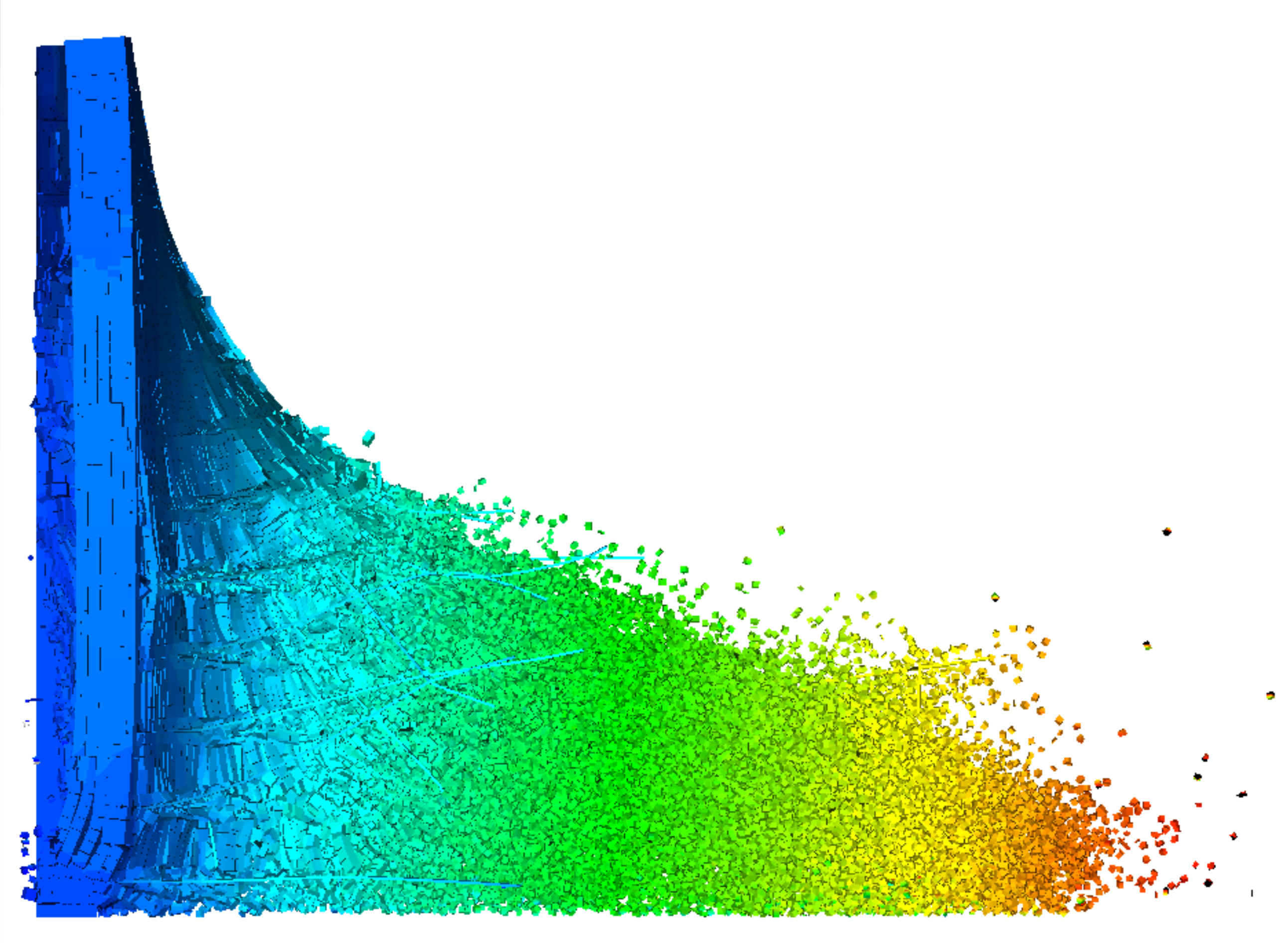
Simulation-Based Design Of Reinforced Concrete Walls To Prevent Sympathetic Detonation In Explosive Facilities



2018 IESSE- Structural Effects II- Methods and Applications (20699)

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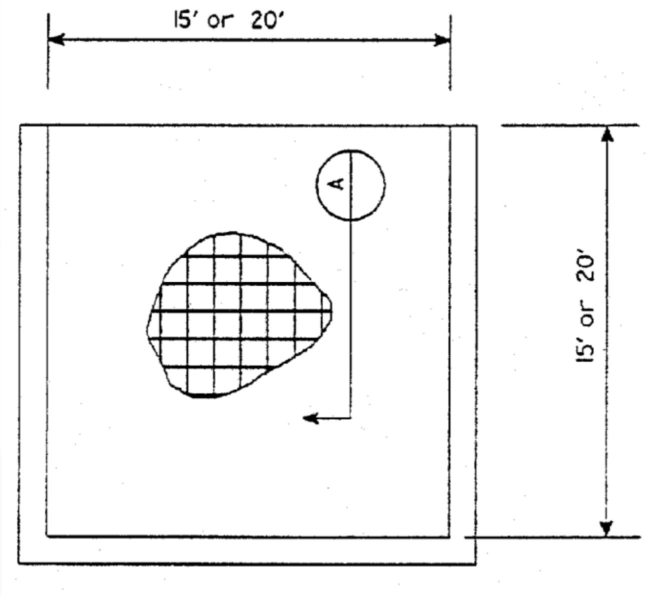
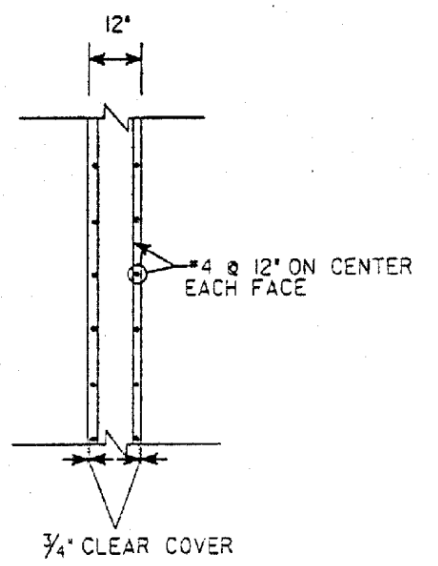
Presentation Outline

1- Introduction

1.1 Background

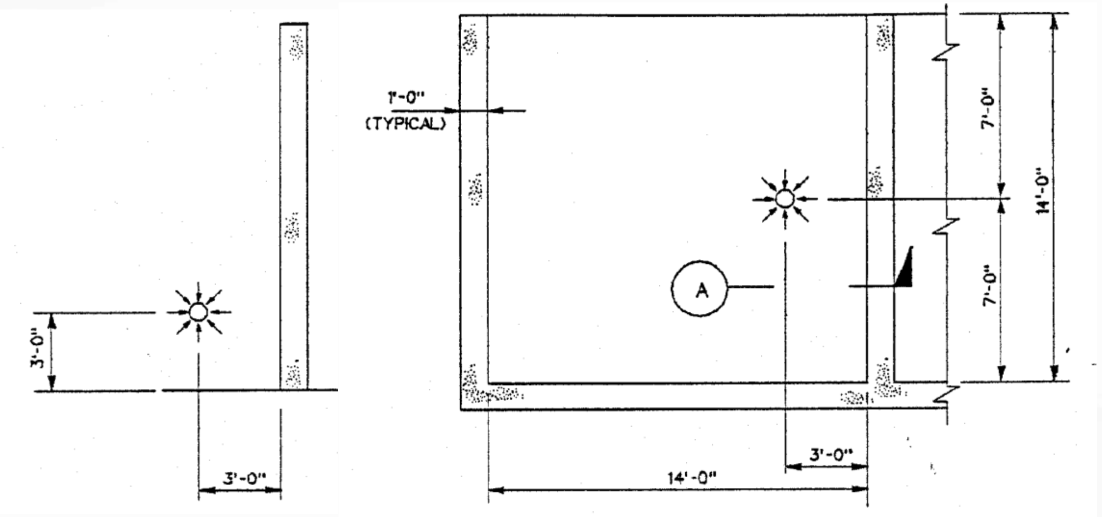
- In DOD 6055.9-STD, a **dividing wall** is defined as a "wall designed to prevent, control, or delay propagation of an explosion between quantities of explosives on opposite sides of the wall."
- DOD 6055.09M references UFC 3-340-02 for the design of **"dividing walls or barriers"** to prevent propagation of explosions using separation by barriers.
- DDESB-KT Memorandum (2003) provided an Updated Guidance for **Substantial Dividing Walls (SDW)** including limits of application, specifics of RC wall construction and maximum NEWs for various sensitivity groups.

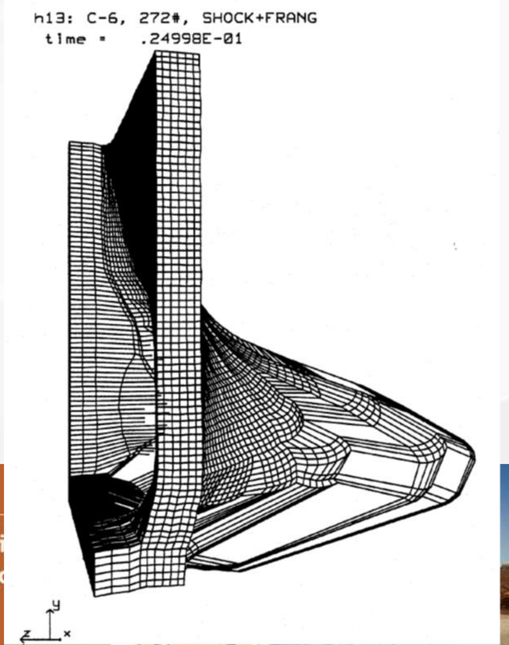




1.2 Previous Research Work

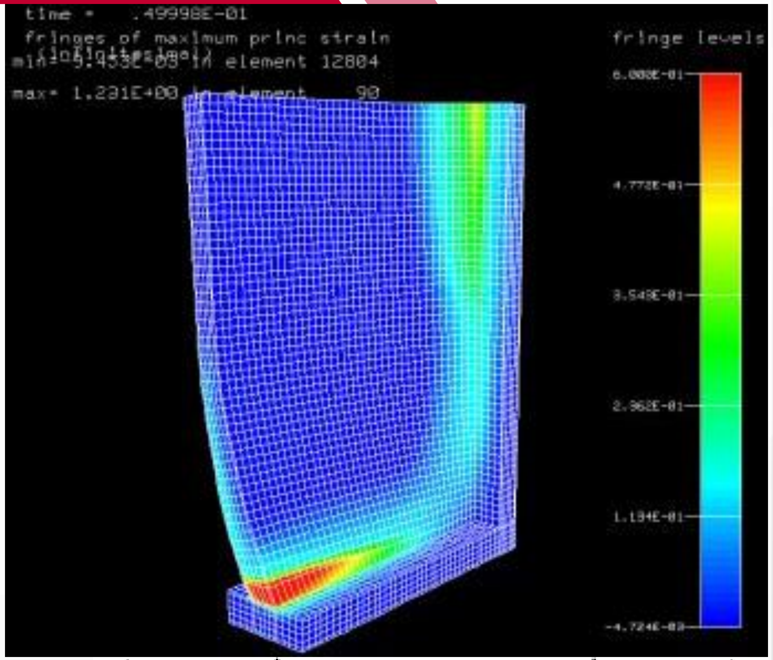
- In 1994, Zehrt and Acosta utilized DYNA3D Hydrocode modeling to simulate Substantial Dividing Wall (SDW) response to close-range blast effects.
- Despite the limitations of the adopted FEM approach they concluded that the predicted fragment velocities and extents of wall damage agree closely with the actual test data.

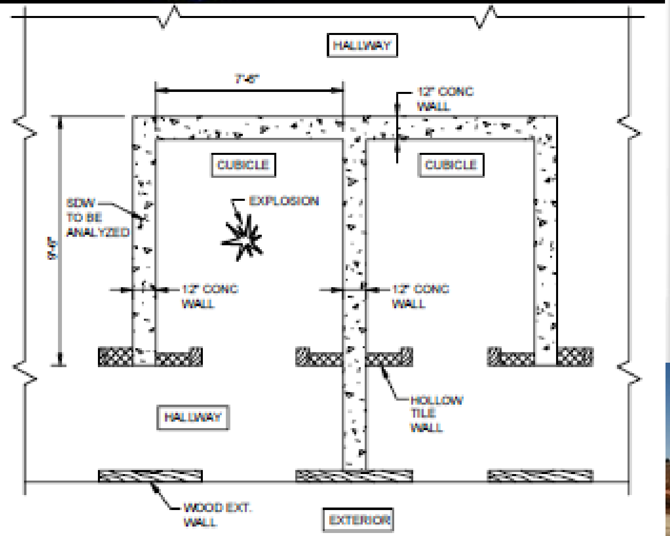




1.2 Previous Research Work

- In 1998, Bogozian and Zehrt utilized DYNA3D Hydrocode modeling to simulate Substantial Dividing Wall (SDW) response to close-range blast effects.
- Their work highlighted the importance of adequately considering the gas phase of partially confined detonations on the integrity of SDWs.
- Their FEM models over-predicted wall responses by an order of magnitude due to uncertainties of blast loading and FEM modeling.





1.3 Current Research- Objectives

- Investigate the adequacy of a design-oriented analytical approach that can be used to design new and/or evaluate Reinforced Concrete (RC) walls used to prevent propagation of detonation in explosive facilities.
- Illustrate the applicability of the approach to compute the blast rating of sample RC walls of specific dimensions, material properties, and boundary conditions.

1.3 Current Research- Methodology

- The current study adopted a robust numerical technique, Applied Element Method (AEM), to simulate the dynamic responses and damage mechanisms of Reinforced Concrete (RC) walls exposed to close-range blast effects.
- All study analytical models were developed and executed using Extreme Loading for Structure (ELS) software by Applied Science International (ASI) which incorporates the AEM technique.

1.3 Current Research- Methodology

- A Validation case was developed using information obtained from a published research paper by Zehrt and Acosta to verify the adequacy of the ELS software to simulate RC wall response (i.e. damage and fragmentation) when subjected to close-range blast environment.
- Once validated, ELS models were developed to investigate three other cases involving RC walls with varying thicknesses and exposed to blast from varying charge weights.

2- Study Parameters

2.1 Investigated Cases

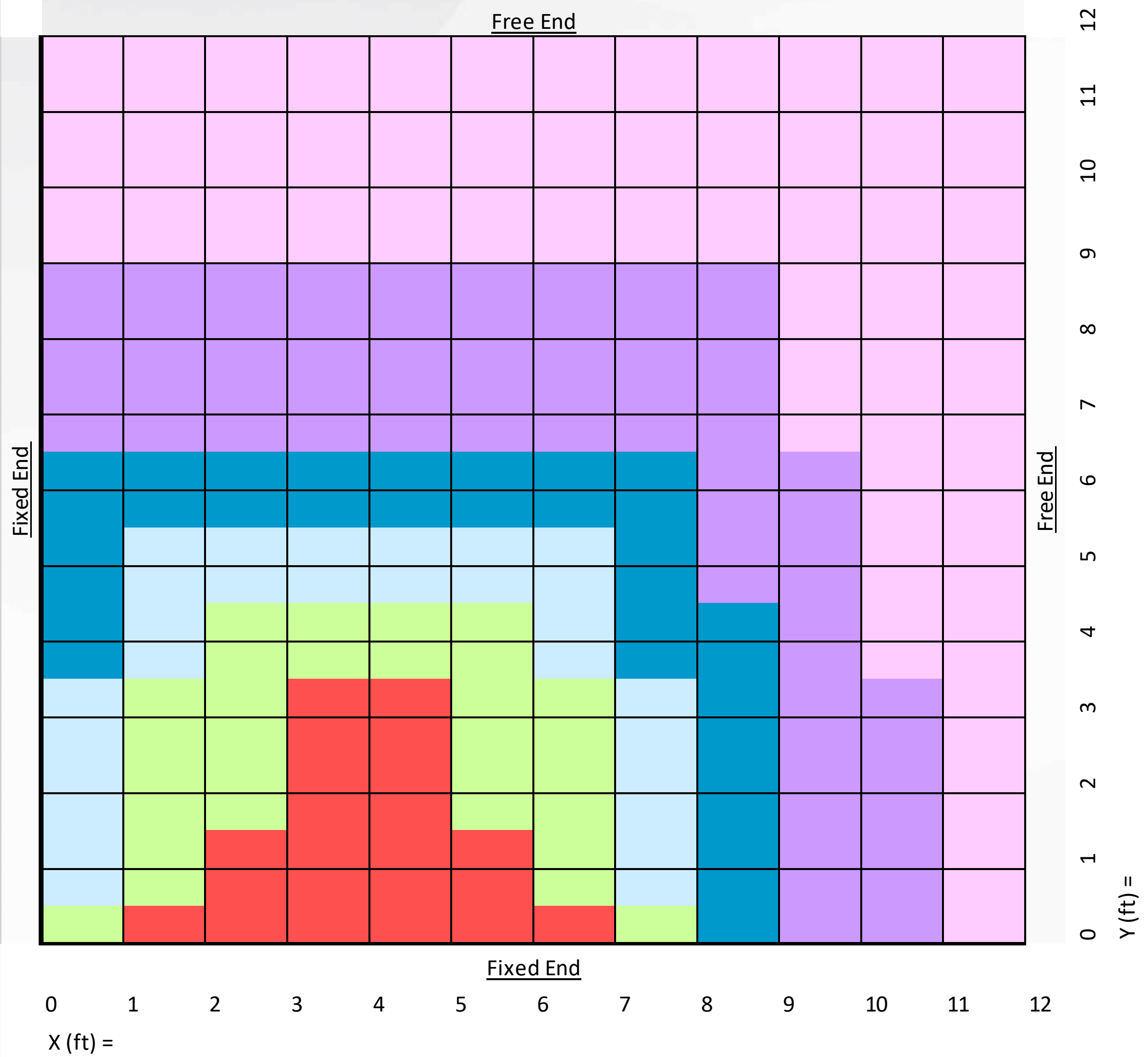
Validation Case
RC Substantial Dividing Wall
12 ft x 12 ft x 12 in
#4 @ 12 in Each way, Each Face
Horiz Rebar on the Outside
3/4 in Clear Cover to the Horiz Rebar
2 Adjacent Sides Fixed
3000 psi Concrete
40000 psi Rebar
272 lbs @ 2.5 ft from Wall and Floor

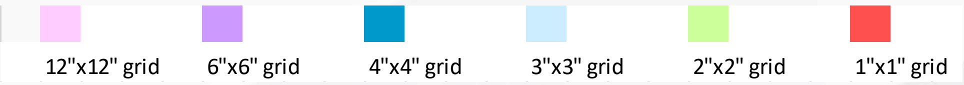
Case-1
RC Substantial Dividing Wall
12 ft x 12 ft x 12 in
#4 @ 12 in Each way, Each Face
Horiz Rebar on the Outside
3/4 in Clear Cover to the Horiz Rebar
2 Adjacent Sides Fixed
4000 psi Concrete
60000 psi Rebar
615 lbs @ 3.0 ft from Wall and Floor

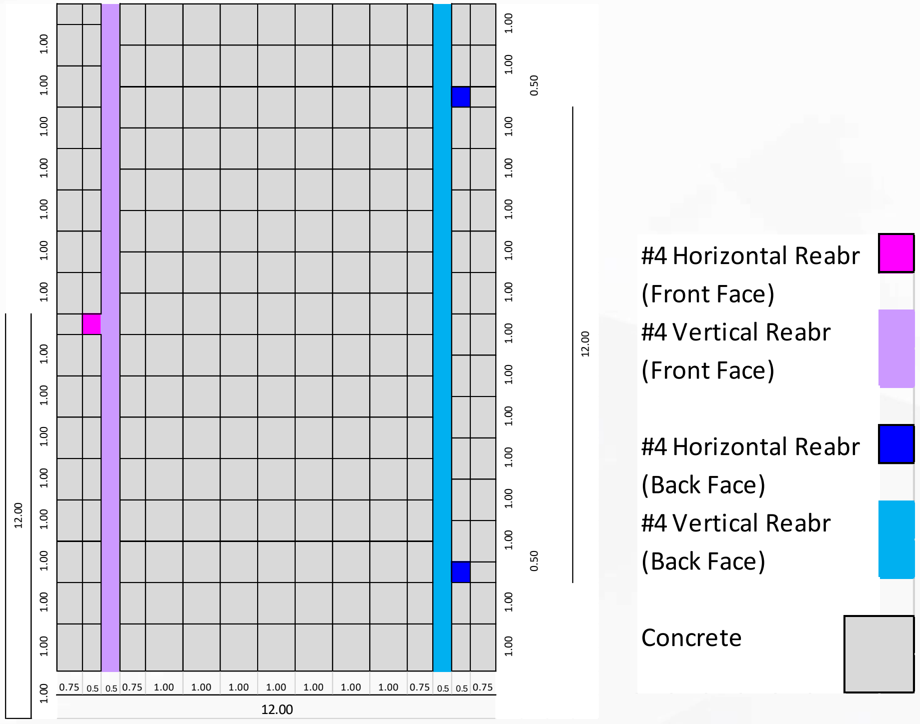
Case-2
RC Substantial Dividing Wall
12 ft x 12 ft x 10 in
#4 @ 12 in Each way, Each Face
Horiz Rebar on the Outside
3/4 in Clear Cover to the Horiz Rebar
2 Adjacent Sides Fixed
4000 psi Concrete
60000 psi Rebar
420 lbs @ 3.0 ft from Wall and Floor

Case-3
RC Substantial Dividing Wall
12 ft x 12 ft x 8 in
#4 @ 12 in Each way, Each Face
Horiz Rebar on the Outside
3/4 in Clear Cover to the Horiz Rebar
2 Adjacent Sides Fixed
4000 psi Concrete
60000 psi Rebar
270 lbs @ 3.0 ft from Wall and Floor

