Behavior of Concrete Barriers for Bridges in New Jersey

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Objectives

1. Present research outcomes on MASH TL-4, TL-5 and TL-6 concrete Barriers carried out during last four years.
   - Demand models for three barrier types
   - Performance Based Approach
2. Behavior of F-shape NJDOT barriers through numerical simulations.

Recommended Loads Table for TL-4 barriers by TTI

SUMMARY OF *MASH* TL-4 LOADS ON RIGID BARRIERS

Design Forces and Designations	Barrier Height (in.)			
	36	39	42	Tall
F_t Lateral (kip)	67.2	72.3	79.1	93.3
F_L Long. (kip)	21.6	23.6	26.8	27.5
F_v Vertical (kip)	37.8	32.7	22	NA
L_t and L_L (ft)	4	5	5	14
H_e (in.)	25.1	28.7	30.2	45.5

L_t = longitudinal distribution of F_t
H_e = vertical resultant height of F_t

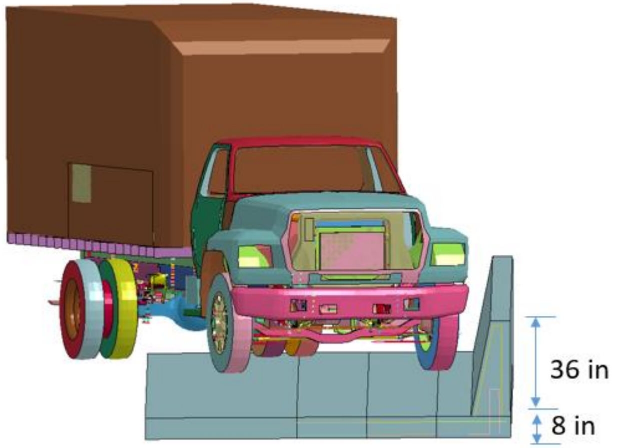
Need for Research

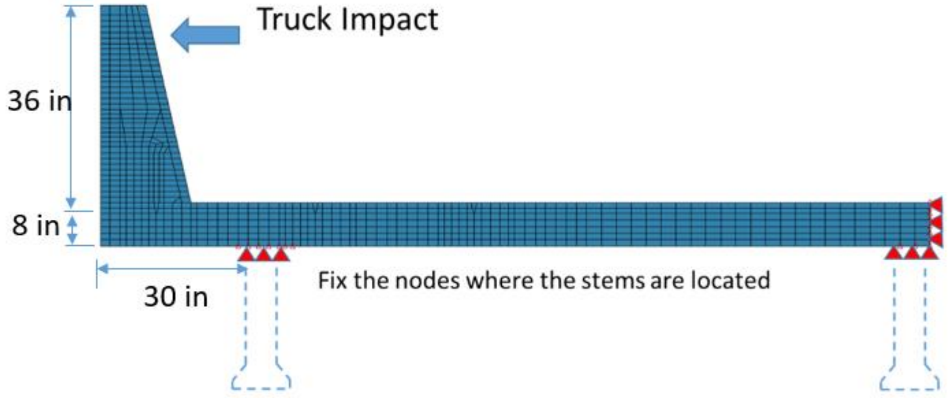
- TTI **rigid barrier assumption** – may overestimate peak dynamic loads.
- Independent verifications of the simulation results.
- Existing **yield line approach** in LRFD may underestimate the actual barrier capacity, which may also affect the demand model for the design.

Due to variations in barrier height, TTI recommended 80 kips (42") as the average static force for railing design. （It is 54 kips in current AASHTO Section 13)

Investigation of Demand on TL-4 Concrete Barriers

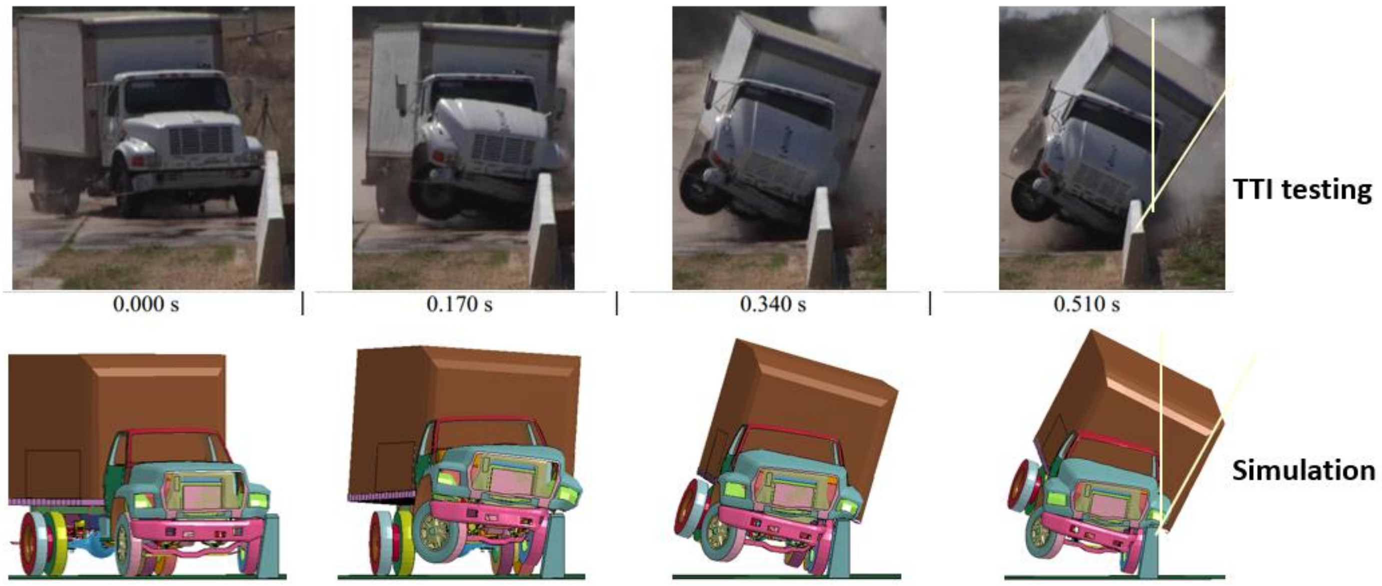
TL-4 barrier impact setup in LS-DYNA





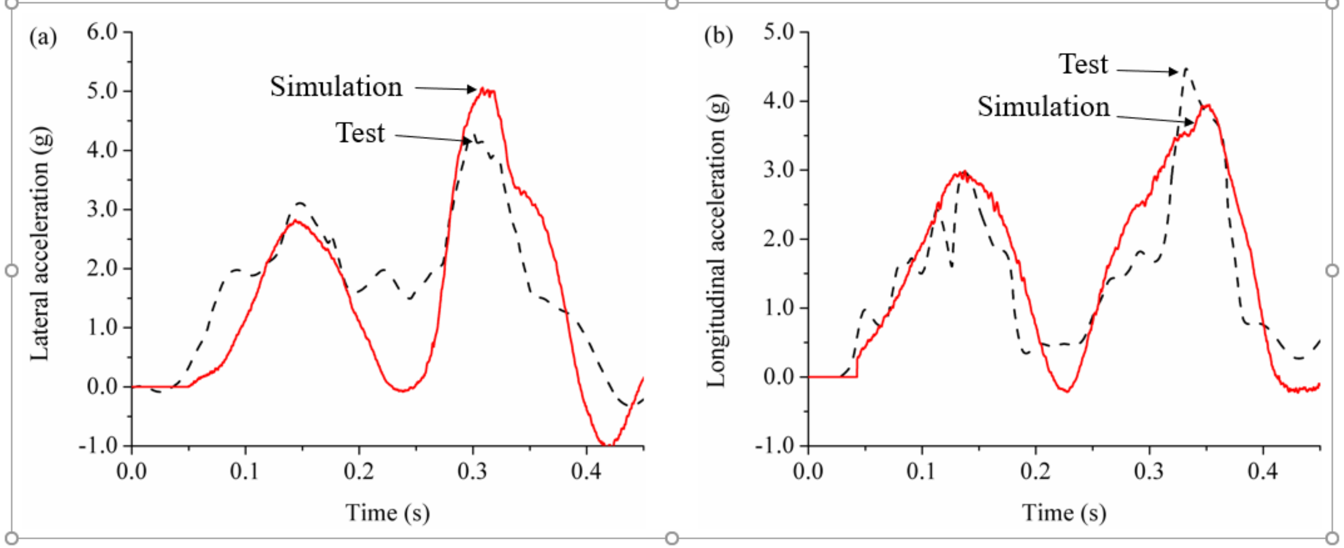
Comparison with Single-slope barrier testing (36 in)

Impact Process Comparison



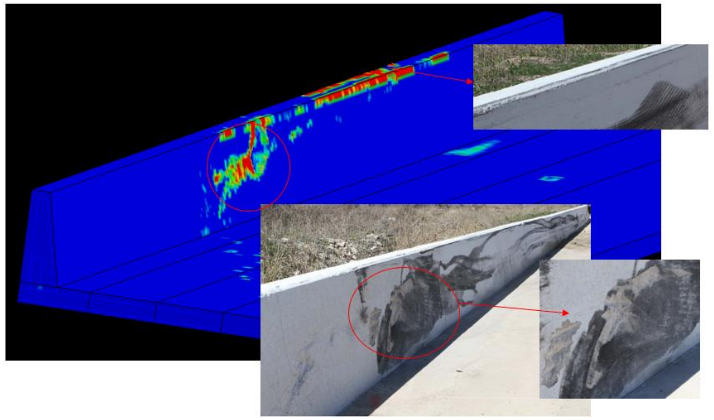
Simulations Versus Testing

Acceleration of the truck at the center of gravity during the impact.



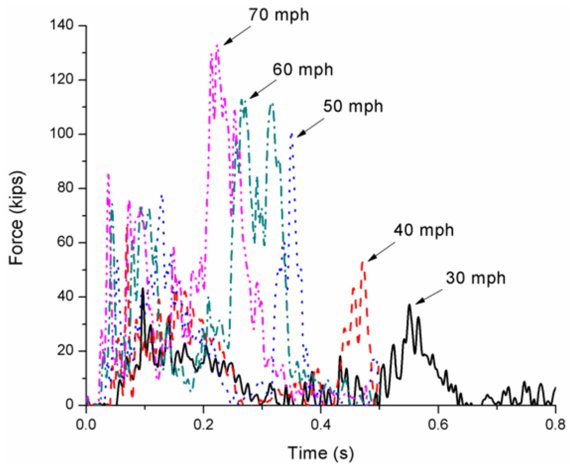
Damage Mode of the TL-4 Concrete Barrier

- Damage comparison between the test and simulations.
- The simulated damage mode matched the testing results.



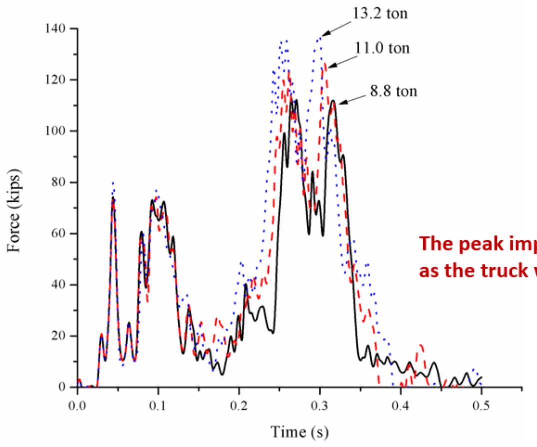
Investigation of Demand on TL-4 Concrete Barriers

Effect of the truck velocity (**SAE 60Hz filter**)



Force time-histories of 8.8-ton truck with various speeds

Effect of the truck weight (SAE 60Hz filter)

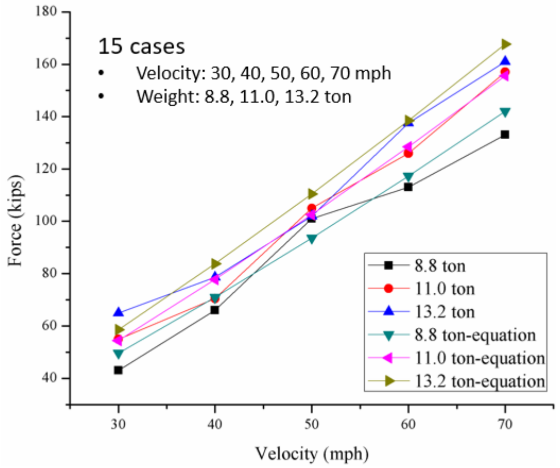


Force time-histories of 60-mph truck with various weights

The peak impact force increases as the truck weight increases.

TL-4 Demand Model

- Equation of the dynamic peak force(SAE 60Hz filter)



$$F = 0.30V^{1.24}W^{0.41}$$

F: Peak force (kips)

V: Velocity (mph)

W: Truck weight (ton)

Such model will give bridge owners a framework to design barriers based on

- ***Speed higher than MASH speed,***
- ***Desired truck loading instead of a prescribed load.***

Performance-based design

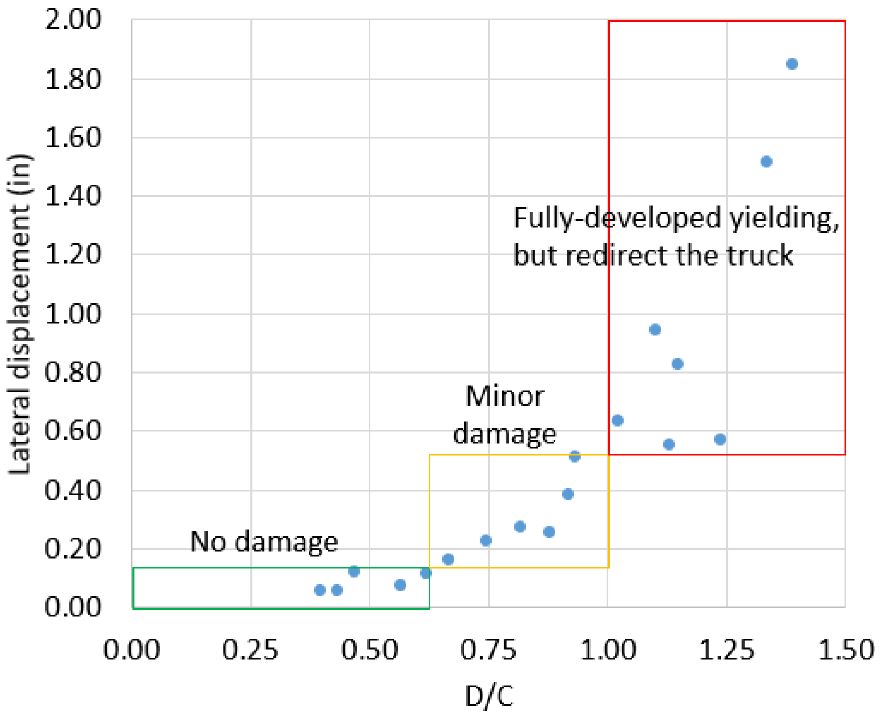
- Lateral deformation of the barrier versus D/C ratio

  Dynamic demand (D)/Capacity (C)

  D is the dynamic impact force $D = F = 0.30V^{1.24}W^{0.41}$

  C is the barrier capacity

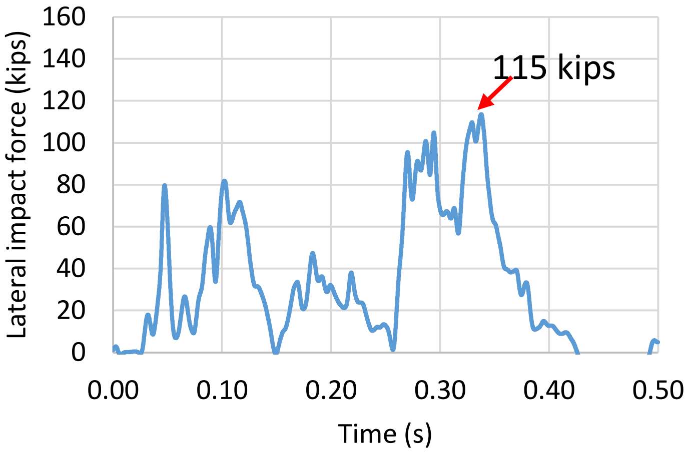
  Plot Lateral Displacement versus D/C ratio for 18 cases of simulation



Performance Level	Damage State	D/C	Displacement (in)
Immediate use	No damage	[0.00, 0.60]	[0.00, 0.10]
Damage control	Minor	[0.60, 1.00]	[0.10, 0.50]
Near collapse	Fully-developed yielding	[1.00, 1.50]	[0.50, 2.00]

- **Example**: MASH TL-4 (W = 11 tons, V = 56 mph)

$$F = 0.30 \times 56^{1.24} 11^{0.41} = 118 kips$$



For minor damage, D/C is between [0.6, 1.0]

Required capacity range for minor damage

= [118/1.0, 118/0.6] = [118, 196].

