

Advanced Modeling of Blast Response of Reinforced Concrete Walls with and without FRP Retrofit



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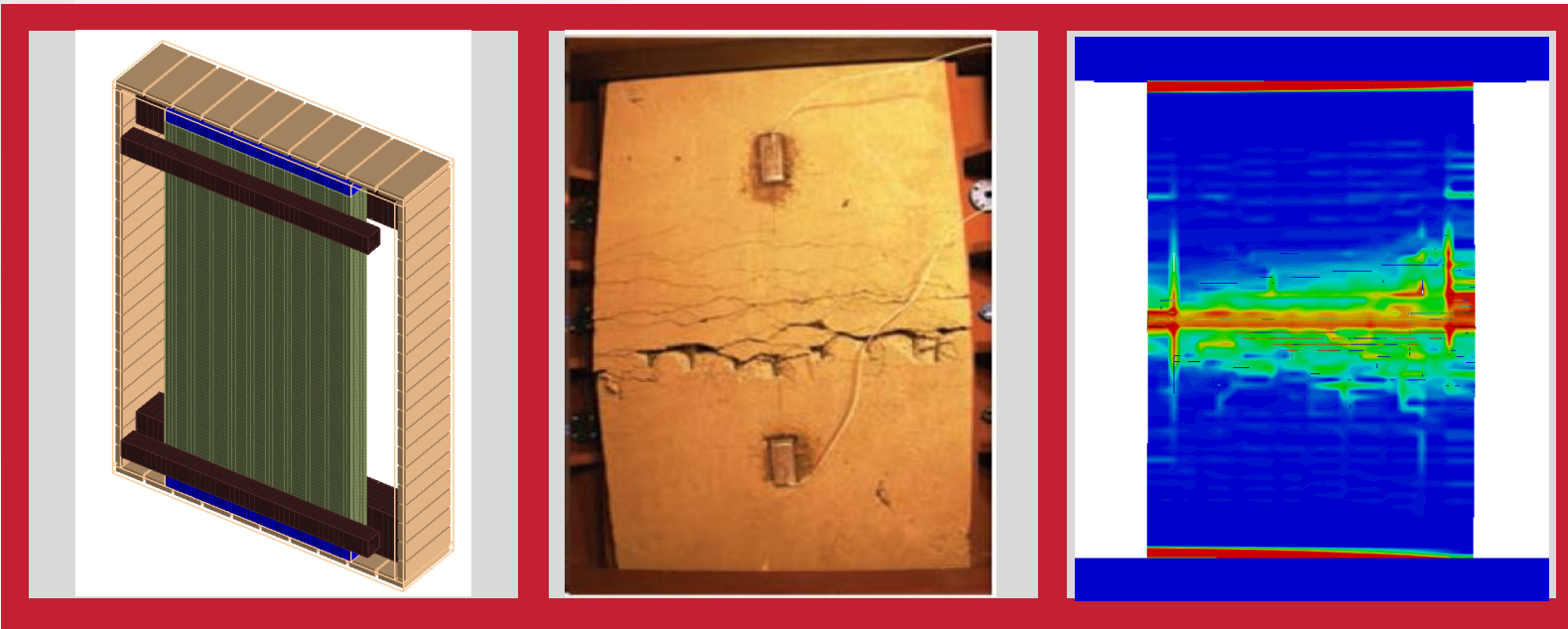
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Session on: FRP Design Methodology and Applications for Blast and Impact-Resistant Structures

Sponsored By: ACI Committee 370 and 440

3/28/2018



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Introduction

2

Study Parameters

3

Simulation Approaches and Models

4

Predicted Blast Responses

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Concluding Remarks

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Future Research Work

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Questions

Previous Research Work

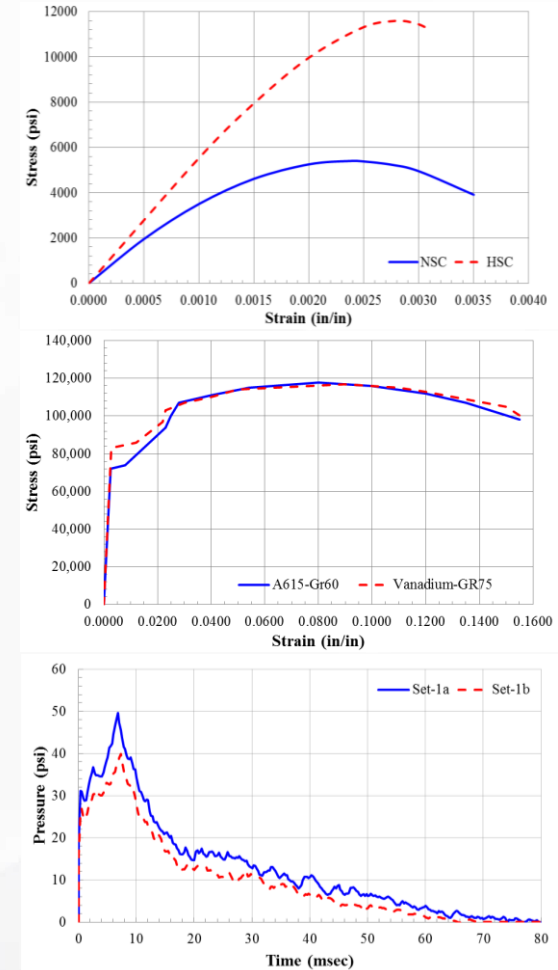
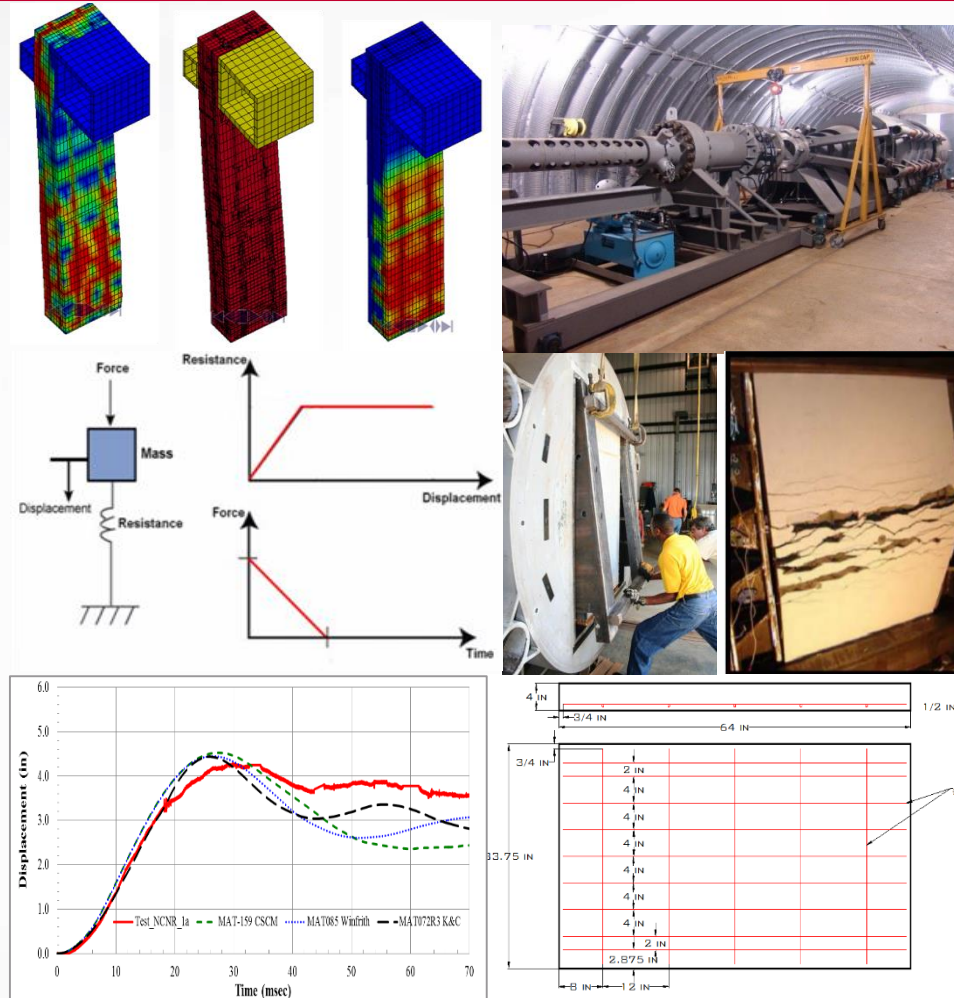
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Blast Blind Simulation Contest

- **UMKC** Planned and Executed a Testing Program for **NSCNR** and **HSCVR** Specimens at the Blast Loading Simulator (**BLS**), ERDC, Vicksburg, MS
- On 2013, **NSF/ ACI 447** Organized **Blast Blind Simulation Contest** based on Available Test Information.
- Response Prediction Using **Various Simulation Techniques** (FEM and SDOF)
- Objective was to Understand **Prediction Capabilities and Limitations** of Available Simulation Techniques



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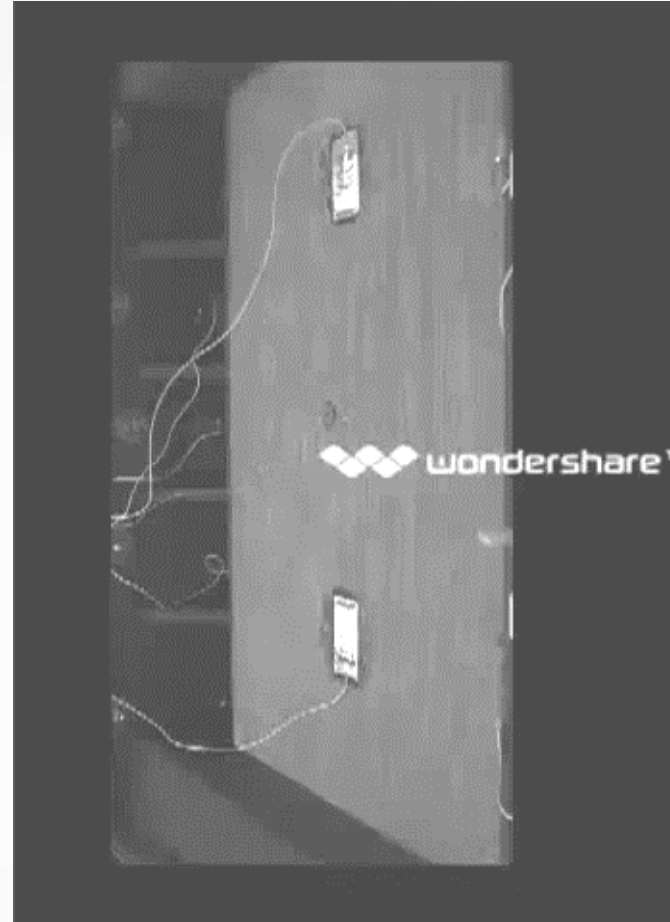
Blast Blind Simulation Contest

NSC/NR

- 5400 psi Concrete
- 72000 psi Rebar
- 52" Span, 34" Wide, 4" Thick
- 9 #3 Bars @ 1.0" from Unloaded Face
- Simply Supported Ends

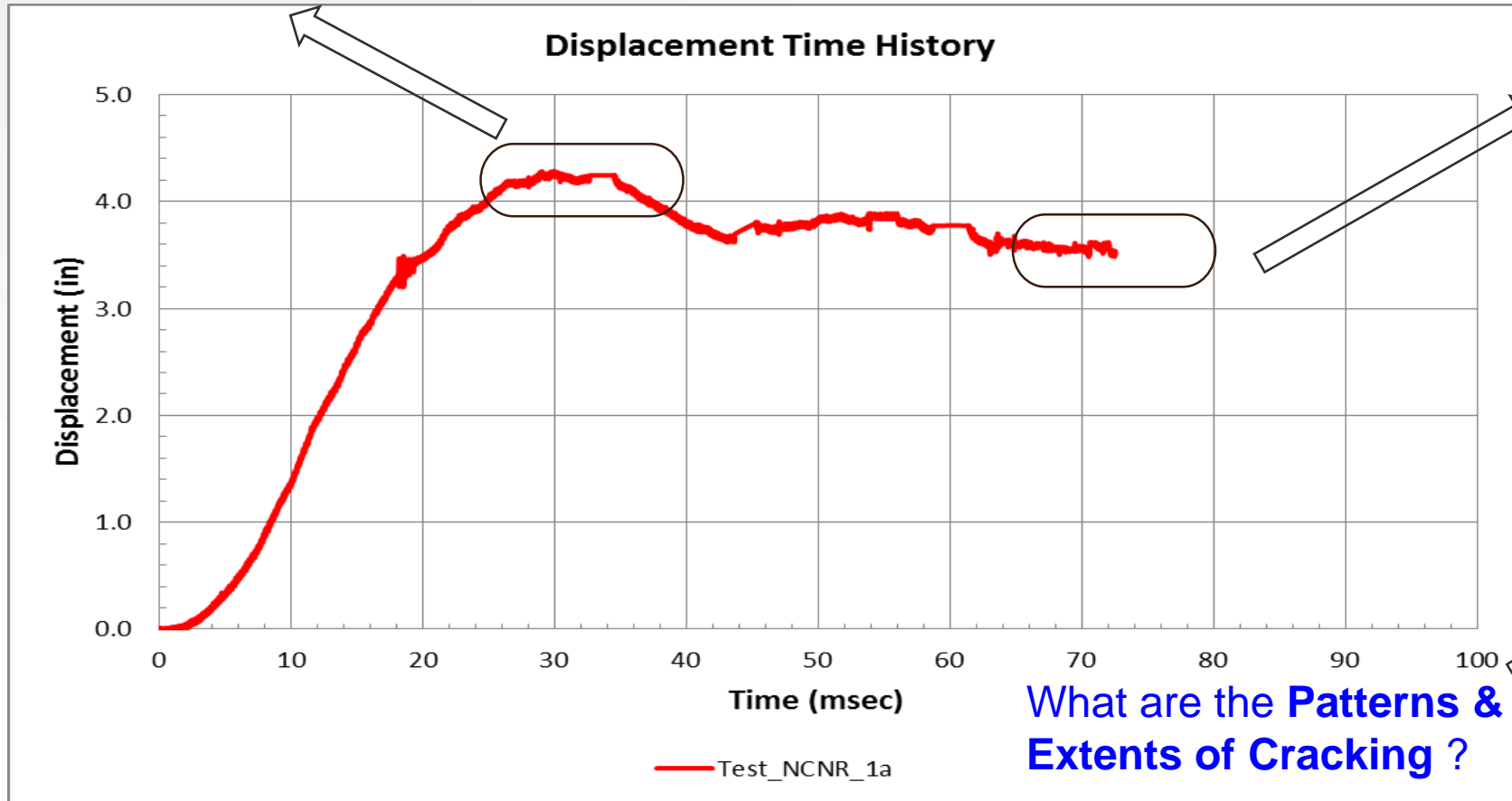
Blast Load

- $P_{\max} = 50$ psi
- $I_{\text{tot}} = 1020$ psi.msec



Blast Blind Simulation Contest

What is the **Maximum Displacement** and At What Time ?



What is the **Residual Displacement** ?

What are the **Patterns & Extents of Cracking** ?



Current Research Work

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Objectives

- ❖ **Investigate the Effectiveness** of Different FRP Retrofit Schemes to Improve the Blast Resistance of One-way RC Slabs.
- ❖ **Evaluate the Adequacy** of Various Simulation Approaches to Predict the Blast Response of Both Unretrofitted and FRP-Retrofitted RC Slabs with Sufficient Accuracy.
- ❖ **Identify the Primary Factors** Affecting the Blast Response Predictions of FRP-Retrofitted RC Slabs.

Methodology

- ❖ Utilize and Compare Different **Simulation Techniques and Tools** including **SDOF** (RCBlast and SBEDS) and **AEM** (ELS Software).
- ❖ Utilize the ACI contest's Testing Setup and Measurement for the NSC/NR RC Slab Specimen to **Validate the Adequacy** of Selected Simulation Tools.
- ❖ Consider **Different FRP Configurations** to Cover a Wide Range of Retrofit Schemes and to Provide a Useful Evaluation of Possible Retrofit Options.

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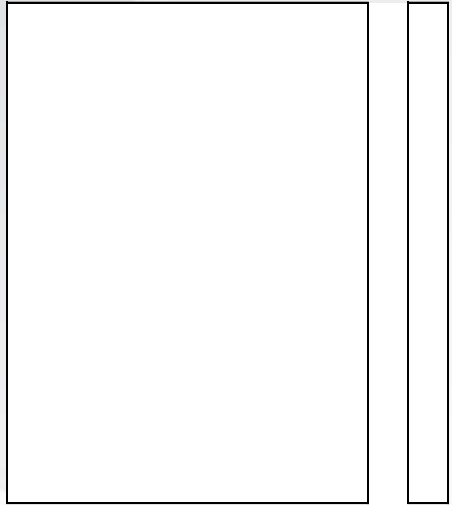
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Future Research Work

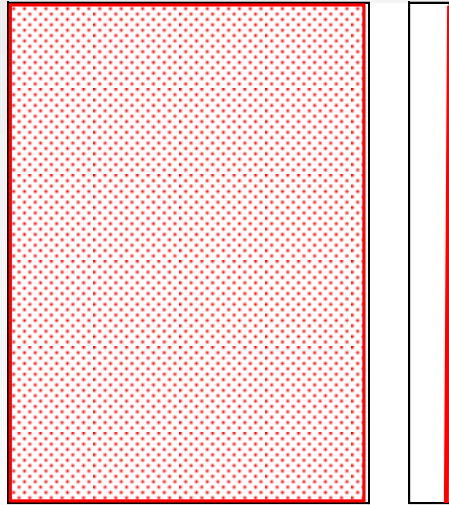
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Questions

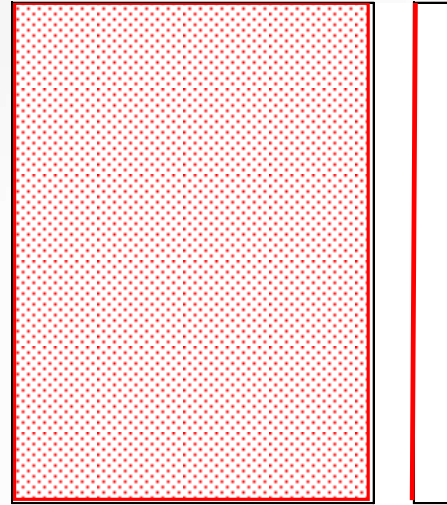
Investigated Cases



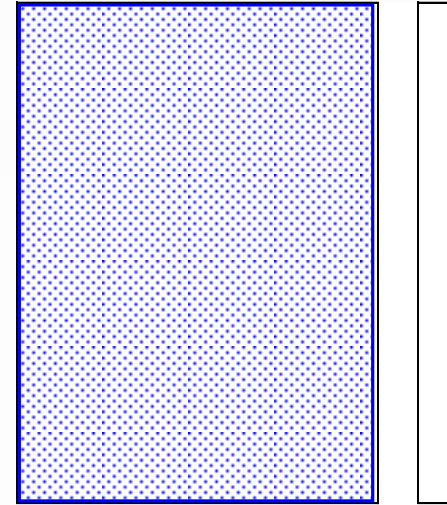
Case 1
Unretrofitted
(Control)



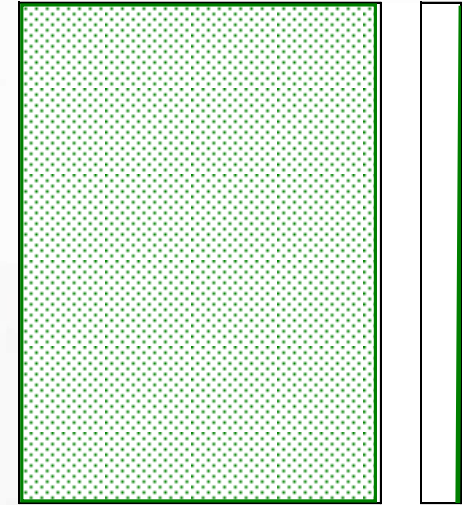
Case 2
Retrofitted
CFRP / 1 Layer
@ Back Face