2.2 Wall Configuration- Discretization

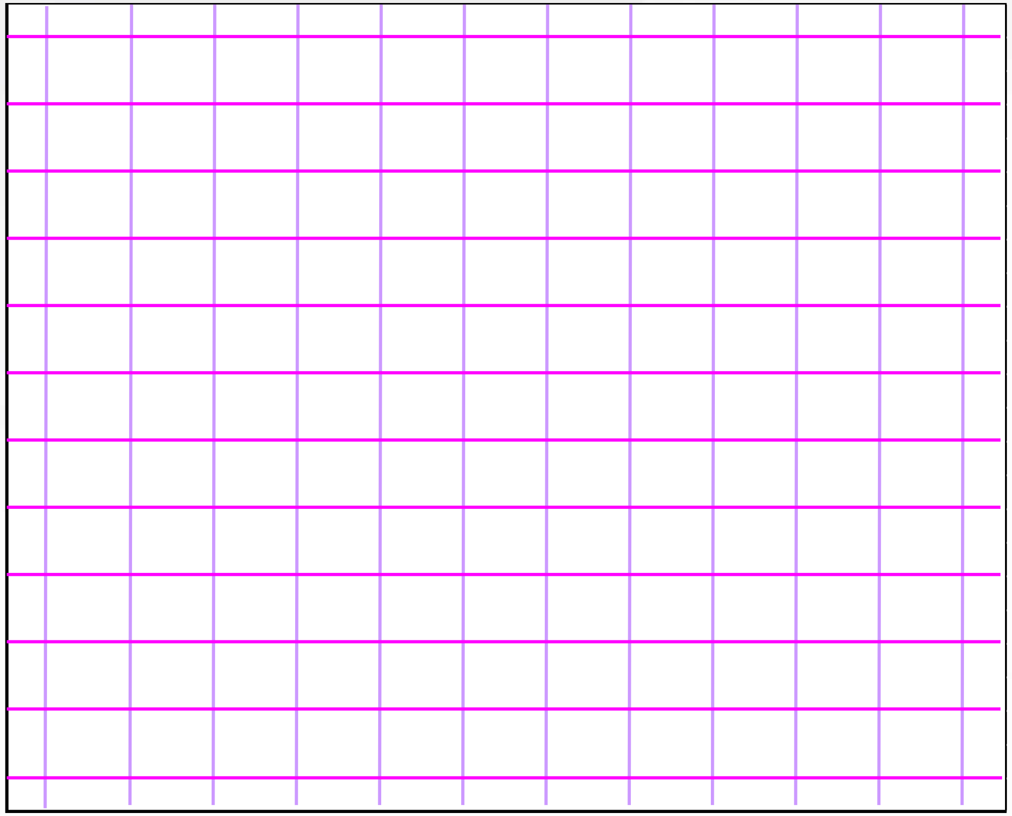




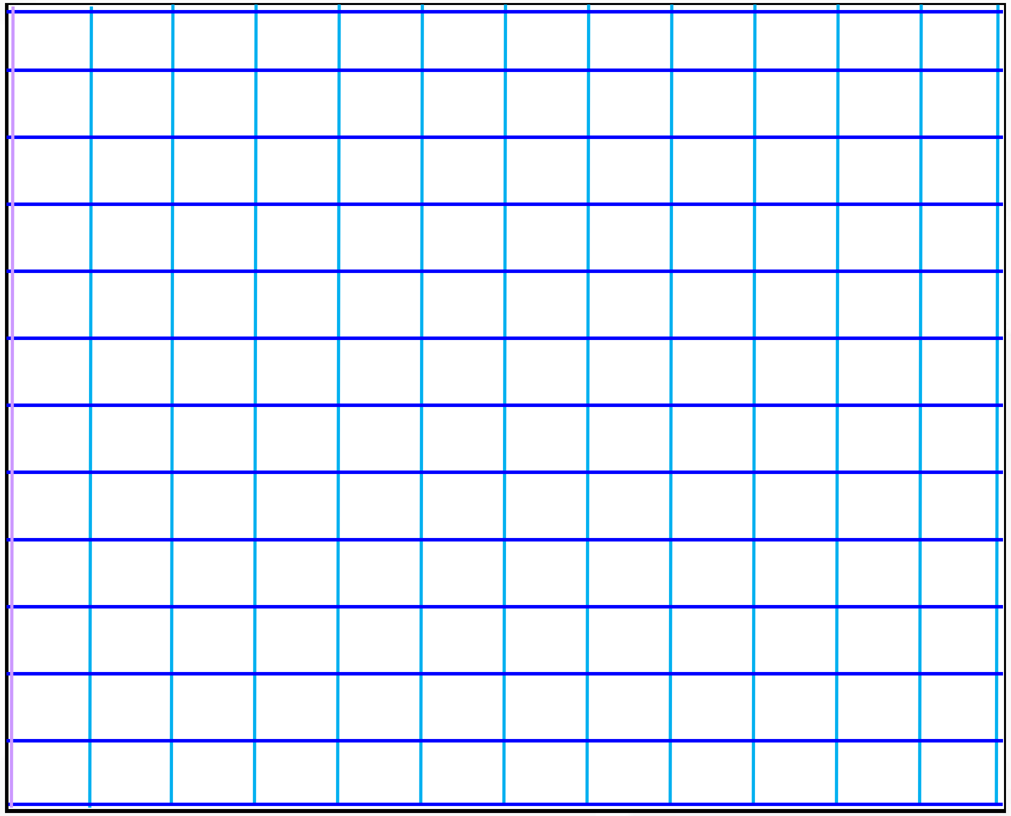


Simulation-Based Design Of Reinforced Concrete Walls To Prevent Sympathetic Detonation In Explosive Facilities

2.2 Wall Configuration- Reinforcement

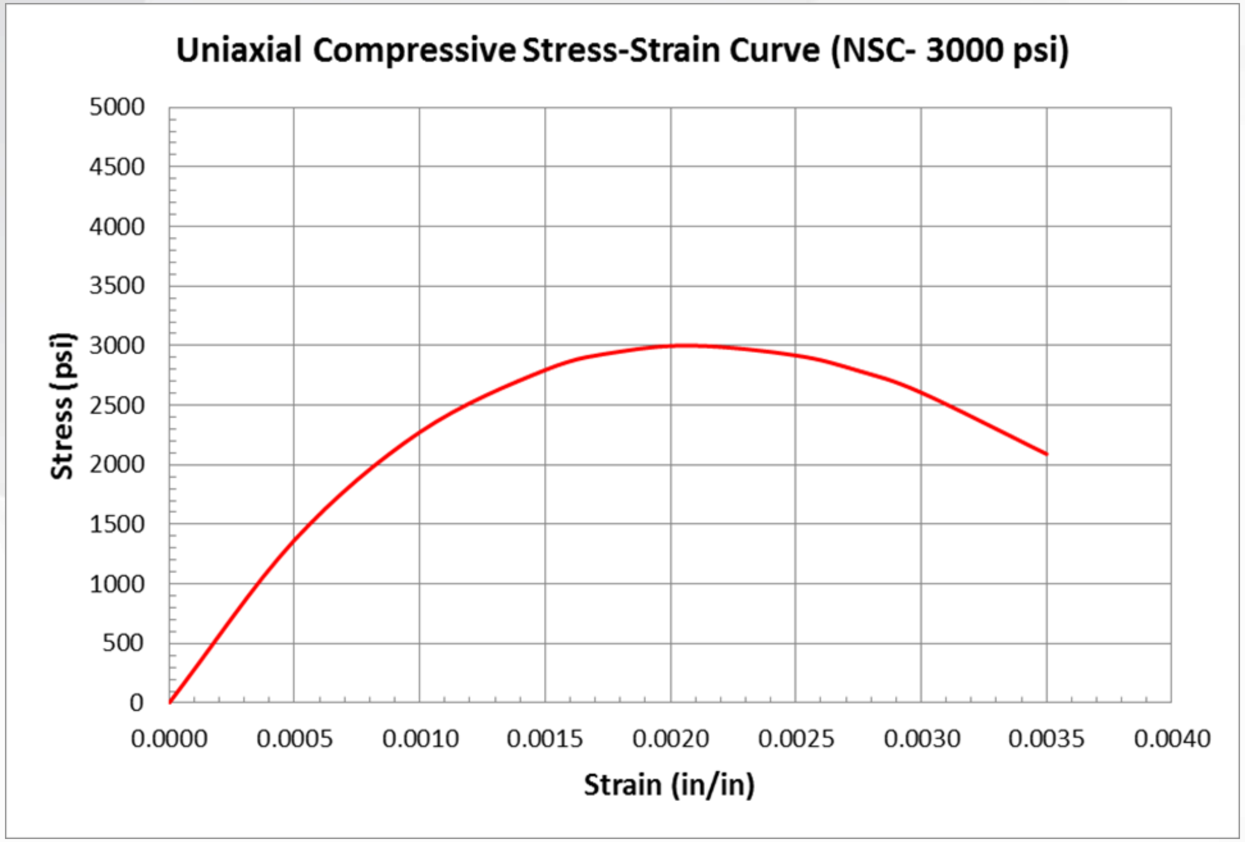


Front Face Rebar (#4 @ 12” EW)

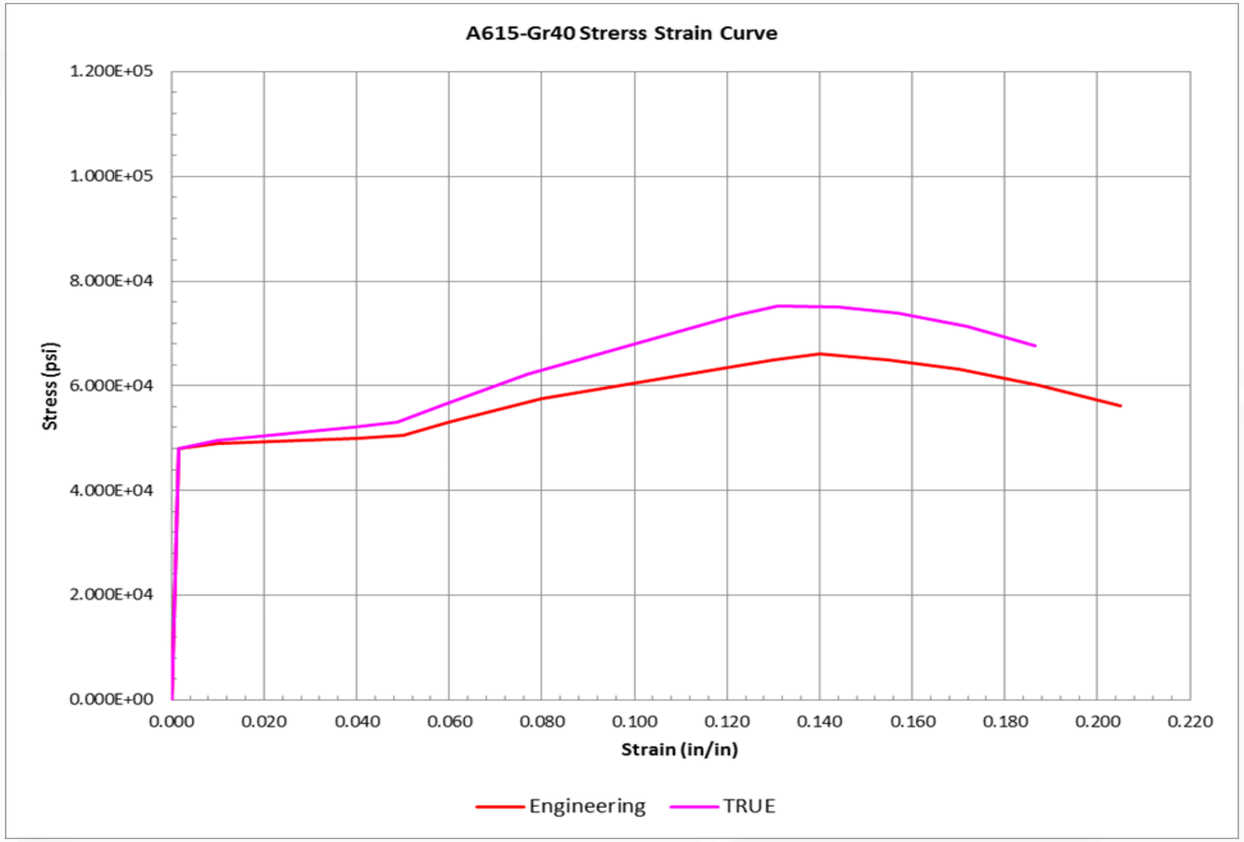


Back Face Rebar (#4 @ 12” EW)

2.3 Material Properties- Validation Case

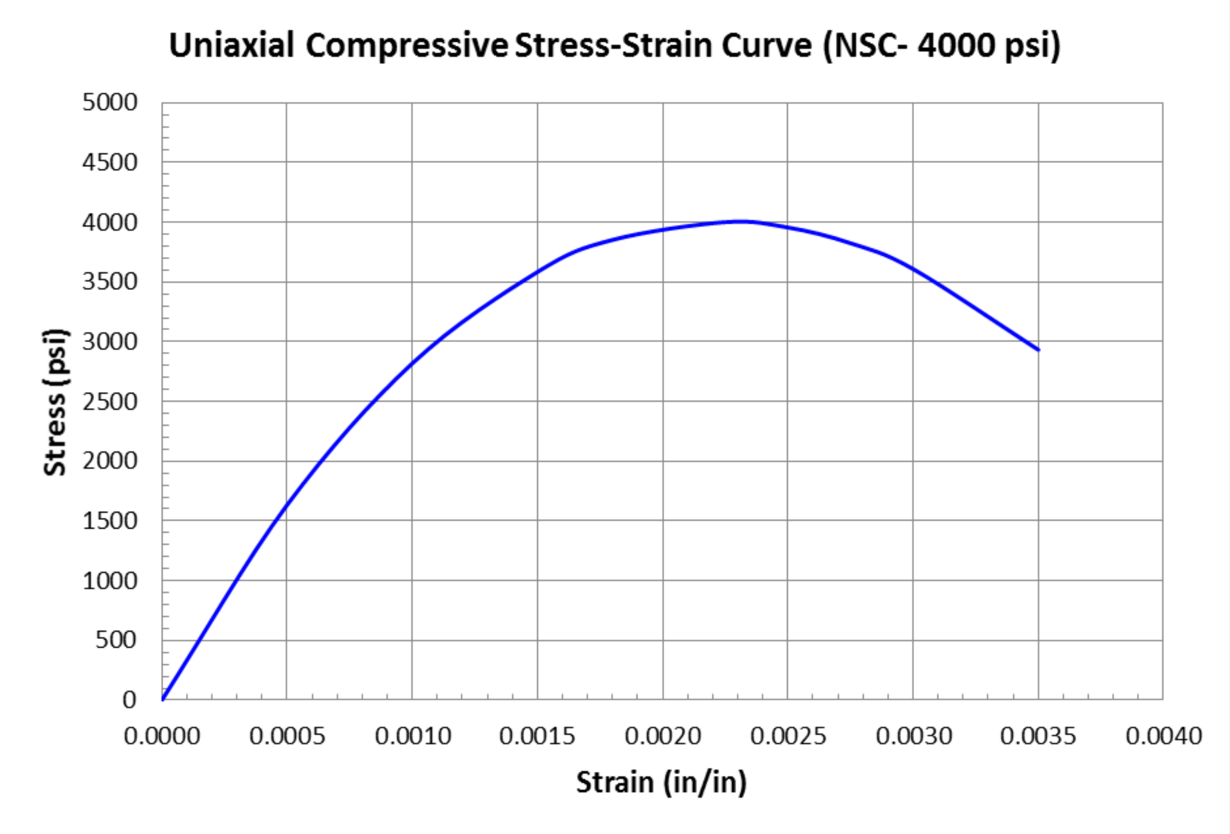


Stress-Strain Curve (Concrete)

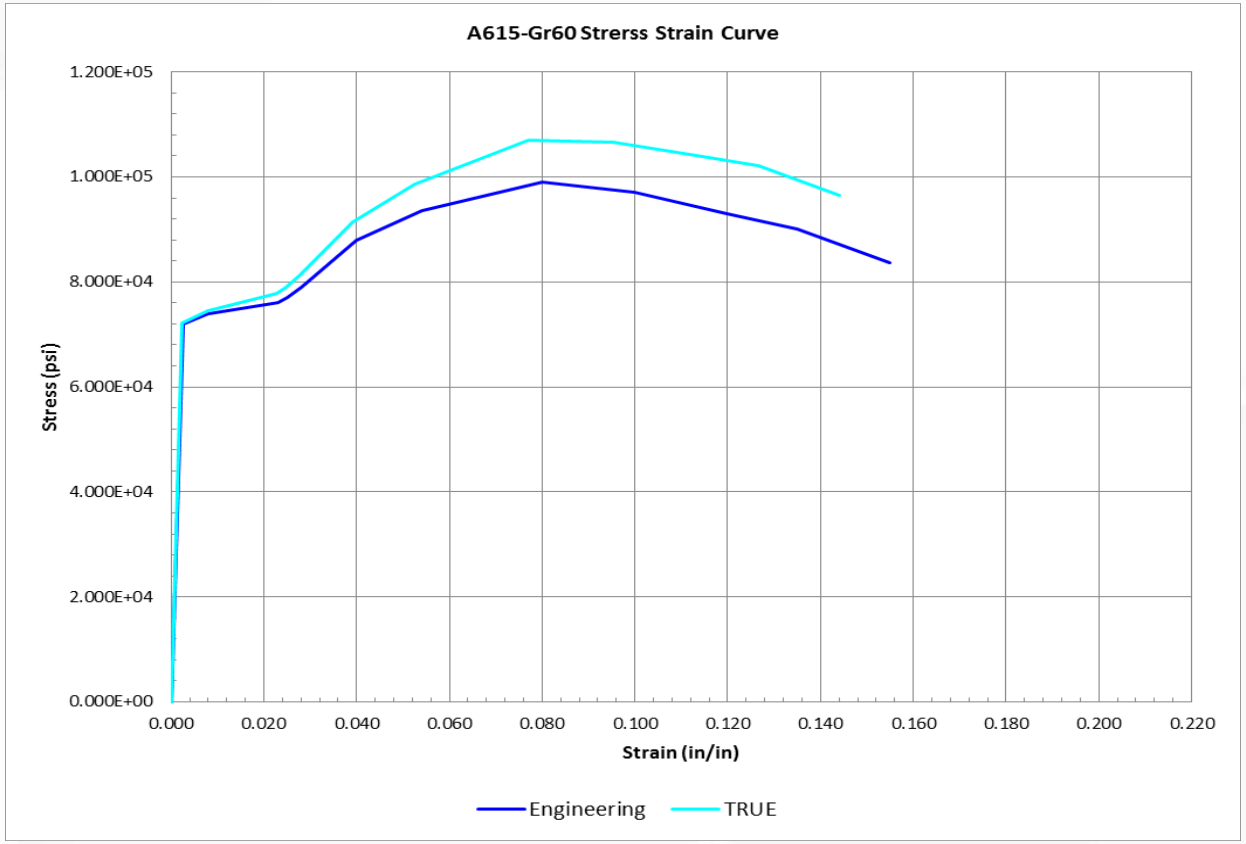


Stress-Strain Curve (Reinf. Steel)

2.4 Material Properties- Other Cases



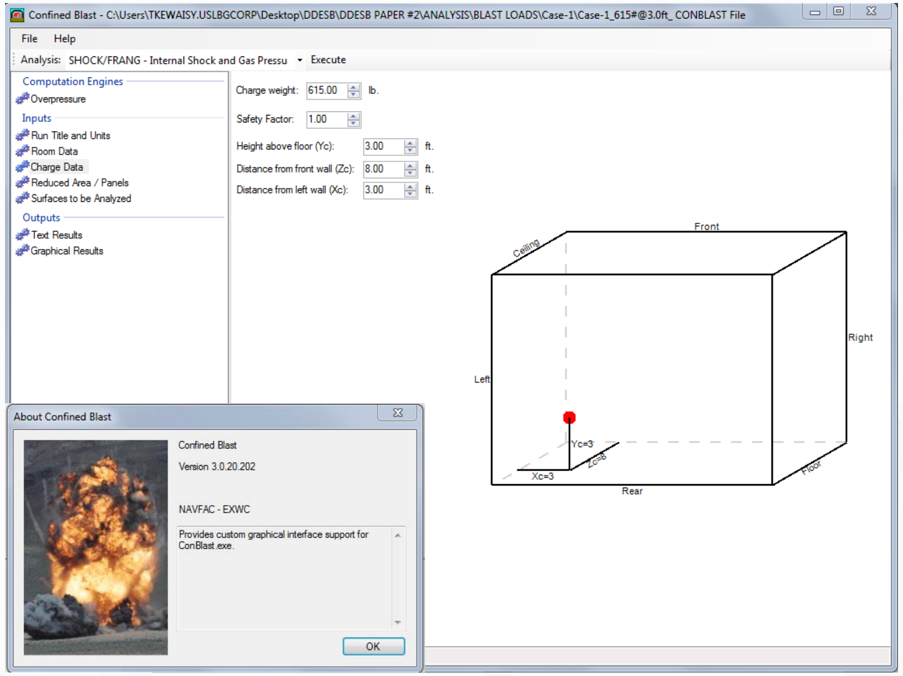
Stress-Strain Curve (Concrete)

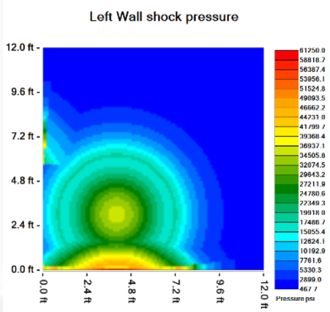


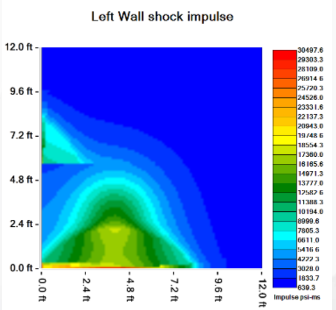
Stress-Strain Curve (Reinf. Steel)

