FIRE © IMPACT © BLAST
REPAIRS AFTER EXTRAORDINARY EVENTS

Wednesday
November 9
11:15 AM – 12:00 PM

2022 ICRI Fall Convention | Atlanta, GA | November 7-9

Bomb Blast Primer

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Woodstock, Georgia

ICRI
CONCRETE REPAIR
Restore | Repurpose | Renew

Today's Presenter

- **Scott L Weiland PE SE**
  - Principal, Innovative Engineering Inc.
  - Education
    - BSCE **University of Michigan**
    - Graduate Studies in **Structural Dynamics:**
      - San Jose State University
      - Georgia Institute of Technology
    - **Security Engineering:** USACE Protective Design Center
    - **Interagency Security Committee (ISC)** Risk Management Process: ARA
    - Counter Terrorism Workshop for Improvised Explosive Devices (IED) and Vehicle-Borne Improvised Explosive Devices (VBIED) - **Department of Homeland Security (DHS)**
  - Registration: PE in 40 States + PR & GU
  - **26 Years Physical Security Engineering**

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Learning Objectives

- Blast Theory
- Blast Analysis
- Blast Design
- Progressive Collapse

Explosives

- **Explosion**
  - Sudden Release of Energy
  - Audible Sound
- Types of Explosions
  - **Expansion**
    - Bursting Pressure Vessel
    - Boiling Liquid Expanding Vapor Explosions (BLEVES)
    - Rapid Phase Transitions (RPT's)
  - **Oxidation**
    - Vapor Cloud Explosions
    - Dust Explosions
    - **Condensed Phase Explosion (High Energy Explosives)**

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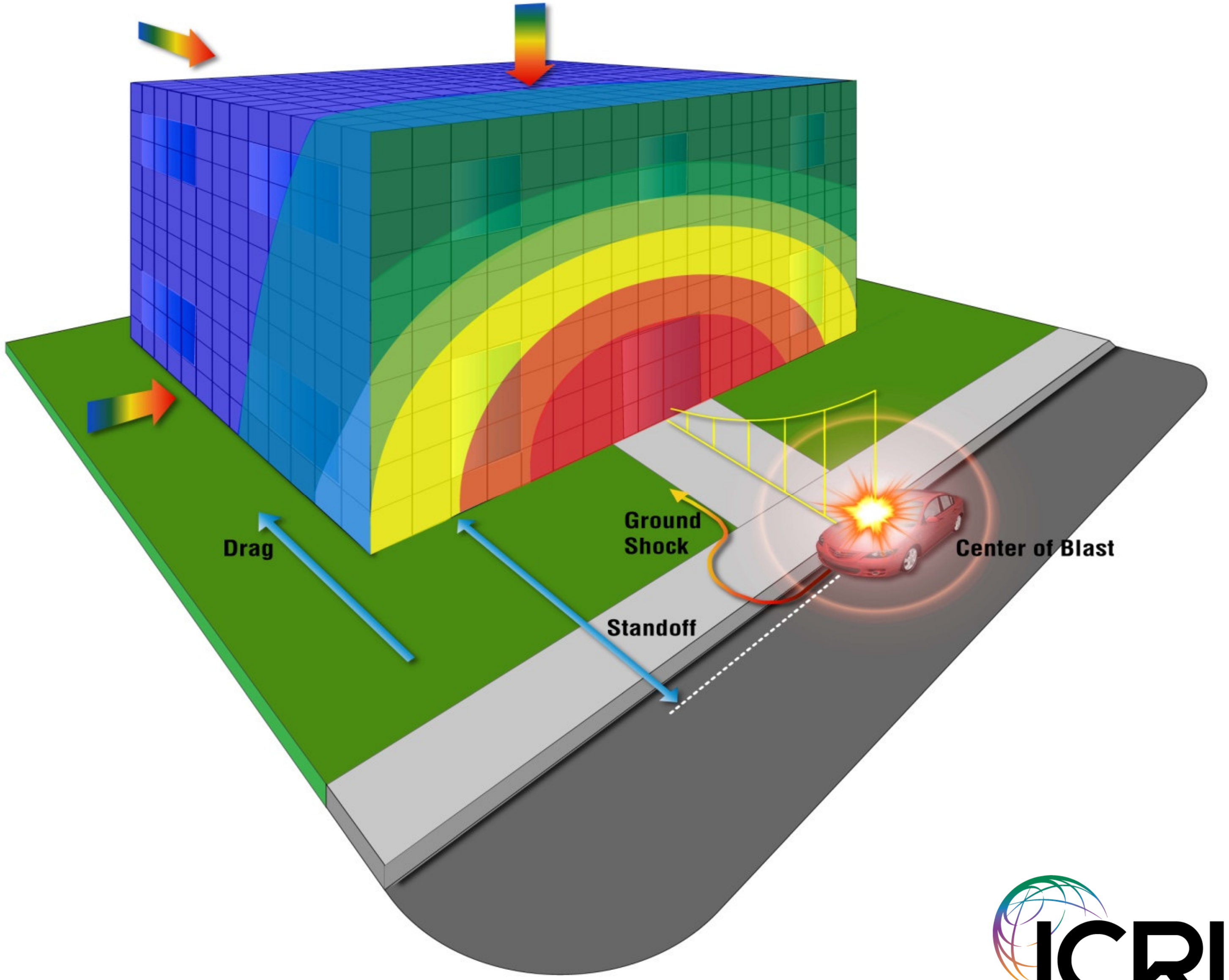
Blast Theory - Definitions

- **Aggressor**
- Tactic – Stationary Bomb
- **Standoff**
- Shock Wave
- **Reflective Pressure**
- **Side-On/Incident Pressure**
- Dynamic (Blast Wind) Pressure
- Hardening
- Asset



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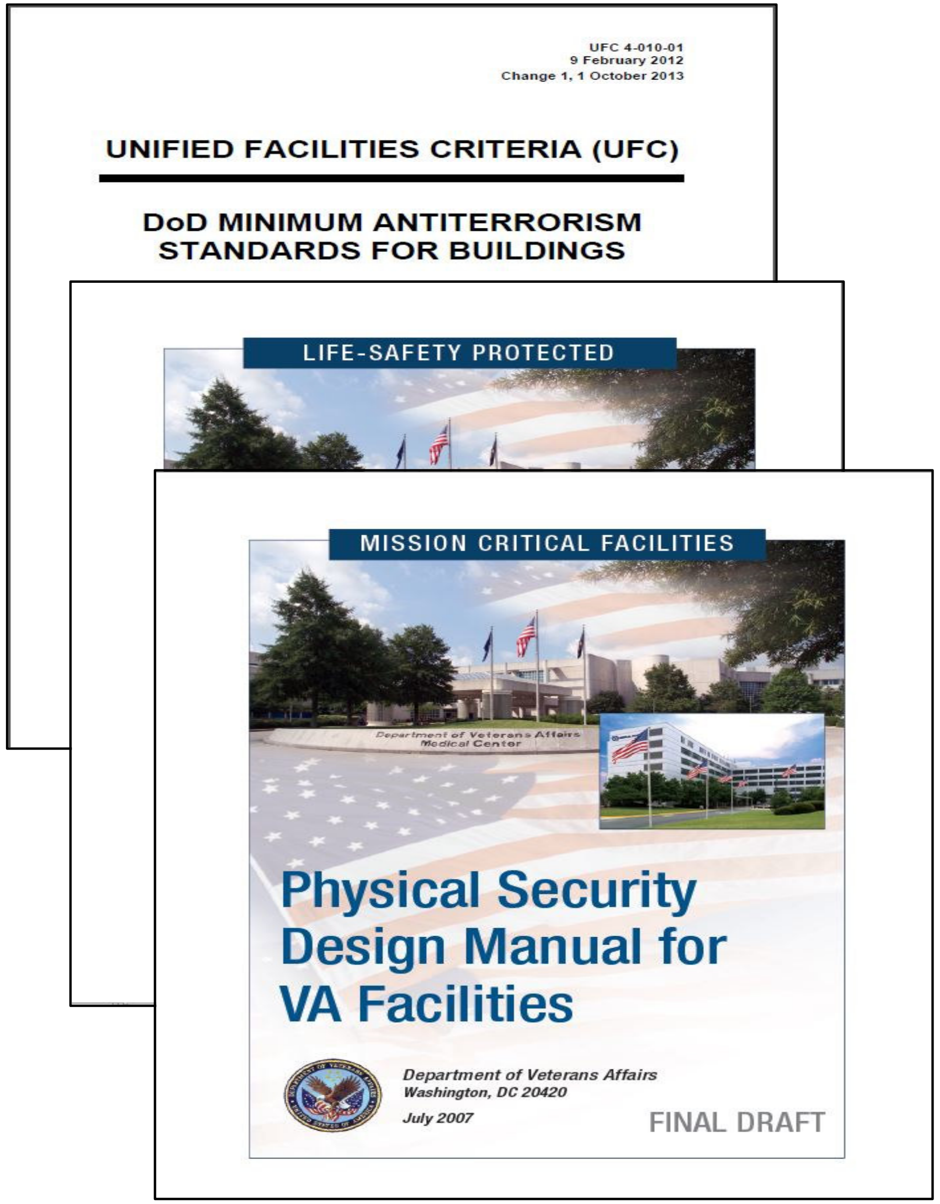
Risk Reduction Criteria

- Prominent Design Criteria
  - GSA Facility Security Requirements for Explosive Devices Applicable to Facility Security Levels III and IV, GSA's Interpretation of the Interagency Security Committee (ISC) Physical Security Criteria. (FOUO)
  - DoD Minimum Antiterrorism Standards for Buildings, UFC 4-010-01
  - VA Physical Security Design Manuals (PSDM) for Life Safety & Mission Critical Facilities
- Minimum Standards
- Need to be adapted to private facilities



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Pressure Shock Wave

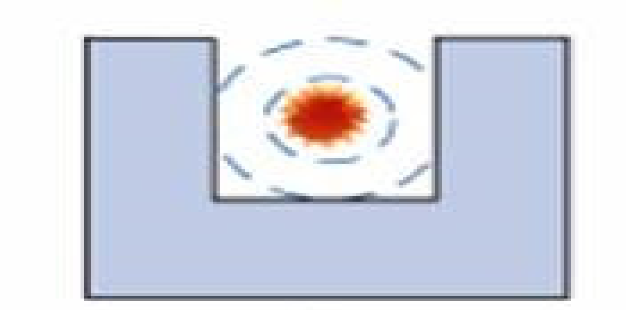
Blast Theory – Pressure Wave

- Supersonic pressure wave caused by detonation
- Like water wave including reflections and refractions and reformation

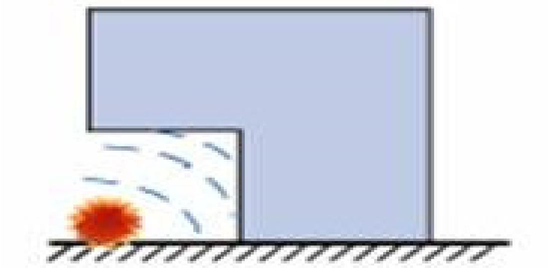
Blast Theory – Vehicle Bomb

- Surface Burst (VBIED)
- Pressure Radiates
- Reflected Pressure
- Refracted Pressure
- Side-On Pressure

