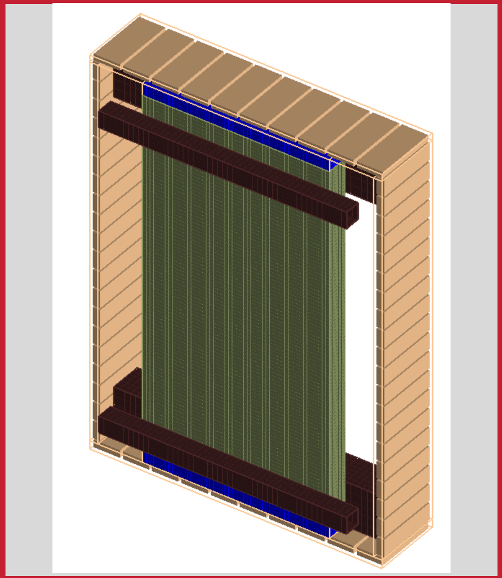
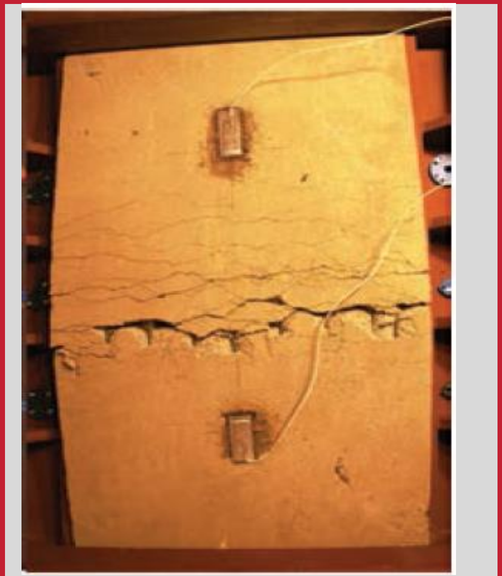
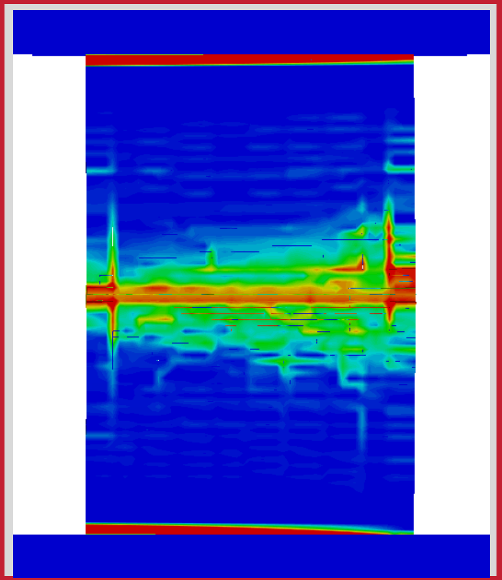
Advanced Modeling of Blast Response of Reinforced Concrete Walls with and without FRP Retrofit







TAREK H. KEWAISY
PhD, PE, PMP, BSCP
Principal Associate
tkewaisy@louisberger.com

AHMED A. KHALIL
PhD, PE
Senior Structural Consultant
khalilaa@appliedscienceint.com

AYMAN ELFOULY
PE
Senior Structural Engineer
elfouly@appliedscienceint.com

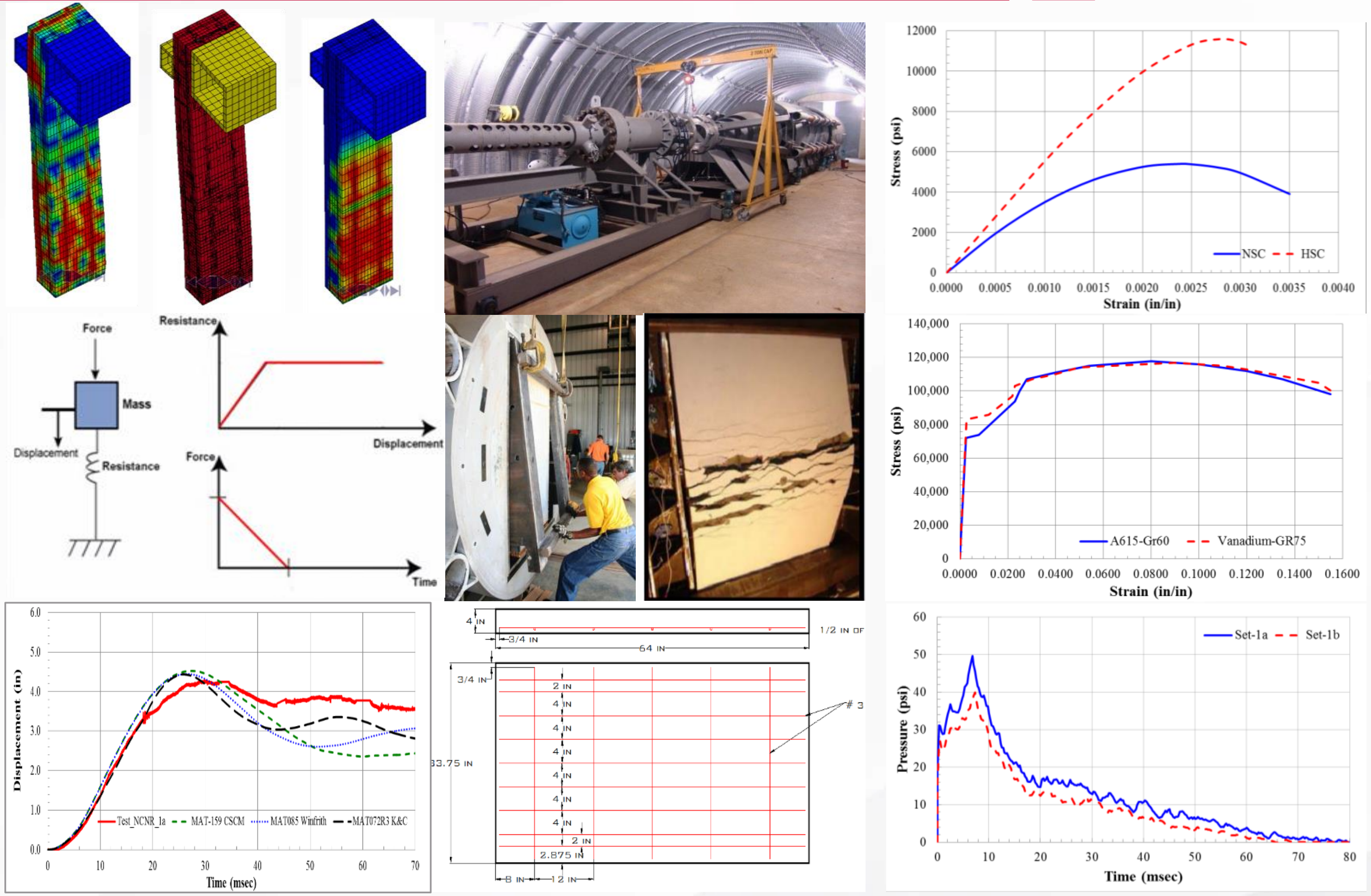
Session on: FRP Design Methodology and Applications for Blast and Impact-Resistant Structures
Sponsored By: ACI Committee 370 and 440

3/28/2018

Previous Research Work

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



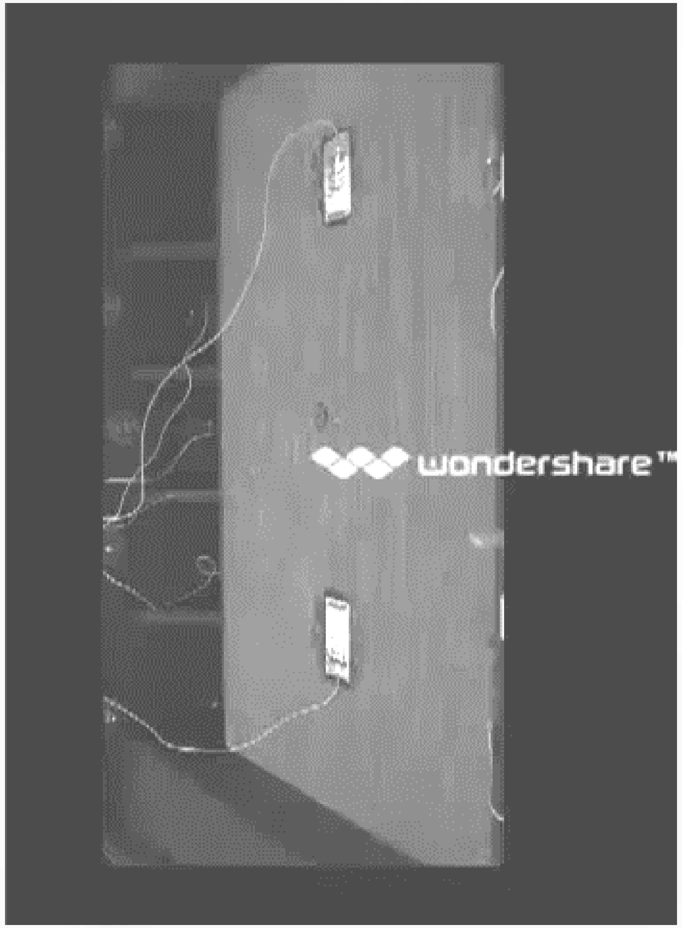
Blast Blind Simulation Contest

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

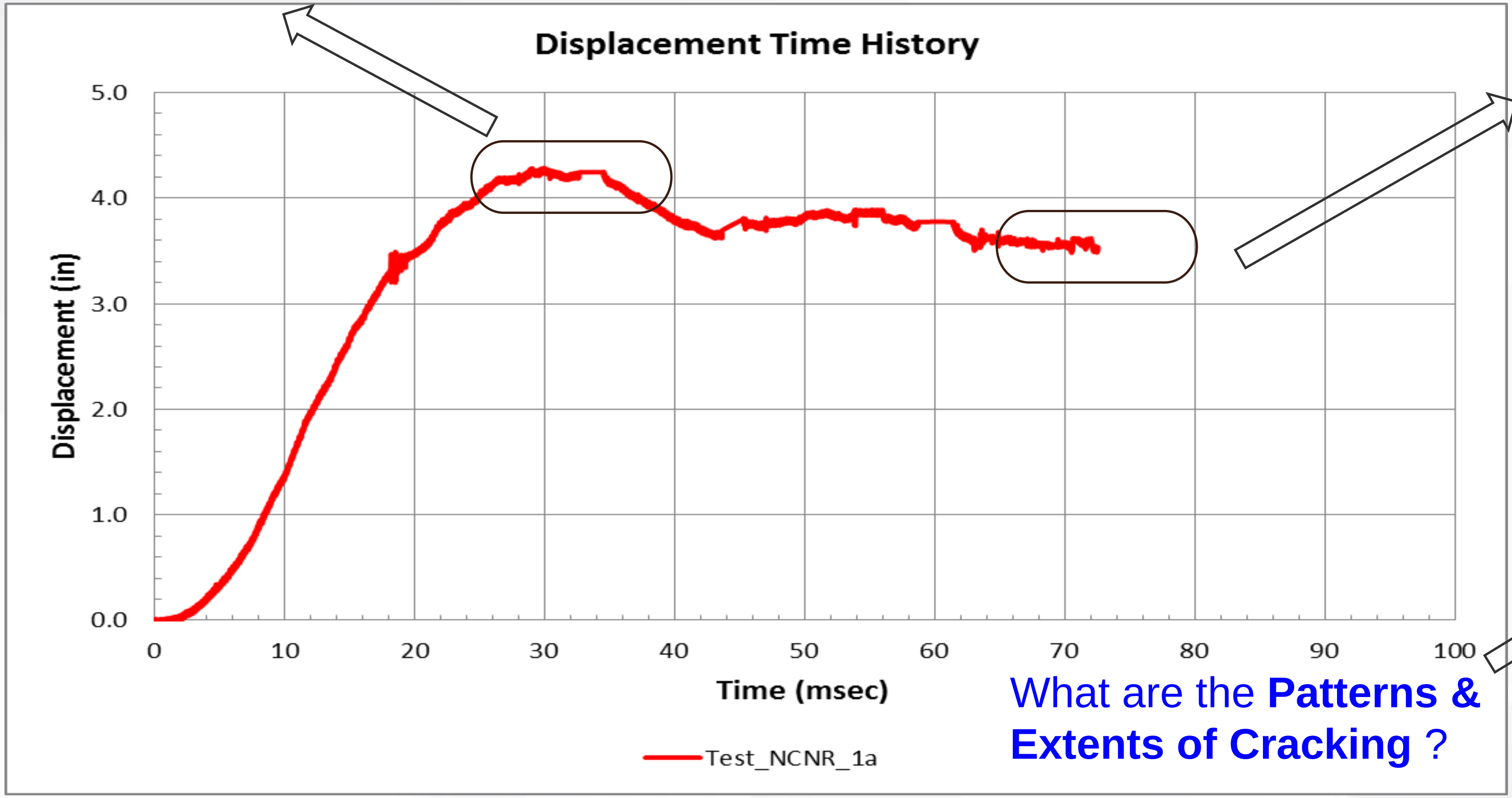
- P_{max} = 50 psi
- I_{tot} = 1020 psi.msec



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

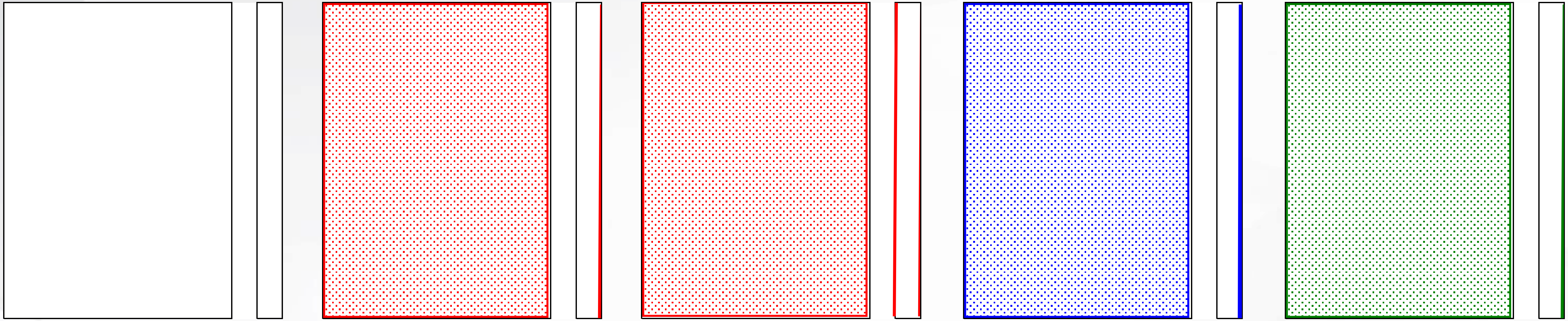
Objectives

- **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.

Investigated Cases



Case I
Unretrofitted
(Control)

Case 2
Retrofitted
CFRP / 1 Layer
@ Back Face

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

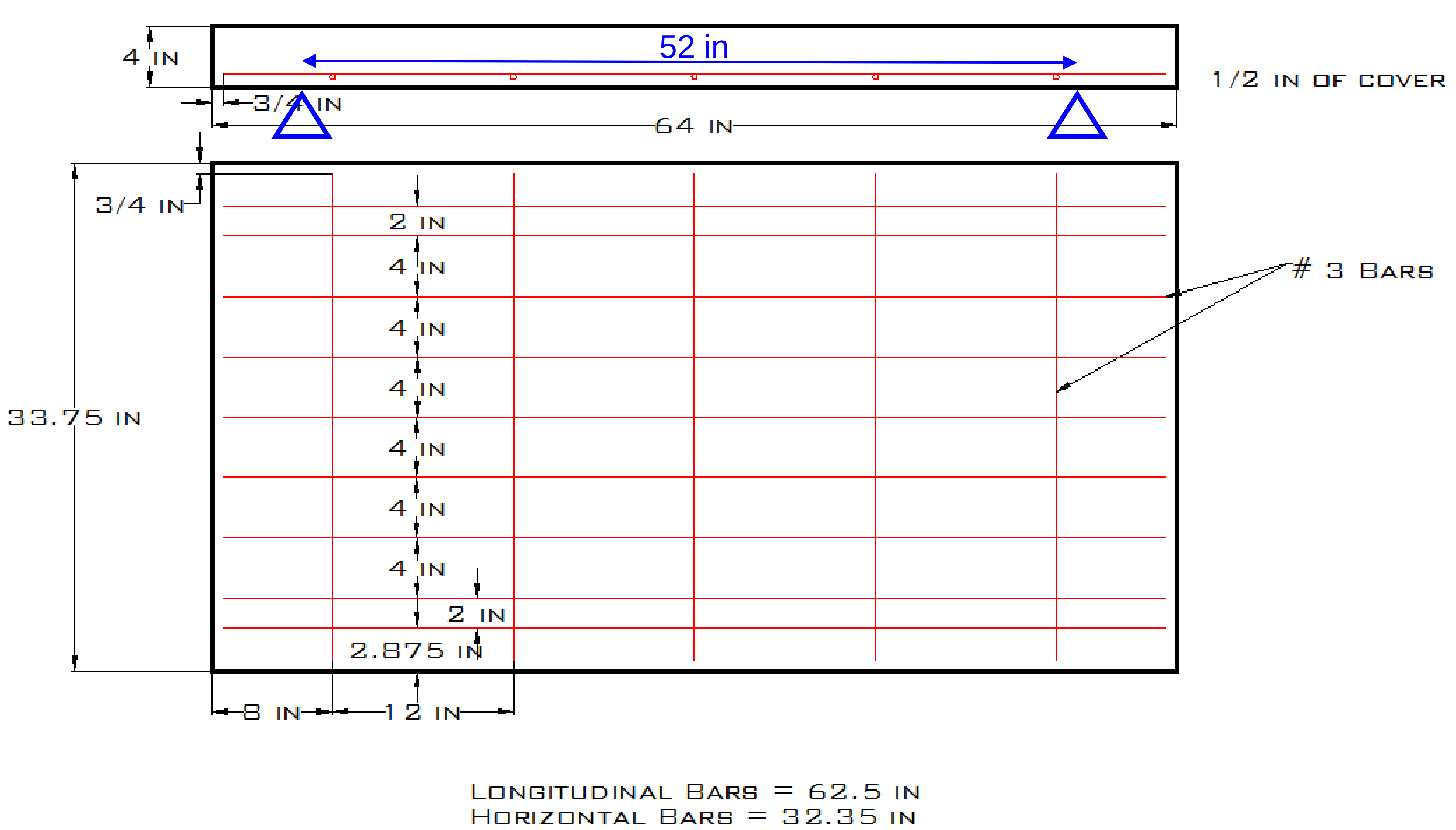
Case 4
Retrofitted
CFRP / **2 Layers**
@ Back Face

