Performance Based Design for Bridge Piers Impacted by Heavy Trucks

Anil K. Agrawal, Ph.D., P.E., Ran Cao and Xiaochen Xu
The City College of New York, New York, NY

Sherif El-Tawil, Ph.D.
University of Michigan, Ann Arbor, MI

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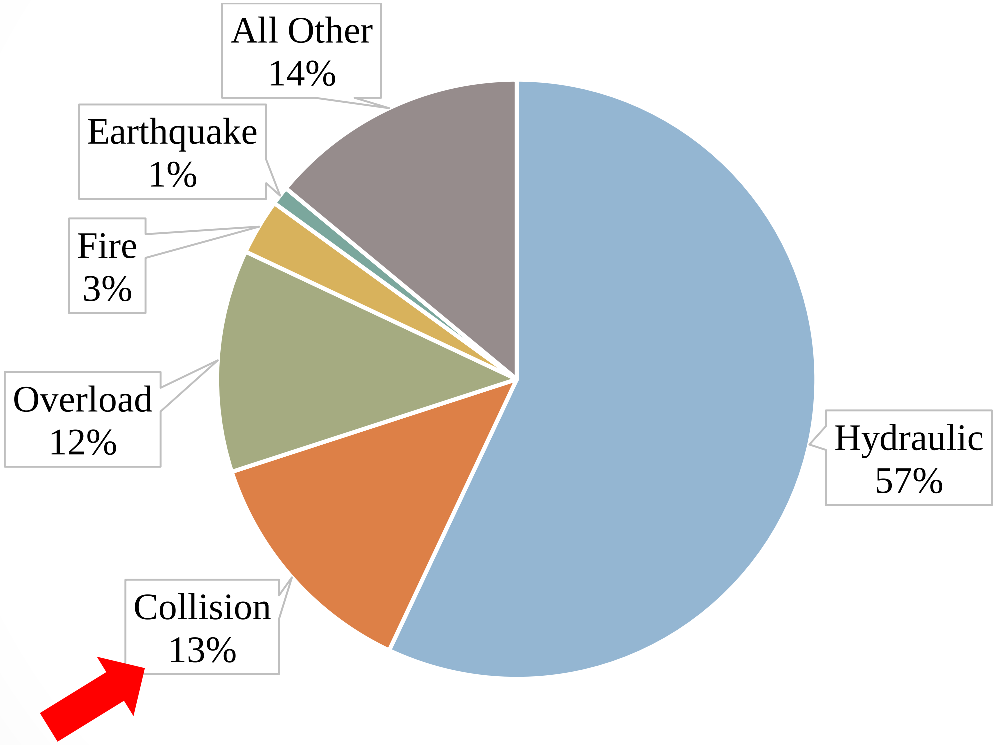
Objectives of the project

- Develop bridge design guidelines to achieve desired performance levels during heavy vehicular impact.
  - A methodology to predict impact loads based on weight and velocity
  - Definition of performance levels
  - Approach to achieve desired performance level
  - Step by step examples illustrating performance based design and
  - Demonstration of effectiveness of the design through numerical simulations validated through physical large scale tests.

❑Introduction



Causes of failure of bridges.

Introduction

Truck Impact on Piers of Tancahua Street Bridge over IH-37, Corpus Christi, Texas on May 14, 2014.

Introduction

Truck impact on Bridge on 26 ½ Road over IH-70, Grand Junction, Colorado

Introduction

Truck impact on Mile Post 519 Bridge over IH-20, Canton, TX

Introduction

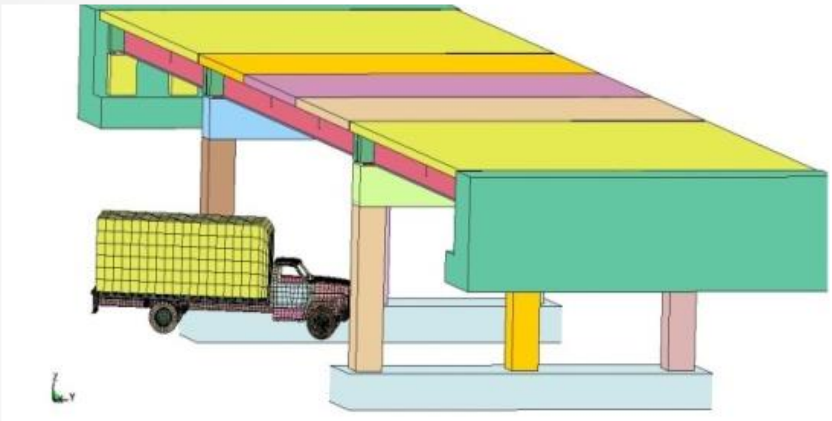
Truck impact on FM 2110 bridge over IH-30, Texarkana, Texas on Aug. 8th, 1994.

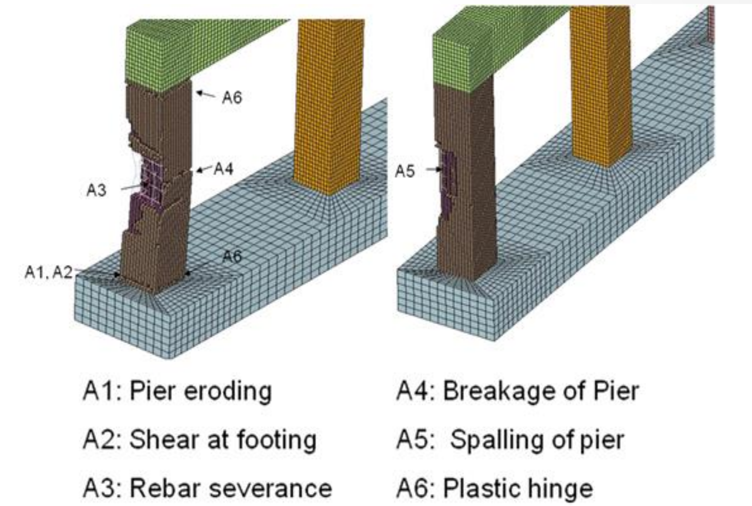
Introduction

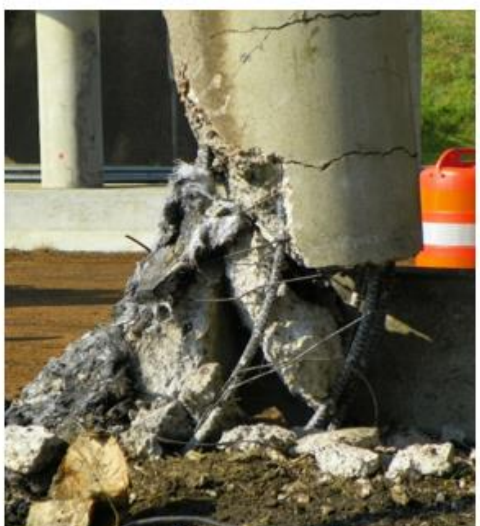
Truck impact on SH-14 Bridge Over IH-45, Corsicana, Texas

Introduction

Damage modes during vehicular impacts







Texas I45 Bridge Accident in 2014.

Primarily shear failure mode dominant during accidents.

Introduction

Full-Scale Testing at TTI

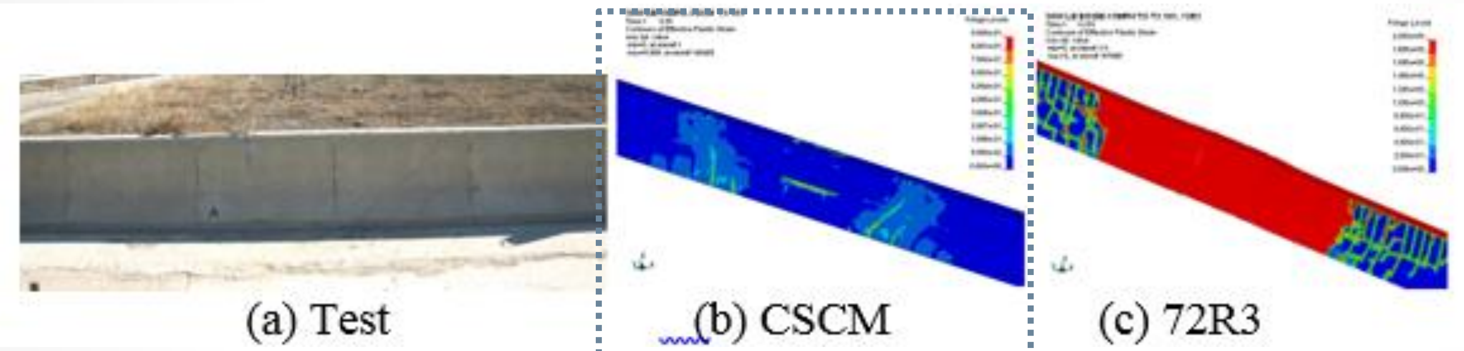
- Tests based on impact by truck on rigid piers.
- Results don't apply to concrete piers that are damaged, resulting in significant loss of energy.
- Test results don't provide a basis for performance based approach.

Material Model

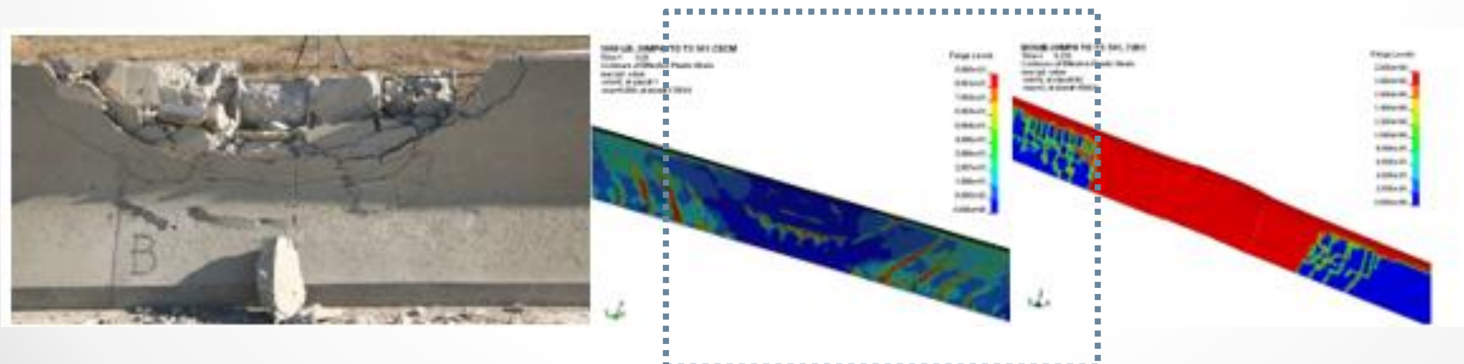
Bogie Impact Test

CONCRETE MATERIAL MODELS: MAT 72 VERSUS MAT 159 (CSCM)

Better matching between test and FEM



Damage profile for the 15 mph test.