Blast Theory - Shapes That Affect Blast

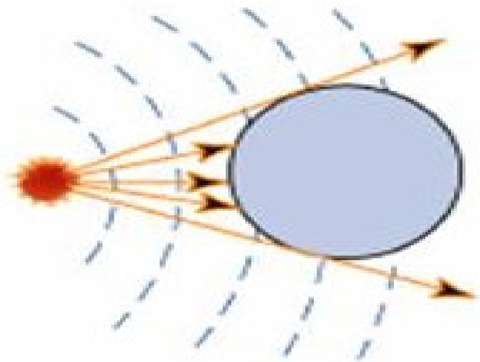


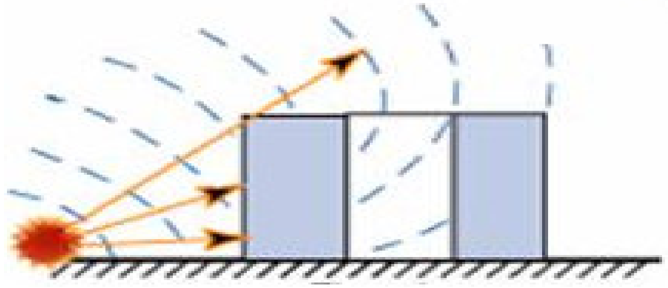
Re-entrant corners



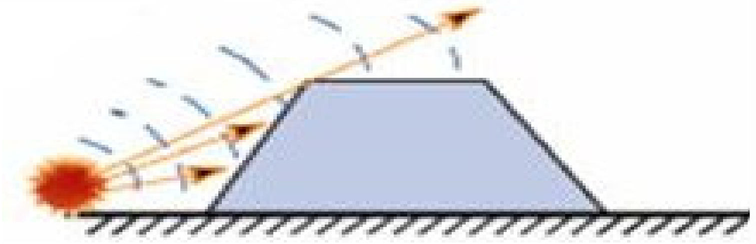
Overhang

Round Shape

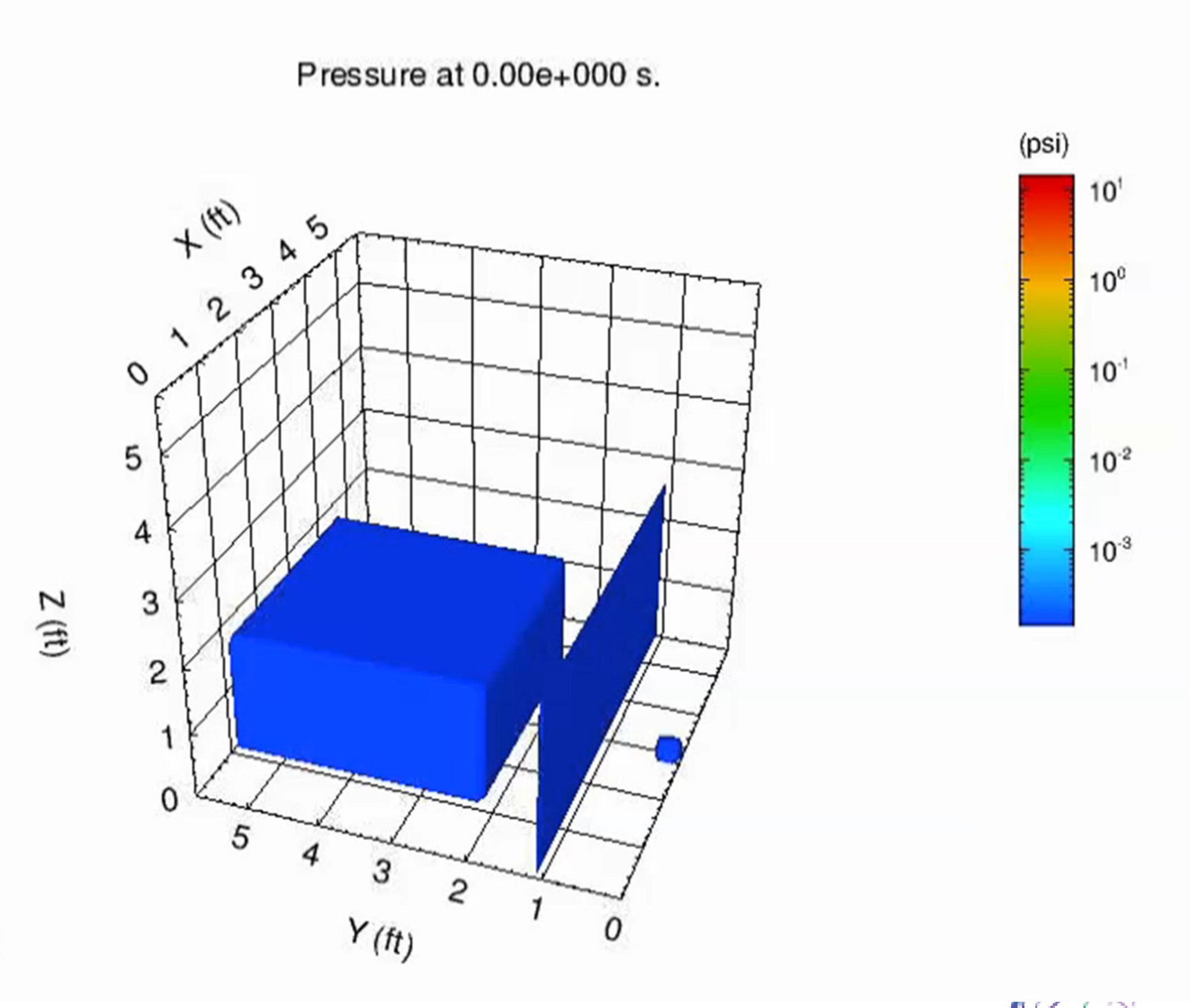




Blast Wall

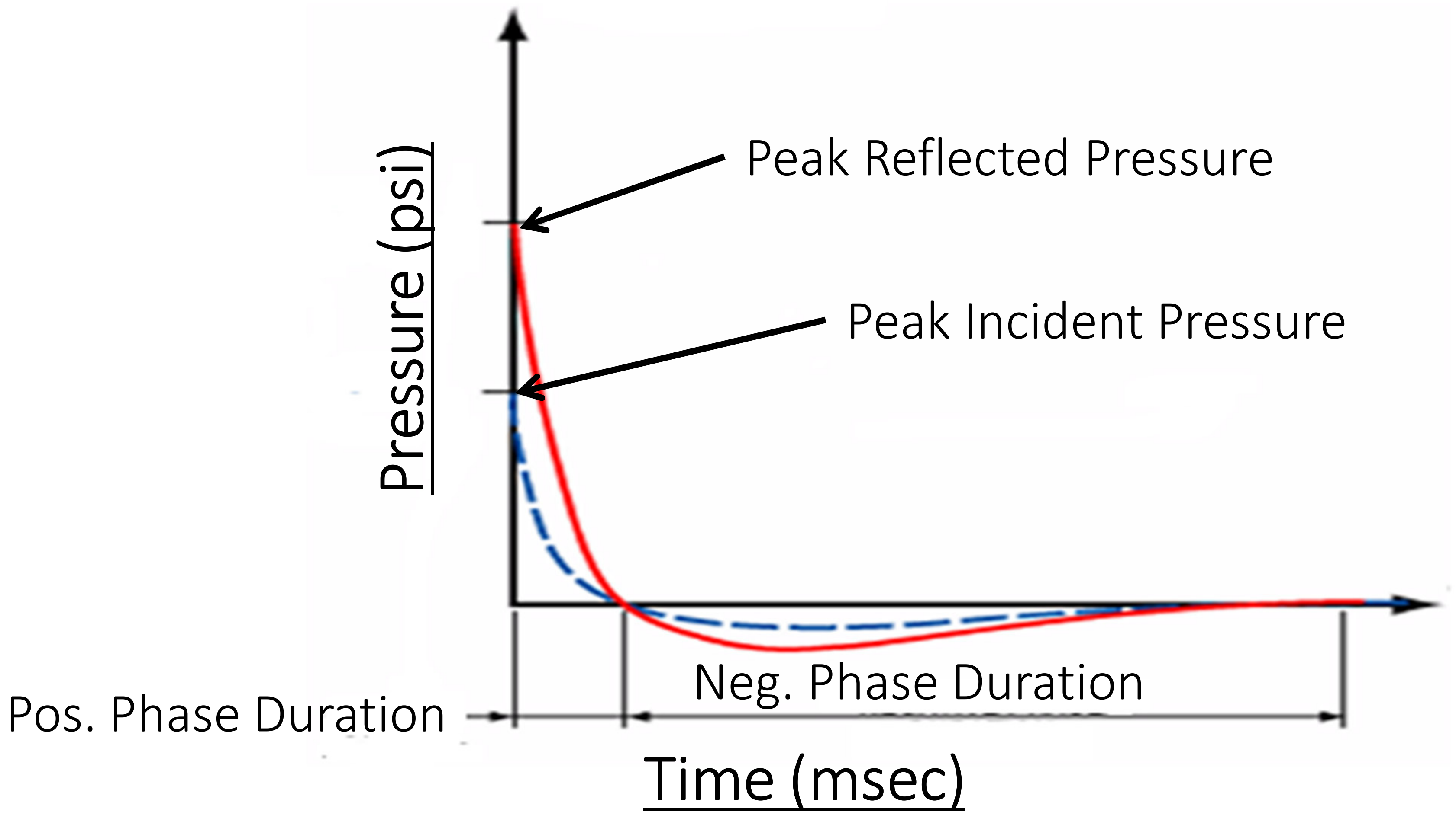


Berm



Blast Wall - CFD

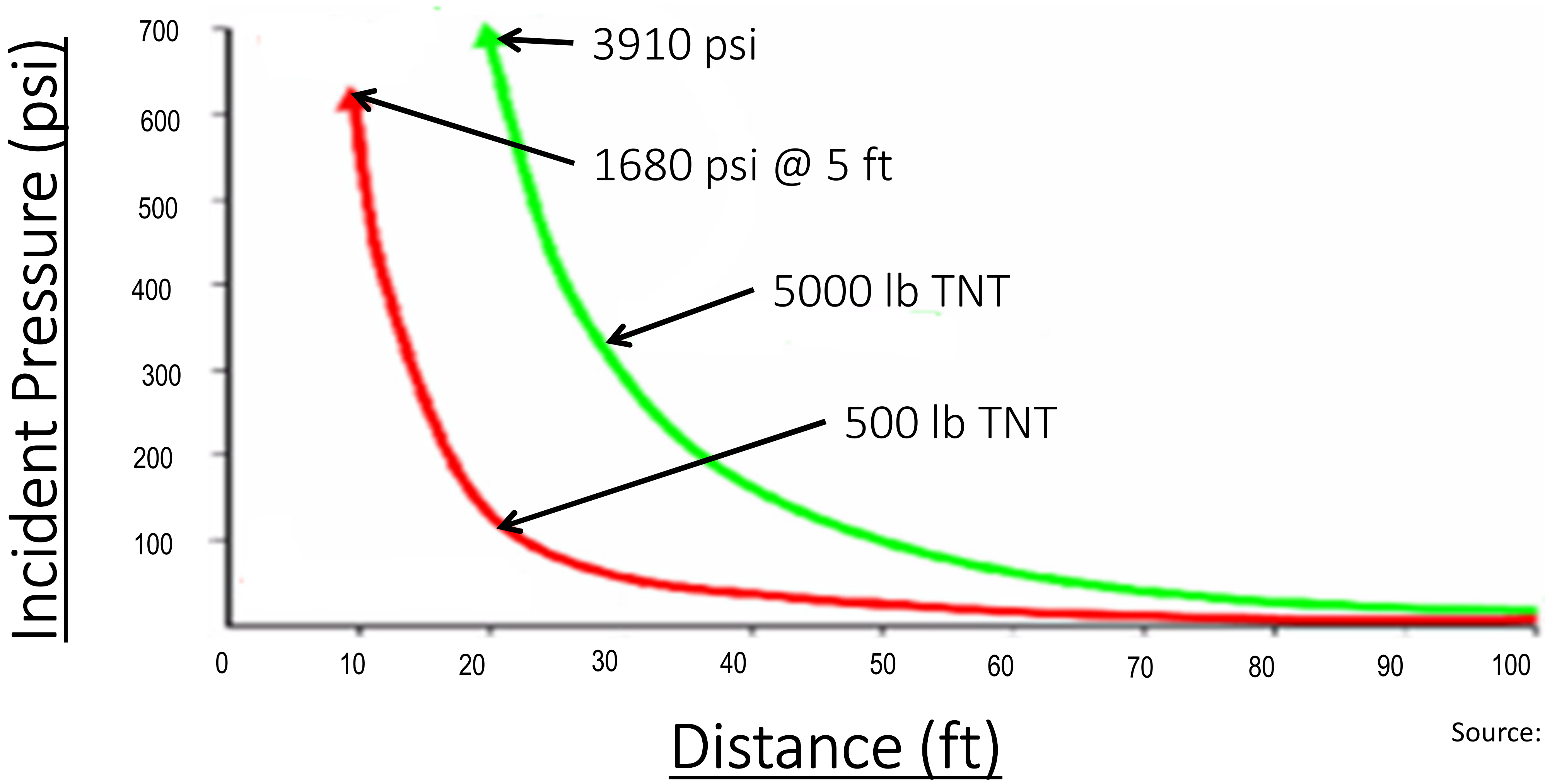
Blast Theory – Time History



Source: FEMA 427

- Pressures decay exponentially with time.
- Dynamic, non-linear, time history analysis.

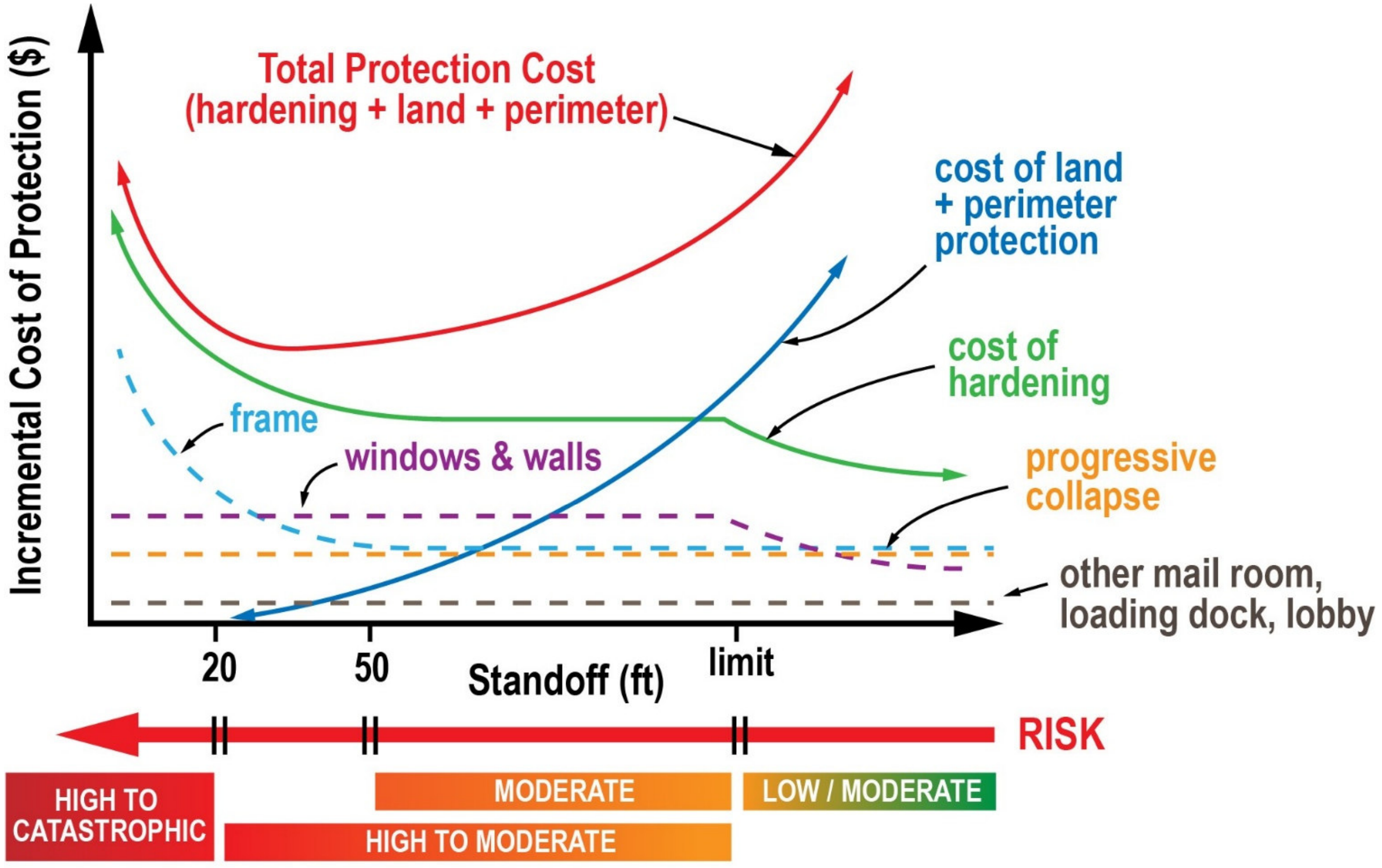
Blast Theory - Distance



Source: FEMA 427

- Pressures decay with the cube root of the distance from the explosion.

Blast Theory - Optimum Standoff



Plots showing relationships between cost of upgrading various building components, standoff distance, and risk

- **Optimum Stand-Off**
  - More Stand-Off = Less Hardening, More Land
  - Less Stand-Off = More Hardening, Less Land

Source: FEMA 427

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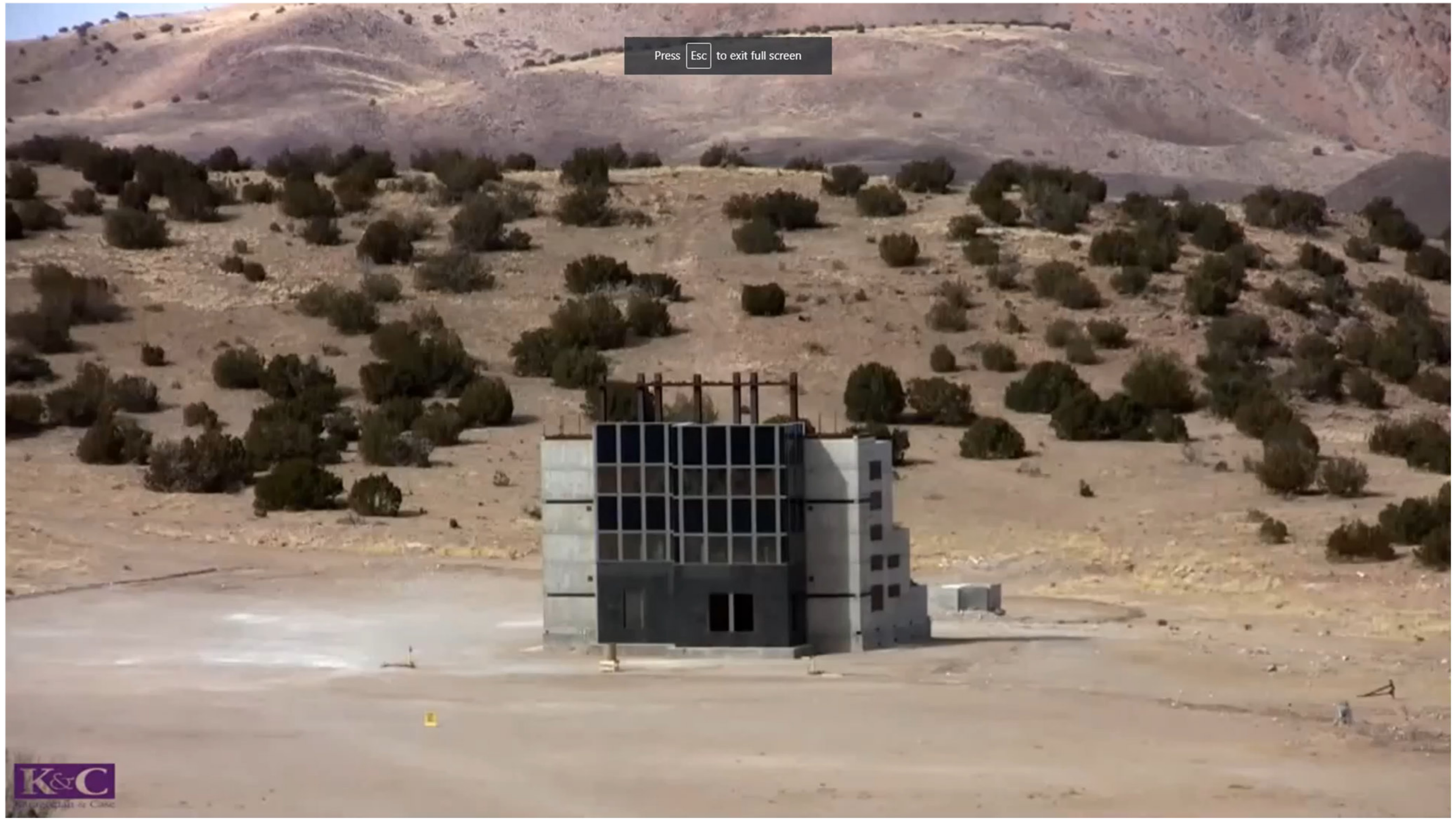
Blast Theory - Explosion

- Karagozian & Case, Inc.
- State Department
- Retrofit curtainwall system



Blast Theory - Explosion

- Shock Wave
- Reflected Pressure
- Rebound
- Side-On Pressure

Blast Theory - Explosion

- Shock Wave
- Reflected Pressure Wave
- Rebound

Blast Design – Conservation of Energy

Energy Equation

- $W_P = W_K + W_S$
  - W_P = *Blast Energy*
  - W_K = *Kinetic Energy*
  - W_S = *Strain Energy*