Case 5
Retrofitted
GFRP / 1 Layer
@ Back Face

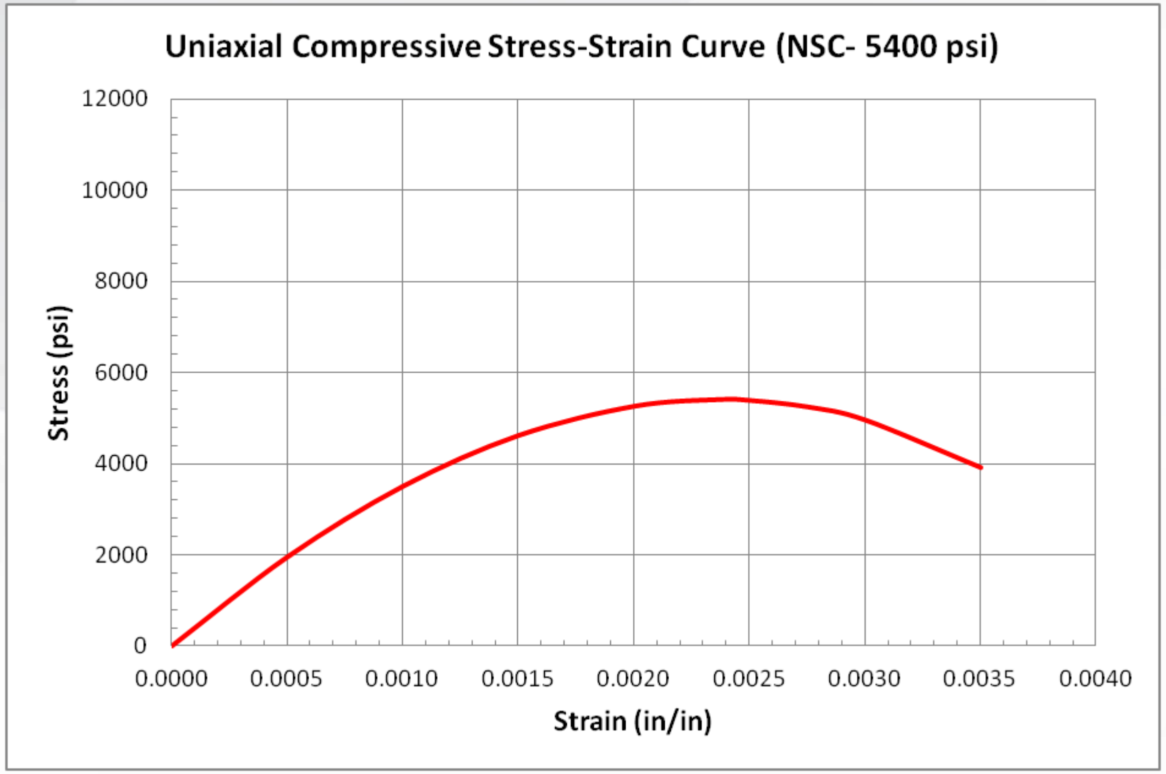
Investigated Cases

	Symbol	Unit	Case I	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) No of Layers (Front)	n_{back} n_{face}		N/A N/A	1 0	1 1	2 0	1 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	$\varepsilon_{fu}{}^*$	in/in	N/A	0.010	0.010	0.010	0.022
FRP Elastic Modulus	E_f	ksi	N/A	13900	13900	13900	3790

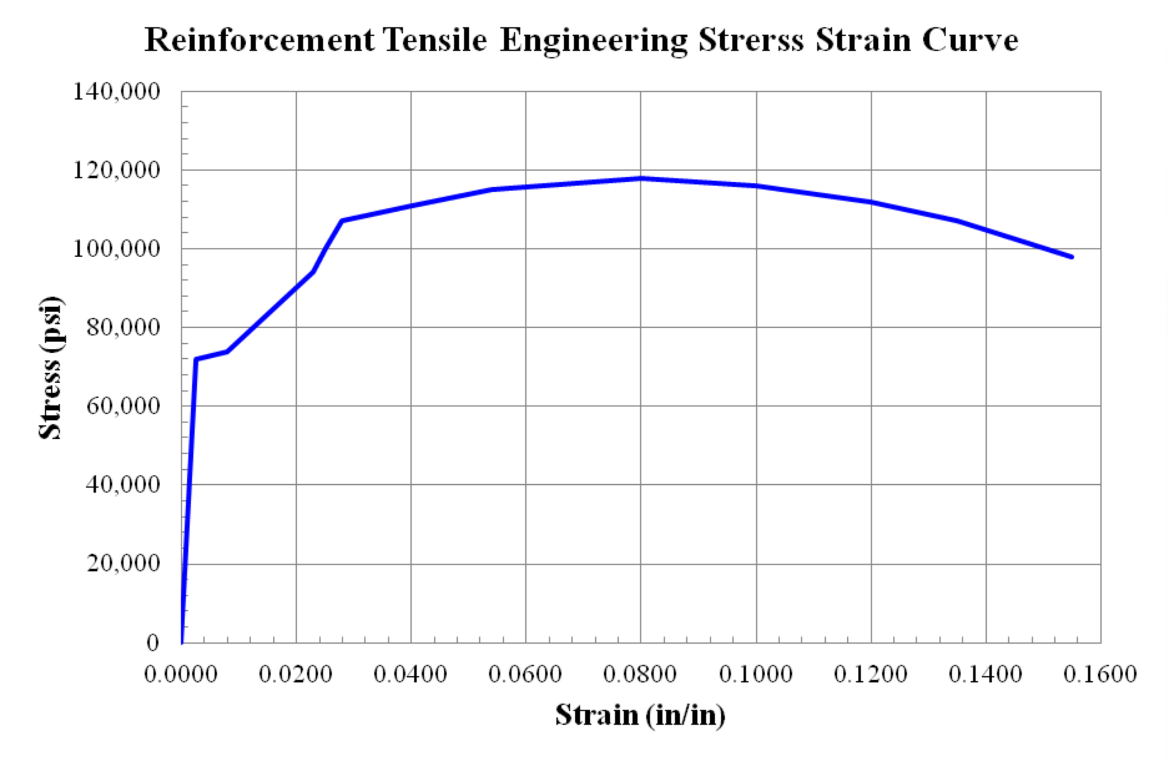
RC Slab Configuration



Material Properties

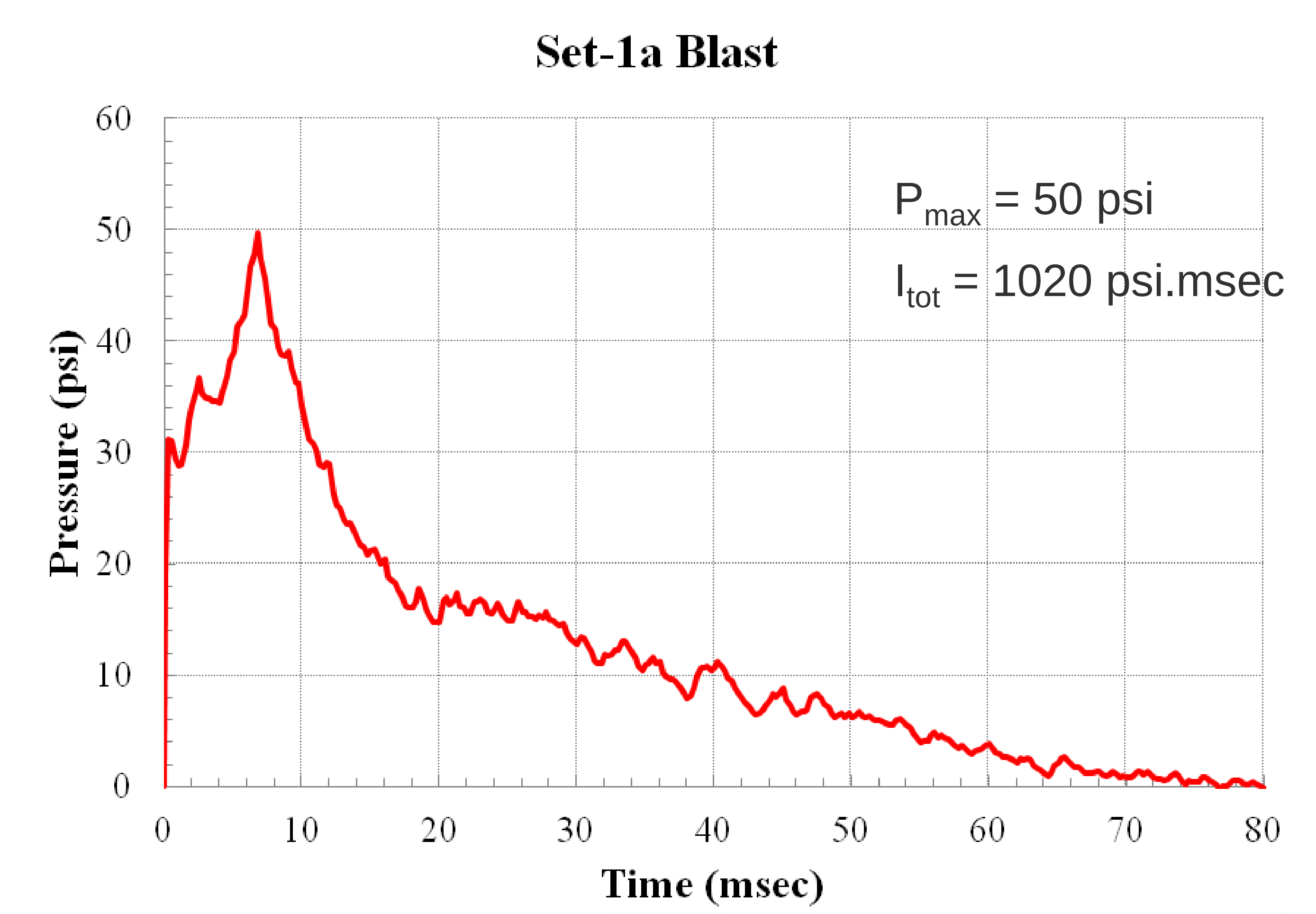


Normal Strength Concrete



Normal Strength Rebar

Blast Load

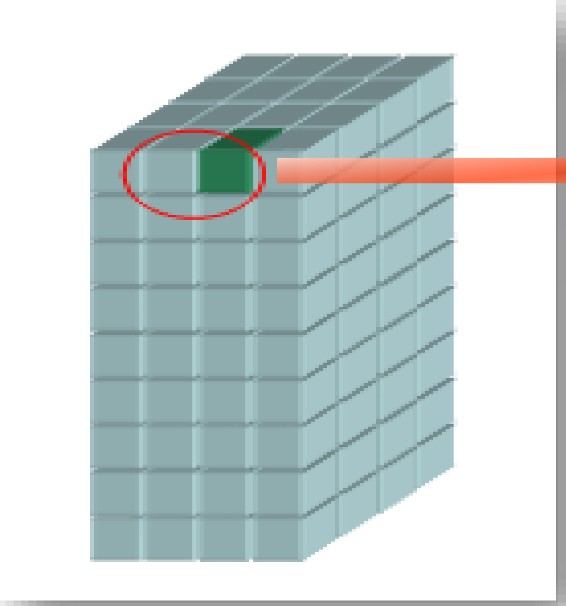


Reflected Pressure-Time Record

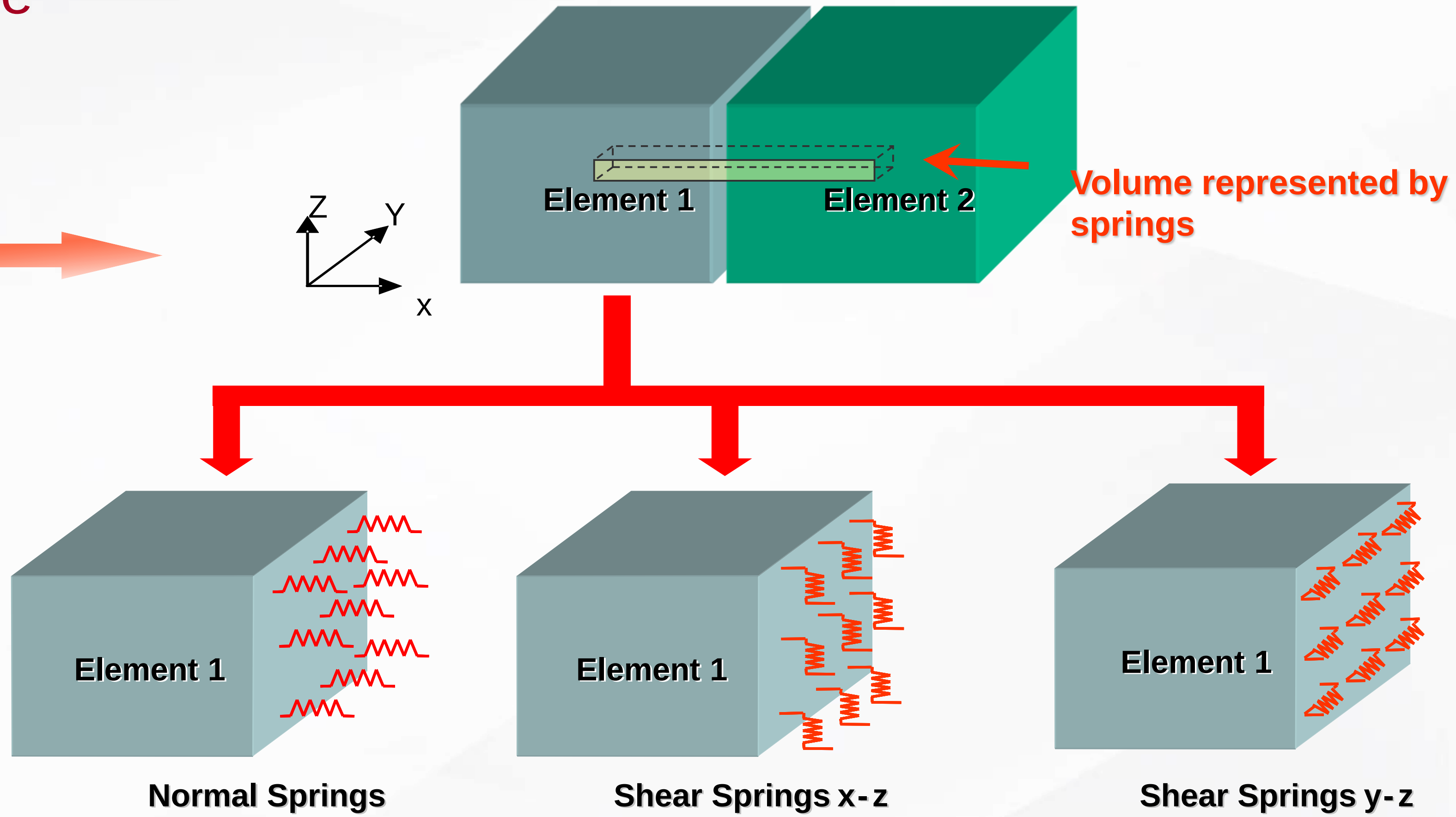
Applied Element Method (AEM)

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

Implemented in ELS software



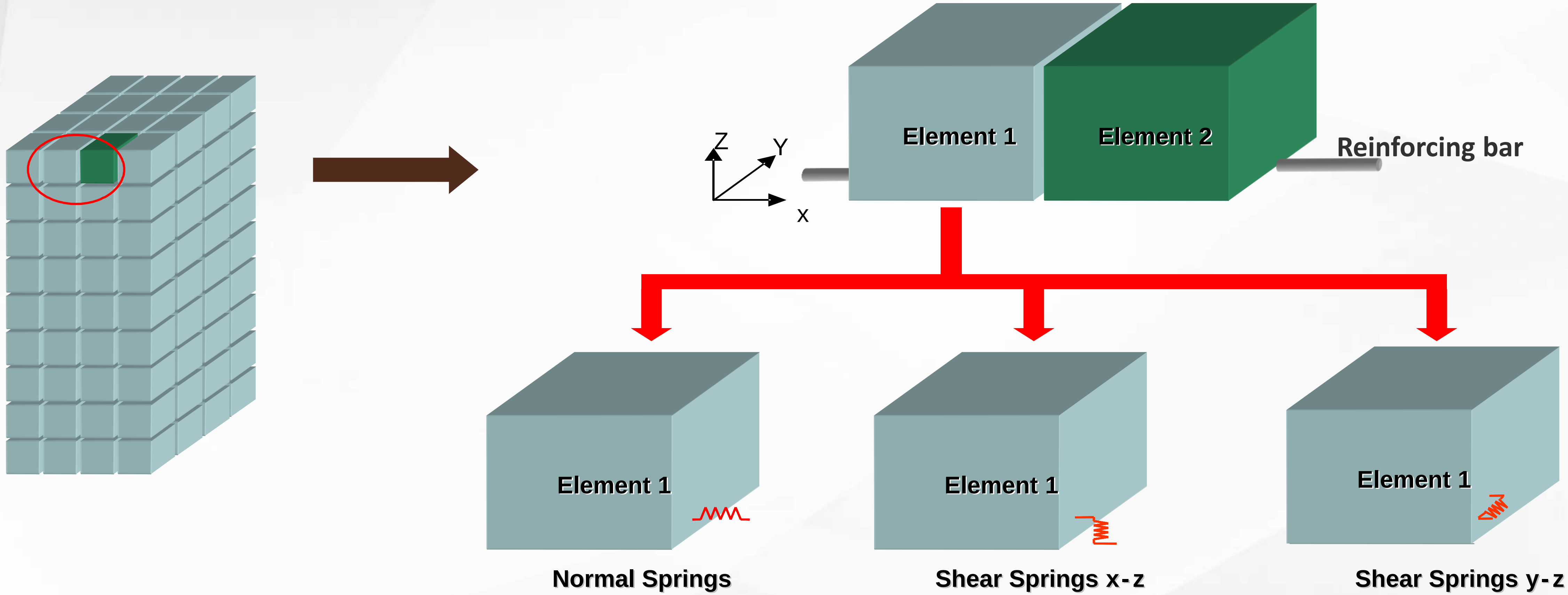
Matrix Springs



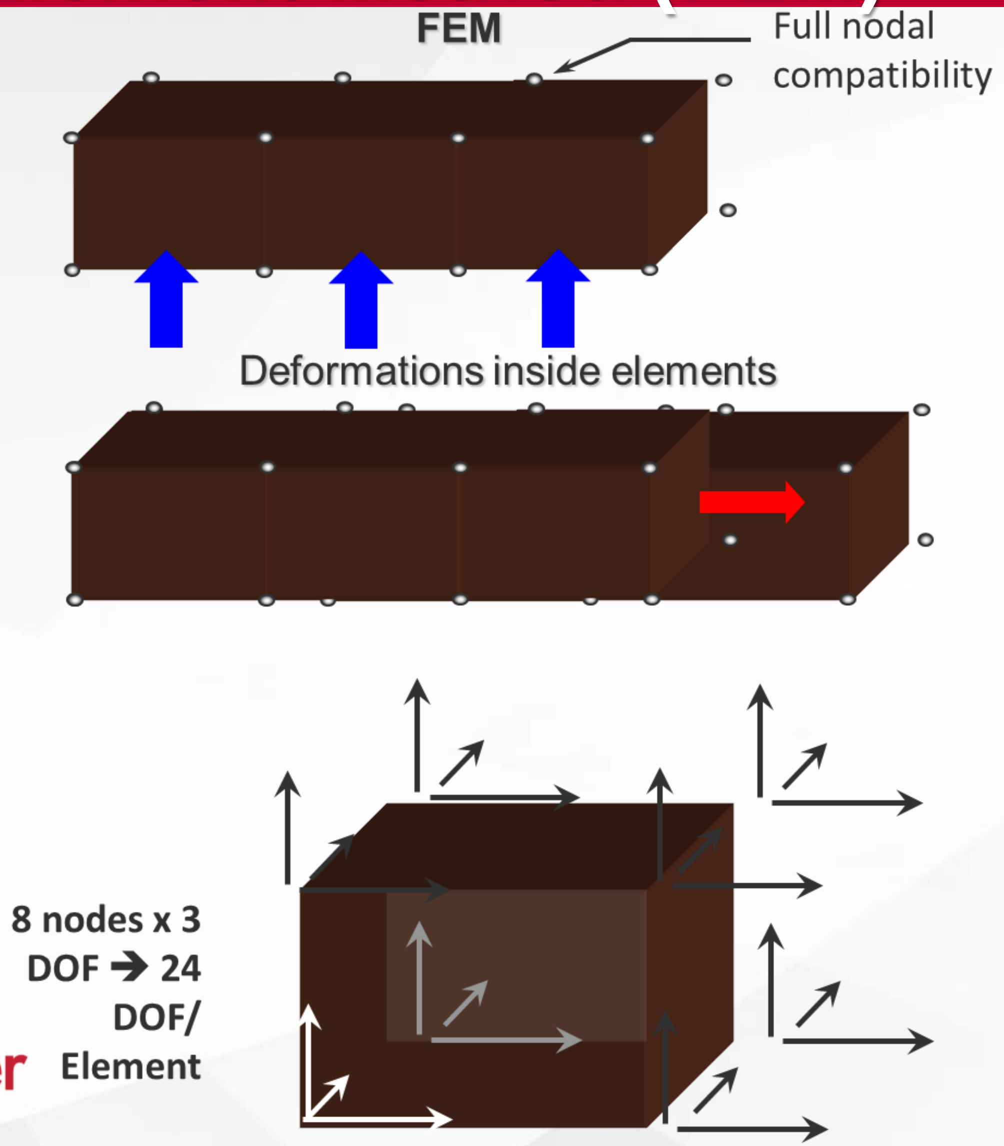
The continuum is discretized into **Elements** connected together with **Nonlinear Springs**.
The springs represent **Material** behavior, Axial and Shear **Deformations**.

