NAVAL
POSTGRADUATE
SCHOOL

FLUID STRUCTURE INTERACTION ON COMPOSITE STRUCTURES: EXPERIMENTAL & NUMERICAL STUDIES

Y. W. Kwon
Distinguished Professor
Dept. of Mech. & Aero. Engineering
Naval Postgraduate School
Monterey, California, USA

Multiphysics Conference, December 13-14, 2012

Overview

- Introduction
- Objectives
- Experimental Impact Study
- Effect of Nanomaterials (CNT/CNF)
- Computational Modeling and Simulation
- Conclusions

Introduction

- Increasing use of composite materials for naval applications
  - Surface ship hull structures
  - Superstructures, Sonar domes, etc.
- Polymer composite materials are much lighter than metals
  - Sandwich structures even lighter than standard laminated composite structures
- The fluid effects are important on sandwich and/or laminated polymer composite structures because of their low densities.

Objectives

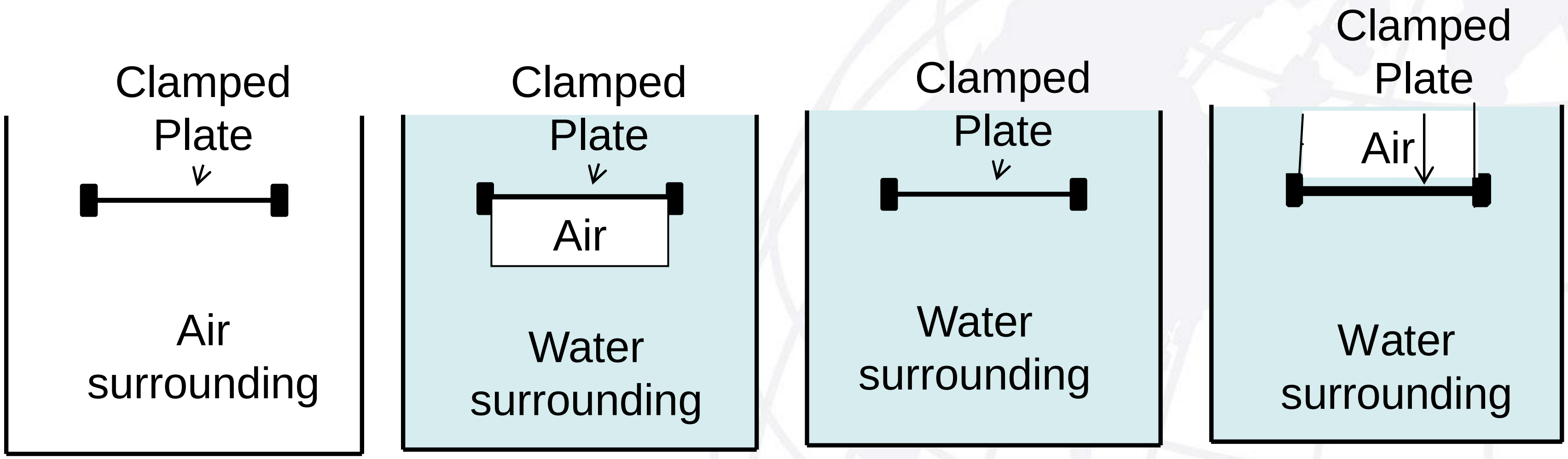
- To understand and predict the effects of Fluid-Structure Interaction (FSI) on dynamic response and failure of laminated or sandwich polymer composite structures when in contact with water
- To conduct experimental study to measure the effect of FSI on laminated or sandwich composite structures
- To study the effect of locally distributed CNT & CNF on the interface strength under FSI
- To develop multiphysics based computational techniques for FSI

Experimental Impact Study

- In order to evaluate the FSI effects on composites, the same impact loading conditions are applied to the same composite structure, either immersed in water (called wet structure) or in air (called dry structure) without causing damage.
- The same impact loading conditions are applied to composite structures causing damage under dry and wet structures.

Impact Conditions

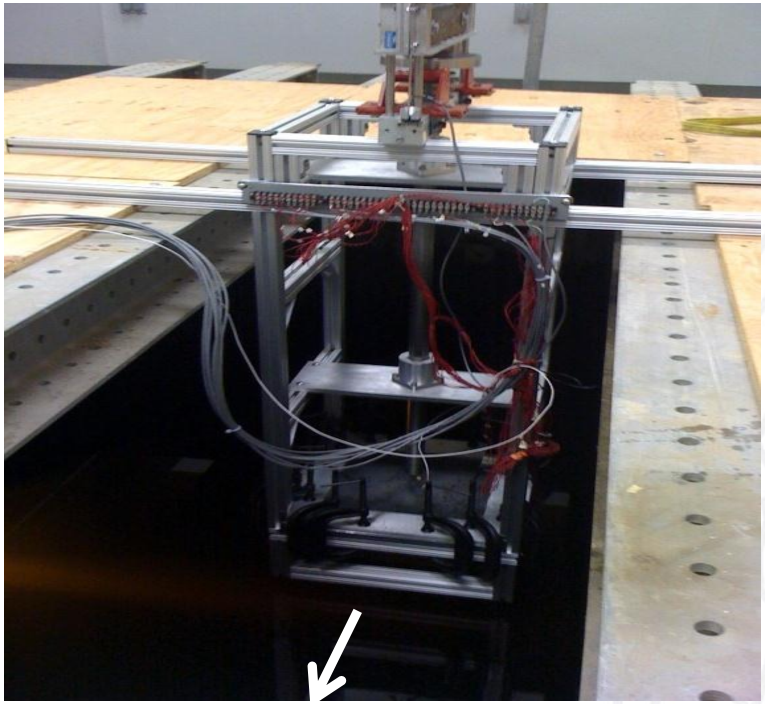
- (A): Air-backed dry impact => Dry impact (Baseline)
- (B): Air-backed wet impact
- (C): Water-backed wet impact
- (D): Water-backed dry impact
- Impact on the top surface of the plate

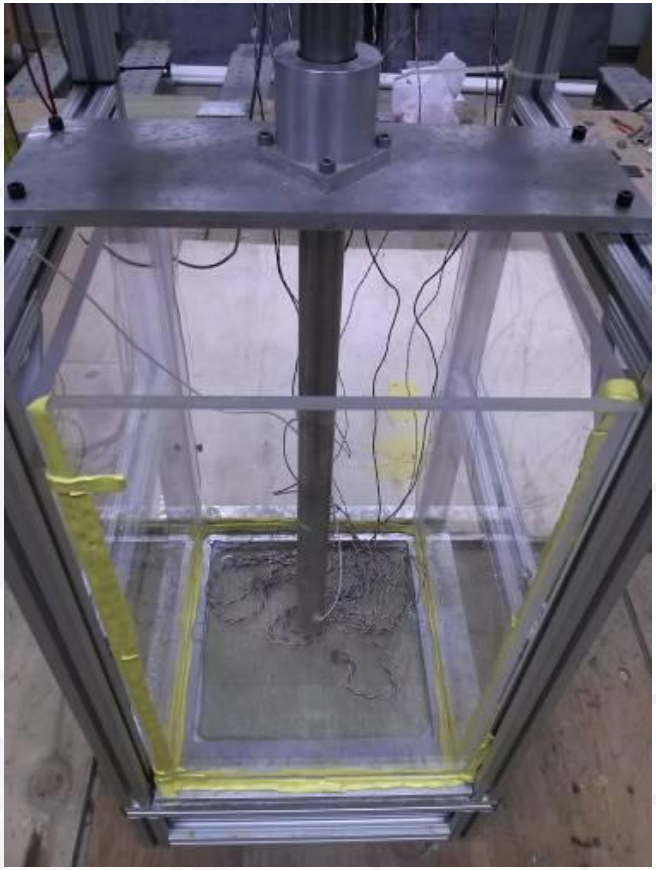


(A) (B) (C) (D)

Impact Testing Equipment

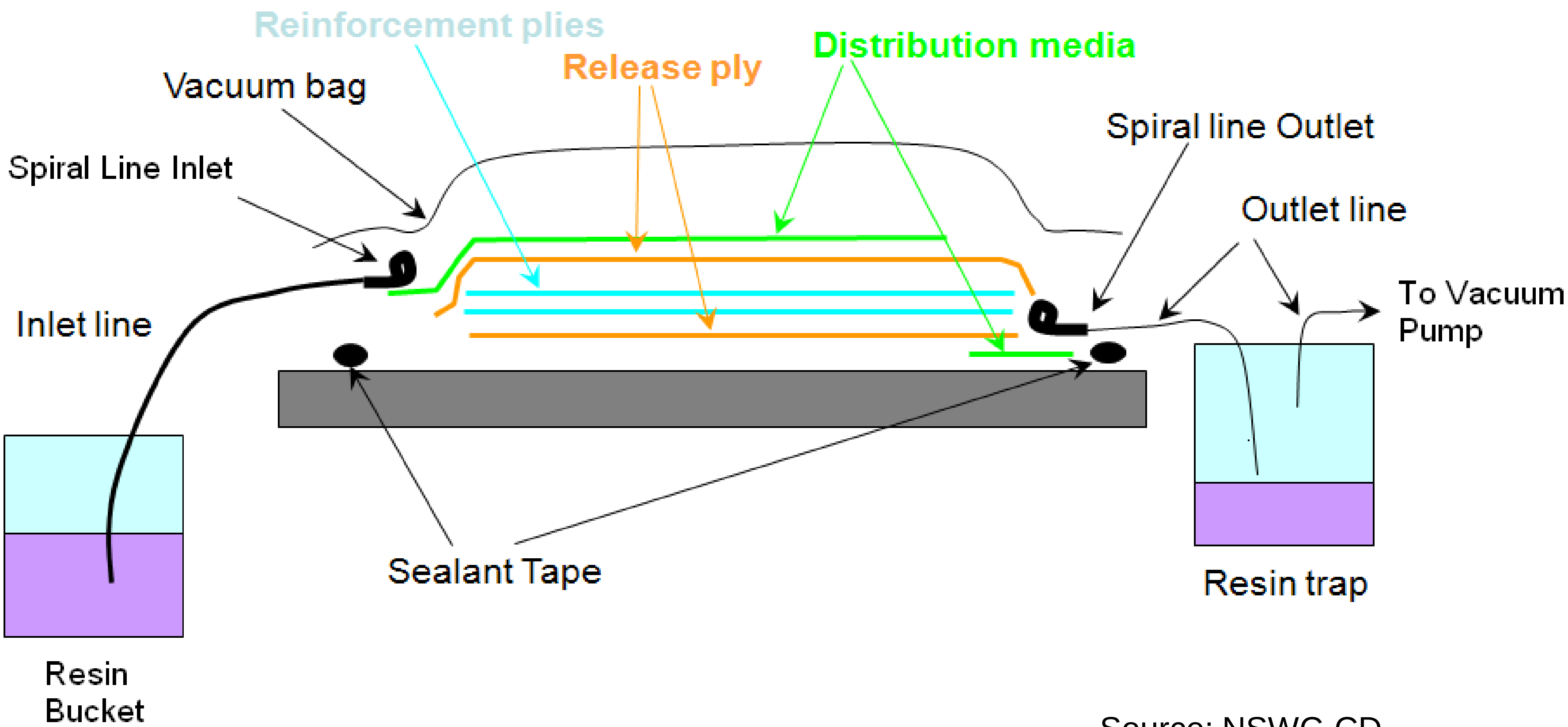
- Free fall impact machine
- Anechoic water tank





Vacuum Assisted Resin Transfer Molding (VARTM)

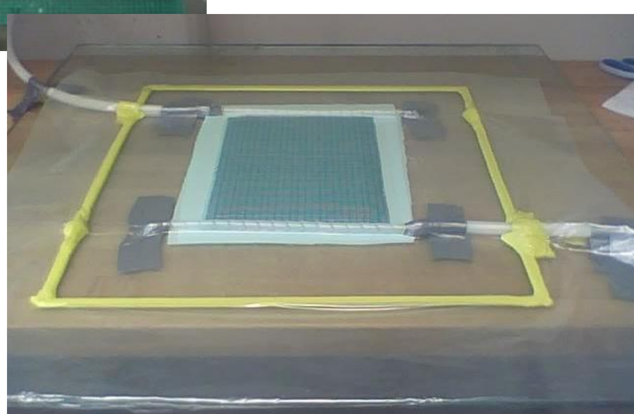
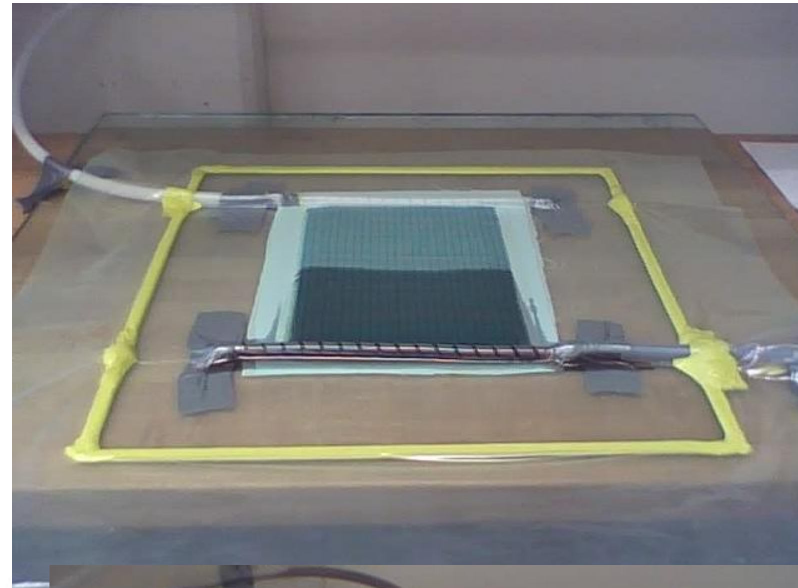
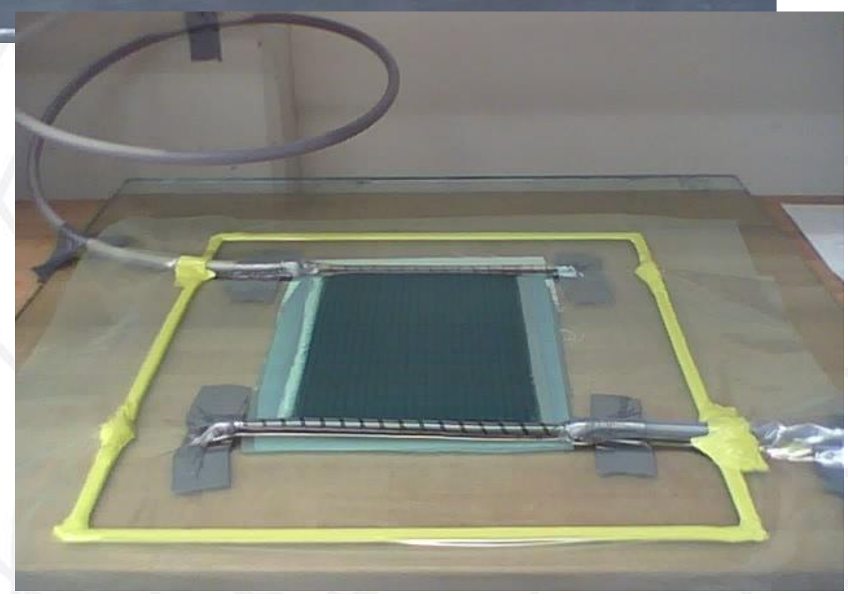
- Schematic of VARTM



Source: NSWC-CD

VARTM Technique

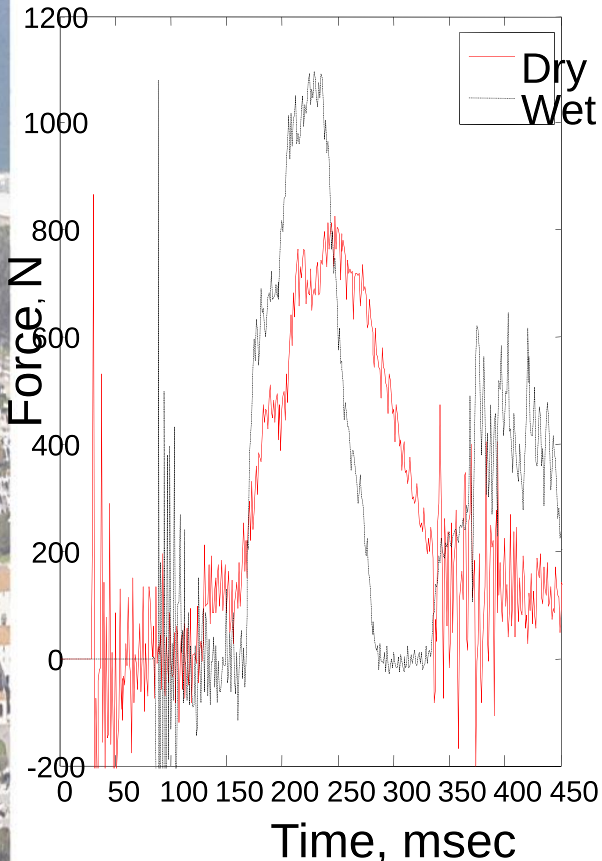


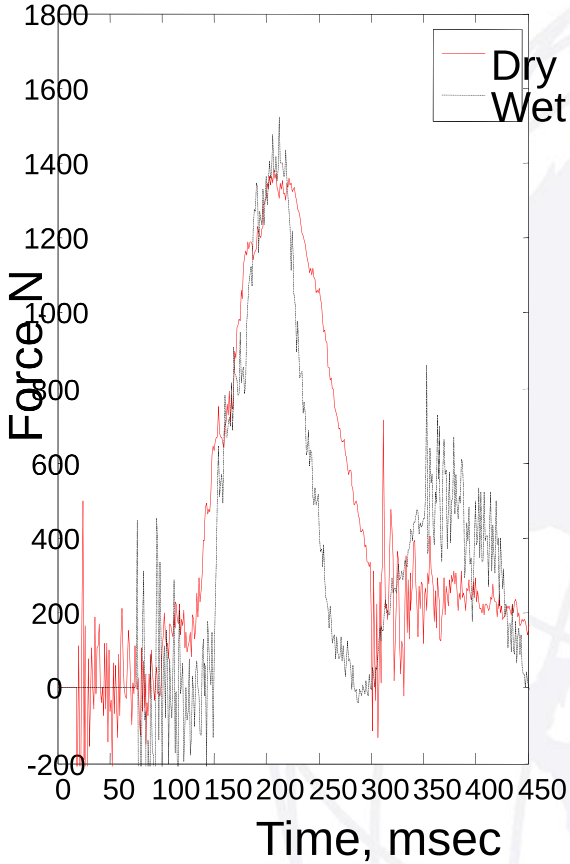
Water-Backed Dry Impact

- Impact force comparison between dry and wet case

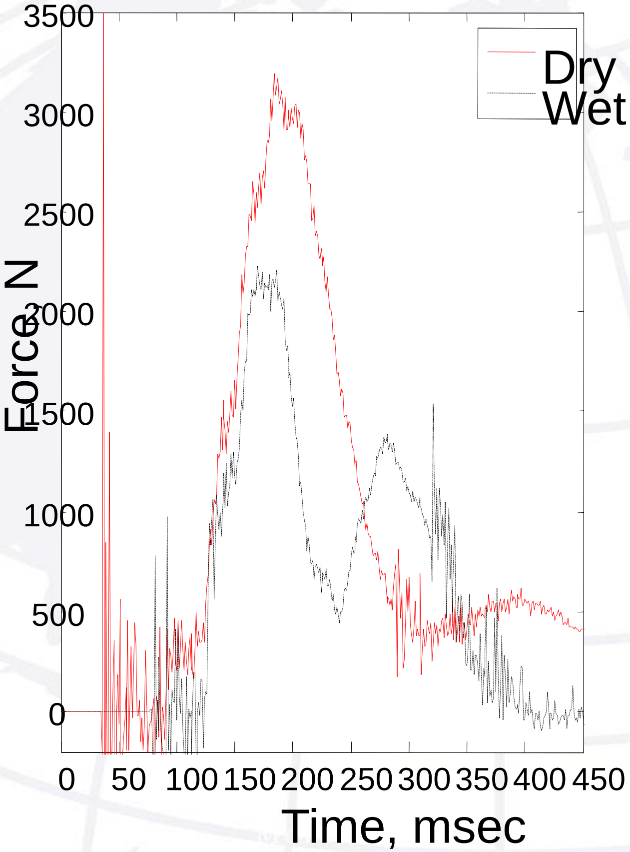
no damage (15 cm)



damage for wet (20 cm)



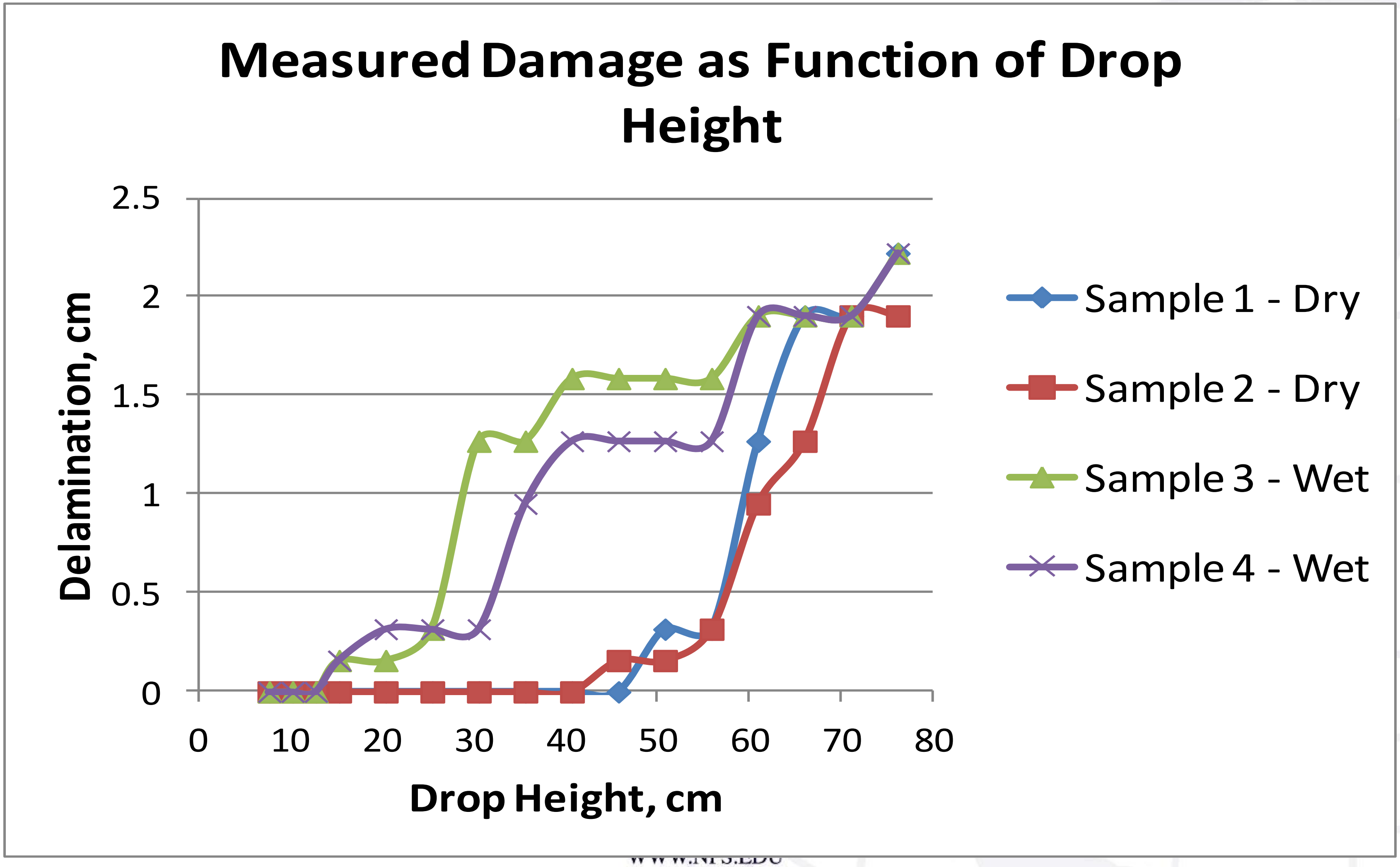
damage for both (50 cm)



NAVAL POSTGRADUATE SCHOOL

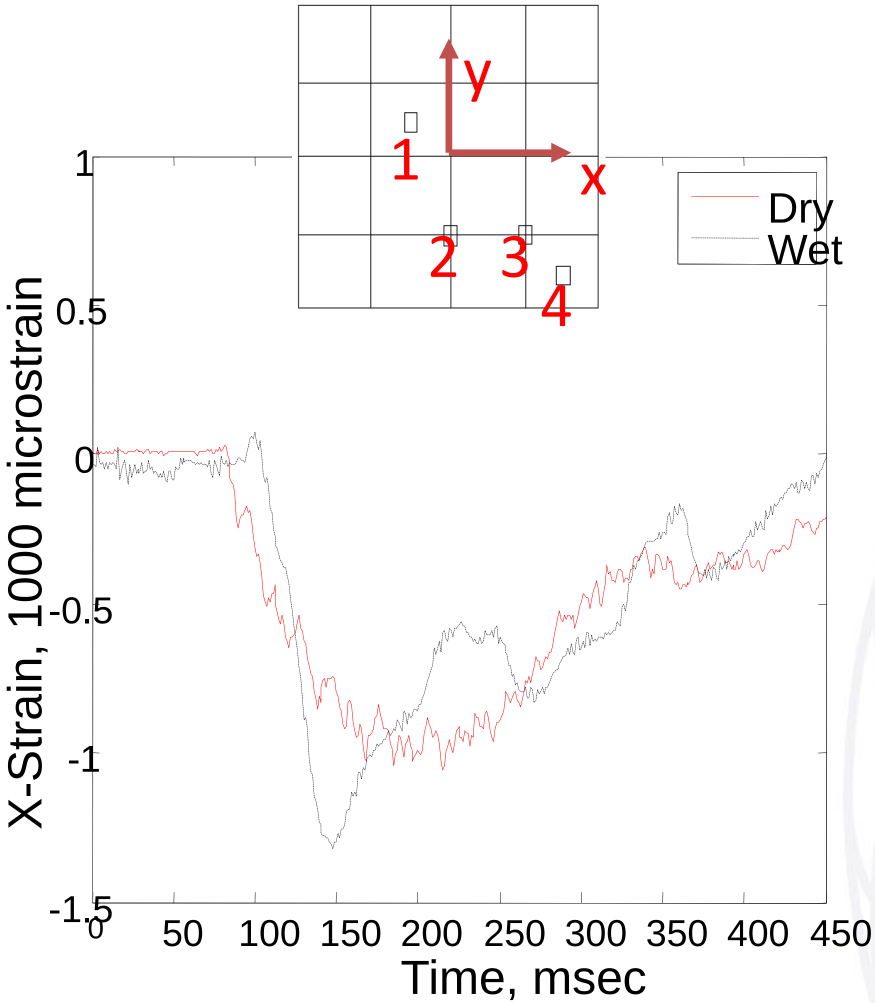
Water-Backed Dry Impact

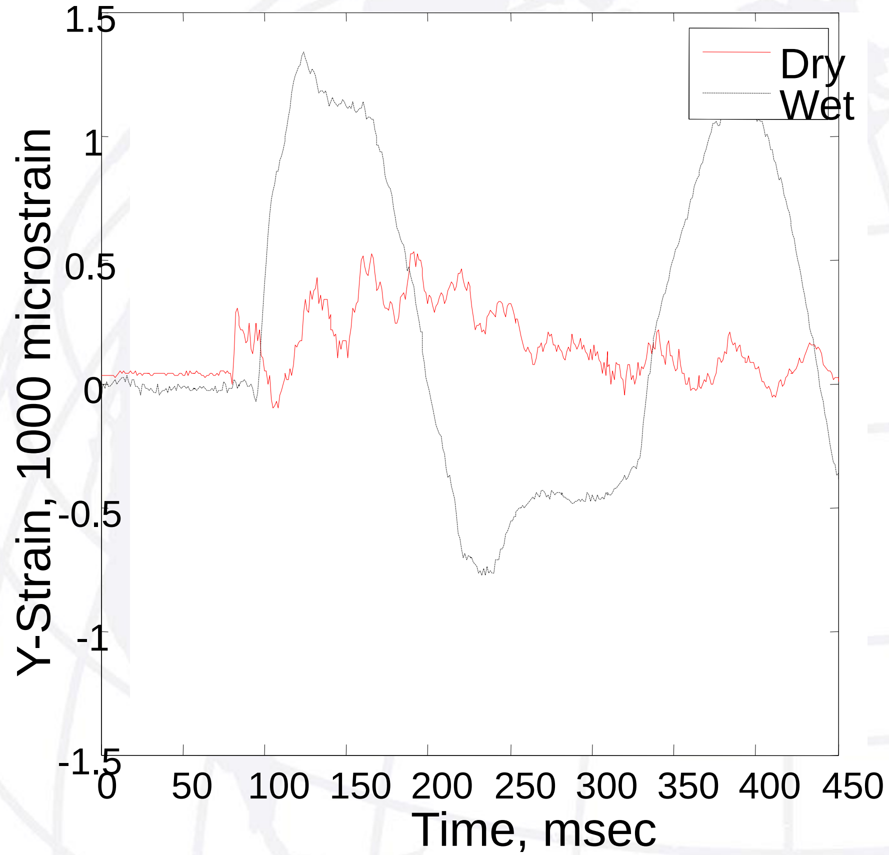
- Damage growth along with the drop height



