Development of MASH Computer Simulated Steel Bridge Rail and Transition Details

Task 6: Transition for 4-Bar BR MASH TL4

Project # : NETC 18-1
Federal Project No. : 2343018

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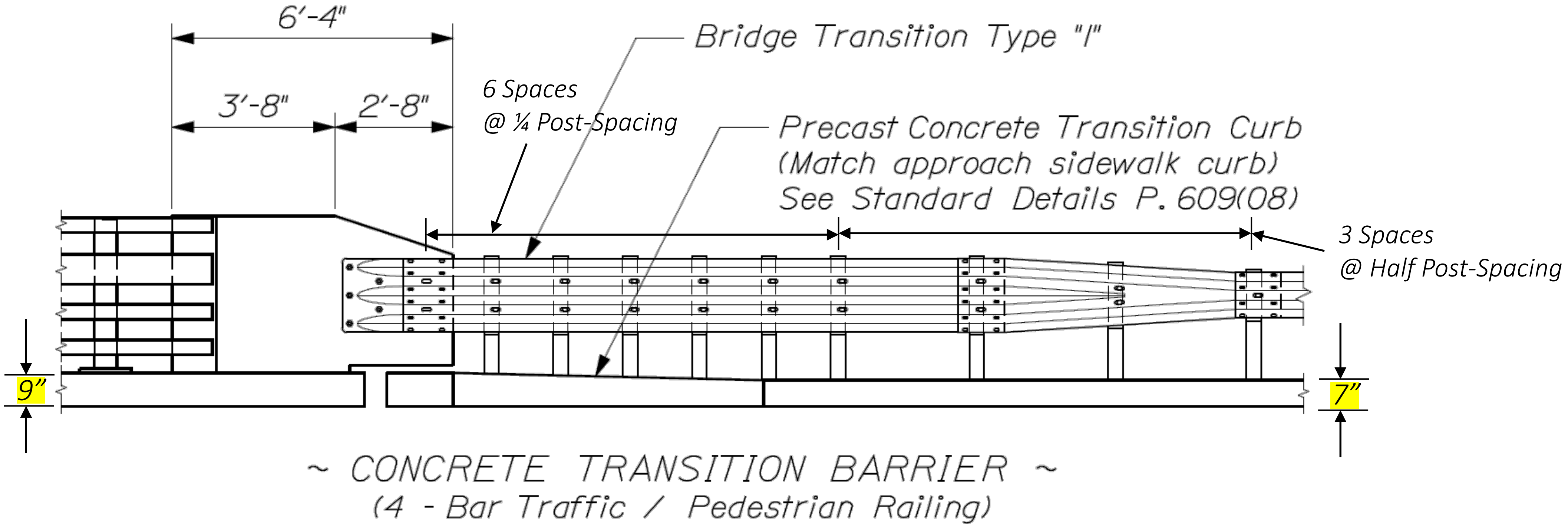
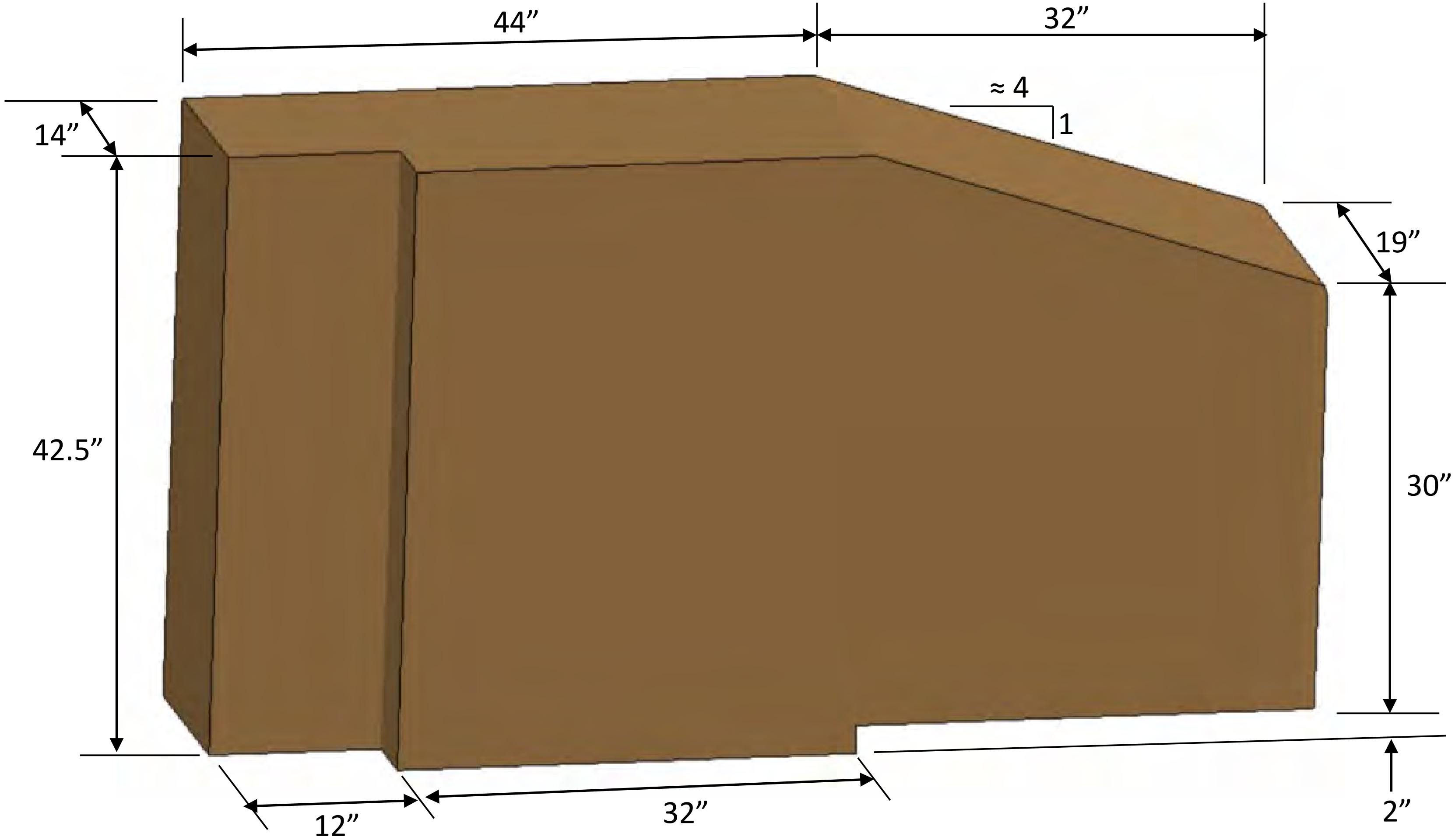


Task 6: Evaluation of Transition for 4-Bar Bridge Rail

Concrete Buttress



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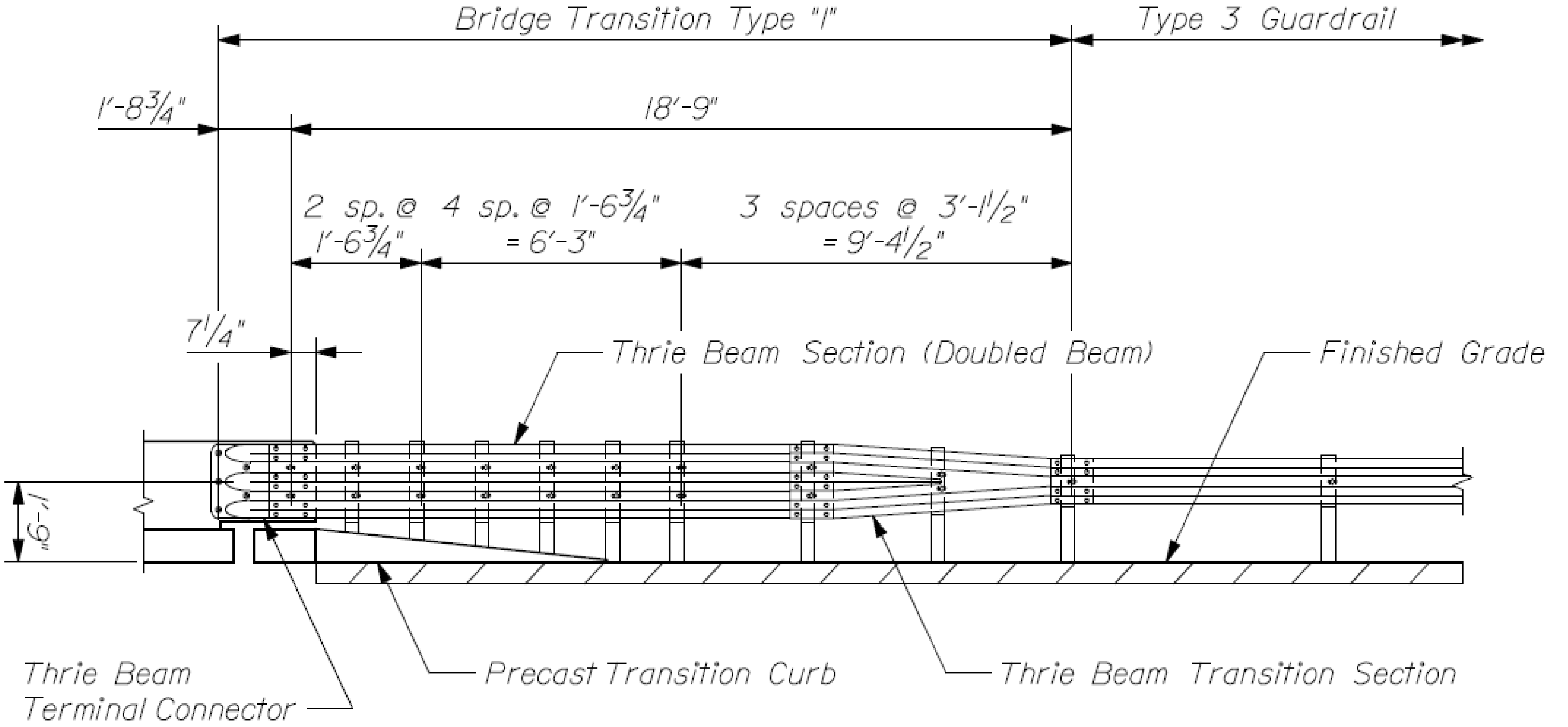

Bridge Transition Type I

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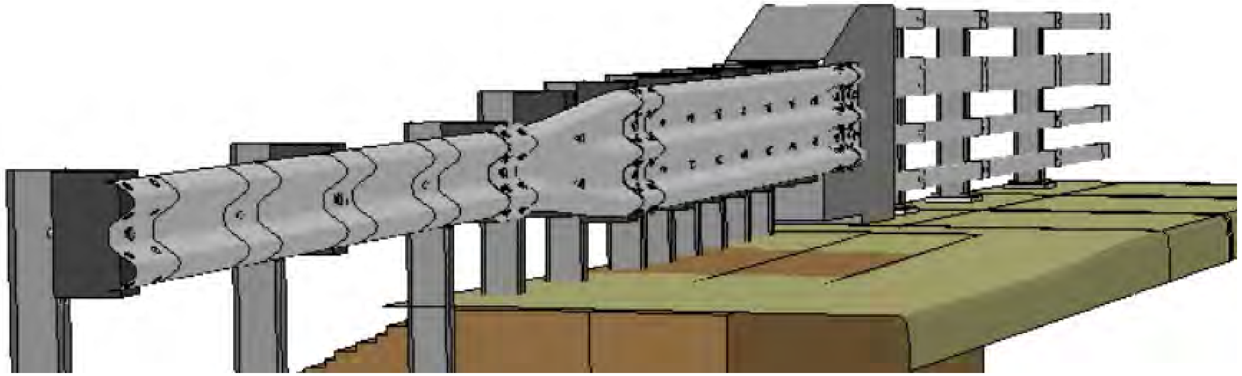
MEDOT Transition

The transition system for the 4-Bar bridge rail was modeled based on the detailed drawing from MEDOT



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MEDOT Transition

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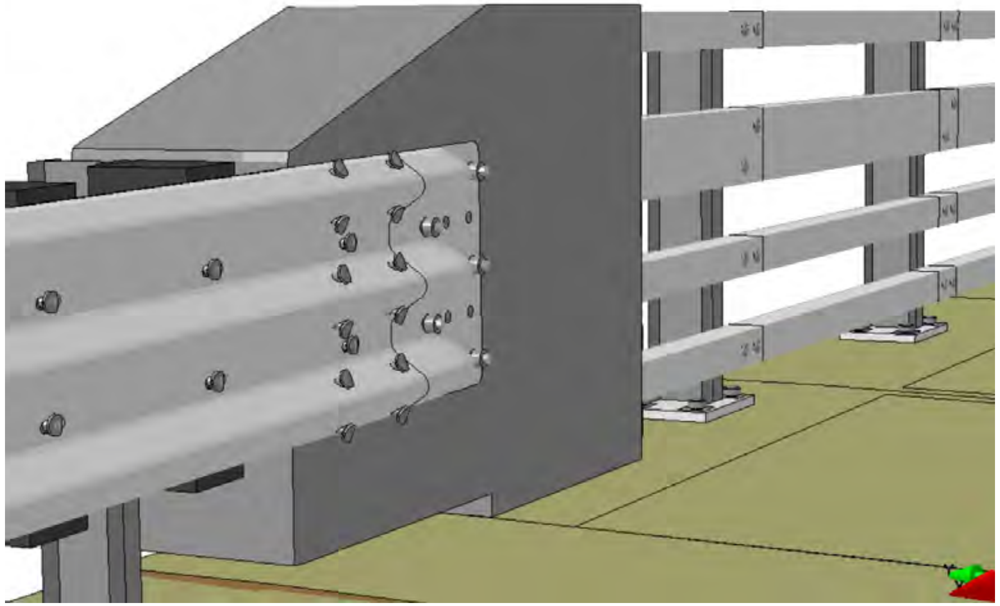

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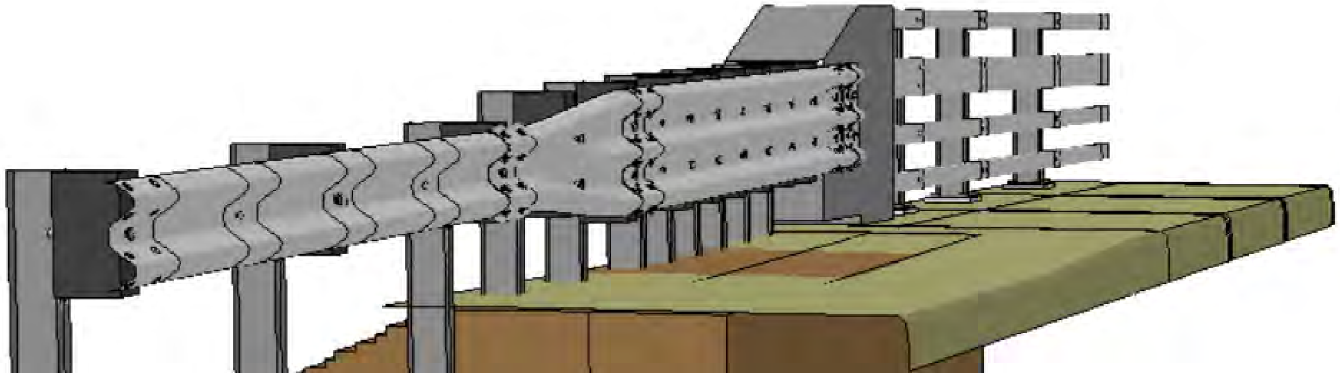
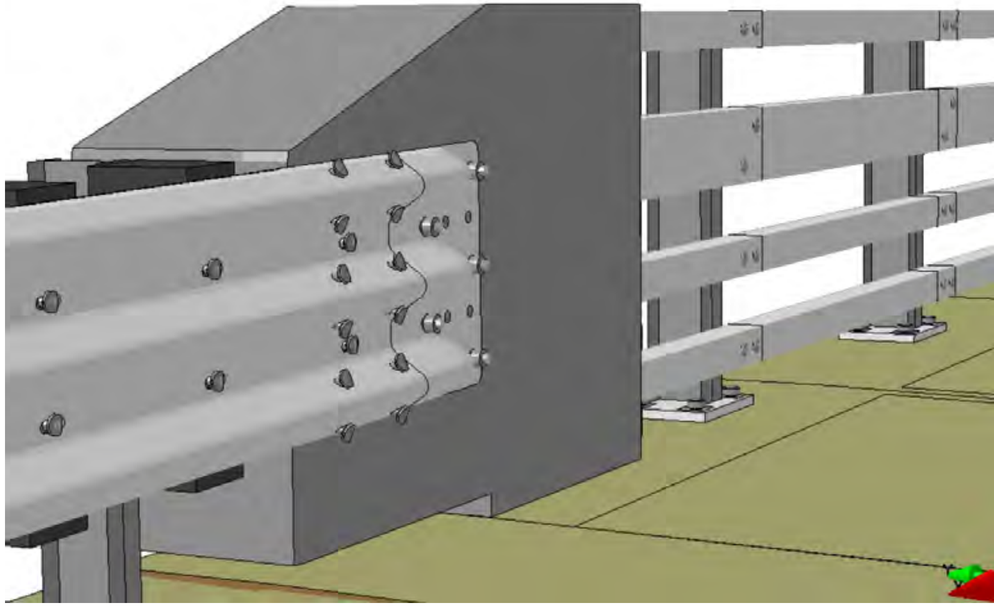
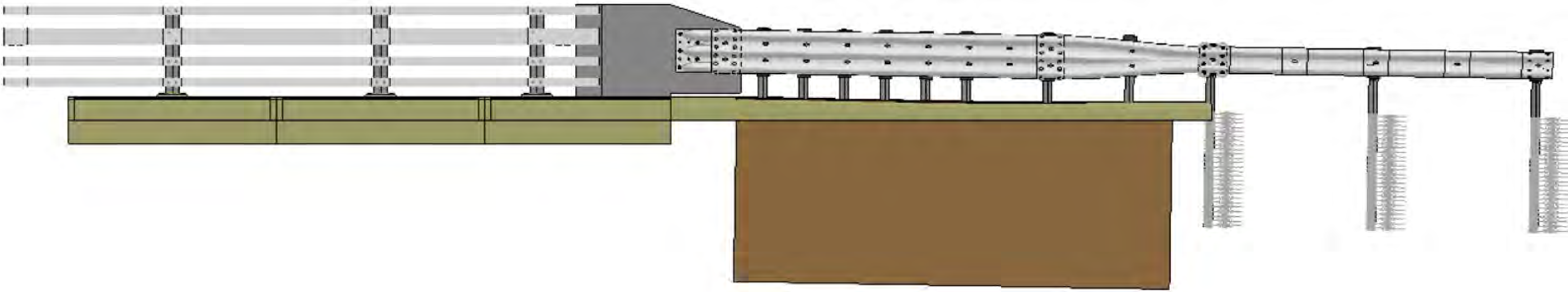
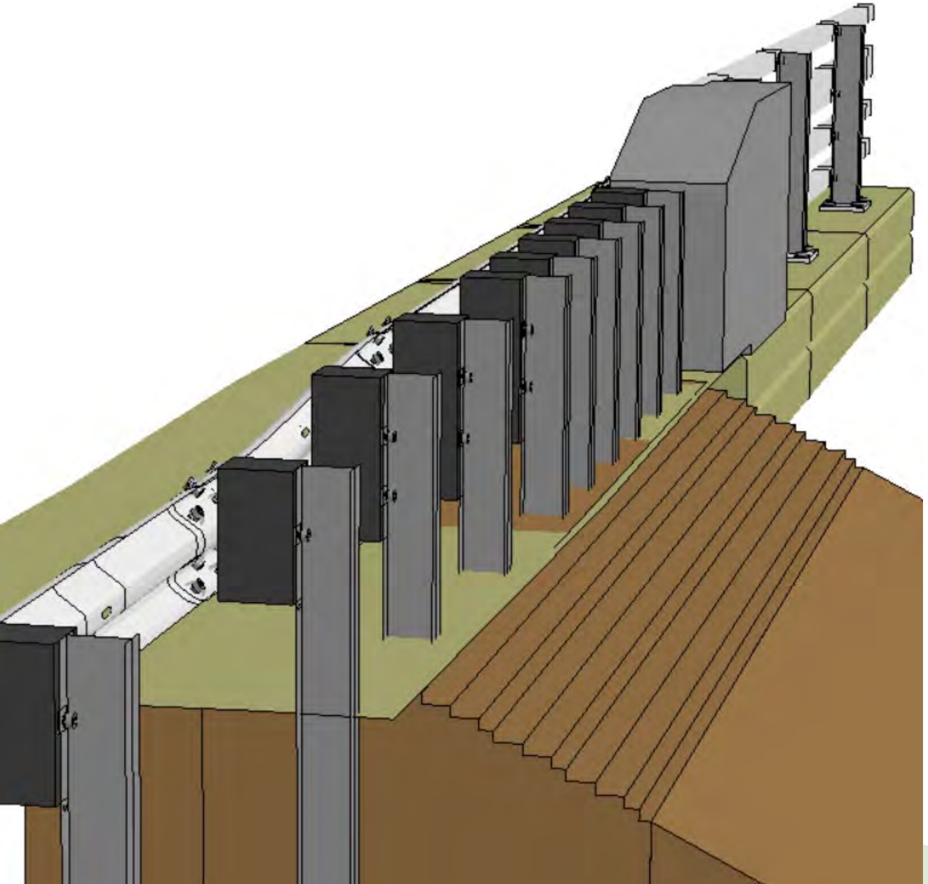






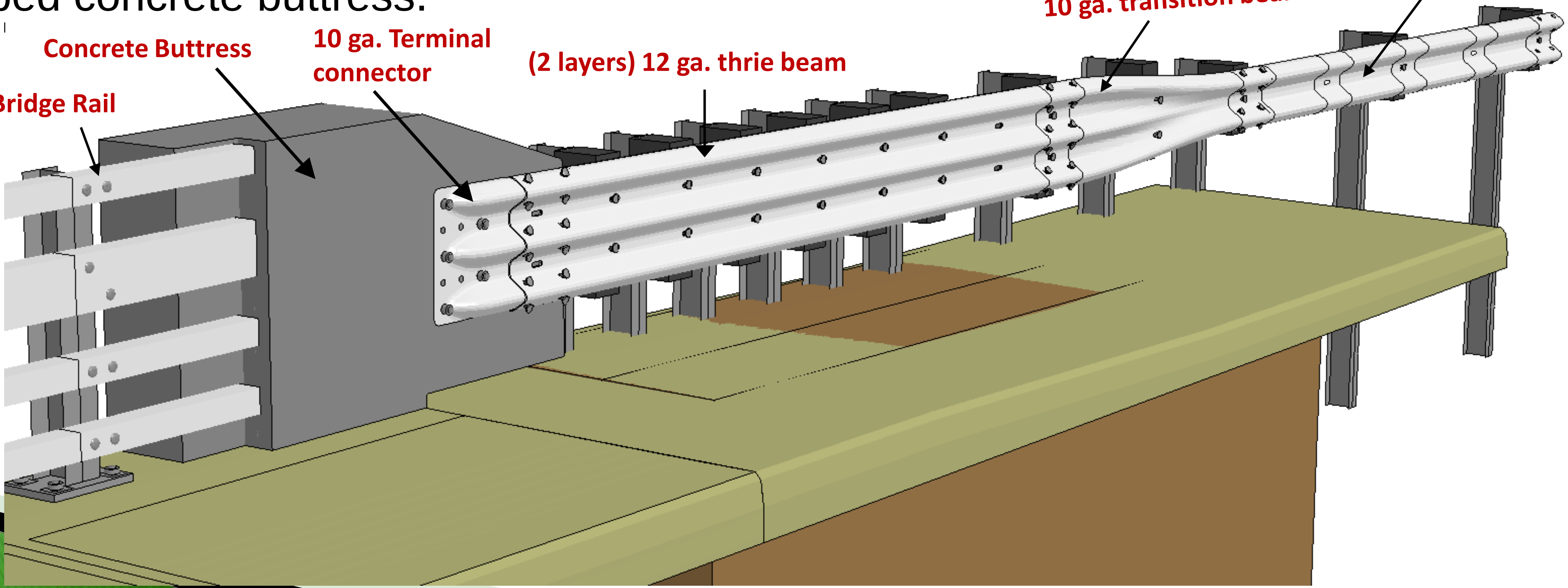



Posts in asphalt

Model Development of the MEDOT Transition

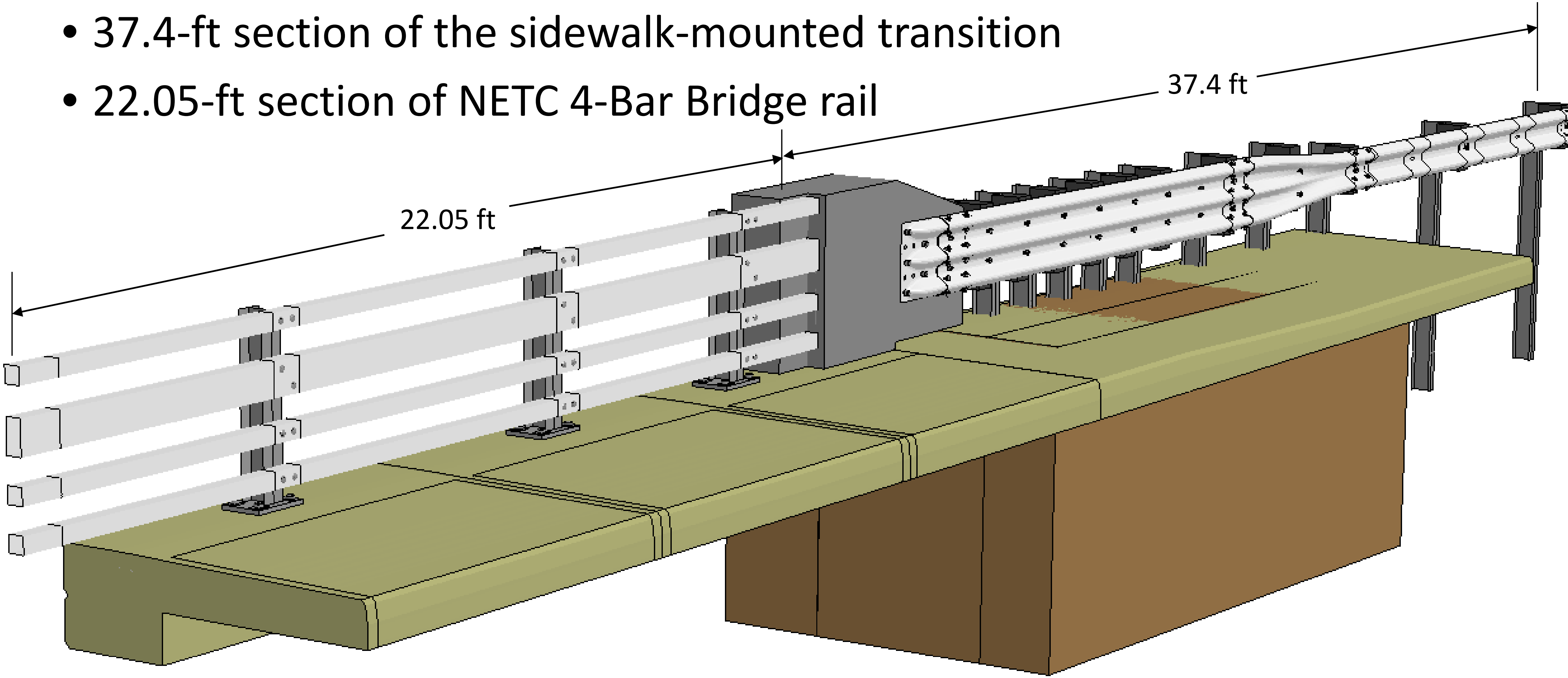
The transition design includes four primary elements:

1) 10-gauge w-beam to thrie-beam transition with “half” post-spacing,
2) A two-layer, 12-gauge thrie-beam section with further decreased post spacing,
3) 10-ga. thrie-beam terminal connector
4) Shaped concrete buttress.



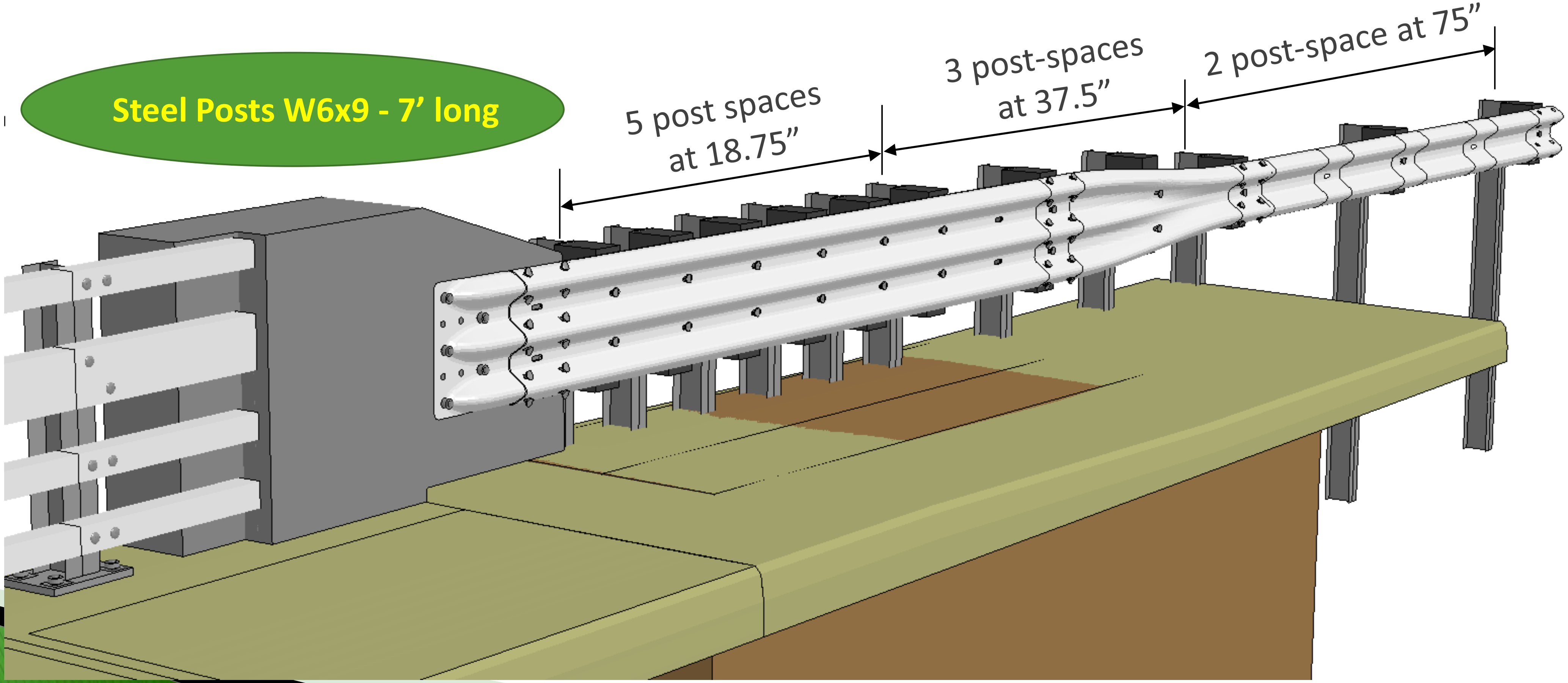
FEA Model

- 37.4-ft section of the sidewalk-mounted transition
- 22.05-ft section of NETC 4-Bar Bridge rail



Barrier Model

- Location and size of transition posts



Materials

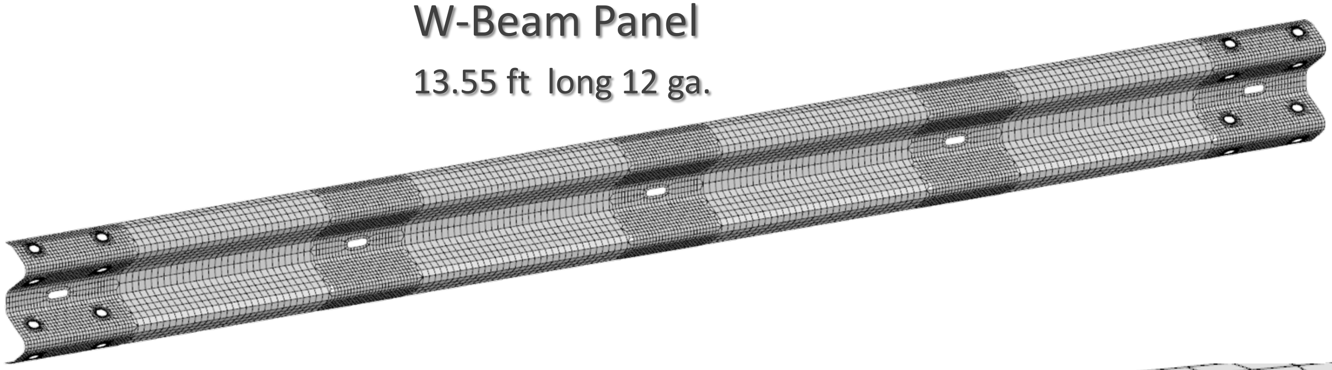
- **All steel materials were modeled in LS-DYNA using material model *Mat_Piecewise_Linear_Plasticity.** The Young's modulus was set to 29,000 ksi and Poisson's ratio was set to 0.33. The piecewise-linear stress-strain characterization for each component varied depending on steel type and grade.
- The material for all **thrie-beam and w-beam rails were modeled as AASHTO M180 Class A Type II**, with minimum yield and tensile strength of 60 ksi and 72 ksi, respectively.
- All **steel posts** were modeled as **AASHTO M183** steel; the material characterization was based on stress-strain curves from tensile tests.[Wright96] Yield strength = 45.7 ksi (true stress).
- All **blocks** were modeled using material model *Mat_Wood_Pine with properties corresponding to **Grade 1 Pine**.
- **Concrete** modeled with unconfined compressive strength of **5 ksi**.
- All the **post-bolts** in the transition were modeled as **ASTM A307 Grade A** with yield strength of 46 ksi and ultimate strength of 62 ksi (engineering stress) or 72.8 ksi (true stress).
- Soil model calibrated to Tests MGSATB-5 and -6.

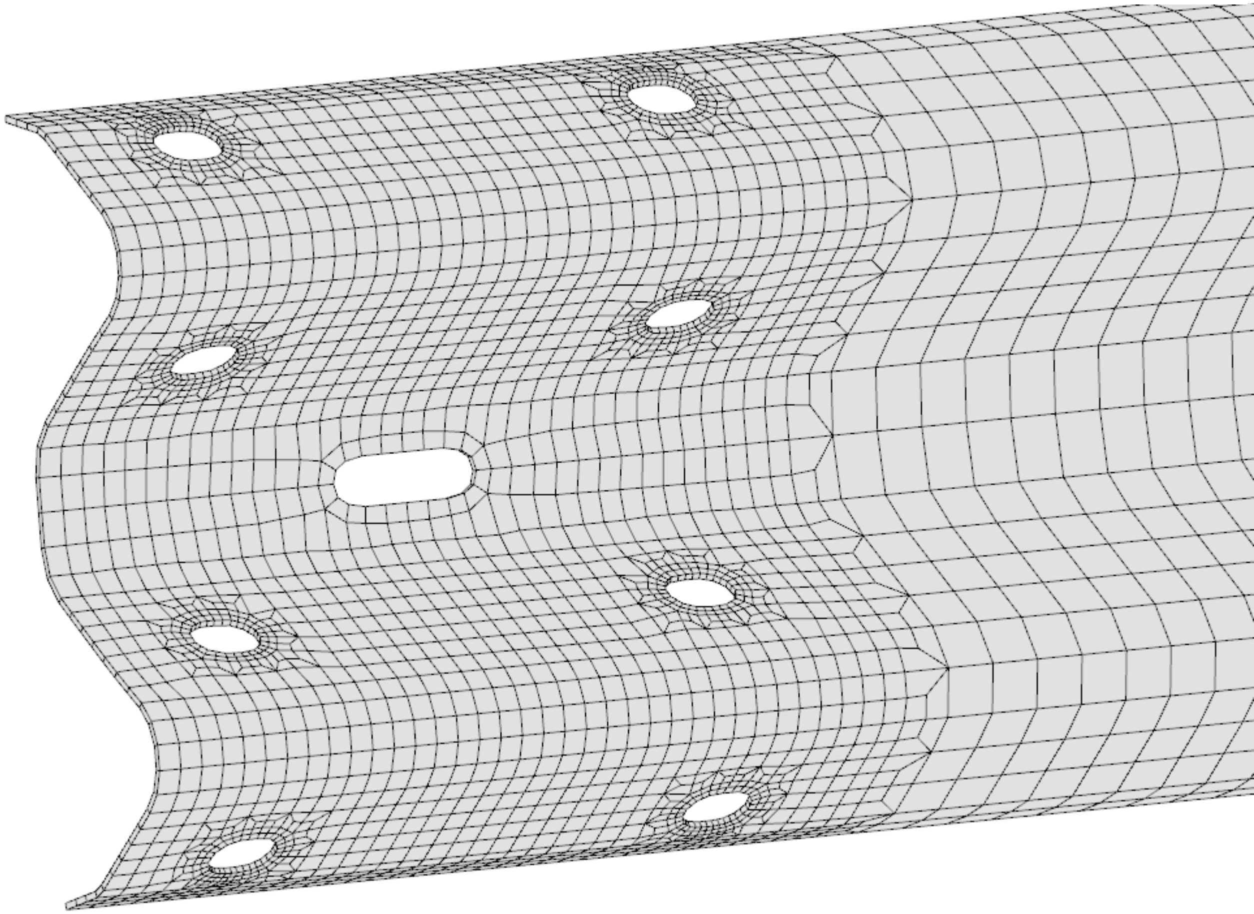
W-Beam Panel

- Standard w-beam rail with dimensions and thickness conforming to AASHTO RWM03a.
- The material for the w-beam was modeled as AASHTO M180 Class A Type II.
- The rail was modeled with thin-shell Belytschko-Tsay elements (Type 2 in LS-DYNA) with three integration points through the thickness.
    - The sections of rail between post connection points were meshed with a nominal element size of 0.79 x 0.83 inches.
    - The sections at the post connection points were meshed with a nominal element size of 0.39” x 0.39”.
    - The elements around the edge of the splice-bolt holes were meshed with nominal element size of 0.12 inches.

W-Beam Panel

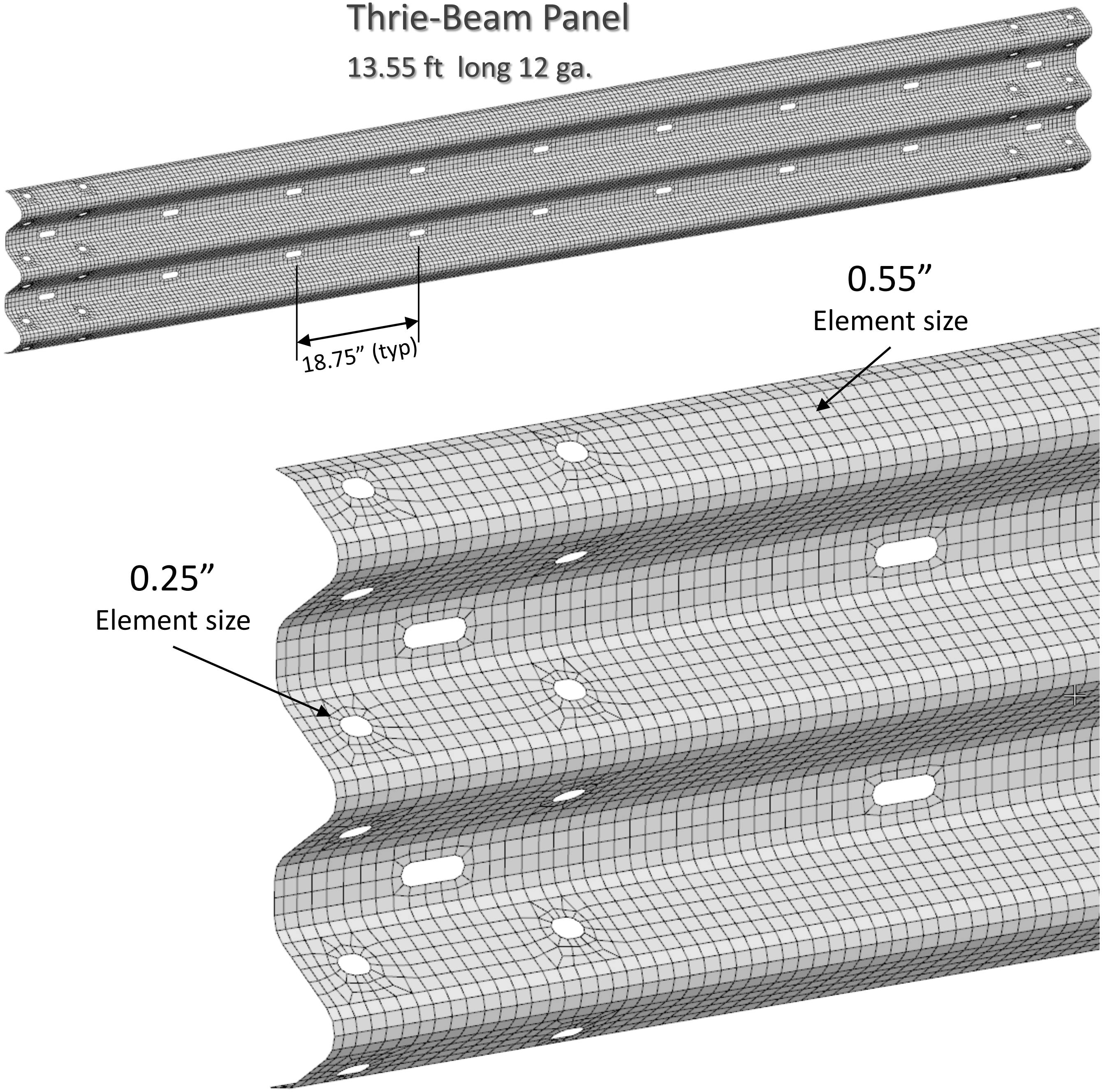
13.55 ft long 12 ga.





Thrie-Beam Panel

- The thrie-beam panel was modeled 13.55 ft long with 12-ga thickness.
- Slotted post-bolt holes were located at nine (9) locations on the panel at 18.75-inch spacing.
- The material was modeled as AASHTO M180 Class A Type II steel.
- The rail was modeled with thin-shell Belytschko-Tsay elements (Type 2 in LS-DYNA) with five (5) integration points through the thickness.
    - The panel was meshed with a nominal element size of 0.55 x 0.55 inches.
    - The elements around the edge of the splice-bolt holes were meshed with nominal element size of 0.25 inches.

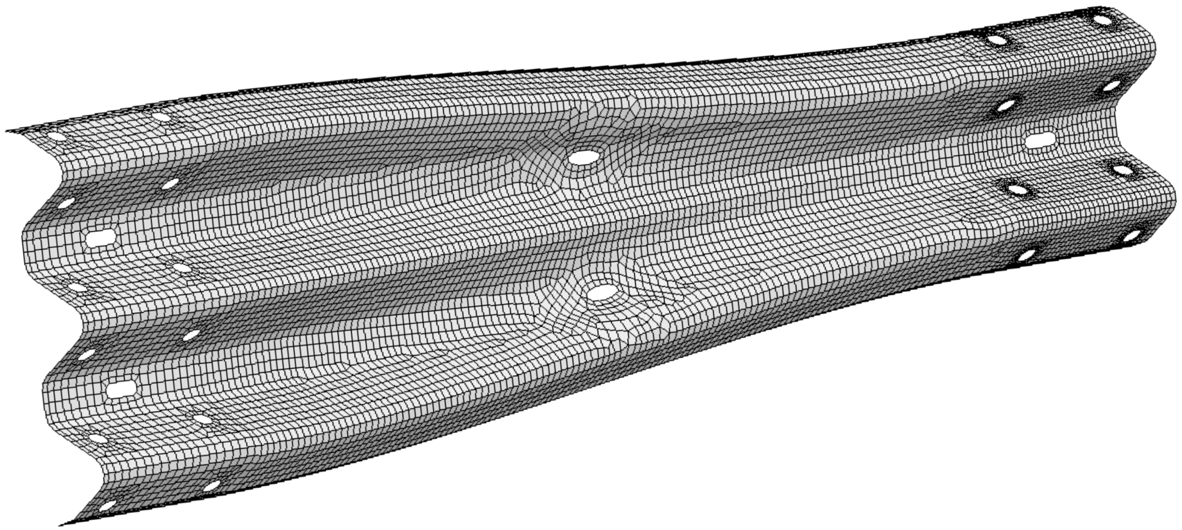


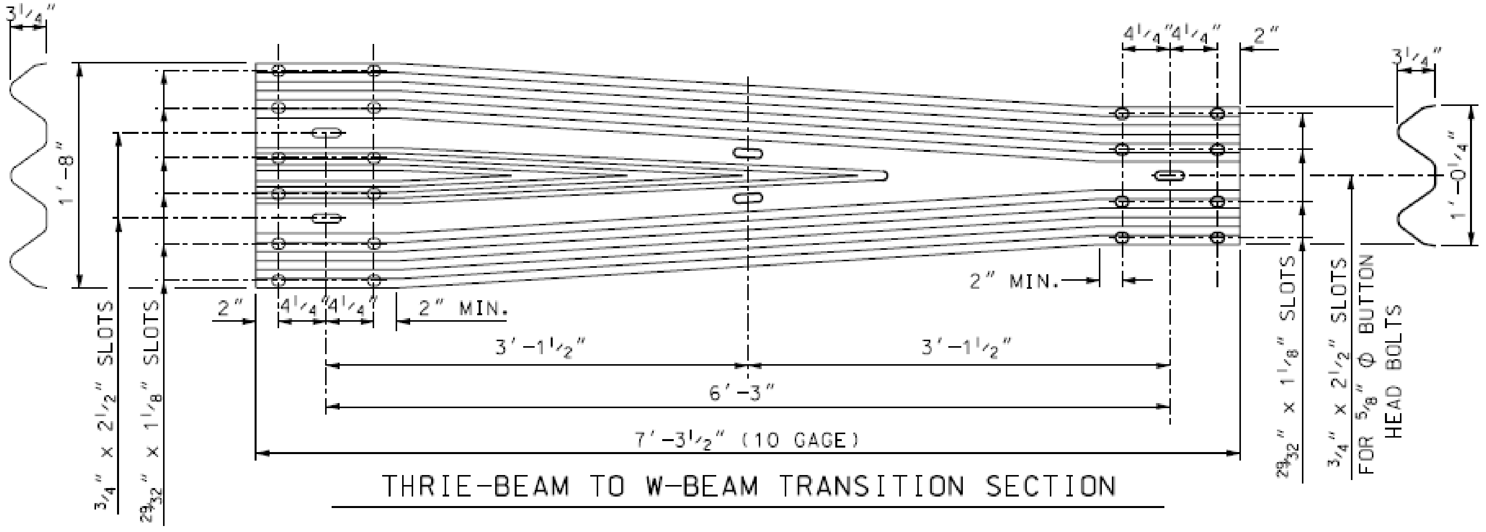
Transition Panel

7.29 ft long 10 ga.

Thrie-Beam Transition Panel

- The geometry for the transition panel created in AutoCAD by the research team based on the dimensions in the detail drawings.
- The material was modeled as AASHTO M180 Class A Type II steel.
- The rail was modeled with thin-shell Belytschko-Tsay elements (Type 2 in LS-DYNA) with three integration points through the thickness.
  - The W-Beam section was meshed identical to the standard w-beam model at the post connection points (see previous slide).
  - The remainder of the panel was meshed with a nominal element size of 0.55 x 0.55 inches.
  - The smallest elements were located around the edge of the splice-bolt holes with nominal element size of 0.25 inches.



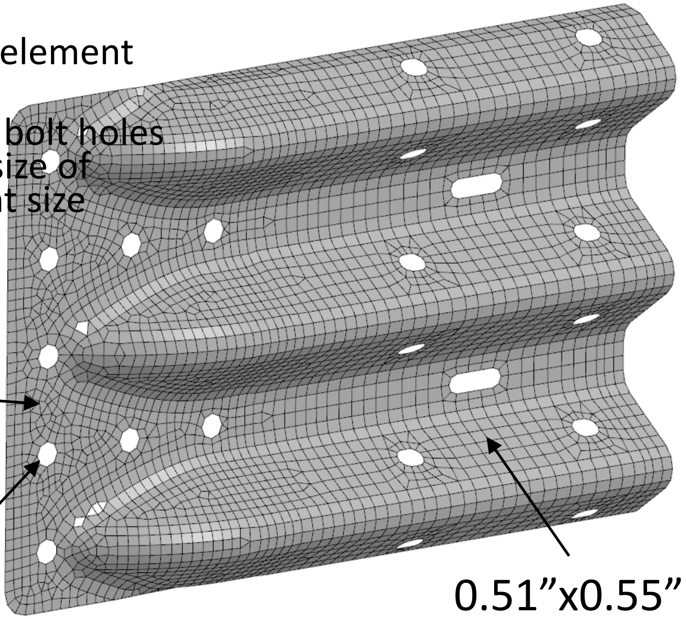


Thrie-Beam Terminal Connector

- The geometry for the thrie-beam terminal connector was developed in a previous project and conforms to the dimensions in the detail drawings.
- The material was modeled as AASHTO M180 Class A Type II steel.
- The part was modeled with thin-shell Belytschko-Tsay elements (Type 2 in LS-DYNA) with five (5) integration points through the thickness.
  - The part was meshed with a nominal element size of 0.51 x 0.55 inches.
  - The elements around the edge of the bolt holes were meshed with nominal element size of 0.38 inches, with the smallest element size being 0.25.

Terminal Connector

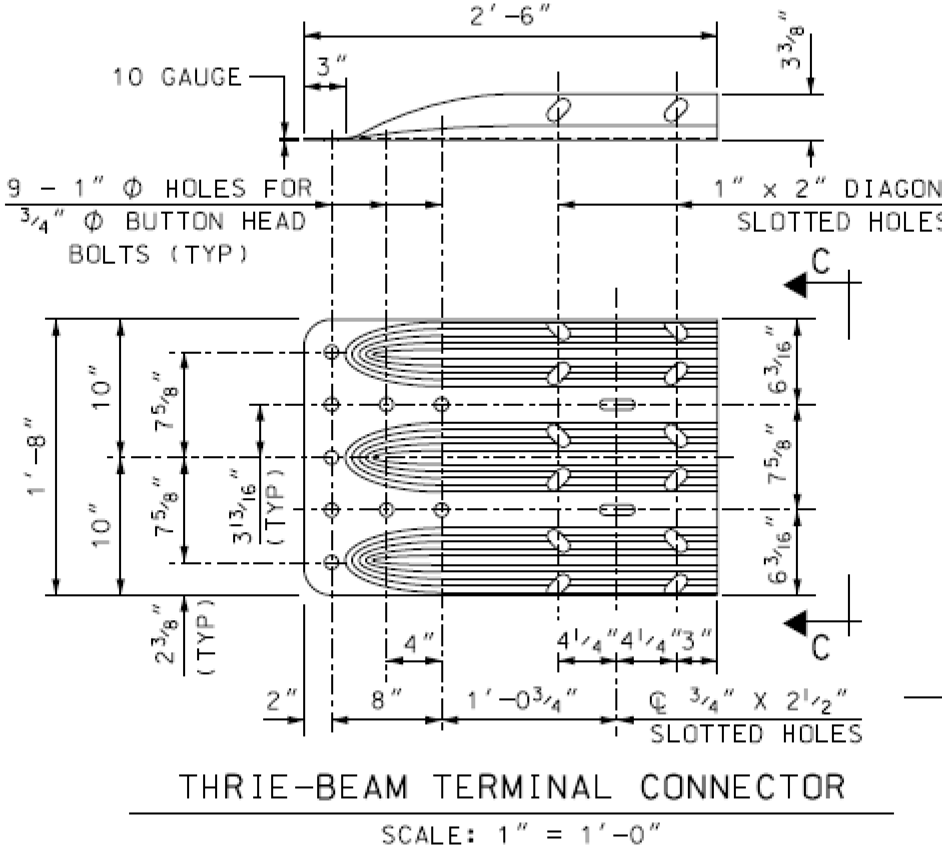
2.5 ft long 10 ga.



