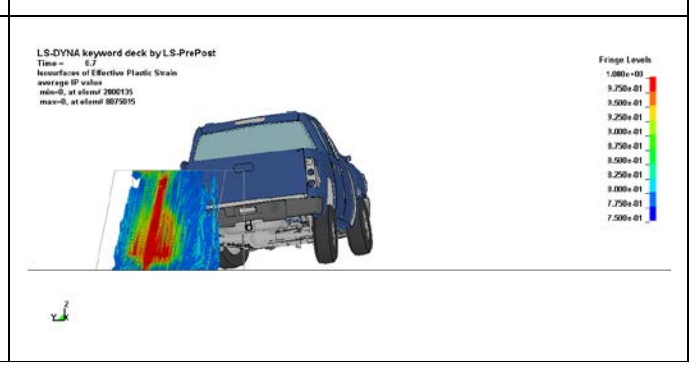
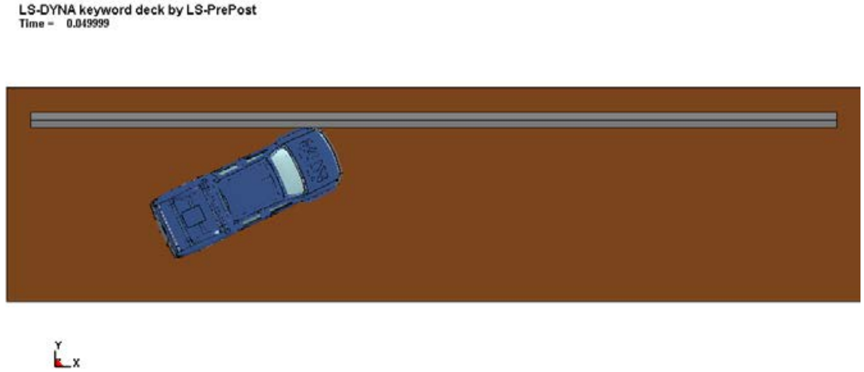
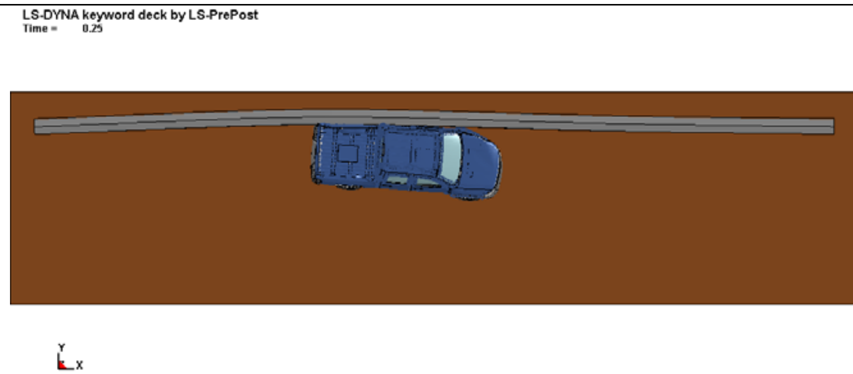
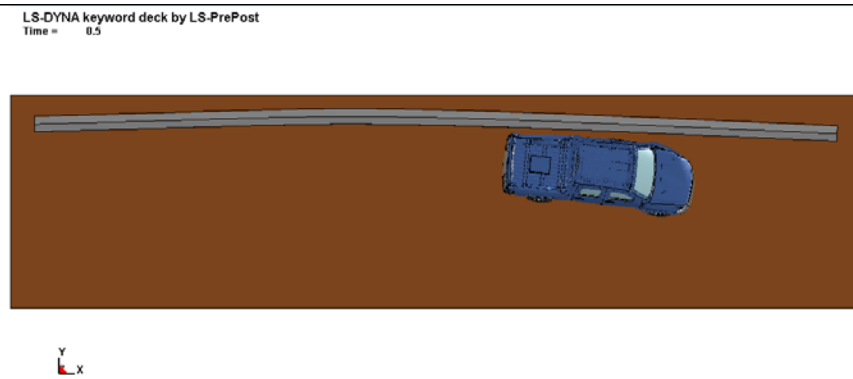
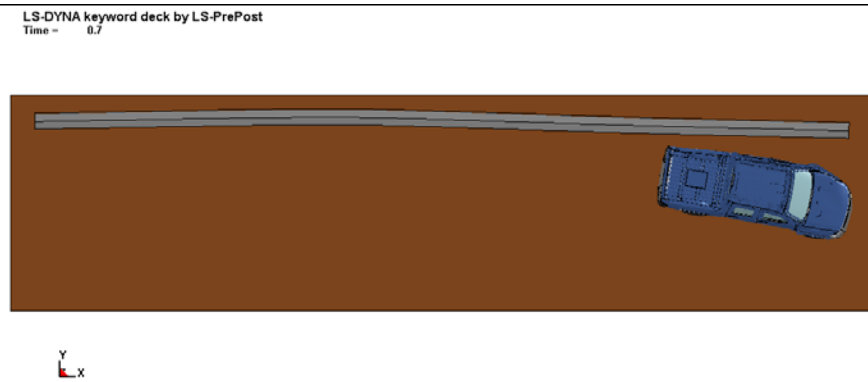
Perpendicular View	Oblique View - Barrier Strains
	
	
	
	

Table 4.6. Sequential Images of the 2270P Vehicle Interaction with the 51-inch Tall Vertical Median Wall Model for *MASH* TL 3-11 Impact (Top View).

Top View





4.3.3.5 Occupant Risk Assessment

The TRAP program was used to evaluate occupant risk factors based on the applicable *MASH* safety evaluation criteria. The modeled 2270P vehicle remained upright during and after the modeled collision event. Figure 4.17 shows vehicle roll and pitch angles throughout the impact event against the 51-inch high vertical median wall. Maximum roll and pitch angles resulted to be -12.3 degrees and -4.7, degrees respectively.

4.3.3.6 Results

Figure 4.18 summarizes results for *MASH* Test 3-11 simulation with a 2270P vehicle impacting a 51-inch high vertical median wall. Results showed that the 51-inch tall vertical median wall performed adequately by containing and redirecting the impacting 2270P vehicle. The free standing barrier slid 13 inches from its initial position during the impact event. The barrier, however, did not show any potential for tipping over and allowing the impacting vehicle for intrusion in the opposing lane. Also, simulations indicate the 2270P vehicle maintaining stability during the *MASH* TL 3-11 impact conditions event.

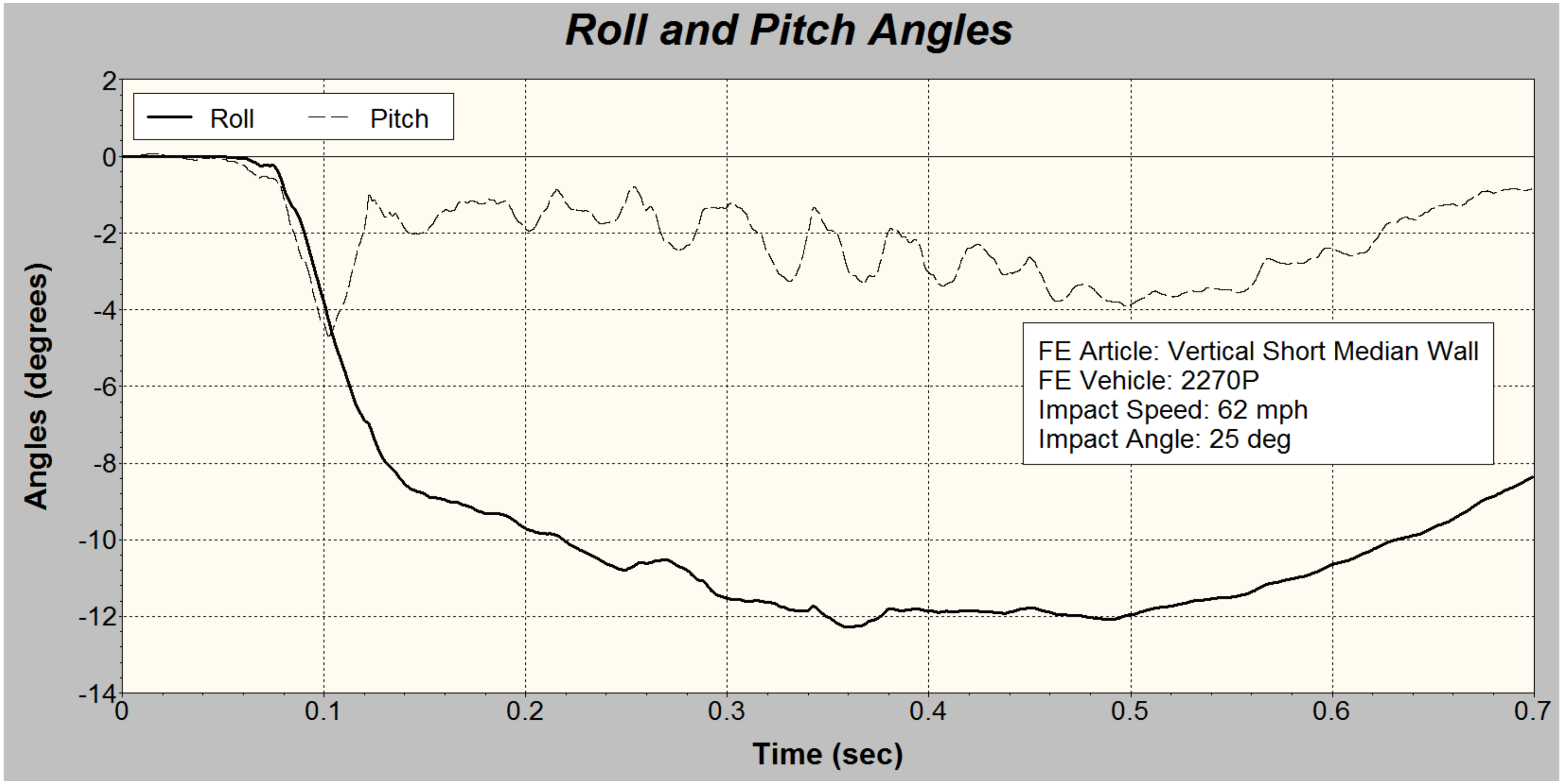
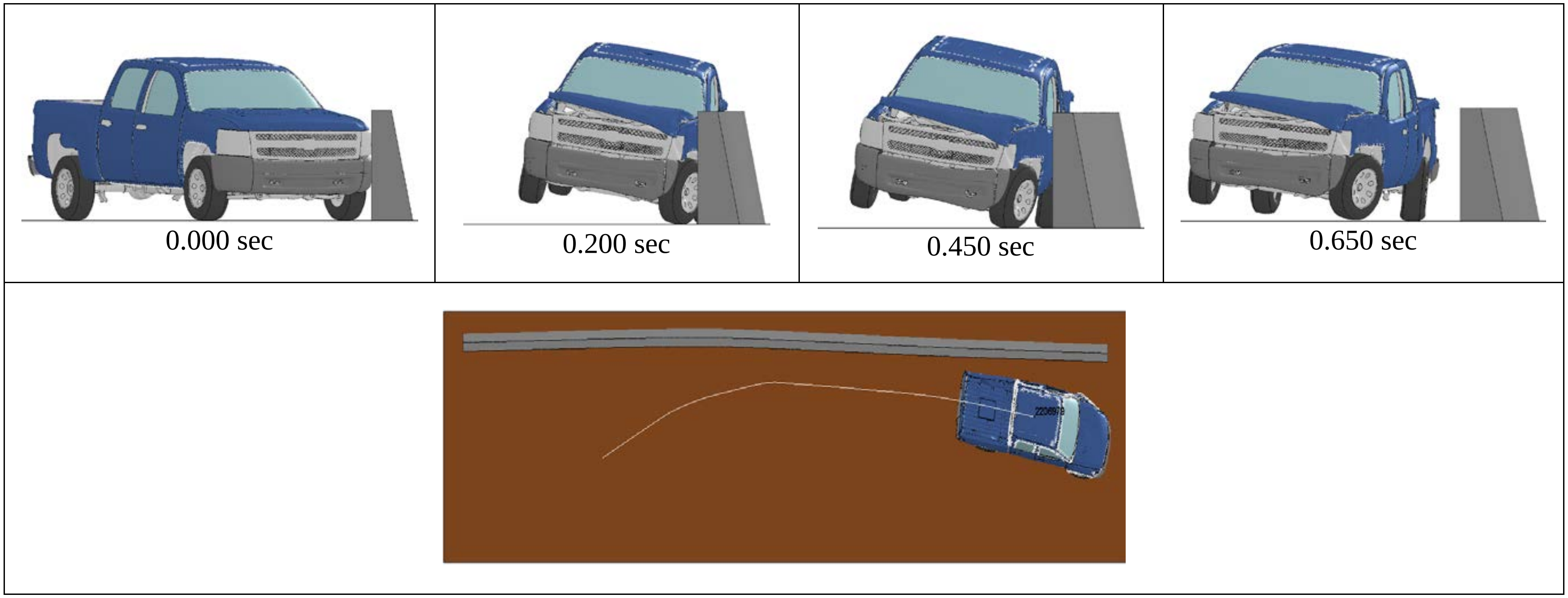


Figure 4.17. Roll and Pitch Angles for *MASH* TL 3-11 Impact (Vertical Median Wall – 51-inch).



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

Test Article
Type .... Median Barrier for Grade Separation
Name............................... 51" Concrete Vertical Median Wall
Installation Length .... 80 ft
Material or Key Elements. Steel Reinforced Concrete Barrier

Test Vehicle
Type/Designation............. 2270P
Make and Model .... Finite Element Silverado Pickup
Curb .... 5035 lb
Test Inertial...................... 5035 lb
Dummy............................ No Dummy
Gross Static..................... 5035 lb

Impact Conditions
Speed ....62.0 mi/h
Angle ....25 degrees
Location/Orientation............One Third of Barrier Length

Exit Conditions
Speed ....49.6 mi/h
Angle ....9.7 degrees

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

Vehicle Stability
Maximum Yaw Angle .... 35.2 degree
Maximum Pitch Angle .... -4.7 degree
Maximum Roll Angle .... -12.3 degree
Vehicle Snagging .... No
Vehicle Pocketing .... No

Test Article Deflections
Dynamic.................................... 13 inches
Permanent .... 13 inches
Working Width .... N/A

Vehicle Damage
VDS .... N/A
CDC.. N/A
Max. Exterior Deformation .... N/A
OCDI .... N/A
Max. Occupant Compartment Deformation .... N/A

Figure 4.18. Summary of Results for *MASH* Test 3-11Simulation (Vertical Median Wall – 51-inch).

4.3.4 *MASH* TL 3-11: 80-ft Vertical Median Wall 112.5-inches Tall

This section contains results from a simulated *MASH* TL 3-11 impact into an 80-ft long, 112.5-inch tall vertical median wall segment. The authors decided to use FE simulations to evaluate the 112.5-inch free standing median wall structural capacity and the vehicle stability during the *MASH* TL 3-11 impact event.

4.3.4.1 Barrier Performance

Figure 4.19 contains images of the barrier before impact and at final configuration. A maximum barrier deformation of 0.1 ft (1.5 inches) was reached at approximately 0.5 seconds after impact. Figure 4.19(a) and 4.19(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 4.19(b) and 4.19(d) show the front and overhead views of the barrier and impacting vehicle at final configuration. The barrier was impacted at the one-third point of the installation.

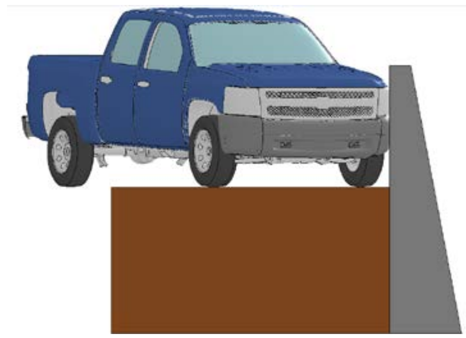
For this FE model, soil was modeled by using LS-DYNA *MAT_GEOLOGIC_CAP_MODEL. Thus, FE initialization was required to ensure soil and concrete barrier models would have a realistic initial geotechnical pressure at the time of vehicle impact. FE model initialization was achieved by adding gravity to the whole model and a damping factor only to the barrier and soil parts. The impact time was delayed accordingly to ensure initialization was completed before the vehicle would impact the barrier.

4.3.4.2 Energy Values

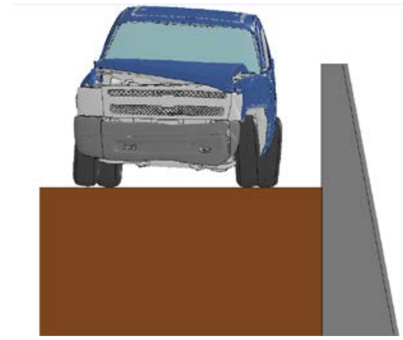
Since this is a closed system and energy is conserved, the sum of the kinetic energy, hourglass energy, sliding energy, and internal energy at any time during the simulation should equate to the initial kinetic energy of the vehicle. As shown in Figure 4.20, approximately 11 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). Approximately 1 percent of the initial kinetic energy is converted into hourglass energy. Approximately 11 percent of the initial kinetic energy is converted into sliding interface energy. Seventy one percent of the initial kinetic energy has yet to be dissipated by the system at the time of final impact configuration, mainly due to the remaining velocity of the vehicle.

4.3.4.3 Plastic Strain

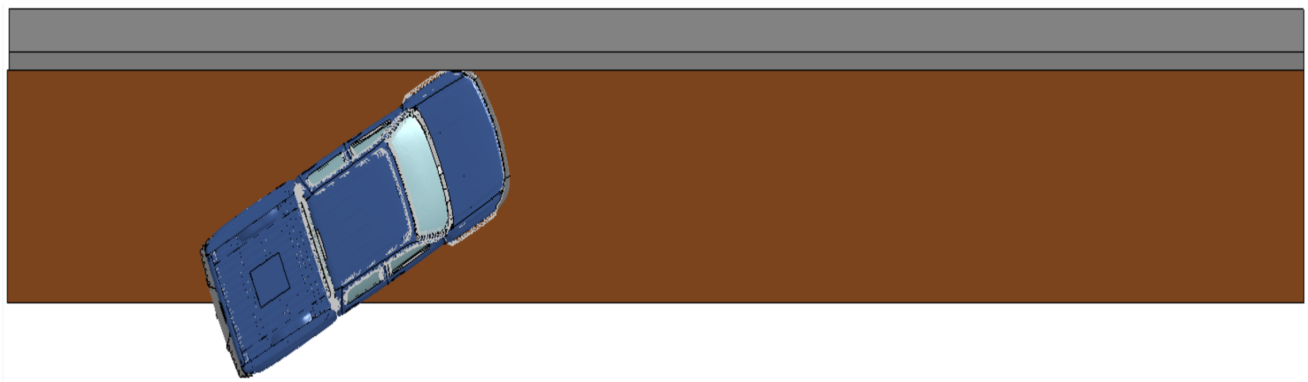
Plastic strain contours shown in Figure 4.21 are used to visualize possible barrier failure locations. Blue color represents regions with little to no plastic strain. Red color represents regions with plastic strains equal to or greater than 15 percent. Plastic strains greater than 15 percent for steel material indicate regions where local steel failure is likely to occur.



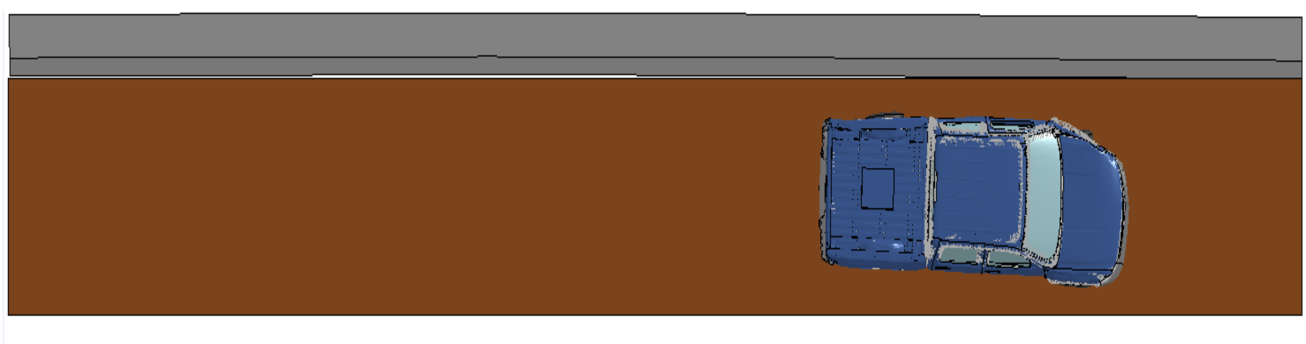
(a) Front View At Impact



(b) Front View At Final Configuration



(c) Top View At Impact



(d) Top View At Final Configuration

Figure 4.19. Initial and Deflected Shape of Barrier for *MASH* TL 3-11 Impact (Vertical Median Wall - 112.5-inch).