Water-Backed Dry Impact

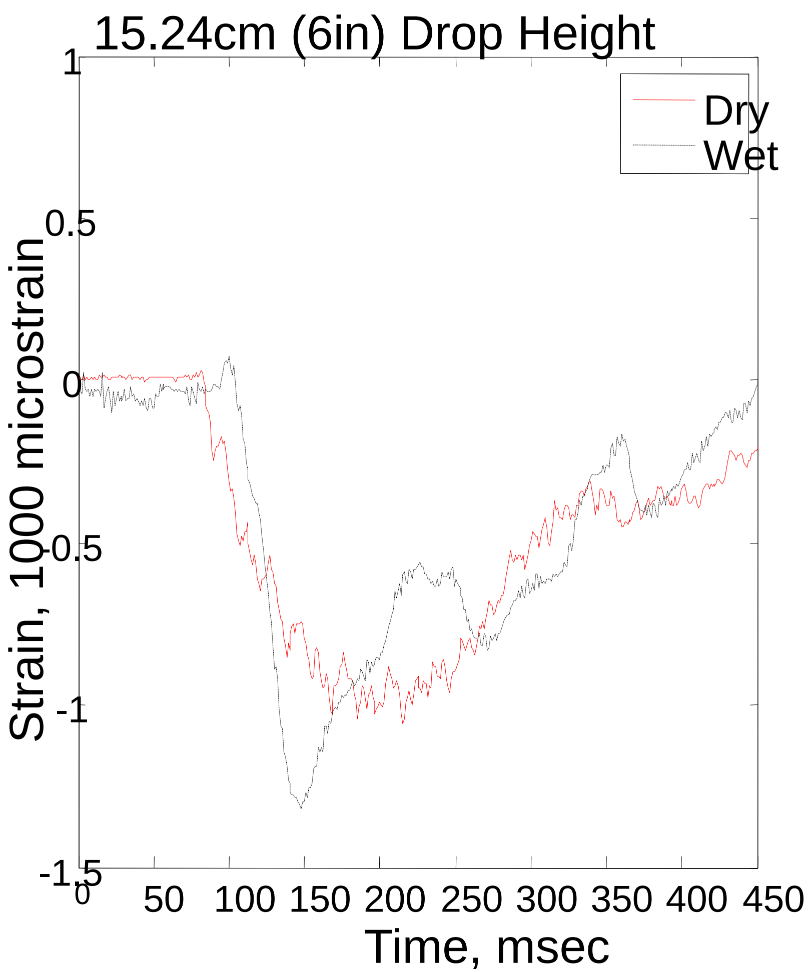
- Normal strains at gage #2 (no damage)

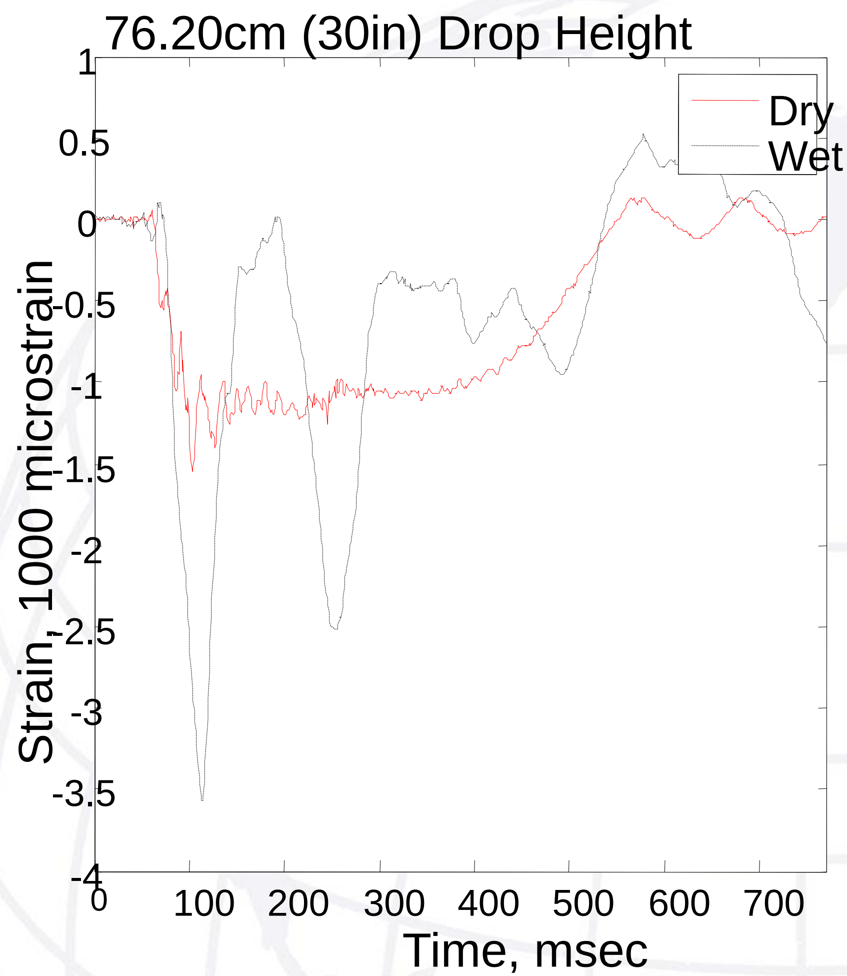




Water-Backed Dry Impact

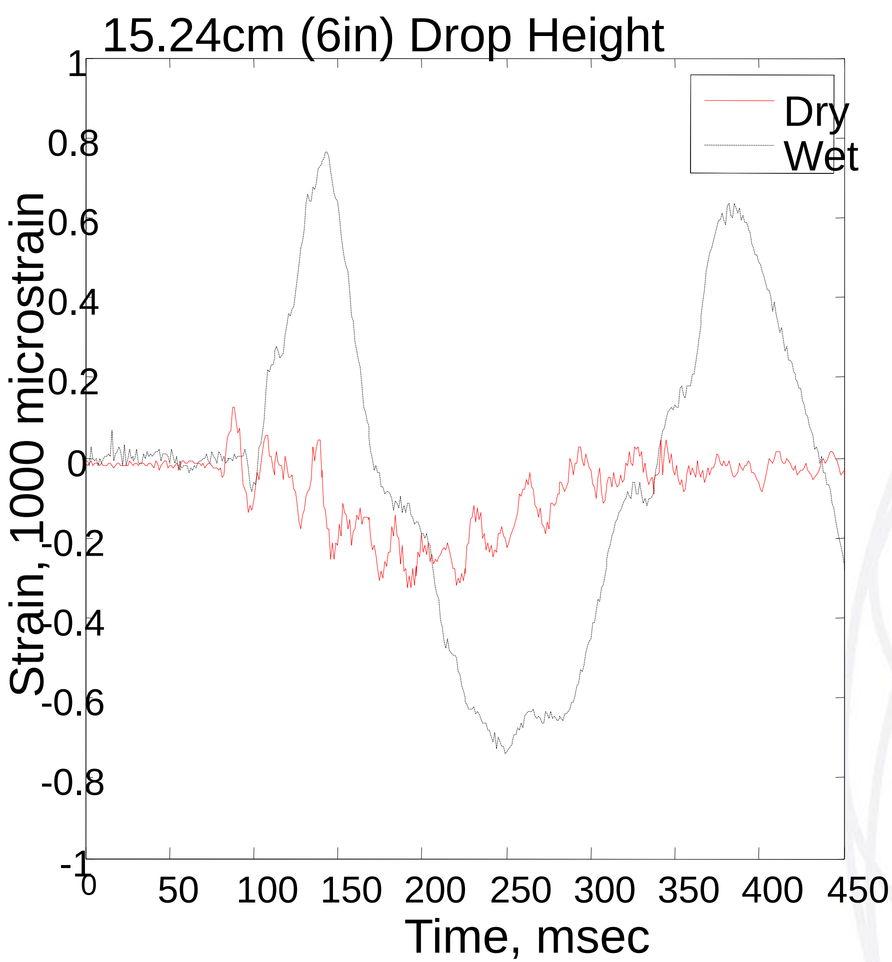
- Normal strains along x-axis at gage #2

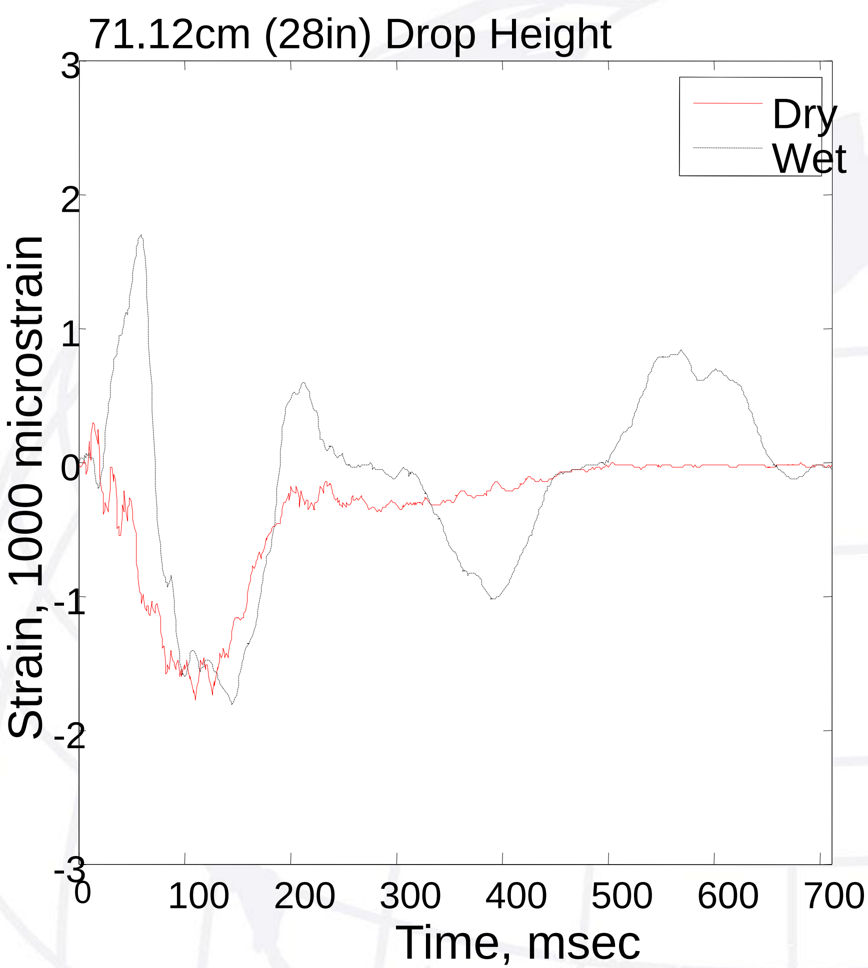




Water-Backed Dry Impact

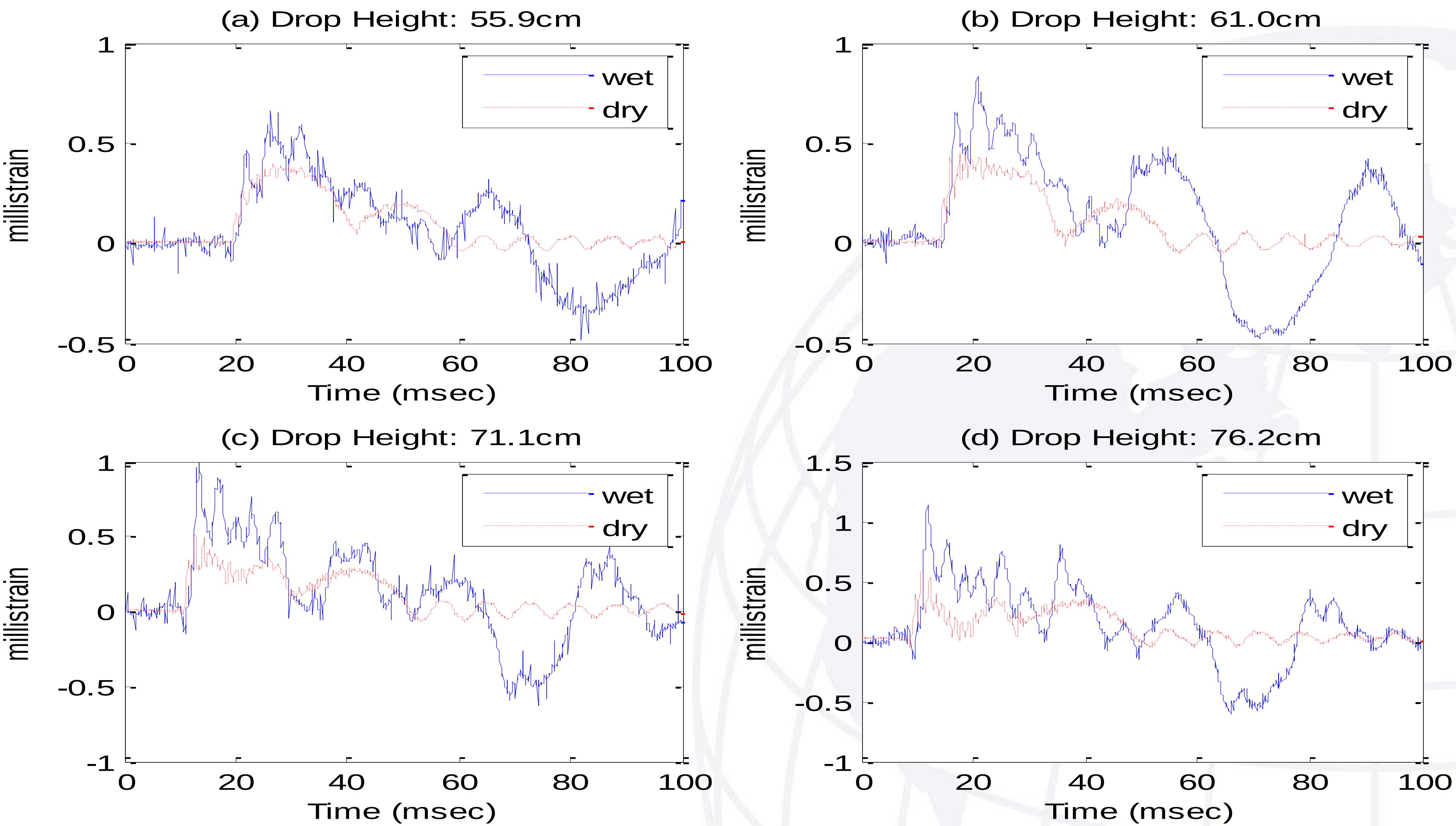
- Normal strains along x-axis at gage #3



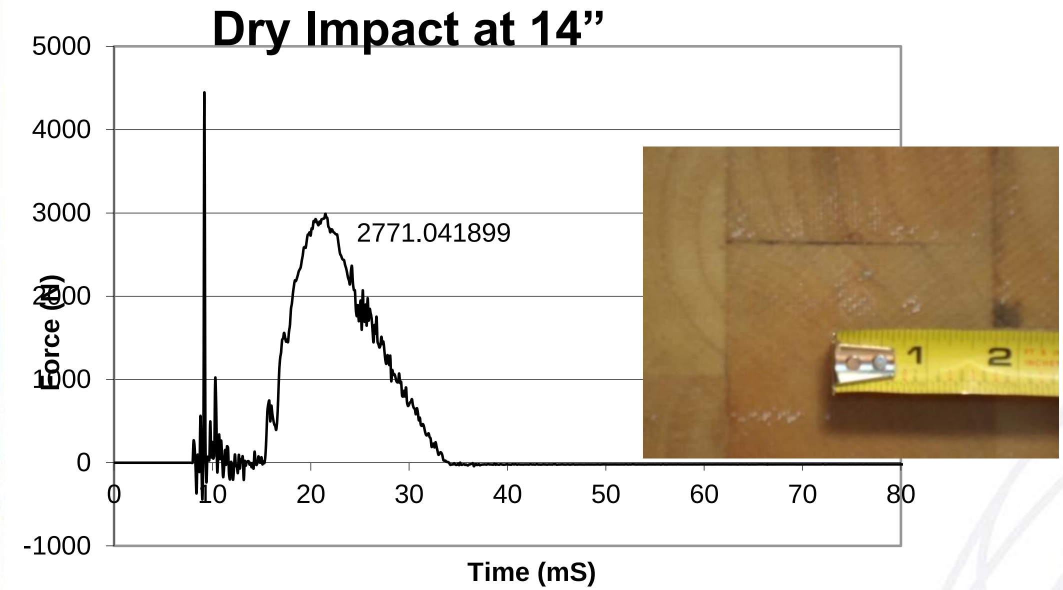


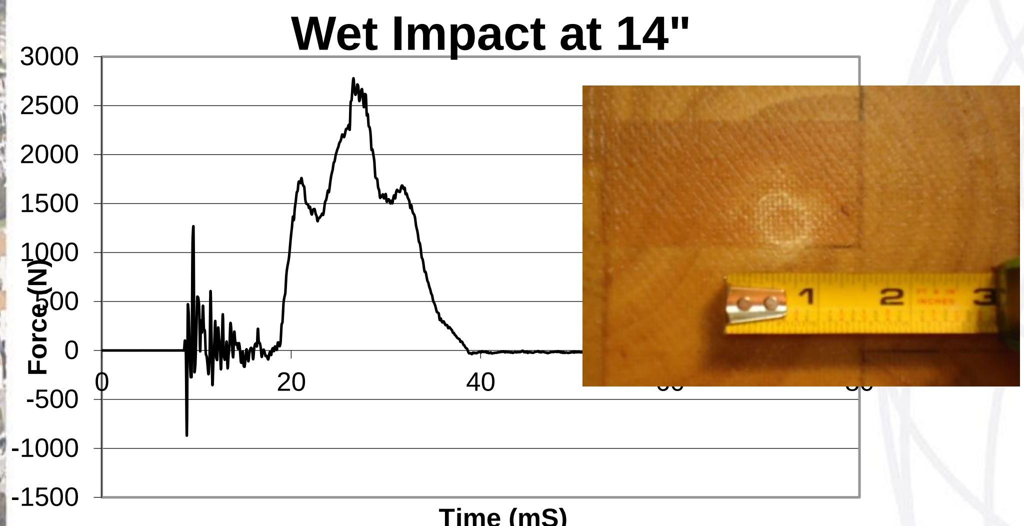
Water-backed Wet Impact

- Strain-y at gage #4 vs. drop height



Dry & Wet Impact on E-glass Plate





FSI Effect on Composite Plate

- Natural Frequency

		T (sec)	ωd (rad/sec)
Dry	**ε2x**	0.010	645.758
	ε1x	0.010	657.592
	ε2y	0.010	655.875
	ε1y	0.010	655.875
Water-backed wet	**ε2x**	0.034	187.463
	ε1x	0.033	189.442
	ε2y	0.033	189.442
	ε1y	0.033	189.157
Air backed wet	**ε2x**	0.026	241.660
	ε1x	0.026	242.471
	ε2y	0.026	242.004
	ε1y	0.025	247.244

17

FSI Effect on Composite Plate

- Added Virtual Mass Increment Factor β

$$\varpi_w = \frac{\varpi_d}{\sqrt{1+\beta}}$$

	Wet ωn (rad/sec)	Dry ωn (rad/sec)	β factor
Water-backed ε2x	173.3422	615.6221	11.61
ε1x	176.6594	661.6360	13.03
ε2y	179.1838	633.4428	11.50
ε1y	173.2472	614.7481	11.59
Air-backed ε3x	223.4895	615.6221	6.59
ε1x	238.2935	661.6360	6.71
ε2y	226.9937	633.4428	6.79
ε1y	226.8572	614.7481	6.34

E-glass Sandwich Composites

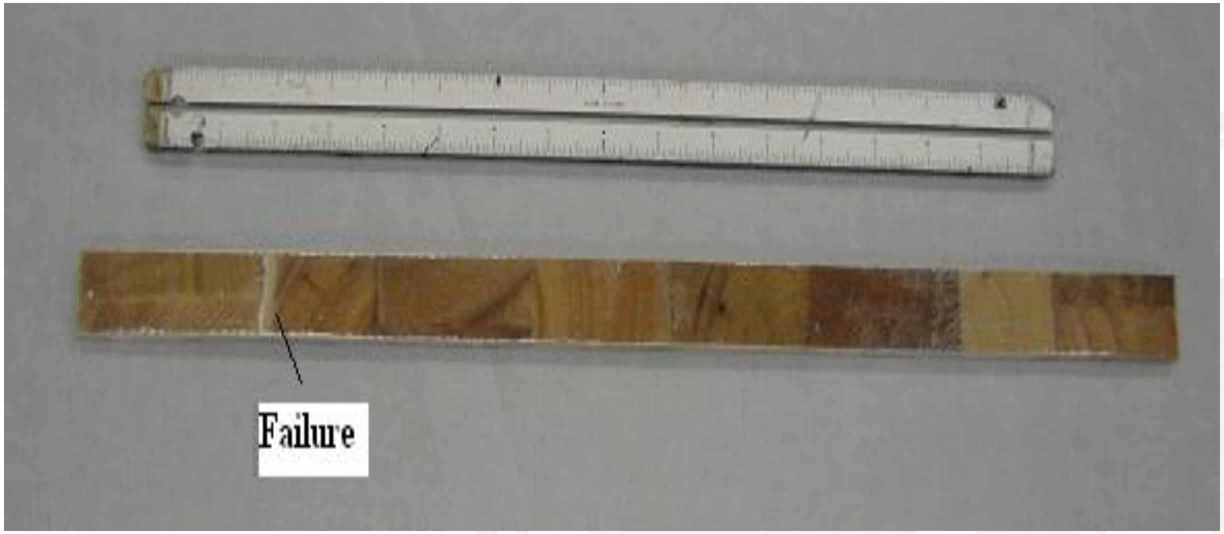
- ¼" Balsa core
- 2-3 plies 6 oz E-glass skin
- Derakane 530A vinyl ester resin
- 1" beams

Progressive Impact on E-glass Sandwich Beam

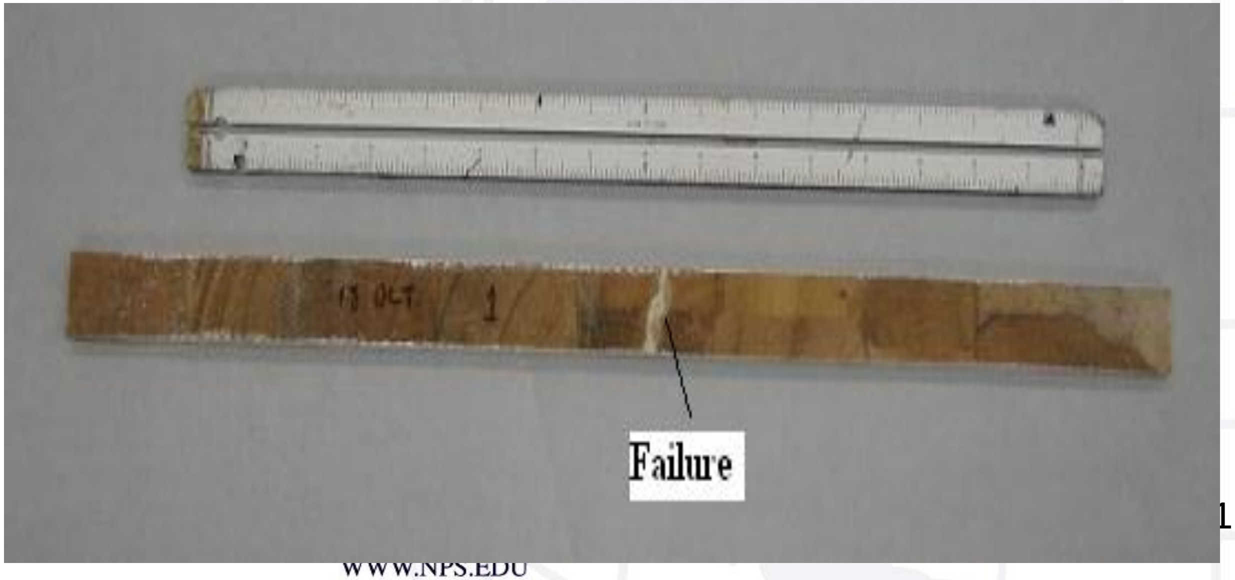
	Impact Test Specimen	Drop Height (mm)						Failure Site
		355.6	406.4	457.2	558.8	609.6	660.4	
Force (N)	Wet Test #1	805	869	885*	-	-	-	Mid-span
	Wet Test #2	916	1030	1090*	-	-	-	Mid-span
	Avg. Wet test	861	950	988				
	Dry Test #1	720	767	792	912	1032*		Boundary
	Dry Test #2	829	892	905	934	990	1010*	Boundary
	Avg. Dry Test	774	830	849	923	1011	1010	