0.25”
Smallest element size

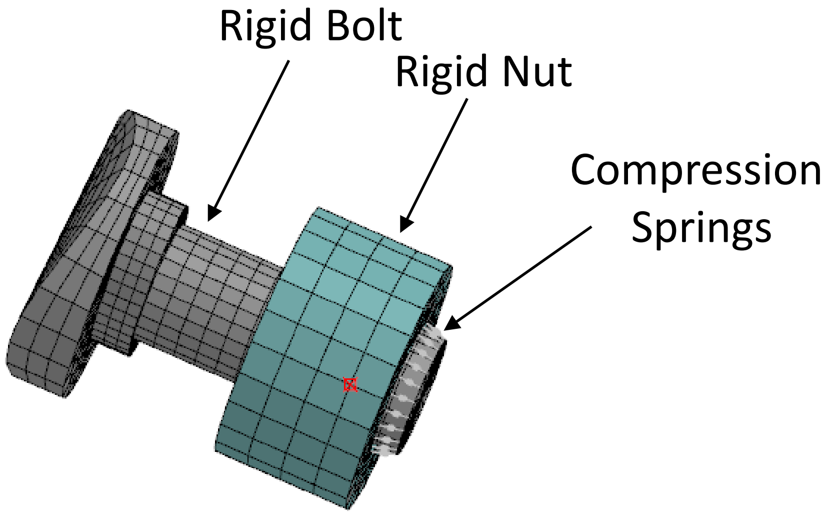
0.38”
Element size

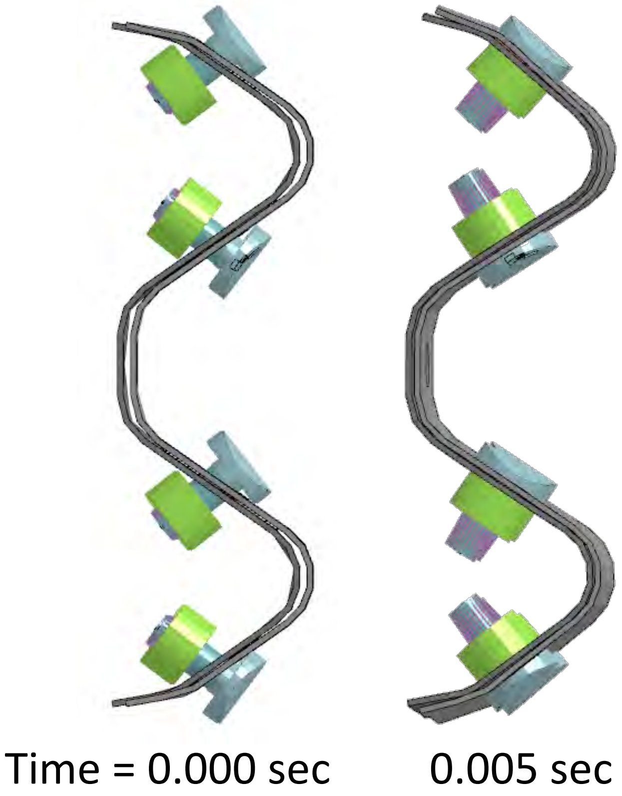
0.51”x0.55”
Element size



Splice Bolts

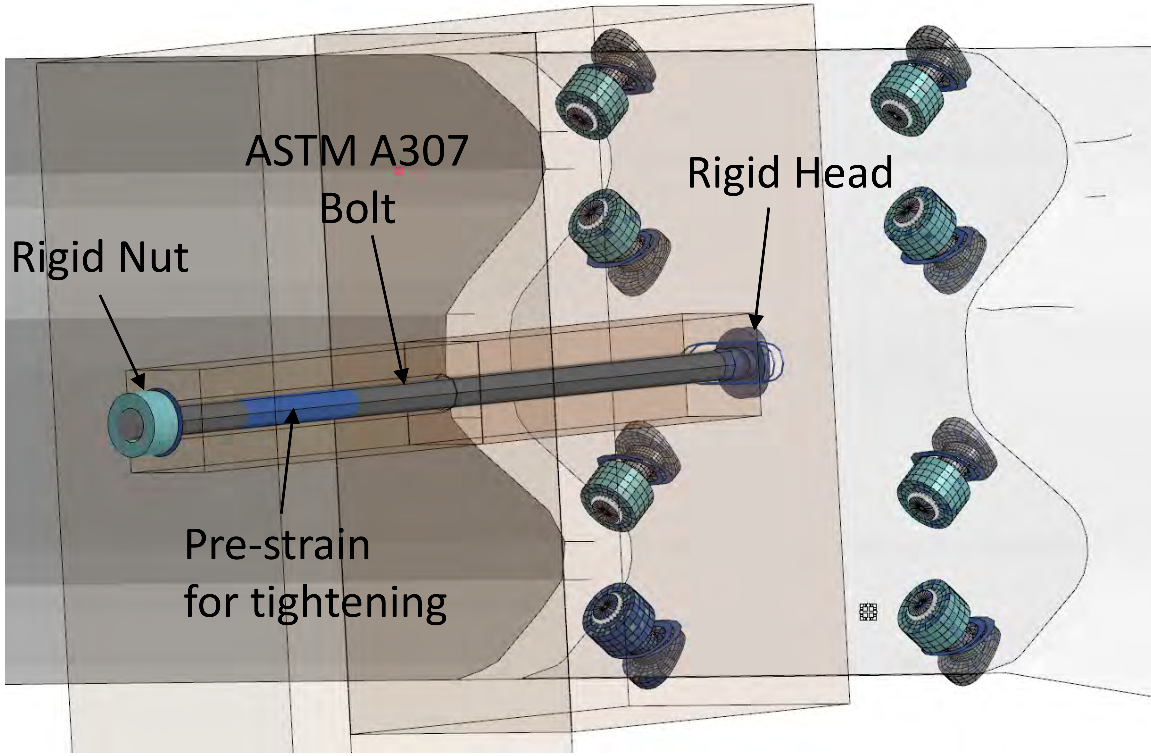
- Splice-bolt hardware seldom fails during impact, thus the material properties for the bolts and nuts were modeled with rigid material behavior.
  - Failure of the splice connection is generally due to the “rigid” bolts rotating and tearing through the relatively thin w-beam material.
  - Therefore, the bolts were modeled with geometric fidelity in order to obtain accurate force distribution and stress concentrations in the w-beam splice holes.
- The dimensions of the bolt hardware were modeled according to the standard drawing FBB01 for guardrail bolt and recessed nut (designation from AASHTO’s *A Standardized Guide to Highway Barrier Hardware*).
- Compression springs and dampers were attached between the end of the bolt and the nut to push the nut onto the bolt and clamp the rail panels together.
- The dampers are modeled as one-way dampers that “lock” the nut onto the bolt by preventing the nut from reversing direction.
- The images on the left show the bolt and rail position at time equal zero and at time equal 0.005 seconds.





Post Bolts

- The 5/8-inch diameter button-head post bolts were modeled with Hughes-Liu beam elements (Type 1 in LS-DYNA) with properties corresponding to ASTM A307.
- The bolt-head, nut and the washer were modeled with rigid material properties, since the effects of deformation of these components were expected to be negligible compared to the effects of bolt deformations.
- To tighten the bolt and clamp the rail to the post:
  - The nut was rigidly constrained to the end of the bolt,
  - A gradual pre-strain condition was then applied to 3-inch long section of the bolt in order to shrink the bolt approximately 3/8 inch in approximately 0.01 seconds.



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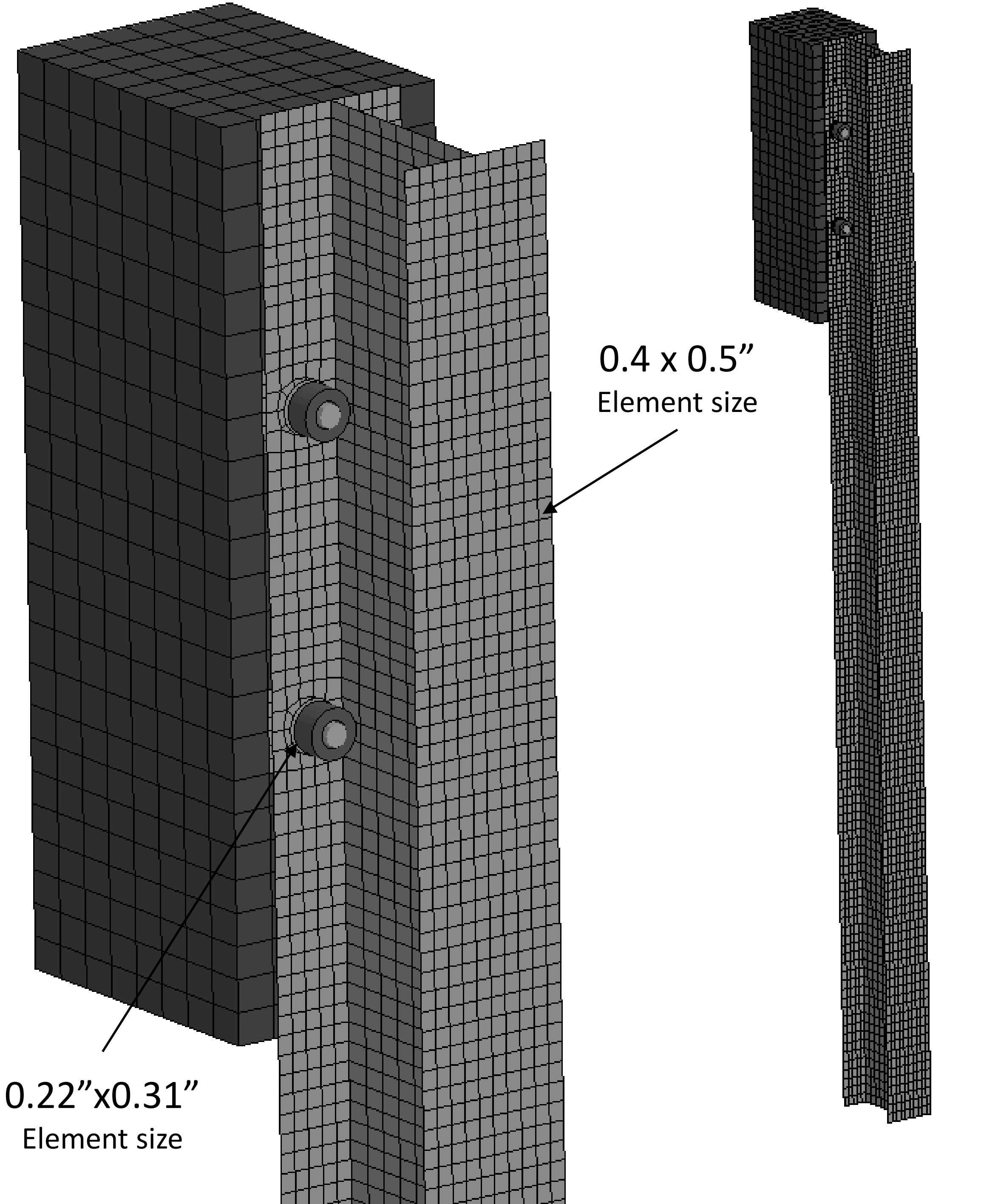
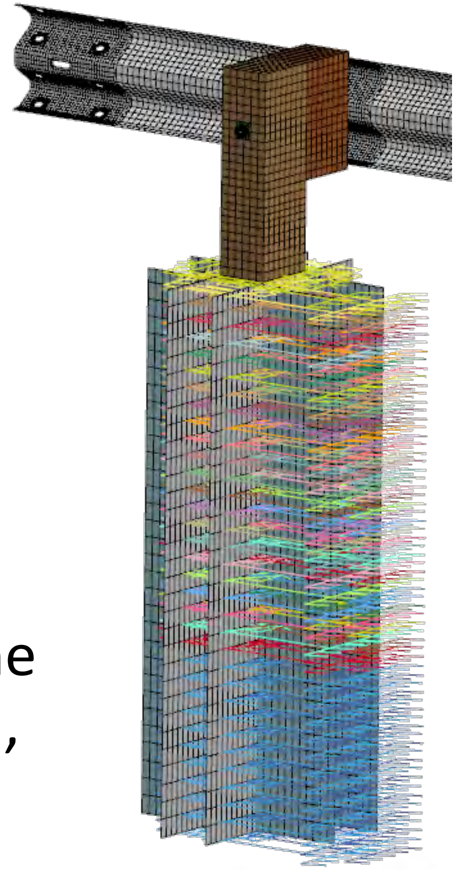
Steel Posts and Blockouts

- The posts in the transition were modeled as W6x9 and 7 feet long.
- The material for the post model conformed to AASHTO M183.
- The post was modeled with thin-shell Belytschko-Tsay elements (Type 2 in LS-DYNA) with five (5) integration points through the thickness.
- The flange and web were meshed with a nominal element size of 0.4 x 0.5 inches.
- The elements around the edge of the mounting holes were meshed with nominal element size of 0.22 x 0.31 inches.
- The blockout was modeled as Grade 1 Pine.
  - Solid elements with single integration point.
  - Nominal element size of 1”x 1”.
  - The mesh in the post-bolt region was meshed with a nominal element size of 0.33”x0.33”.
  - The mesh of the post-bolt region was “tied” to the elements of the post using the *Contact_Tied option in LS-DYNA.

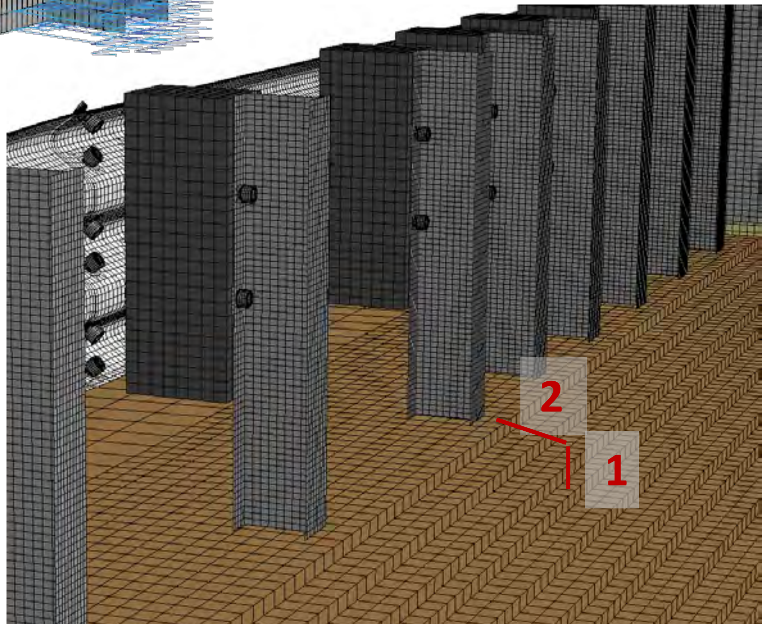


Soil Model

- Two methods were used:
  - Discrete elements (i.e., springs and dampers) were used to model the soil in the w-beam section (computational efficiency).
  - Solid element were used in the impact region on the transition where the posts were closely spaced (i.e., thrie-beam sections).
  - The continuum soil model included a 2:1 slope starting just behind the thrie-beam posts.
  - Both models were calibrated to the MGSATB test series performed by MwRSF (refer to Task 2b for details).



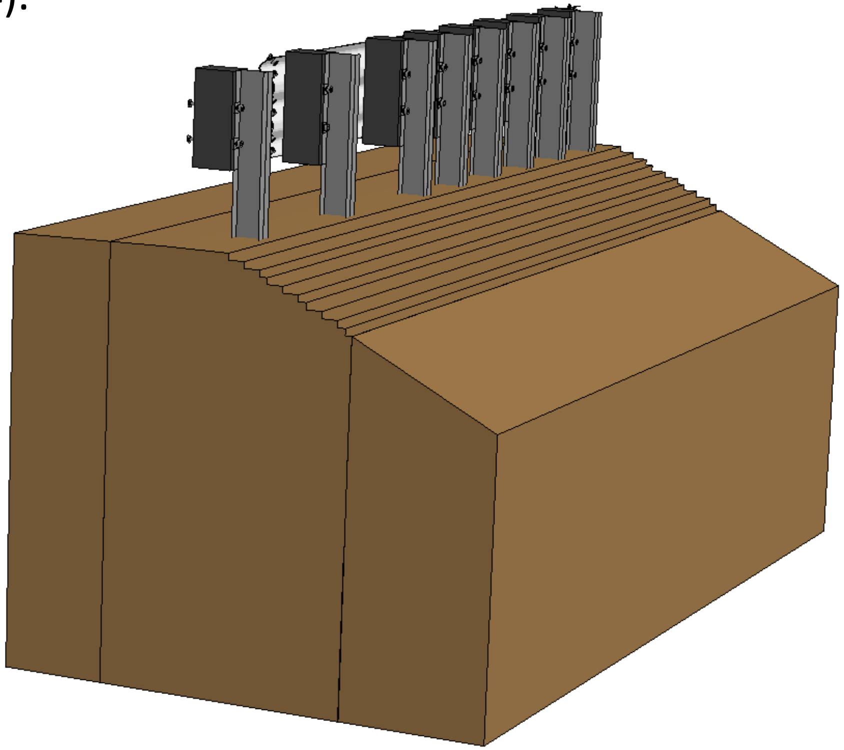
Soil Spring Model

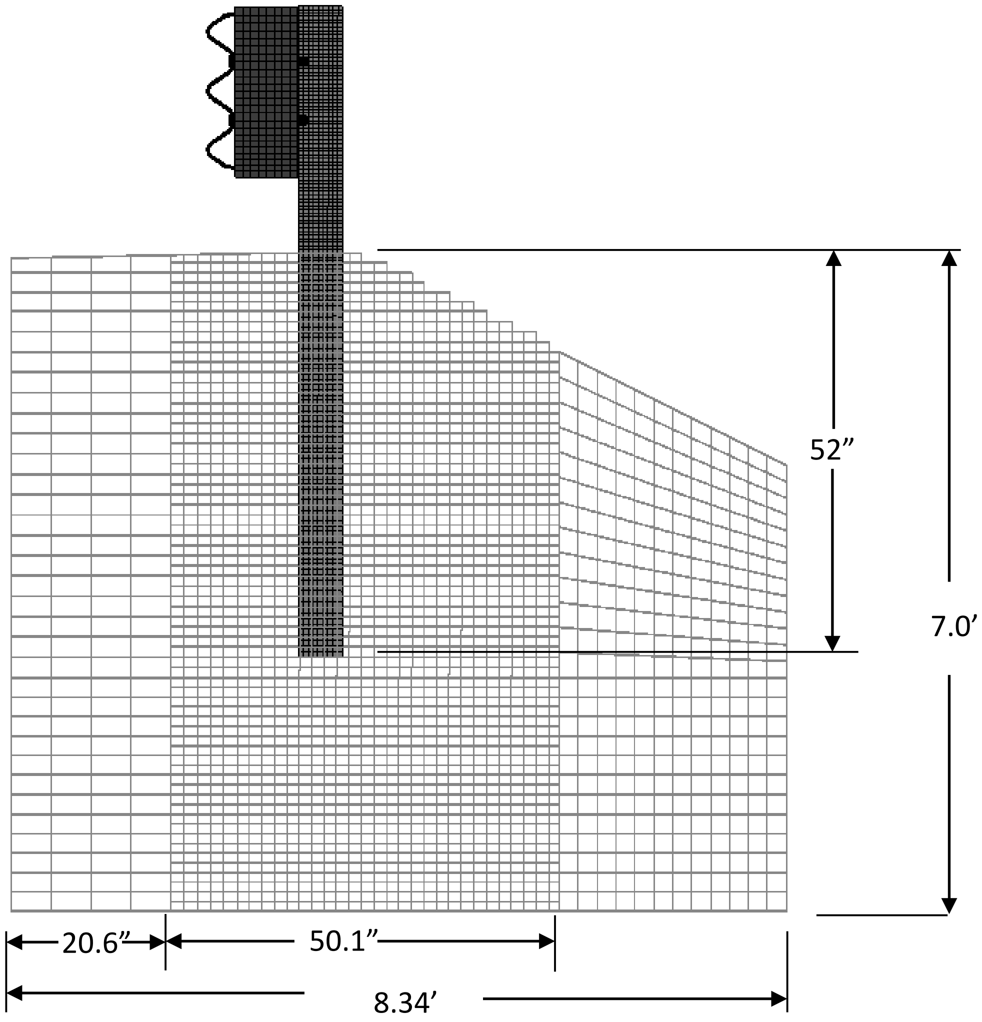


Soil Continuum Model (Solid Elements)

Soil Model

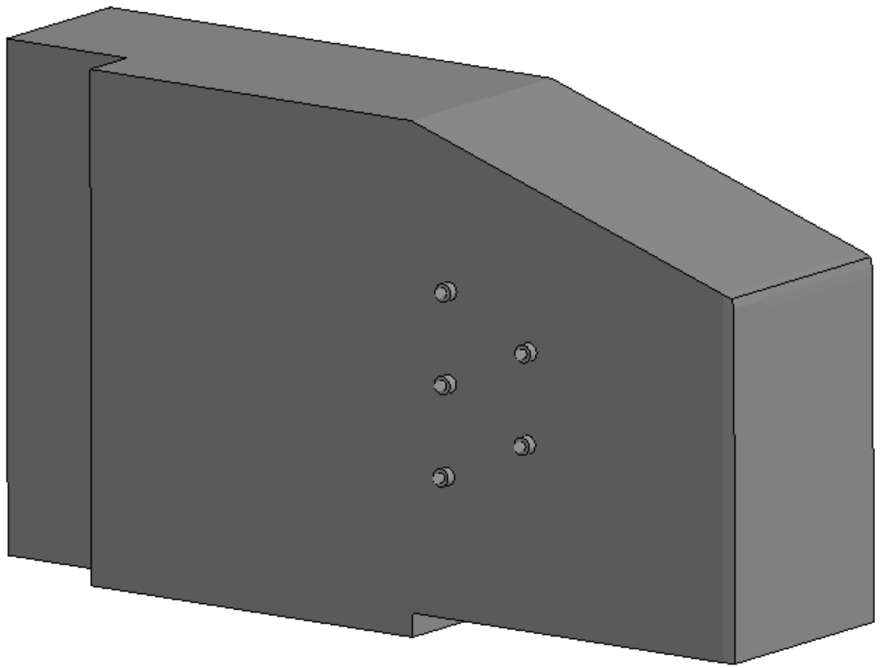
- Soil continuum model
  - Length = 16.7 feet
  - Lateral width = 8.34 feet
  - Vertical depth = 7.0 feet
- The material was modeled using the Drucker-Prager material model. This material model was calibrated based on comparison to full-scale tests (see Task 2b and Task 4).

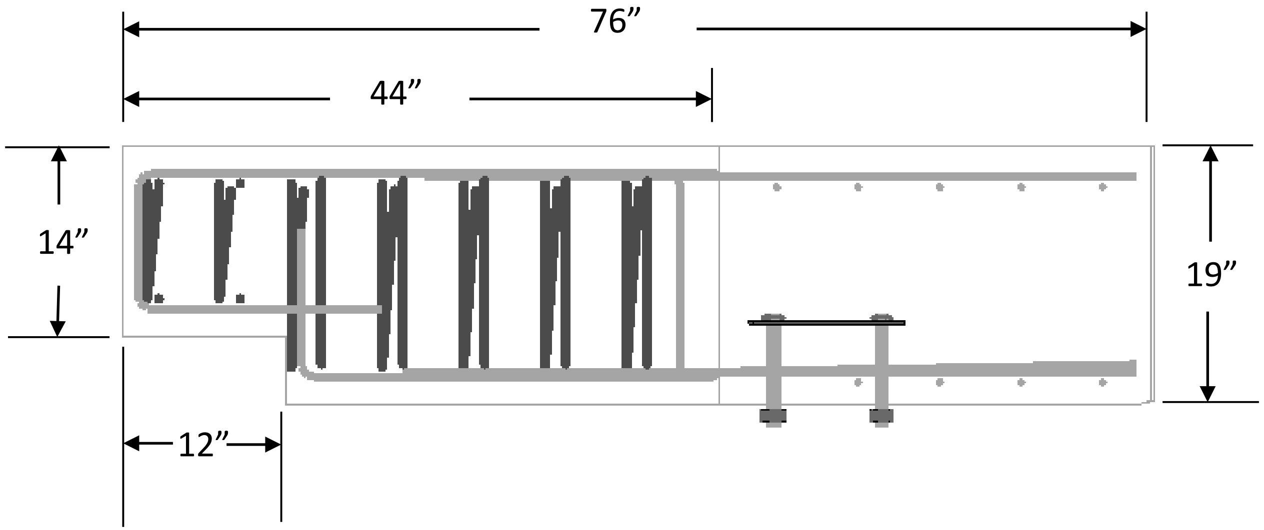


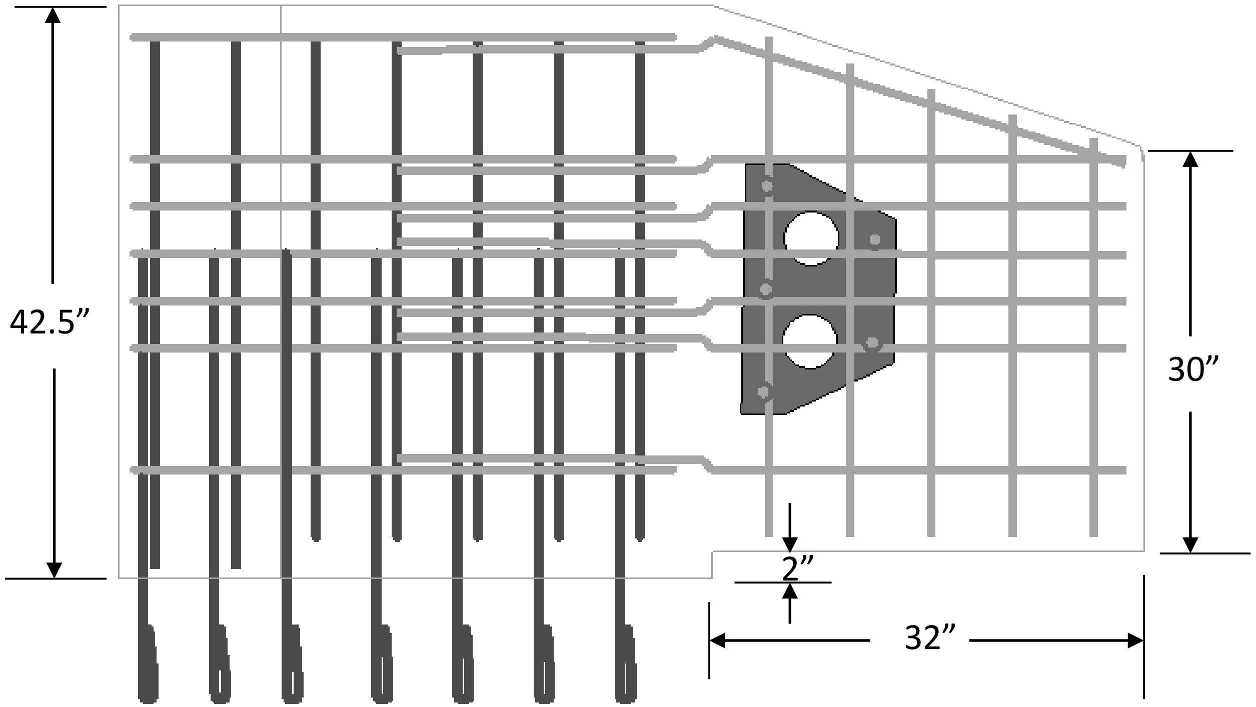


Shaped Buttress

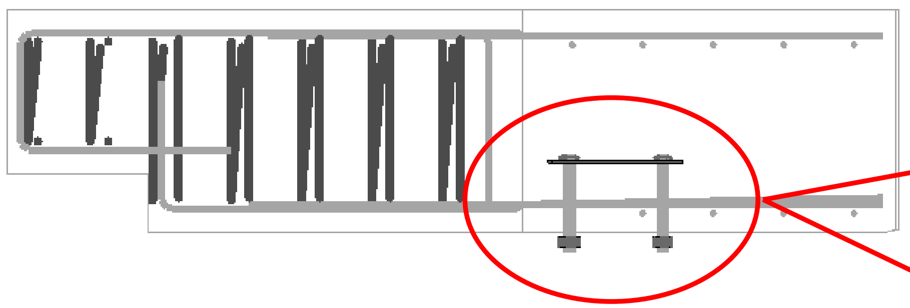
- The model for the shaped concrete buttress section was developed based on the drawing details on pages 526(22) and 526(34-38) of the MEDOT Standard Details.
- The concrete was modeled using Mat_RHT in LS-DYNA with properties consistent with 5 ksi concrete.
- The steel reinforcing was modeled according to the drawing details.
  - The dark shaded bars are #6 bars
  - The lighter shaded bars are #5 bars

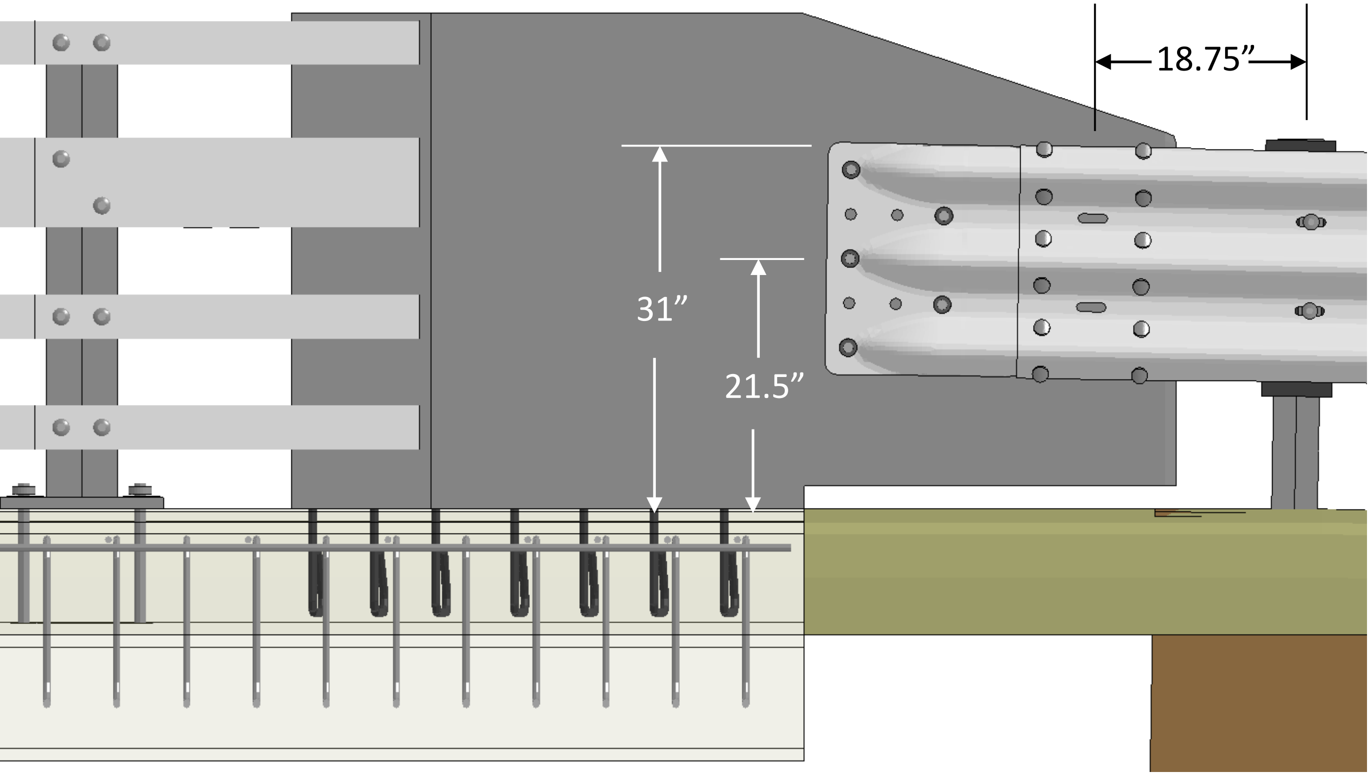


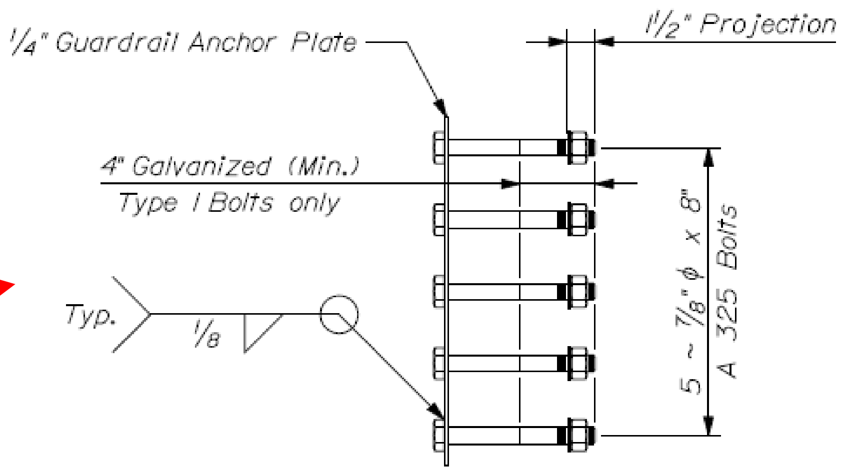


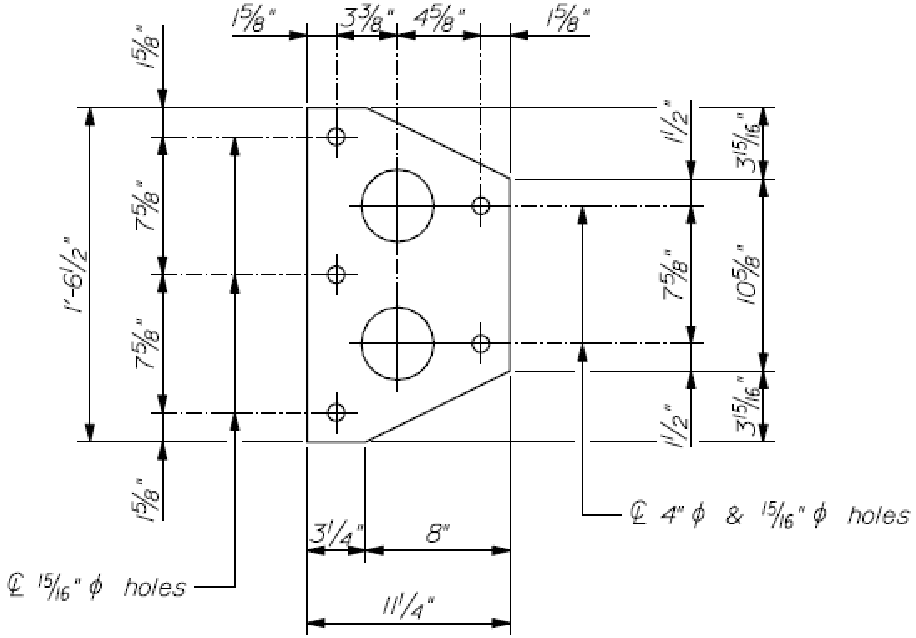


Guardrail Anchorage







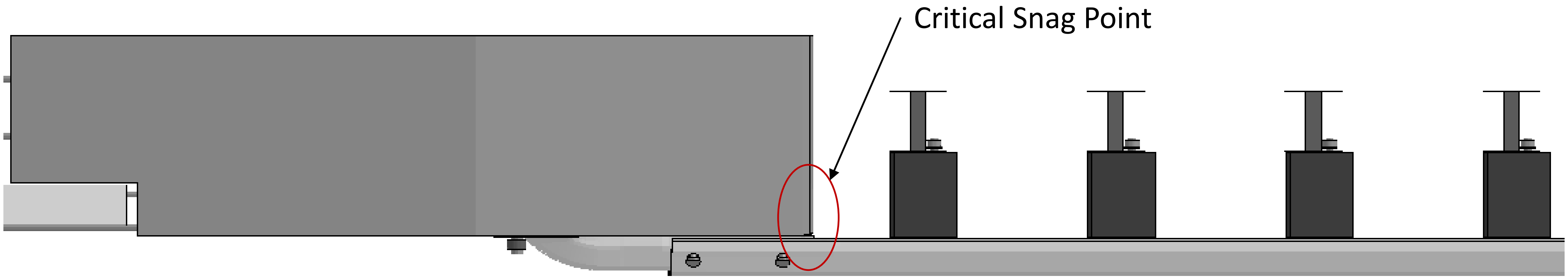


Notes

- Bridge Transition Type “I”
  - Page 606(21) or page 229 of pdf

Determining Critical Impact Point

- The critical impact point for all cases were designed to maximize potential for snag on the end of the concrete buttress.



Determination of CIP for Test 4-20

- CIP was determined using FEA based with respect to maximizing potential for snag on the end of the concrete buttress.
  - OIV and ORA since these metrics are used directly in crashworthy assessments in MASH
- Analysis Cases (5 cases):
  - Impact points 4.0 ft, 4.5 ft, 5.0 ft, 5.5 ft, and 6.0 ft from the end of the abutment.
  - These analyses were conducted for 0.15 seconds of impact for the purpose of determining the critical impact point for maximizing vehicle accelerations and maximizing forces on the barrier at the junction point of the thrie-beam and the concrete abutment.

CIP Analysis Cases

IP 4.0 ft

IP 4.5 ft

IP 5.0 ft

IP 5.5 ft

IP 6.0 ft

CIP Analysis Cases Movies

IP 4.0 ft

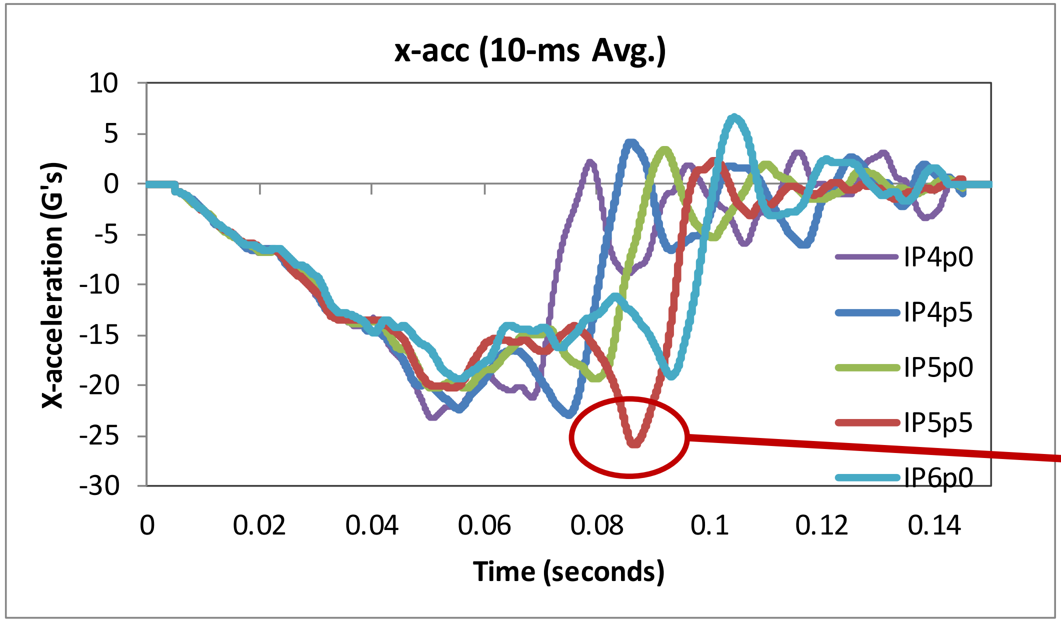
IP 4.5 ft

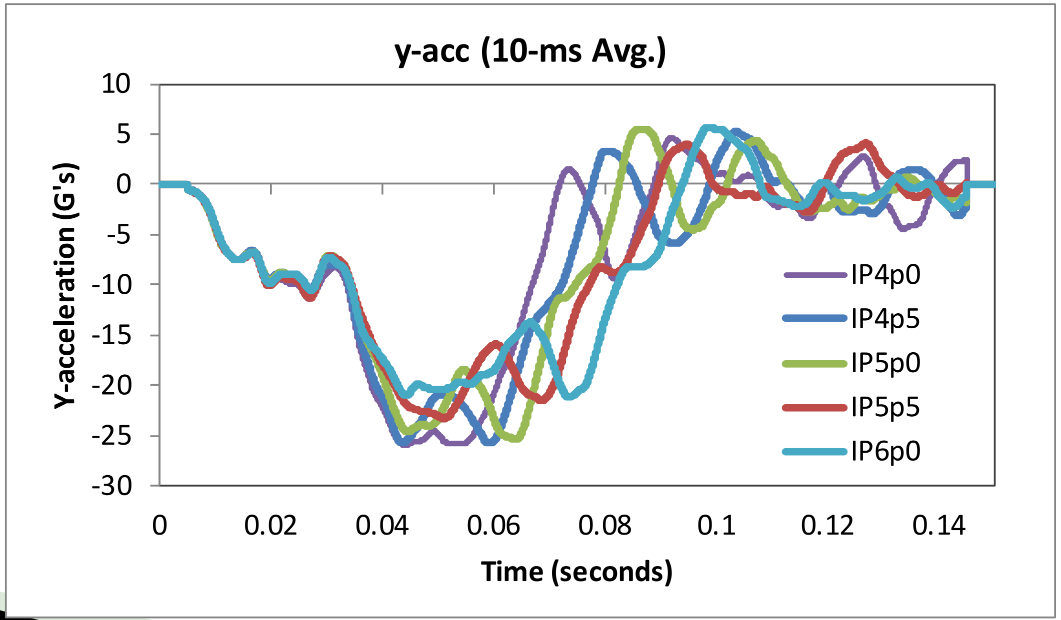
IP 5.0 ft

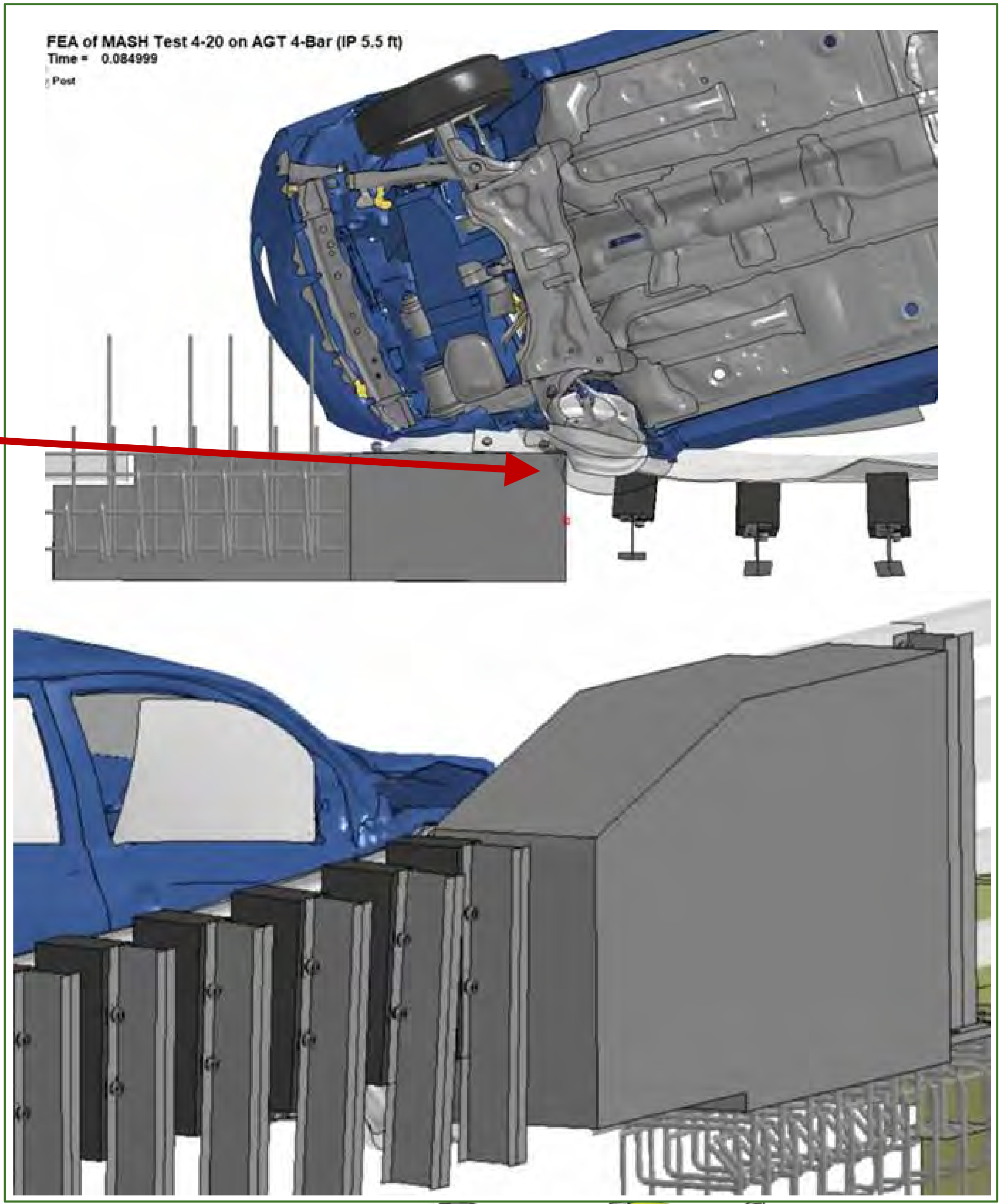
IP 5.5 ft

IP 6.0 ft

Acceleration-time Histories







Time of contact with abutment

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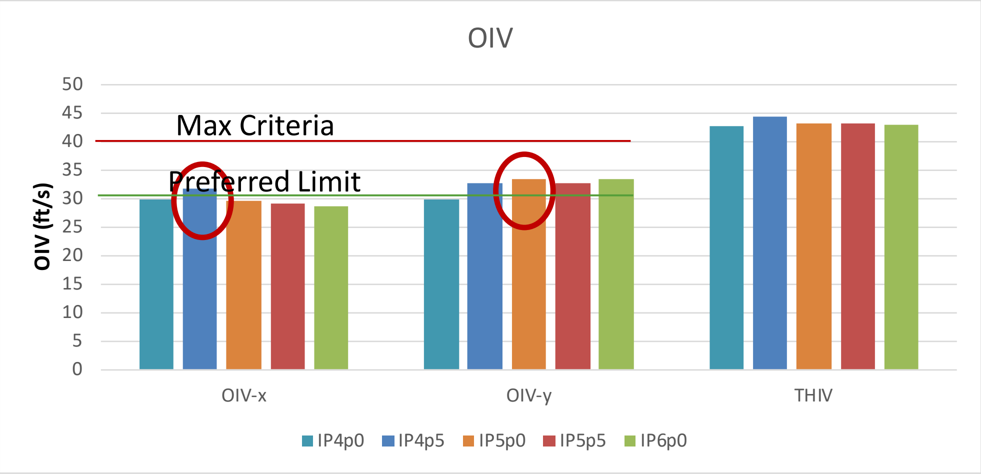
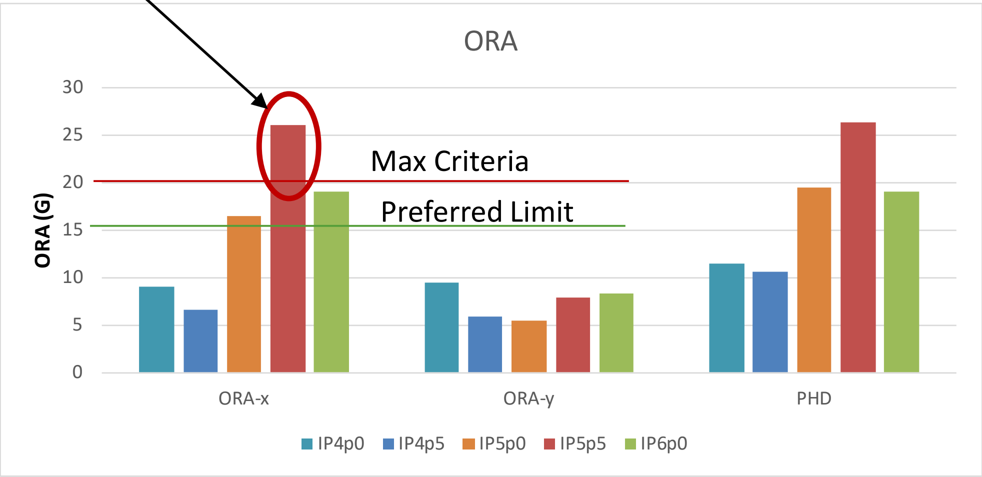
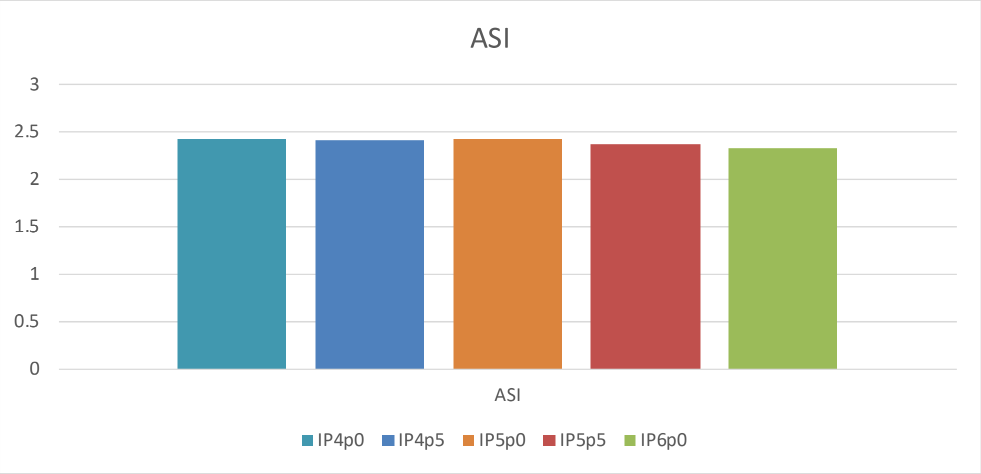
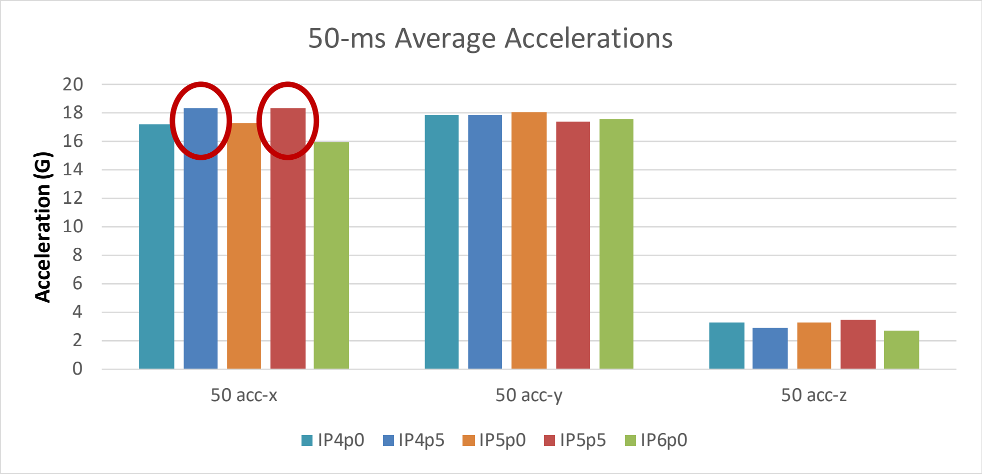
TRAP Results

Fails ORA criteria









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Summary on CIP Calculations

- From visual inspection of the analysis videos, the greatest potential for the wheel of the vehicle to snag on the abutment was at IP 5.5 ft.
- OIV:
  - **All cases were at or just above recommended limits**
- ORA:
  - **IP5.5 ft** resulted in excessive occupant ridedown acceleration in the longitudinal direction, thus **failing MASH criteria**.
  - Case IP 6.0 ft was also near critical limits

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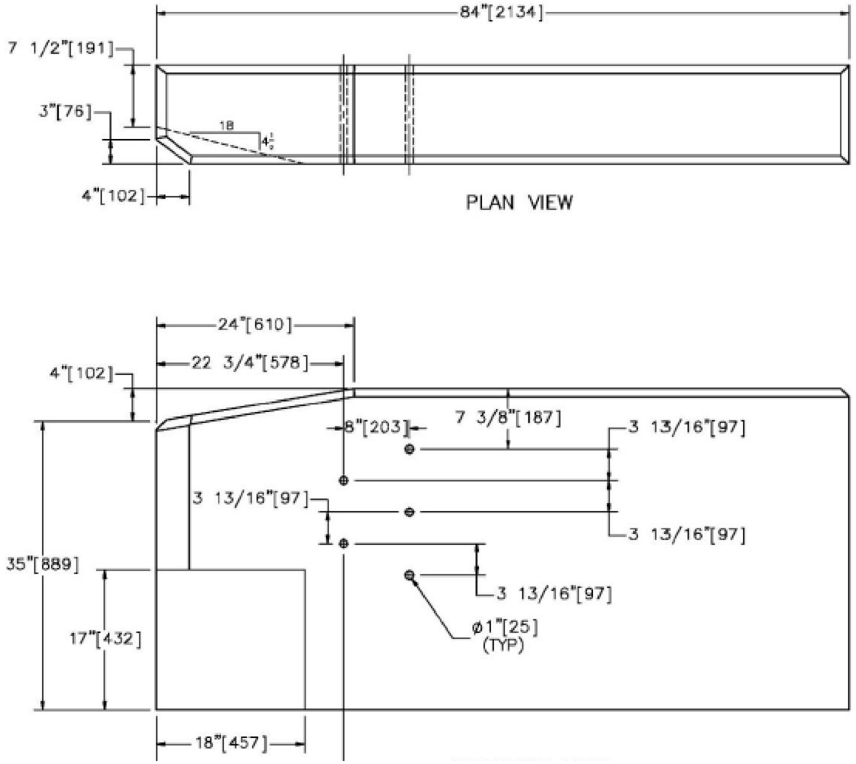
Conclusions on CIP Selection

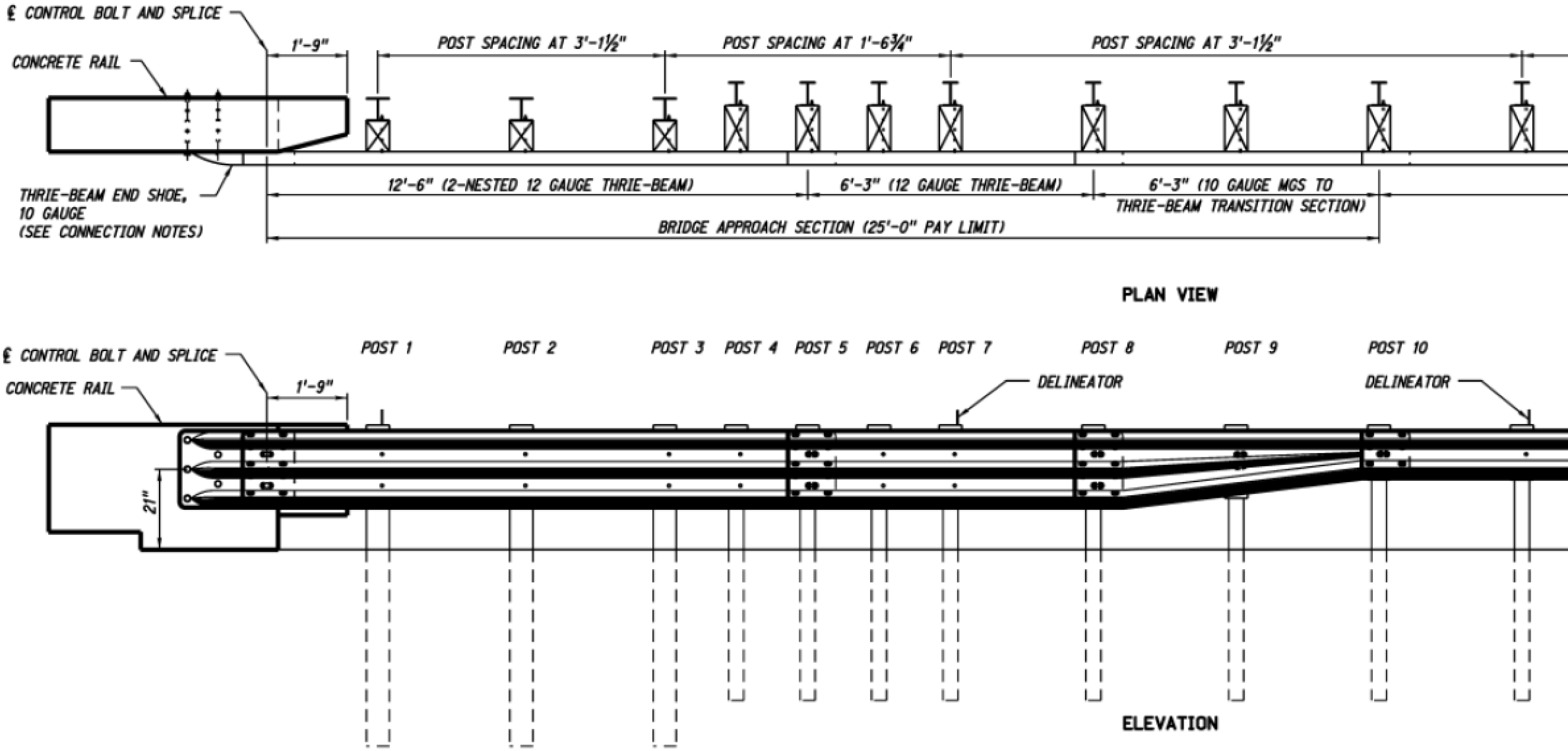
- Greatest potential for pocketing and highest ORA occurred at IP 5.5 ft;
- Therefore, the **CIP** was selected as **5.5 ft upstream of the buttress**.