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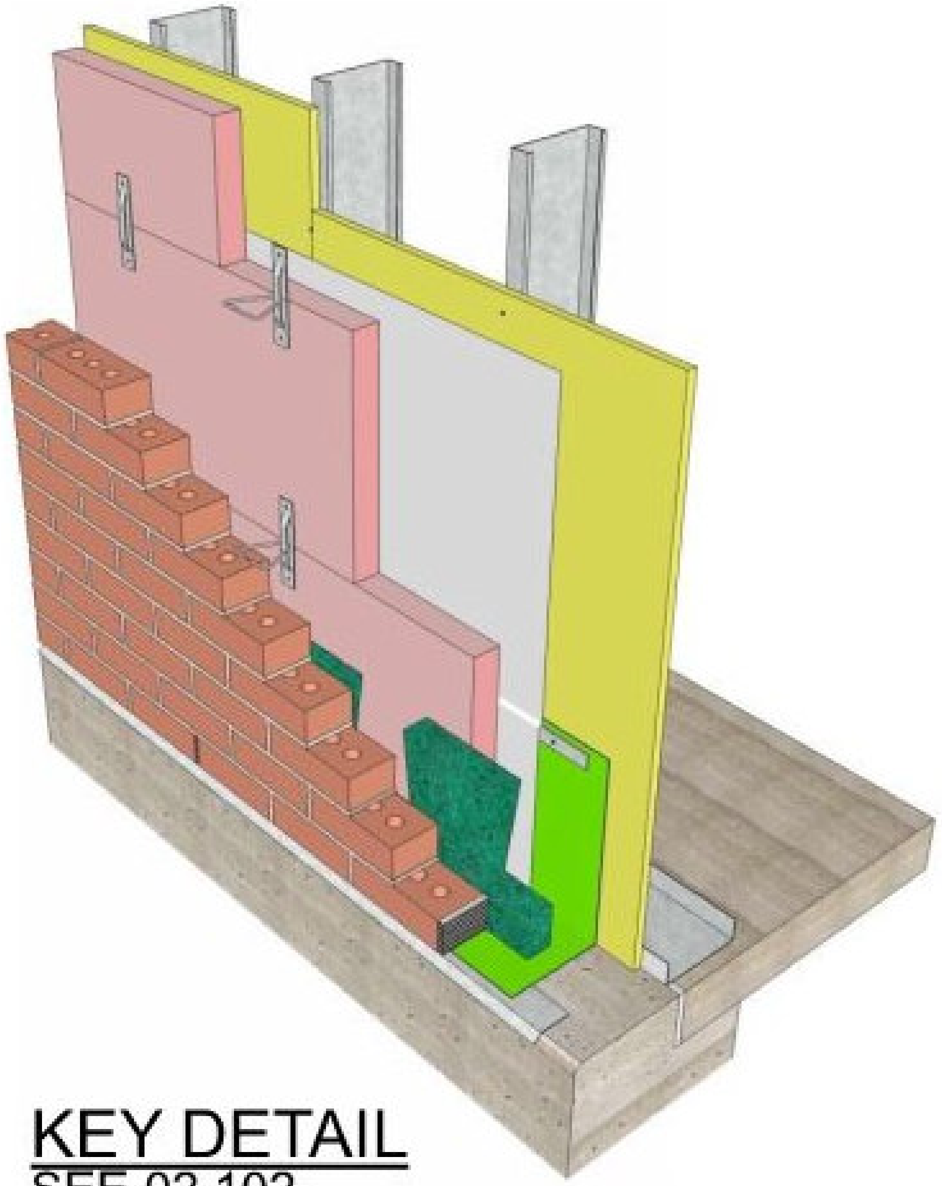
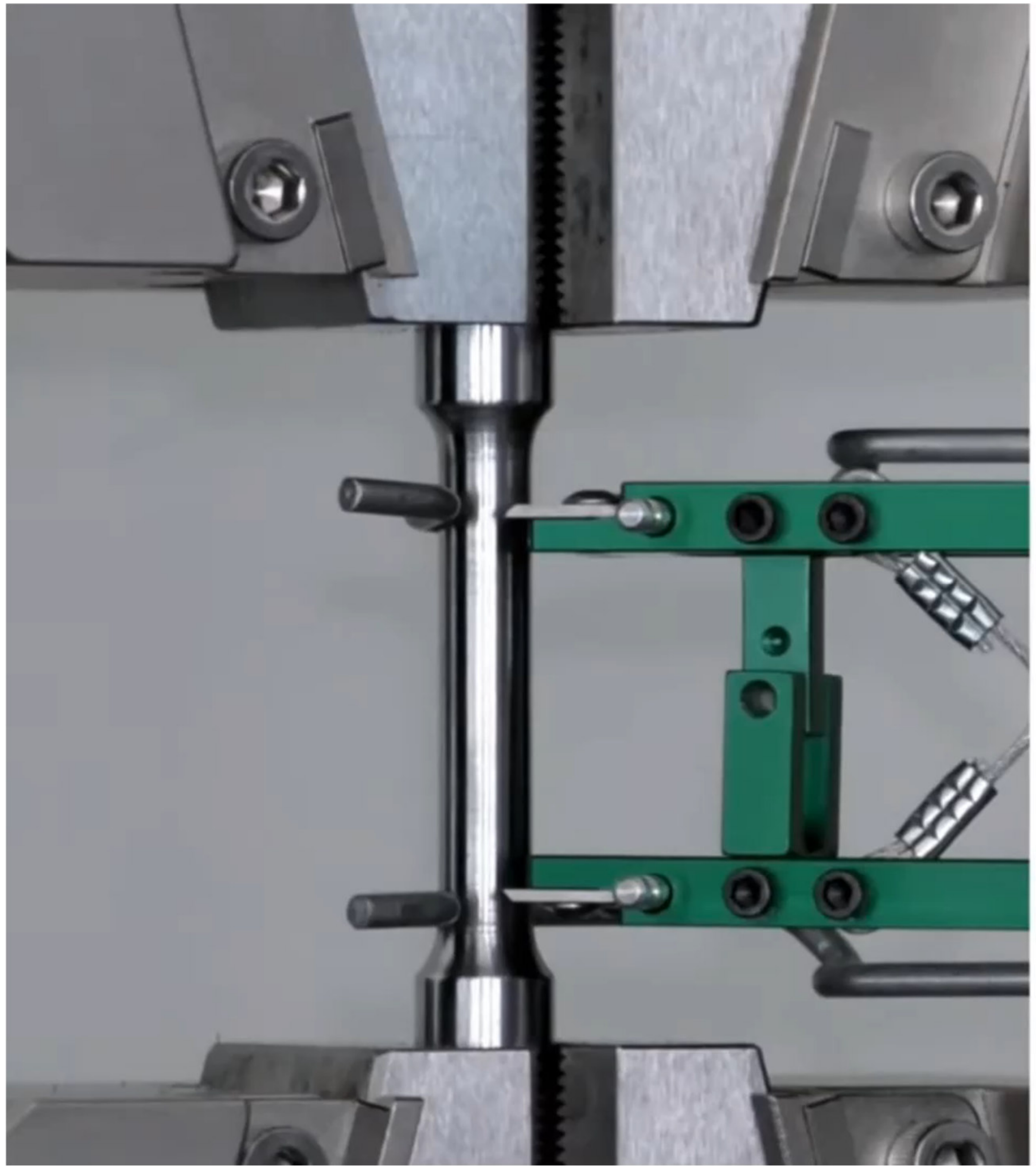
Blast Design – Kinetic Energy