Case 3
Retrofitted
CFRP / 1 Layer
@ **Both Front &
Back Faces**



Case 4
Retrofitted
CFRP / **2 Layers**
@ Back Face

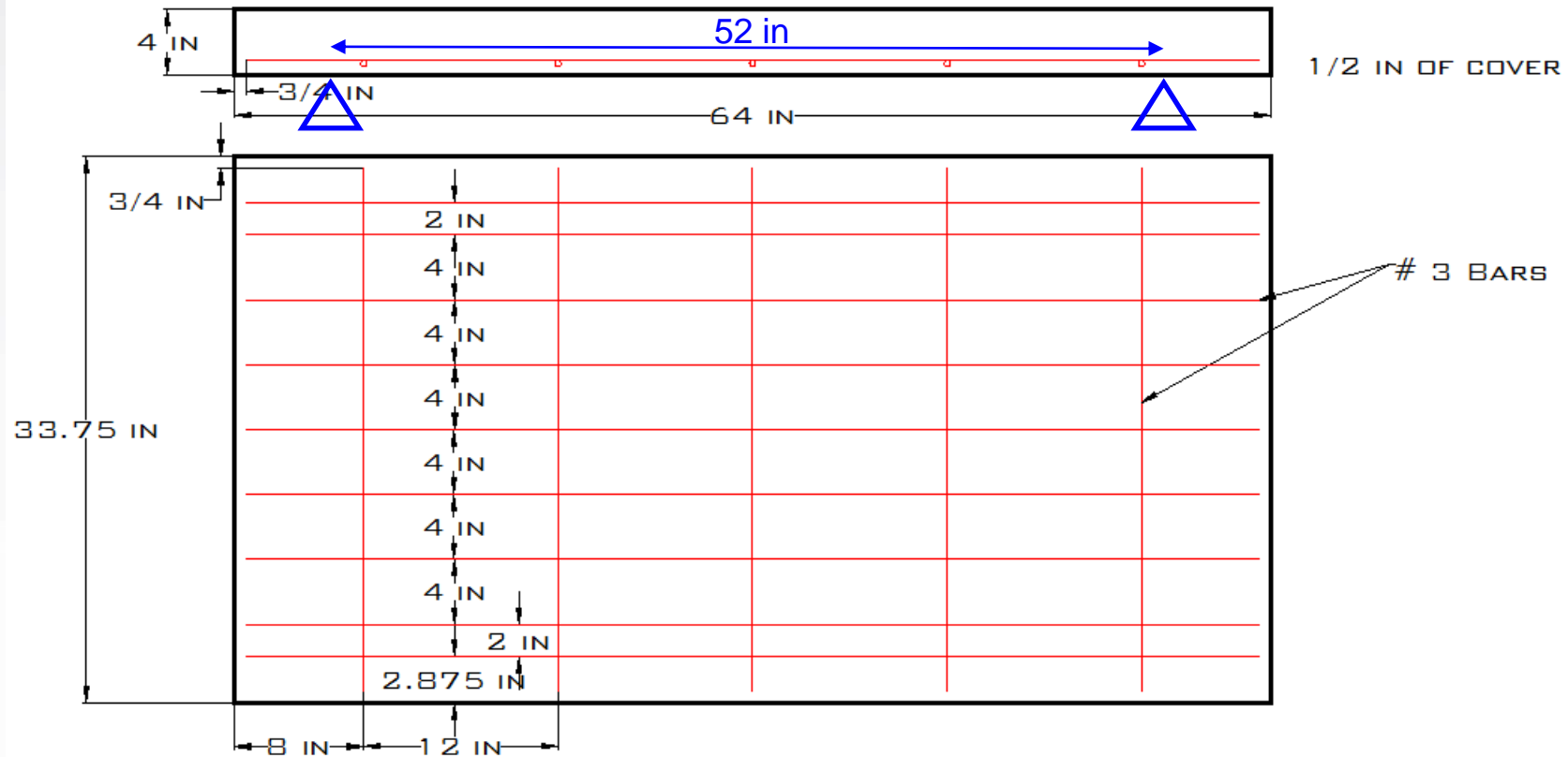


Case 5
Retrofitted
GFRP / 1 Layer
@ Back Face

Investigated Cases

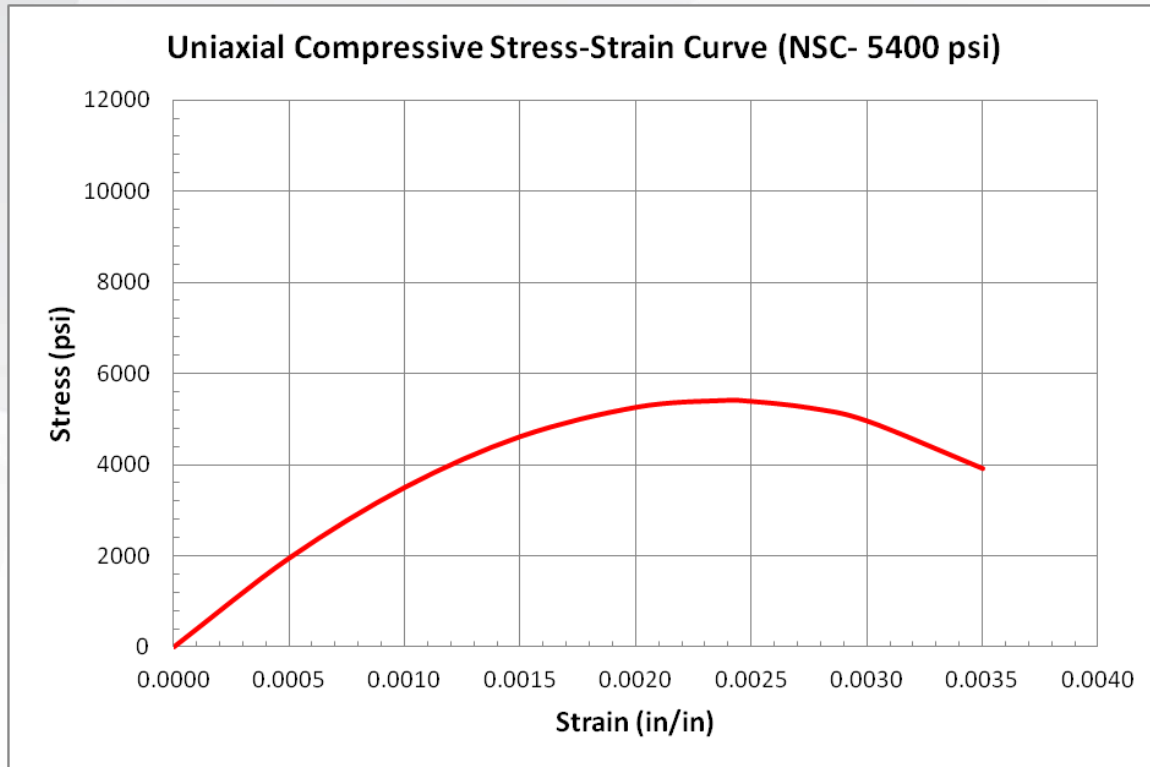
	Symbol	Unit	Case 1 	Case 2 	Case 3 	Case 4 	Case 5
Conc. Comp. Strength	f'_c	ksi	5.4	5.4	5.4	5.4	5.4
Rebar Yield Strength	f_y	ksi	60	60	60	60	60
FRP Type			N/A	CFRP	CFRP	CFRP	GFRP
FRP Location			N/A	Back Only	Back & Front	Back Only	Back Only
No of Layers (Back)	n_{back}		N/A	1	1	2	1
No of Layers (Front)	n_{face}		N/A	0	1	0	0
Layer Thickness	t_f		N/A	0.04	0.04	0.04	0.04
FRP Tensile Strength	f_{fu}^*	ksi	N/A	143	143	143	83.4
FRP Rupture Strain	ϵ_{fu}^*	in/in	N/A	0.010	0.010	0.010	0.022
FRP Elastic Modulus	E_f	ksi	N/A	13900	13900	13900	3790

RC Slab Configuration

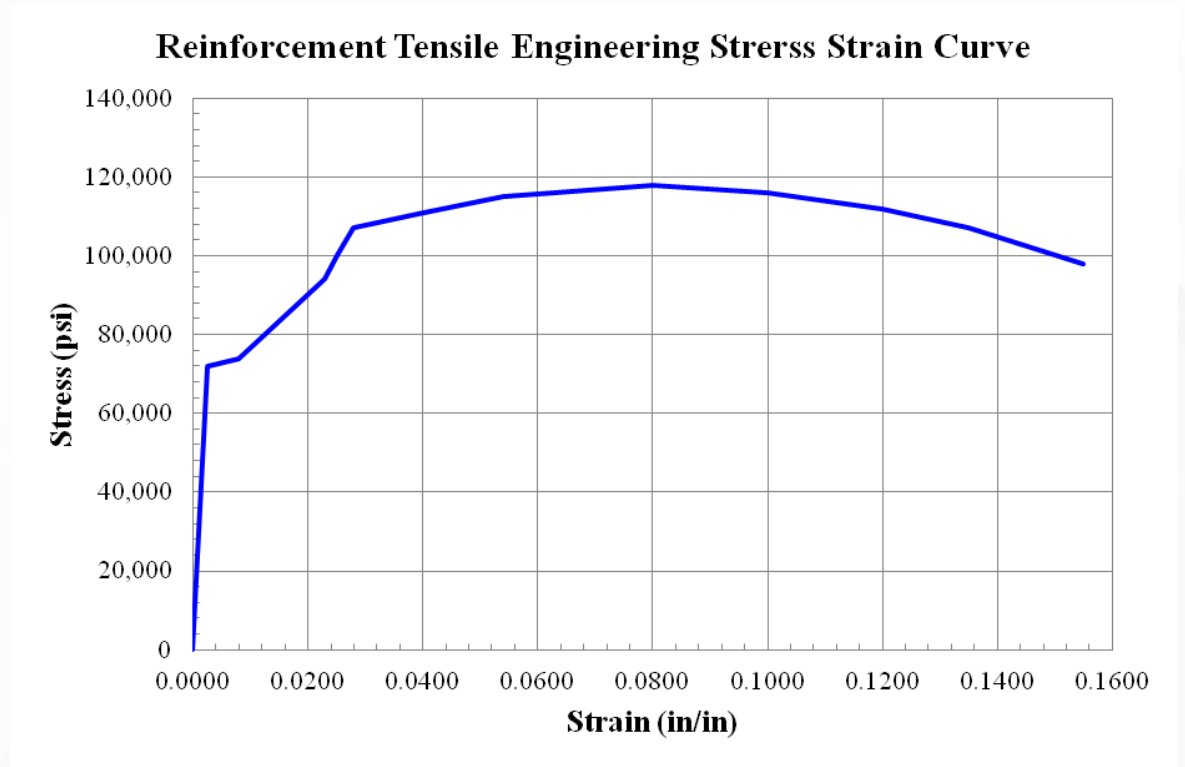


LONGITUDINAL BARS = 62.5 IN
HORIZONTAL BARS = 32.35 IN

Material Properties



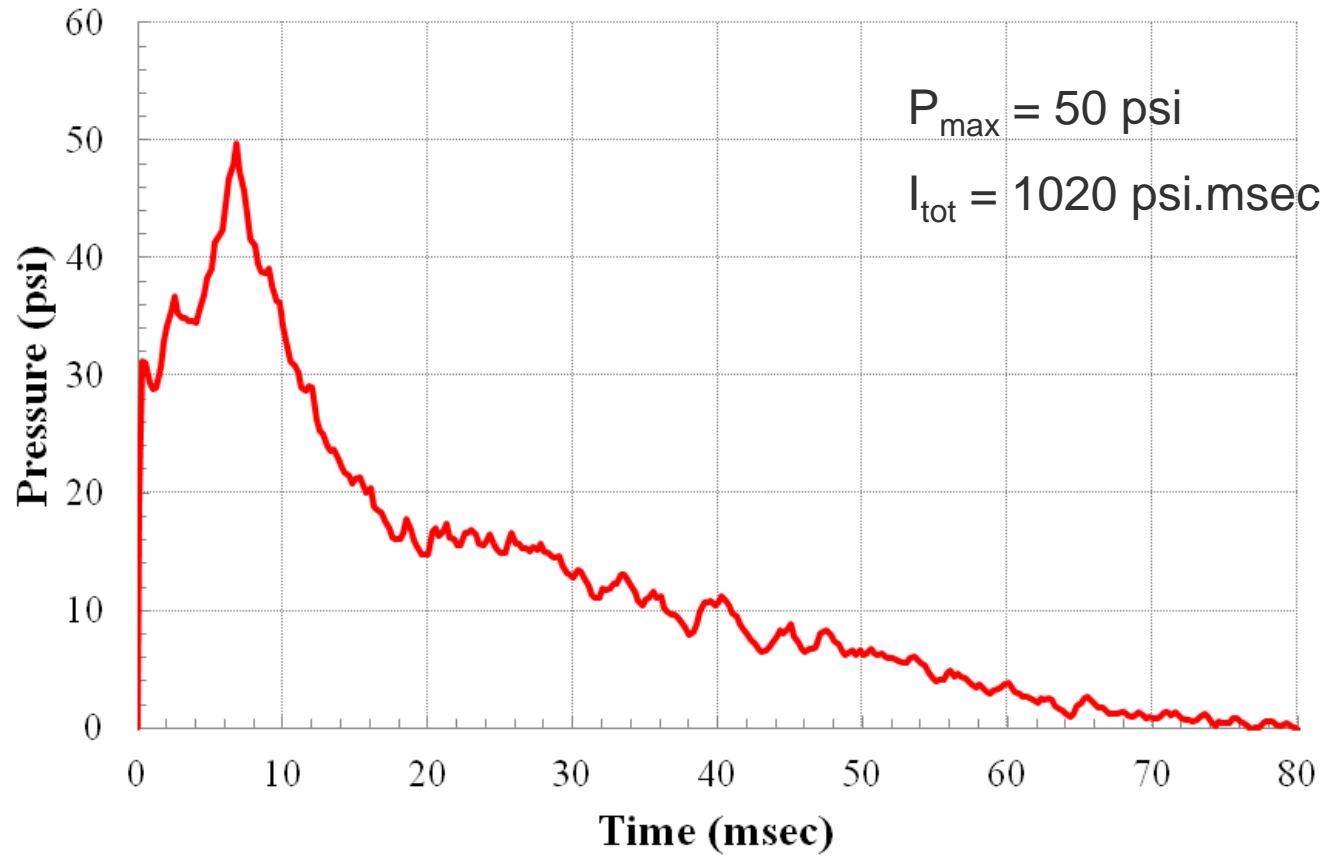
Normal Strength Concrete



Normal Strength Rebar

Blast Load

Set-1a Blast



Reflected Pressure-Time Record

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Applied Element Method (AEM)

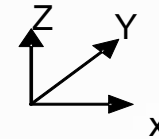
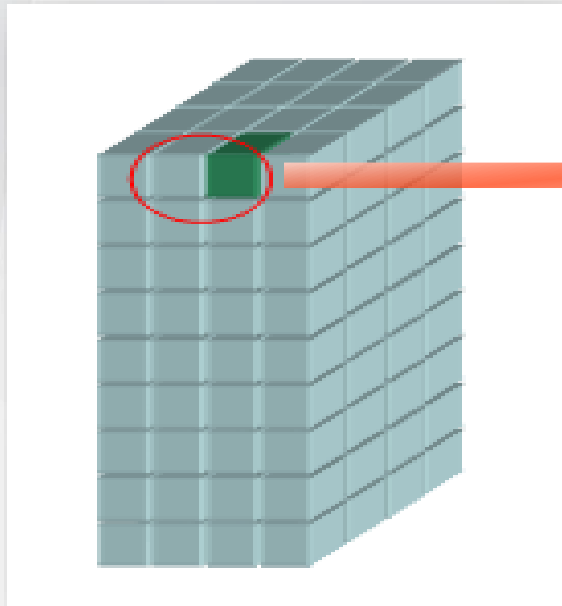
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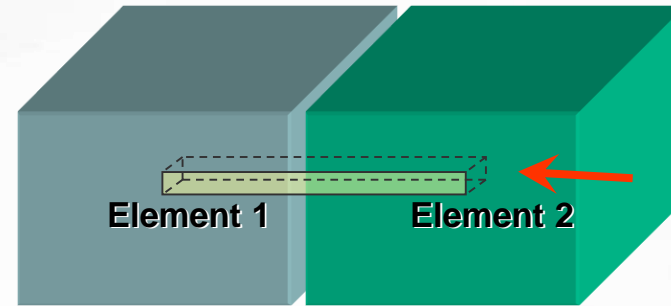


Applied Element Method (AEM) in Extreme Loading for Structures (ELS)

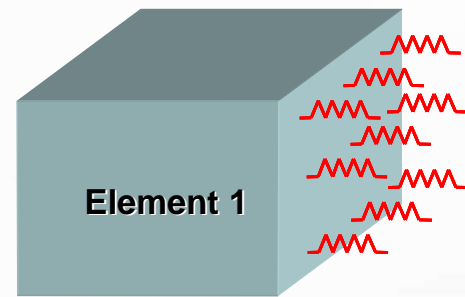
Implemented in ELS software



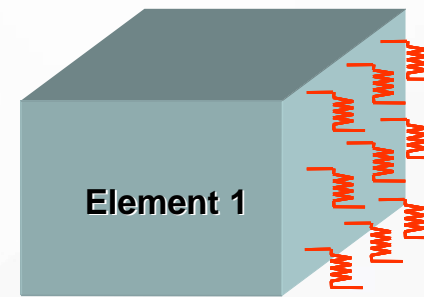
Matrix Springs



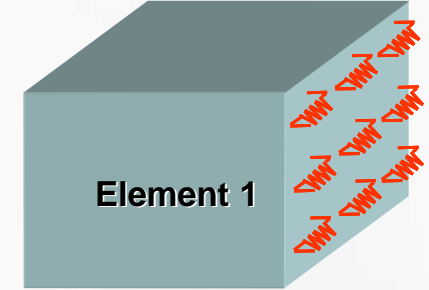
Volume represented by springs



Normal Springs



Shear Springs x-z



Shear Springs y-z

The continuum is discretized into **Elements** connected together with **Nonlinear Springs**.

The springs represent **Material** behavior, Axial and Shear **Deformations**.

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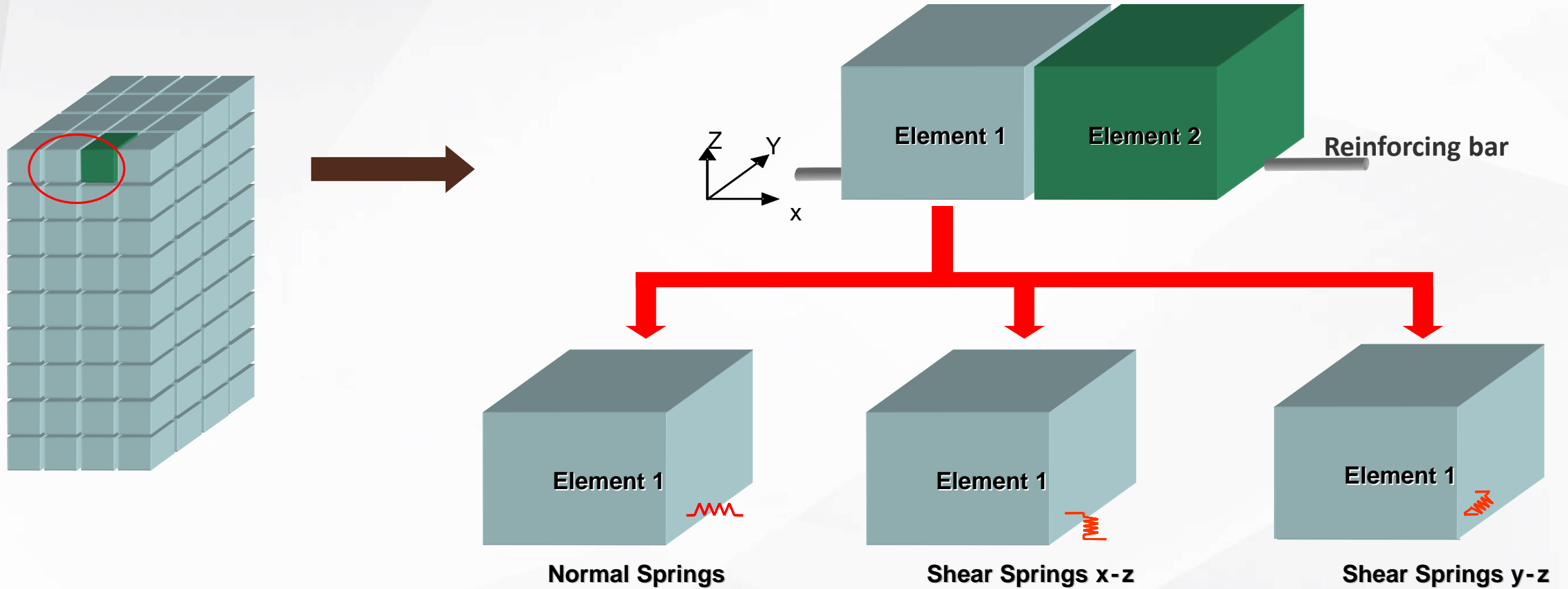