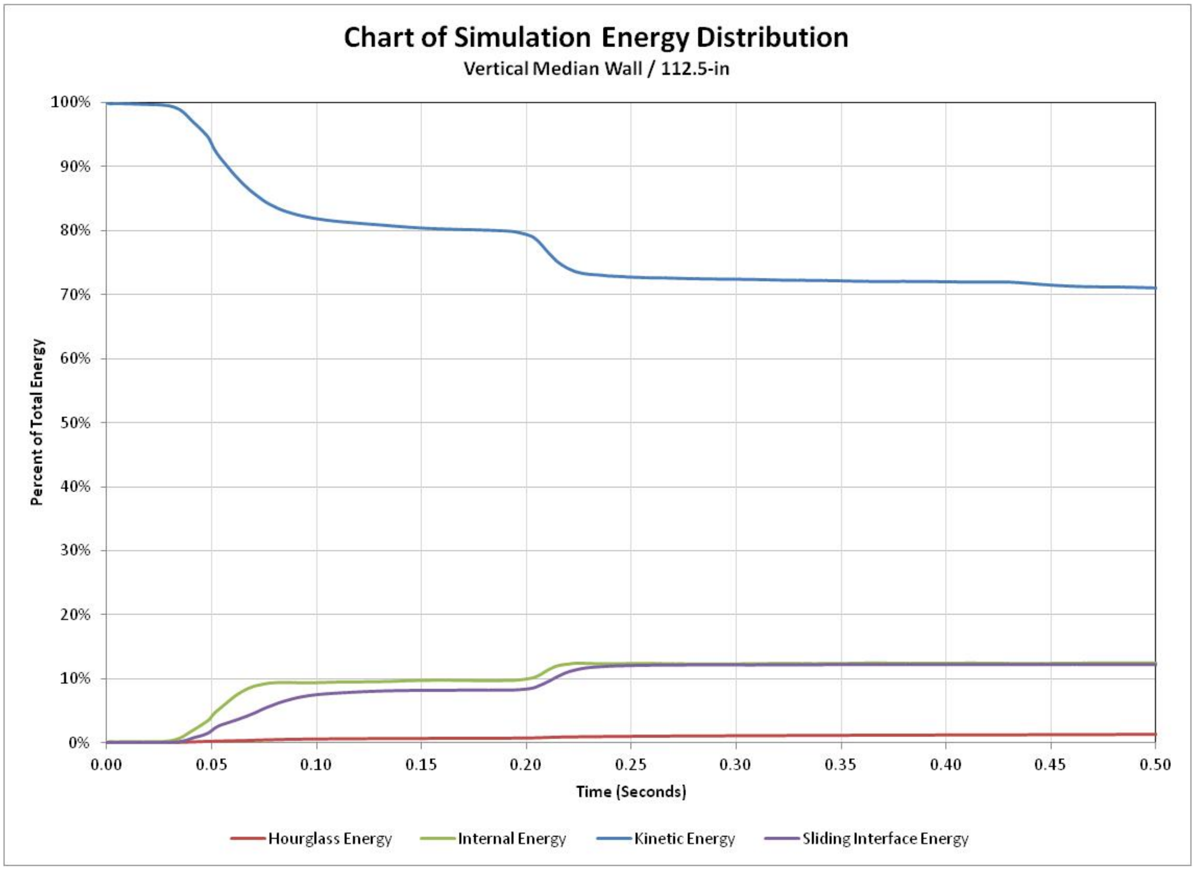
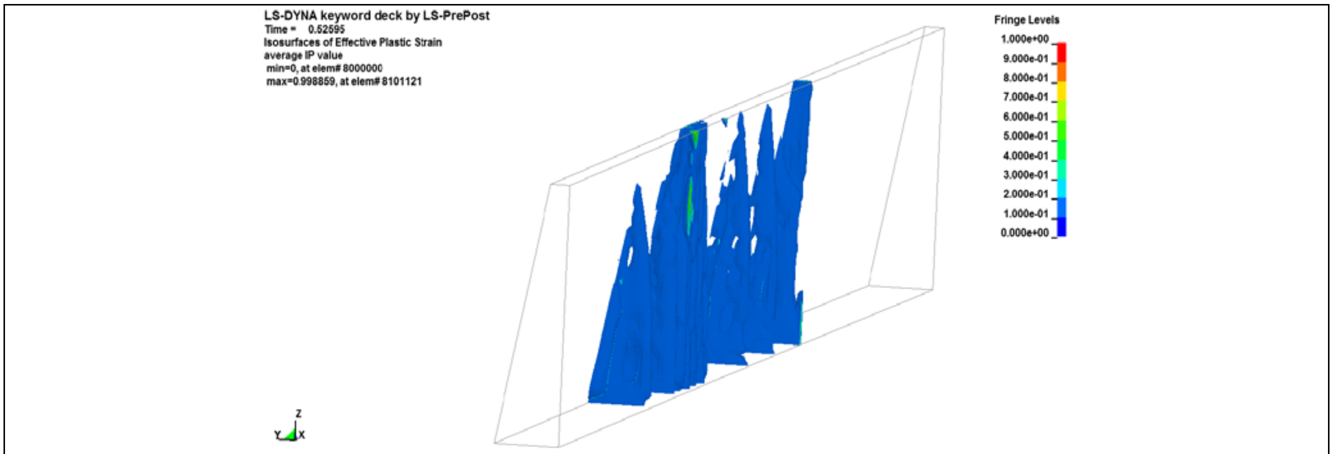


Figure 4.20. Energy Distribution Time History for *MASH* TL 3-11 Impact (Vertical Median Wall - 112.5-inch).

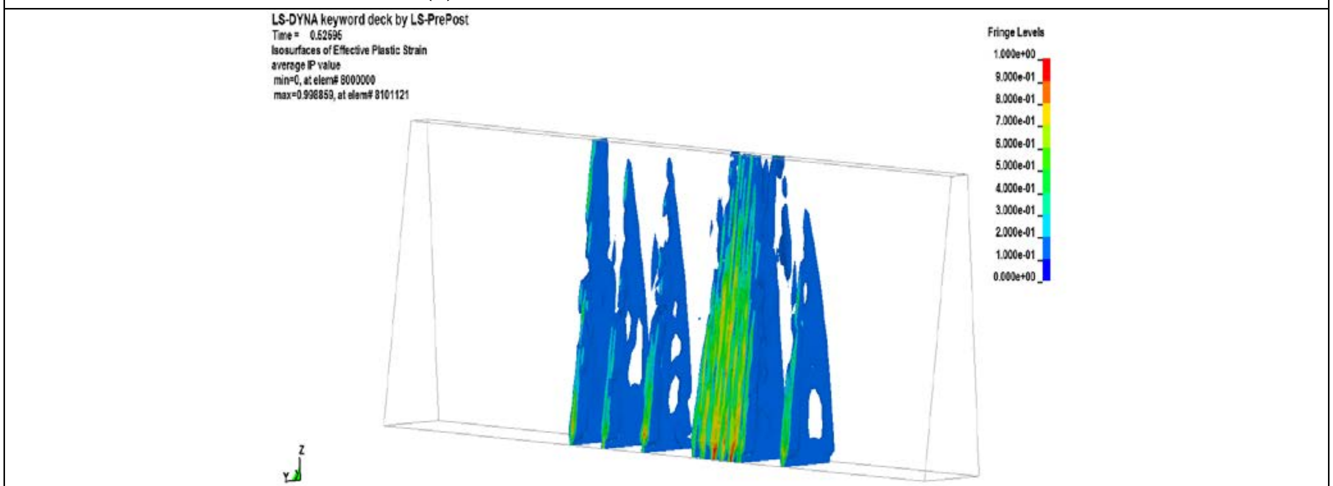
4.3.4.4 Concrete Foundation Stresses

Figure 4.21 shows the plastic strains in (a) the front and (b) the back side of the barrier. Areas shown in Figure 4.21(b) are areas where damage to the concrete barrier is likely to occur. It is likely that cracks will form in these locations at the back side of the barrier; it is unlikely, however, that a catastrophic failure of the concrete barrier will occur.

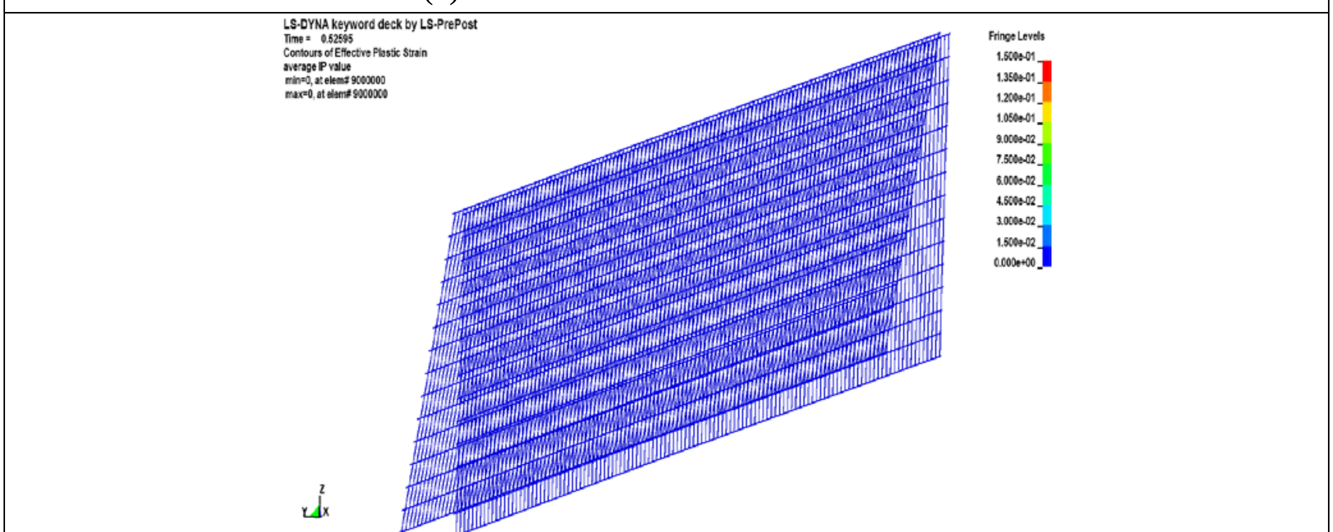
Figure 4.21(c) shows the plastic strains in the rebar structure of the barrier. Blue regions represent regions with little to no plastic strain. Red regions represent regions with plastic strains equal to or greater than 15 percent. As shown in Figure 4.21(c), there are no high plastic strain regions in the rebar cage.



(a) Front Side of the Concrete Barrier



(b) Back Side of the Concrete Barrier



(c) Barrier Steel Reinforcement

Figure 4.21. Concrete Stresses for *MASH* TL 3-11 Impact (Vertical Median Wall - 112.5-inch).

Tables 4.7 and 4.8 show frames from FE simulation of impact against the modeled 112.5-inch tall vertical median wall.

Table 4.7. Sequential Images of the 2270P Vehicle Interaction with the 112.5-inch Tall Vertical Median Wall Model for *MASH* TL 3-11 Impact (Perpendicular and Oblique Views).

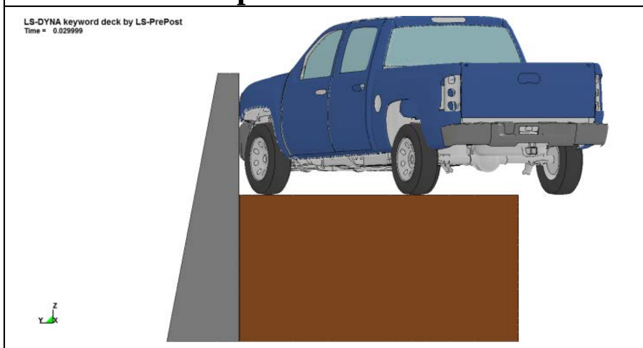
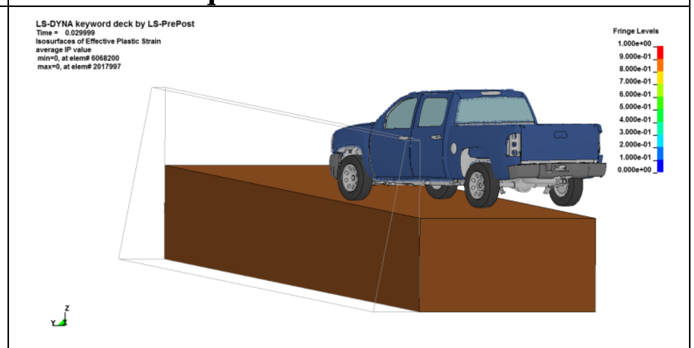
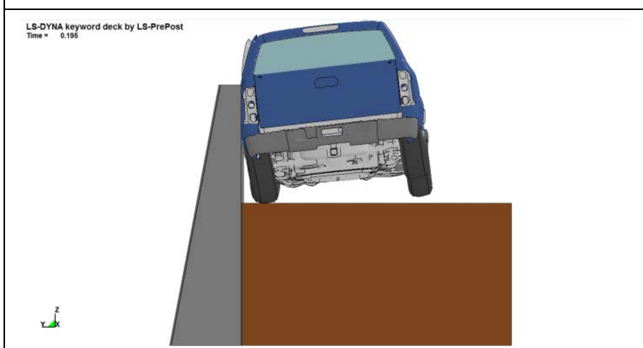
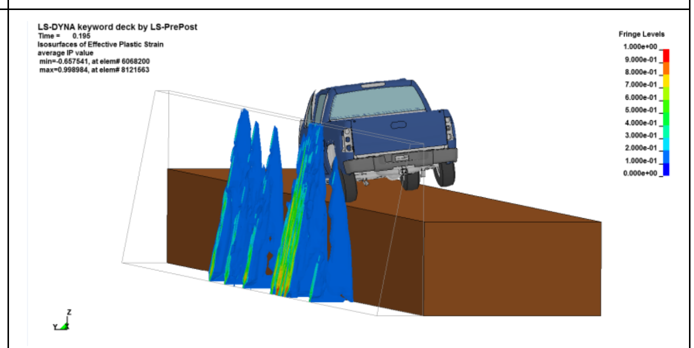
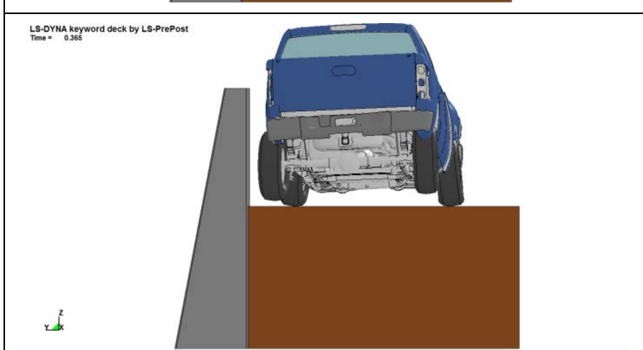
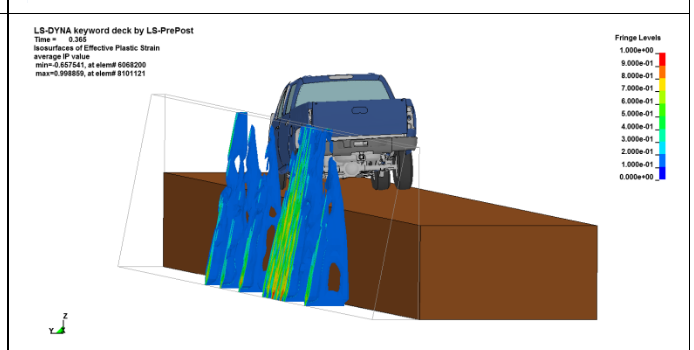
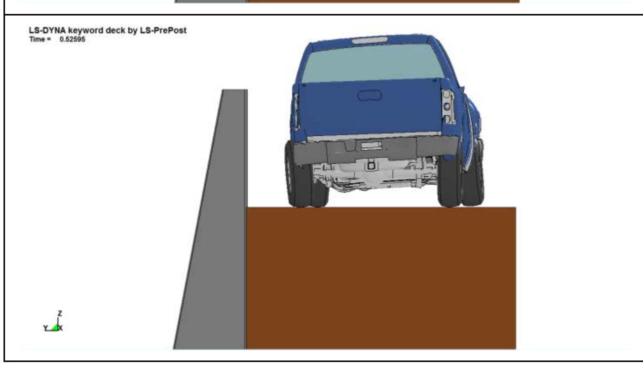
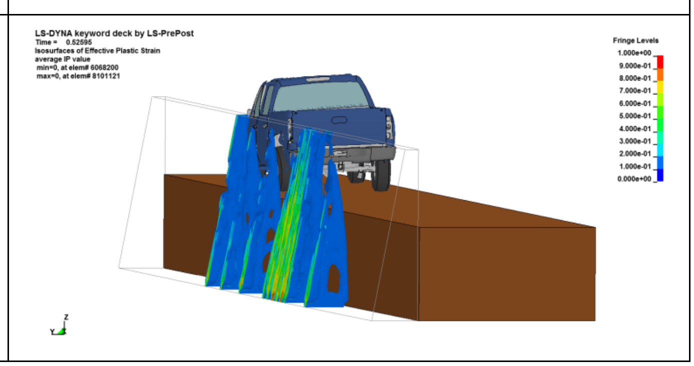
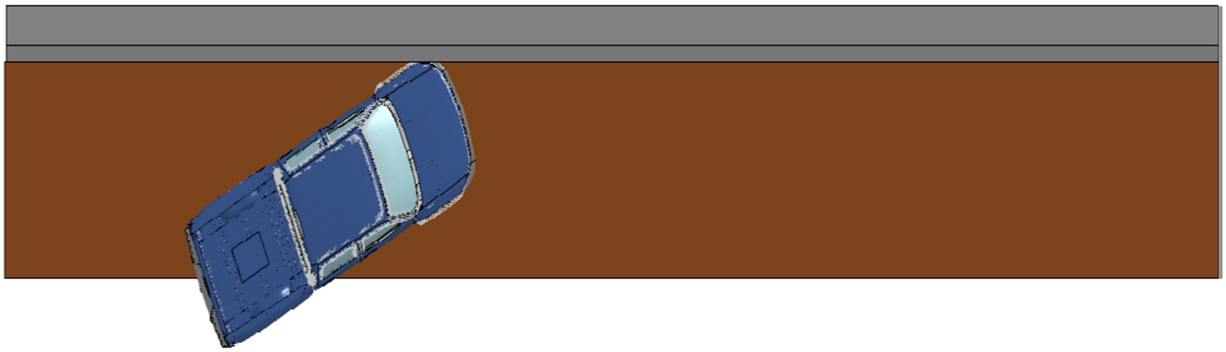
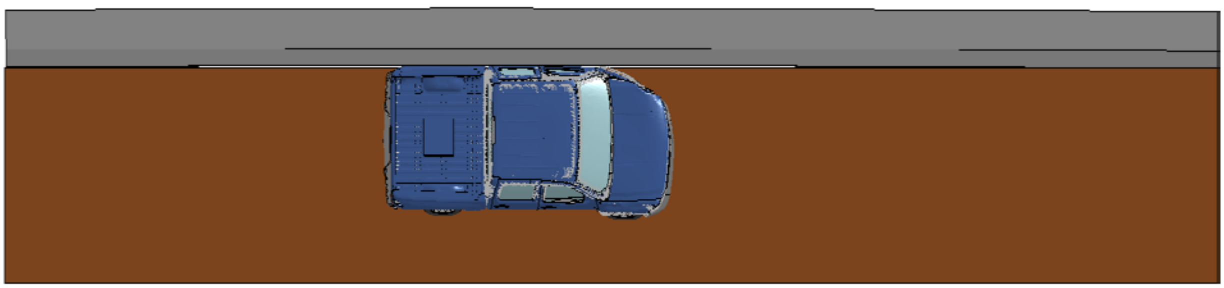
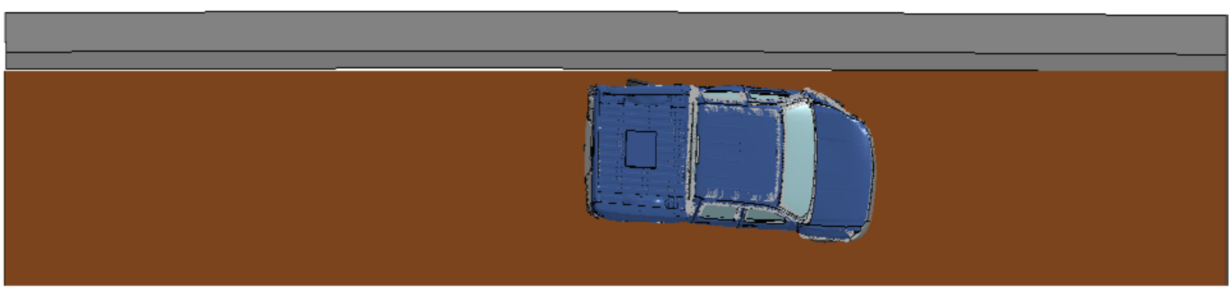
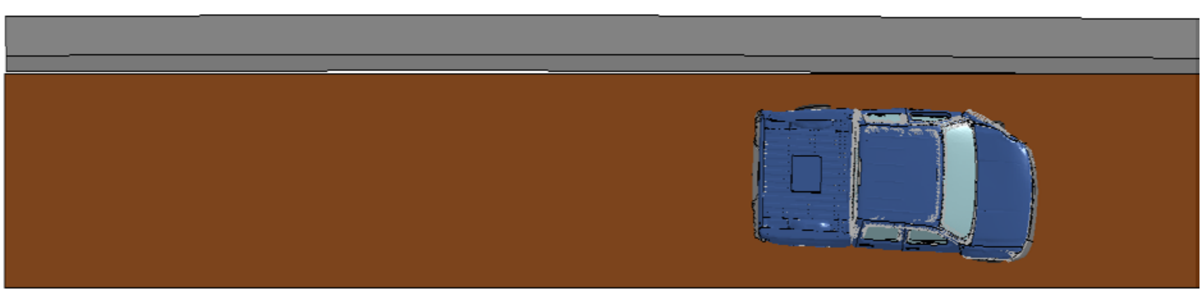
Perpendicular View	Oblique View - Barrier Strains
	
	
	
	

Table 4.8. Sequential Images of the 2270P Vehicle Interaction with the 112.5-inch Tall Vertical Median Wall Model for *MASH* TL 3-11 Impact (Top View).