Comparison to Test 3-20 on Similar System

- Test No. 34AGT-2
- Agency: MwRSF
- Date: 5/9/17
- Test Article: 34-in. (864-mm) Tall Thrie Beam AGT
- CIP = 5.42 ft upstream of abutment



System Drawings

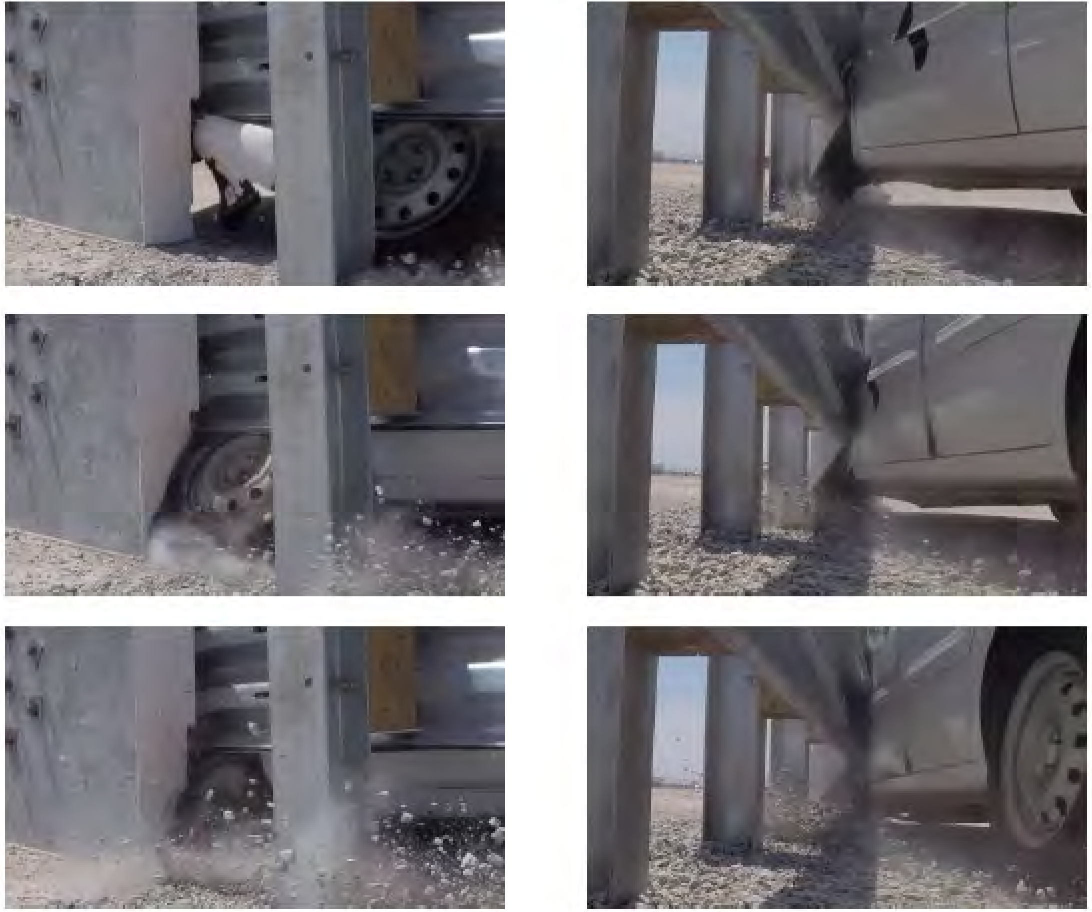


Results

Both Transducers placed near center of gravity but yielded very different result for long ORA

Test 34AGT-2

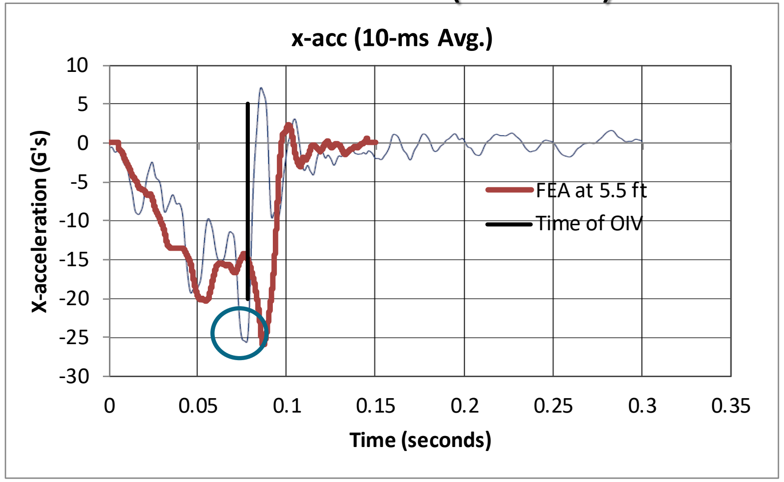
Evaluation Criteria		Transducer: SLICE-1	Transducer: SLICE-2 (primary)	MASH 2016 Limit	FEA MEDOT
OIV ft/s (m/s)	Longitudinal	-20.54 (-6.26)	-22.65 (-6.90)	±40 (12.2)	29.5
	Lateral	35.29 (10.76)	32.71 (9.97)	±40 (12.2)	32.8
ORA g's	Longitudinal	-25.55	-10.84	±20.49	26.0
	Lateral	-12.69	14.70	±20.49	7.9
MAX ANGULAR DISP. deg.	Roll	-15.3	-10.0	±75	
	Pitch	-6.0	-5.5	±75	
	Yaw	96.4	94.9	not required	
THIV – ft/s (m/s)		38.39 (11.70)	36.65 (11.17)	not required	43.3
PHD – g's		13.44	15.07	not required	26.4
ASI		2.43	2.30	not required	2.37

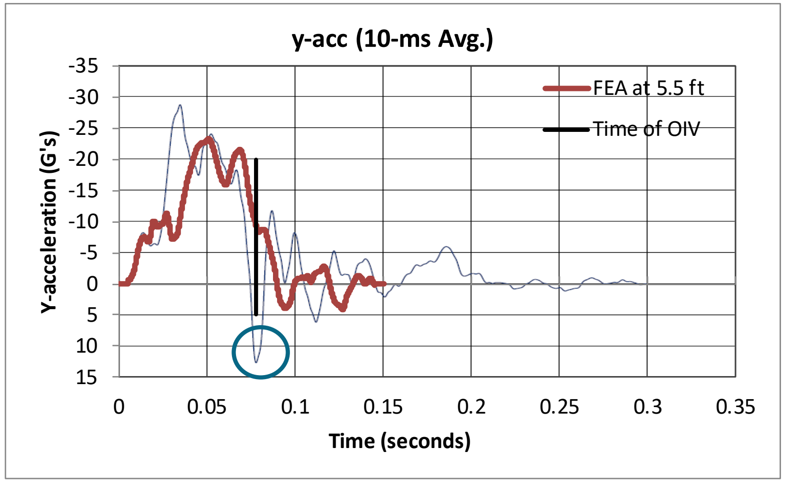


Comparison of FEA to Test 34AGT-2

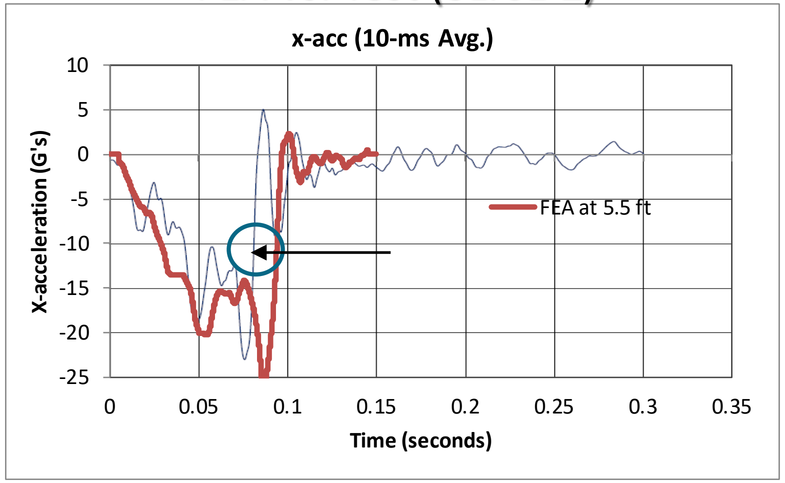
- Test ORA circled

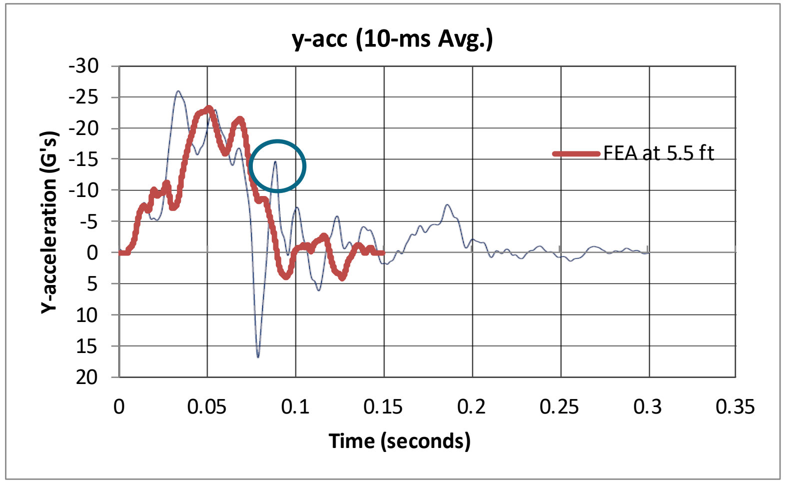
FEA vs. Test (SLICE 1)

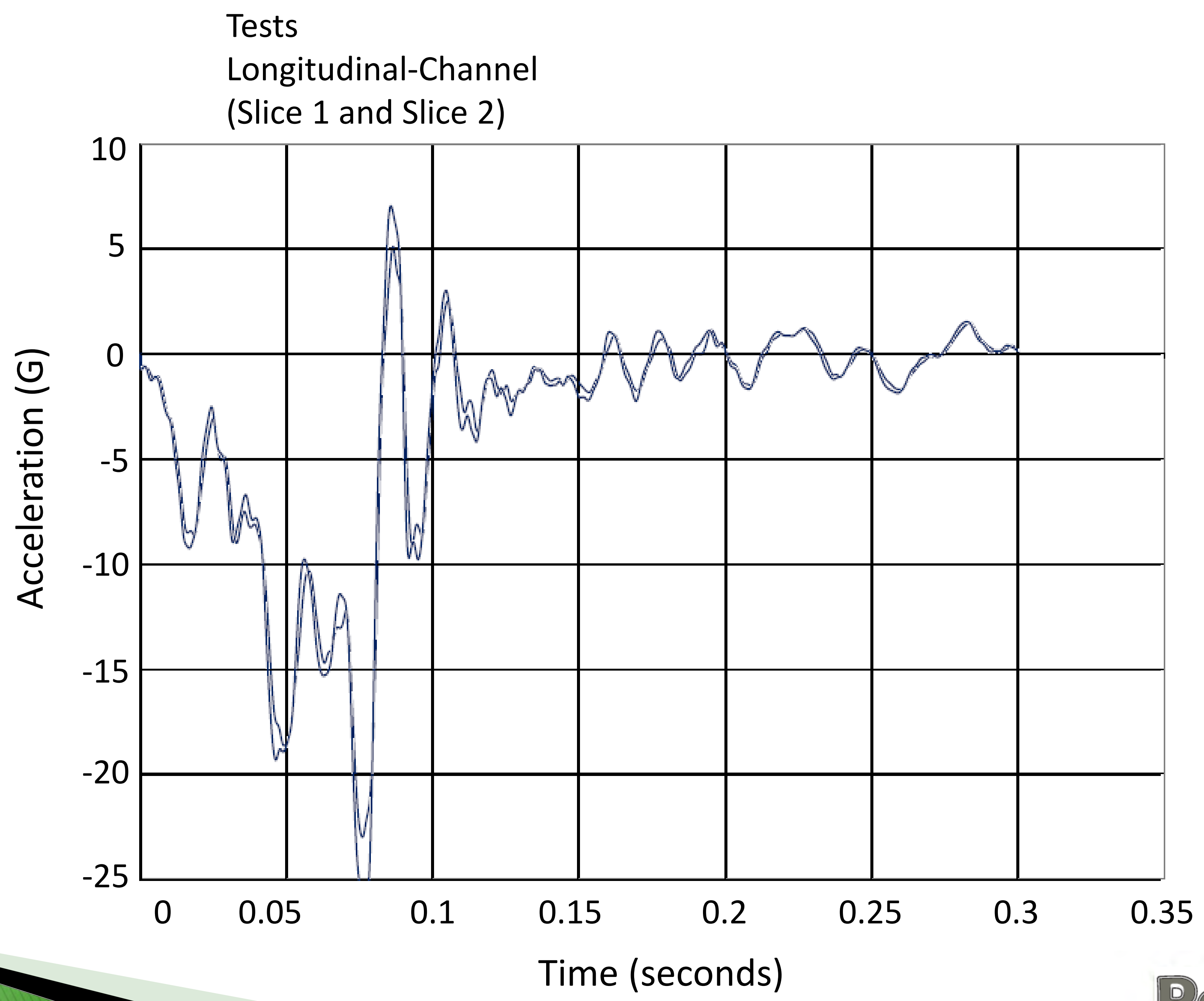




FEA vs. Test (SLICE 2)







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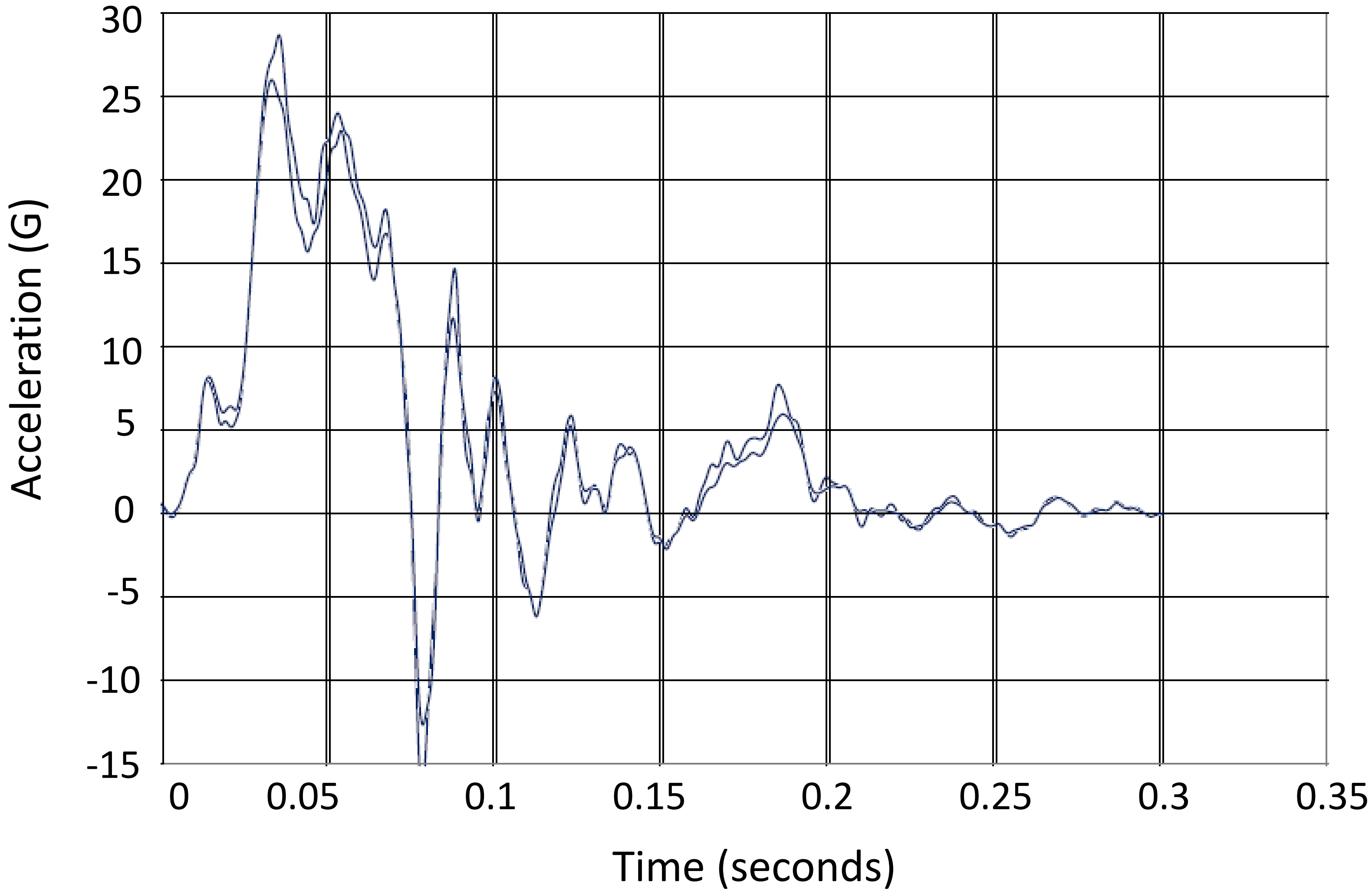
Tests
Lateral-Channel
(Slice 1 and Slice 2)



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Results

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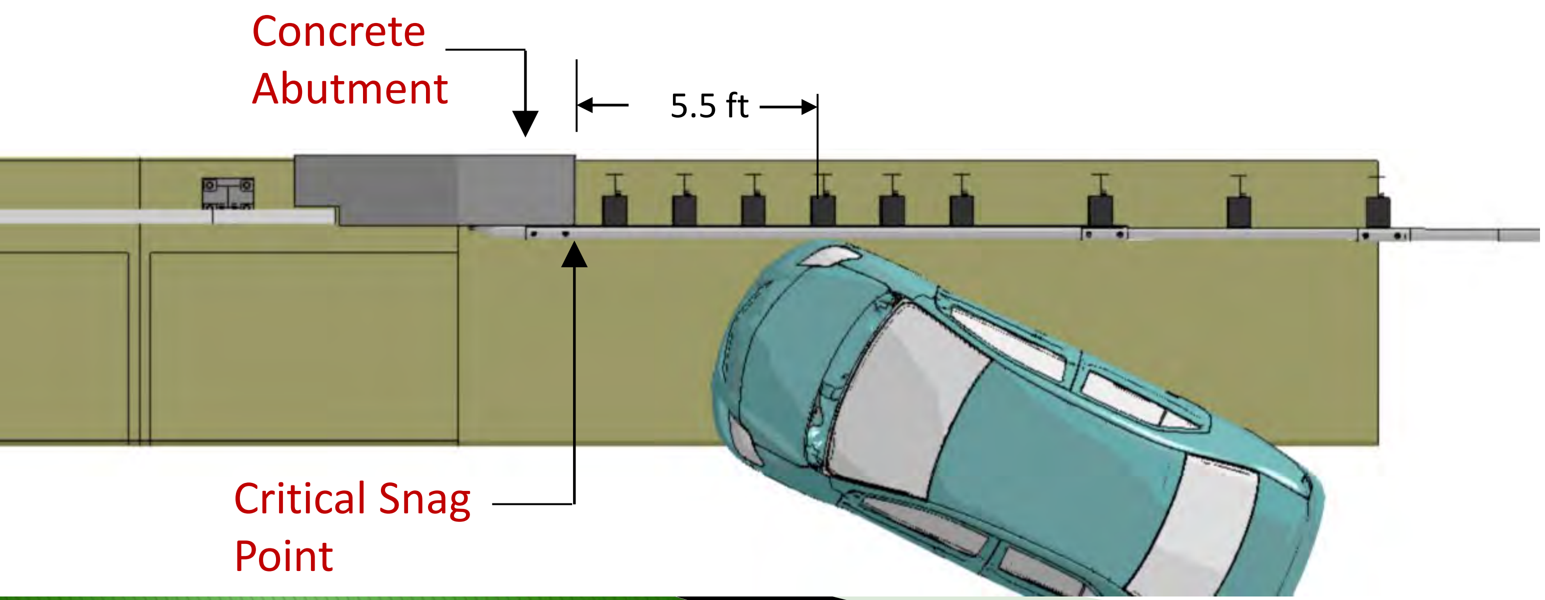
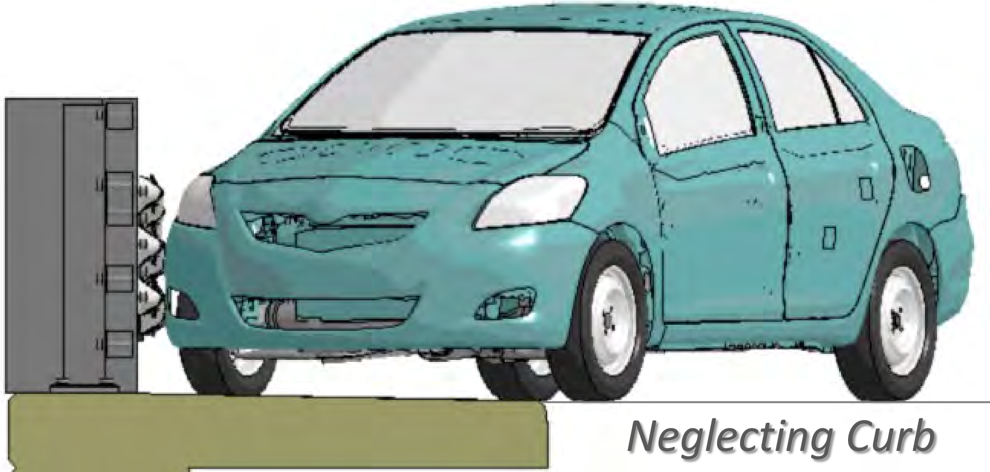
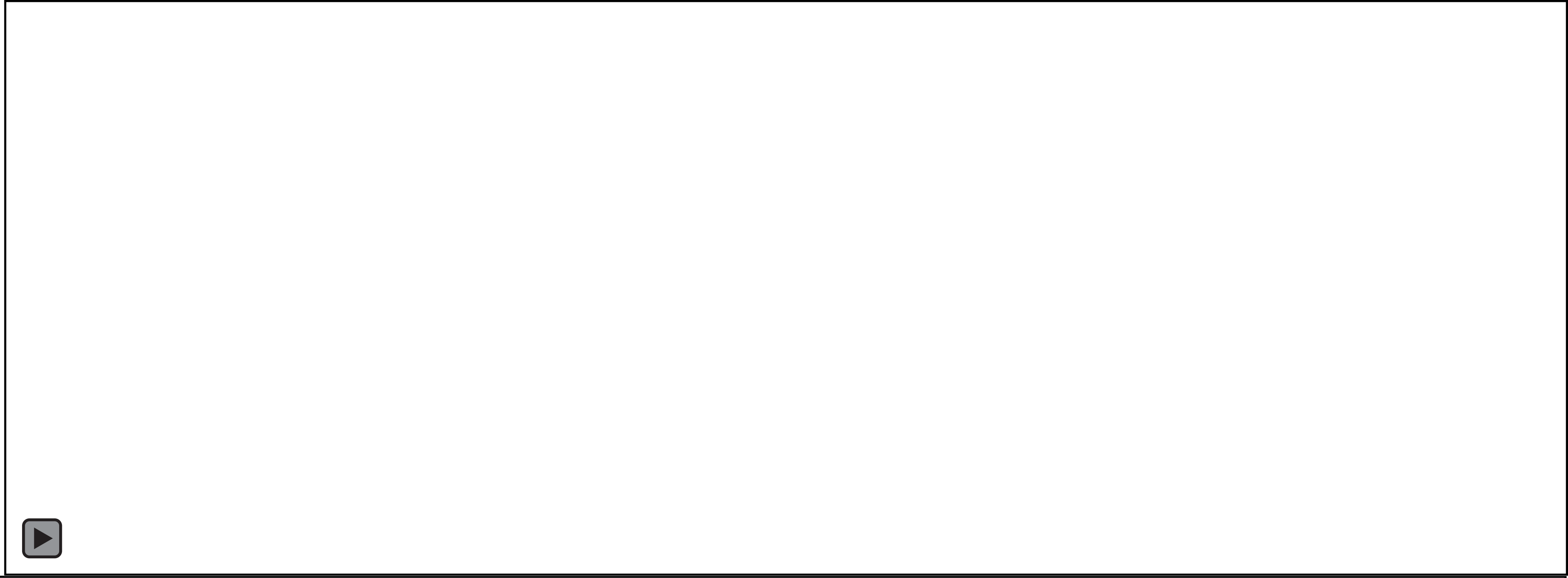
MASH Test 4-20 Simulation on the MEDOT Transition for 4-Bar Bridge Rail

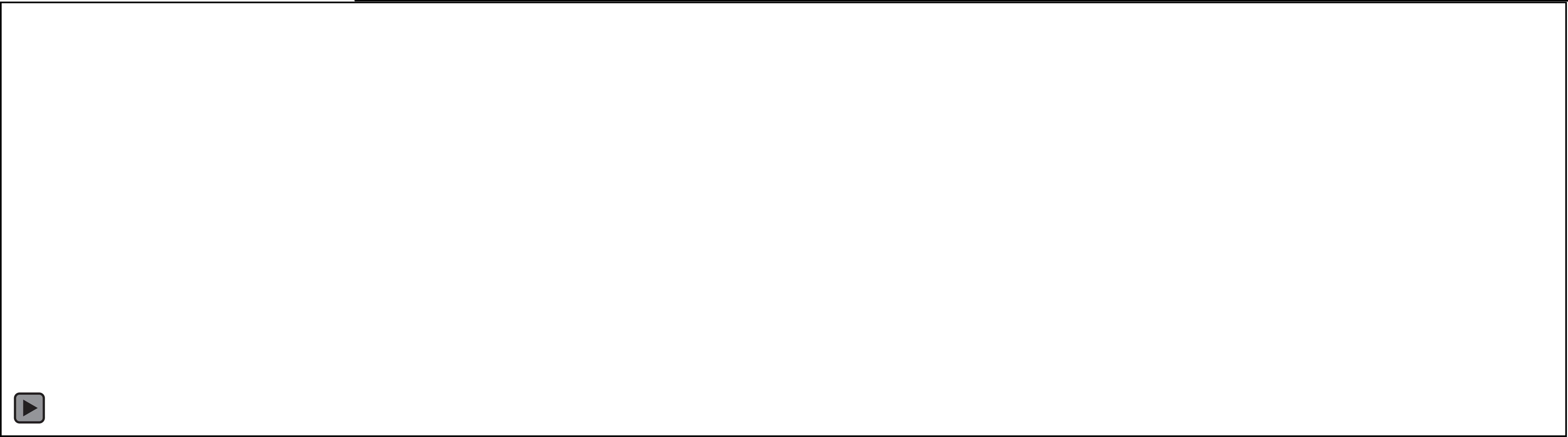
- Impact Conditions
  - Impact Speed = 62.1 mph (100 km/hr)
  - Impact Angle = 25 degrees
  - Impact Point = 5.5 ft upstream from end of concrete abutment
- Vehicle Model
  - YarisC_V1l_R160407.k
  - Vehicle Mass = 1,177 kg (2,595 lb)





Movies





Movies

Movies

TRAP – Summary Table

Occupant Risk Factors		MASH Test 4-20
Occupant Impact Velocity (ft/s)	x-direction	29.2
	y-direction	32.8
	at time	at 0.0767 seconds on right side of interior
THIV (ft/s)		43.3 at 0.0767 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-26 (0.0816 - 0.0916 seconds)
	y-direction	-7.9 (0.0787 - 0.0887 seconds)
PHD (g's)		26.4 (0.0814 - 0.0914 seconds)
ASI		2.37 (0.0371 - 0.0871 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-18.4 (0.0427 - 0.0927 seconds)
	y-direction	-17.4 (0.0225 - 0.0725 seconds)
	z-direction	-3.5 (0.0605 - 0.1105 seconds)
Maximum Angular Disp. (deg)	Roll	5.4 (0.6324 seconds)
	Pitch	-6.8 (0.2502 seconds)
	Yaw	-73.7 (0.6324 seconds)

MASH Criteria

> 30 ft/s (preferred)
< 40 ft/s (limit) ✓

> 15 G (preferred)
> 20.49 G (limit) ☒

< 75 deg ✓

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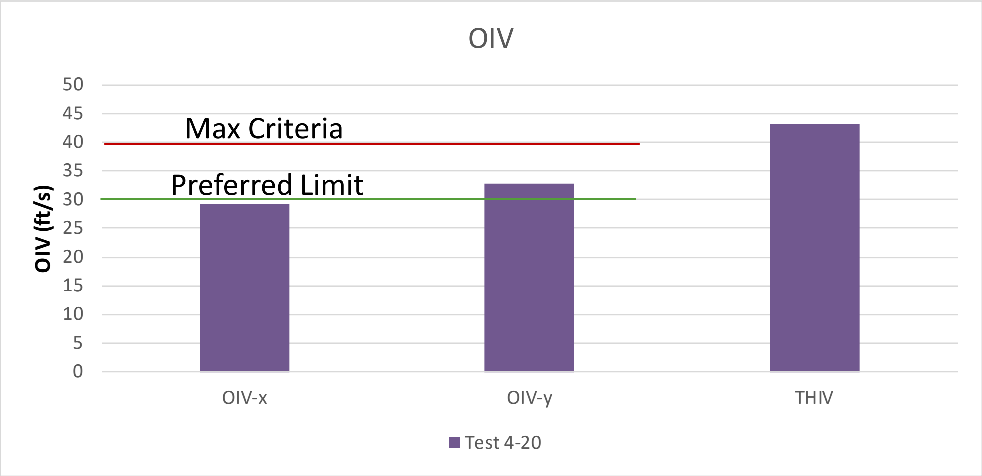
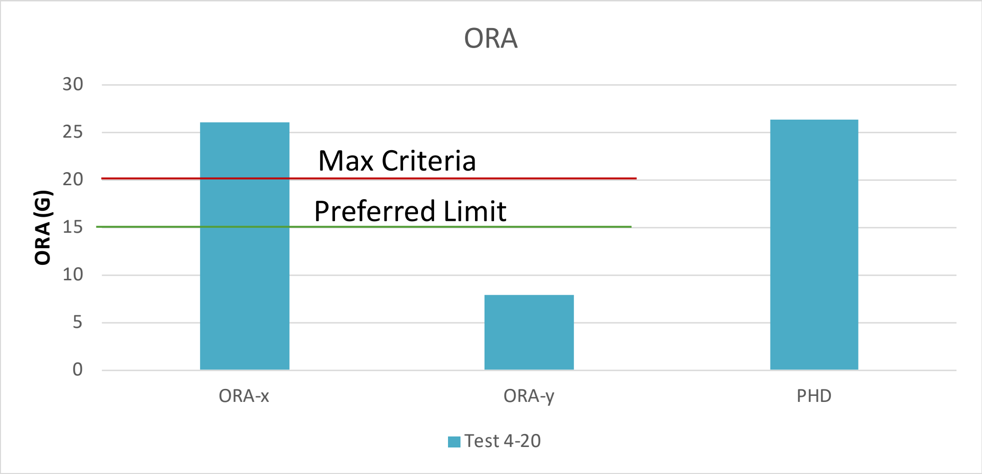
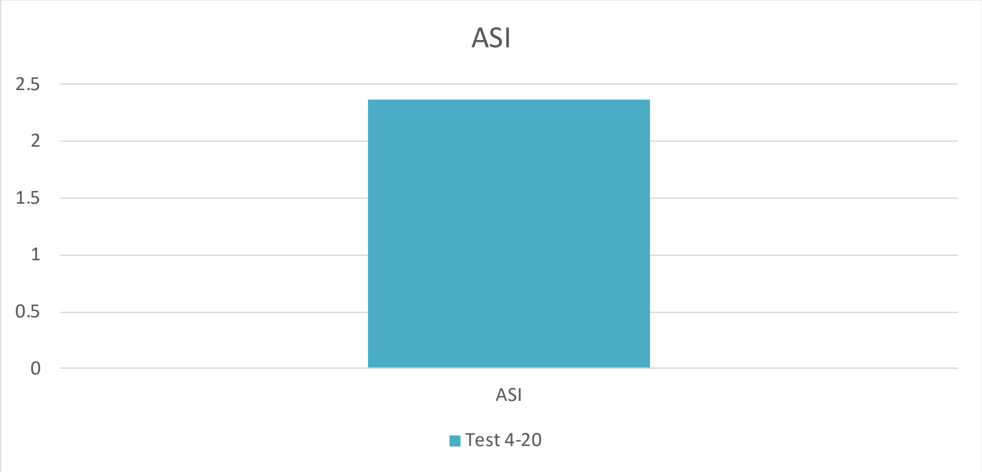
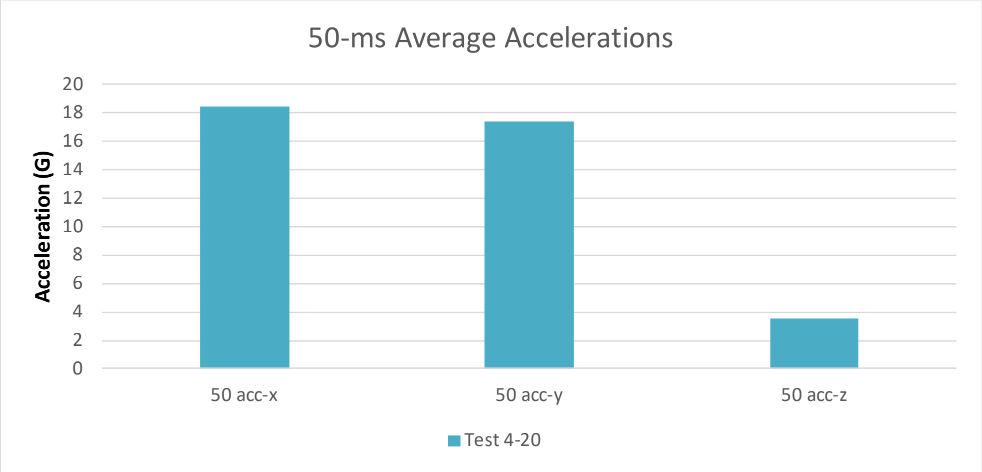
TRAP









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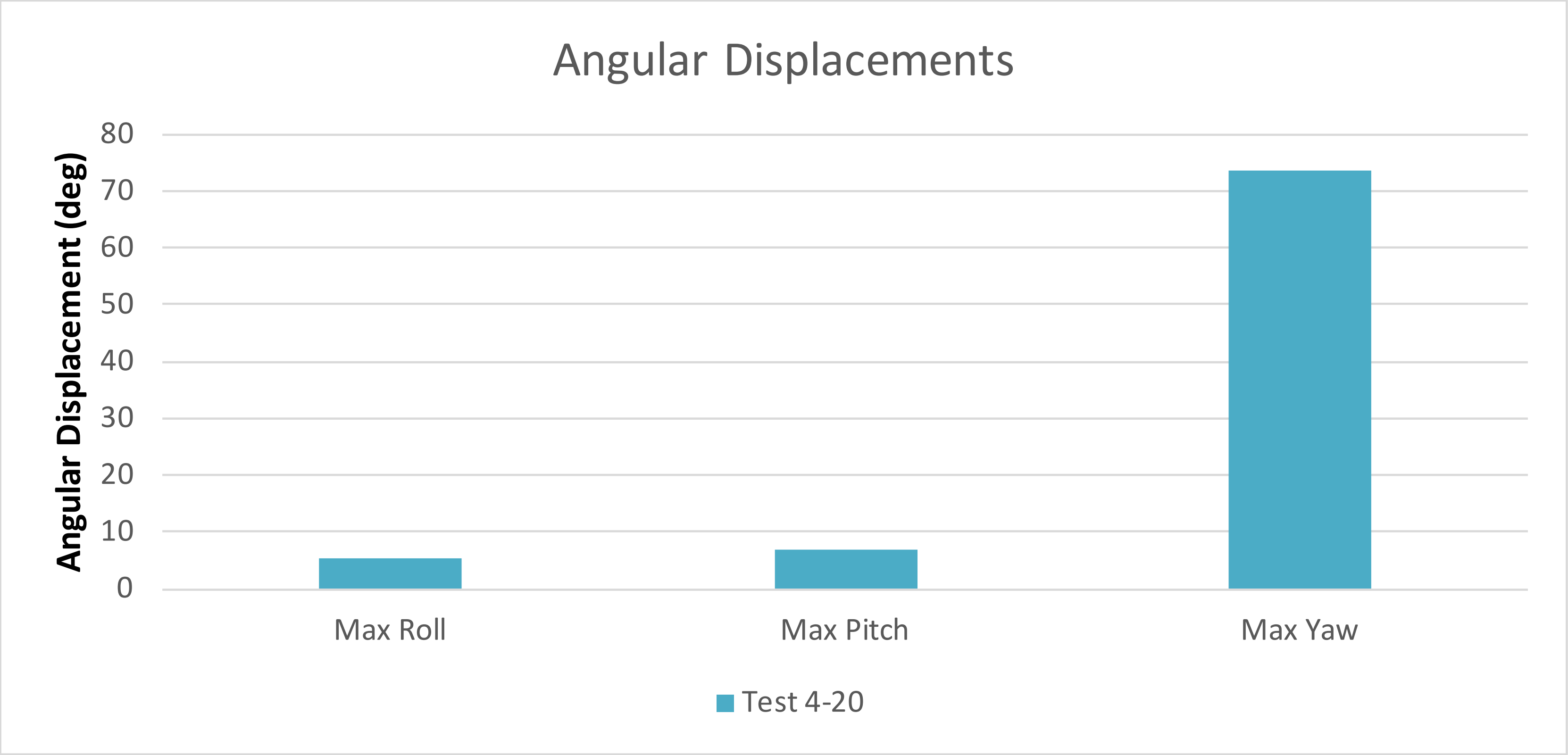
TRAP



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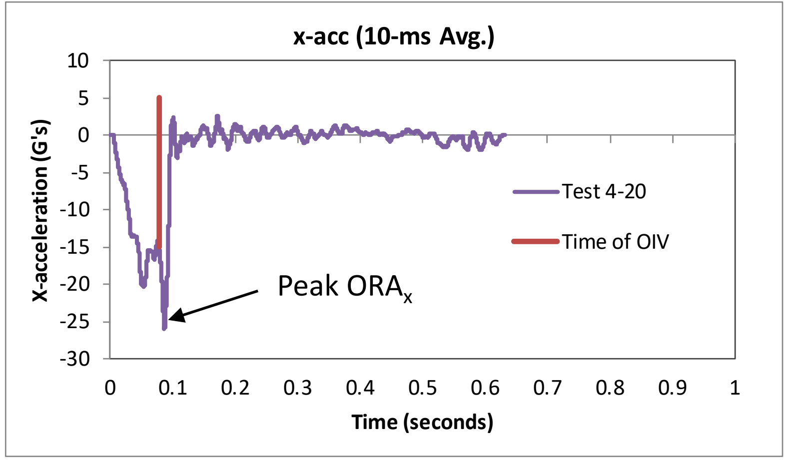
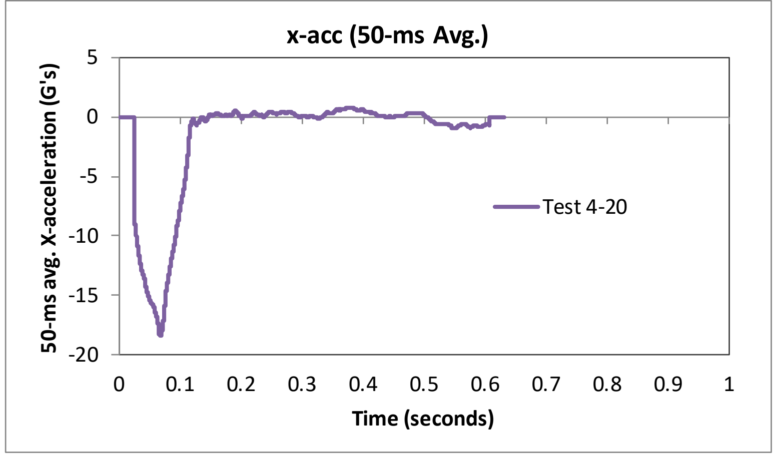
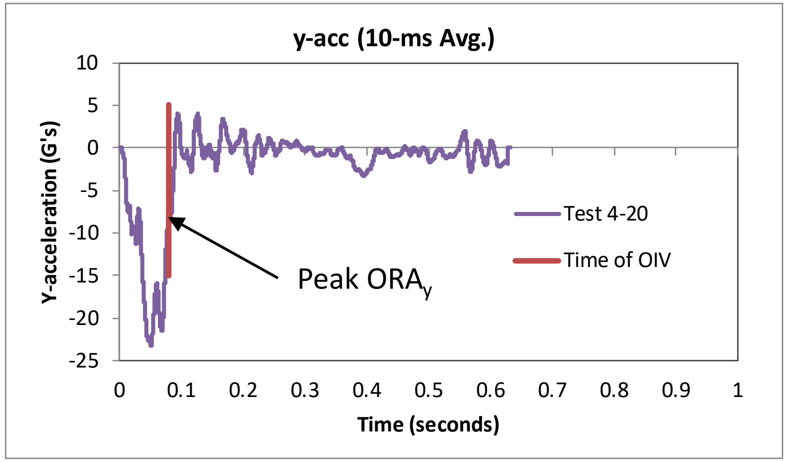
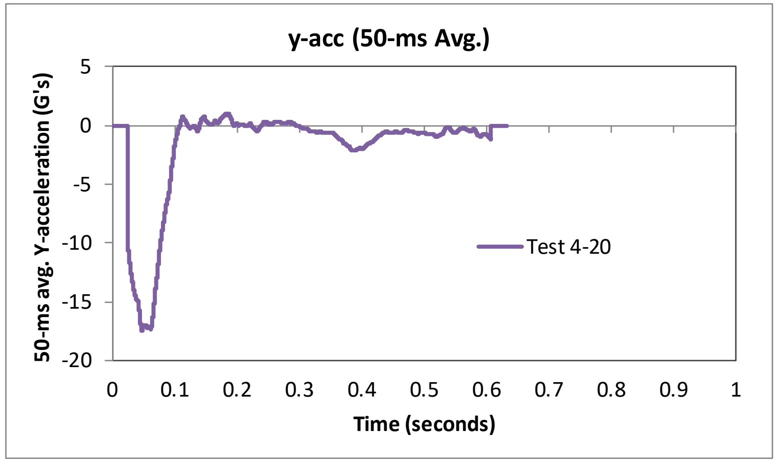
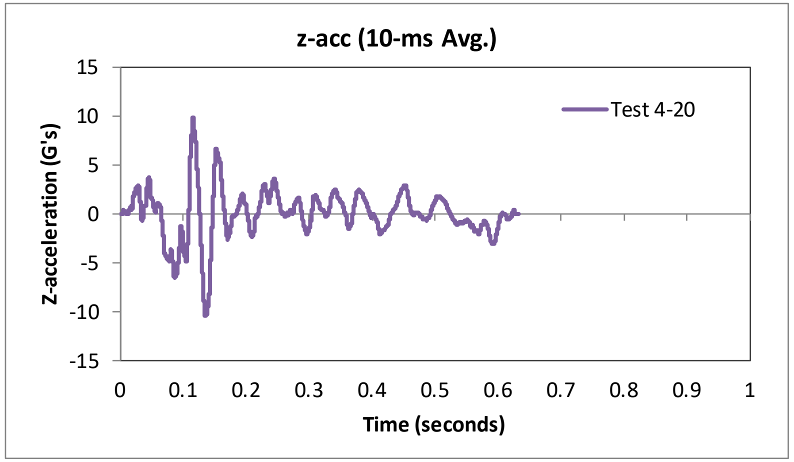
Acceleration Plots

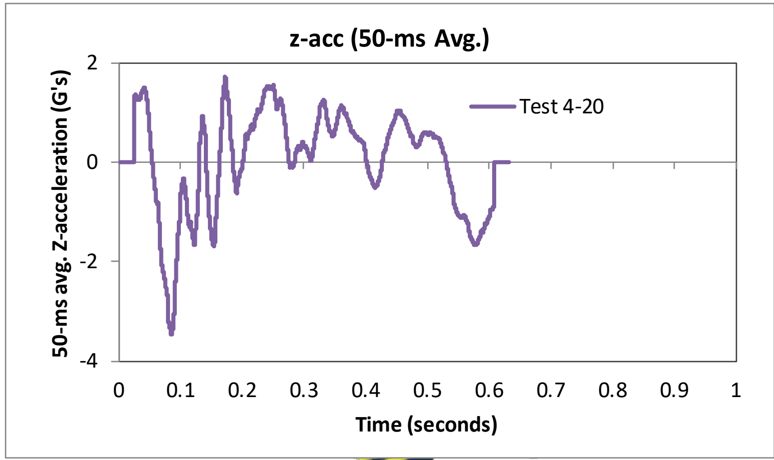




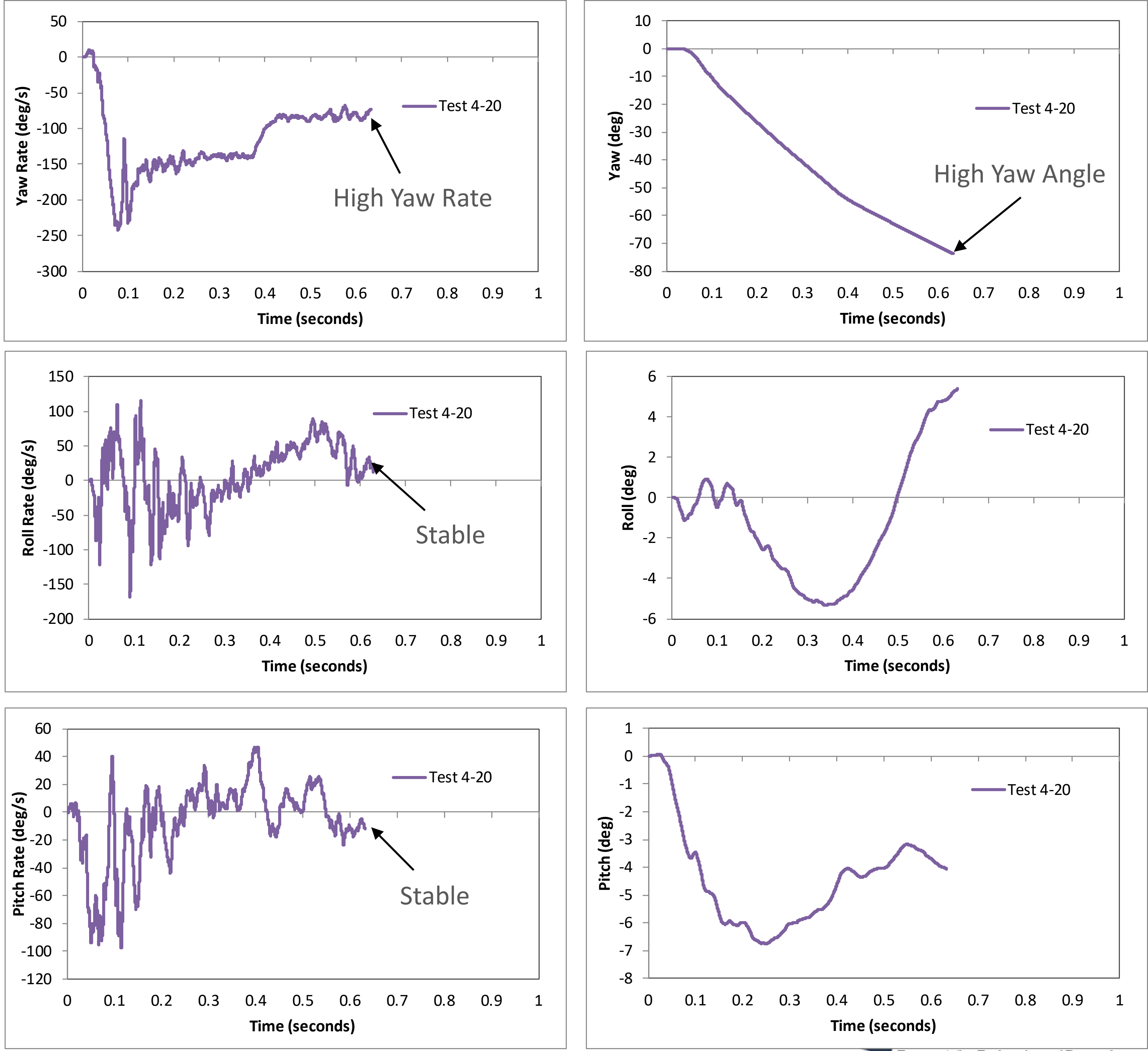




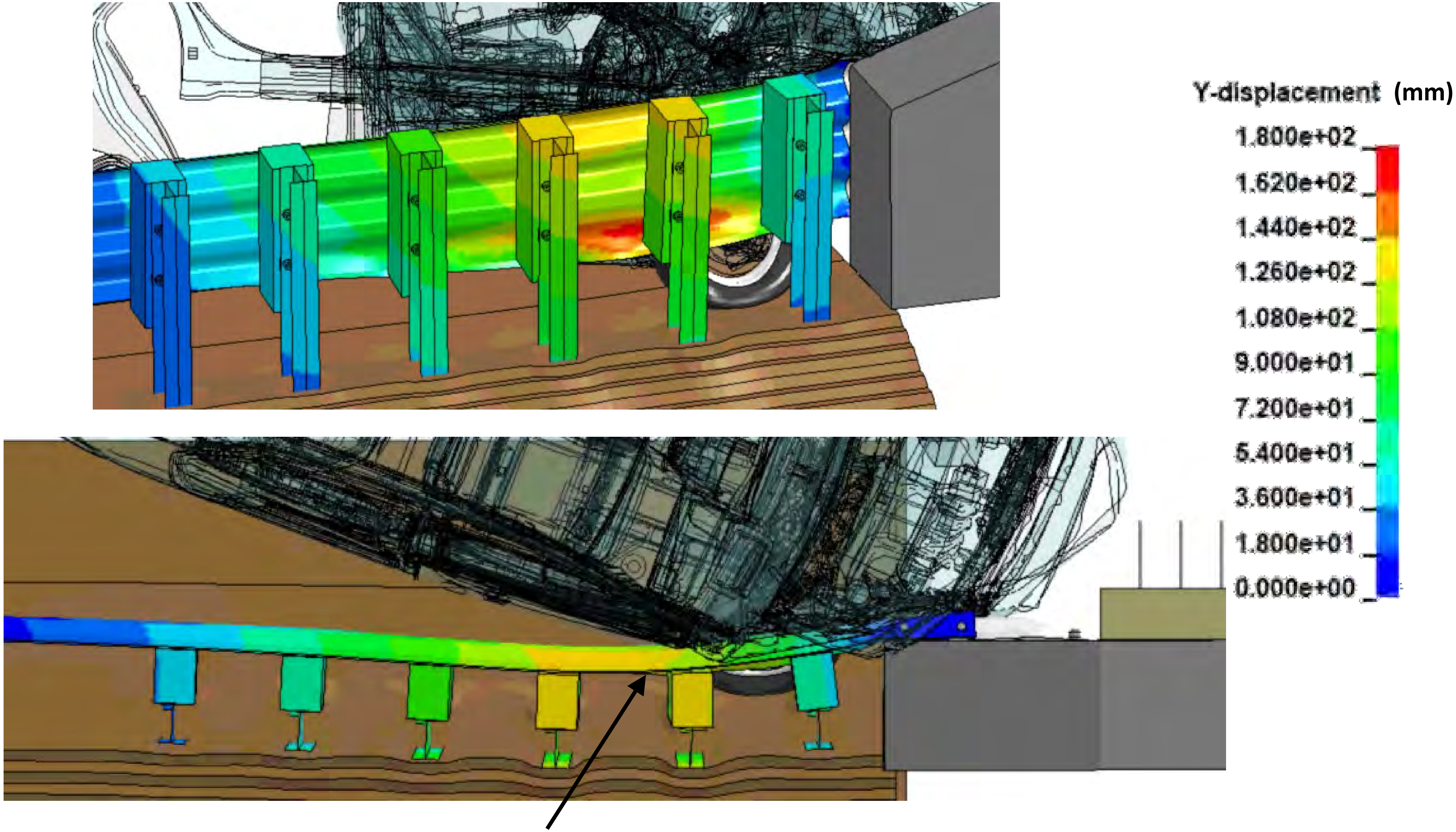




Angular Rate and Displacement Plots

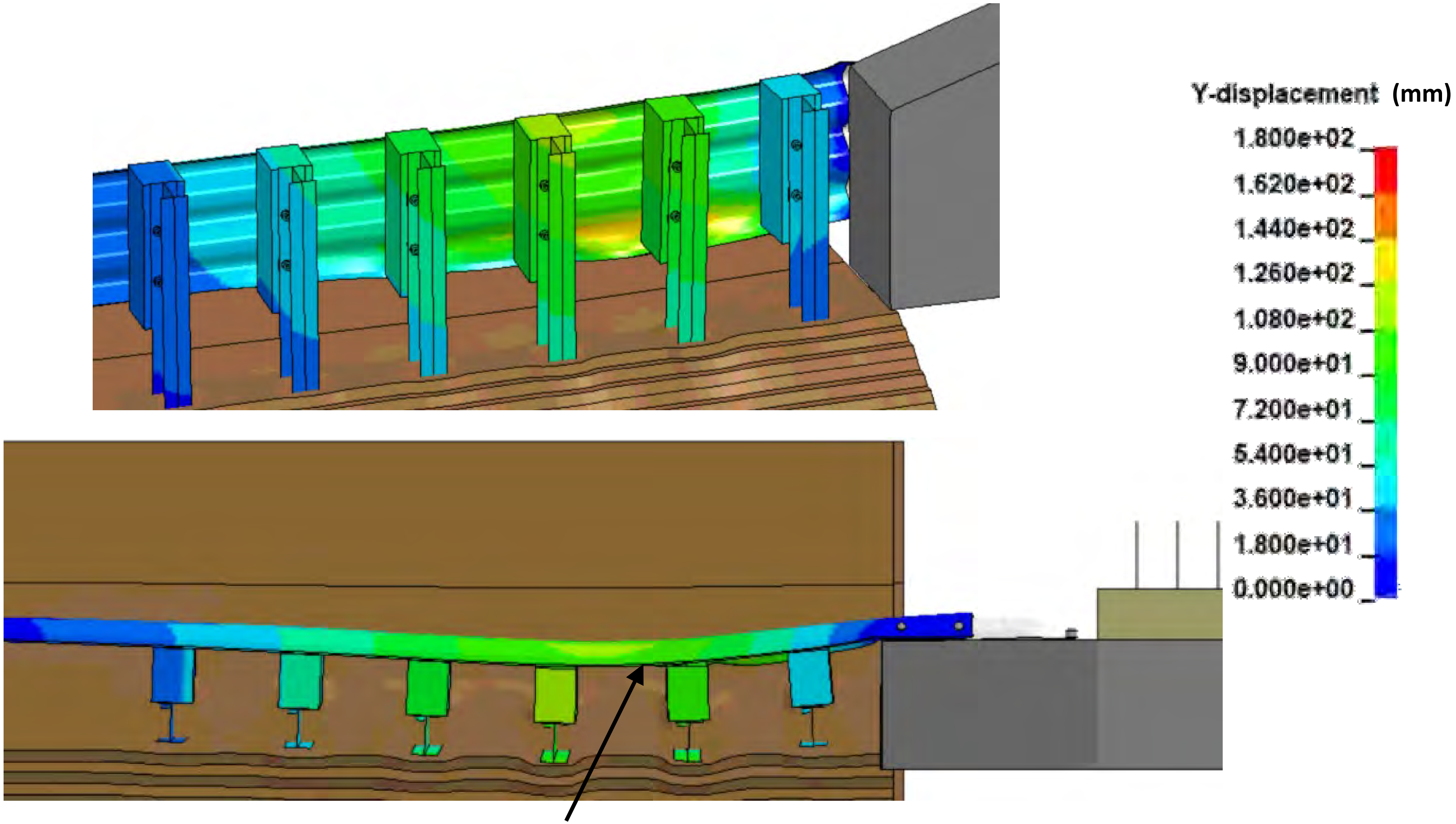


Lateral Dynamic Deflection



Maximum dynamic deflection = 6.93 in (176 mm)

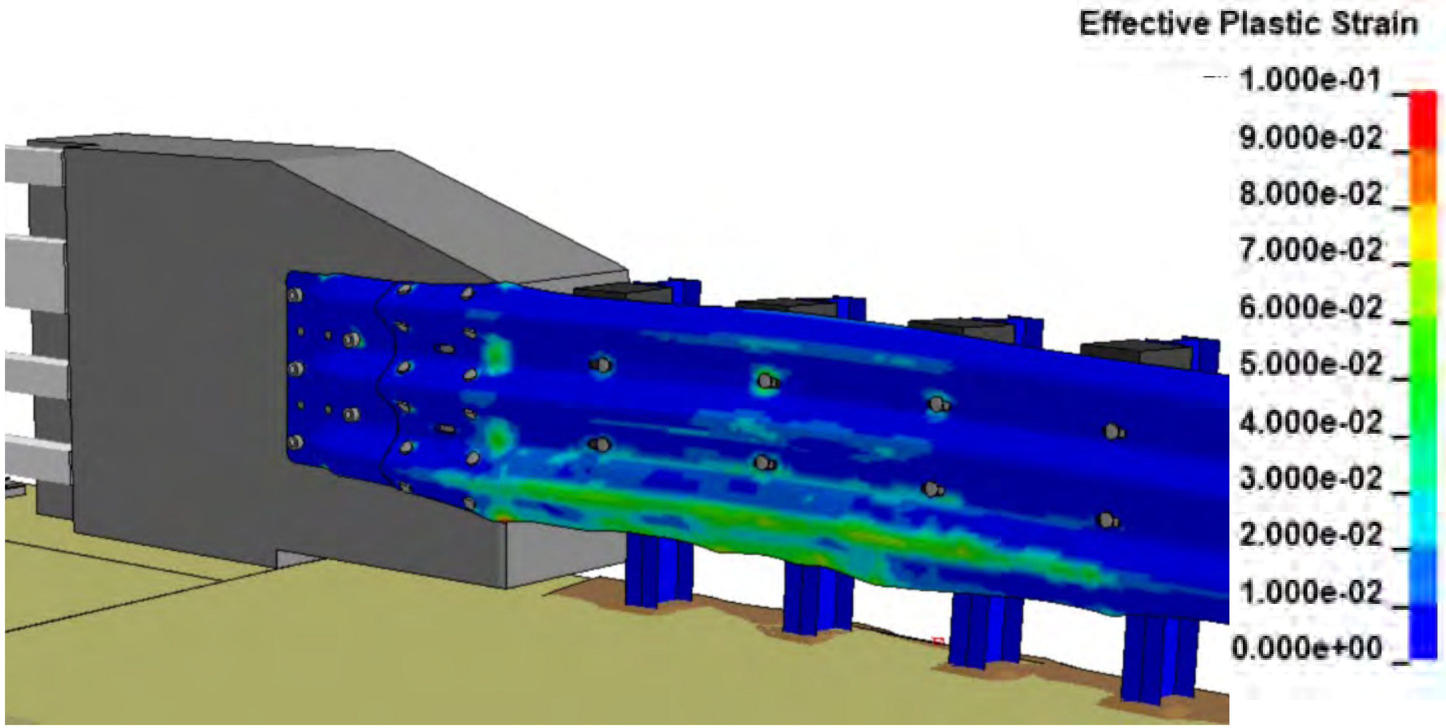
Lateral Permanent Deflection

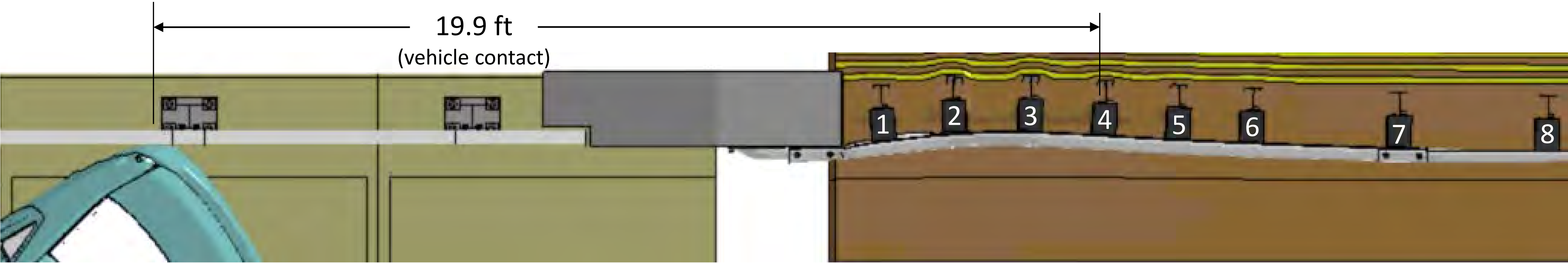


Maximum permanent deflection = 5.7 in (146 mm)

Barrier Damage

- Primary plastic deformations of the steel components of the transition were limited to the thrie-beam and thrie-beam terminal connector, with a sharp kink in the rail at the edge of the buttress.
- There was also soil displacement at Posts 1 – 6 approaching the buttress.
- The vehicle was in contact with the system for approximately 19.9 ft.