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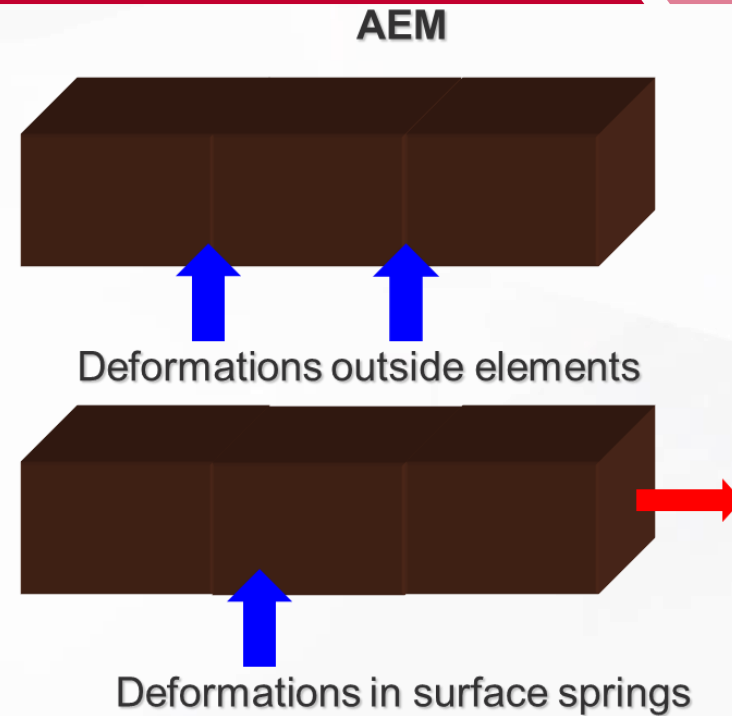
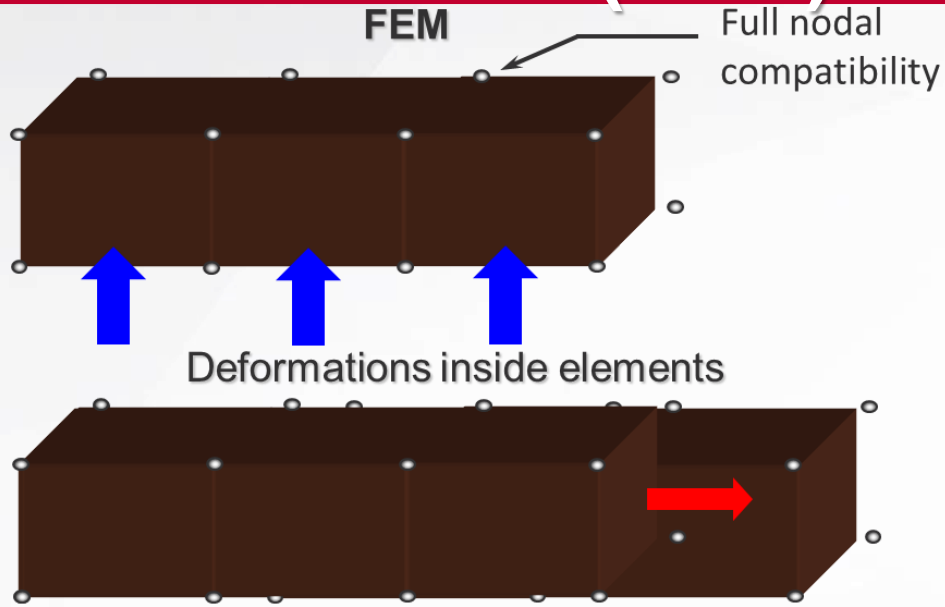


Applied Element Method (AEM) in Extreme Loading for Structures (ELS)

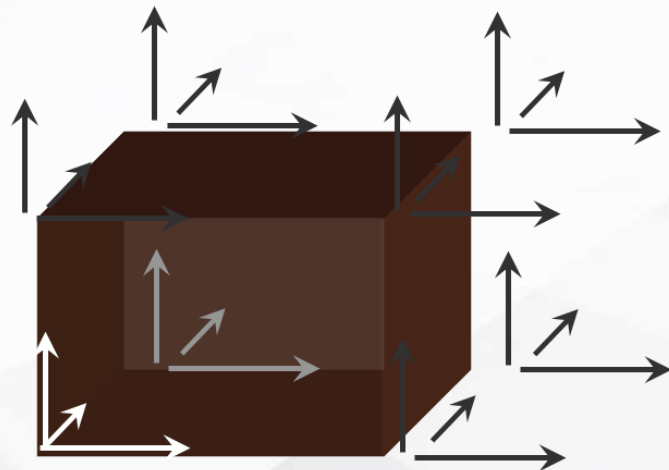
Extreme Loading Software (ELS) - Reinforcing bars springs



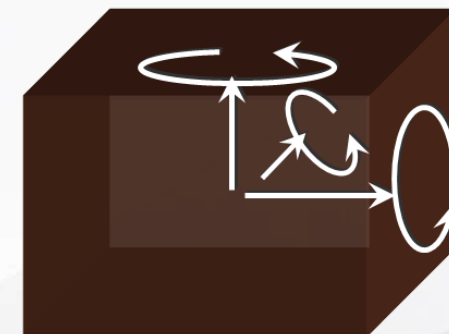
Applied Element Method (AEM) vs Finite Element Method (FEM)



8 nodes x 3
DOF → 24
DOF/
Element

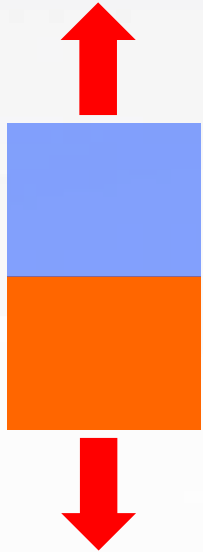


6 DOF/ Element

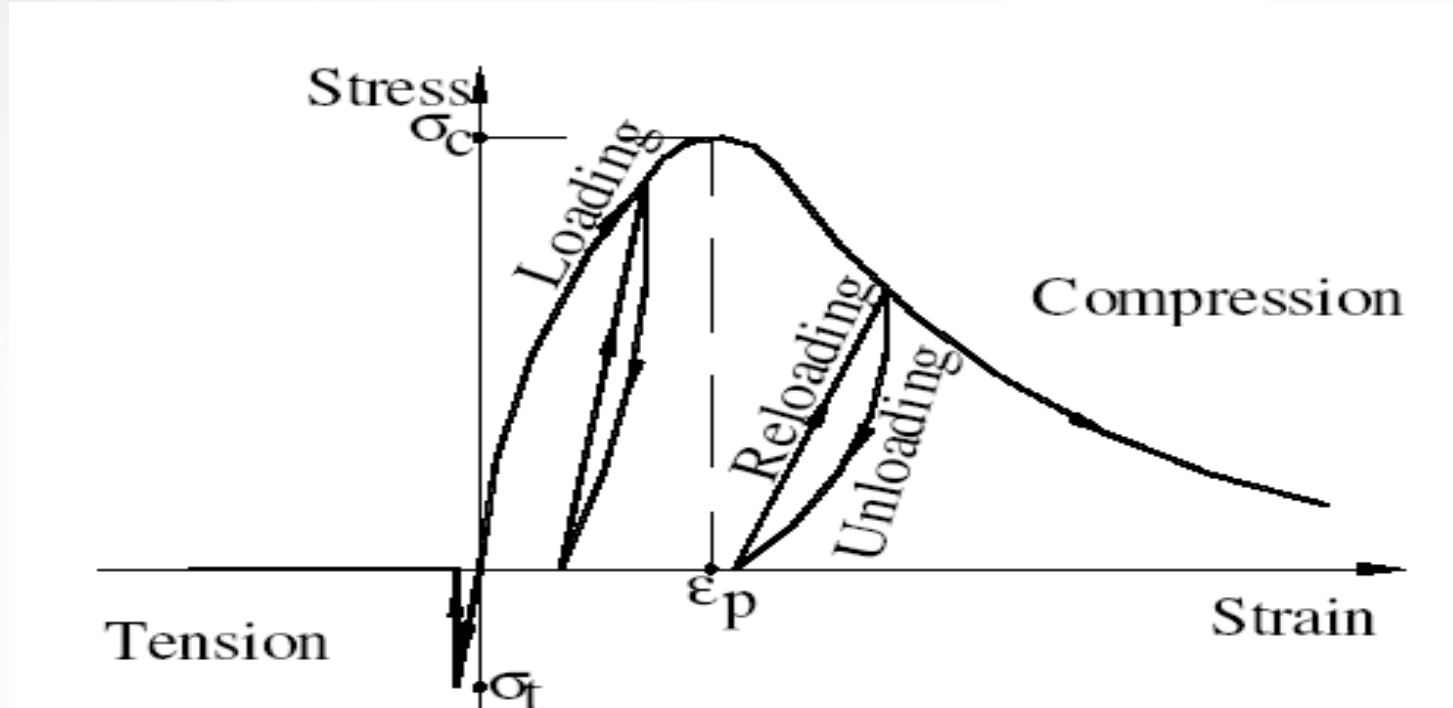


Applied Element Method (AEM): Constitutive Material Models

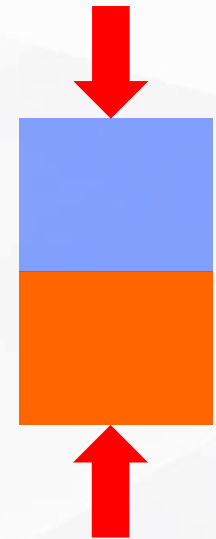
AEM - Nonlinear Material Models



Tension



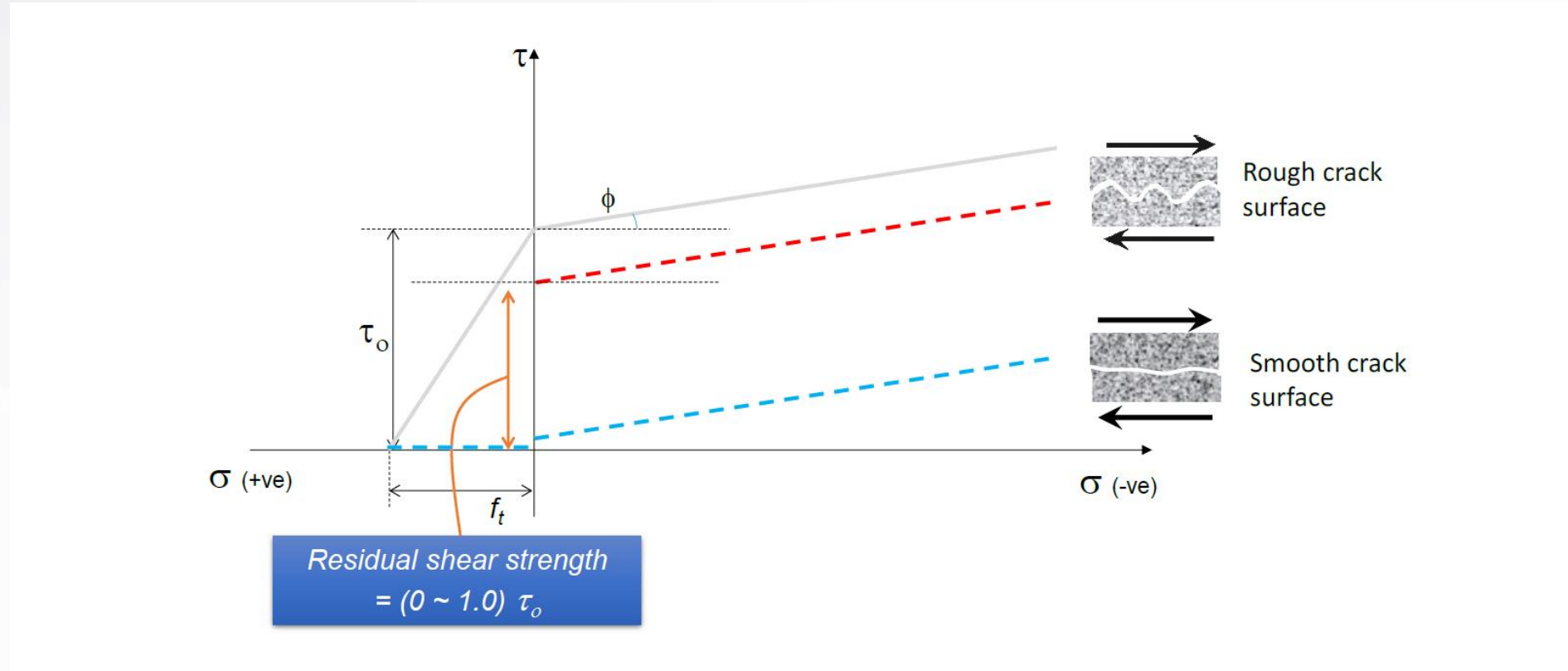
Fully path-dependent model for concrete
(Okamura and Maekawa, 1991)



Compression

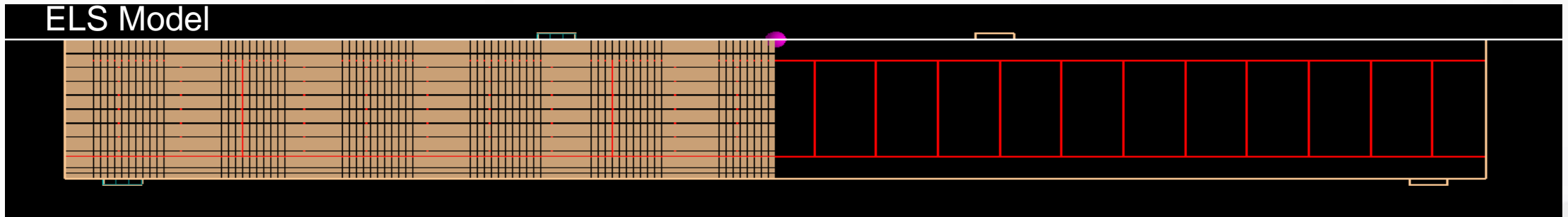
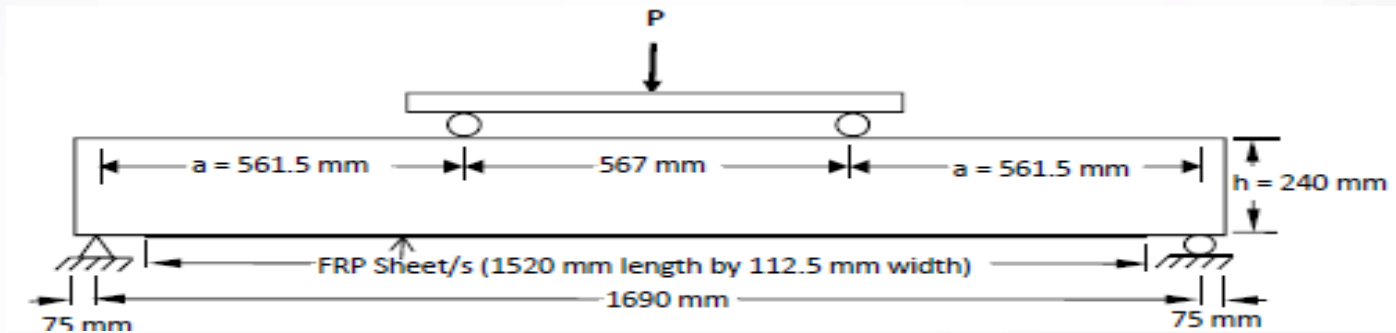
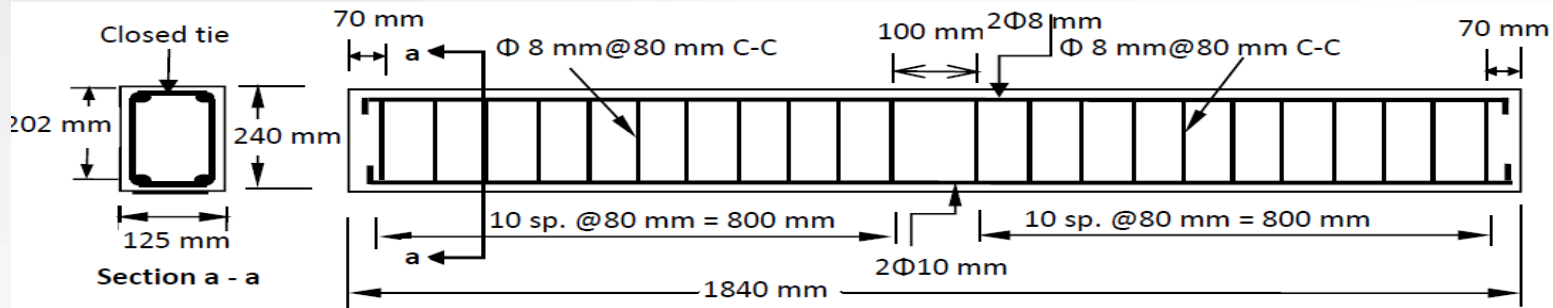
Applied Element Method (AEM): Constitutive Material Models

AEM - Nonlinear Material Models



Shear model for concrete

AEM/ ELS Validated Case: Testing of FRP Retrofitted Concrete Beam



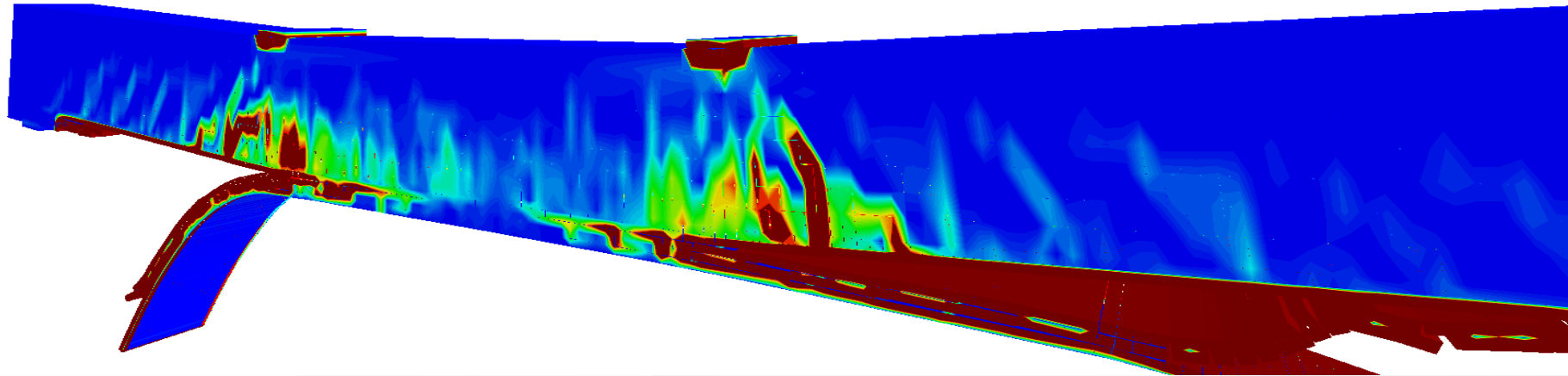
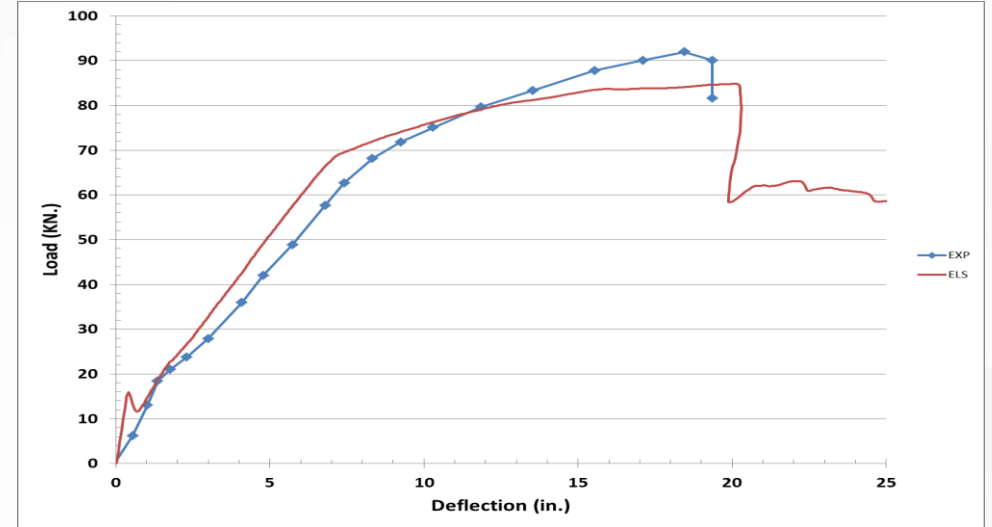
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AEM/ ELS Validated Case: Testing of FRP Retrofitted Concrete Beam