Top View





4.3.4.5 Occupant Risk Assessment

TRAP was used to evaluate occupant risk factors based on the applicable *MASH* safety evaluation criteria. The modeled 2270P vehicle remained upright during and after the modeled collision event. Figure 4.22 shows vehicle roll and pitch angles throughout the impact event against the 112.5-inch high vertical median wall. Maximum roll and pitch angles resulted to be -8.1 degrees and -4.9 degrees, respectively.

4.3.4.6 Results

Figure 4.23 summarizes results for *MASH* Test 3-11 simulation with a 2270P vehicle impacting a 112.5-inch high vertical median wall. Results showed that the 112.5-inch tall vertical median wall performed adequately by containing and redirecting the impacting 2270P vehicle. The free standing barrier slid less than a couple of inches from its initial position during the impact event. The barrier, however, did not show any potential for tipping over and allowing the impacting vehicle for intrusion in the opposing lane. Also, simulations indicate the 2270P vehicle maintaining stability during the *MASH* TL 3-11 impact conditions event.

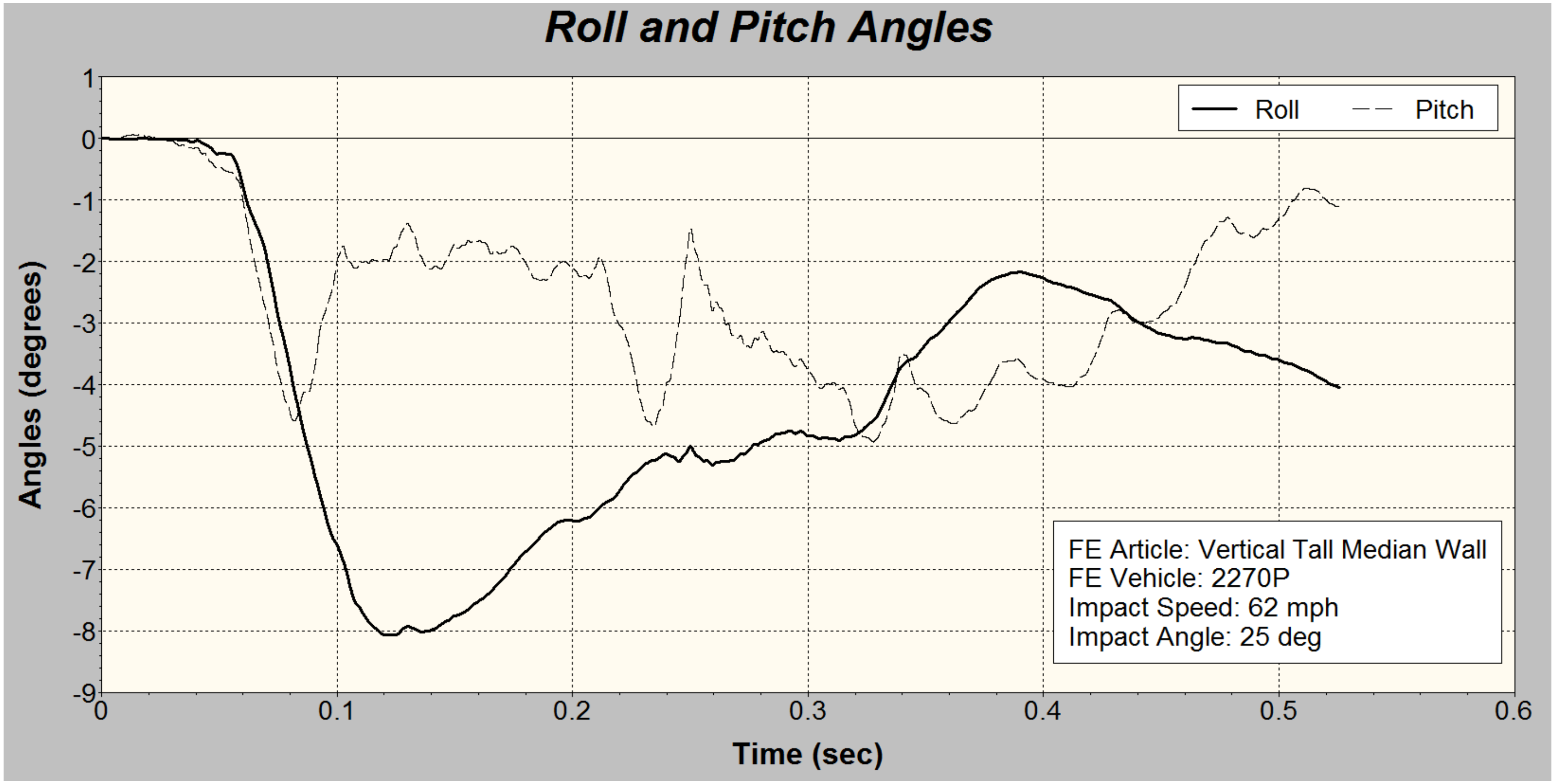
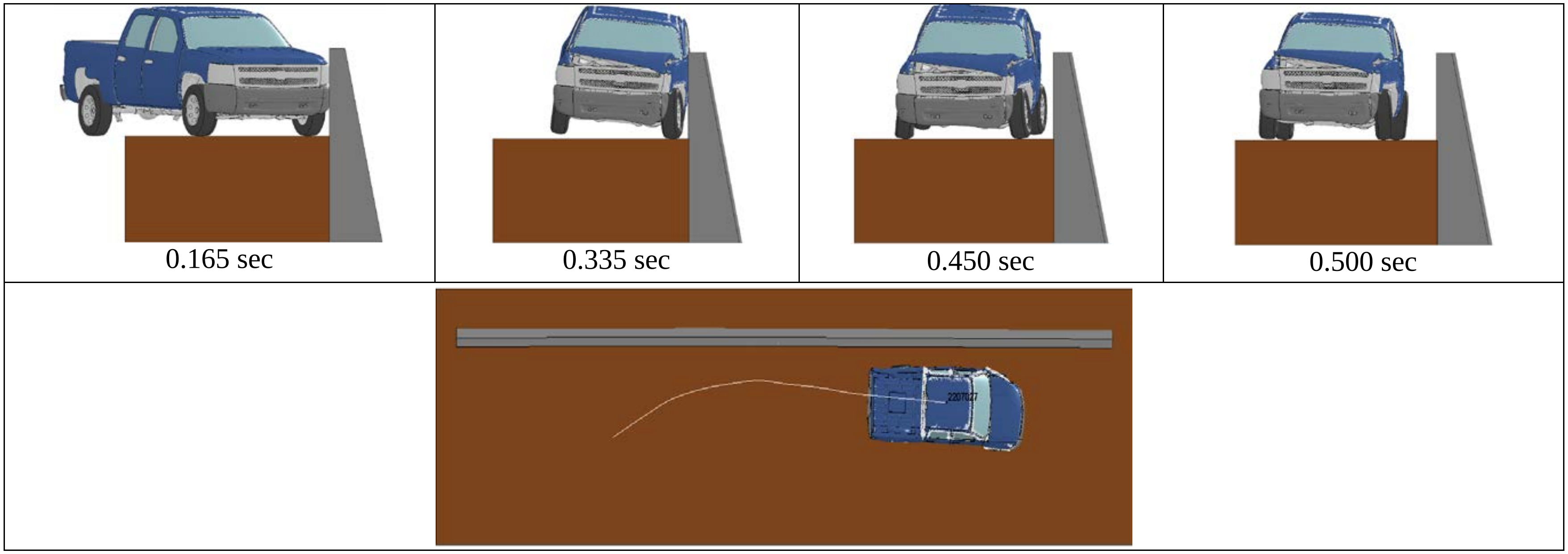


Figure 4.22. Roll and Pitch Angles for *MASH* TL 3-11 Impact (Vertical Median Wall - 112.5-inch).



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

Test Article
- Type .... Median Barrier for Grade Separation
- Name.............................. 112.5" Concrete Vertical Median Wall
- Installation Length .... 80 ft
- Material or Key Elements. Steel Reinforced Concrete Barrier

Test Vehicle
- Type/Designation............. 2270P
- Make and Model .... Finite Element Silverado Pickup
- Curb .... 5035 lb
- Test Inertial...................... 5035 lb
- Dummy............................ No Dummy
- Gross Static..................... 5035 lb

Impact Conditions
- Speed ....62.0 mi/h
- Angle ....25 degrees
- Location/Orientation............One Third of Barrier Length

Exit Conditions
- Speed ....51.1 mi/h
- Angle ....1.8 degrees

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

Vehicle Stability
- Maximum Yaw Angle .... 29.3 degree
- Maximum Pitch Angle ....-4.9 degree
- Maximum Roll Angle ....-8.1 degree
- Vehicle Snagging......................No
- Vehicle Pocketing ....No

Test Article Deflections
- Dynamic...................................1.5 inches
- Permanent ....1.5 inches
- Working Width ....N/A

Vehicle Damage
- VDS..N/A
- CDC..N/A
- Max. Exterior Deformation ....N/A
- OCDI ....N/A
- Max. Occupant Compartment Deformation........................N/A

Figure 4.23. Summary of Results for *MASH* Test 3-11 Simulation (Vertical Median Wall - 112.5-inch).

5. OPTIMIZATION

5.1 OPTIMIZATION OF BARRIER SECTION LENGTH

In a second phase of this project, researchers were asked to evaluate the single slope median wall according to *MASH* TL-4 requirements. For this type of evaluation, the researchers decided to perform an optimization of the single slope median wall. Optimization of the barrier was made by evaluating the minimum joint spacing between barrier segments required to resist soil forces and *MASH* TL-4 impact conditions. From this moment on, minimum joint spacing will be referred to as minimum barrier segment length. The *MASH* TL-4 barrier was evaluated according to the LRFD method by applying a lateral design load of 75,000 kip to the very top of the barrier. Researchers developed a conservative static engineering analysis, without including the dynamic barrier inertial resistance after the impact event. By applying the load to the top of the barrier, the researchers considered the worst impact location for the median wall. In fact, while the single unit truck bumper would impact the barrier at a location below the maximum height (thus, below 52.5 inches), the vehicle's bed and cargo would impact the barrier at a level close to its maximum height.

Figure 5.1 shows the results of the optimization process for *MASH* TL-4 impact conditions. The minimum segment length for the 112.5-inch sloped median wall to sustain soil forces and *MASH* TL-4 impact conditions resulted to be 33 ft. The minimum segment length for the 51-inch sloped median wall to sustain *MASH* TL-4 impact conditions resulted to be 60 ft.

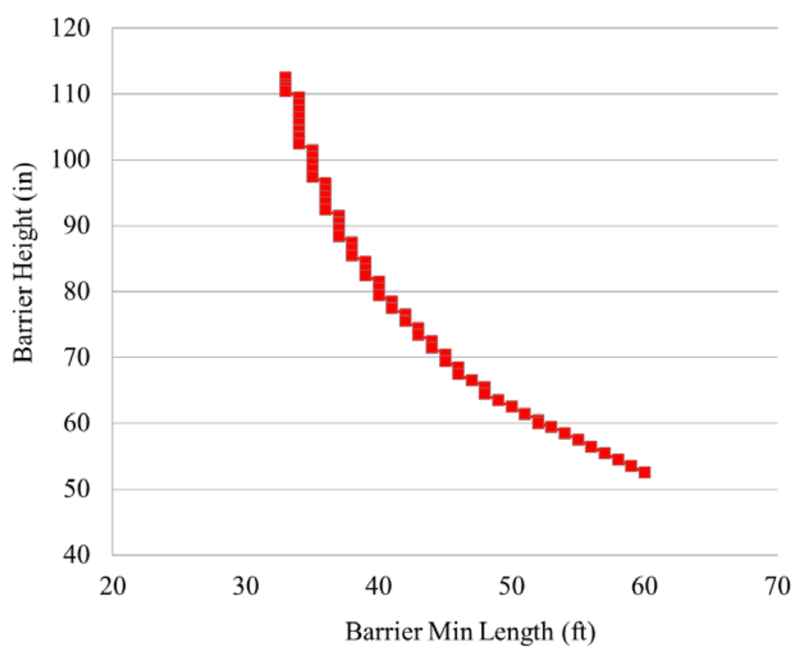


Figure 5.1. Optimization of Sloped Median Wall Minimum Segment Length for *MASH* TL-4 Impact Condition.

Researchers used FE simulations to verify the structural and stability of the median wall for *MASH* TL-4 impact conditions. Impacts simulations of a 22,000-lb single unit truck against the 112.5-inch and the 51-inch versions of the single sloped median wall were performed. When modeling the segments for *MASH* TL-4 impact condition simulations, the researchers decided to model a 35-ft median wall segment length for impact with the 112.5-inch barrier and a 60-ft median wall segment length for impact with the 51-inch barrier. *MASH* TL-4 FE results are reported in Chapter 5.2.

After optimization of the median barrier for *MASH* TL-4 impact conditions, the researchers decided to perform an optimization of the barrier also for *MASH* TL-3 impact conditions. An optimization evaluation for *MASH* TL-3 impact conditions was not included as an objective of this research, thus time and resources were very limited for this additional evaluation. Optimization of the barrier was made by evaluating the minimum barrier segment length needed to resist soil forces and *MASH* TL-3 impact conditions. The *MASH* TL-3 barrier was evaluated according to the LRFD method by applying a lateral design load of 54,000 kip to the very top of the barrier to account for the worst possible impact condition.

Figure 5.2 shows the results of the optimization process for *MASH* TL-3 impact conditions. The minimum segment length for the 112.5-inch sloped median wall to sustain soil forces and *MASH* TL-3 impact conditions resulted to be 24 ft. The minimum segment length for the 51-inch sloped median wall to sustain *MASH* TL-3 impact conditions resulted to be 45 ft.

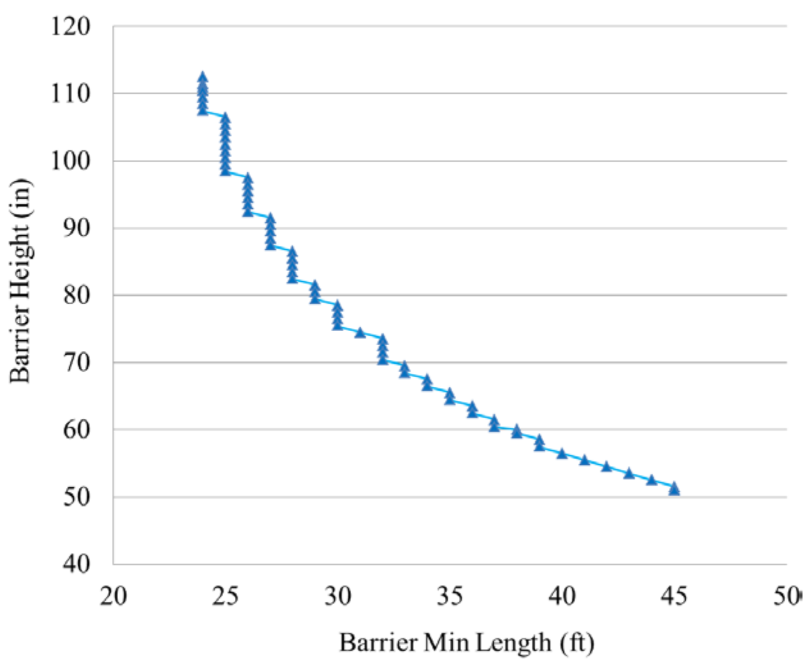


Figure 5.2. Optimization of Sloped Median Wall Minimum Segment Length for *MASH* TL-3 Impact Condition.

MASH TL-3 FE results are reported in a subsequent section of this chapter. FE simulations were limited to the evaluation of the 112.5-inch tall version of the median barrier, due to time and budget limitations.

5.2 *MASH* TL-4 FINITE ELEMENT SIMULATIONS

5.2.1 *MASH* TL 4-12: 35-ft Single Sloped Median Wall Segment 112.5 inches Tall

This section contains results from a simulated *MASH* TL 4-12 impact into a 35-ft long, 112.5-inch tall sloped median wall segment. The authors decided to use FE simulations to evaluate the 112.5 inches free standing median wall structural capacity and the vehicle stability during the *MASH* TL 4-12 impact event.

5.2.1.1 Barrier Performance

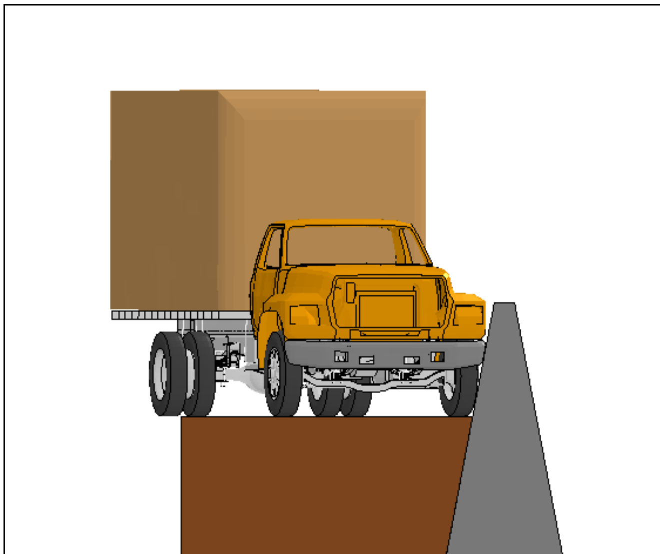
Figure 5.3 contains images of the barrier before impact and at final configuration. The barrier was impacted at the one-third point of the installation. After the impact event, the barrier displacement from the original position resulted to be less than 3 inches. Figure 5.3(a) and 5.3(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 5.3(b) and 5.3(d) show the front and overhead views of the barrier and impacting vehicle at final configuration.

5.2.1.2 Energy Values

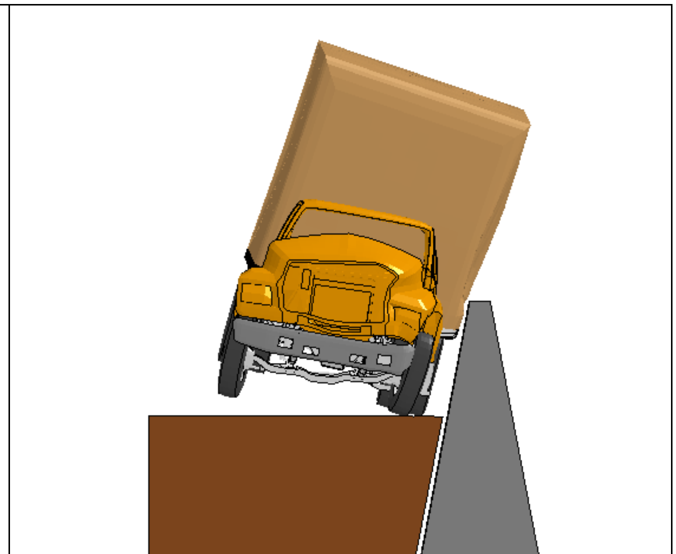
As shown in Figure 5.4, approximately 5 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). Hourglass energy does not give any significant contribution. Approximately 18 percent of the initial kinetic energy is converted into sliding interface energy. Seventy-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.