2.5 Blast Loads

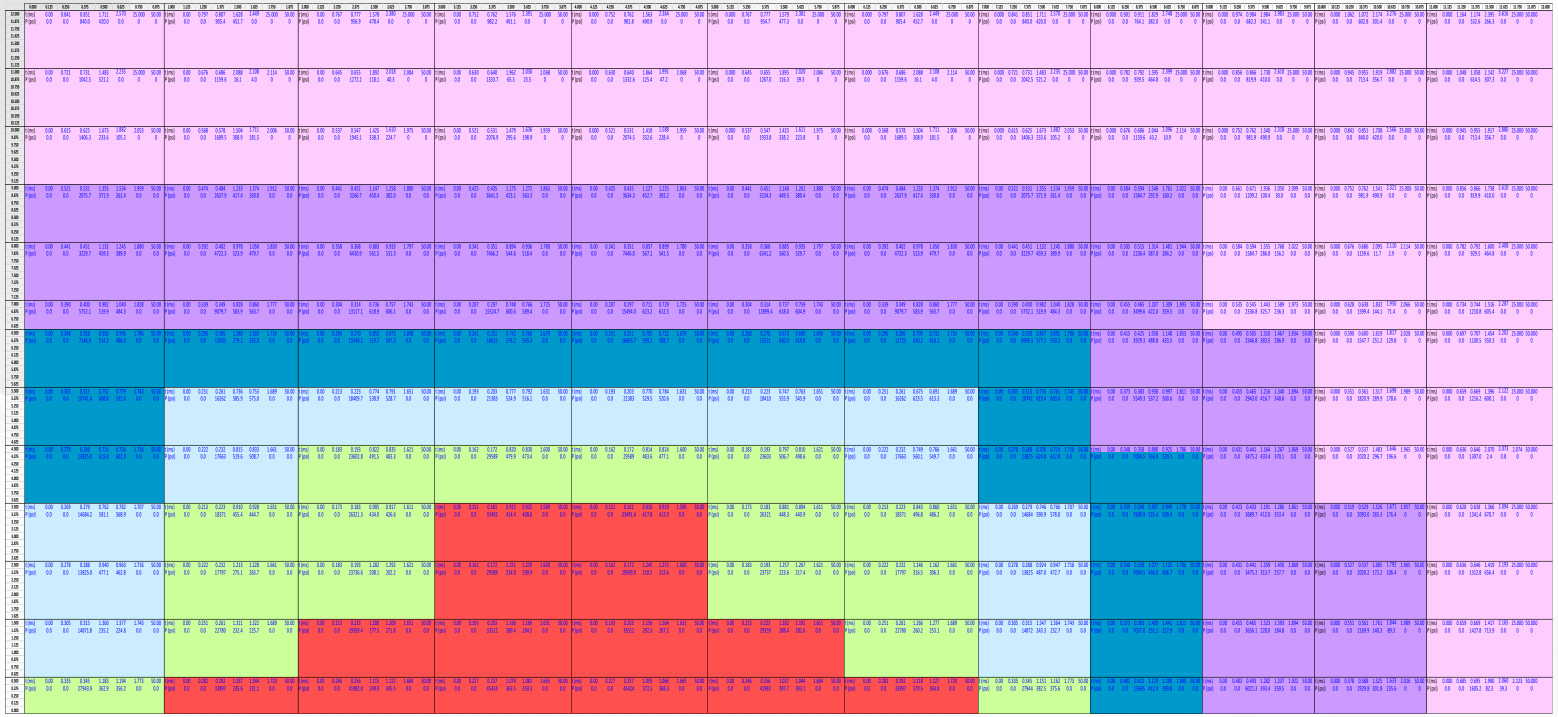
- **ConBlast (Confined Blast)** is used to Model and Compute Confined/ Partially Confined Blast Environment using SHOCK & FRANG Programs.
- For each investigated case, the **Blast Pressure Time Histories** (including Shock & Gas Phases) were computed at various target locations on surface of the RC Wall.



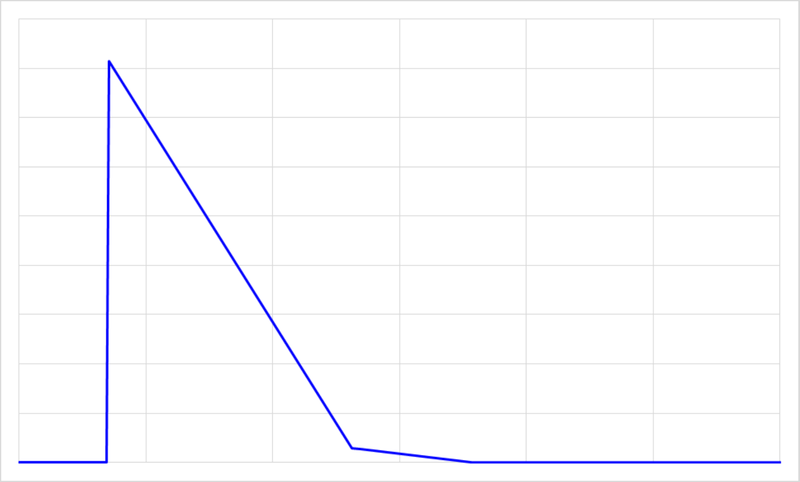




2.5 Blast Loads

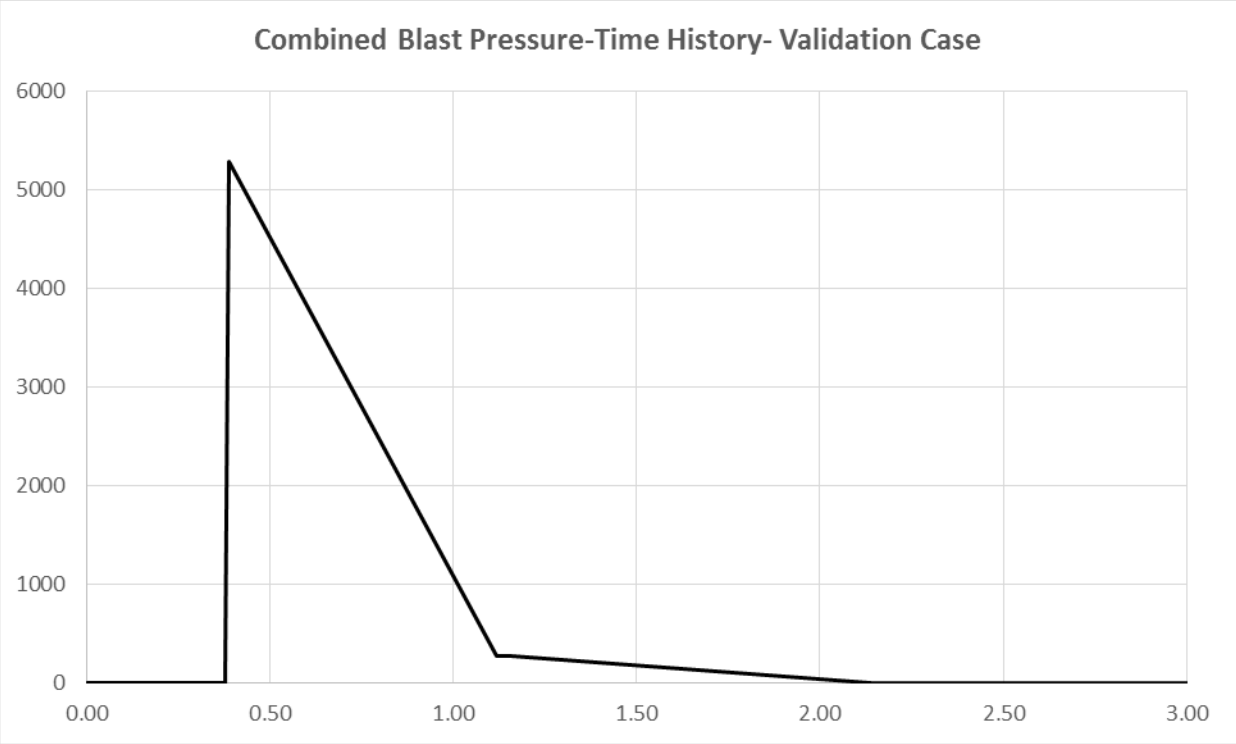


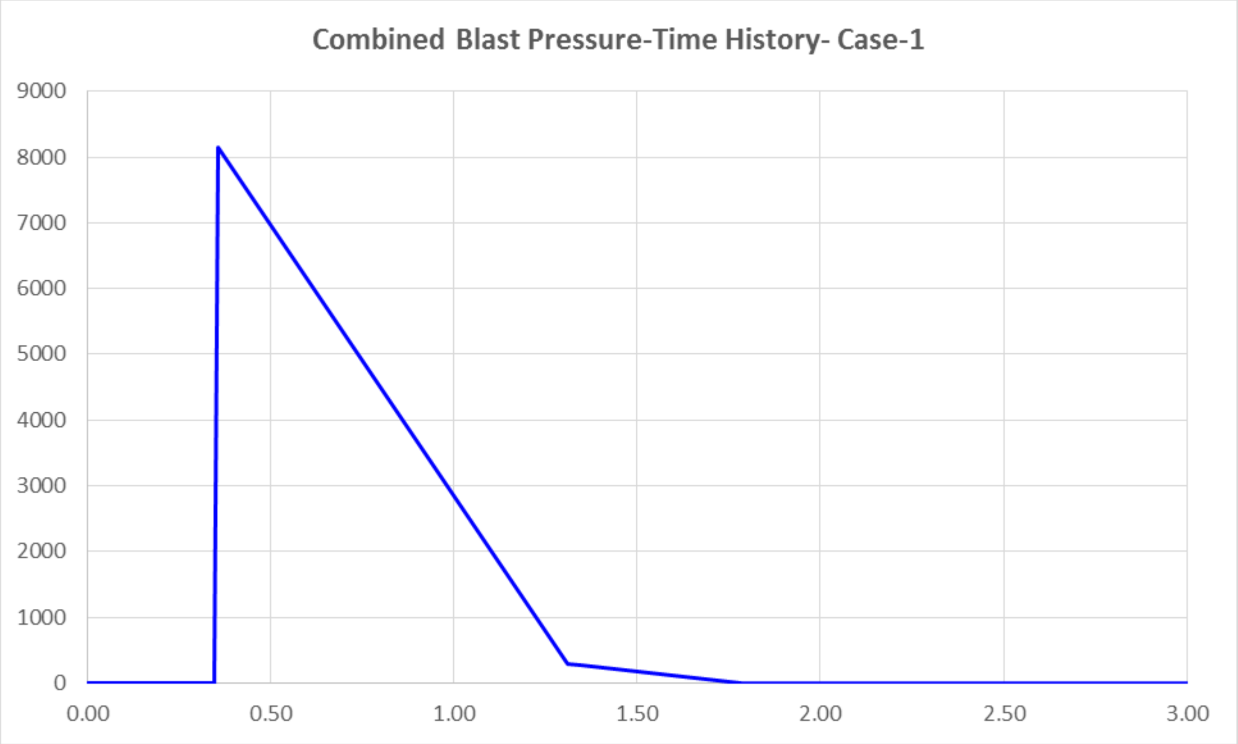
Idealized Loading Regions



Idealized Blast Load Curve

2.5 Blast Loads





272 # @ 2'-6"

P_{av} = 5294 psi

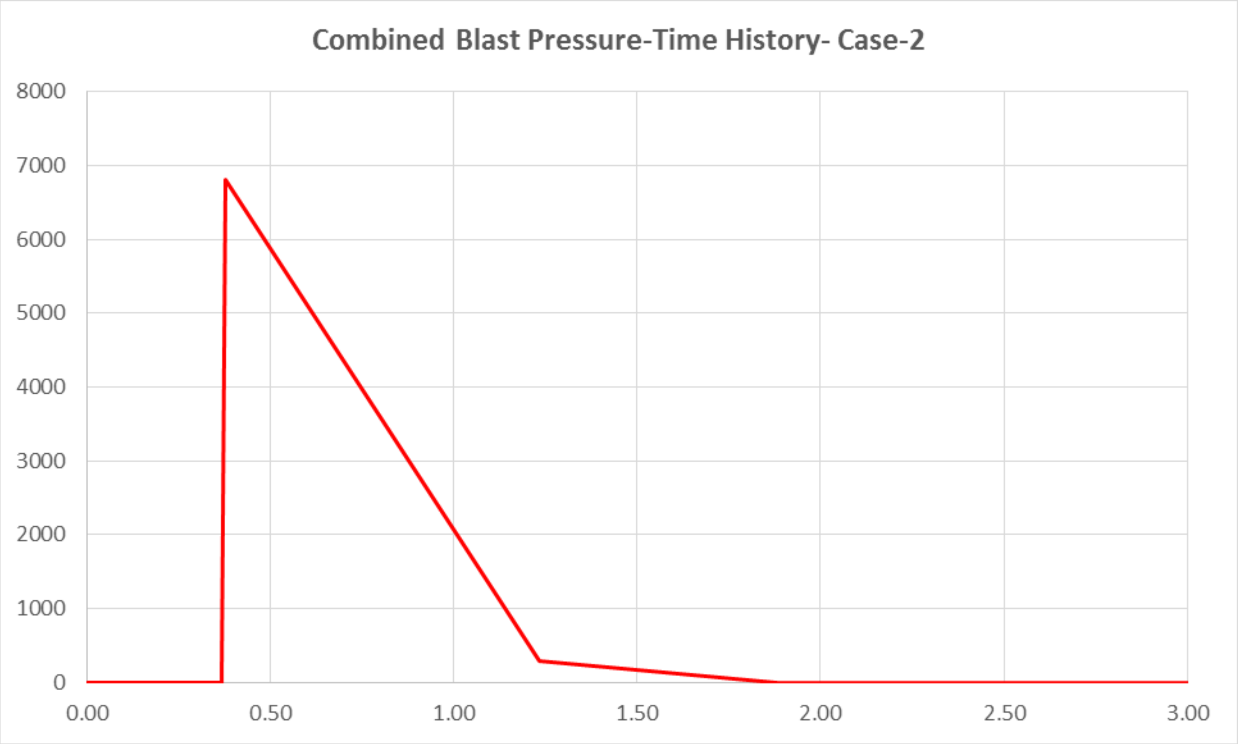
I_{av} = 2456 psi.msec

615 # @ 3'-0"

P_{av} = 8140 psi

I_{av} = 4660 psi.msec

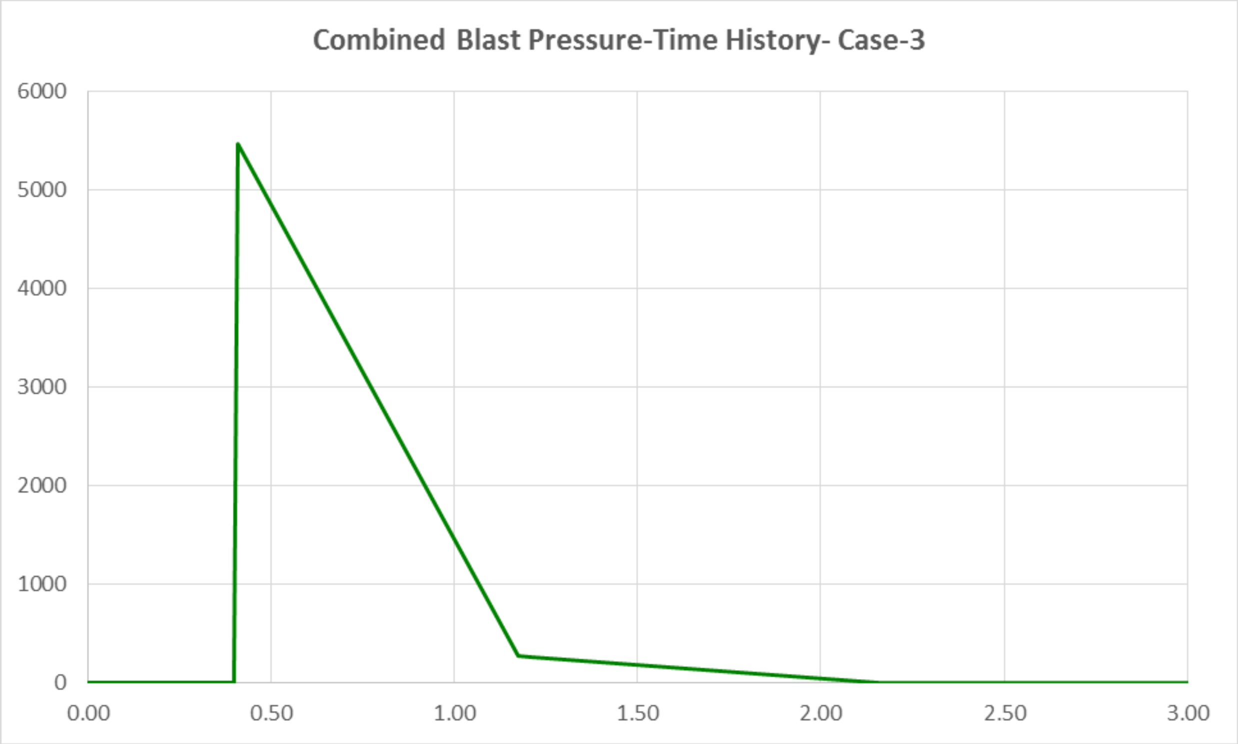
2.5 Blast Loads



420 # @ 3'-0"

P_{av} = 6815 psi

I_{av} = 3542 psi.msec



270 # @ 3'-0"

P_{av} = 5469 psi

I_{av} = 2609 psi.msec

2.6 Performance Criteria

HP Magazine Sensitivity Groups		Unit Impulse and Energy Loads	
Group No.	Group Description	Impulse, I_{thres} (psi-sec)	Energy, KE_{thres} (ft-k/in^2)
1	Robust	45	24.5
2	Non-Robust	67	24.5
3	Fragmenting	53	8.49
4	Cluster Bombs/ Dispenser Munitions	25.6	3.77
5	SD Sensitive	5.23	0.3

Used in Current Study

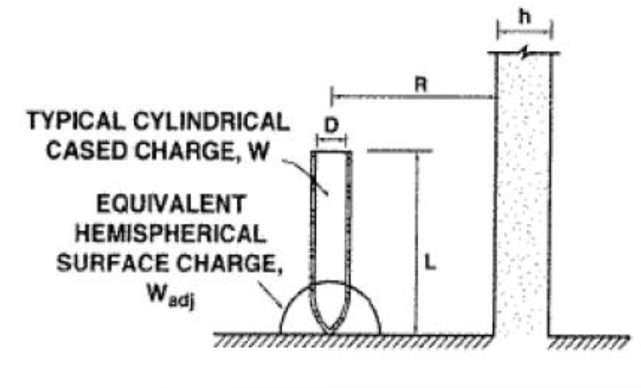
Sympathetic Detonation (SD) Threshold Criteria for A/E of Various Sensitivity Groups

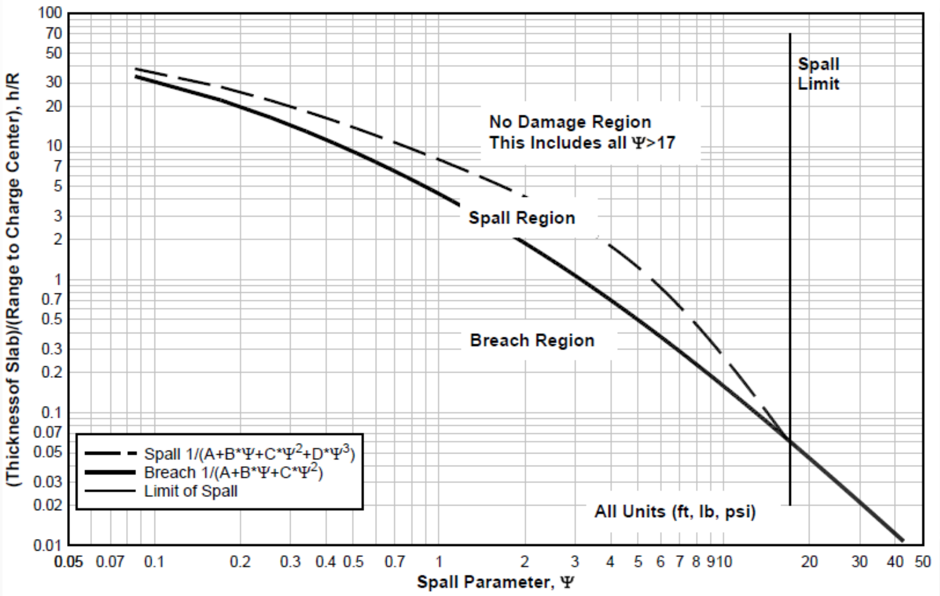
Ref: "High Performance Magazine Non-Propagation Wall Design Criteria", Technical Report TR-2112-SHR, **Hager, Tancreto, Swisdak**, Naval Facilities Engineering Service Center, June 2002

3. Simulation Approach and Model

3.1 UFC 3-340-02 Section 4-55

- Empirical Design **Based on Testing Data**
- Allows the Estimation of RC wall Thickness Based on **Acceptable Concrete Damage.**
- Concrete Damage Varies from "**Minor Spall**" to "**Breach**" and is Expressed in Terms of **Spall Parameter Ψ.**
- Spall Parameter Ψ depends on many factors including: **Charge** Weight & Shape, **Standoff**, **Concrete** Strength, and **Wall** Thickness.
- Acceptable Damage and Required Thickness Depend on Explosive's **Sensitivity Group (SG)**