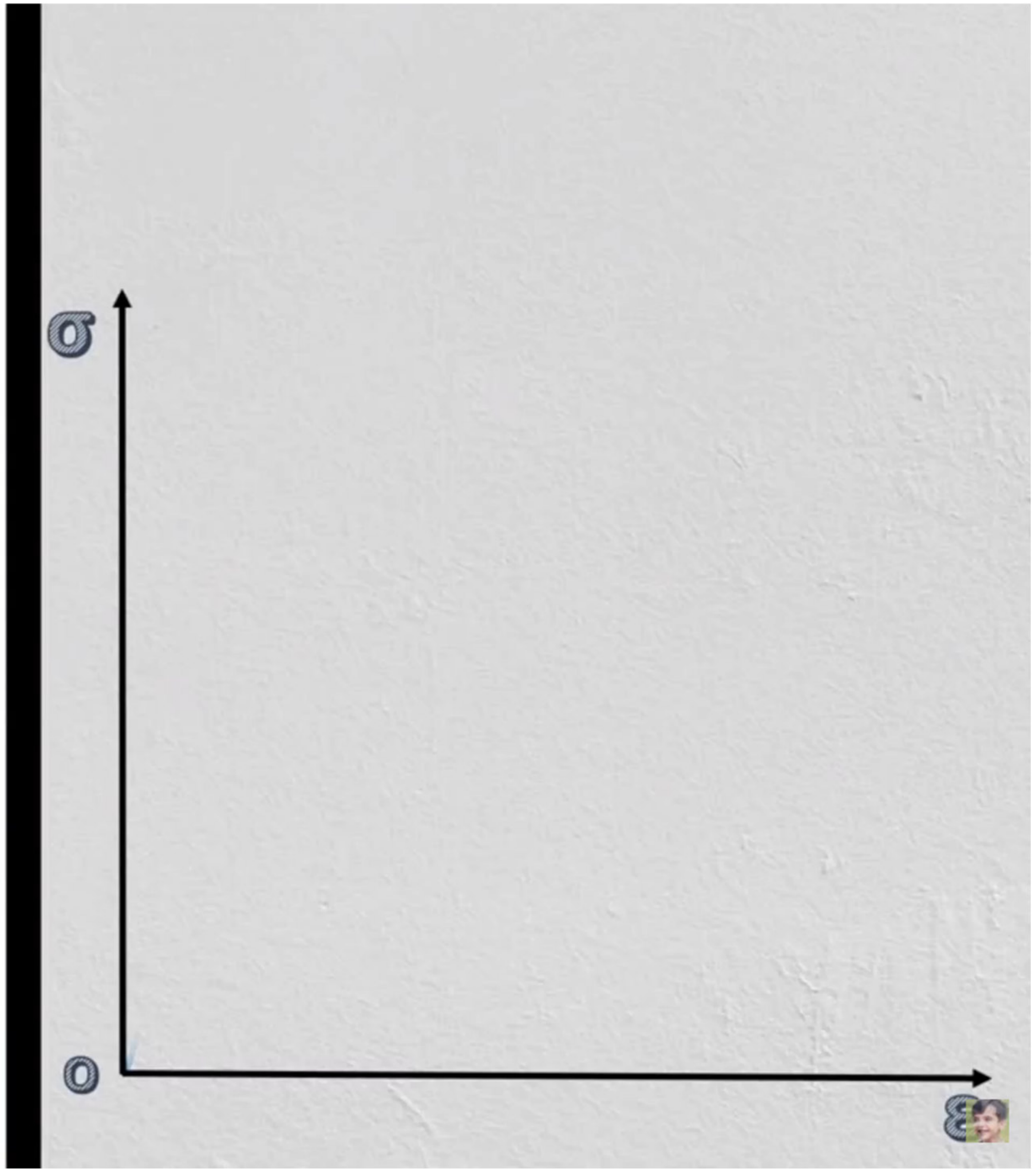
$$W_K = \frac{m_e * V^2}{2}$$



KEY DETAIL
SEE 02.102
Masonry Wall Institute

Blast Design – Strain Energy – Ductility

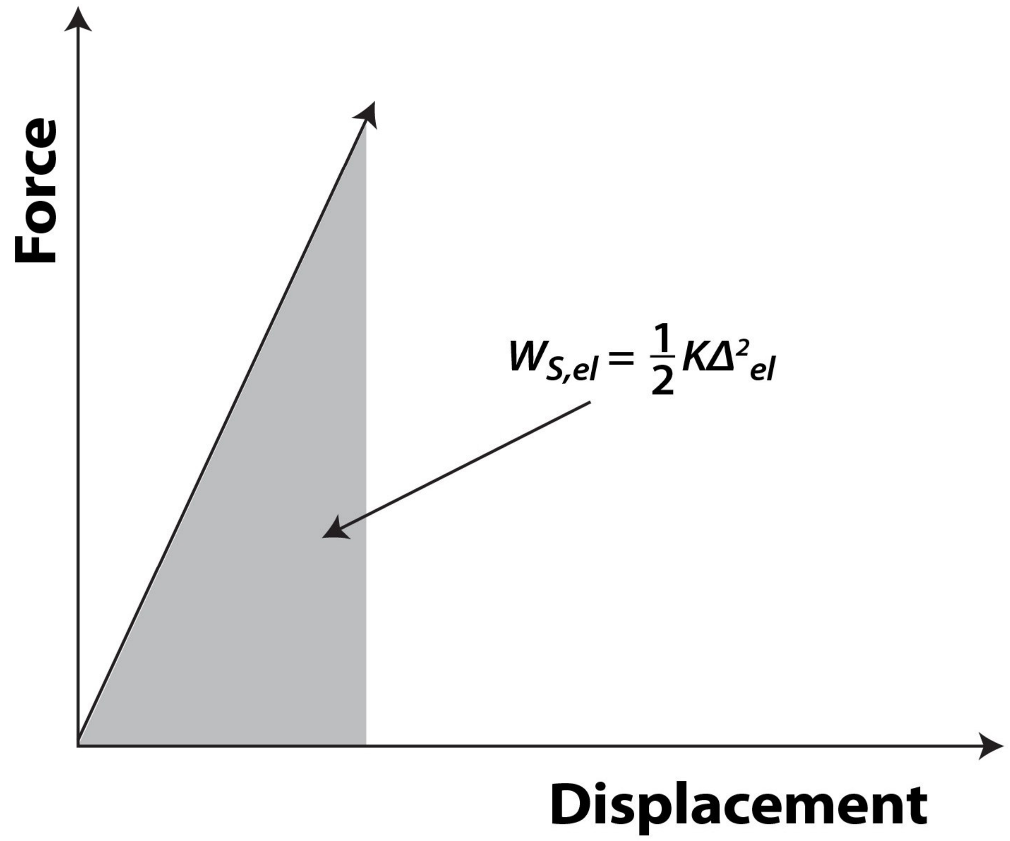




- Regions
  - Elastic
  - Plastic
- Area = Strain Energy

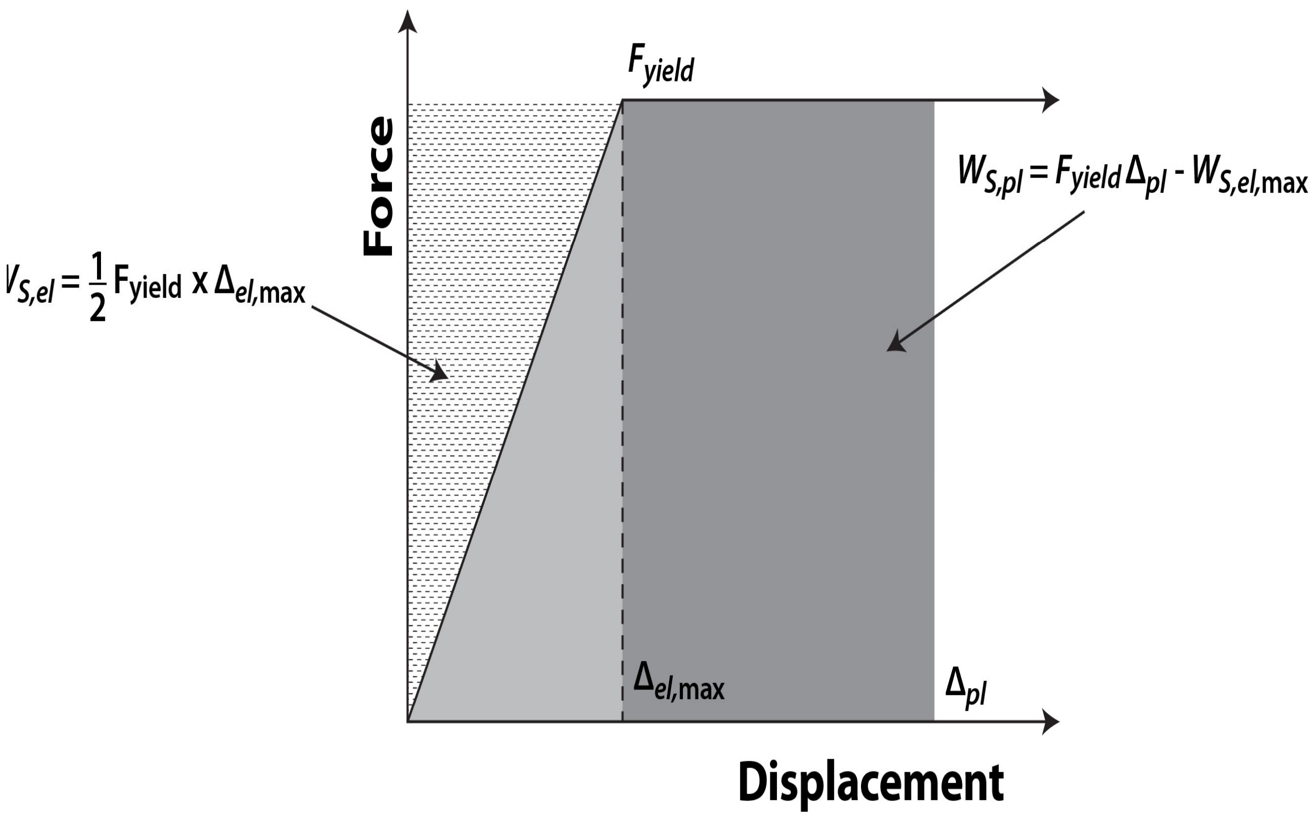
Blast Design – Strain Energy

Linear Elastic Behavior



$\mu = 1.0$

Linear Elastic-Plastic Behavior



$\mu > 2.0$

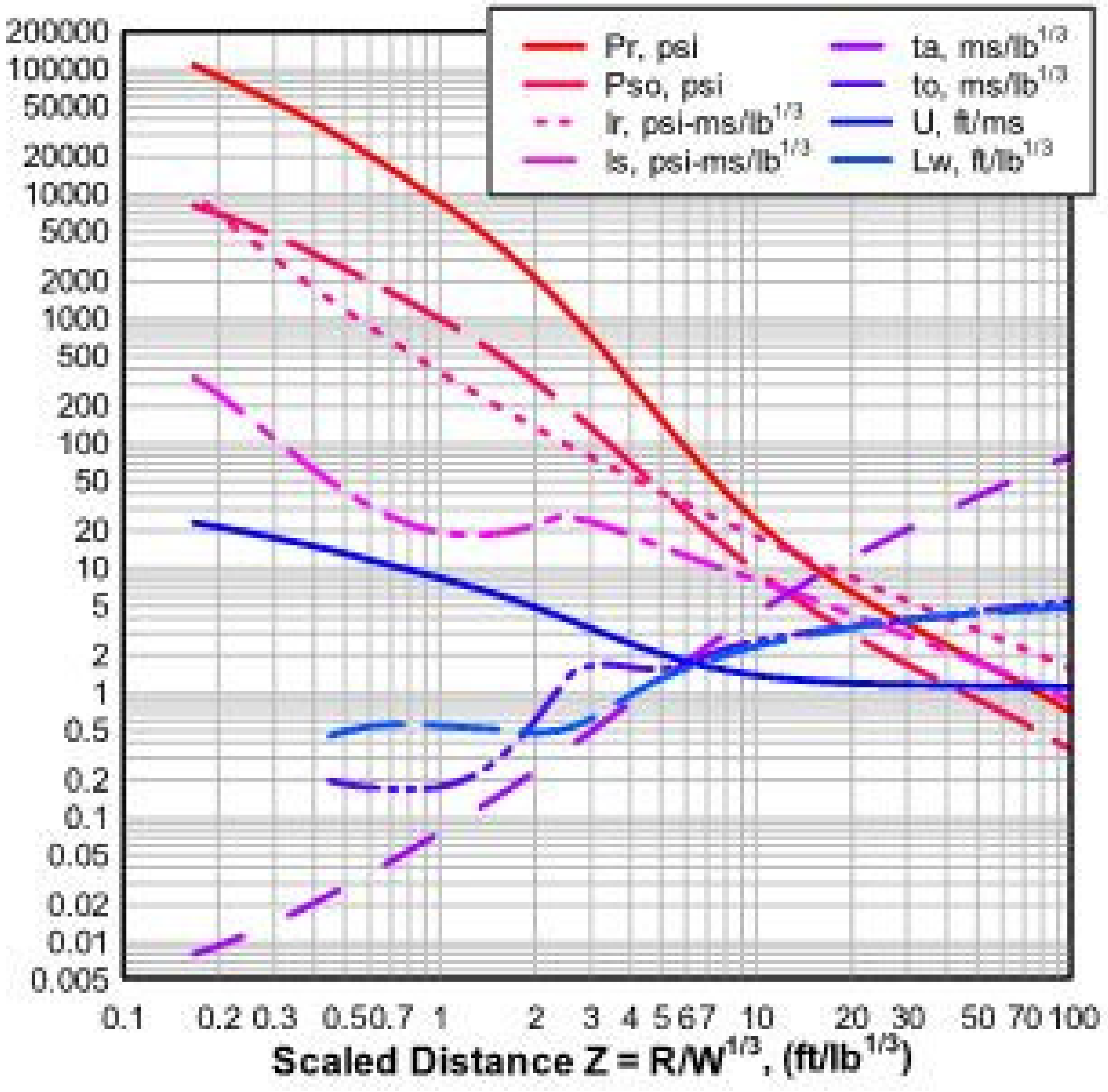
Blast Theory – Energy Absorption

- Laminated Glass
  - 1st Level
    - 2 ½”
    - Forced Entry Resistant
    - Ballistic Resistant
    - Blast Resistant
  - 2nd & 3rd Level
    - 2”
    - Blast Resistant

Blast Design Process

1. Explosion Hazard
2. Blast Loads
3. Trial Structural System
4. Dynamic Material Properties
5. Structural Analysis – Primary members
6. Structural Design – Secondary Members
7. Performance Criteria
8. Drawings & Details

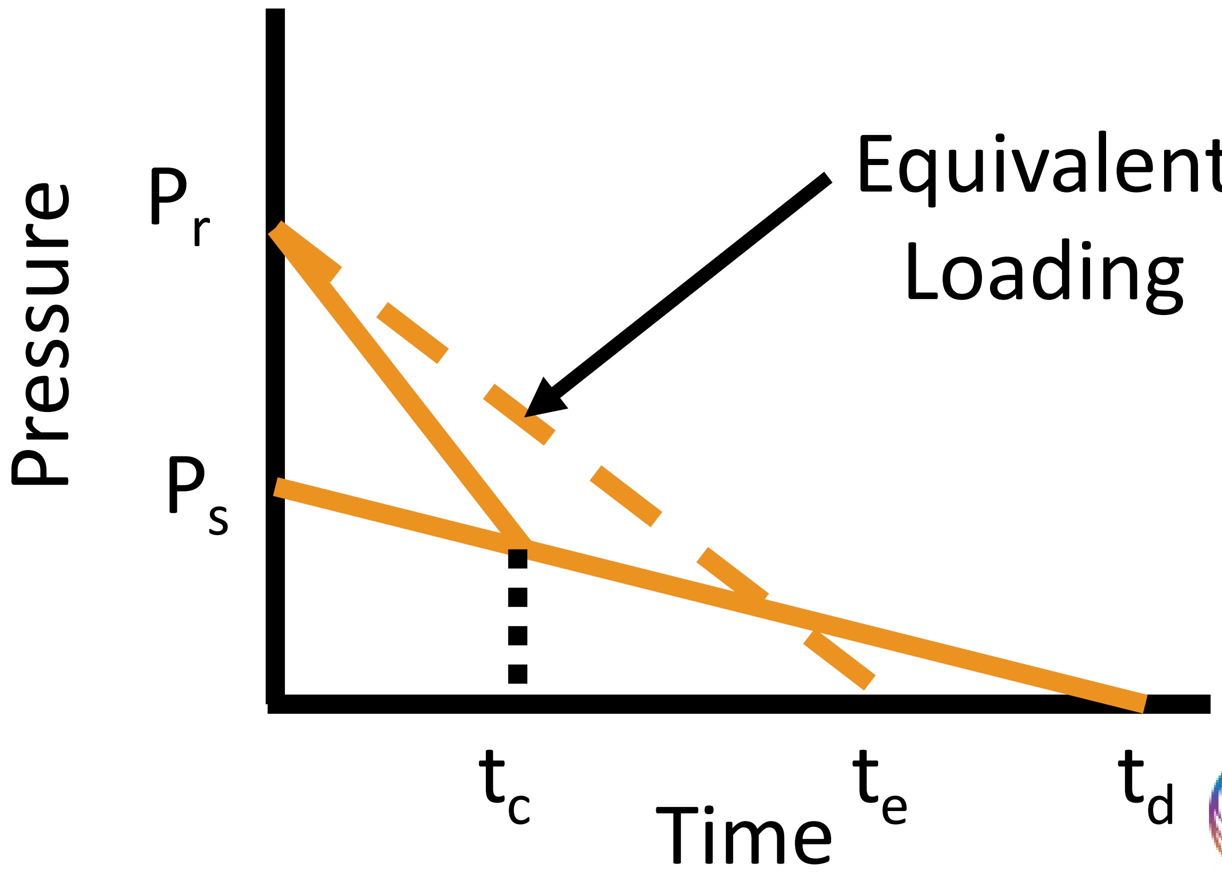
Blast Loads - Charts



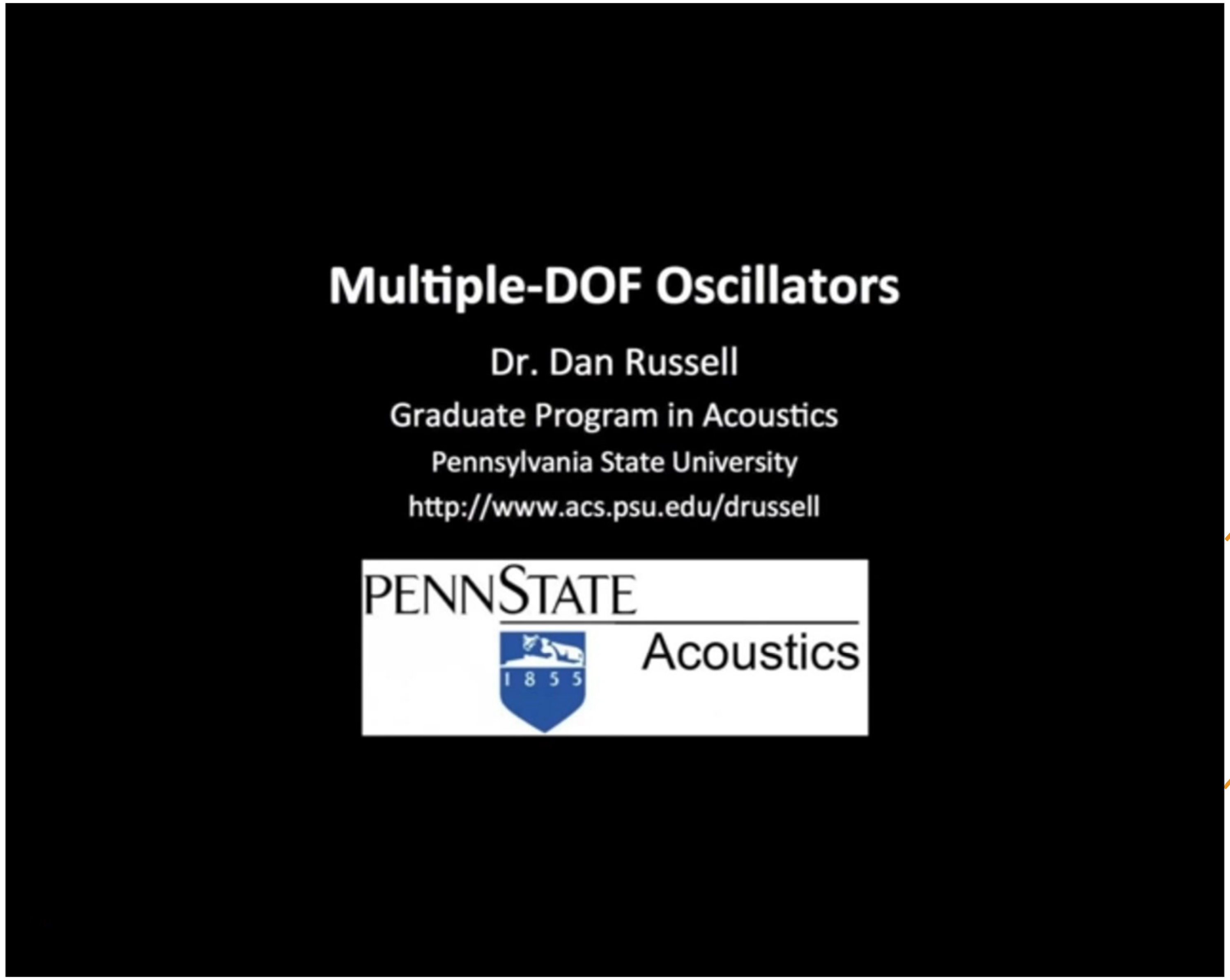
Scaled Distance $Z = R/W^{1/3}$

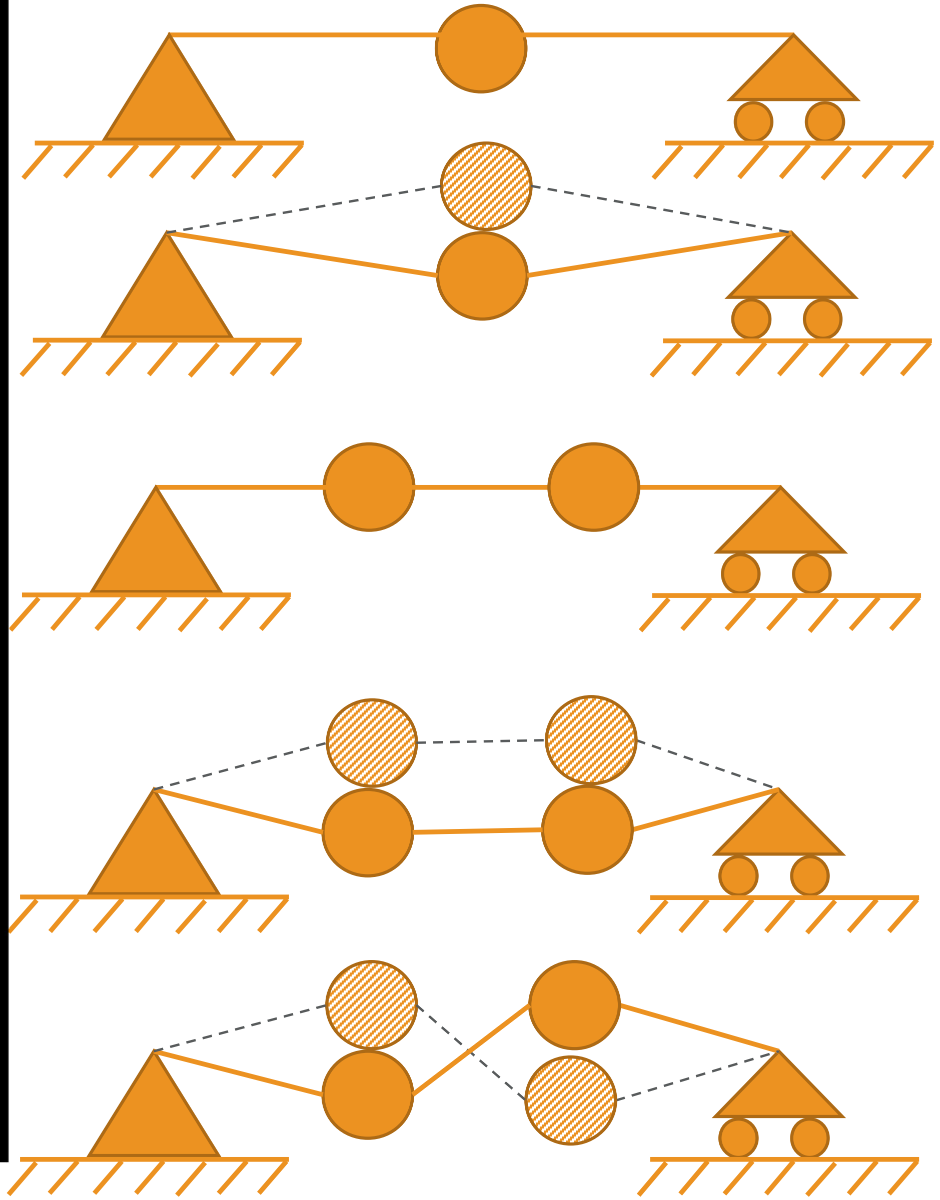
R = Stand-Off Distance

W = Equivalent TNT Charge Weight



Equivalent SDOF & MDOF Systems





SDOF

1 Mode Shape

1 Natural Frequency

MDOF (2)