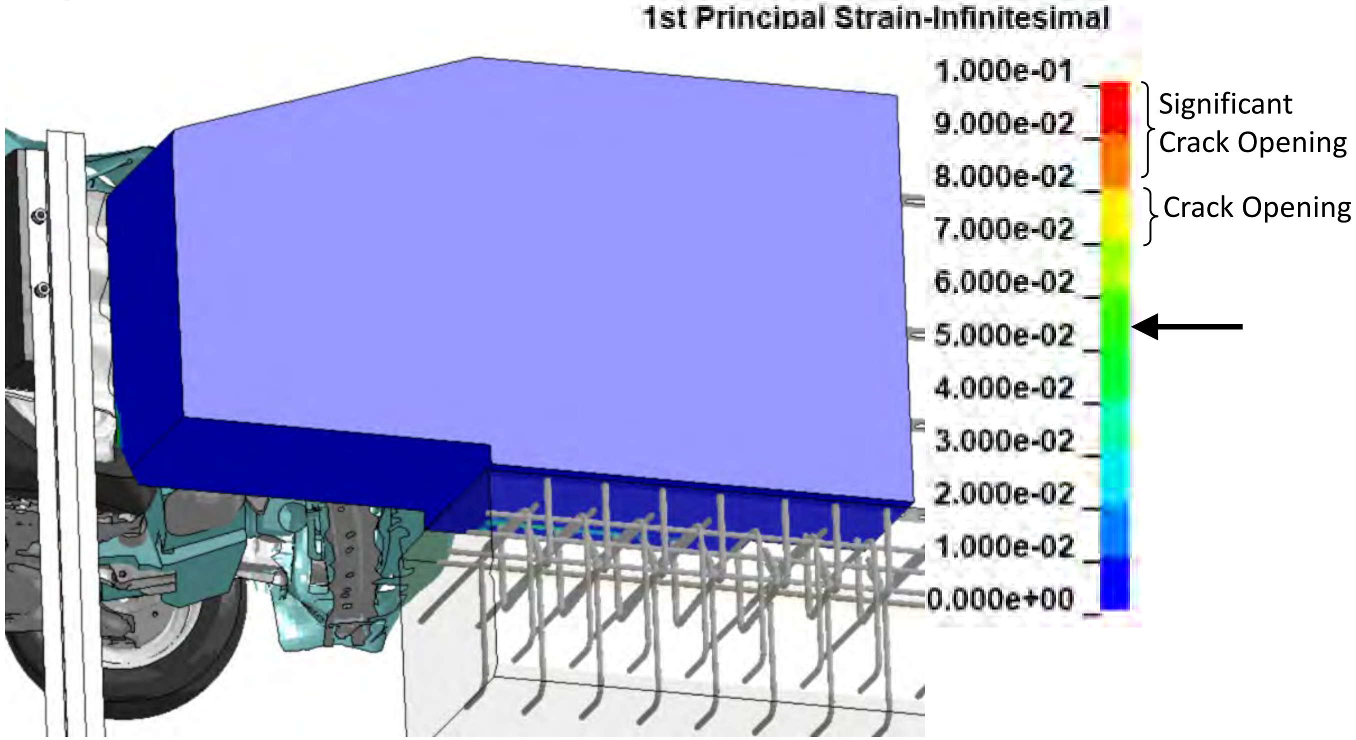




Concrete Buttress Damage

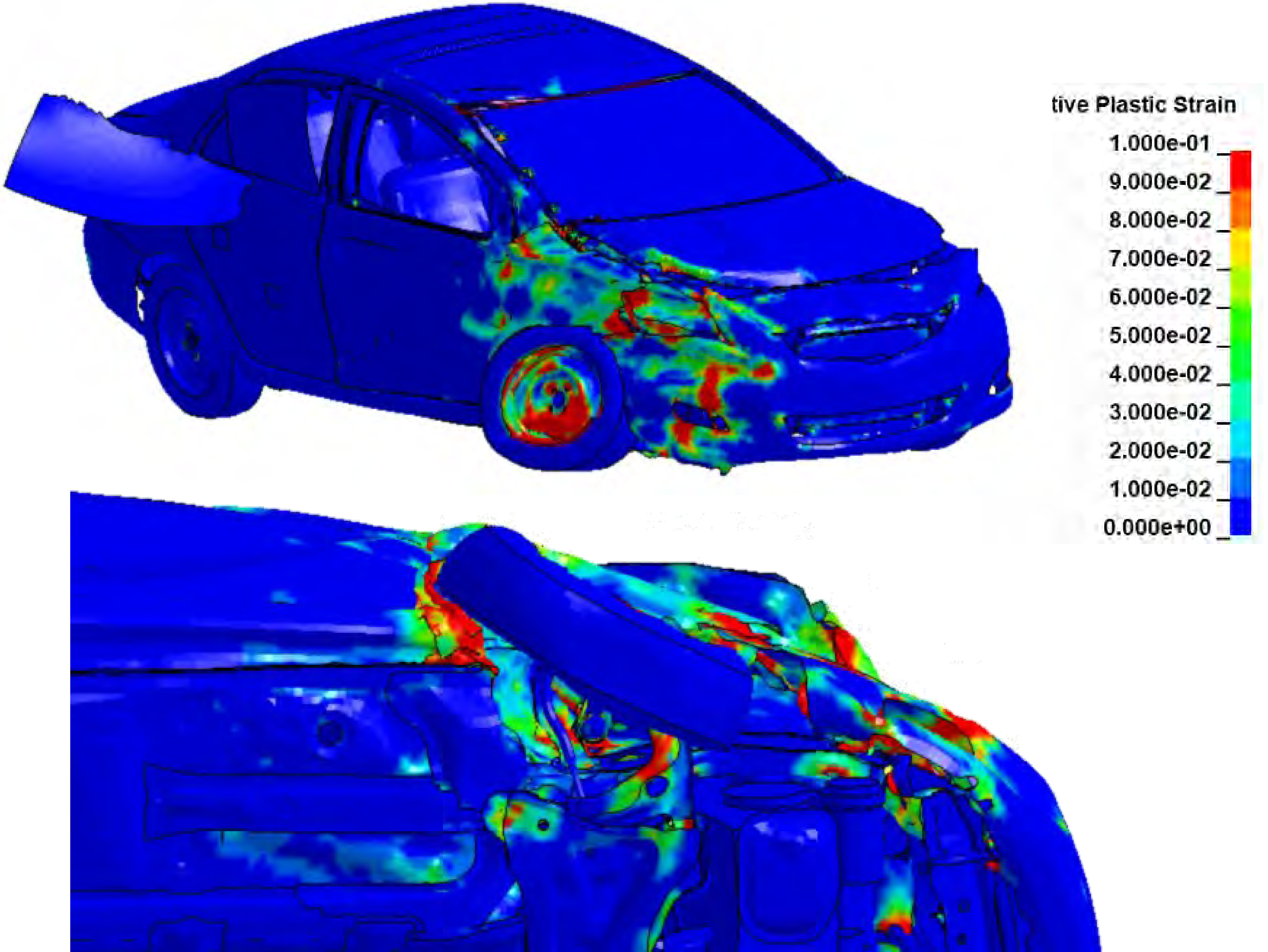
- The damage to the buttress was negligible with strains limited to the joint connection between the buttress and bridge deck.
  - Max dynamic 1st Prin. Strain = 0.054
  - Final 1st Prin. Strain = 0.015

Dynamic at time = 0.085 seconds



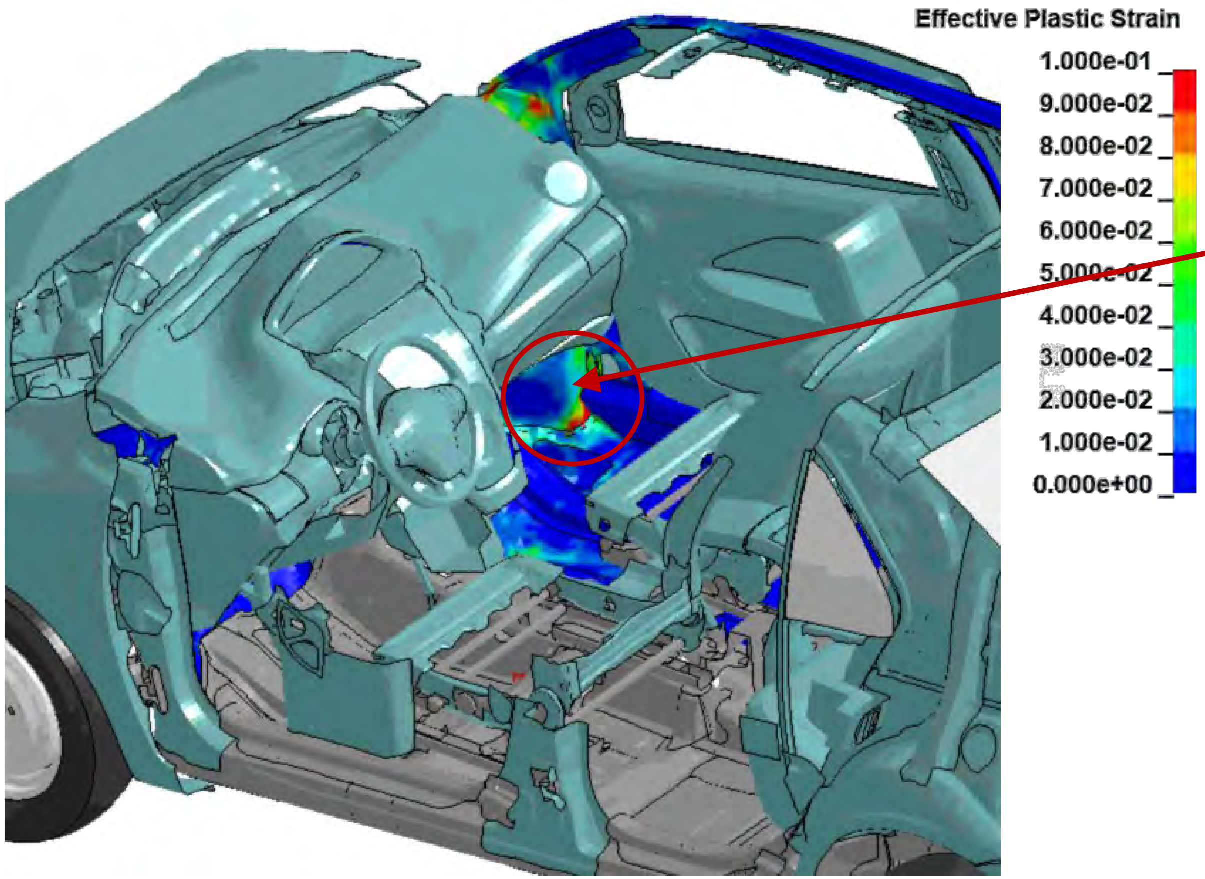
Effective Plastic Strain for Small Car Test

There was significant damages to the front-right corner of the vehicle, including the front fender, the front suspension, front wheel, and the leading edge of the front door on the impact side, the A-pillar, both passenger windows, and the right edge of the windshield at the A-pillar on the impact side.



Occupant Compartment Intrusion

Occupant Compartment Intrusion (OCI)



- Maximum OCI of the floor, doors, and side panels was ≈**3.4 inches** (87 mm) and occurred at the right-front toe-pan at the wheel well
  - *(Maximum allowable is 9").*
- *The lateral deformation of the A-pillar was **2 inches***
  - *(Maximum allowable = 3")*

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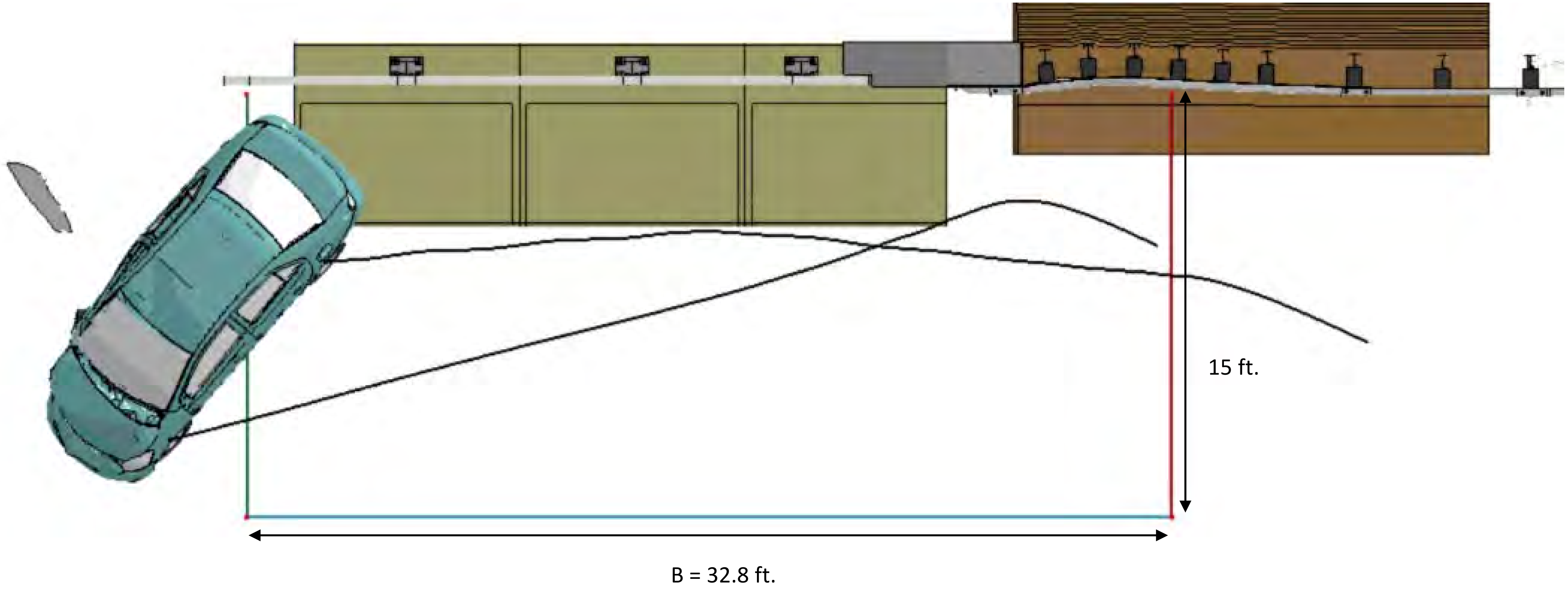
Exit Box – MEDOT Trans– Test 4-20

The driver-side front tire wheel track was used to determine the beginning location of the exit box. From MASH pg. 97: “All wheel tracks of the vehicle should not cross the parallel line within the distance B.”



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Conclusions on Test 4-20 on the MEDOT Transition

- The barrier successfully contained and redirected the 1100C vehicle.
- The vehicle remained upright and relatively stable through impact and redirection, although the yaw angle and yaw rate was somewhat high.
  - Max Roll = **5.4 degrees,** Max Pitch = **6.8 degrees**.
  - Yaw Angle at Analysis Termination = **73.7 degrees**
  - Yaw Rate at Analysis Termination ≈ **75 deg/s**
- The OIV was within critical limits, but the maximum ORA exceeded critical limits specified in MASH (i.e., > 20.49 G).
  - OIV_x = **29.2 ft/s** and OIV_y = **32.8 ft/s**
  - ORA_x = **26 G** and ORA_y = **7.9 G**
- The maximum occupant compartment deformation was 3.4 inches (well below critical limit of 9”);
- The lateral deformation of the A-pillar was 2 inches (below critical limit of 3”)
- The vehicle also **remained within the “exit box”** limits; however, the yaw angle at analysis termination indicated that the vehicle may enter back into travel lanes.
- The damages to the transition were moderate and within expectations, including kinking of the thrie-beam, lateral deflection of several posts and corresponding soil displacement at those posts.
- The damages to the concrete buttress were negligible.
- The greatest deformation of the barrier occurred on the lower corrugation of the thrie-beam between Posts 2 and 3 (relative to the nose of the buttress) and was:
  - Max Dynamic = **6.9 inches**; Max Permanent = **5.7 inches**

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Conclusions on Test 4-20 on the MEDOT Transition

Evaluation Factors		Evaluation Criteria	Results
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
Occupant Risk	D	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, to occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.	Pass
	F	The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.	Pass
	H	The longitudinal and lateral occupant impact velocity (OIV) shall not exceed 40 ft/s (12.2 m/s), with a preferred limit of 30 ft/s (9.1 m/s)	Pass
	I	The longitudinal and lateral occupant ridedown acceleration (ORA) shall not exceed 20.49 G, with a preferred limit of 15.0 G	**Fail**

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Determination of CIP for Test 4-21

- CIP was determined using FEA based on maximizing potential for snag on the end of the concrete buttress.
  - Pocketing
    - Maximum relative deflection between thrie-beam and buttress
  - Peak accelerations relative to critical snag point
    - Peak longitudinal acceleration (e.g., generally identifies snag)
    - Peak lateral acceleration (e.g., point of highest lateral force)
  - OIV and ORA since these metrics are used directly in crashworthy assessments in MASH
  - Impact severity and kinetic energy at time of impact with critical snag point
- Analysis Cases (5 cases):
  - Impact points 5.5 ft, 6.0 ft, 6.5 ft, 7.0 ft, and 7.5 ft from the end of the buttress.
  - These analyses were conducted for 0.15 seconds of impact for the purpose of determining the critical impact point for maximizing vehicle accelerations and maximizing forces on the barrier at the junction point of the thrie-beam and the concrete buttress.

CIP Analysis Cases

IP 5.5 ft

IP 6.0 ft

IP 6.5 ft

IP 7.0 ft

IP 7.5 ft

CIP Analysis Cases

IP 5.5 ft

IP 6.0 ft

IP 6.5 ft

IP 7.0 ft

IP 7.5 ft

CIP Analysis Cases (1st Principle Strain Contour)

IP 5.5 ft

Max Strain = 0.109

IP 6.0 ft

Max Strain = 0.094

IP 6.5 ft

Max Strain = 0.112

IP 7.0 ft

Max Strain = 0.101

IP 7.5 ft

Max Strain = 0.078

Case IP 5.5ft – 7.0ft indicate concrete failure around first 2-3 stirrups on traffic side of abutment

CIP Analysis Cases (1st Principle Strain Contour)

IP 5.5 ft

IP 6.0 ft

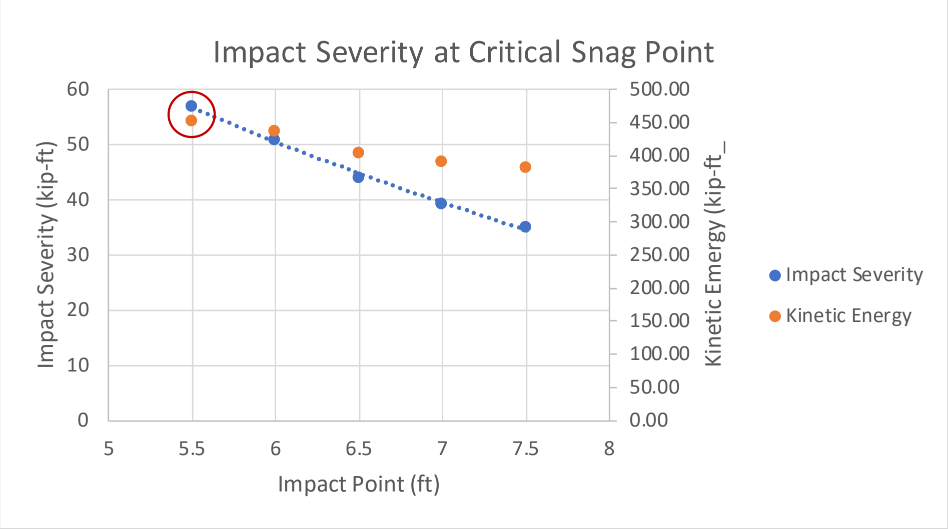
IP 6.5 ft

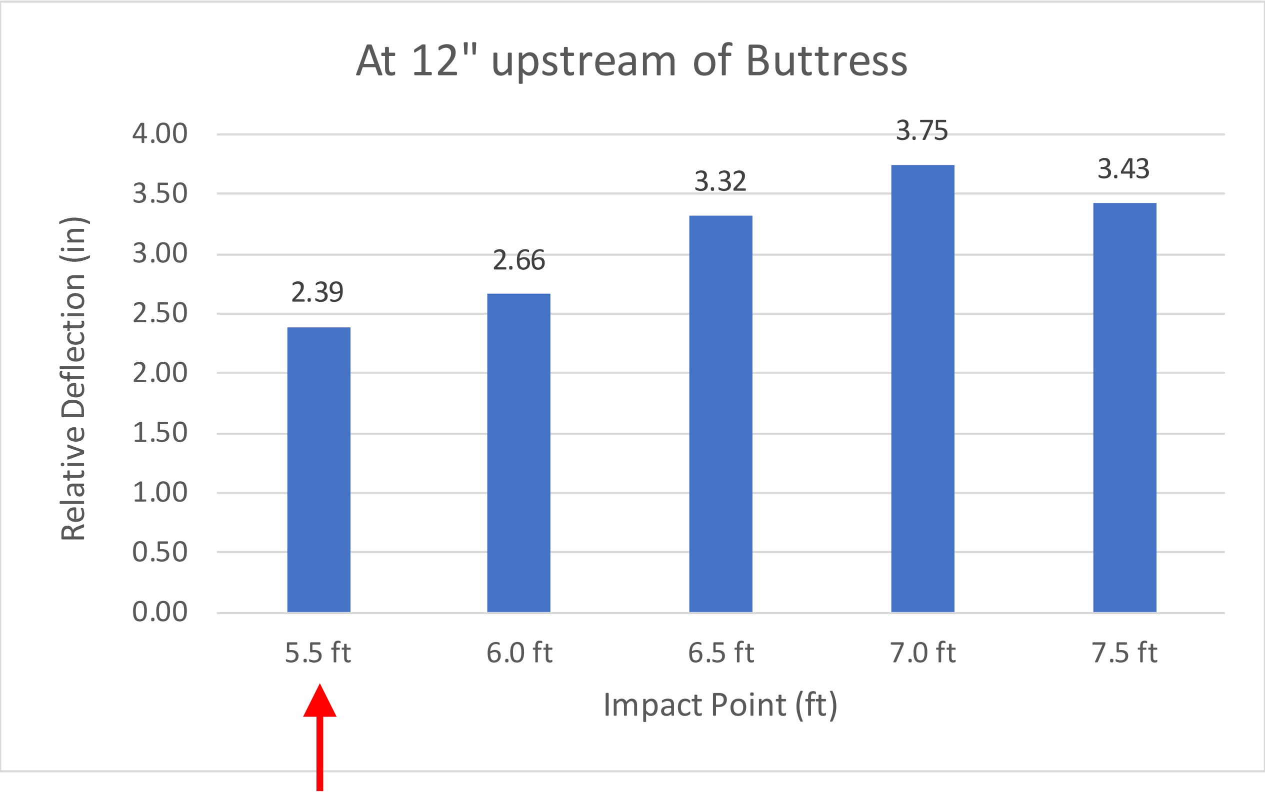
IP 7.0 ft

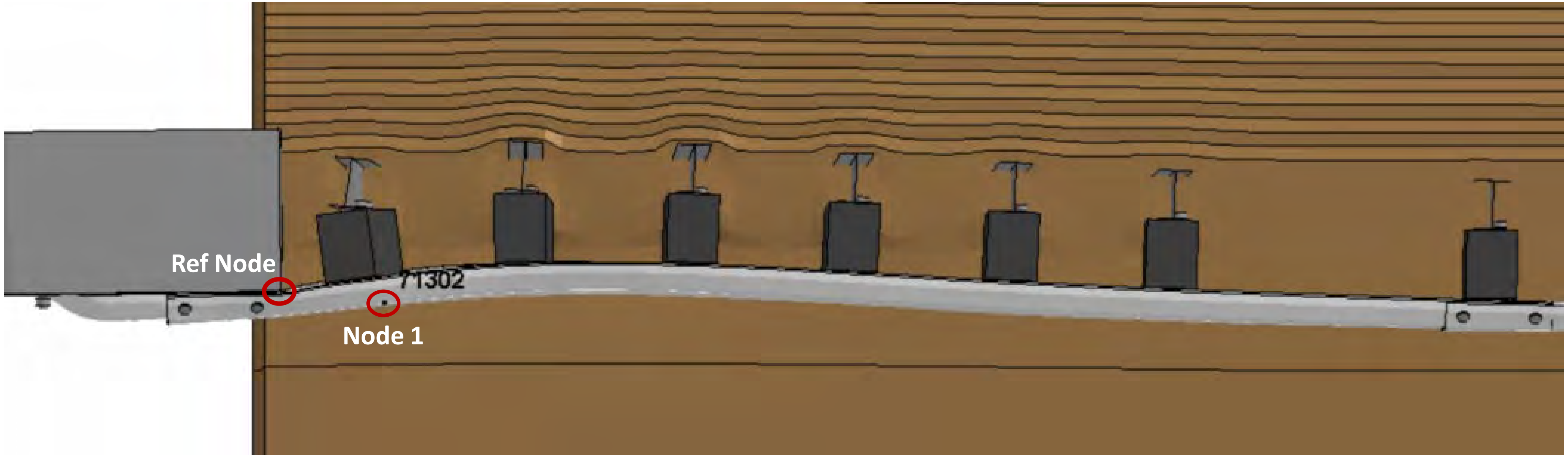
IP 7.5 ft

Case IP <u>5.5ft</u> and <u>6.5ft</u> significant cracking of concrete sidewalk/deck on field side of abutment