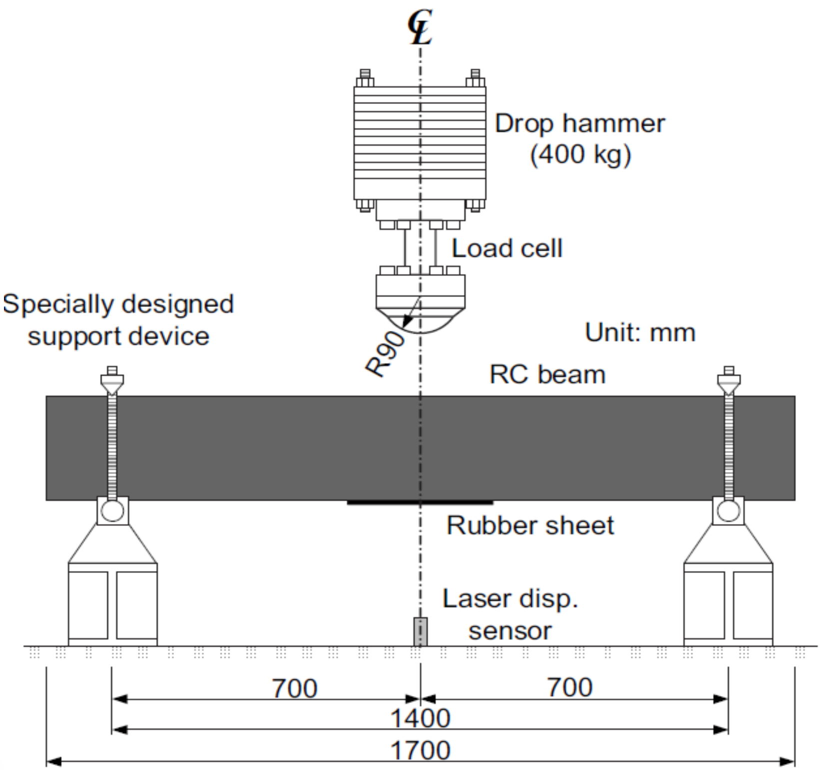


Damage profile for the 20 mph test.

Material Model

CALIBRATION OF CONTINUOUS SURFACE CAP MODEL

Impact Test by Fujikake et al. (2009)

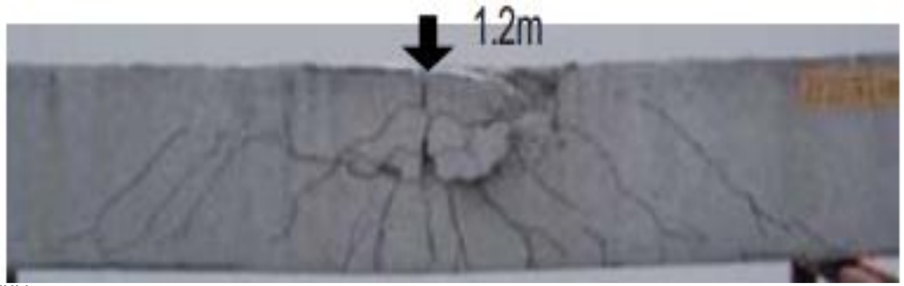


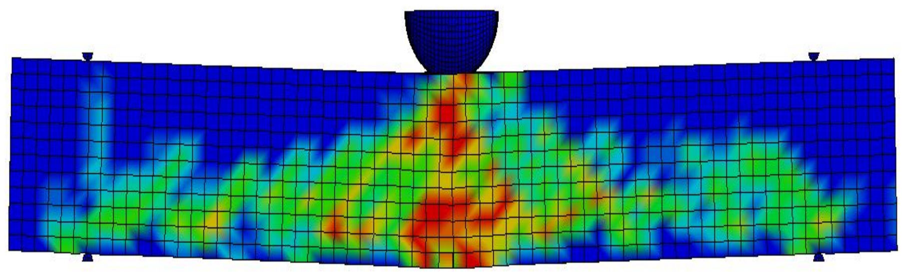
RC beam hammer impact test setup.

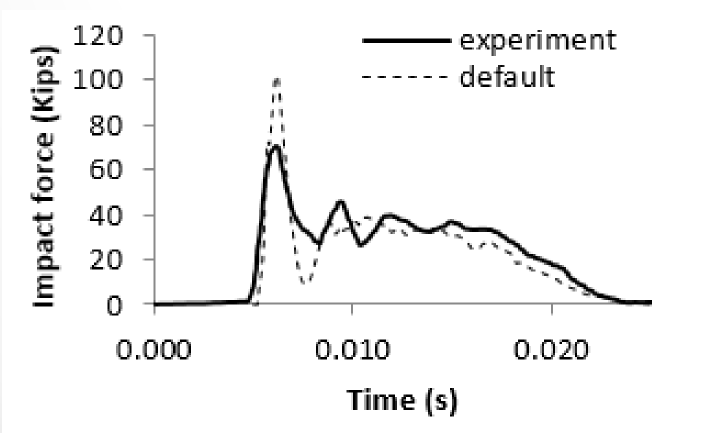
Material Model

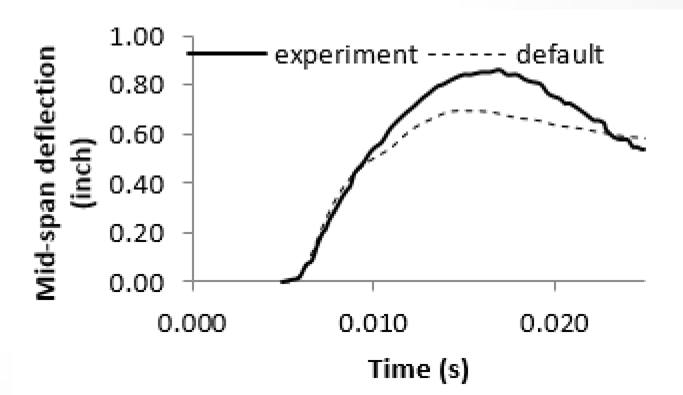
CALIBRATION OF CONTINUOUS SURFACE CAP MODEL

Default CSCM Parameters









Large Scale Testing and Simulation

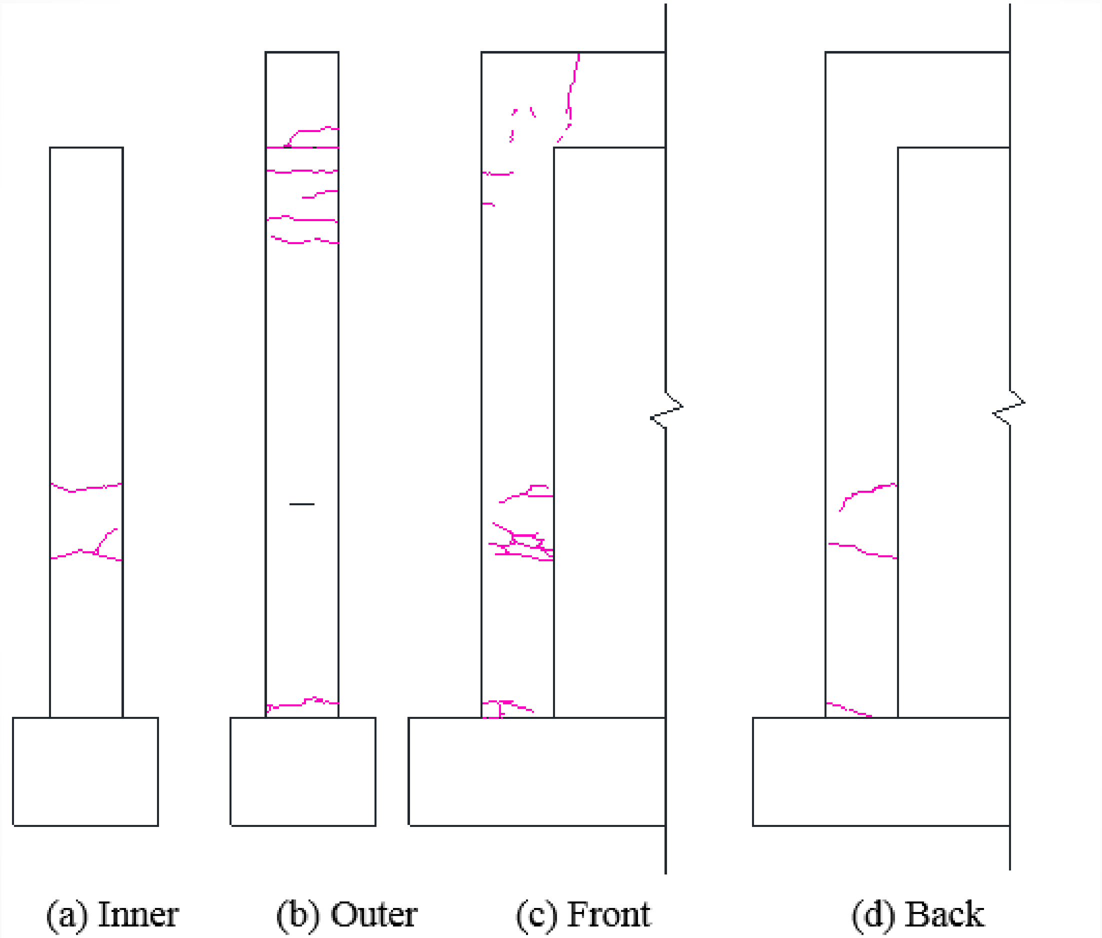
Test Setup

Setup of field test.