2 Mode Shape

2 Natural Frequencies

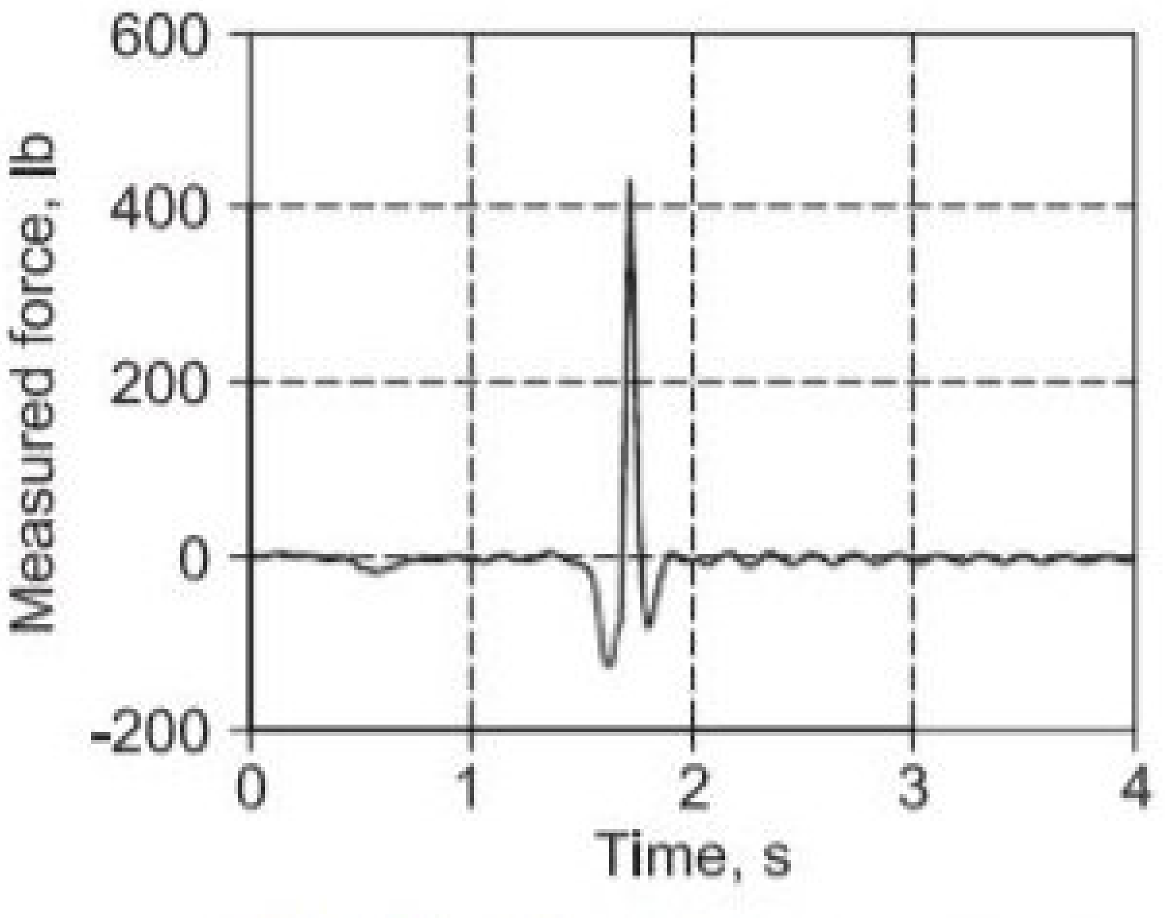
1st Mode Shape

1st Natural Frequency

2nd Mode Shape

2nd Natural Frequency

Dynamic Analysis (Static – Dynamic = Time)



(a) Heel-drop dynamic force waveform

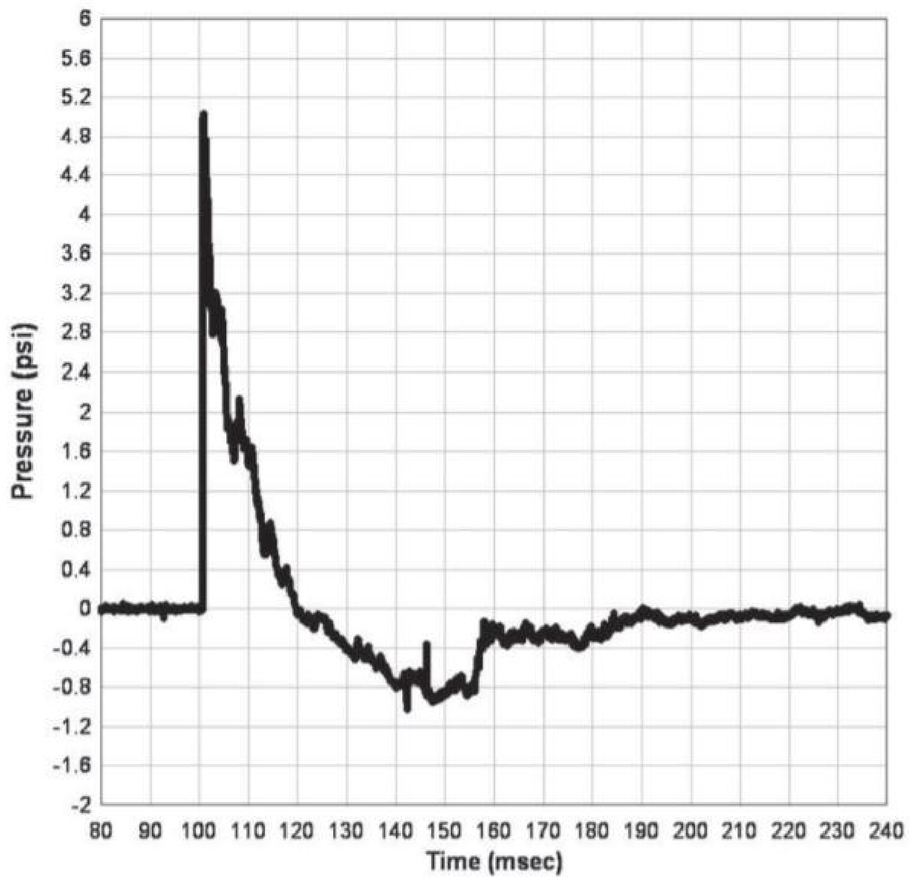


Fig. 1-1. Pressure gauge trace from high-energy explosive detonation.

Time >> Natural Period = Static

Time << Natural Period = Dynamic

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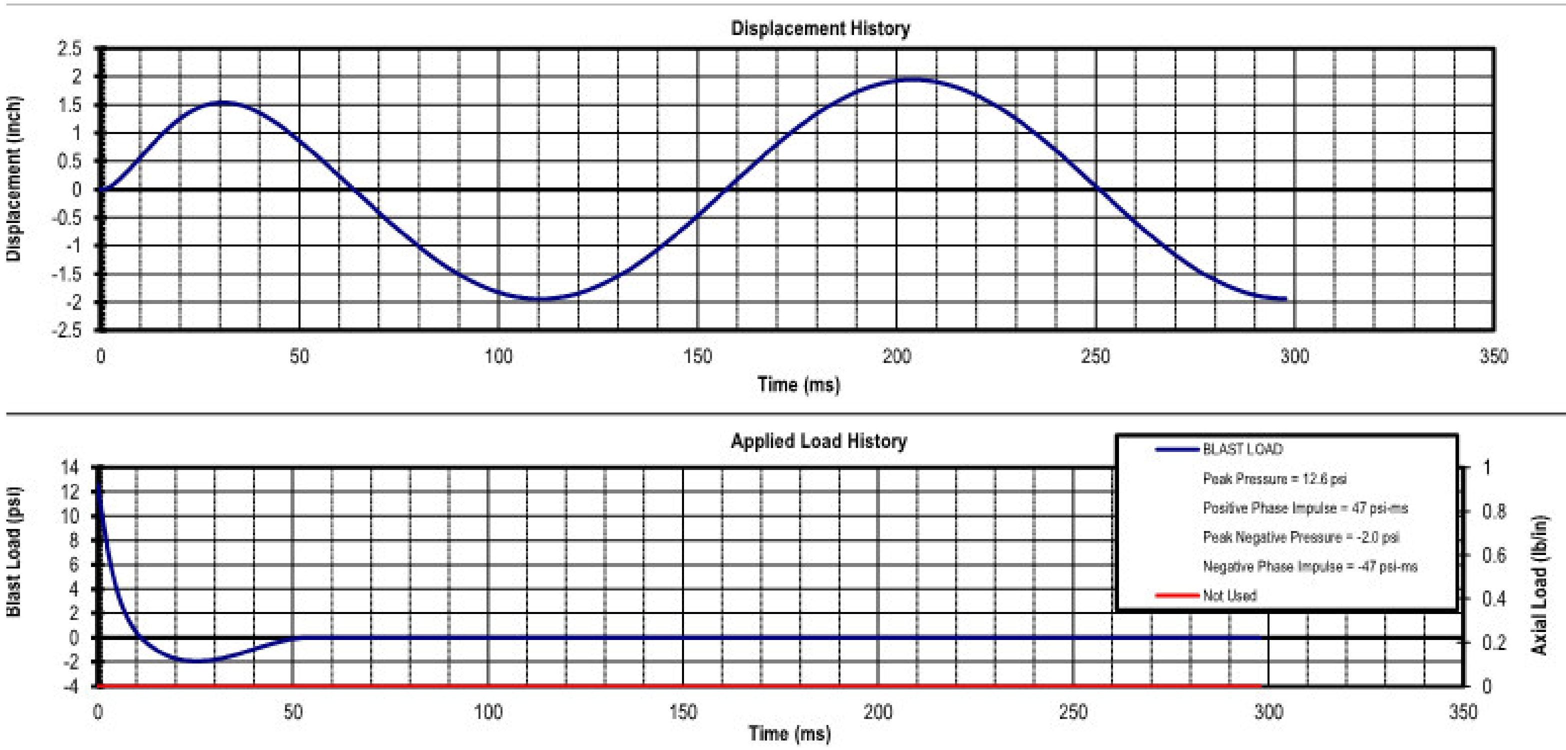
Analysis Methods

- Static Equivalent Elastic Analysis
  - Member Remains Elastic
  - DLF
  - Too Conservative
  - 1.0DL + .25LL + 1.0 B
- Dynamic Finite Element Analysis
  - Non-Linear
  - Special Software
  - Too Time Consuming
  - Allowable Deformation



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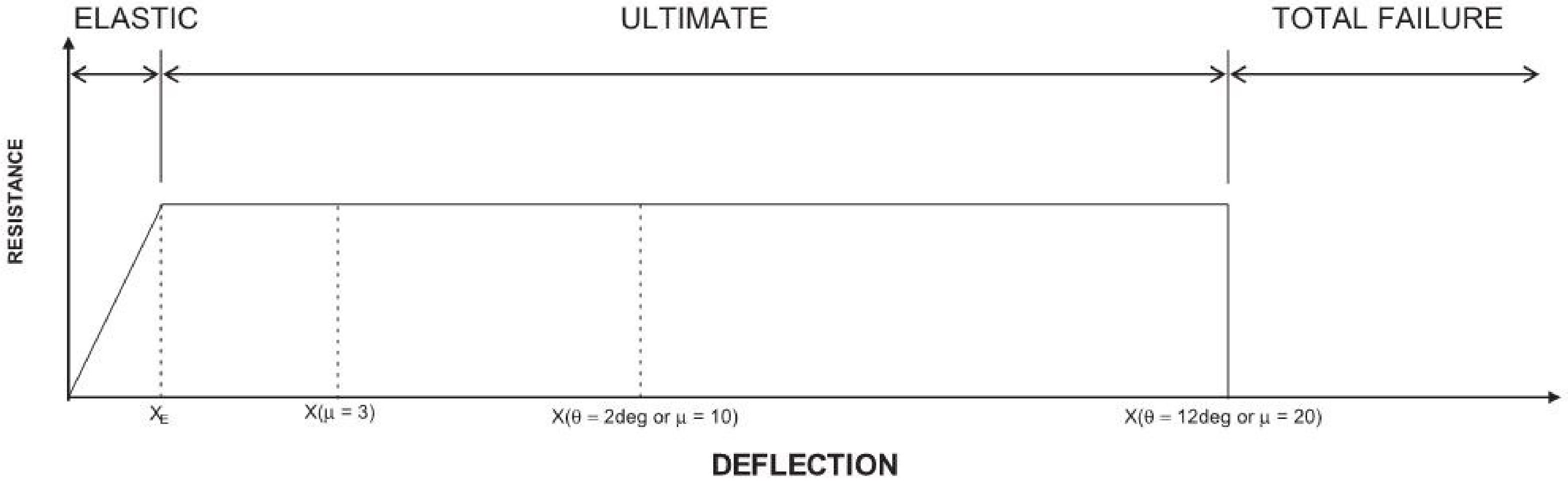
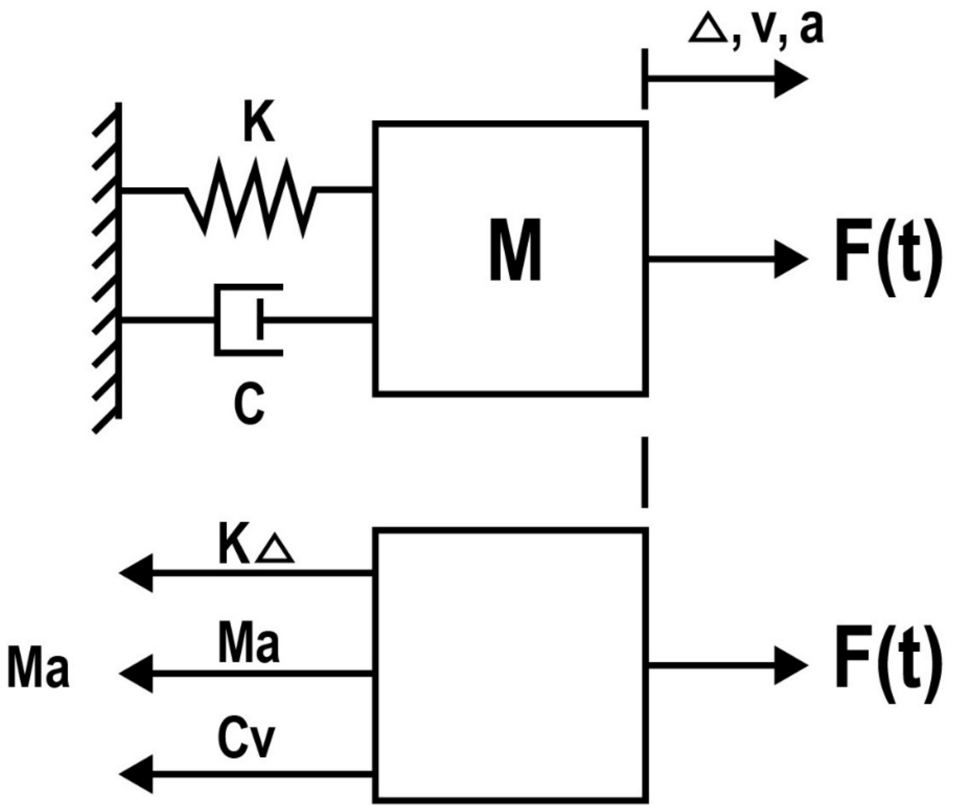
Analysis Methods - SDOF

- **Equivalent Single Degree of Freedom System (SDOF)**
  - Assumes Flexural Member Response is Dominant Failure Mode
  - Allows Both Elastic & Plastic Deformation (Non-Linear)
  - Time-Step Dynamic Analysis
  - Allowable Deformation at Mid-Span