5.2.1.3 Plastic Strain

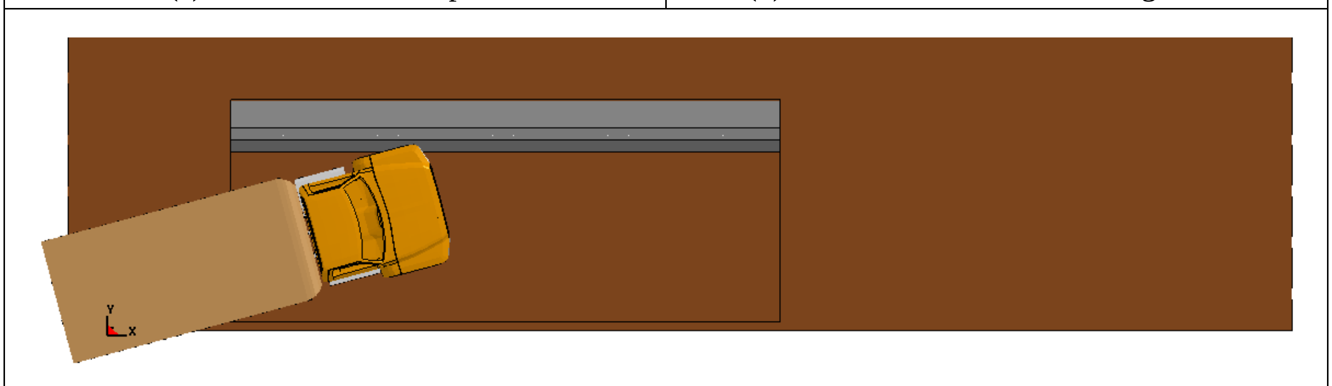
Plastic strain contours, shown in Figure 5.5, are used to visualize possible barrier failure locations. Blue color represents regions with little to no plastic strain. Red color represents regions with plastic strains equal to or greater than 15 percent. Plastic strains greater than 15 percent for steel material indicate regions where local steel failure is likely to occur.



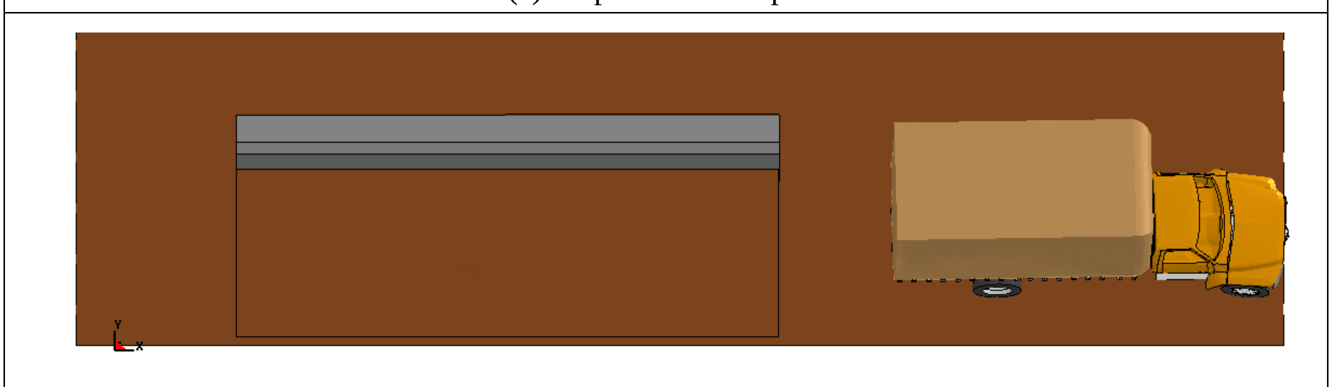
(a) Front View At Impact



(b) Front View At Final Configuration



(c) Top View At Impact



(d) Top View At Final Configuration

Figure 5.3. Initial and Deflected Shape of Barrier for *MASH* TL 4-12 Impact (Sloped Median Wall – 112.5-inch).

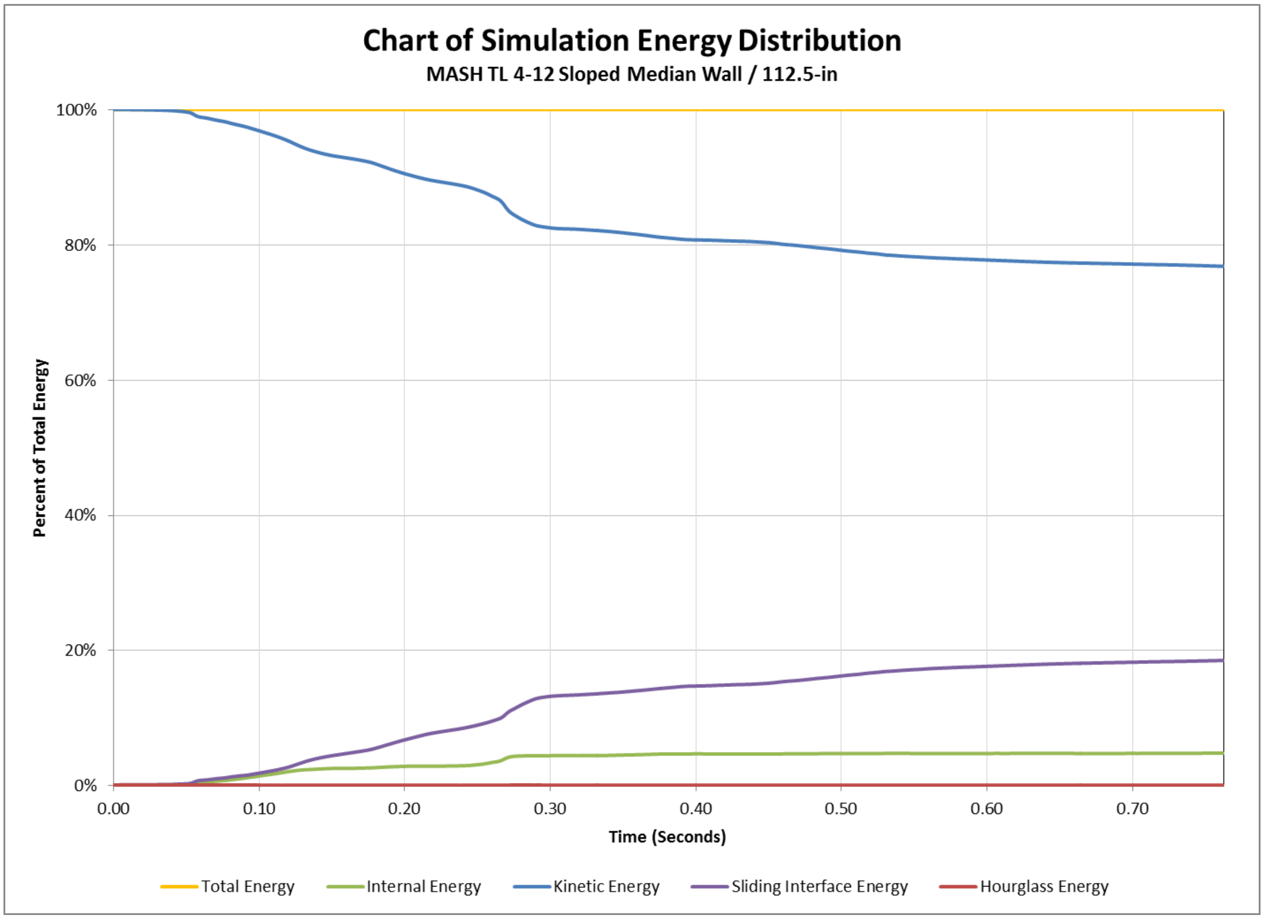


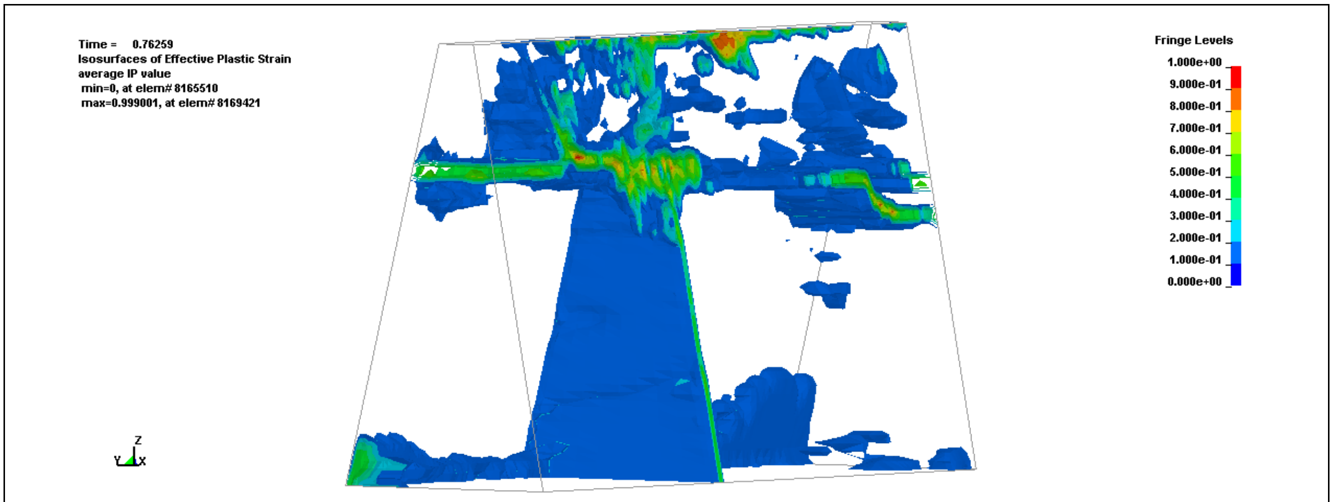
Figure 5.4. Energy Distribution Time History for *MASH* TL 4-12 Impact (Sloped Median Wall – 112.5-inch).

5.2.1.4 Concrete Barrier Stresses

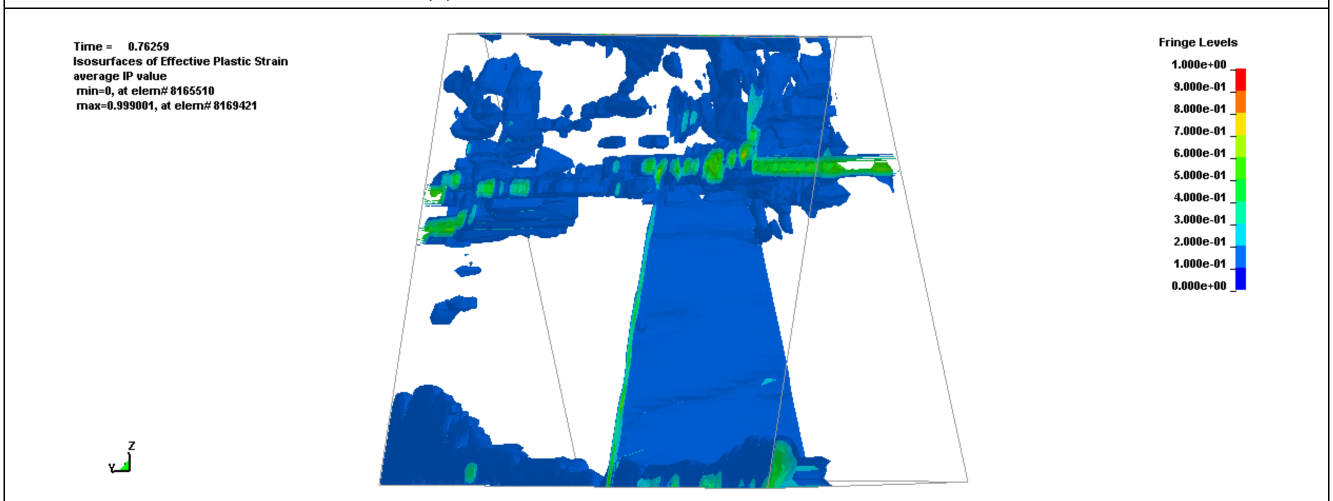
Figure 5.5 shows the plastic strains in (a) the front and (b) the back side of the barrier. There is only a small area located at the top of the barrier, at impact location, where the plastic strains suggest damage to the concrete barrier is likely to occur. It is likely that cracks will form in this location; it is unlikely, however, that a catastrophic failure of the concrete barrier will occur.

Figure 5.5(c) shows the plastic strains in the rebar structure of the barrier. Blue regions represent regions with little to no plastic strain. Red regions represent regions with plastic strains equal to or greater than 15 percent. As shown in Figure 5.5(c), there are no high plastic strain regions in the rebar cage.

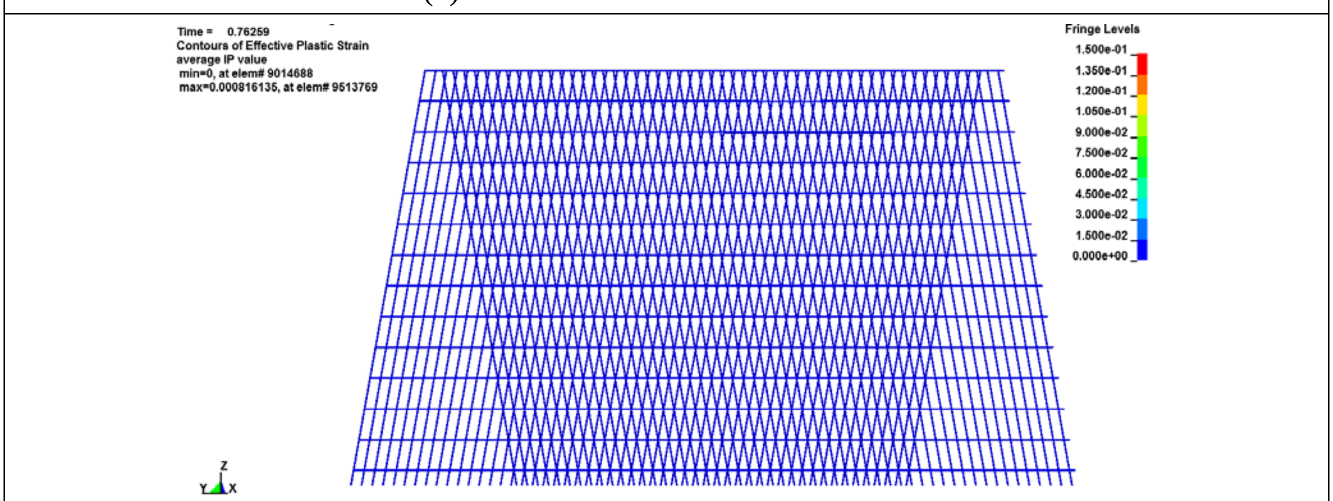
Tables 5.1 and 5.2 show frames from FE simulation of *MASH* TL 4-12 impact against the modeled 112.5-inch tall sloped median wall.



(a) Front Side of the Concrete Barrier



(b) Back Side of the Concrete Barrier



(c) Barrier Steel Reinforcement

Figure 5.5. Concrete Stresses for *MASH* TL 4-12 Impact (Sloped Median Wall – 112.5-inch).

Table 5.1. Sequential Images of the 10000S Vehicle Interaction with the 112.5-inch Tall Sloped Median Wall Model for *MASH* TL 4-12 Impact (Perpendicular and Oblique Views).

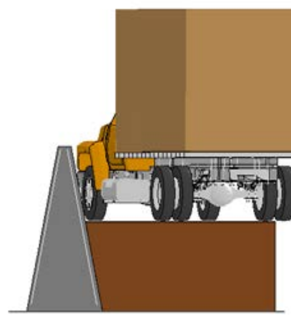
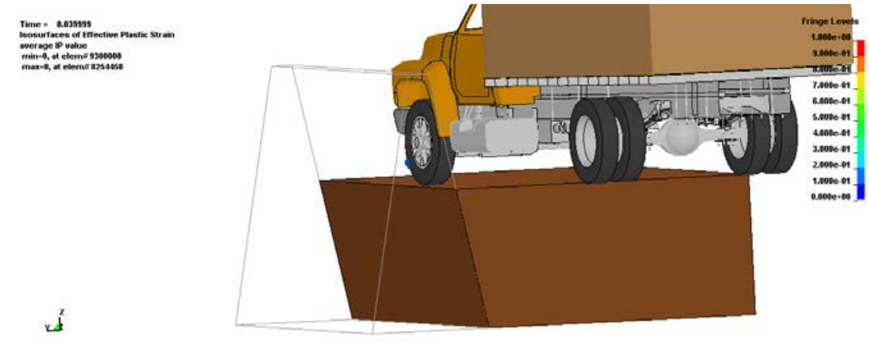
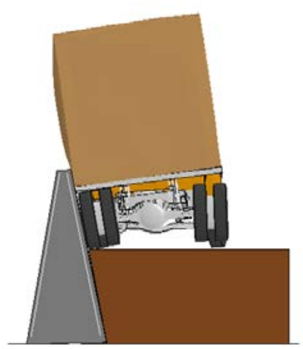
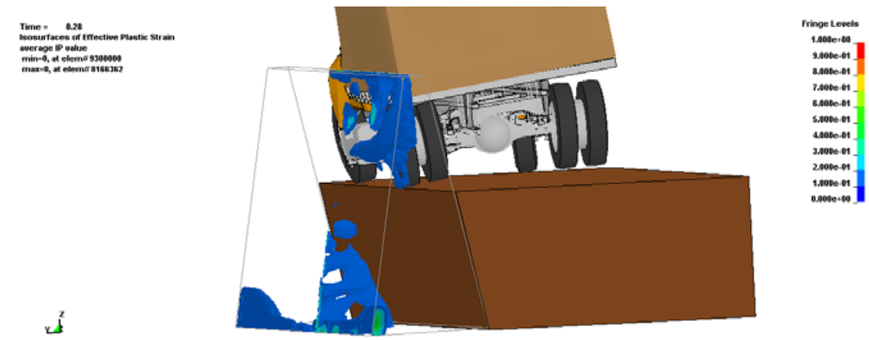
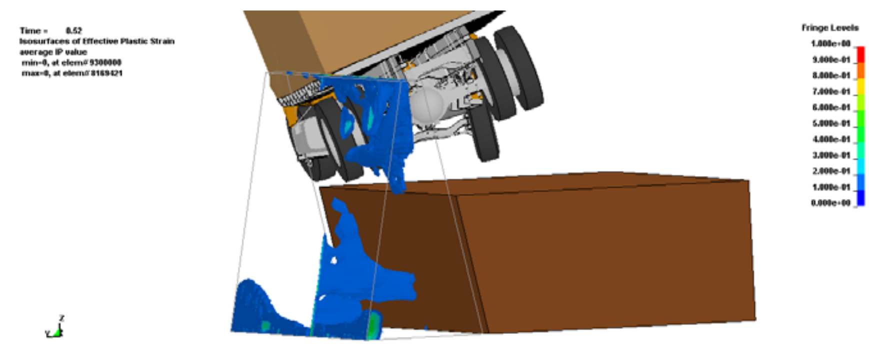
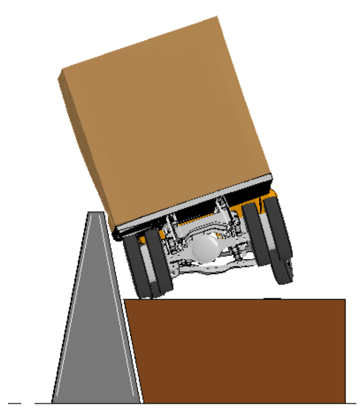
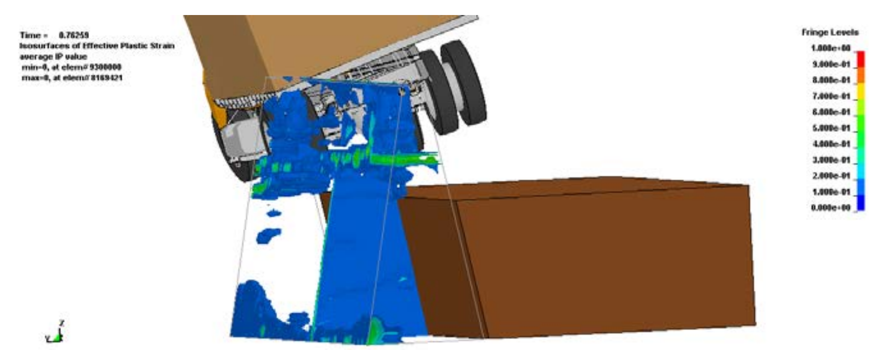
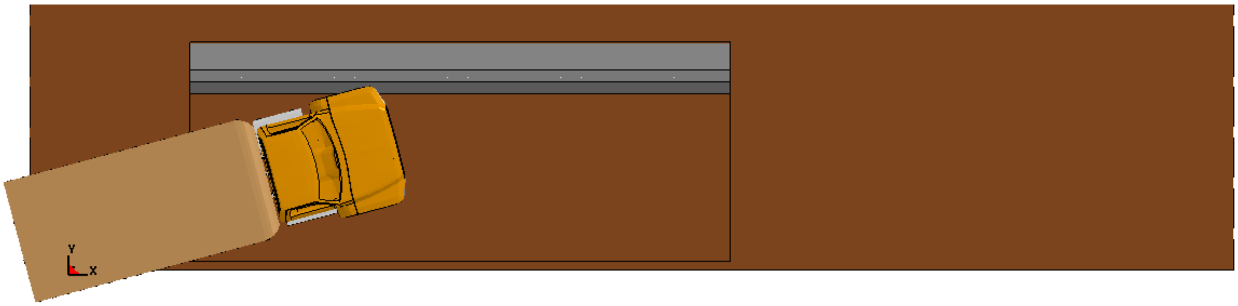
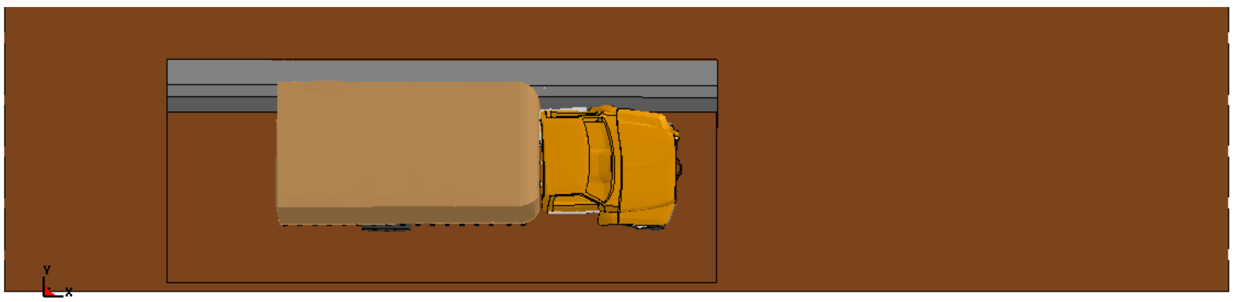
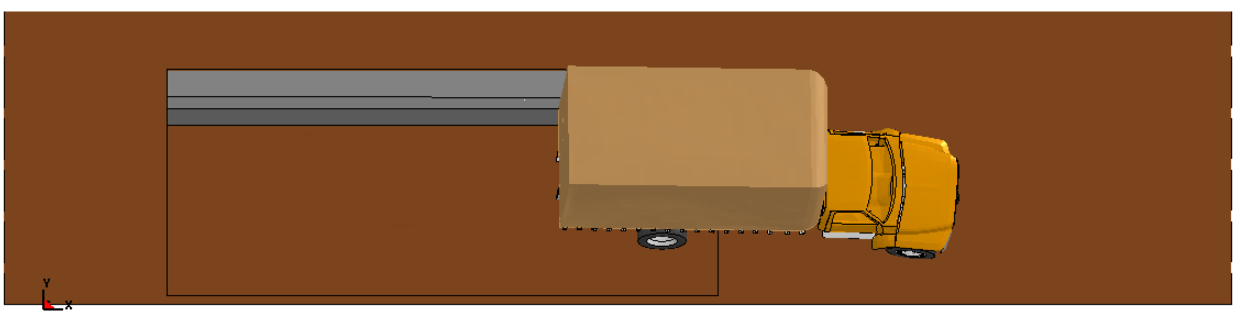
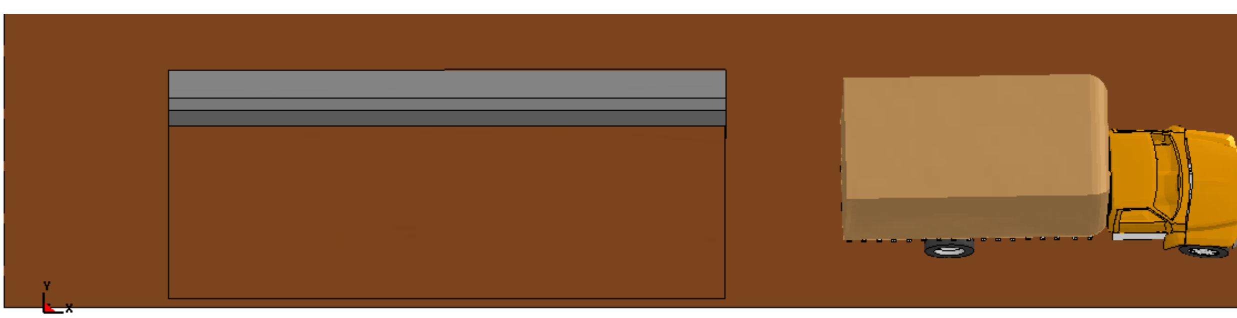
Perpendicular View	Oblique View - Barrier Strains
	