Failure of Sandwich Beam

Dry Impact Failure

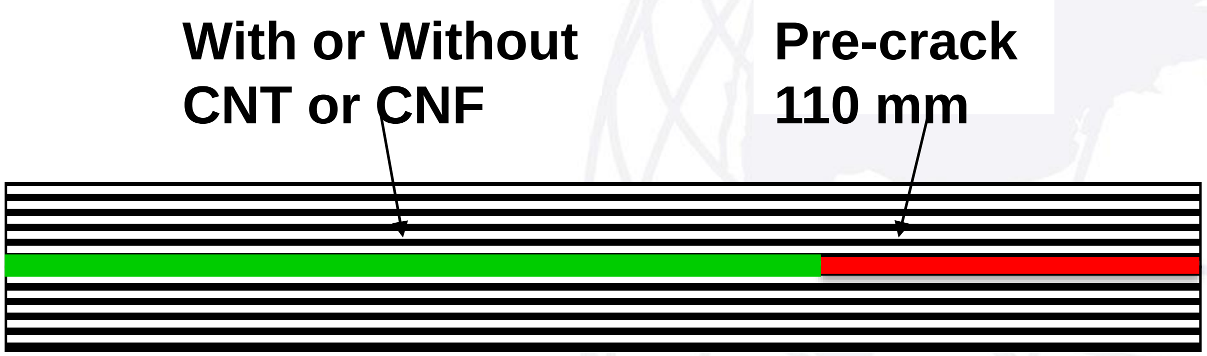


Wet Impact Failure



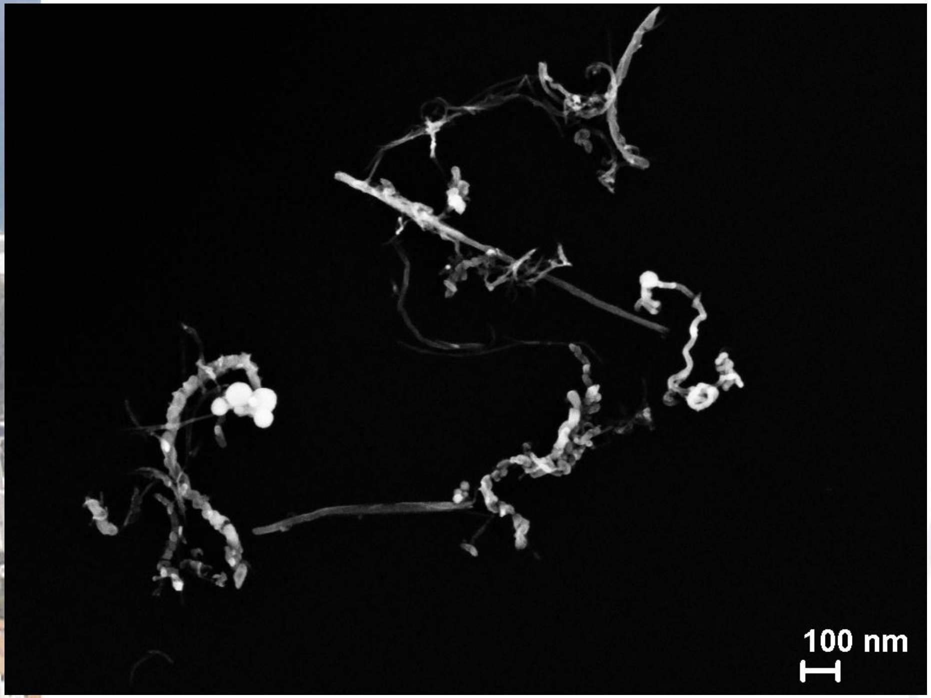
Carbon Fiber Composite Beam

- Pre-cracked beam, 300 mm x 25 mm
- Clamped at both ends
- Impact to the top center
- Strain gage attached to the bottom center

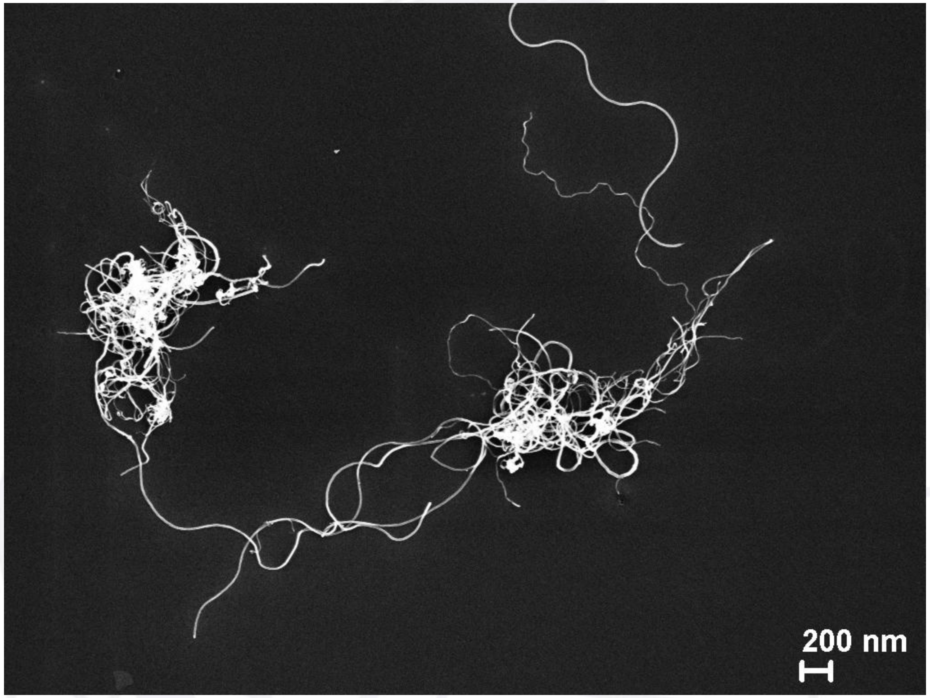


Pristine and Functionalized CNTs

- **SEM showing comparison**



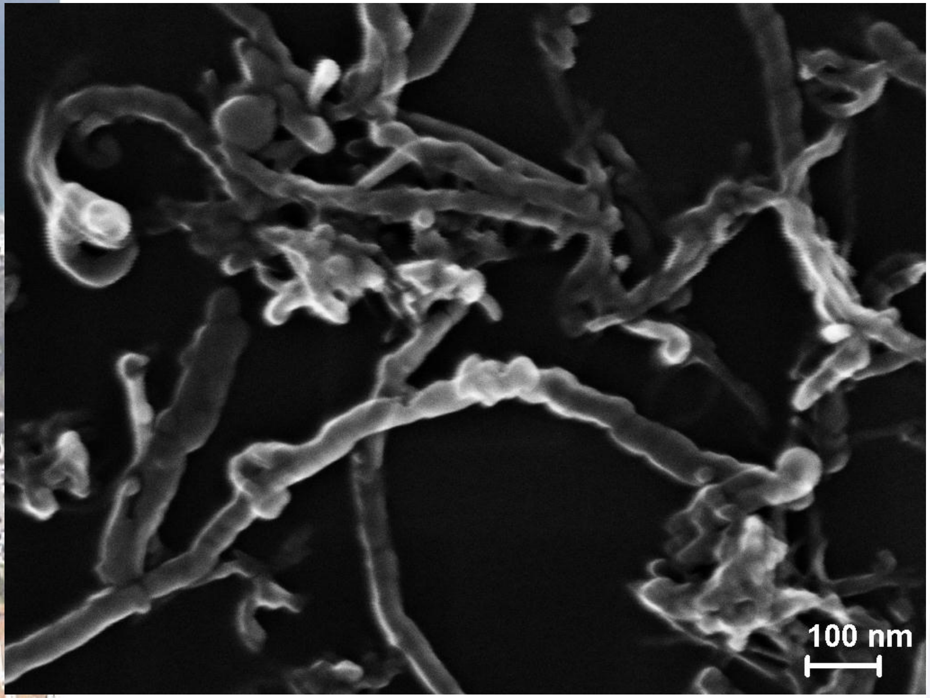
Functionalized MWNT



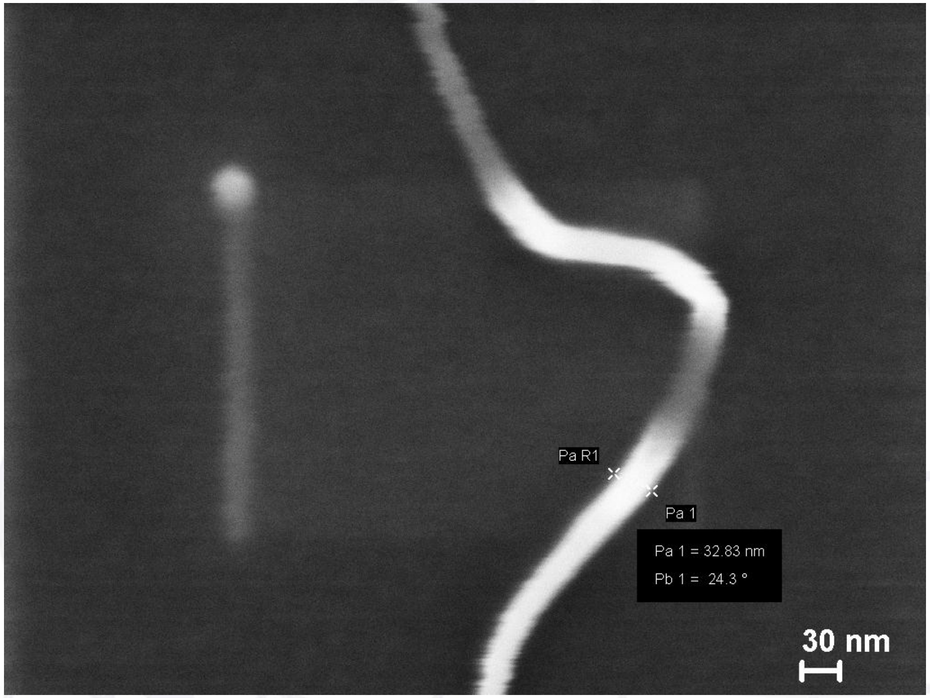
Pristine CNT

Pristine and Functionalized CNT

- **SEM showing comparison**



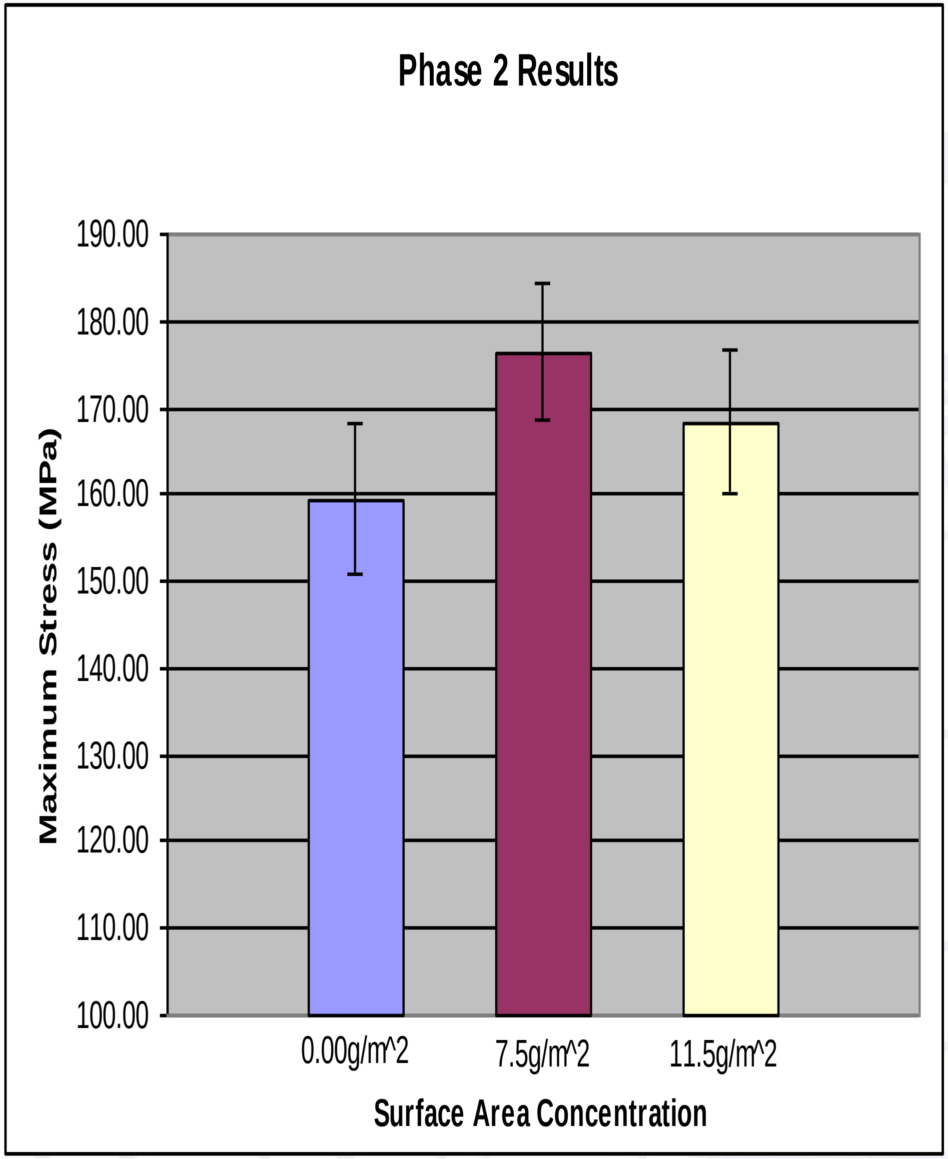
Functionalized MWNT



Pristine CNT

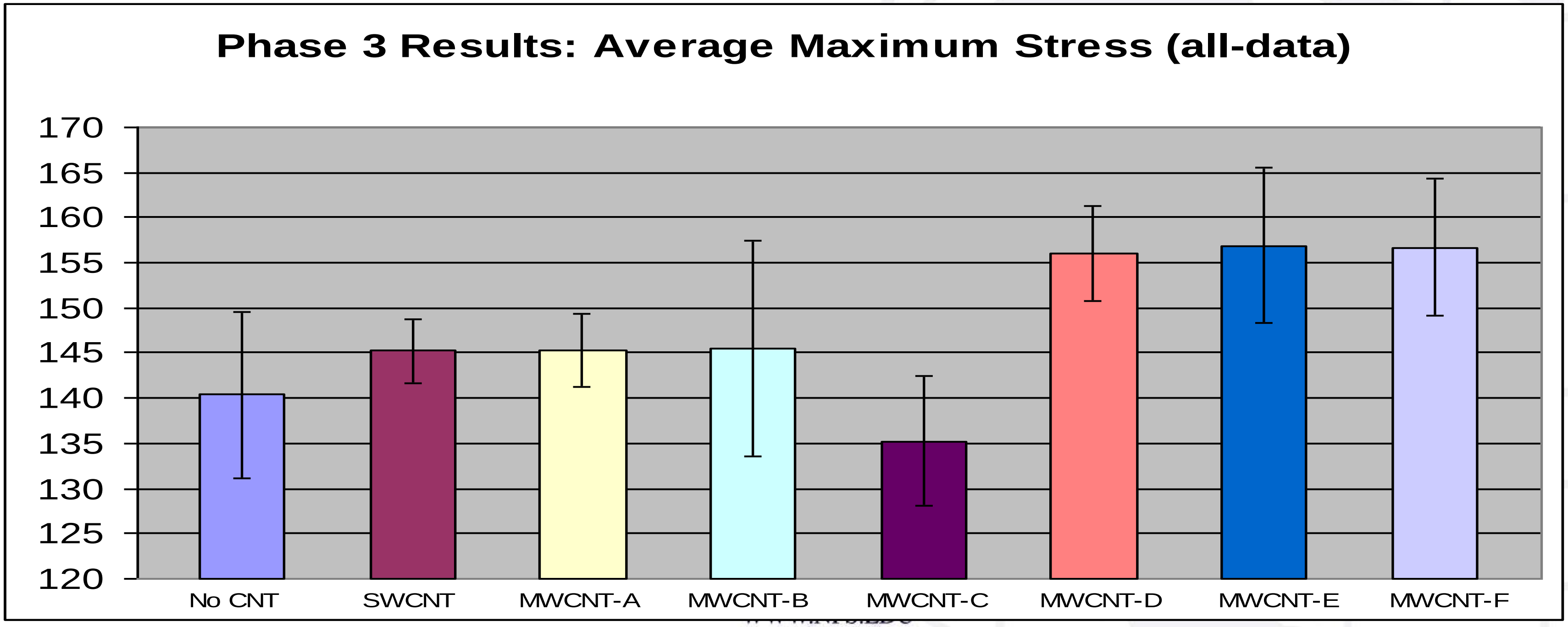
Interface Strength with CNT

- Comparison of two concentrations of CNT
  - 7.5g/m^2 and the 11.5g/m^2 resulted in strength increase over the non-reinforced composite joints
  - 7.5g/m^2 provided the greatest strength increase (10.6%)
  - Standard deviation shows no overlap between the results of the non-reinforced and 7.5g/m^2 concentration level

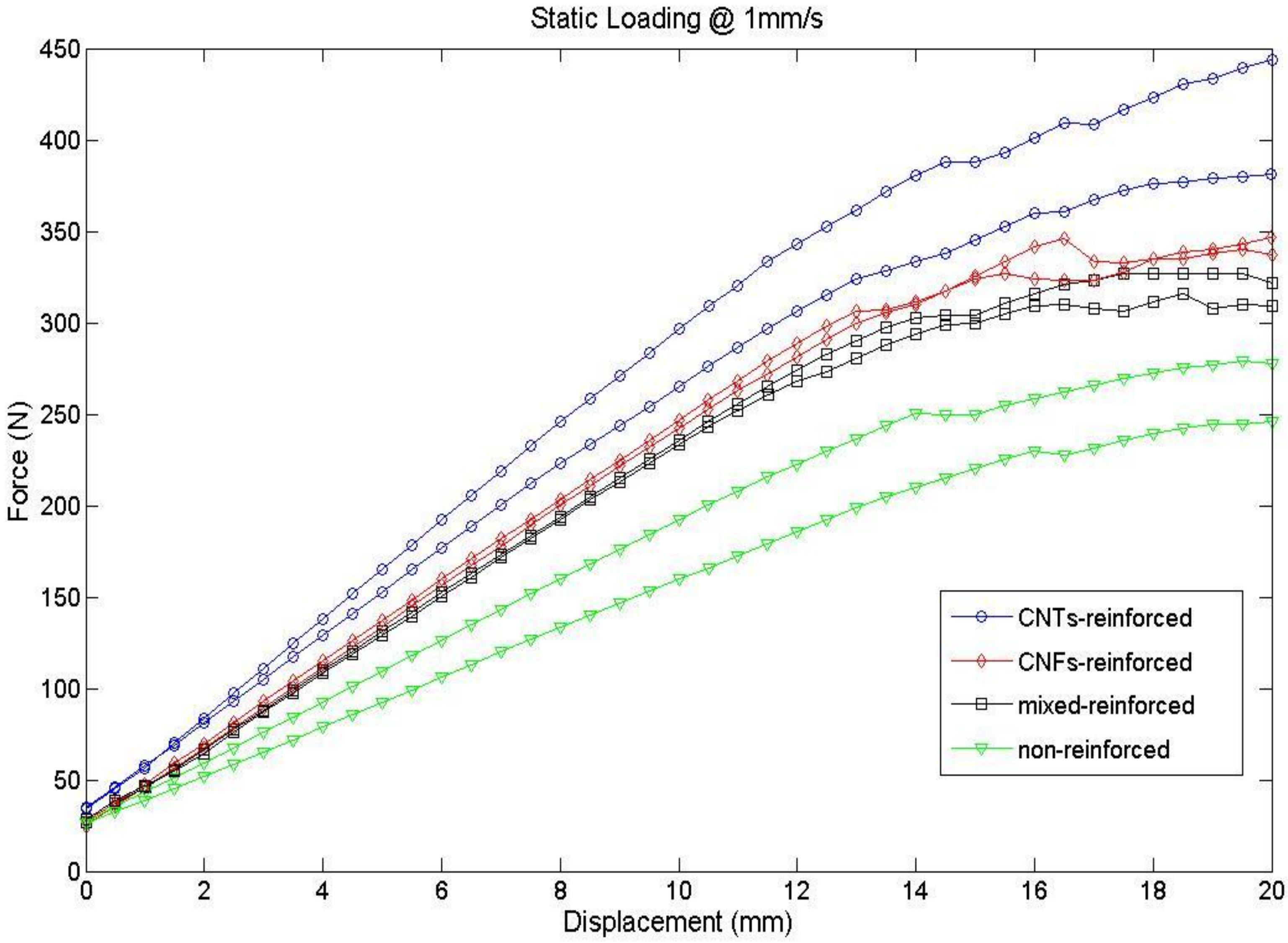


Interface Strength with CNT

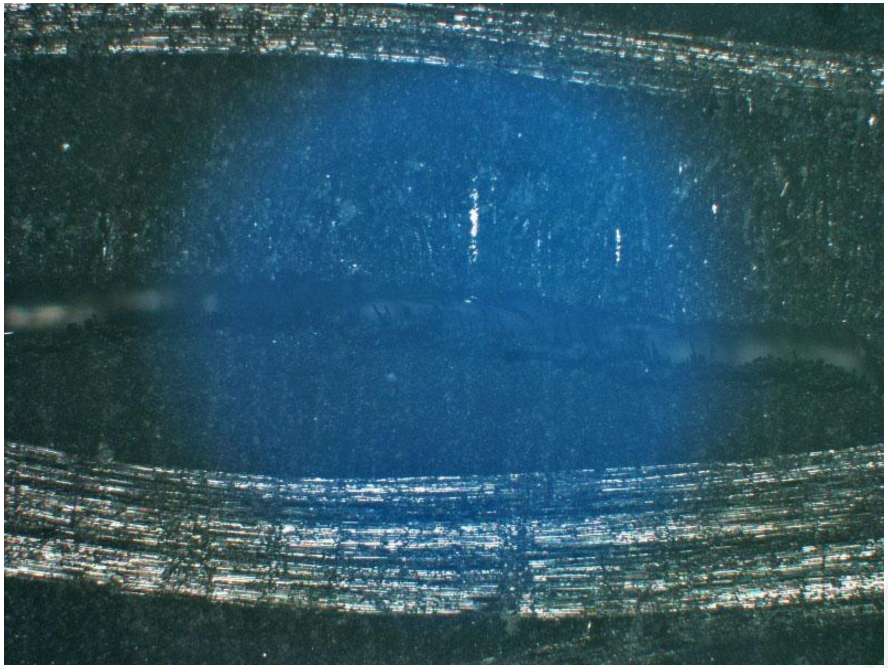
- Failure Stress
  - All five trials were used for stress data analysis
  - 3 types of MWCNT provided a strength increase greater than 11%
  - Best based on strength increase and smallest standard deviation.
    - D = 30 +/-15nm, L = 5-20 microns, Purity > 95%