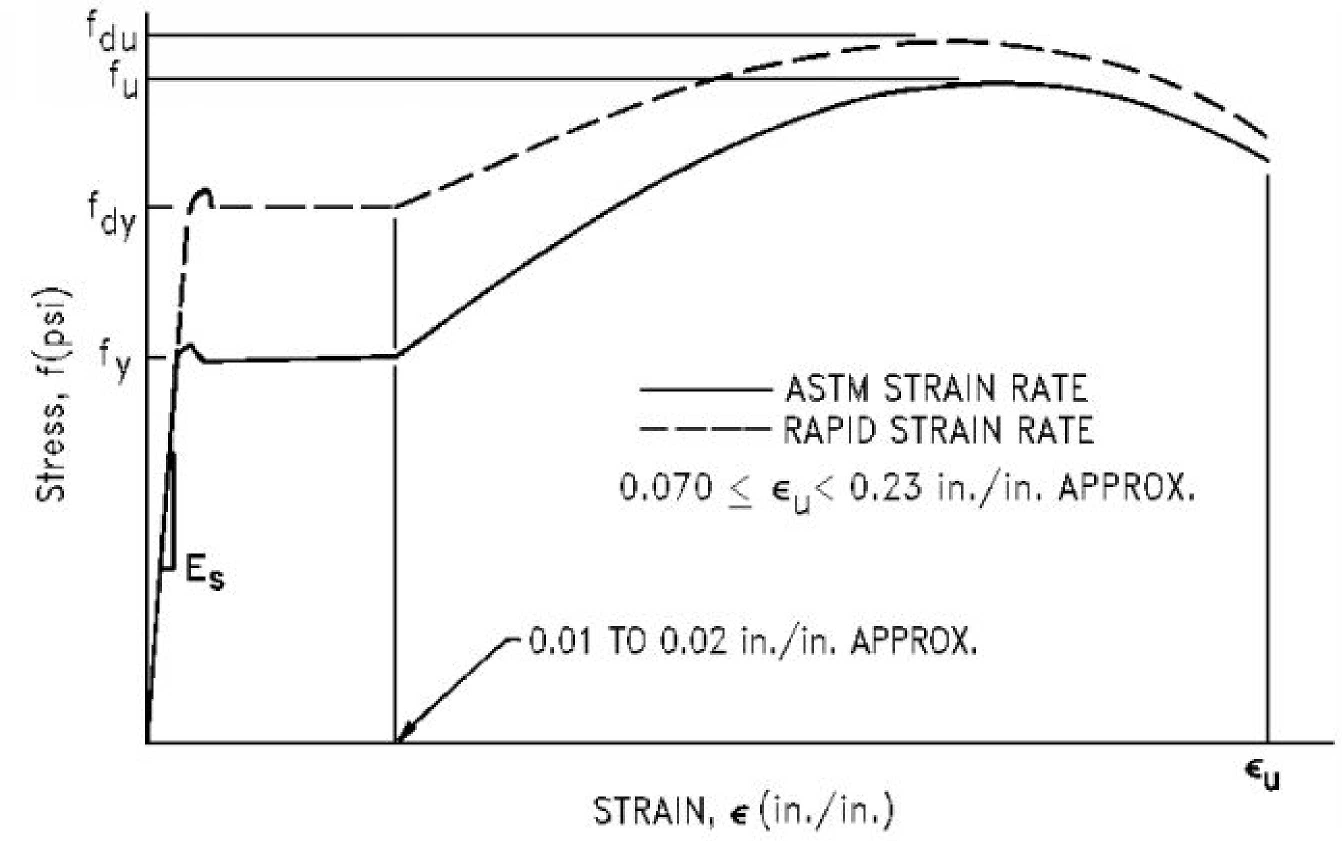
Equivalent SDOF System



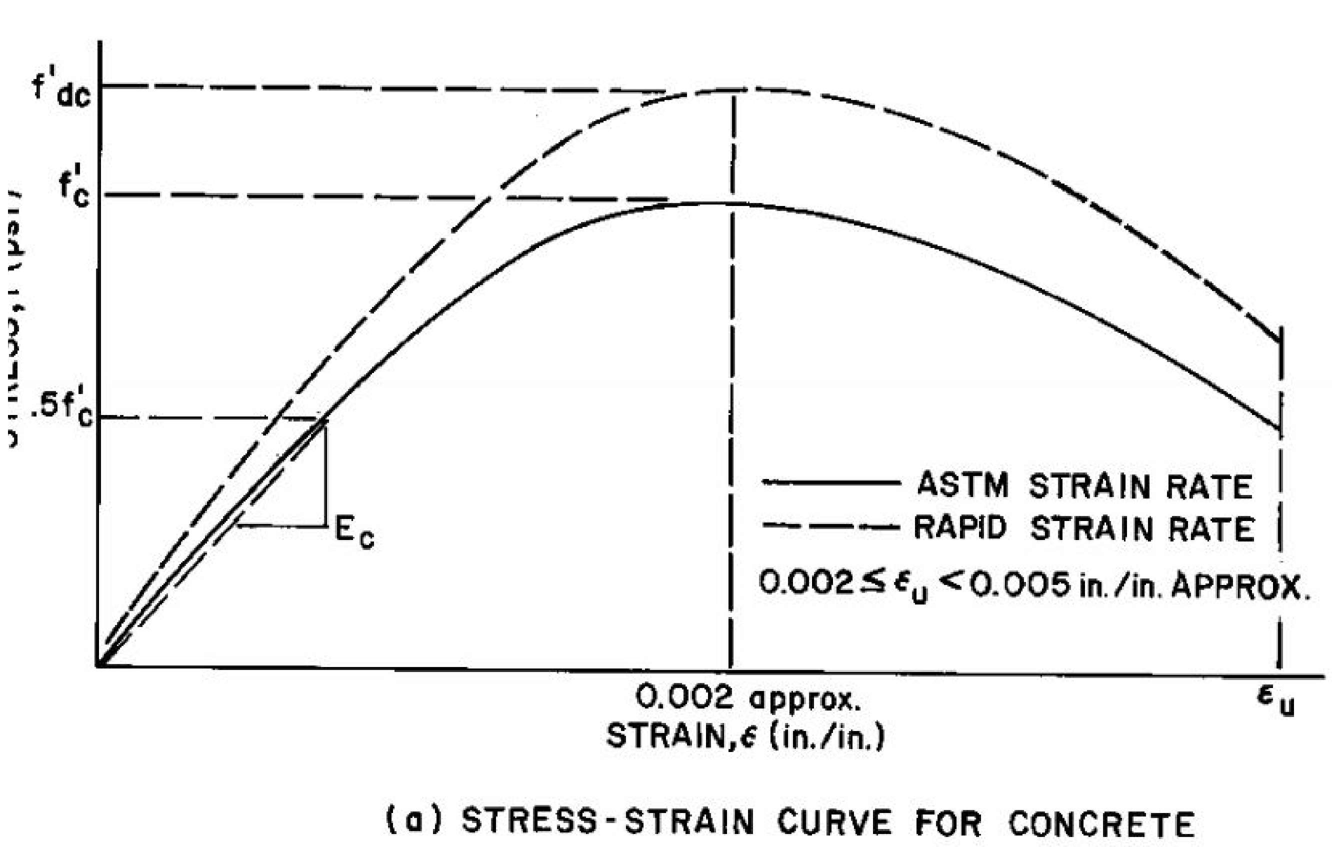
Equation of Motion

$$K_{LM} \cdot Ma(t) + C \cdot v(t) + K\Delta(t) = F(t)$$

Dynamic Strength Increase



Stress-Strain Curve for Steel

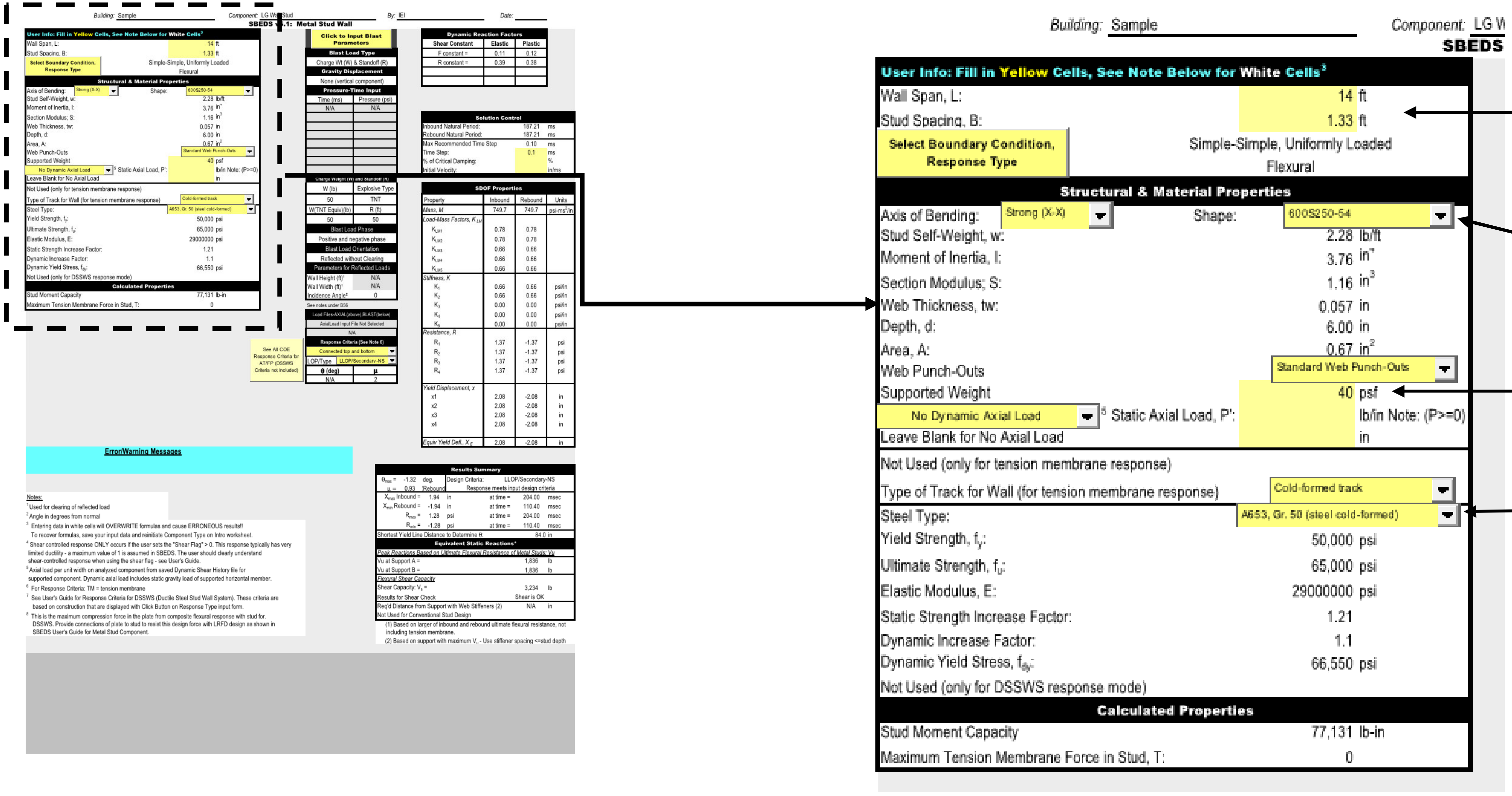


Stress-Strain Curve for Concrete

Performance Criteria

Member		B1		B2		B3		B4	
		μ	θ	μ	θ	μ	θ	μ	θ
Flexure	Compact or seismic member	1	-	3	3°	12	10°	25	20°
	Non compact member	.7		.85		1.0		1.2	
	Plate [2]	4	1°	8	2°	20	6°	40	12°
Combined Flexure & Compression	Compact or seismic member[2]	1	-	3	3°	3	3°	3	3°
	Non compact member [3]	.7		.85		.85		.85	
Compression [4]		0.9		1.3		2		3	

SDOF – SBEDS - Input



Define Span, Spacing and End Fixity

Define Section

Define Supported Weight

Define Material Properties

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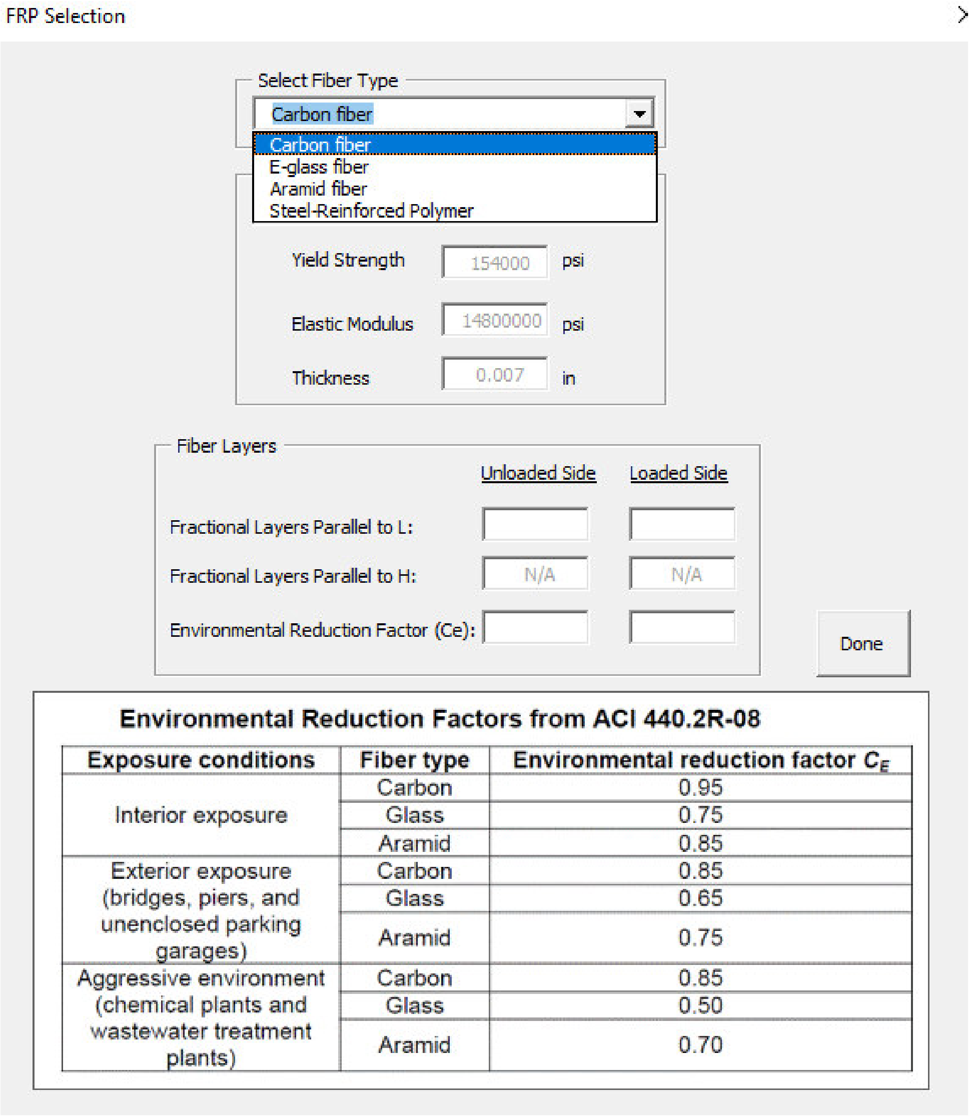
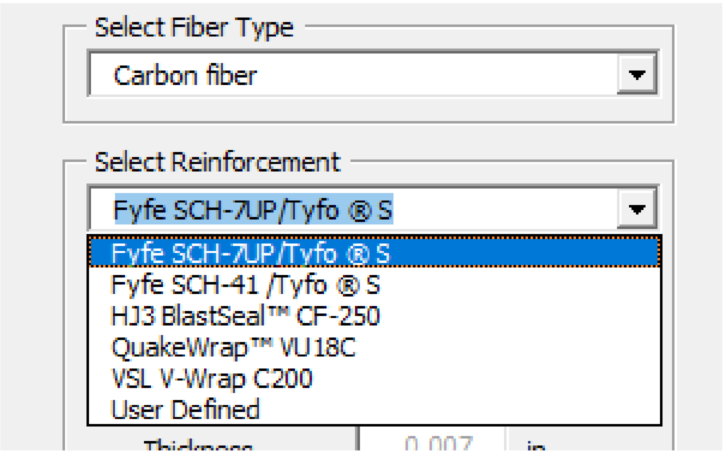
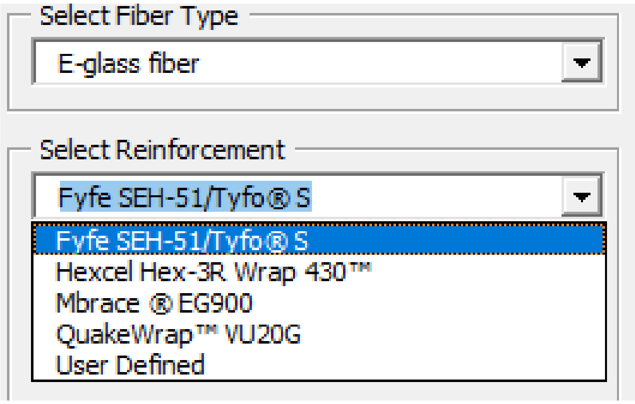
SDOF – SBEDS – FRP Retrofit

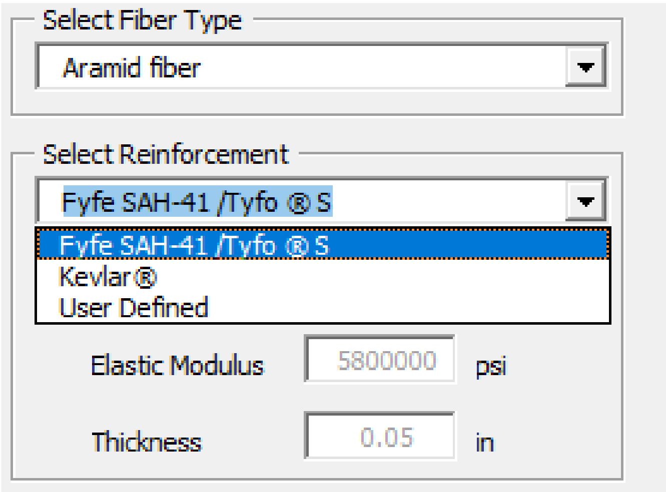


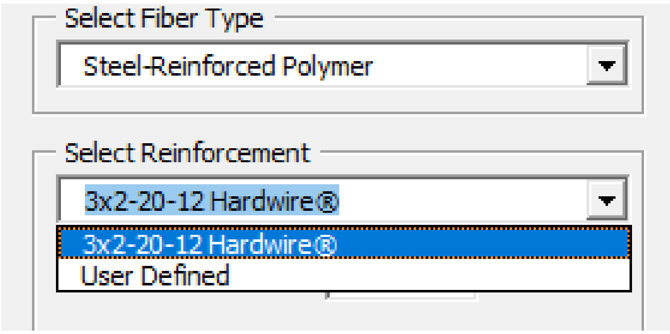
Environmental Reduction Factors from ACI 440.2R-08