	
	
	

Table 5.2. Sequential Images of the 10000S Vehicle Interaction with the 112.5-inch Tall Sloped Median Wall Model for *MASH* TL 4-12 Impact (Top View).

Top View





5.2.1.5 Occupant Risk Assessment

The modeled 10000S vehicle remained upright during and after the modeled collision event. Figure 5.6 shows vehicle roll, pitch, and yaw angles throughout the impact event against the 112.5-inch high sloped median wall. Stability of the vehicle was evaluated using the TRAP program. Maximum roll, pitch, and yaw angles resulted in -12.4, 4.1, and 17.6 degrees, respectively. Previous test experience showed that occupant risk results are not a concern for impact of vehicles against single sloped concrete barrier, since they all remained in the range required by *MASH* criteria. As consequence, occupant risk values were not evaluated for this finite element simulation.

5.2.1.6 Results

Figure 5.7 summarizes results for *MASH* Test 4-12 simulation with a 10000S vehicle impacting a 112.5-inch high sloped median wall. Results showed that the 112.5-inch tall single sloped median wall performed adequately by containing and redirecting the impacting 10000S vehicle. The free standing barrier slid almost 3 inches from its initial position during the impact event. However, the barrier did not show any potential for tipping over and allowing the impacting vehicle for intrusion in the opposing lane. Also, simulations indicate the 10000S vehicle maintains stability during the *MASH* TL 4-12 impact conditions event.

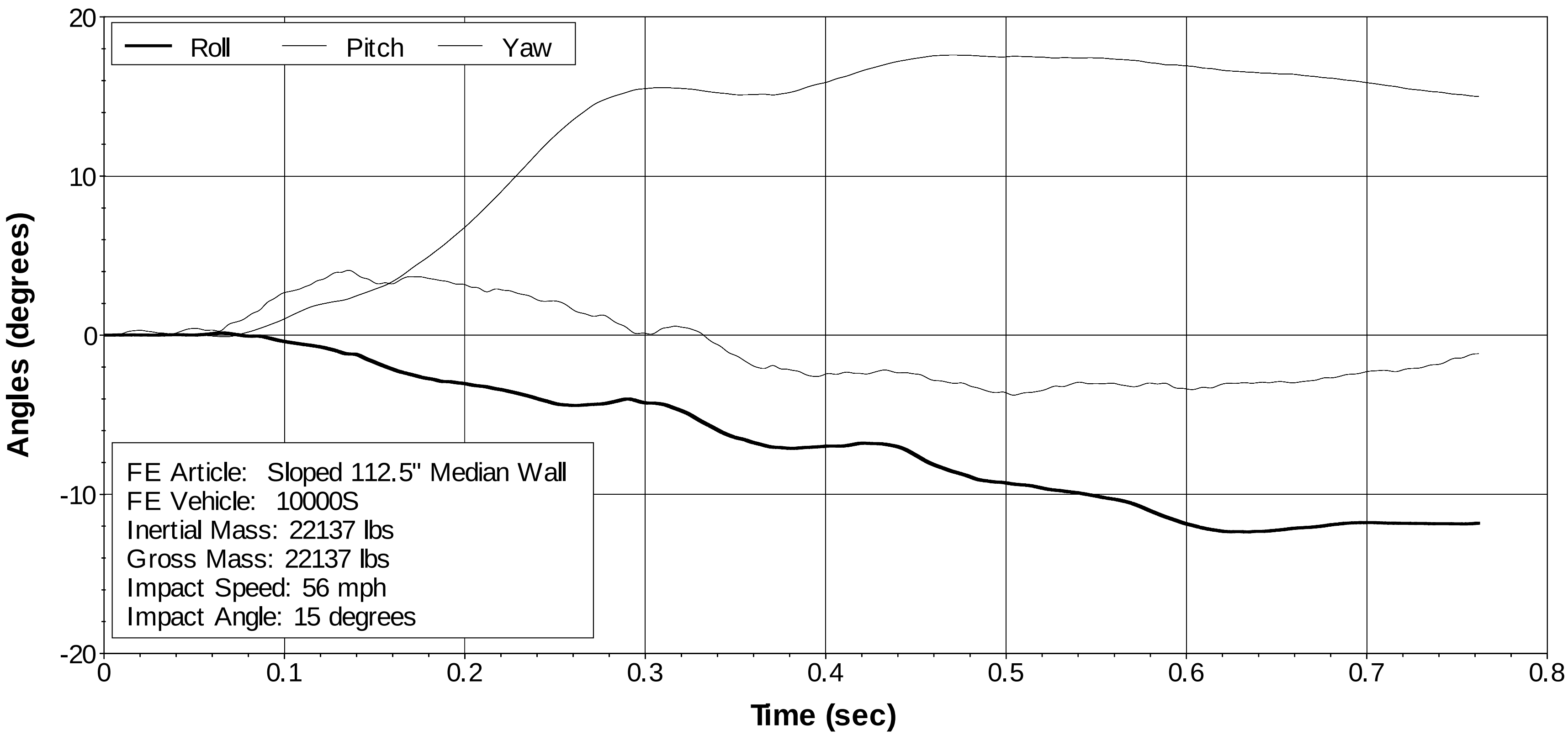
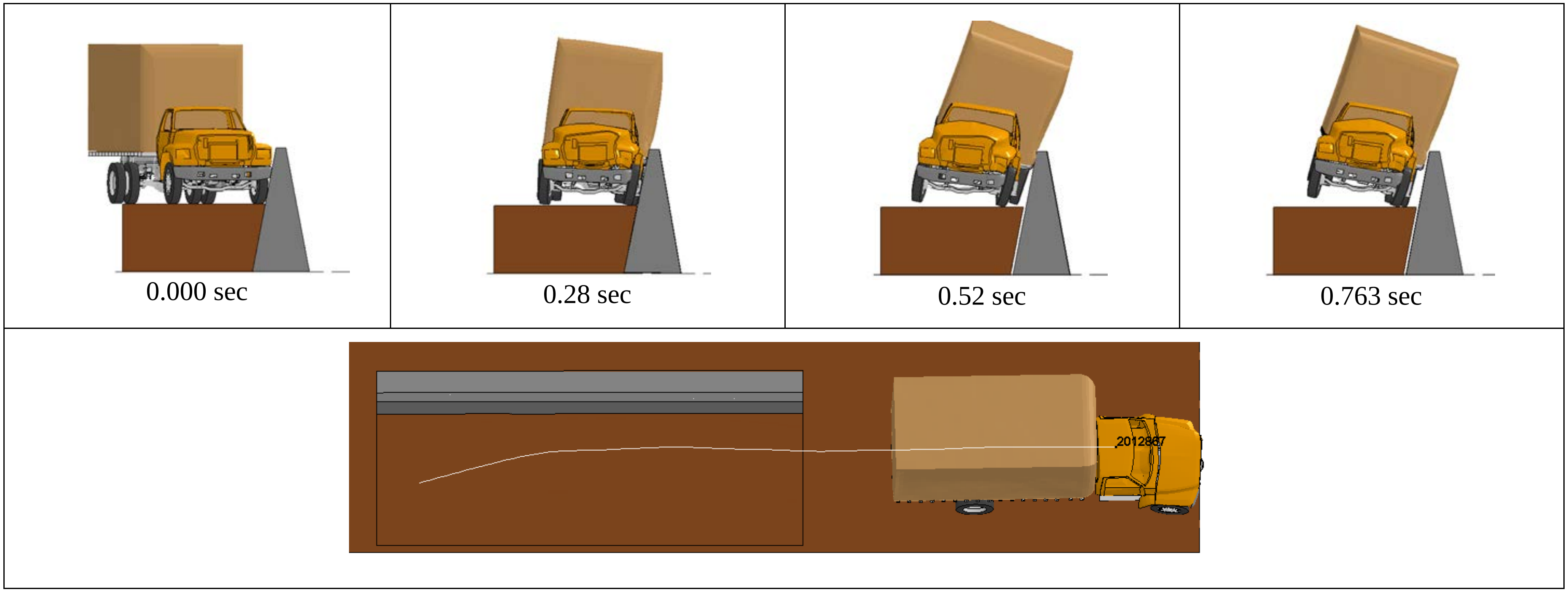


Figure 5.6. Roll, Pitch, and Yaw Angles for *MASH* TL 4-12 Impact (Sloped Median Wall – 112.5-inch).



General Information

Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard Test No.	*MASH* Test 4-12
Date	N/A

Test Article

Type	Median Barrier for Grade Separation
Name	112.5" Concrete Single Sloped Median Wall Segment
Installation Length	35 ft
Material or Key Elements	Steel Reinforced Concrete Barrier, Free Standing Barrier

Test Vehicle

Type/Designation	10000S
Make and Model	Finite Element Single Unit Truck
Curb	22137 lb
Test Inertial	22137 lb
Dummy	No Dummy
Gross Static	22137 lb

Impact Conditions

Speed	56 mi/h
Angle	15 degrees
Location/Orientation	One Third of Barrier Length

Exit Conditions

Speed	48.5 mi/h
Angle	1.8 degrees

Post-Impact Trajectory

Stopping Distance	N/A

Vehicle Stability

Maximum Yaw Angle	17.6 degree
Maximum Pitch Angle	4.1 degree
Maximum Roll Angle	-12.4 degree
Vehicle Snagging	No
Vehicle Pocketing	No

Test Article Deflections

Dynamic	N/A
Permanent	< 3 inches
Working Width	N/A

Vehicle Damage

VDS	N/A
CDC	N/A
Max. Exterior Deformation	N/A
OCDI	N/A
Max. Occupant Compartment Deformation	N/A

Figure 5.7. Summary of Results for *MASH* Test 4-12 Simulation (Sloped Median Wall - 112.5-inch).

5.2.2 *MASH* TL 4-12: 60-ft Single Sloped Median Wall Segment 51 inches Tall

This section contains results from a simulated *MASH* TL 4-12 impact into a 60-ft long, 51-inch tall sloped median wall segment. Sheikh et al. (2011) have determined a minimum height for *MASH* TL-4 bridge rails of 36 inches. A full-scale crash test was performed on the 36-inch tall Single Slope Traffic Rail (SSTR) according to test requirements *MASH* TL-4 (Sheikh et al., 2011). The single slope barrier was constructed with an 11-degree slope on the traffic-side face, while the field side of the barrier was vertical. The barrier was 13 inches wide at the base and 7.5 inches wide at the top. The 150-ft segment of the 36-inch tall SSTR successfully contained and redirected the 10000S vehicle. The barrier evaluated in this project was designed with a single slope on both sides; it is 9 inches wide on the top and 28.5 inches wide at the bottom. Although the wall segment here evaluated is 60 ft (versus 150 ft of the SSTR barrier), the height of the wall segment is 51 inches. Thus, the stiffness and the structural capacity of the two barriers were considered comparable. Because the SSTR barrier successfully contained the single unit truck with the previously performed crash test, the researchers predict that the designed single sloped median wall segment would have the structural capacity of containing the 10000S, considering the actual dimensions. Still, the researchers decided to use FE simulations to evaluate the 51-inch free standing median wall and the vehicle’s stability during the *MASH* TL 4-12 impact event.

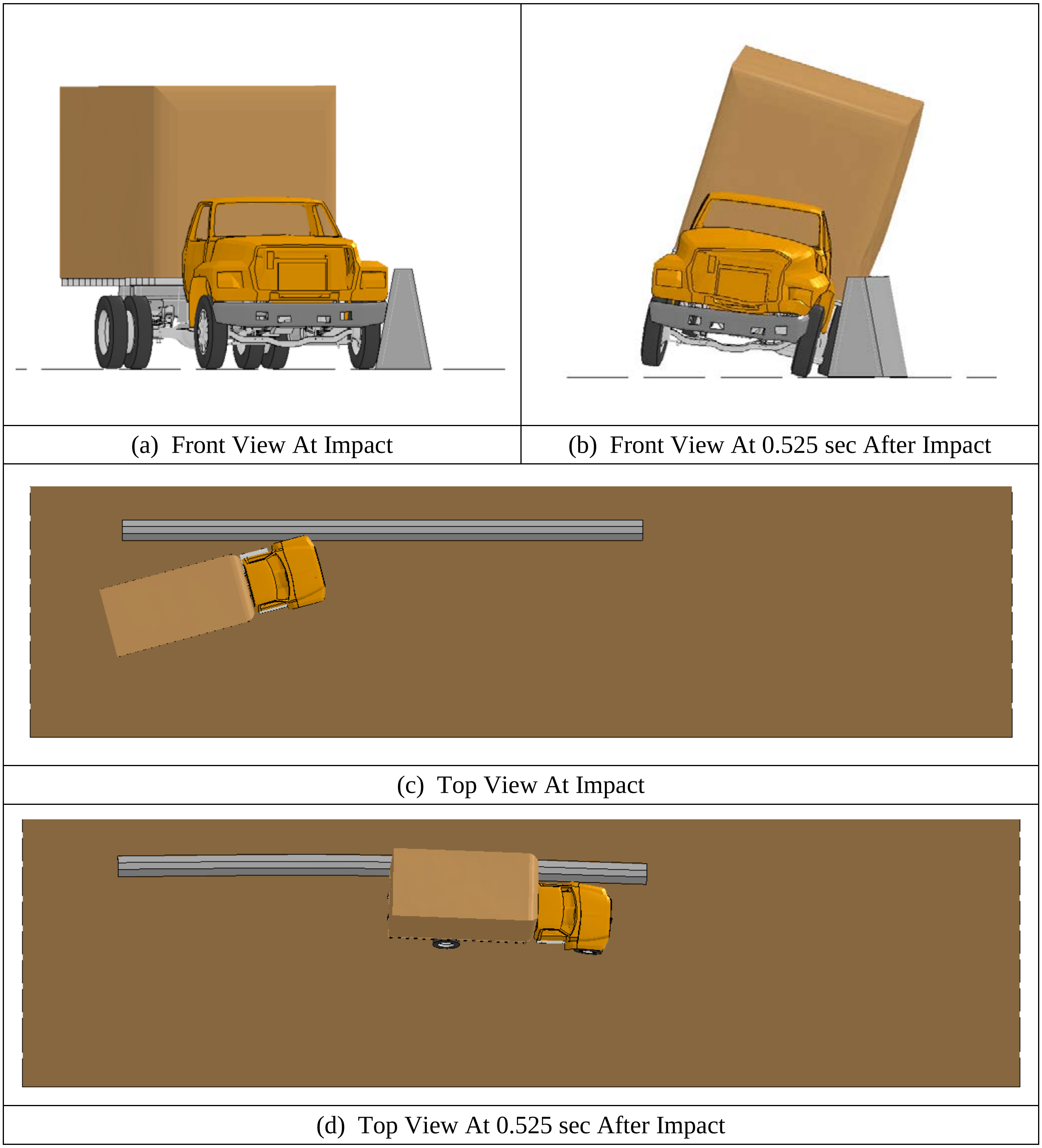
5.2.2.1 Barrier Performance

Figure 5.8 contains images of the barrier before impact and at 0.525 seconds after initial impact. The barrier was impacted at the one-third point of the installation. At 0.525 sec from the impact event, the barrier displacement from the original position resulted to be a little over a foot. Figure 5.8(a) and 5.8(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 5.8(b) and 5.8(d) show the front and overhead views of the barrier and impacting vehicle at 0.525 seconds after impact.

5.2.2.2 Energy Values

As shown in Figure 5.9, at 0.525 seconds after initial impact with the barrier, approximately 4 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). Hourglass energy does not give any significant contribution. Approximately 18 percent of the initial kinetic energy is converted into sliding interface energy. Seventy eight percent of the initial kinetic energy has yet to be dissipated by the system at 0.525 seconds after impact, mainly due to the remaining velocity of the vehicle.

Table 5.3 shows frames from FE simulation of *MASH* TL 4-12 impact against the modeled 112.5-inch tall sloped median wall.



(a) Front View At Impact

(b) Front View At 0.525 sec After Impact

(c) Top View At Impact

(d) Top View At 0.525 sec After Impact

Figure 5.8. Initial and Deflected Shape of Barrier for *MASH* TL 4-12 Impact (Sloped Median Wall – 51-inch).