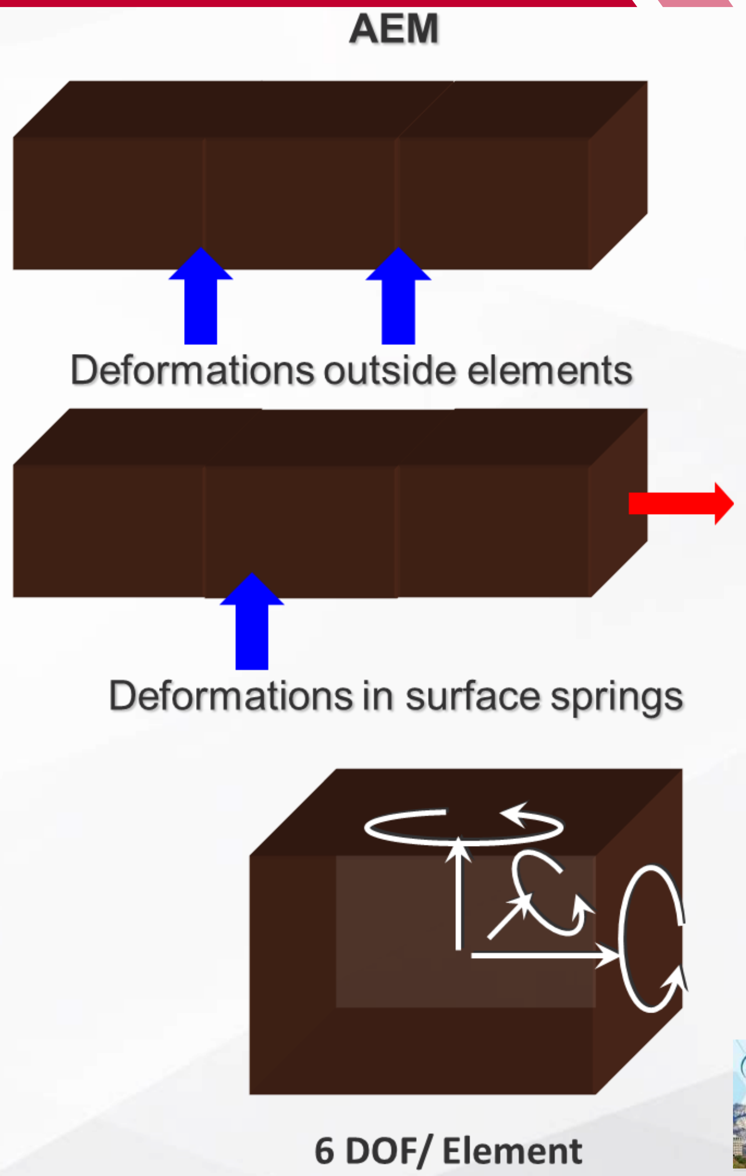
Applied Element Method (AEM) in Extreme Loading for Structures (ELS)

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



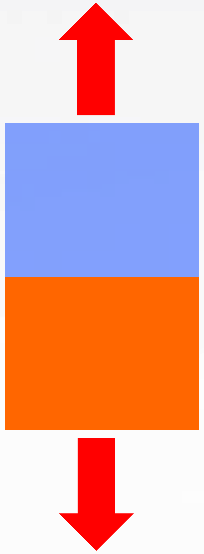
Applied Element Method (AEM) vs Finite Element Method (FEM)

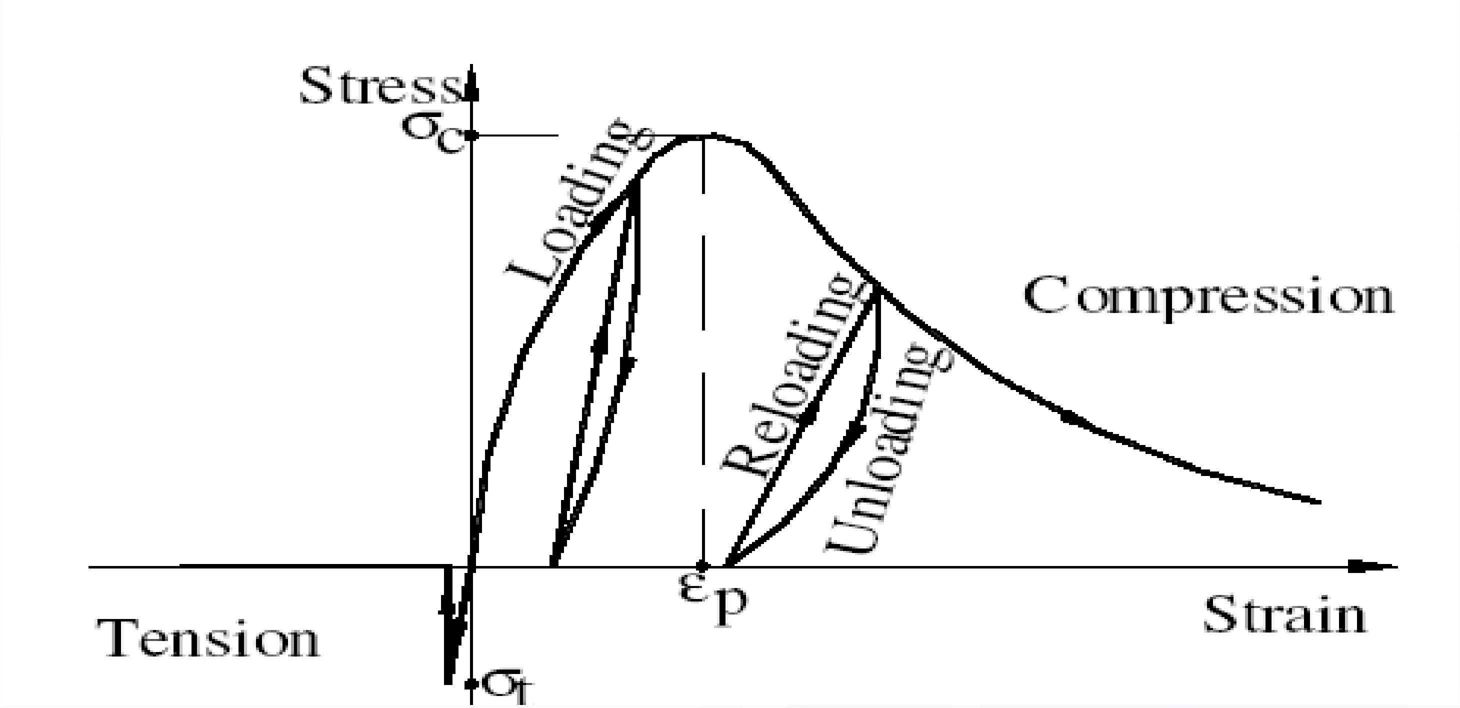


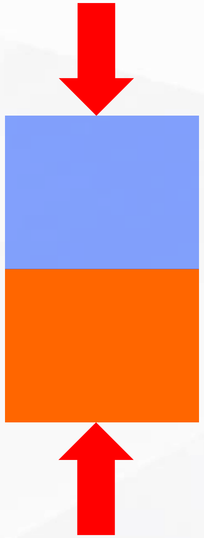


Applied Element Method (AEM: Constitutive Material Models

AEM - Nonlinear Material Models







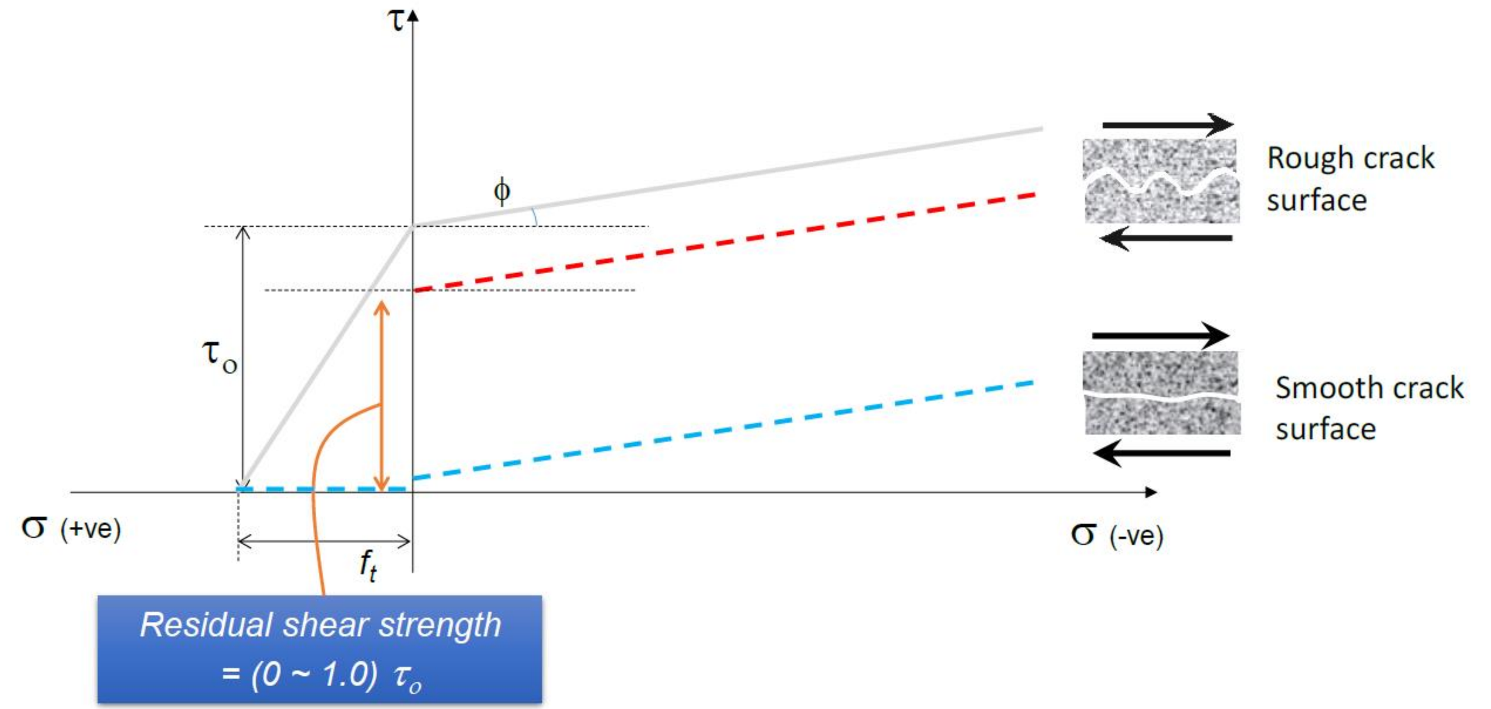
Tension

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

Compression

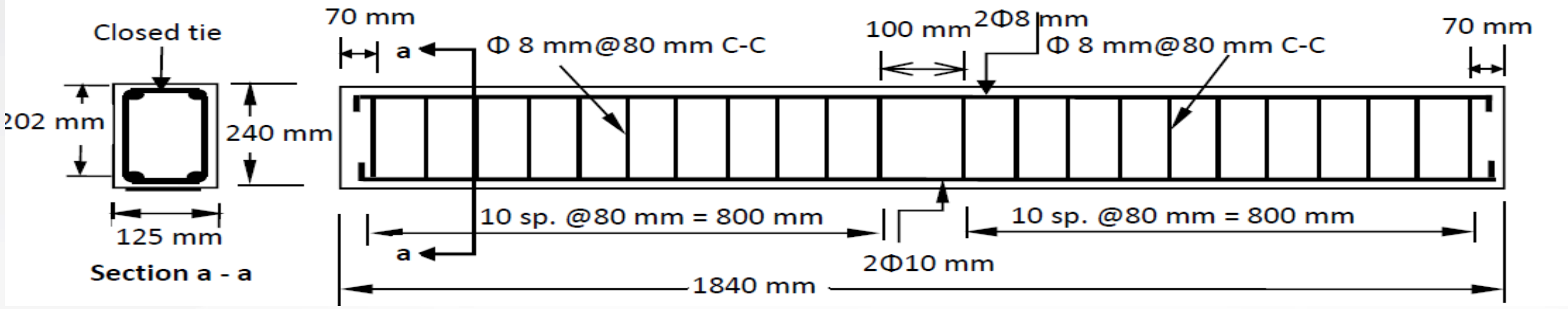
Applied Element Method (AEM: Constitutive Material Models