Exposure conditions	Fiber type	Environmental reduction factor C_E
Interior exposure	Carbon	0.95
	Glass	0.75
	Aramid	0.85
Exterior exposure (bridges, piers, and unenclosed parking garages)	Carbon	0.85
	Glass	0.65
	Aramid	0.75
Aggressive environment (chemical plants and wastewater treatment plants)	Carbon	0.85
	Glass	0.50
	Aramid	0.70

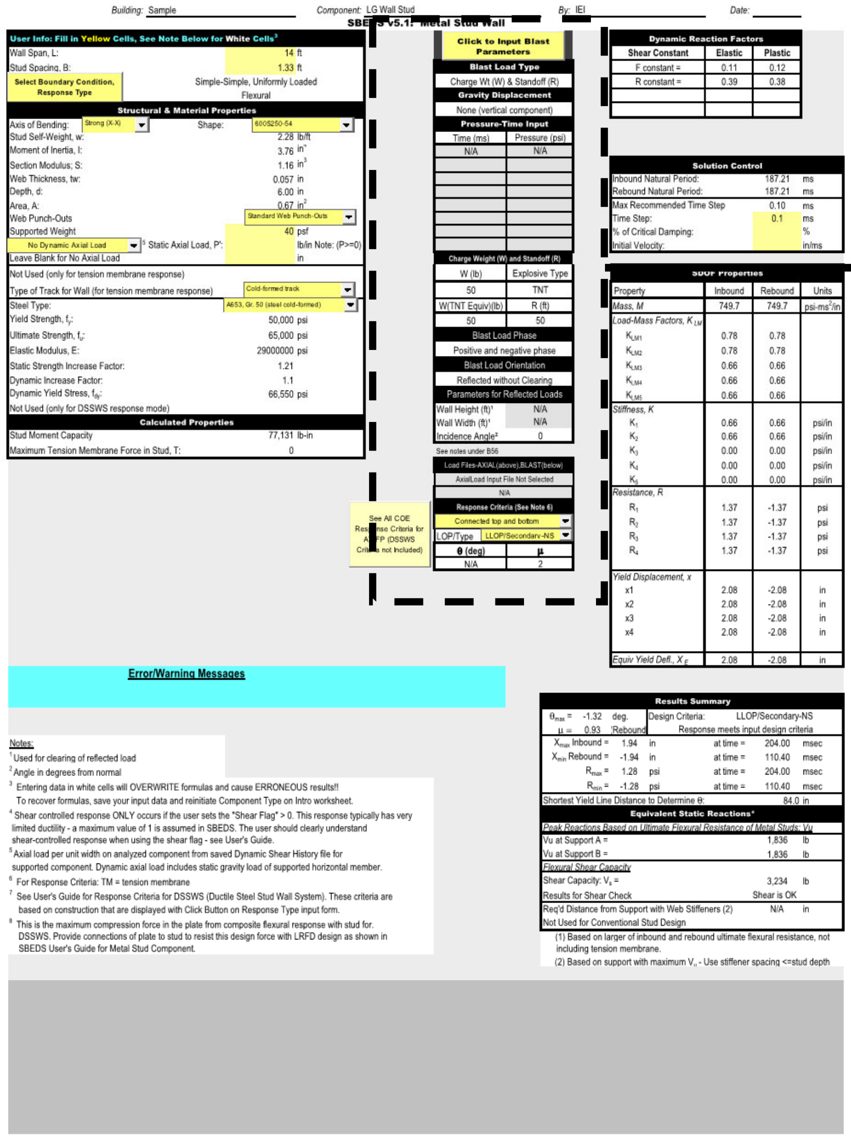


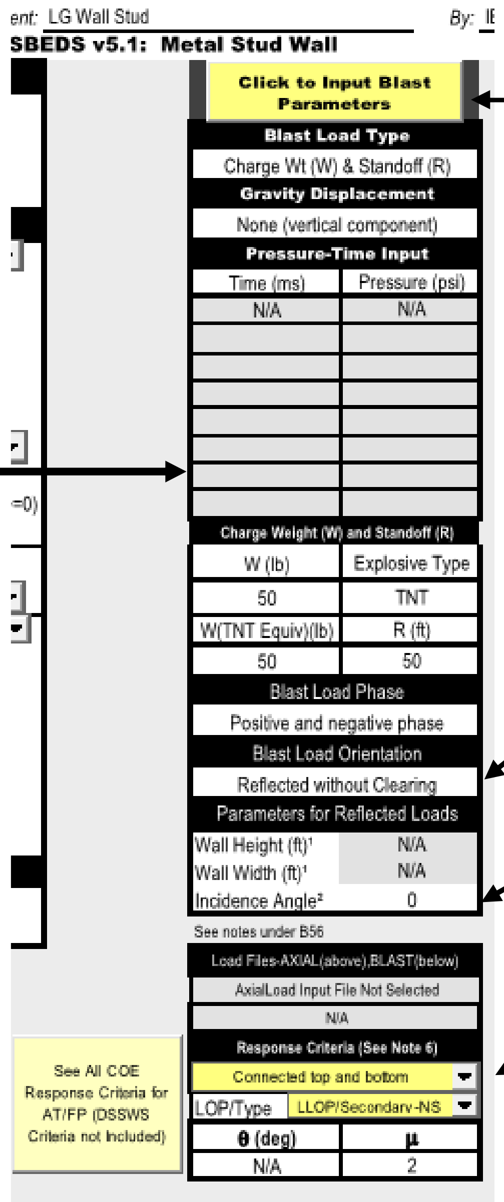






SDOF – SBEDS - Input





Define **Blast Parameters** (Charge weight and standoff or Time History or multiple charge weights or standoffs)

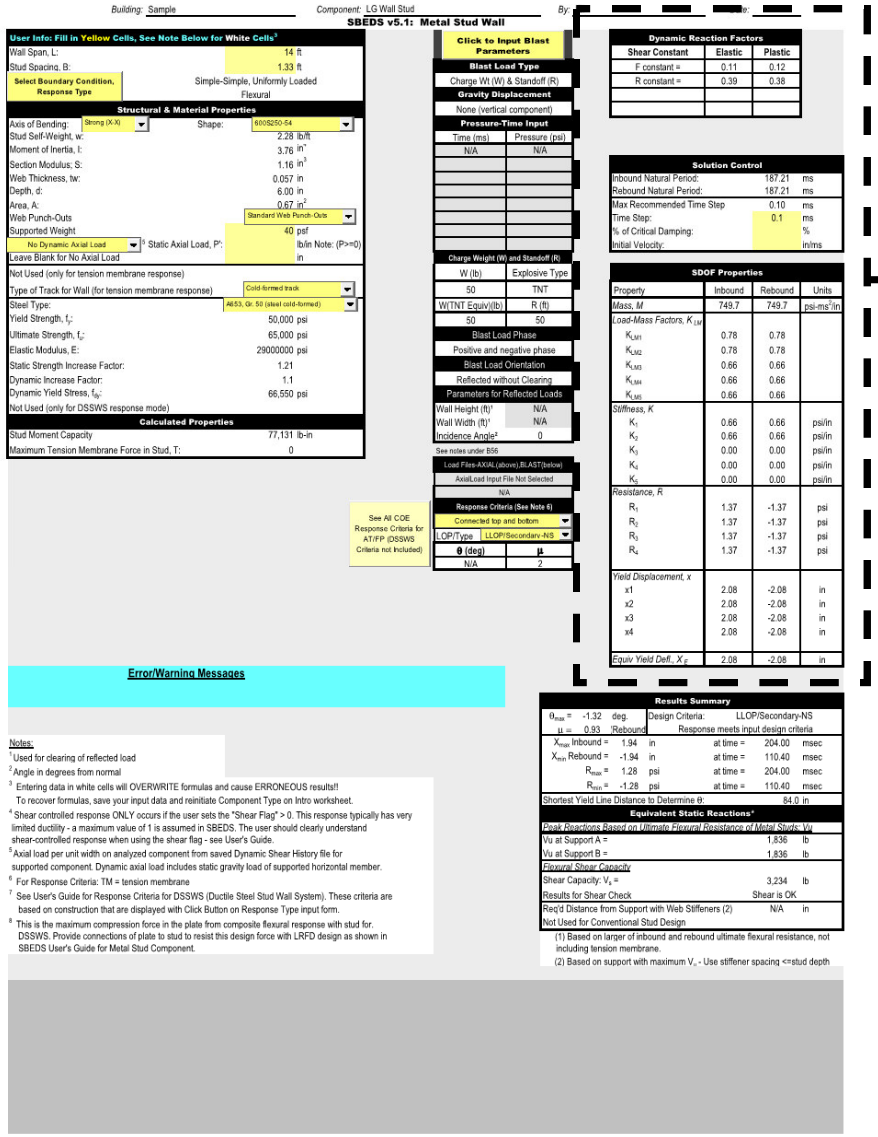
Define Blast Phase and Blast Orientation

Reflected pressures with and without clearing or side-on pressure

Incidence Angle

Define Performance Criteria

SDOF – SBEDS - Input



Dynamic Reaction Factors		
Shear Constant	Elastic	Plastic
F constant =	0.11	0.12
R constant =	0.39	0.38

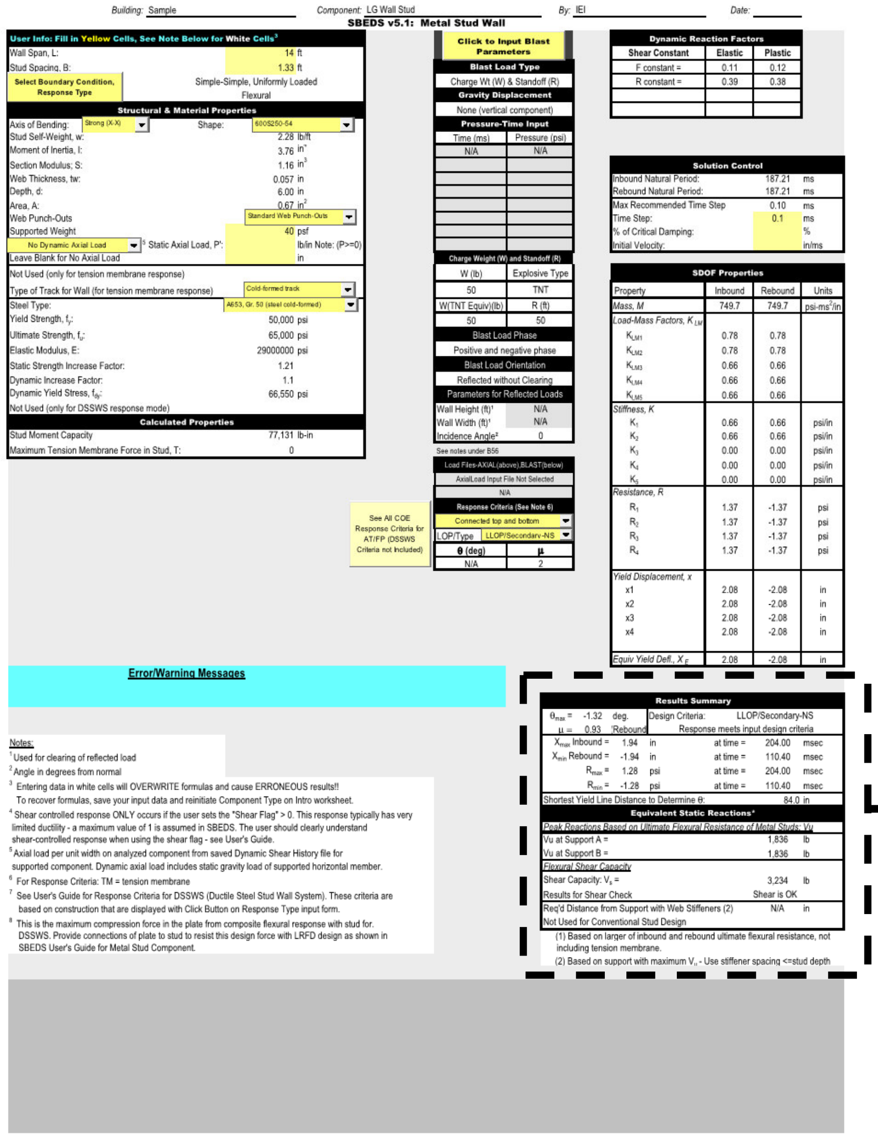
Solution Control		
Inbound Natural Period:	187.21	ms
Rebound Natural Period:	187.21	ms
Max Recommended Time Step	0.10	ms
Time Step:	0.1	ms
% of Critical Damping:		%
Initial Velocity:		in/ms

SDOF Properties			
Property	Inbound	Rebound	Units
Mass, M	749.7	749.7	psi-ms^2/in
Load-Mass Factors, K_{LM}			
K_{LM1}	0.78	0.78	
K_{LM2}	0.78	0.78	
K_{LM3}	0.66	0.66	
K_{LM4}	0.66	0.66	
K_{LM5}	0.66	0.66	
Stiffness, K			
K_1	0.66	0.66	psi/in
K_2	0.66	0.66	psi/in
K_3	0.00	0.00	psi/in
K_4	0.00	0.00	psi/in
K_5	0.00	0.00	psi/in
Resistance, R			
R_1	1.37	-1.37	psi
R_2	1.37	-1.37	psi
R_3	1.37	-1.37	psi
R_4	1.37	-1.37	psi
Yield Displacement, x			
x1	2.08	-2.08	in
x2	2.08	-2.08	in
x3	2.08	-2.08	in
x4	2.08	-2.08	in
Equiv Yield Defl., X_E	2.08	-2.08	in

Define Time Step, Damping and Initial Velocity. Typically, damping and initial velocity are zero. For most applications 0.1 is the maximum recommended time step

Load Mass Factors are determined by the program based on the inputs and Resulting Resistance and Yield Displacements are calculated

SDOF – SBEDS - Output



Results Summary

θ_{max} = -1.32 deg.		Design Criteria: LLOP/Secondary-NS			
μ = 0.93 'Rebound		Response meets input design criteria			
X_{max} Inbound =	1.94	in	at time =	204.00	msec
X_{min} Rebound =	-1.94	in	at time =	110.40	msec
R_{max} =	1.28	psi	at time =	204.00	msec
R_{min} =	-1.28	psi	at time =	110.40	msec
Shortest Yield Line Distance to Determine θ:				84.0	in

Equivalent Static Reactions¹

Peak Reactions Based on Ultimate Flexural Resistance of Metal Studs: Vu		
Vu at Support A =	1,836	lb
Vu at Support B =	1,836	lb
Flexural Shear Capacity		
Shear Capacity: V_s =	3,234	lb
Results for Shear Check	Shear is OK	
Req'd Distance from Support with Web Stiffeners (2)	N/A	in
Not Used for Conventional Stud Design		

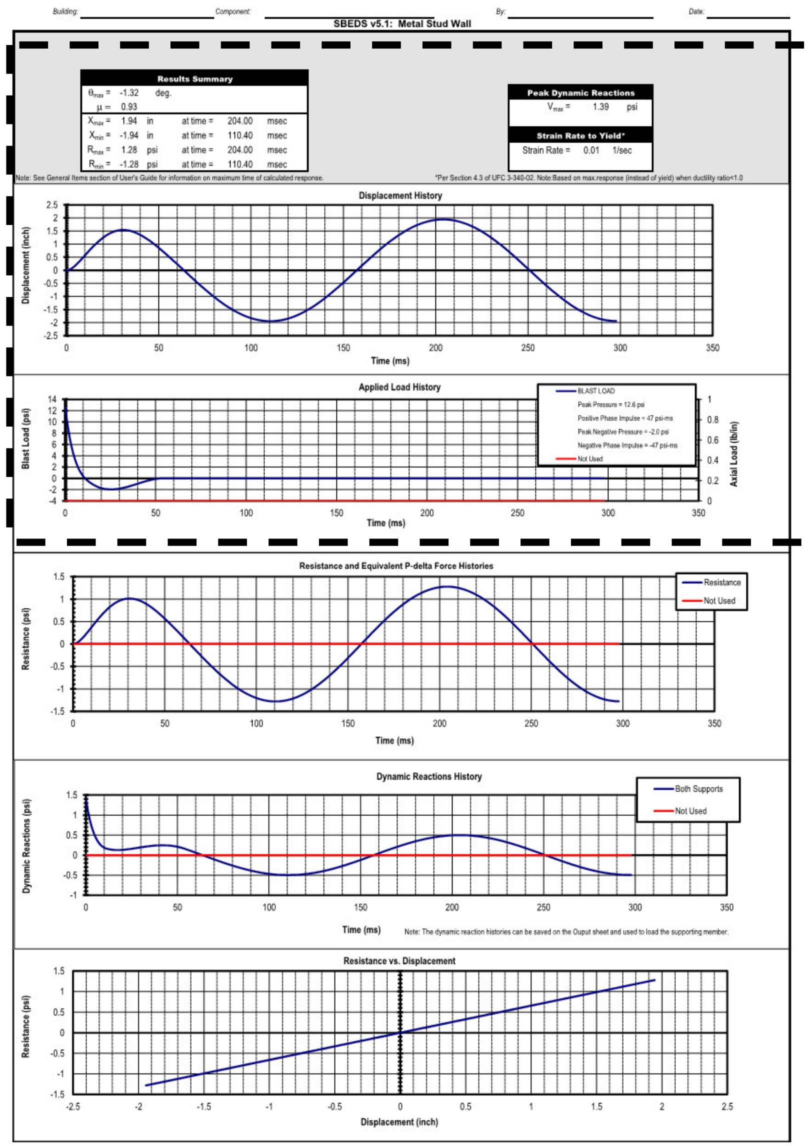
(1) Based on larger of inbound and rebound ultimate flexural resistance, not including tension membrane.