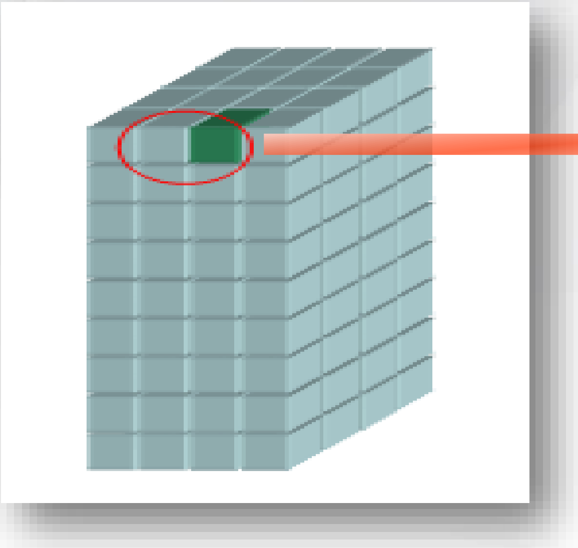
3.1 UFC 3-340-02 Section 4-55

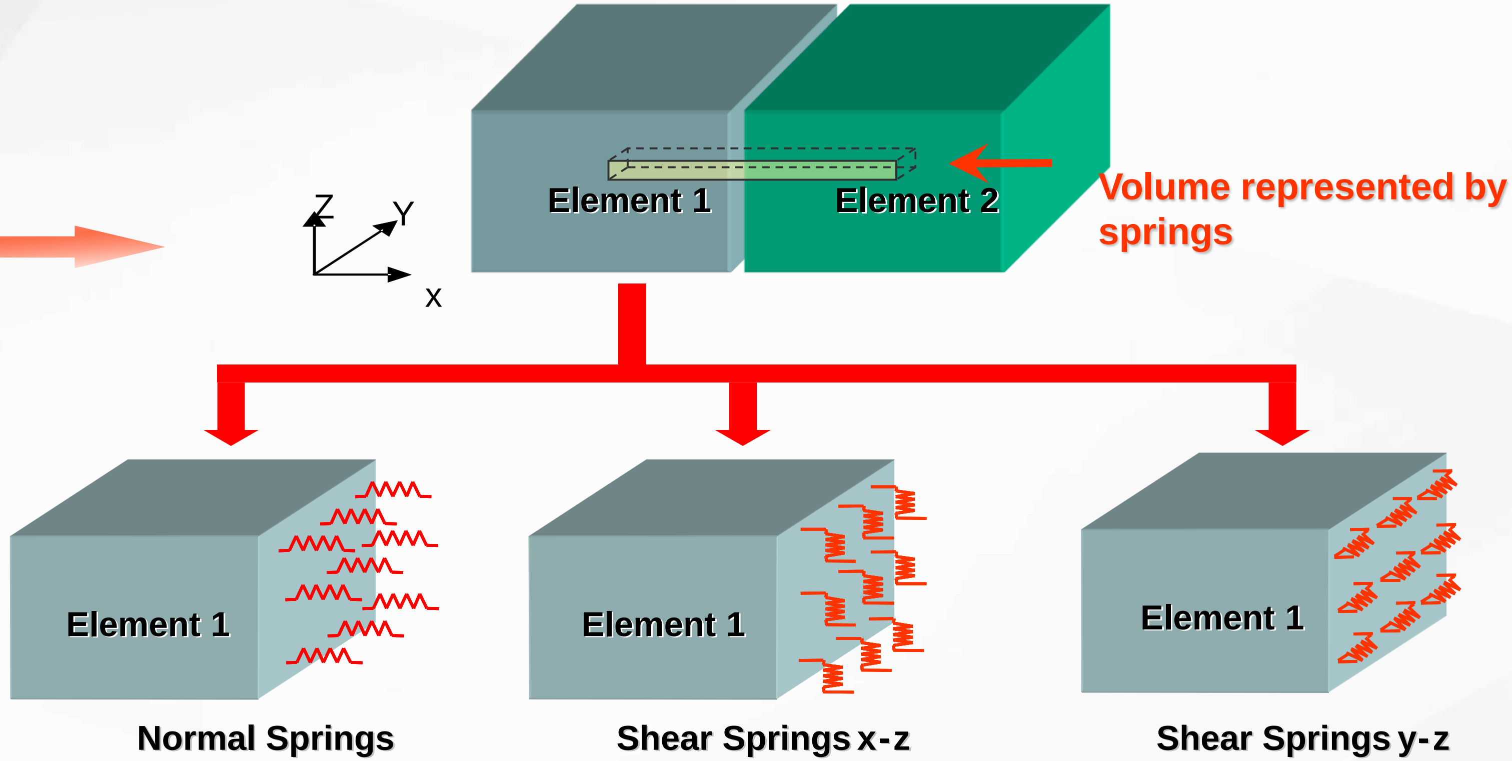
Material	DDESB KT-Memorandum (SG1 to SG4)	Case-1 (12-in) Wall (SG1 to SG4)	Case-2 (10-in) Wall (SG1 to SG4)	Case-3 (8-in) Wall (SG1 to SG4)
Charge Weight (TNT Equiv.) (W) *(lbs)*	**425**	**615**	**420**	**270**
Charge Size (L x D) *(ft x ft)*	0.833 x 1.040	0.833 x 1.200	0.833 x 1.040	0.833 x 0.900
Range (R) *(ft)*	3'-0"	3'-0"	3'-0"	3'-0"
Concrete Compressive Strength *(psi)*	**2500**	**4000**	**4000**	**4000**
Wall Thickness (h) *(in)*	**12**	**12**	**10**	**8**
Spall Parameter Ψ	0.355	0.361	0.404	0.464
Spall Threshold $(h/R)_{Spall}$	2.617	2.567	2.208	1.801
Breach Threshold $(h/R)_{Breach}$	1.053	1.030	0.872	0.710
Design Thickness: Range Ratio (h/R)	**0.284**	**0.278**	**0.237**	**0.193**
Design/ Spall Ratio $(h/R)/ (h/R)_{Spall}$	10.9 %	10.8 %	10.7 %	10.7 %
Design/ Breach Ratio $(h/R)/ (h/R)_{Breach}$	27.0 %	27.0 %	27.1 %	27.2 %
Expected Damage Level	**Breach**	**Breach**	**Breach**	**Breach**

3.1 UFC 3-340-02 Section 4-55

Material	DDESB KT-Memorandum (SG5)	Case-1 (12-in) Wall (SG5)	Case-2 (10-in) Wall (SG5)	Case-3 (8-in) Wall (SG5)
Charge Weight (TNT Equiv.) (W) *(lbs)*	**20**	**28**	**21**	**15**
Charge Size (L x D) *(ft x ft)*	0.833 x 0.376	0.833 x 0.423	0.833 x 0.382	0.833 x 0.340
Range (R) *(ft)*	3'-0"	3'-0"	3'-0"	3'-0"
Concrete Compressive Strength *(psi)*	**2500**	**4000**	**4000**	**4000**
Wall Thickness (h) *(in)*	**12**	**12**	**10**	**8**
Spall Parameter Ψ	0.789	0.794	0.879	0.995
Spall Threshold $(h/R)_{Spall}$	0.678	0.669	0.532	0.395
Breach Threshold $(h/R)_{Breach}$	0.306	0.303	0.256	0.208
Design Thickness: Range Ratio (h/R)	**0.314**	**0.311**	**0.261**	**0.210**
Design/ Spall Ratio $(h/R)/\ (h/R)_{Spall}$	46.3 %	46.6 %	49.1 %	53.2 %
Design/ Breach Ratio $(h/R)/\ (h/R)_{Breach}$	102.4 %	102.7 %	101.9 %	101.3 %
Expected Damage Level	**Major Spall**	**Major Spall**	**Major Spall**	**Major Spall**

3.2 Applied Element Method (AEM) in Extreme Loading for Structures (ELS)

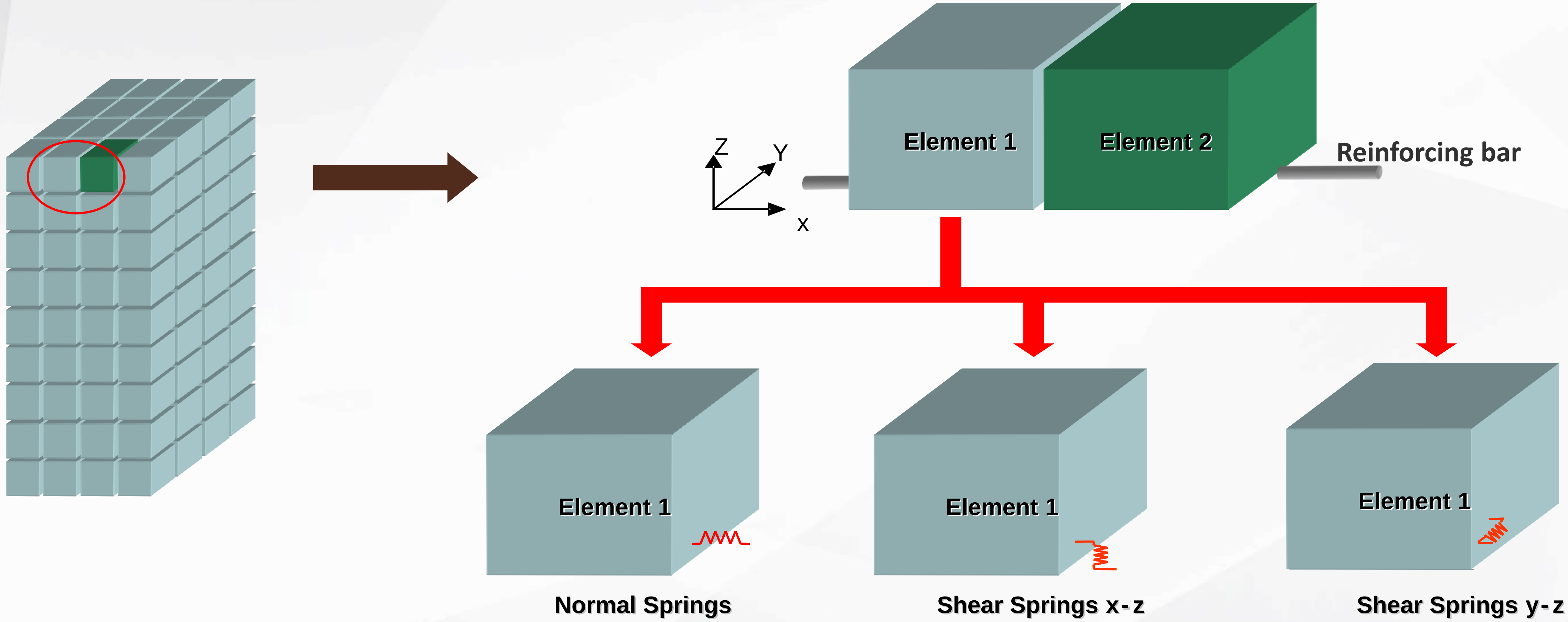




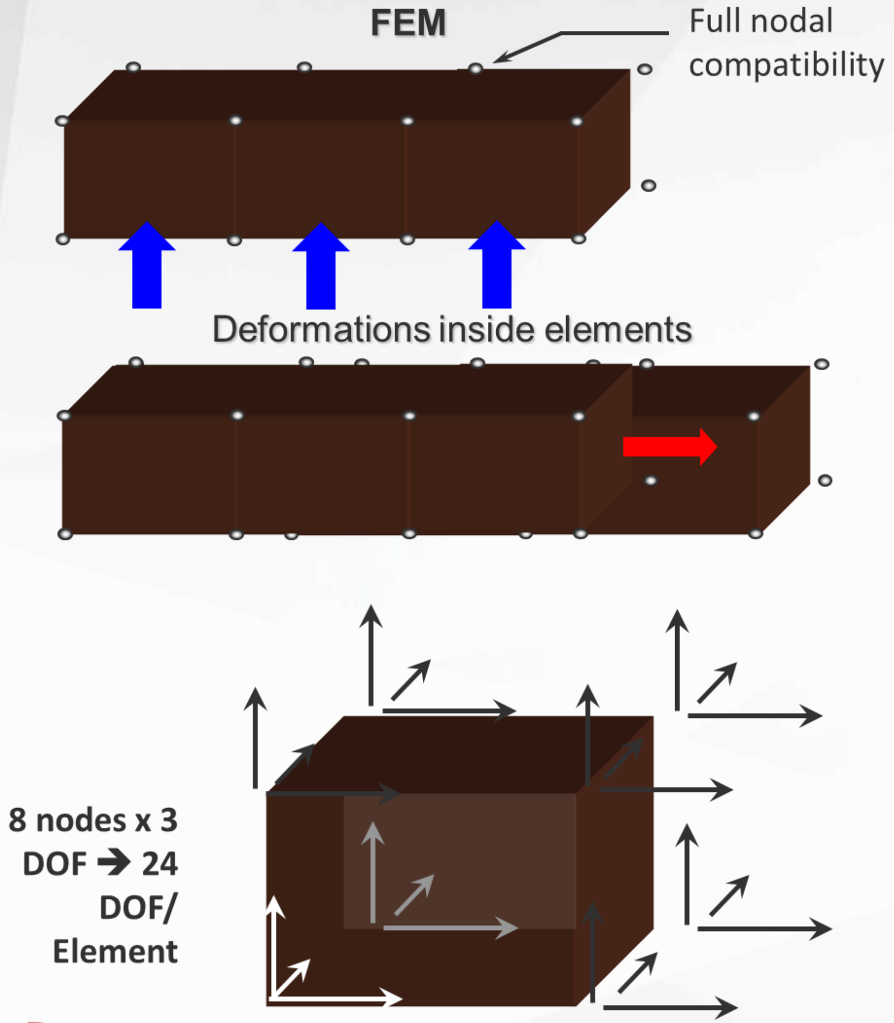
The continuum is discretized into **Elements** connected together with **Nonlinear Springs**. The springs represent **Material** behavior, Axial and Shear **Deformations**.

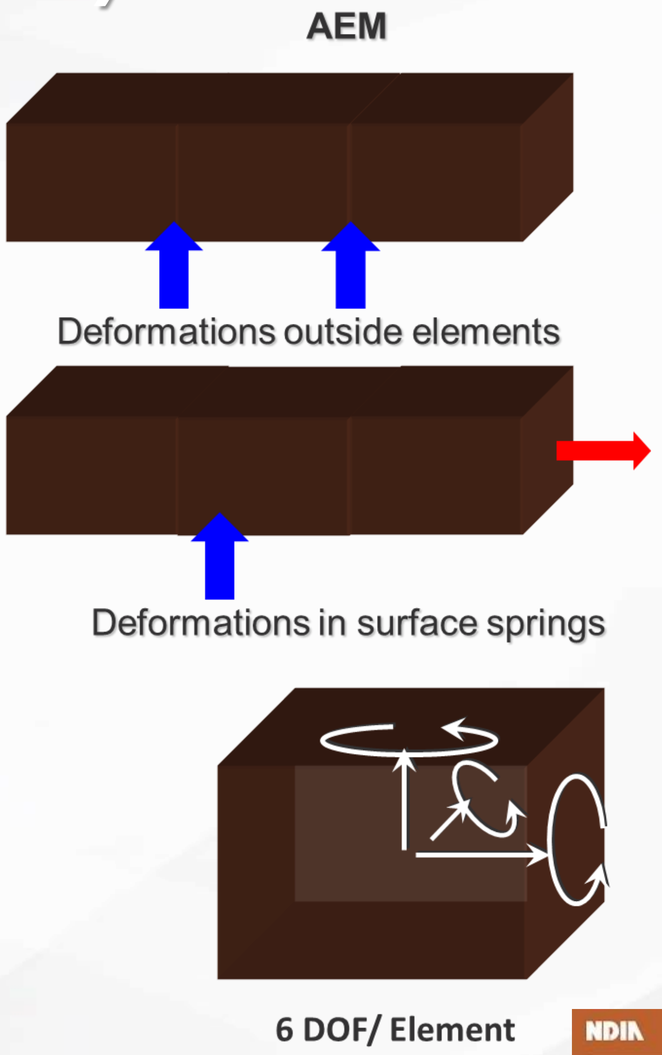
3.2 Applied Element Method (AEM) in Extreme Loading for Structures (ELS)

Extreme Loading Software (ELS) - reinforcing **bars springs**



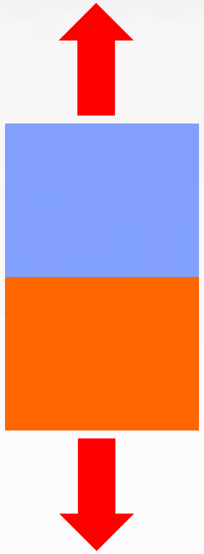
3.2 Applied Element Method (AEM) vs Finite Element Method (FEM)

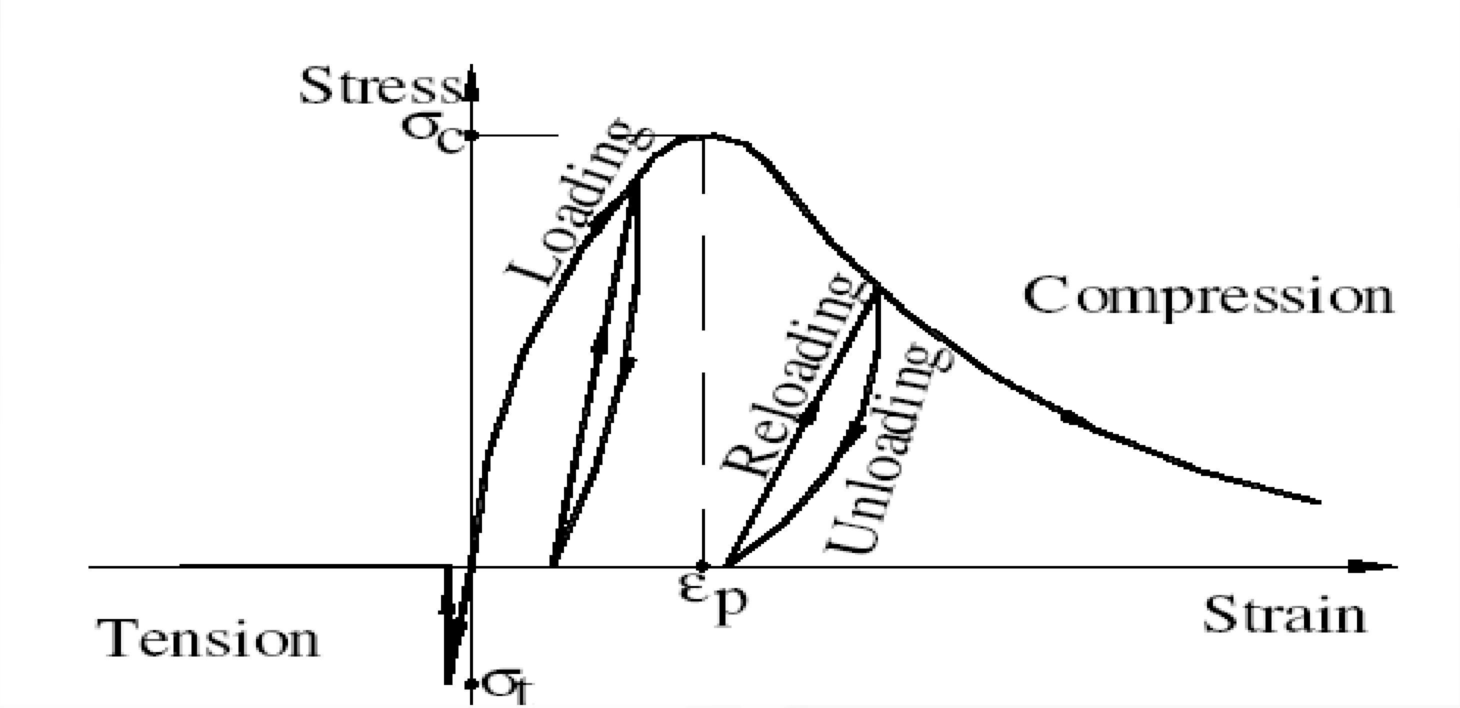


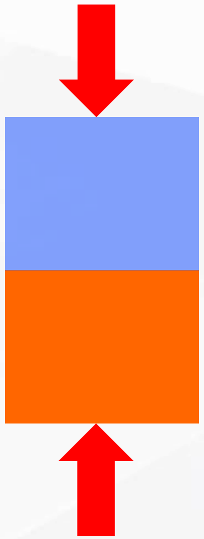


3.2 Applied Element Method (AEM: Constitutive Material Models)

AEM - Nonlinear Material Models







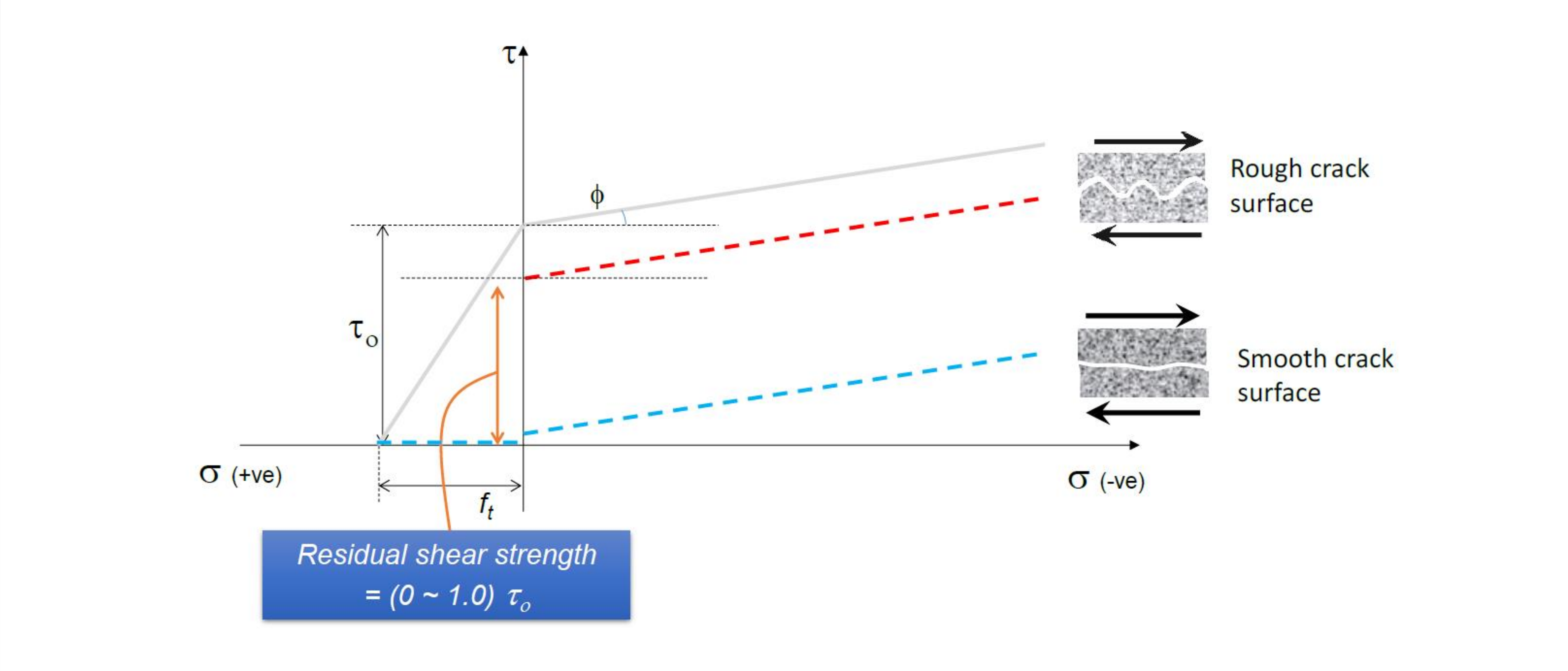
Tension

Fully path-dependent model for concrete
(Okamura and Maekawa, 1991)