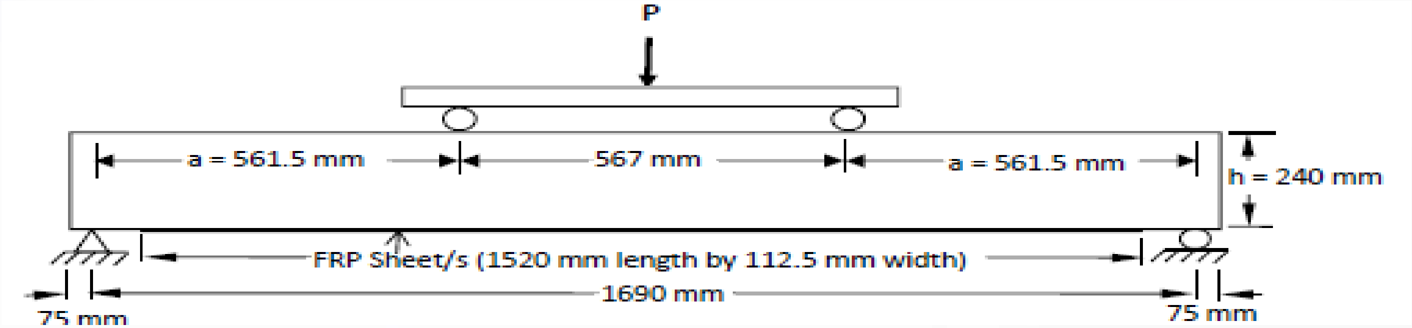
AEM - Nonlinear Material Models

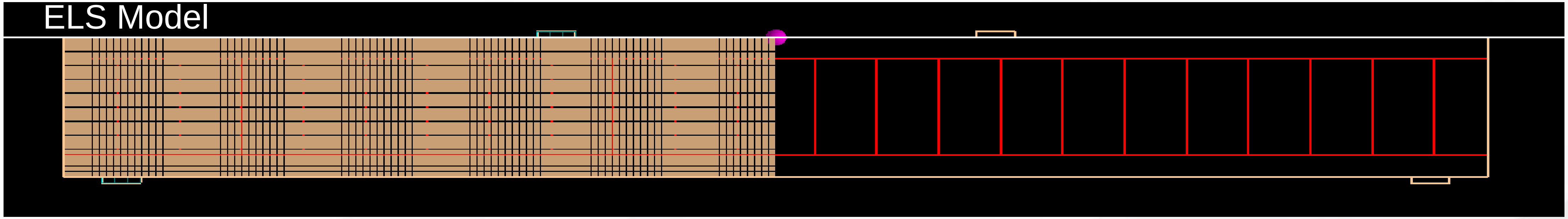


Sheart model for concrete

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







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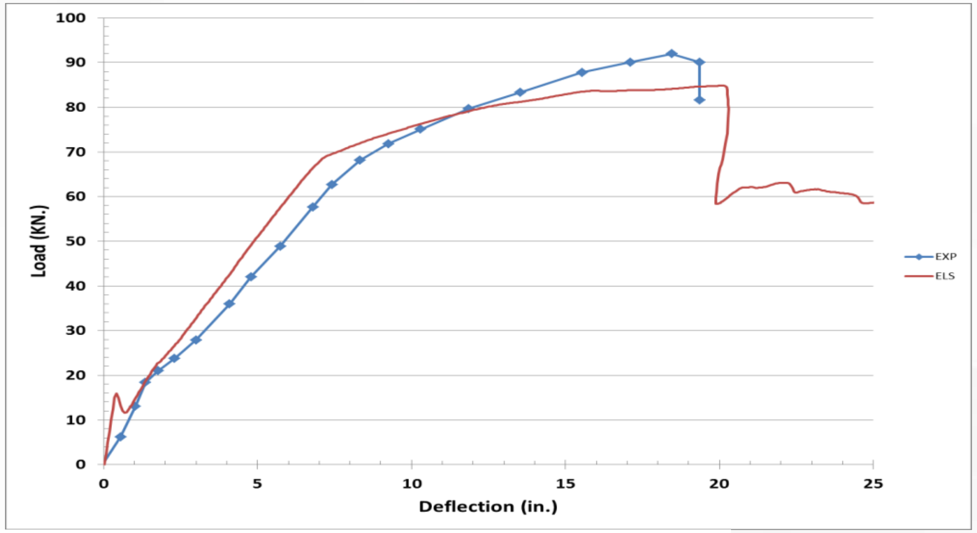
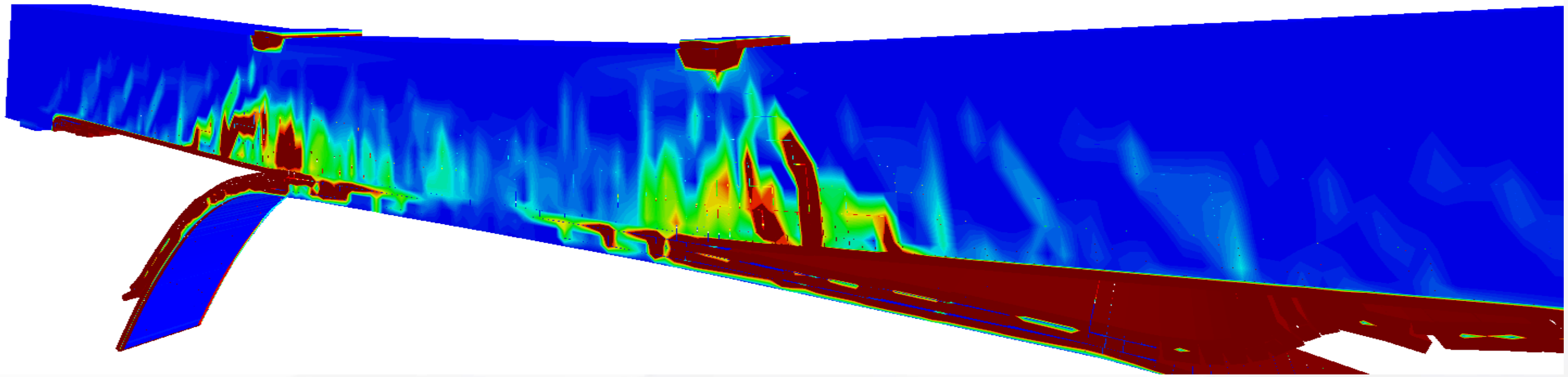
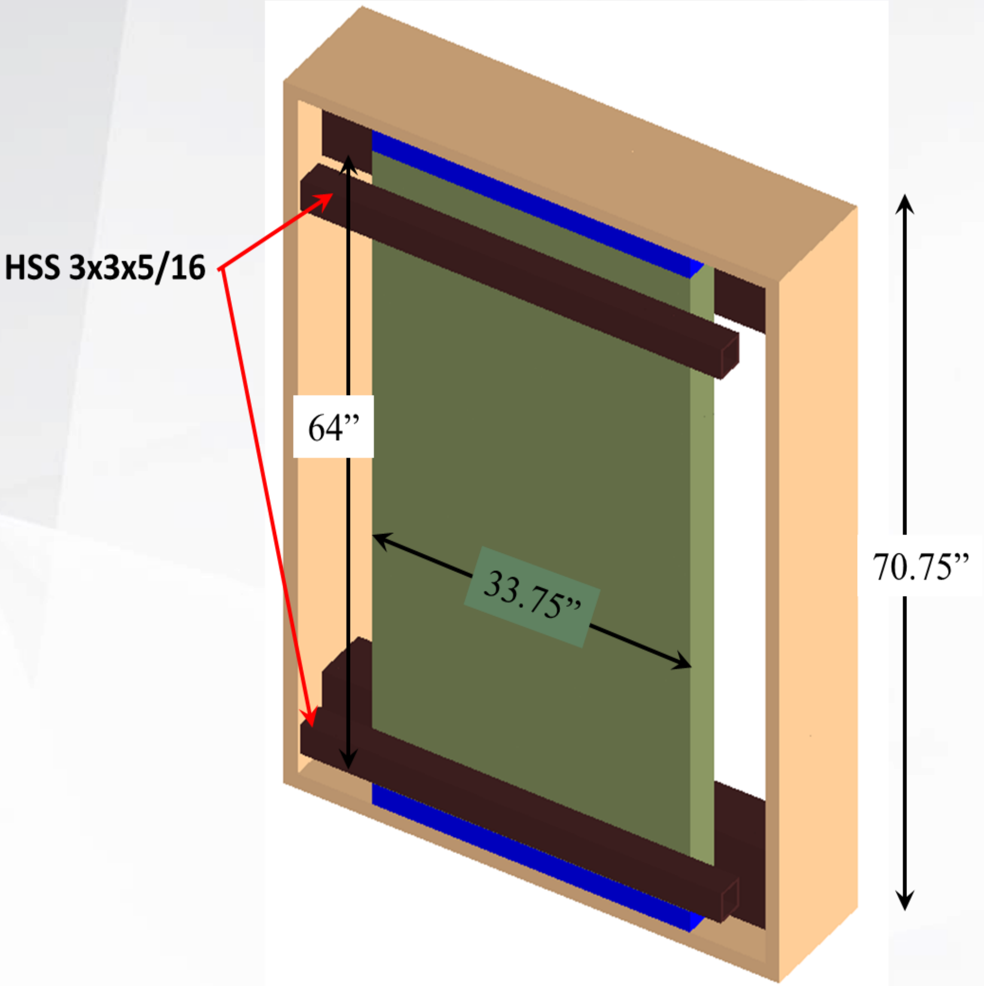
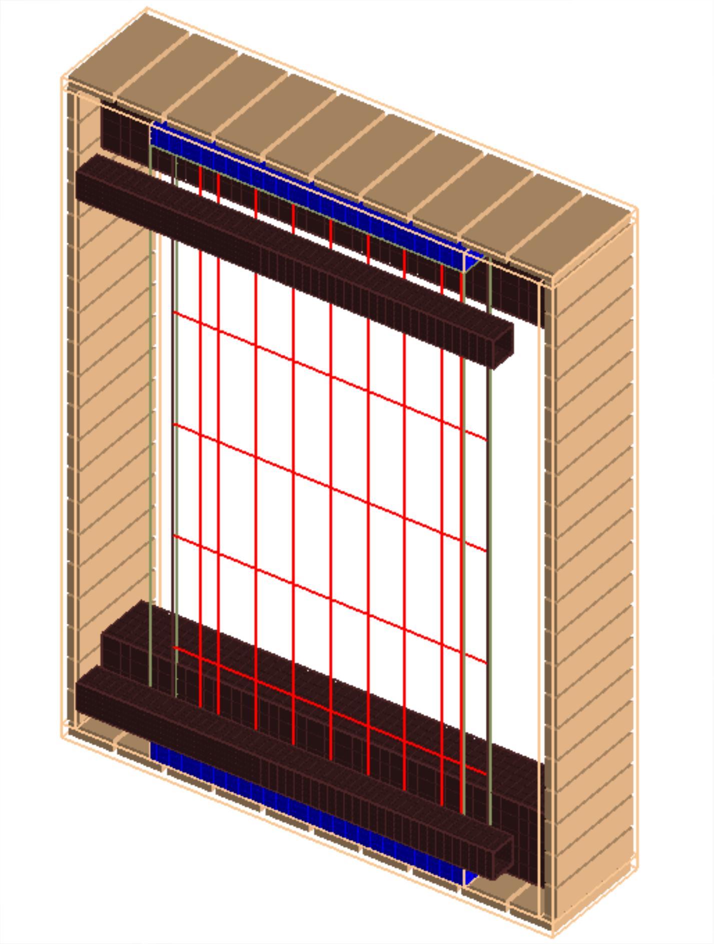
AEM/ ELS Validated Case: Testing of FRP Retrofitted Concrete Beam

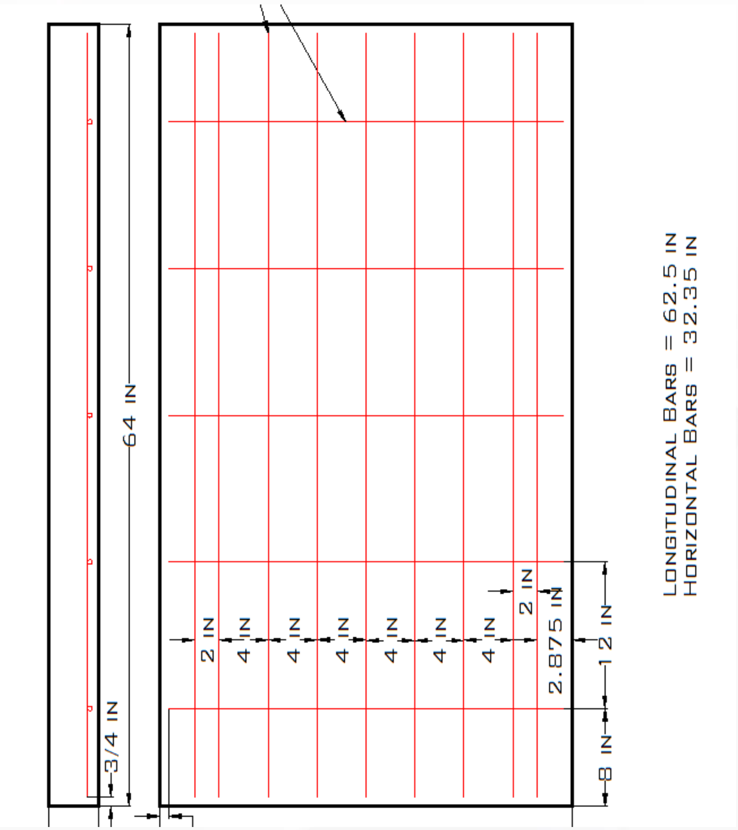




AEM/ ELS Model



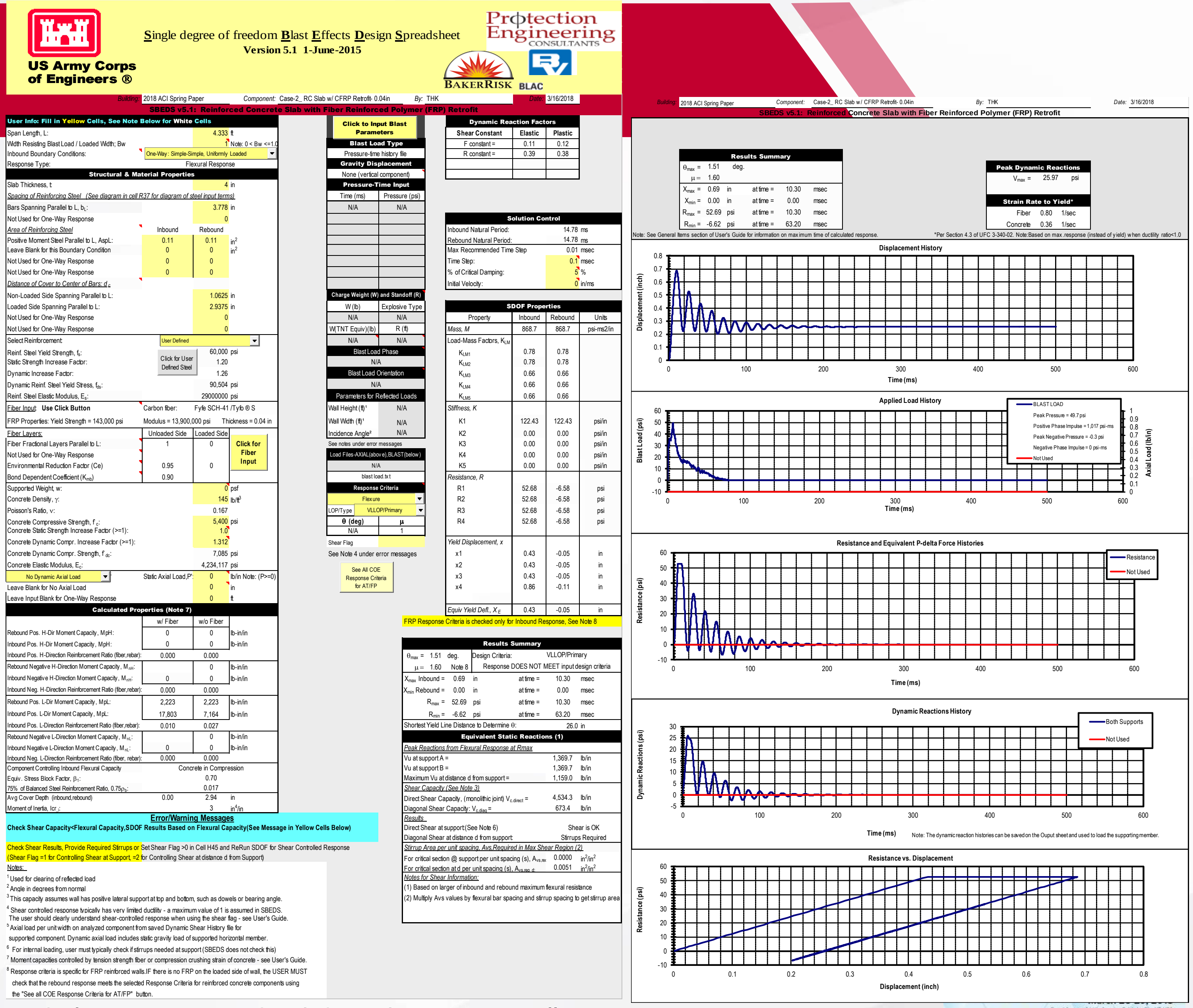




Single Degree Of Freedom (SDOF)

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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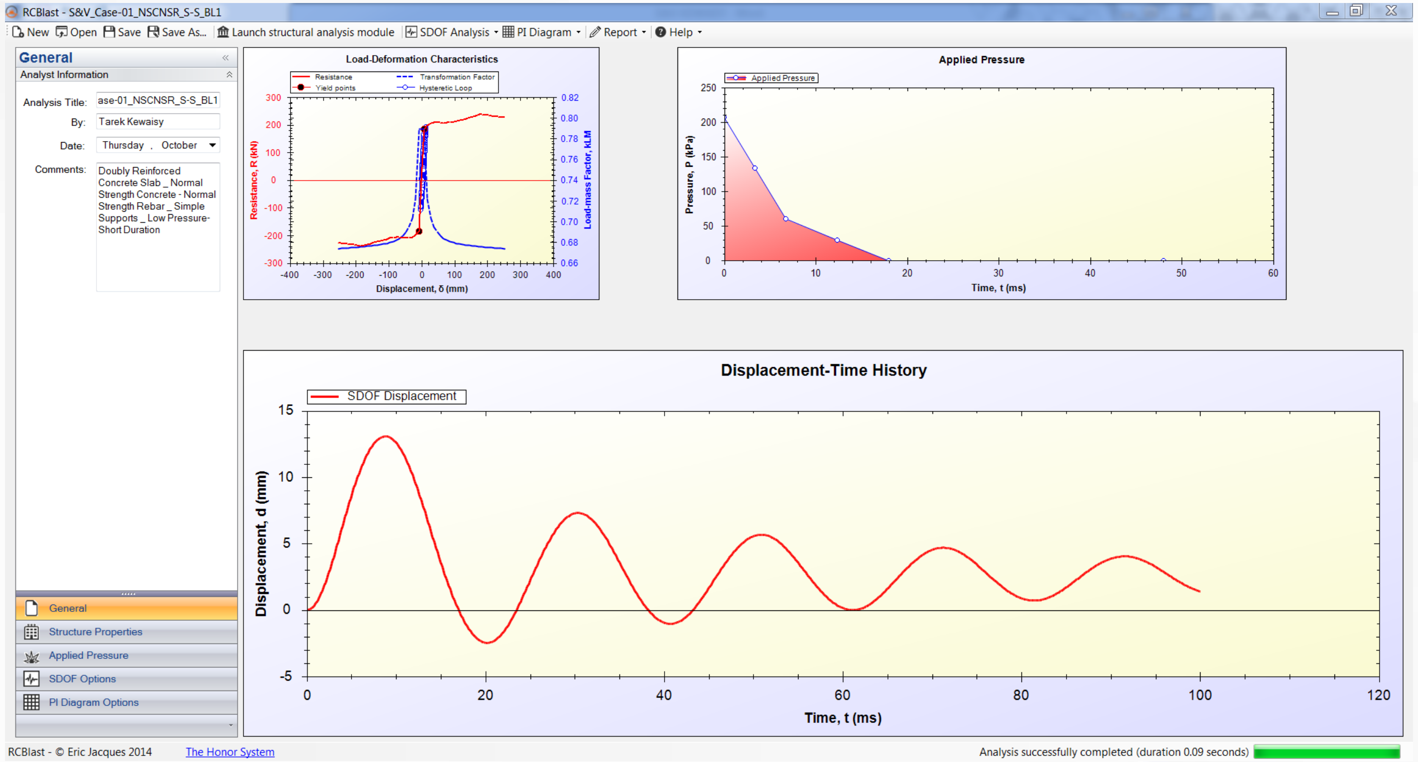
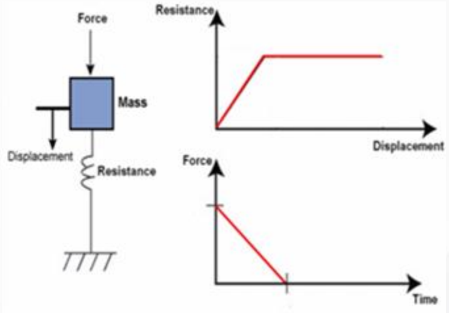
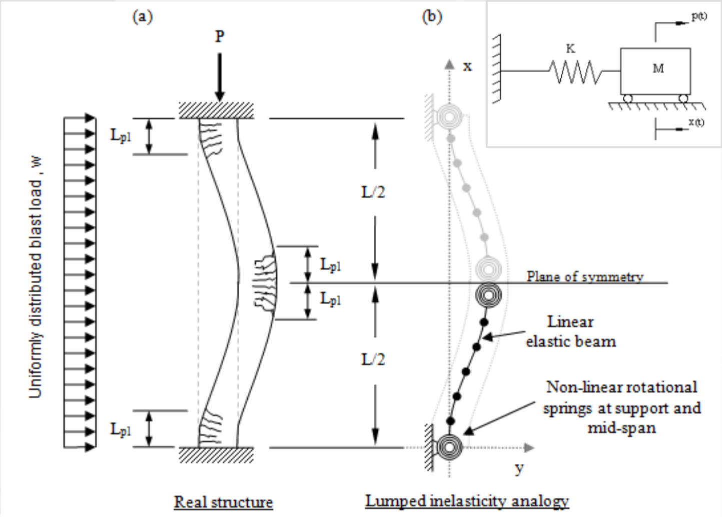
RCBlast