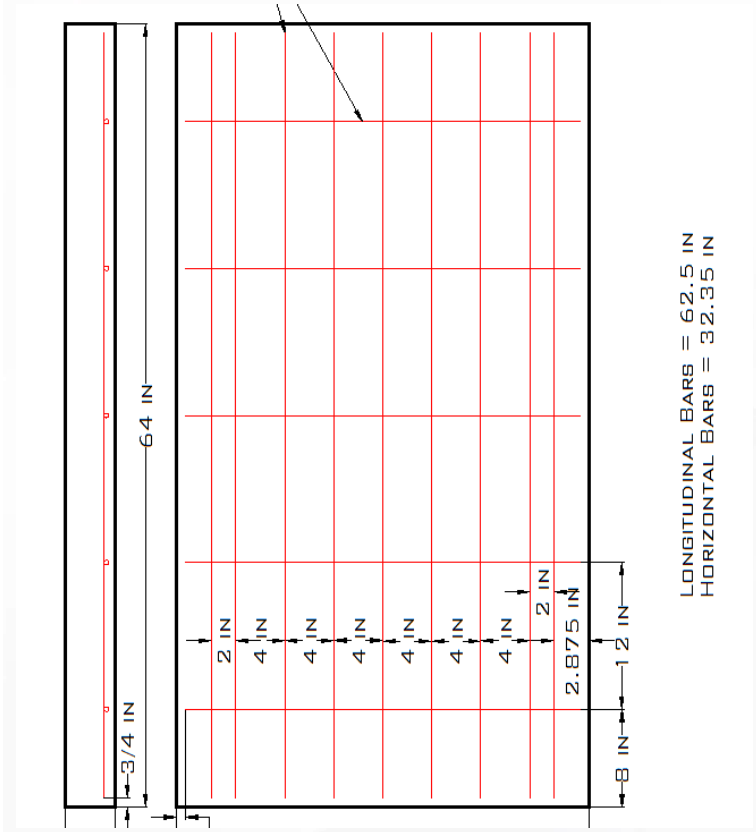
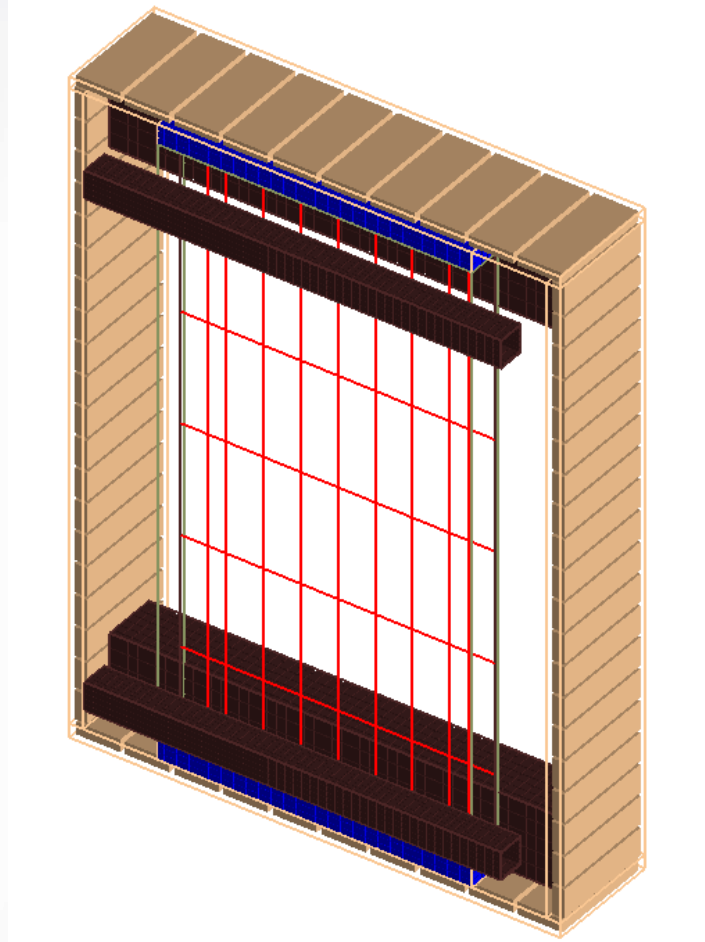
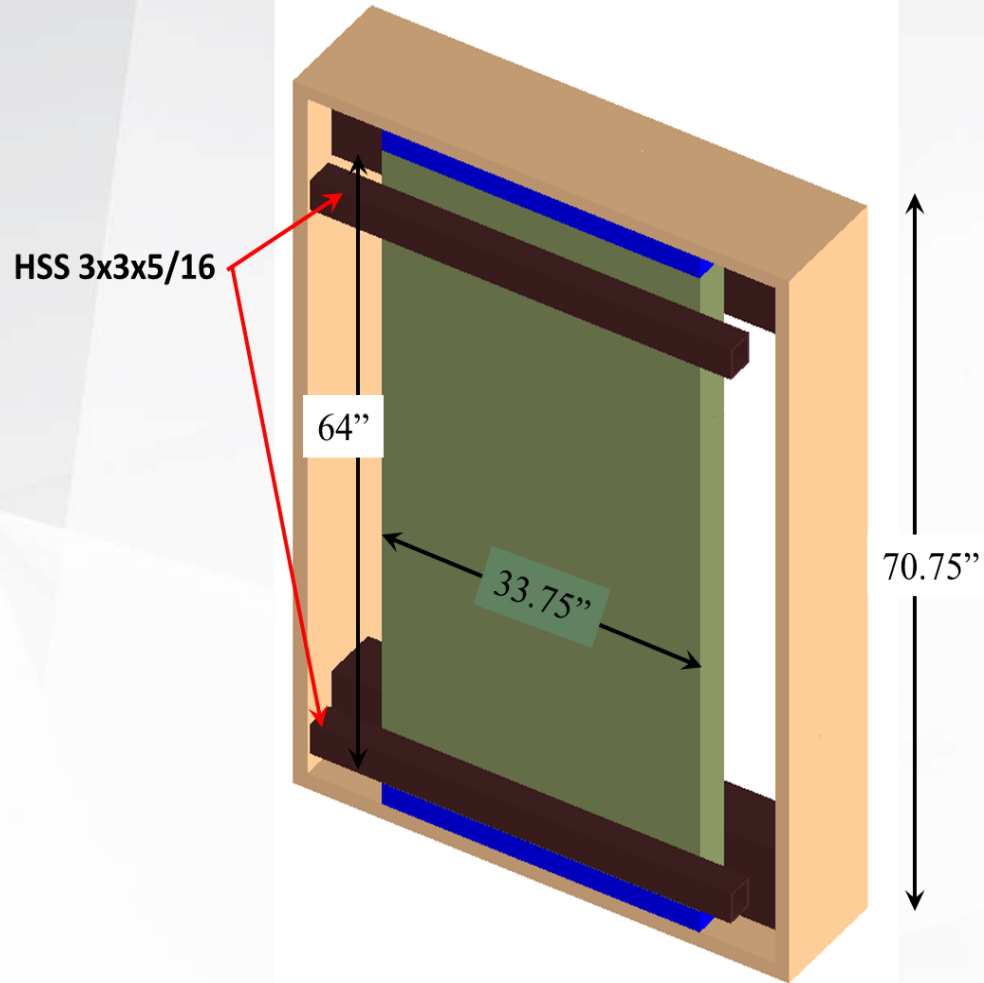
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AEM/ ELS Model



Single Degree Of Freedom (SDOF)

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SBEDS


- Developed by **BakerRisk/PEC/ B&V** and Distributed by **USACE PDC**
- SDOF** Approach
- Various Structural Components of Different Materials Including **RC and RC w/FRP** Components
- Hysteretic** Response
- Time History** Loading
- P-I** Option
- Industry Standard **ATFP** Design Tool

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3/28/2018



Single degree of freedom **Blast Effects Design Spreadsheet**
Version 5.1 1-June-2015



Protection Engineering Consultants



BAKERISK BLAC

2018 ACI Spring Paper
Component: Case-2, RC Slab w/ FRP Retrofit 0.04in
By: THK
Date: 3/16/2018

SBEDS v5.1: Reinforced Concrete Slab with Fiber Reinforced Polymer (FRP) Retrofit

User Info: Fill in Yellow Cells, See Note Below for White Cells

Span Length, L: 4.333 ft	
Width of Reinforcing Steel: 3.778 in	
Inbound Boundary Conditions: One-Way Simple, Uniformly Loaded	
Response Type: Flexural Response	

Structural & Material Properties	
Slab Thickness, t: 4 in	
Spacing of Reinforcing Steel (See diagram in cell #17 for diagram of steel post-tension):	
Bars Spanning Parallel to L, b _s :	3.778 in
Not Used for One-Way Response:	0
Area of Reinforcing Steel	
Positive Moment Steel Parallel to L, A _{s1} :	Inbound: 0.11 in ² , Rebound: 0.11 in ²
Leave Blank for this Boundary Condition:	0, 0 in ²
Not Used for One-Way Response:	0, 0
Not Used for One-Way Response:	0, 0
Distance of Cover to Center of Bar, d:	0, 0
Non-Loaded Side Spanning Parallel to L:	1.0625 in
Loaded Side Spanning Parallel to L:	2.9375 in
Not Used for One-Way Response:	0
Not Used for One-Way Response:	0
Selected Reinforcement:	User Defined
Rein. Steel Yield Strength, f _y :	60,000 psi
Static Strength Increase Factor:	1.20
Dynamic Increase Factor:	1.26
Dynamic Rein. Steel Yield Stress, f _{yd} :	90,504 psi
Rein. Steel Elastic Modulus, E _s :	29,000,000 psi
FRP Input: Use Click Button	Carbon Fiber: Fyfe SCH-41 (T)ly@S
FRP Properties: Yield Strength = 143,000 psi	Modulus = 13,900,000 psi
Thickness = 0.04 in	
Fiber Layers	
Fiber Fractional Layers Parallel to L:	Unloaded Side: 1, Loaded Side: 0
Not Used for One-Way Response:	
Environmental Reduction Factor (C _e):	0.95
Bond Dependent Coefficient (K _{bc}):	0.90
Support Weight, w:	0 pcf
Concrete Density, γ _c :	145 lb/ft ³
Poisson's Ratio, ν _c :	0.167
Concrete Compressive Strength, f _c :	5,400 psi
Concrete Static Strength Increase Factor (≥1):	1.0
Concrete Dynamic Compr. Increase Factor (≥1):	1.312
Concrete Dynamic Compr. Strength, f _{cd} :	7,085 psi
Concrete Elastic Modulus, E _c :	4,234,117 psi
No Dynamic Axial Load:	Static Axial Load, P ₀ : 0 lb
Leave Blank for No Axial Load:	0 in
Leave Input Blank for One-Way Response:	0 ft

Calculated Properties (Note 7)			
Rebound Pos. H-Dir Moment Capacity, M _{pr} :	0	0	0-in-in
Inbound Pos. H-Dir Moment Capacity, M _{pr} :	0	0	0-in-in
Inbound Pos. L-Direction Reinforcement Ratio (fiber, rear):	0.000	0.000	
Rebound Negative H-Direction Moment Capacity, M _{pr} :	0	0	0-in-in
Inbound Negative H-Direction Moment Capacity, M _{pr} :	0	0	0-in-in
Inbound Neg. H-Direction Reinforcement Ratio (fiber, rear):	0.000	0.000	
Rebound Pos. L-Dir Moment Capacity, M _{pr} :	2.223	2.223	0-in-in
Inbound Pos. L-Dir Moment Capacity, M _{pr} :	17.803	7.164	0-in-in
Inbound Pos. L-Direction Reinforcement Ratio (fiber, rear):	0.010	0.027	
Rebound Negative L-Direction Moment Capacity, M _{pr} :	0	0	0-in-in
Inbound Negative L-Direction Moment Capacity, M _{pr} :	0	0	0-in-in
Inbound Neg. L-Direction Reinforcement Ratio (fiber, rear):	0.000	0.000	
Component Controlling Inbound Flexural Capacity:		Concrete in Compression	
Flex. Shear Block Factor, β _s :		0.70	
75% of Balanced Steel Reinforcement Ratio, 0.75ρ _b :		0.017	
Avg Cover Depth (inbound/rebound):	0.00	2.94	in
Moment of Inertia, I _{cr} :		3	in ⁴

Error/Warning Messages

Check Shear Capacity < Flexural Capacity. SDOF Results Based on Flexural Capacity (See Message in Yellow Cells Below)

Check Shear Results. Provide Required Strips or Set Shear Flag >0 in Cell H45 and ReRun SDOF for Shear Controlled Response (Shear Flag #1 for Controlling Shear at Support >2 by Controlling Shear at distance d from Support)

Notes:

- Used for clearing of reflected load
- Angle in degrees from normal
- This capacity assumes wall has positive lateral support at top and bottom, such as dowels or bearing angle.
- Shear controlled response typically has very limited ductility - a maximum value of 1 is assumed in SBEDS. The user should clearly understand shear controlled response when using the shear flag - see User's Guide.
- Axial load per unit width on analyzed component from saved Dynamic Shear History file for supported component. Dynamic axial load includes static gravity load of supported horizontal member.
- For internal loading, user must typically check if stirrups needed at support (SBEDS does not check this)
- Moment capacities controlled by tension strength fiber or compression crushing strain of concrete - see User's Guide.
- Response criteria is specific for FRP reinforced walls. If there is no FRP on the loaded side of wall, the USER MUST check that the rebound response meets the selected Response Criteria for reinforced concrete components using the "See at COE Response Criteria for ATFP" button.

Click to Input Blast Parameters

Blast Load Type

Pressure-time history file

None (vertical component)

Gravity Displacement

Pressure-time input

Time (ms): N/A, Pressure (psi): N/A

Charge Weight (W) and Standoff (R)

W (lb): N/A, Explosive Type: N/A

W (TNT Equiv./lb): N/A, R (ft): N/A

Blast Load Phase

Blast Load Orientation: N/A

Parameters for Reflected Loads

Wall Height (ft): N/A

Wall Width (ft): N/A

Incidence Angle (deg): N/A

Load Files (A)(above), (B)(below): N/A

Click to Input SDOF Properties

Resistance, R

Property	Inbound	Rebound	Units
Mass, M	868.7	868.7	psi-m ² /in
Load-Mass Factors, K ₁			
K ₁	0.78	0.78	
K ₂	0.78	0.78	
K ₃	0.66	0.66	
K ₄	0.66	0.66	
K ₅	0.66	0.66	

Stiffness, K

Property	Inbound	Rebound	Units
R1	52.68	-5.58	psi
R2	52.68	-5.58	psi
R3	52.68	-5.58	psi
R4	52.68	-5.58	psi

Yield Displacement, x

Property	Inbound	Rebound	Units
x1	0.43	-0.05	in
x2	0.43	-0.05	in
x3	0.43	-0.05	in
x4	0.86	-0.11	in
Equip Yield Defl., X _e	0.43	-0.05	in

FRP Response Criteria is checked only for Inbound Response. See Note 8

Dynamic Reaction Factors

Factor	Elastic	Plastic
F constant	0.11	0.12
R constant	0.39	0.38

Results Summary

μ _{max} = 1.51 deg	Design Criteria: VLL0P/Primary
μ = 1.60	Response DOES NOT MEET input design criteria
X _{max} Inbound = 0.69 in	at time = 10.30 msec
X _{max} Rebound = 0.00 in	at time = 0.00 msec
R _{max} = 52.69 psi	at time = 10.30 msec
R _{min} = -6.62 psi	at time = 63.20 msec

Equivalent Static Reactions (1)

V _u at support A = 1,369.7 lb/in
V _u at support B = 1,369.7 lb/in
Maximum V _u at distance d from support = 1,159.0 lb/in
Shear Capacity (See Note 2) = 4,534.3 lb/in
Direct Shear Capacity, (monolithic joint) V _{u,dir} = 673.4 lb/in
Diagonal Shear Capacity, V _{u,diag} = 673.4 lb/in

Basic:

Direct Shear at support (See Note 6) Shear is OK

Diagonal Shear at distance d from support Strips Required

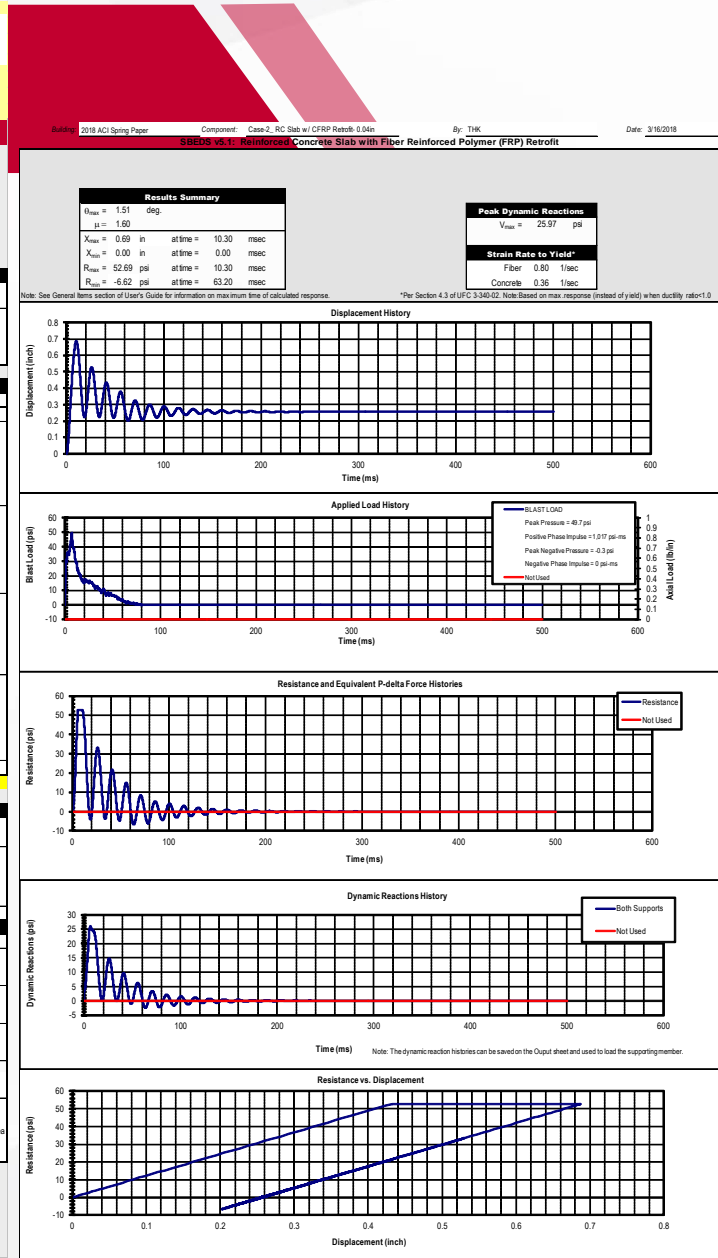
Strip Area per unit spacing, A_s Required in Max Shear Region (2)

For critical section @ support per unit spacing (s), A_{s,req} = 0.000 in²/in

For critical section @ d from support per unit spacing (s), A_{s,req} = 0.0051 in²/in

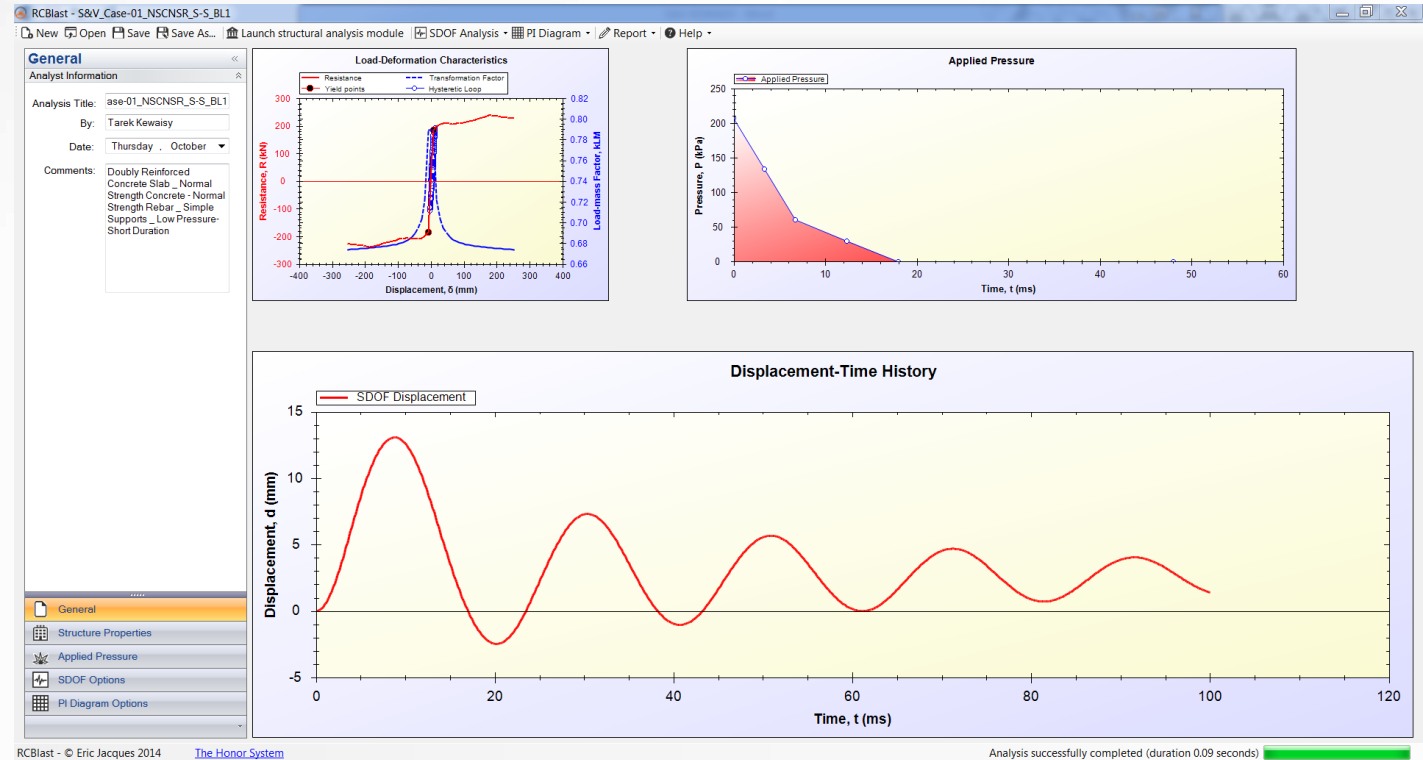
Notes for Shear Information:

- Based on larger of inbound and rebound maximum flexural resistance
- Multiply A_s values by flexural bar spacing and stirrup spacing to get stirrup area



RCBlast

- Developed by **Eric Jacques**
- **SDOF** Approach
- **RC and RC w/FRP** Components
- **Hysteretic** Response
- **Plastic-Hinge** Length
- **Time History** Loading
- **P-I** Option
- Experimentally **Verified**