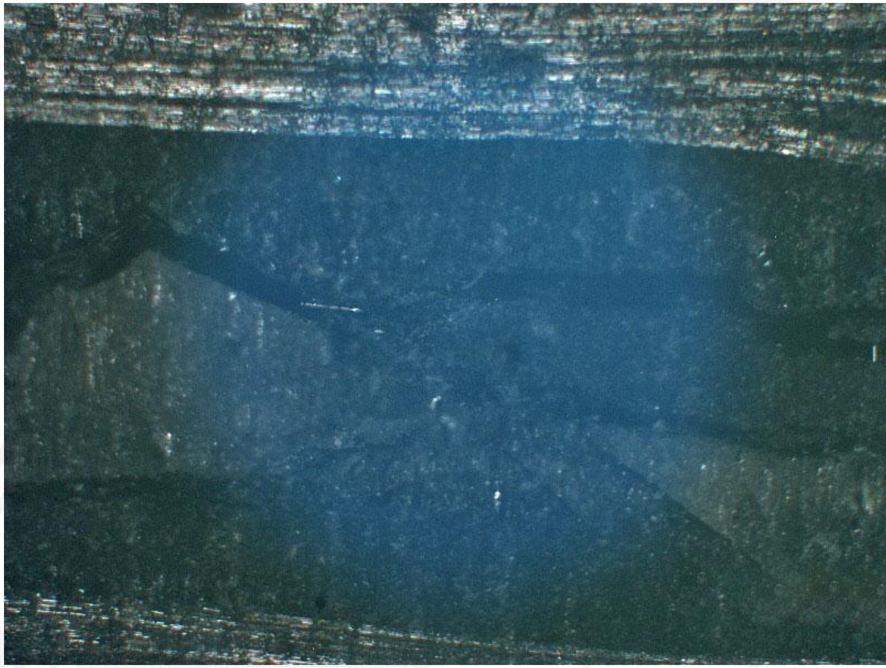
Static Three-Point Bending Load



Interface Cracks under Dry Impact

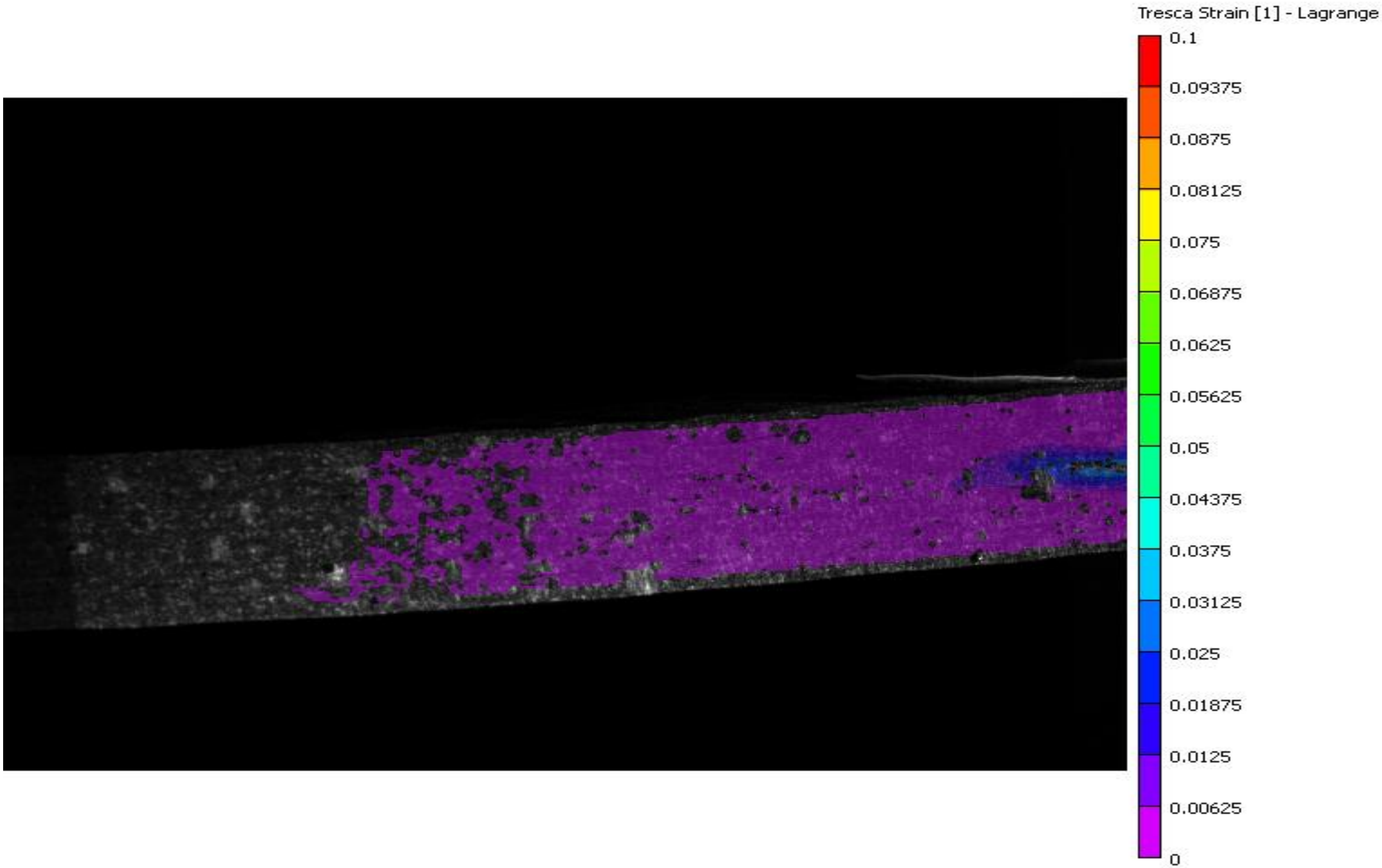


Without CNT

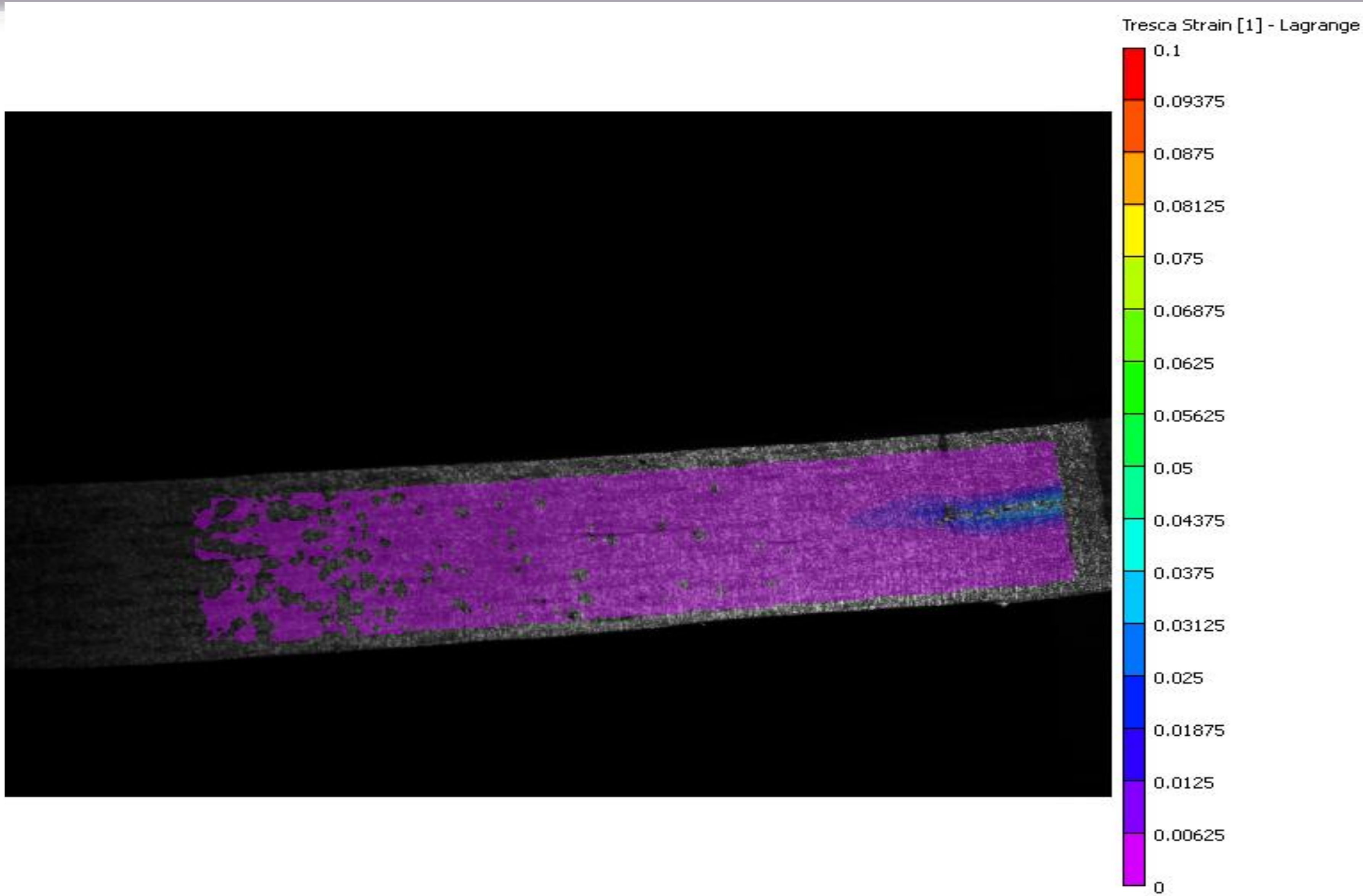


With CNT

Interface Crack Growth w/o CNT

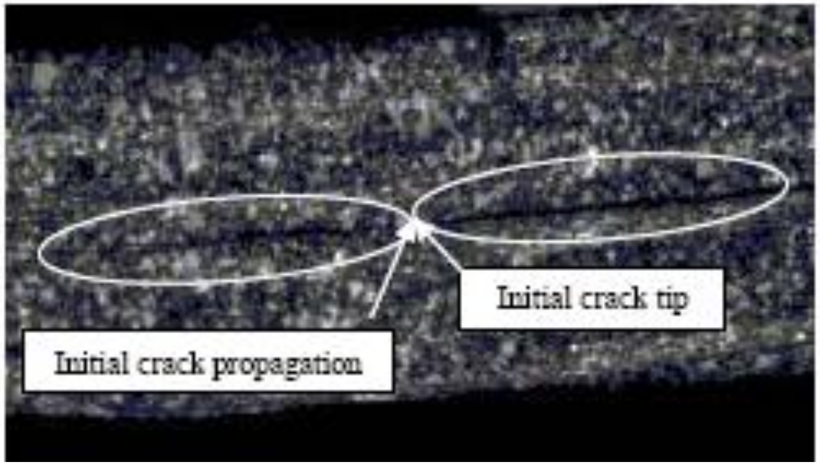


Interface Crack Growth w/ CNT



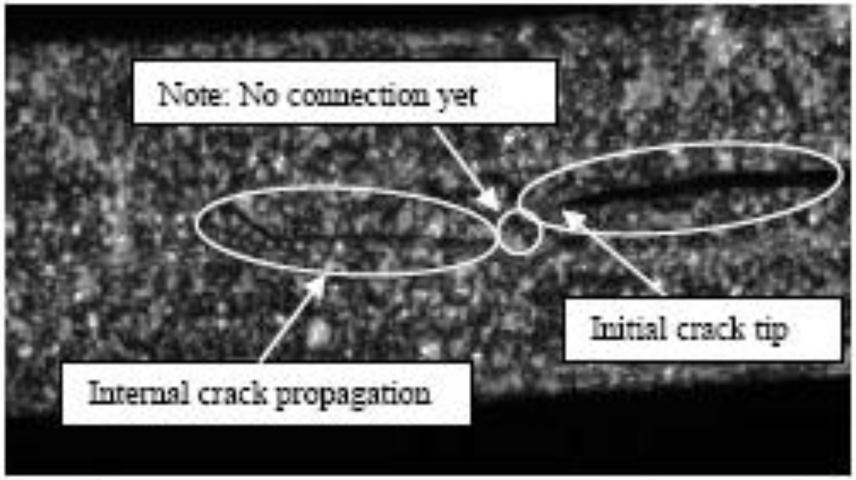
Mode II Crack Propagation

- Non-reinforced



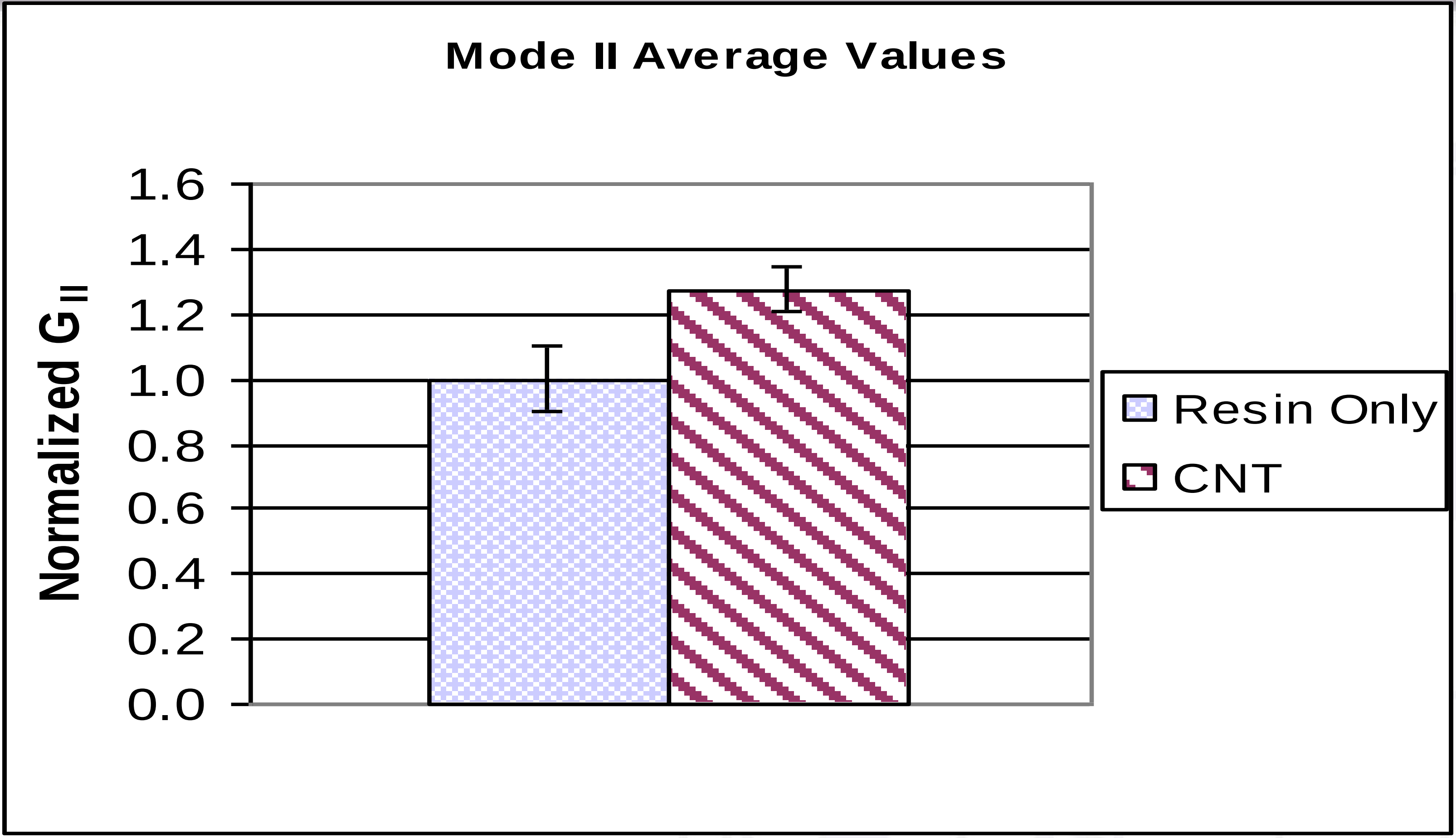
Crack grows from initial crack tip

- CNT reinforced



Crack begins away from initial crack site and connects to initial crack

Mode II Results

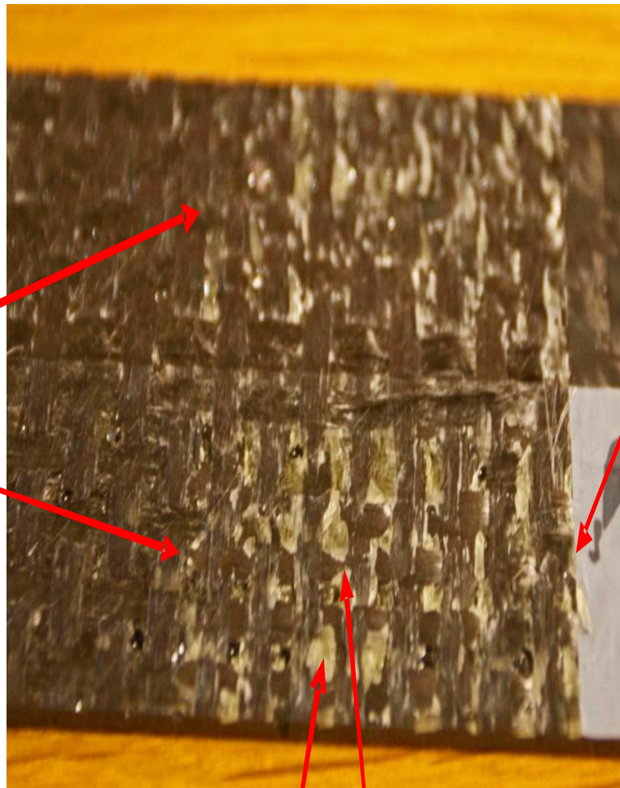


- CNT reinforcement results in 30.5% increase in Mode II critical energy release rate (calculated via compliance method)

Dry Beam with and without CNT

- w/o CNT   w/ CNT

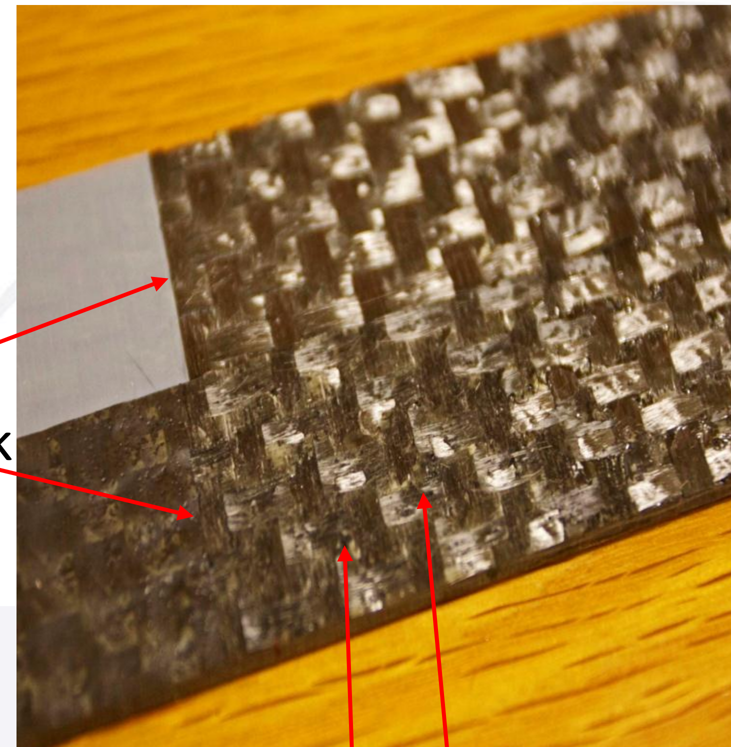
end of crack



Pre- Crack

Broken resin

Pre- crack



Broken carbon fibers

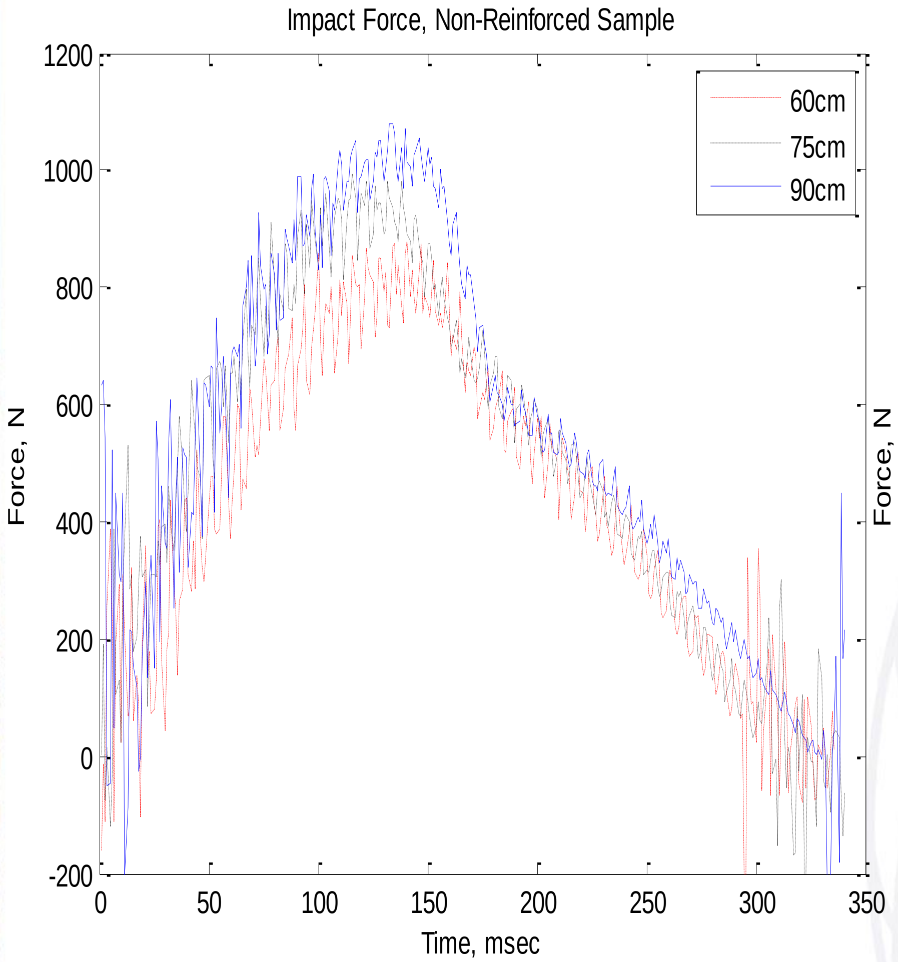
Failure under Dry Impact

- CNTs-reinforced failed at higher impact energy
- No significant improvement for CNFs-reinforced samples over non-reinforced samples
- Failure defined as crack growth to the center of the beam

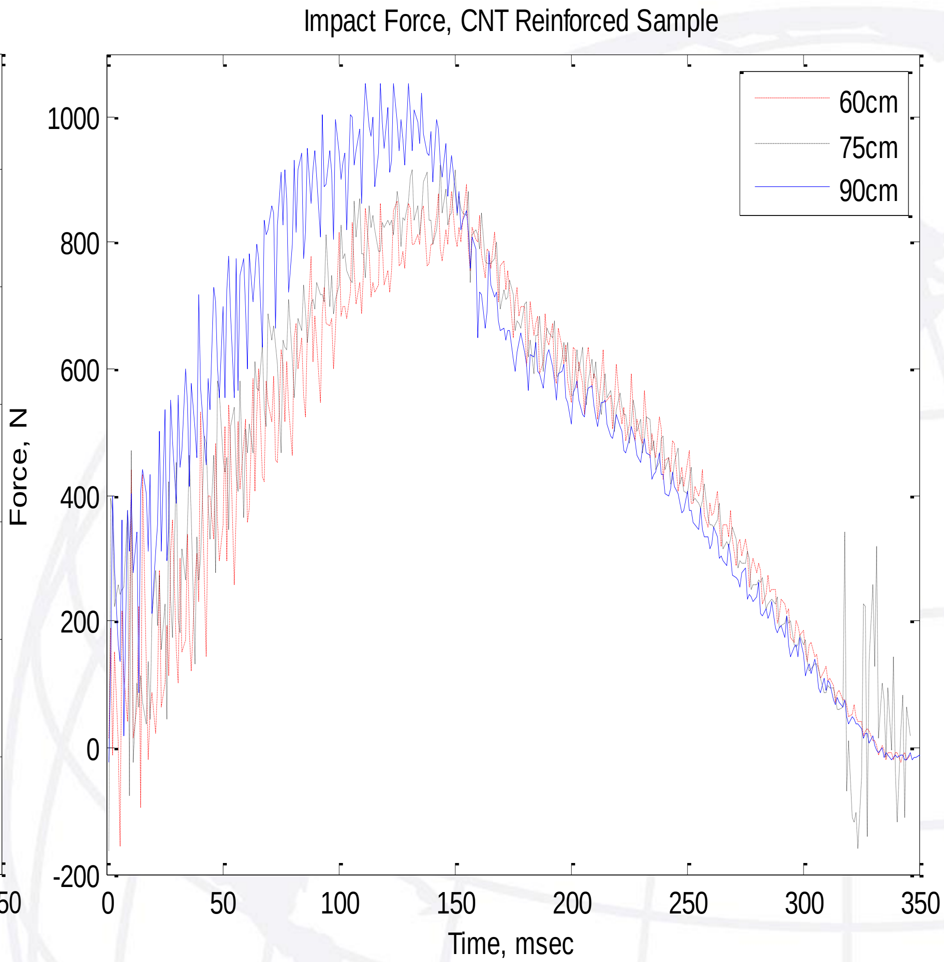
	90cm height
CNTs-reinforced	9.5mm (no failure at this impact height)
CNFs-reinforced	66% failure, 10mm for non-failure samples
Non-reinforced	66% failure, 12mm for non-failure samples

