

Hybrid Simulation Evaluation of the Suspended Zipper Frame

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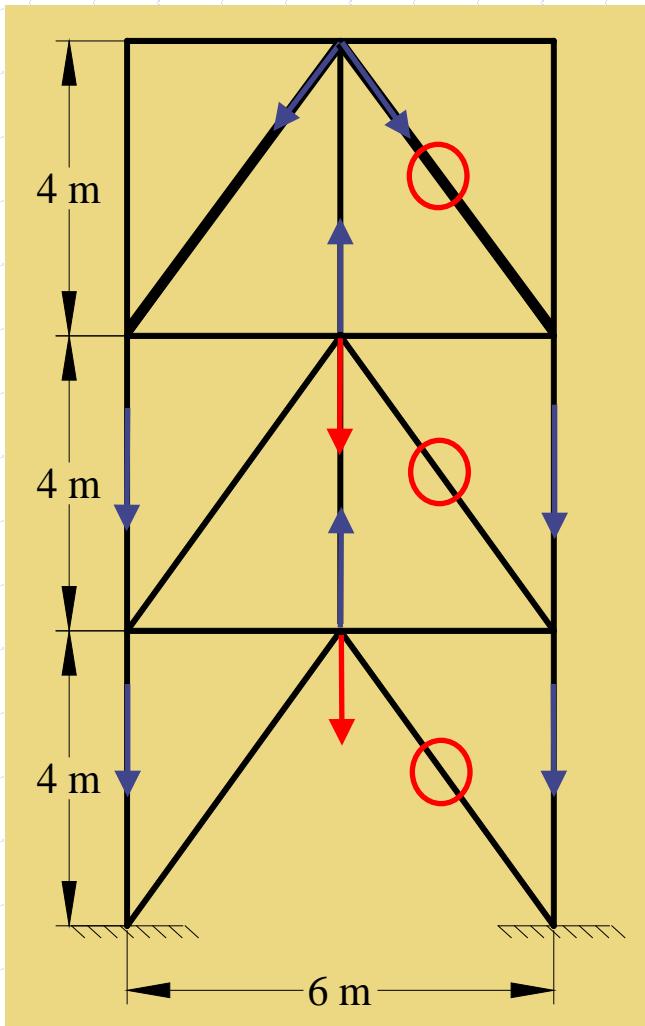
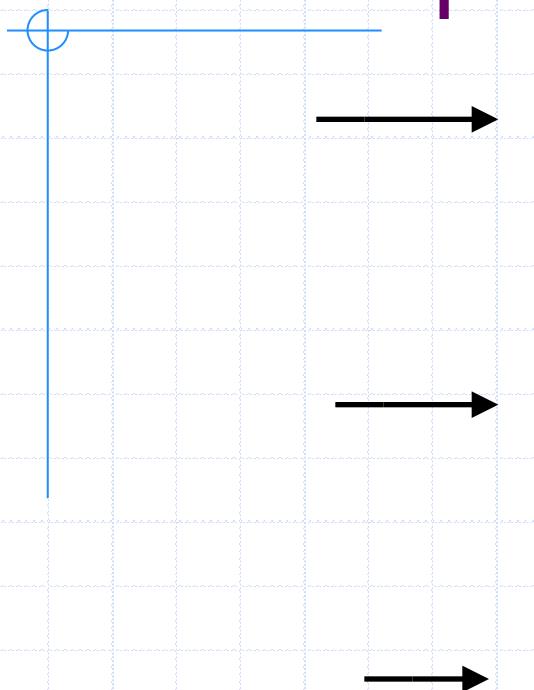
The George E. Brown, Jr. Network for Earthquake Engineering Simulation



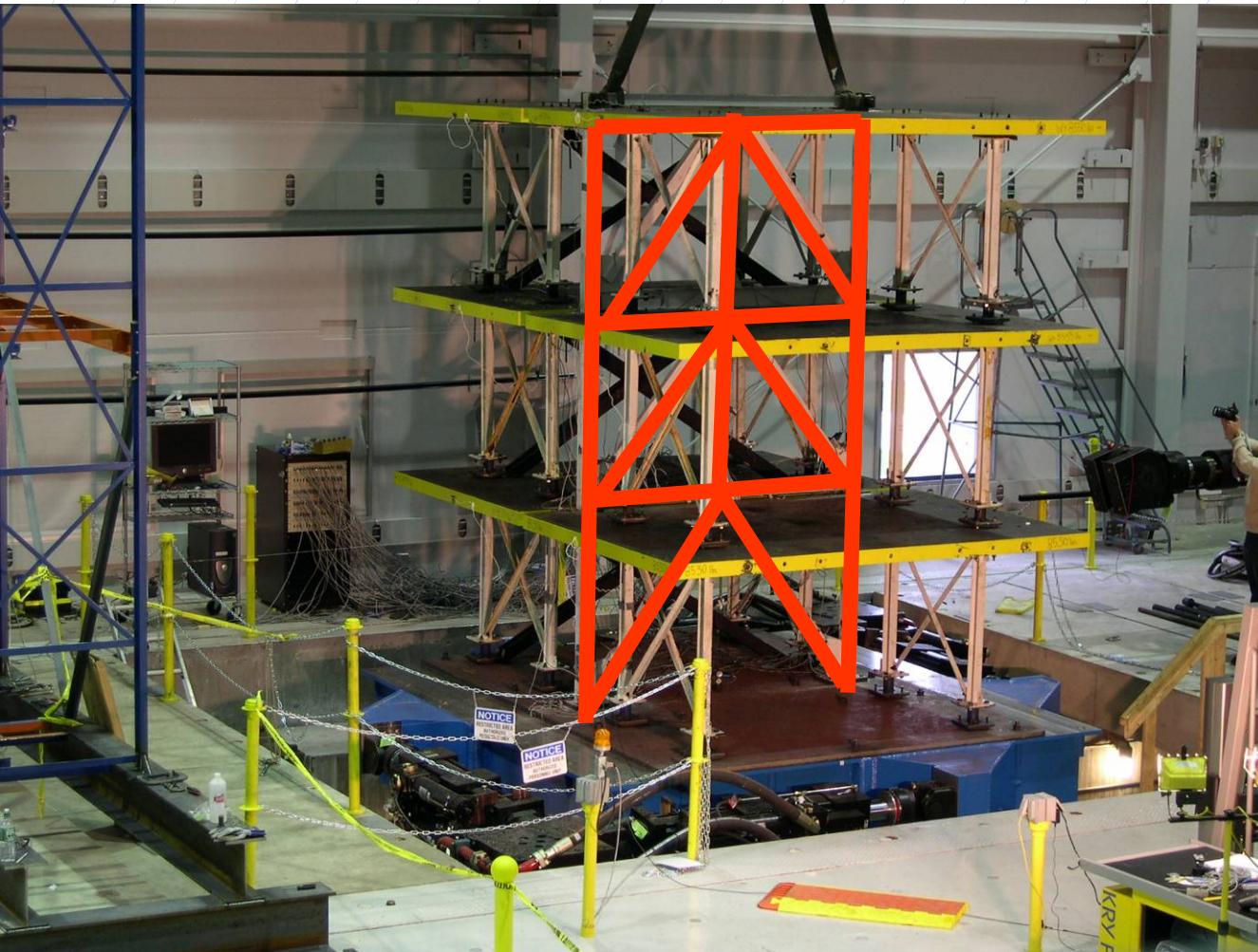
Introduction

- ◆ Example of the hybrid simulation test.
 - NEES suspended zipper brace frame test.
- ◆ OpenSees Navigator
 - Graphic user interface for OpenSees.
- ◆ Example application
 - Three span bridge, Two story Shear,...