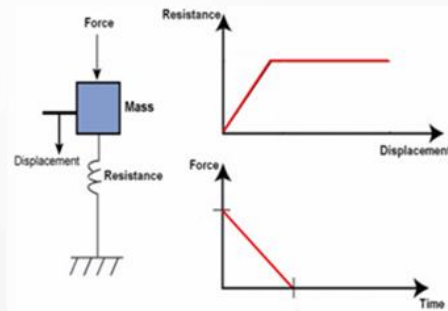


Louis Berger

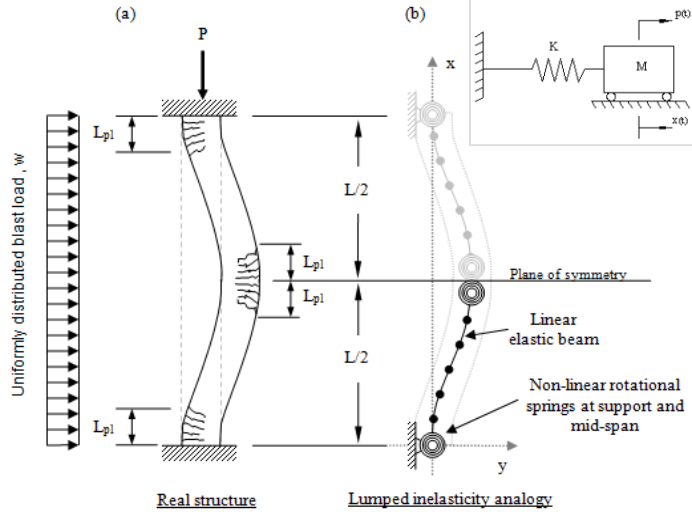


3/28/2018

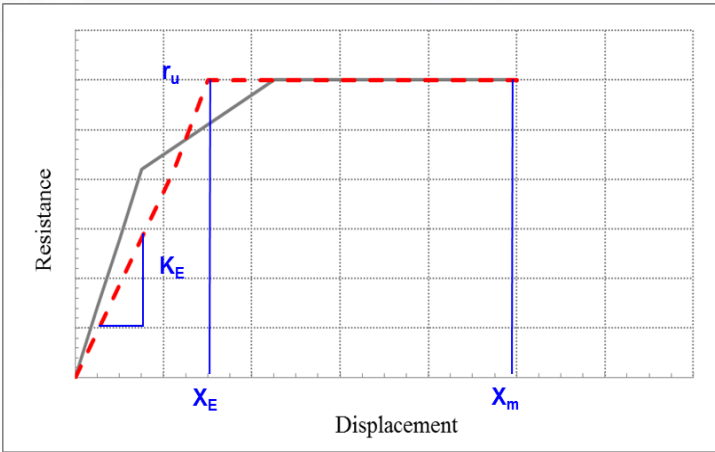
Advanced Modeling of Blast Response of Reinforced Concrete Walls with and without FRP Retrofit



SDOF Parameters- RC Blast

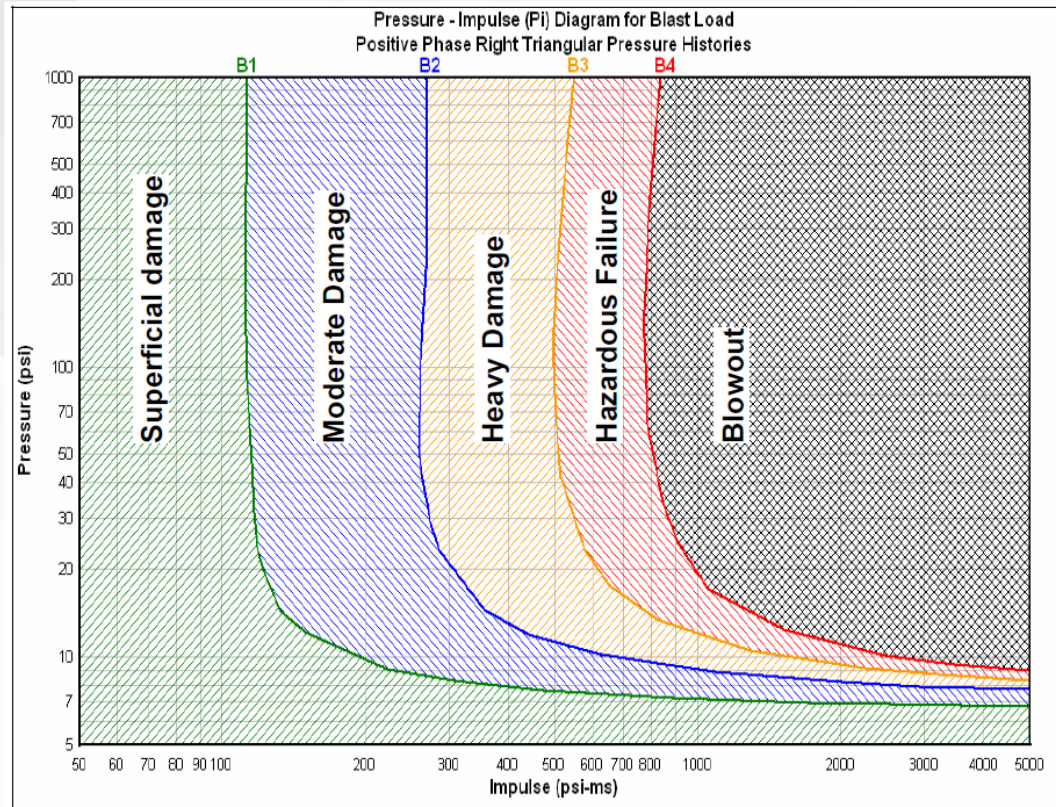


Parameter	Case-1 Unretrofitted	Case-2 CFRP 0.04" Back Face	Case-3 CFRP 0.04" Back & Front	Case-4 CFRP 0.08" Back Face	Case-5 GFRP 0.04" Back Face
M psi.ms ² /in	869	869	869	869	869
k_{E+} psi/in	47.0	65.5	65.3	133.0	54.5
k_{E-} psi/in	4.0	5.3	5.3	5.9	4.3
r_{e+} psi	20.80	36.84	36.83	60.94	30.10
r_{e-} psi	5.84	7.14	7.12	7.10	6.44
r_{u+} psi	25.43	63.33	64.09	76.12	40.55
r_{u-} psi	5.99	10.58	10.70	10.64	8.94
x_{E+} in	0.443	0.562	0.564	0.458	0.552
x_{E-} in	1.462	1.352	1.352	1.211	1.496
T_{N+} ms	23.87	20.21	20.24	14.19	22.15
T_{N-} ms	81.87	71.21	71.26	67.56	78.87



Damage Levels / Response Limits (RC Only)

USACE/ PDC-TR 06-08: Single-Degree-of-Freedom Structural Response Limits for Anti-terrorism Design



Maximum Rotations Limits

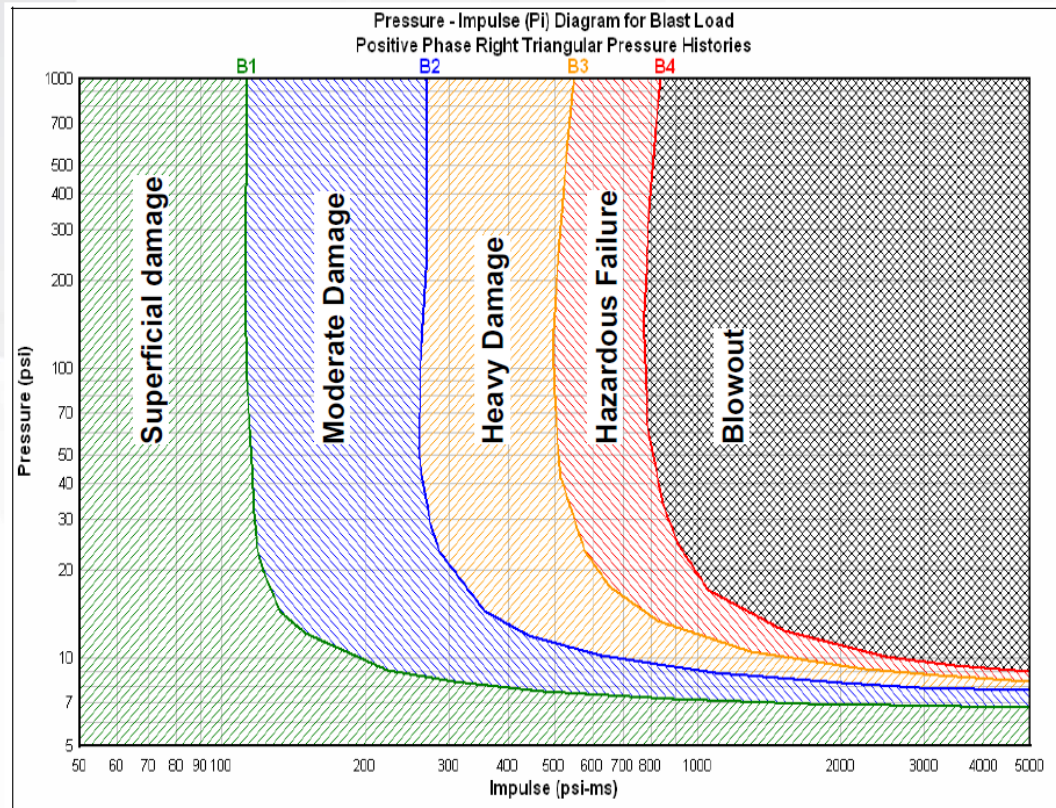
Damage Level B1		Damage Level B2		Damage Level B3		Damage Level B4		Damage Level B5	
Superficial Damage		Moderate Damage		Heavy Damage		Hazardous Failure		Blowout	
μ	θ	μ	θ	μ	θ	μ	θ	μ	θ
1.0	-	-	2°	-	5°	-	10°	-	> 10°

Maximum Displacement Limits

DL (B1)	DL (B2)	DL (B3)	DL (B4)	DL (B5)
Superficial	Moderate	Heavy	Hazardous	Blowout
X_{max}/L	X_{max}/L	X_{max}/L	X_{max}/L	X_{max}/L
0.0175	0.070	0.175	0.353	> 0.353
X_{max} (L=52in)	X_{max} (L=52in)	X_{max} (L=52in)	X_{max} (L=52in)	X_{max} (L=52in)
≈ 0.907 in	0.907 in	2.275 in	4.585 in	> 4.585 in

Damage Levels / Response Limits (RC W/ FRP)

SBEDS v5.1: SBEDS v5.1: Reinforced Concrete Slab with Fiber Reinforced Polymer (FRP) Retrofit



Maximum Rotations Limits (Primary)

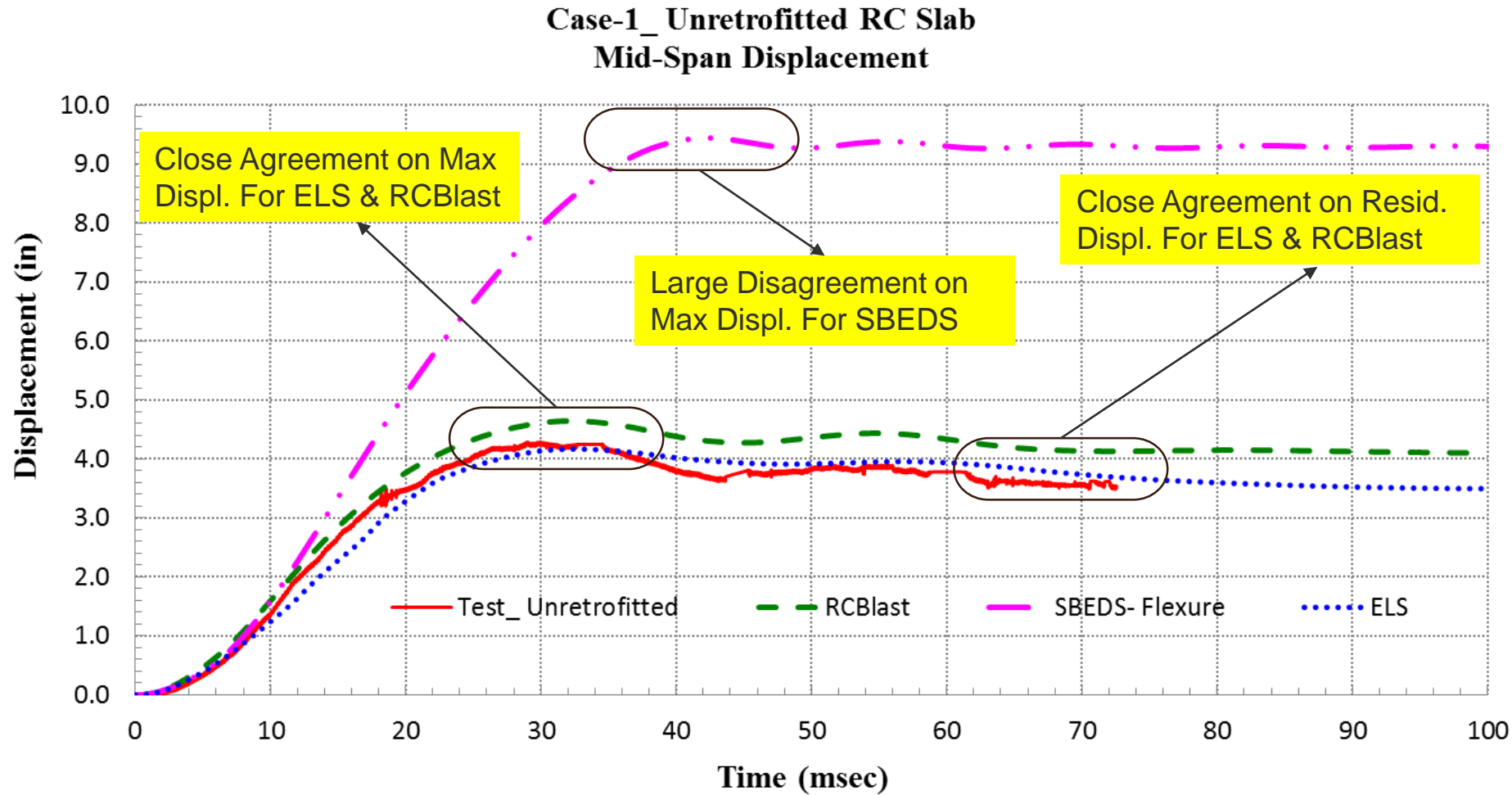
Damage Level B1		Damage Level B2		Damage Level B3		Damage Level B4		Damage Level B5	
Superficial Damage		Moderate Damage		Heavy Damage		Hazardous Failure		Blowout	
μ	θ	μ	θ	μ	θ	μ	θ	μ	θ
< 0.5	-	0.5	-	0.75	-	1.0	-	> 1.0	-

Maximum Rotations Limits (Secondary)

Damage Level B1		Damage Level B2		Damage Level B3		Damage Level B4		Damage Level B5	
Superficial Damage		Moderate Damage		Heavy Damage		Hazardous Failure		Blowout	
μ	θ	μ	θ	μ	θ	μ	θ	μ	θ
0.5	-	0.75	-	1.0	-	1.3	-	> 1.3	-

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Case-1: Peak Displacement Response

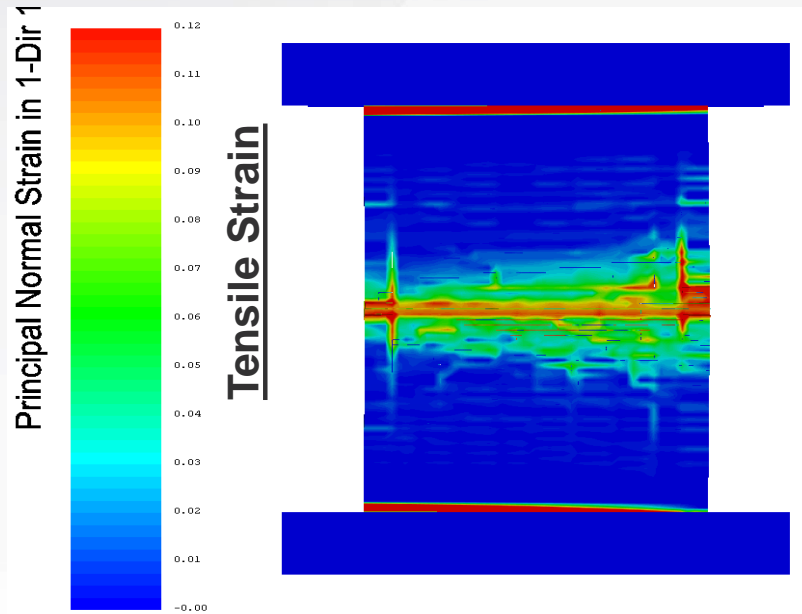


Unretrofitted
RC Slab
(Control Case)