Actual capacity of the barrier

= 125 kips. (pushover analysis)

Actual D/C ratio

= 118/125 = 0.94, between [0.6, 1.0]

Actual displacement of the barrier

= 0.3 in. (truck impact simulation)

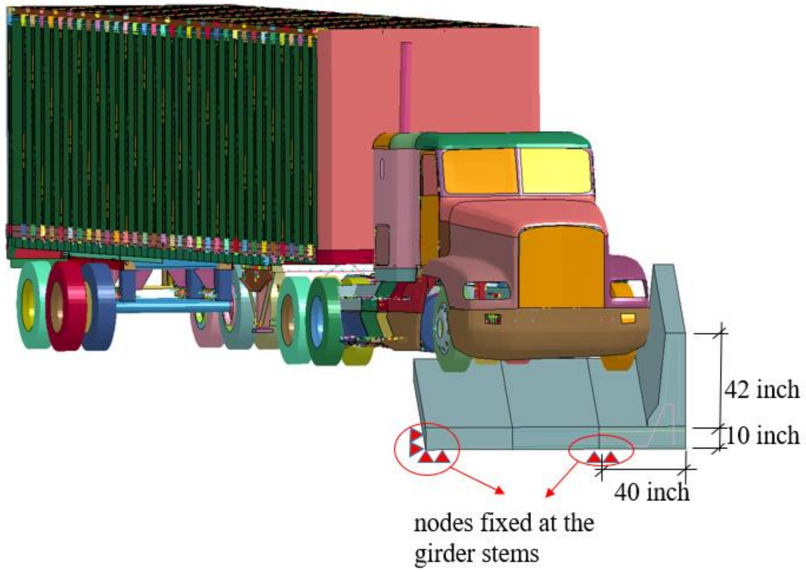
Actual damage mode: minor

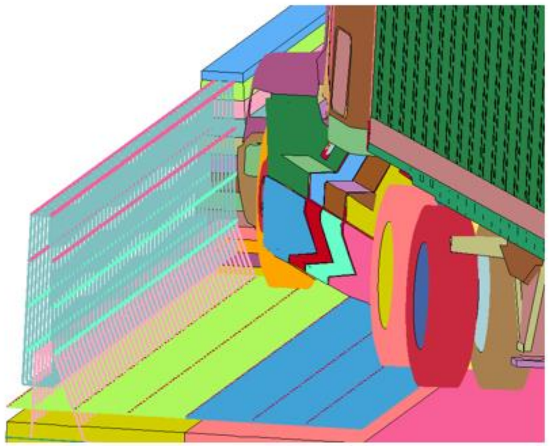
- MASH TL-4 Barrier Design Table

	No damage	Minor damage	Fully-developed yielding
Peak dynamic force (MASH)	118 kips	118 kips	118 kips
Required Capacity at yield	118/0.6 = 196 kips	118 kips	118/1.5 = 78 kips
Expected deformation	[0.0 in, 0.1 in]	[0.1 in, 0.5 in]	[0.5 in, 2.0 in]

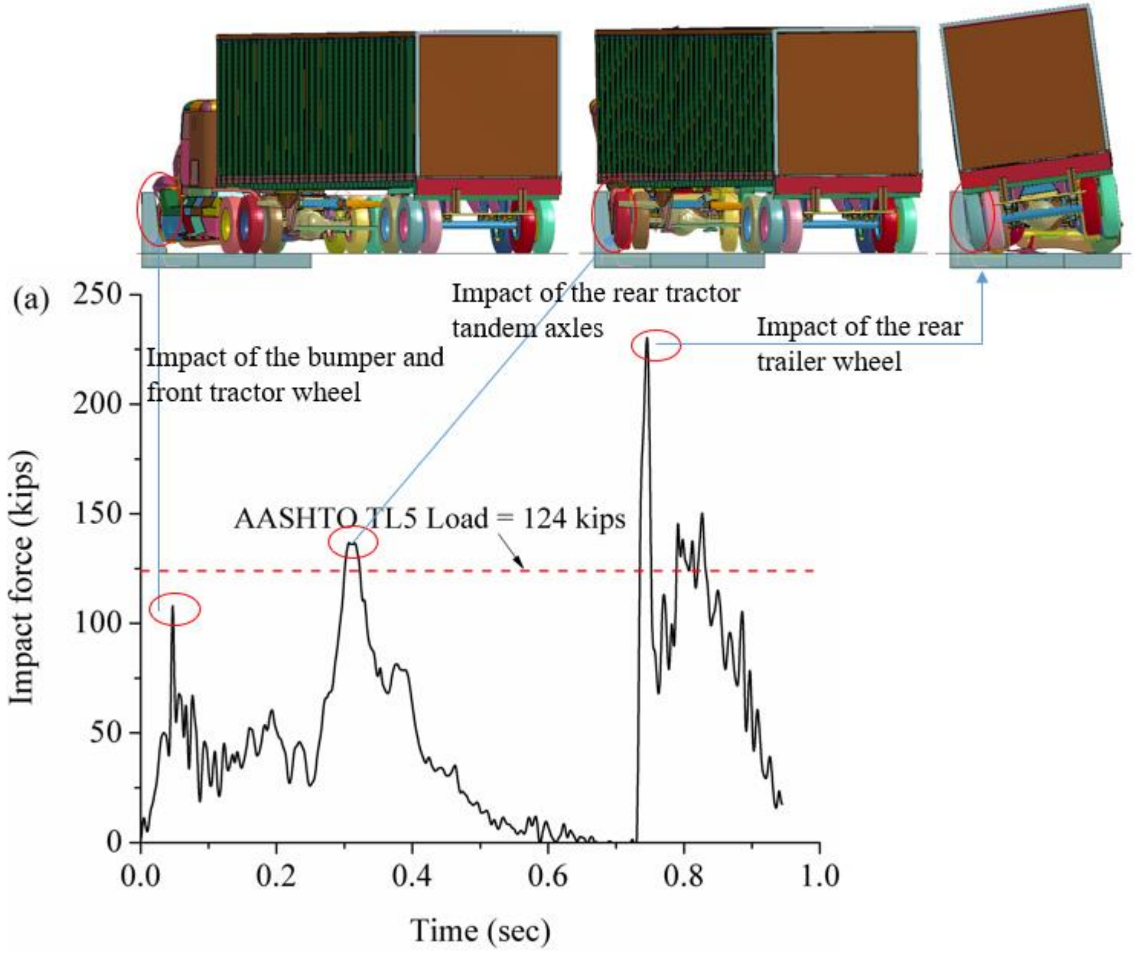
Investigation of Demand on TL-5 Concrete Barriers.

MASH TL-5 Truck Simulation Setup in LS-DYNA



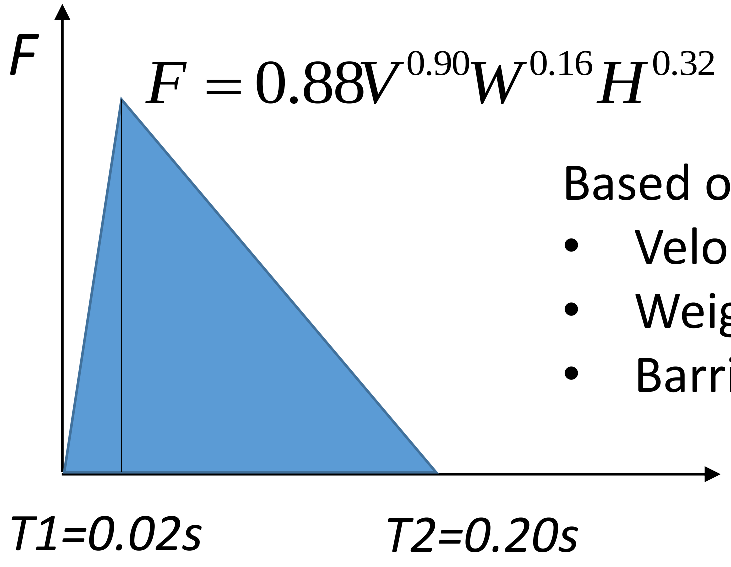


The impact process consists of three major events.



Proposed Pulse Loading Model for TL-5 Barriers

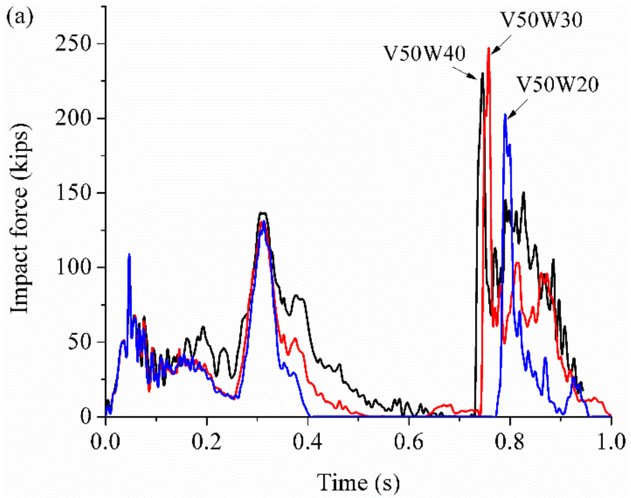
The pulse model was calibrated against the truck simulation to cause similar barrier deformations as the truck impact loading.

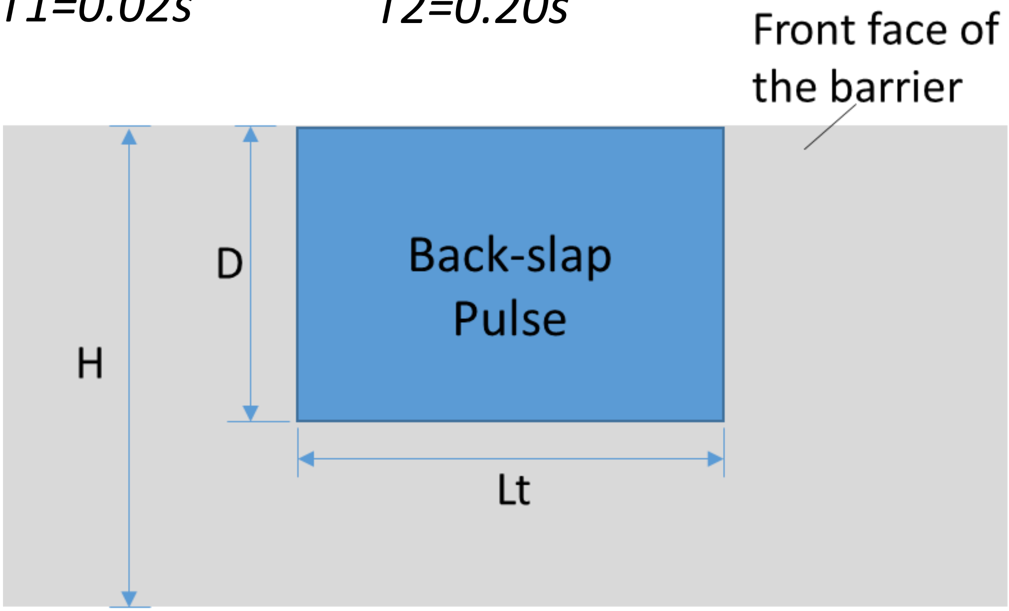


$$F = 0.88V^{0.90}W^{0.16}H^{0.32}$$

Based on Parametric Study on:

- Velocity (V): 40, 50, 60, 70 mph.
- Weight (W): 20, 30, 40 US ton.
- Barrier height (H): 42”, 48”, 54”.



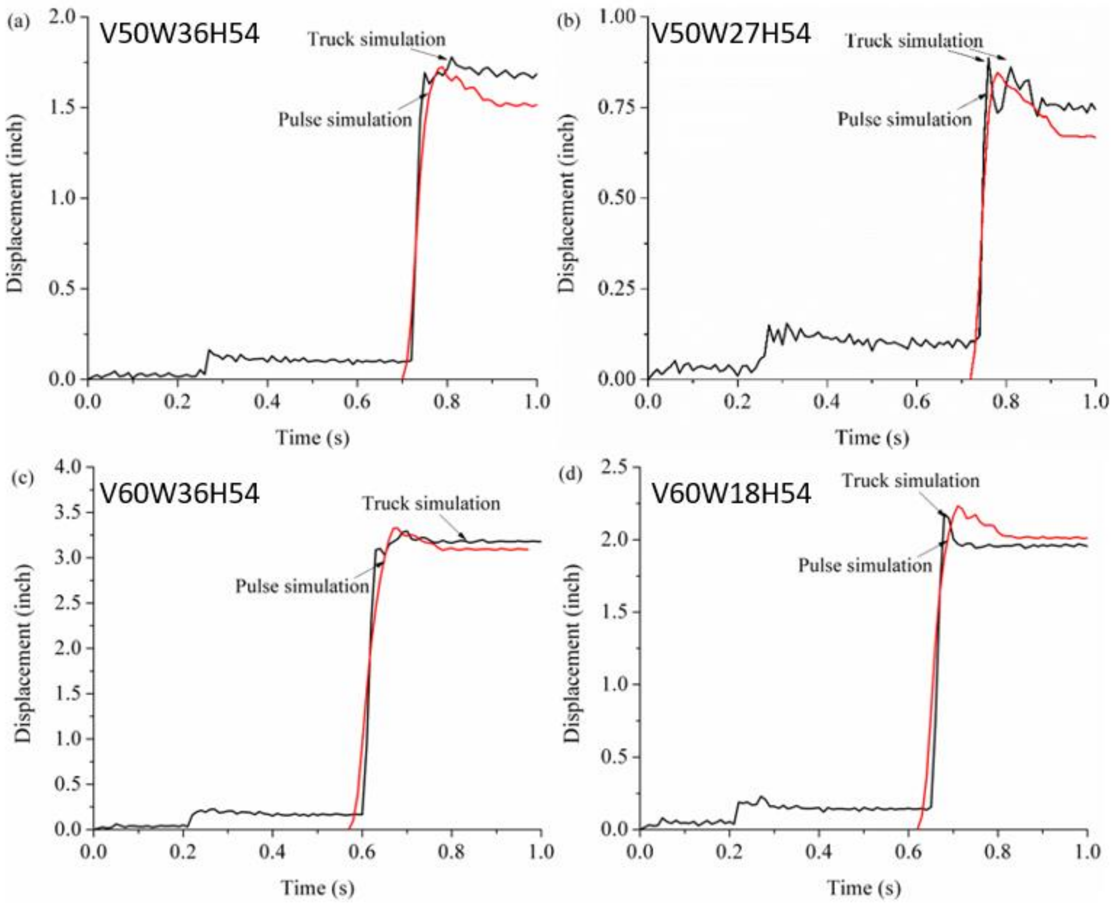


Application of the pulse model

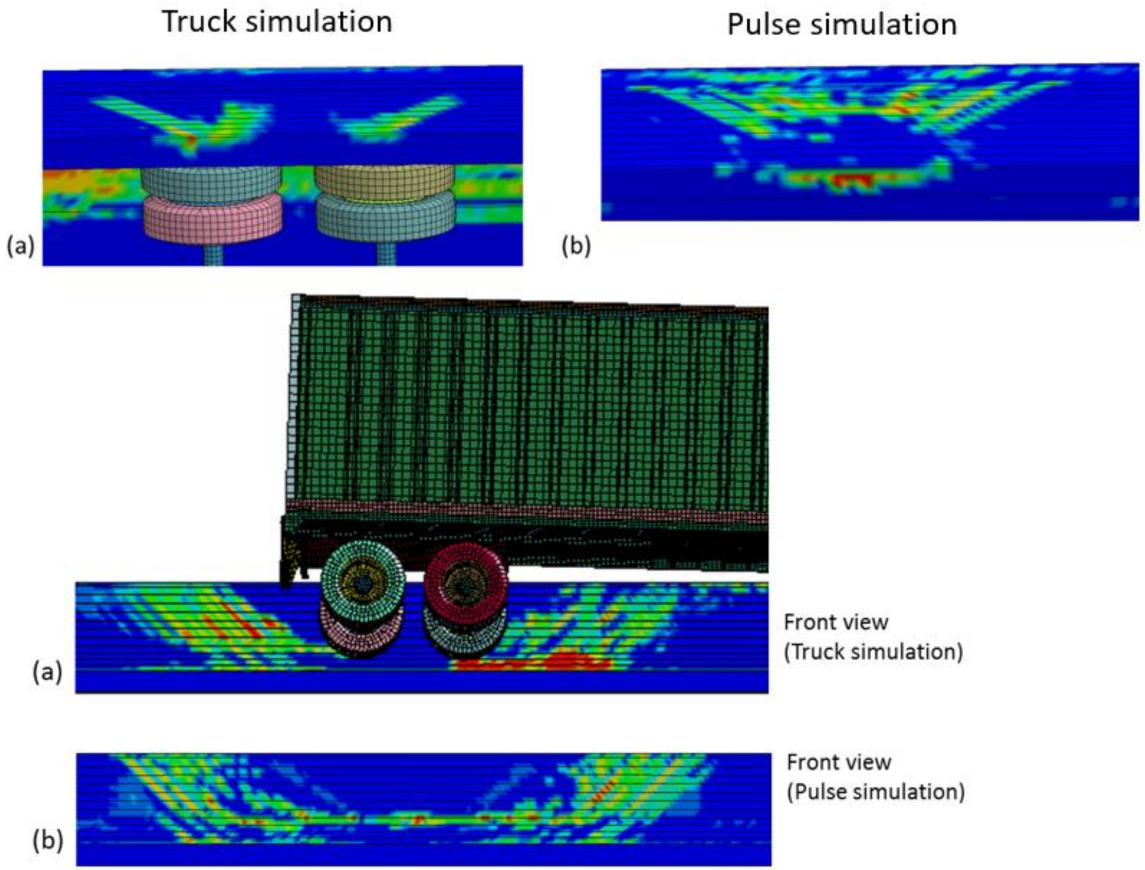
H (inch)	D (inch)	Lt (inch)
42	26.0	100
48	36.0	100
54	46.8	100