Suspended Braced Frame



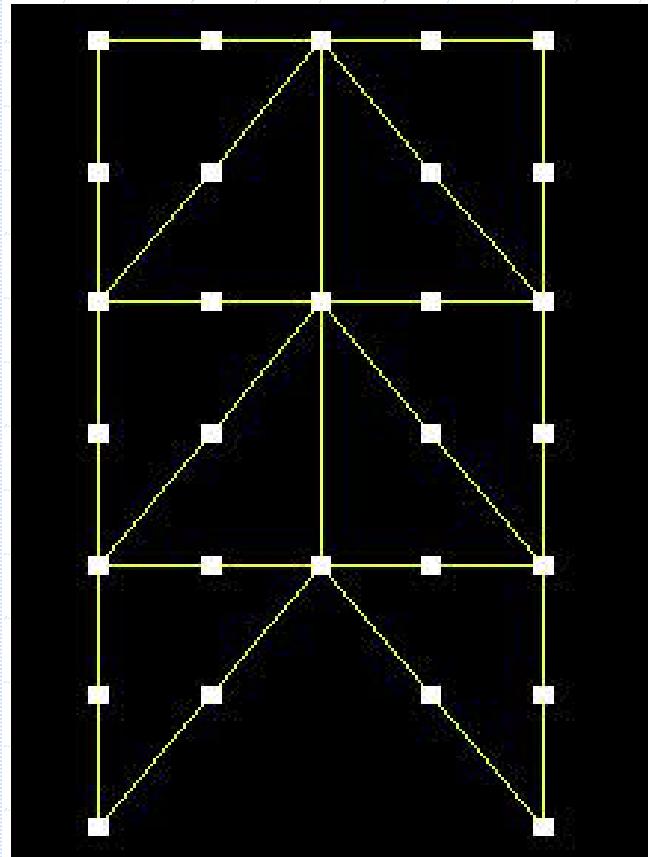
Buffalo Shaking Table Test



GT Quasi-Static Test

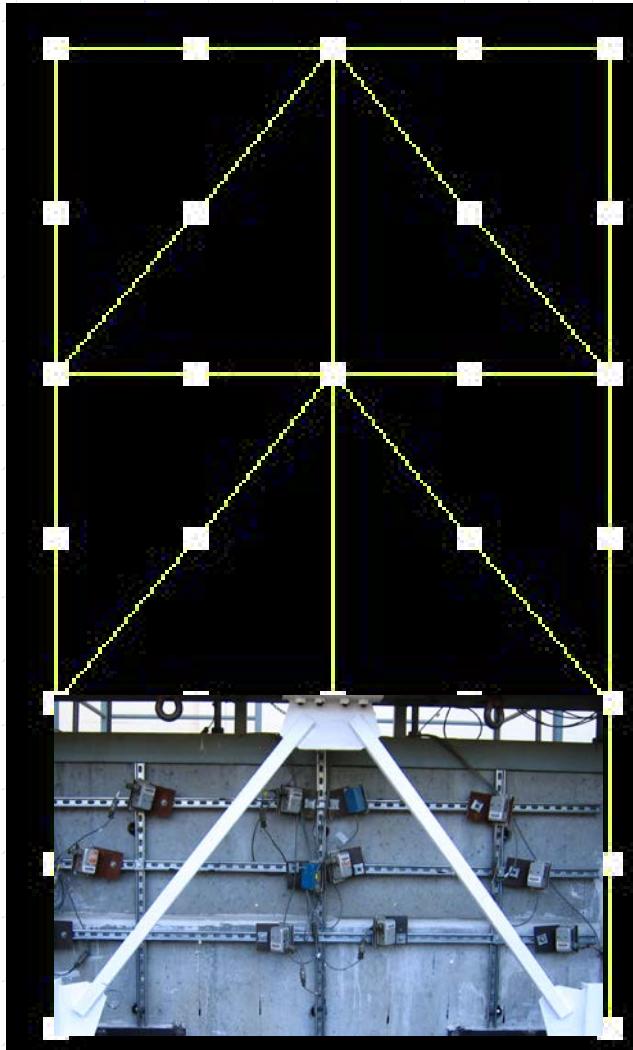


Experimental Testing



Analytical Simulation

CUB Hybrid Simulation Test

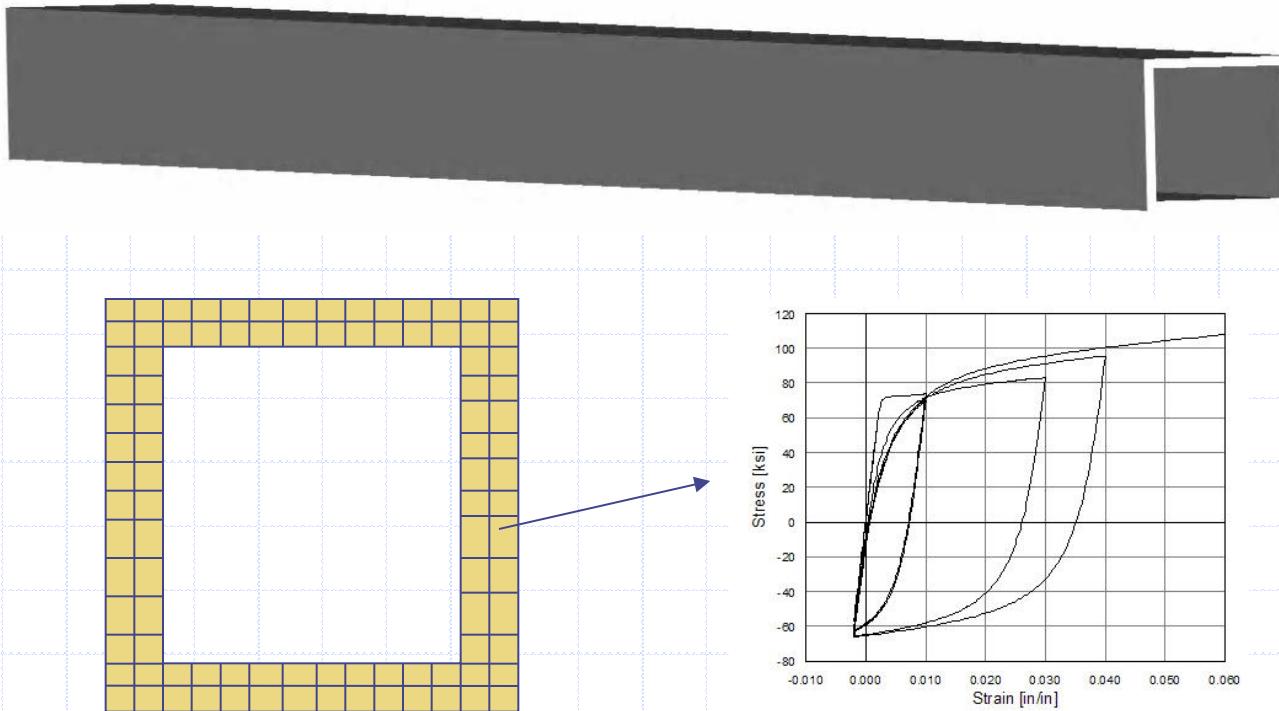


Challenge of the zipper frame test

- ◆ Combine OpenSees with experimental elements
 - Nonlinear buckling behavior accounted in both analytical and experimental elements
- ◆ Analytical simulation of the brace
 - Modeling the analytical brace using OpenSees
 - Component testing of the brace sub-assembly
- ◆ Hybrid simulation of the frame
 - Experimental Testing Architecture
 - New Experimental Framework
 - Solution Algorithm