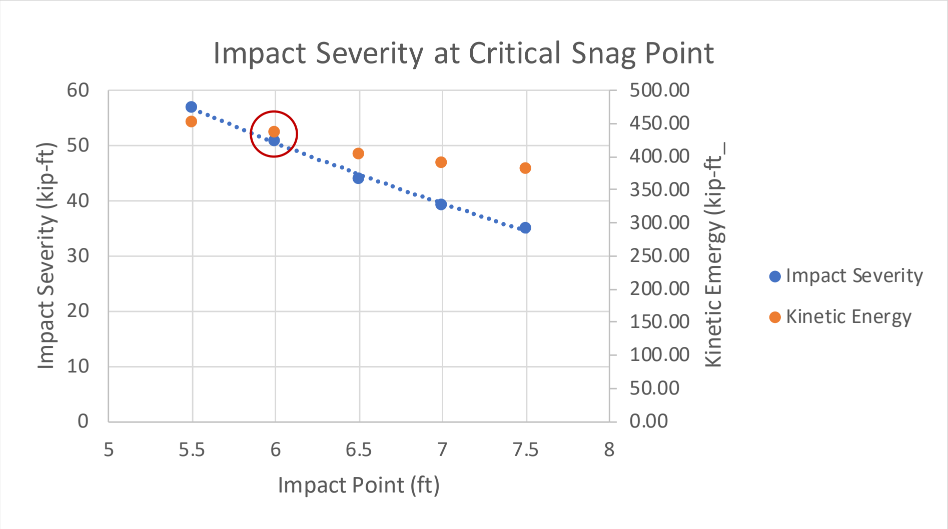
Pocketing, IS and Kinetic Energy

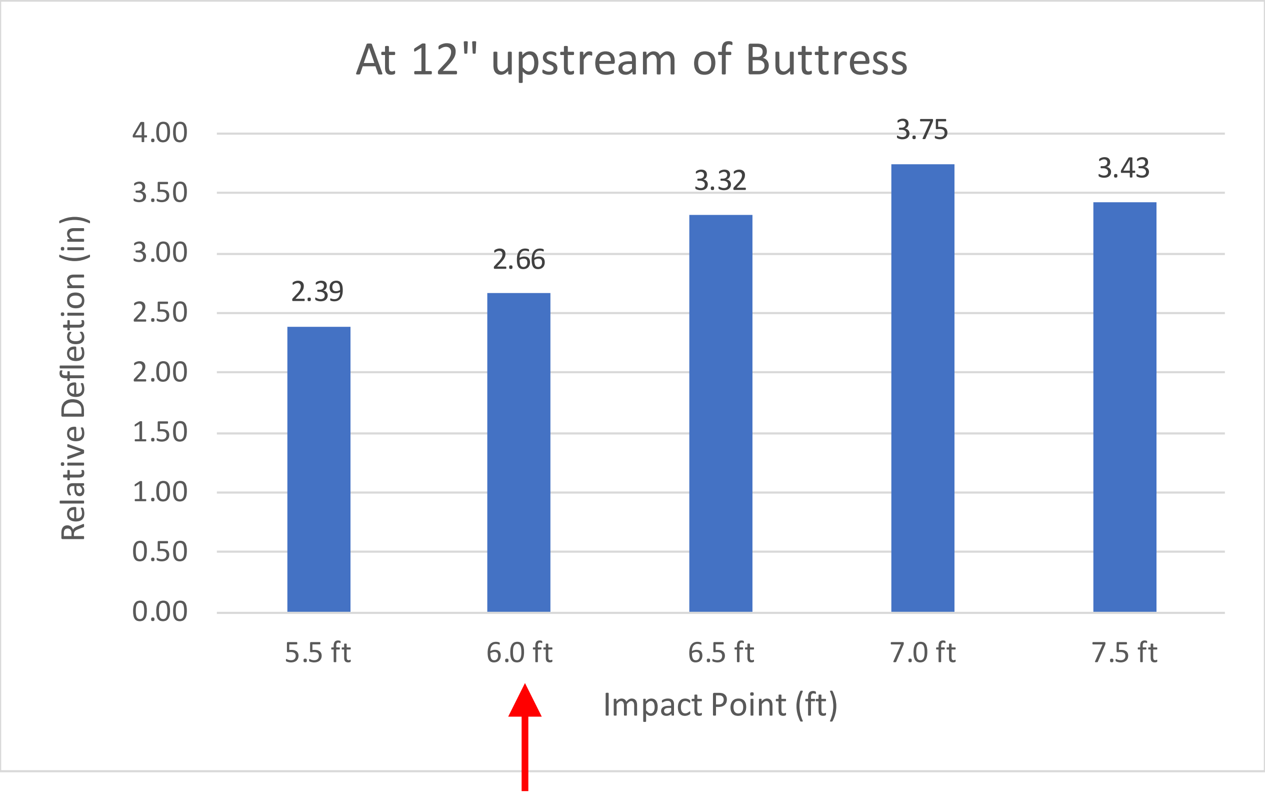


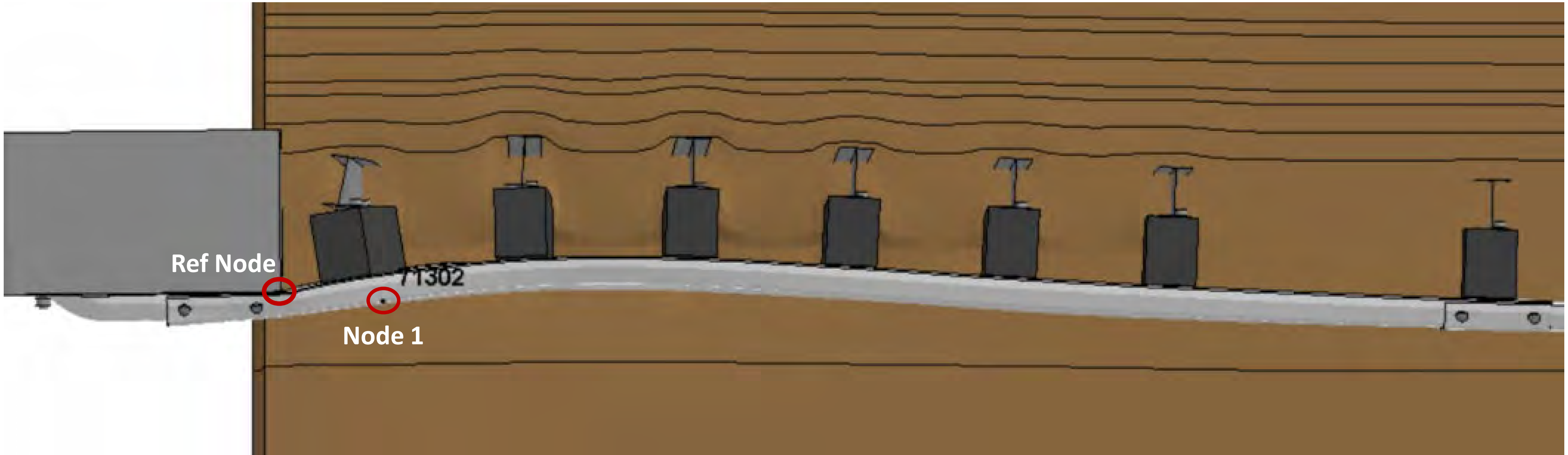




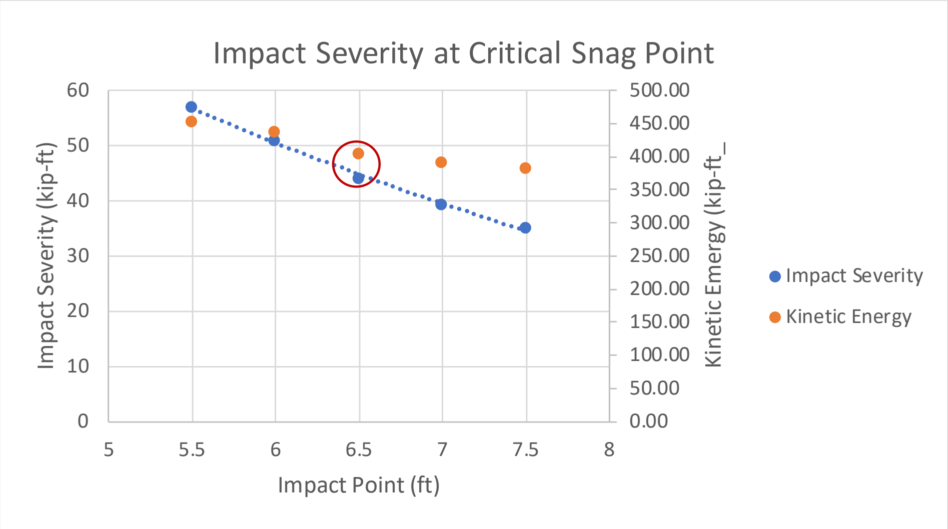
Pocketing, IS and Kinetic Energy

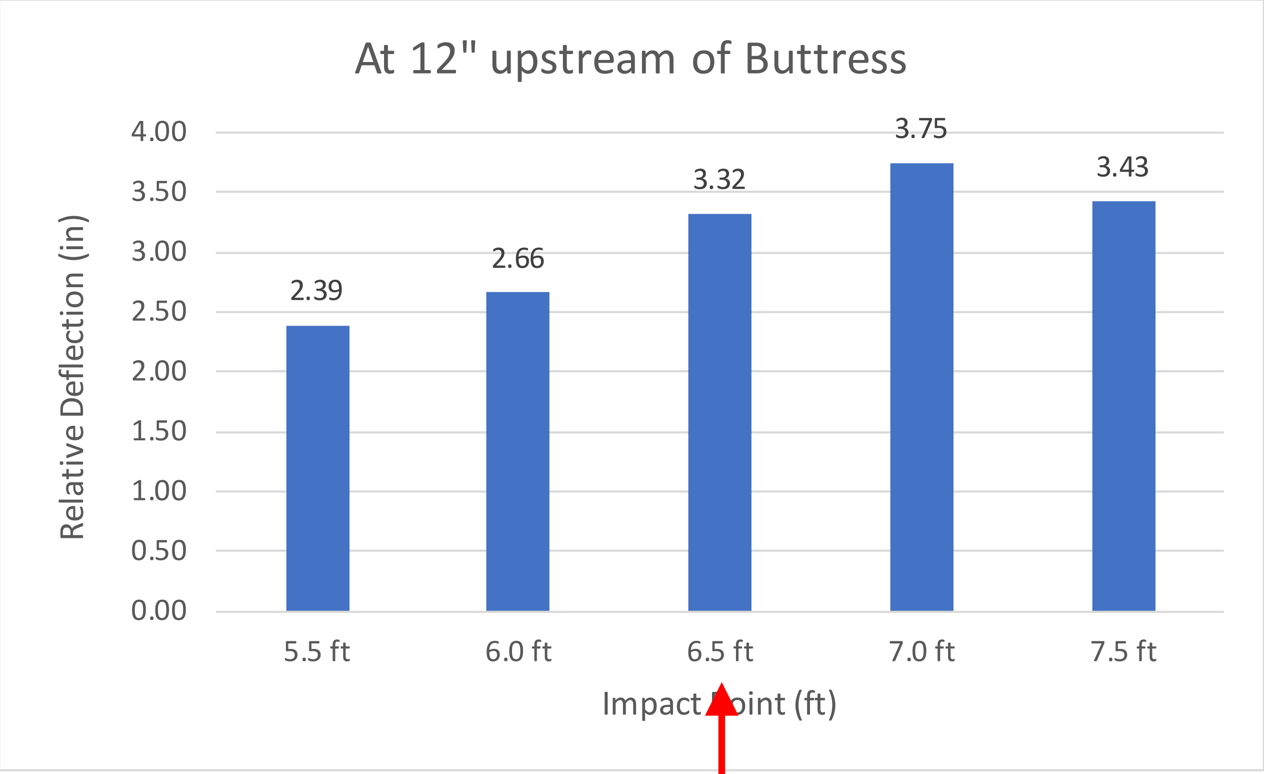


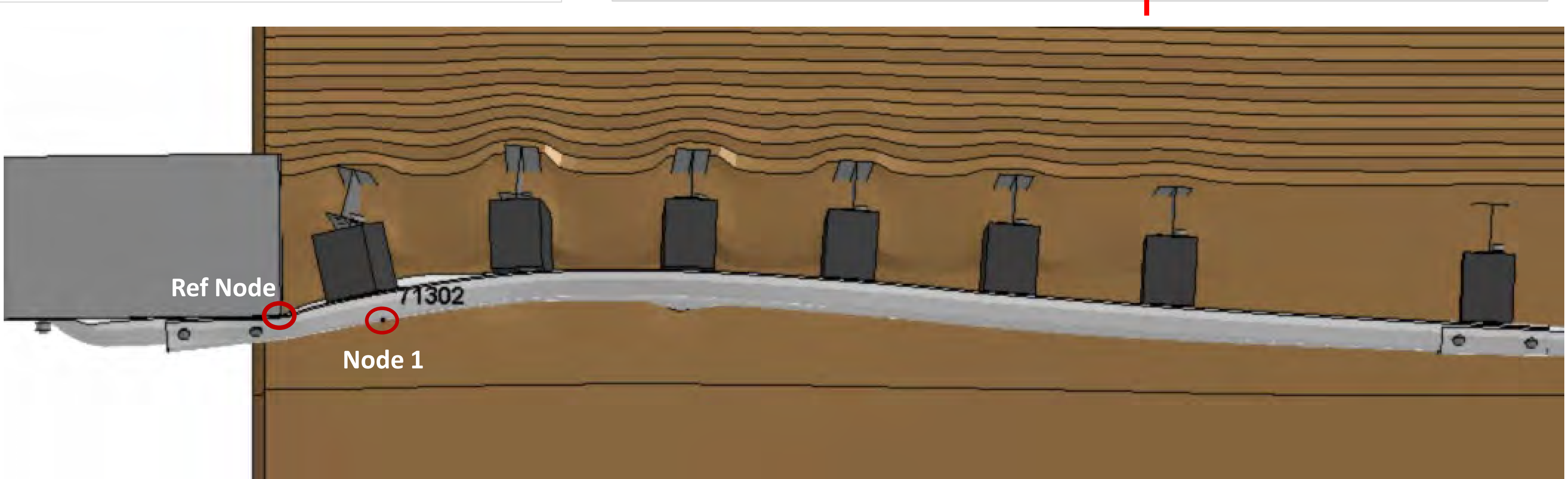




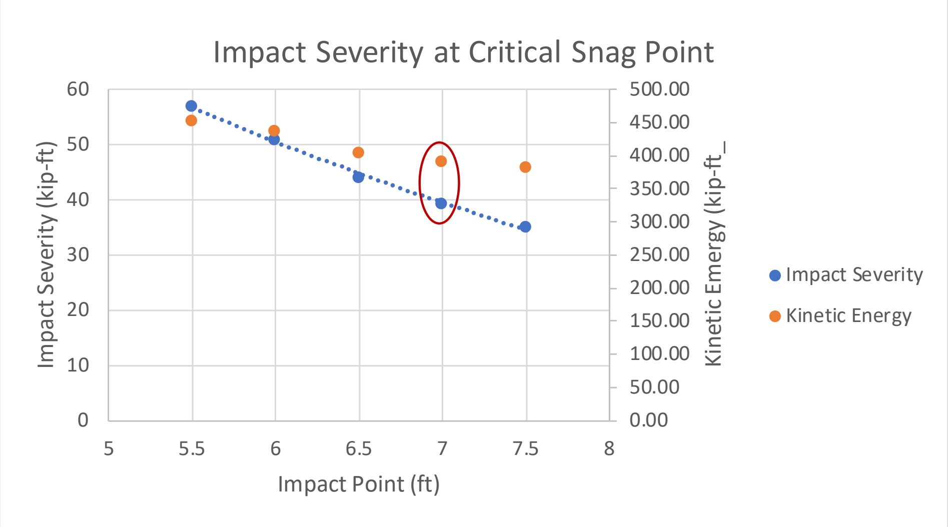
Pocketing, IS and Kinetic Energy

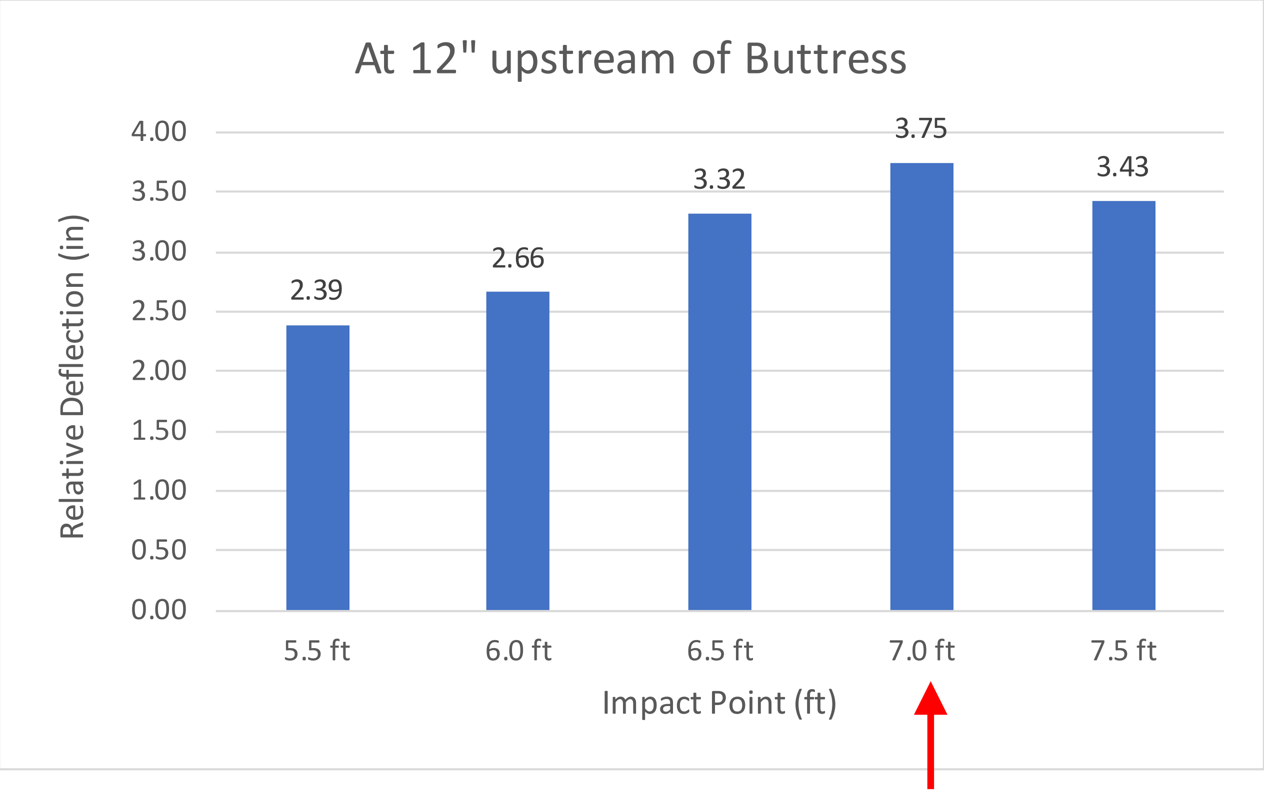


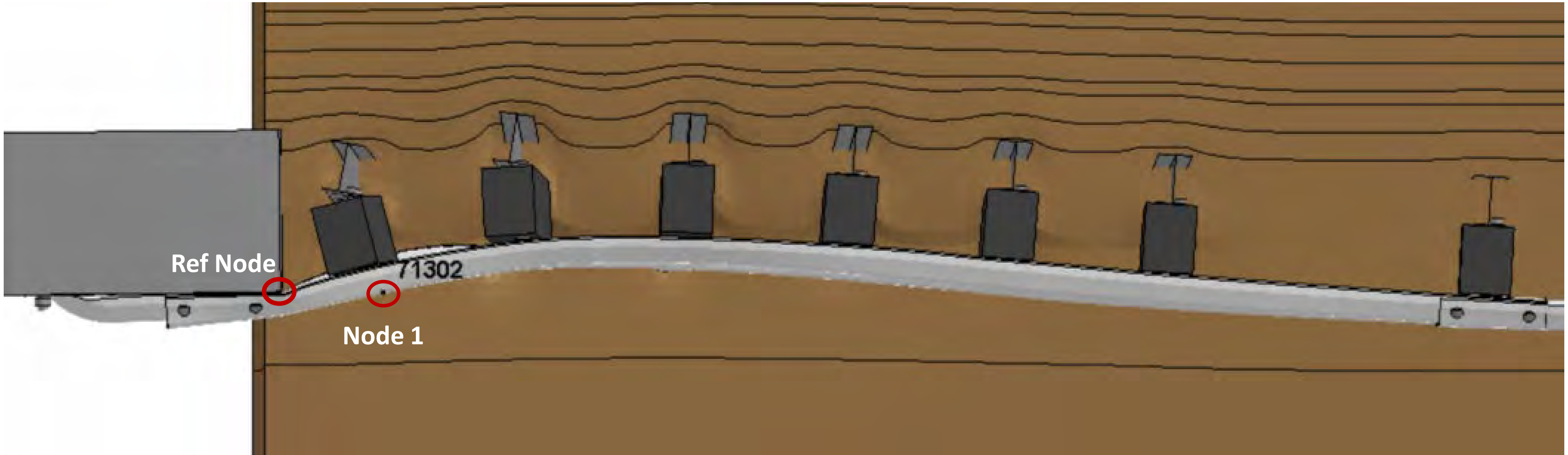




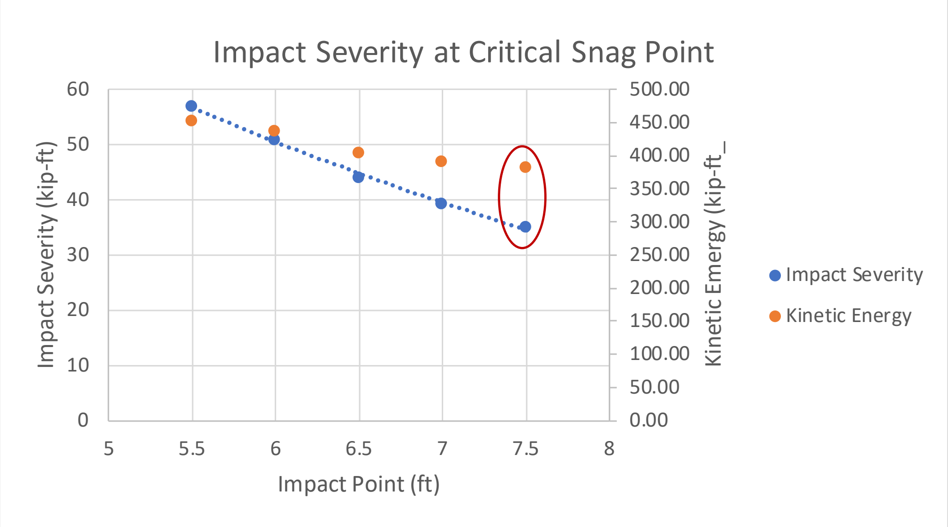
Pocketing, IS and Kinetic Energy

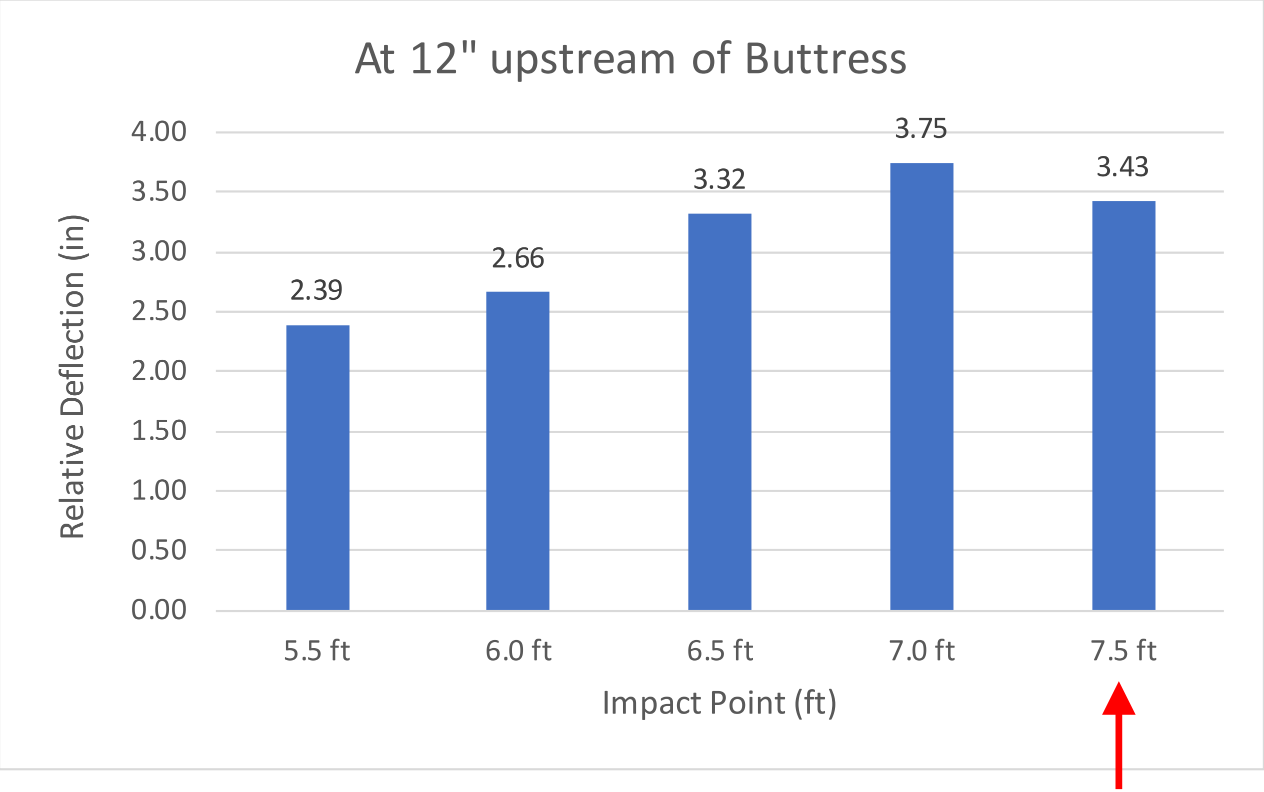


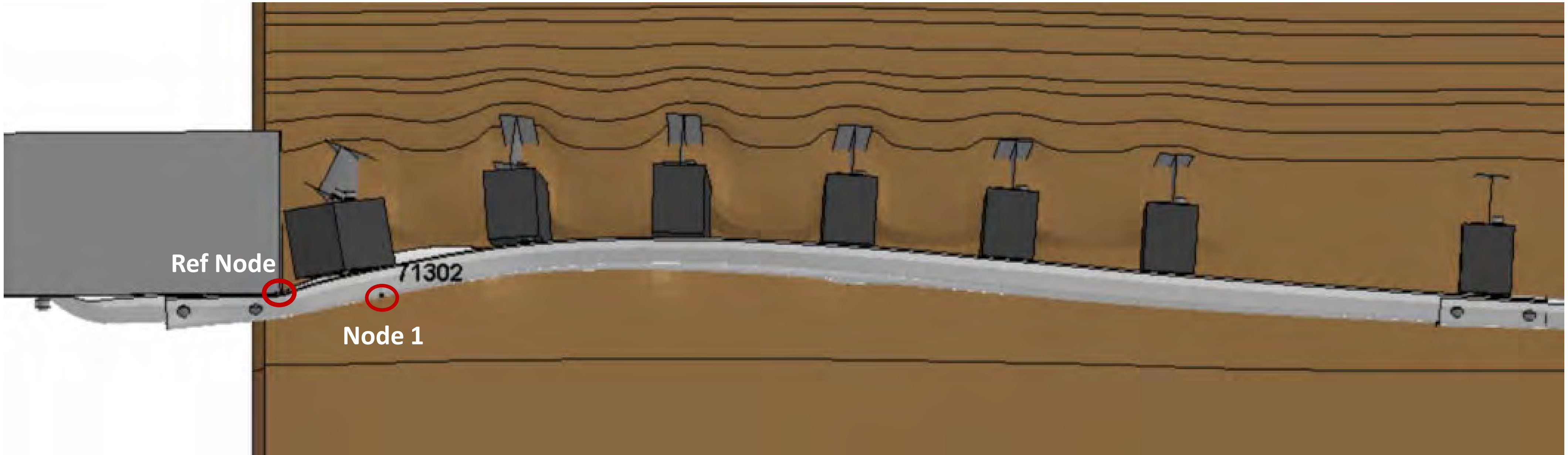




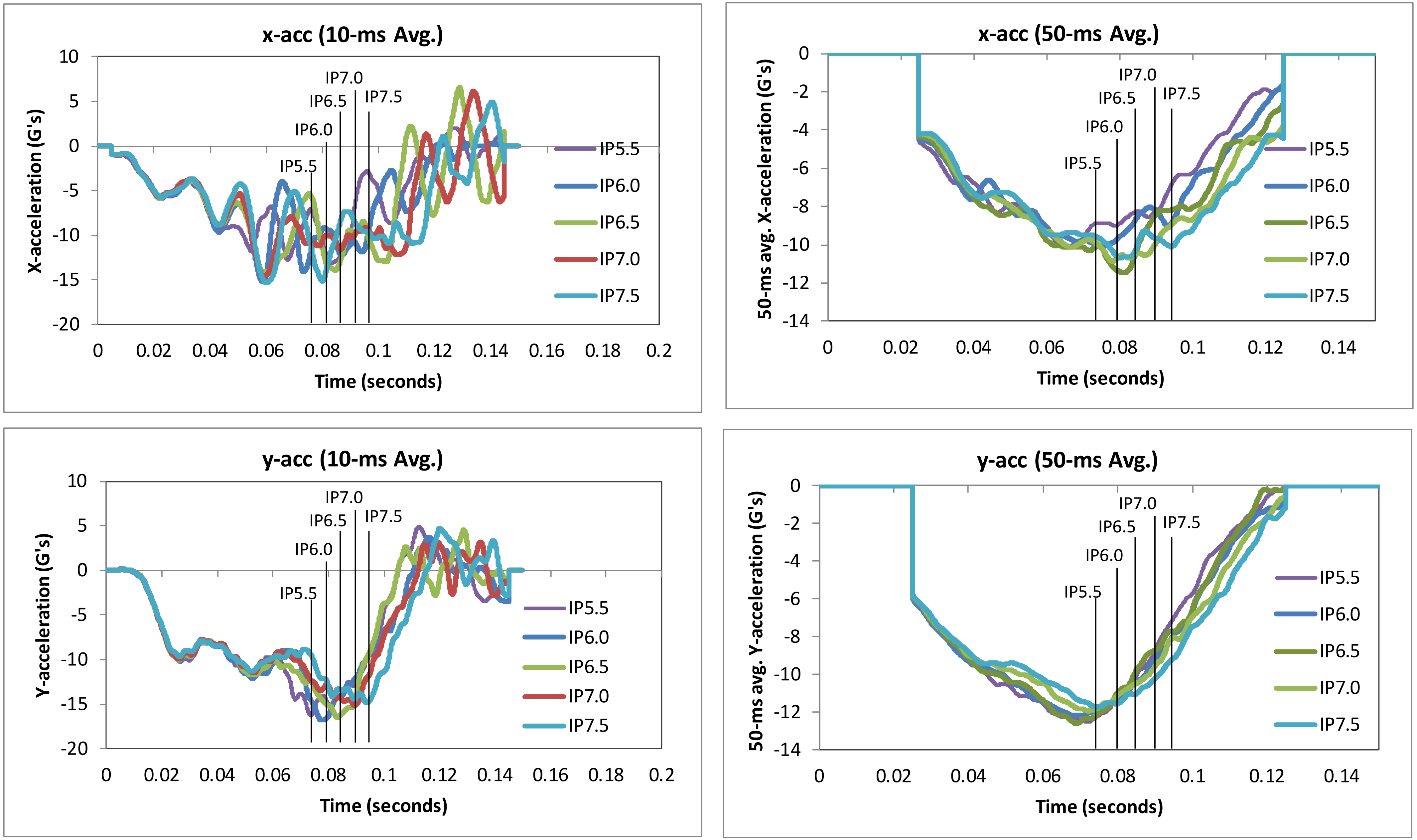
Pocketing, IS and Kinetic Energy





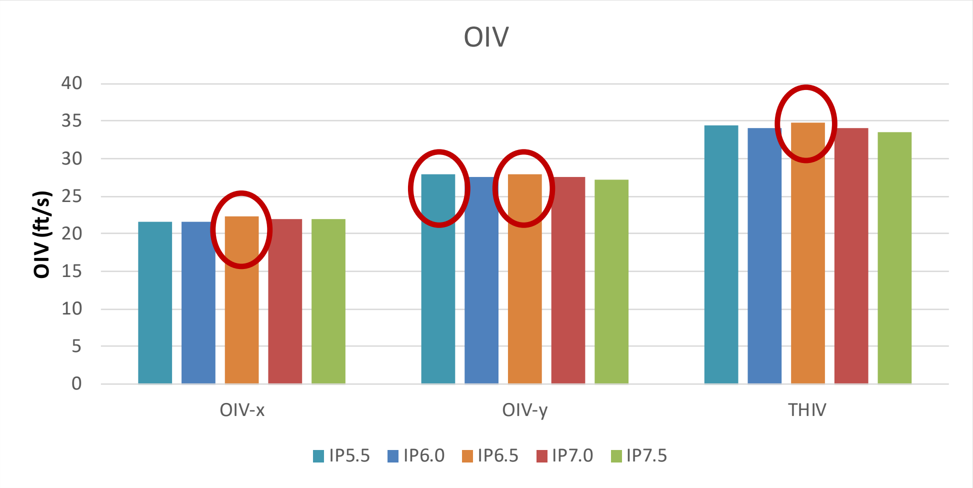


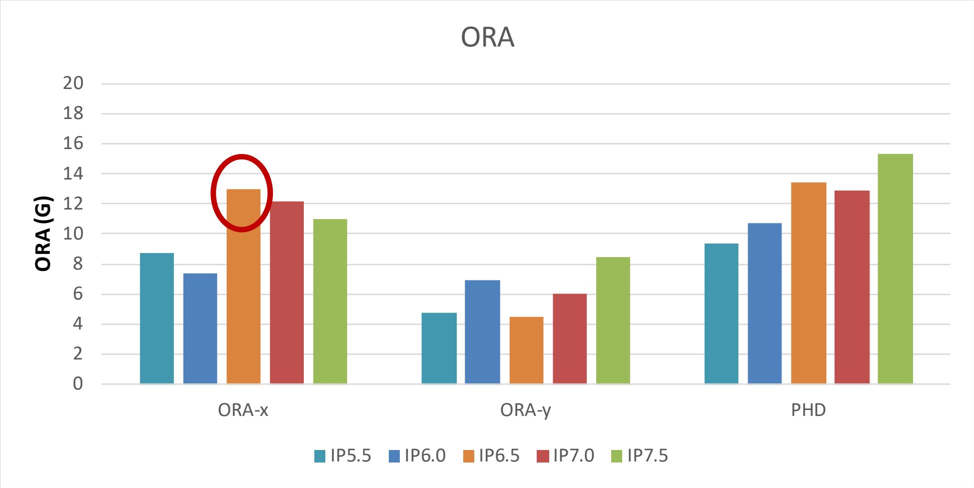
Acceleration-time Histories

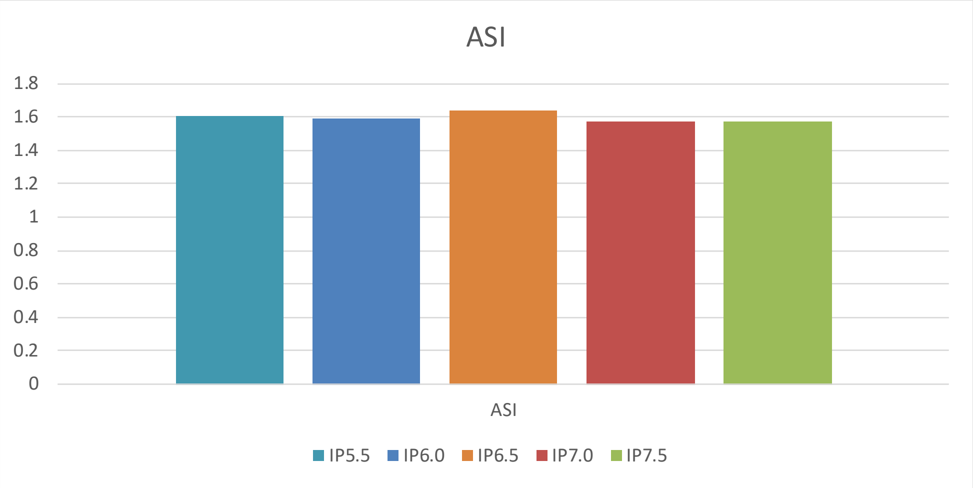


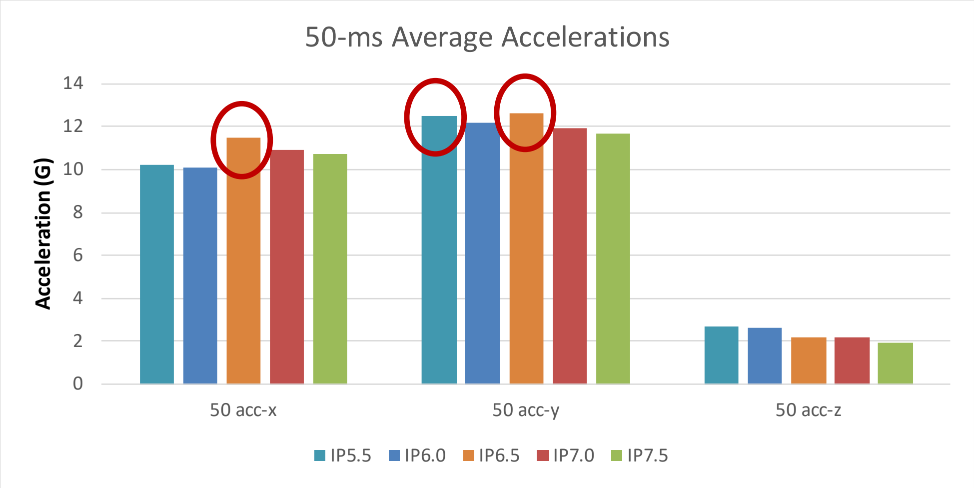
Time of contact with abutment

TRAP Results









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Summary on CIP Calculations

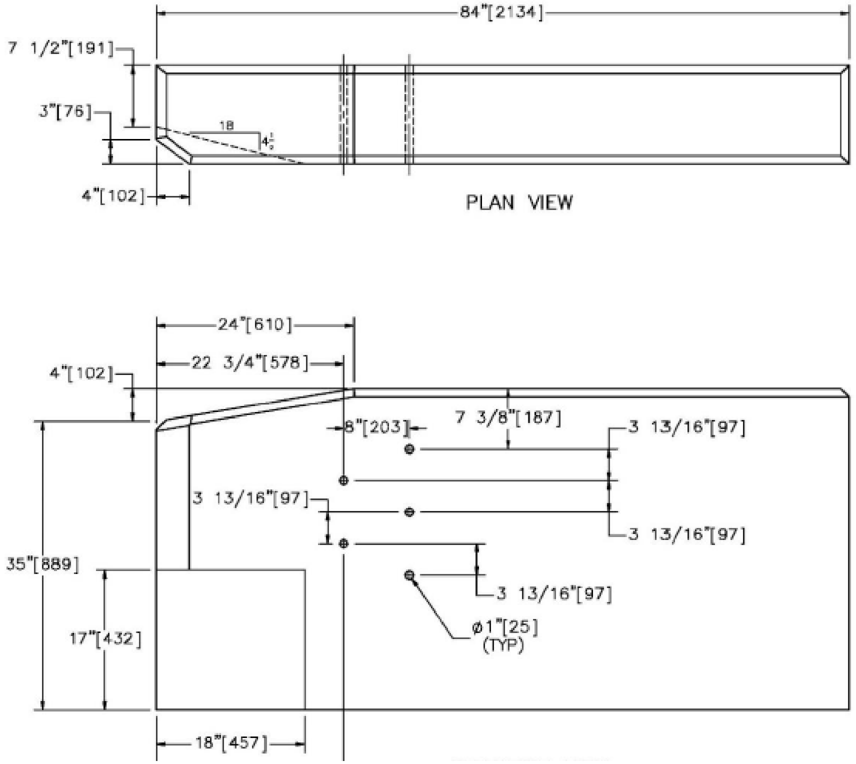
- Maximum loading on the abutment and sidewalk/deck (e.g., highest strains on concrete around rebar at cold-joint):
  - Highest: **IP 6.5 ft**
  - 2nd Highest: IP 5.5 ft
  - Concrete failure on abutment at cold joint on traffic side of abutment for Cases **IP 5.5ft – 7.0ft**
- Pocketing (Greatest relative deflection of thrie-beam rail approaching within 1-ft of the abutment):
  - Case **IP7.0 ft**
- OIV:
  - **Essentially the same for all cases**; however,
    - highest lateral acceleration occurred for Cases 5.5 ft – 6.5 ft
- ORA:
  - Highest longitudinal: **IP 6.5 ft**
  - Note: Tail-slap had not yet occurred, thus maximum lateral ORA resulting from that event not available.

Conclusions on CIP Selection

- Greatest potential for pocketing occurred for IP 7.0 ft
- Greatest ORA occurred for IP 6.5 ft
- Thus the **CIP** was selected as the midpoint between the two at **6.75 ft upstream of the buttress**.
- The damage to the concrete on the abutment and sidewalk did not significantly influence the crashworthiness of the system.

Comparison to Test 3-21 on Similar System

- Test No. 34AGT-1
- Agency: MwRSF
- Date: 3/17/17
- Test Article: 34-in. (864-mm) Tall Thrie Beam AGT
- CIP = 7.5 ft upstream of abutment



Results Comparison

Test 34AGT-1 at IP7.5 ft

Evaluation Criteria		Transducer: SLICE-1	Transducer: SLICE-2 (primary)
OIV ft/s (m/s)	Longitudinal	-21.06 (-6.42)	-20.18 (-6.15)
	Lateral	24.62 (7.50)	25.92 (7.90)
ORA g's	Longitudinal	-10.05	-10.77
	Lateral	10.44	8.85
MAX ANGULAR DISP. deg.	Roll	-15.1	-12.0
	Pitch	-3.3	-4.4
	Yaw	39.6	38.9
THIV – ft/s (m/s)		30.78 (9.38)	31.50 (9.60)
PHD – g's		10.71	11.15
ASI		1.49	1.59

FEA Results on MEDOT Transition

Occupant Risk Factors		MASH T4-12 (Cabin Accelerometers) IP5.5	IP6.0	IP6.5	IP7.0	IP7.5
Occupant Impact Velocity (ft/s)	x-direction	**21.7**	**21.7**	**22.3**	**22.0**	**22.0**
	y-direction	**27.9**	**27.6**	**27.9**	**27.6**	**27.2**
	at time	at 0.0926 seconds on right side of interior	at 0.0929 seconds on right side of interior	at 0.0930 seconds on right side of interior	at 0.0942 seconds on right side of interior	at 0.0950 seconds on right side of interior
THIV (ft/s)		34.4 at 0.0926 seconds on right side of interior	34.1 at 0.0929 seconds on right side of interior	34.8 at 0.0930 seconds on right side of interior	34.1 at 0.0942 seconds on right side of interior	33.5 at 0.0950 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	**-8.7** (0.0993 - 0.1093 seconds)	**-7.4** (0.1052 - 0.1152 seconds)	**-13** (0.0976 - 0.1076 seconds)	**-12.2** (0.1019 - 0.1119 seconds)	**-11** (0.0985 - 0.1085 seconds)
	y-direction	**4.8** (0.1075 - 0.1175 seconds)	**-6.9** (0.0969 - 0.1069 seconds)	**4.5** (0.1238 - 0.1338 seconds)	**-6** (0.0968 - 0.1068 seconds)	**-8.5** (0.0977 - 0.1077 seconds)
PHD (g's)		9.4 (0.0926 - 0.1026 seconds)	10.7 (0.0929 - 0.1029 seconds)	13.4 (0.0974 - 0.1074 seconds)	12.9 (0.0942 - 0.1042 seconds)	15.3 (0.0950 - 0.1050 seconds)
ASI		1.61 (0.0440 - 0.0940 seconds)	1.59 (0.0432 - 0.0932 seconds)	1.64 (0.0439 - 0.0939 seconds)	1.57 (0.0528 - 0.1028 seconds)	1.57 (0.0548 - 0.1048 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-10.2 (0.0408 - 0.0908 seconds)	-10.1 (0.0504 - 0.1004 seconds)	-11.5 (0.0563 - 0.1063 seconds)	-10.9 (0.0531 - 0.1031 seconds)	-10.7 (0.0552 - 0.1052 seconds)
	y-direction	-12.5 (0.0470 - 0.0970 seconds)	-12.2 (0.0430 - 0.0930 seconds)	-12.6 (0.0439 - 0.0939 seconds)	-11.9 (0.0470 - 0.0970 seconds)	-11.7 (0.0494 - 0.0994 seconds)
	z-direction	-2.7 (0.0876 - 0.1376 seconds)	-2.6 (0.0888 - 0.1388 seconds)	-2.2 (0.0947 - 0.1447 seconds)	-2.2 (0.1000 - 0.1500 seconds)	-1.9 (0.0483 - 0.0983 seconds)
Maximum Angular Disp. (deg)	Roll	**6.8** (0.1156 seconds)	**7.6** (0.1176 seconds)	**8.7** (0.1163 seconds)	**9.1** (0.1247 seconds)	**9.7** (0.1287 seconds)
	Pitch	**1.7** (0.1428 seconds)	**1.6** (0.1479 seconds)	**1.4** (0.1439 seconds)	**1.5** (0.1481 seconds)	**1** (0.1466 seconds)
	Yaw	**-19.6** (0.1500 seconds)	**-20** (0.1500 seconds)	**-20** (0.1500 seconds)	**-20** (0.1500 seconds)	**-20.1** (0.1500 seconds)

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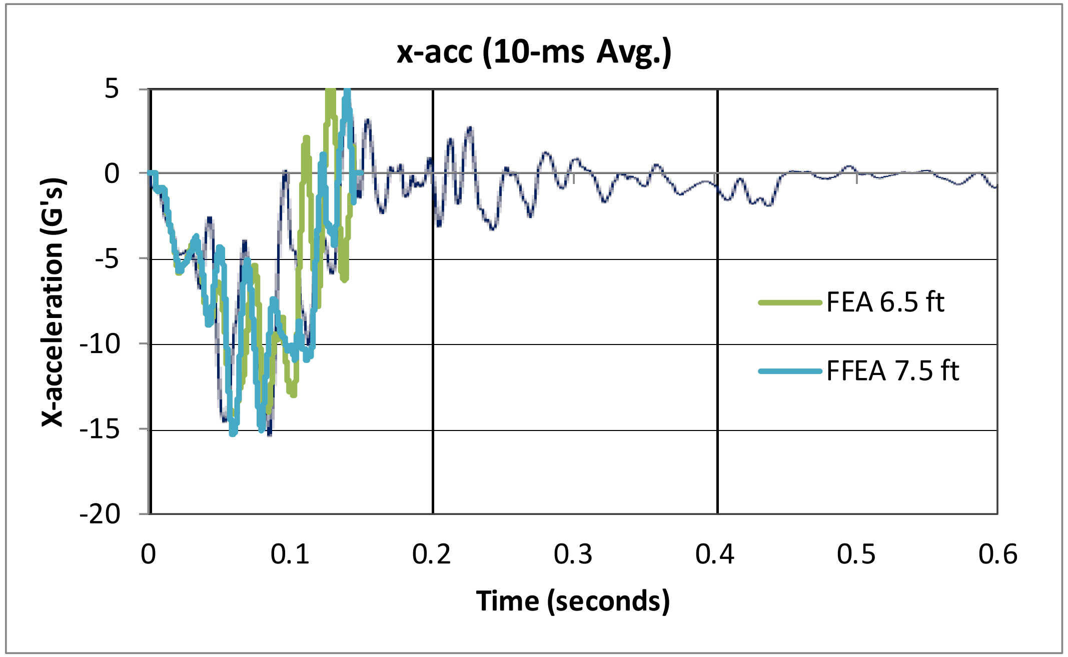
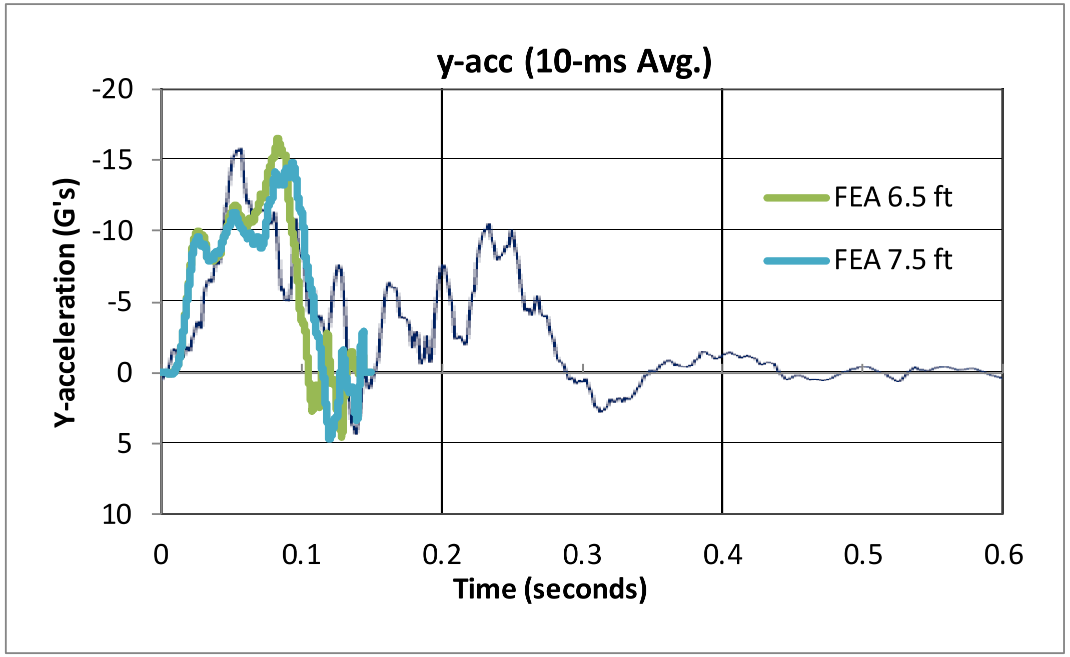
Comparison of FEA to Test 34AGT-1





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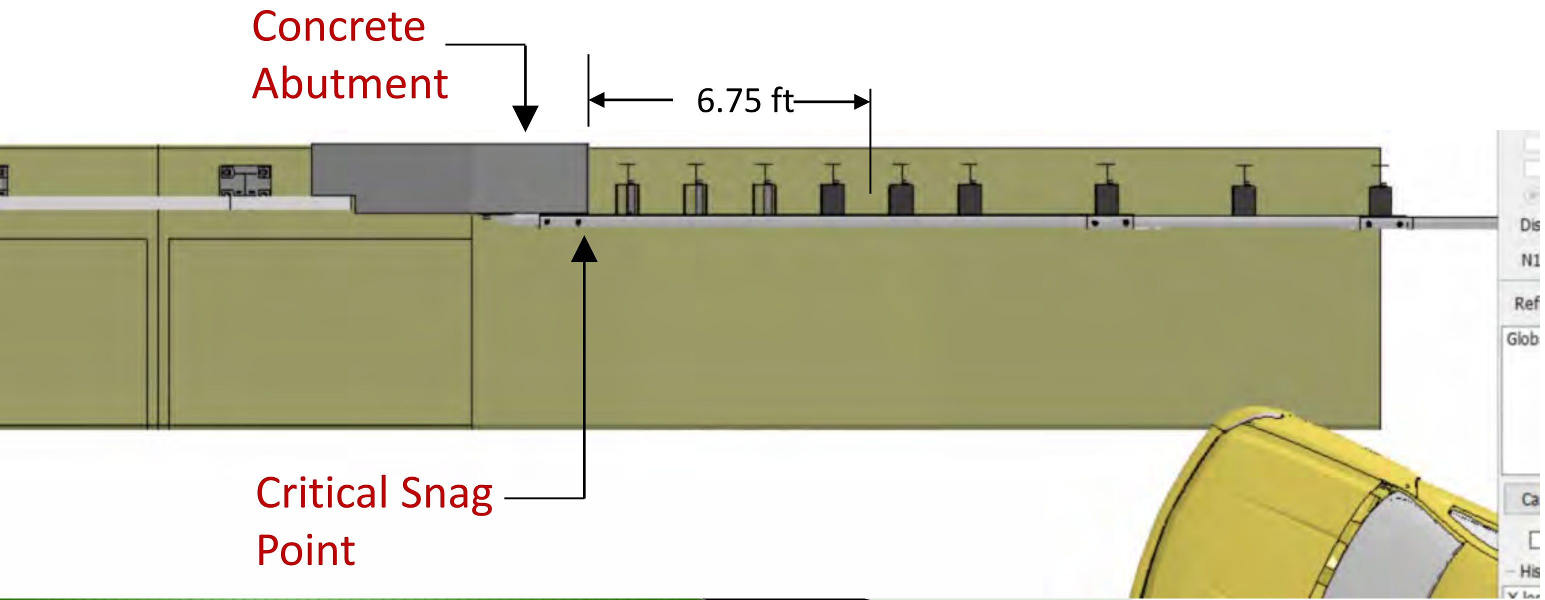
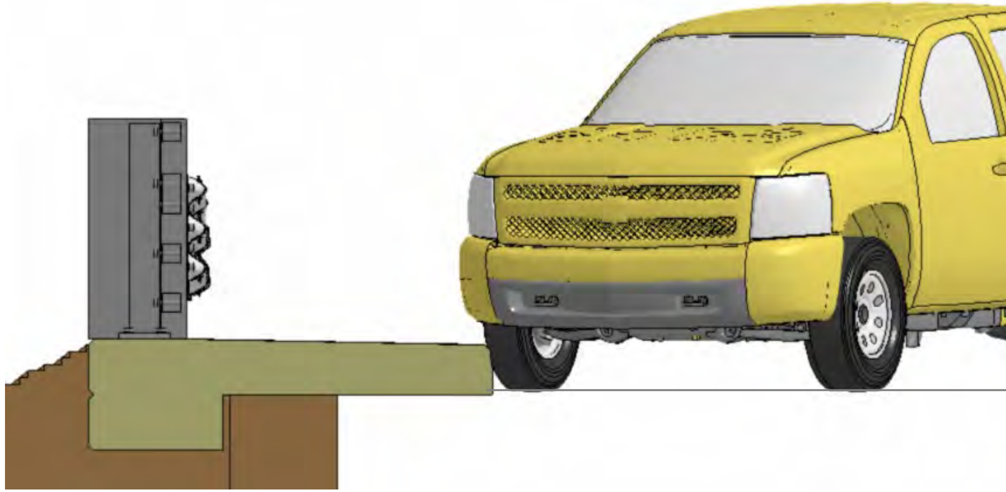
MASH Test 4-21 Simulation on the MEDOT Transition for 4-Bar Bridge Rail

- Impact Conditions
  - Impact Speed = 62.1 mph (100 km/hr)
  - Impact Angle = 25 degrees
  - Impact Point upstream from end of concrete buttress
    - *Target = 6.75 ft*
    - *Actual = 6.5 ft*

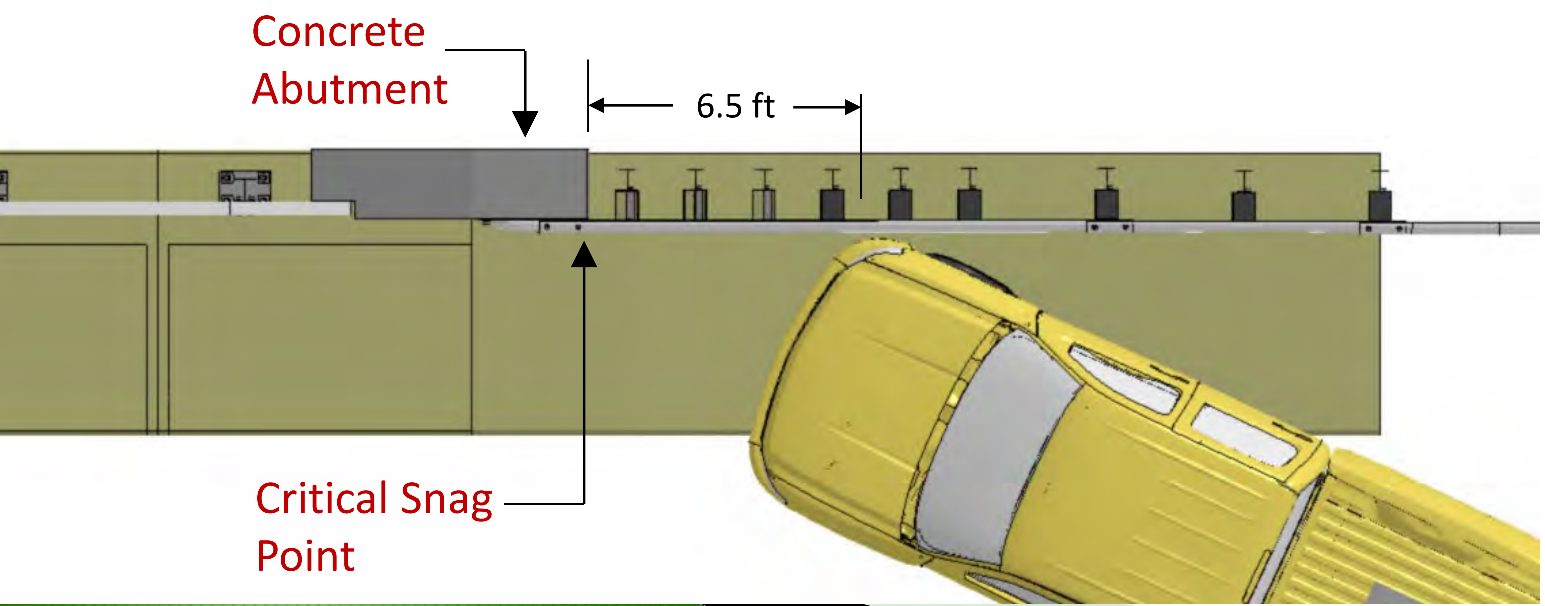
- Vehicle Model
  - SilveradoC_V3a_V180201_TireRS_35psi.k
  - Vehicle Mass = 2,268 kg (5,001 lb)

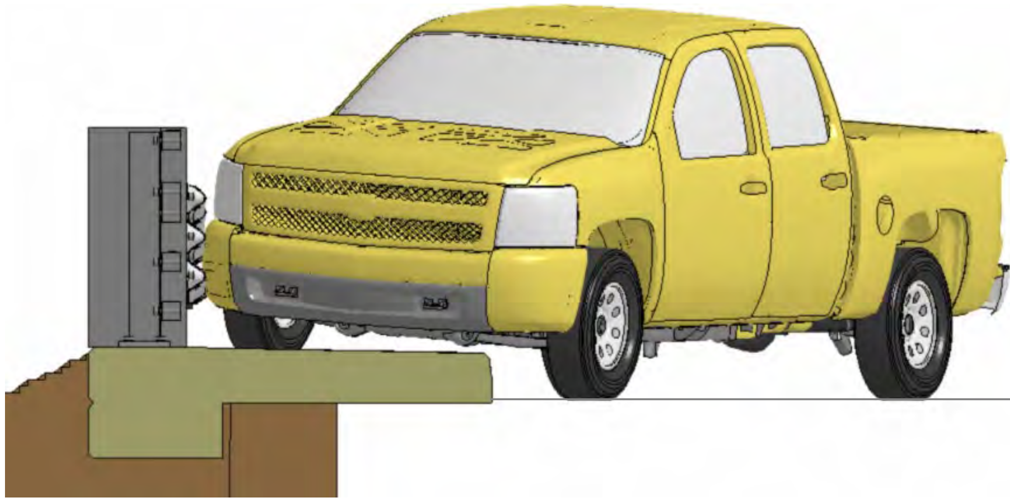




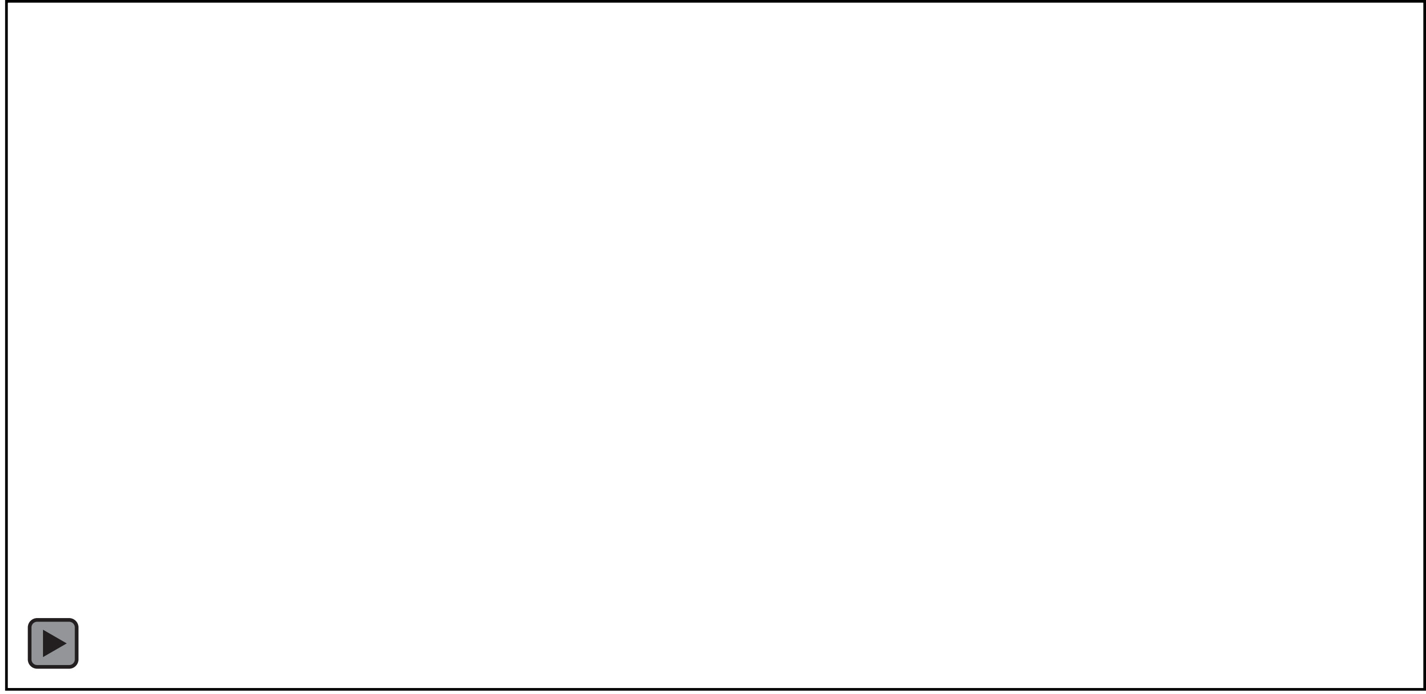
MASH Test 4-21 Simulation on the MEDOT Transition for 4-Bar Bridge Rail

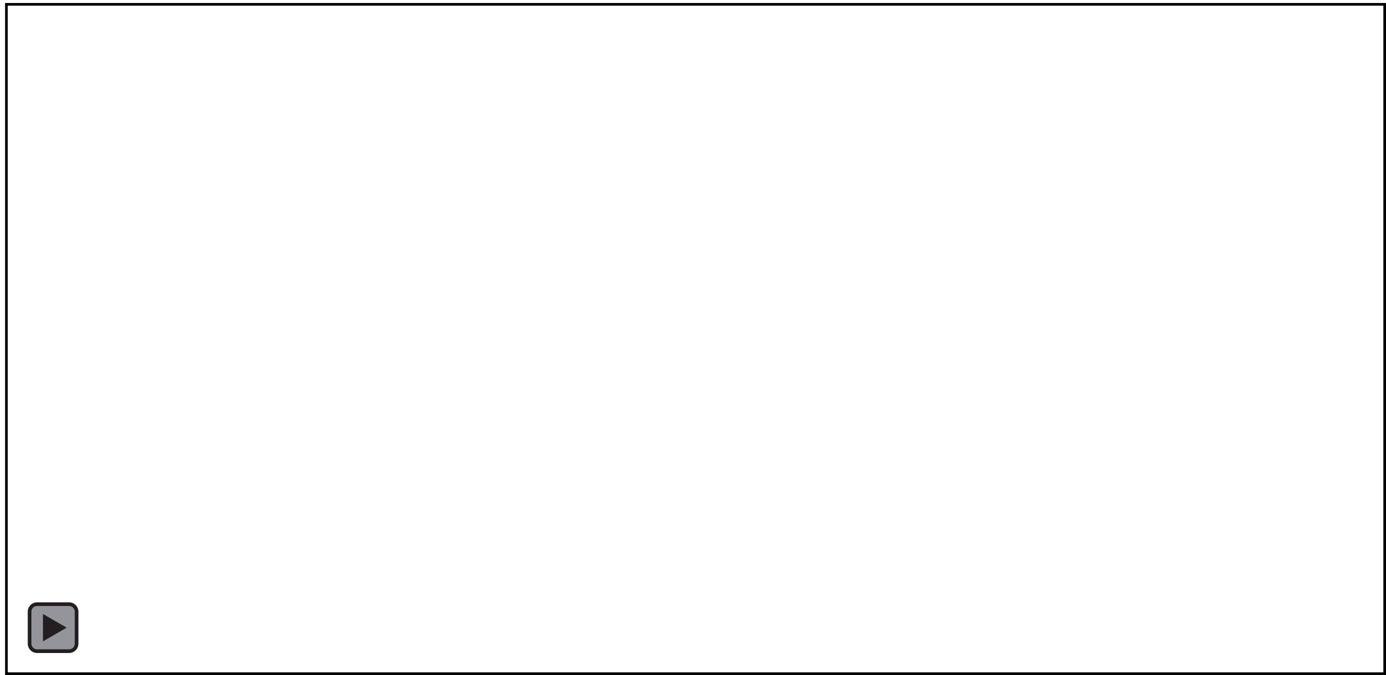
- Impact Conditions
  - Impact Speed = 62.1 mph (100 km/hr)
  - Impact Angle = 25 degrees
  - Impact Point upstream from end of concrete abutment
    - *Target = 6.75 ft*
    - *Actual = 6.5 ft*
- Vehicle Model
  - SilveradoC_V3a_V180201_TireRS_35psi.k
  - Vehicle Mass = 2,268 kg (5,001 lb)





Movies





Mov

Movies

Movies

TRAP – Summary Table

Occupant Risk Factors		MASH Test 4-21
Occupant Impact Velocity (ft/s)	x-direction	21.0
	y-direction	28.2
	at time	at 0.1943 seconds on right side of interior
THIV (ft/s)		34.1 at 0.1943 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-9.4 (0.1970 - 0.2070 seconds)
	y-direction	-17.3 (0.3543 - 0.3643 seconds)
PHD (g's)		17.6 (0.3543 - 0.3643 seconds)
ASI		1.72 (0.1474 - 0.1974 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-10.2 (0.1496 - 0.1996 seconds)
	y-direction	-13.3 (0.1470 - 0.1970 seconds)
	z-direction	-5.2 (0.1721 - 0.2221 seconds)
Maximum Angular Disp. (deg)	Roll	15.4 (0.6858 seconds)
	Pitch	-9.6 (0.7410 seconds)
	Yaw	-36.8 (0.3638 seconds)

MASH Criteria

< 30 ft/s (preferred) ✓
< 40 ft/s (limit)

> 15 G (preferred)
< 20.49 G (limit) ✓

< 75 deg ✓

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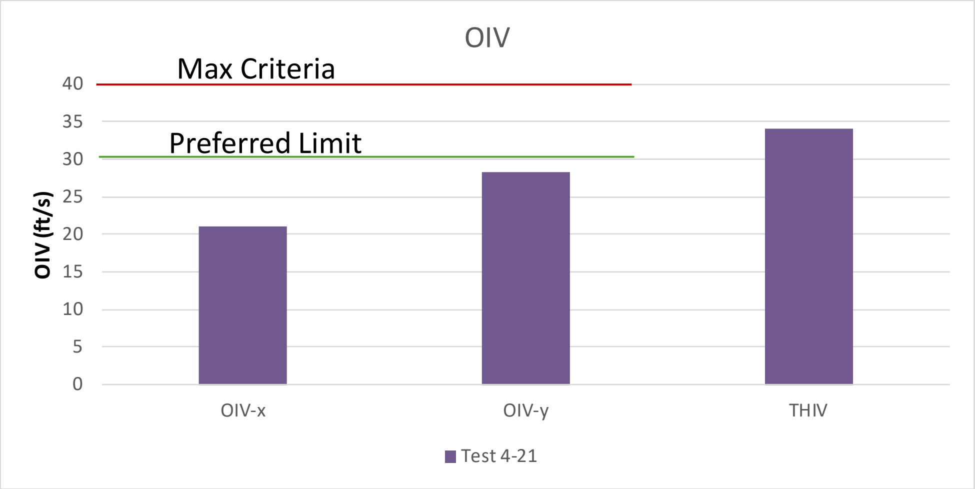
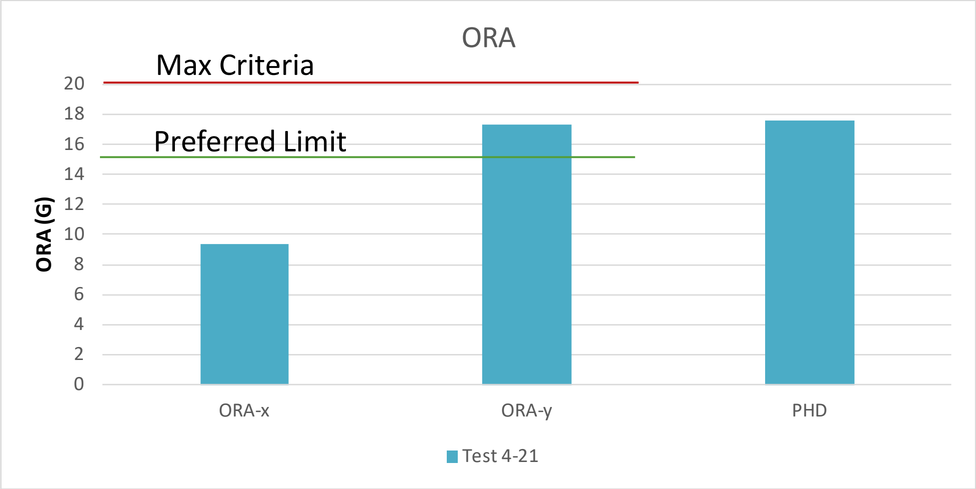
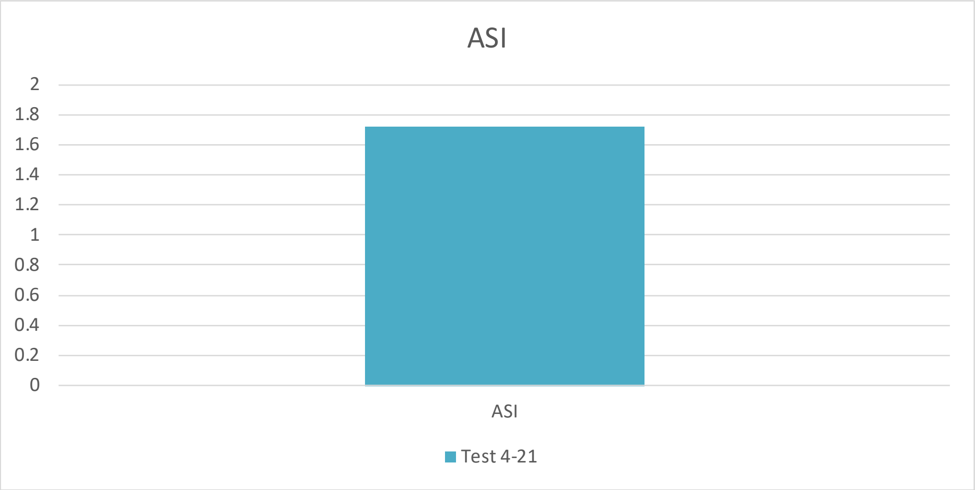
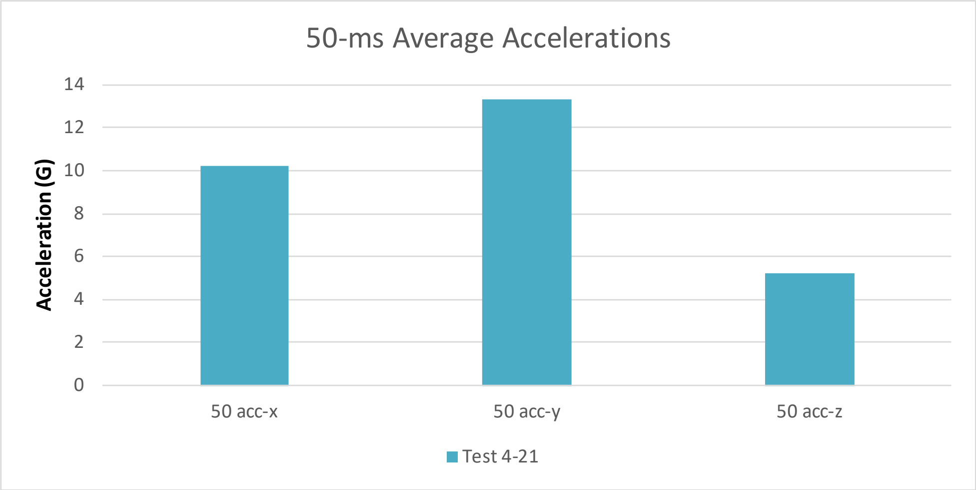
TRAP









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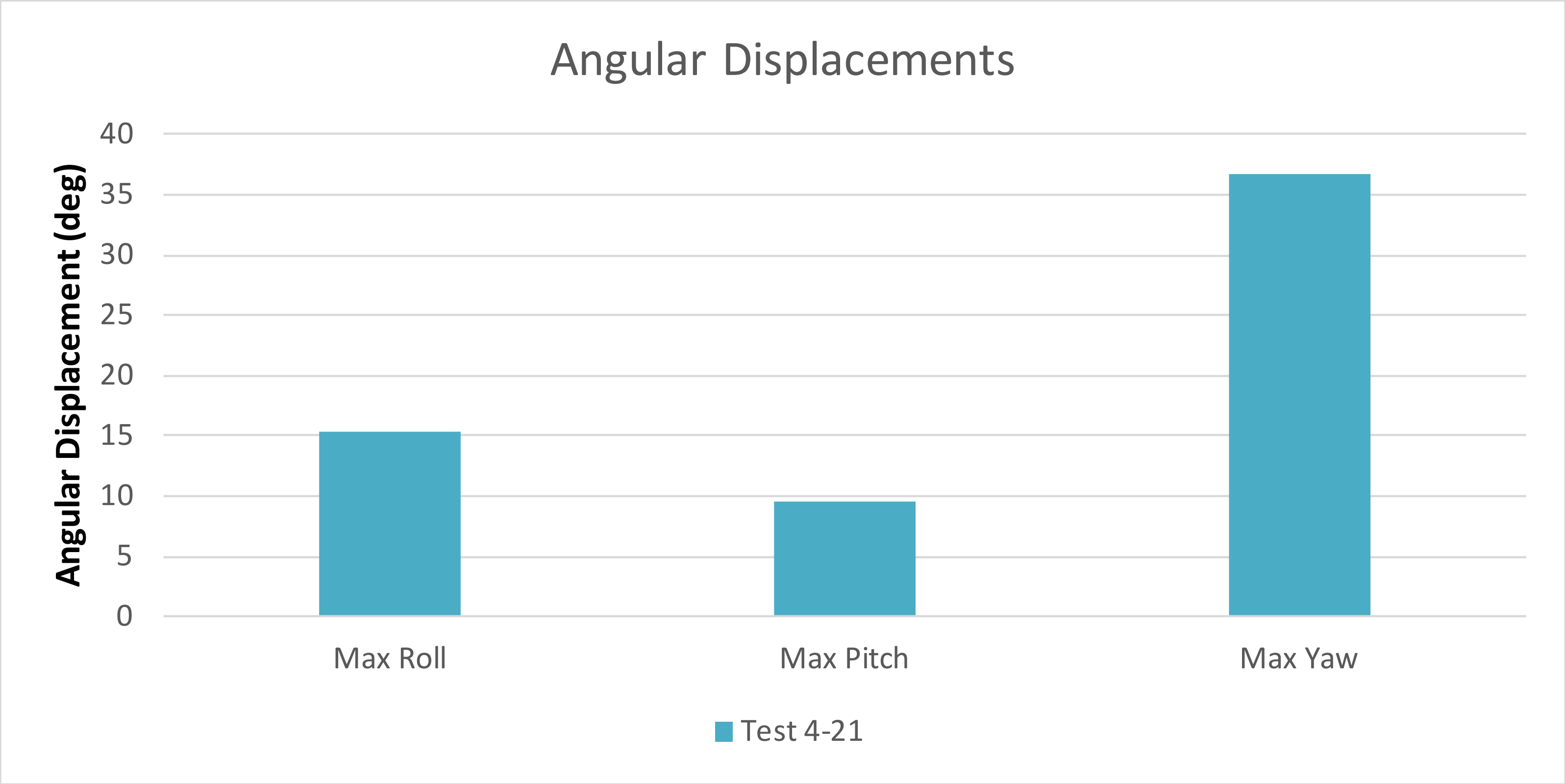
TRAP