Validation of the Proposed Pulse Model

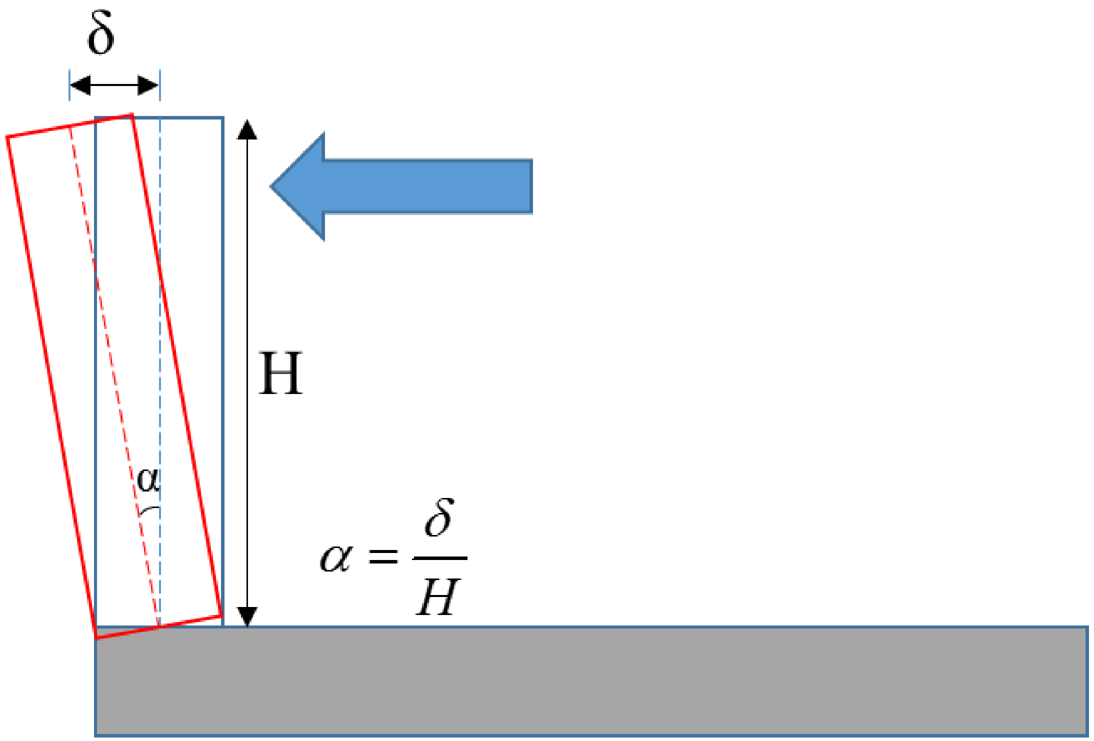
Deformations of the barrier

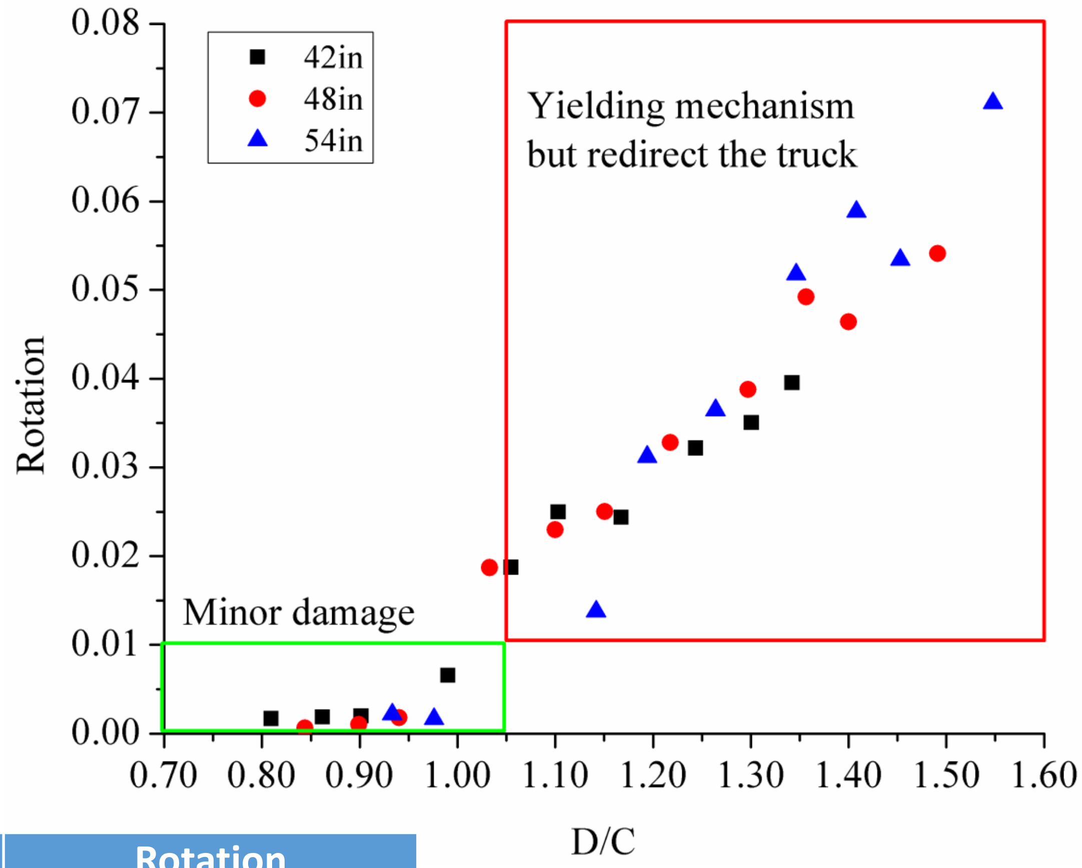


Damage contours of the barrier



Performance based design (PBD) chart for TL-5 barriers





Performance level	Damage state	D/C	Rotation
Immediate use	Minor damage	[0.00, 1.05]	[0.000, 0.010]
Need repair/ replacement	Yielding mechanism but redirect the truck	[1.05, 1.60]	[0.010, 0.080]

Comparison of the TL-5 Demand Model

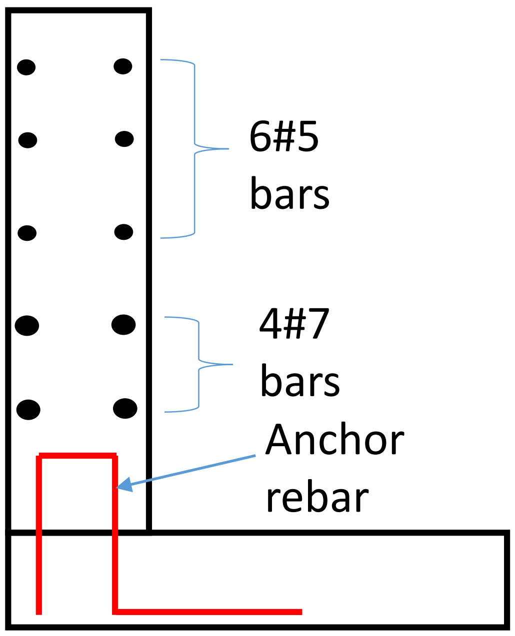
	42-inch barrier (kips)	48-inch barrier (kips)	54-inch barrier (kips)
AASHTO (static load)	124.00	124.00	124.00
TTI (static load) (Bligh et al. 2017)	159.00	261.80	295.50
Pulse model (peak dynamic load)	176.49	184.09	191.07

Static versus Dynamic demands

Comparison of the current static design method and PBD

- **Example: 54-in vertical wall**

fc=3.6ksi
Fy=40ksi
Longbar: 4#7 and 6#5 bars
The anchoring rebar/wall thickness was designed to achieve the demand requirement.



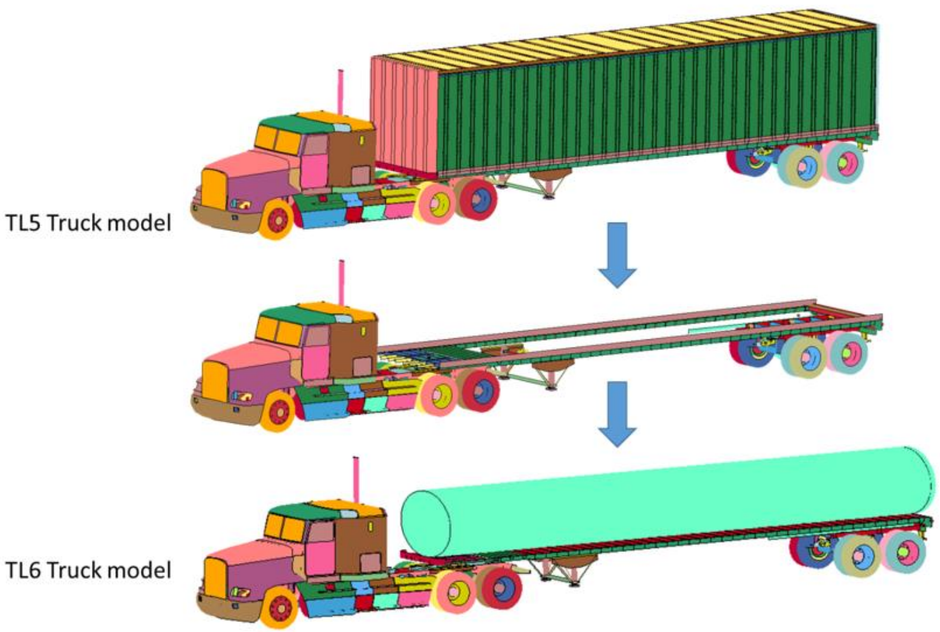
Framework	Demand (kips)	D/C	Required capacity (kips)	YLM	Anchoring rebar and wall thickness	Predicted performance	Actual performance
AASHTO	124	1.00	124	V-shape	**#5 @ 7” 12" thick**	N/A	Yield mechanism but redirect the truck
TTI (Bligh et al. 2017)	296	1.00	296	V-shape	**#5 @ 4” 17" thick**	N/A	Minor
Our PBD	191	1.60	119	W-shape	**#5 @ 10” 12" thick**	Yield mechanism but redirect the truck	Yield mechanism but redirect the truck
Our PBD	191	1.05	191	W-shape	**#5 @ 8” 15" thick**	Minor.	Minor.

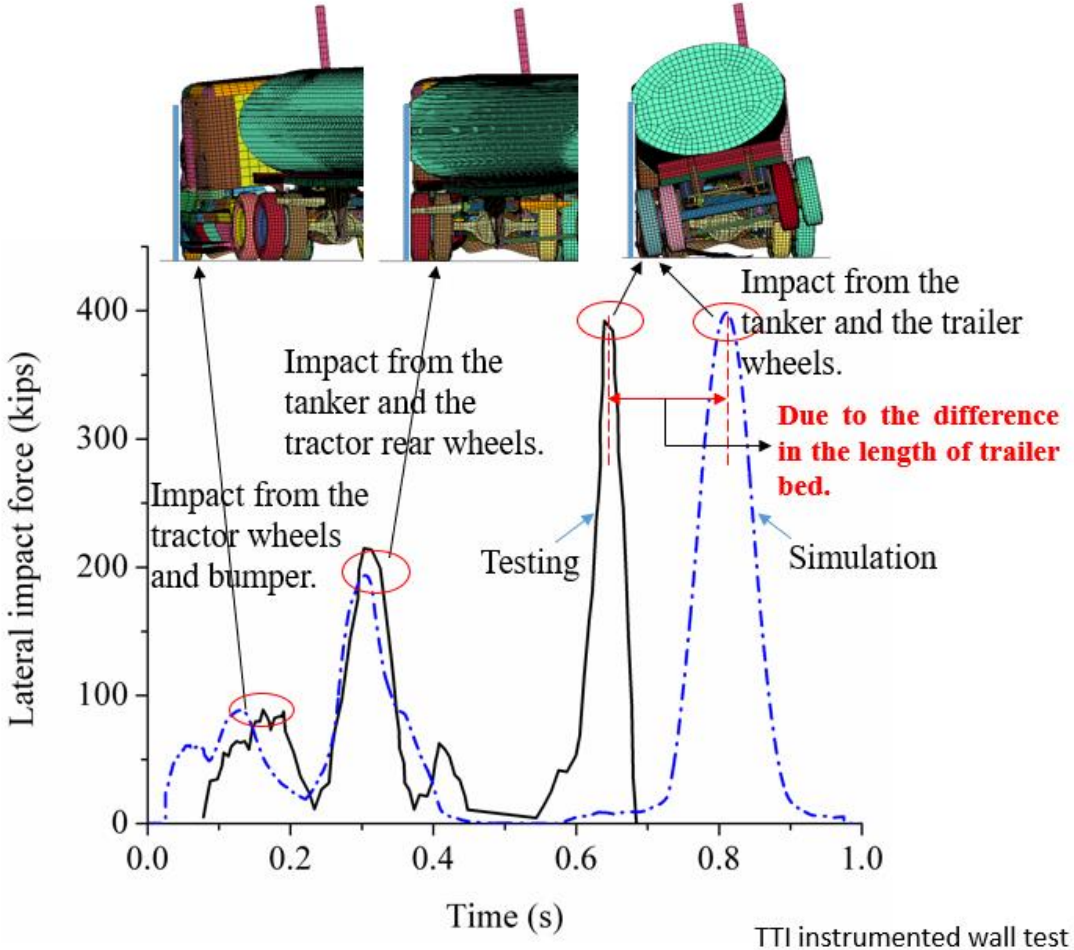
The current AASHTO design could lead to a yielding performance of the barrier. A similar barrier performance can be achieved by the PBD method *with less rebar detailing*.

Investigation of Demand on TL-6 Concrete Barriers.

- No well-calibrated tanker-trailer models are currently available.
- Carried out development of the TL-6 tractor-tanker trailer model in LS-DYNA.

- Impact testing with vertical wall by TTI (1989)
- The impact process consisted of three major events.

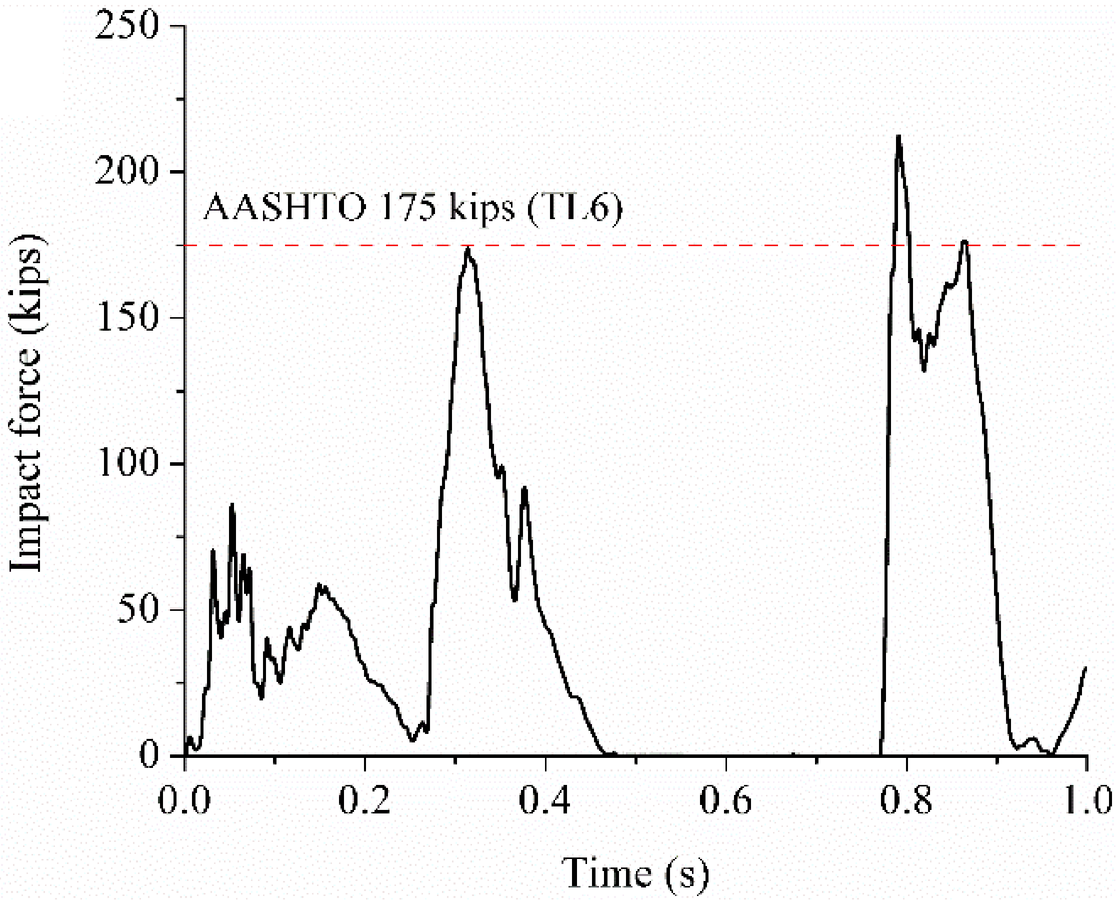


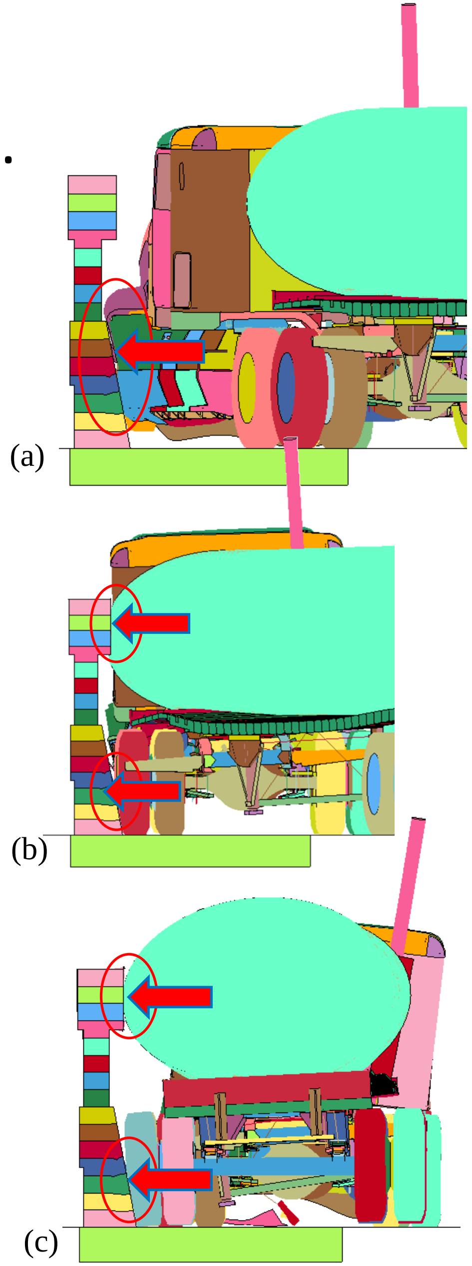


TTI instrumented wall test (Beason and Hirsch 1989)

Impact process of TL-6 truck with concrete barrier

- The impact process consisted of three major events.





Impact from the tractor wheels and bumper.