Large Scale Testing and Simulation

Test Results

Cracks on Impacted Weak Pier

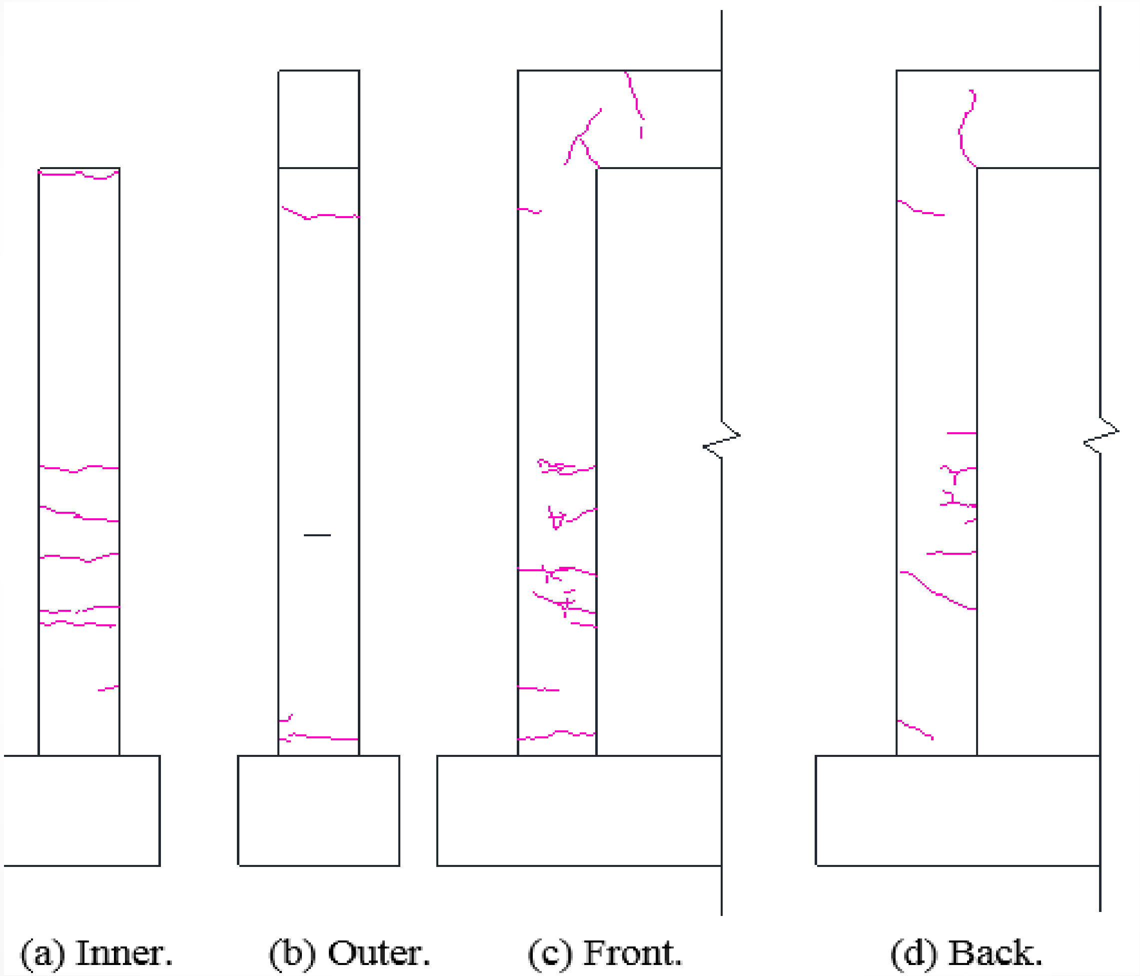


Permanent crack pattern on four sides of weak pier

Large Scale Testing and Simulation

Test Results

Cracks on Impacted Weak Pier

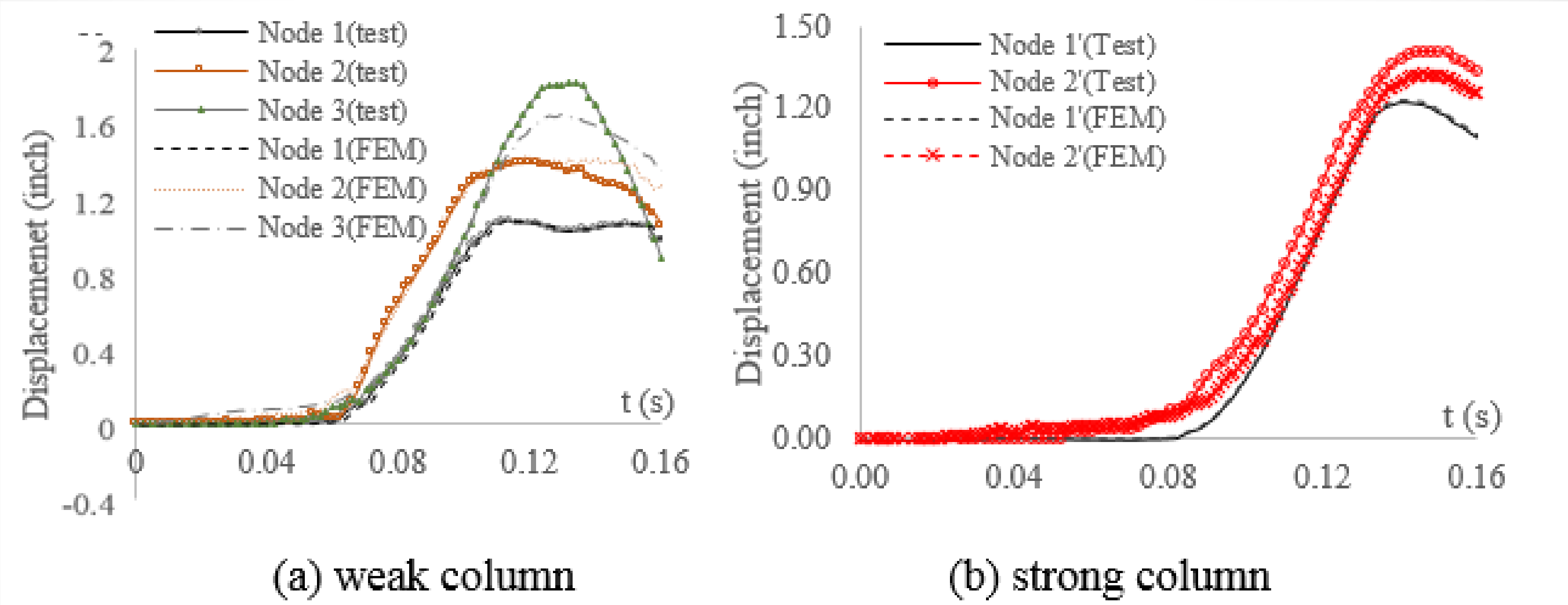


Permanent crack pattern of four sides of strong pier.

Large Scale Testing and Simulation

EXPERIMENTAL VS. COMPUTATIONAL RESULTS

Displacement Time History



Critical points displacement for the impacting into the weak and strong column scenario.

Heavy Vehicle Simulation

Truck Model

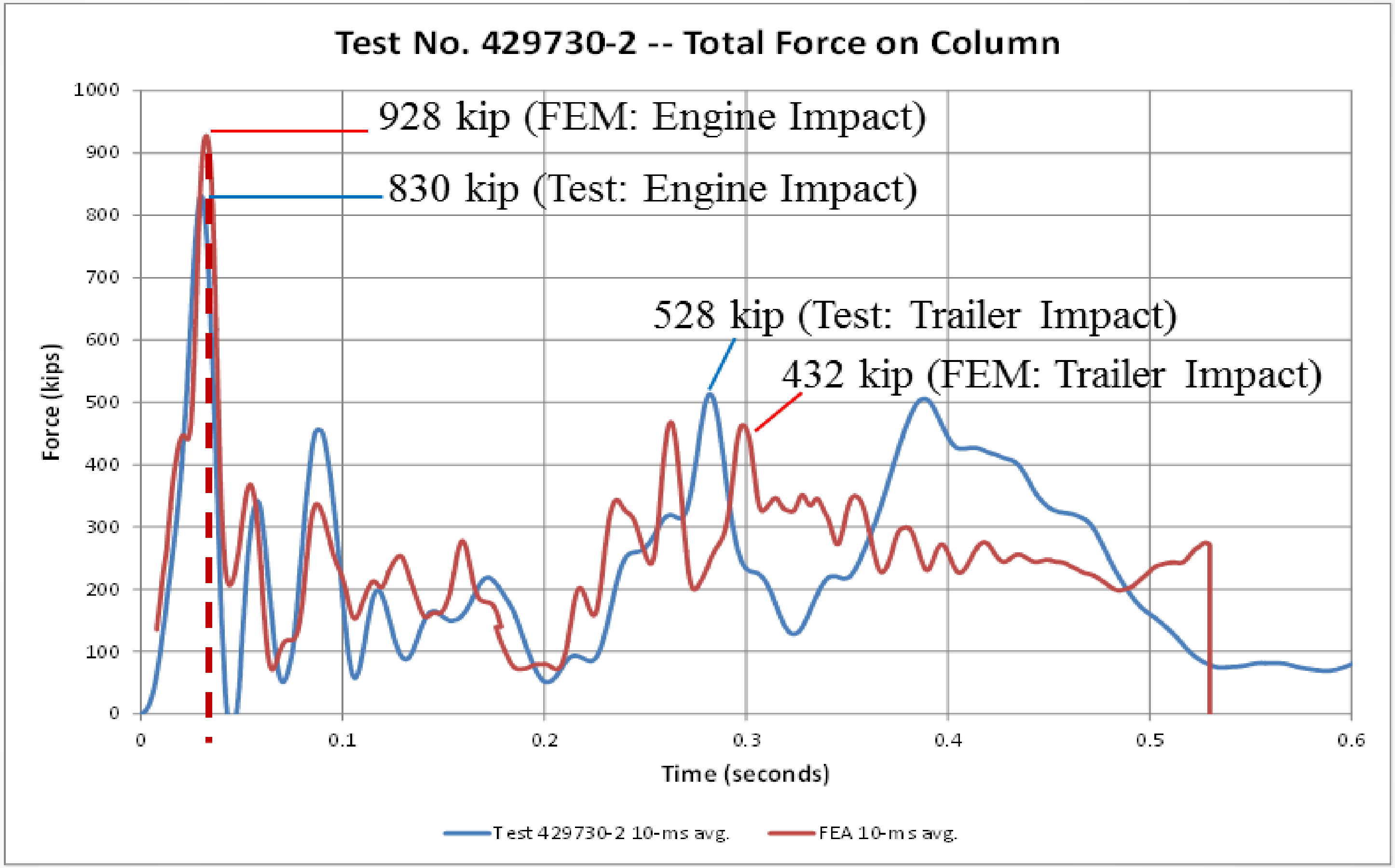
(a) Engine impact on pier during field testing (b) Engine impact on pier in LS-DYNA

Engine impacts with the rigid steel pier during test and simulations.

(a) Trailer impact on pier during field testing (b) Trailer impact on pier in LS-DYNA

Trailer impacts with pier during test and LS-DYNA simulation.

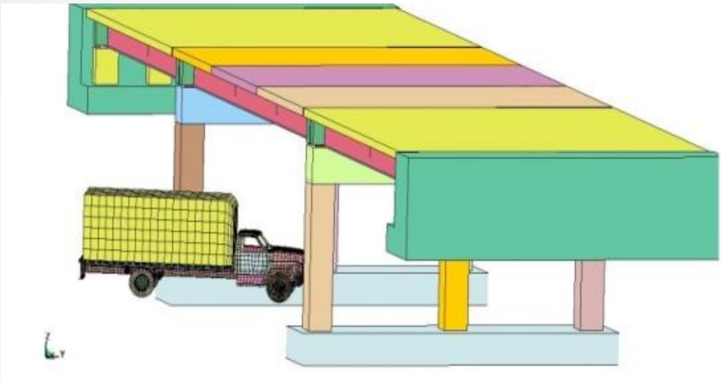
Heavy Vehicle Simulation



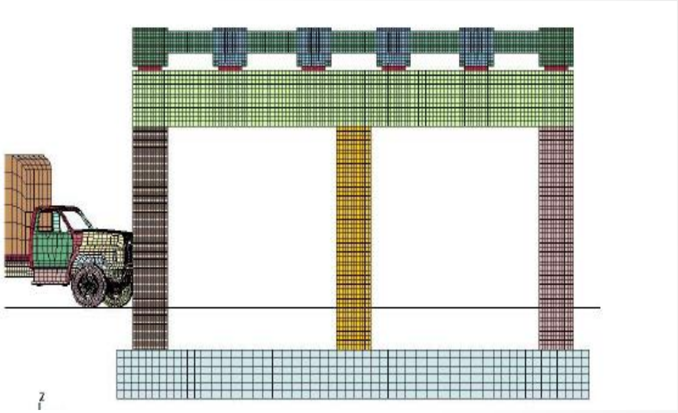
Impact force time histories during the test and FEM simulation in LS-DYNA.