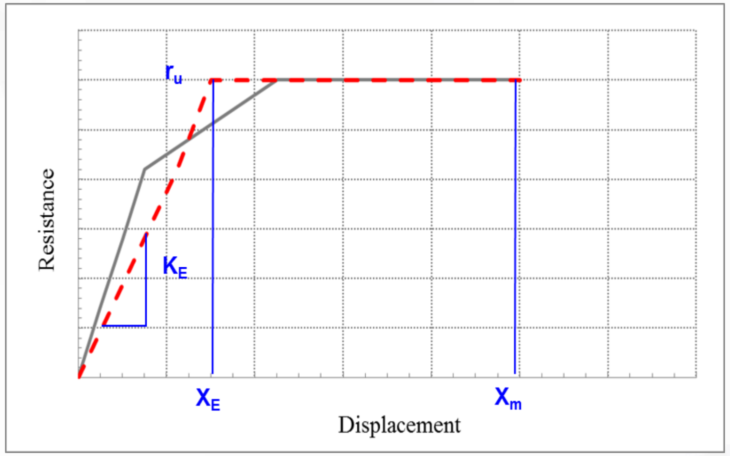
- Developed by **Eric Jacque**
- **SDOF** Approach
- **RC and RC w/FRP** Components
- **Hysteretic** Response
- **Plastic-Hinge** Length
- **Time History** Loading
- **P-I** Option
- Experimentally **Verified**





SDOF Parameters- RCBlast

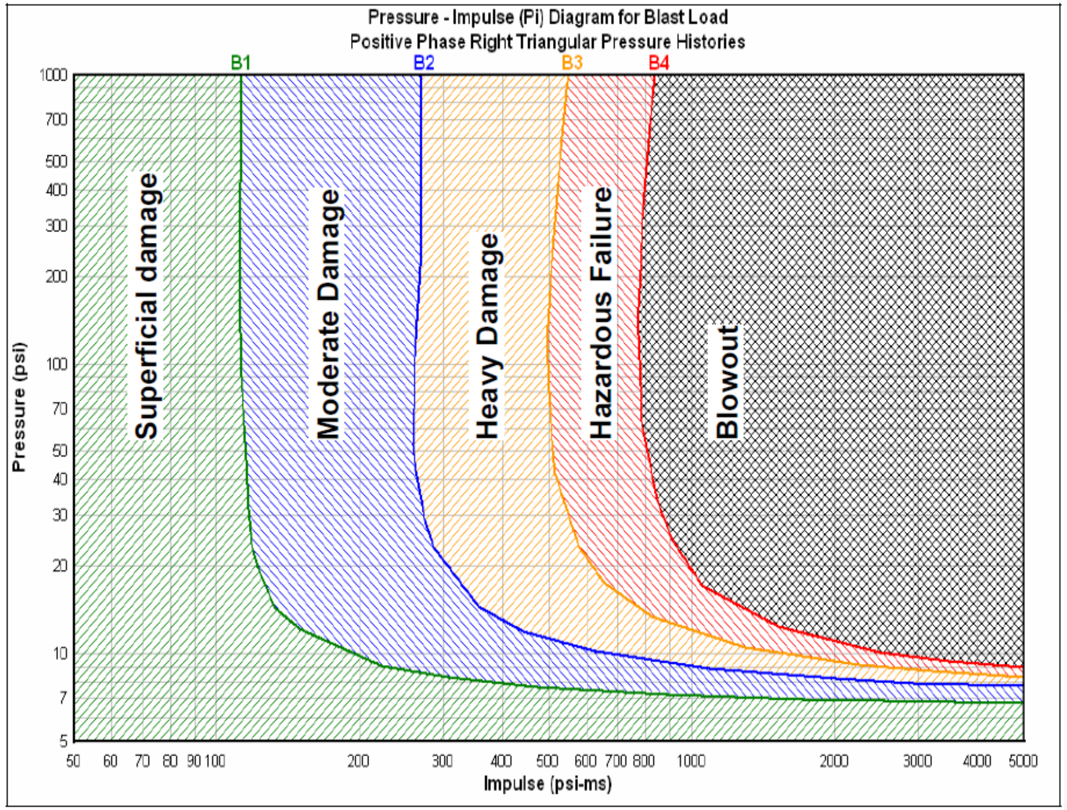




Parameter	Case-1 Unretrofitted	Case-2 CFRP 0.04" Back Face	Case-3 CFRP 0.04" Back & Front	Case-4 CFRP 0.08" Back Face	Case-5 GFRP 0.04" Back Face
M psi.ms^2/in	**869**	**869**	**869**	**869**	**869**
k_{E+} psi/in	**47.0**	**65.5**	**65.3**	**133.0**	**54.5**
k_{E-} psi/in	4.0	5.3	5.3	5.9	4.3
r_{e+} 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

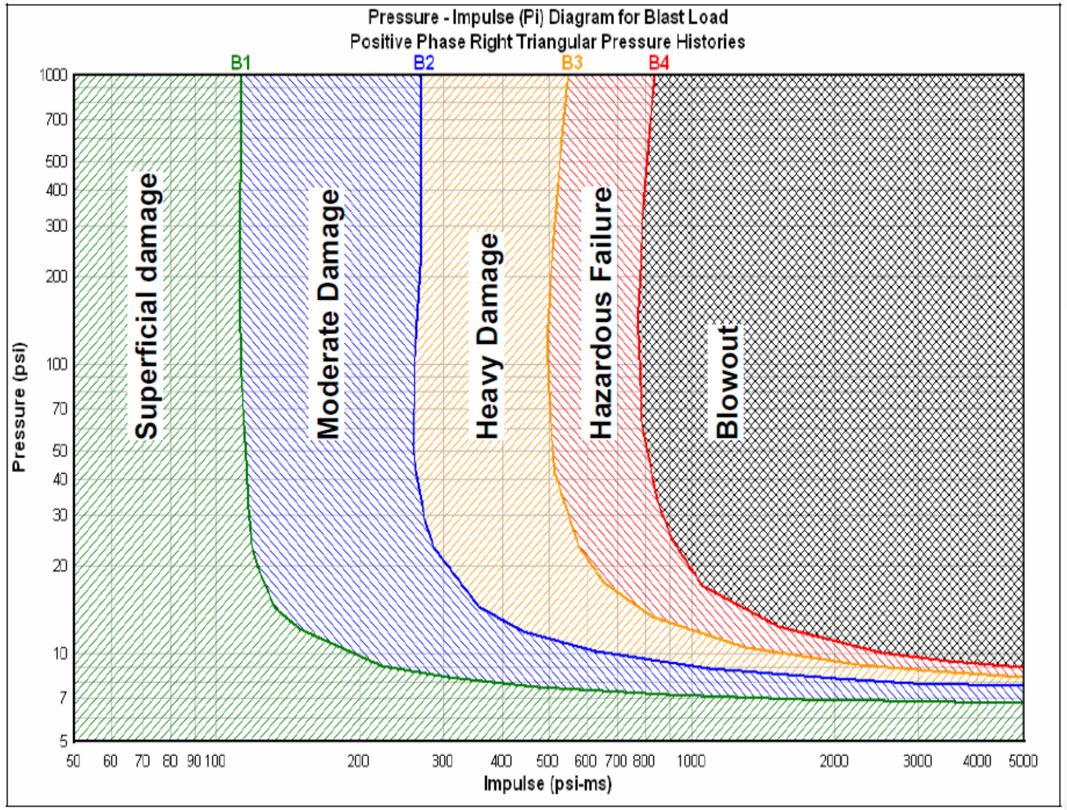
Damage Level B1		Damage Level B2		Damage Level B3		Damage Level B4		Damage Level B5	
Superficial Damage		Moderate Damage		Heavy Damage		Hazardous Failure		Blowout	
μ	θ	μ	θ	μ	θ	μ	θ	μ	θ
1.0	-	-	2 °	-	5 °	-	10 °	-	> 10 °

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	-

1 Introduction

2 Study Parameters

3 Simulation Approaches and Models

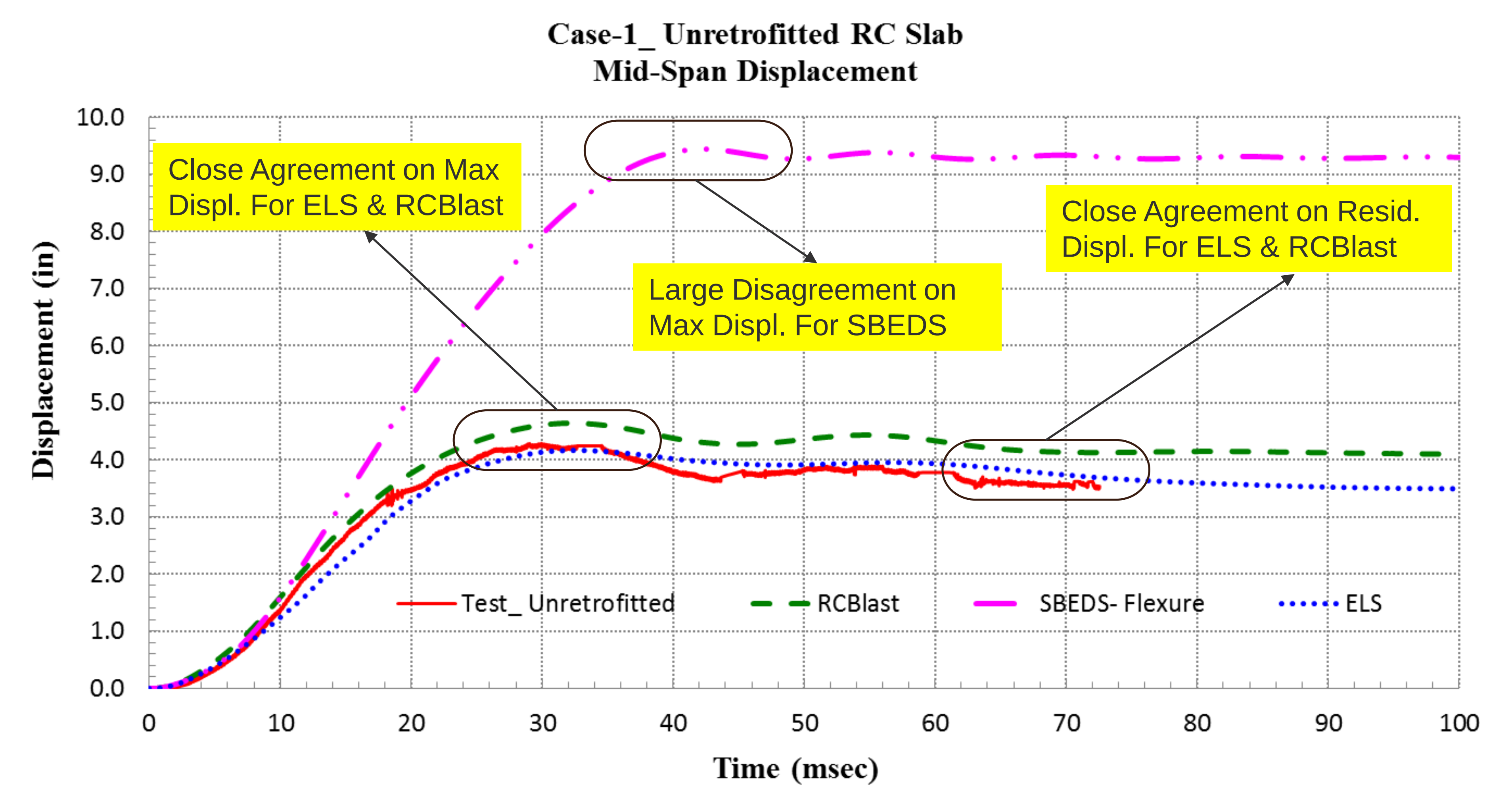
4 Predicted Blast Responses

5 Concluding Remarks

6 Future Research Work

7 Questions

Case-1: Peak Displacement Response



Unretrofitted

RC Slab

(Control Case)

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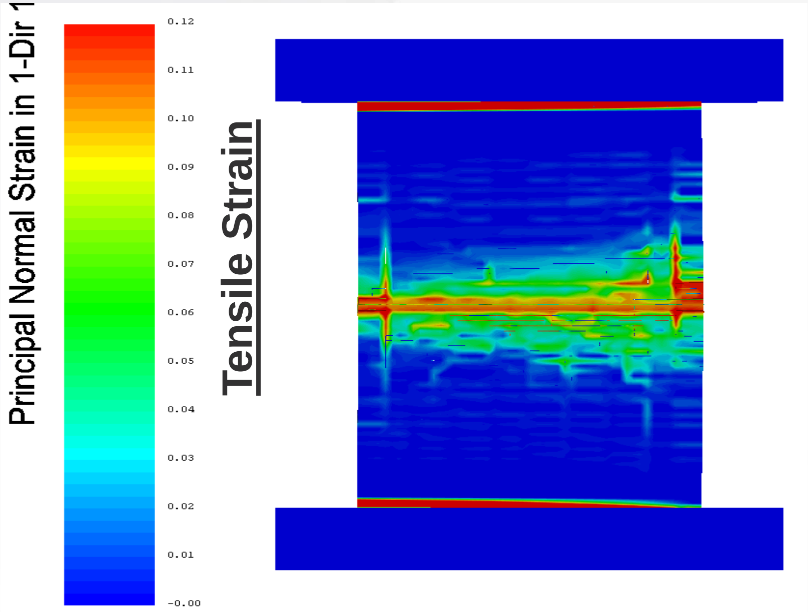
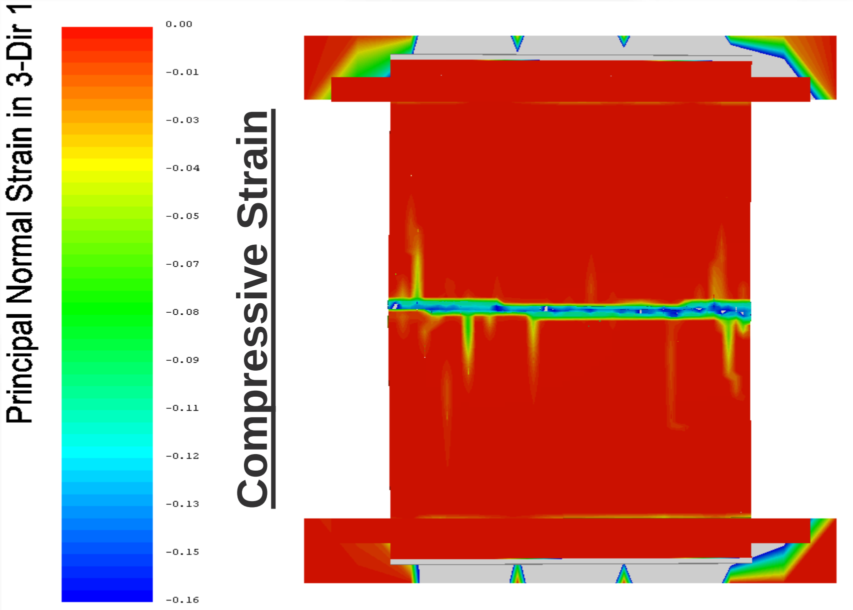
CASE-1: AEM/ ELS Simulation