Water-backed air impact on beams

Impact force w/o CNT

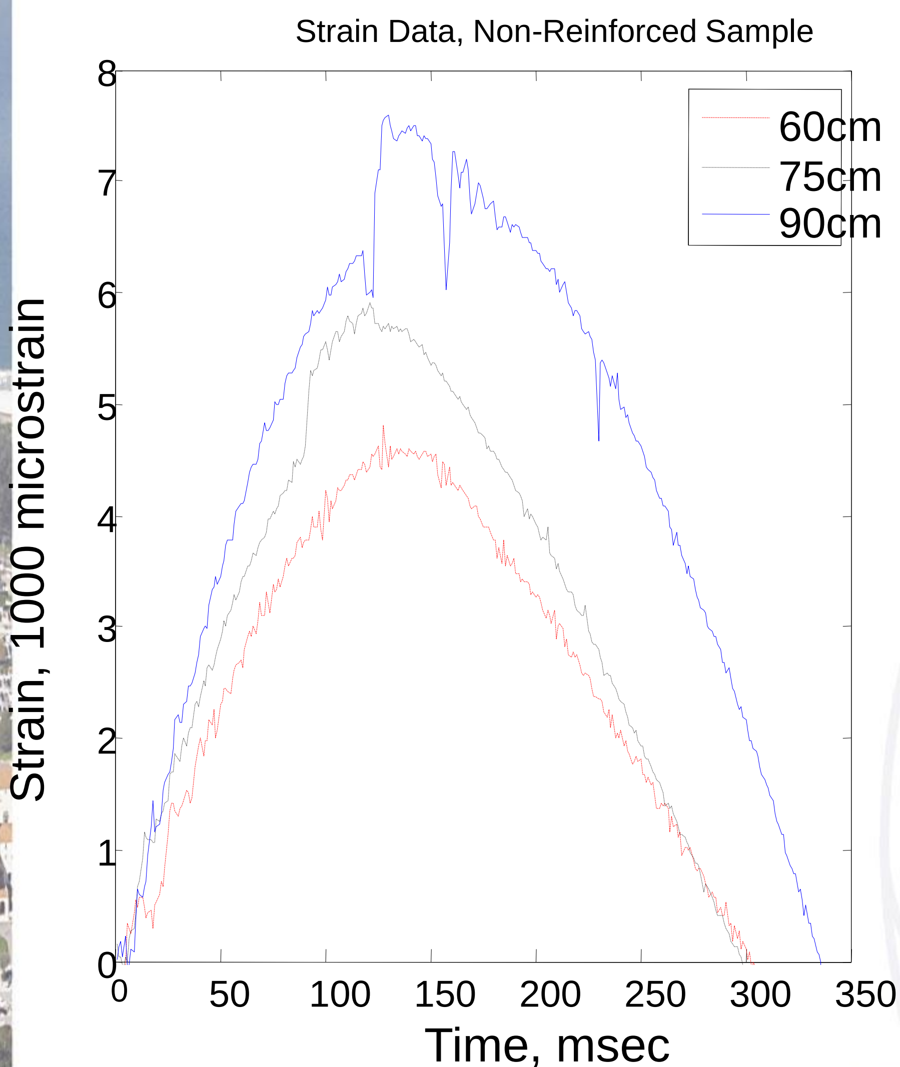


Impact force w/ CNT

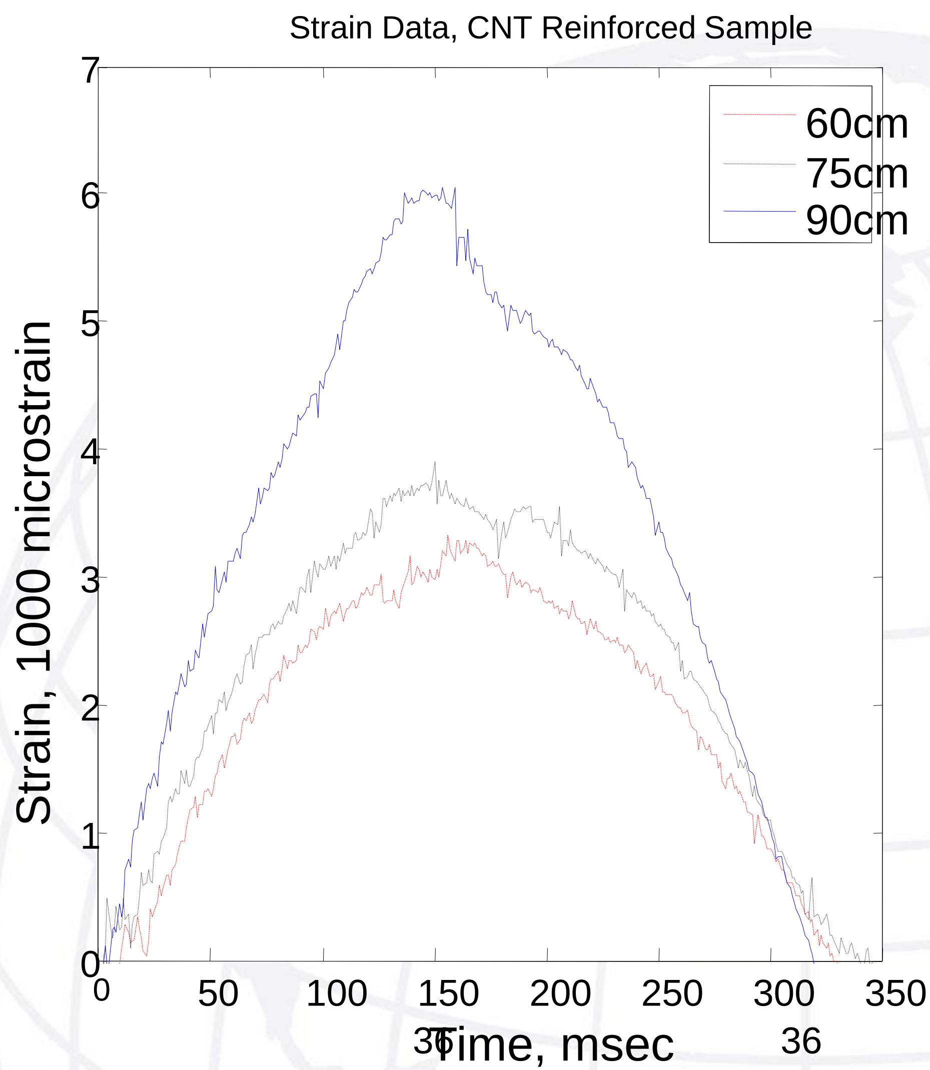


Water-backed air impact on beams

Strain w/o CNT

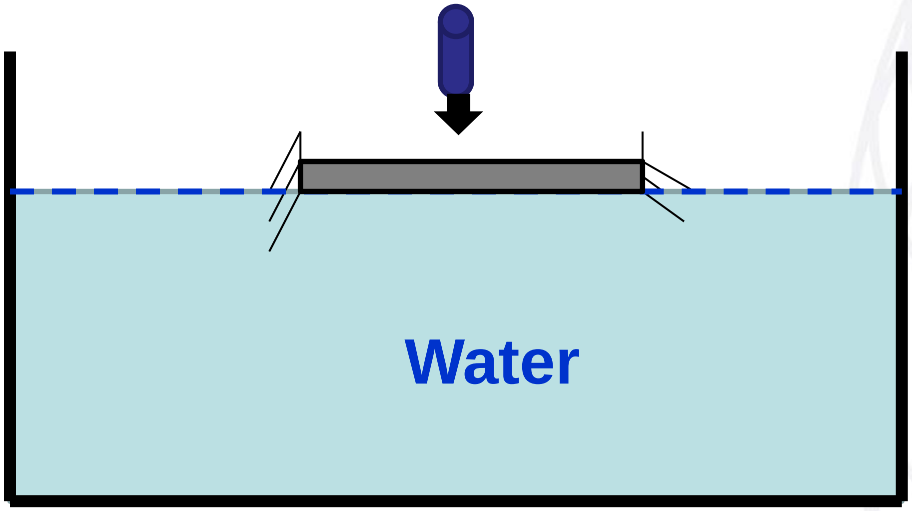


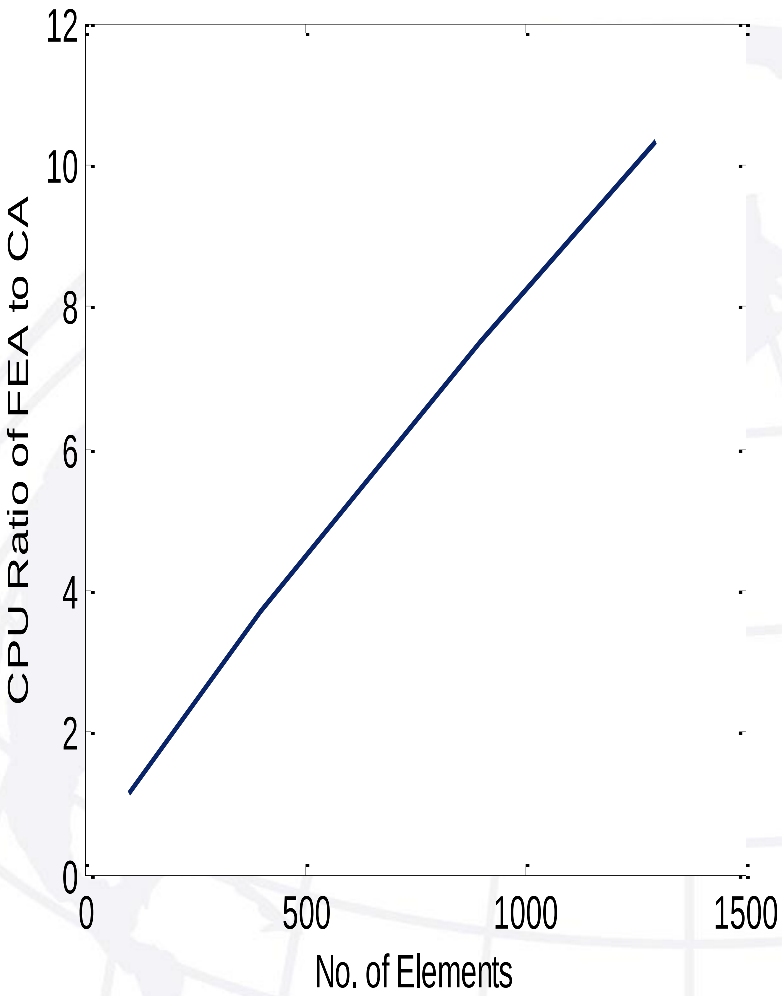
Strain w/ CNT



Computational Model

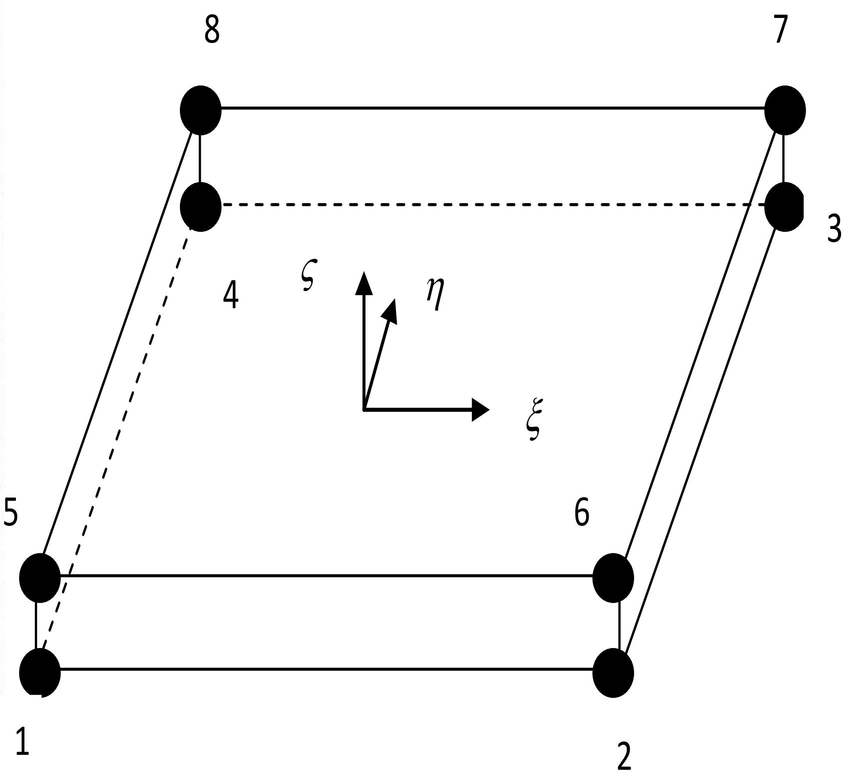
- Developed 2-D and 3-D models
- Structure: CG- or DG-FEM
- Fluid: FEM, LBM, CA
- Fluid-Structure Interaction
- Fluid analysis is the major computational cost.

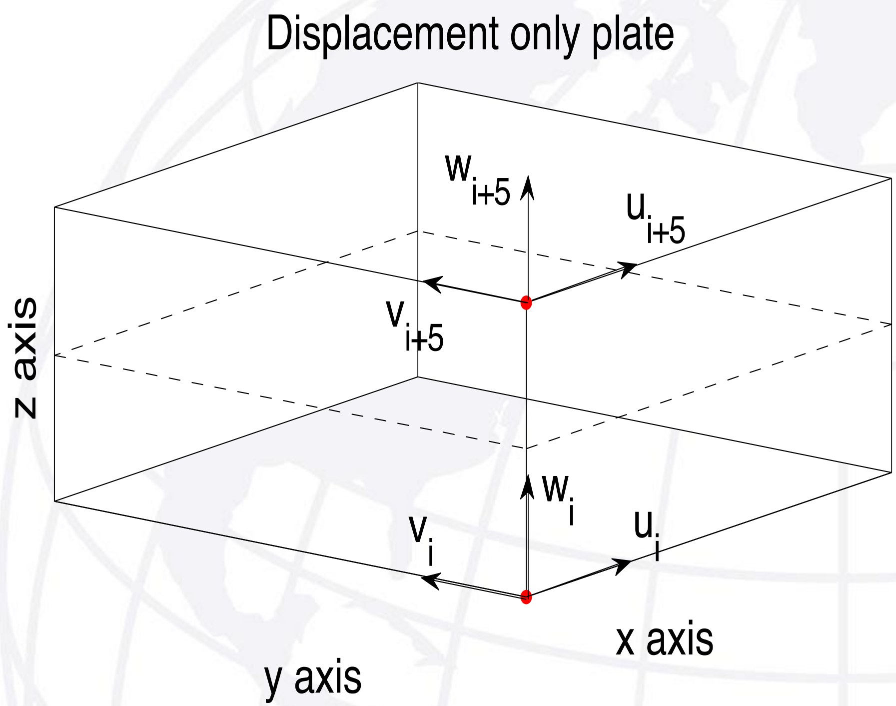




Solid-like Shell Element

- Shell element with displacement DOFs and no rotational DOFs
- Easy to model multiple layers through thickness

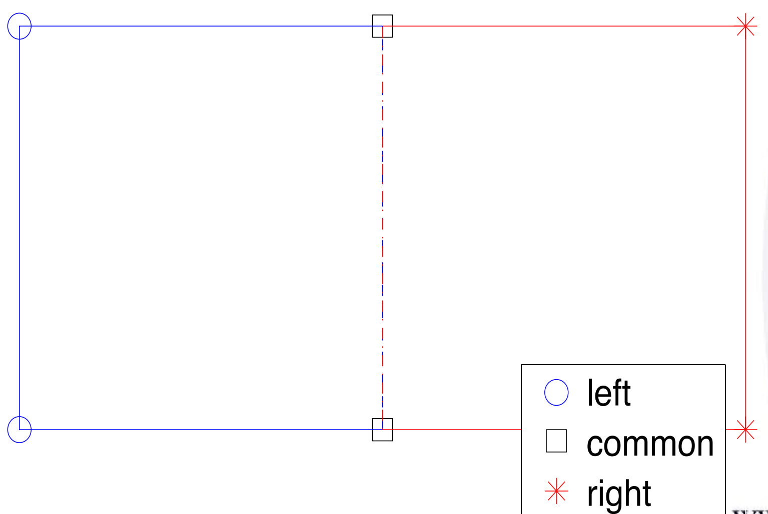




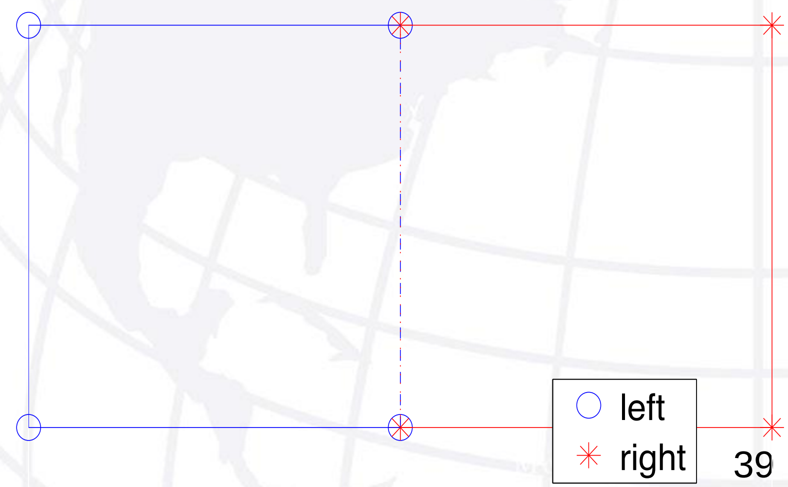
CG & DG Formulations

- Continuous Galerkin (CG) as well as Discontinuous Galerkin (DG) formulations were used.
- DG is useful to model failure along element interface such as delamination.

Continuous Element Connectivity



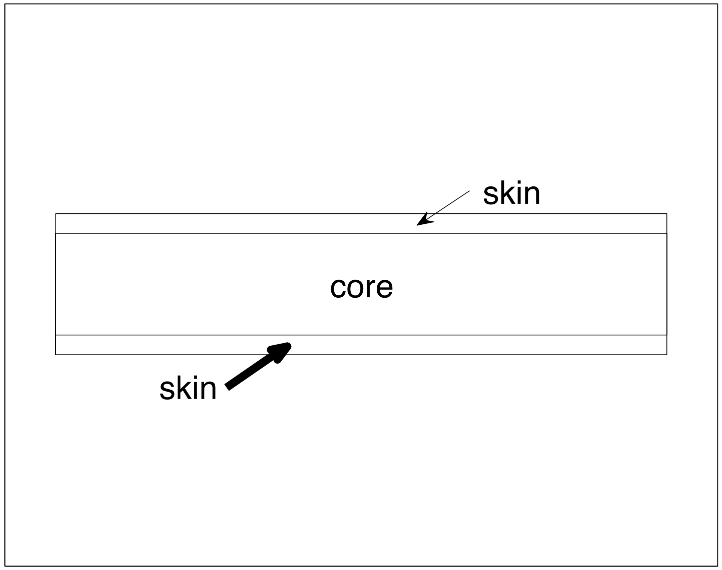
Discontinuous Element Connectivity



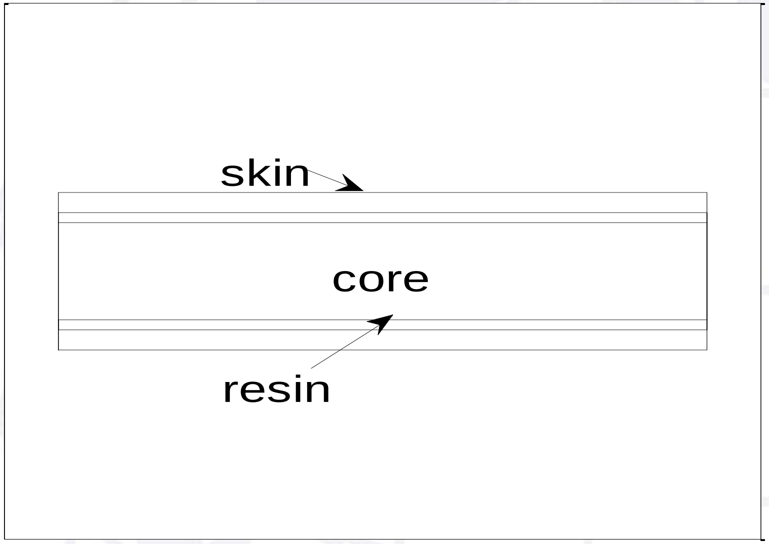
CG & DG Formulations

- Effect of resin layers in numerical modeling

Three layer plate model



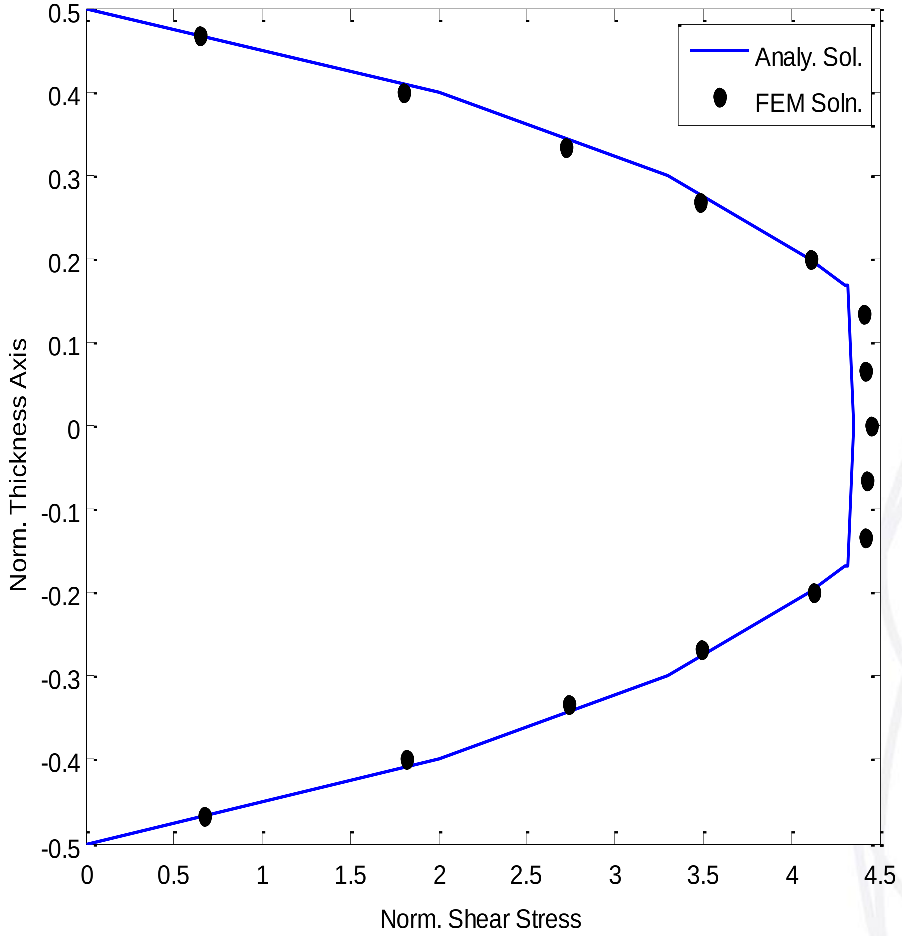
Five layer plate model



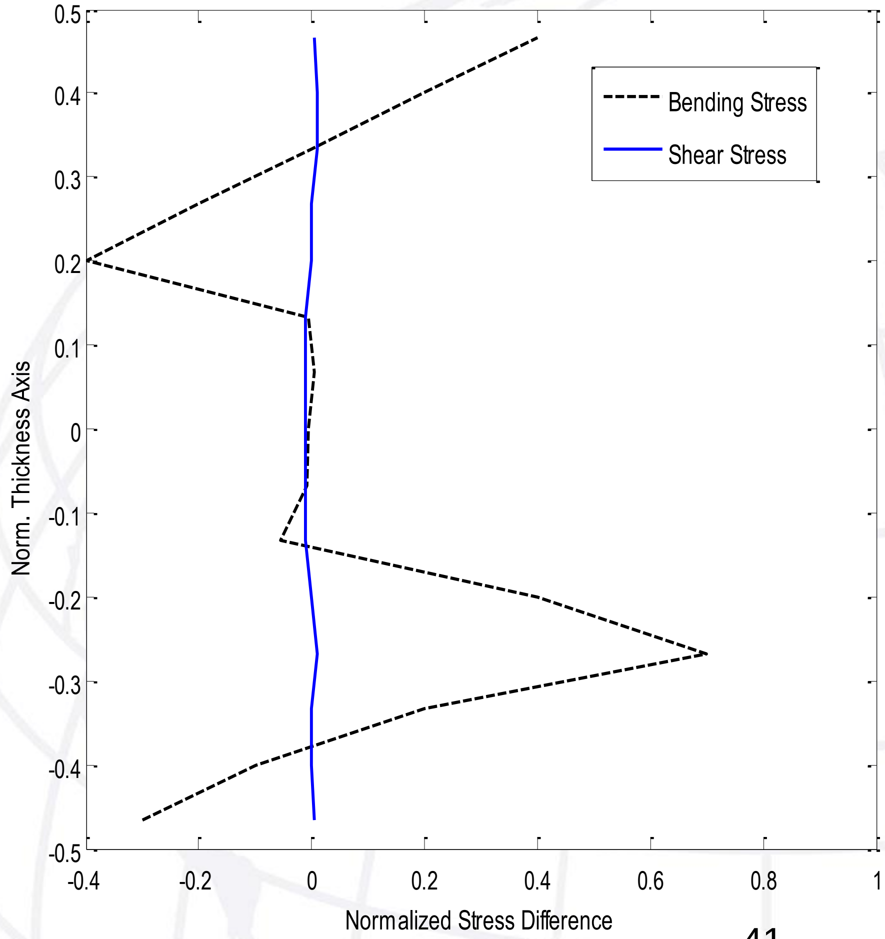
Static Bending of Laminated Plate

- 0/90/0 layers

Transv. Shear Stress

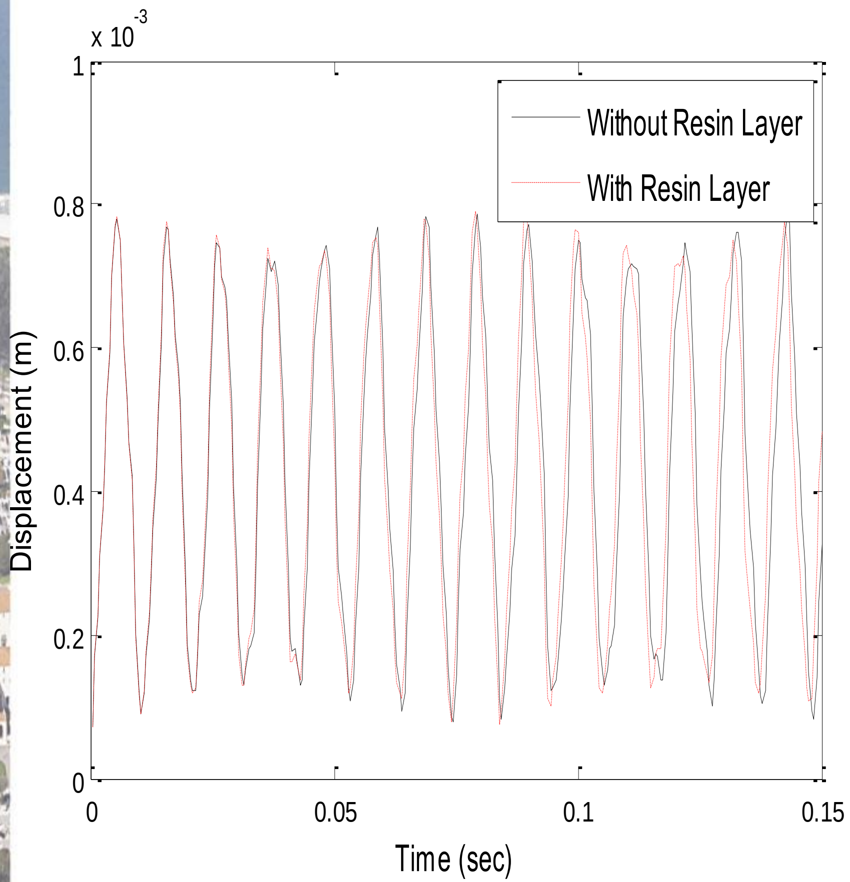


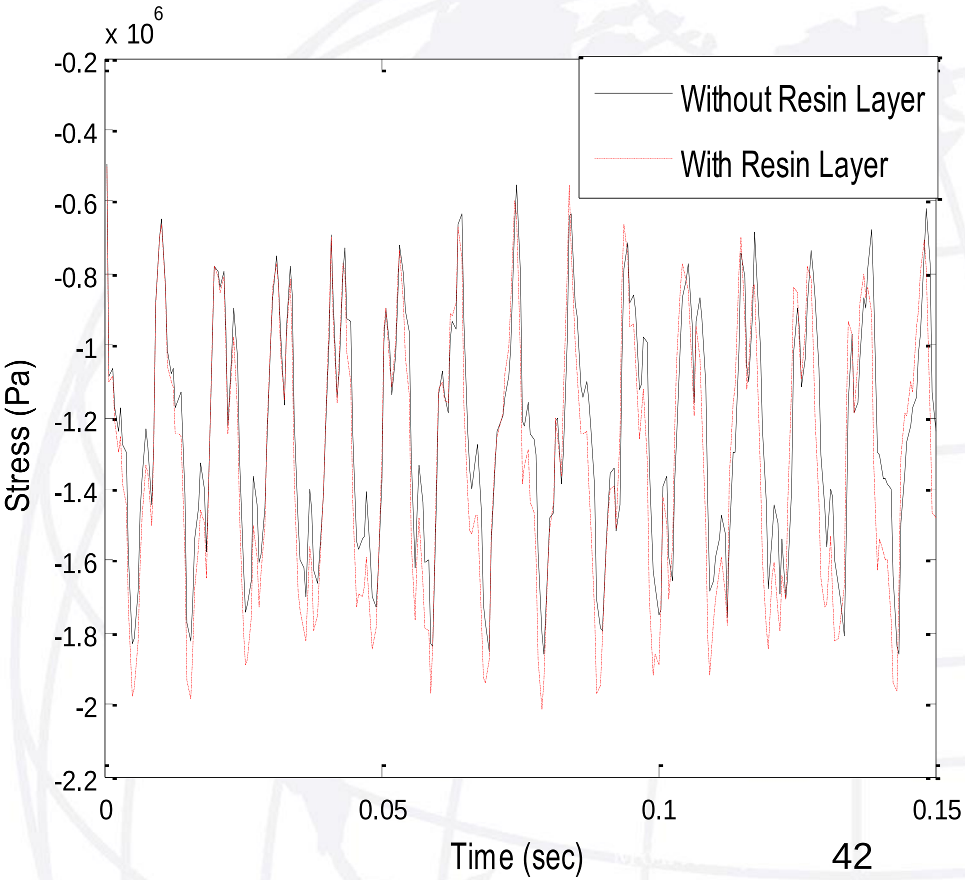
Diff. of w/ & w/o resin layer



Dynamics of Sandwich Plate

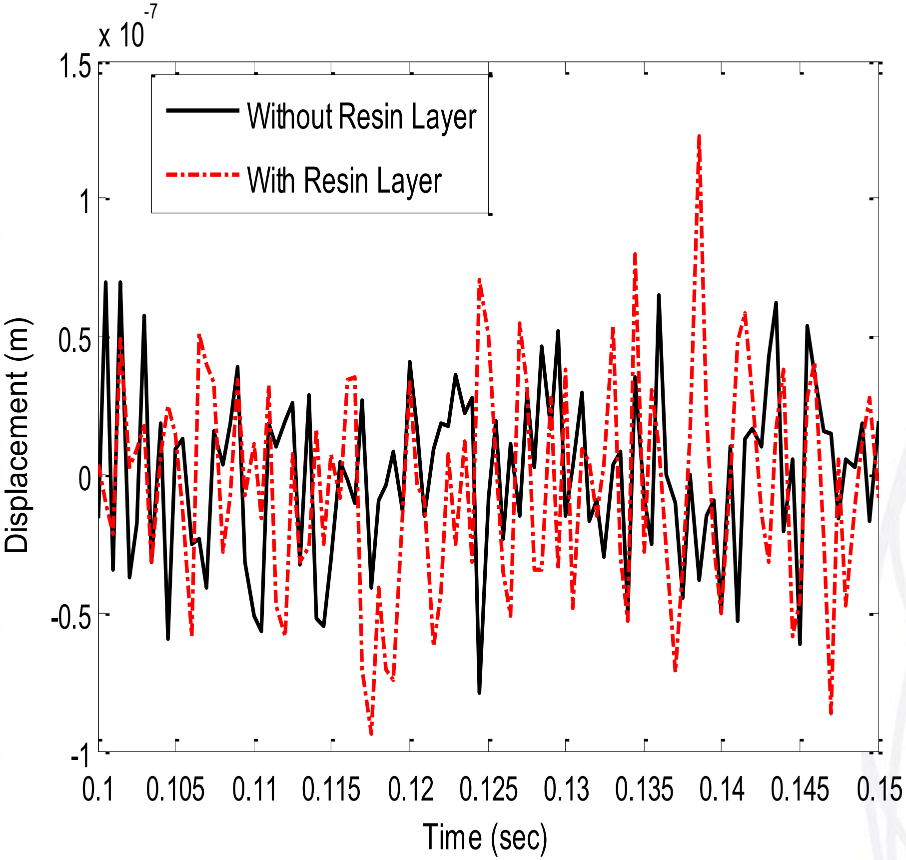
- Comparison between with and without resin layers