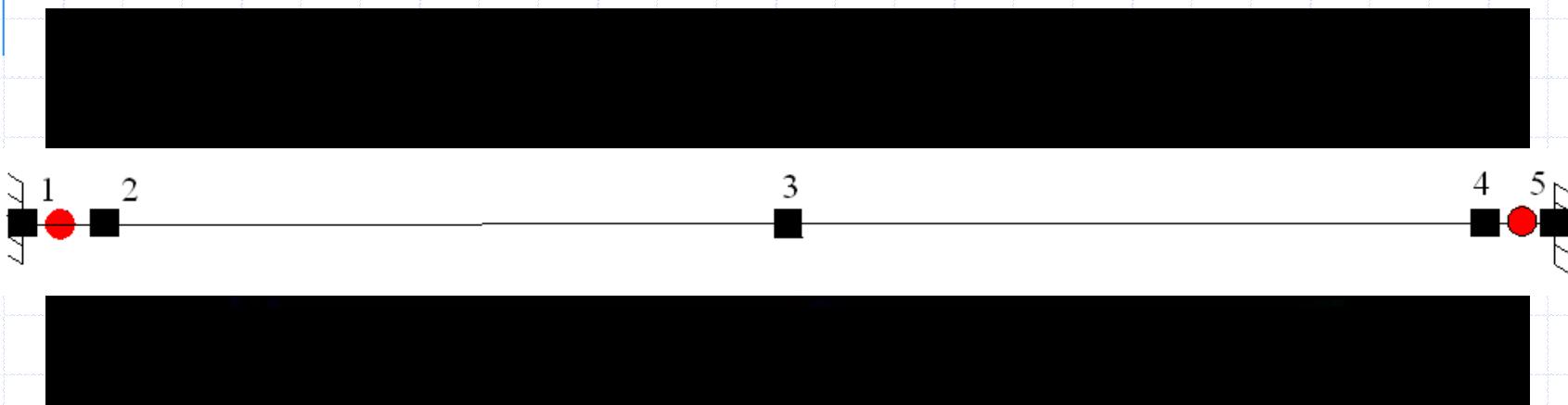
Analytical simulation of the brace

◆ Modeling of the analytical brace



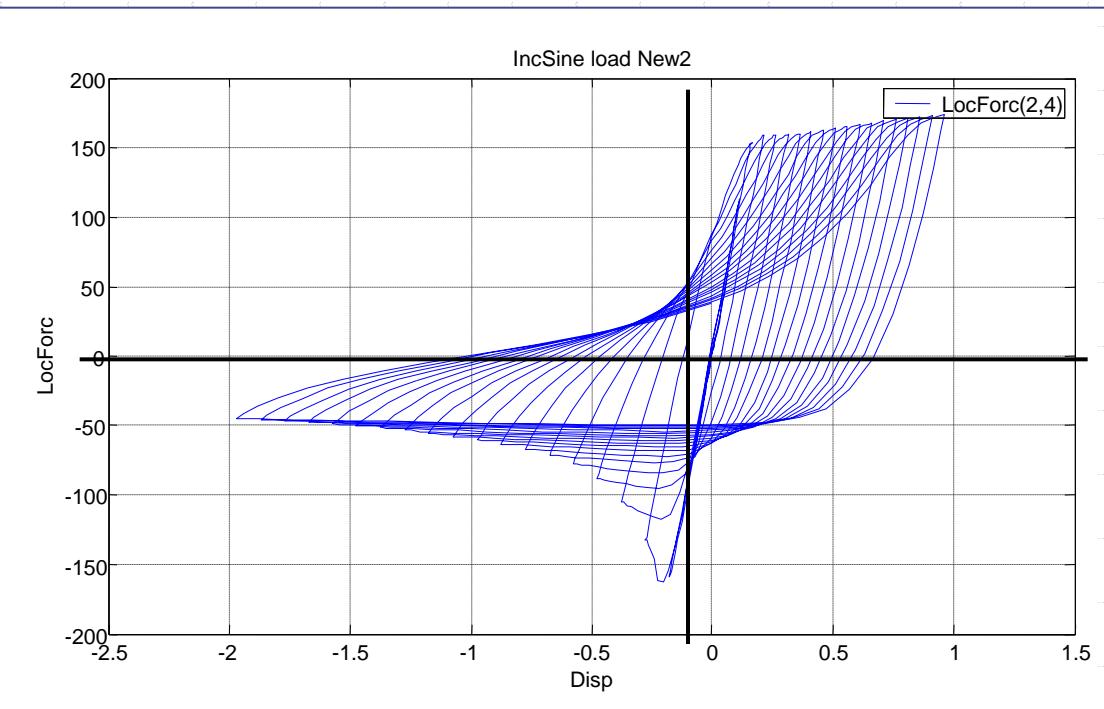
Analytical simulation of the brace

- ◆ Brace behavior under cyclic displacement loading



Analytical brace

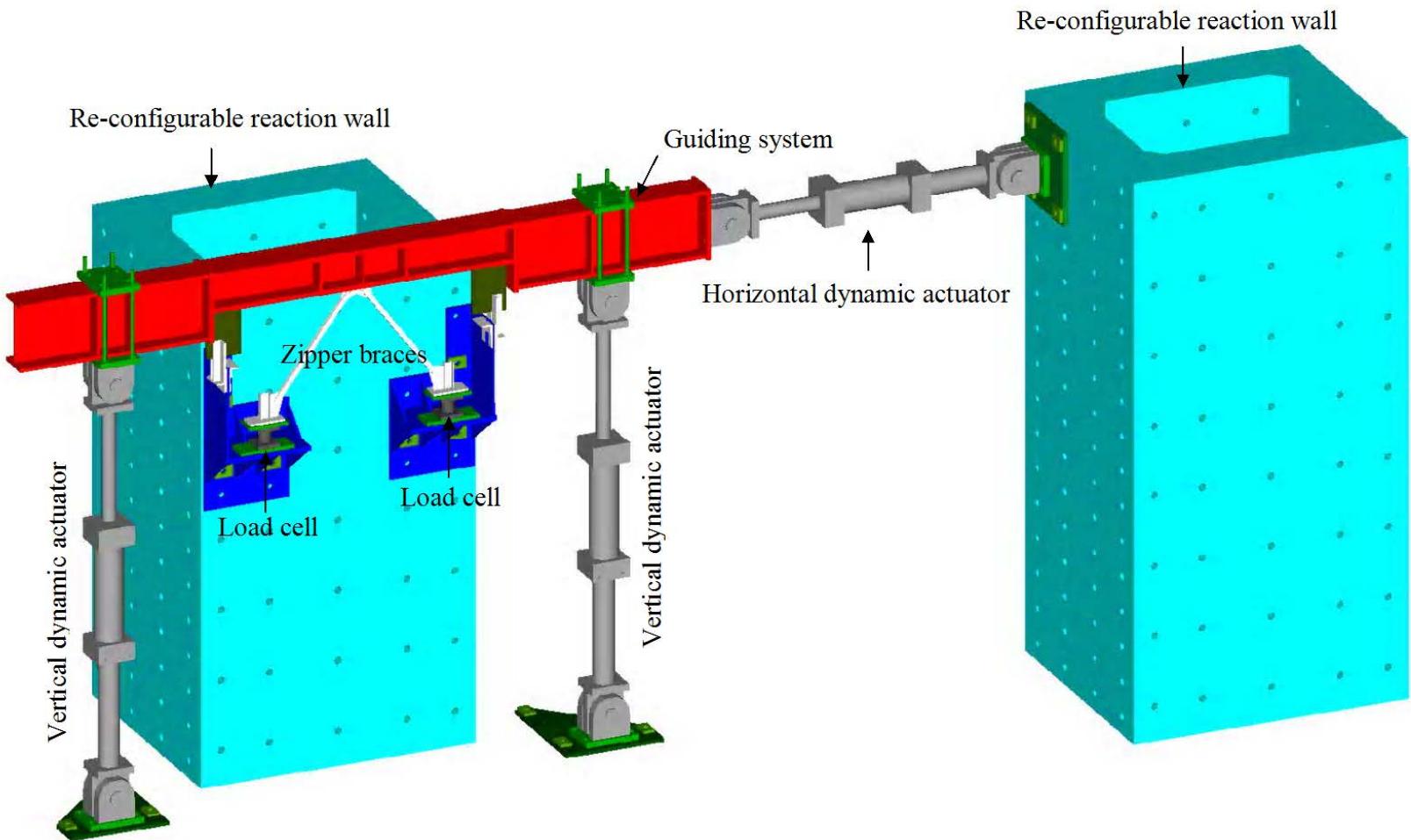
◆ Hysteresis loop (Analytical)



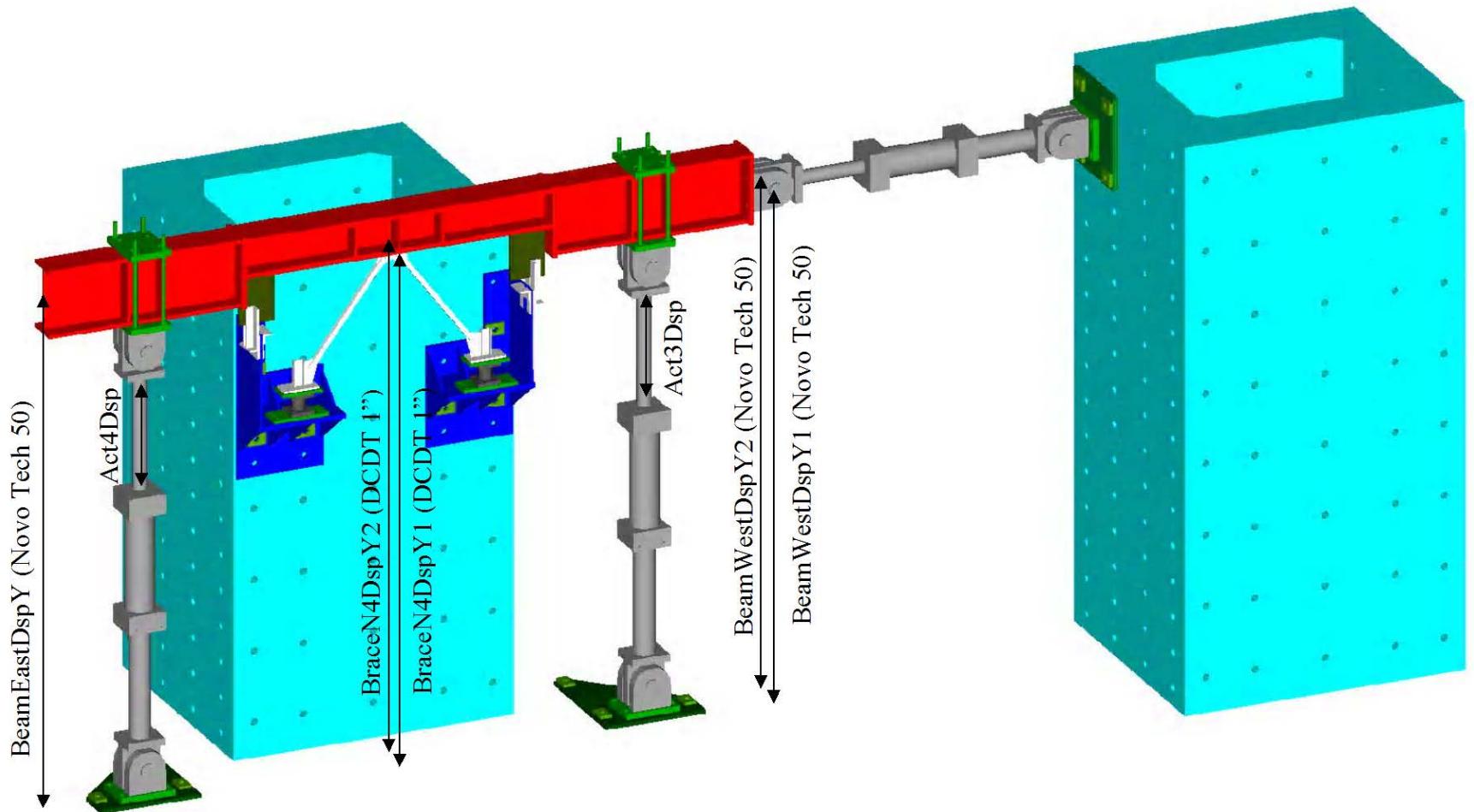
Scope of the test

- ◆ Analytical simulation of the brace
 - Modeling the analytical brace using OpenSees
- ◆ Quasi-Static testing of the brace
 - Component testing of the brace sub-assembly
- ◆ Hybrid simulation of the frame
 - Analytical model + experimental sub-assembly