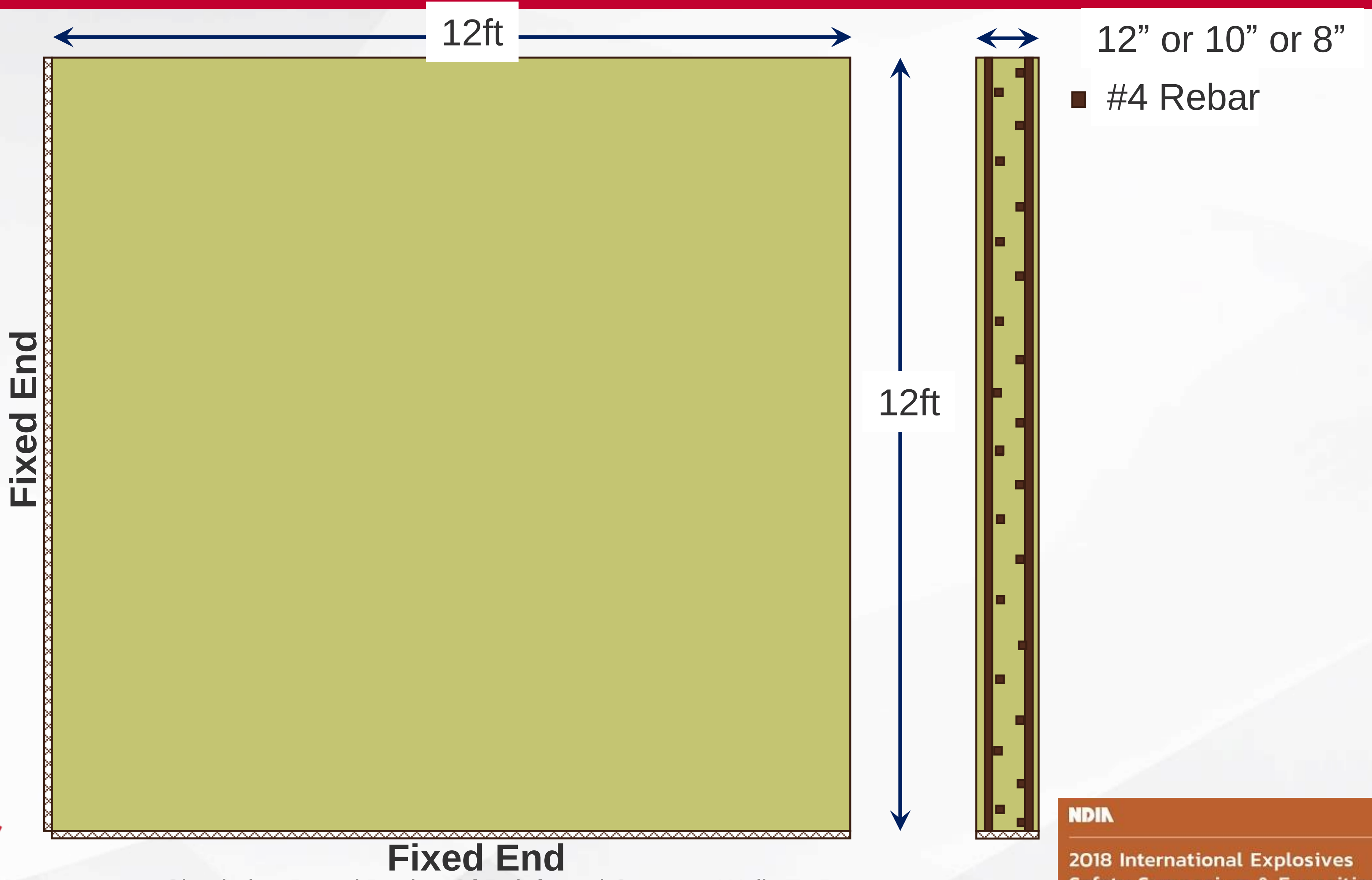
Compression

3.2 Applied Element Method (AEM: Constitutive Material Models)

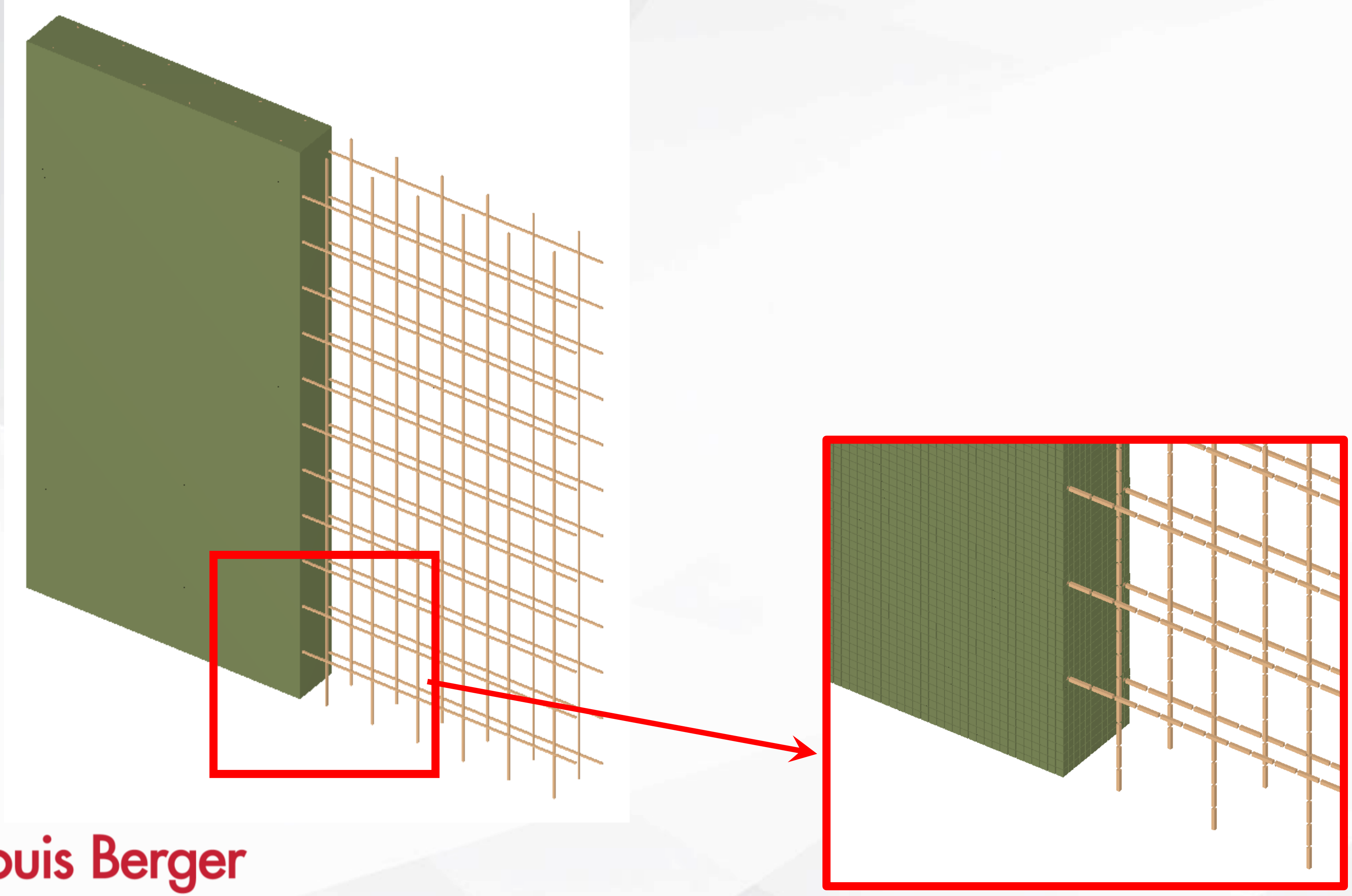
AEM - Nonlinear Material Models

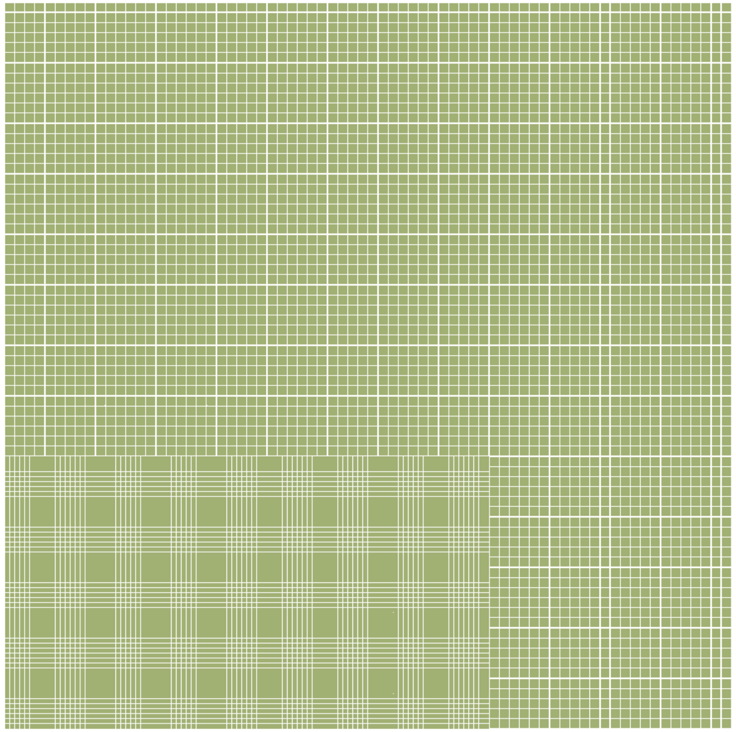


3.3 AEM/ ELS Model- Geometry



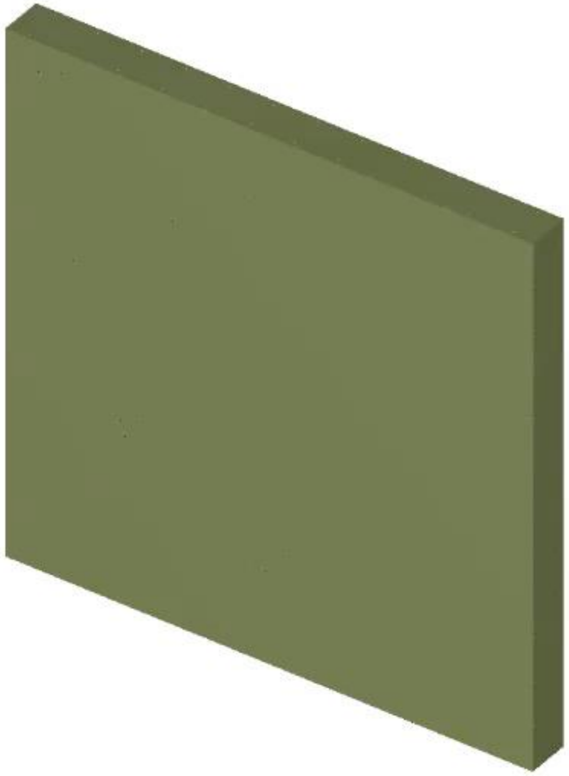
3.3 AEM/ ELS Model- Meshing



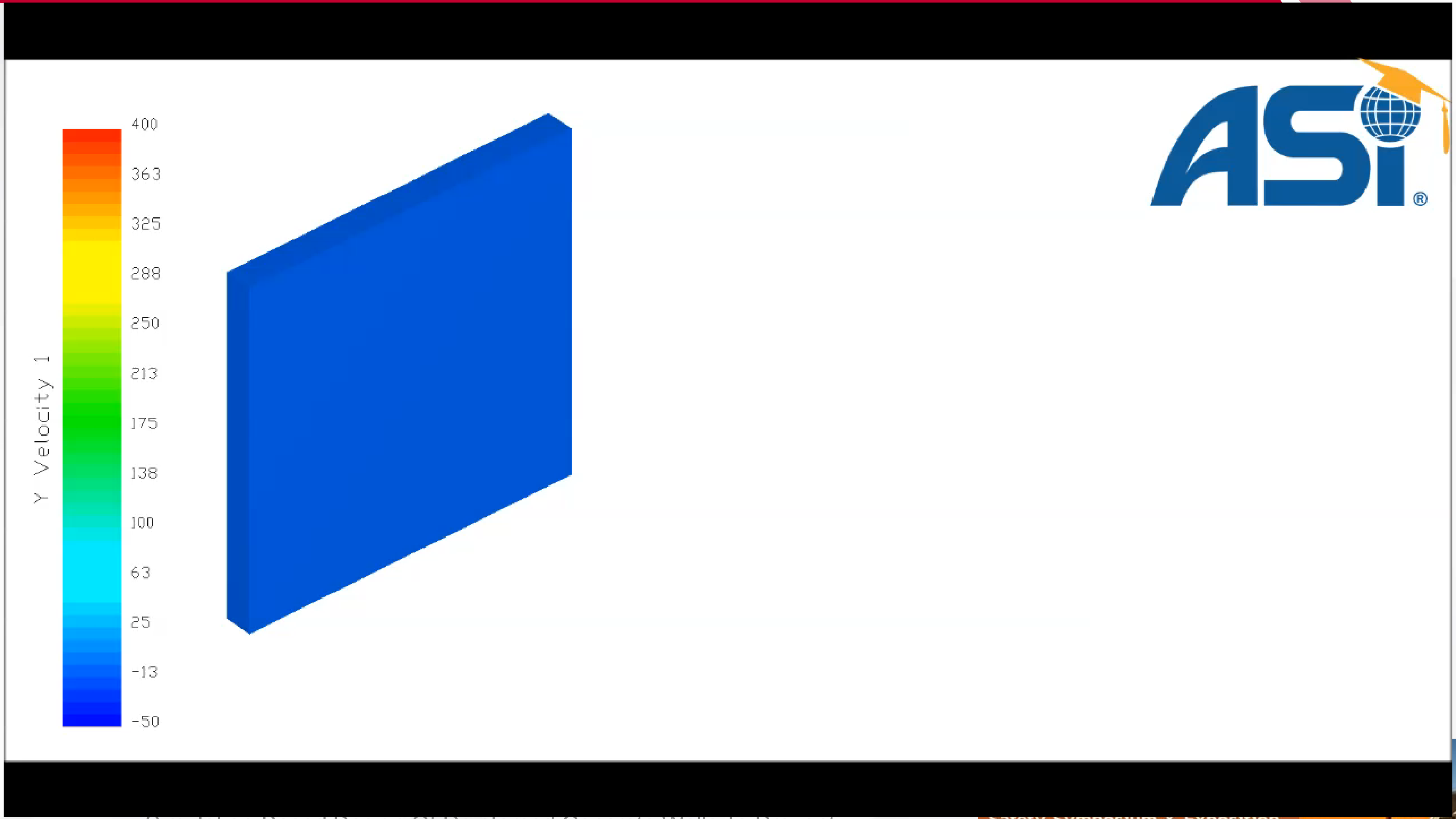


4- Predicted Blast Responses

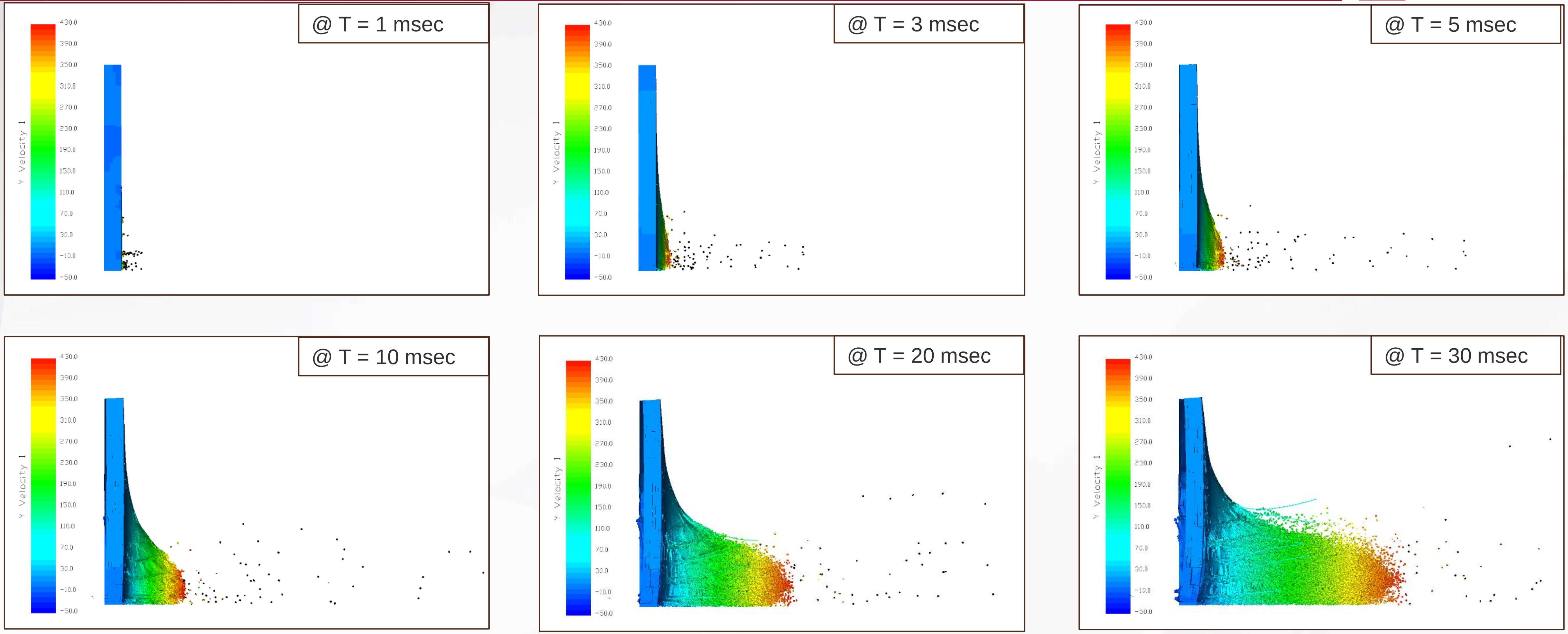
4.1 Validation Case (12-in RC Wall / 272# @ 2’-6”)