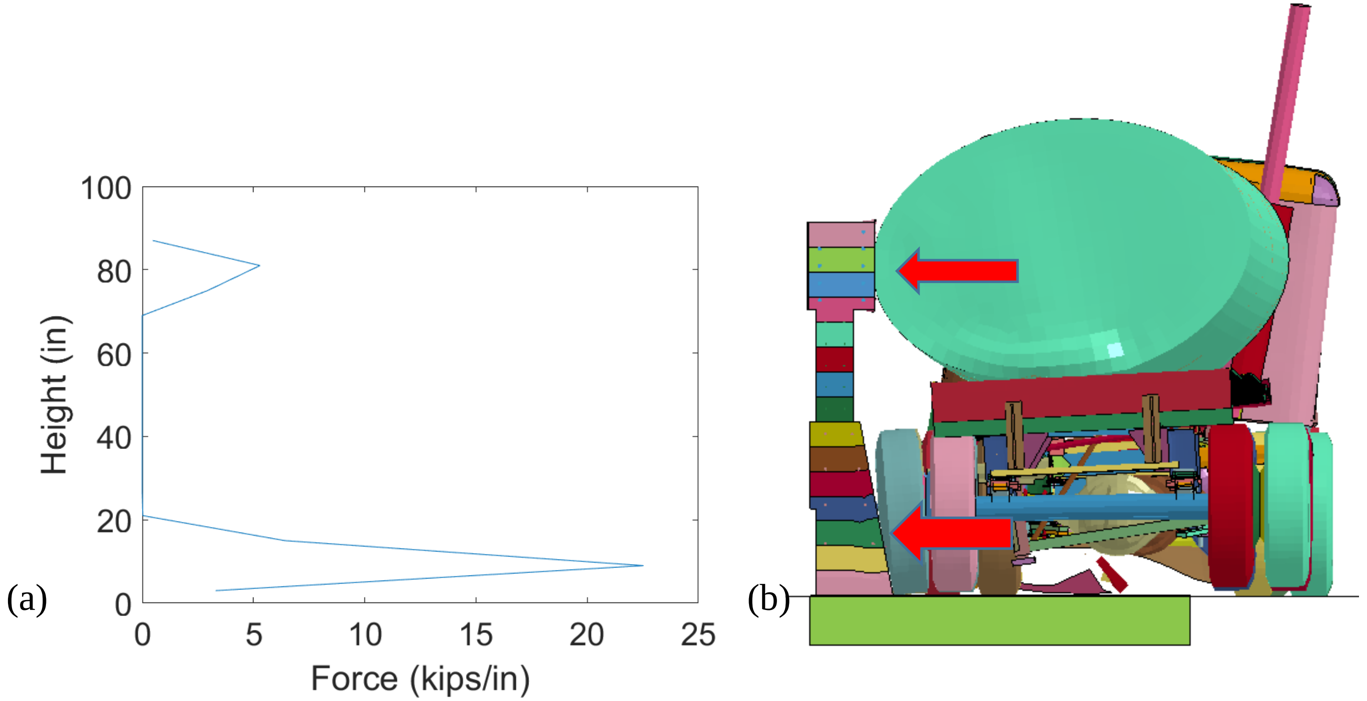
Impact from the tanker and the tractor rear wheels.

Impact from the tanker and the trailer wheels.

Back-slap force distribution for TL-6 truck under MASH condition

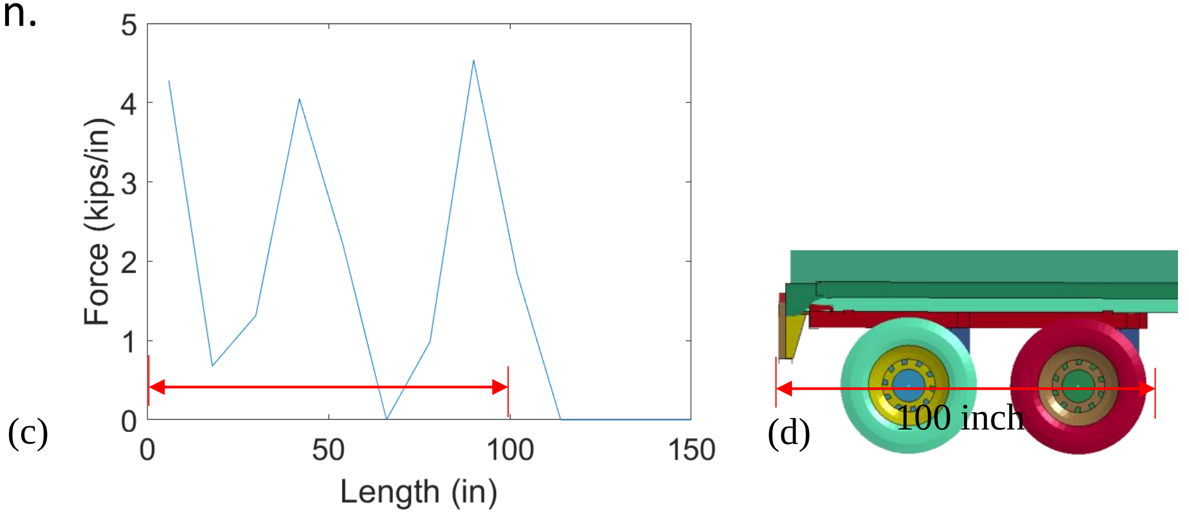
➢ Vertical direction.

- Impact loading was applied at two different heights.



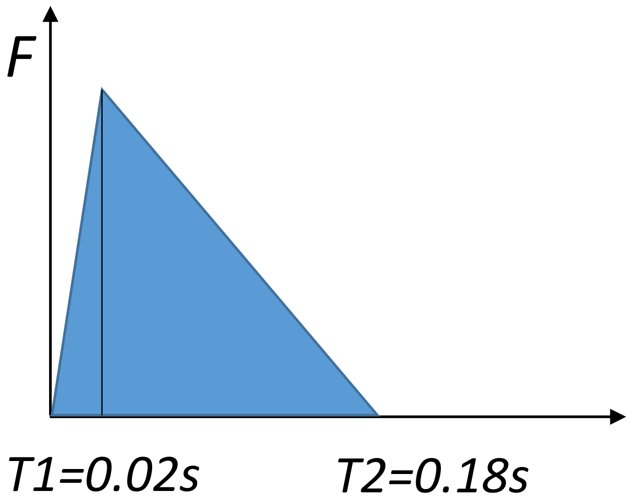
➢ Horizontal direction.

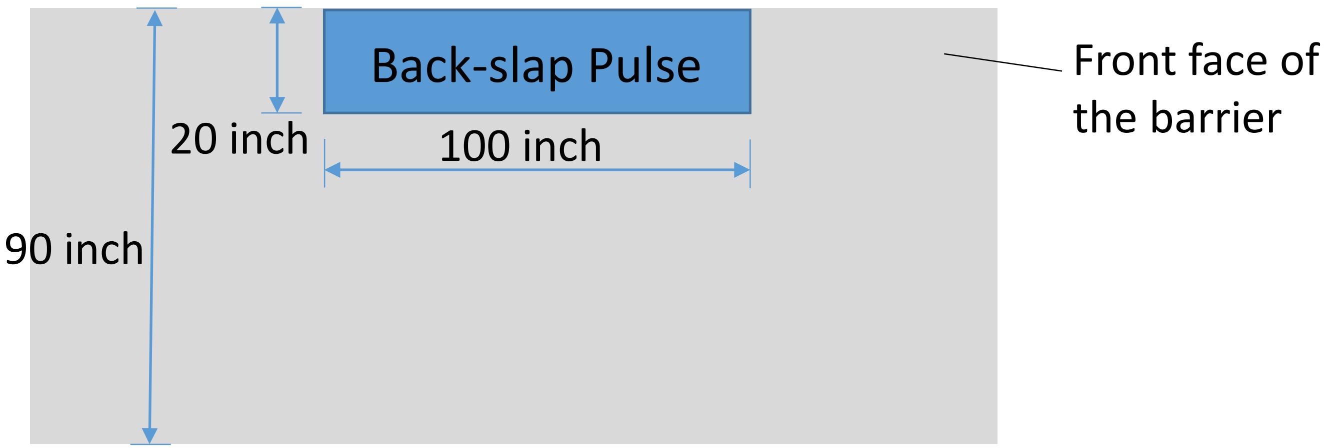
- Impact loading was distributed in a length of 100 inch.



Pulse Model for TL-6 Concrete Barriers

$$F = 4.50 \times 10^{-3} V^{1.91} W^{0.67}$$

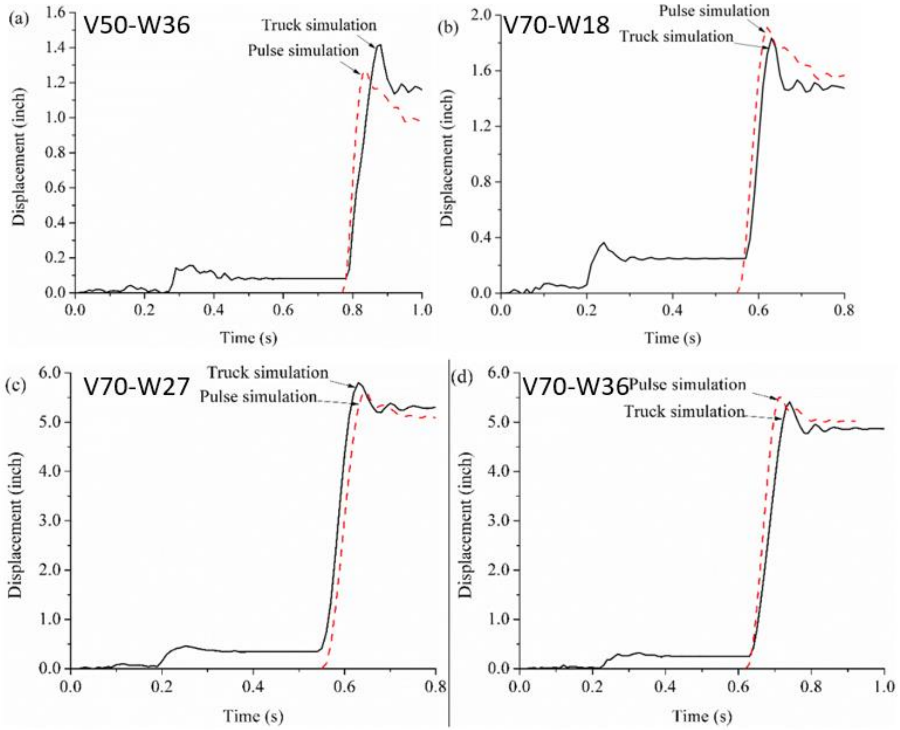




- Velocity (V): 40, 50, 60, 70 mph.
- Weight (W): 20, 30, 40 US ton.

The pulse model was calibrated against the truck simulation to cause similar barrier deformations as the truck impact loading.

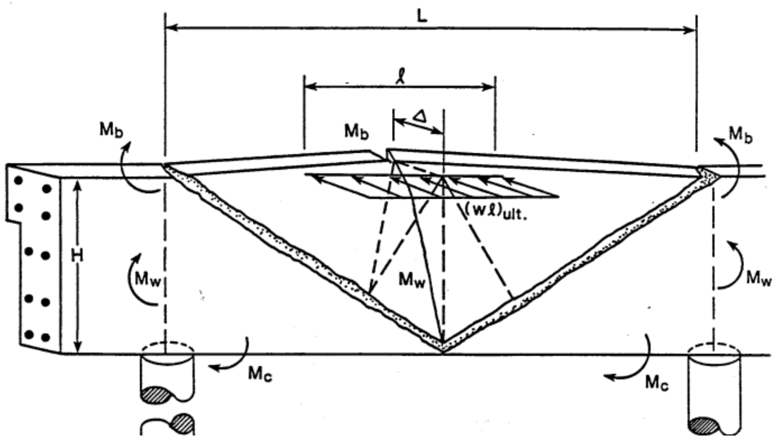
Deformations of the barrier



W-shape yield line method for estimating barrier capacity

W-shape yield line method for estimating barrier capacity

- ❑Current approach: V-shape yield line theory (AASHTO)
  - Conflict with load calculations (rigid barrier).
  - Simplified yielding-line pattern.

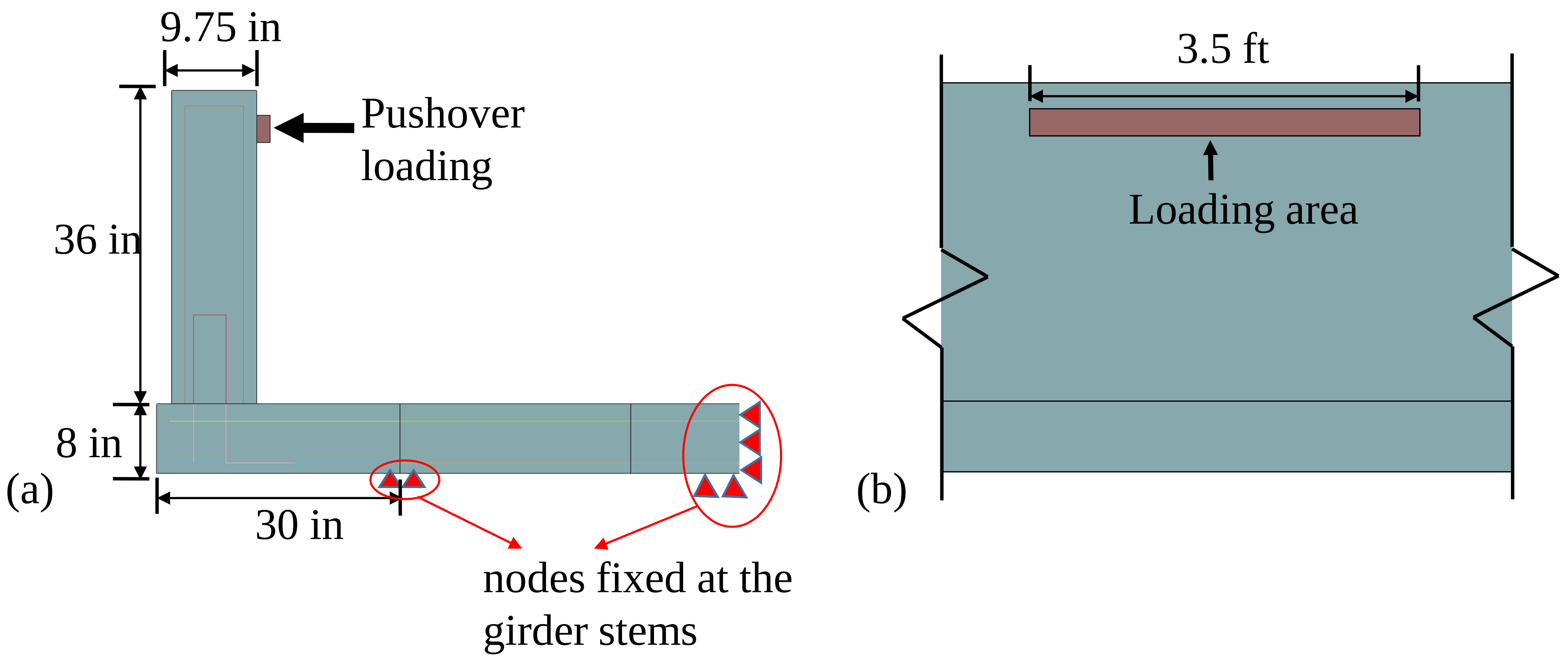


V-shape yield line pattern (AASHTO)

- ❑New approach – pushover analysis
  - Similar to the “pushover curve” in earthquake engineering.
  - Load versus deformation curve.