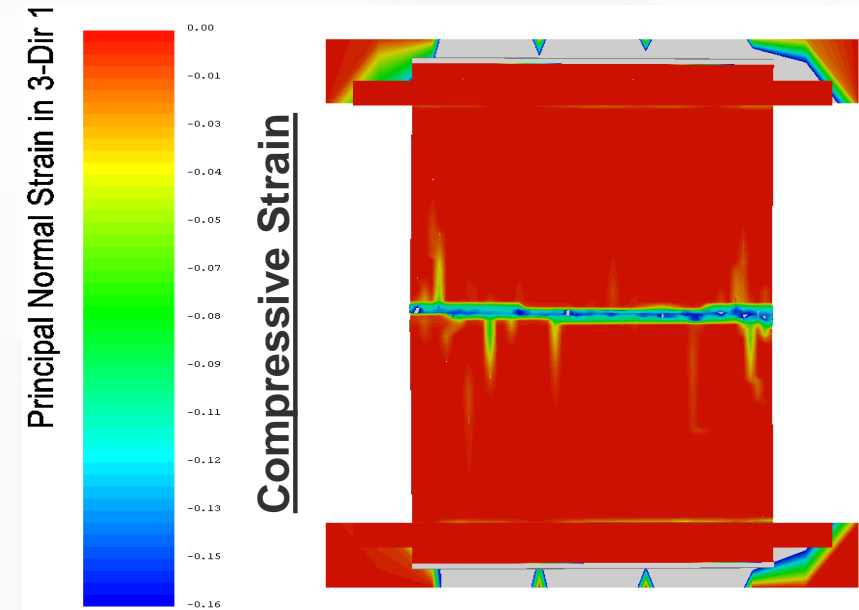
CASE-1: AEM/ ELS Simulation



Back Face



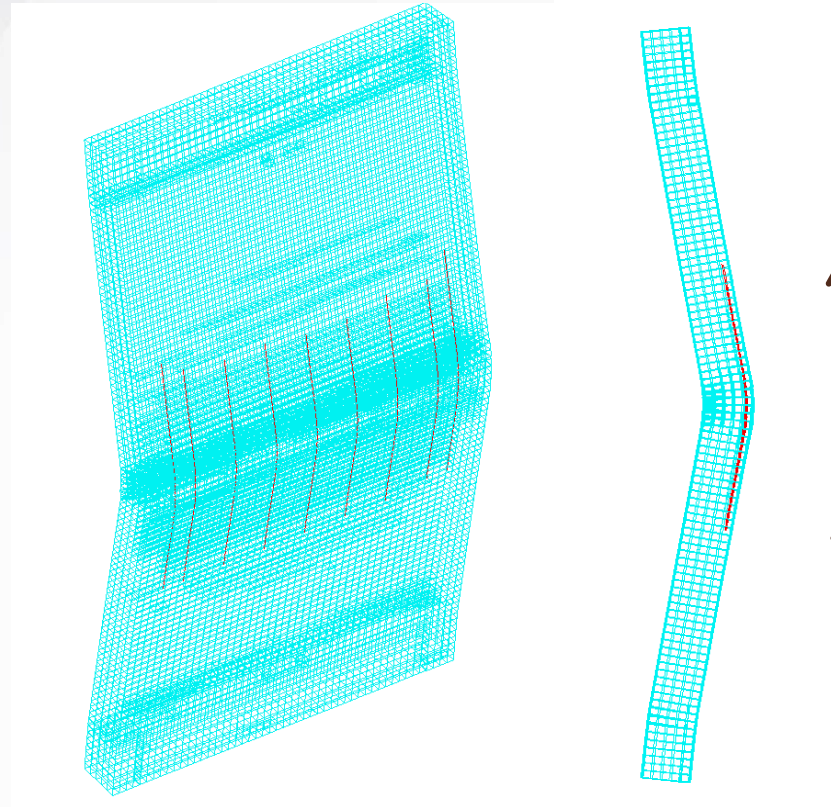
Front Face



CASE-1: AEM/ ELS Simulation

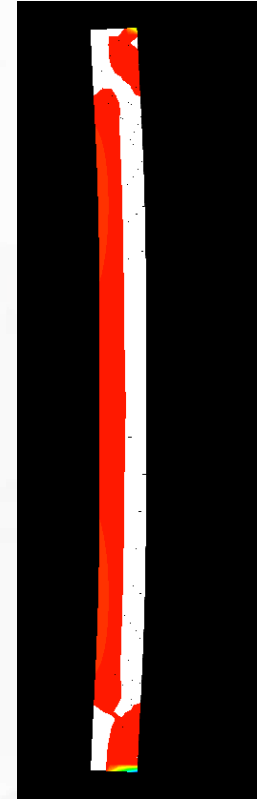


Back Face



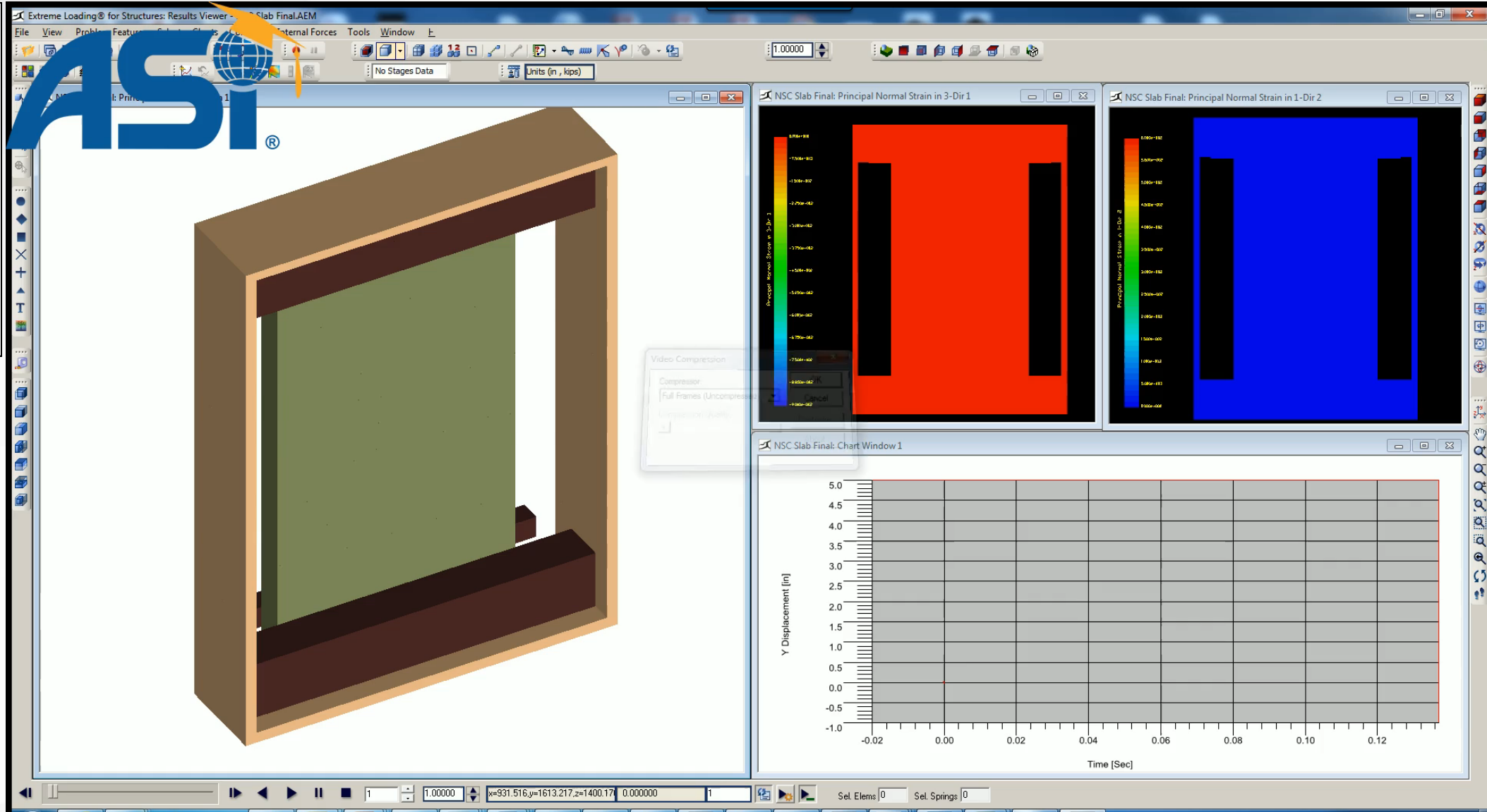
Yielded Steel Bars Marked in Red

Extent of
plasticity



At any load step open cracks have
no tensile or shear strength

Case-1: AEM/ ELS Simulation



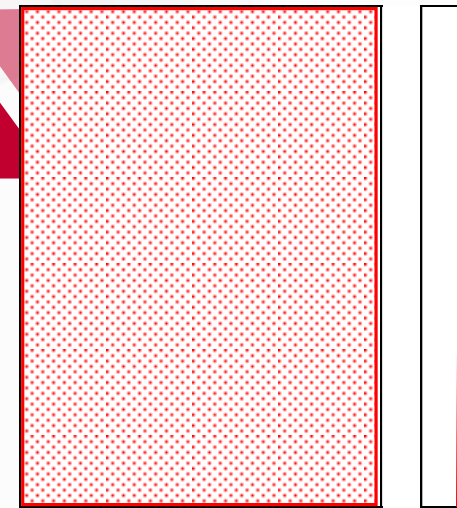
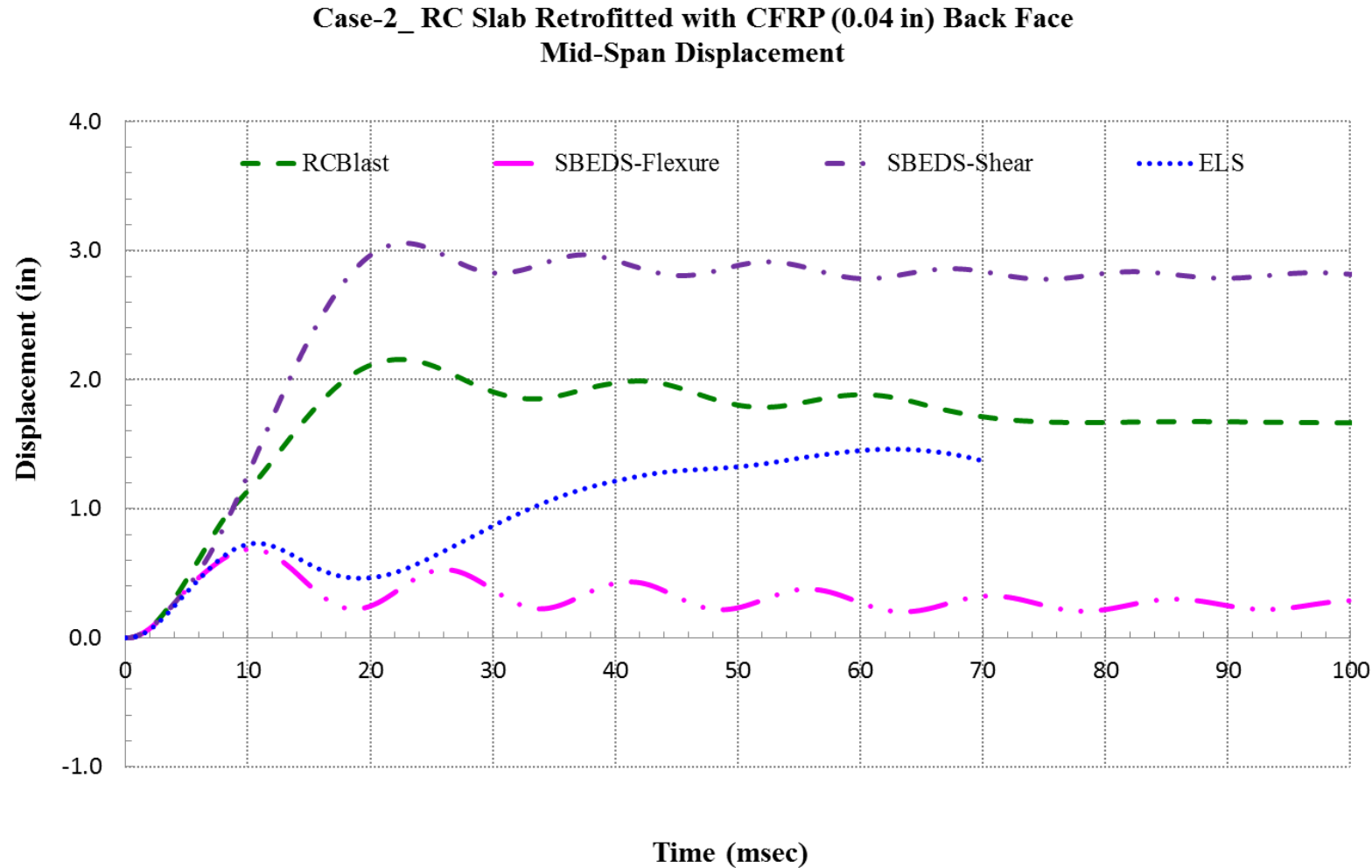
Louis Berger



Advanced modeling of Blast Response of Reinforced concrete walls with and without FRP Retrofit

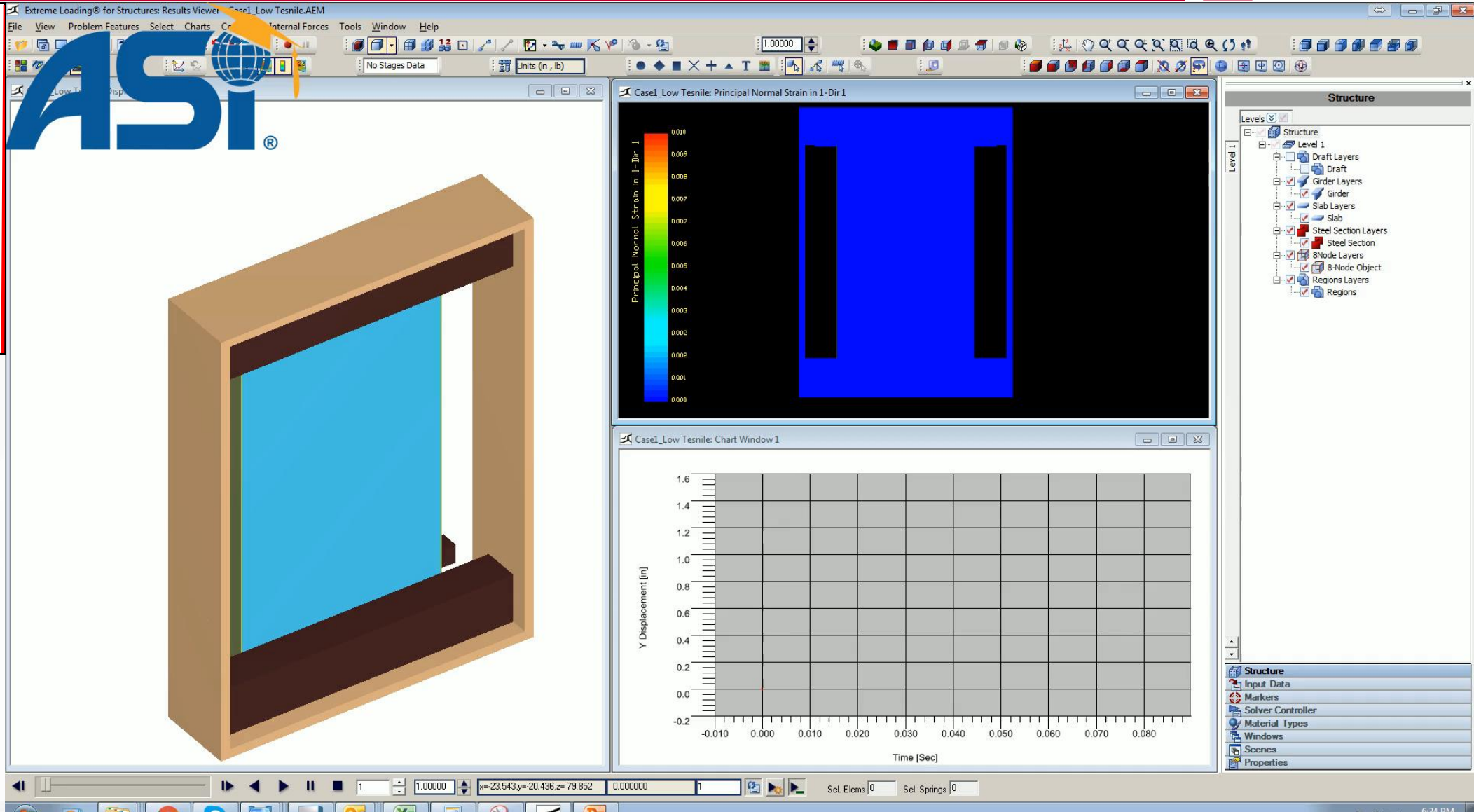
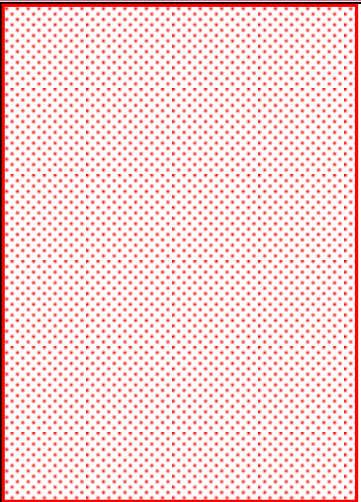


Case-2: Peak Displacement Response



CFRP
Retrofitted RC
Slab
(Single Layer-
0.04in - Back
Face Only)

Case-2: AEM/ ELS Simulation



Louis Berger

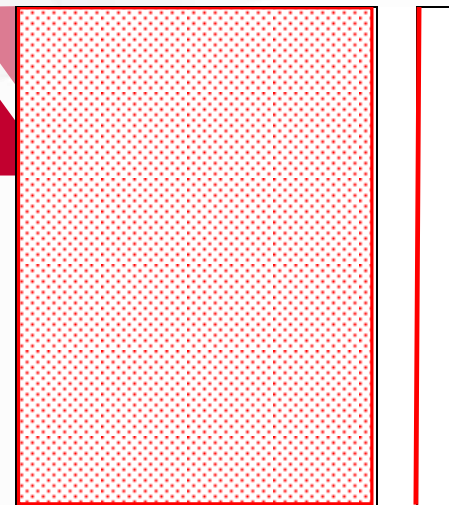
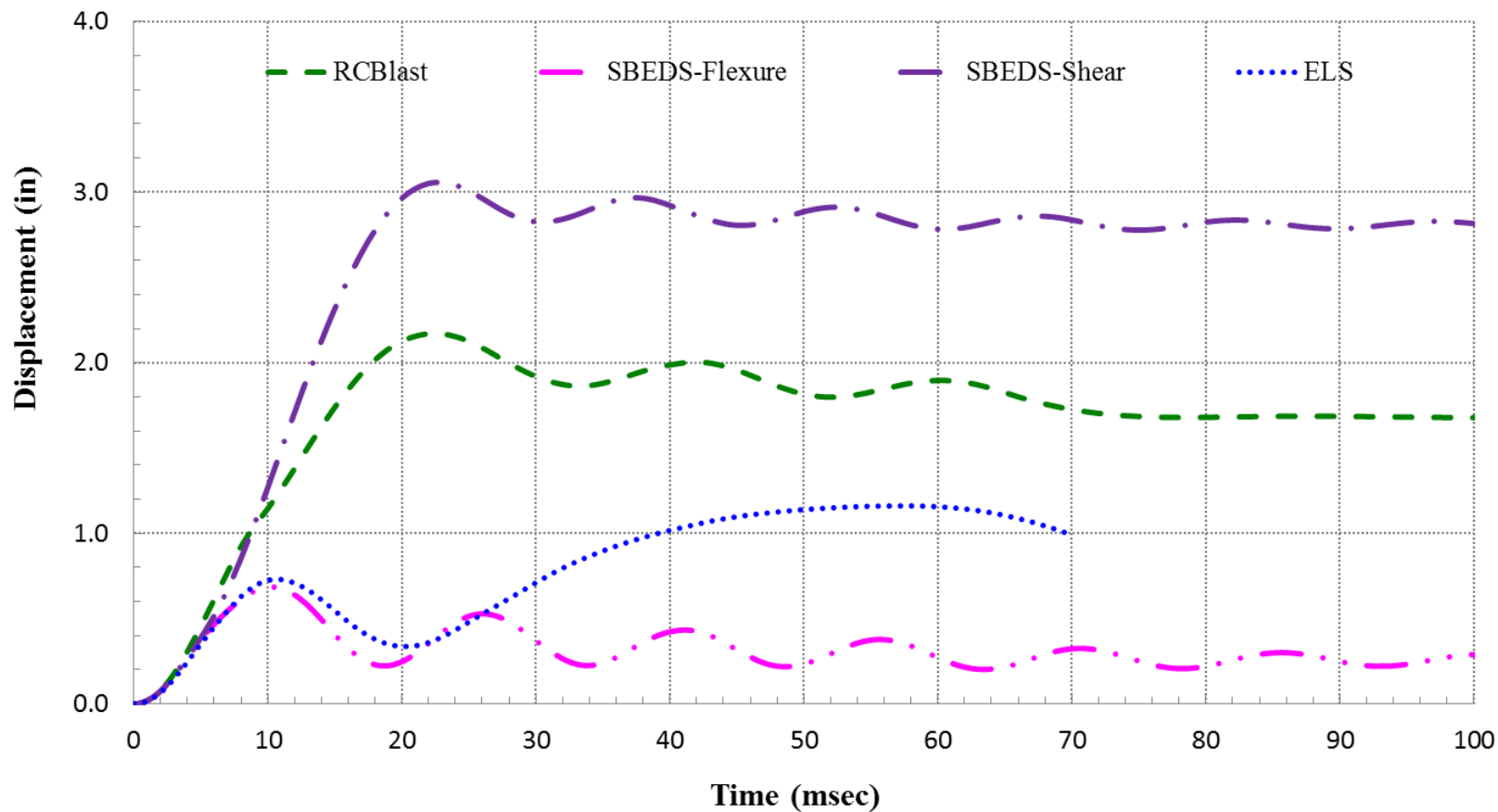


with and without FRP Retrofit



Case-3: Peak Displacement Response

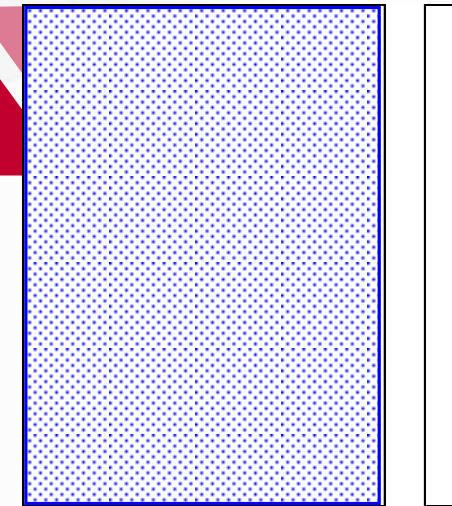
Case-3_ RC Slab Retrofitted with CFRP (0.04 in) Back & Front Faces
Mid-Span Displacement



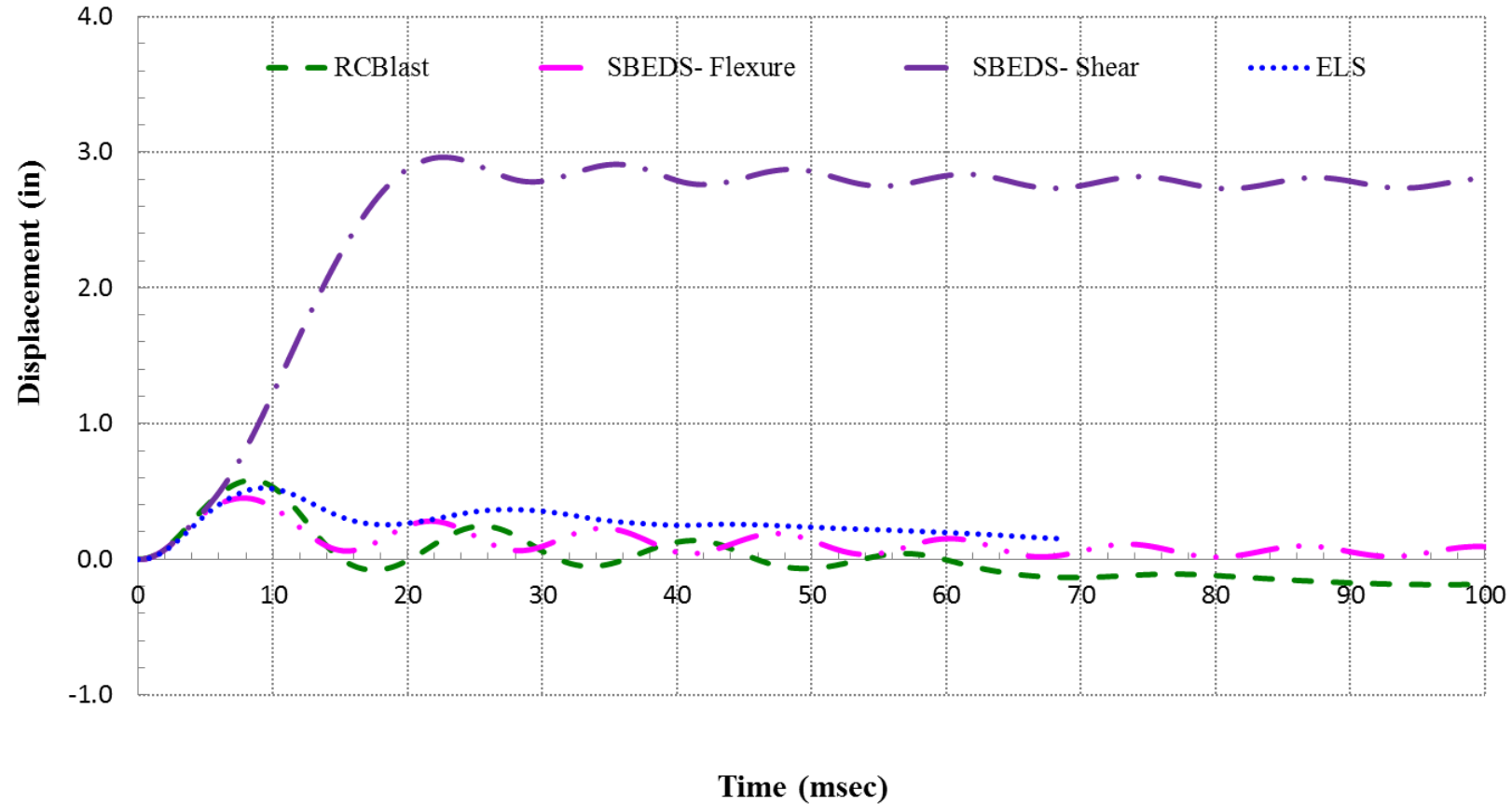
CFRP
Retrofitted RC
Slab

(Single Layer-
0.04in - Back &
Front Faces

Case-4: Peak Displacement Response



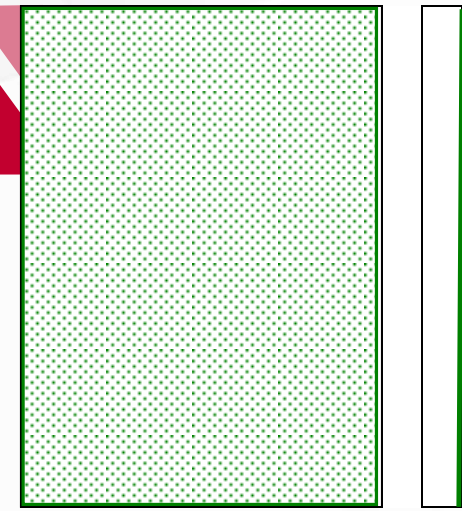
Case-4_ RC Slab Retrofitted with CFRP (0.08 in) Back Face
Mid-Span Displacement