4.1 Validation Case (12-in RC Wall / 272# @ 2'-6")



4.1 Validation Case (12-in RC Wall / 272# @ 2'-6")

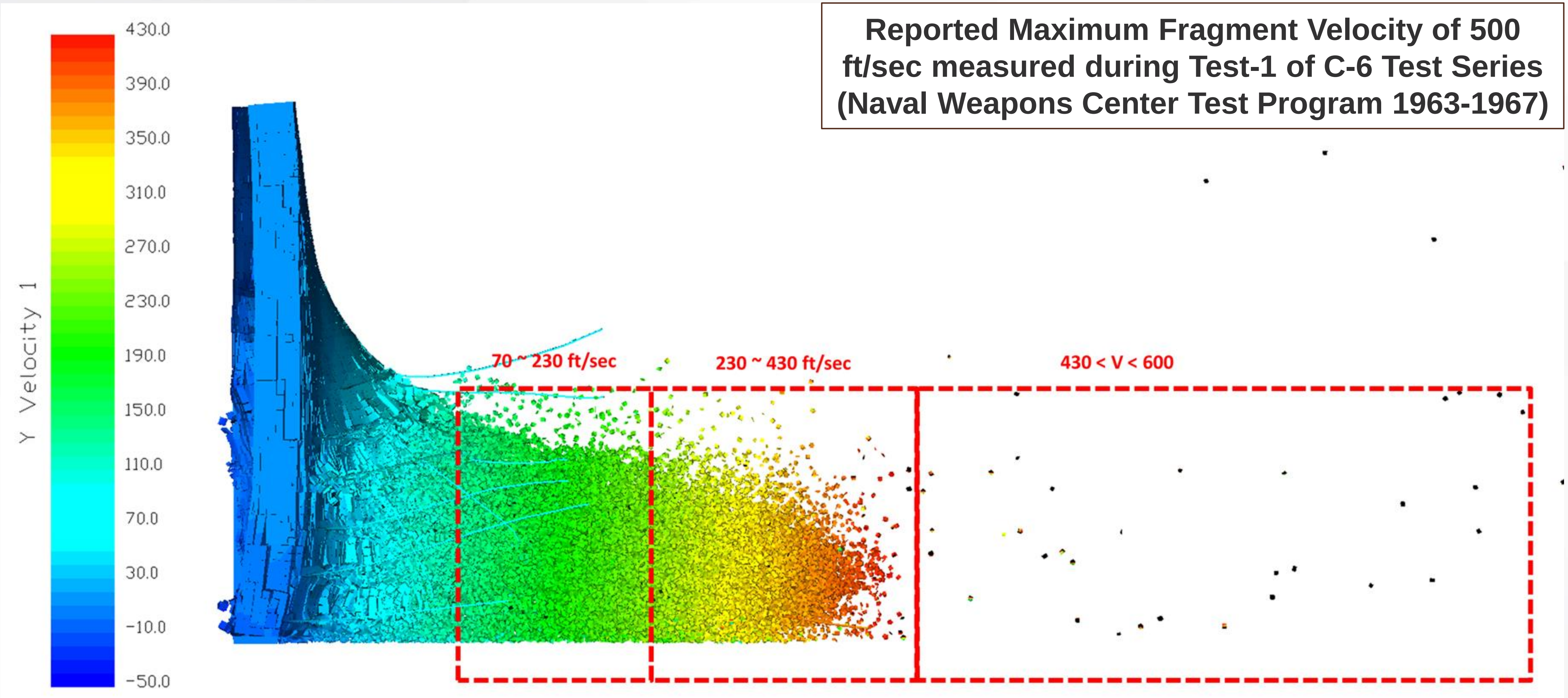


Wall Fragmentation Progression over Time

Louis Berger

ASI

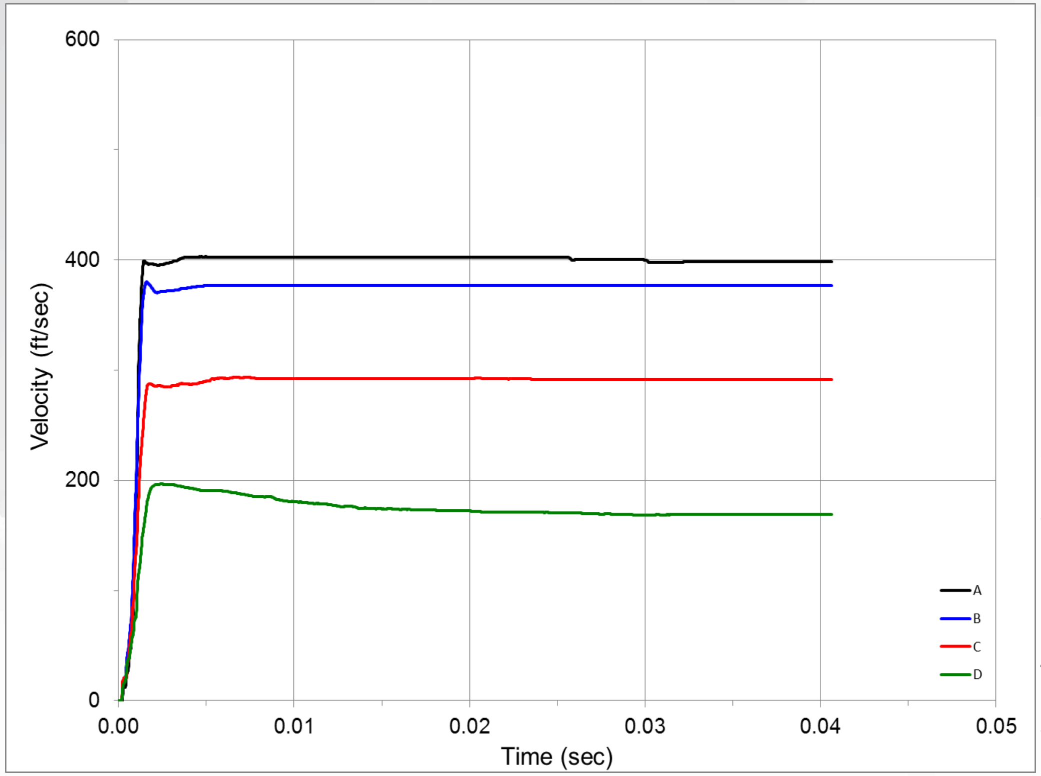
4.1 Validation Case (12-in RC Wall / 272# @ 2'-6")



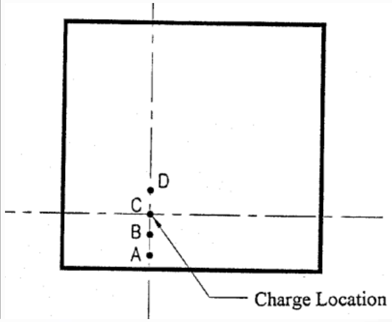
Reported Maximum Fragment Velocity of 500 ft/sec measured during Test-1 of C-6 Test Series (Naval Weapons Center Test Program 1963-1967)

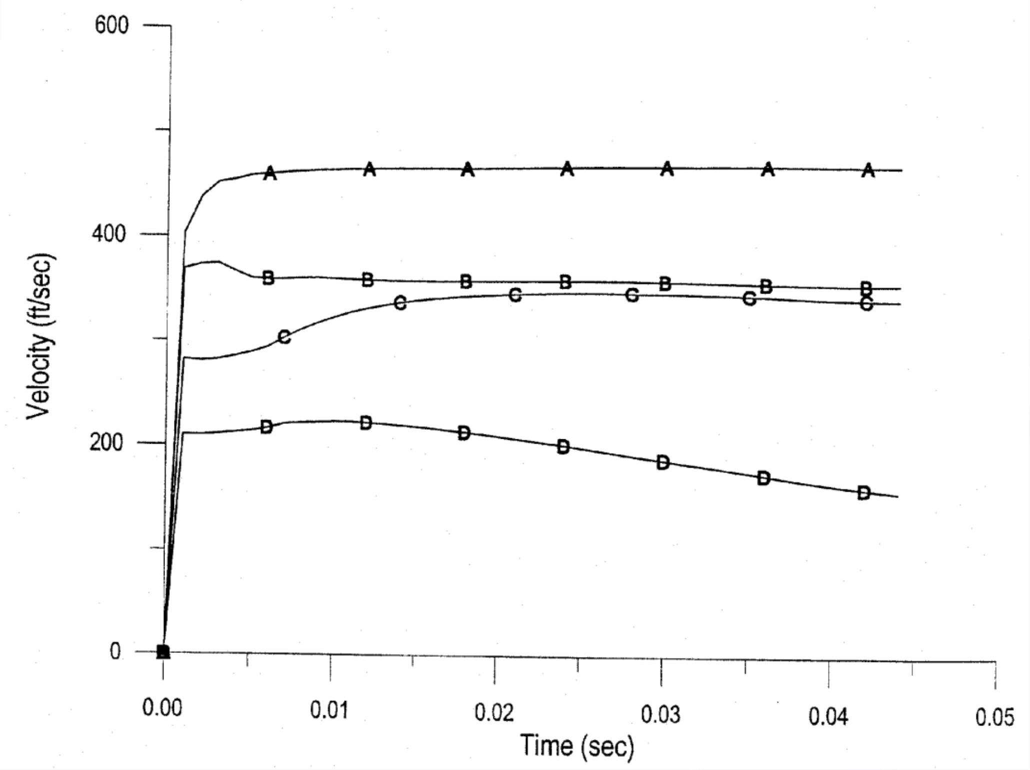
Wall Fragmentation Progression over Time

4.1 Validation Case (12-in RC Wall / 272# @ 2'-6")



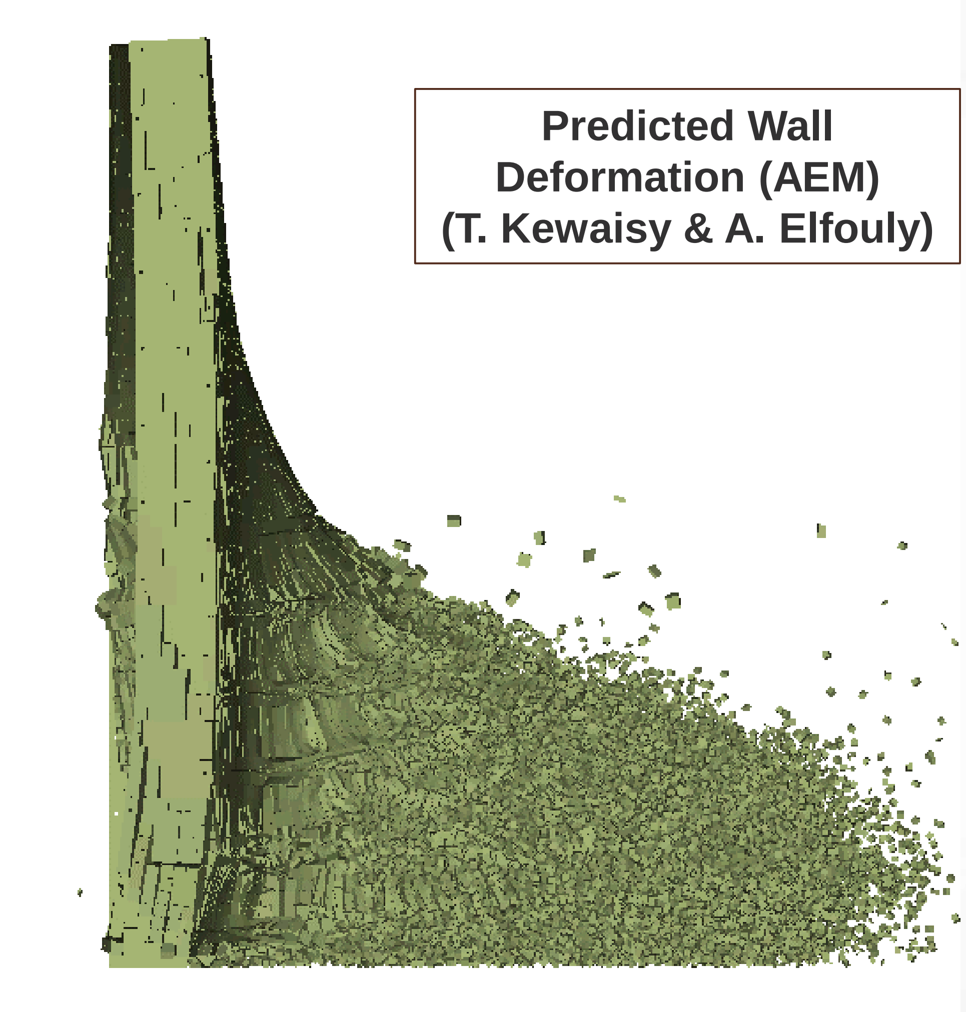
Predicted Wall Fragment Velocities (AEM by T. Kewaisy & A. Elfouly)

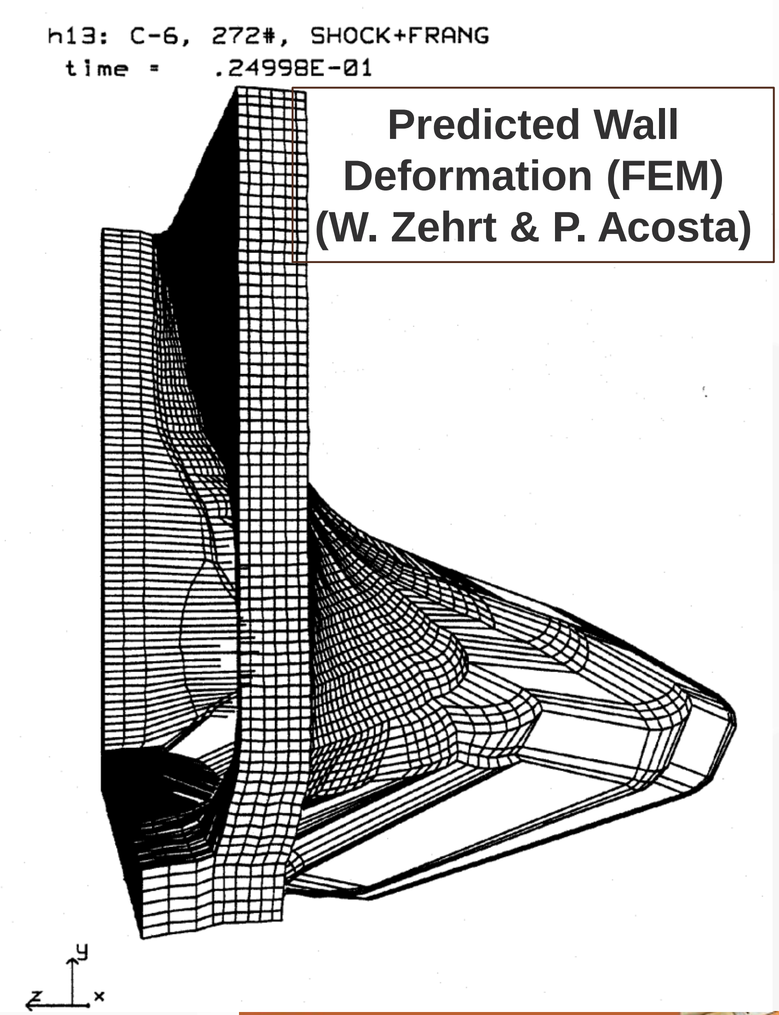




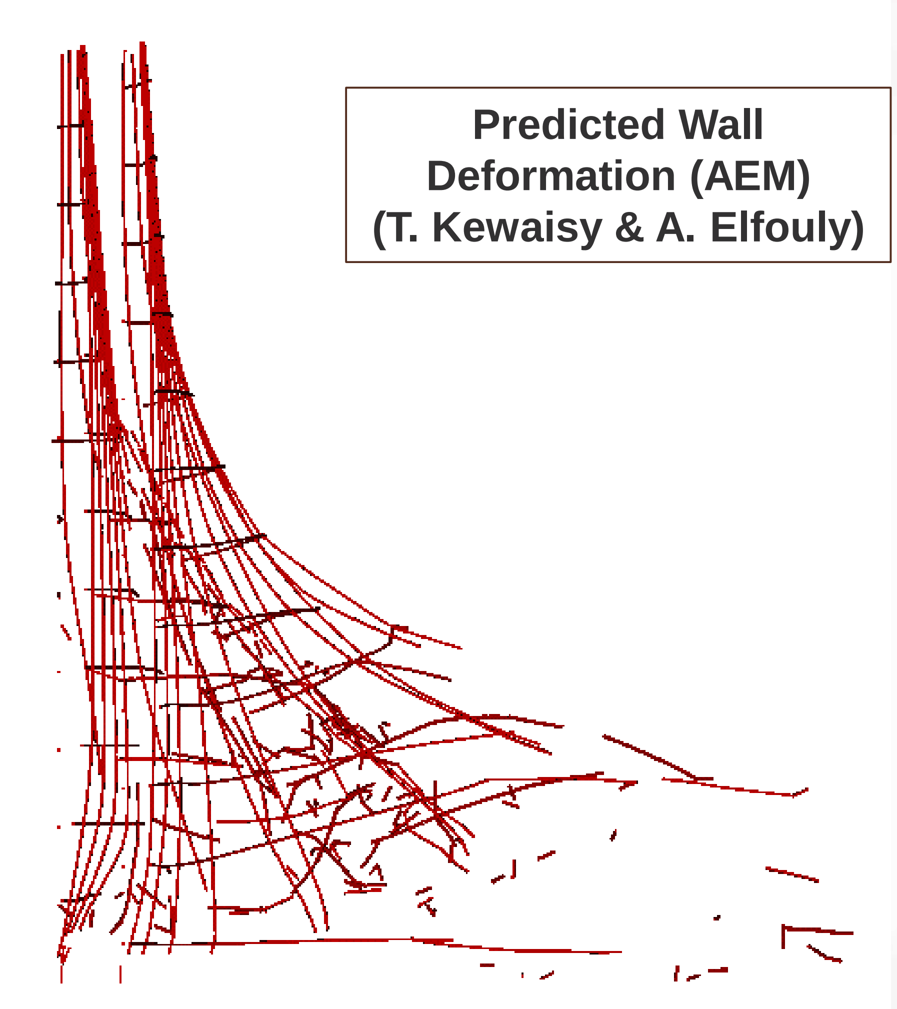
Predicted Wall Fragment Velocities (FEM by W. Zehrt & P. Acosta)

4.1 Validation Case (12-in RC Wall / 272# @ 2'-6")

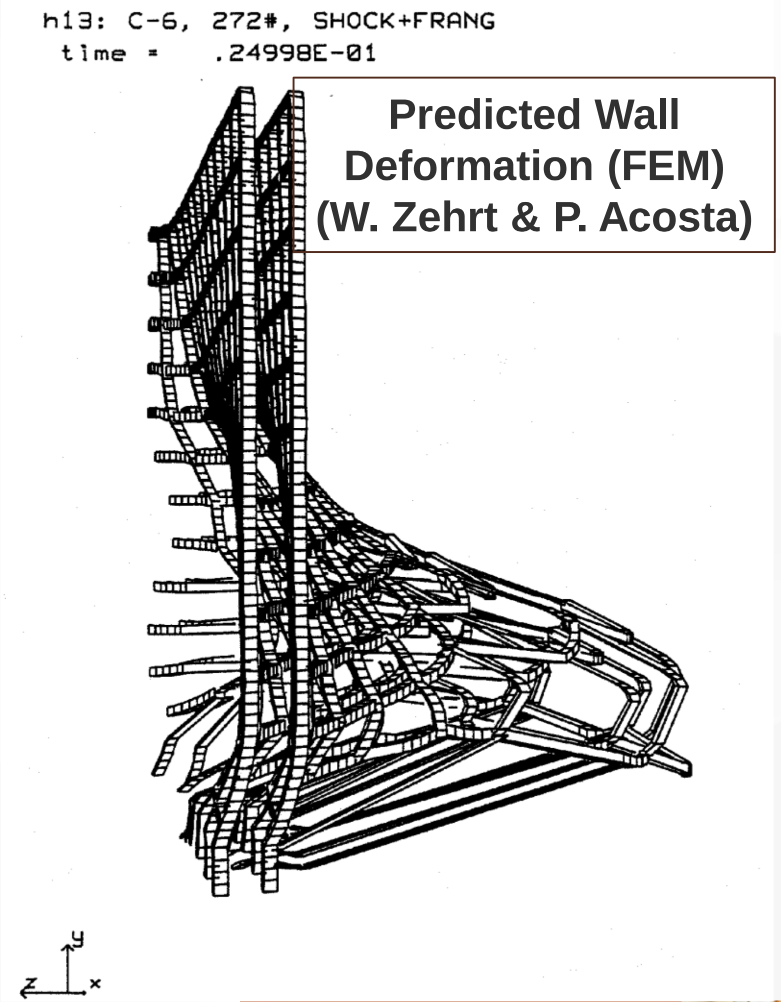




4.1 Validation Case (12-in RC Wall / 272# @ 2’-6”)



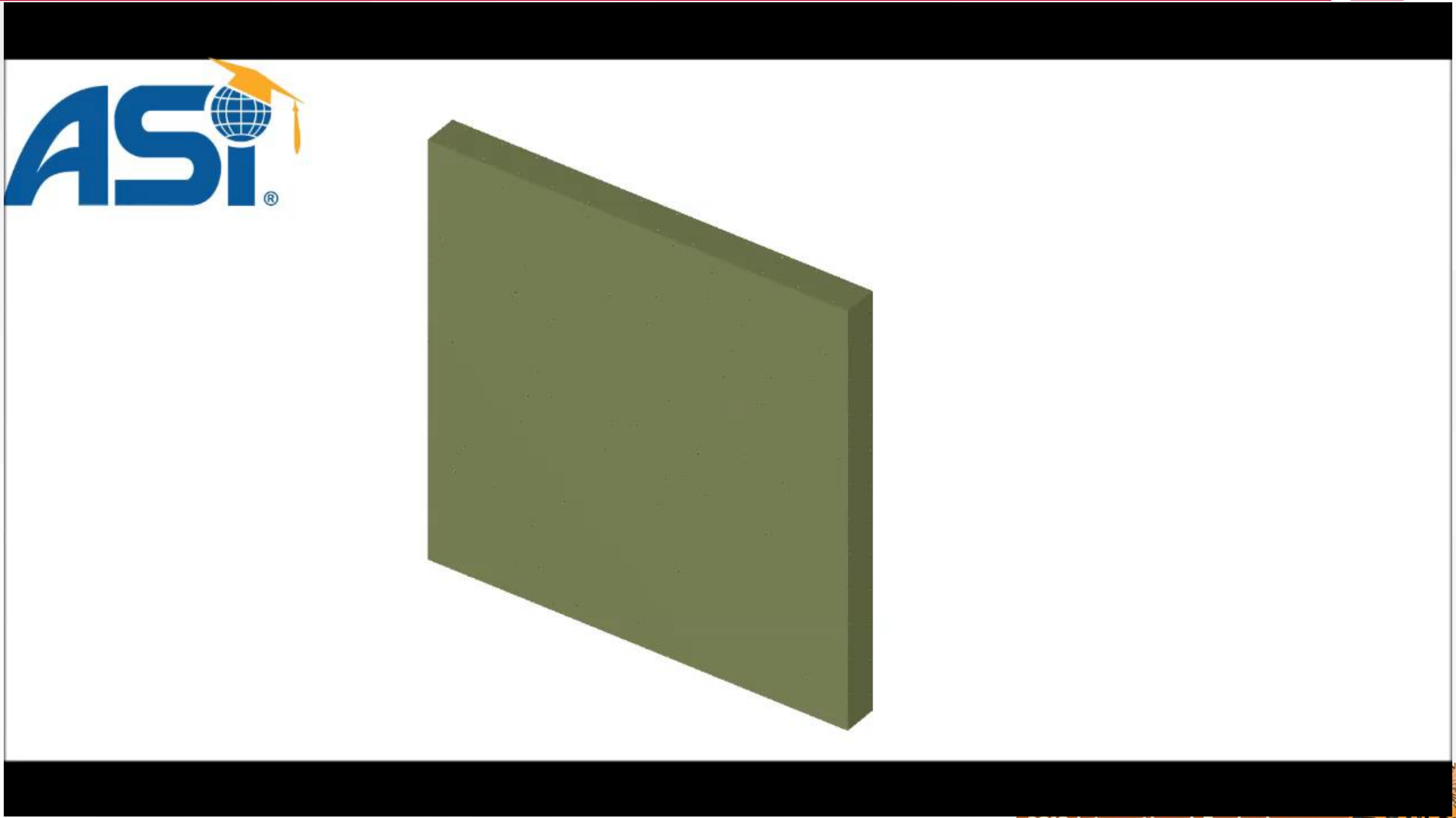
Predicted Wall Deformation (AEM)
(T. Kewaisy & A. Elfouly)