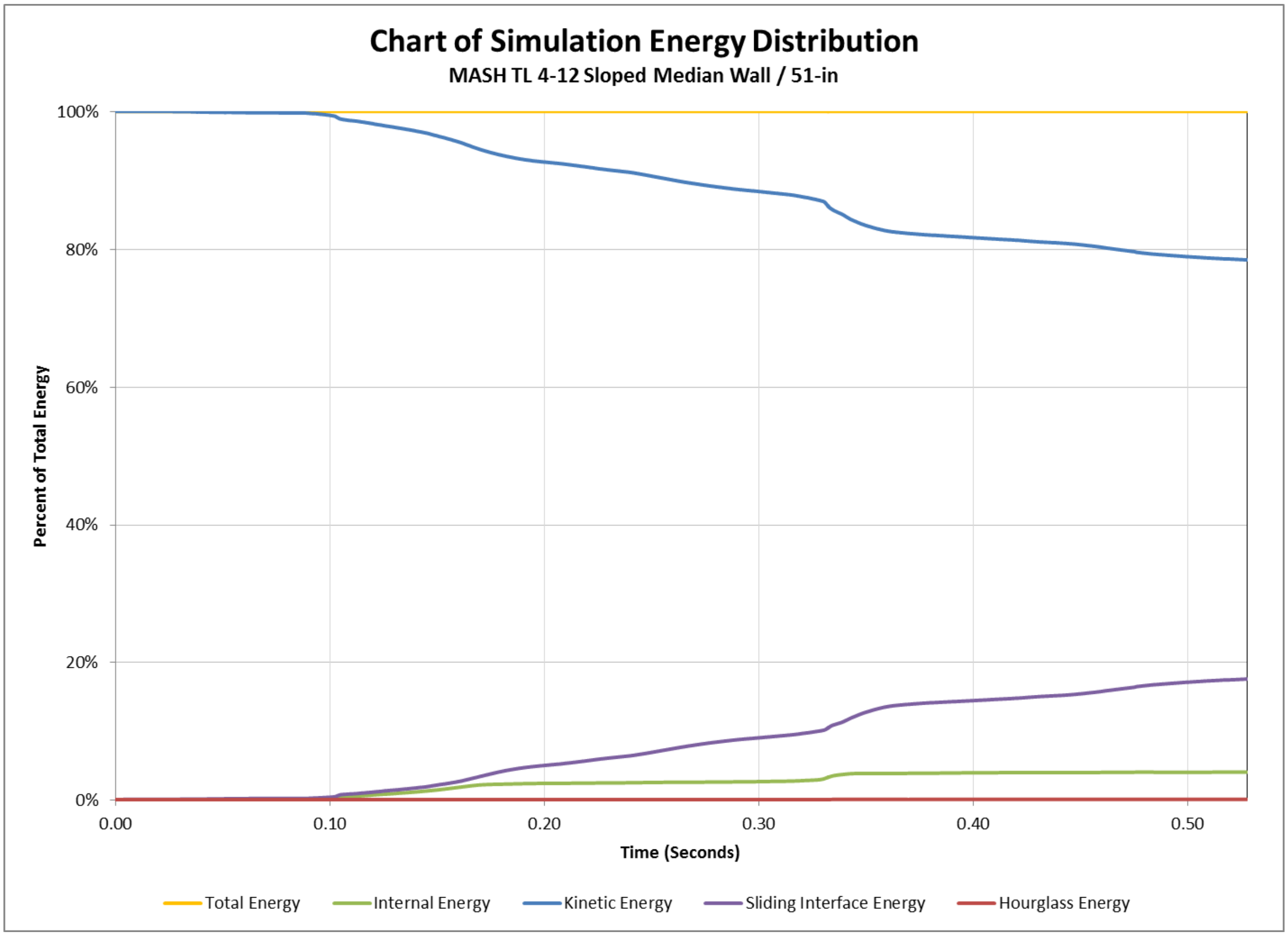
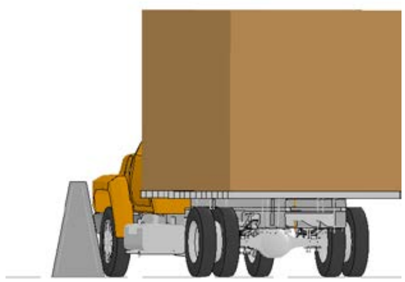
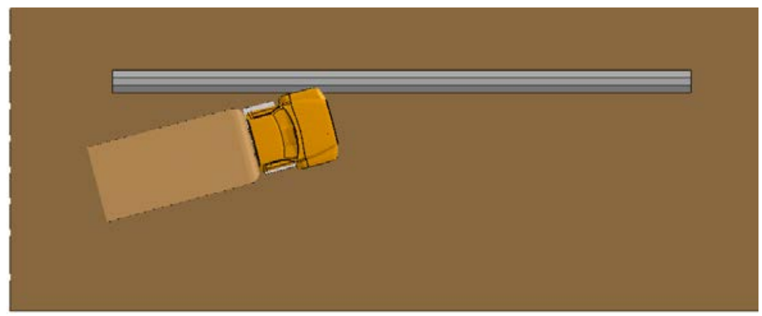
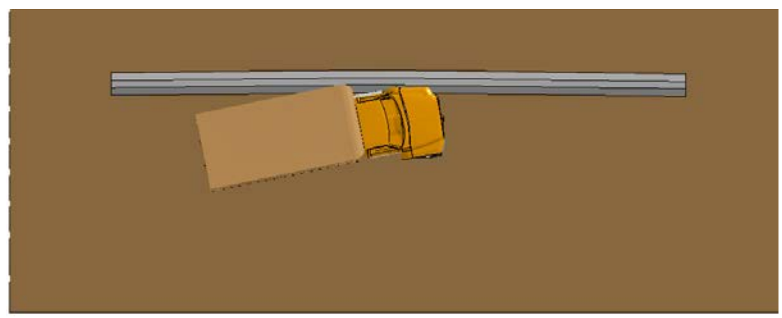
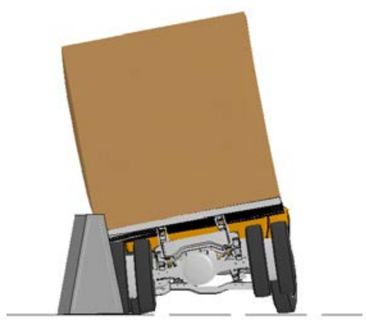
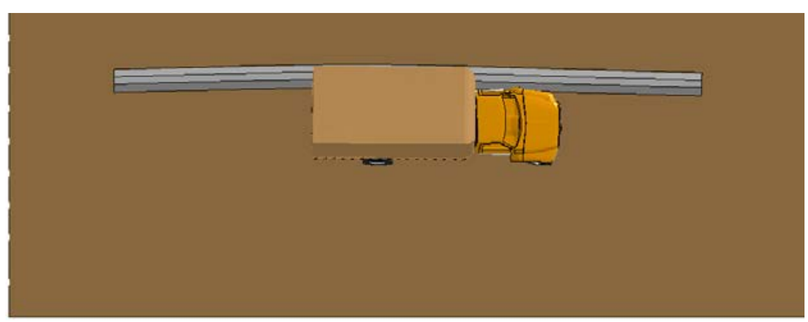
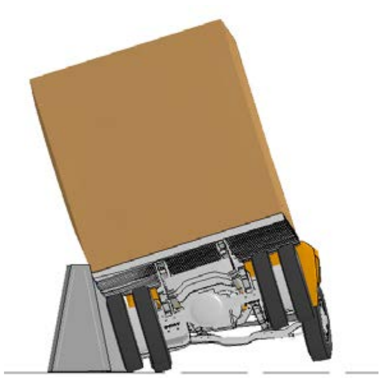
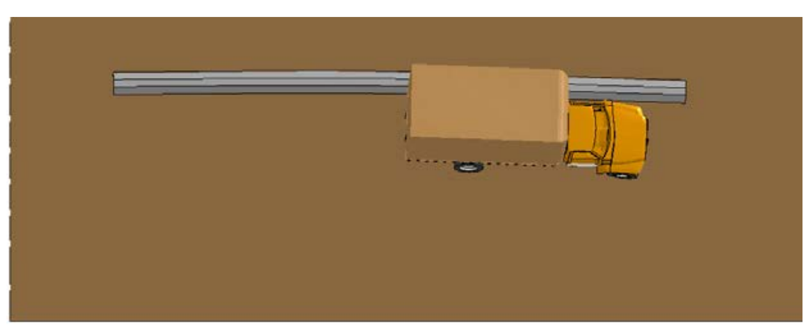


Figure 5.9. Energy Distribution Time History for *MASH* TL 4-12 Impact (Sloped Median Wall – 51-inch).

Table 5.3. Sequential Images of the 10000S Vehicle Interaction with the 51-inch Tall Sloped Median Wall Model for *MASH* TL 4-12 Impact (Perpendicular and Oblique Views).

Perpendicular View	Top View
	
	
	
	

5.2.2.3 Occupant Risk Assessment

The modeled 10000S vehicle remained upright during the modeled collision event. Figure 5.10 shows vehicle roll, pitch, and yaw angles throughout the impact event against the 51-inch high sloped median wall. Stability of the vehicle was evaluated using the TRAP program. Maximum roll, pitch, and yaw angles resulted in -8.9, 3.7, and 17.3 degrees, respectively. Previous test experience showed that occupant risk results are not a concern for impact of vehicle against single sloped concrete barrier, since they all remained in the range required by *MASH* criteria. As a consequence, occupant risk values were not evaluated for this finite element simulation.

5.2.2.4 Results

Figure 5.11 summarizes the results for *MASH* Test 4-12 simulation with a 10000S vehicle impacting a 51-inch high sloped median wall. Considering the dimensions of the simulated single sloped median wall and past TL-4 crash tests on a comparable reinforced concrete bridge rail, the simulated test article is considered structurally adequate to contain the impacting single unit truck (10000S) vehicle according to *MASH* Test Level 4-12 conditions.

FE simulation of the 10000S vehicle impacting the single sloped median wall at 56 mph and 15 degrees impact conditions was run until 0.525 seconds. The FE simulation did not show any vehicle roll initiation during the simulated time (maximum roll was calculated to be 17.3 degrees). During the simulation time, the free standing barrier slid (~ 1 ft sliding distance), but did not show any potential for tipping over. Although at 0.525 seconds, the barrier still had some residual sliding velocity due to impact event, the researchers do not consider the remaining velocity to be a concern for invasion of the barrier in the opposing lane or for initiation of barrier tipping. Also, the researchers decided to be conservative during their simulation evaluation, since the barrier was modeled as a 51-inch free standing single sloped wall, while in real life, the barrier is a 52.5-inch tall single sloped wall with 1.5 inches of asphalt. It is believed that the 1.5 inches of asphalt would help with the containment of the sliding barrier and with higher energy dispersion during the impact event. In addition, it is believed that in real life, the 52.5-inch median wall would represent a stiffer barrier than the modeled 51-inch barrier. For all these reasons, the researchers consider the 51-inch tall single sloped median wall adequate to maintain stability during impact with a 10000S vehicle at 56 mph and 15 degrees impact conditions. The 10000S vehicle is also considered to maintain stability during the *MASH* TL 4-12 impact conditions event.

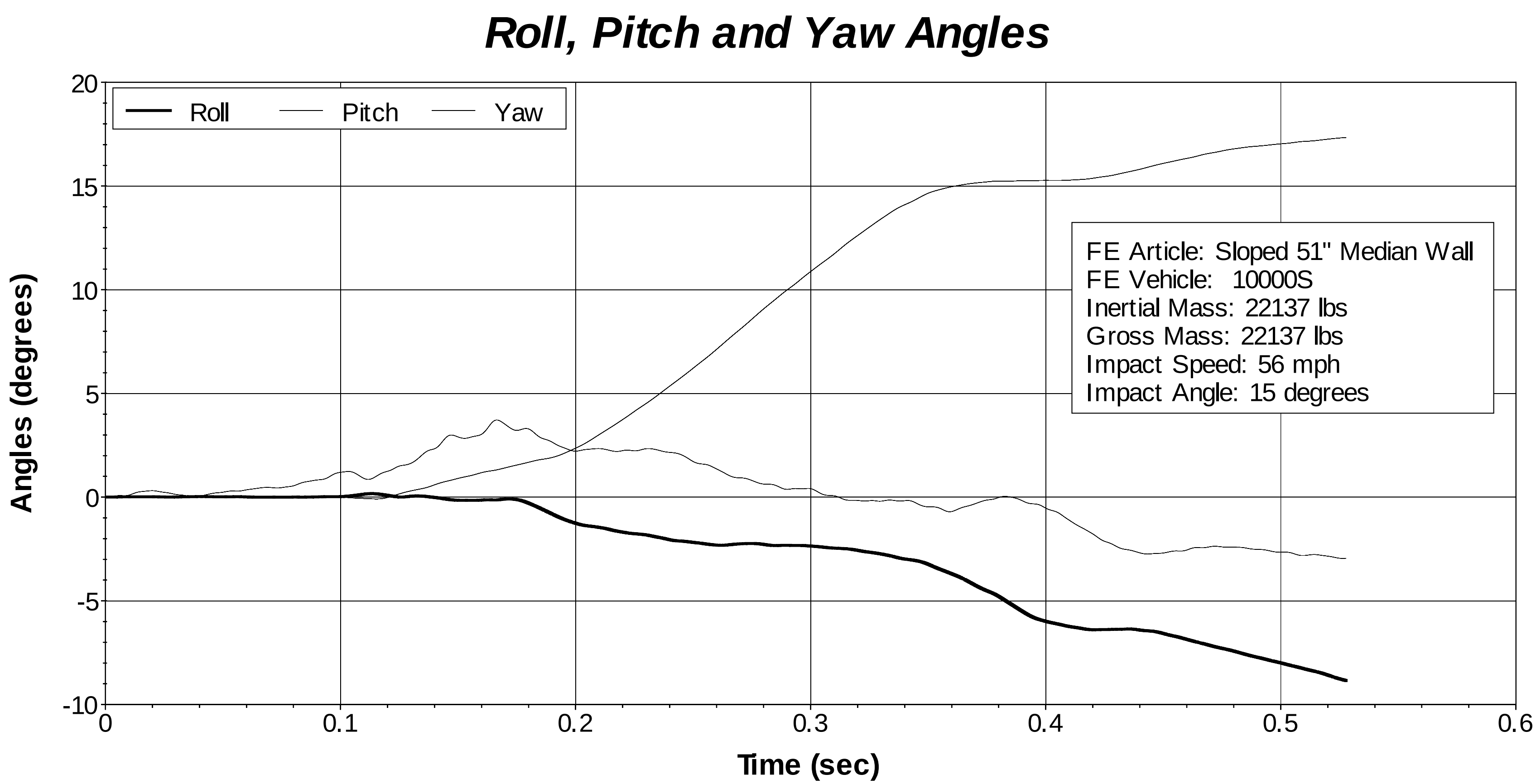
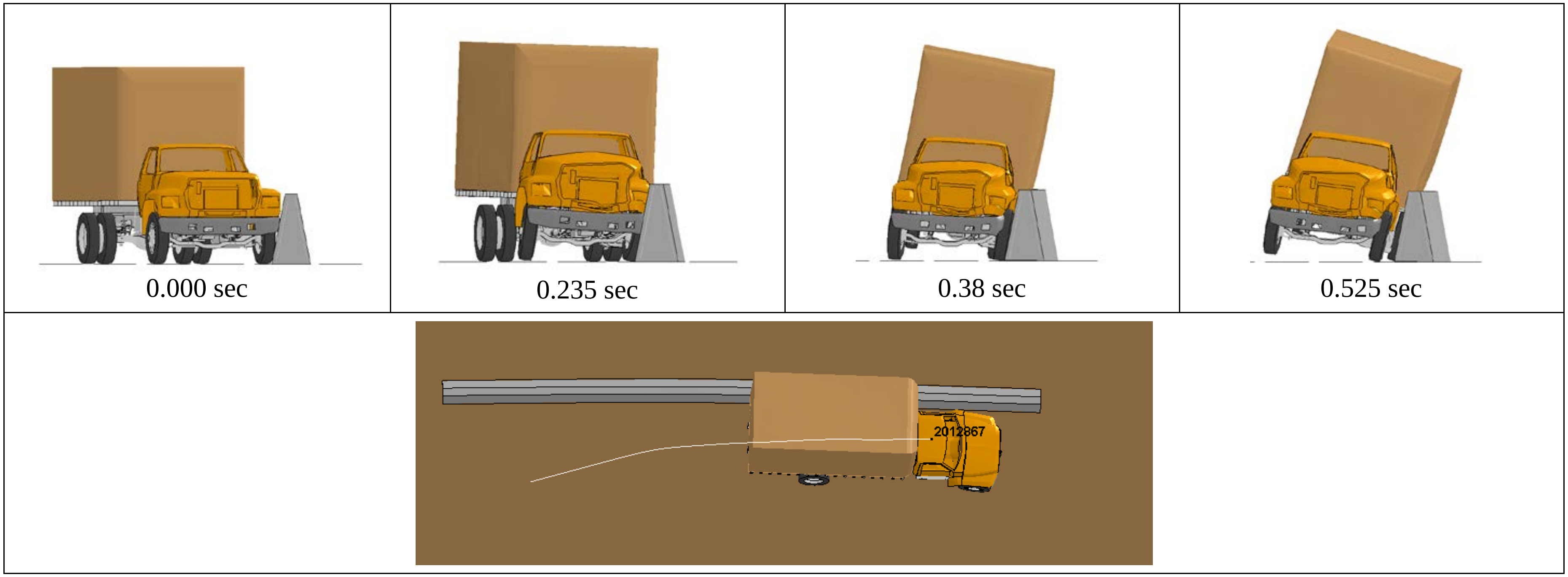


Figure 5.10. Roll, Pitch, and Yaw Angles for *MASH* TL 4-12 Impact (Sloped Median Wall – 51-inch).



General Information
Test Agency .... Texas A&M Transportation Institute (TTI)
Test Standard Test No. ... *MASH* Test 4-12
Date .... N/A

Test Article
Type................................ Median Barrier for Grade Separation
Name .... 51" Concrete Single Sloped Median Wall Segment
Installation Length .... 60 ft
Material or Key Elements Steel Reinforced Concrete Barrier, Free Standing Barrier

Test Vehicle
Type/Designation 10000S
Make and Model.............. Finite Element Single Unit Truck
Curb .... 22137 lb
Test Inertial .... 22137 lb
Dummy............................ No Dummy
Gross Static..................... 22137 lb

Impact Conditions
Speed.................................56 mi/h
Angle..................................15 degrees
Location/Orientation ....One Third of Barrier Length

Exit Conditions
Speed.................................49.7 mi/h
Angle..................................2.2 degrees

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

Vehicle Stability
Maximum Yaw Angle .... -8.9 degree
Maximum Pitch Angle .... 3.7 degree
Maximum Roll Angle................. 17.3 degree
Vehicle Snagging...................... No
Vehicle Pocketing..................... No

Test Article Deflections
Dynamic .... ~ 1 foot
Permanent................................ ~ 1 foot
Working Width .... N/A

Vehicle Damage
VDS.. N/A
CDC .... N/A
Max. Exterior Deformation .... N/A
OCDI .... N/A
Max. Occupant Compartment Deformation........................ N/A

Figure 5.11. Summary of Results for *MASH* Test 4-12 Simulation (Sloped Median Wall – 51-inch).

5.3 *MASH* TL-3 FINITE ELEMENT SIMULATIONS

5.3.1 *MASH* TL 3-11: 24-ft Single Sloped Median Wall Segment 112.5 inches Tall

This section contains results from a simulated *MASH* TL 3-11 impact into a 24-ft long, 112.5-inch tall sloped median wall segment. The researchers decided to use FE simulations to evaluate the 24-ft long, 112.5-inch tall free standing median wall structural capacity and the vehicle stability during the *MASH* TL 3-11 impact event.