Heavy Vehicle Simulation

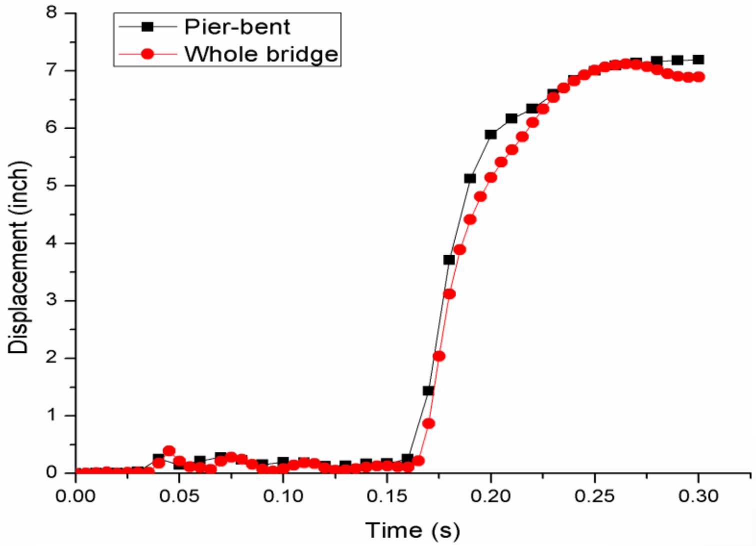
Modeling of Pier



Whole Bridge



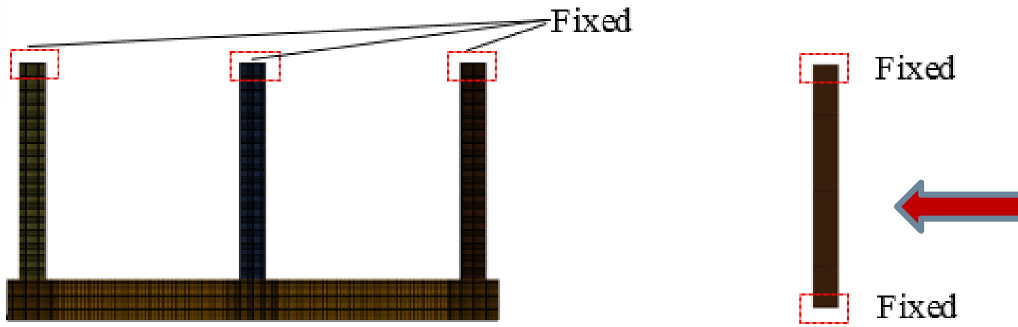
Pier bent Model



Displacement time history at impact point

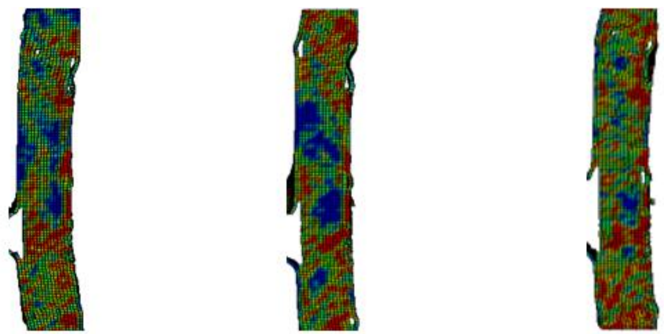
Heavy Vehicle Simulation

Modeling of Pier

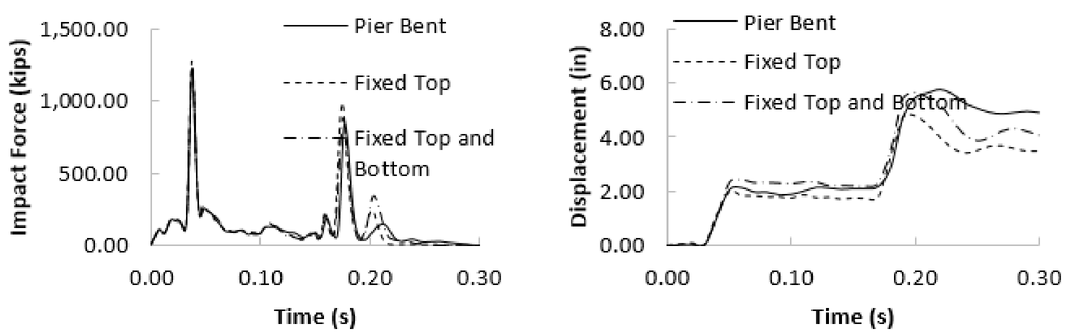


(a) Fixed top. (b) Fixed top and bottom.

Fixed-Fixed Model of pier sufficient



(a) Pier bent (b) Pier with fixed top (c) Pier with fixed top and bottom.



(a) Impact force time history. (b) Displacement time history at impact point.

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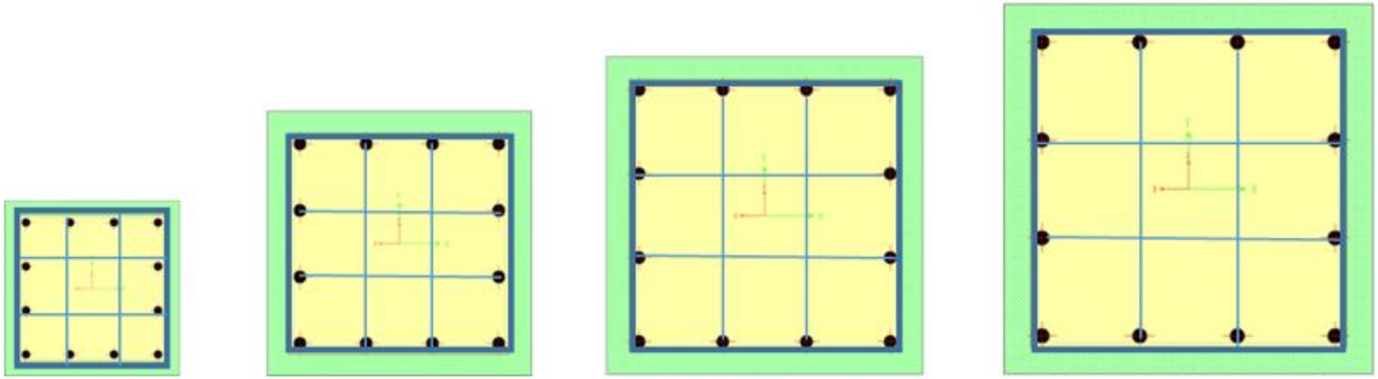
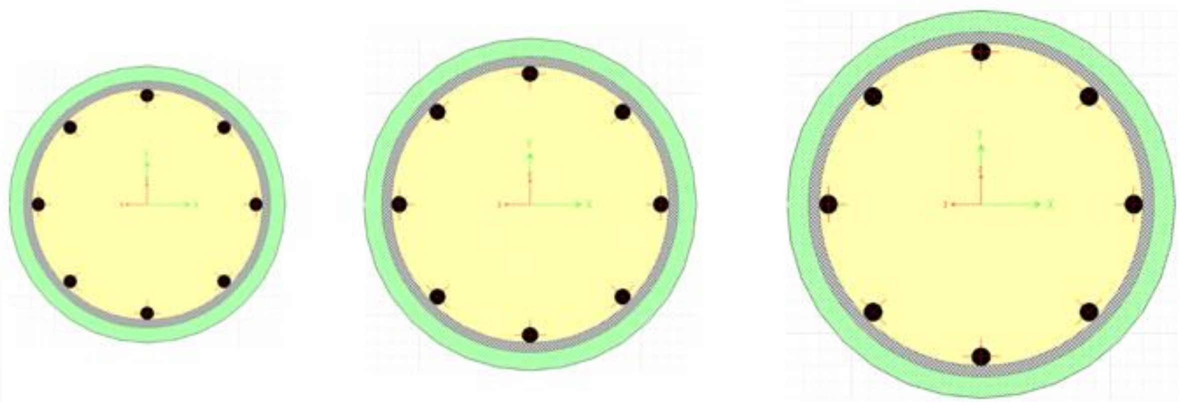
Heavy Vehicle Simulation

Example Piers



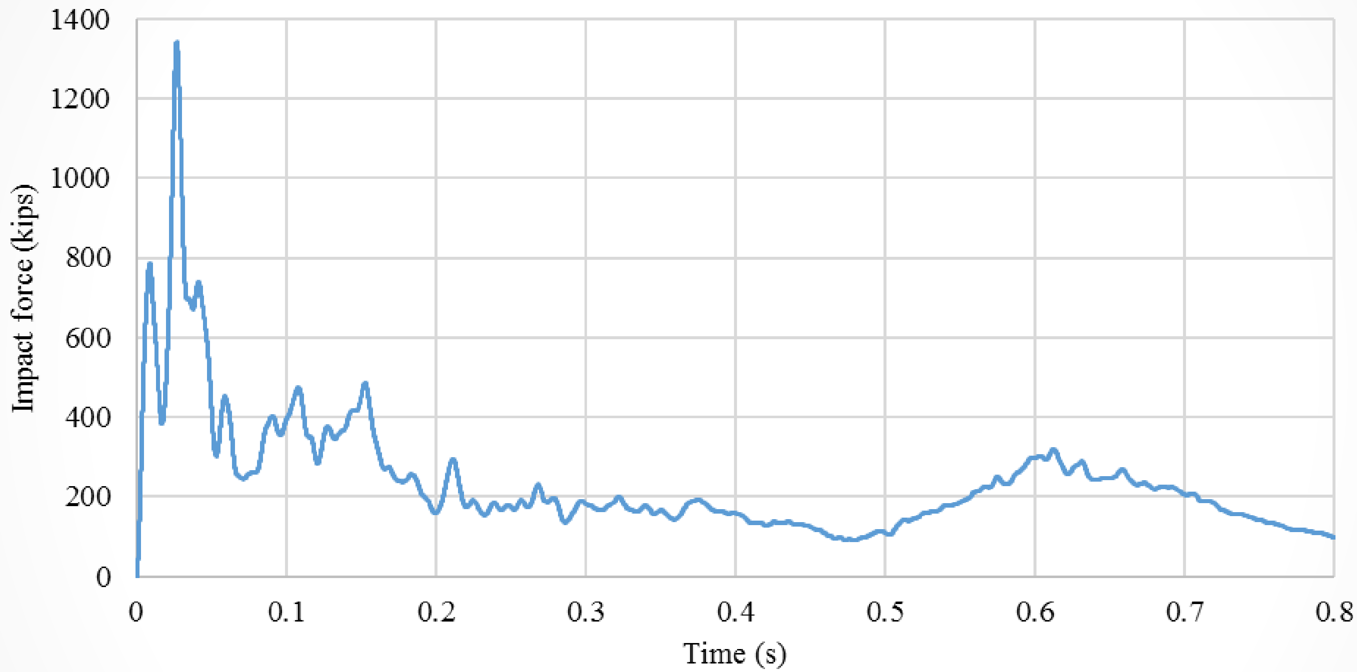
(a) 24 inch (b) 30 inch (c) 36 inch (d) 42 inch