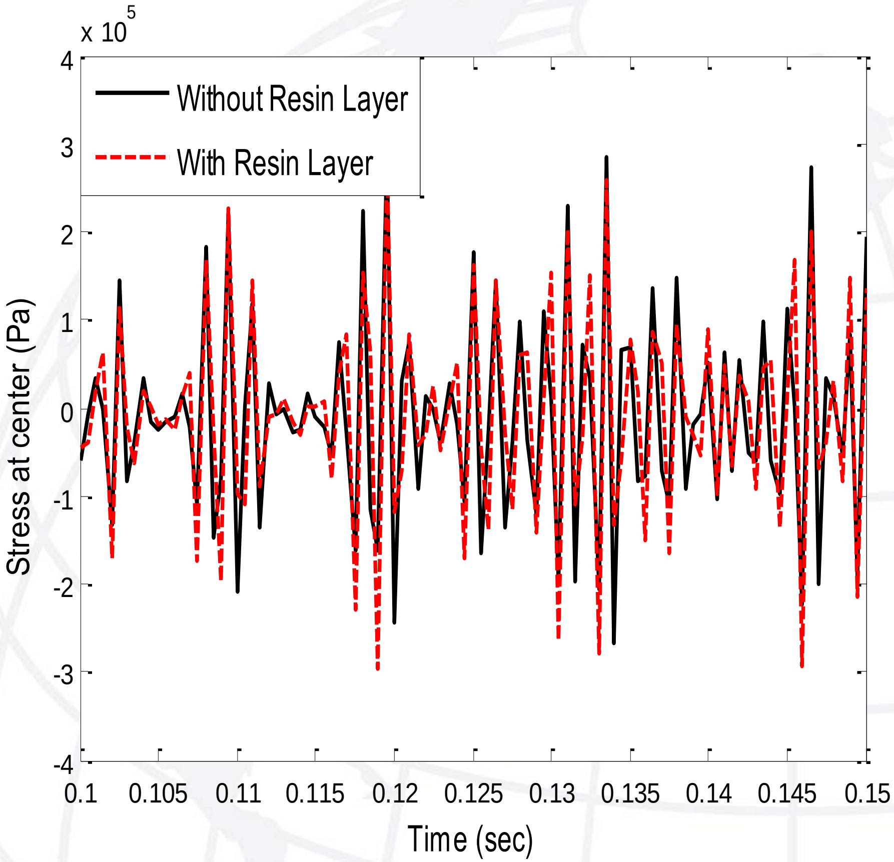




Dynamics of Sandwich Cylinder

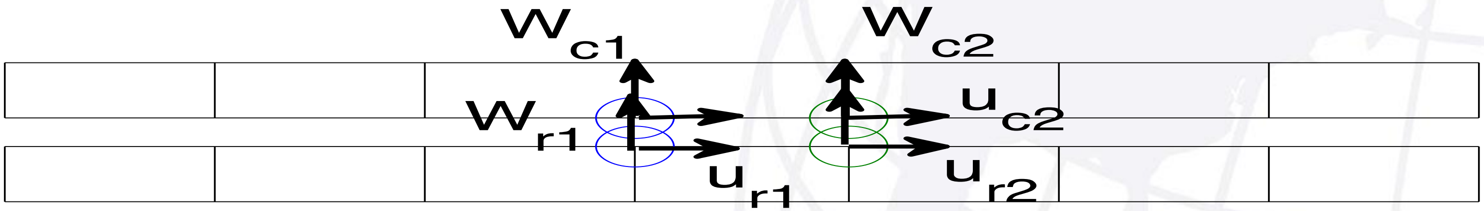
- Comparison between with and without resin layers





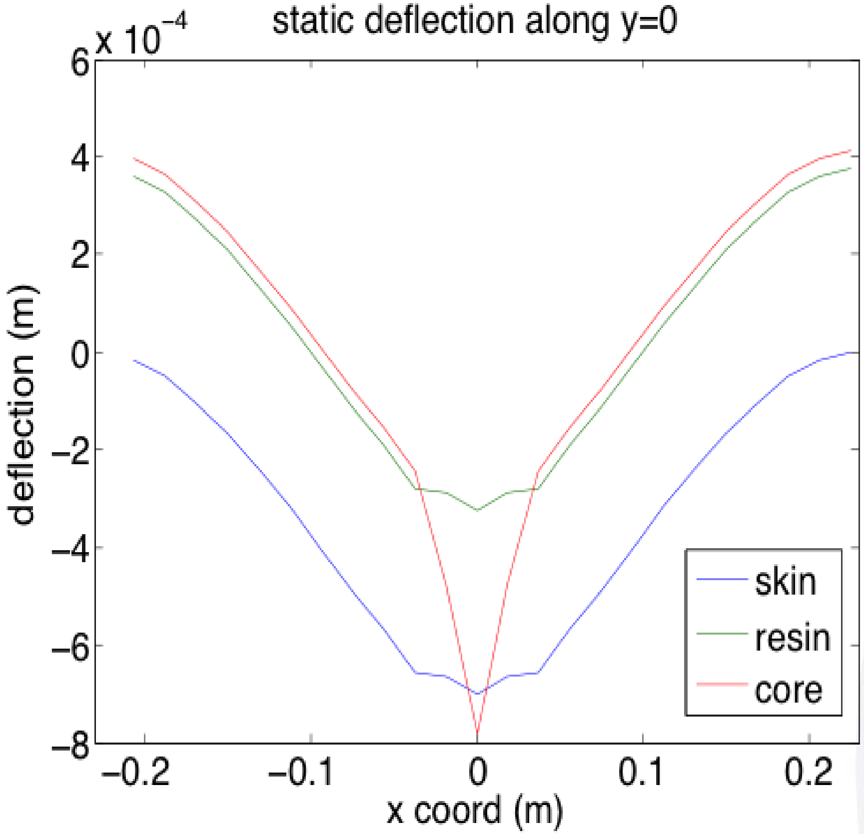
Delamination Model

- CG: Reduced modulus of resin layer
- DG: Separation of resin/skin interface
  - Partial (tangential) disconnection
  - Full (both normal and tangential) disconnection

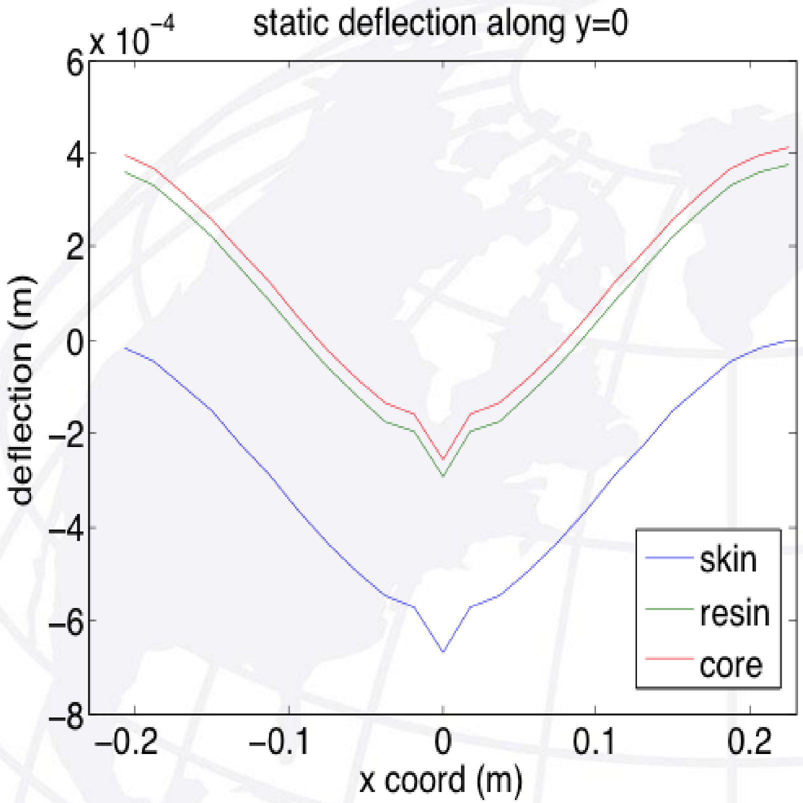


Disconnection Model with DG

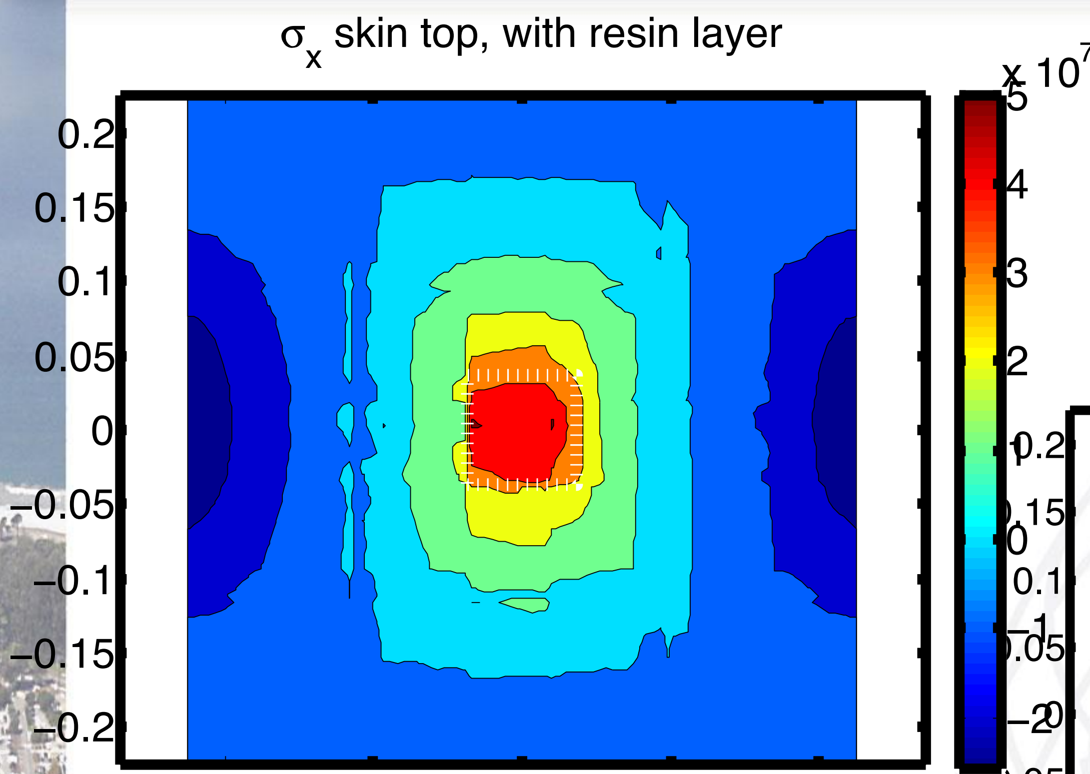
- Full Disconnection



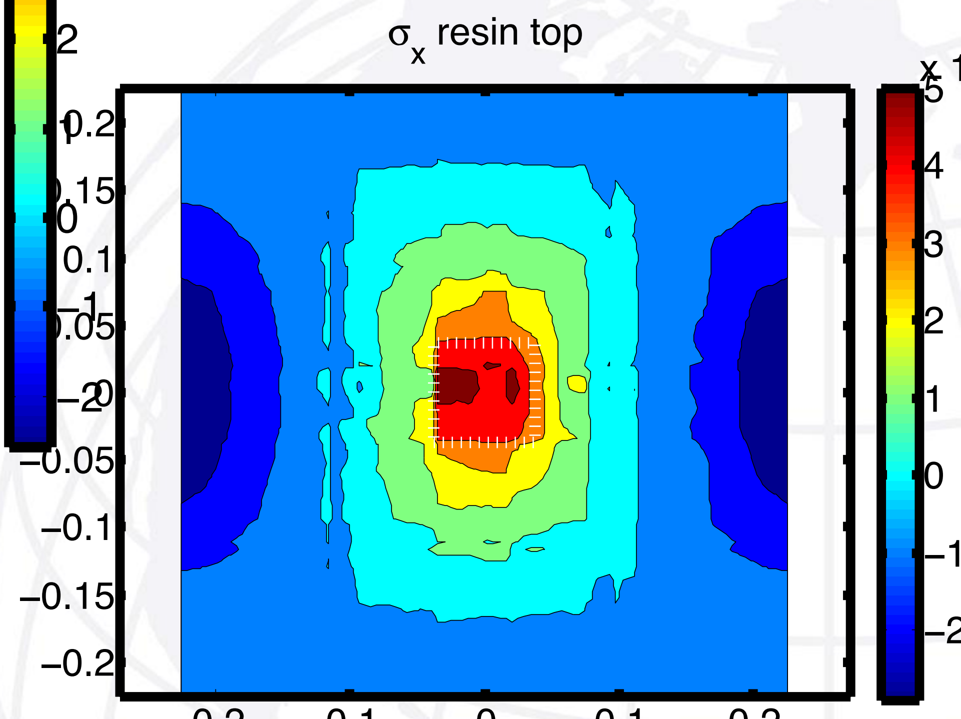
- Partial Disconnection



Full Disconnection with DG

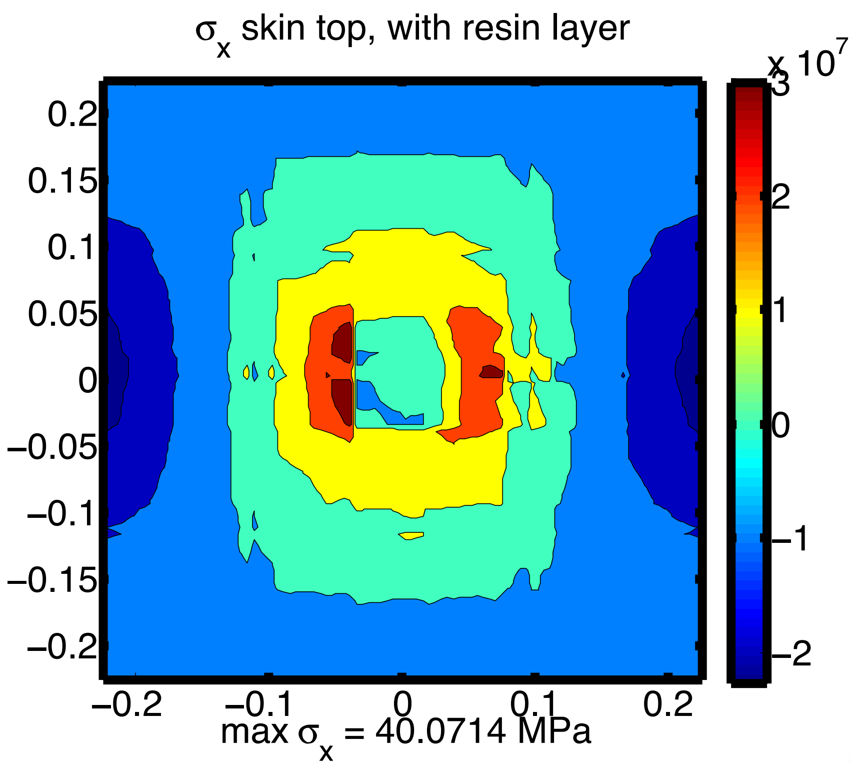


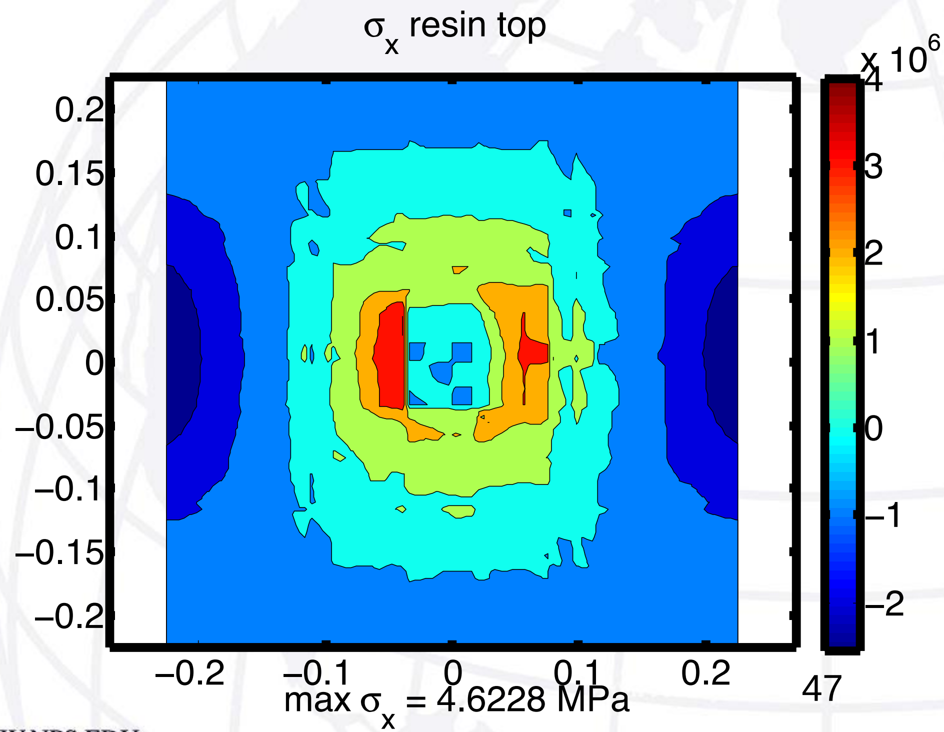
max σ_x = 54.1636 MPa



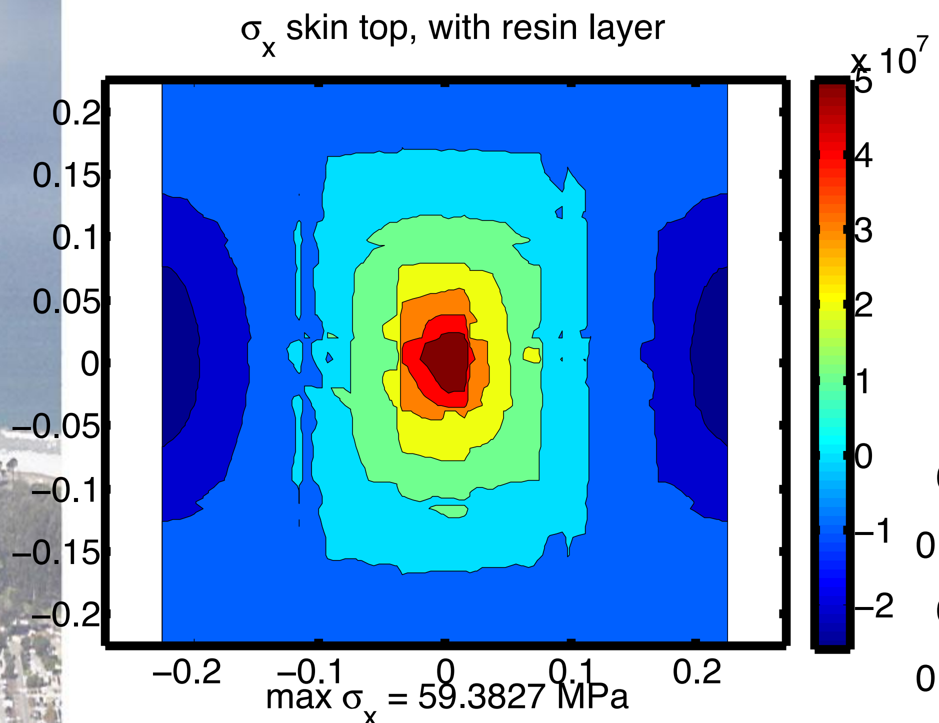
max σ_x = 6.1467 Mpa

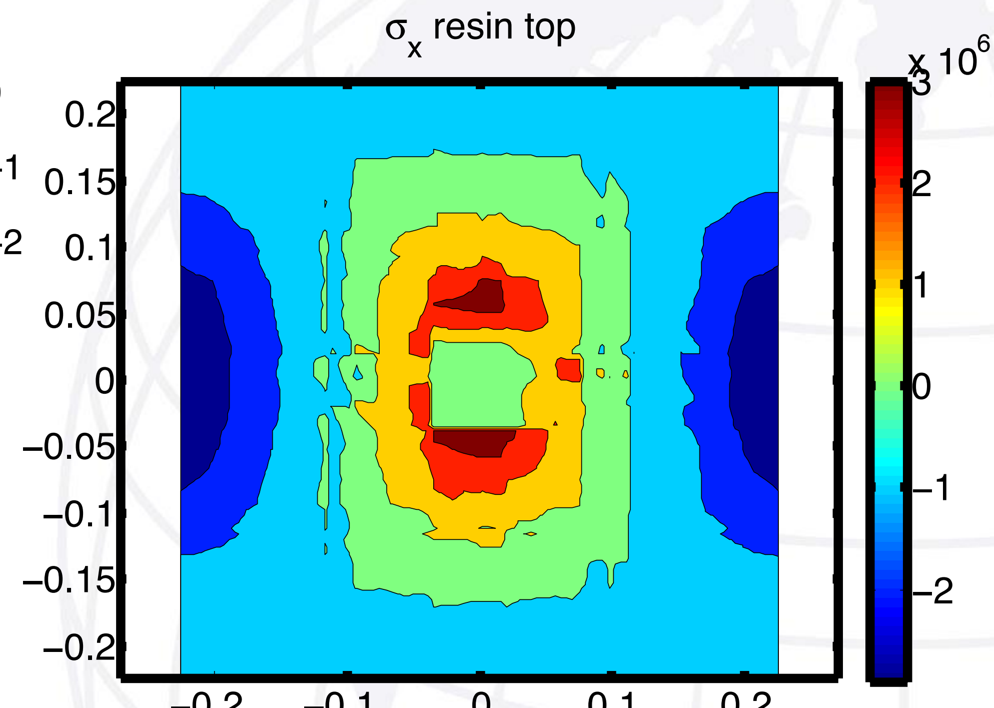
Partial DIsconnection with DG





Reduced Modulus with CG





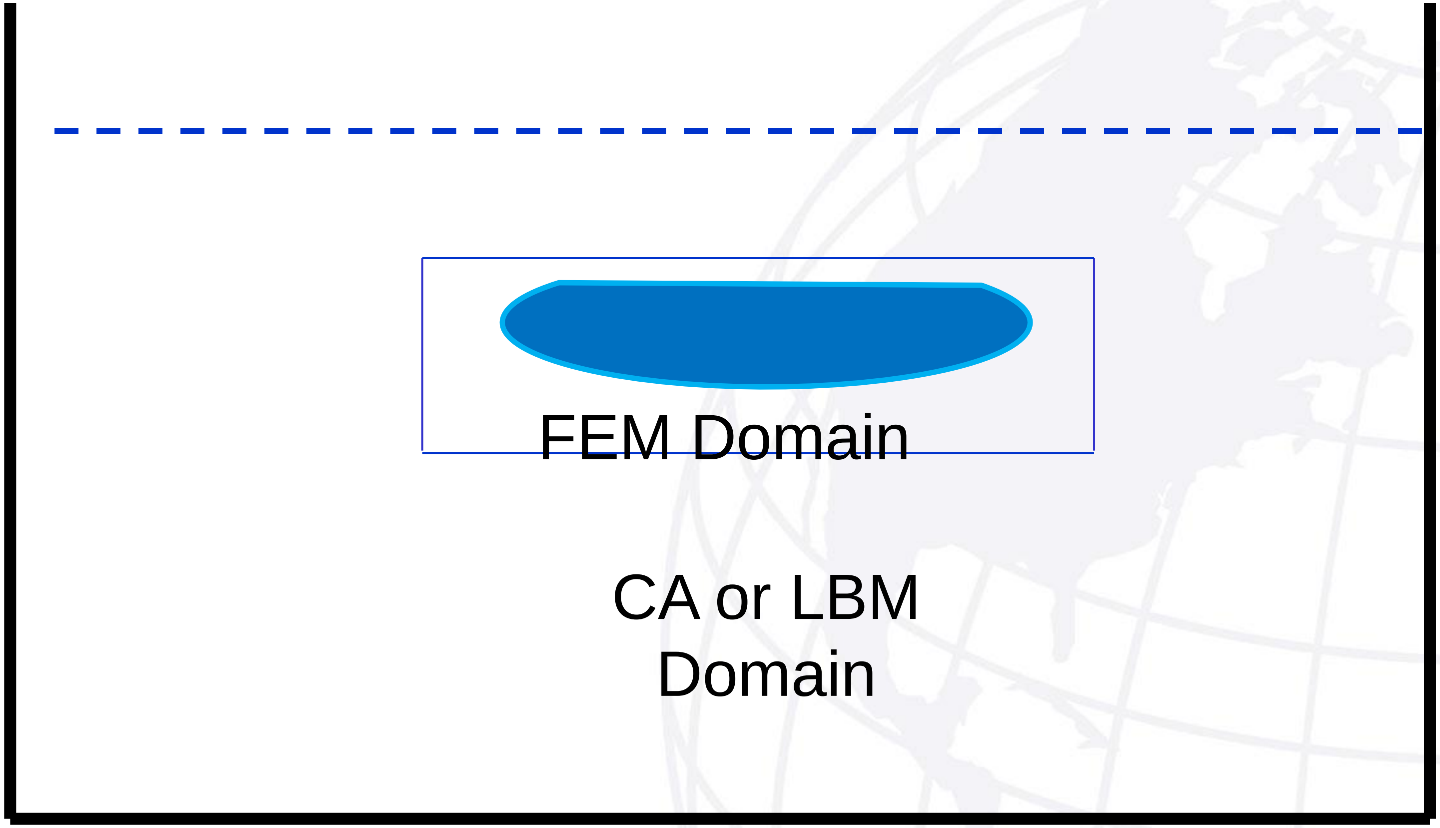
Delamination in Composite

- Comparison of three different models

	Undamaged	Full Disconnection	Partial Disconnection	Reduced Modulus
	Max. stress Location	Max stress Location	Max stress Location	Max stress Location
Skin	center	center	zone edge	center
Core	center	center	zone edge	center
Resin top	center	center	zone edge	zone edge
Resin bottom	center	center	zone edge	zone edge