W-shape yield line method for estimating TL-4 barrier capacity

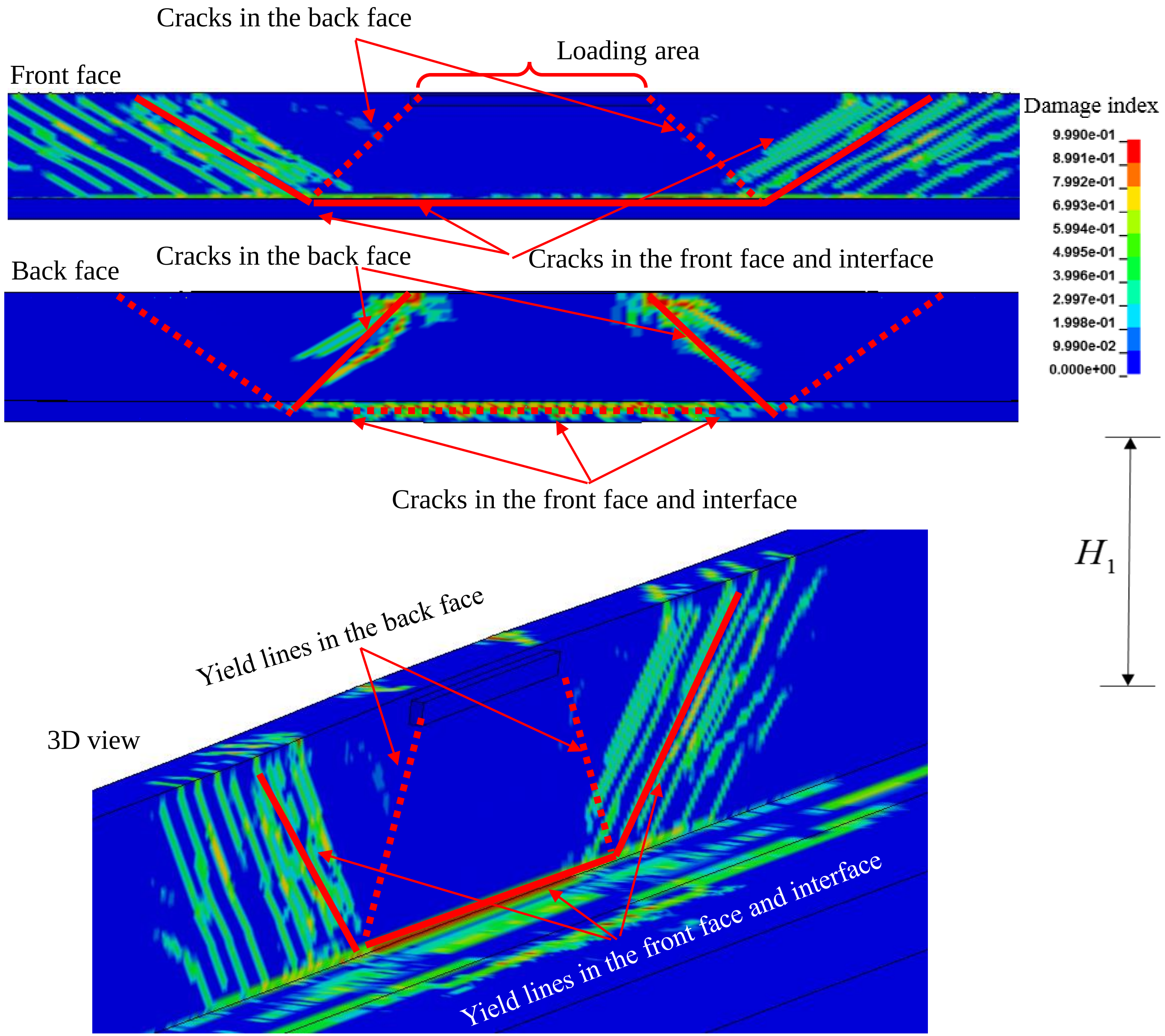
Pushover Simulation Setup in LS-DYNA



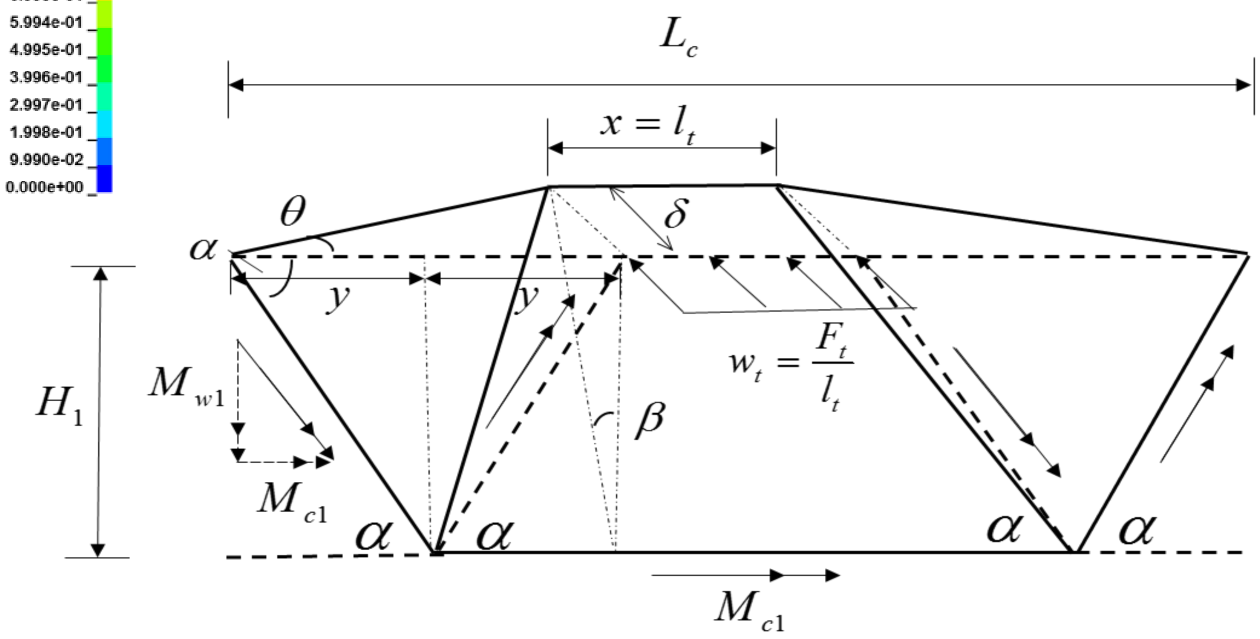
- Design based on an actual TL-4 concrete barrier.

W-shape Yield Line Mechanism

Damage mode of the barrier from the pushover simulations.



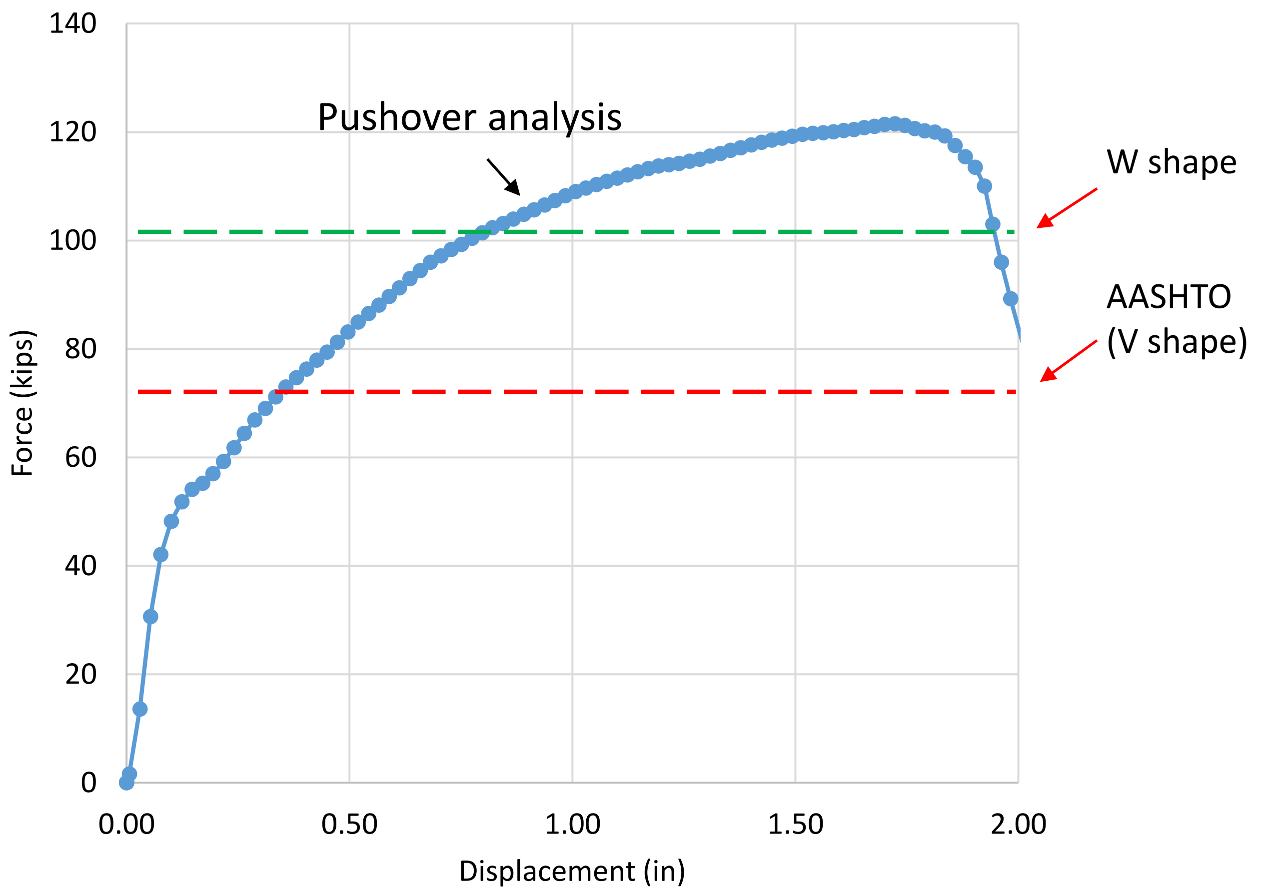
Proposed W-shape Yield Line Method

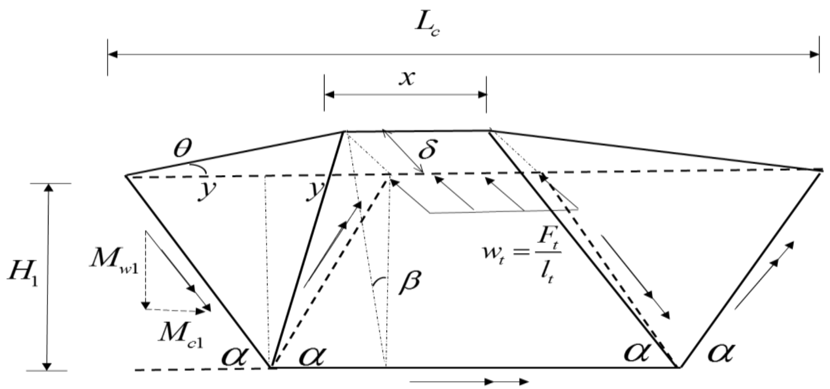


$$R_w = F_t = \frac{2M_{w1}}{H_1} + 6M_{c1} + \frac{M_{c1} l_t}{H_1}$$

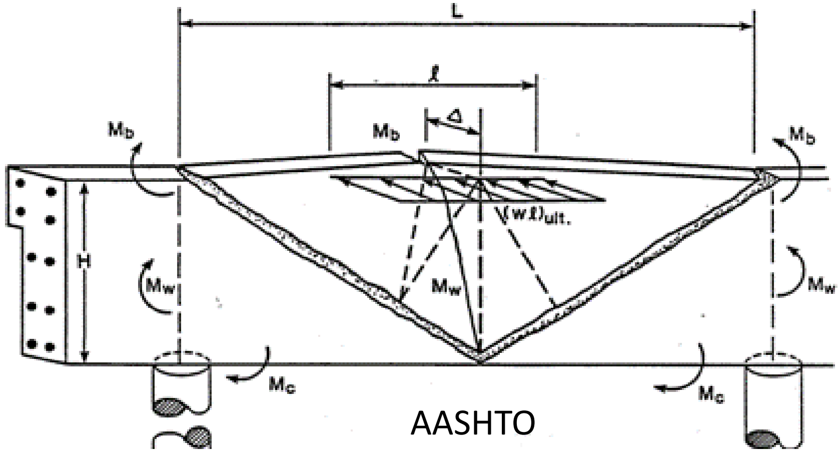
$$L_c = 4H_1 + l_t$$

Comparison between W-shape and AASHTO V-Shape YLM





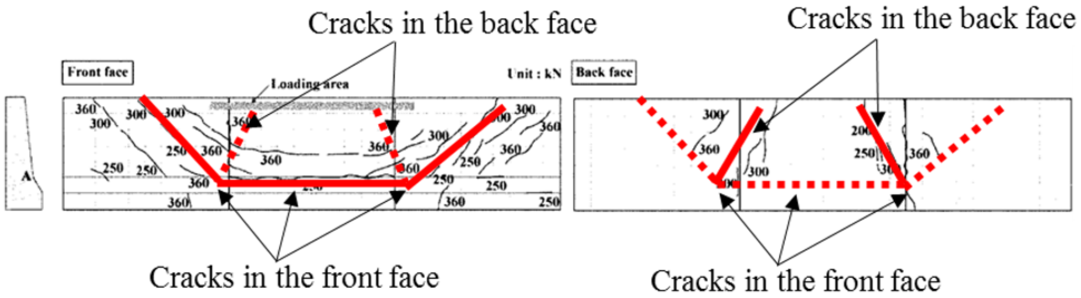
W shape



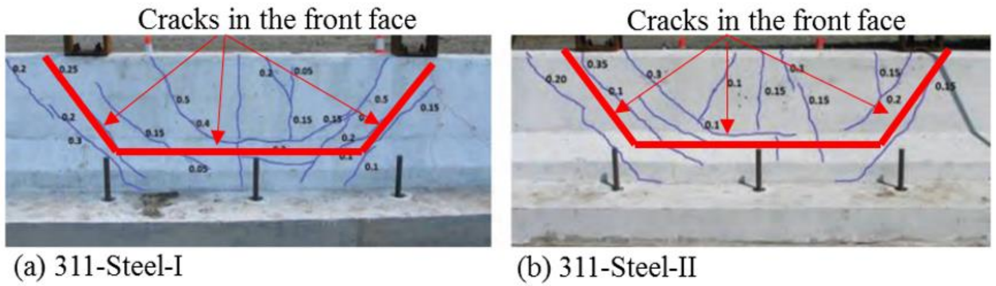
AASHTO
(V shape)

W shape YLM results matched the pushover results better than the AASHTO V-shape YLM.

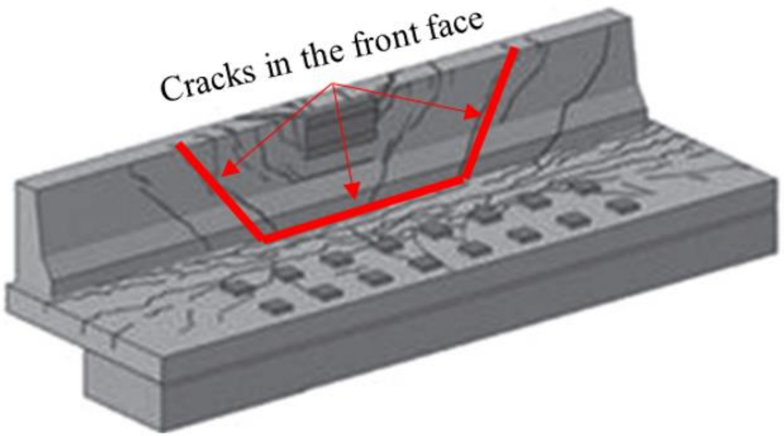
Observations from Tests in the Literature



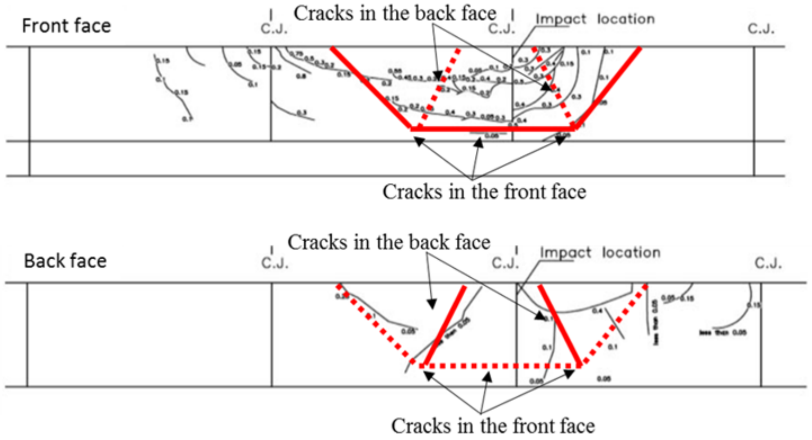
Yield line patterns of the concrete barrier under quasi-static loading (Jeon et al. 2011)



Yield line patterns of the concrete barrier under pendulum-impact loading (Ahmed et al. 2013).



Yield line patterns of the concrete barrier under quasi-static loading (Namy et al. 2015).



Yield line patterns of the concrete barrier under truck impact loading (Sennah and Khederzadeh 2014).

Bridge Railing Overhang Design Example 1

V-shape versus W-shape YLM

34in-F shape barrier (MnDOT)

	Collision force, $4/3*F_t$ (kips)	Barrier capacity, R_w (kips)	Yield line length, Lc (ft)	Distribution length, (Lc + 2H) (ft)	Uniform tensile force using $4/3*F_t$ (kips/ft)	Design moment Mc (kips-ft/ft)
V-shape YLM (AASHTO)	72.00	122.00 (reported)	10.20	15.86	4.54	14.62
W-shape YLM	72.00	130.00	14.83	20.49	3.51	11.30

Design could be reduced by 23%

- **The force distribution length estimated by W-shape YLM is much longer than that estimated by the V-shape YLM in the current AASHTO.**
- **Using W-shape YLM could lead to more economical design of the deck overhang.**

Bridge Railing Overhang Design Example 2

V-shape versus W-shape YLM

36in-single slope barrier (TTI)

	Collision force, $4/3*F_t$ (kips)	Barrier capacity, R_w (kips)	Yield line length, Lc (ft)	Distribution length, (Lc + 2H) (ft)	Uniform tensile force using $4/3*F_t$ (kips/ft)	Design moment Mc (kips-ft/ft)
V-shape YLM (AASHTO)	72.00	82.73	8.90	14.91	4.83	16.08
W-shape YLM	72.00	118.43	15.50	21.50	3.35	11.16

Design could be reduced by 30%

- **The force distribution length estimated by W-shape YLM is much longer than that estimated by the V-shape YLM in the current AASHTO.**
- **Using W-shape YLM could lead to more economical design of the deck overhang.**

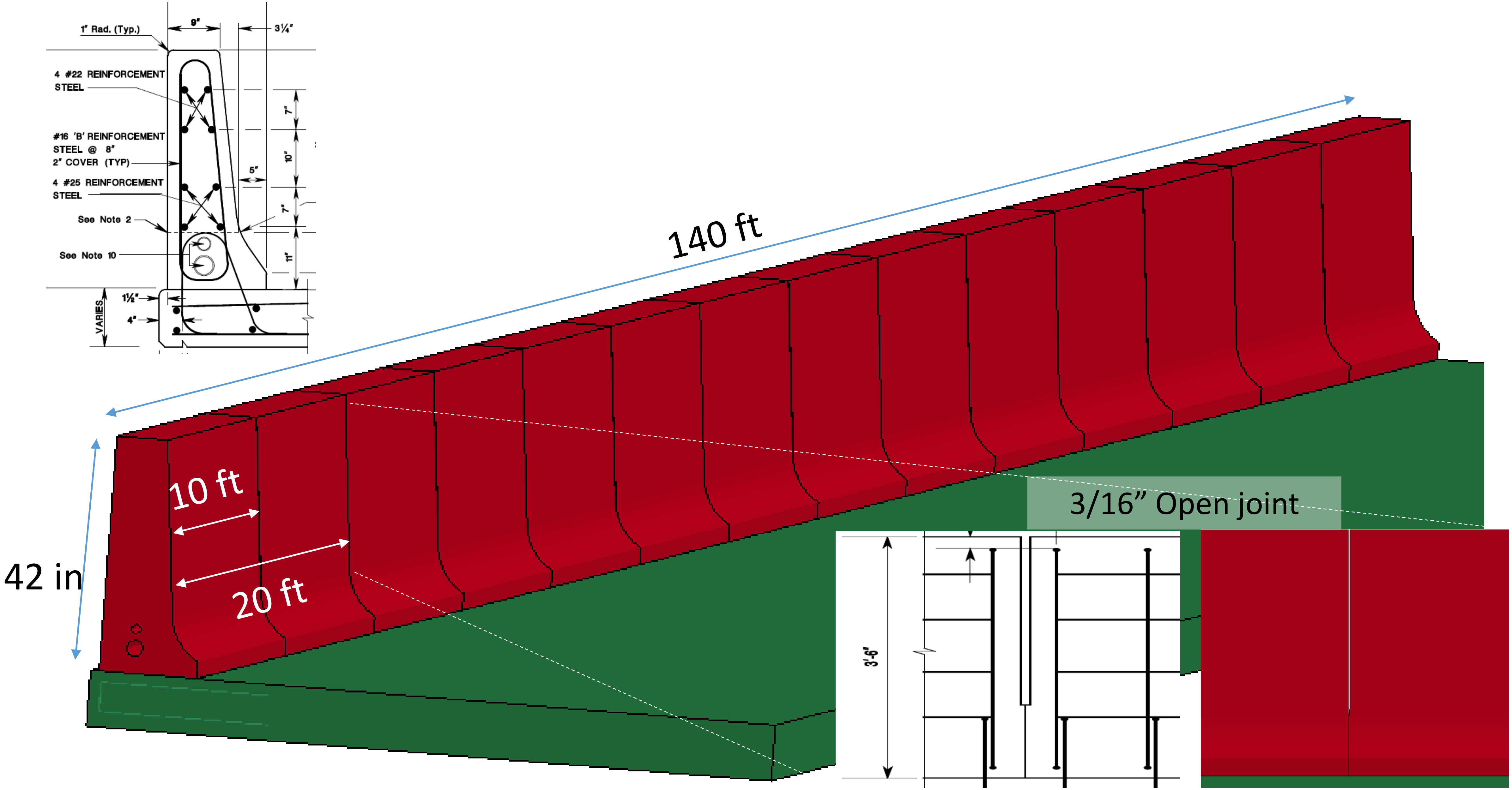
TL-5 Crash simulation of the NJDOT F-Shape Barrier

Objective

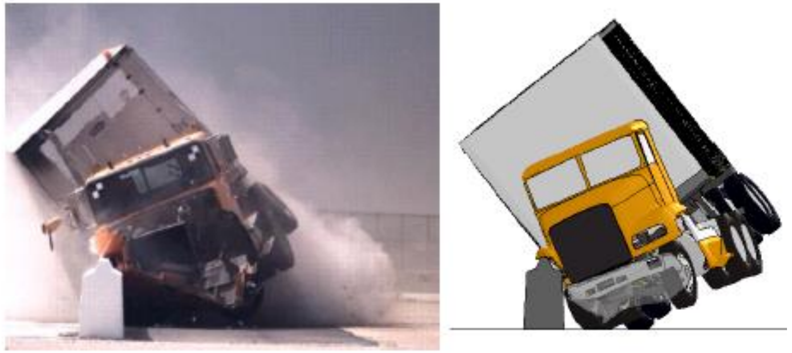
- Use FE simulations to evaluate the performance of a new precast MASH TL-5 concrete barriers.