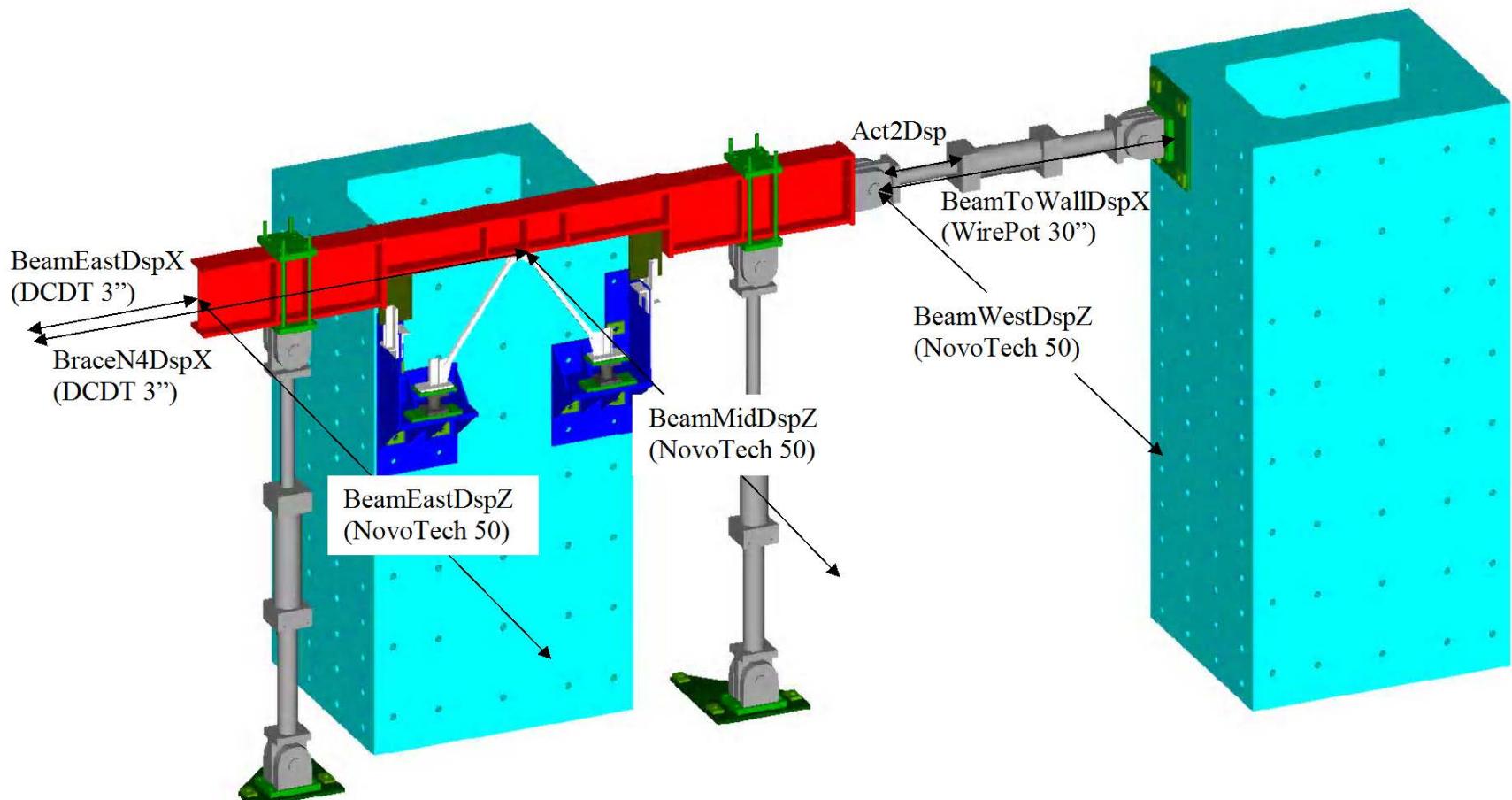
Test Setup



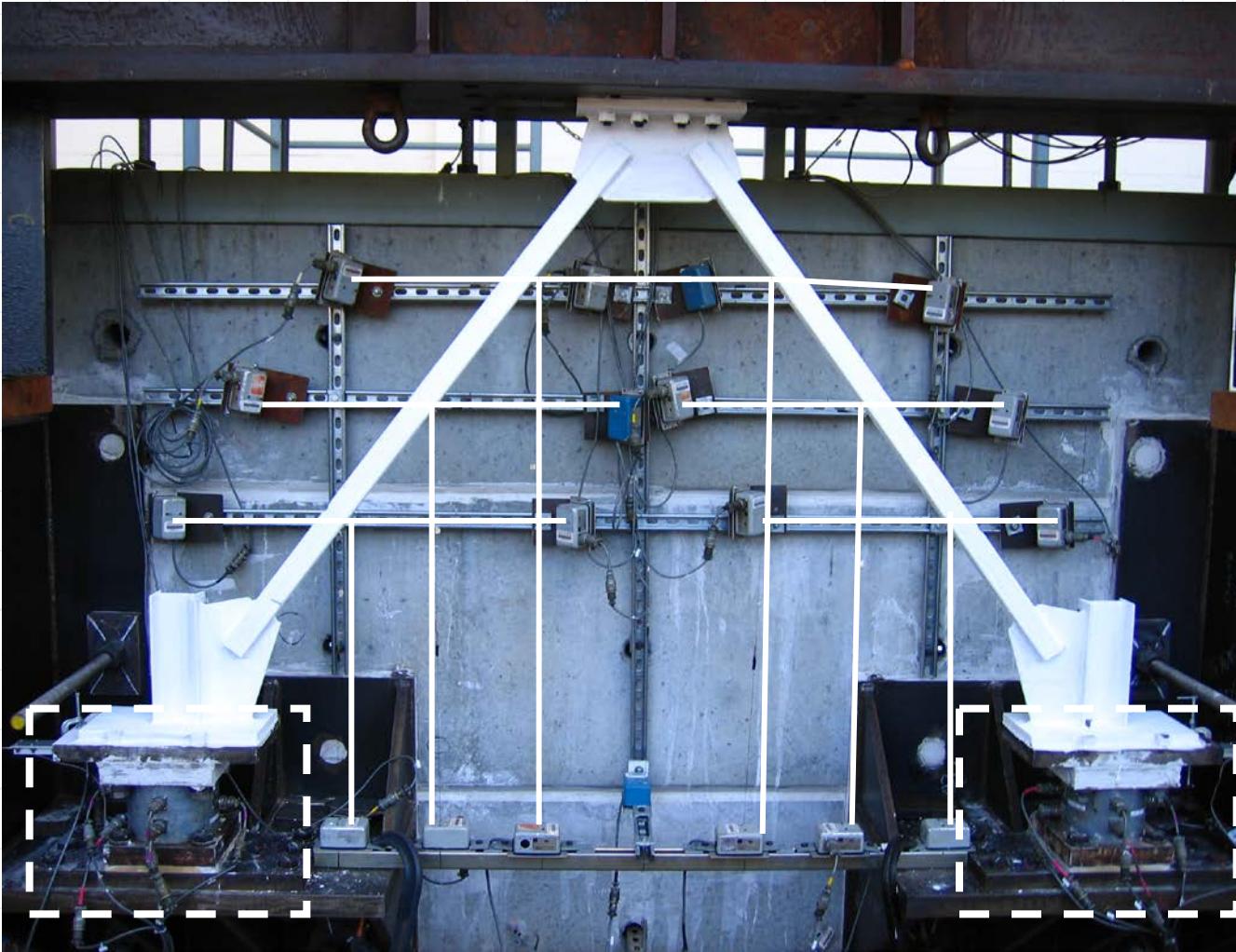
Instrumentation



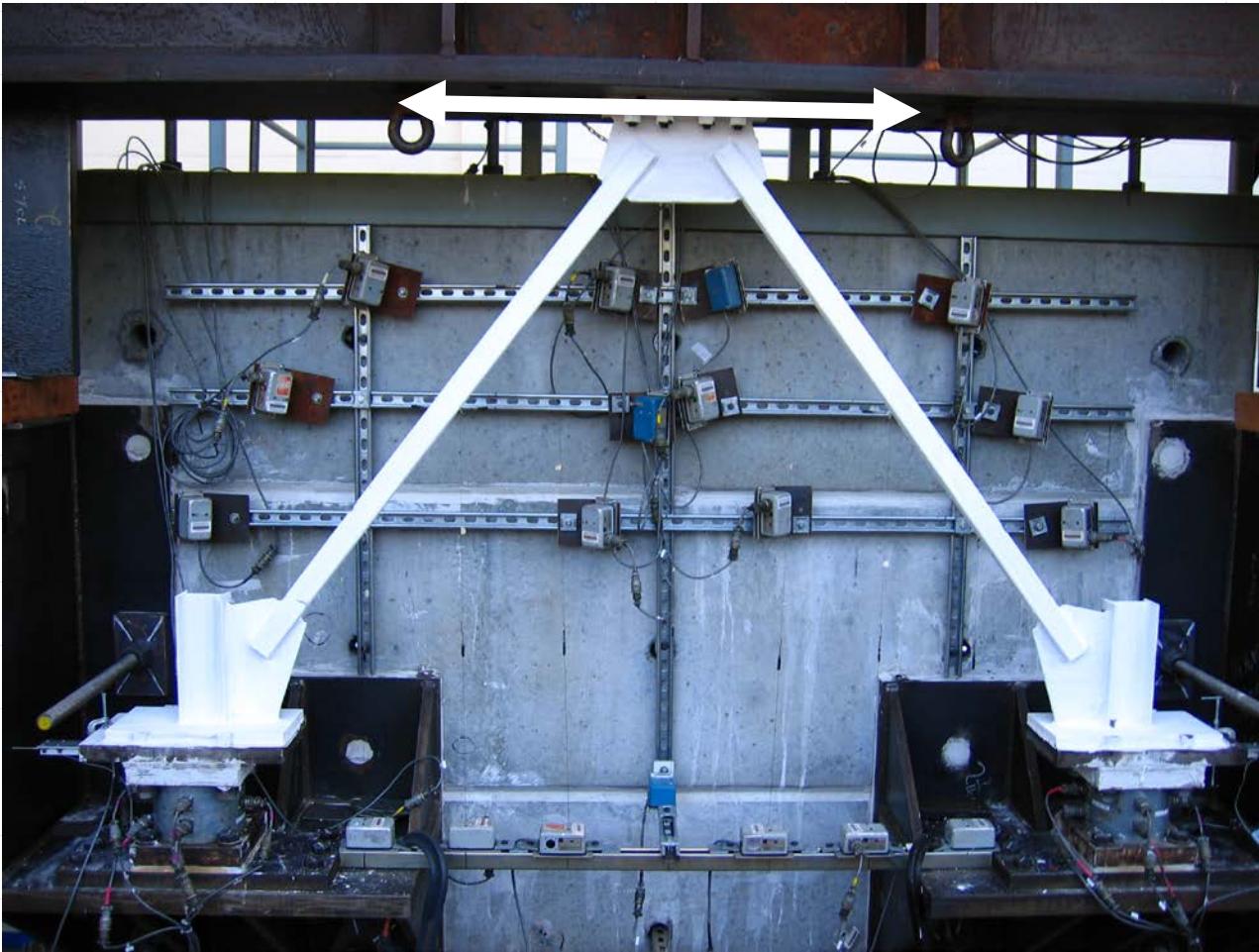
Instrumentation