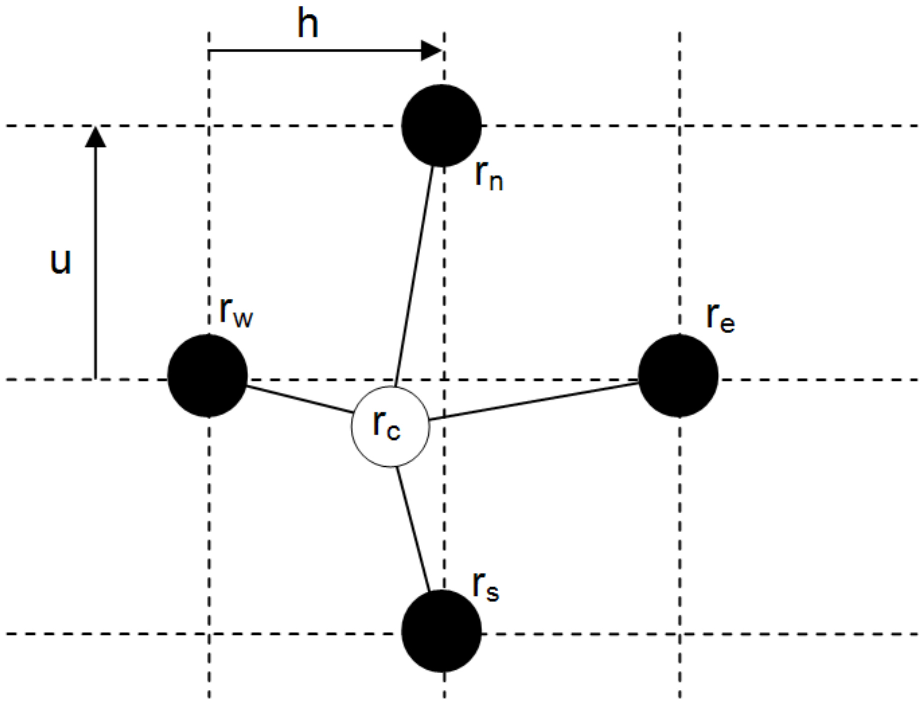
Fluid Medium

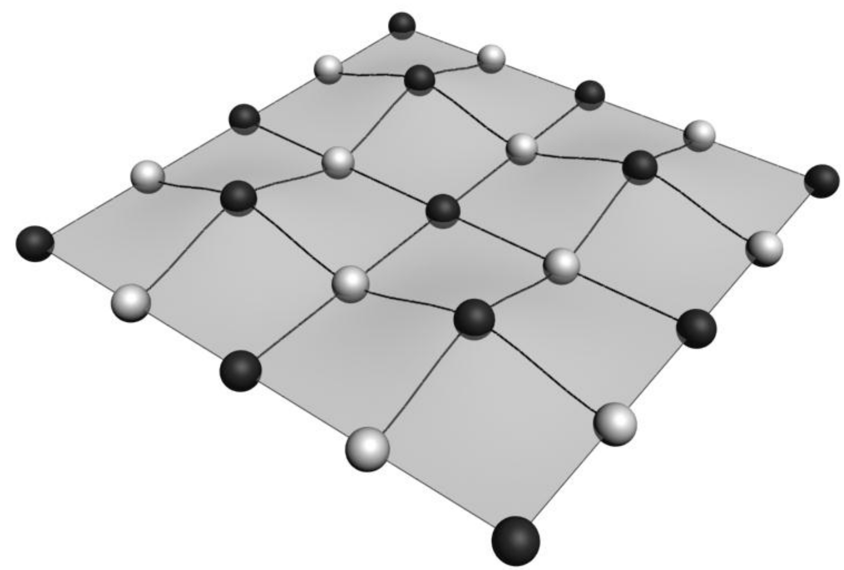
- Fluid Domain: FEM, CA, LBM



CA Rule for 2-D Wave Equation

$$r_c(t+\Delta t) = \frac{r_e(t) + r_w(t) + r_n(t) + r_s(t) - 2r_c(t)}{2}$$





3-D Wave Equation

- CA rule for 3-D

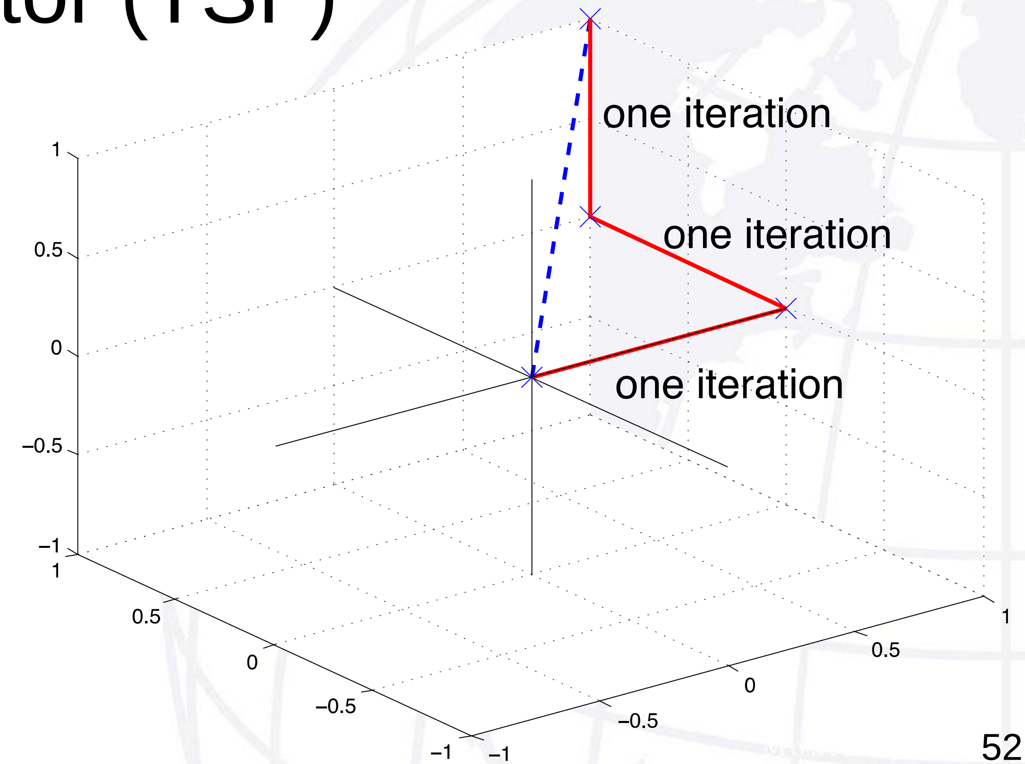
ϕ(C,t+1)=(ϕ(N,t)+ϕ(S,t)+ϕ(E,t)+ϕ(W,t)+ϕ(F,t)+ϕ(B,t) -3ϕ(C,t-1))/3

- Time Scale Factor (TSF)

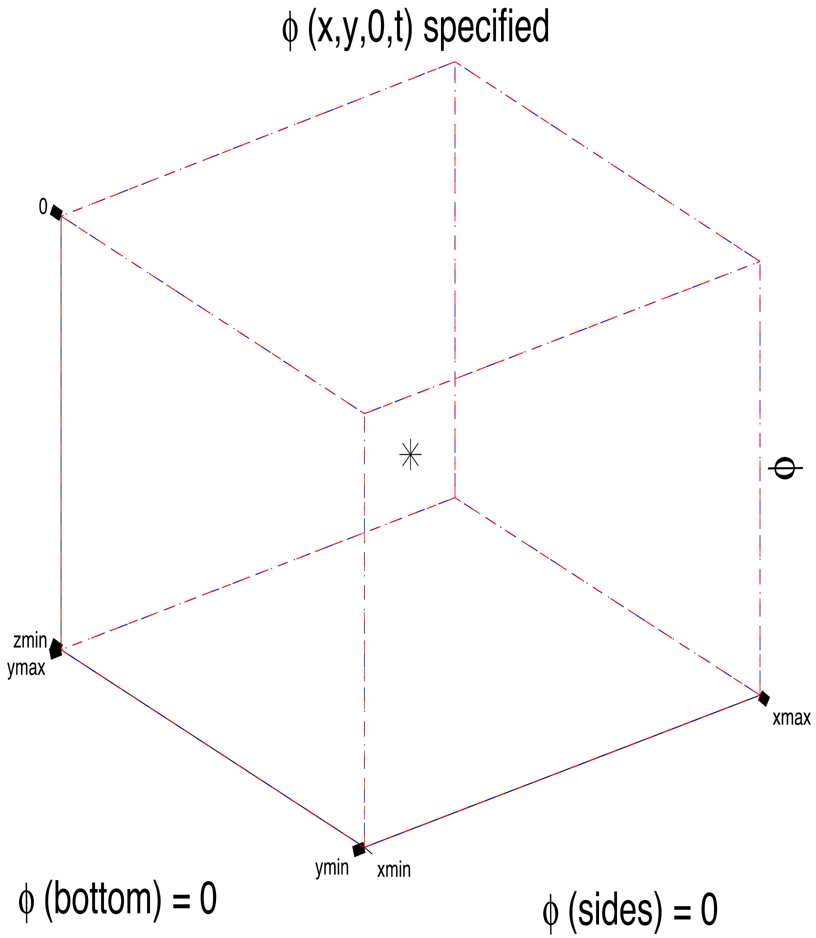
$$3TSF = \frac{dx\sqrt{3}}{c}$$

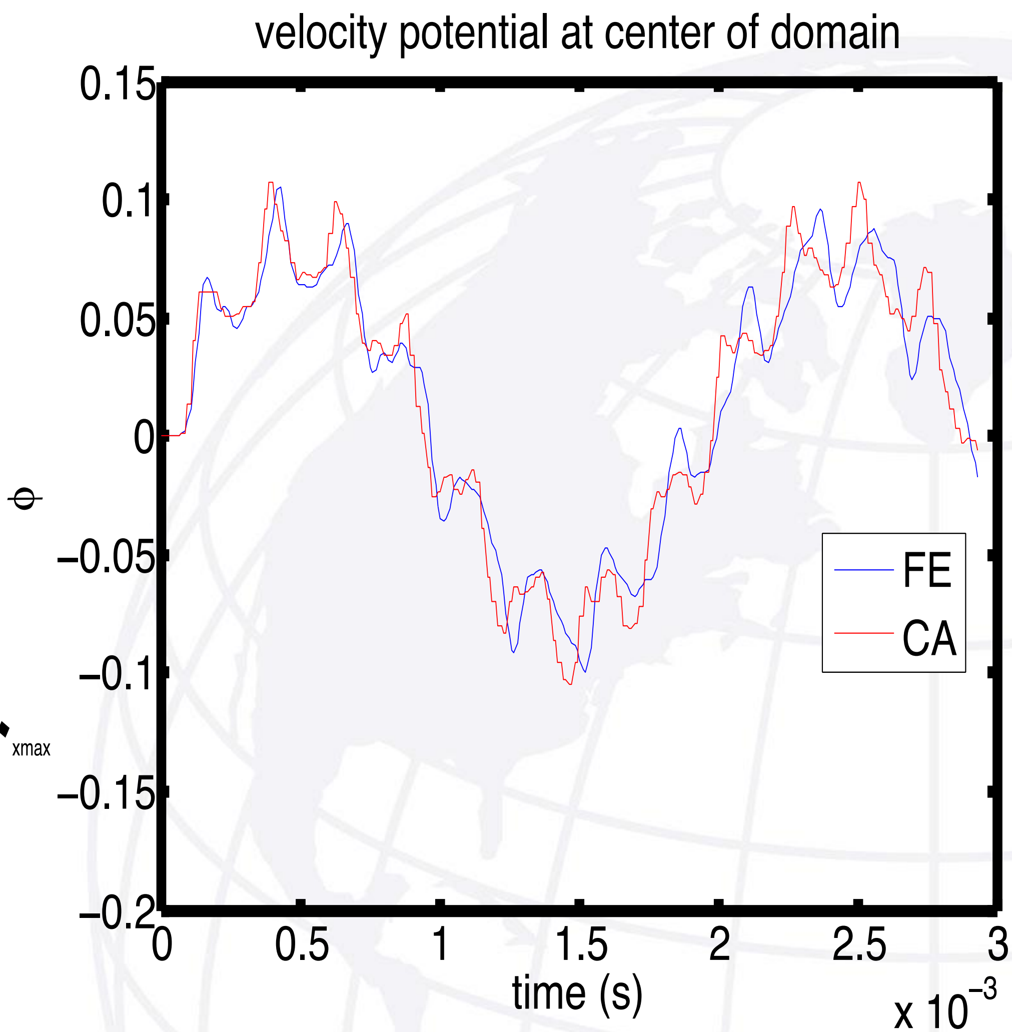
$$TSF = \frac{dx\sqrt{3}}{3c}$$

$$TSF = \frac{dx}{c\sqrt{3}} = dt$$



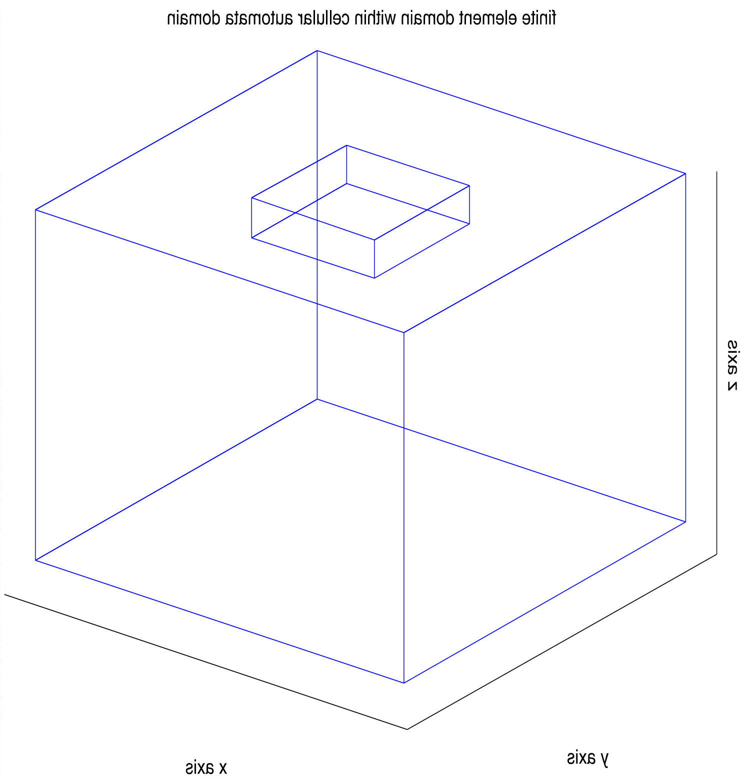
Comparison of CA and FEM

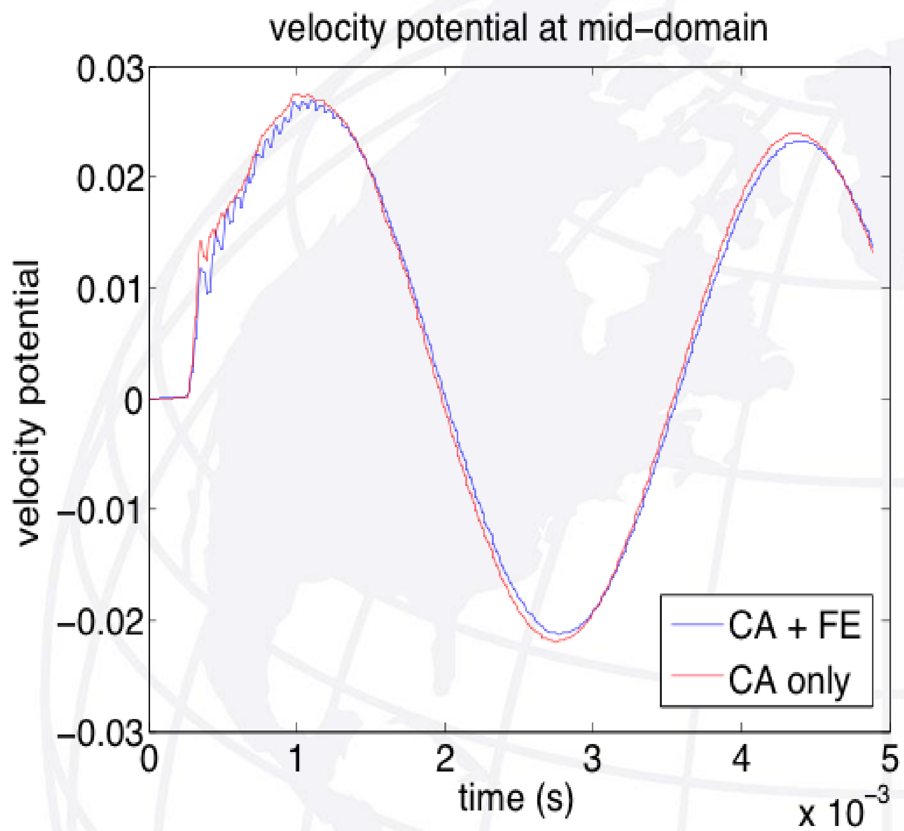




Coupling FE & CA Models

- Comparison FE inside CA vs. CA alone





Lattice Boltzmann Method

- Classical LBM (CLBM)

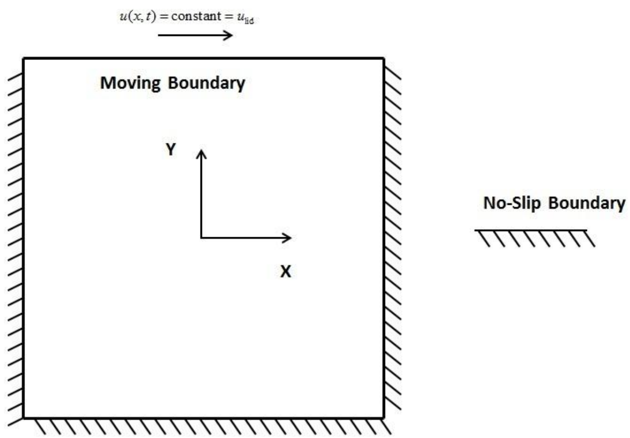
$$f_i(\vec{x}+\vec{e}_i\Delta x, t+\Delta t) - f_i(\vec{x},t) = \Omega_i(f(\vec{x},t)) \quad (i = 0,1,\cdots,n)$$

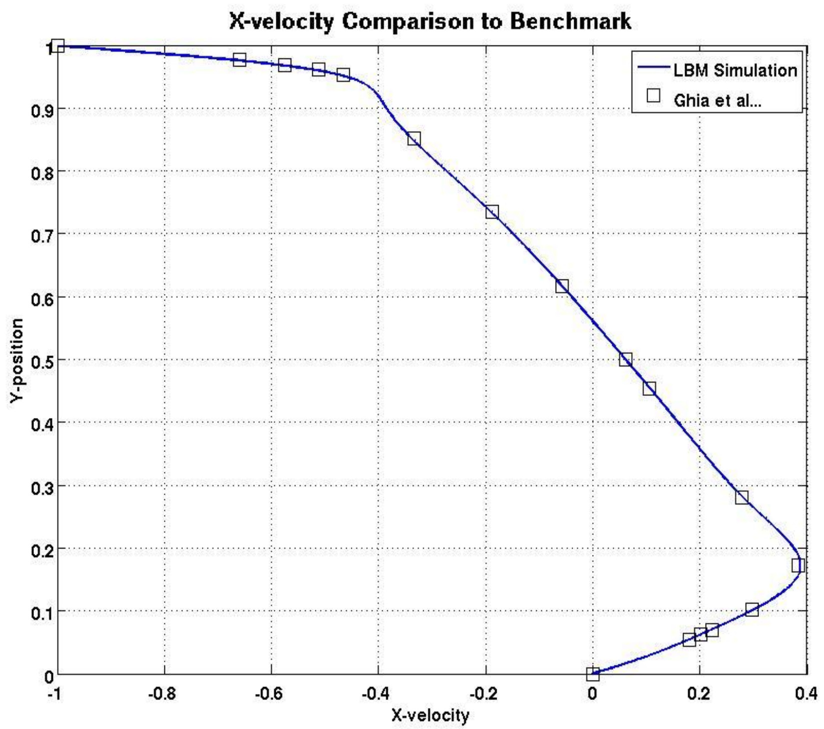
- $f_i(\vec{x},t)$: probability of finding a particle at lattice site $\vec{x}$ and time *t*, which moves along the *i-th* lattice direction with the local particle velocity $\vec{e}_i$.

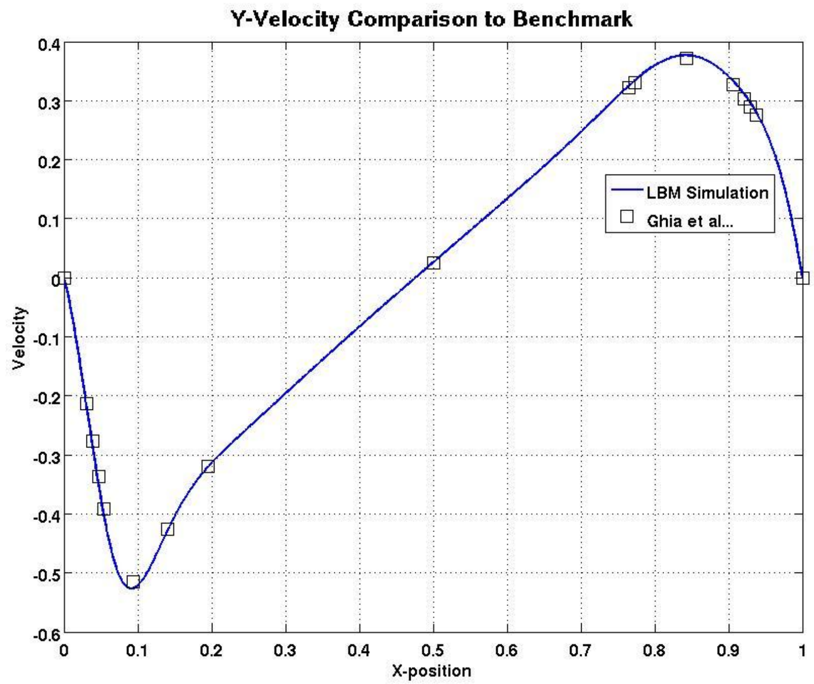
- FE-Based LBM (FELBM)

$$\frac{\partial f_\alpha}{\partial t} + \vec{e}_\alpha \cdot \nabla f_\alpha + \frac{1}{\tau}\left(f_\alpha - \tilde{f}_\alpha\right) = 0$$