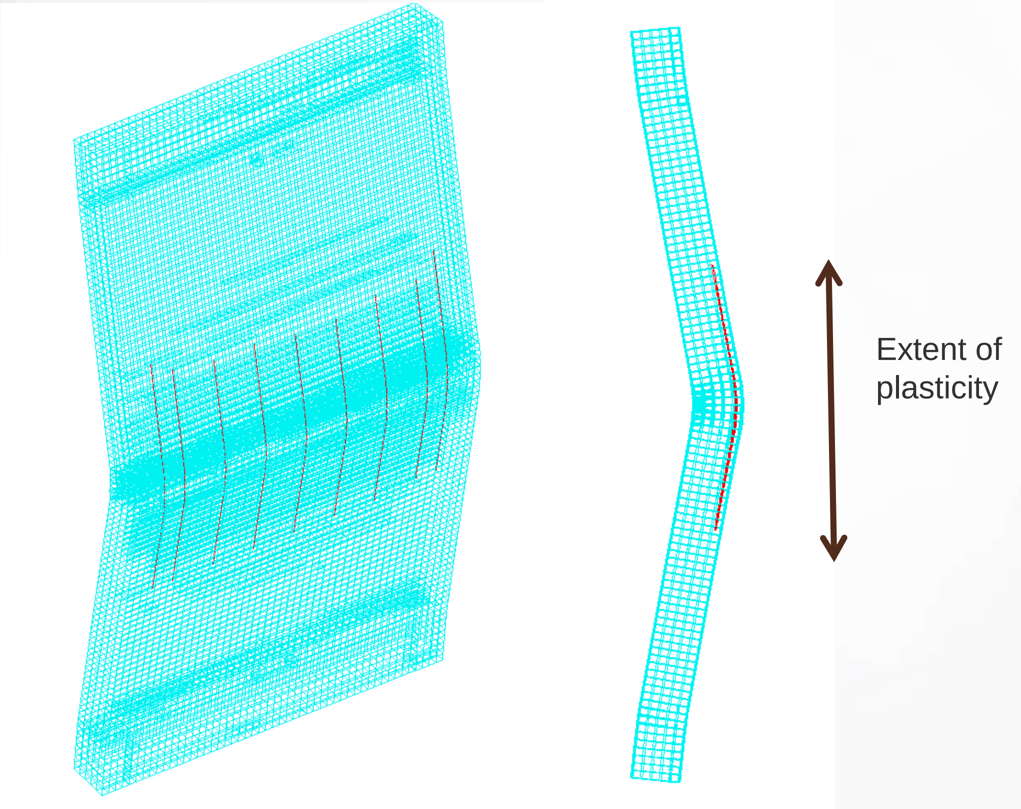
Back Face

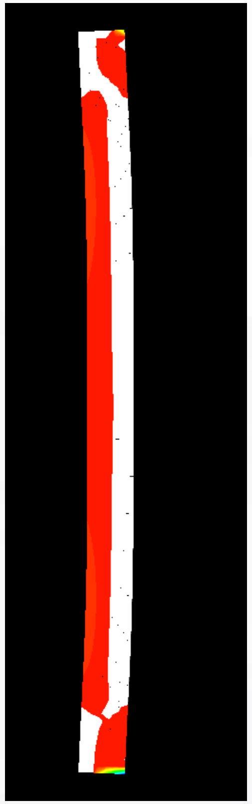


Front Face



CASE-1: AEM/ ELS Simulation





Back Face

Yielded Steel Bars Marked in Red

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

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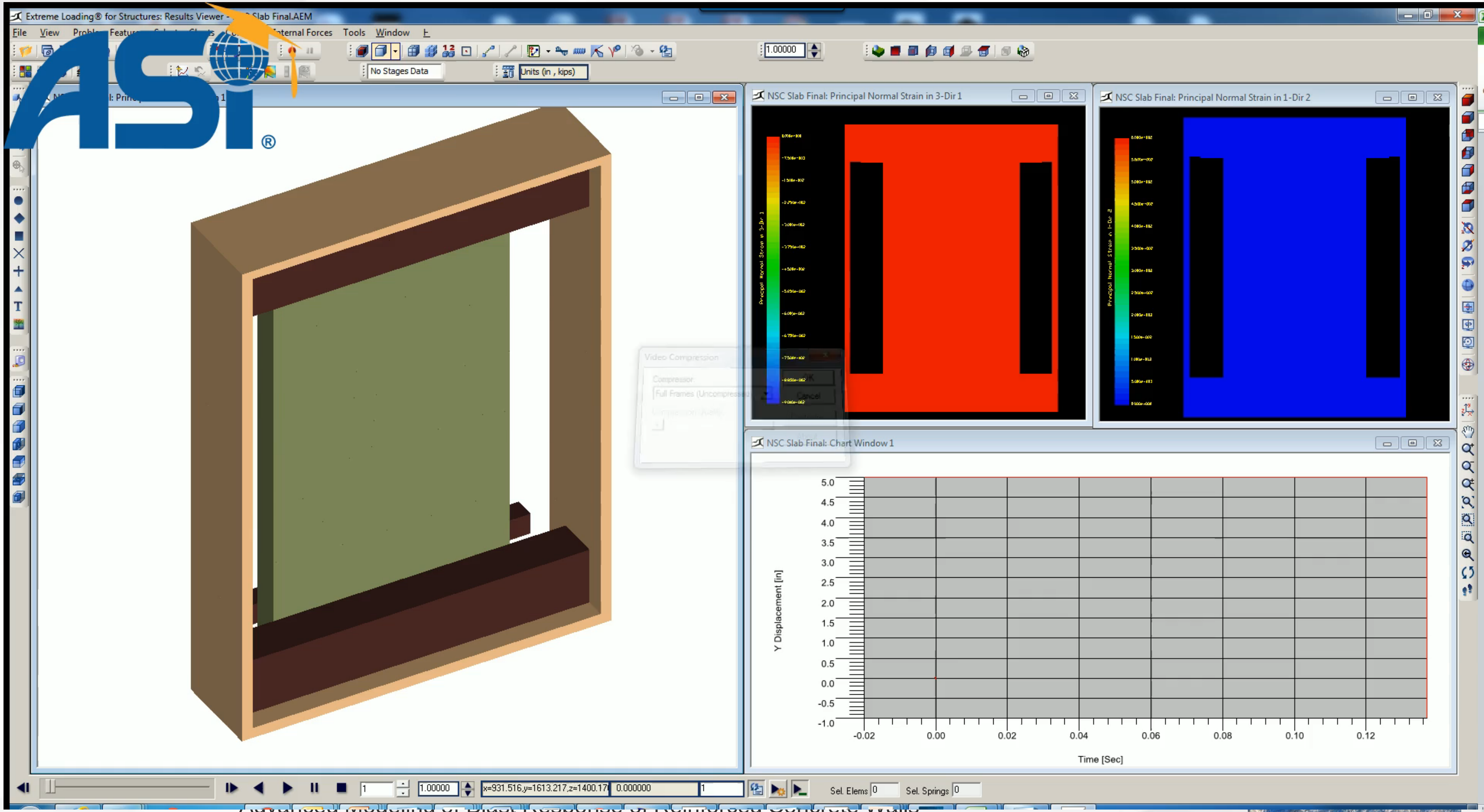
The Concrete Convention and Exposition

Case-1: AEM/ ELS Simulation



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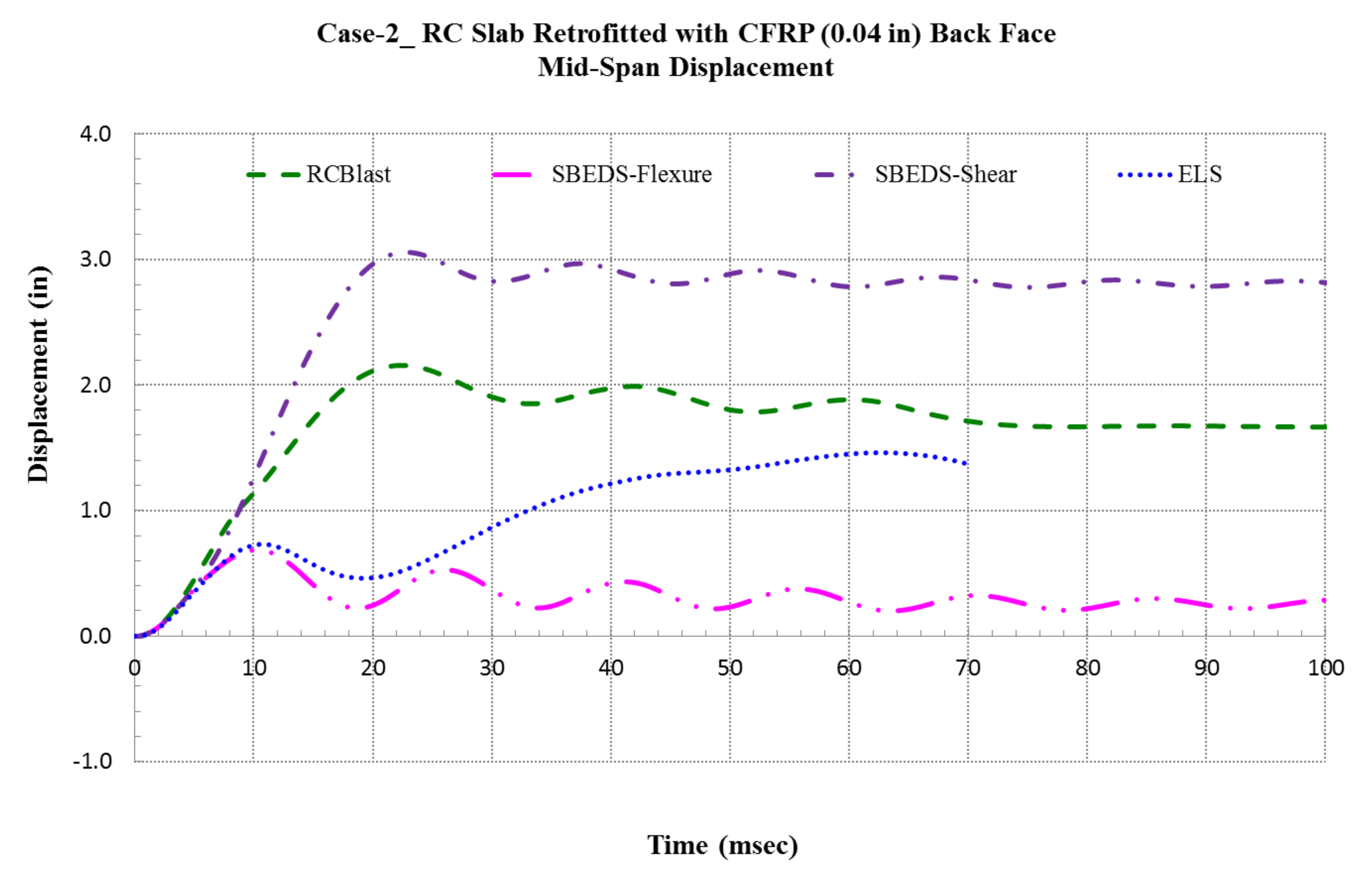
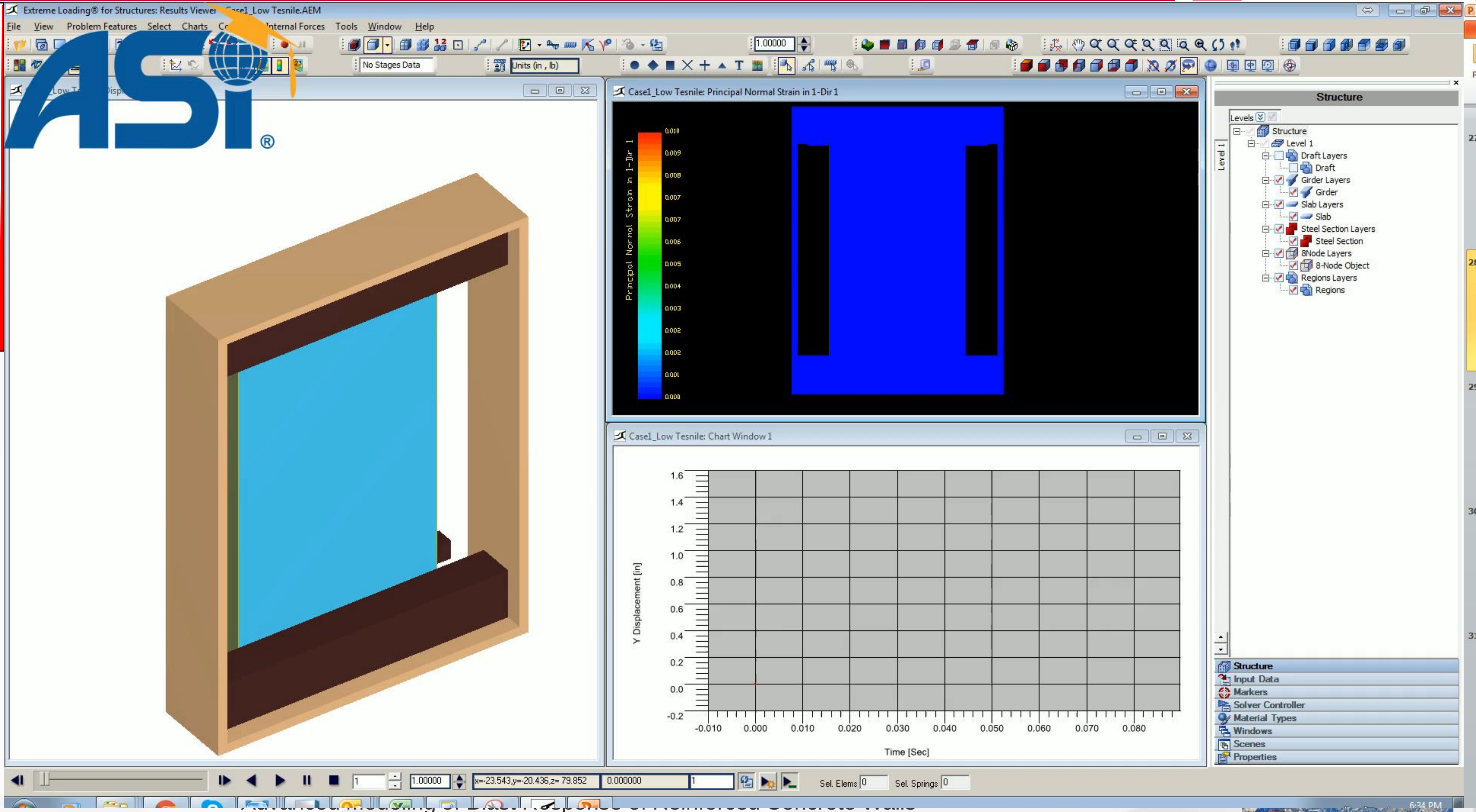
Case-2: Peak Displacement Response



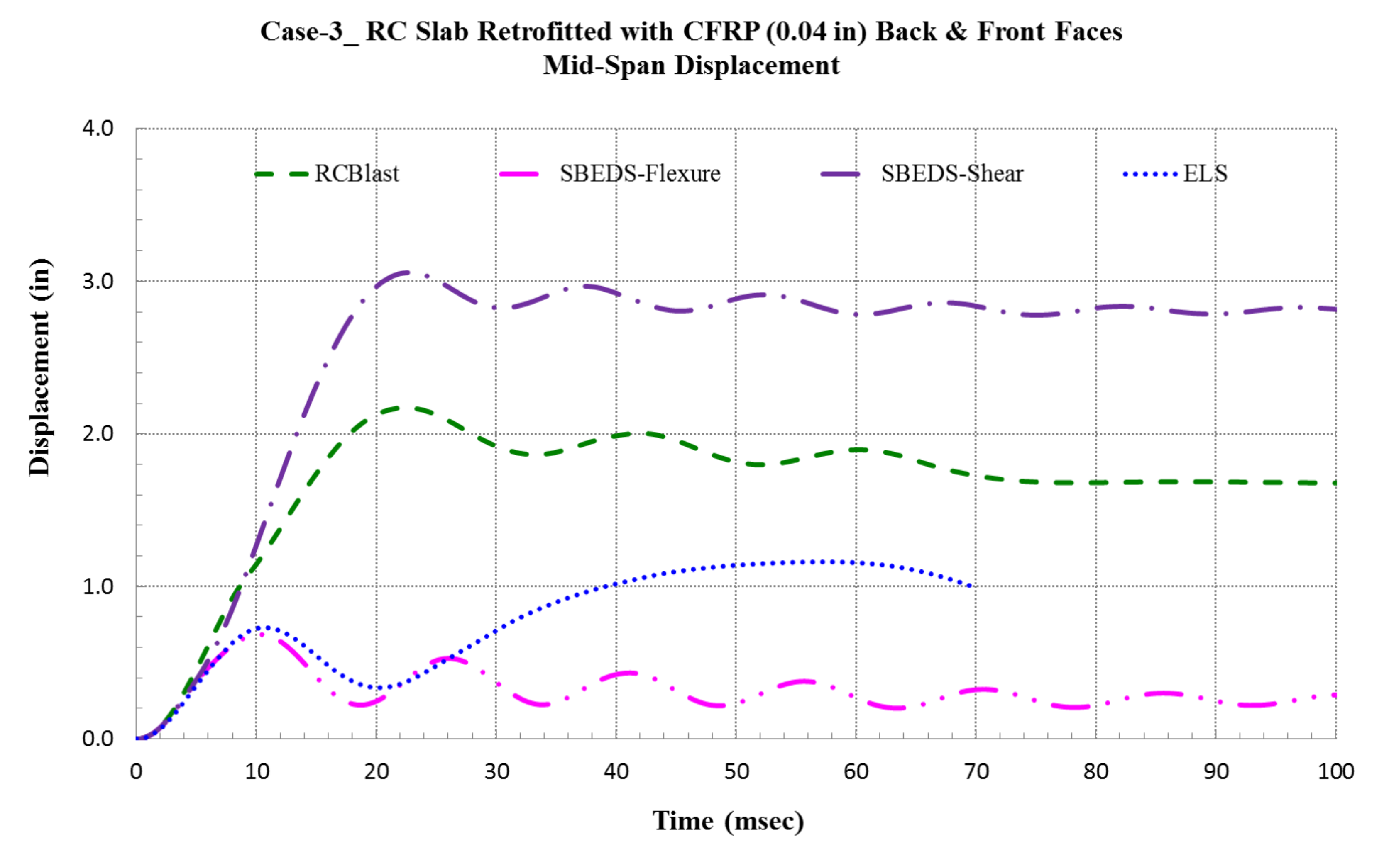
CFRP Retrofitted RC Slab

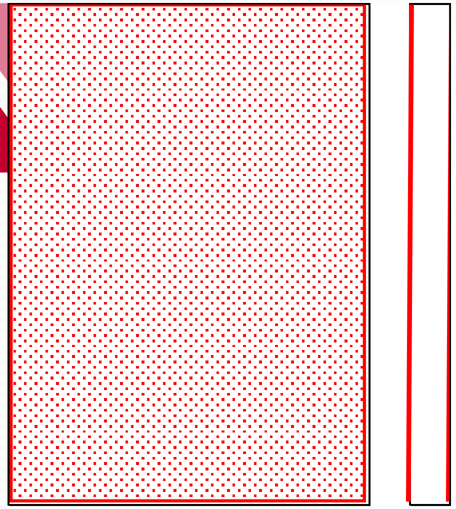
(Single Layer- 0.04in - Back Face Only)