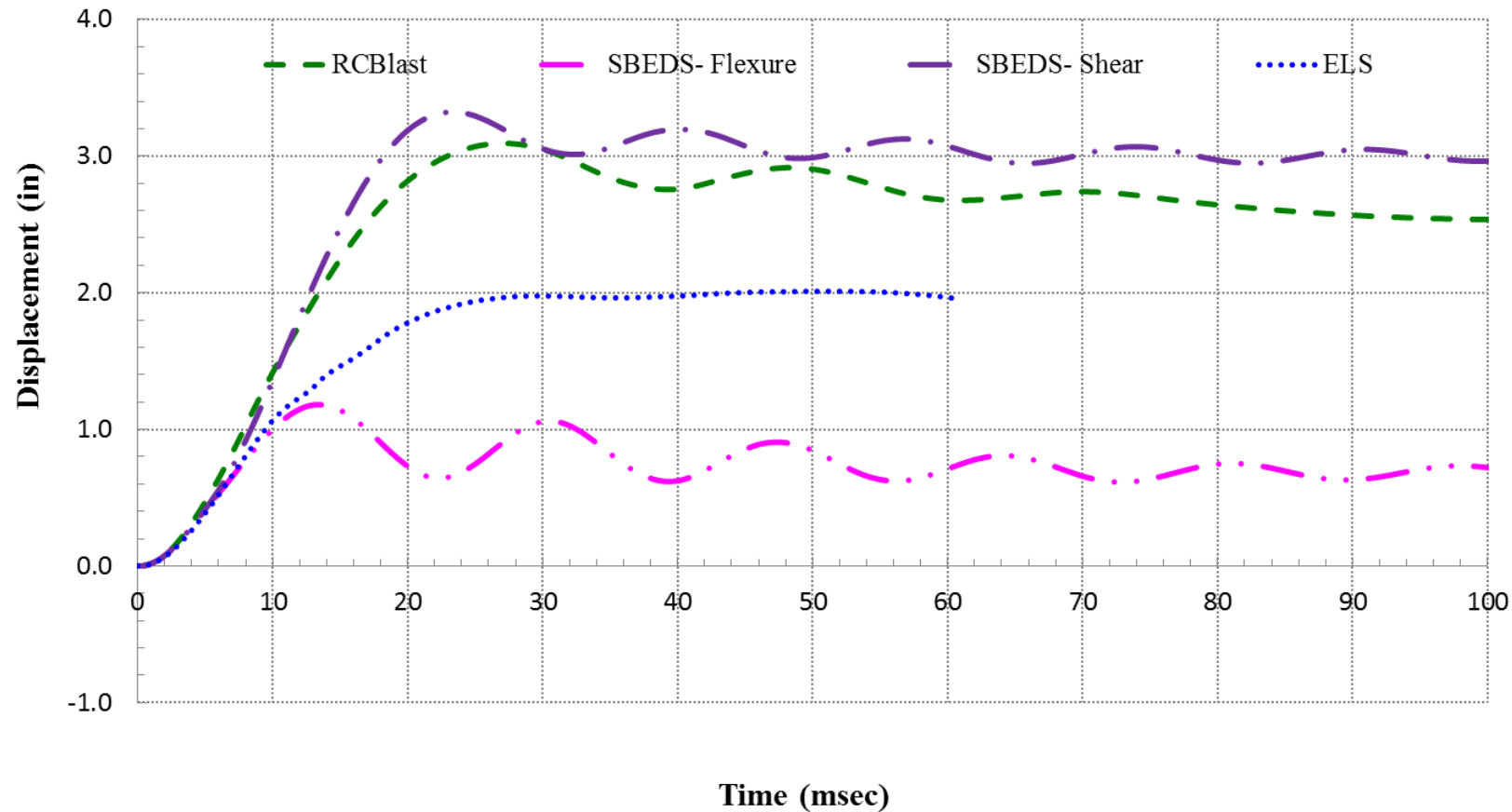
CFRP
Retrofitted RC
Slab

(Double Layers-
0.08in - Back
Face Only)

Case-5: ELS , SBEDS & RCBlast Simulations

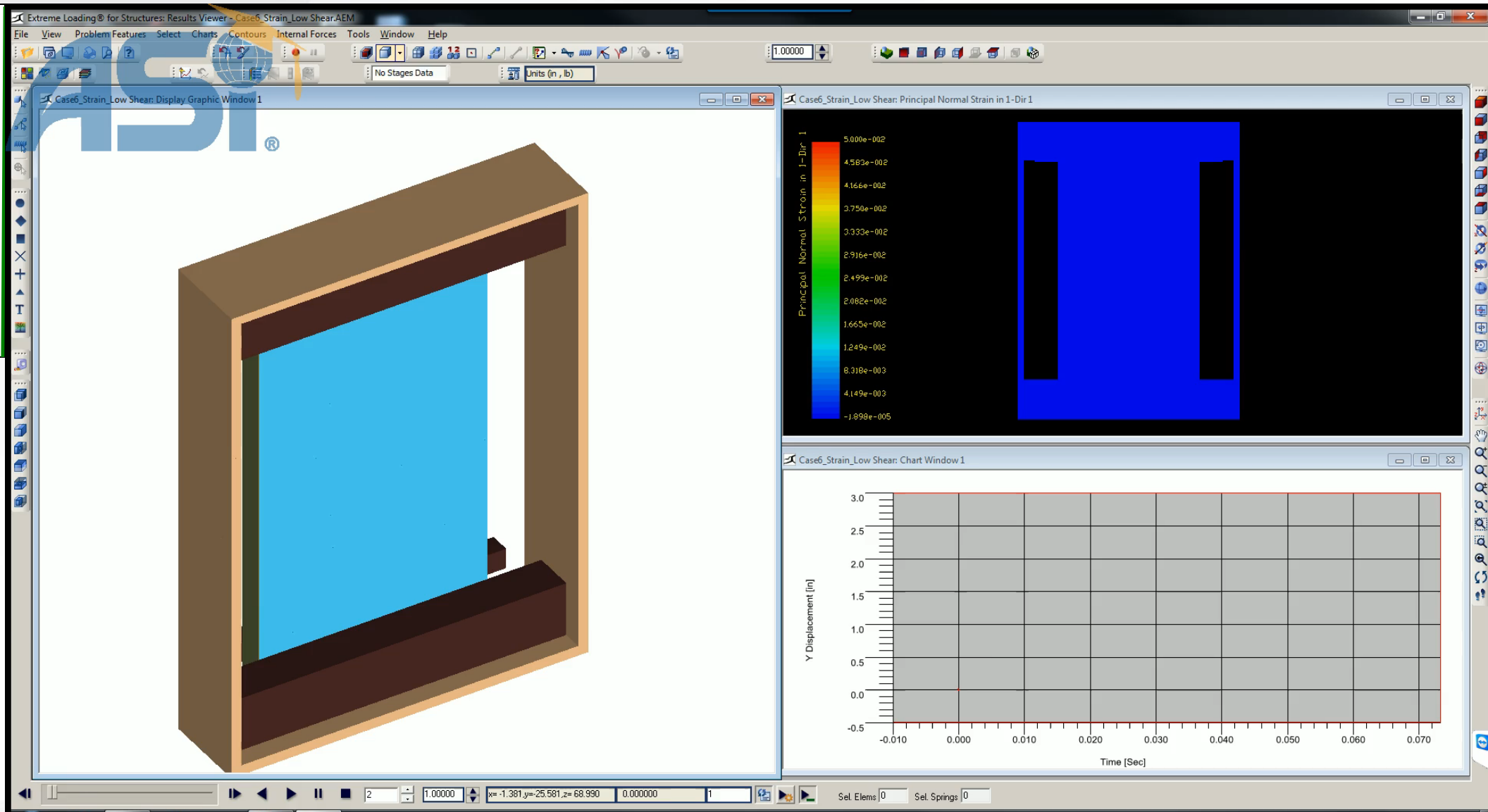
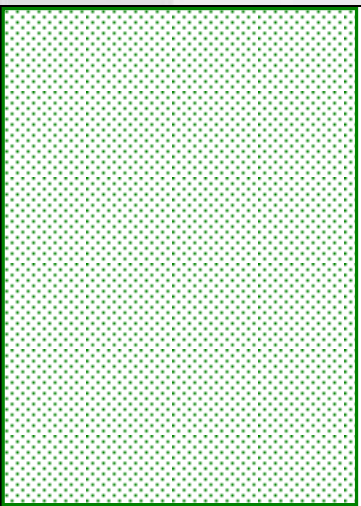


Case-5_ RC Slab Retrofitted with GFRP (0.04 in) Back Face
Mid-Span Displacement



GFRP
Retrofitted RC
Slab
(Single Layer-
0.04in - Back
Face Only)