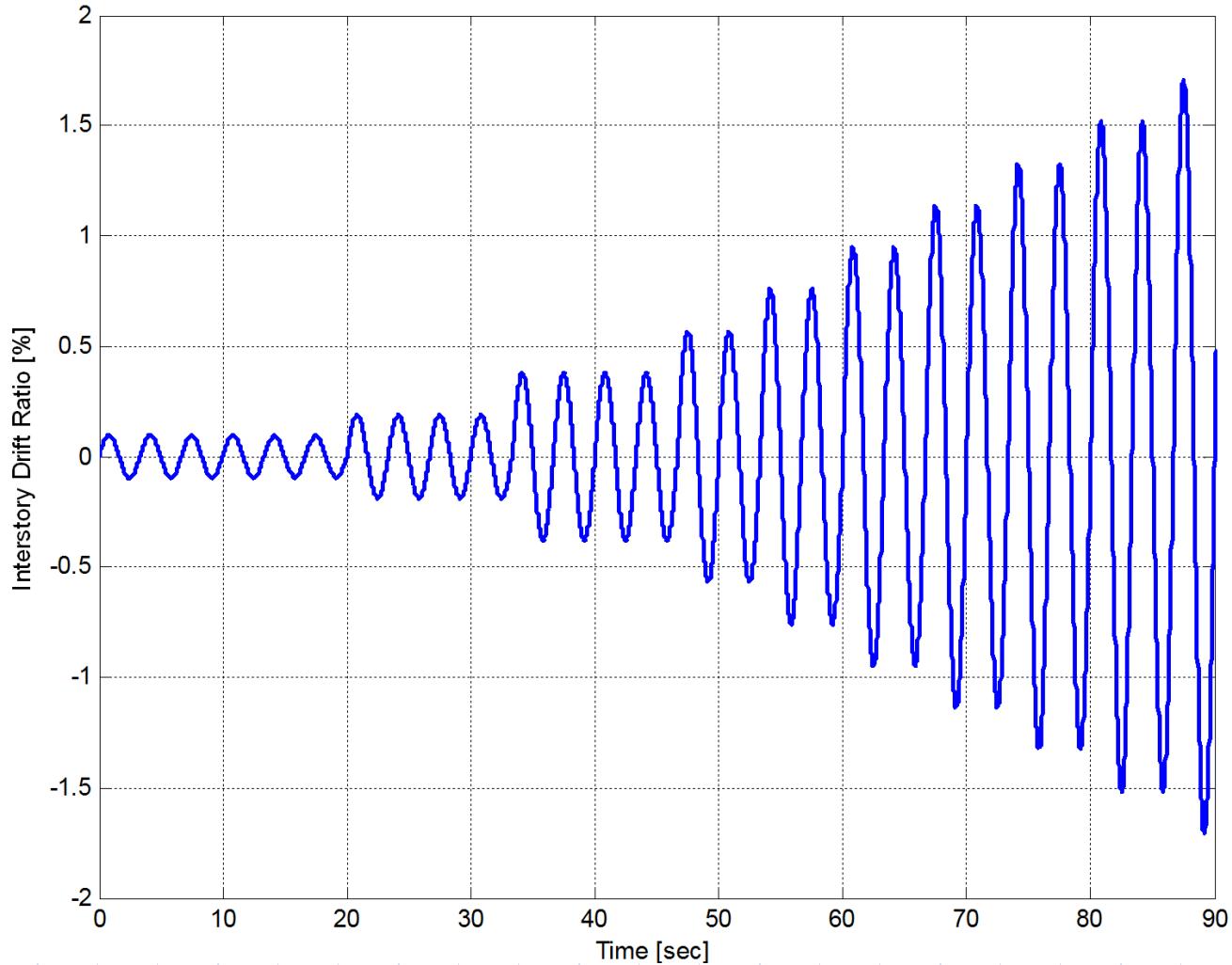
Instrumentation



Quasi-Static Test

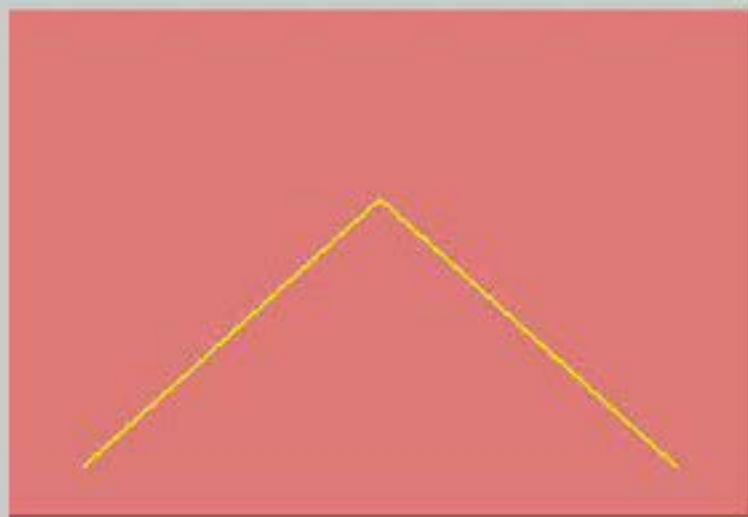
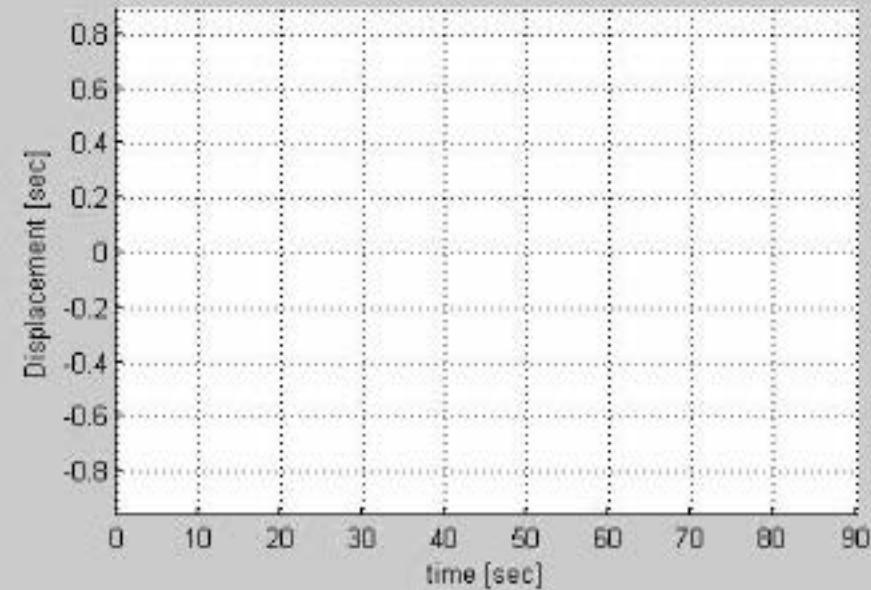