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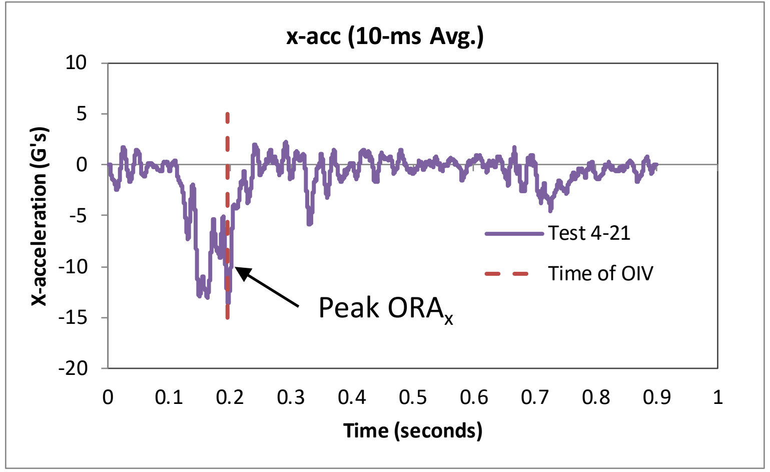
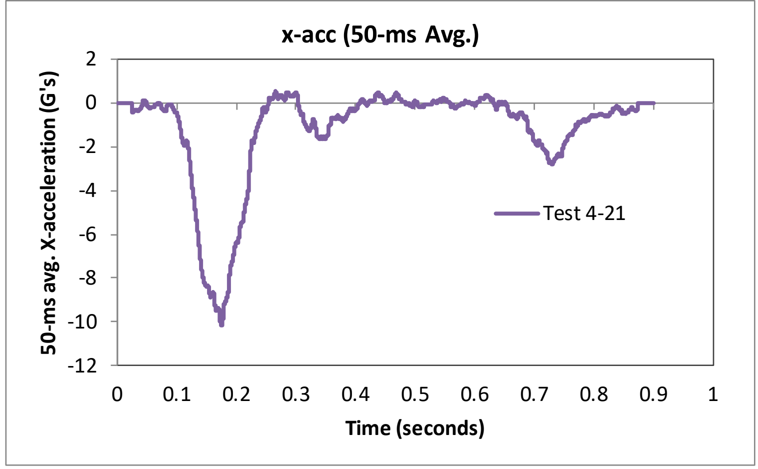
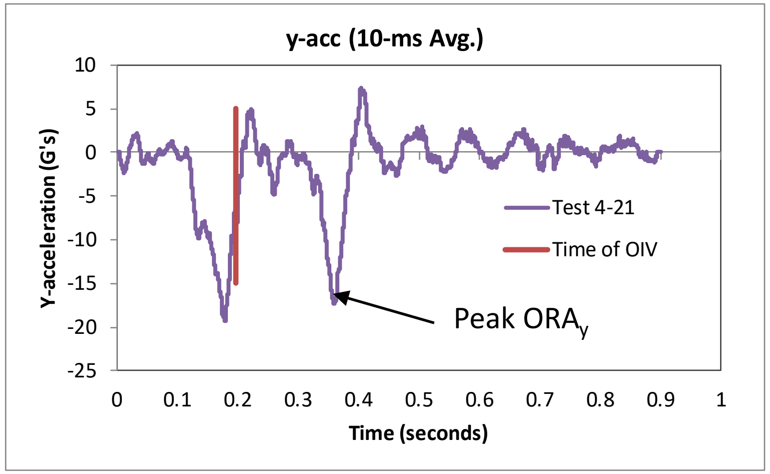
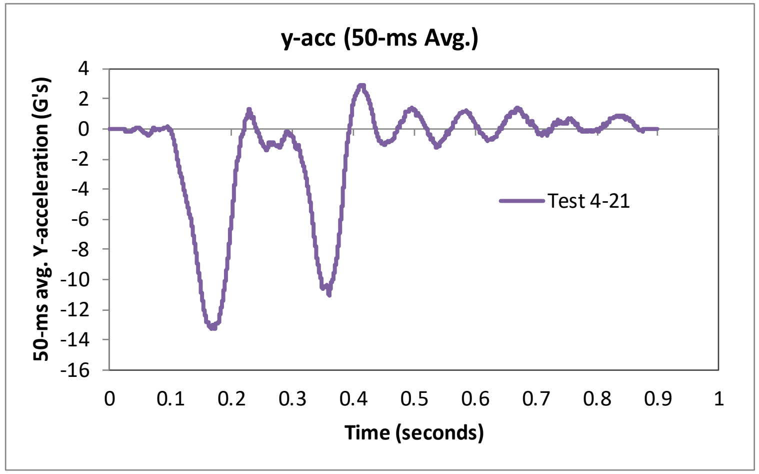
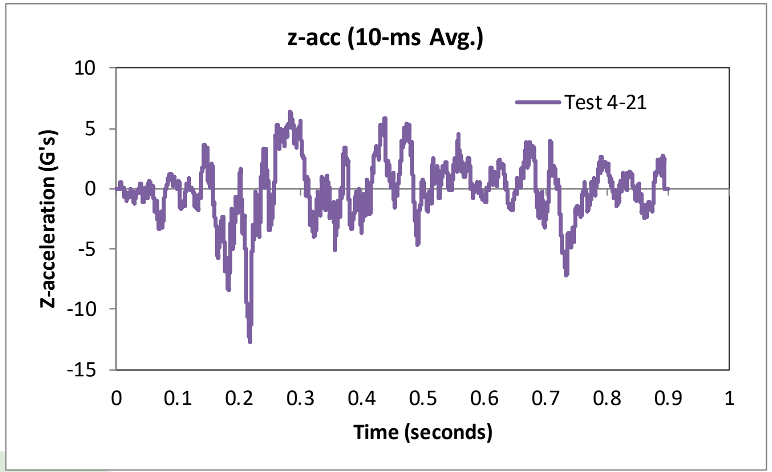
Acceleration Plots

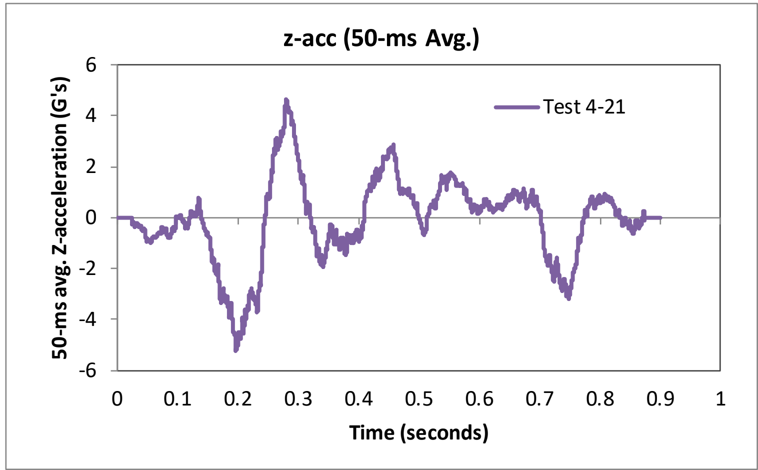




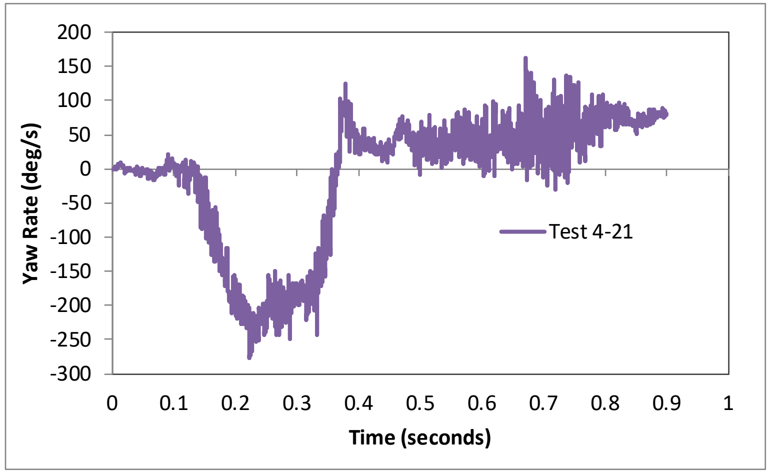


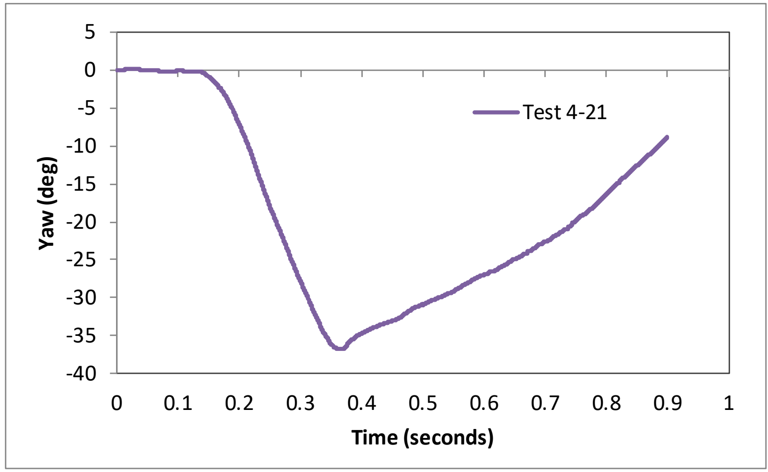


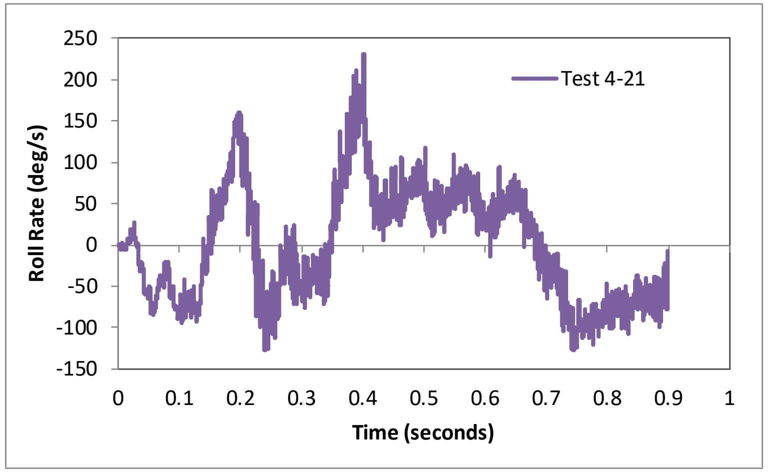


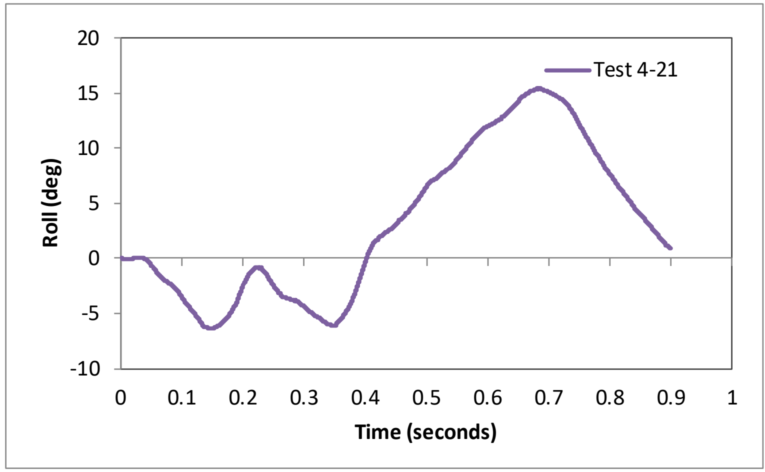


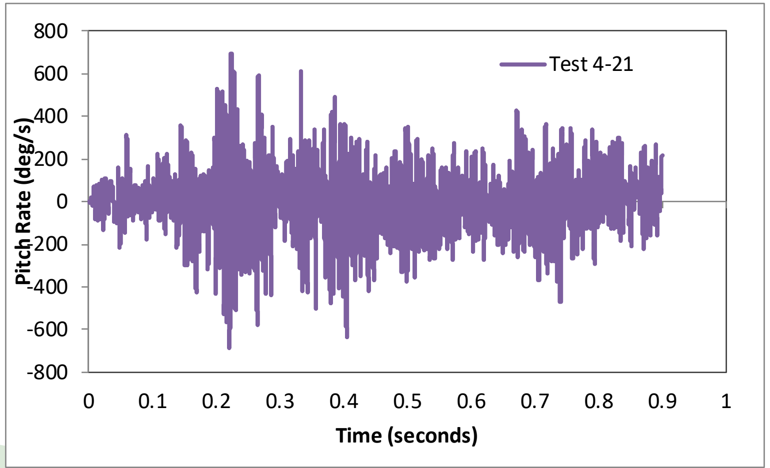
Angular Rate and Displacement Plots

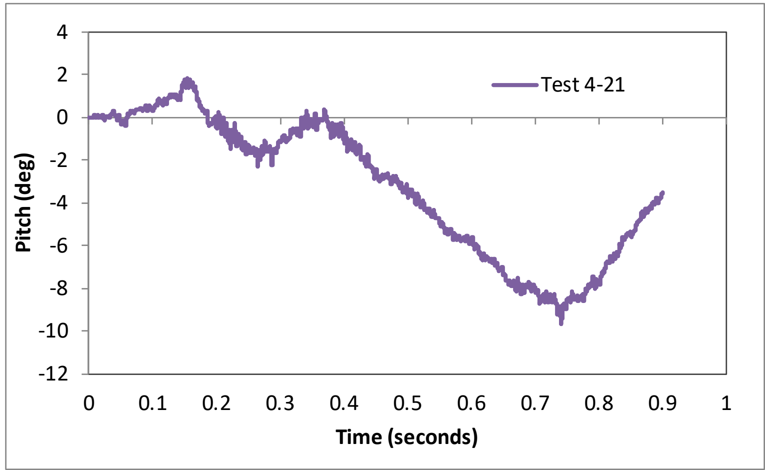




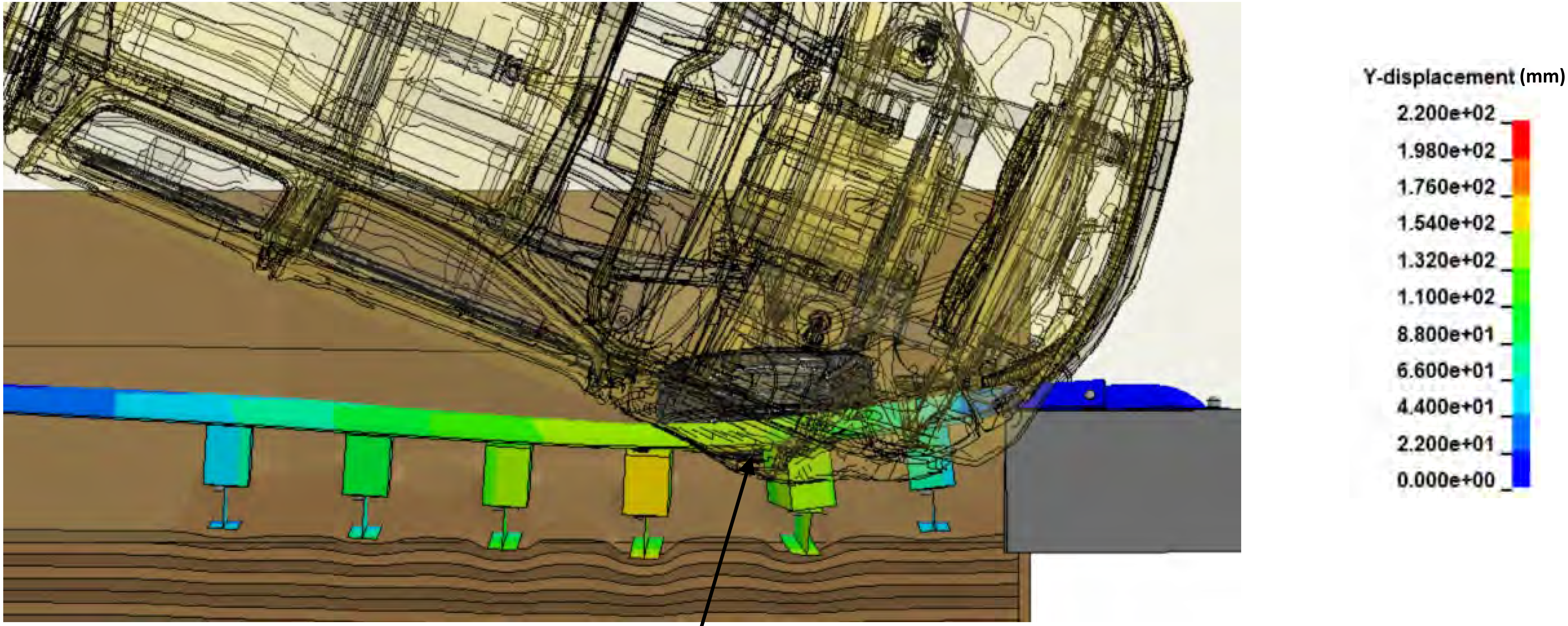






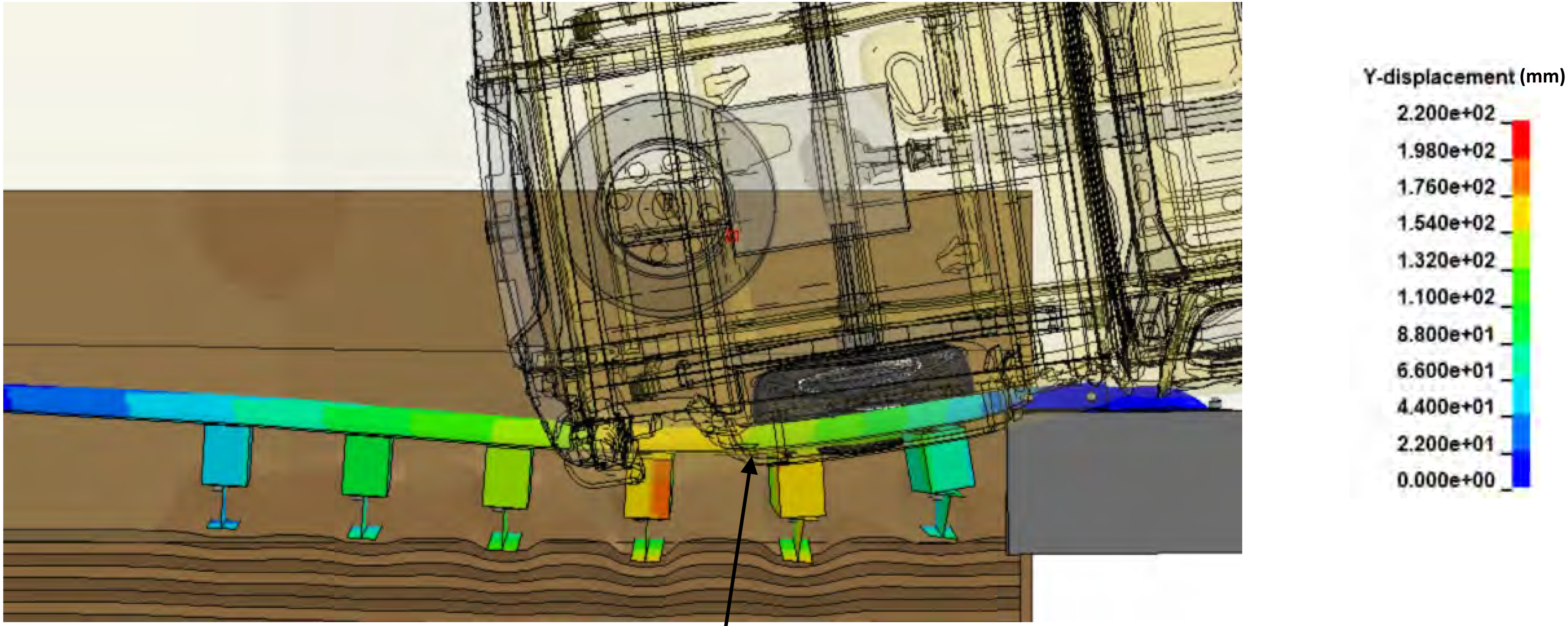


Lateral Dynamic Deflection
1st Peak



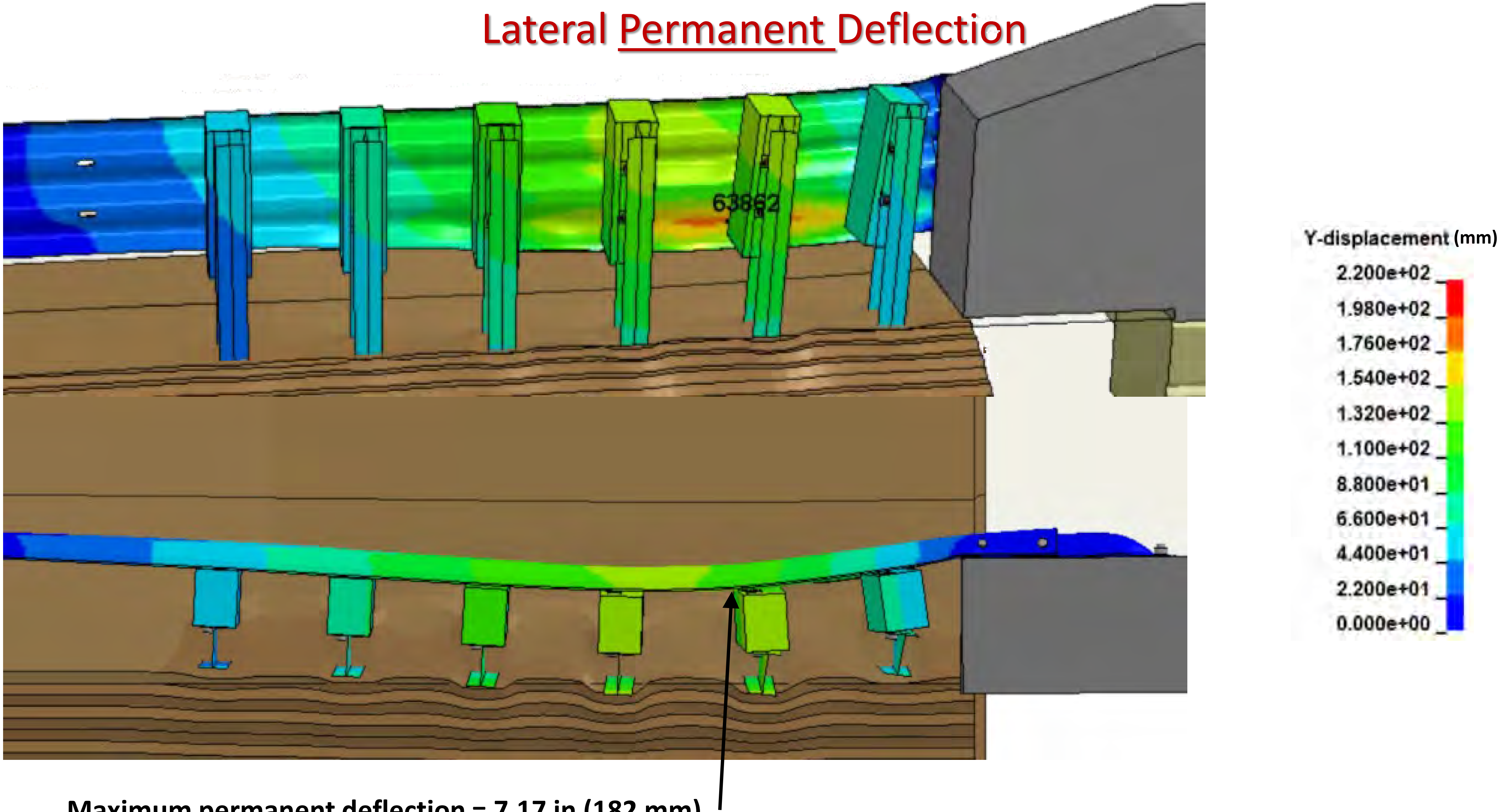
1st Peak dynamic deflection = 8.11in (206 mm)

Lateral Dynamic Deflection
2nd Peak



Maximum dynamic deflection = 8.34 in (212 mm)

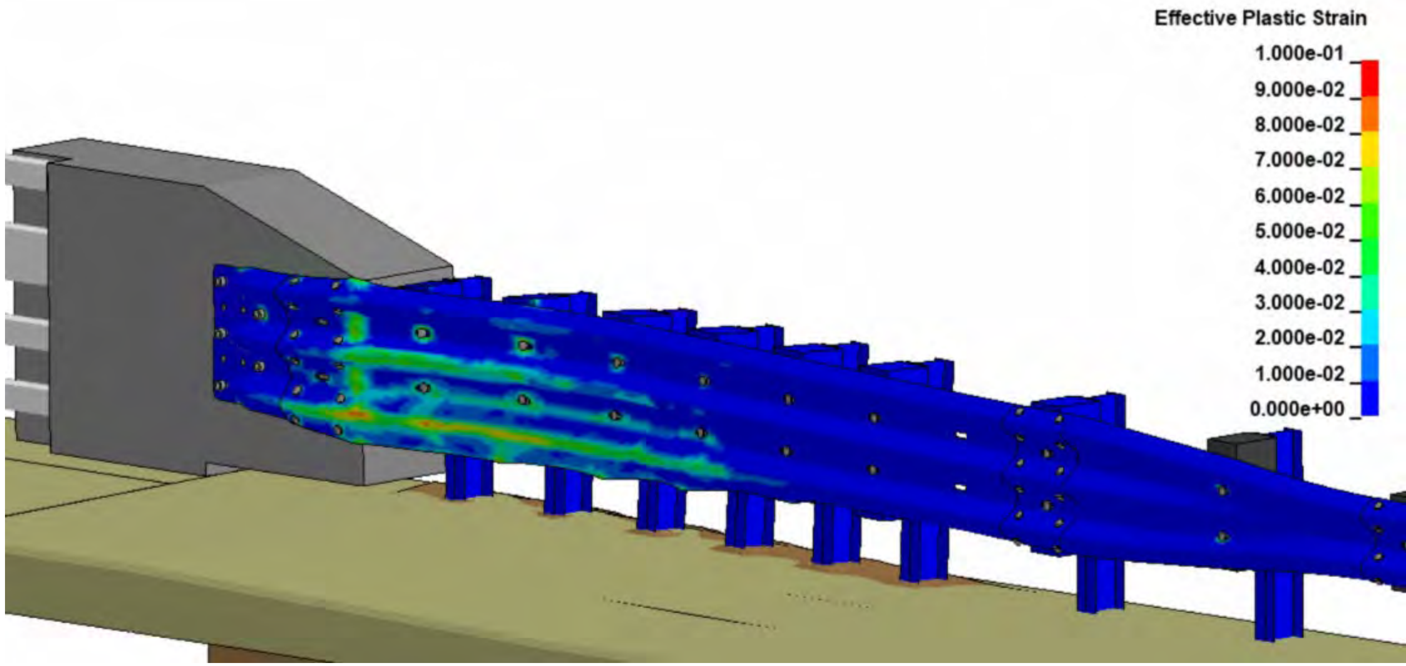
Lateral Permanent Deflection

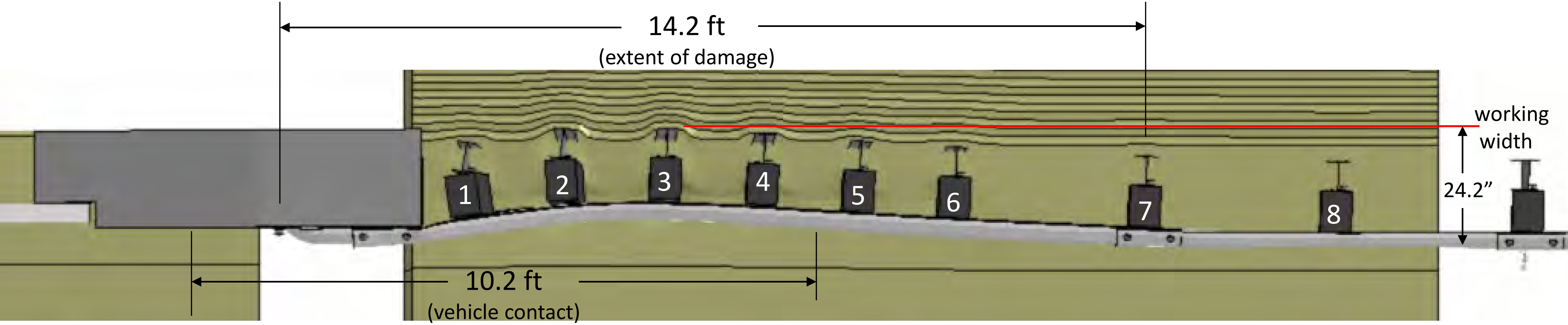


Maximum permanent deflection = 7.17 in (182 mm)

Barrier Damage

- Primary plastic deformations of the steel components of the transition were limited to the thrie-beam and thrie-beam terminal connector. There was also soil displacement at 7 posts approaching the abutment.
- Total length of system deformation was approximately 14.2 ft extending from the Post 7 to the downstream end of the terminal connector.
- The vehicle was in contact with the system for approximately 10.2 ft.
- The maximum working width = 24.2 in
    - Measured as maximum dynamic lateral position of Post 3 (top-back of post) relative to the initial face of the thrie-beam.

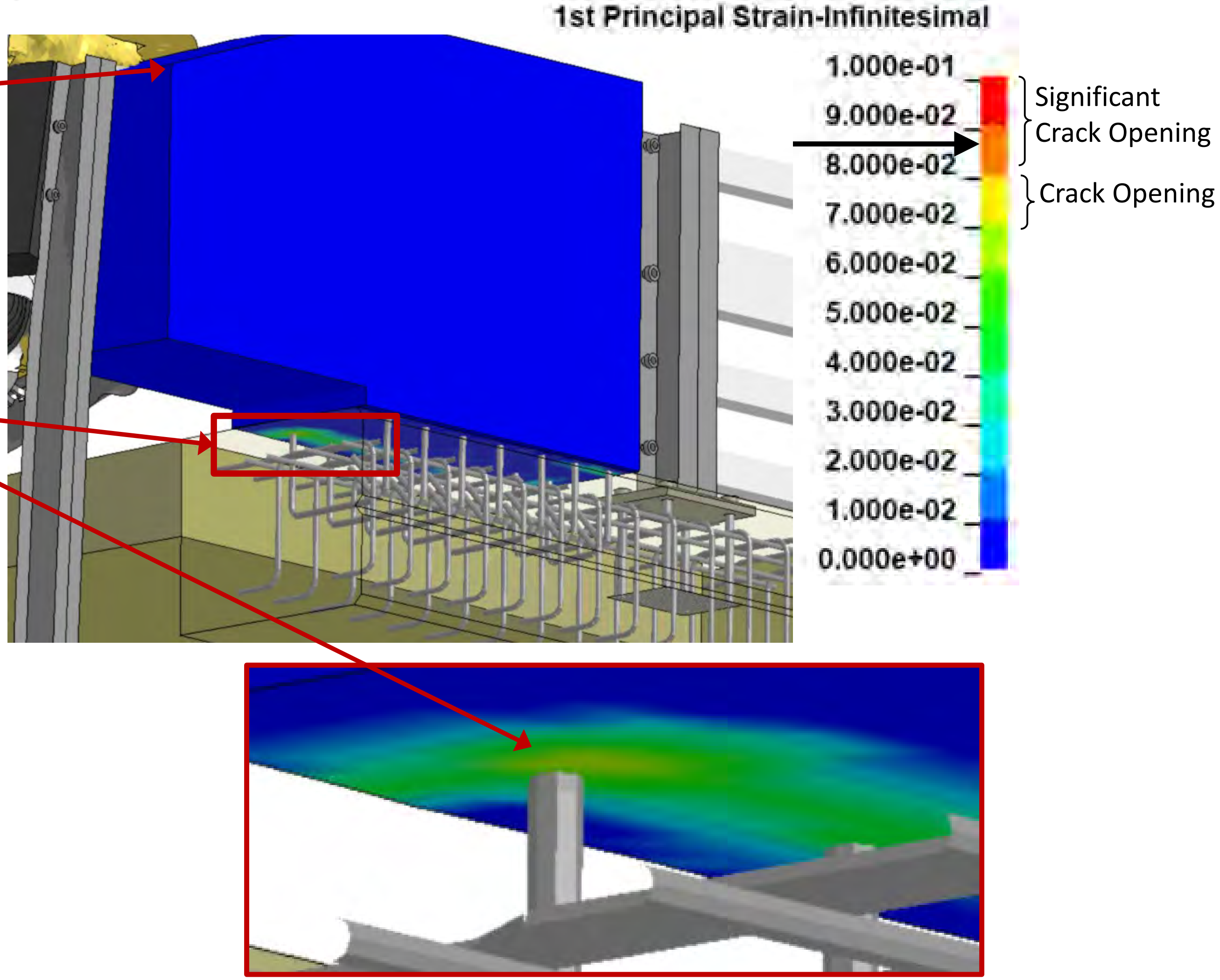




Concrete Abutment Damages

- The maximum lateral deflection at the end of the abutment nose was 0.76 inches (19.2 mm).
- The damage to the abutment was limited to the rebar-joint between the abutment and the curb at two stirrup locations on the upstream end of the abutment on the <u>traffic side</u>.
  - Max dynamic 1st Prin. Strain = 0.088 at 0.195 seconds
  - Final 1st Prin. Strain = 0.037
- The level of strain indicates that concrete damage (significant cracks) is likely to occur at those locations.

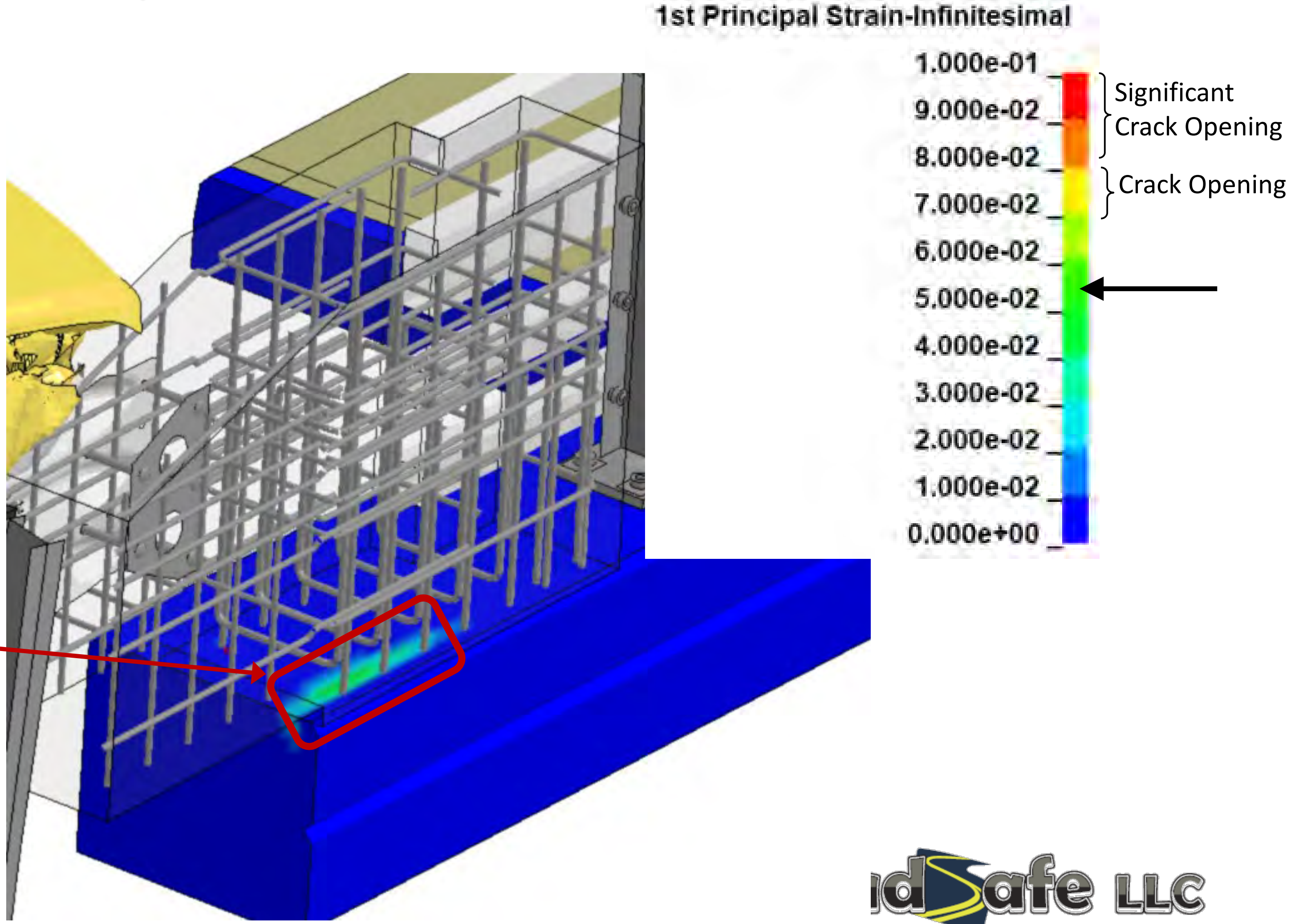
Dynamic at time = 0.195 seconds



Concrete Curb Damages

- The analysis indicated that damage to the curb/deck was not likely.
- The highest strains on the curb was at the rebar-joint between the abutment and the top of the curb at three stirrup locations at the upstream end of the abutment on the field side.
  - Max dynamic 1st Prin. Strain = 0.056 at 0.195 seconds
  - Final 1st Prin. Strain = 0.019

Dynamic at time = 0.195 seconds



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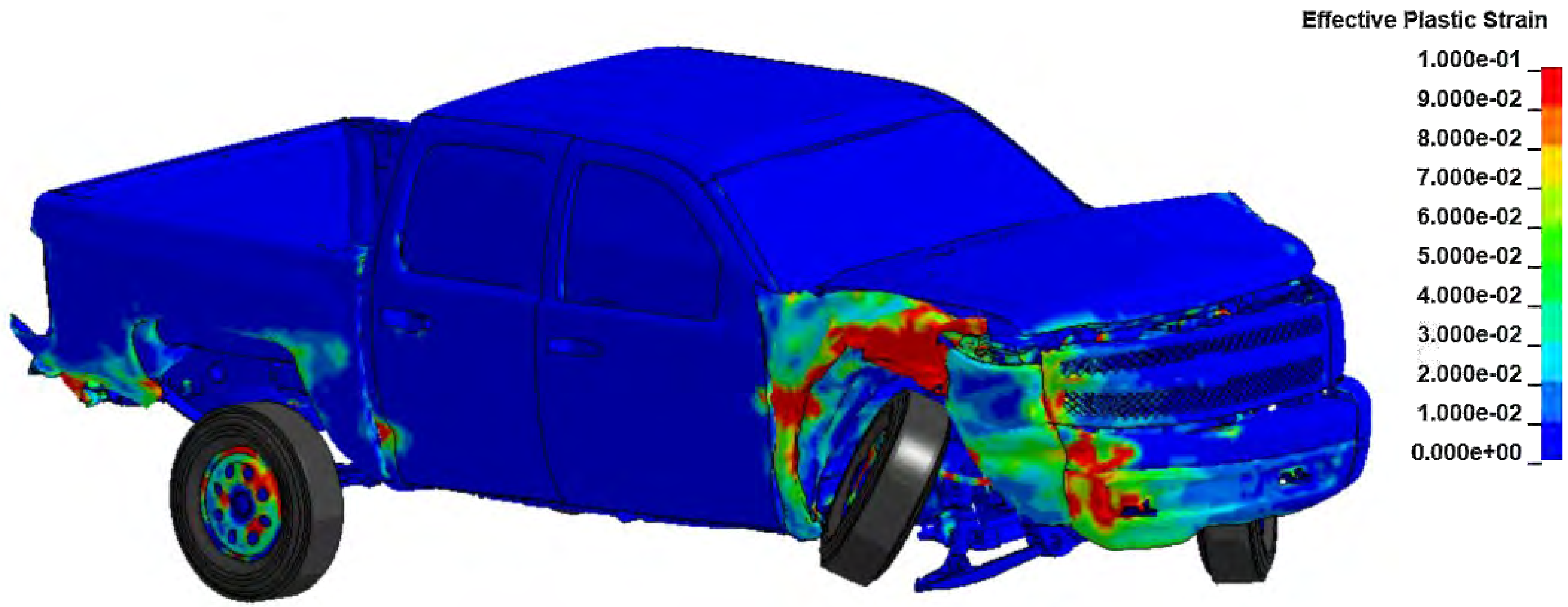
Effective Plastic Strain for Pickup Test



The most severe damages were to the front bumper, the front fender, the upper control arm of front suspension, fail ball joint on lower control arm, front and rear wheels, rear edge of rear door, front edge of truck bed, rear quarter panel of truck bed and rear bumper.

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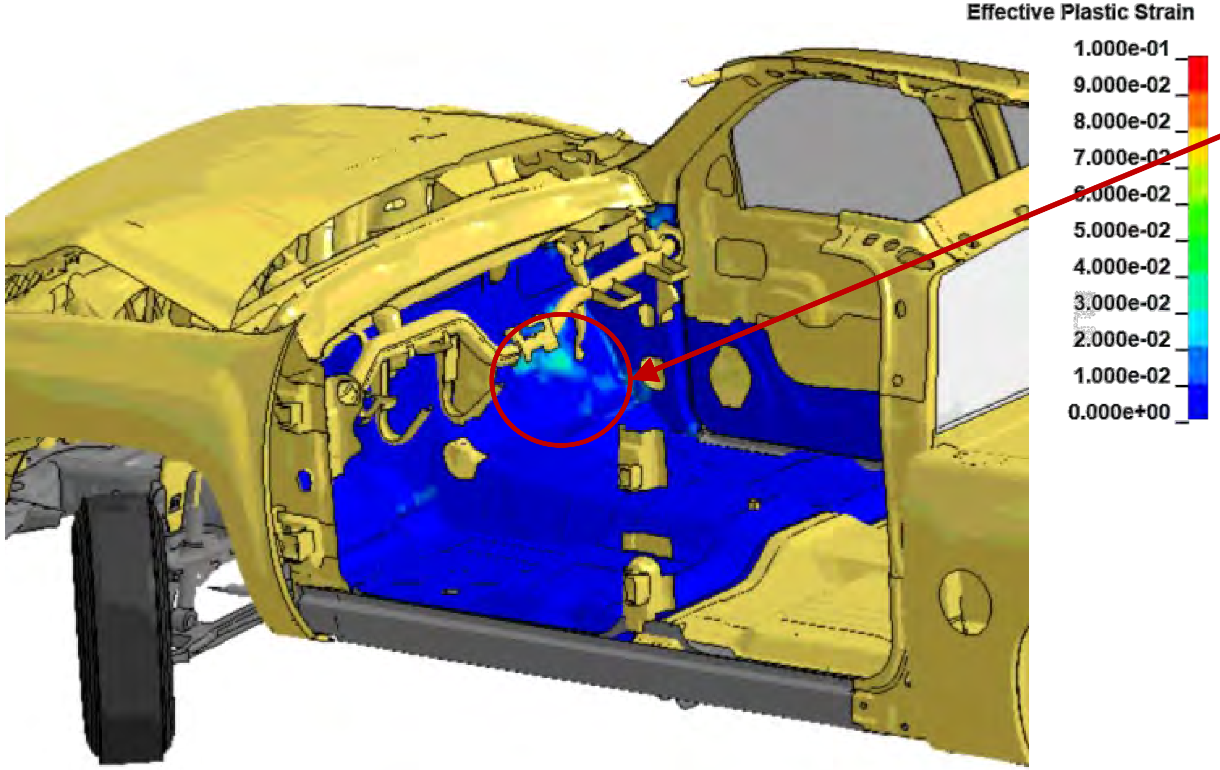
Occupant Compartment Intrusion

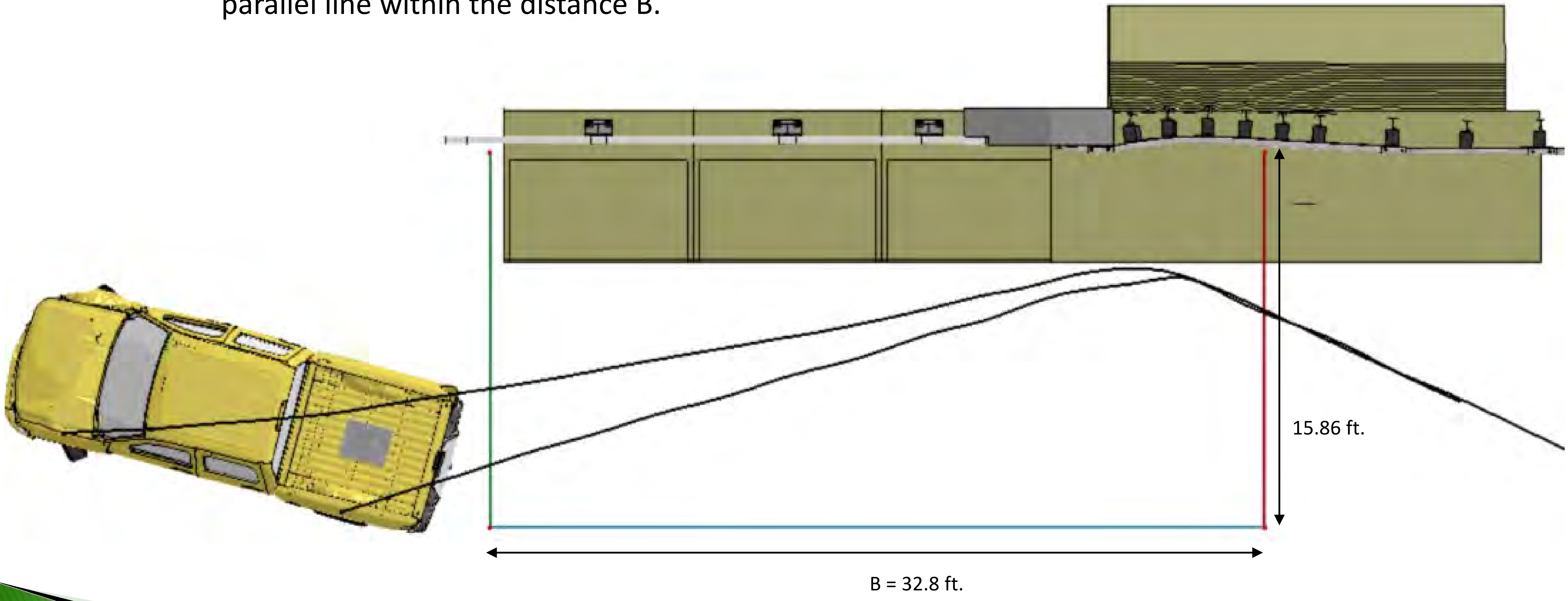
Occupant Compartment Intrusion (OCI)



OCI was ≈ 1 inch (23 mm) and occurred at the lower right-front corner of the top-pan at the wheel well.

Exit Box – 4-Bar Trans – Test 4-21

The driver-side front tire wheel track was used to determine the beginning location of the exit box. From MASH pg. 97: "All wheel tracks of the vehicle should not cross the parallel line within the distance B."



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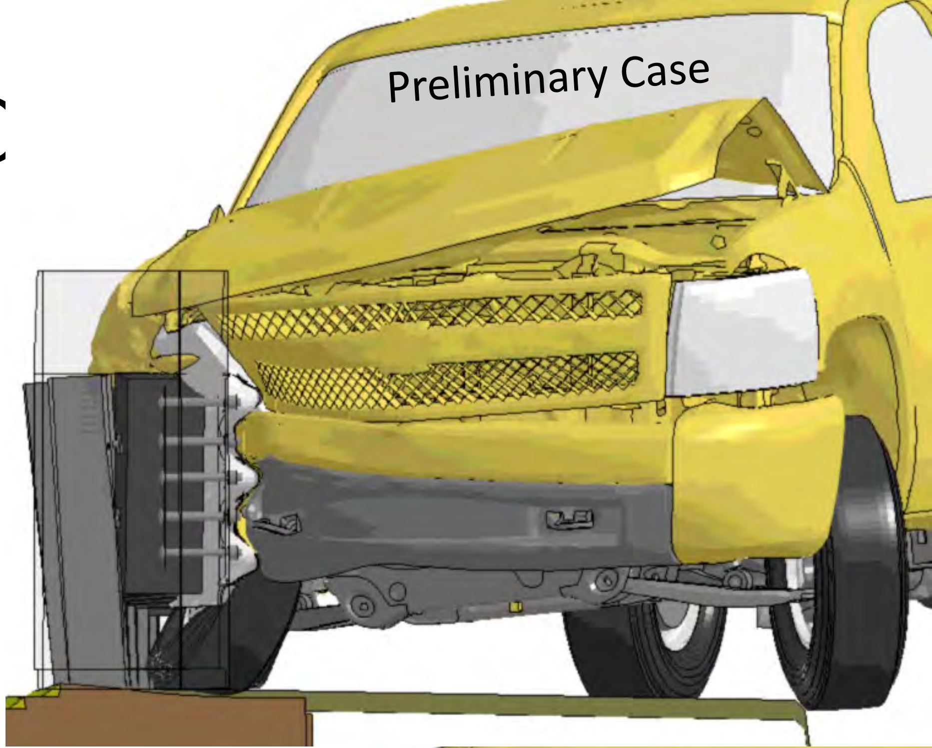
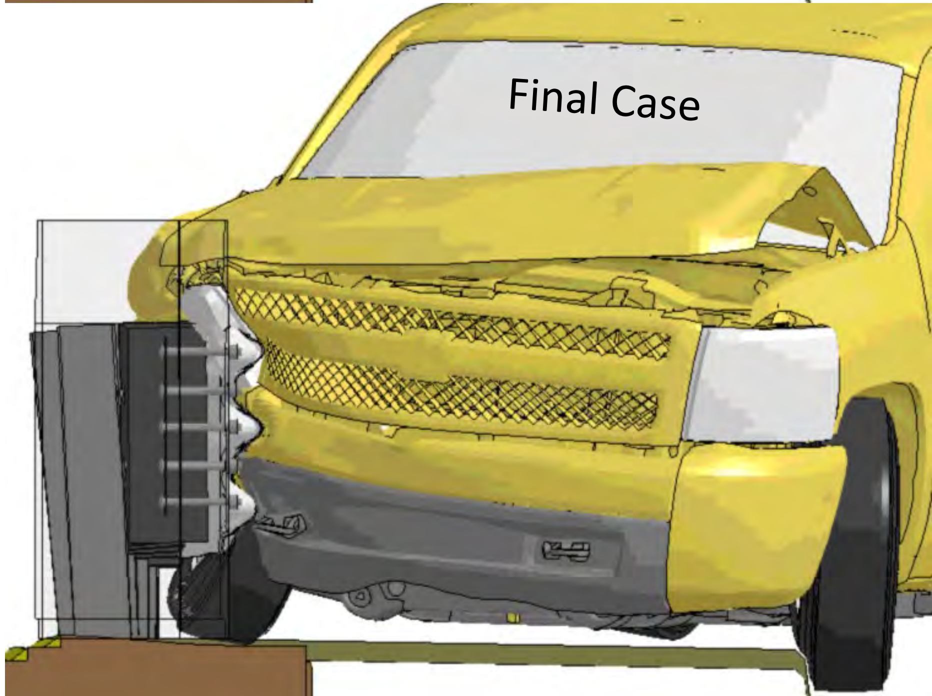
Conclusions on Test 4-21 on the MEDOT Transition

- The barrier successfully contained and redirected the 2270P vehicle.
- The vehicle remained upright and stable through impact and redirection, with relatively low angular displacements
  - Max Roll = **15.4 degrees** and Max Pitch = **9.6 degrees**.
- The OIV was within preferred limits and the maximum ORA was within critical limits specified in MASH.
  - OIV_x = **21.0 ft/s** and OIV_y = **28.2 ft/s**
  - ORA_x = **9.4 G** and ORA_y = **17.3 G**
- The occupant compartment deformation was ≈ 1 inch and well below critical limits.
- The vehicle also **remained well within the "exit box"** limits and showed no sign of entering back into travel lanes at aggressive angle.
- The damages to the transition were significant, but within expectations, and included kinking of the thrie-beam, lateral deflection of several posts and corresponding soil displacement at those posts.
- The damages to the concrete buttress were minimal except for probable cracking of the concrete at the junction between the buttress and bridge deck.
- The greatest deformation of the barrier occurred on the lower corrugation of the thrie-beam between Posts 2 and 3 (relative to the nose of the buttress) and was:
  - Max Dynamic = **8.34 inches**; Max Permanent = **7.17 inches**

Conclusions on Test 4-21 on the MED Transition

- The snag on the end of the buttress was much less pronounced for this case, where the pickup traversed the sidewalk before striking the barrier, compared to the preliminary analysis case in which the pickup was positioned at the barrier at the start of the analysis.
  - Preliminary Case: ORA_x = 13 G
  - Final Case: ORA_x = 9.4 G
- This was a result of the vehicle "attitude" at the time of impact with the buttress (e.g., combination of vertical trajectory, roll, pitch, yaw angles and rates).
- Although the final analysis case indicated better performance, there may be other impact conditions that would result in similar performance as the preliminary analysis case, such as:
  - Different curb height,
  - Slightly different impact point fore or aft of the case evaluated,
  - etc.
- Both cases, however, indicated that the system would pass MASH, but with ORA values above recommended limits.