- Provide design recommendations for the proposed TL-5 barrier based on MASH truck crash simulations.

TL-5 Barrier Model

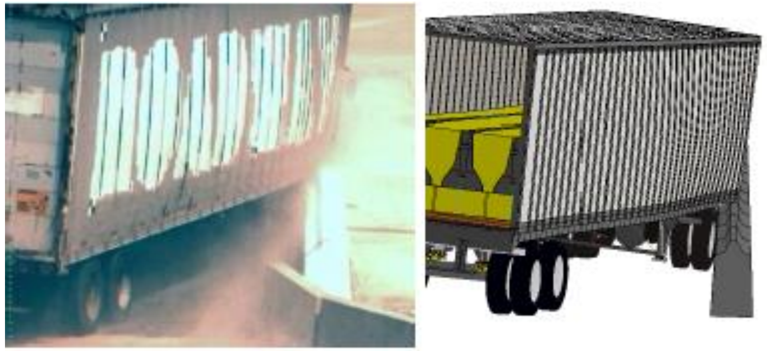


TL-5 Tractor-trailer Calibration (Miele et al. 2010)



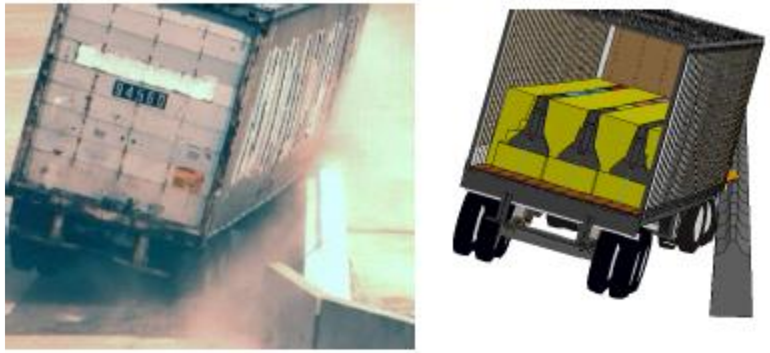
n. Time = 1.3 second

o. Time = 1.4 second



e. Time = 0.4 second

f. Time = 0.5 second



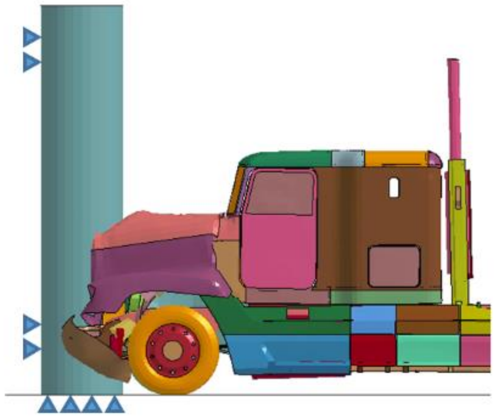
Source: Midwest

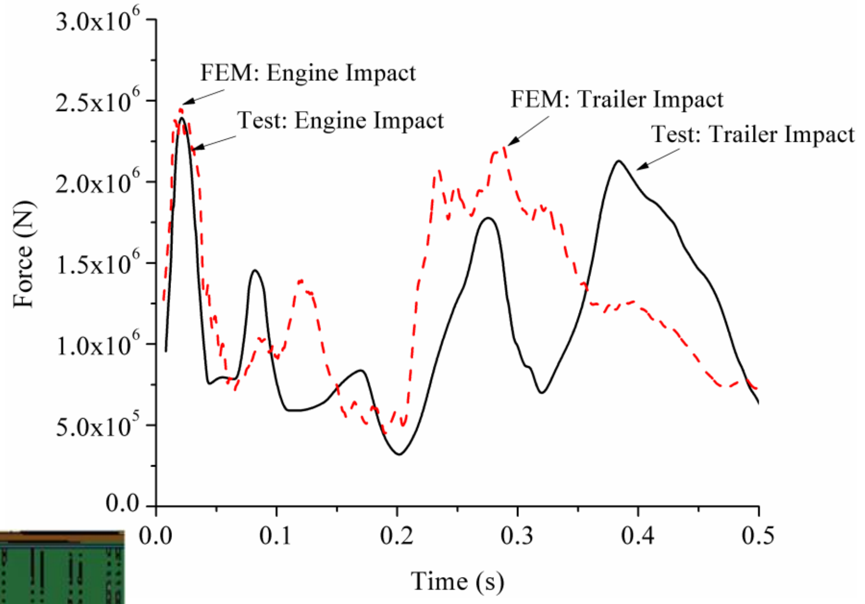
TL-5 Tractor-trailer Validation

- Agrawal et al. 2018

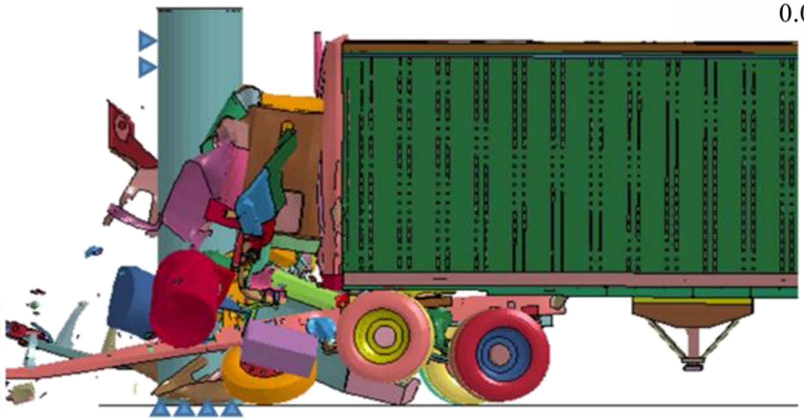
(a)

(b)



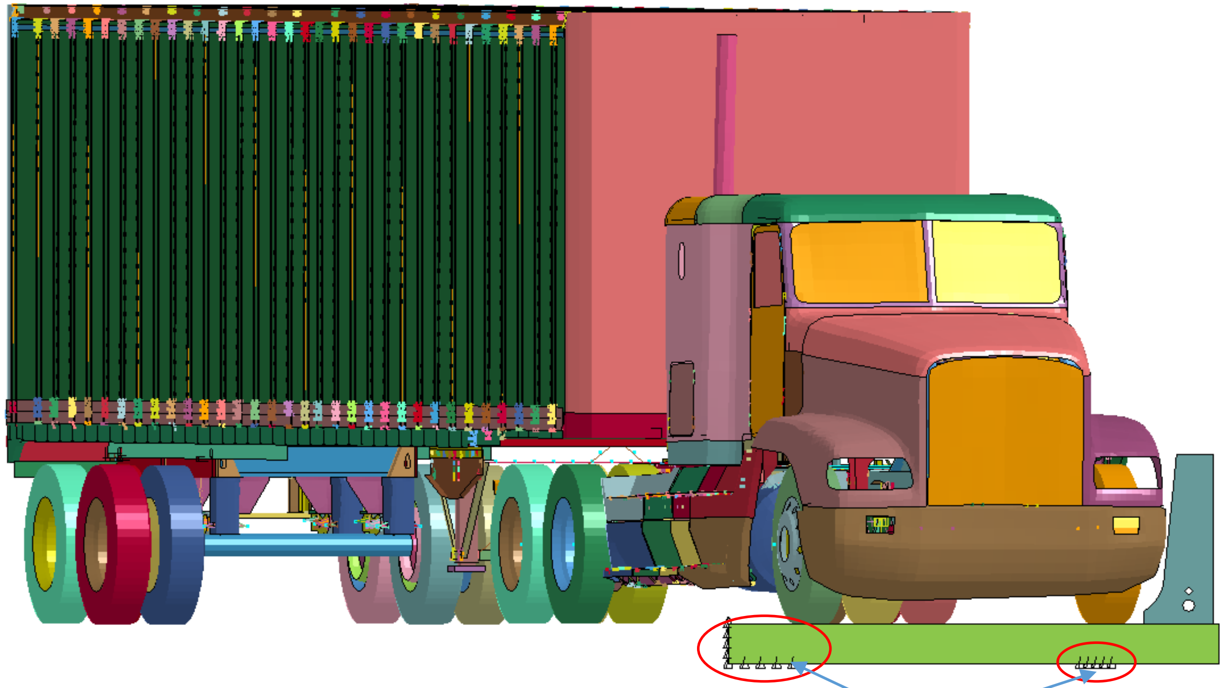


(a)



Testing by TTI (2010)