(e) 30-in circular pier (f) 36-in circular pier (g) 42-in circular pier

Heavy Vehicle Simulation

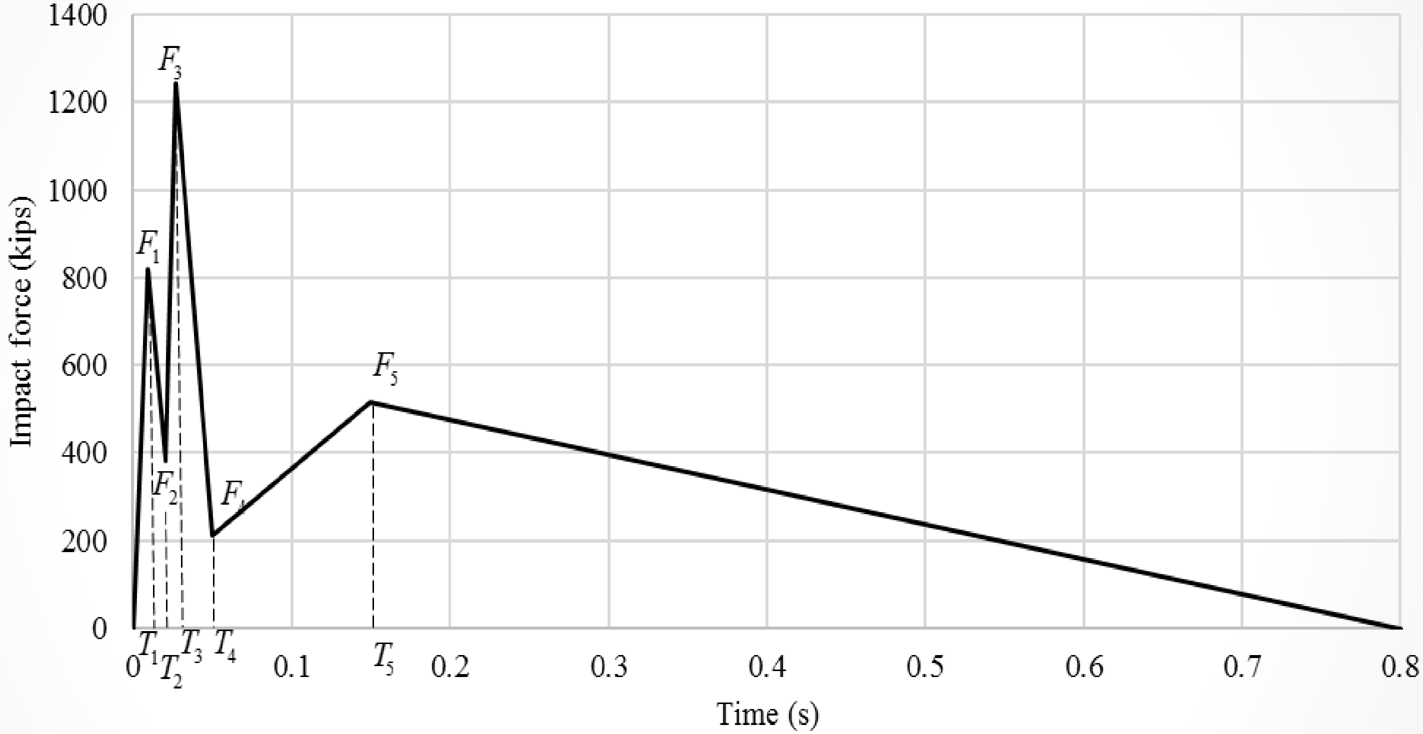
Vehicular Impact Force for Tractor-Semitrailers



Time history for impact force by the tractor-semitrailer on a rectangular concrete pier.

Heavy Vehicle Simulation

Modelling of Vehicular Impact Force

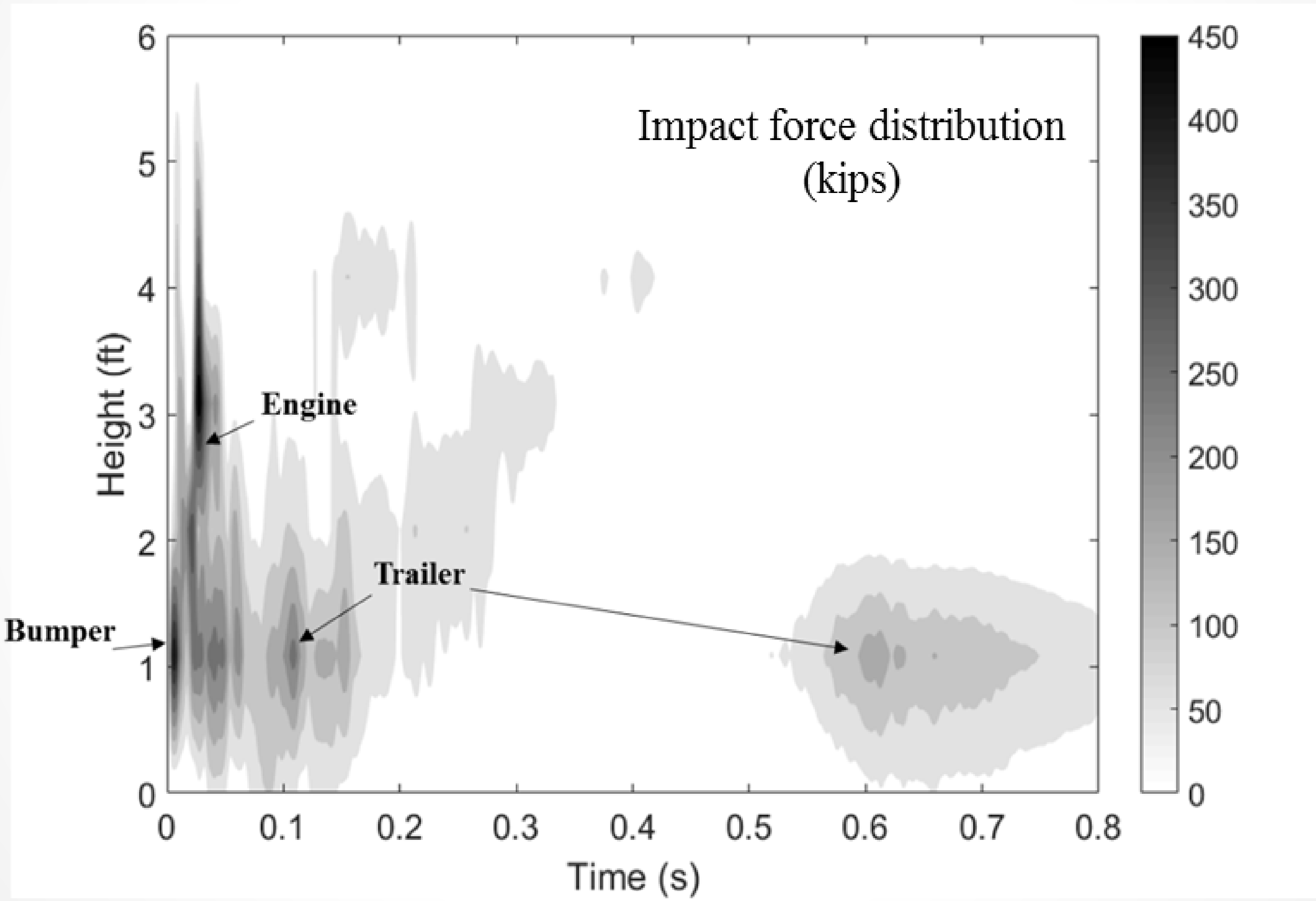


Proposed triangular pulse model for heavy vehicle impacts on bridge pier.

Heavy Vehicle Simulation

Modelling of Vehicular Impact Force

Points of Application of Pulse Impact

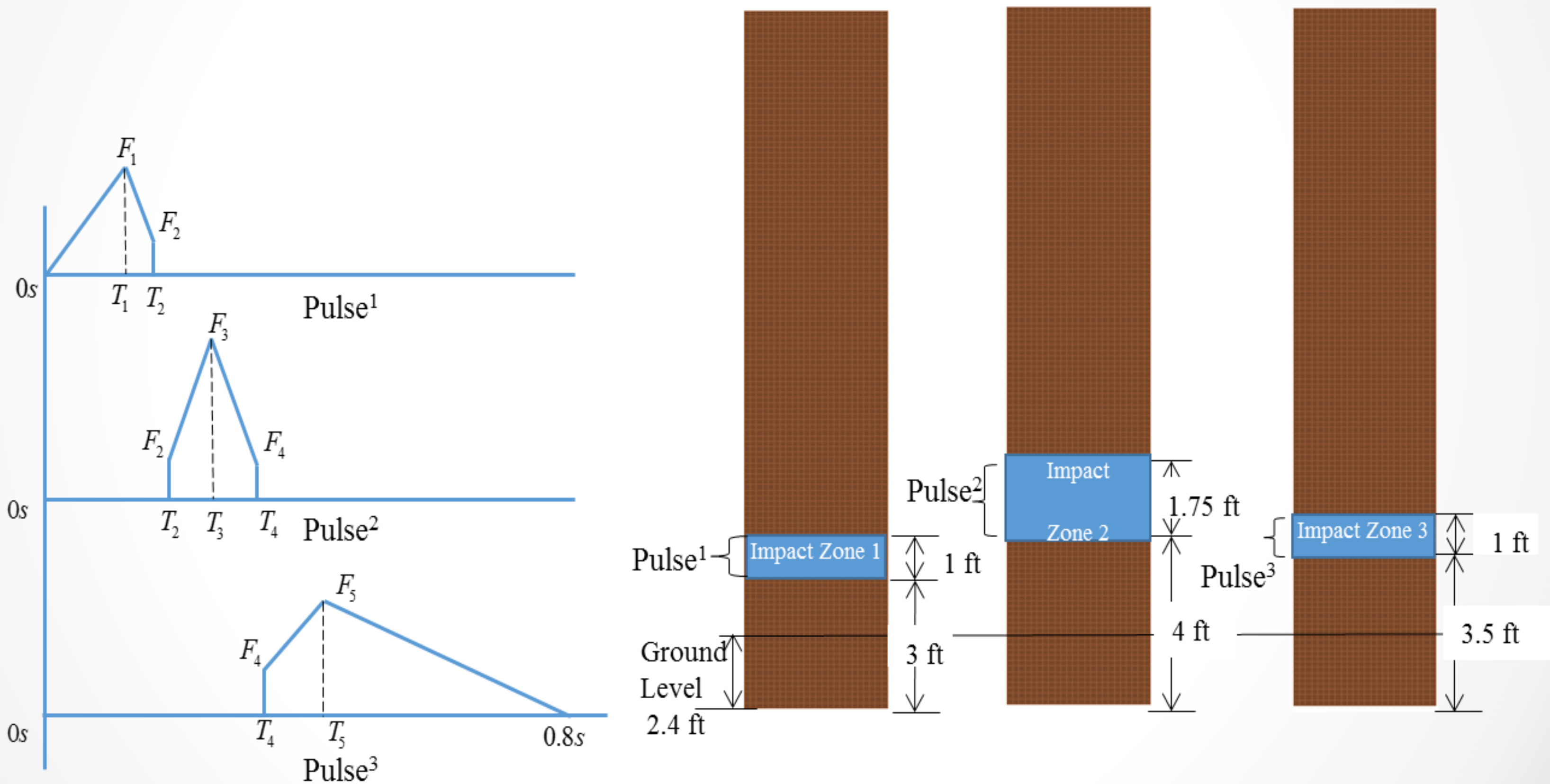


Contours of impact force distribution along the height of the pier for case P36_V50_M40 (unit: kips).

Heavy Vehicle Simulation

Modelling of Vehicular Impact Force

Points of Application of Pulse components



Application of impact pulse loading function of the pier.