Predicted Wall Deformation (FEM)
(W. Zehrt & P. Acosta)

4.2 Case-1 (12-in RC Wall / 615# @ 3'-0")

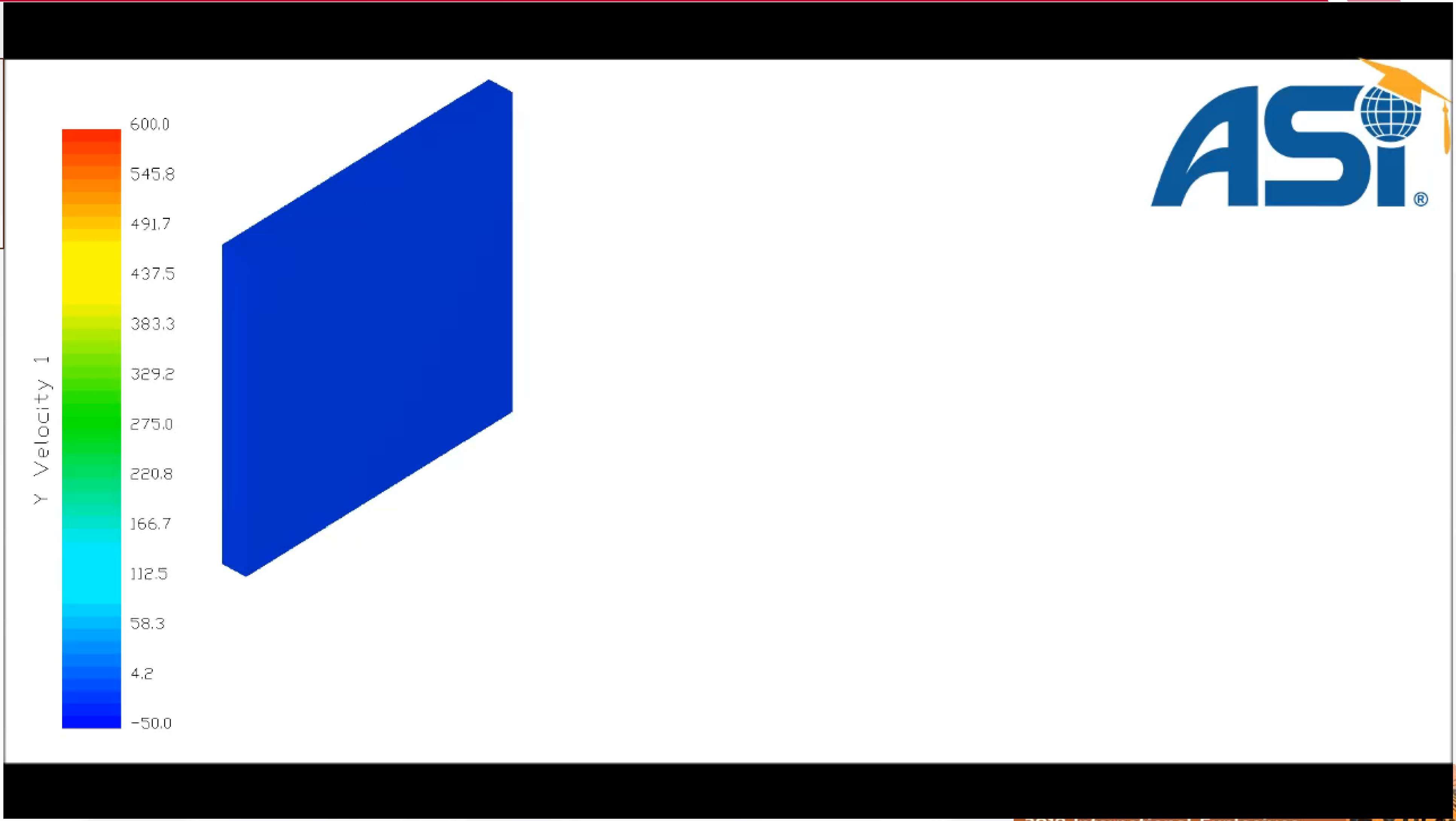
Wall Structural Response History



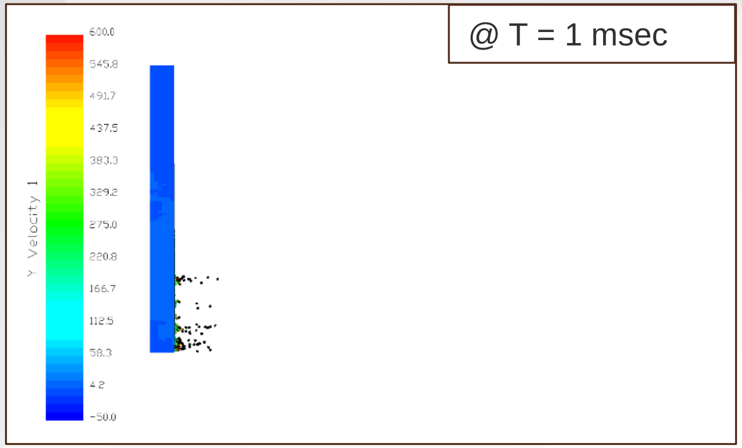
Louis Berger

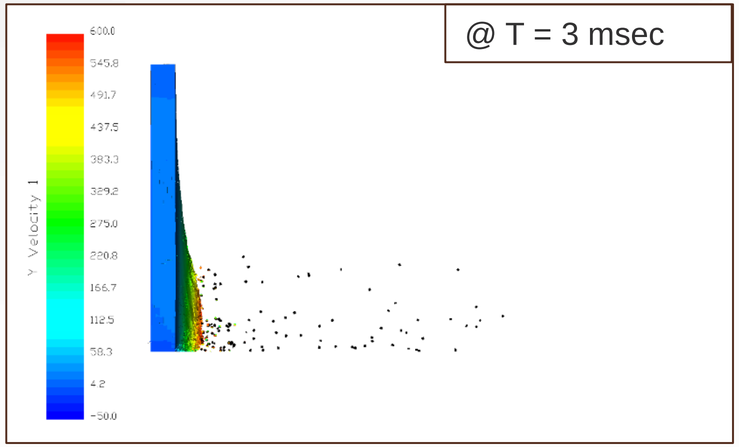
4.2 Case-1 (12-in RC Wall / 615# @ 3'-0")

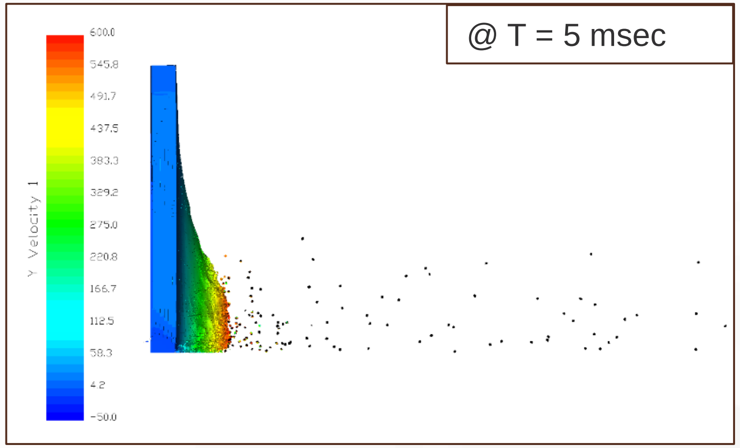
Wall Fragment Velocity Profile

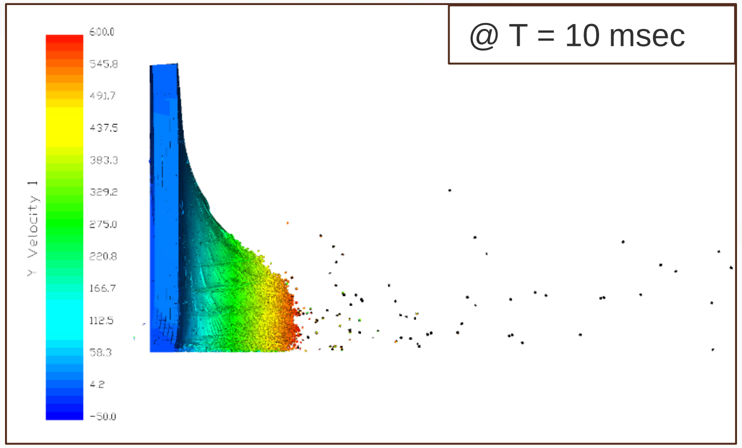


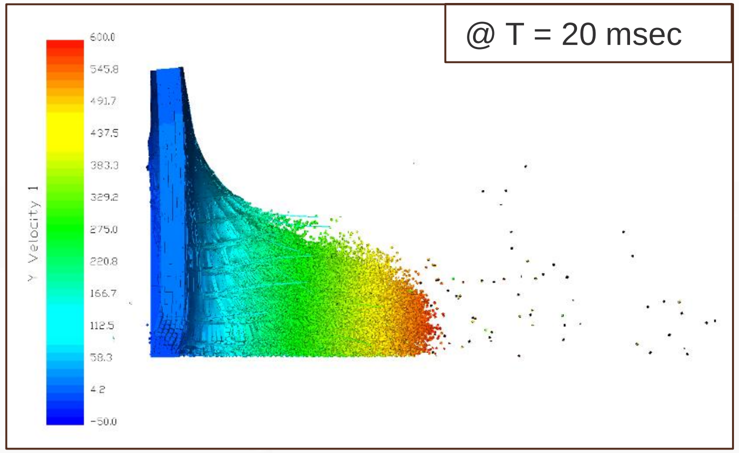
4.2 Case-1 (12-in RC Wall / 615# @ 3’-0”)

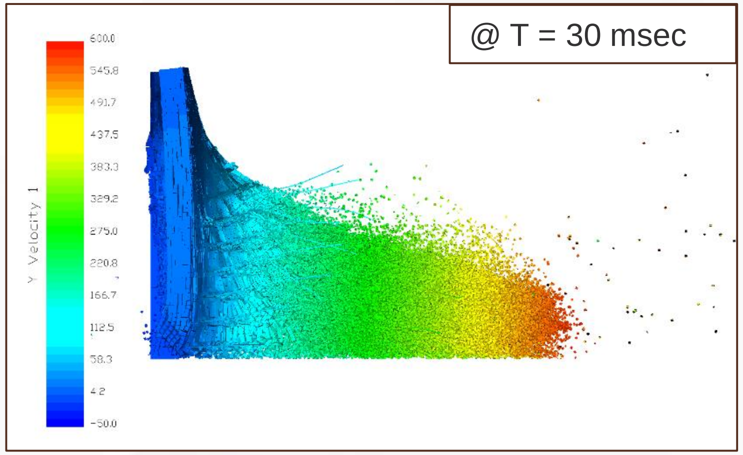






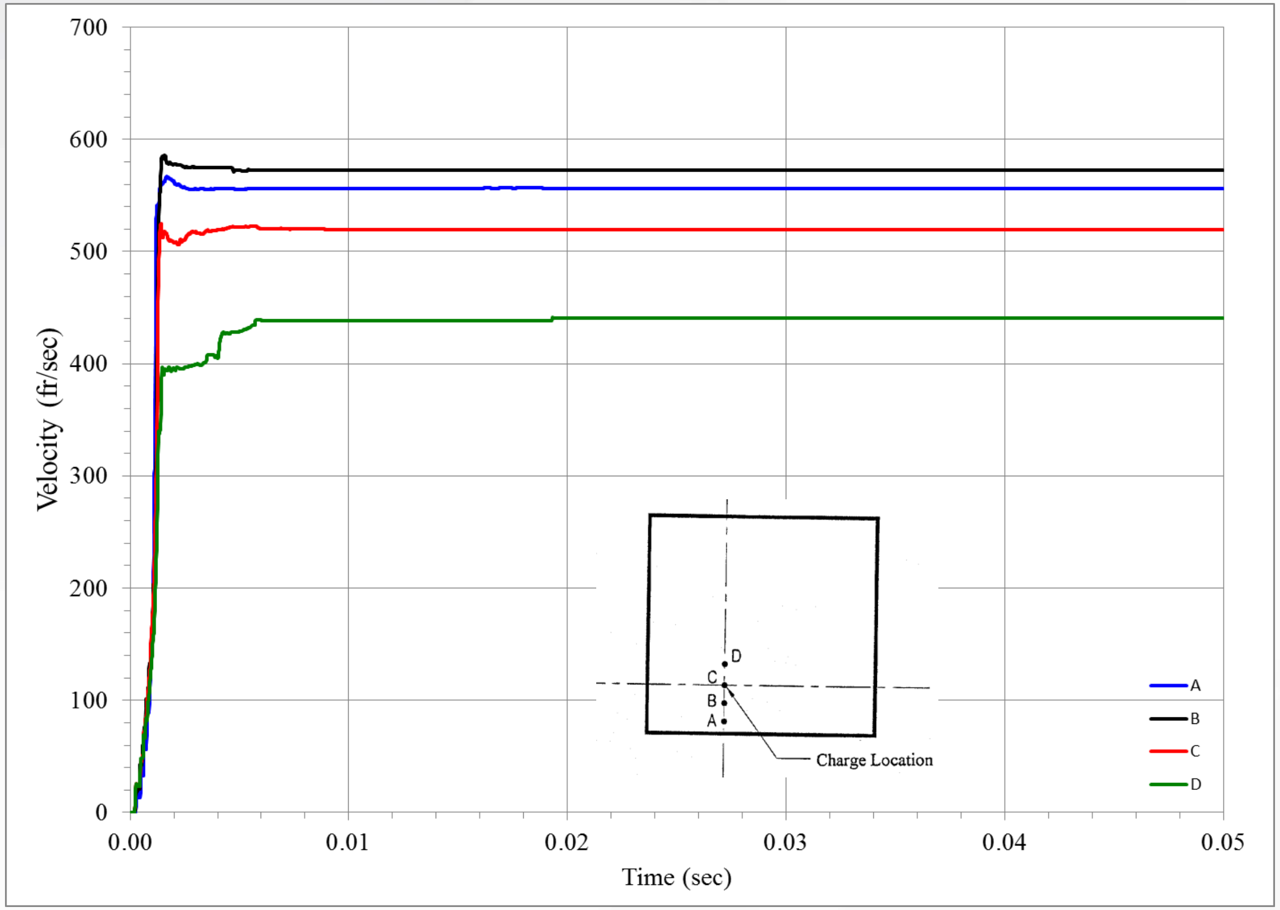






Wall Fragmentation Progression over Time

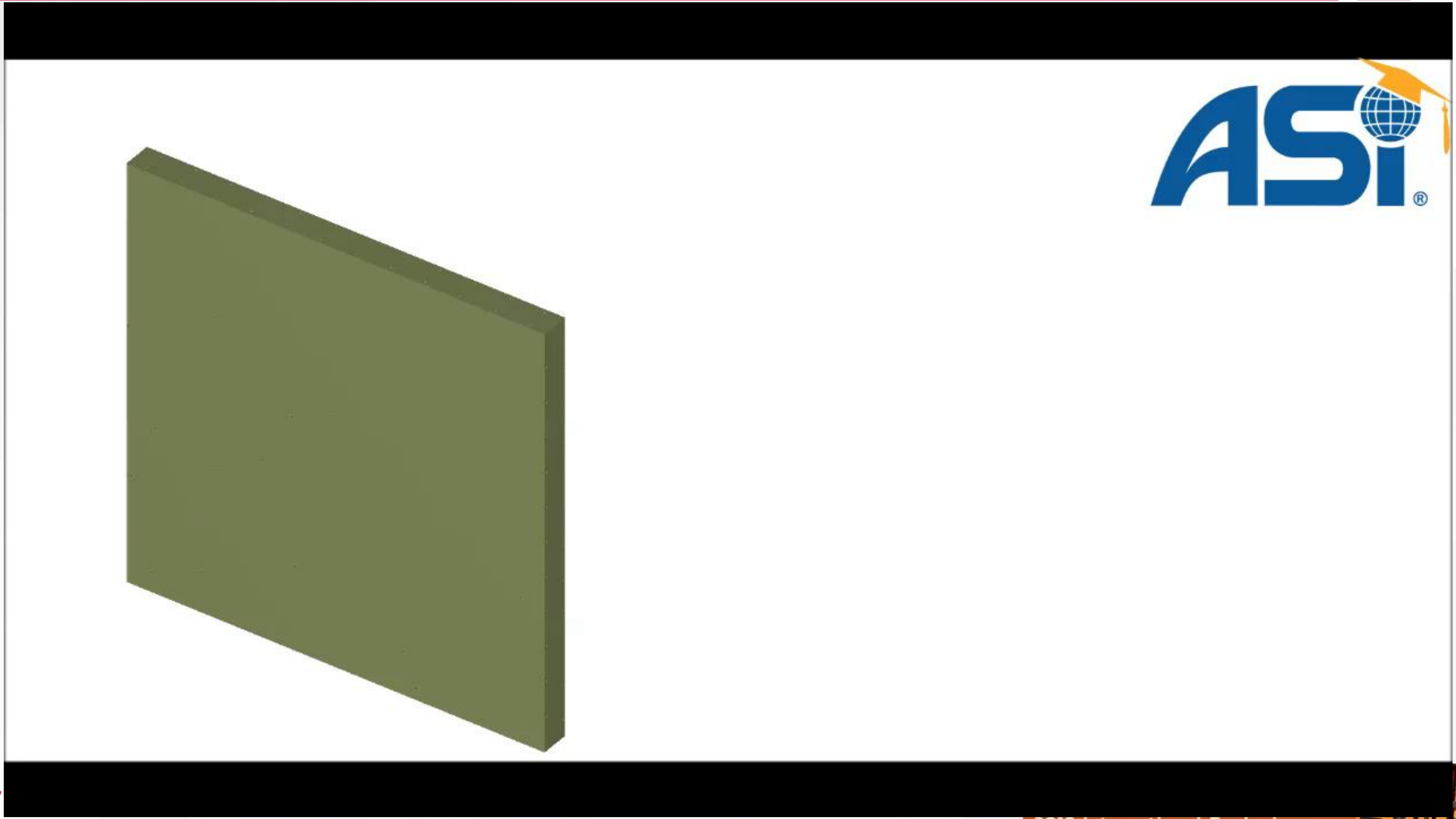
4.2 Case-1 (12-in RC Wall / 615# @ 3'-0")