Case-2: AEM/ ELS Simulation



Case-3: Peak Displacement Response

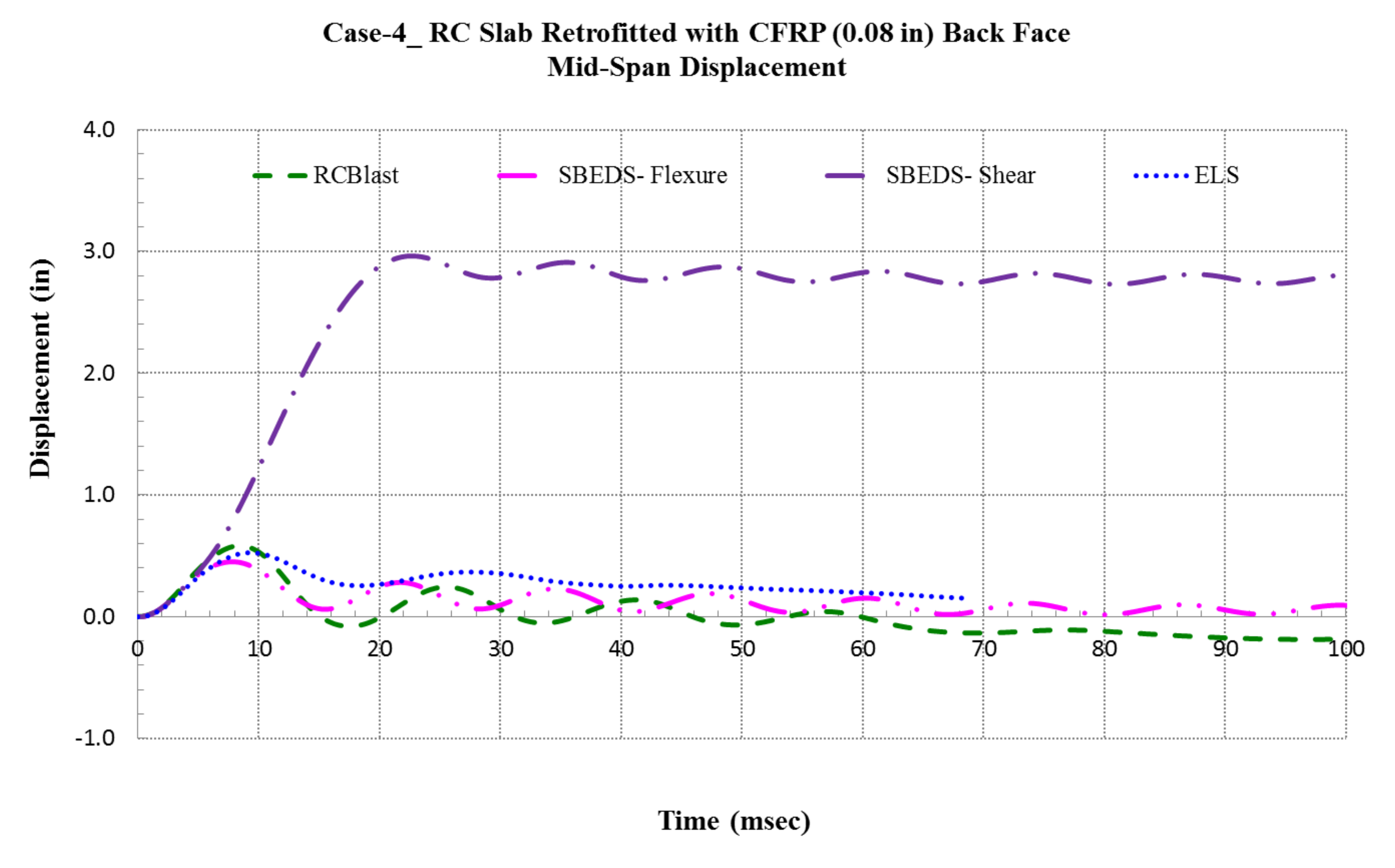


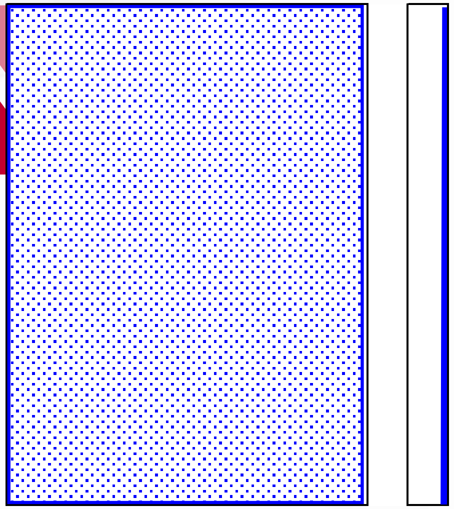


CFRP Retrofitted RC Slab

(Single Layer- 0.04in - Back & Front Faces

Case-4: Peak Displacement Response

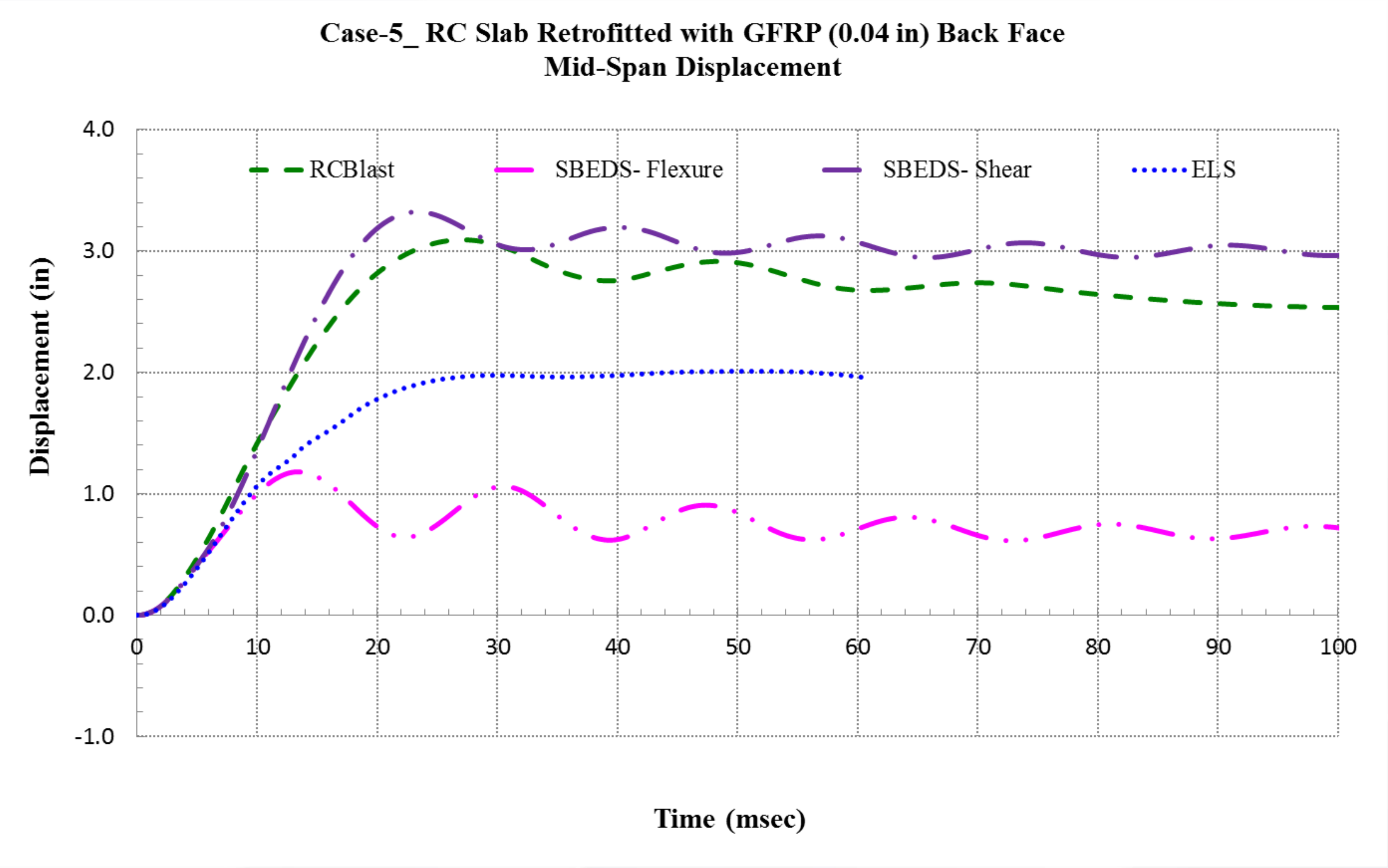


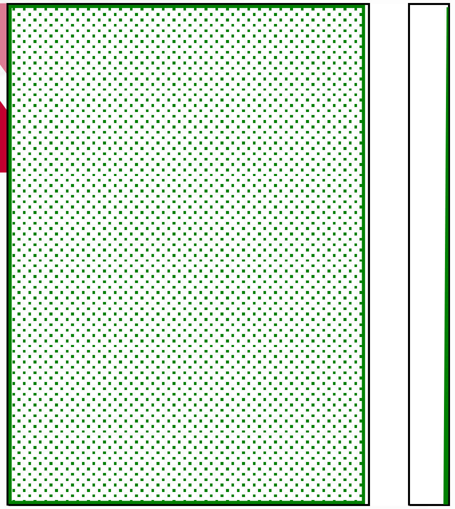


CFRP Retrofitted RC Slab

(Double Layers- 0.08in - Back Face Only)

Case-5: ELS , SBEDS & RCBlast Simulations





GFRP Retrofitted RC Slab

(Single Layer- 0.04in - Back Face Only)

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ASI

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

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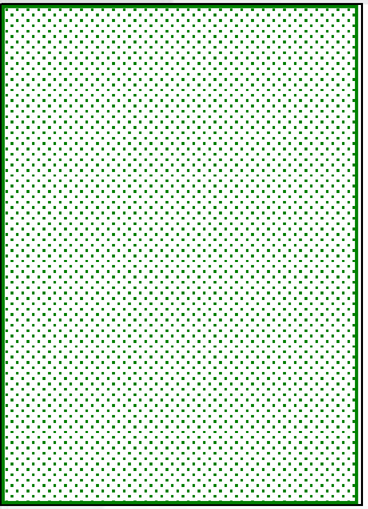
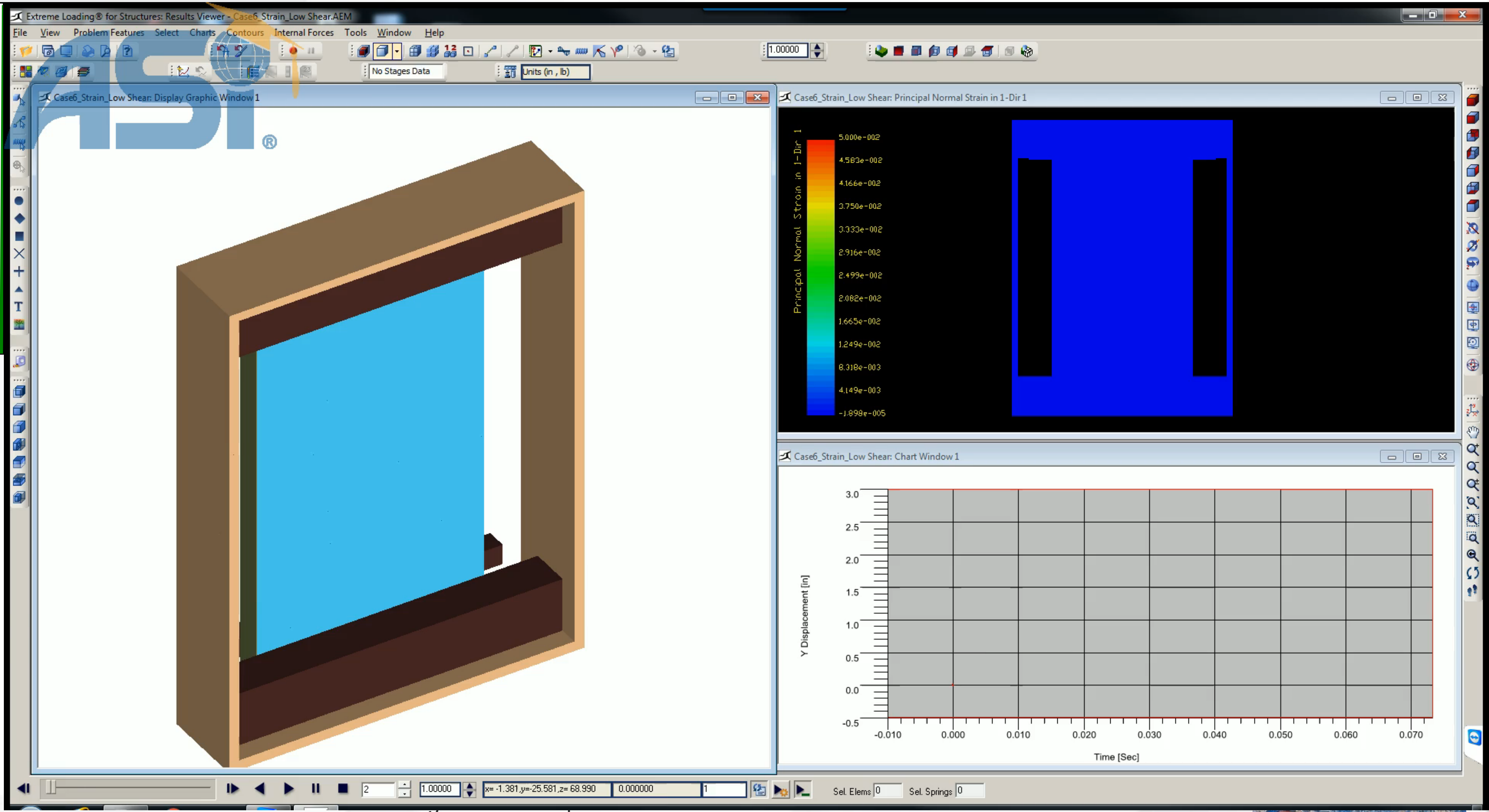
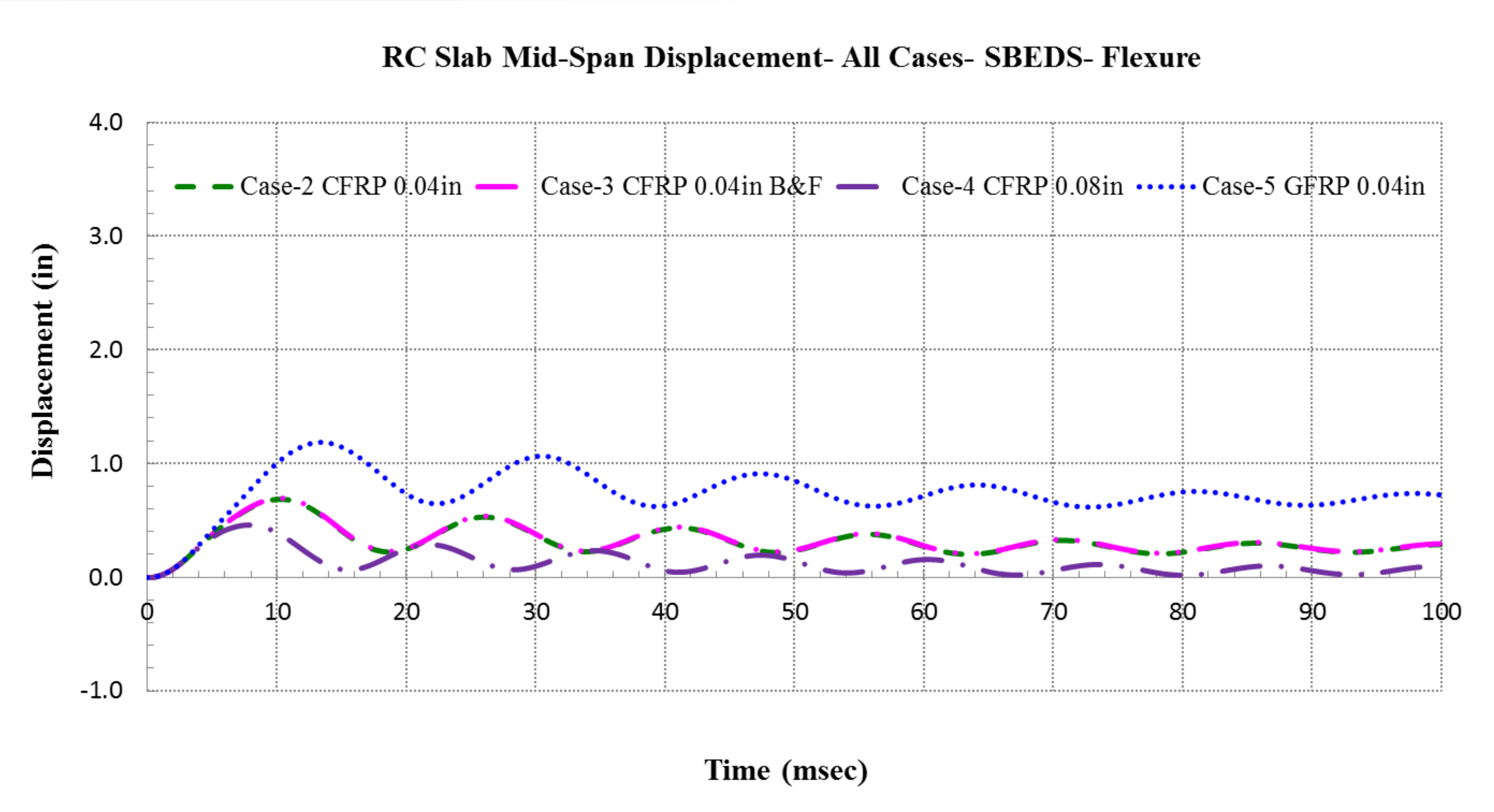
Case-5: AEM/ ELS Simulation





with and without FRP Retrofit

All Cases: SDOF- SBEDS- Flexure



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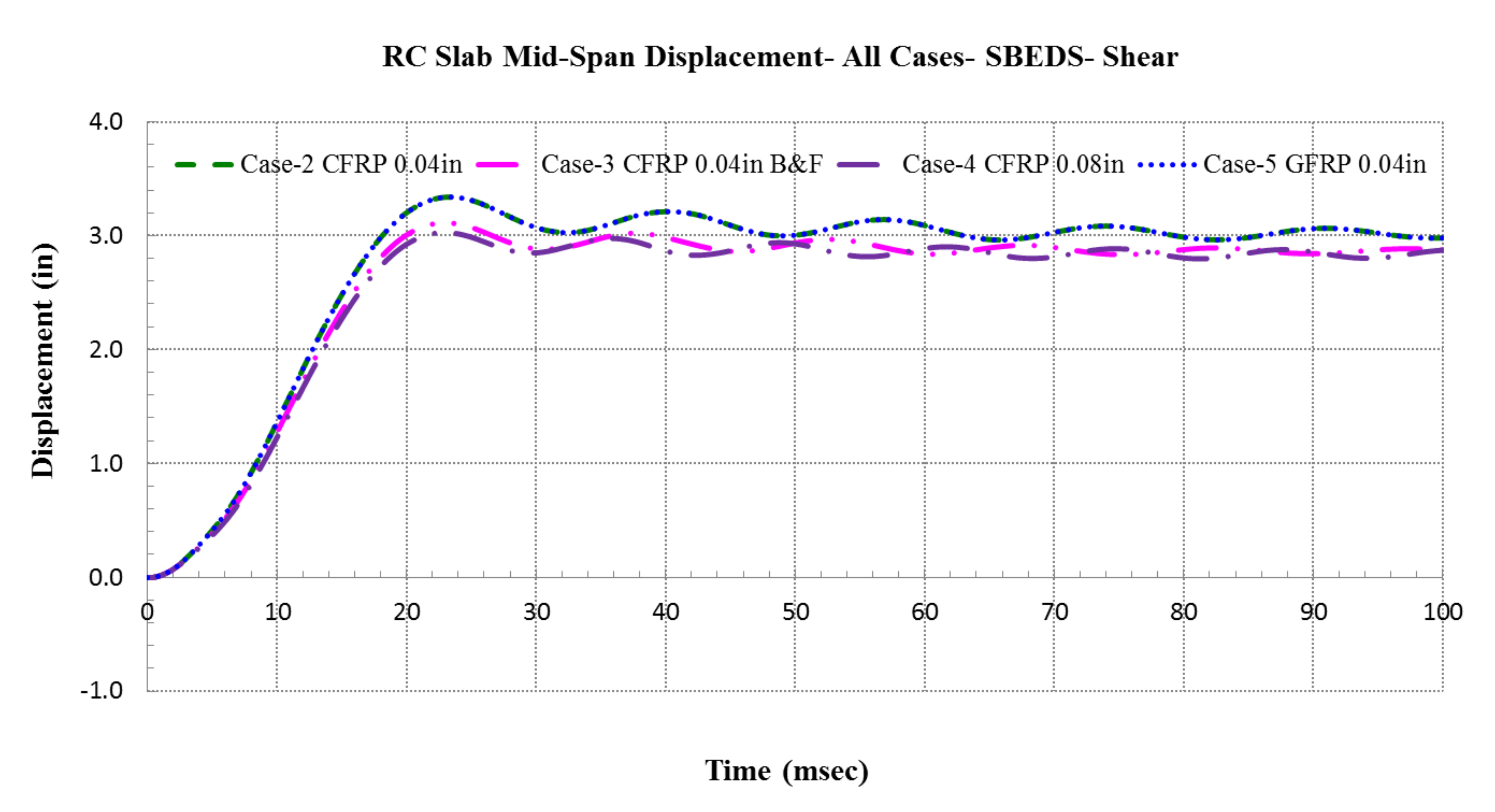
All Cases: SDOF- SBEDS- Shear