Heavy Vehicle Simulation

Pulse Parameters Based on Nonlinear Regression

$$F_1(kips) = 109\,V^{0.52}\left(\frac{b}{36}\right)^{0.33}$$

$$F_2(kips) = 52\,V^{0.51}\left(\frac{b}{36}\right)^{-0.84}$$

$$F_3(kips) = 30\,V^{0.95}$$

$$F_4(kips) = 3\,V^{1.08}\left(\frac{b}{36}\right)^{-0.75}$$

$$F_5(kips) = 0.05\,V^{1.77}W^{0.61}\left(\frac{b}{36}\right)^{1.14}$$

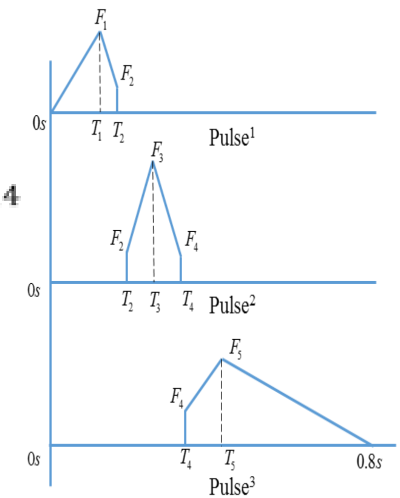
$$T_1(s) = 0.27\,V^{-0.86}$$

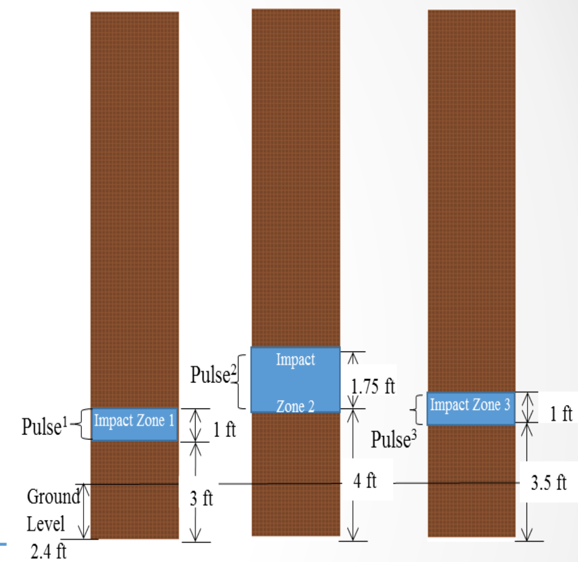
$$T_2(s) = 1.49\,V^{-1.09}\left(\frac{b}{36}\right)^{0.64}$$

$$T_3(s) = 1.04\,V^{-0.93}$$

$$T_4(s) = 2.96\,V^{-1.05}\left(\frac{b}{36}\right)^{-1.21}$$

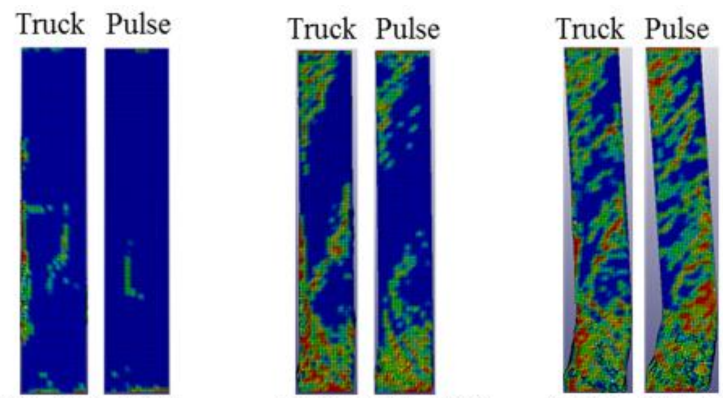
$$T_5(s) = 0.22$$



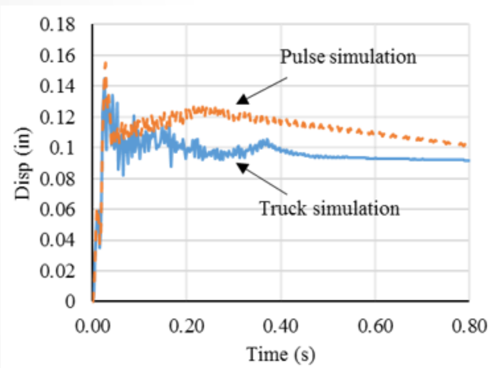


Heavy Vehicle Simulation

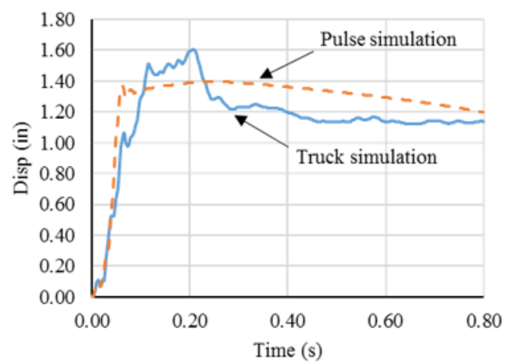
Truck Impact Versus Pulse Loading



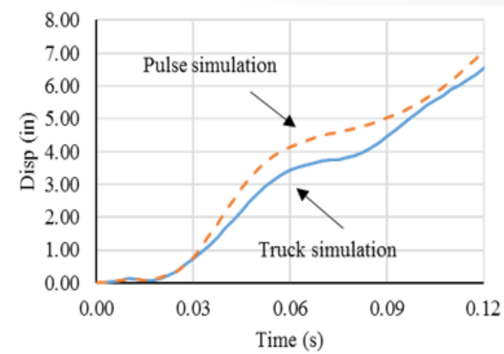
(a) P3_V60_W30 (b) P2_V50_W20 (c) P2_V60_W30



(a) Minor damage: P3_V60_W30.



(b) Moderate damage: P2_V50_W20.



(c) Severe damage: P2_V60_W30.

Performance-Based Design Approach

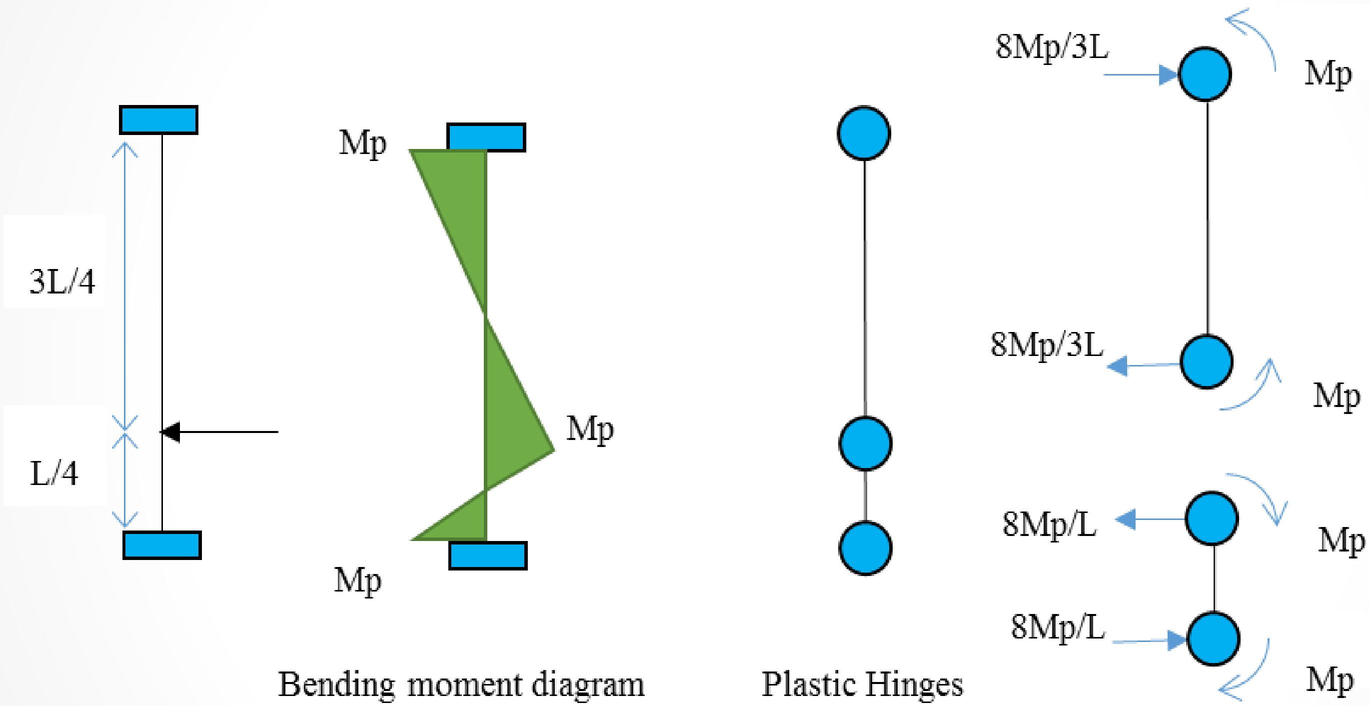
Heavy Vehicle Impacts

- Concept developed primarily in earthquake engineering.
- Performance-based design philosophy entails estimation of seismic demands in the system and its components and checking to see if they exceed the capacity associated with a required performance objective for a given hazard intensity level.
- Commonly accepted performance levels:
  - ❑ Immediate Occupancy (IO)
  - ❑ Collapse Prevention (CP)
- Only preliminary development in PBD for vehicular impacts.

Performance-Based Design Approach

Heavy Vehicle Impacts

Capacity Design of Bridge Piers

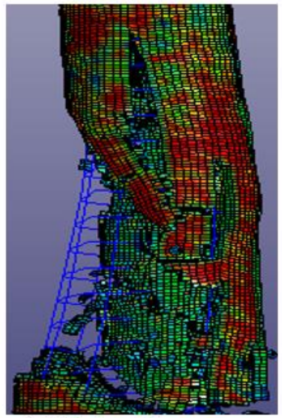


Capacity design is the process whereby plastic hinge mechanisms are promoted by providing over strength in shear at critical locations. *Plastic hinging is a more ductile mechanism than shear failure and can lead to increased collapse resistance.*

Performance-Based Design Approach

Heavy Vehicle Impacts

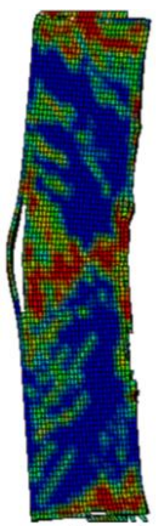
Shear Failure Versus Ductile Failure



(a) FE simulation.

(b) Texas I45 bridge accident 2014.

Shear failure of bridge piers: **Not Preferred**



(a) FE simulation.