5.3.1.1 Barrier Performance

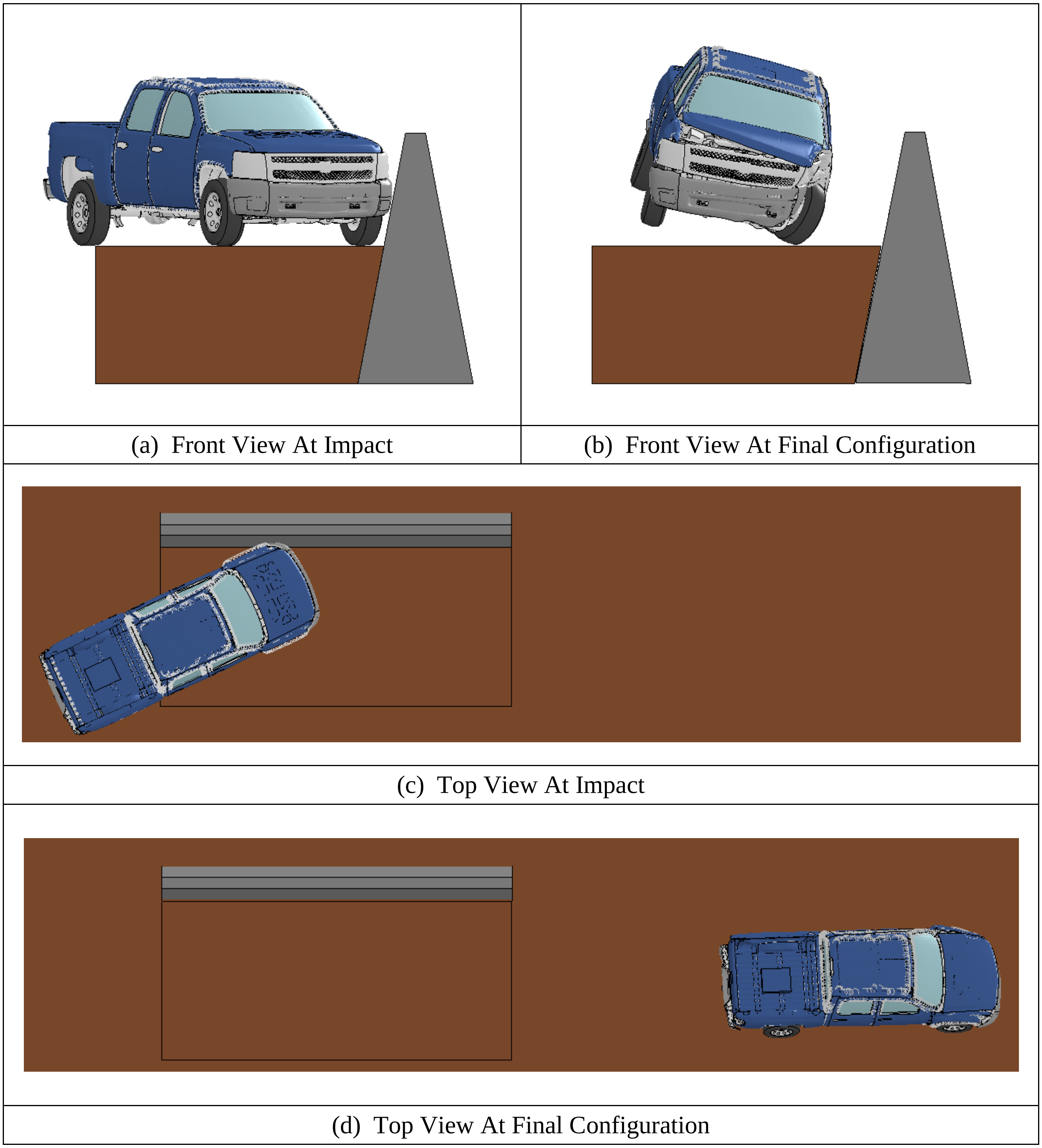
Figure 5.12 contains images of the barrier before impact and at final configuration. The barrier was impacted at the one-third point of the installation. After the impact event, the barrier displacement from the original position resulted to be less than 1 inch. Figure 5.12(a) and 5.12(c) show the front and overhead views of the barrier and impacting vehicle at initial configuration. Figure 5.12(b) and 5.12(d) show the front and overhead views of the barrier and impacting vehicle at final configuration.

5.3.1.2 Energy Values

As shown in Figure 5.13, approximately 13 percent of the initial kinetic energy of the impacting vehicle is converted into internal energy (damage or deformation of the vehicle and barrier components). Hourglass energy does not give any significant contribution. Approximately 18 percent of the initial kinetic energy is converted into sliding interface energy. Sixty eight percent of the initial kinetic energy has yet to be dissipated by the system at the time of final impact configuration, mainly due to the remaining velocity of the vehicle.

5.3.1.3 Plastic Strain

Plastic strain contours shown in Figure 5.14 are used to visualize possible barrier failure locations. Blue color represents regions with little to no plastic strain. Red color represents regions with plastic strains equal to or greater than 15 percent. Plastic strains greater than 15 percent for steel material indicate regions where local steel failure is likely to occur.



(a) Front View At Impact

(b) Front View At Final Configuration

(c) Top View At Impact

(d) Top View At Final Configuration

Figure 5.12. Initial and Deflected Shape of Barrier for *MASH* TL 3-11 Impact (Sloped Median Wall – 112.5-inch).

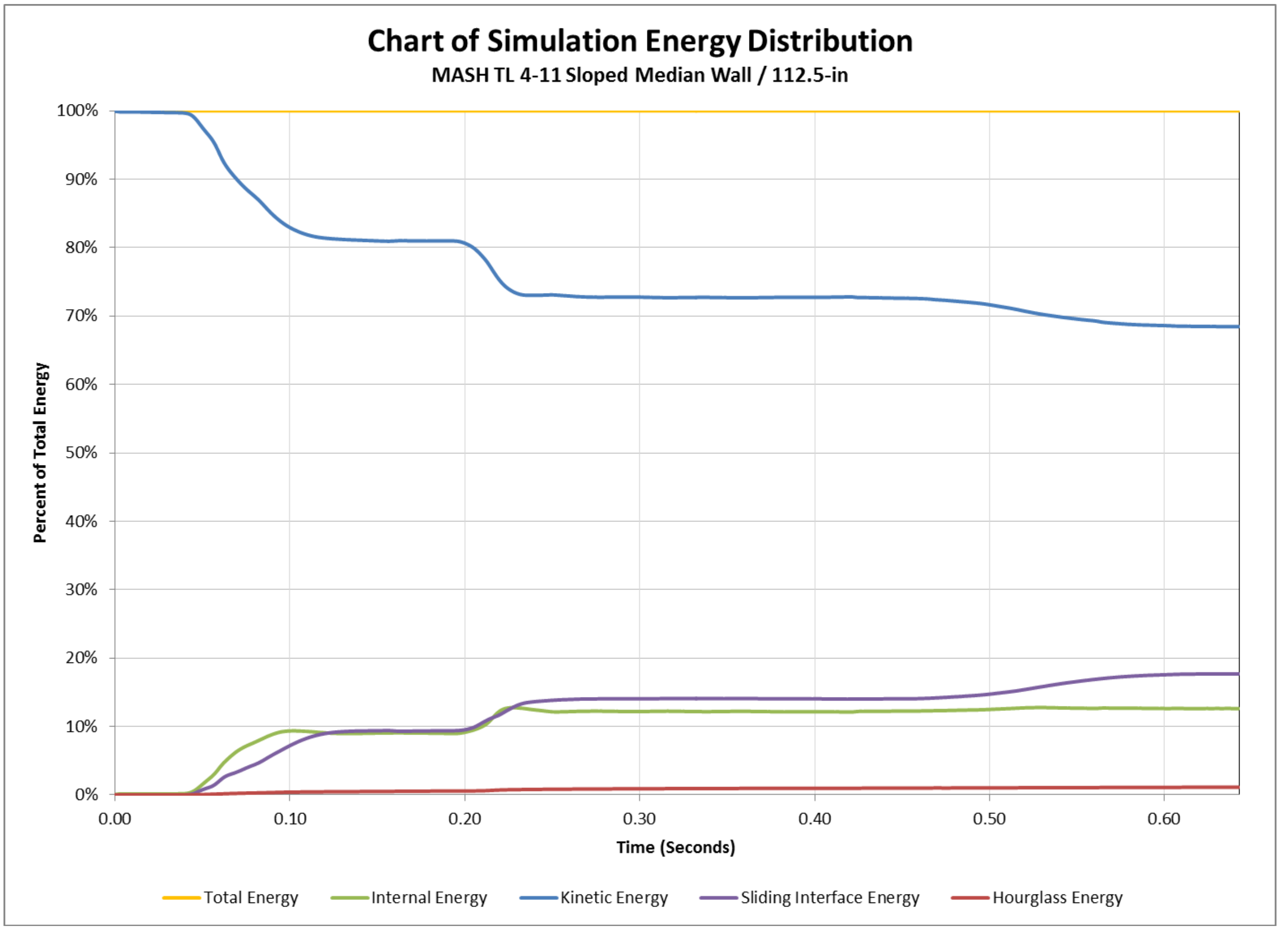


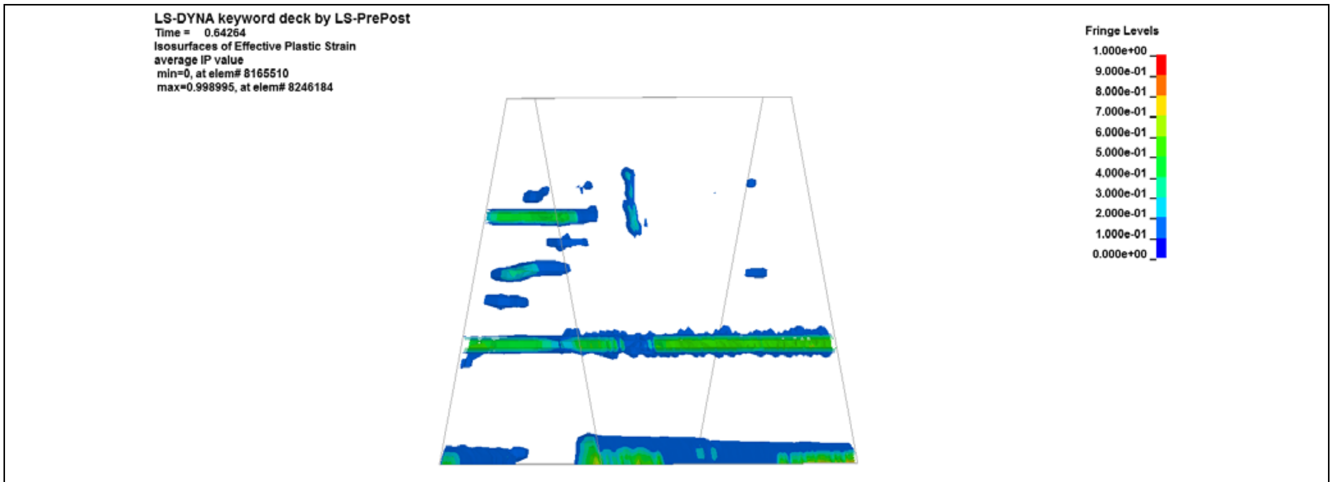
Figure 5.13. Energy Distribution Time History for *MASH* TL 3-11 Impact (Sloped Median Wall – 112.5-inch).

5.3.1.4 Concrete Barrier Stresses

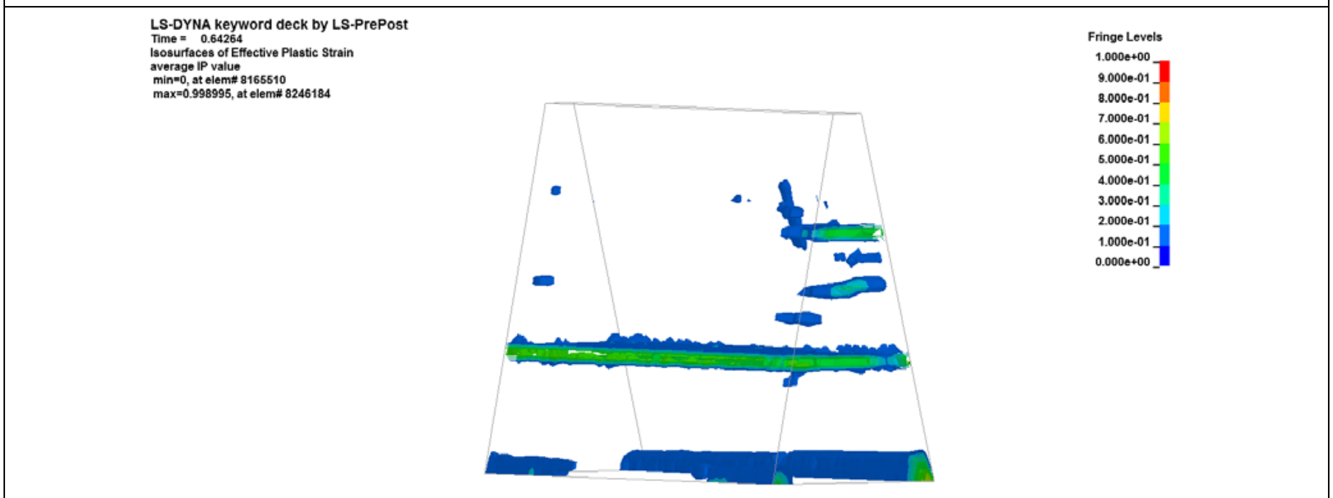
Figure 5.14 shows the plastic strains in (a) the front and (b) the back side of the barrier. There appear to be no high plastic strain region in the barrier as a result of the vehicle impact. It is unlikely that failure of the concrete barrier will occur.

Figure 5.14(c) shows the plastic strains in the rebar structure of the barrier. Blue regions represent regions with little to no plastic strain. Red regions represent regions with plastic strains equal to or greater than 15 percent. As shown in Figure 5.14(c), there are no high plastic strain regions in the rebar cage.

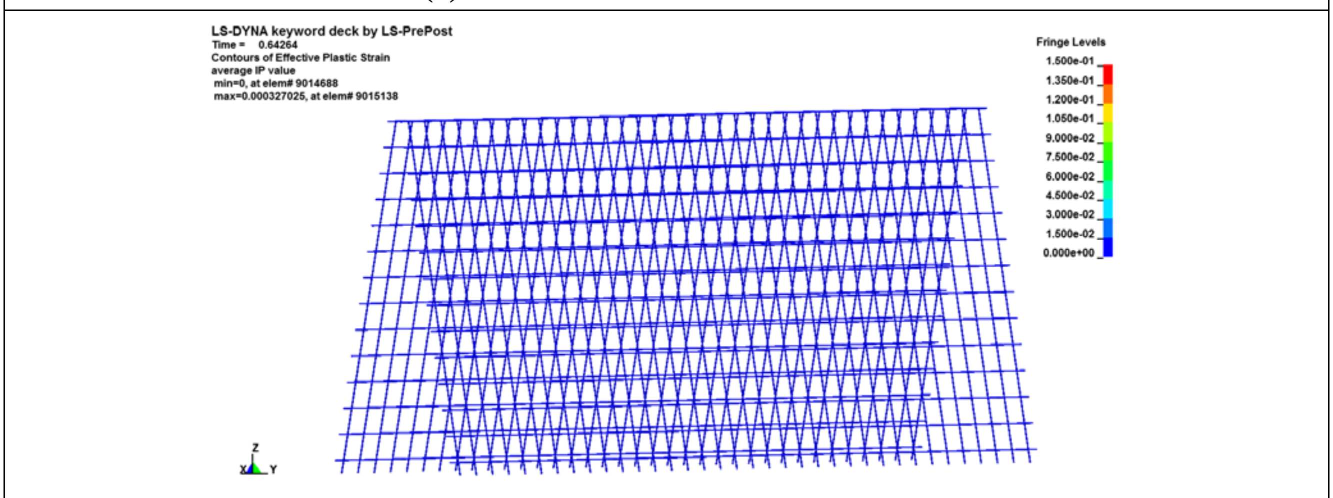
Tables 5.4 and 5.5 show frames from FE simulation of *MASH* TL 3-11 impact against the modeled 112.5-inch tall sloped median wall.



(a) Front Side of the Concrete Barrier



(b) Back Side of the Concrete Barrier



(c) Barrier Steel Reinforcement

Figure 5.14. Concrete Stresses for *MASH* TL 3-11 Impact (Sloped Median Wall – 51-inch).

Table 5.4. Sequential Images of the 2270P Vehicle Interaction with the 112.5-inch Tall Sloped Median Wall Model for *MASH* TL 3-11 Impact (Perpendicular and Oblique Views).