Simulation Setup in LS-DYNA



900,000 elements

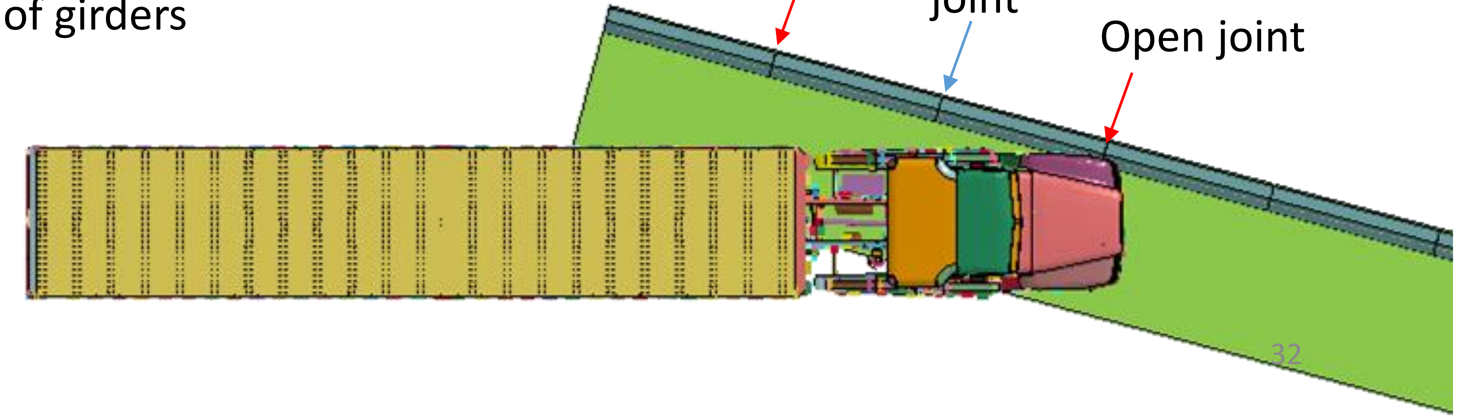
Nodes fixed at the
location of girders

MASH TL-5 Impact Condition:
- 50 mph
- 80,000 lb
- 15 degree impact angle

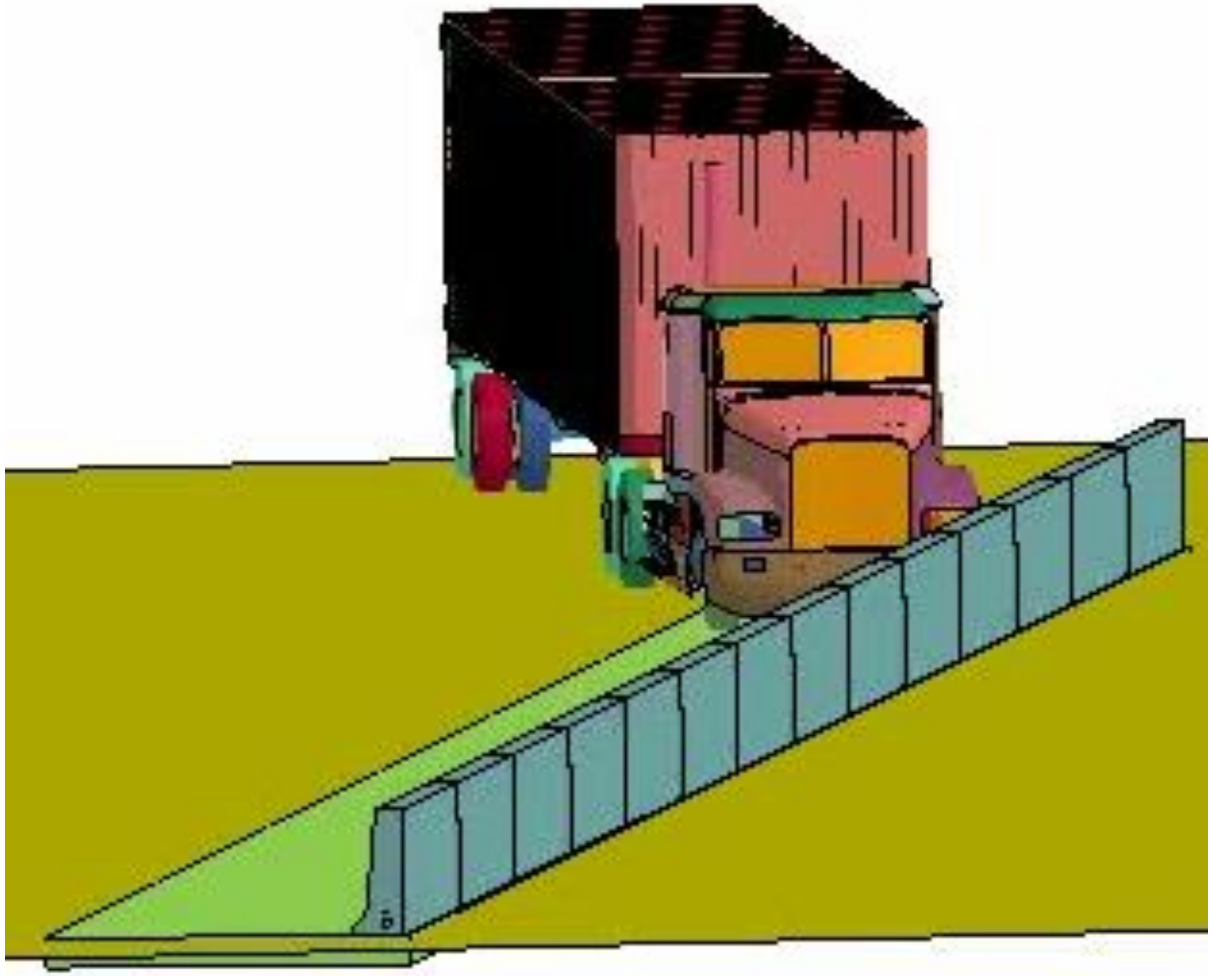
Open joint

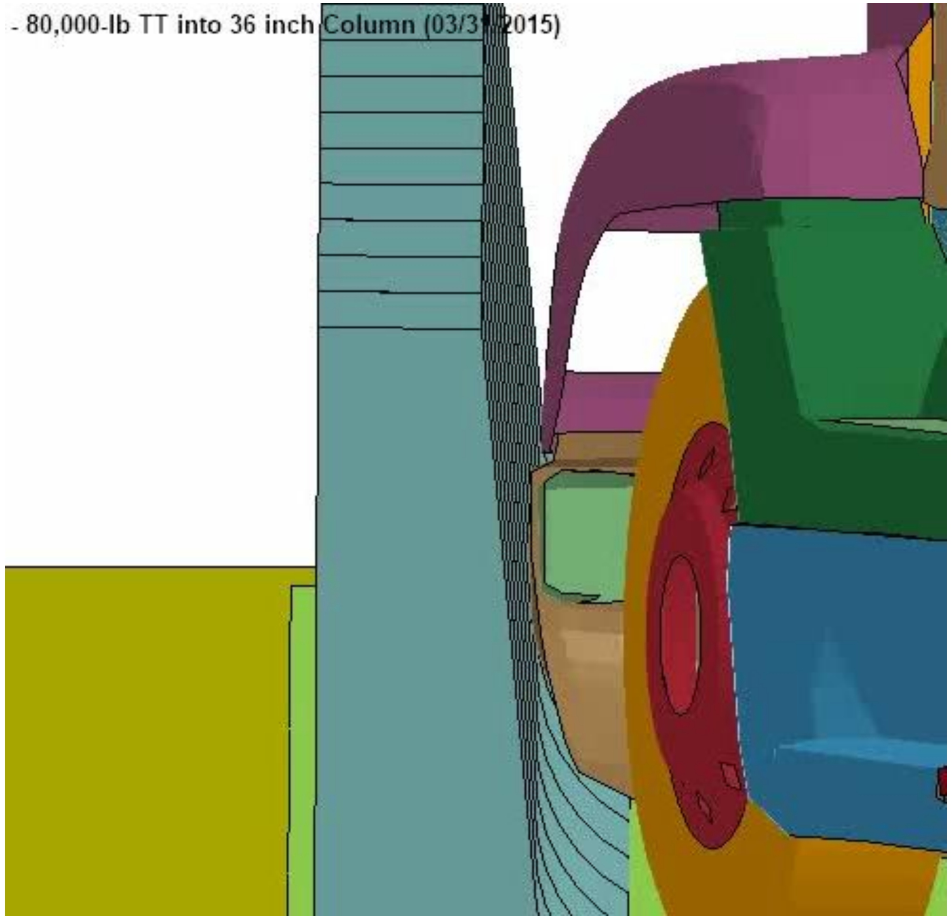
Contraction
joint

Open joint

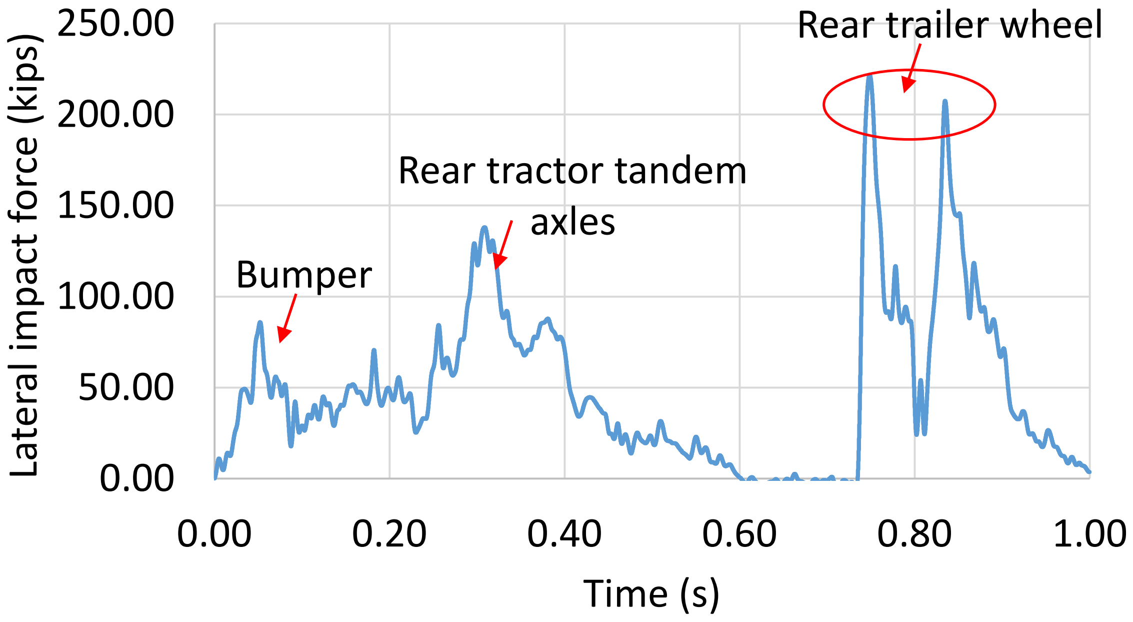


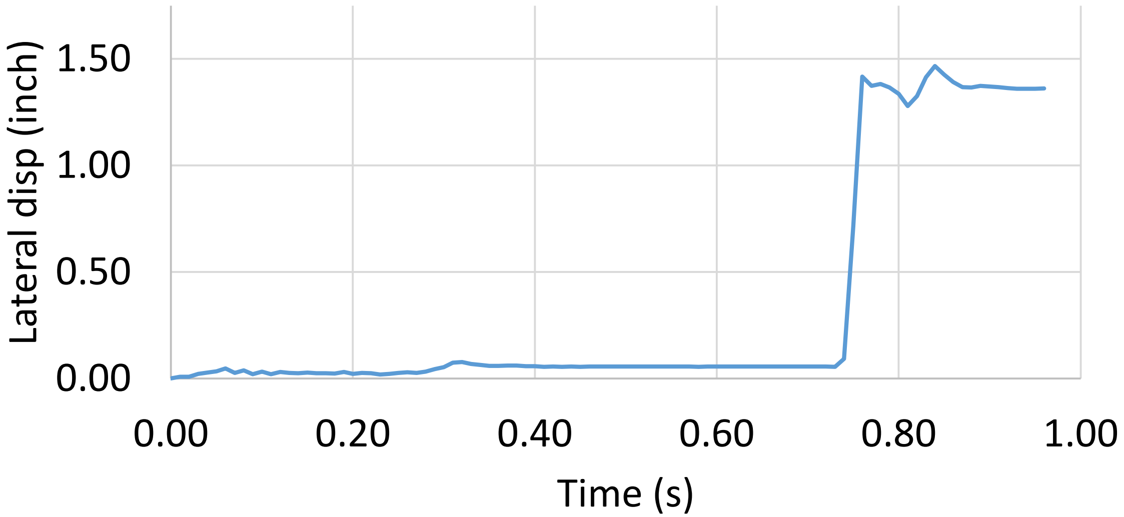
Simulation Videos

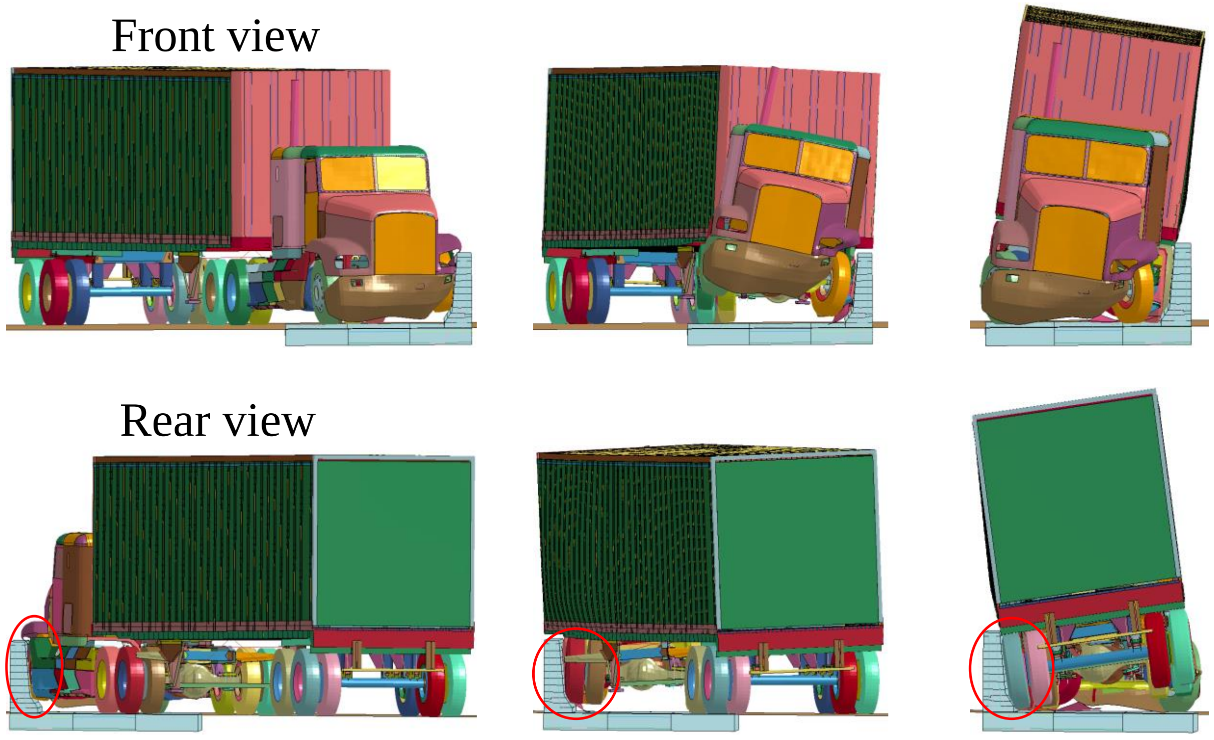




Impact response of TL-5 barrier







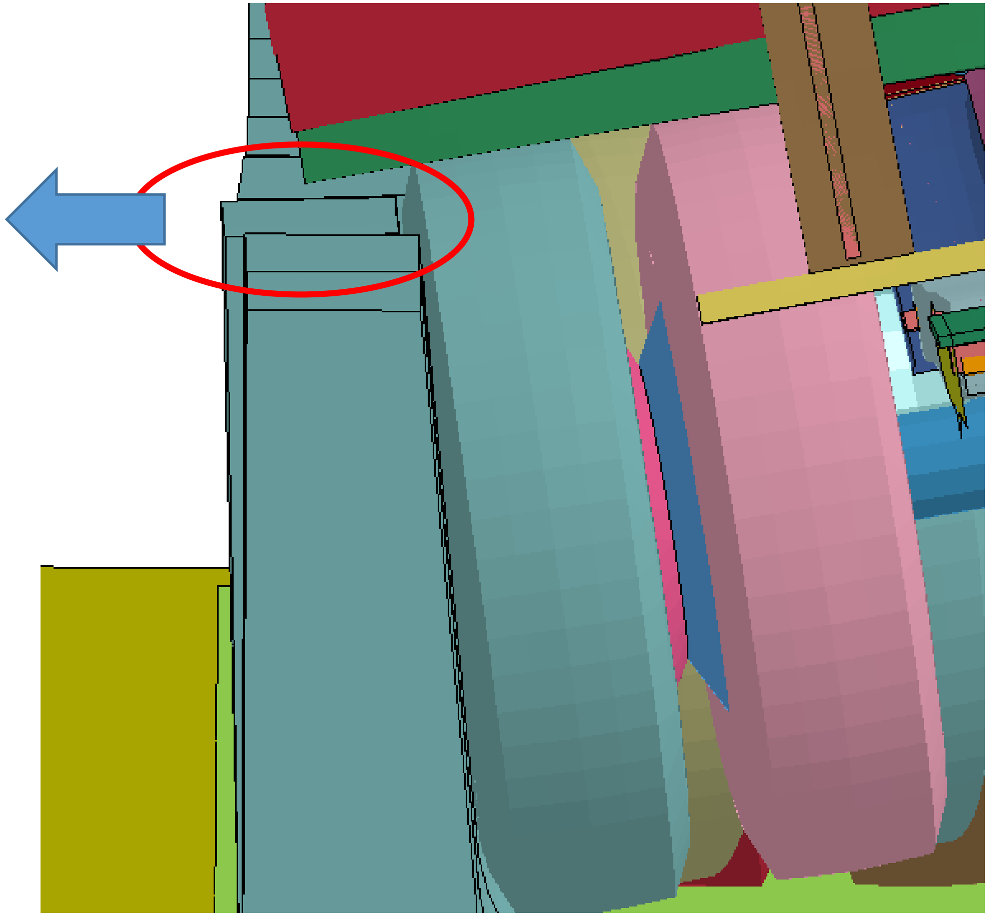
Impact of the bumper and front tractor wheel