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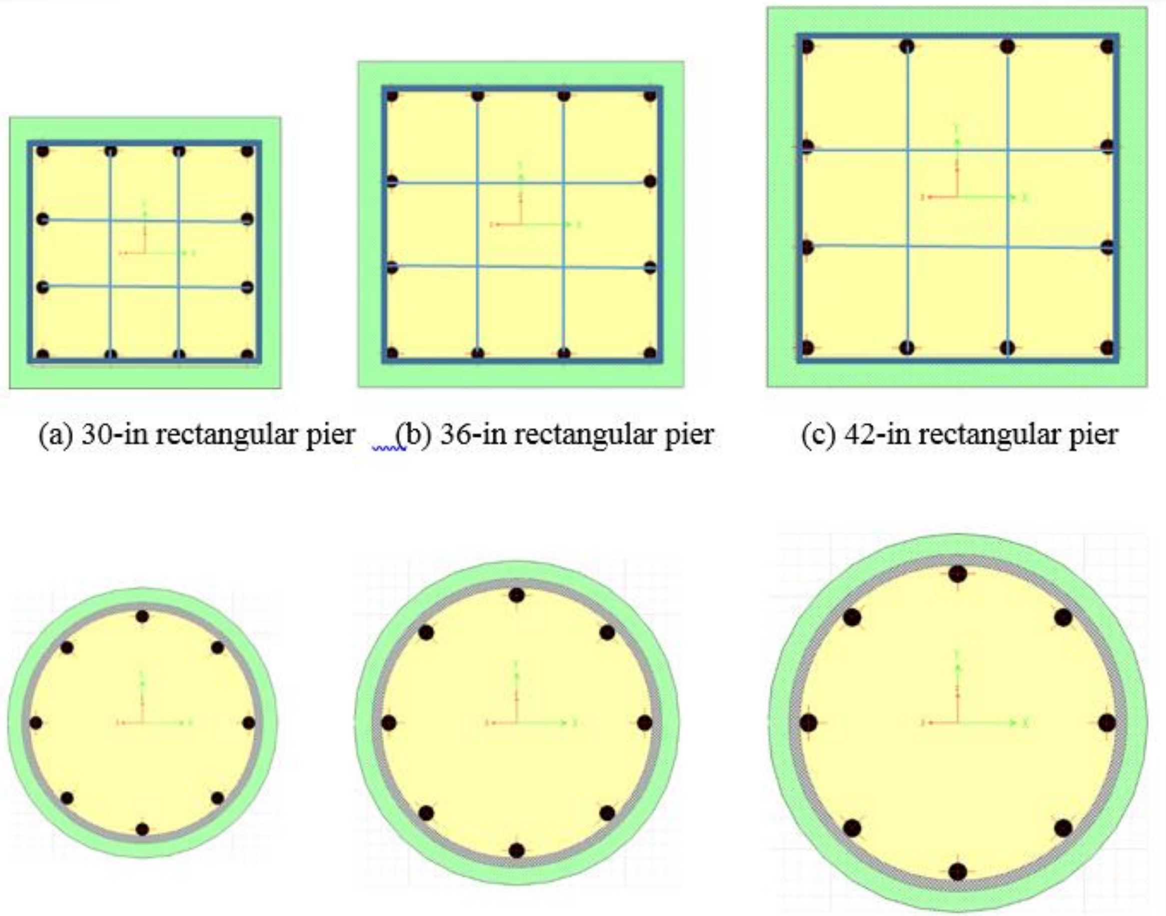
(b) Minnesota I90 bridge accident (2003).

Shear failure of bridge piers: **Preferred**

Capacity design reduces the occurrence of shear failure

Performance-Based Design Approach

Capacity Design of Bridge Piers



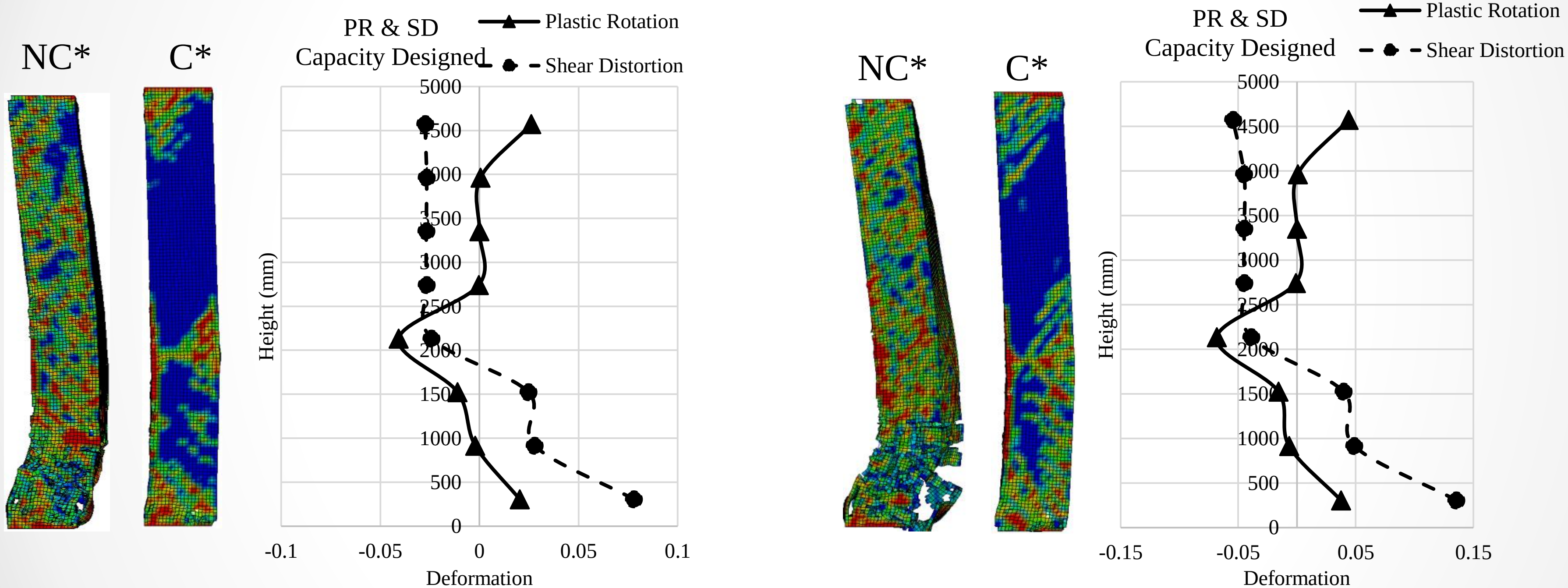
(a) 30-in rectangular pier (b) 36-in rectangular pier (c) 42-in rectangular pier

(d) 30-in circular pier (e) 36-in circular pier (f) 42-in circular pier

Performance-Based Design Approach

Heavy Vehicle Impacts

Plastic Rotation Versus Shear Distortion



(a) P30_V60_W40　　(b) P30_V70_W40

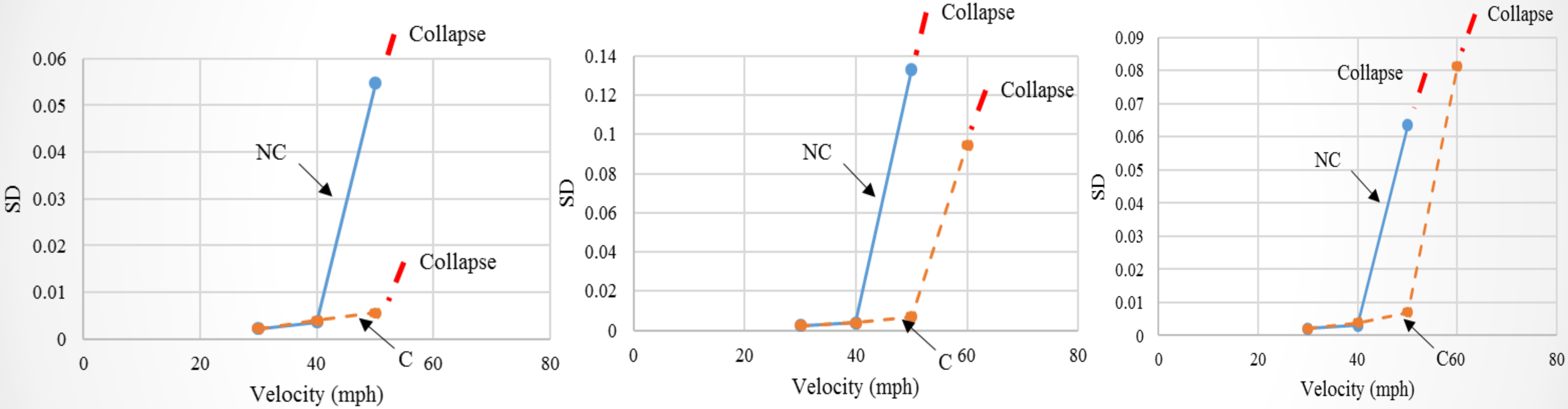
*NC – non capacity design, *C – capacity designed

Shear distortion and plastic rotation results for two selected cases.

Performance-Based Design Approach

Heavy Vehicle Impacts

Capacity Versus Non-Capacity Designed Piers



(a) 40-Ton truck.

(b) 30-Ton truck.

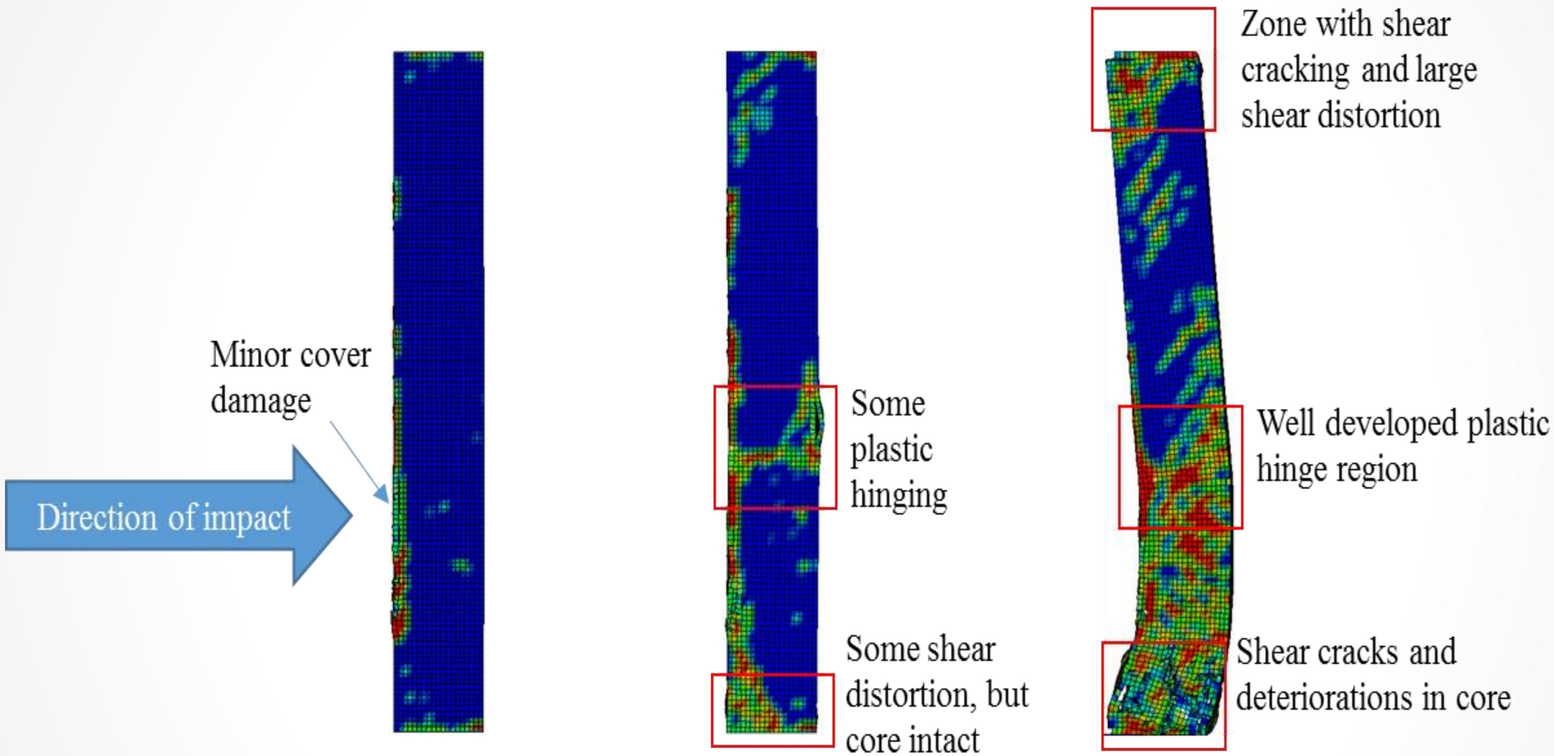
(c) 20-Ton truck.