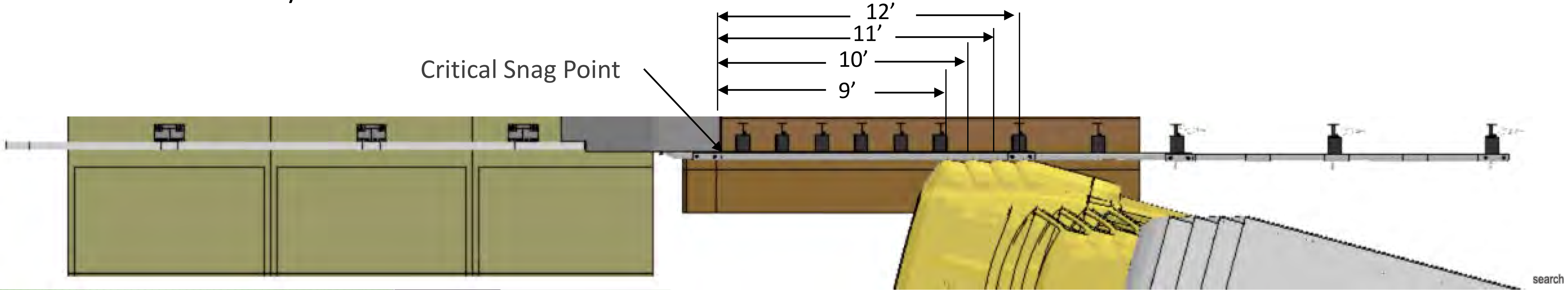


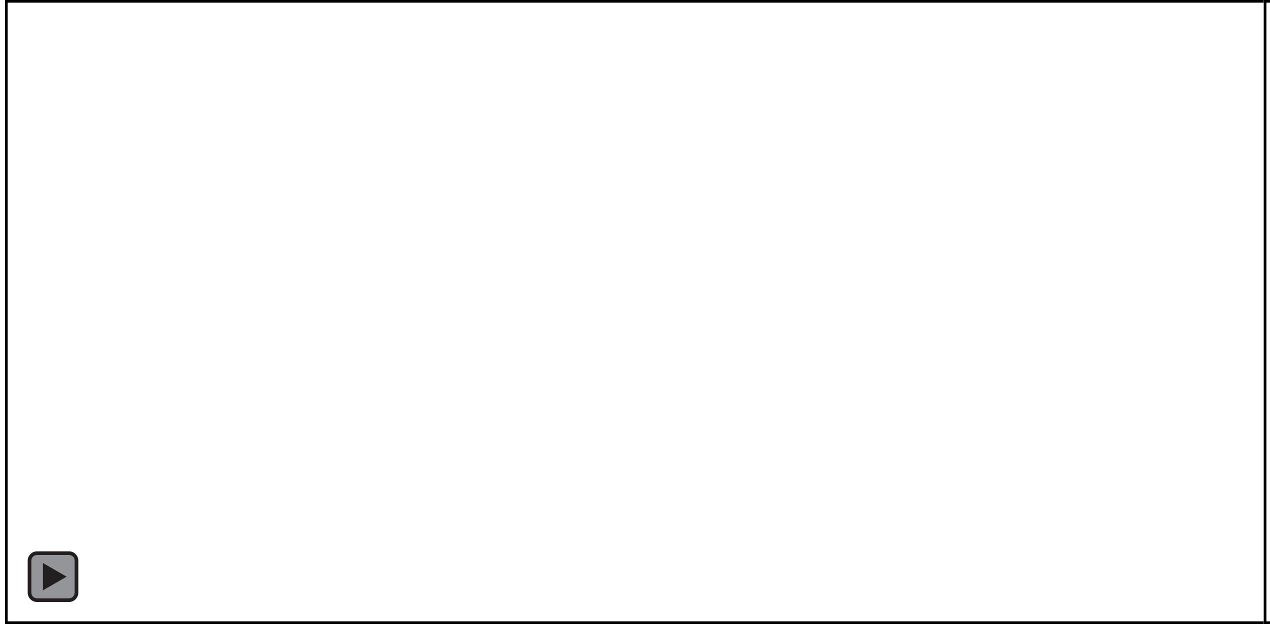
Conclusions on Test 4-21 on the MEDOT Transition

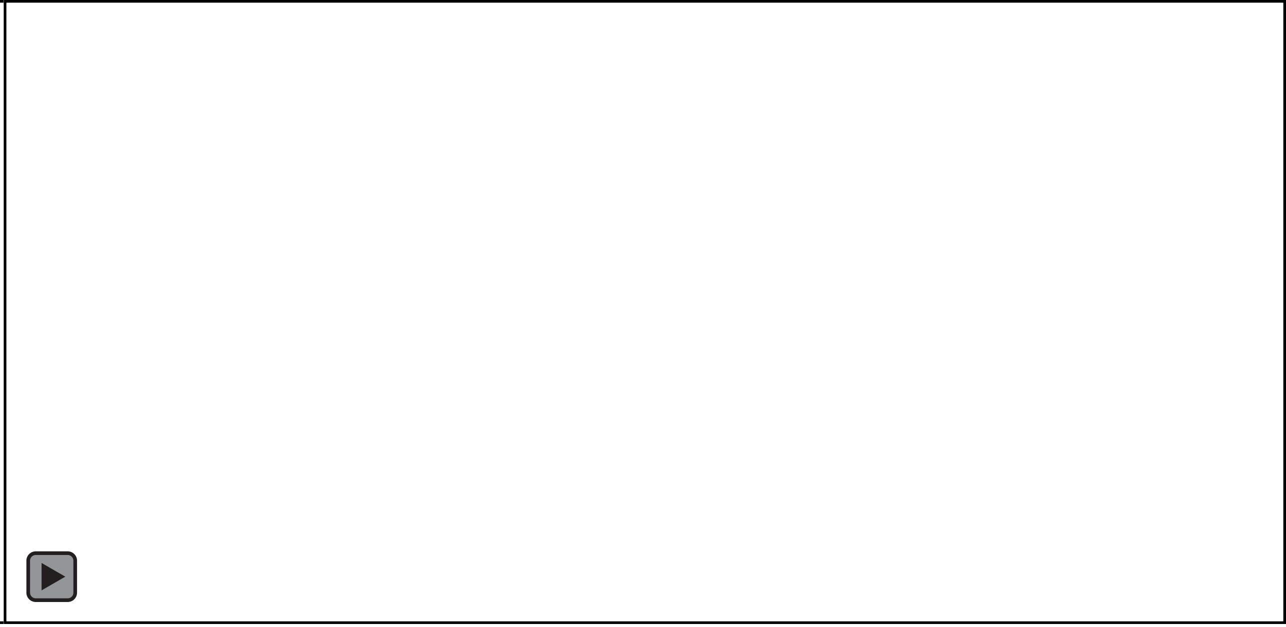
Evaluation Factors		Evaluation Criteria	Results
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
Occupant Risk	D	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, to occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.	Pass
	F	The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.	Pass
	H	The longitudinal and lateral occupant impact velocity (OIV) shall not exceed 40 ft/s (12.2 m/s), with a preferred limit of 30 ft/s (9.1 m/s)	Pass
	I	The longitudinal and lateral occupant ridedown acceleration (ORA) shall not exceed 20.49 G, with a preferred limit of 15.0 G	Pass

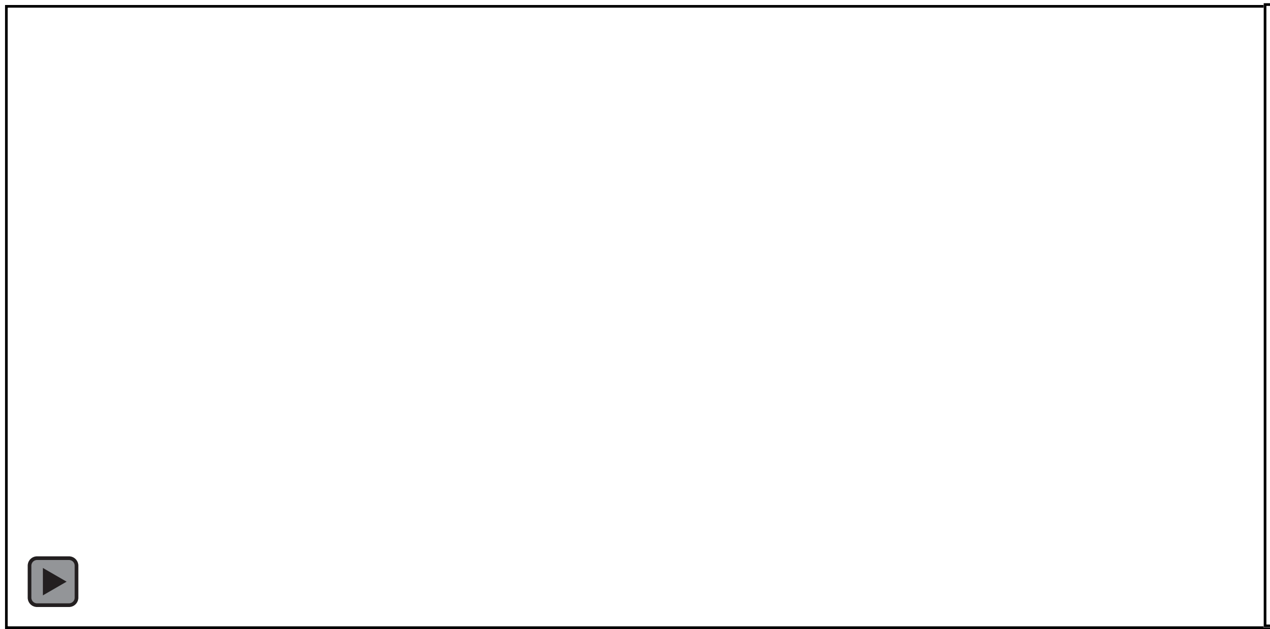
Determination of CIP for Test 4-22

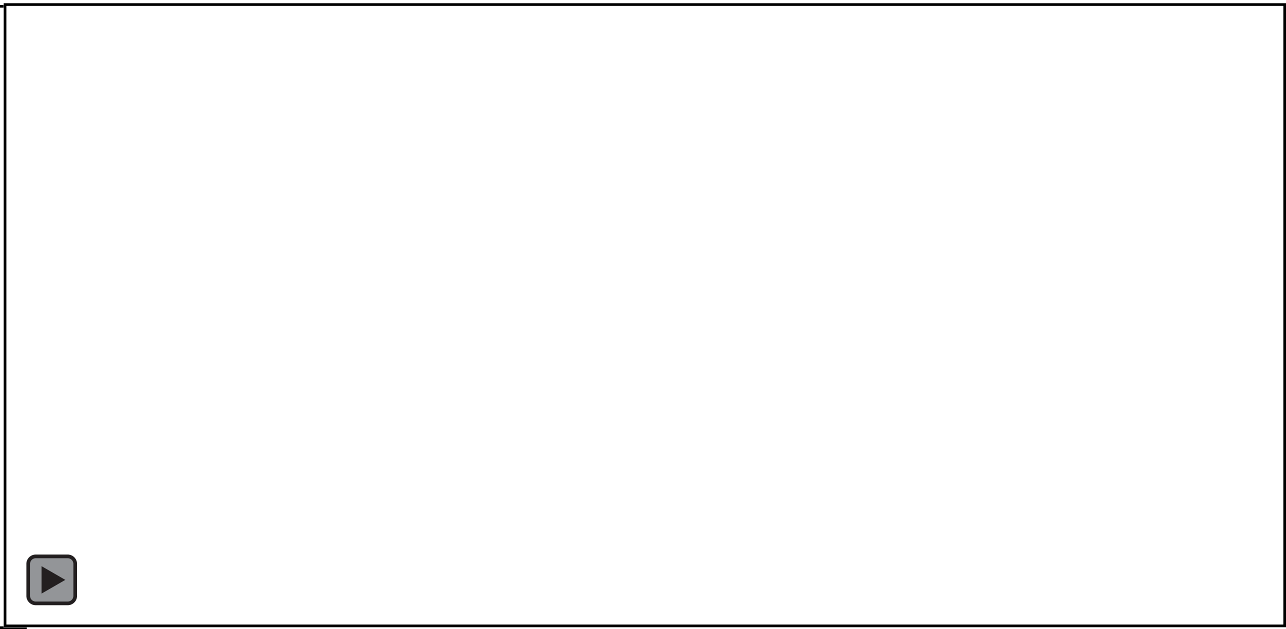
- CIP was determined using FEA based on maximizing potential for snag on the end of the concrete buttress.
  - Pocketing
    - Maximum relative deflection between thrie-beam and buttress
  - Peak accelerations relative to critical snag point
    - Peak longitudinal acceleration (e.g., generally identifies snag)
    - Peak lateral acceleration (e.g., point of highest lateral force)
  - Impact Forces
- Analysis Cases (4 cases):
  - Impact points 9 ft, 10 ft, 11 ft and 12 ft from the end of the buttress.
  - Effects of sidewalk on vehicle dynamics prior to impact are ignored (for the CIP determination)
  - These analyses were conducted for 0.4 seconds.

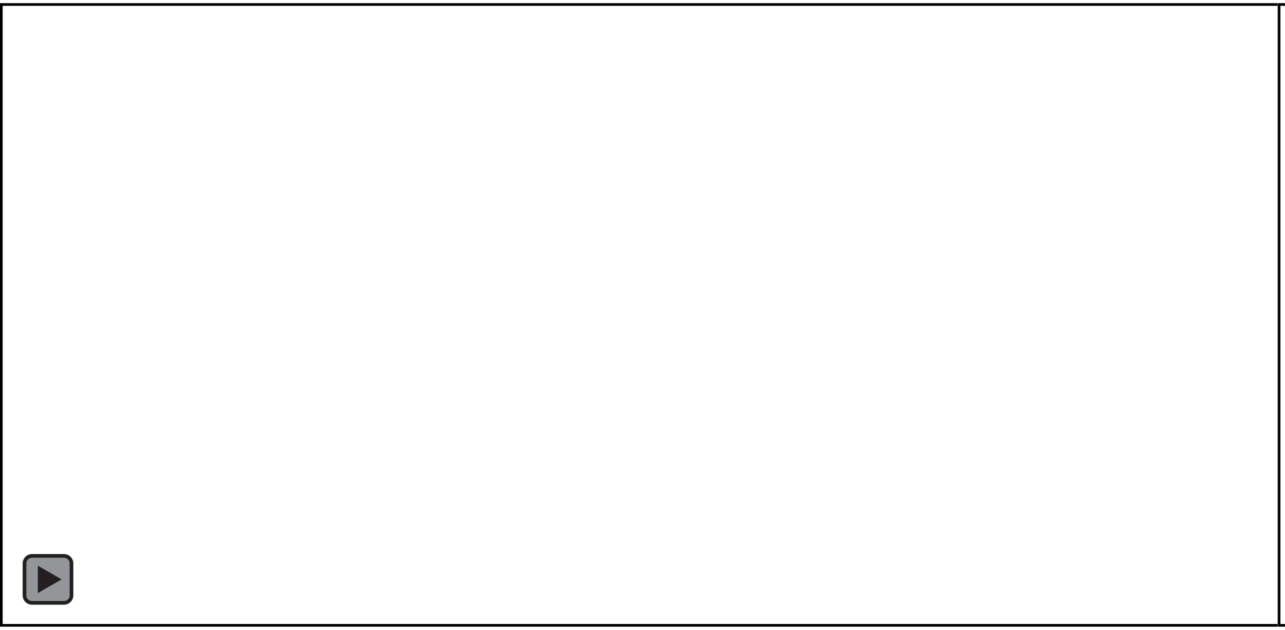
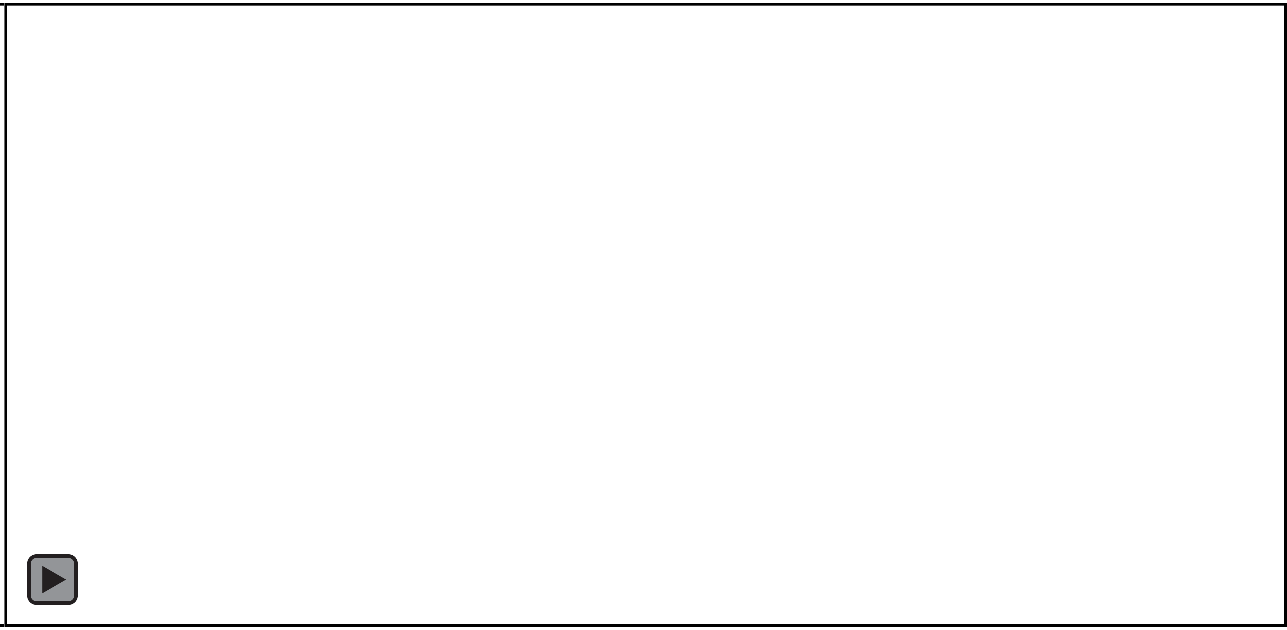
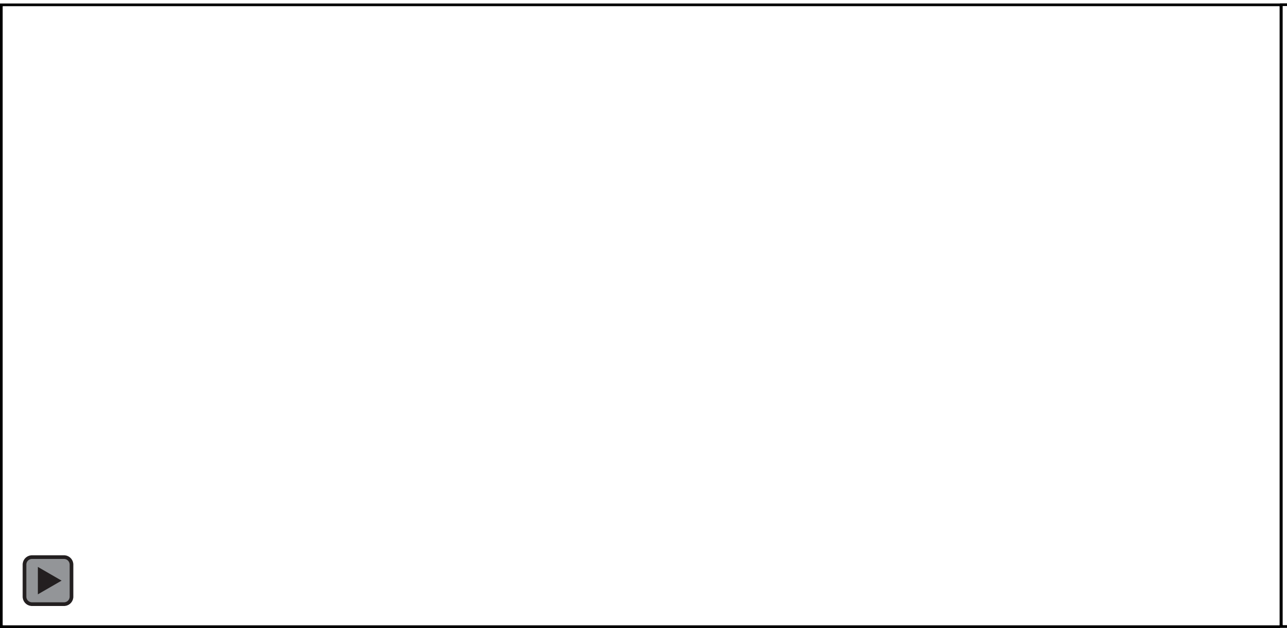
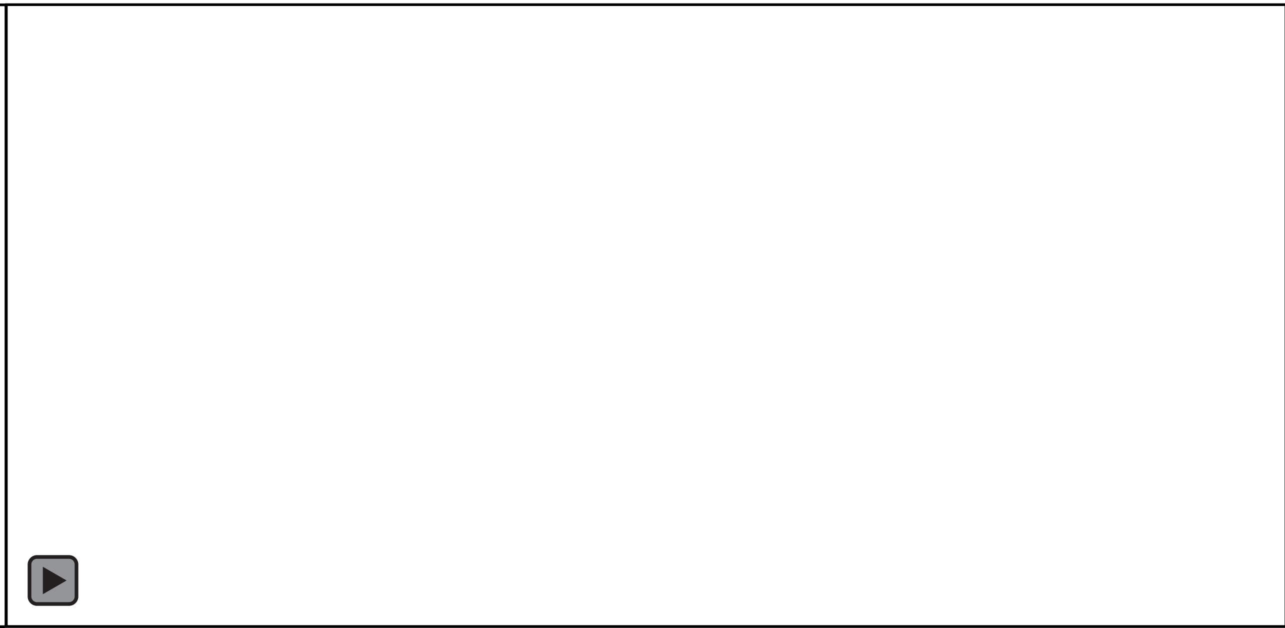


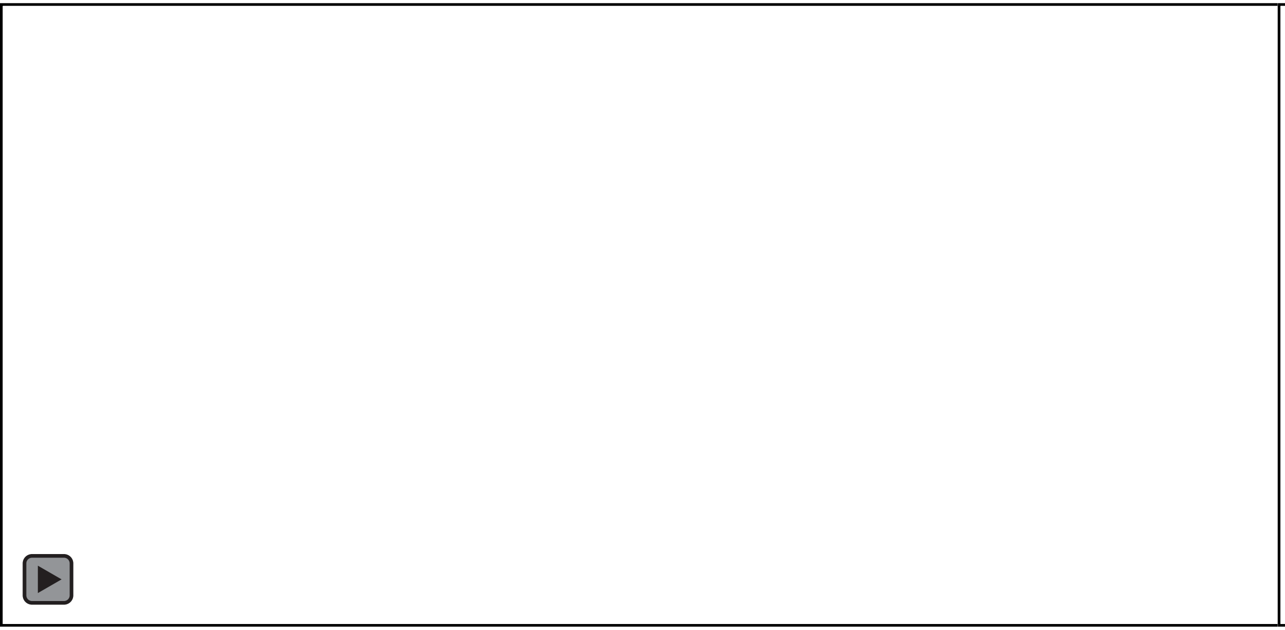


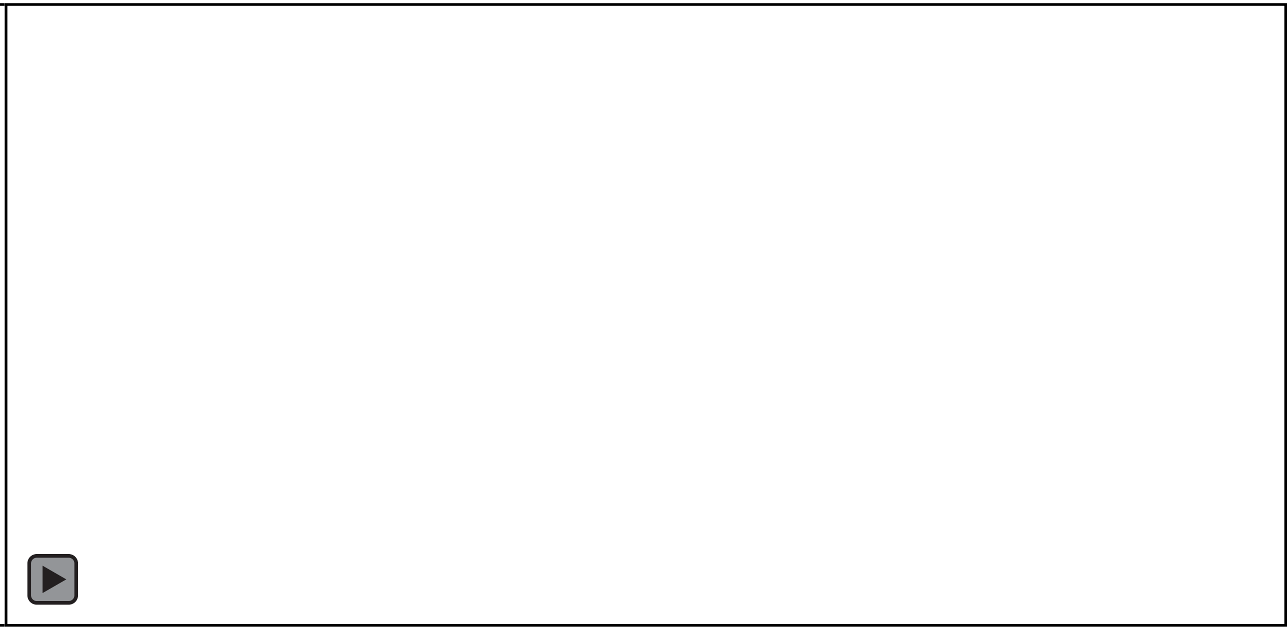


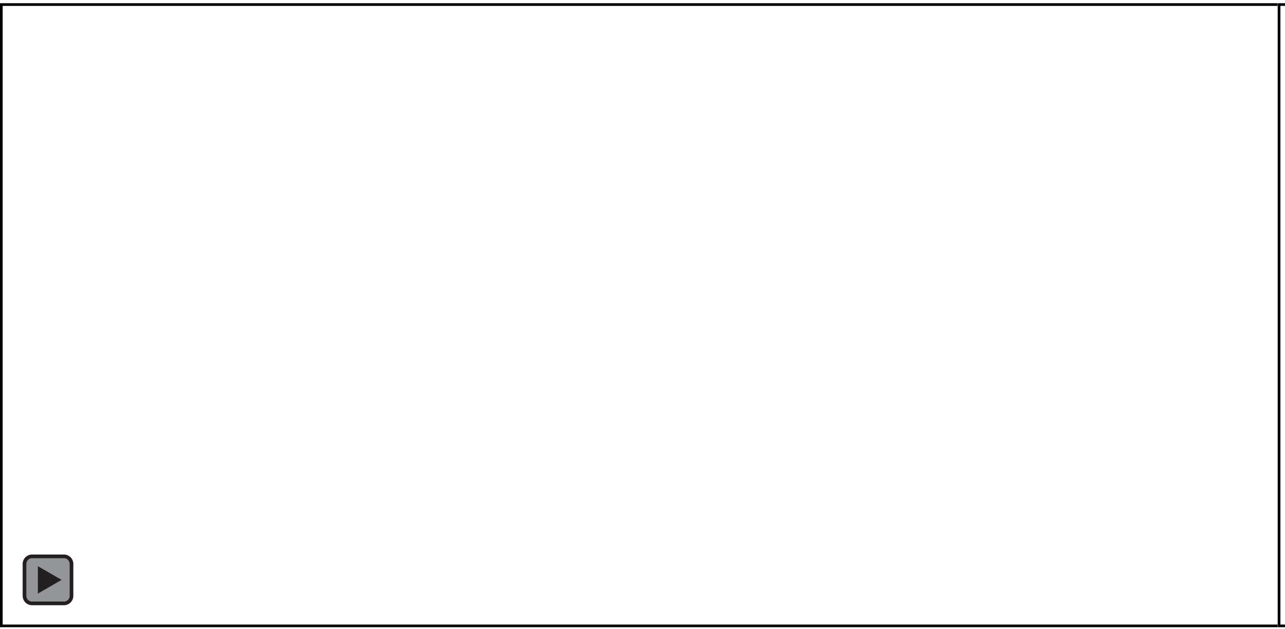


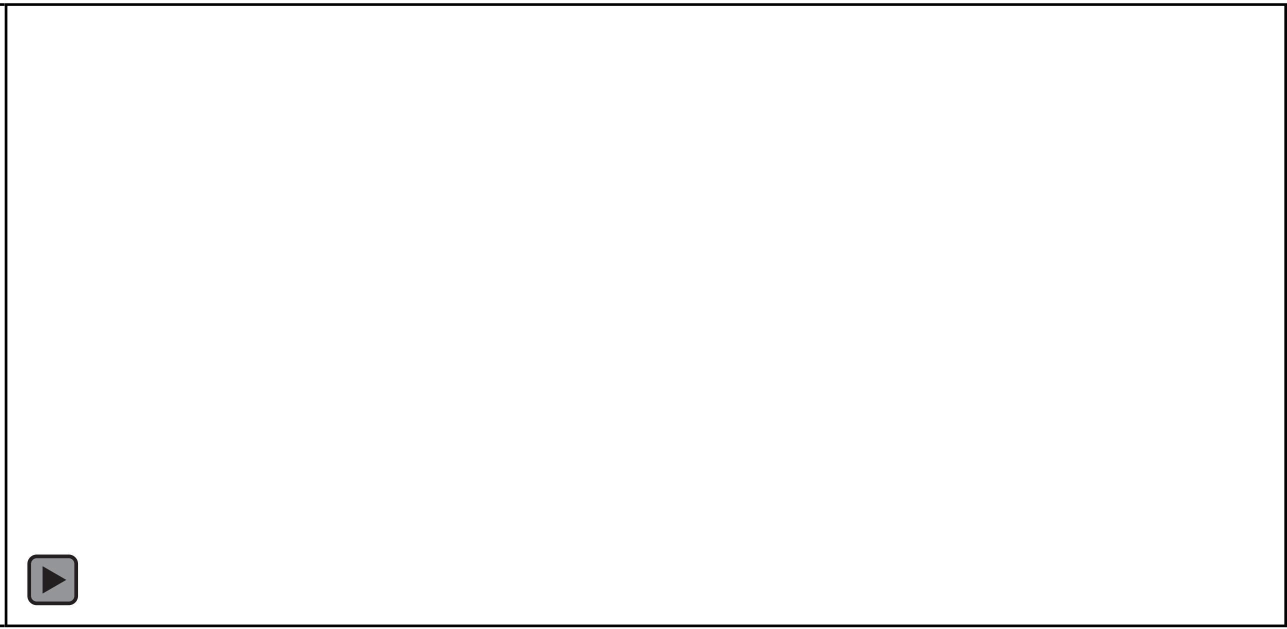




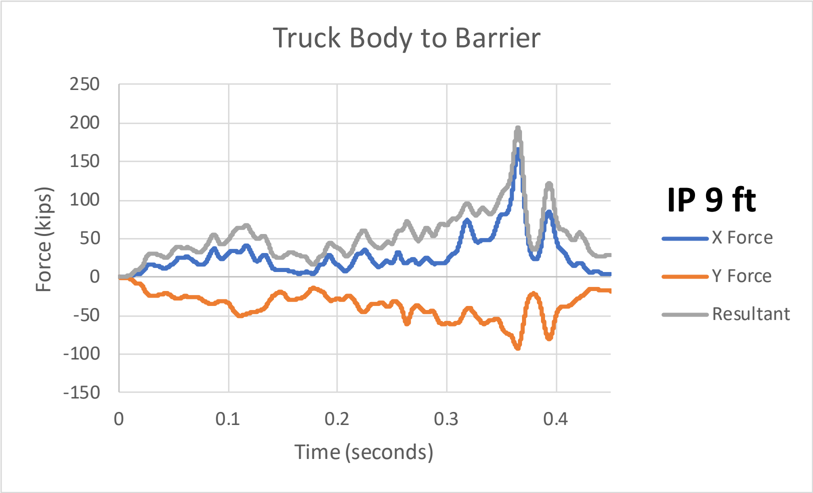


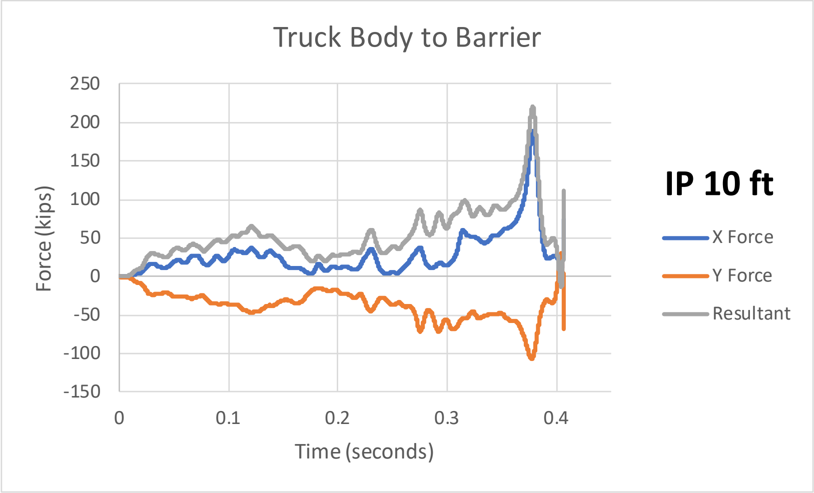


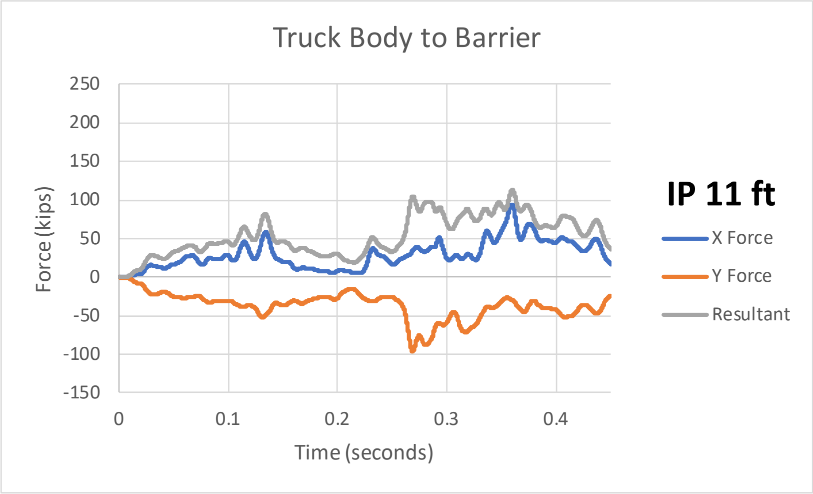


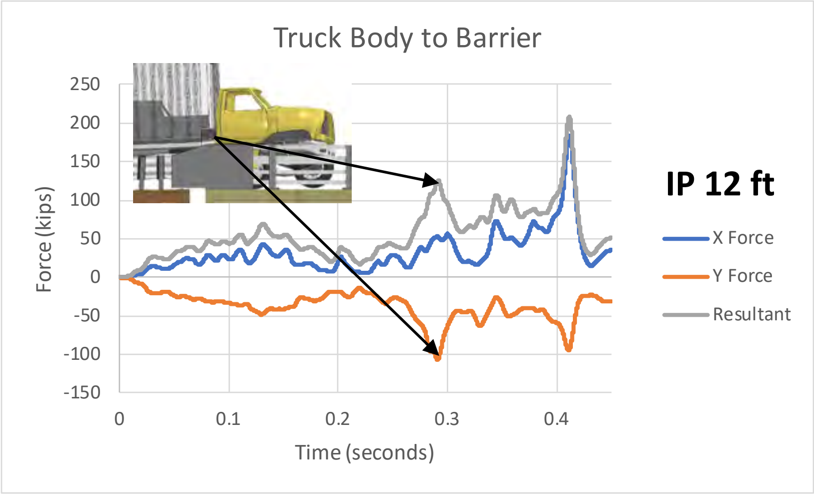
Impact Forces

- The impact force from the tandem wheel set was essentially equal for all case (except IP11)
- The force from the front edge of cargo box reached peak magnitude for IP 12 ft.
- IP 12 ft was therefore selected as CIP.









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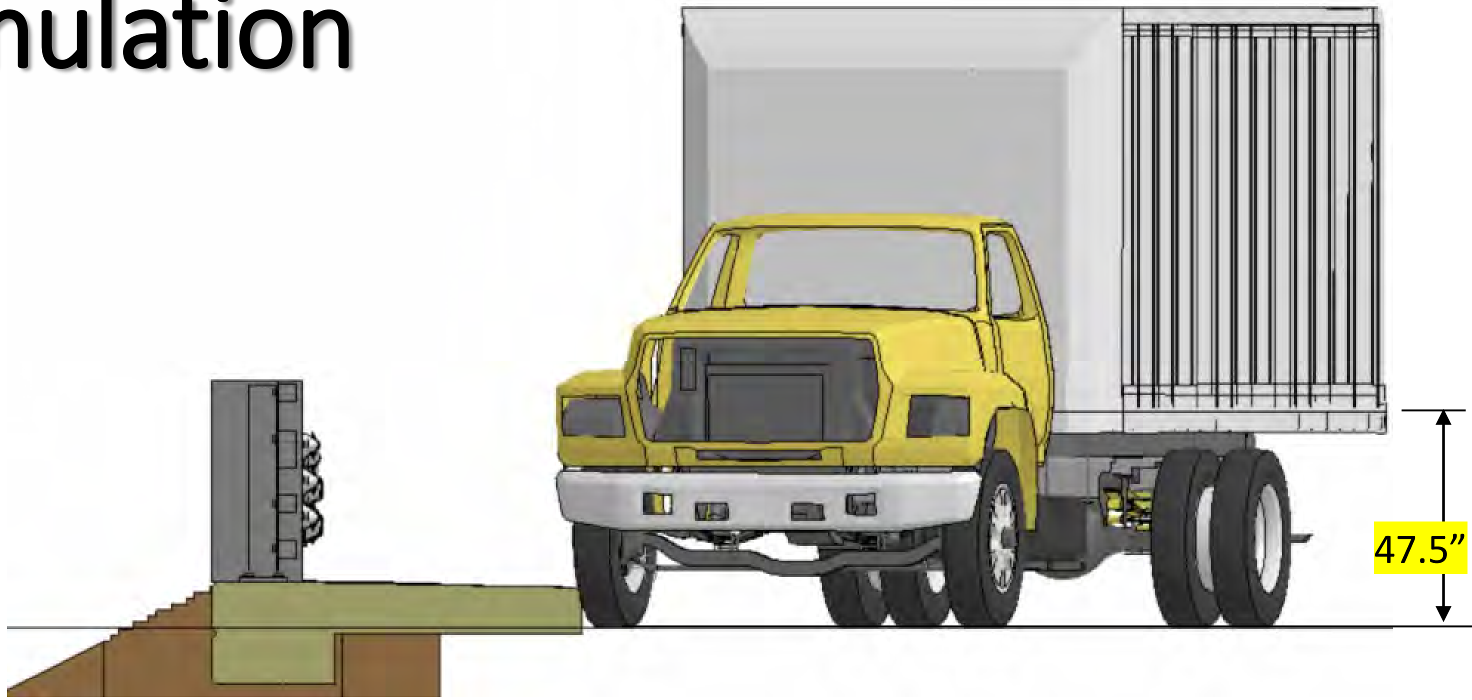
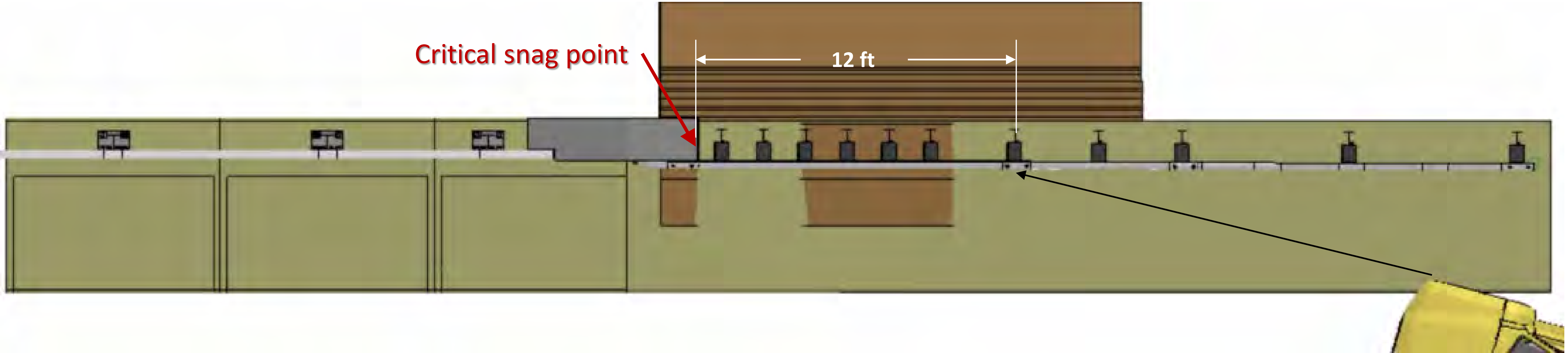
MASH Test 4-22 Simulation

- **Impact Conditions**
  - Mass = 22,061 lb
  - Impact Speed = 56 mph (90 km/hr)
  - Impact Angle = 15 degrees
  - Impact Point:
    - Target = 12 ft upstream of buttress
    - Actual = 11.5 ft
- **Vehicle Model**
  - F800_No-Box_181114_UboltF0p17.k
  - TruckBox_181114.k
  - F800-SuspenStress_FRONT_35N.k
  - F800-SuspenStress_REAR_60N.k
  - Vehicle Mass = 10,000 kg (22,046 lb)





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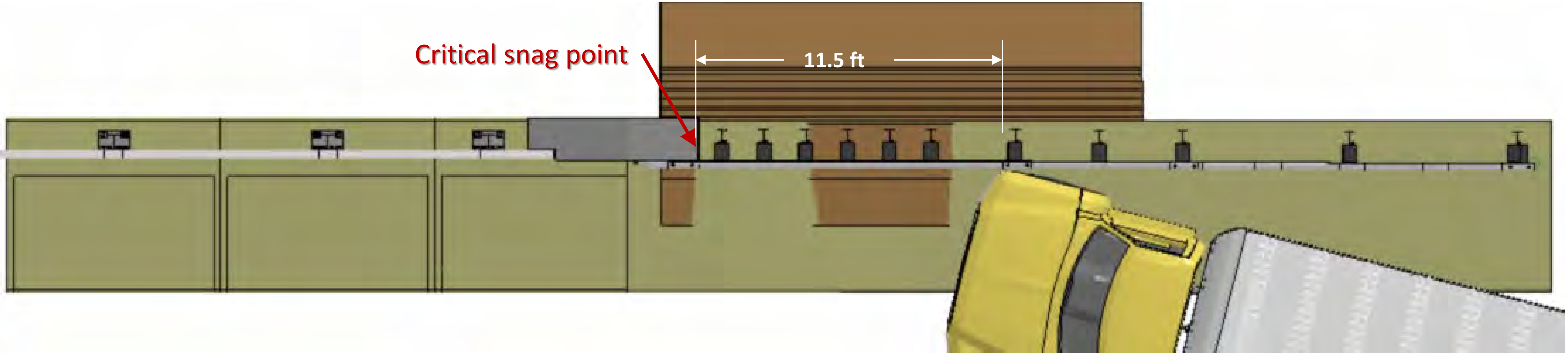

Movies

TRAP – Summary Table

Occupant Risk Factors		MASH Test 4-22
Occupant Impact Velocity (ft/s)	x-direction	8.9
	y-direction	14.4
	at time	at 0.3726 seconds on right side of interior
THIV (ft/s)		16.4 at 0.3726 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-13.9 (0.6320 - 0.6420 seconds)
	y-direction	8.7 (0.6419 - 0.6519 seconds)
PHD (g's)		15 (0.6322 - 0.6422 seconds)
ASI		0.66 (0.6306 - 0.6806 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-5.6 (0.5916 - 0.6416 seconds)
	y-direction	5 (0.6284 - 0.6784 seconds)
	z-direction	3.4 (0.6310 - 0.6810 seconds)
Maximum Angular Disp. (deg)	Roll	-8.7 (1.3455 seconds)
	Pitch	-12 (0.9437 seconds)
	Yaw	30.4 (1.3455 seconds)

MASH Criteria

< 30 ft/s (preferred) ✓
< 40 ft/s (limit)

< 15 G (preferred) ✓
< 20.49 G (limit)

< 75 deg ✓

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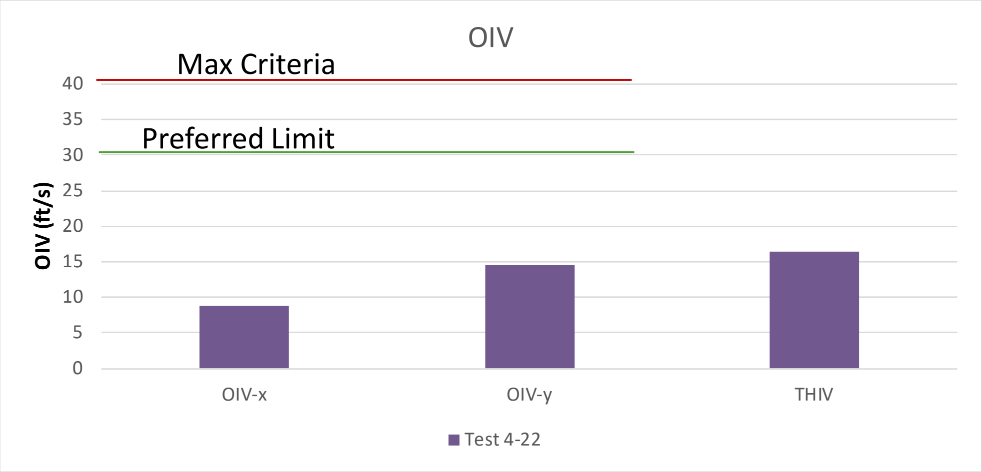
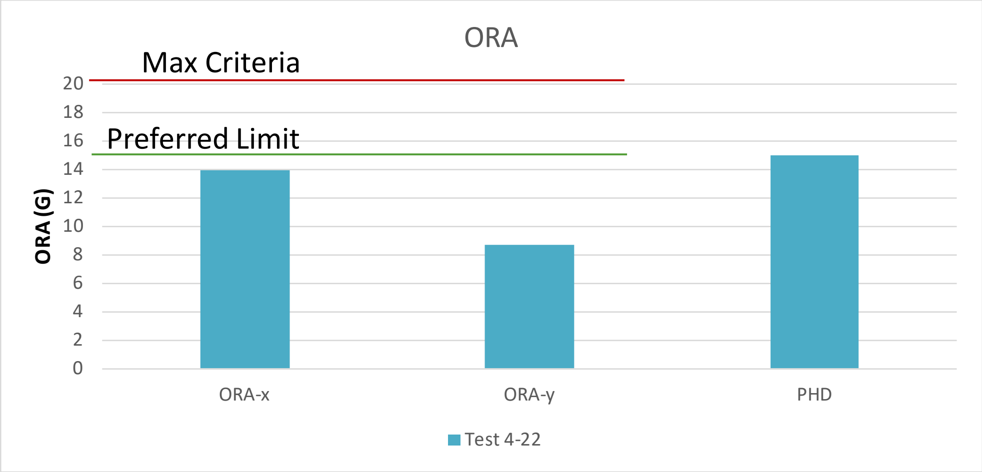
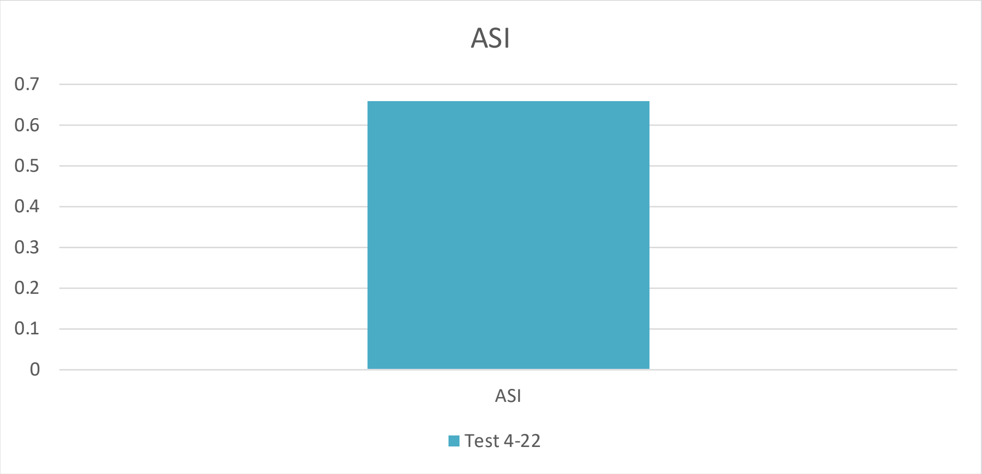
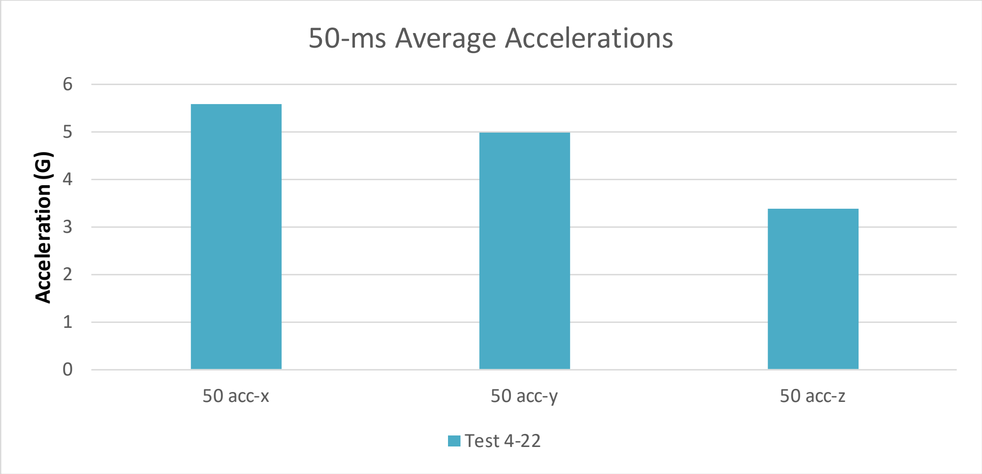
TRAP