Loading History

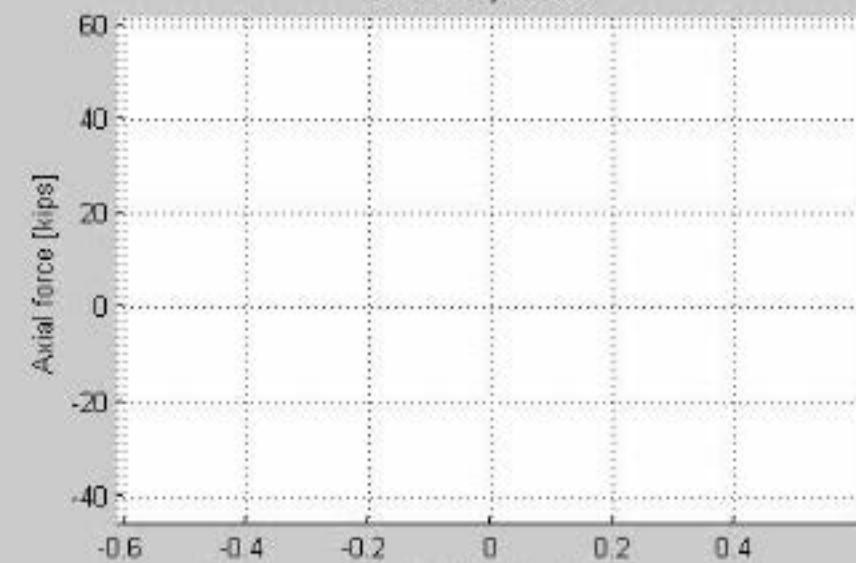


tonyzipperframeRun153.txt

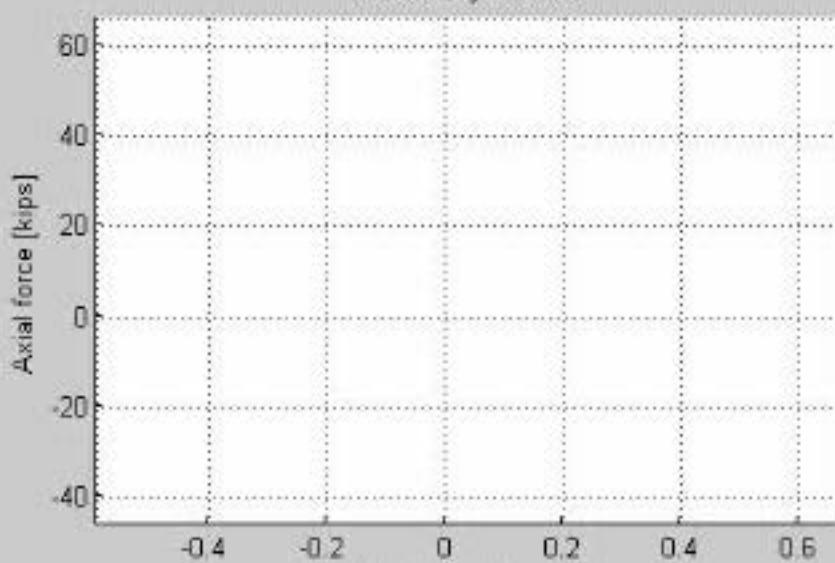
SF = 2.00, Time = 0.00 sec



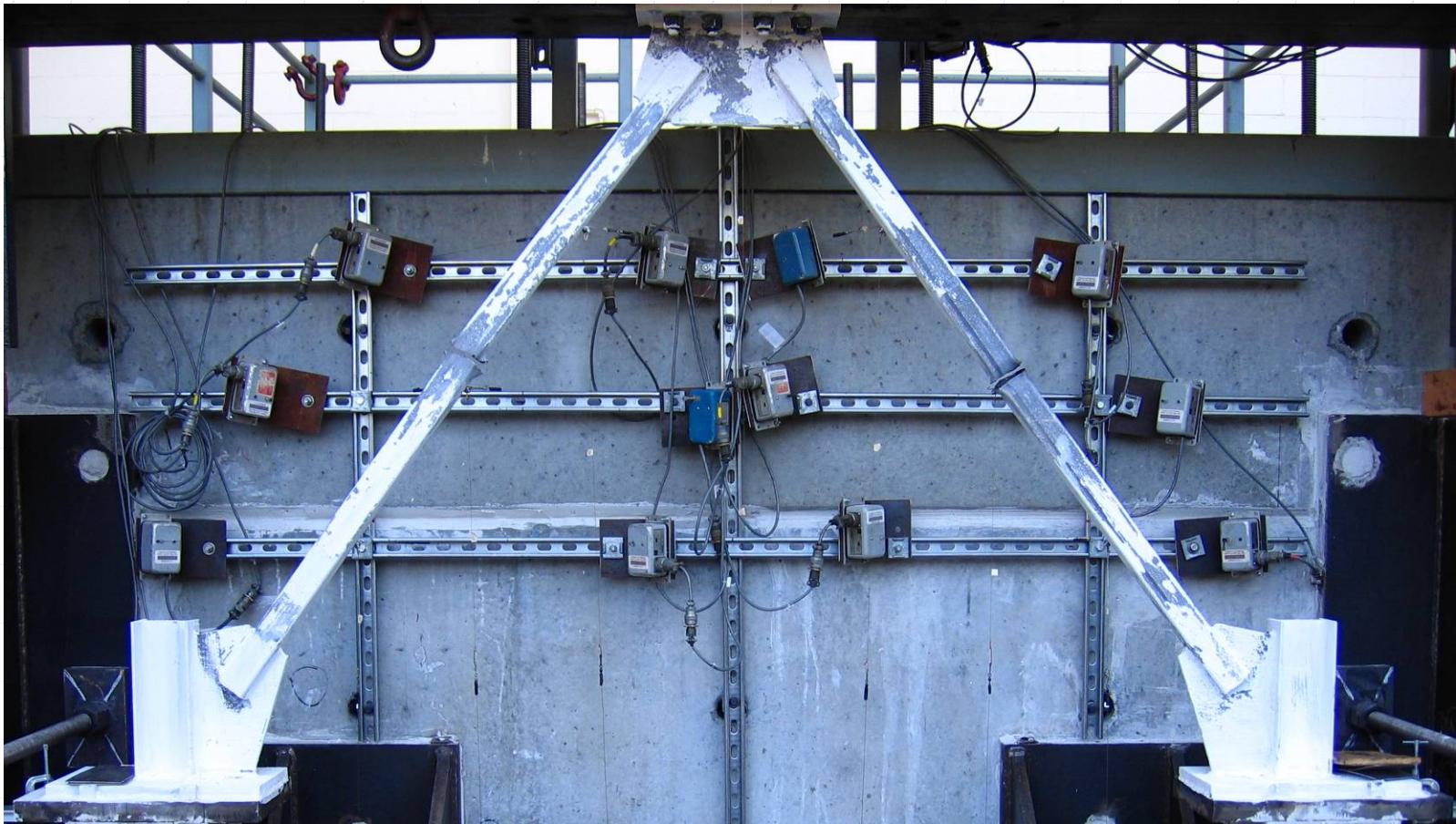
Brace 1 Hysteresis



Brace 2 Hysteresis



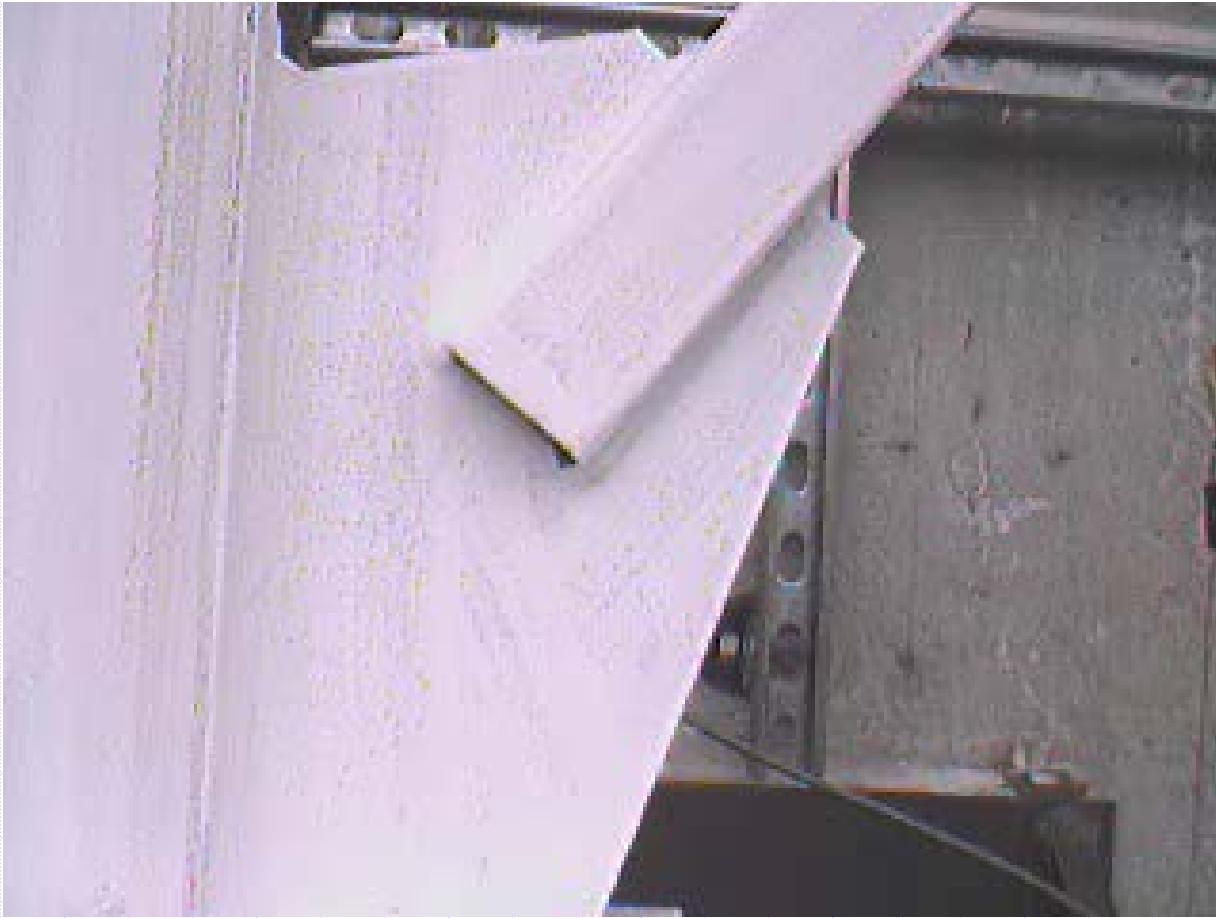
Damaged Specimen



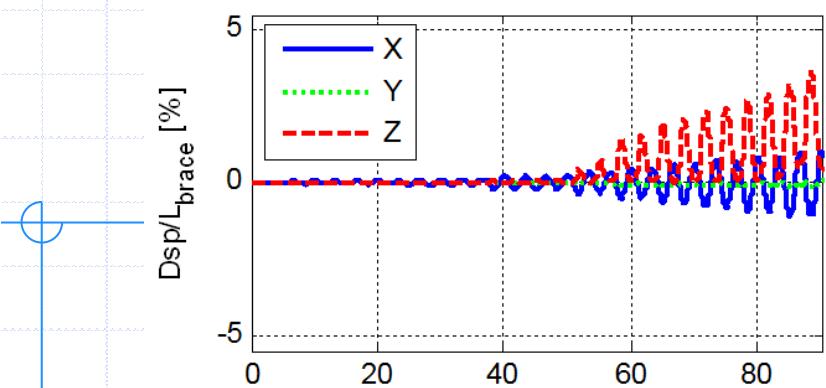