Example: 30 inch rectangular pier

<u>Similar trends are observed in other cases</u>

Performance-Based Design Approach

Design Framework



(a) Minor damage. (b) Moderate damage. (c) Severe damage.

Examples of the various modes of failure by the heavy truck impact

Performance-Based Design Approach

Design Framework

Impacts by Tractor-Semitrailer

Performance levels, corresponding damage state, shear distortion or plastic rotation **(bumper/engine)**.

Performance Level	**Damage State**	**Max (D1/C, D2/C)**	**Max(SD,PR)**
Immediate use	Minor	[0, 2.00]	[0, 0.010]
Damage control	Moderate	[0, 2.75]	[0.010, 0.075]
Near Collapse	Severe	[2.00, 2.75]	[0.075, 0.150]

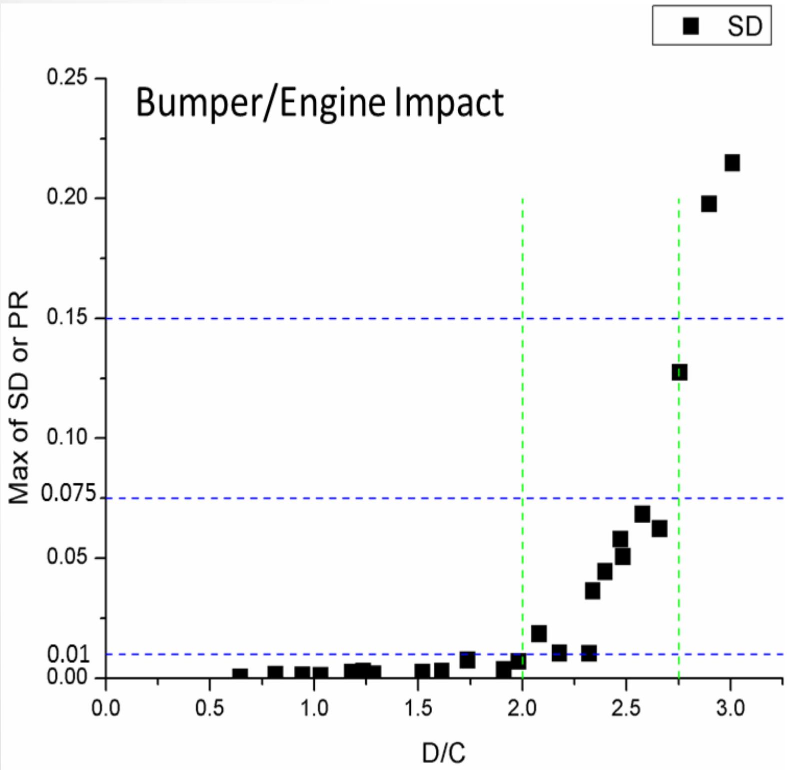
Performance levels, corresponding damage state, shear distortion or plastic rotation (**trailer impact**).

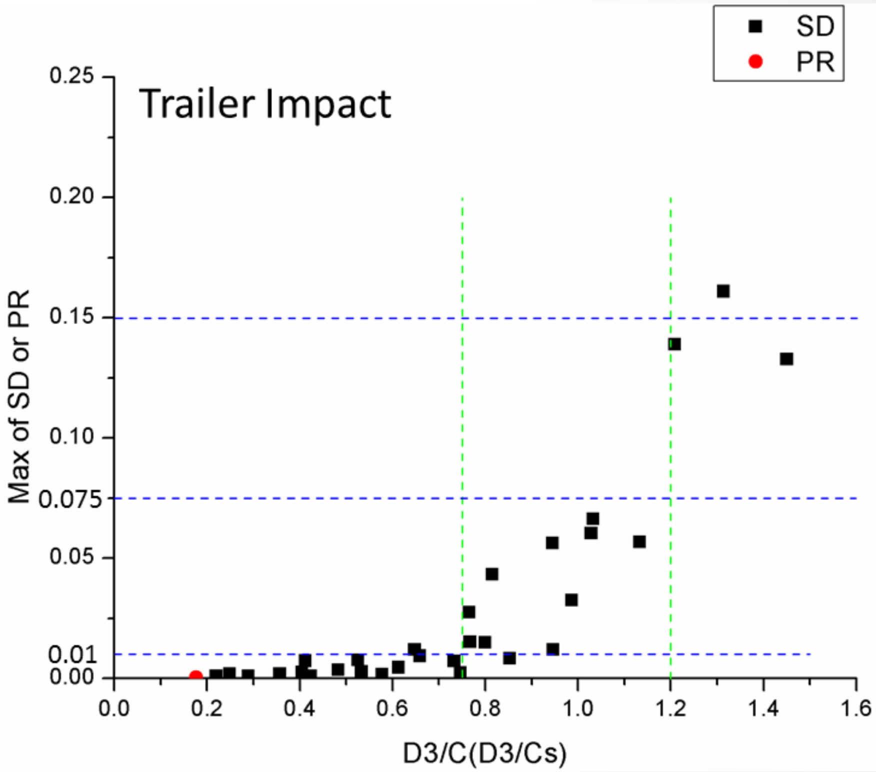
Performance Level	**Damage State**	**D3/C(D3/Cs)**	**Max(SD,PR)**
Immediate use	Minor	[0, 0.75]	[0, 0.010]
Damage control	Moderate	[0.75, 1.20]	[0.010, 0.075]
Near collapse	Severe	[1.20, 1.60]	[0.075, 0.150]

Performance-Based Design Approach

Design Framework

Impacts by Tractor-Semitrailer





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Performance-Based Design Approach

Design Framework

Proposed Performance-Based Design Framework

- Immediate Use (Minor damage): (larger of D1/C or D2/C) < 2.00 for bumper/engine impact and D3/C < 0.75 for trailer impact.
- Damage Control (Moderate damage): (larger of D1/C or D2/C) < 2.75 for bumper/engine impact and 0.75 ≤ D3/Cs < 1.2 for trailer impact.
- Near Collapse (Severe damage): 2.00 ≤ (larger of D1/C or D2/C) < 2.75 for bumper/engine impact and 1.2 ≤ D3/Cs < 1.6 for trailer impact.

Note:

- *D1, D2, and D3 are the base shear demands from bumper, engine, and trailer impact.*
- *C is the shear capacity of the full section (concrete + reinforcement);*
- *Cs is the shear capacity of the steel stirrups.*

Performance-Based Design Procedure

1. Determine design speed and weight of the truck.
2. Determine the desired performance level
   - ✓ Immediate Use (Minor damage)
   - ✓ Damage Control (Moderate damage)
   - ✓ Near Collapse (Severe Damage)
3. Choose a trial pier size.
4. Find elastic base shear demands (D1, D2, and D3) using the pulse model
5. Determine required capacity C = D2/(D/C) ratio. Calculate the required Mp = 5ft * C/2. Select the longitudinal flexural reinforcement to satisfy Mp.
6. Select a stirrup configuration to satisfy C and compute the capacity of the steel stirrups, Cs_{design}. Compute the actual shear capacity C_{design} and moment capacity M_{design}.
7. Use the actual capacity to check if the plastic mechanism is still preferred over shear failure. Use M_{design} in the 3 hinge capacity design configuration to get the shear value, and make sure the shear value is less than the shear capacity (C_{design}). If not, either decrease moment capacity if overdesigned (but not less than Mp) or increase the shear capacity, C_{design}.
8. Calculate the larger of $D1/C_{design}$ and $D2/C_{design}$, associated with bumper and engine impact, respectively, and $D3/C_{design}$ or $D3/Cs_{design}$ for the trailer impact.

Performance-Based Design Procedure

8. Calculate the larger of $D1/C_{design}$ and $D2/C_{design}$, associated with bumper and engine impact, respectively, and $D3/C_{design}$ or $D3/Cs_{design}$ for the trailer impact.

9. Check to see if the computed demand to capacity ratios corresponds to the desired damage level. If not, go back and change the pier size or desired performance level:

   - Immediate Use (Minor damage): (larger of $D1/C_{design}$ or $D2/C_{design}$) < 2.00 for bumper/engine impact and $D3/C_{design}$ < 0.75 for trailer impact.
   - Damage Control (Moderate damage): (larger of $D1/C_{design}$ or $D2/C_{design}$) < 2.75 for bumper/engine impact and $0.75 \leq D3/C_{design} < 1.20$ for trailer impact.
   - Damage Control (Severe damage): 2.00 ≤ (larger of $D1/C_{design}$ or $D2/C_{design}$) < 2.75 for bumper/engine impact and $1.20 \leq D3/Cs_{design} < 1.60$ for trailer impact.

Performance-Based Design Procedure

Validation of the Proposed Framework

Selected cases for validation of proposed method.

Case	Truck Characteristics	Column ID	$D2/C_{design}$	$D3/C_{design}$ ($D3/Cs_{design}$)	Predicted Damage Level	Max (SD, PR)	Actual Damage Level
1	50mph_80kips	1	1.40	0.64	Minor	0.003	Minor
2	60mph_80kips	3	2.22	1.31	Severe	0.161	Severe
3	60mph_40kips	2	2.25	0.78	Moderate	0.030	Moderate
4	60mph_60kips	3	2.22	1.10	Moderate	0.059	Moderate
5	40mph_80kips	3	1.85	0.55	Minor	0.003	Minor

SUMMARY & CONCLUSIONS

- Modeling of concrete piers in LS-DYNA was done using the Continuous Surface Cap Model (CSCM). Based on impact test data available in the literature, input parameters for this model were calibrated so that both the damage modes and force / displacement time-history from numerical simulation match well with those from the test.

- A large scale model of a three-column pier bent was constructed at the Federal Outdoor Laboratory (FOIL) located at the FHWA center in McLean, VA. Two outer piers of the model were impacted by a 2-ton pendulum at approximately 20 mph. Data obtained from this test were used to validate both the material model as well as damage modes observed during numerical simulations.

SUMMARY & CONCLUSIONS

- Based on extensive simulations of collision between a truck model and a calibrated model of a pier, a three-triangular pulse model was proposed for simulating impact by a tractor-trailer on bridge piers. The accuracy of this pulse model was demonstrated through comparison between results using truck impact and pulse application.

- A performance based approach for the design of bridge piers was developed by quantifying damage in terms of plastic rotation and shear distortion and the performance in terms of demand / capacity (D/C) ratios.

- The approach is simple enough for design office use and proposes three levels of performance immediate use, damage control and near collapse. Applicability of the proposed design approach was demonstrated through several cases that were not included in the calibration of the proposed design method.

LIMITATIONS & FUTURE WORK

- The impact on bridge piers is affected by the characteristics of the cargo. In this research, the cargo consisted of sand ballast. Further work is needed to investigate the effect of other cargo types based on data from actual trucks that impacted bridge piers. This work may result in further adjustment of the parameters of the pulse model proposed in this research.
- The pulse equations were derived using a single type of truck that had given bumper characteristics and engine weight. Therefore, in order to generalize the proposed pulse equations, additional studies should be conducted with a variety of truck designs to confirm that they are reasonably representative of the heavy tractor semi-trailer truck population in the US.
- Although the large-scale pendulum test provided valuable information, a full-scale test using a tractor-trailer is needed to further verify damage modes and the proposed performance based approach.

Thank you Very Much.