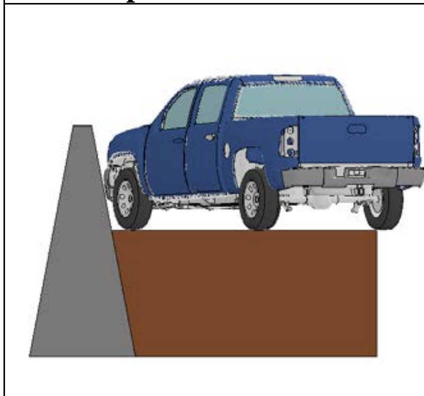
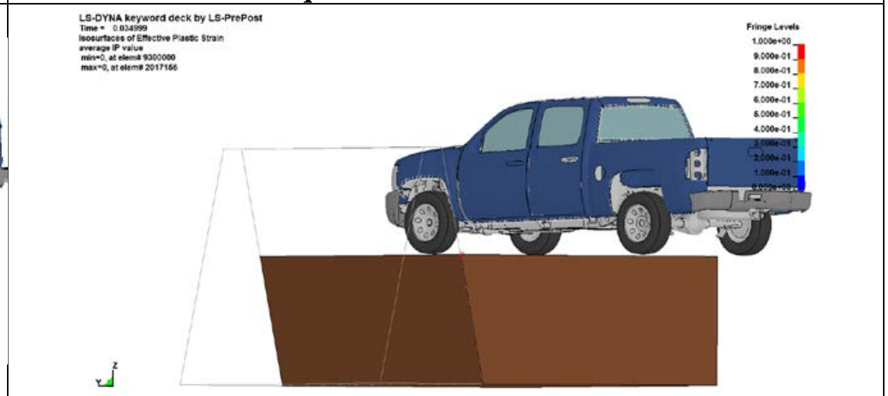
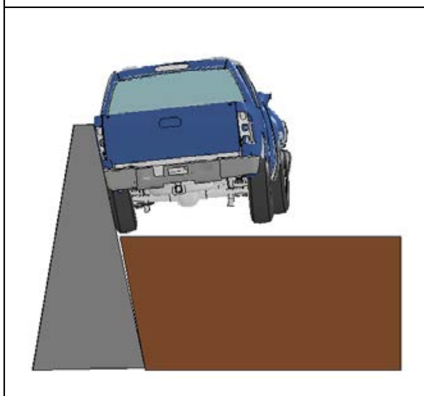
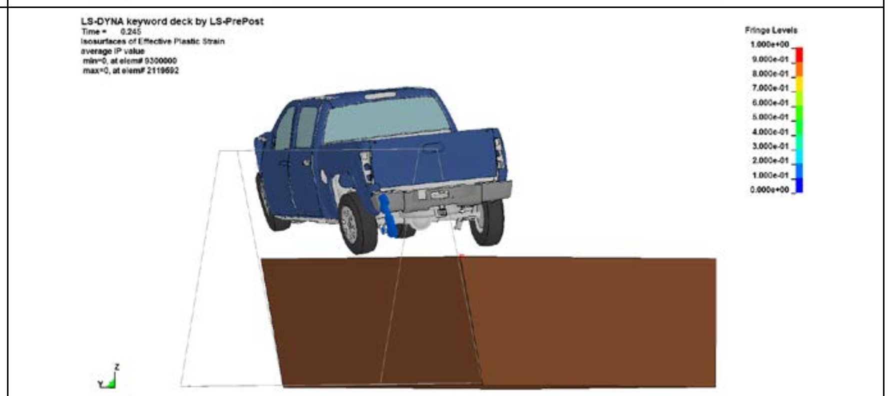
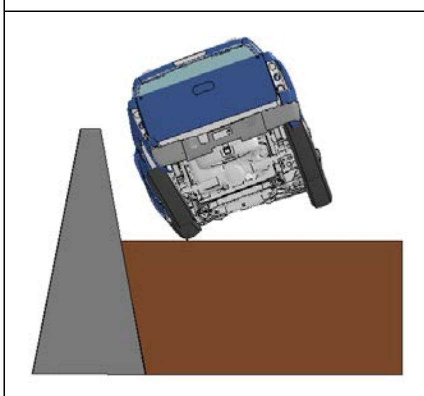
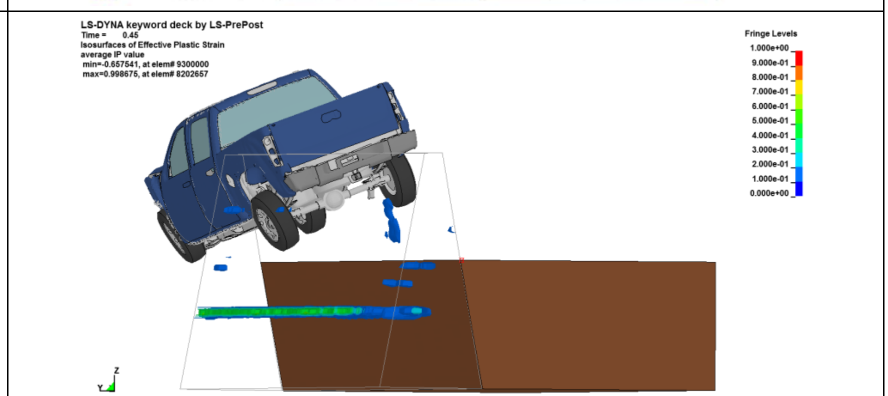
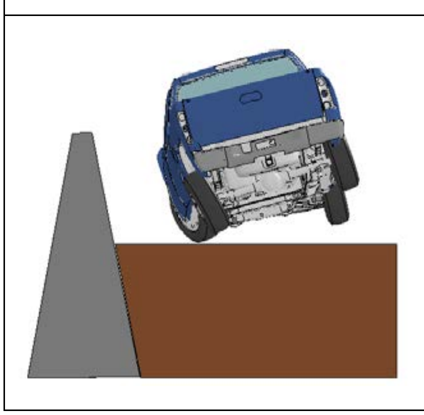
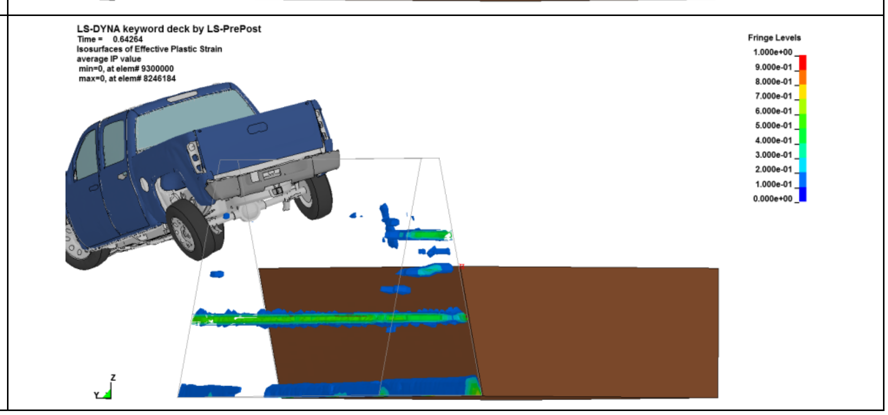
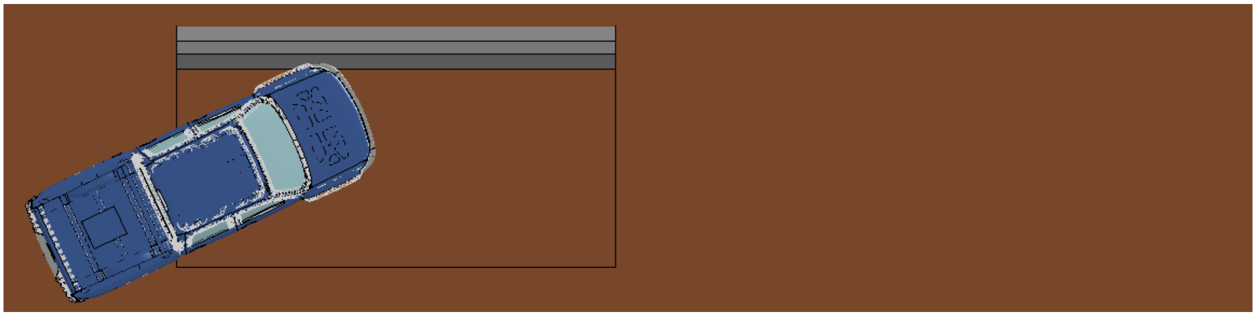
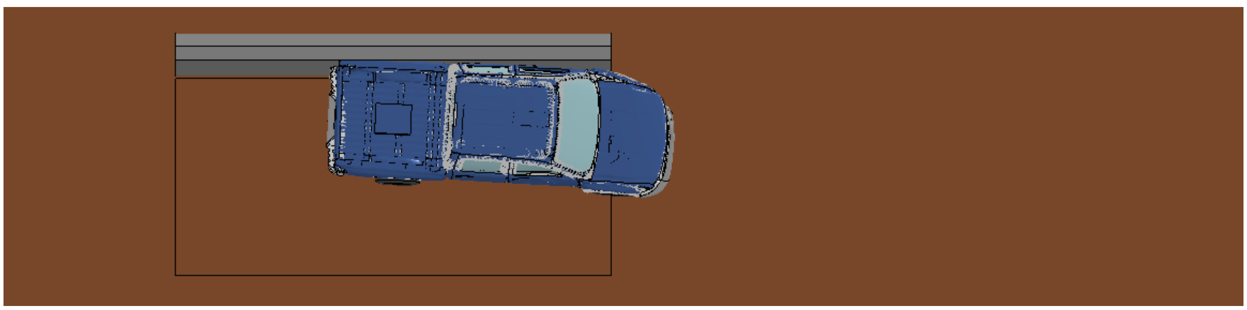
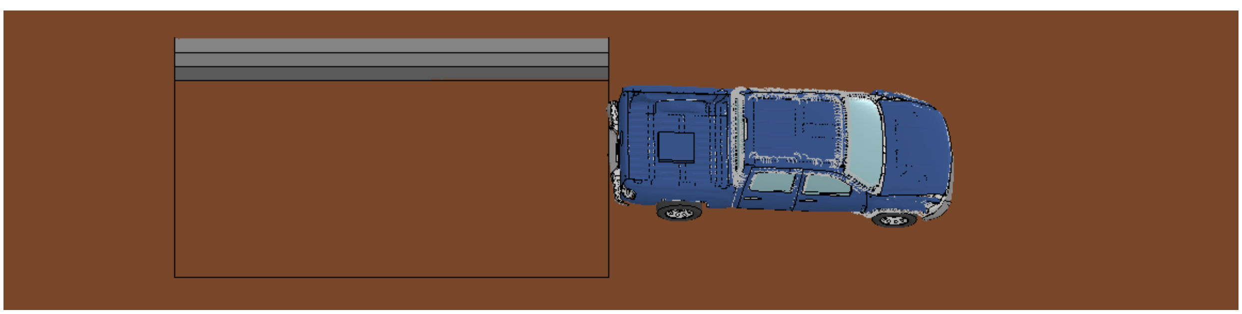
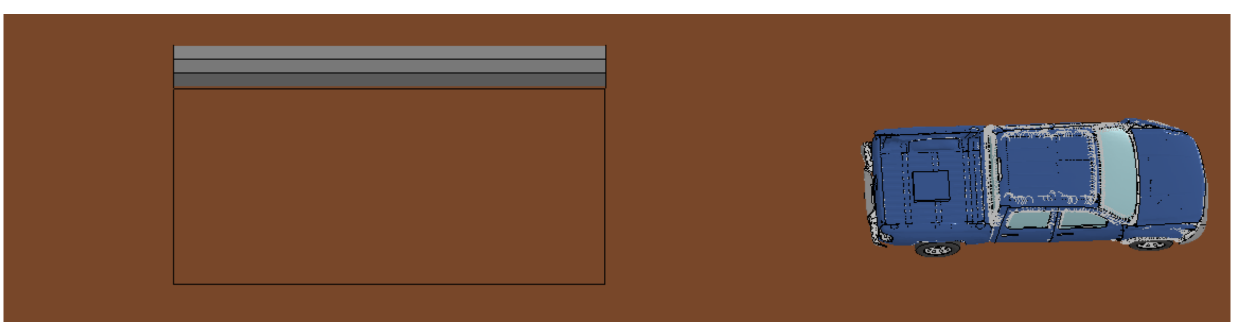
Perpendicular View	Oblique View - Barrier Strains
	
	
	
	

Table 5.5. Sequential Images of the 2270P Vehicle Interaction with the 112.5-inch Tall Sloped Median Wall Model for *MASH* TL 3-11 Impact (Top View).

Top View





5.3.1.5 Occupant Risk Assessment

The modeled 2270P vehicle remained upright during and after the modeled collision event. Figure 5.15 shows vehicle roll, pitch, and yaw angles throughout the impact event against the 51-inch high sloped median wall. Maximum roll, pitch, and yaw angles resulted in -23.9, -9.0, and 28.5 degrees, respectively. Previous test experience showed that occupant risk results are not a concern for impact of vehicle against single sloped concrete barrier, since they all remained in the range required by *MASH* criteria. As consequence, occupant risk values were not evaluated for this finite element simulation.

5.3.1.6 Results

Figure 5.16 summarizes results for *MASH* Test 3-11 simulation with a 2270P vehicle impacting a 112.5-inch high sloped median wall. Results showed that the 112.5-inch tall single sloped median wall performed adequately by containing and redirecting the impacting 2270P vehicle. The free standing barrier slid less than an inch from its initial position during the impact event. However, the barrier did not show any potential for tipping over and allowing the impacting vehicle for intrusion in the opposing lane. Also, simulations indicate the 2270P vehicle maintaining stability during the *MASH* TL 3-11 impact conditions event.

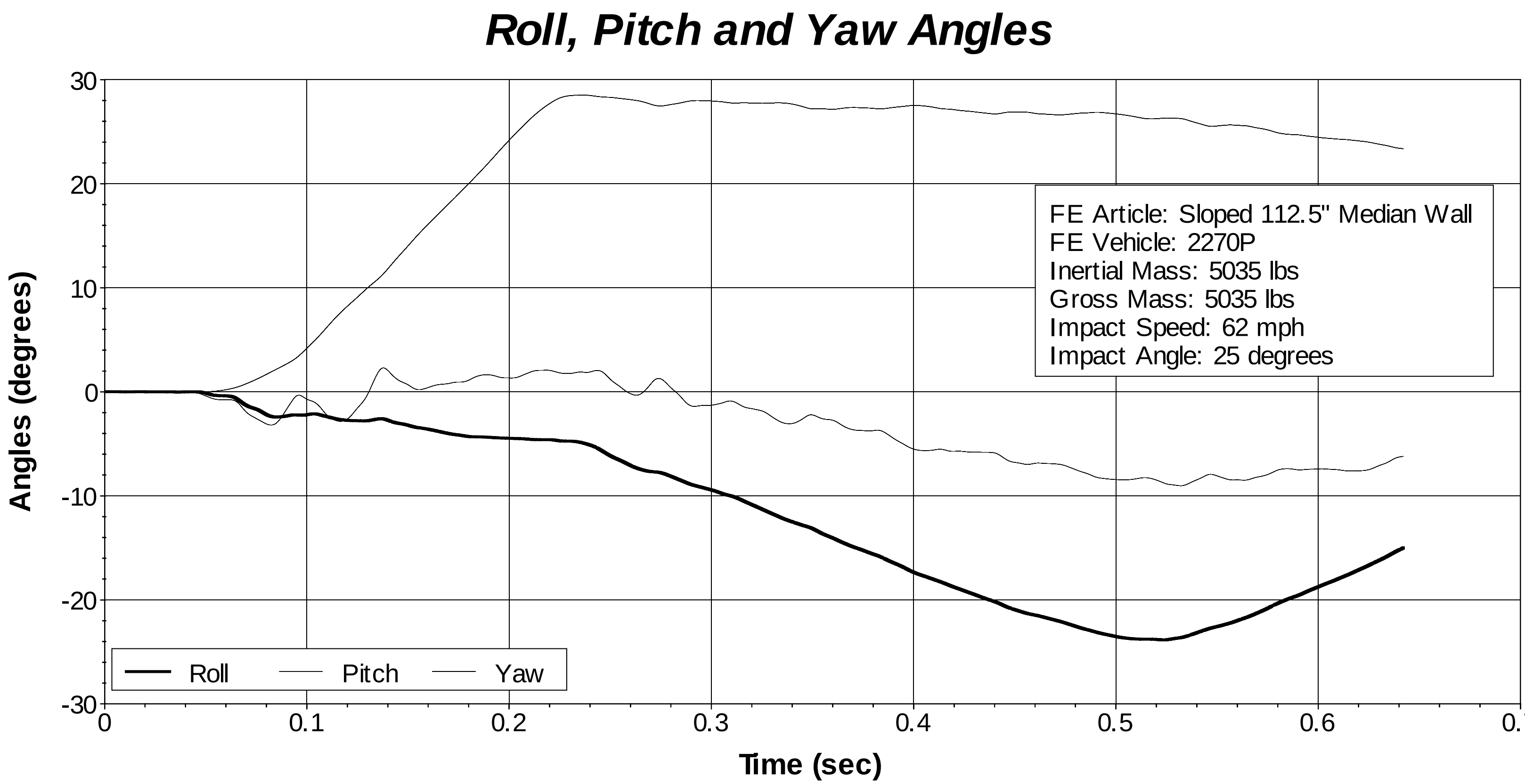
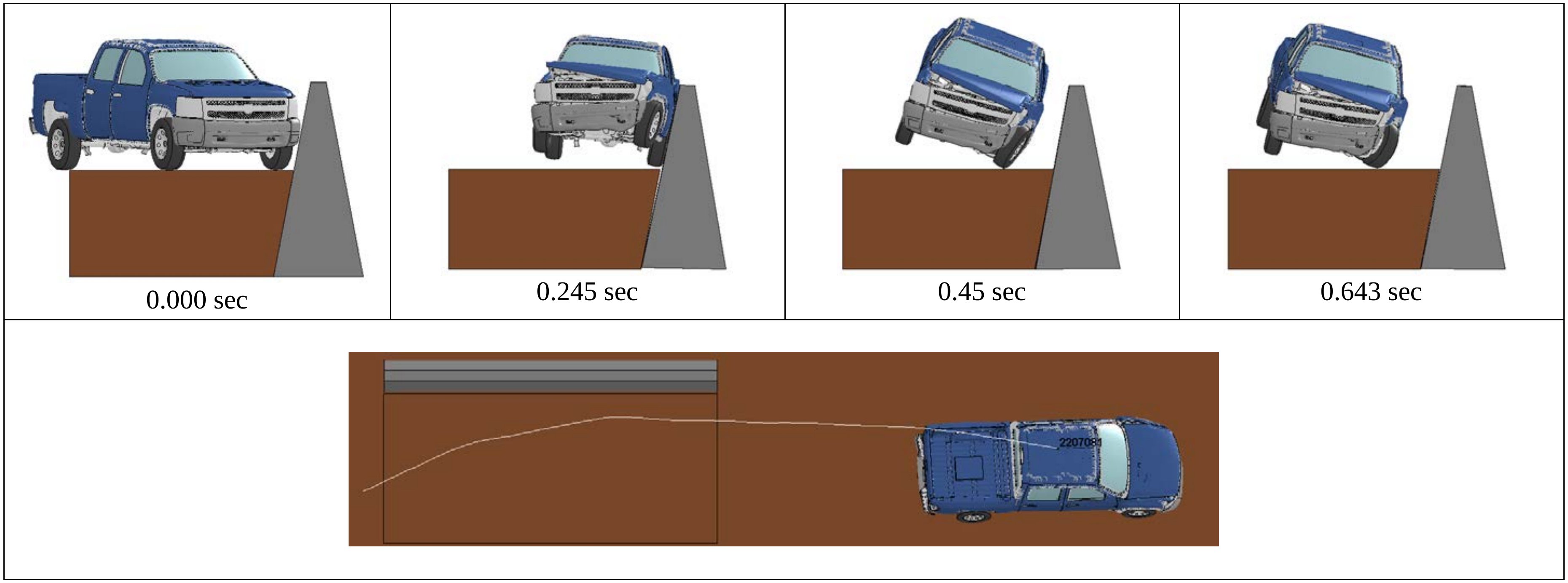


Figure 5.15. Roll, Pitch, and Yaw Angles for *MASH* TL 3-11 Impact (Sloped Median Wall – 112.5-inch).



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

Test Article
- Type................................ Median Barrier for Grade Separation
- Name .... 112.5" Concrete Single Sloped Median Wall Segment
- Installation Length .... 24 ft
- Material or Key Elements Steel Reinforced Concrete Barrier, Free Standing Barrier

Test Vehicle
- Type/Designation 2270P
- Make and Model.............. Finite Element Pickup Truck
- Curb .... 5035 lb
- Test Inertial .... 5035 lb
- Dummy............................ No Dummy
- Gross Static..................... 5035 lb

Impact Conditions
- Speed.................................62 mi/h
- Angle..................................25 degrees
- Location/Orientation ....One Third of Barrier Length

Exit Conditions
- Speed.................................50.78 mi/h
- Angle..................................1.9 degrees

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

Vehicle Stability
- Maximum Yaw Angle................ 28.5 degree
- Maximum Pitch Angle.............. -9.0 degree
- Maximum Roll Angle................ -23.9 degree
- Vehicle Snagging...................... No
- Vehicle Pocketing..................... No

Test Article Deflections
- Dynamic .... < 1 inch
- Permanent................................ < 1 inch
- Working Width .... N/A

Vehicle Damage
- VDS.. N/A
- CDC .... N/A
- Max. Exterior Deformation .... N/A
- OCDI .... N/A
- Max. Occupant Compartment Deformation........................ N/A

Figure 5.16. Summary of Results for *MASH* Test 3-11 Simulation (Sloped Median Wall – 112.5-inch).

6. SUMMARY AND CONCLUSIONS

6.1 SUMMARY

This research was aimed at exploring design options of median barriers for use as grade separation on split level highways to provide design and construction flexibility as shoulder elevations vary along the roadway. The median barrier should also perform as a retaining wall. Strength and stability of the barrier were investigated to evaluate the structural ability to provide adequate stability with respect to sliding, overturning, and bearing capacity. Crashworthiness of the barrier design(s) chosen were investigated through finite element modeling analyses at TL-3 and TL 4.

An initial barrier design, proposed by Tennessee Department of Transportation (TDOT), considered the use of two independent half-size single slope barrier walls backing up to each other. After literature review and investigations of tests conducted at Texas Transportation Institute involving impact of sloped concrete barriers and vertical walls (mechanically stabilized earth, MSE), the researchers proposed a slightly different design of median barrier for grade separation. The new design consisted in removing the small barrier (51-inch barrier) and maintaining only the tall barrier (112.5-inch barrier). Barrier stability, strength analysis, and crashworthiness of the median vertical wall design were evaluated.

Because of the possibility for the median vertical wall proposed design to be considered a hazard for head contact during a vehicle-barrier collision, the researchers and TDOT worked together to propose an alternative median barrier design option which should resolve the head slap concern. The median vertical wall was modified into a single slope median barrier of a total maximum height of 112.5 inches, a soil backfill height of a maximum of 60 inches acting on one side, and 4H:21V slope on both sides of the barrier. Stability and yield line analyses for the sloped barrier design were evaluated. The crashworthiness and stability of the vertical median wall and sloped median wall were evaluated using finite element analyses. These analyses resulted in acceptable barrier performance according to the criteria set forth in *MASH* for longitudinal barriers, and soil retention according to AASHTO 2007.

In a second phase of the project, researchers optimized the minimum barrier segment length needed to resist soil forces and *MASH* TL-3 and 4 impact conditions. The barrier was evaluated according to the LRFD method.

6.2 CONCLUSIONS

The minimum segment length for the 112.5-inch sloped median wall to sustain soil forces and *MASH* TL-4 impact conditions resulted to be 33 ft. The researchers modeled a 35-ft barrier segment for evaluation with computer finite element simulations. The 112.5-inch tall single sloped median wall performed adequately by containing and redirecting the impacting 10000S vehicle. The barrier did not show any potential for tipping over and allowing the impacting vehicle for intrusion in the opposing lane. The 10000S vehicle maintained stability during the *MASH* TL 4-12 impact condition event.

The minimum segment length for the 51-inch sloped median wall to sustain *MASH* TL-4 impact conditions resulted to be 60 ft. The researchers modeled a 60-ft barrier segment for evaluation with computer finite element simulations. The simulated test article is considered structurally adequate to contain the impacting single unit truck (10000S) vehicle according to *MASH* Test Level 4-12 conditions. The FE simulation did not show any vehicle roll initiation during the simulated time (maximum roll was calculated to be 17.3 degrees). During the simulation time, the free standing barrier did not show any potential for tipping over. The 51-inch tall single sloped median wall was judged to adequately maintain stability during impact with a 10000S vehicle. The 10000S vehicle is also considered to maintain stability during the *MASH* TL 4-12 impact condition event.

The minimum segment length for the 112.5-inch sloped median wall to sustain soil forces and *MASH* TL-3 impact conditions resulted to be 24 ft. The researchers modeled a 24-ft barrier segment for evaluation with computer finite element simulations. Results showed that the 112.5-inch tall single sloped median wall performed adequately by containing and redirecting the impacting 2270P vehicle. The free standing barrier slid less than an inch from its initial position during the impact event. However, the barrier did not show any potential for tipping over and allowing the impacting vehicle for intrusion in the opposing lane. Also, simulations indicate the 2270P vehicle maintaining stability during the *MASH* TL 3-11 impact condition event.

The minimum segment length for the 51-inch sloped median wall to sustain *MASH* TL-3 impact condition resulted to be 45 ft. Computer simulations were not run for this particular case. However, based on engineering conservative analysis, the researchers believe that a 45-ft segment of the 51-inch version of the median wall would have the stability and structural capacity to sustain *MASH* TL-3 impact conditions.

This project was not aimed for evaluation of the median wall segments lengths behavior when impacted at locations of discontinuity (i.e., at joint connections between segments).

7. REFERENCES

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