Movie – Out Of Plane Buckling



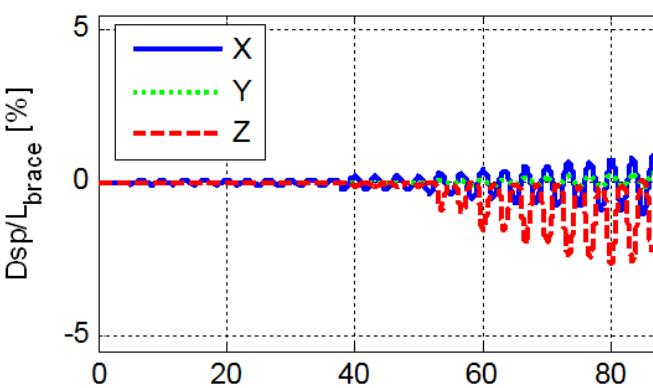
Movie – Gusset Plate



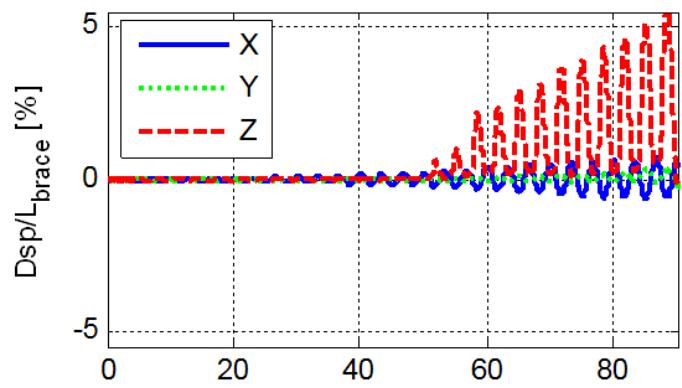
Brace 1 - 3/4 Point



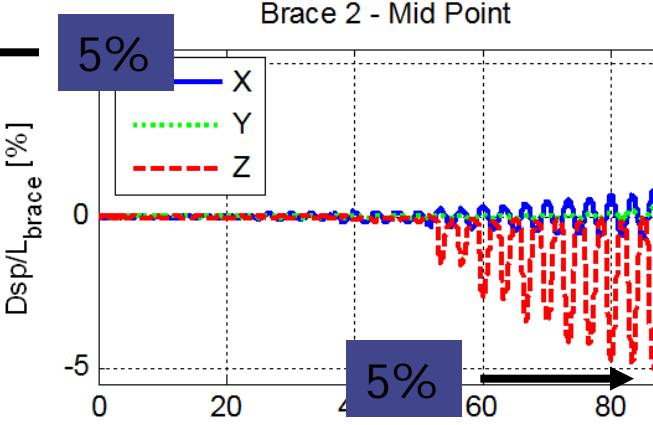
Brace 2 - 3/4 Point



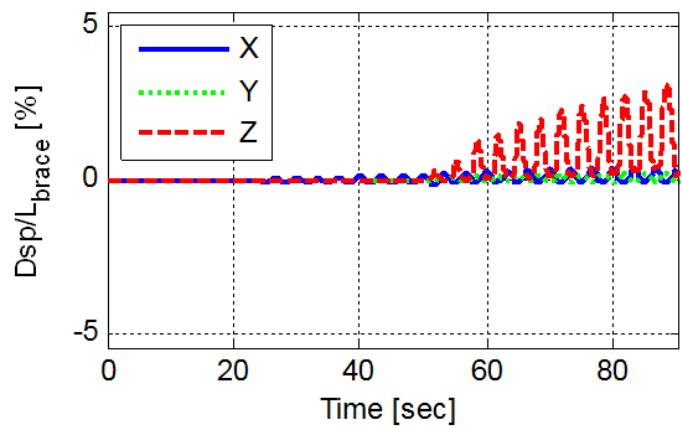
Brace 1 - Mid Point



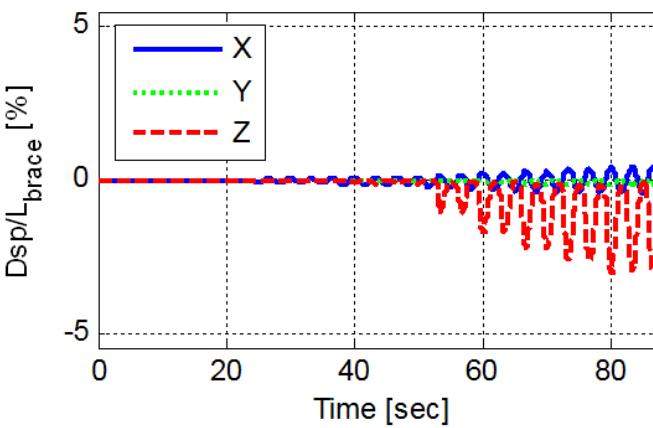