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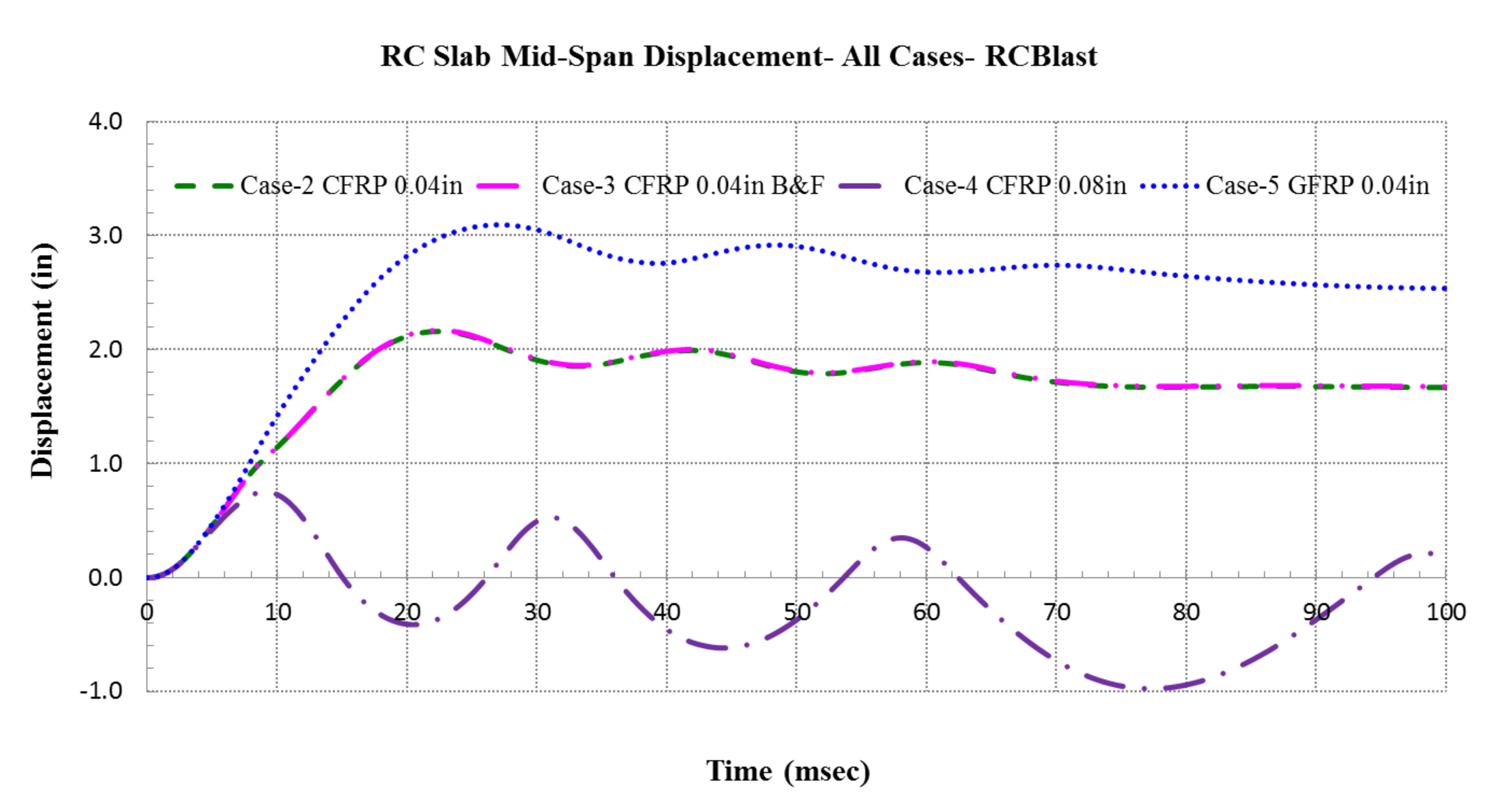
All Cases: SDOF- RCBlast



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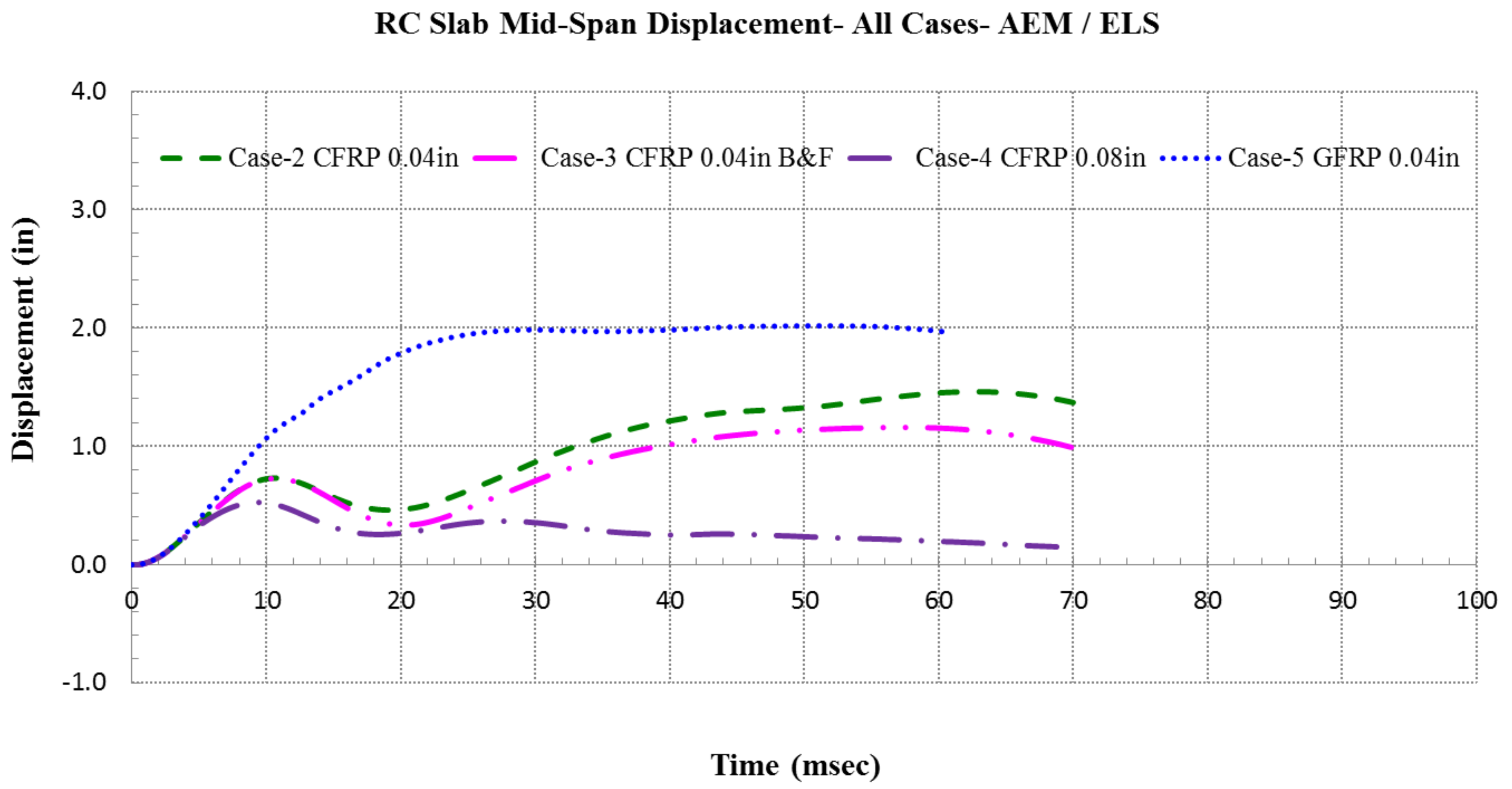
All Cases: AEM- ELS



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1 Introduction

2 Study Parameters

3 Simulation Approaches and Models

4 Predicted Blast Responses

5 **Concluding Remarks**

6 Future Research Work

7 Questions

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 Reponses 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 <u>*SBEDS with Shear Flag*</u>.
- Generally Speaking, RCBlast Response Predictions **Fit Between the Upper and Lower Bounds** of SBEDS Predicted Reponses. 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.

Future Research Work

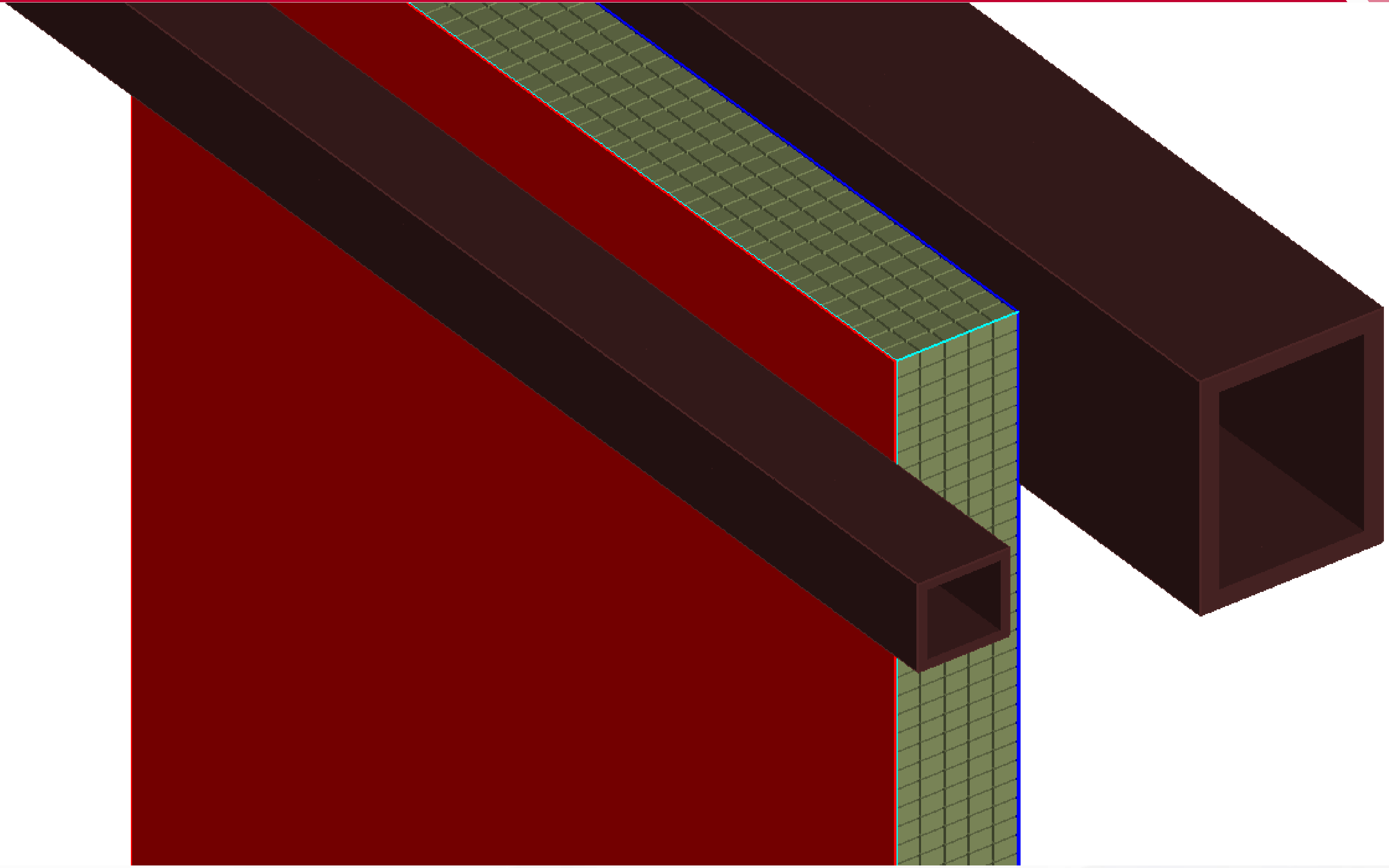
- Perform Additional Validation of Utilized Tools (ELS, RCBlast and SBEDS) to Better Understand Their **Range of Applicability and Modeling Limitations** of FRP Retrofitted RC Elements.
- Identify the Proper Technique(s) to Account for the **Potential Reduction in Blast Resistance of FRP Retrofitted 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

1. Introduction
2. Study Parameters
3. Simulation Approaches
4. Analytical Models
5. Predicted Blast Responses
6. Concluding Remarks
7. **Questions**

Questions

Anchorage

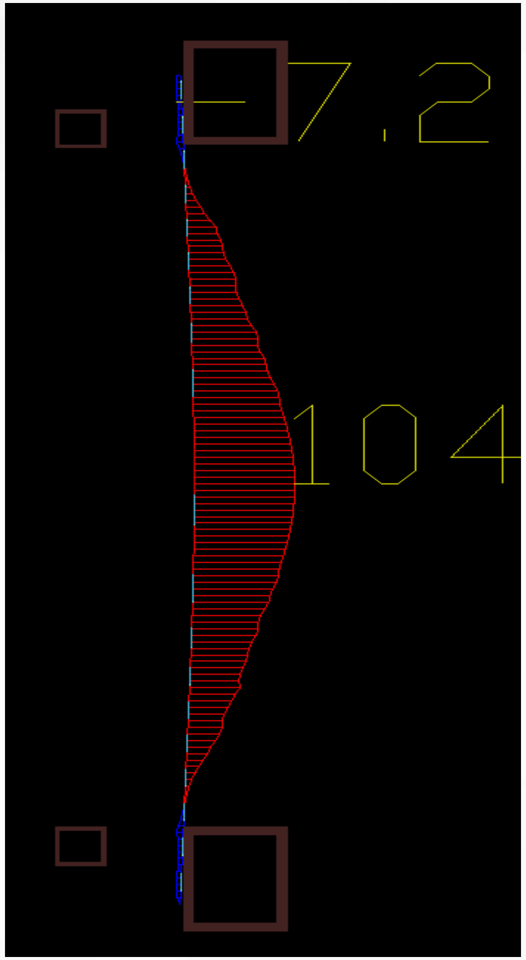
FRP sheets are modeled as extending behind the HSS top and bottom beams.



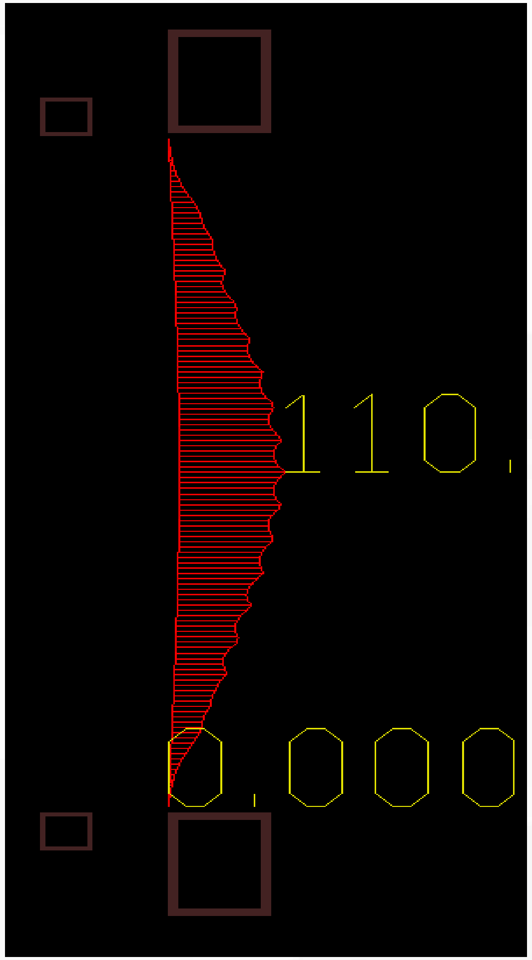
Anchored Sheets

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.

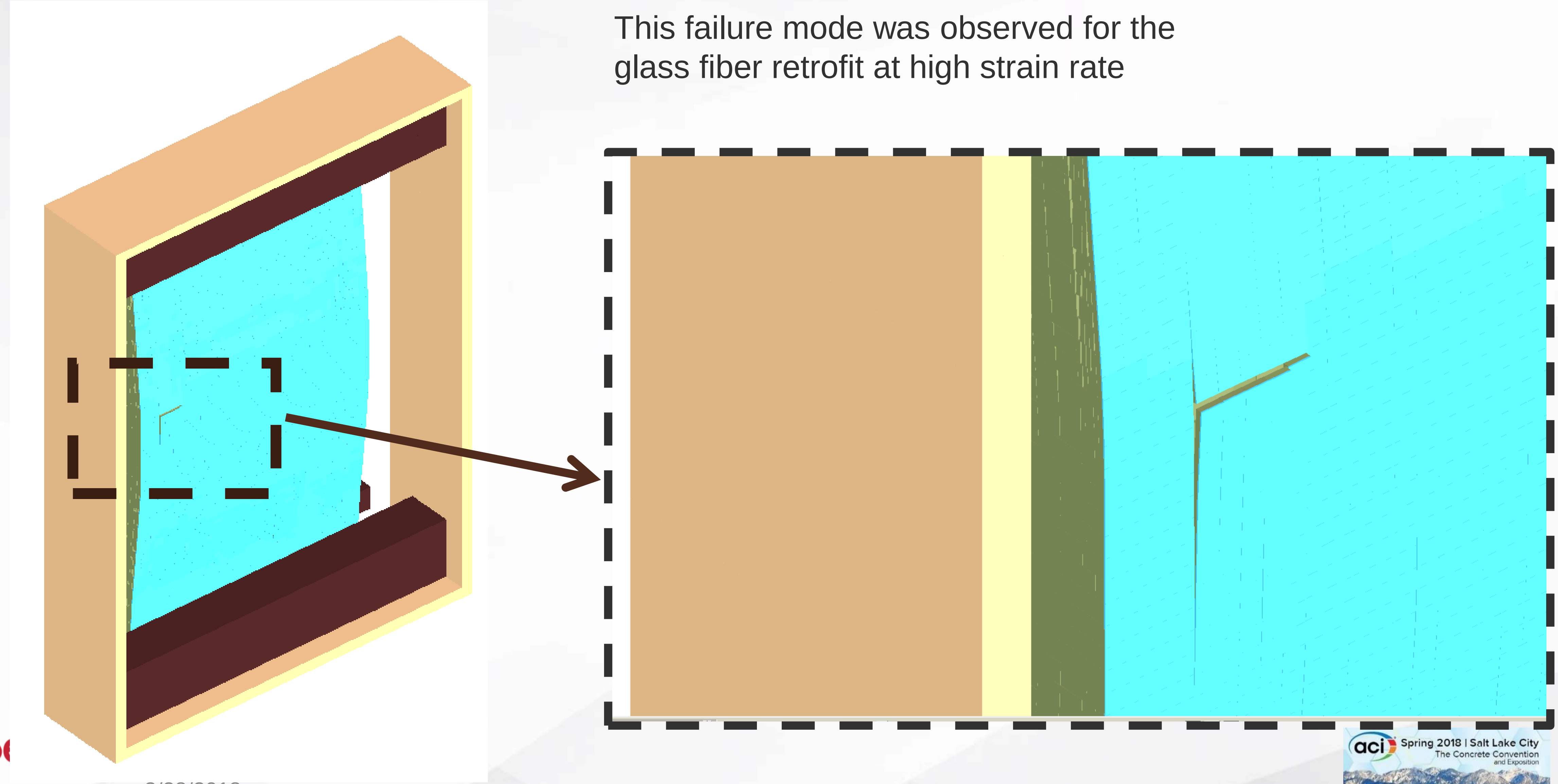


Anchored Sheets



Non-anchored sheets

Debonding of FRP



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

Failure near support