Fragment Velocity Time Histories at Various Positions

4.3 Case-2 (10-in RC Wall / 420# @ 3'-0")

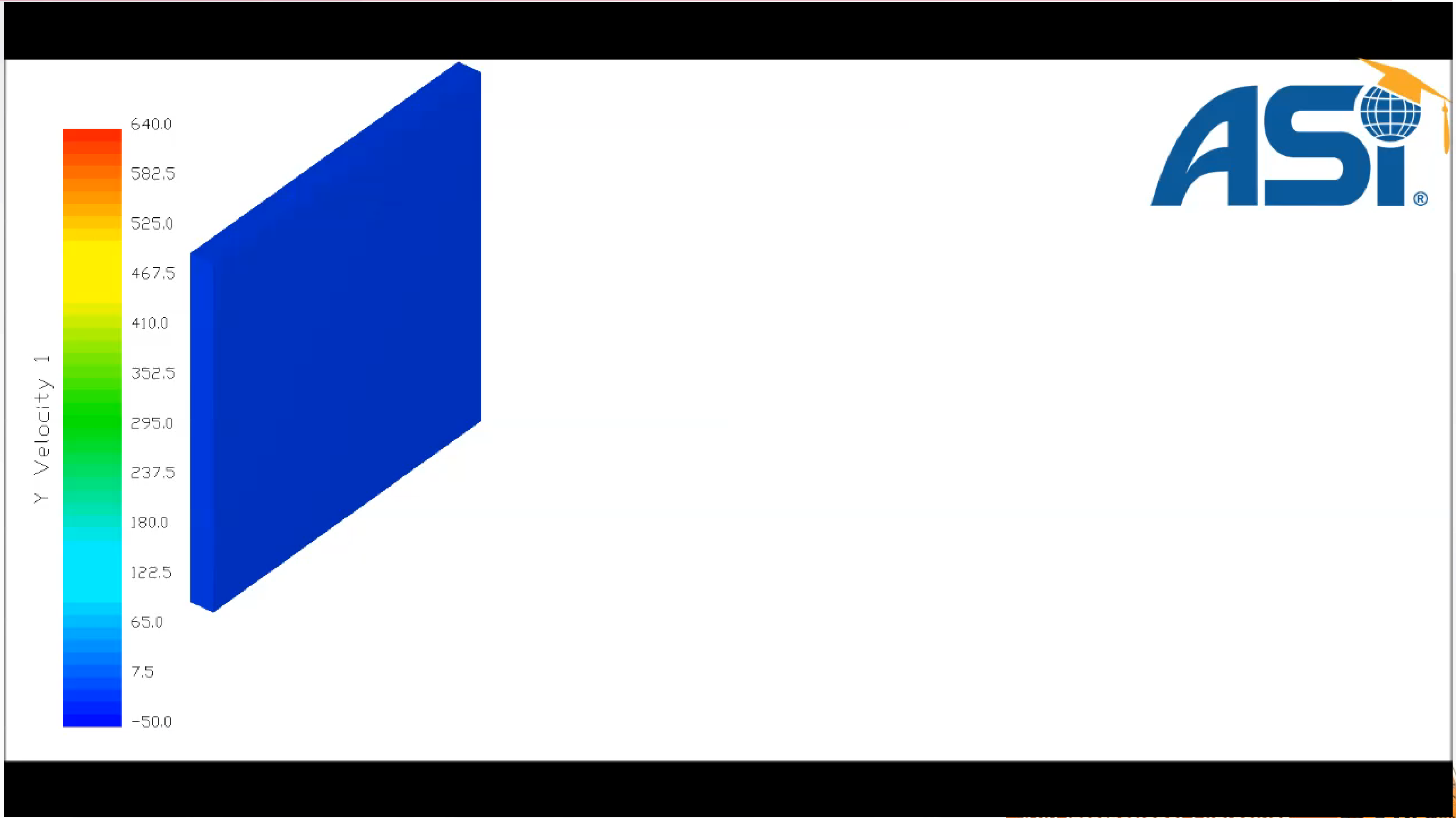
Wall Structural Response History



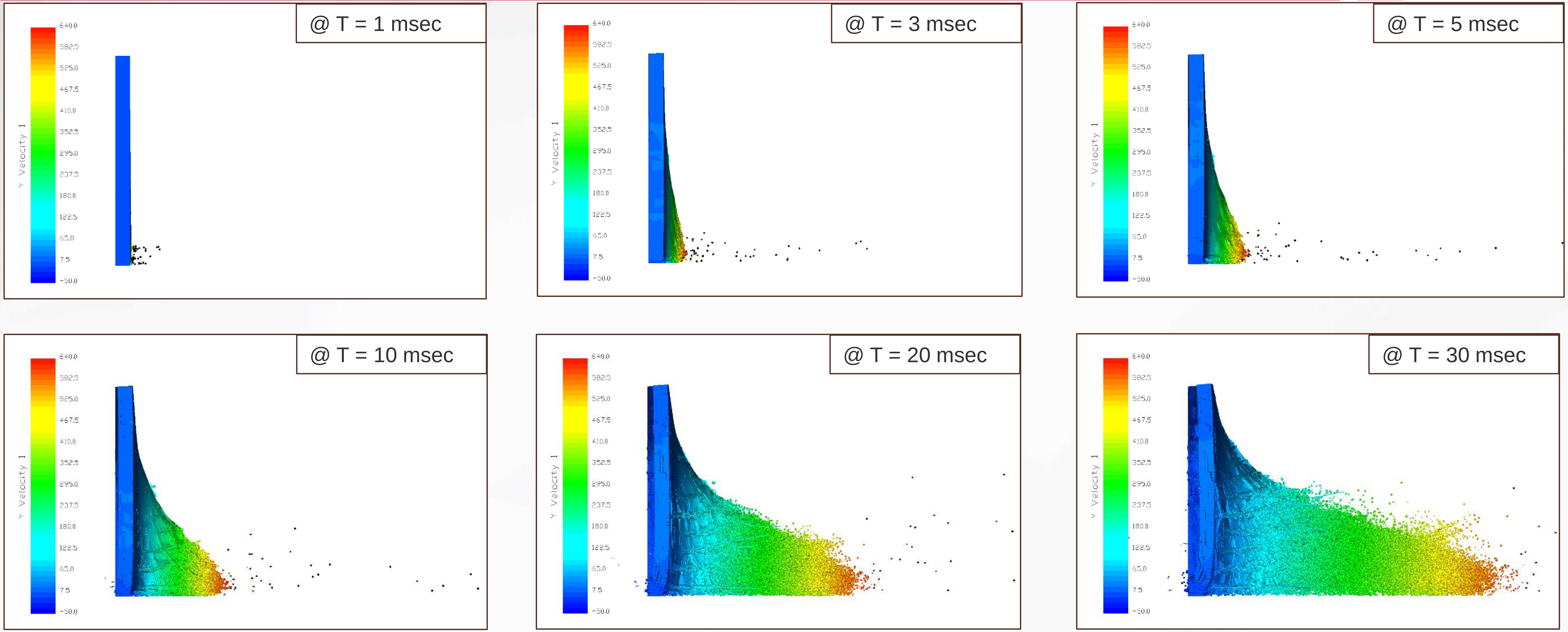
Louis Berger

4.3 Case-2 (10-in RC Wall / 420# @ 3’-0”)

Wall Fragment Velocity Profile

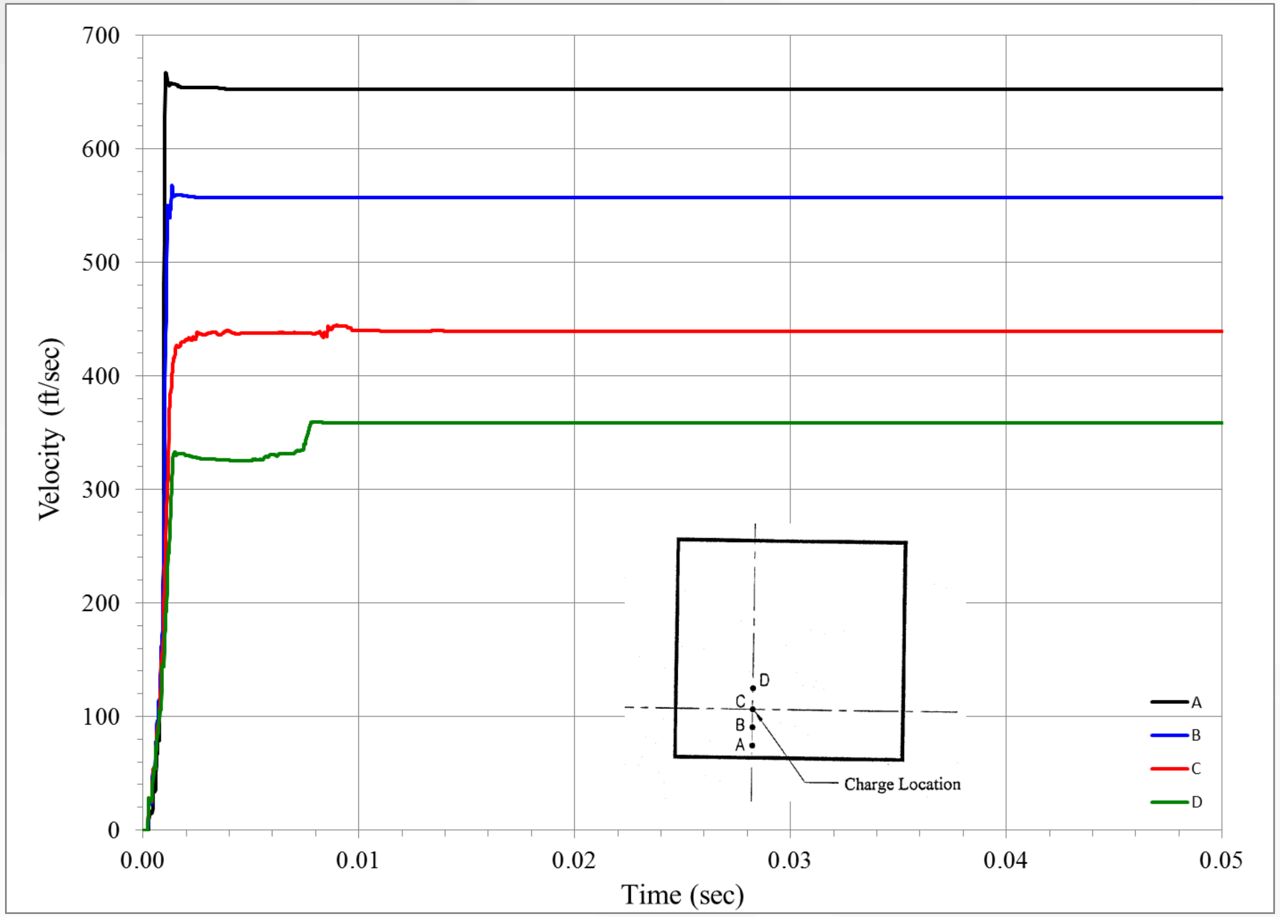


4.3 Case-2 (10-in RC Wall / 420# @ 3'-0")



Wall Fragmentation Progression over Time

4.3 Case-2 (10-in RC Wall / 420# @ 3'-0")



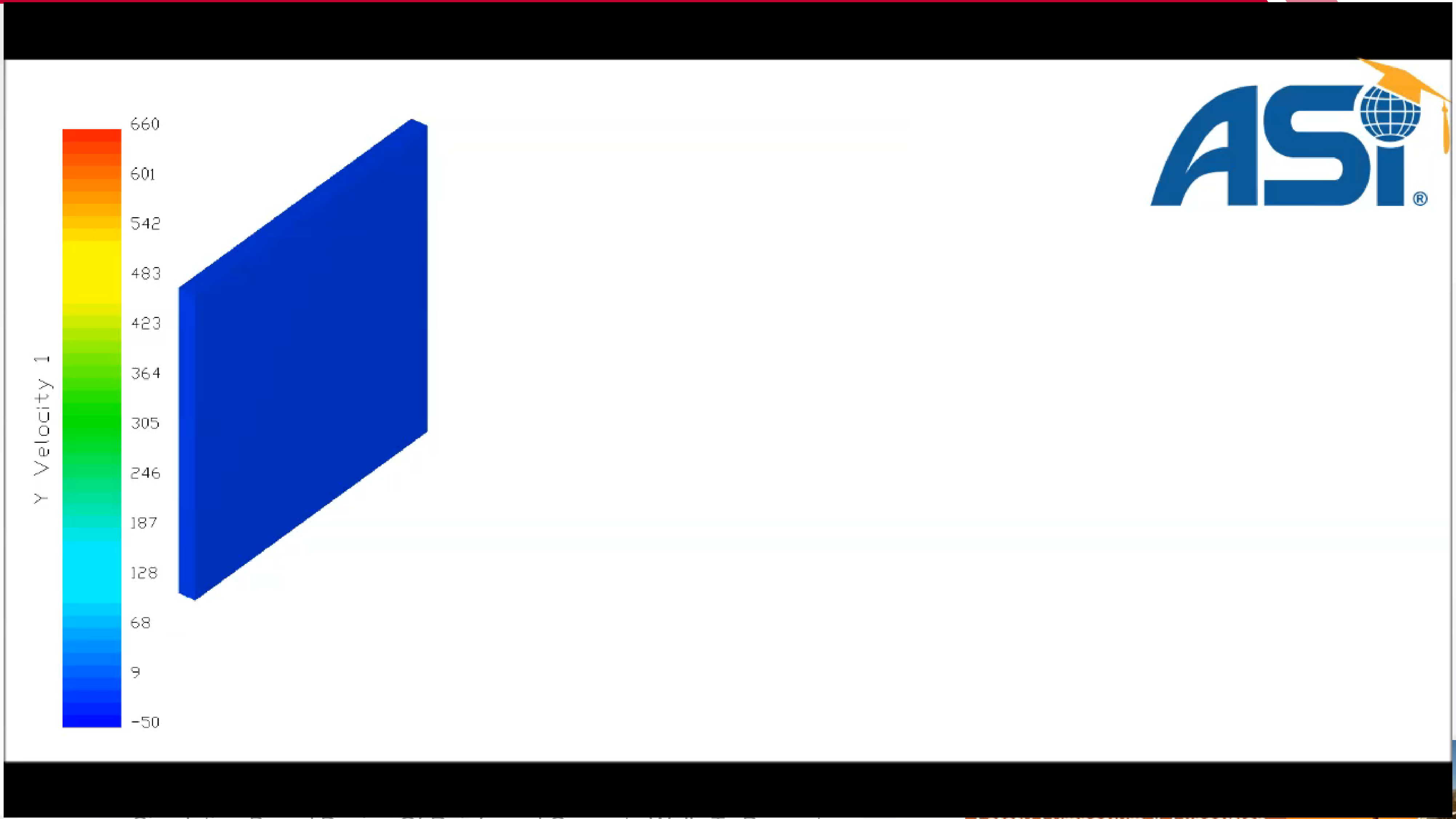
Fragment Velocity Time Histories at Various Positions

4.4 Case-3 (8-in RC Wall / 270# @ 3’-0”)

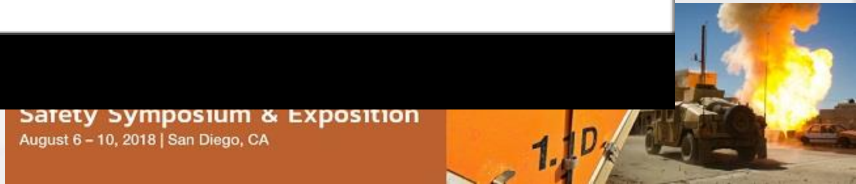
Wall Structural Response History

4.4 Case-3 (8-in RC Wall / 270# @ 3'-0")

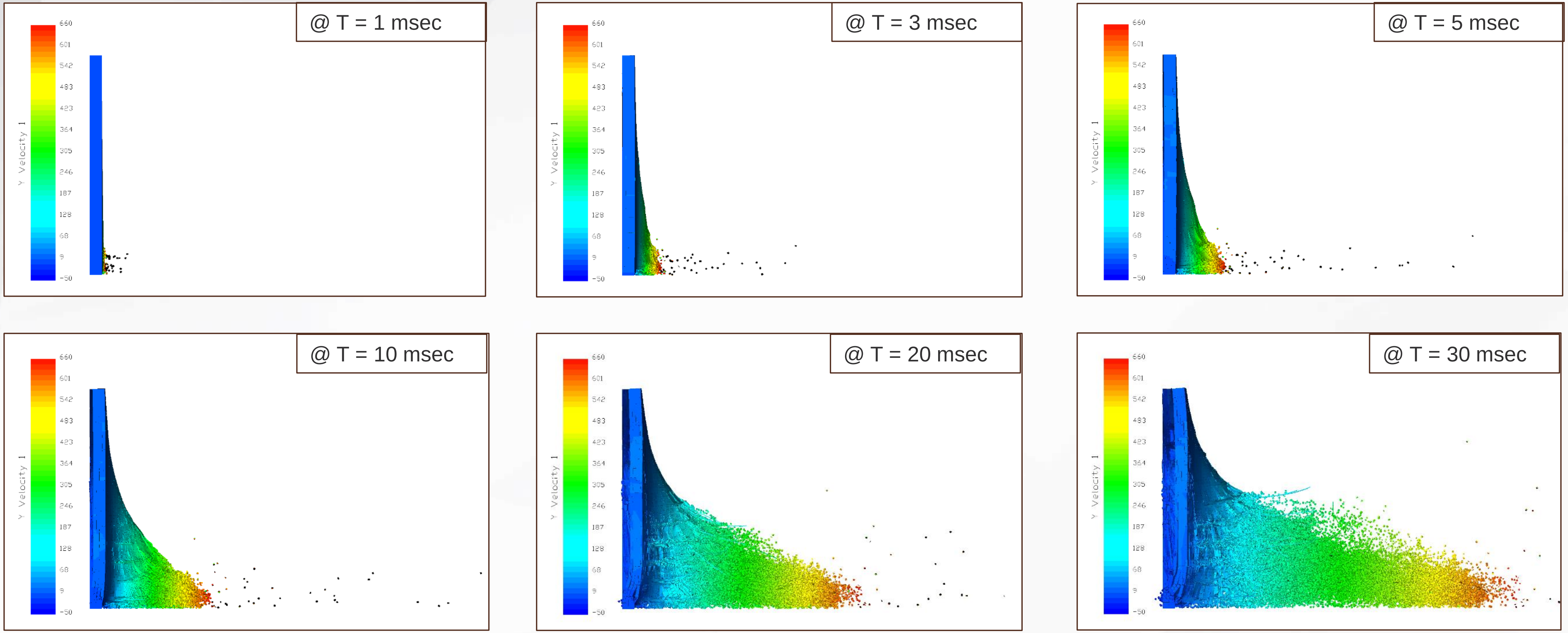
Wall Fragment Velocity Profile



Louis Berger



4.4 Case-3 (8-in RC Wall / 270# @ 3'-0")

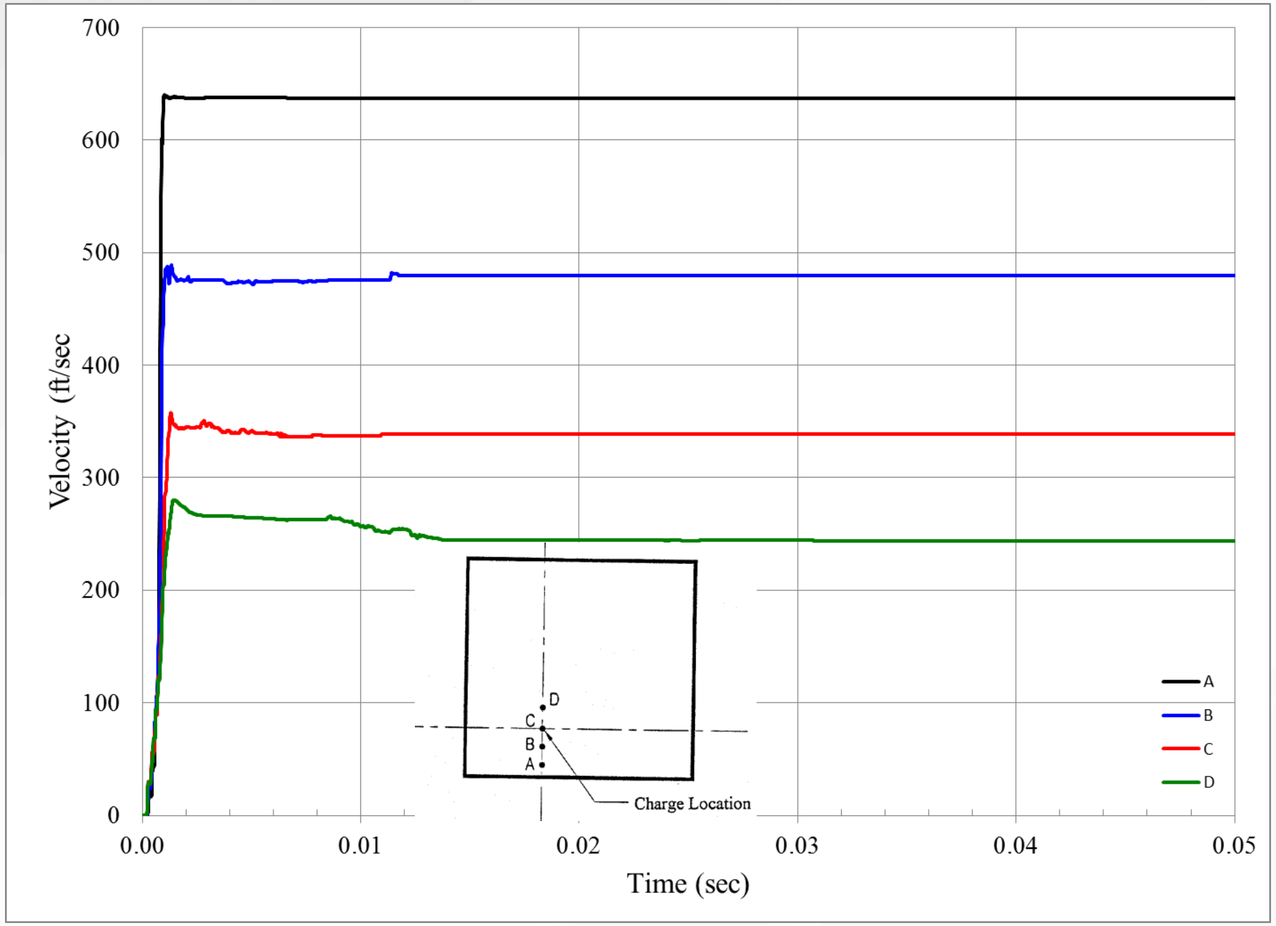


Wall Fragmentation Progression over Time

Louis Berger

ASI

4.4 Case-3 (8-in RC Wall / 270# @ 3'-0")



Fragment Velocity Time Histories at Various Positions

5- Concluding Remarks

Concluding Remarks

- The **Simulation-Based approach** can be used to **optimize the design** of RC walls to prevent sympathetic detonation in explosive facilities. This approach allows protective design engineers to achieve the targeted levels of protection based on a **physics-based rationale** which promotes **construction economy**.
- The Simulation-Based approach **can be improved through calibration** using available testing measurements and observations. This can lead to great savings by **eliminating the need to perform time-consuming and costly blast testing**.

Concluding Remarks

❖ The **AEM technique** implemented in **ELS software** can be used successfully to simulate highly plastic **RC response to close-range blast environment.** The Software proved its capabilities to adequately predict high levels of **structural damage including fragmentation and breaching**.

Concluding Remarks

- The current study utilized the Simulation-Based approach to compute the **SD blast-rating of RC walls** and based on the simulation results using a **maximum fragment velocity (V_{max}= 650 ft/sec**: *based on Impact threshold criterion for SG4)*, it was found that the investigated (12 x 12 ft) RC walls have **SD blast ratings of:**

  615, 420, 270 Lbs of TNT for 12-, 10-, and 8-in Walls.

6- Future Research Work

Future Research Work

Perform **Parametric Studies** to investigate the influence of various design parameters on the blast rating and damage potential of RC walls used to prevent blast propagation including:

1- Blast Environment (charge weight, shape, dimension, casing, range, cubicle size, venting area, blast computation software/ models)

Future Research Work

2- Structural Design Configurations (Material strength, reinforcement details, cubicle/ Wall geometry, varying wall thickness over height, boundary conditions)

3- Numerical Simulation Technique (Constitutive material models, discretization, strain rate effects, end restraints, concrete-rebar interface)

4- Performance Criteria (fragment impact thresholds for various explosive sensitivity groups)

7- Questions