Case-5: AEM/ ELS Simulation



Louis Berger

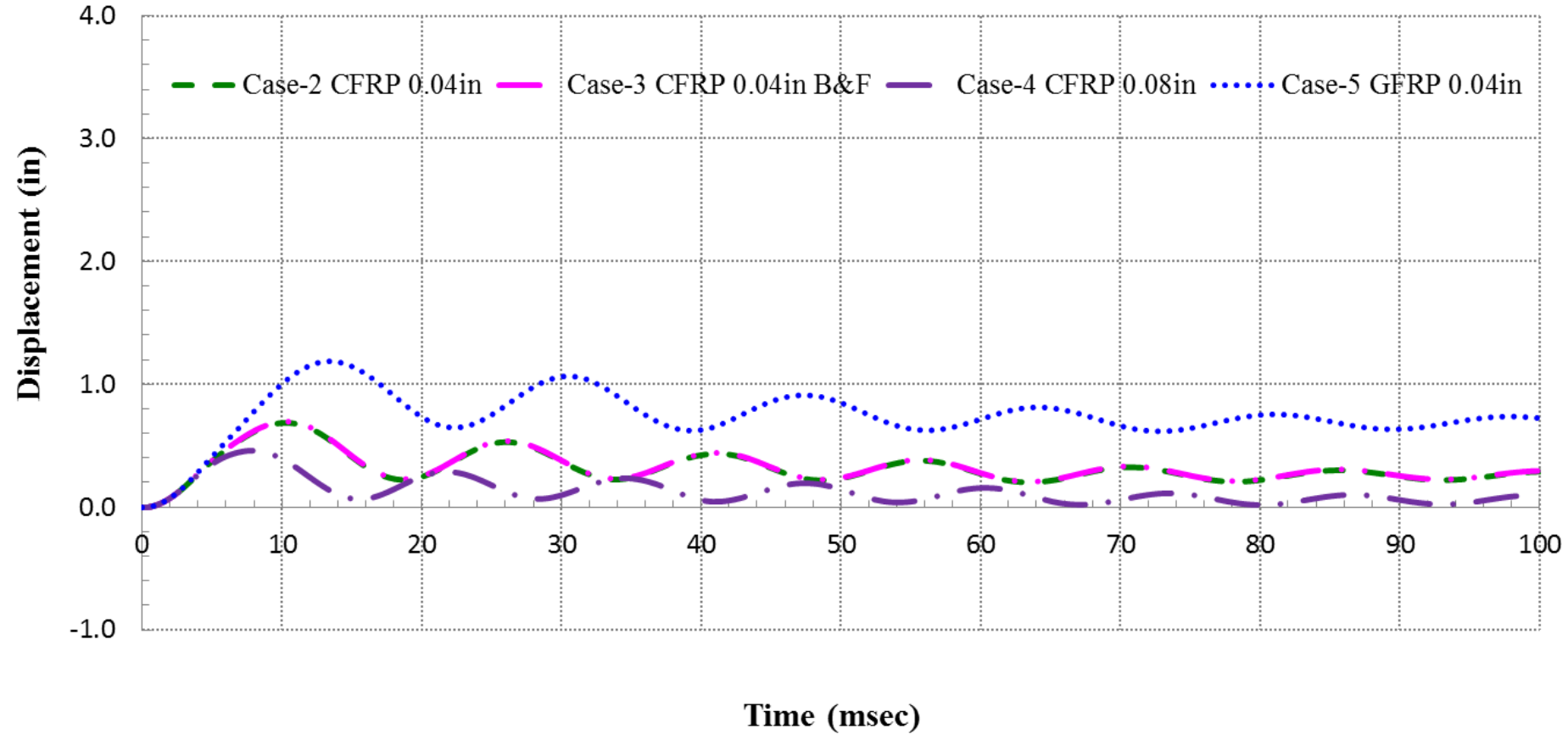


with and without FRP Retrofit



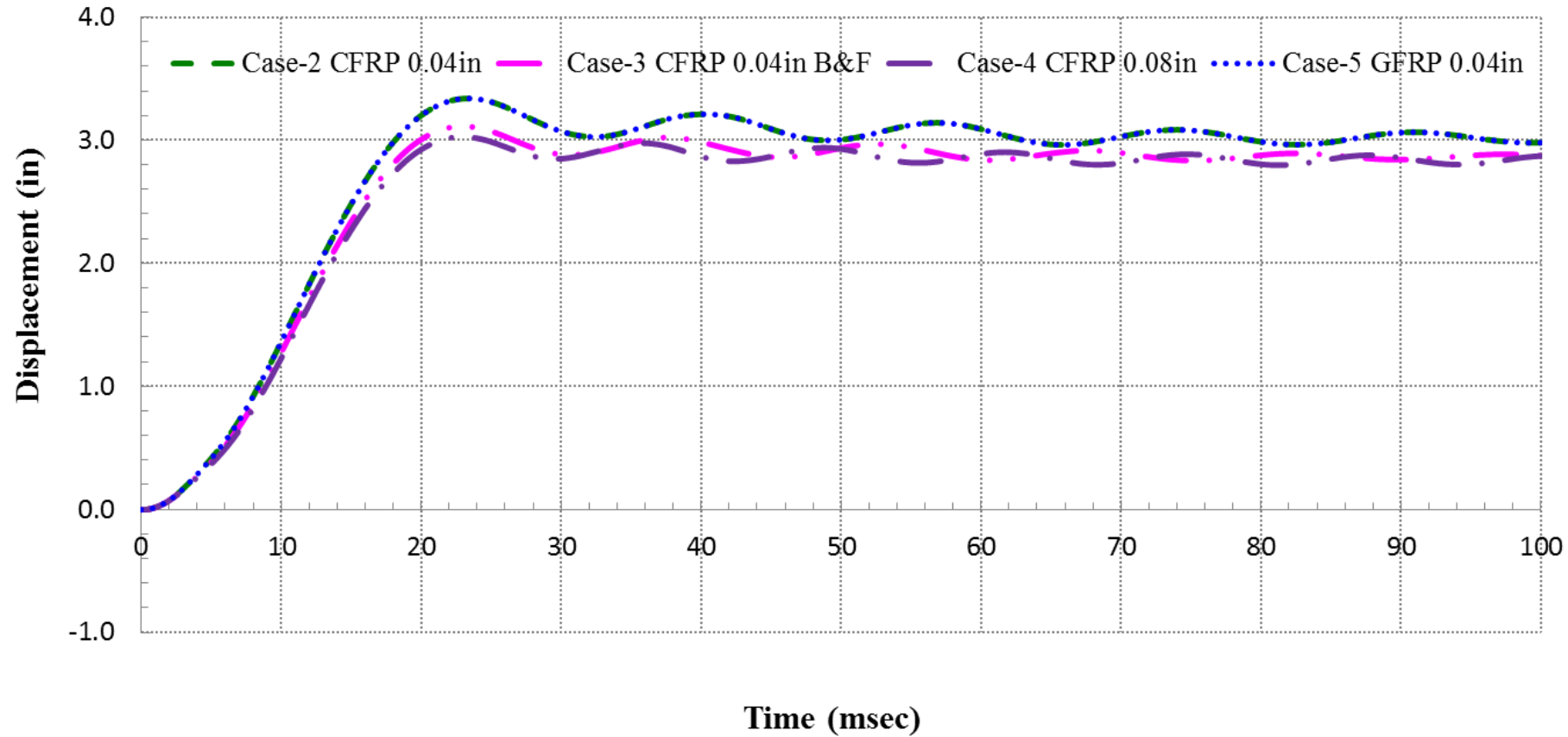
All Cases: SDOF- SBEDS- Flexure

RC Slab Mid-Span Displacement- All Cases- SBEDS- Flexure



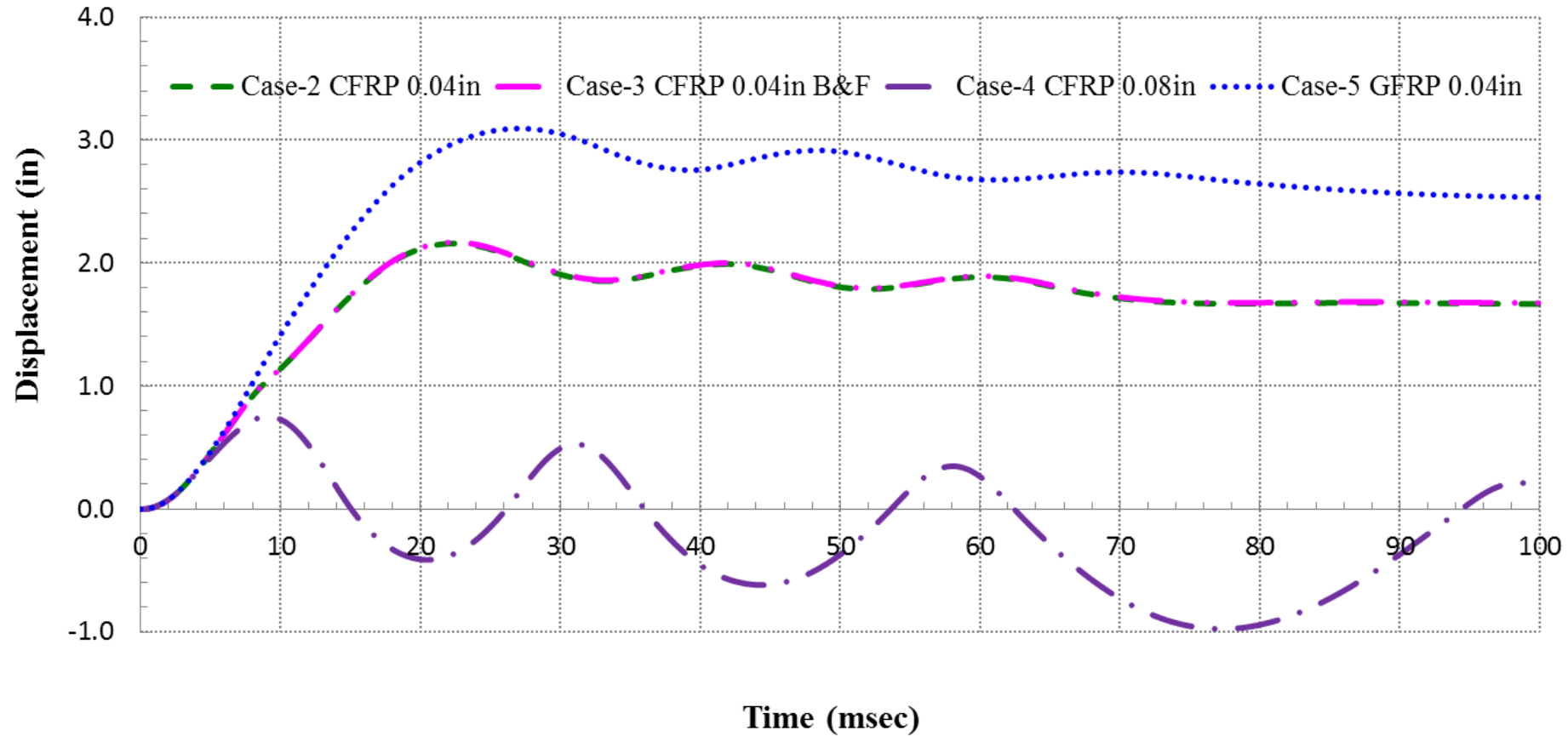
All Cases: SDOF- SBEDS- Shear

RC Slab Mid-Span Displacement- All Cases- SBEDS- Shear



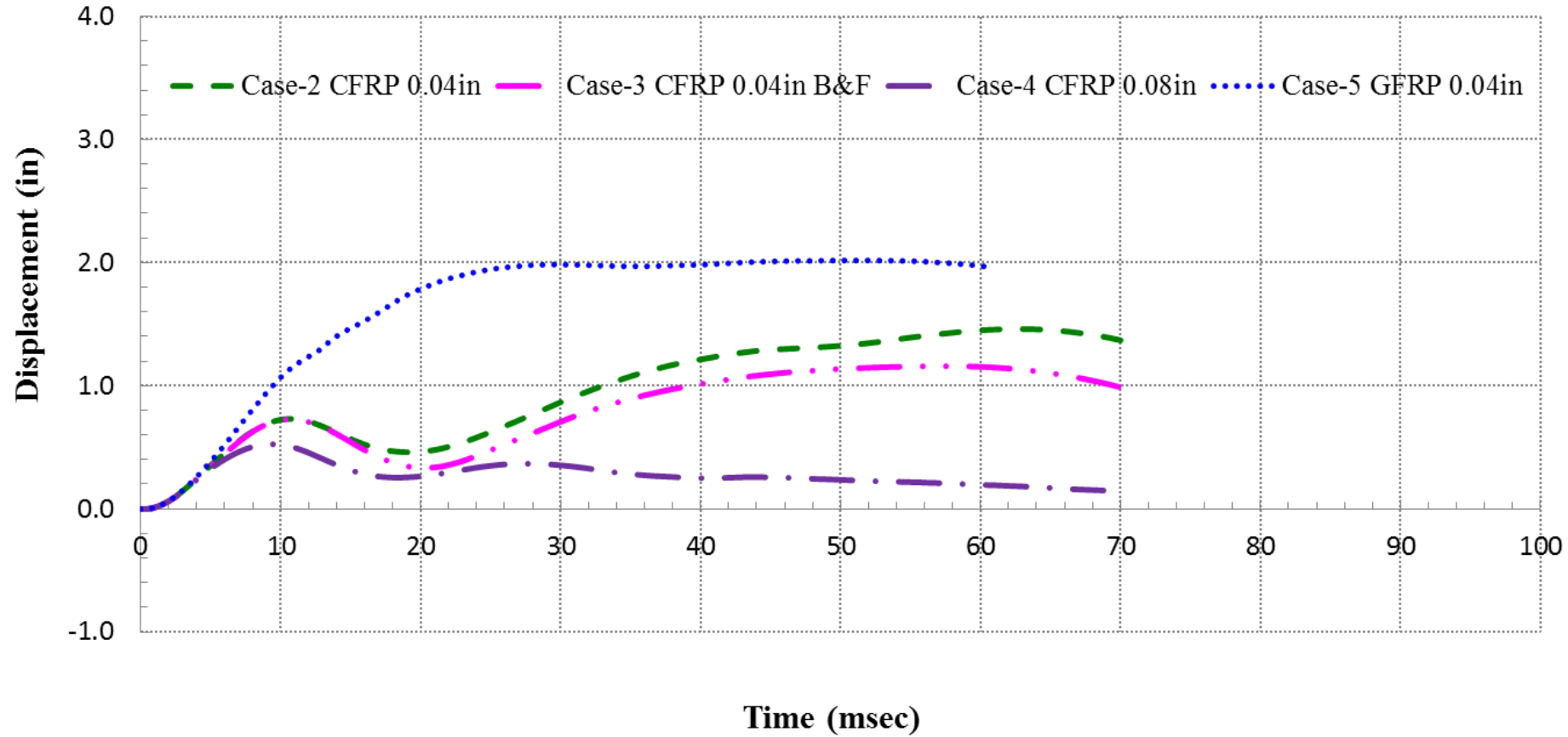
All Cases: SDOF- RCBlast

RC Slab Mid-Span Displacement- All Cases- RCBlast



All Cases: AEM- ELS

RC Slab Mid-Span Displacement- All Cases- AEM / ELS



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Concluding Remarks- General

- The Use of FRP Blast Retrofits, When Designed Properly, Can **Improve the Blast Performance of RC Elements** Through Increased Blast Resistance, Limited Damage and Reduced Structural Response.
- **Major Drawbacks of FRP Retrofits** For Blast Applications:
 - 1- Reduced **Ductility** Due to the FRP Material Behavior,
 - 2- Increased **Shear Demand** Due to Increased Flexural Resistance.
- The Design of FRP Blast Retrofits is Not a Straightforward Task and **Requires Specialized Expertise and Considerable Engineering Judgement** Considering The Current Lack of Clear Guidance.

Concluding Remarks- General

- The Effectiveness of FRP Blast Retrofit of a RC Element is **Limited by the Available Shear Strength** of the Retrofitted Element. Therefore, Increasing the Flexural Capacity of a RC Element Will Most Likely Require a Corresponding Retrofit to **Increase the Shear Strength** of the Element and **to Increase the Load-Carrying Capacity** of Its End Connections.
- **The Use of FRP Retrofit on Both Faces** (Loaded and Unloaded) Proved to Be Unnecessary Considering the Minor Reduction In Blast Response.
- **The Use of Thicker-Than-Necessary FRP Laminates** for Blast Retrofit Does Not Provide Any Practical Advantage As the FRP Effectiveness Is Limited By The Element Shear Strength.

Concluding Remarks- General

- **The Use of the Stronger CFRP Laminates** Provided Higher Blast Resistance and Hence Lower Response Compared to the Weaker GFRP Laminates.
- For FRP Retrofitted RC Slabs, Different SDOF Tools **Produce Significantly Different Blast Response Estimates** Due to the Inherent Variability in Their Analysis Assumptions and Technical Basis for Estimating FRP-RC Slab Resistance and Stiffness.

Concluding Remarks- SDOF Analysis

- Due to Their Modeling Limitations, It is Expected that the Investigated SDOF Tools May **Provide Both an Upper-Bound and a Lower-Bound Blast Responses**. These Responses Bounds Can Still Be Used by the Experienced Blast Specialist to Properly Design a FRP Retrofit System that Meets The Protection Requirements.
- For All Investigated FRP-Retrofitted Cases, **SBEDS Detected Inadequate Shear Resistance of All Retrofitted RC Slabs**. SBEDS with Shear Flag Allows the Designer to Limit the Blast Resistance to That Associated with Shear Capacity which Leads to **Increased Blast Responses**.
- Using SBEDS with Full Blast Resistance Results in **Lower Bound Response Predictions** for FRP Retrofitted Slabs Provided They Possess Adequate Shear Strength.

Concluding Remarks- SDOF Analysis

- Using SBEDS with Limited Blast Resistance Results in **Upper Bound Response Predictions** for FRP Retrofitted Slabs Considering Their Limited Shear Strength.
- It is Not Clear if RCBlast Has Accounted for the Deficient Shear Capacities of All Investigated FRP-Retrofitted Cases. However, with the Exception of Case-4 (0.08 Thick CFRP), **RCBlast Predicted Reduced Flexural Resistances** Similar to Those Computed by *SBEDS with Shear Flag*.
- Generally Speaking, RCBlast Response Predictions **Fit Between the Upper and Lower Bounds** of SBEDS Predicted Responses. This Can Be Explained Considering the **Lower Structural Stiffness Predicted by RCBlast** Compared to SBEDS.

Concluding Remarks- AEM- ELS

- AEM is able to **simulate dynamic behavior** observed in tests **and mode of failure** (concentrated cracking distributed cracking)
- De-bonding strain for FRP can be specified as input value based on experimental results. **Failure of FRP** with thin layer of concrete is **observed in some of the investigated cases.**
- The AEM MDOF analysis **removes the need to figure out the length of the plastic hinge and the “responding” mass.**
- AEM can be used to compare performance for multiple design options.
- Prediction of shear failure mode **requires correct parameters for post cracking residual strength**; further comparison to experimental results is planned.

-
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Future Research Work

- Perform Additional Validation of Utilized Tools (ELS, RCBlast and SBEDS) to Better Understand Their **Range of Applicability and Modeling Limitations** of FRP Retrofitted RC Elements.
- Identify the Proper Technique(s) to Account for the **Potential Reduction in Blast Resistance of FRP Retrofitted RC Elements** Due to The Increased Demand of Shear Strength.
- Investigate Additional Cases that Include Various:
 - **Structural Components** (2-Way Slabs, Beams)
 - **Boundary Conditions** (F-S, F-F, Elastic-Elastic),
 - Levels of **Blast Loading** (Low, Medium, High)
 - Levels of **Materials Strengths** (Concrete, Steel)
 - **Reinforcement Arrangements** (Flexural, Shear) and
 - **FRP Anchorage** Conditions

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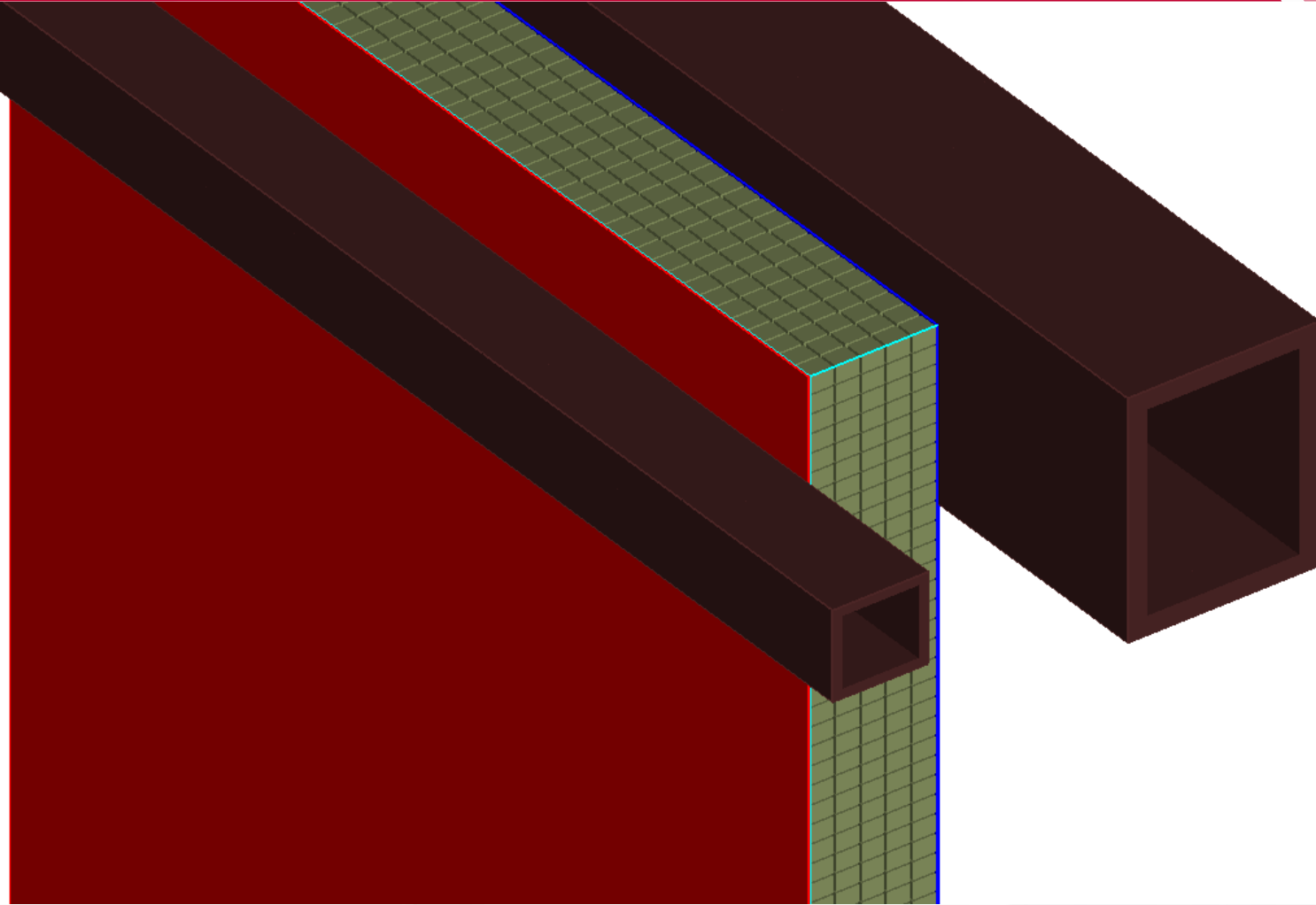
Questions

Louis Berger



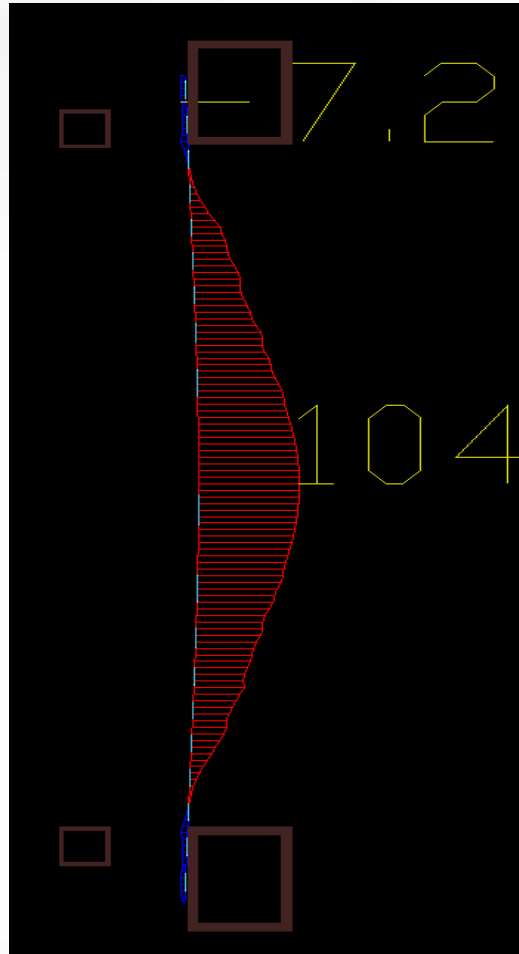
Anchorage

FRP sheets are modeled as extending behind the HSS top and bottom beams.

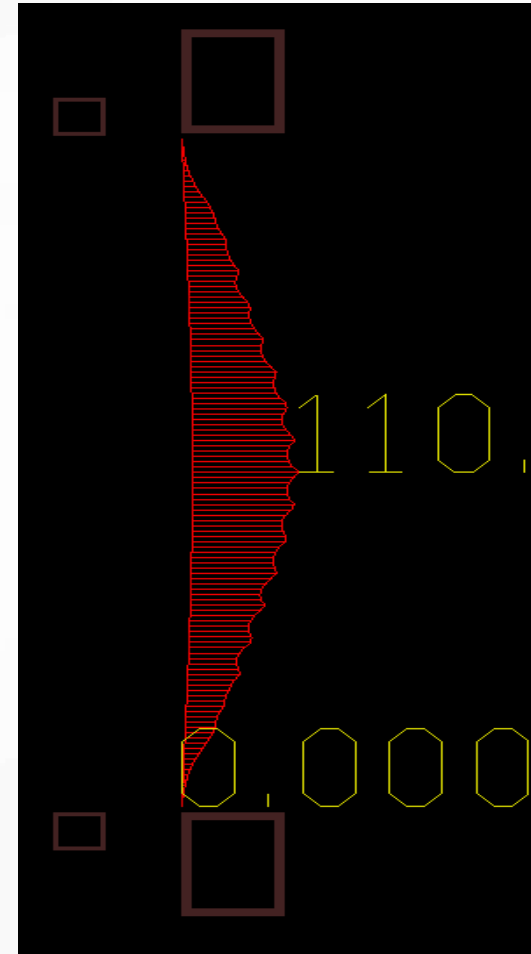


Anchorage

FRP sheets are modeled as extending behind the HSS top and bottom beams (Anchored) in all studied cases. Initial analysis showed that in the studied case, anchorage has no significant effect on the behavior.



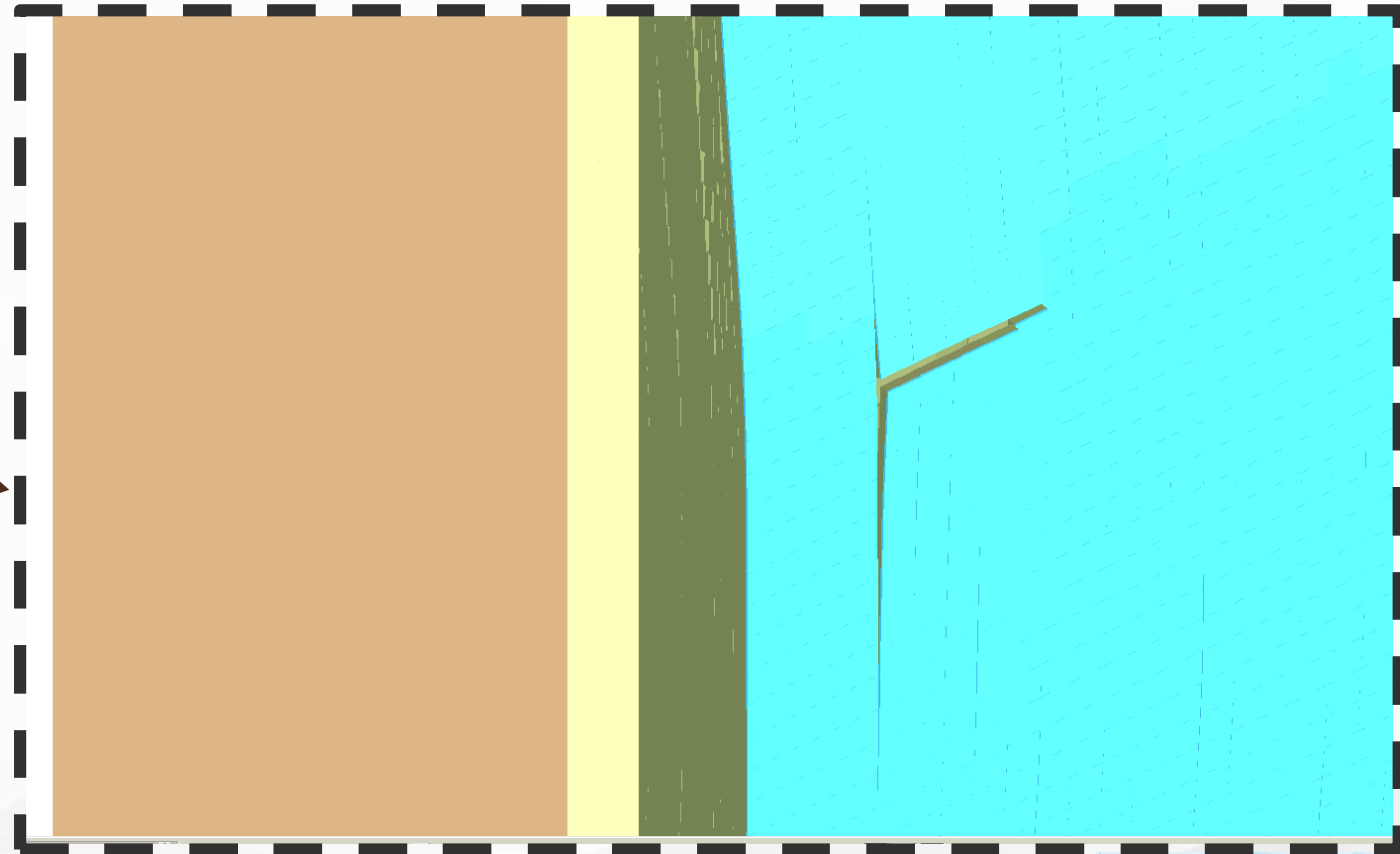
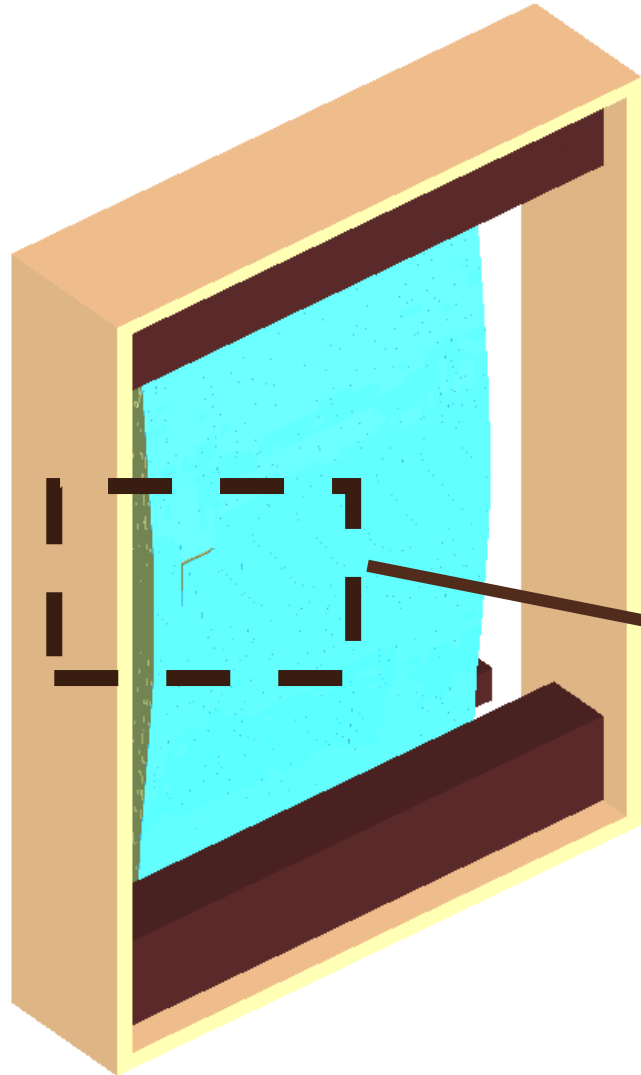
Anchored Sheets



Non-anchored sheets

Debonding of FRP

This failure mode was observed for the glass fiber retrofit at high strain rate



Failure near support