(2) Based on support with maximum V_u - Use stiffener spacing <=stud depth

Response Criterion are checked versus the analysis and maximum resistance and displacement are shown

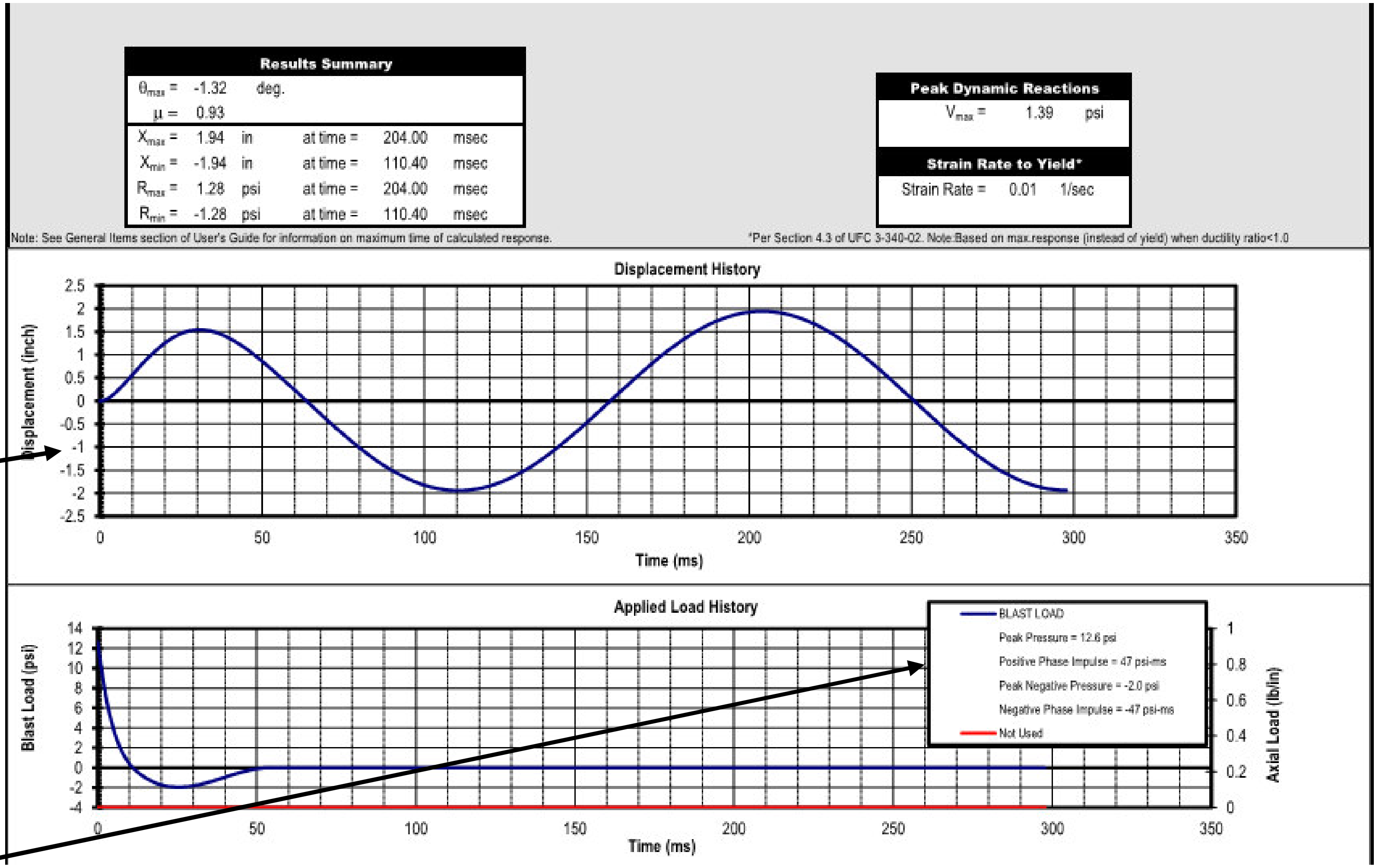
Equivalent Static Reactions are calculated and provided for connection design and shear checks a displayed

SDOF – SBEDS - Output



Graphical output displacement with respect to time is provided

Graphical output showing blast pressure with respect to time is provided along with peak pressures and impulses for positive and negative phases



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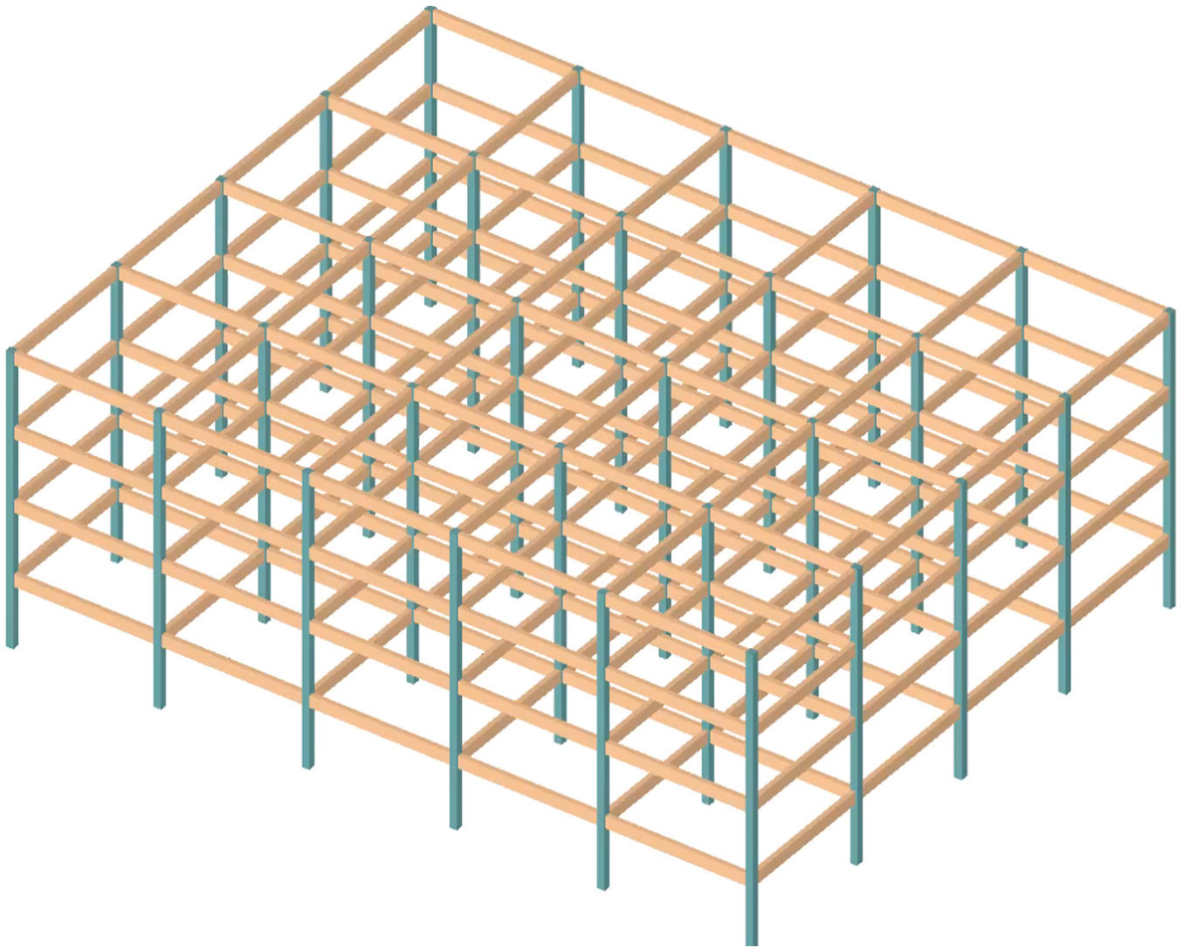
Progressive Collapse



ASI Extreme Loading

"The spread of an initial local failure from building element to building element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it."

Source: UFC 4-010-01

- Threat Independent
- Protect by:
  - Redundancy
  - Local Hardening

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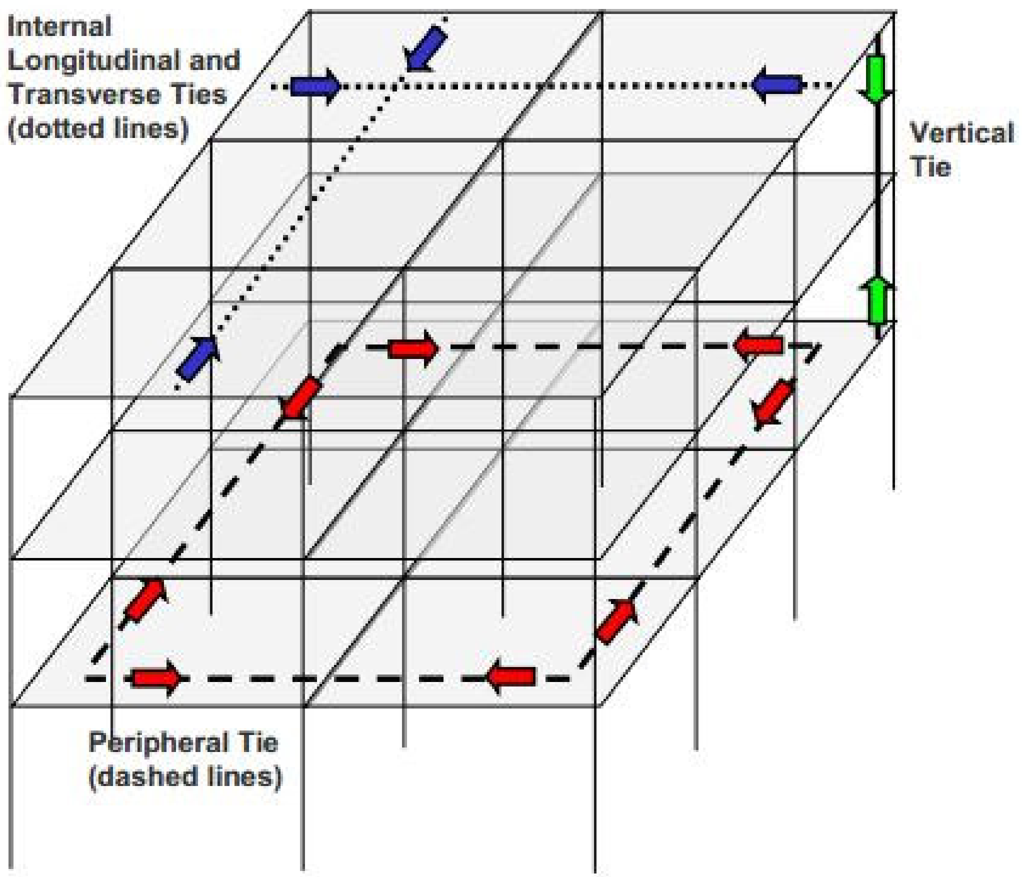
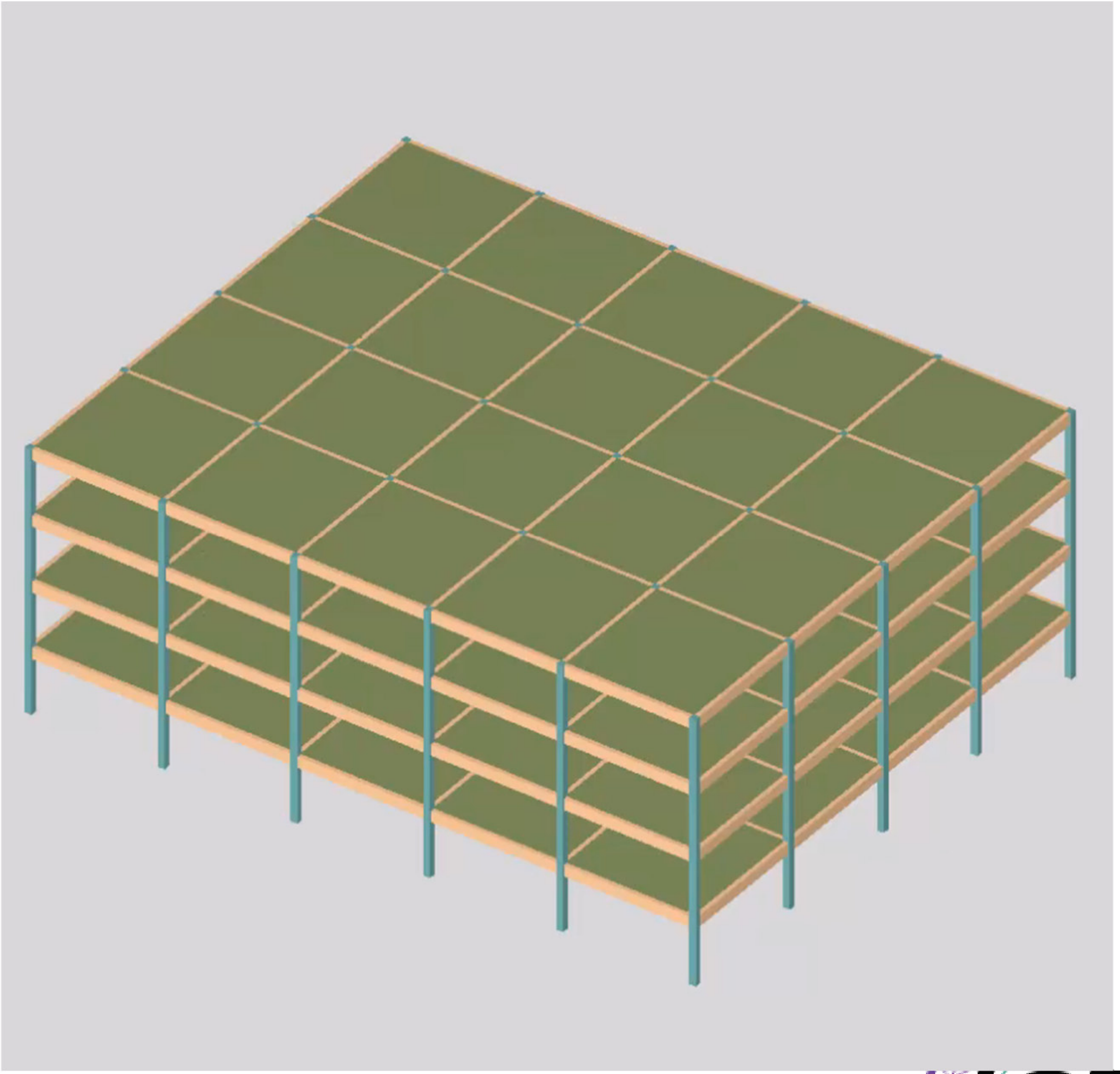
Progressive Collapse

Figure 3-1. Tie Forces in a Frame Structure



NOTE: 1. Peripheral, longitudinal and transverse ties are not required in floors above crawlspaces if public access control is provided.
2. Vertical ties are not required to extend to the foundation and shall be straight. /2/



Learning Objectives

- Blast Theory
- Blast Analysis
- Blast Design
- Progressive Collapse

Questions?

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