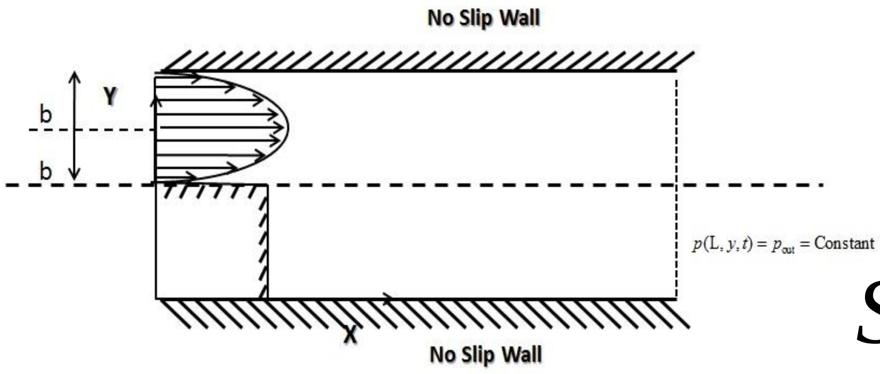
Lid-Driven Cavity

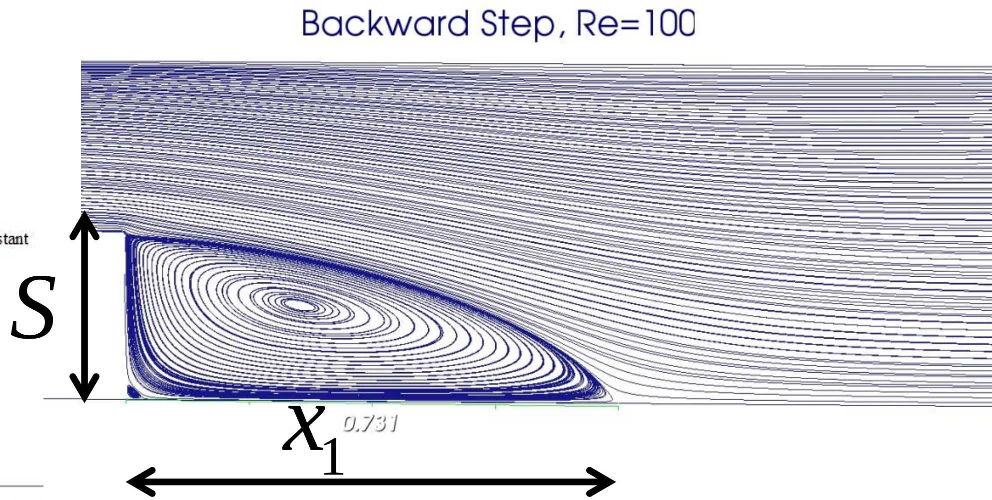


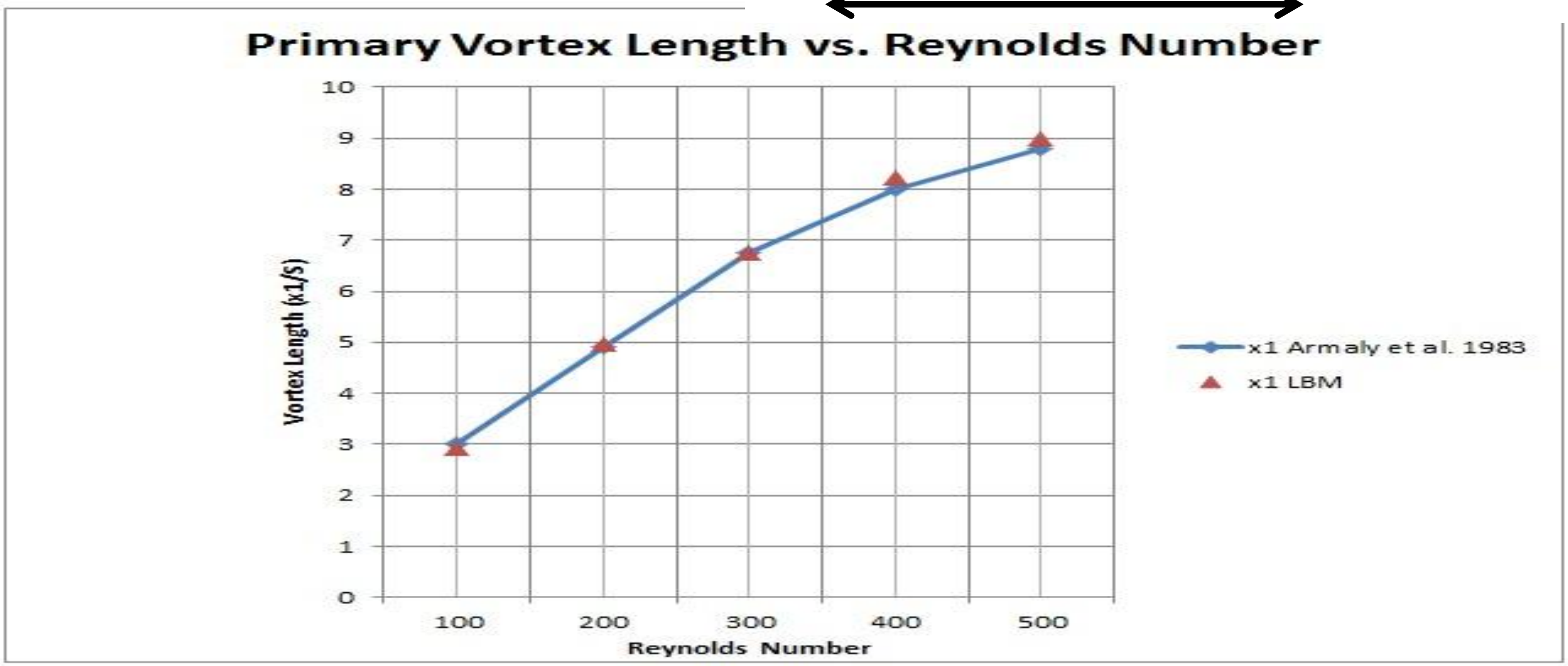




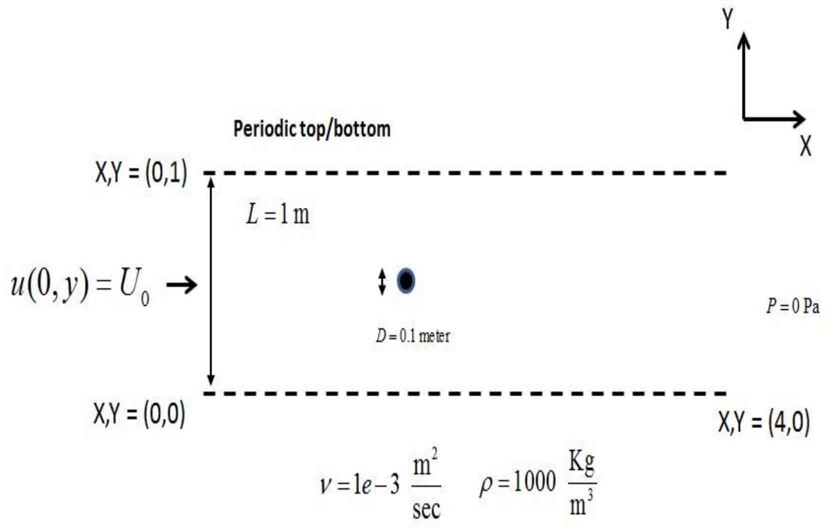
Backward Step

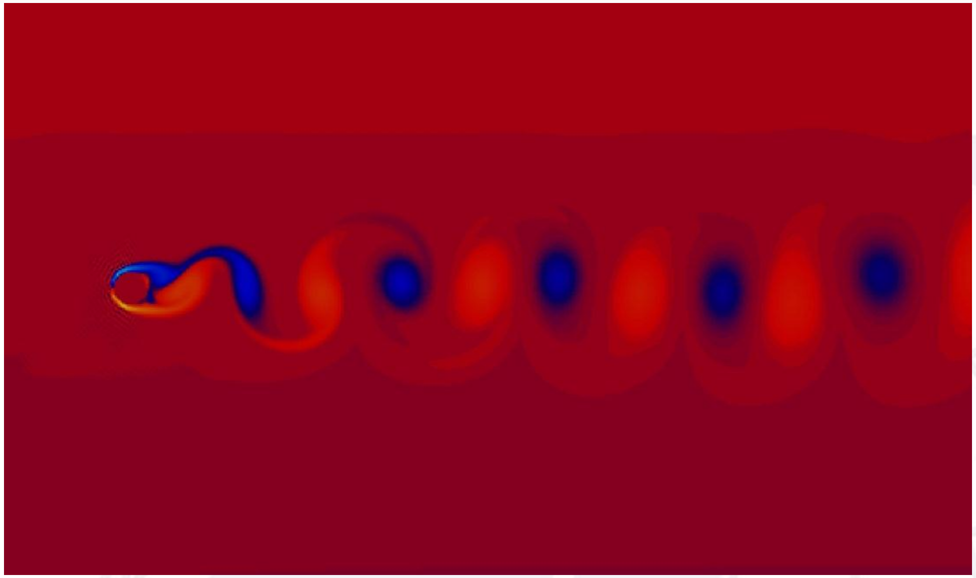


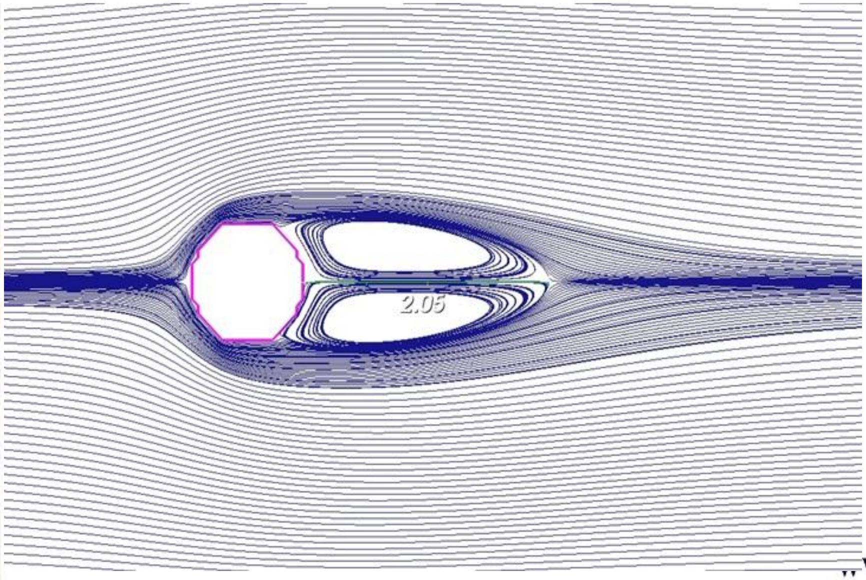




Cylindrical Obstacle





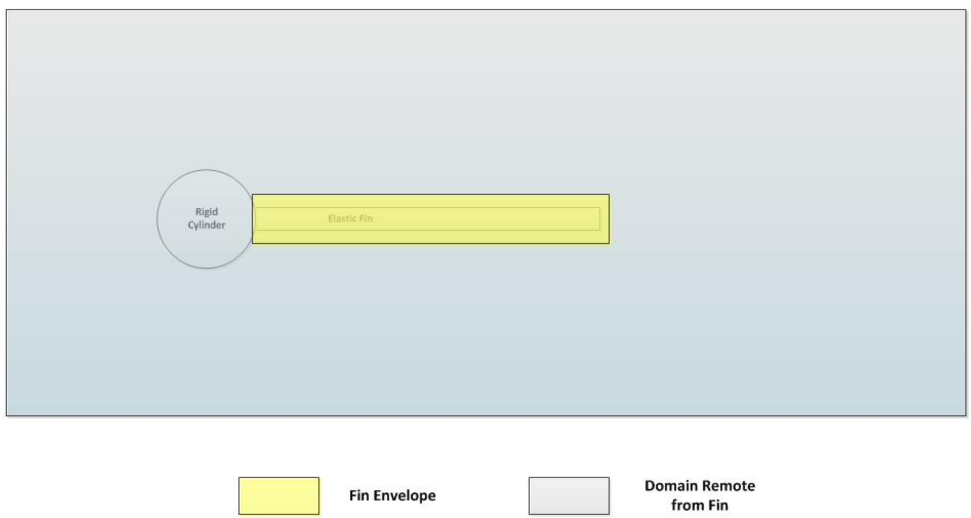


Strouhal No. for Vortex Shedding Frequency

Author	Re = 20	Re = 40
Zhou (2012)	0.92	2.20
Calhoun (2002)	0.91	2.18
Rusell (2003)	.94	2.35
Silva (2003)	1.04	2.55
This work	.95	2.05

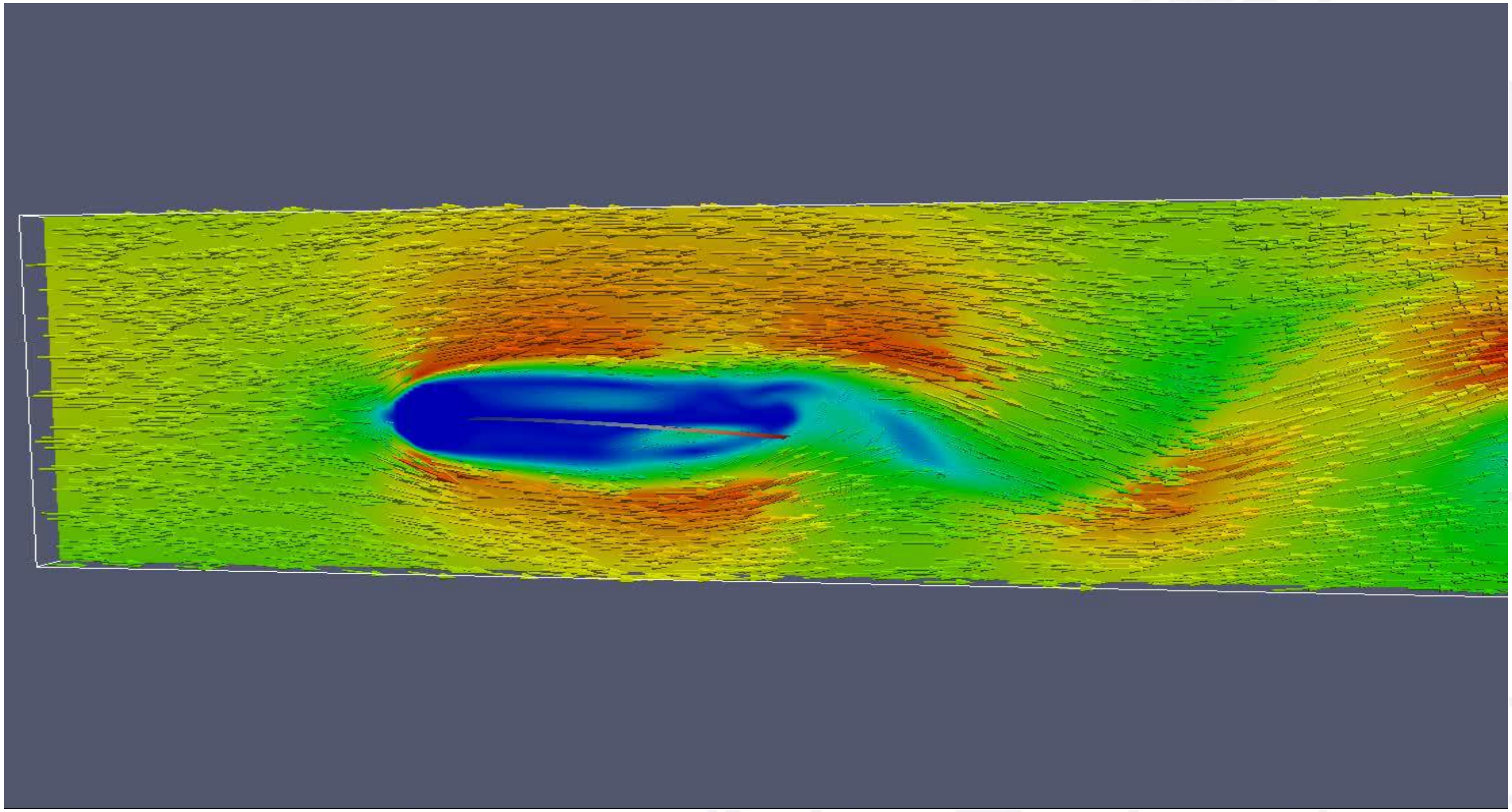
FSI Model

- LBM computations on GPU, structural dynamics on CPU.
- Increase performance by:
  - ✓ Maximize overlap of independent calculations
  - ✓ Maximize use of computational resources

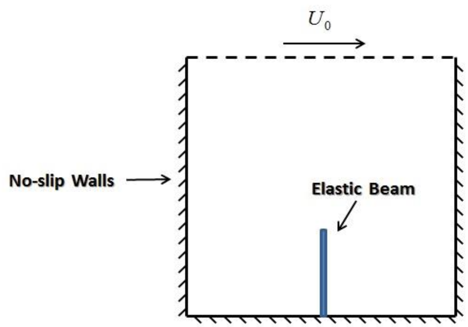


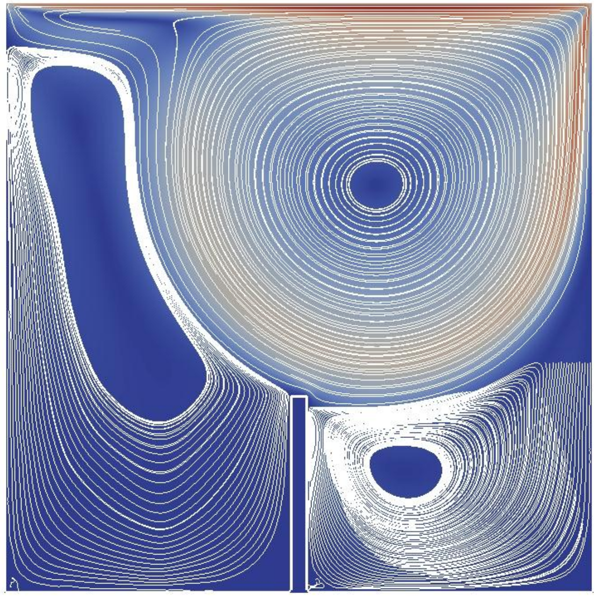
FSI Result

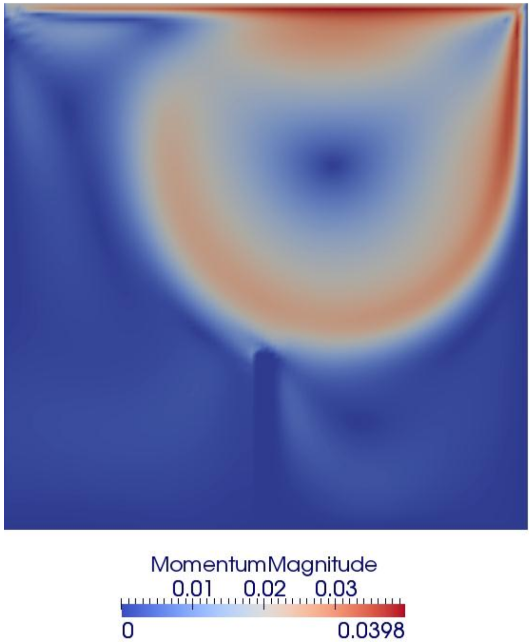
Method	Average time per time-step (sec)	Percent Speedup
Non-Overlapped	0.0305	-
Overlapped	0.0234	23%

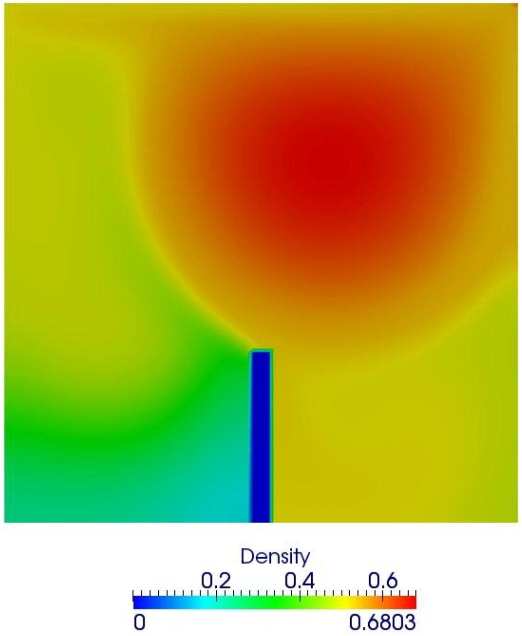


FSI : 2D Lid-Driven Cavity

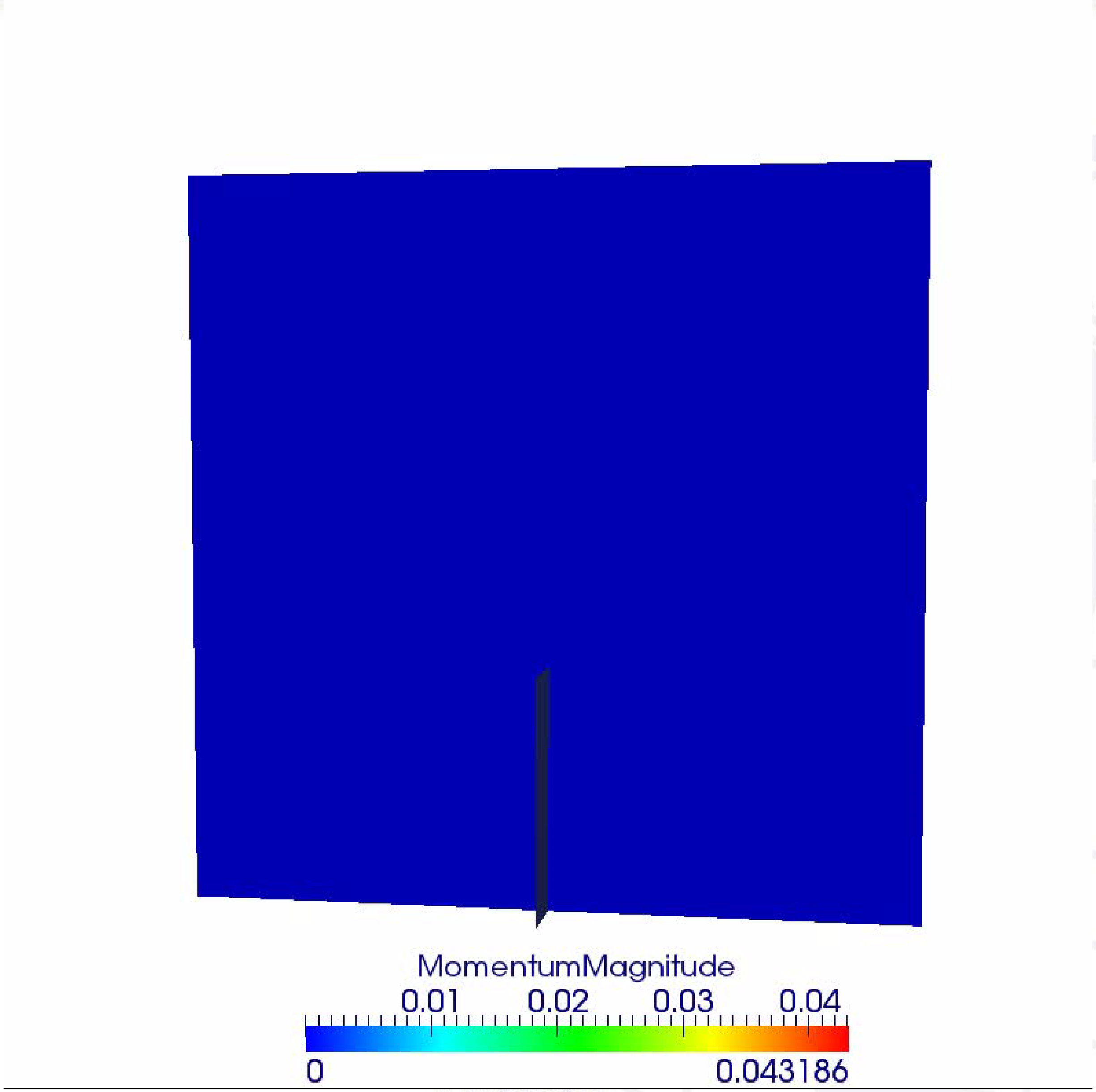






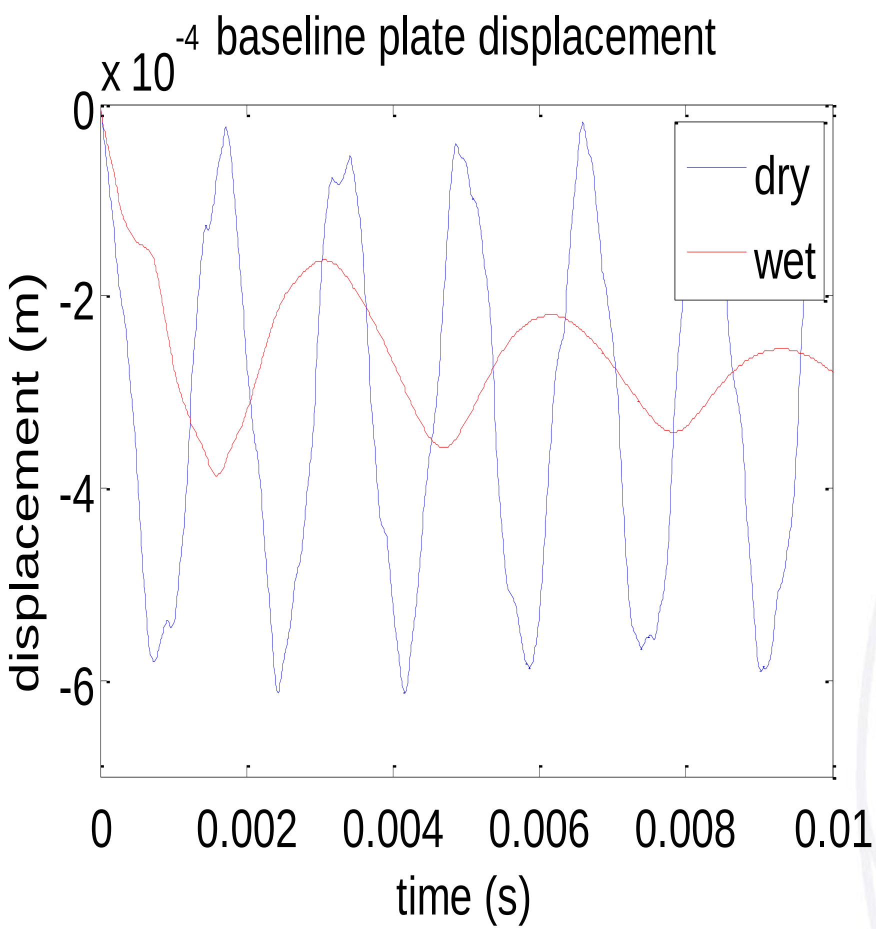


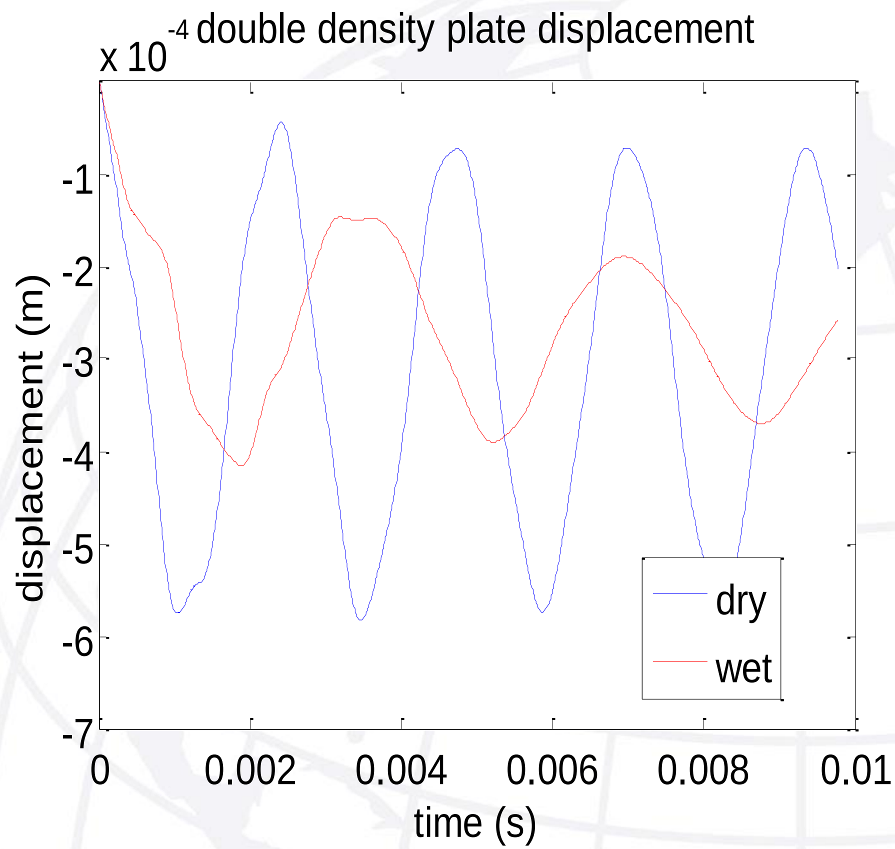
FSI : 2D Lid-Driven Cavity



FSI results

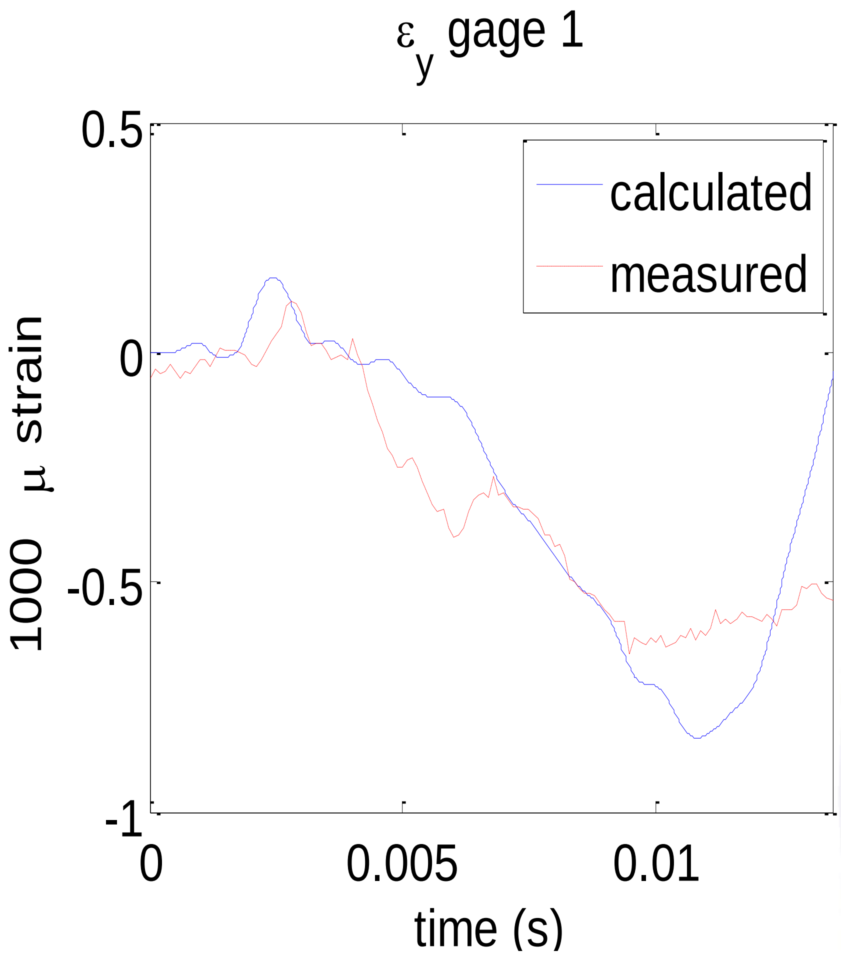
- Comparison with and without FSI

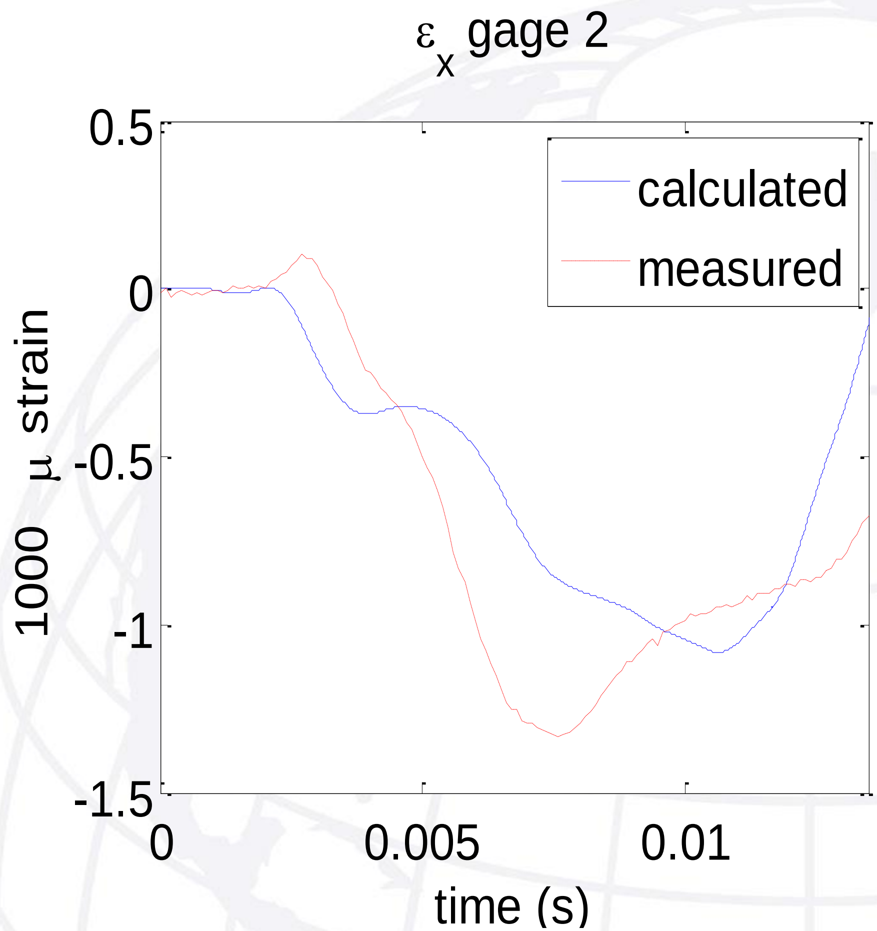




Modeling Validation of Wet Plate

- Comparison between exp. and num. results





Conclusions

- It is essential to include the FSI effect for design and analysis of polymer composite structures which are in contacted with water.
- FSI effect is non-uniform over the composite plate. It is sensitive to boundary conditions.
- Local CNT-reinforcement in a resin interface layer in carbon fiber beams enhanced the fracture toughness significantly.
- Developed Displacement-based shell elements, CA, LBM, FEM, and their coupling tecjniques for FSI.

Thank you for your attention!