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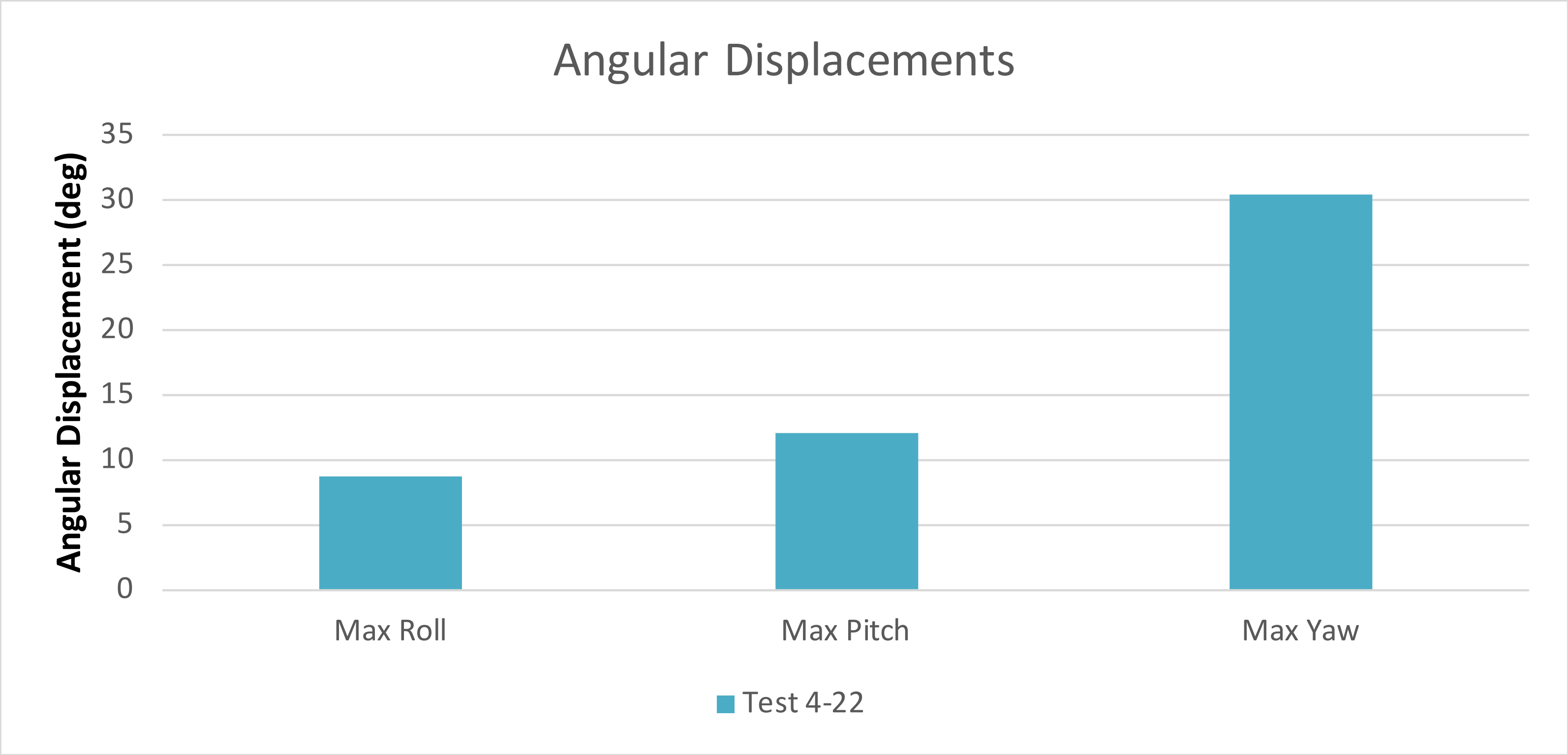
TRAP



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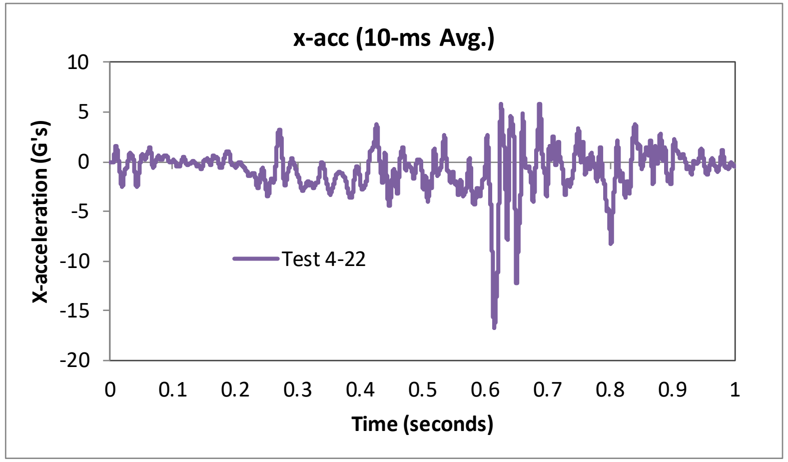
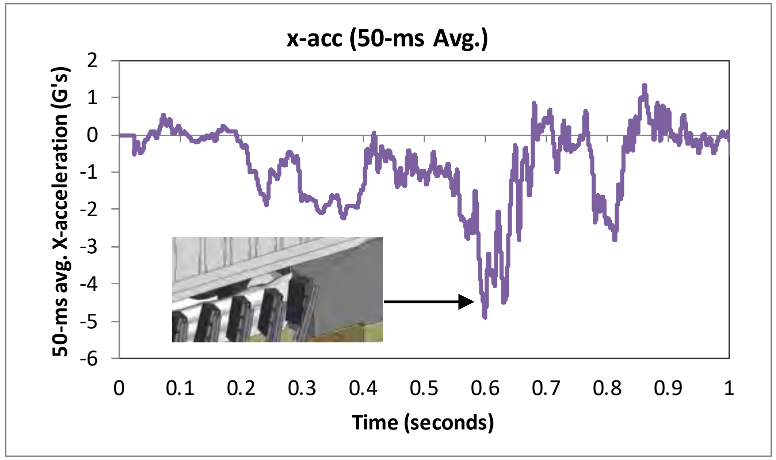
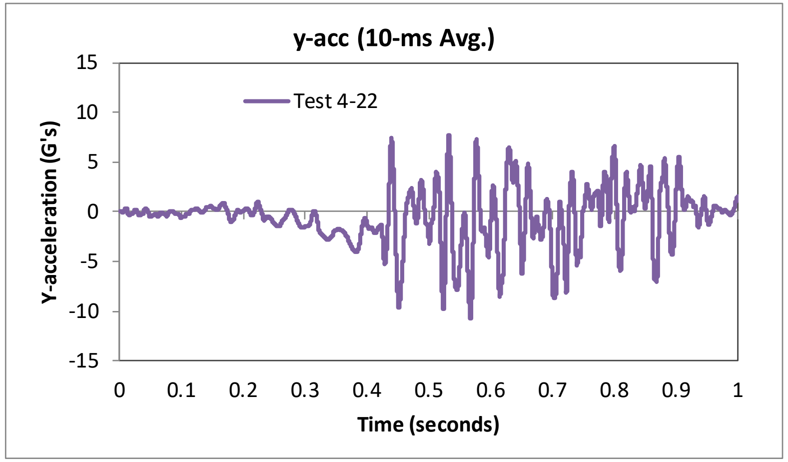
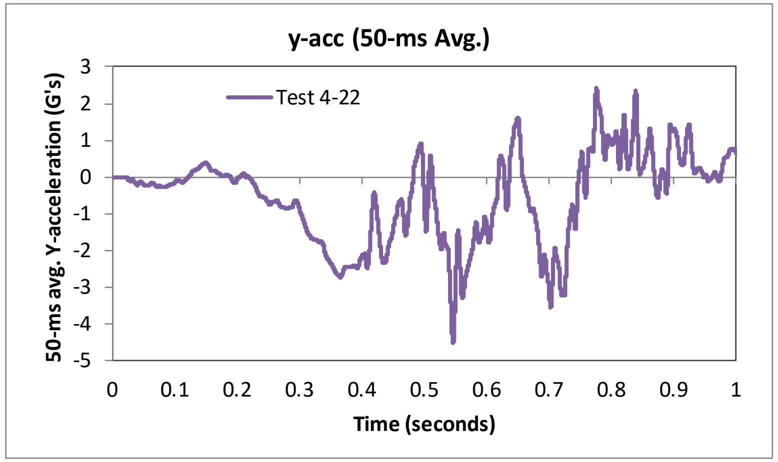
Acceleration Plots

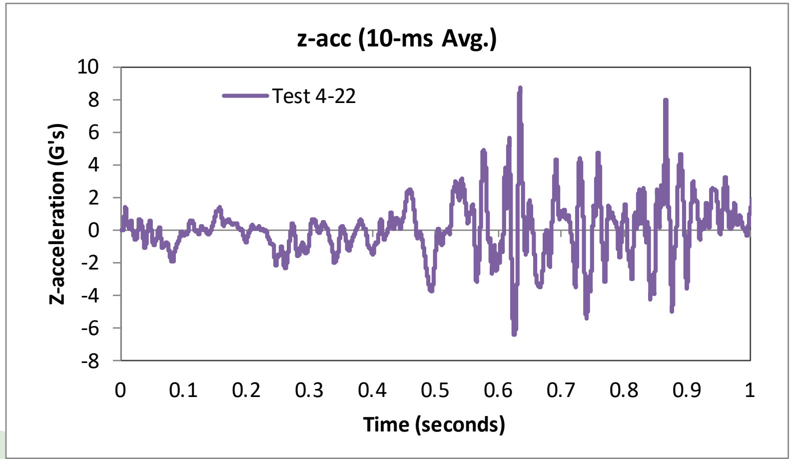
C.G.

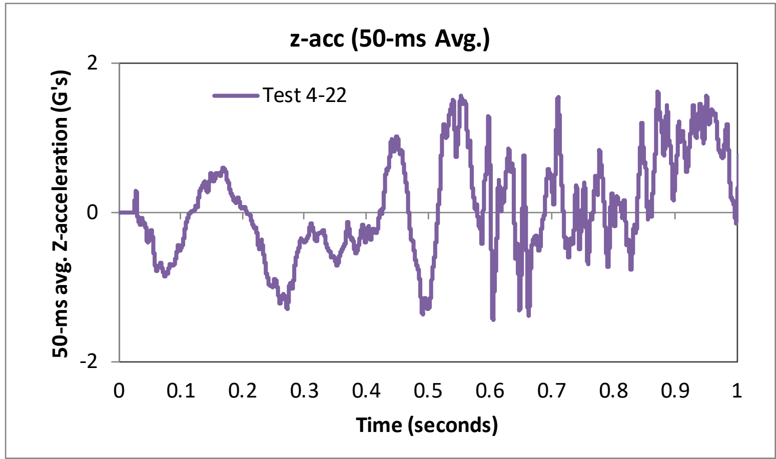






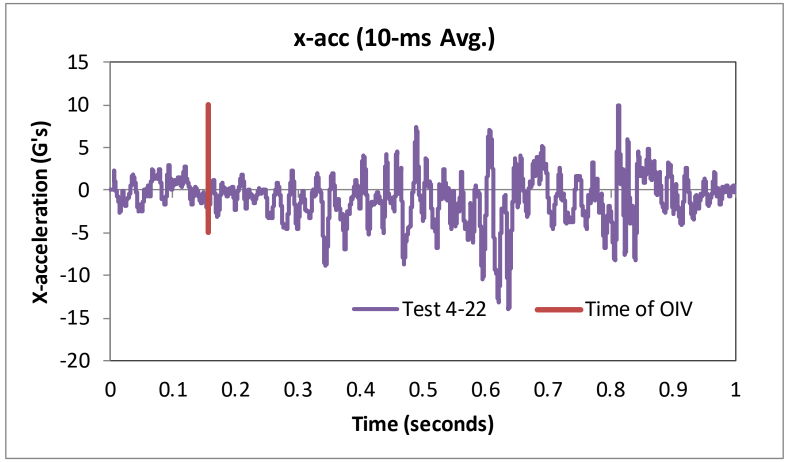


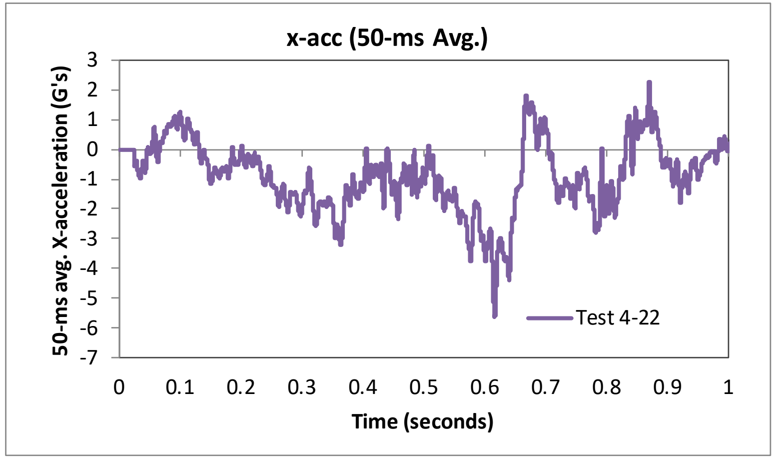


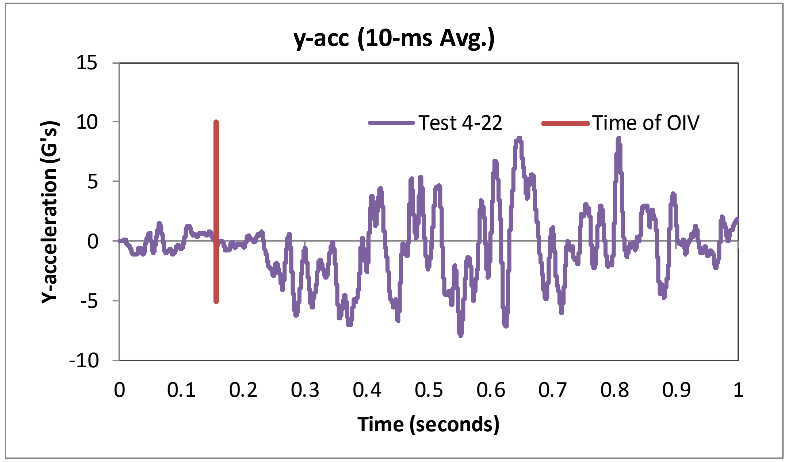


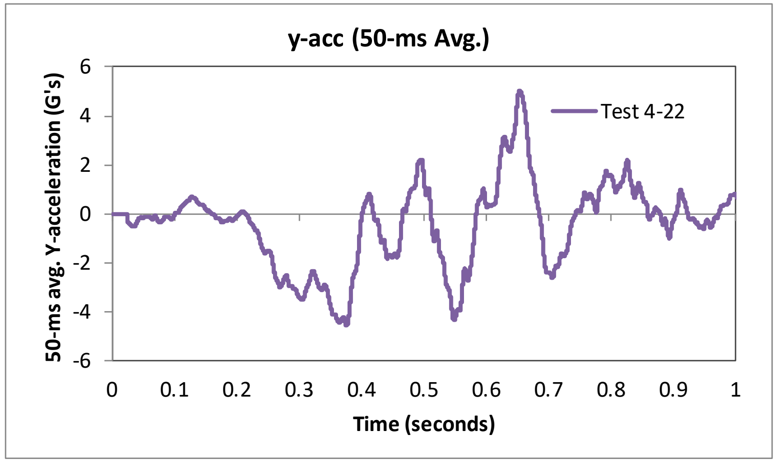
Acceleration Plots

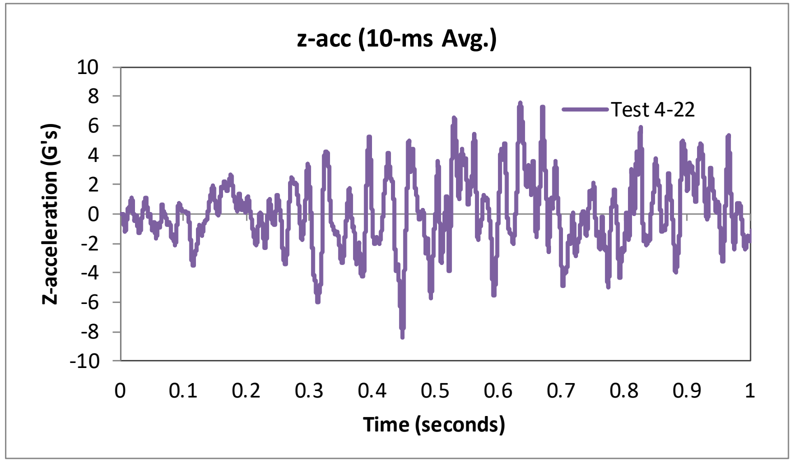
Cabin

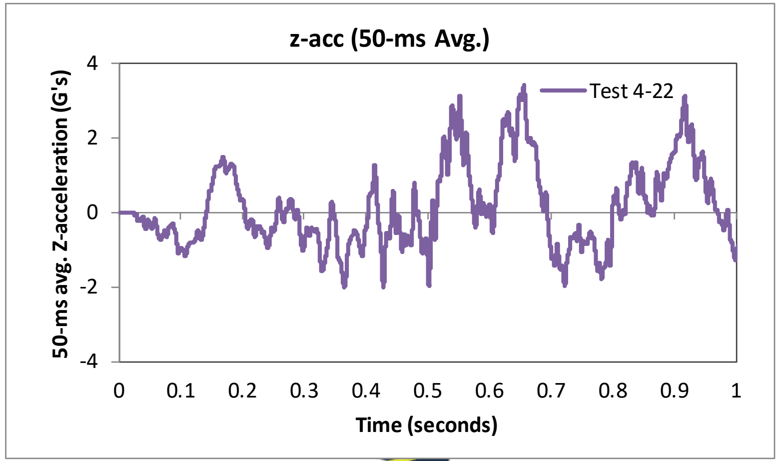






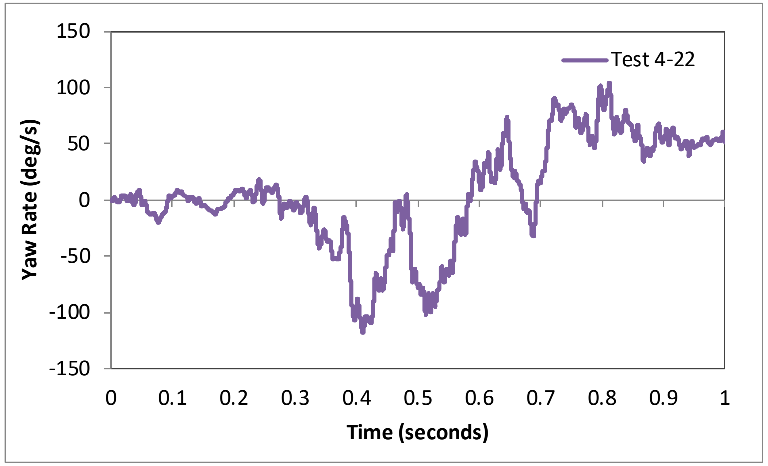


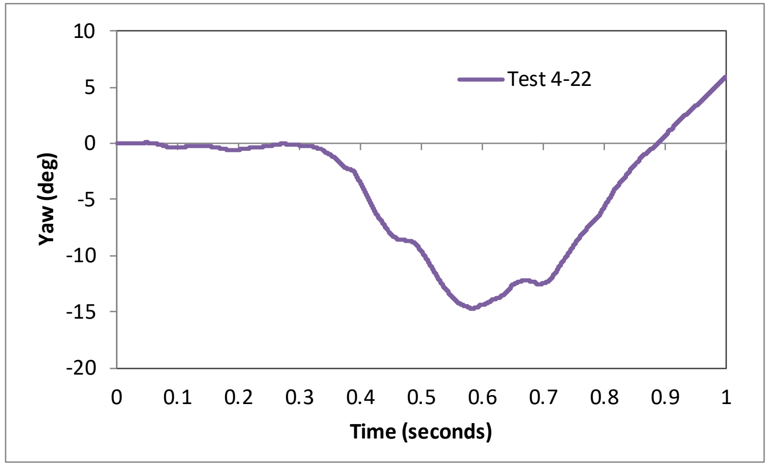


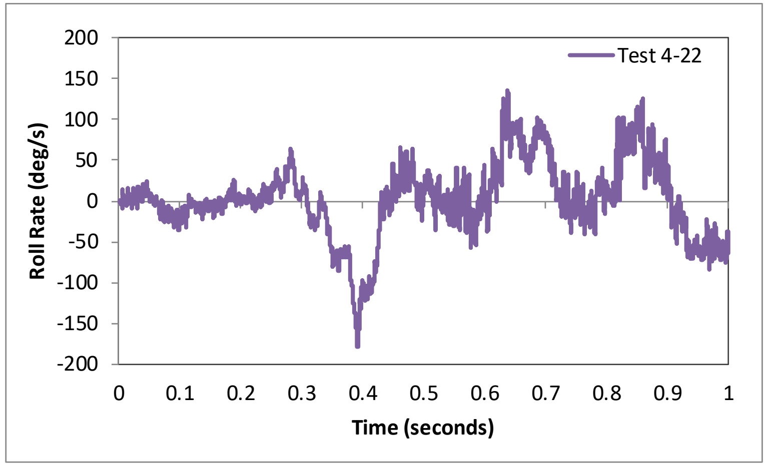


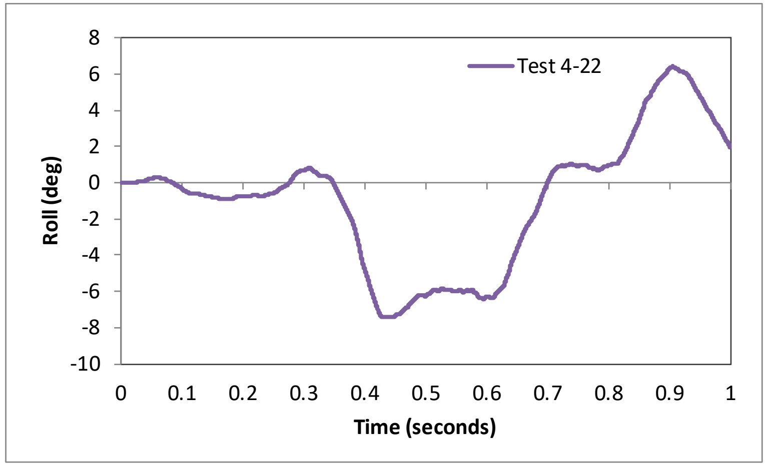
Angular Rate and Displacement Plots

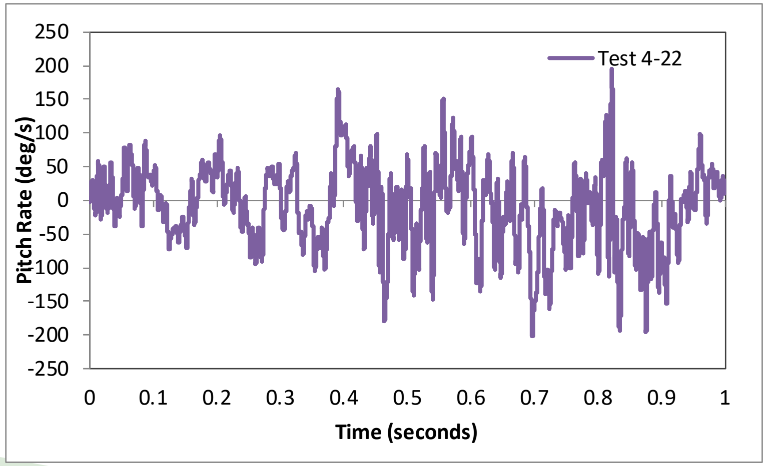
Cabin

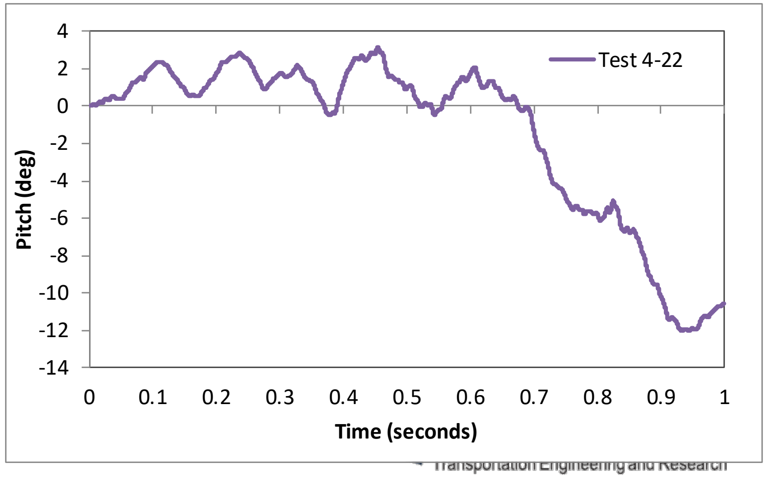




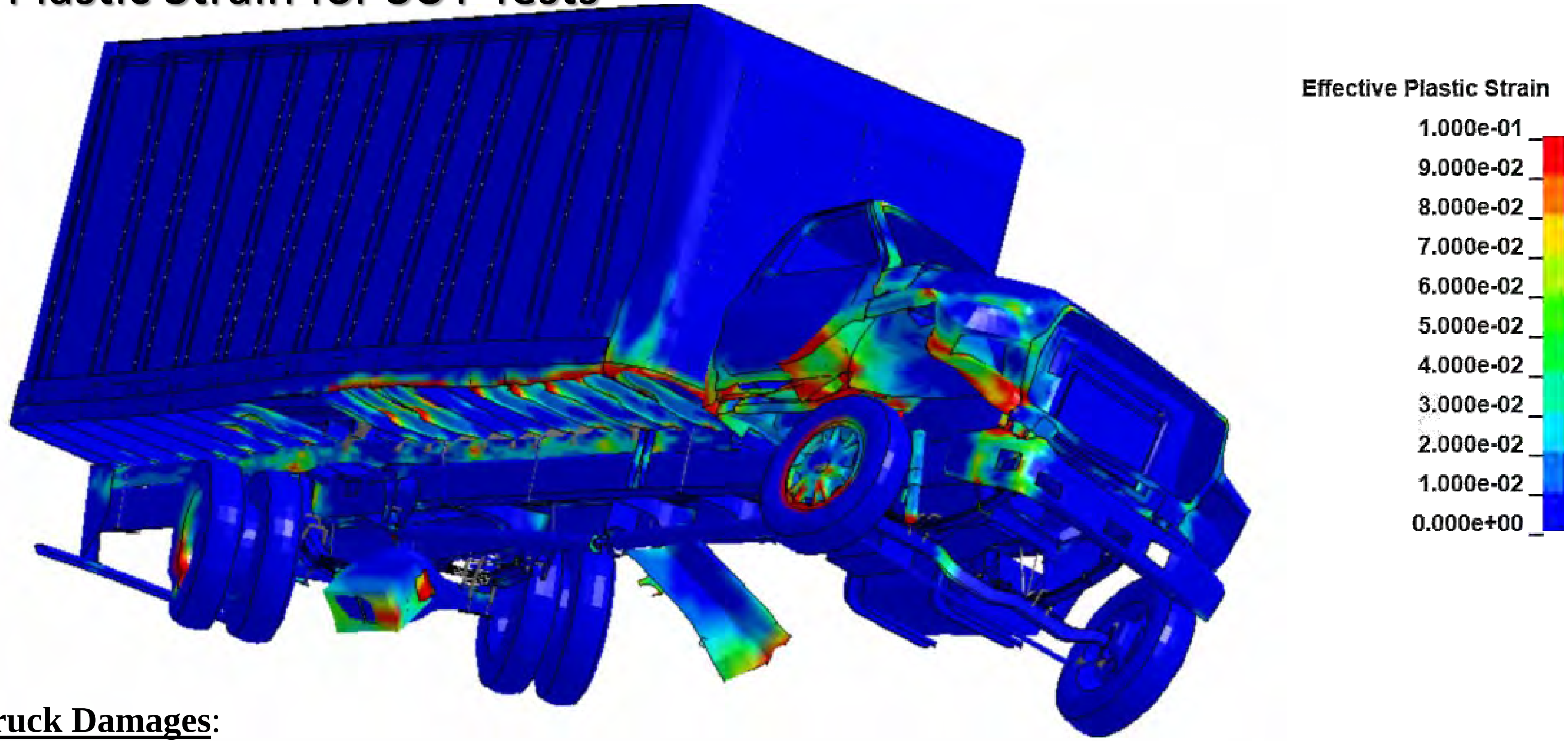








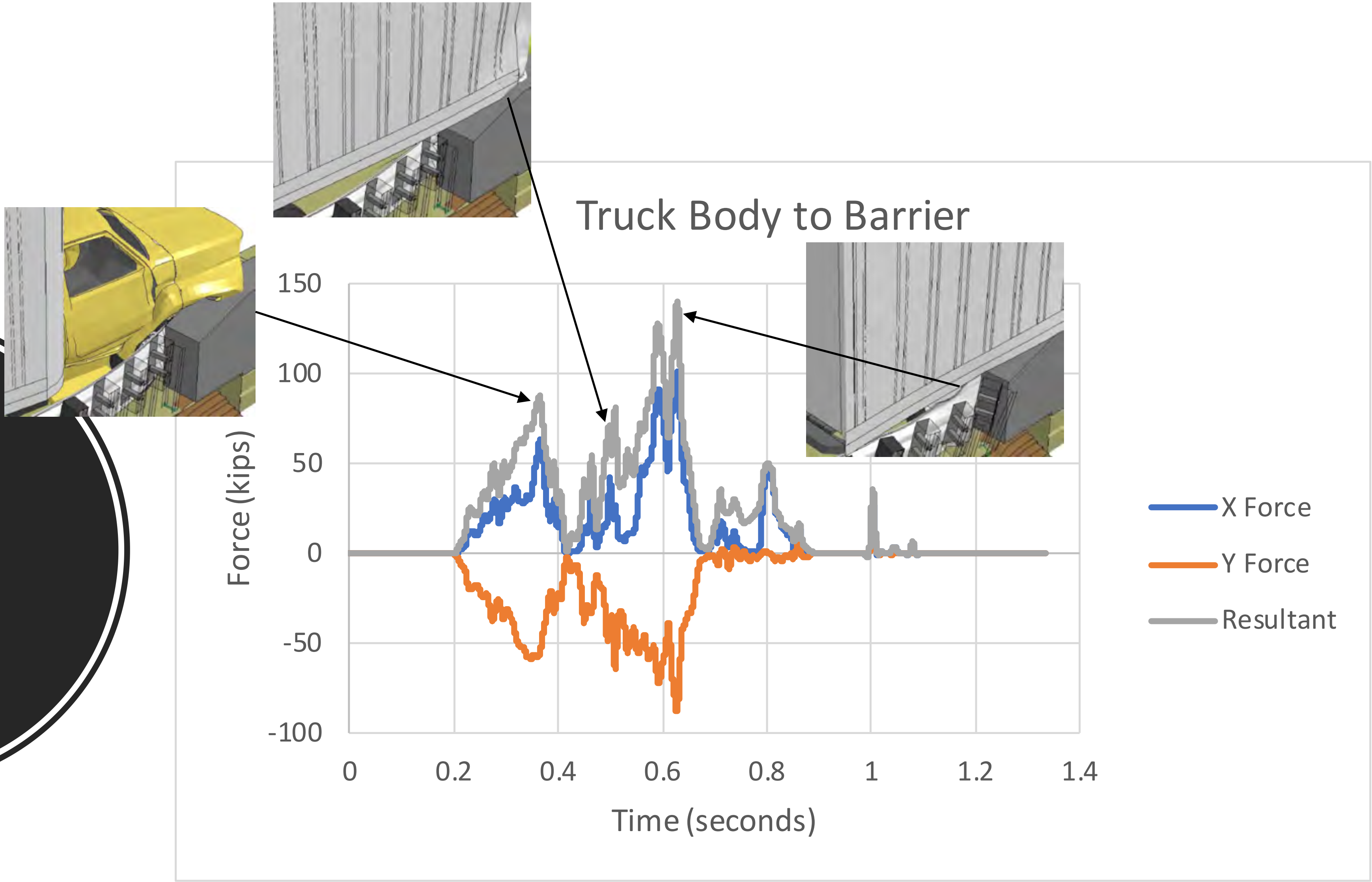
Effective Plastic Strain for SUT Tests



Truck Damages:
The front bumper, front fender, front-right suspension failure, front axle and wheel, side step, lower edge of door and cabin, frame rails, rear suspension failure, and rear outside tandem wheel.

Cargo-Box Damages:
Front-lower corner of box, lateral floor beams, main bed rail, wood flooring, and side rail.

Impact Forces on Barrier



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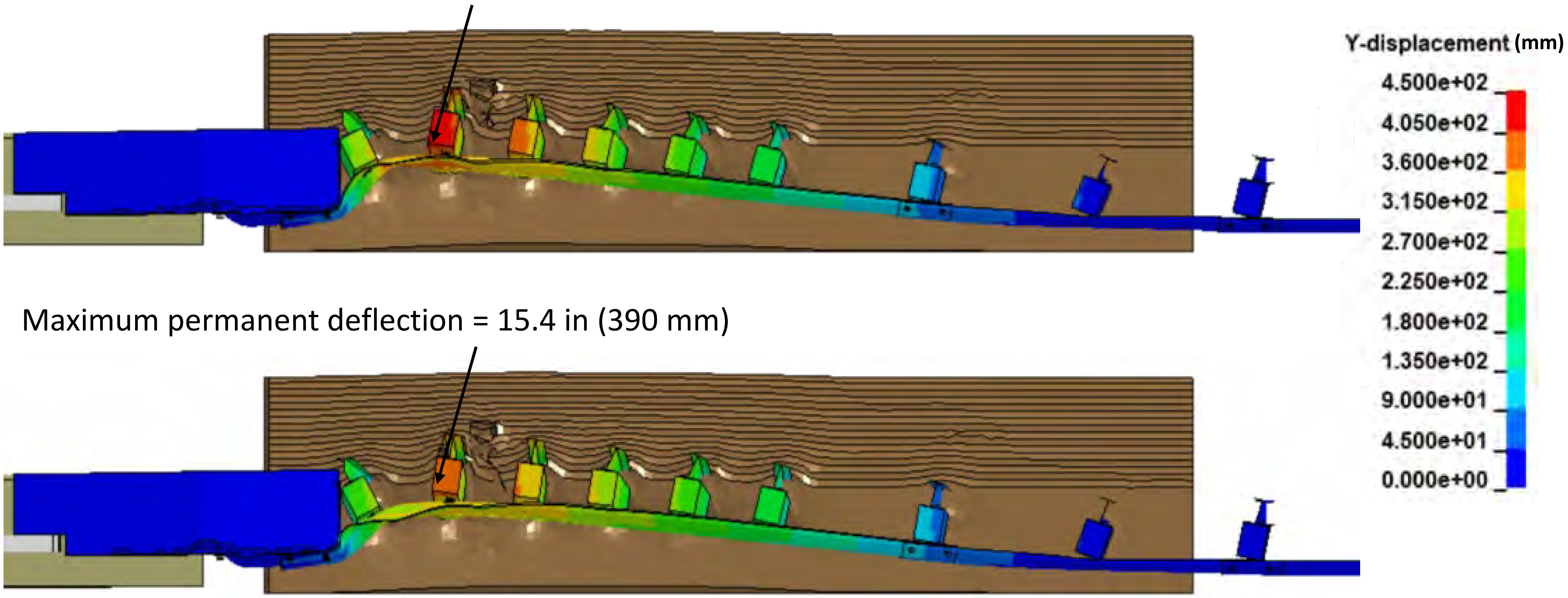
Lateral Deflection

Maximum dynamic deflection = 17 in (433 mm)

Maximum permanent deflection = 15.4 in (390 mm)



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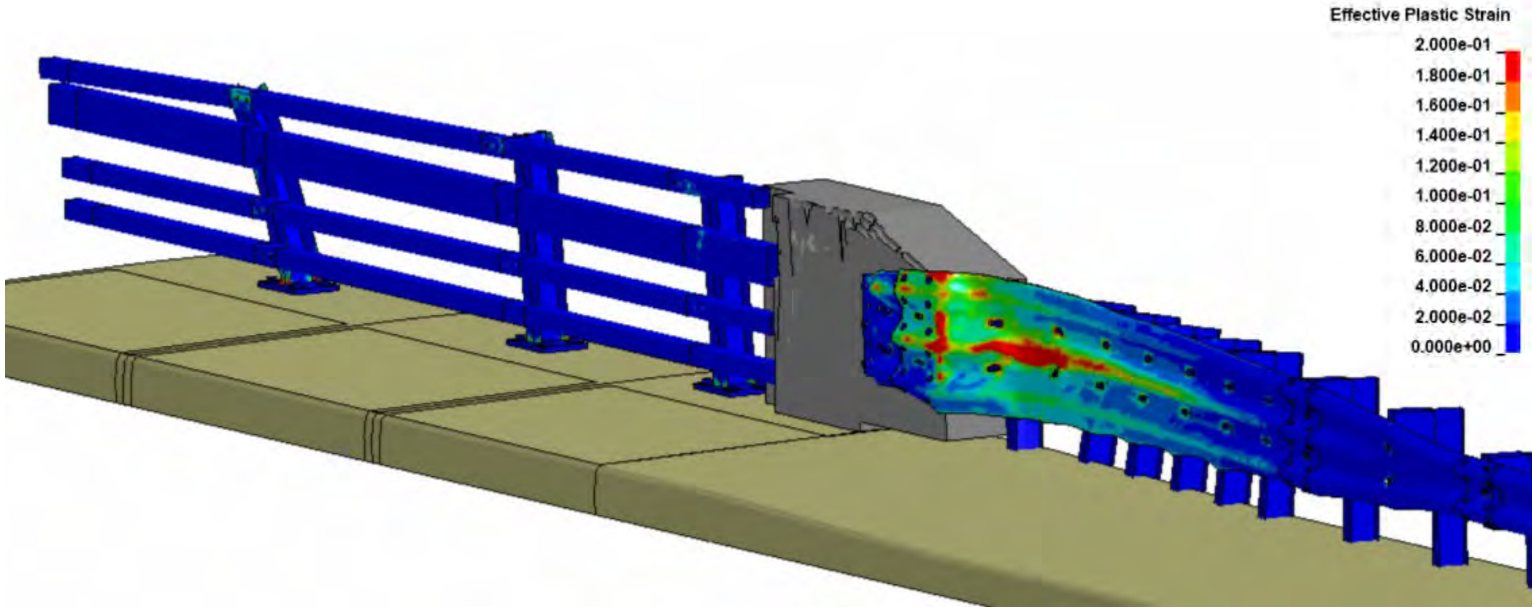
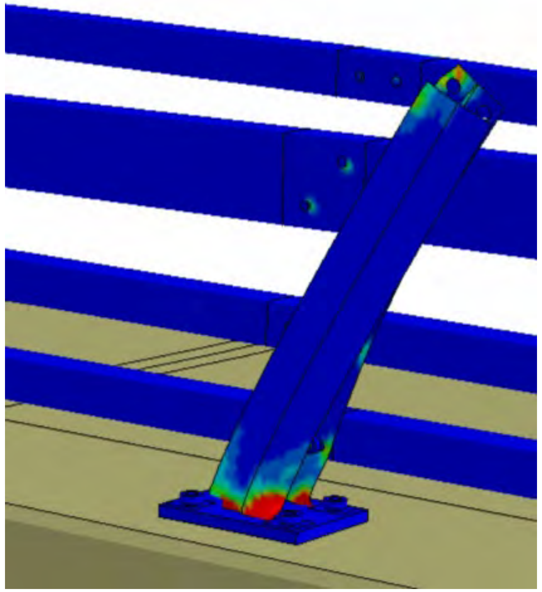
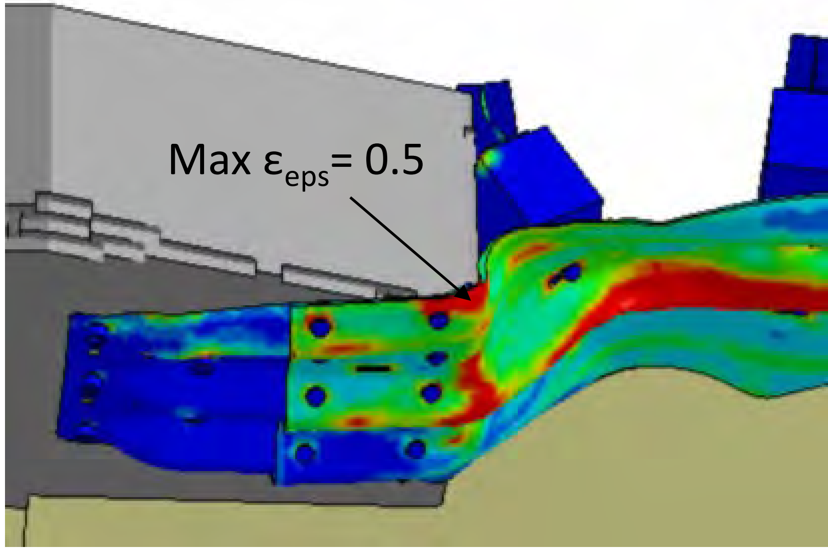
Barrier Damage

- Plastic deformations of the thrie-beam rail were significant at, and near to, the end of the buttress.
- The maximum effective plastic strain was 0.5 at the top edge of the thrie-beam where the rail was pressed against the top corner of the buttress.
- Several of the transition posts near the buttress were also deformed.
- The bridge rail was also damaged, due to the bottom of the cargo box snagging on the tops of the posts.
- The most significant damage to the bridge rail was to the downstream end post, in which the rail mounting bolts sheared off, and the post bent along the longitudinal direction of the rail.
- The vehicle was in contact with the barrier from the point of contact until the truck box slid off the end of the bridge rail at 1.01 seconds.
- The maximum working width prior to exiting the barrier was 3.88 ft resulting from the top-front corner of the cargo box extending over the bridge rail.





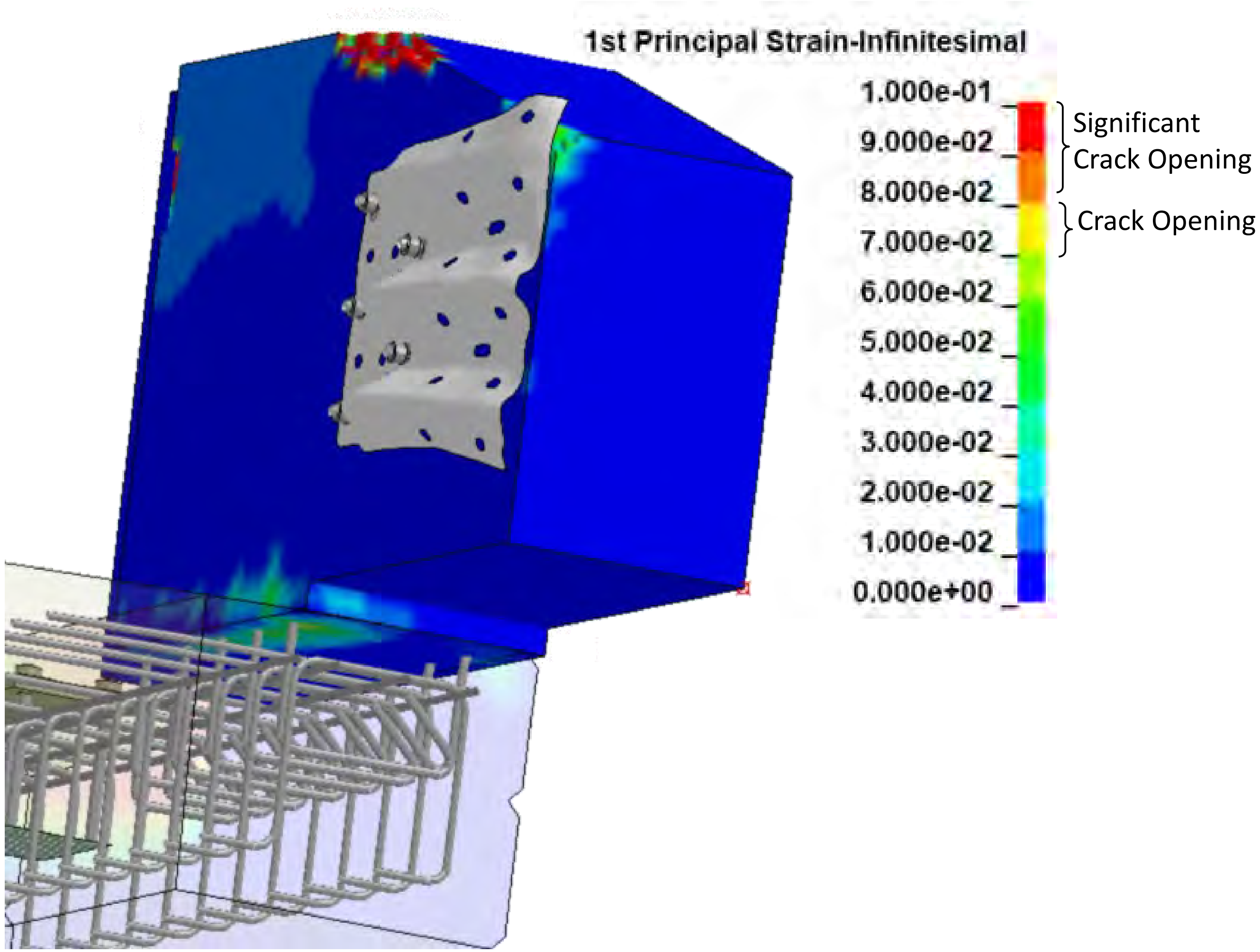
Bridge Rail Post



Thrie-Beam and Buttress

Barrier Damage

- The concrete buttress experienced spalling at the top edge and surface due to the cargo-box impact.
- There was moderate concrete strain at the rebar-joint between the buttress and the curb at three stirrup locations on the upstream end of the buttress on the traffic side. the rebar near the cantilever end.



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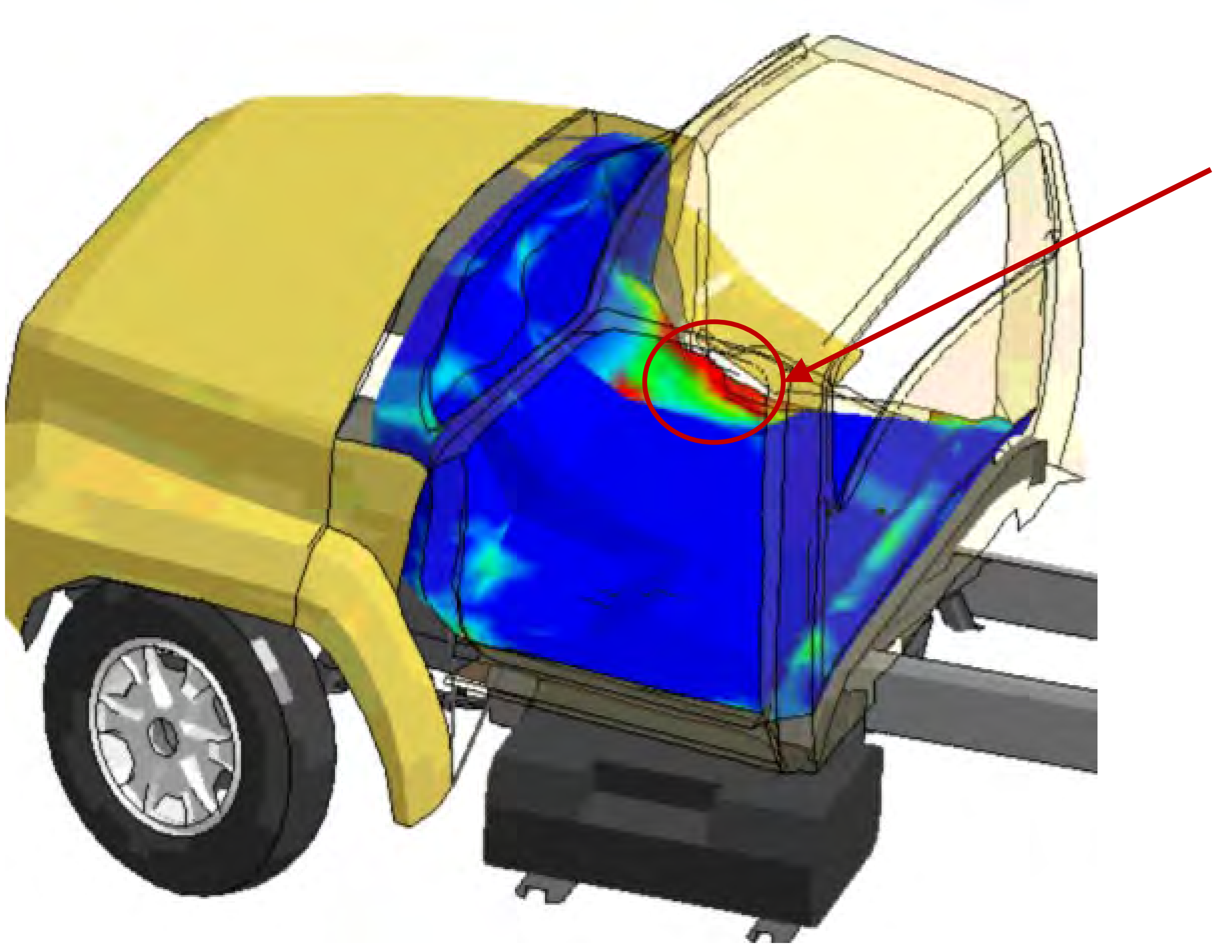
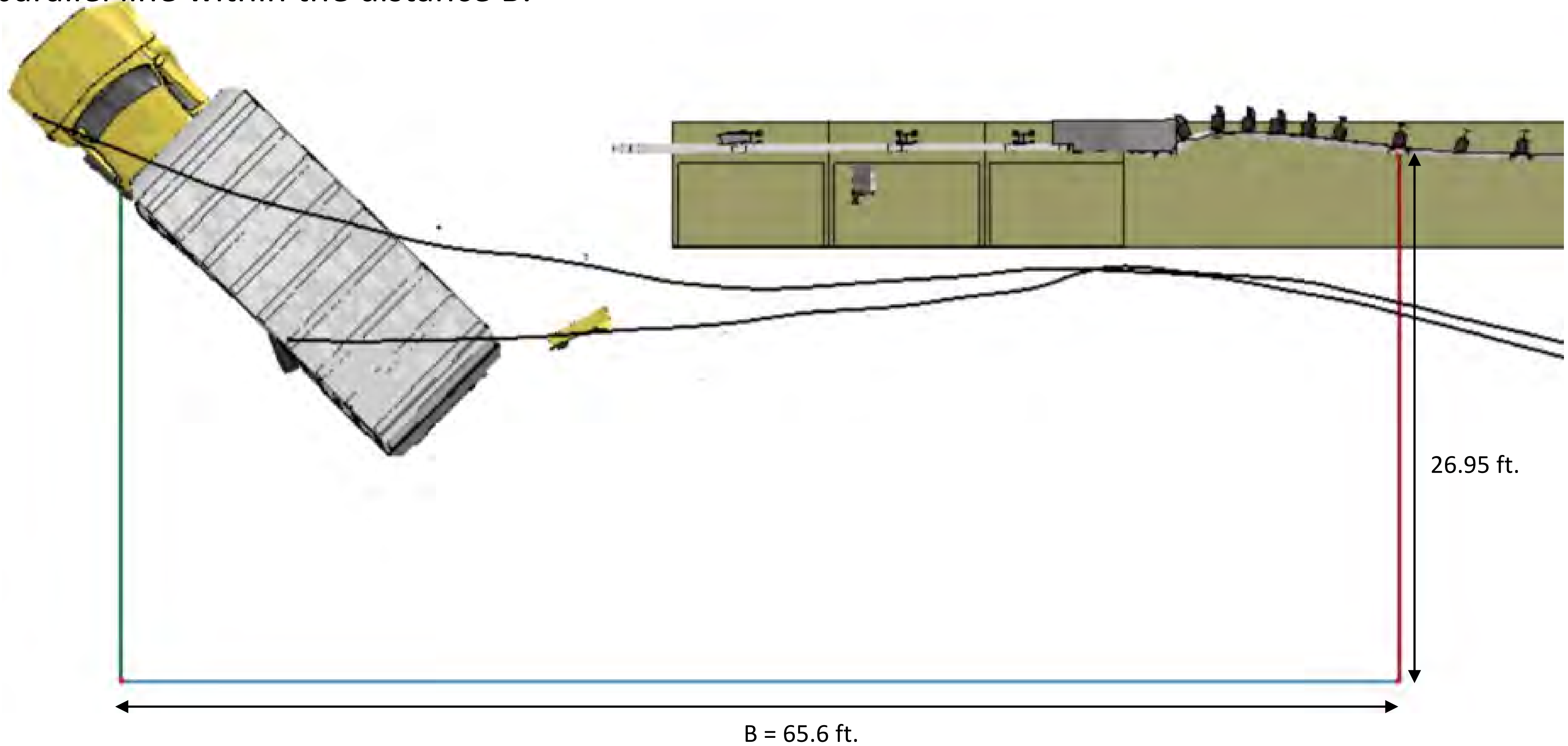
Occupant Compartment Intrusion (OCI)



Maximum OCI was ≈ 5.5 inch (139 mm) and occurred at the lower right-front corner of the toe-pan at wheel well.

Exit Box – Test 4-22

The driver-side front tire wheel track was used to determine the beginning location of the exit box. From MASH pg. 97: "All wheel tracks of the vehicle should not cross the parallel line within the distance B."



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Summary on Test 4-22 on the 4-Bar Trans

- The analysis showed that the barrier contained and redirected the 10,000S vehicle, but with significant damage to the transition and bridge rail elements.
- The **maximum roll angle** of the vehicle:
  - Cabin= **8.7 degrees**.
  - Cargo Box = **17.8 degrees**.
- The **maximum pitch angle** of the vehicle:
  - Cabin = **12.0 degrees**.
  - Cargo Box = **13.4 degrees**.
- The maximum **occupant compartment deformation** was **5.5 inches** and occurred at the lower right-front toe pan. This value is well within acceptable limit of 9 inches.
- The vehicle also **remained within the "exit box"** limits.
- The damage to the transition was significant:
  - Lateral soil displacement at 6 posts
  - Significant plastic deformation of barrier thrie-beam components.
  - Maximum **dynamic deflection = 17 inches** at Post 2 in transition.
  - Maximum **permanent deflection = 15.4 inches** at Post 2 in transition.
- Damage to the bridge rail posts was significant due to the bottom of the cargo-box snagging on the tops of the posts.

Conclusions on Test 4-22 on the 3-Bar Trans

Evaluation Factors		Evaluation Criteria – MASH Test 4-12	Results
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Marginal
Occupant Risk	D	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, to occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.	Pass
	G	It is **preferable, although not essential**, that the vehicle remain upright during and after collision.	Likely Fail

Conclusions for Overall Barrier Performance

- MASH Requirements:
  - Structural Adequacy: (Marginal)
    - The barrier successfully contained and redirected the vehicle for Tests 4-20 and 4-21, but containment was marginal for Test 4-22.
    - There was moderate damage to the transition for Tests 4-20 and 4-21, but significant damage for Test 4-22.
    - Test 4-22 resulted in the bottom of the cargo-bed contacting and snagging on the tops of the bridge rail posts and deforming those posts.
  - Occupant Risk (Fail)
    - Occupant compartment intrusion was below allowable limits for all cases
    - OIV and ORA
      - Small Car : OIV was within critical limits, but ORA exceeded critical limits.
      - Pickup: OIV was within preferred limits; ORA was within critical limits
  - Vehicle Trajectory (PASS)
    - Roll and Pitch for Tests 4-20 (small car) and 4-21 (pickup) were relatively low, and the vehicle remained upright through impact and redirection.
    - Roll and pitch for Test 4-22 (SUT) were relatively low through 1.34 seconds of the impact event; however, given the final orientation, speed and roll rate of the vehicle, <u>it is likely that the tuck will roll over onto its side</u>.