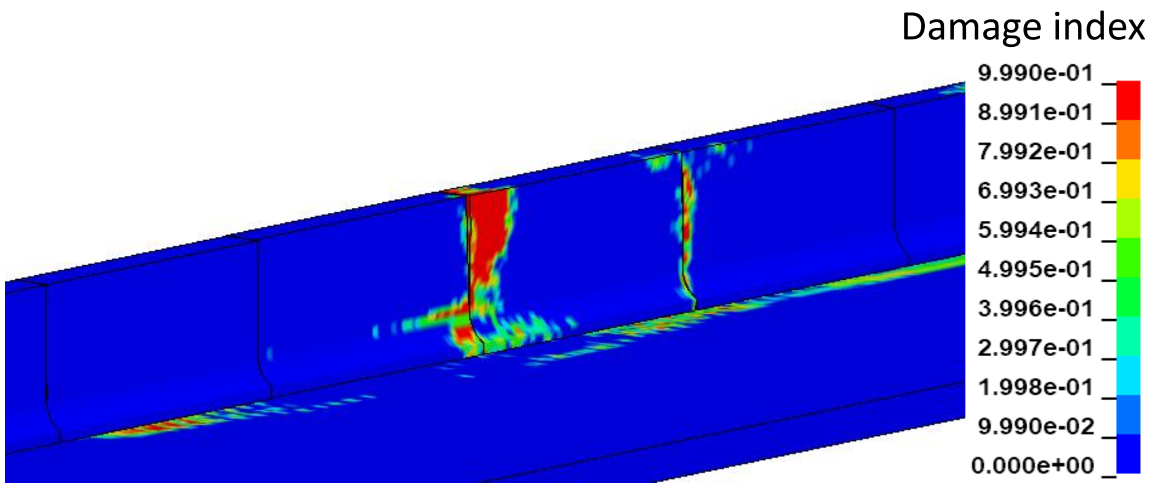
Impact of the rear tractor tandem axles

Impact of the rear trailer wheel

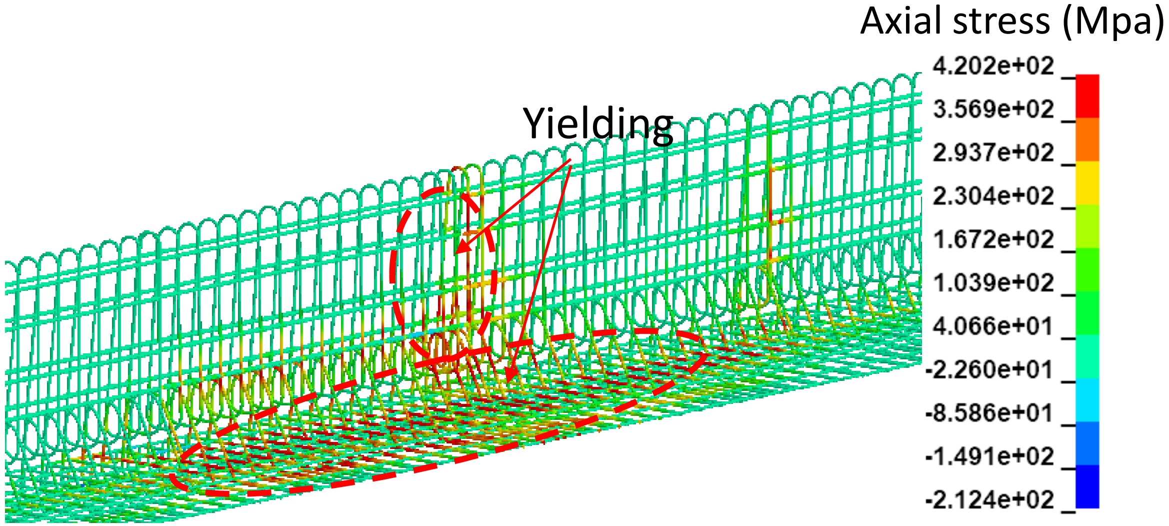
Damage mode of the parapet

- Back-slap



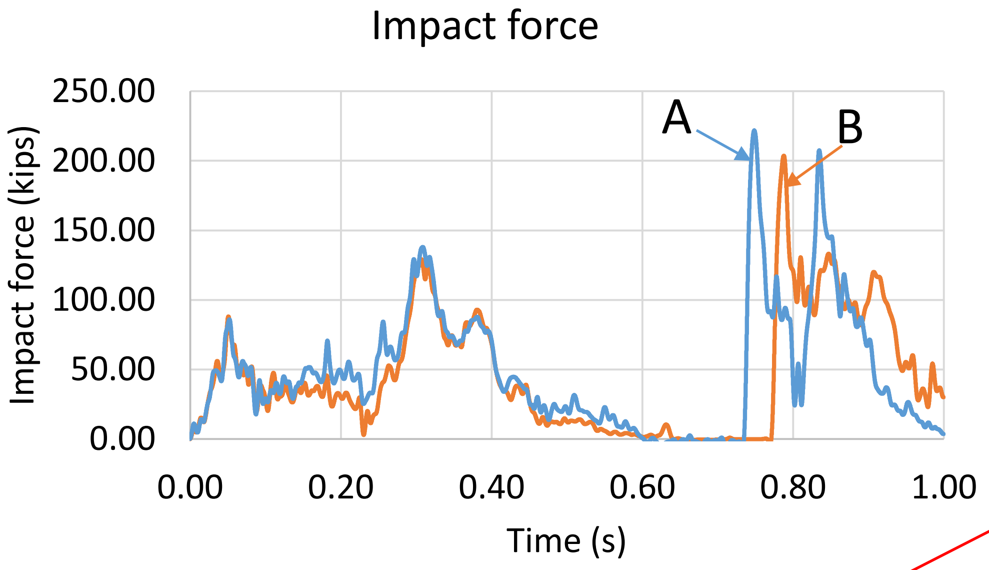


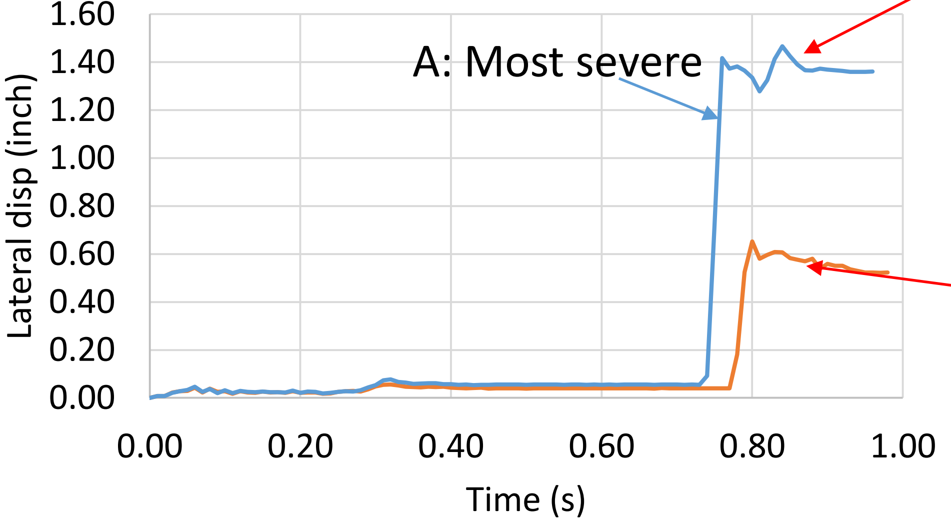
<u>Damage mode of the concrete</u>

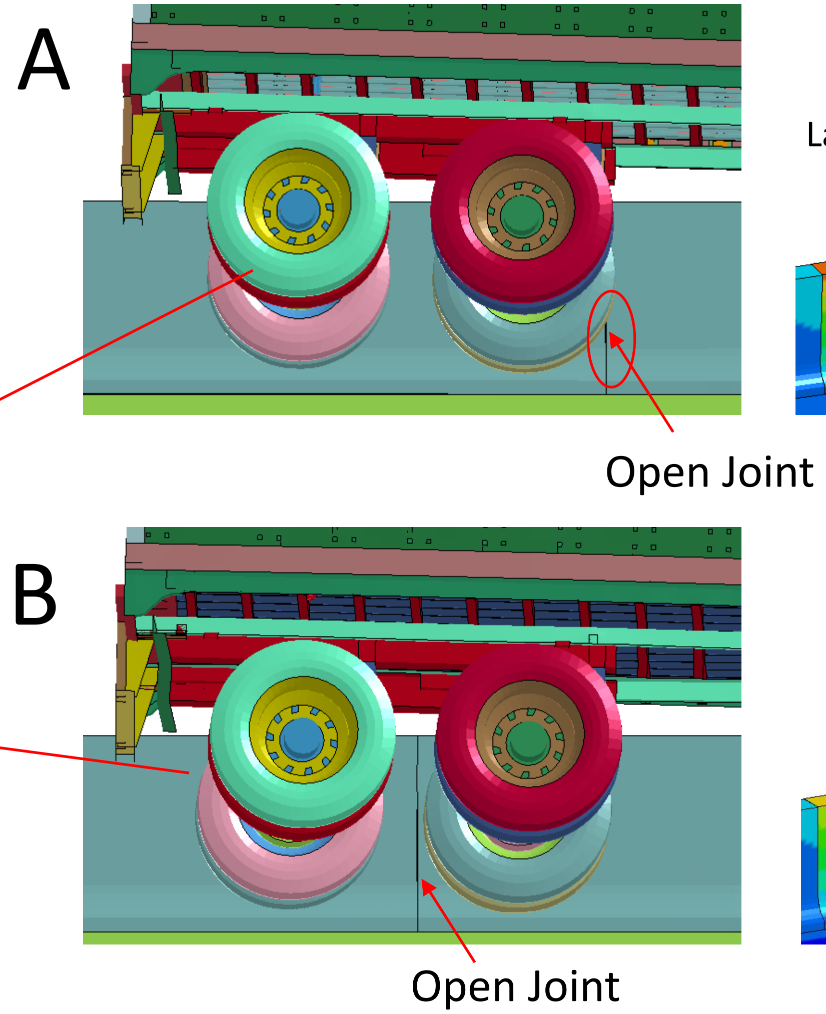


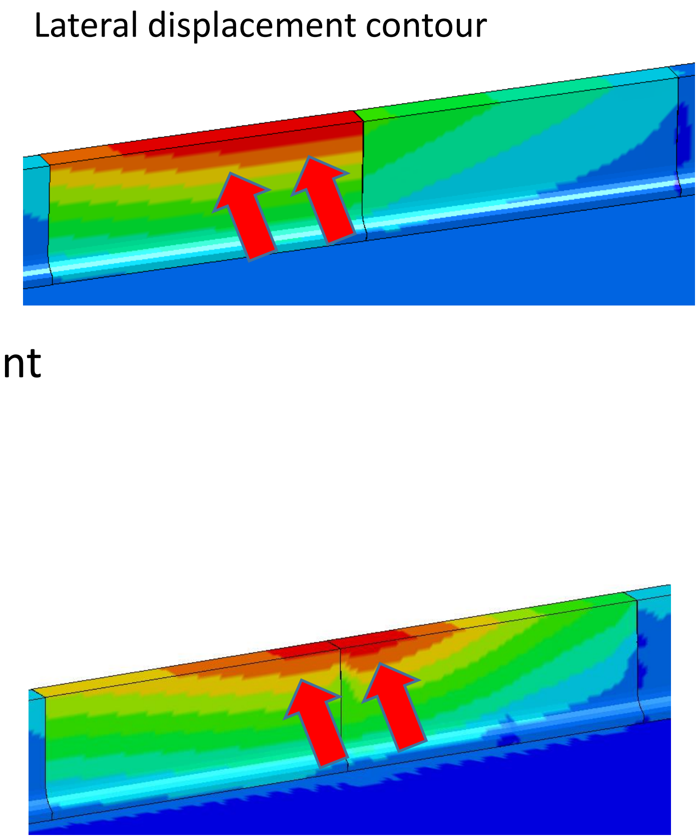
<u>Damage mode of the rebar</u>

Critical Impact Locations at the Open Joint

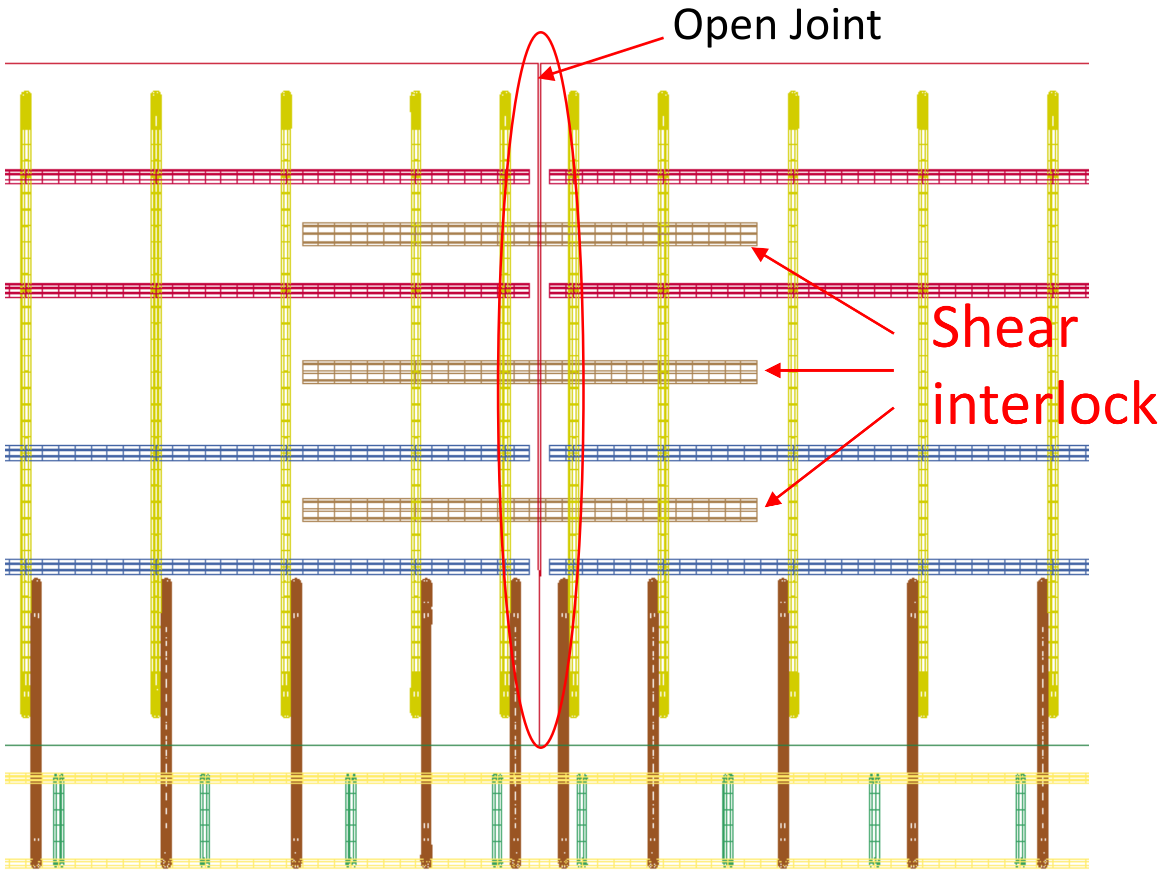


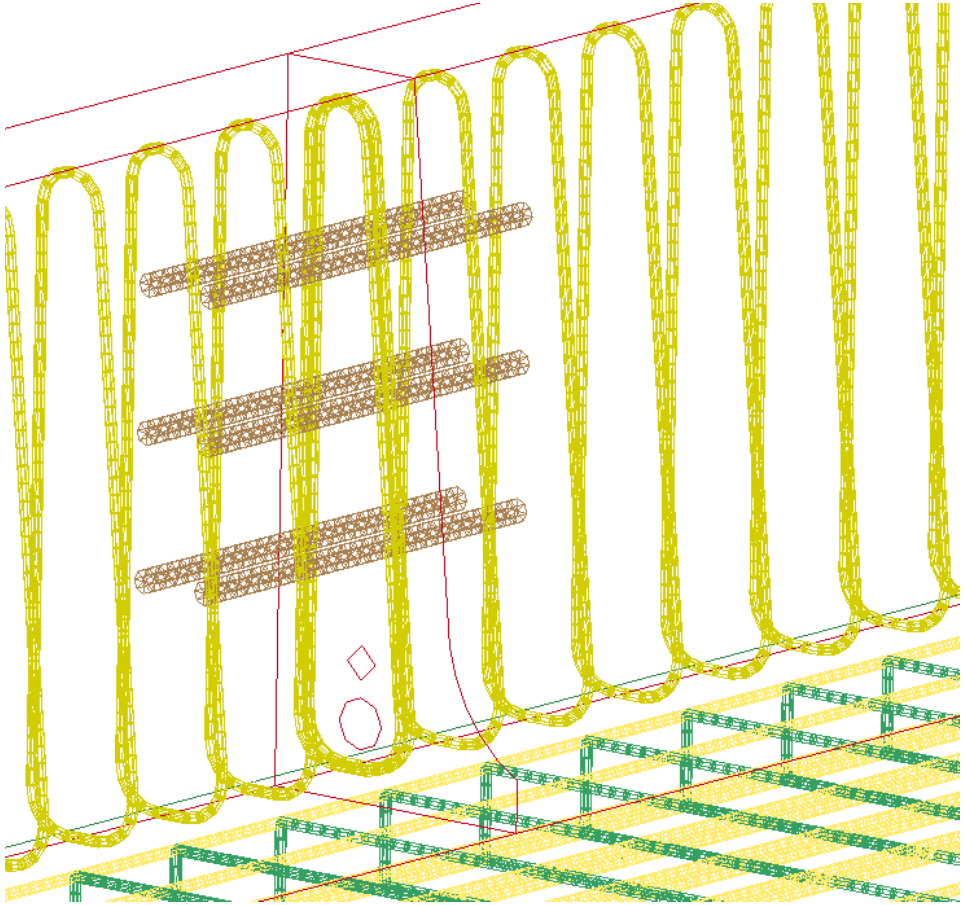






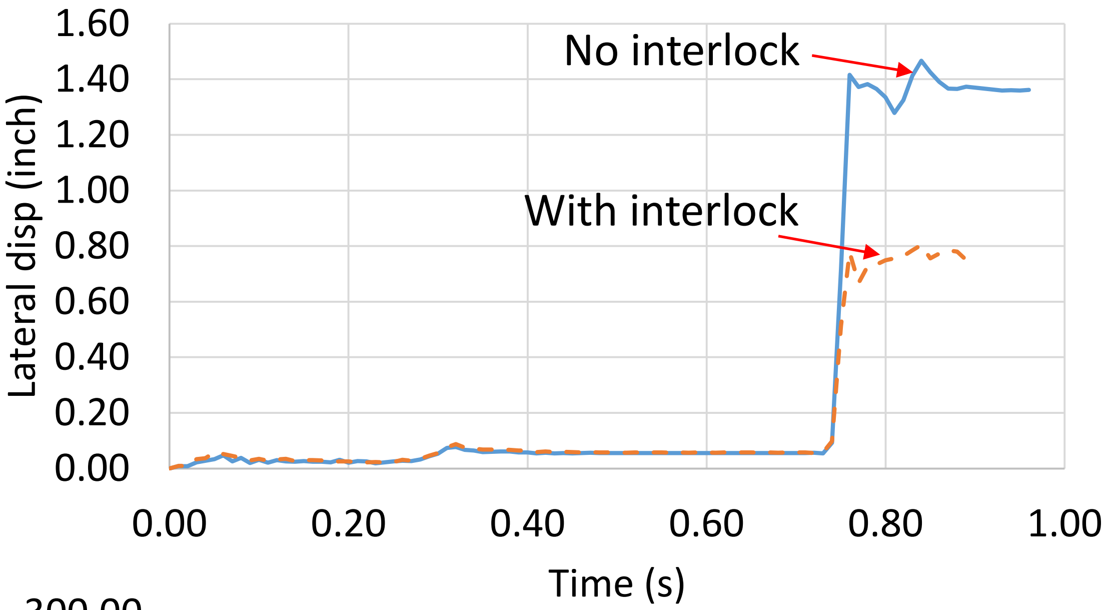
Shear Interlock Modeling

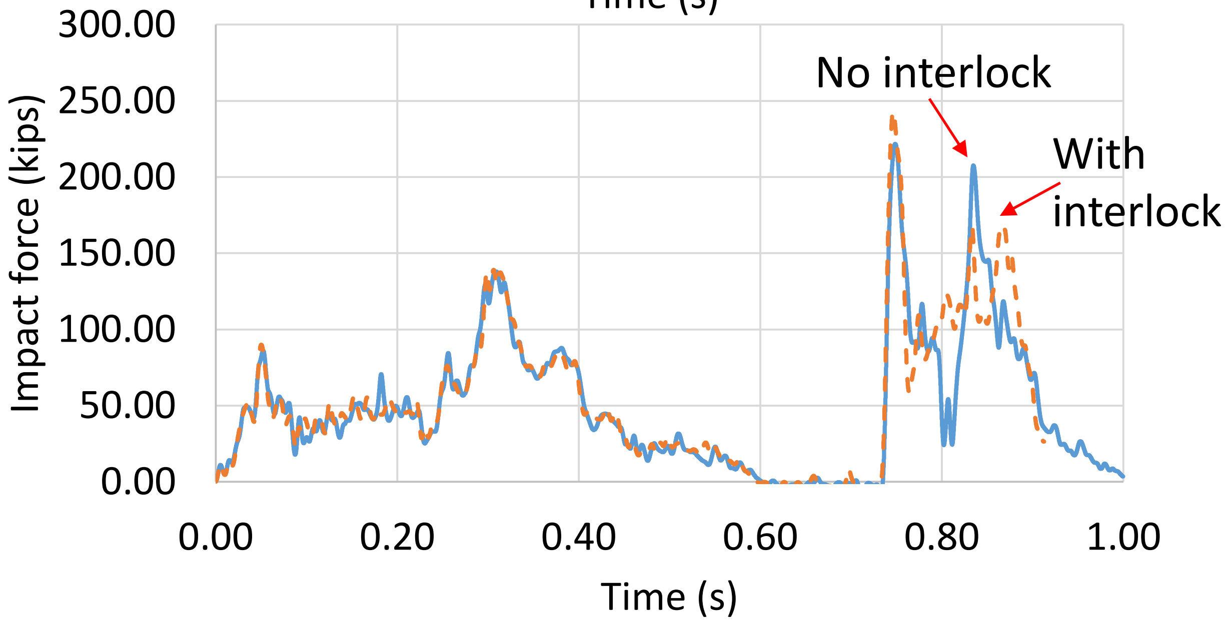




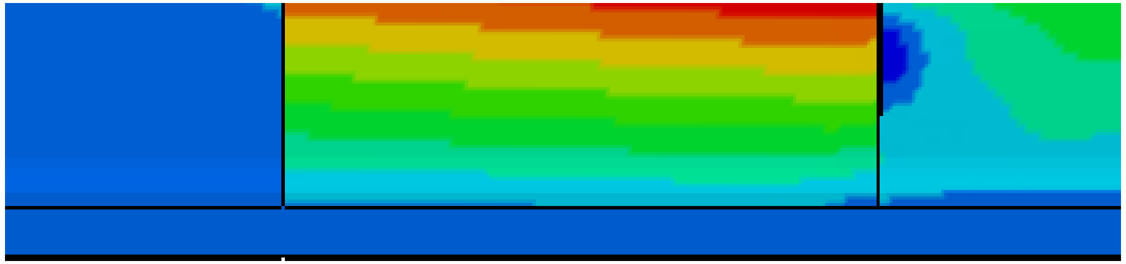
- 6 x #11 bars as shear interlock (2.33 ft long)

Effect of Shear Interlock

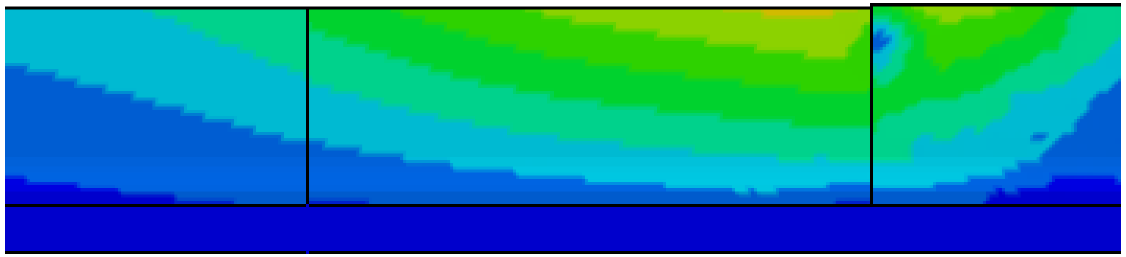




No shear interlock – peak deformation of 1.5 inch



With shear interlock – peak deformation of 0.8 inch



Lateral deformation contour

Design Recommendations

1. Based on the simulation, the proposed TL-5 precast barrier can redirect the colliding tractor-trailer under MASH conditions.

2. The peak impact force was around 220 kips (dynamic).

3. The barrier didn’t fail, but had a permanent lateral deformation of around 1.5 inch.

4. Adding shear interlock between the segments could improve the overall impact performance of the proposed TL-5 barrier significantly. It could help in reducing the frequency of replacing the failed segments due to concentrated impact.