Brace 2 - Mid Point



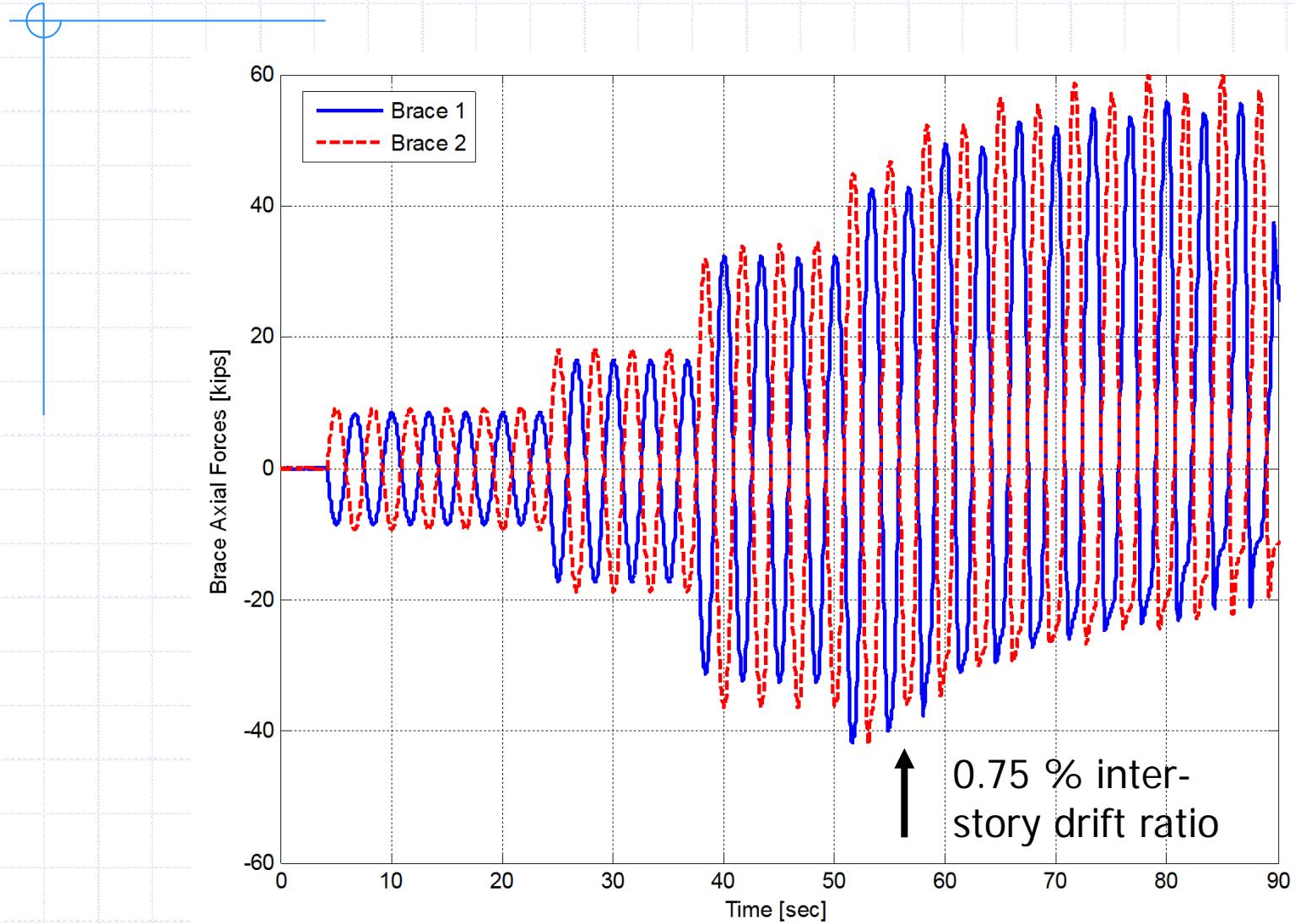
Brace 1 - 1/4 Point



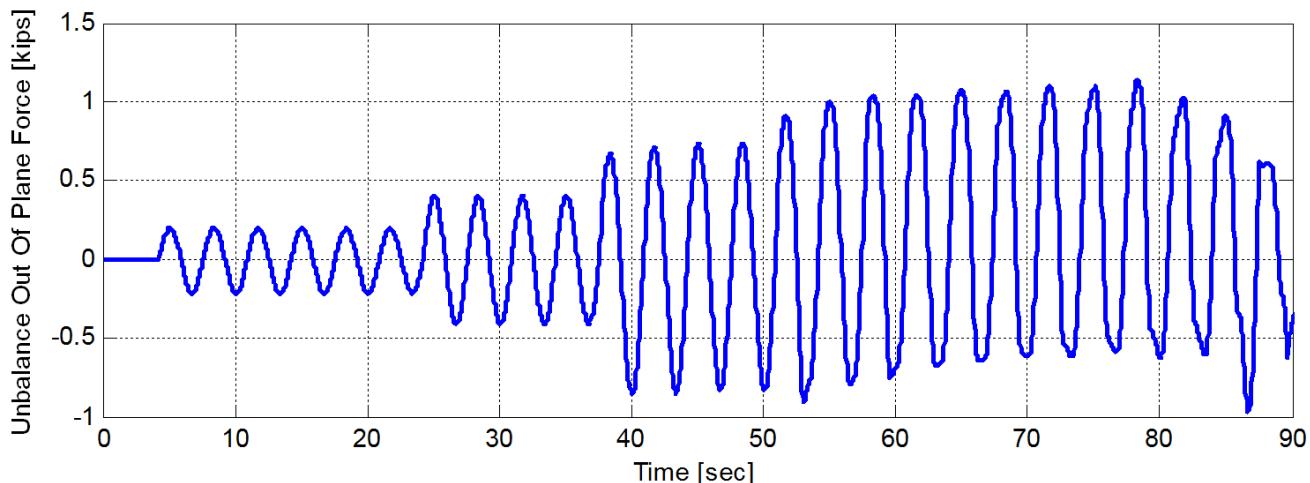
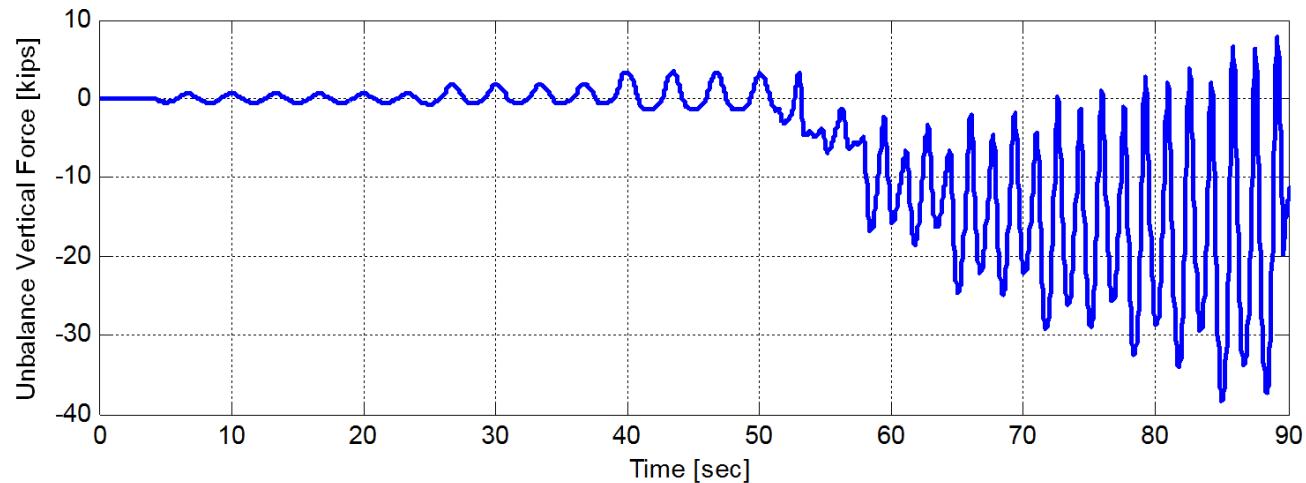
Brace 2 - 1/4 Point



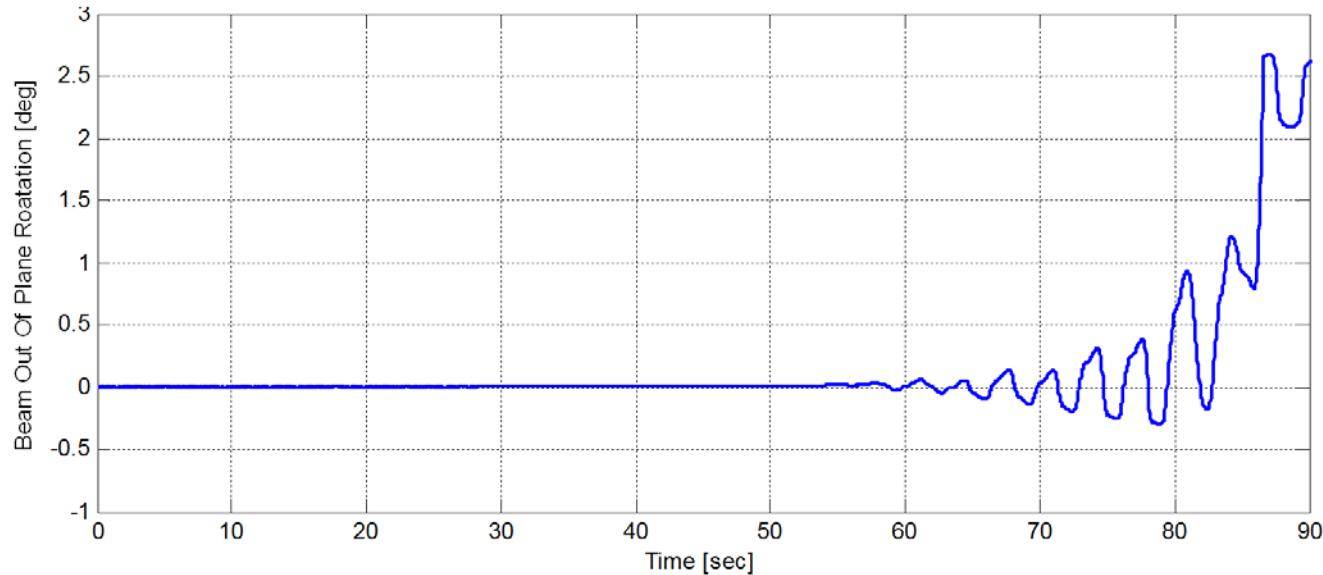
Brace Axial Forces



Unbalanced Forces



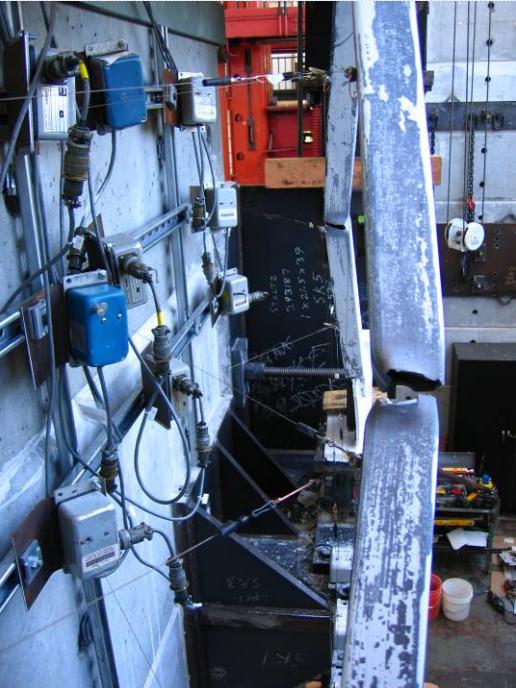
Beam Rotation



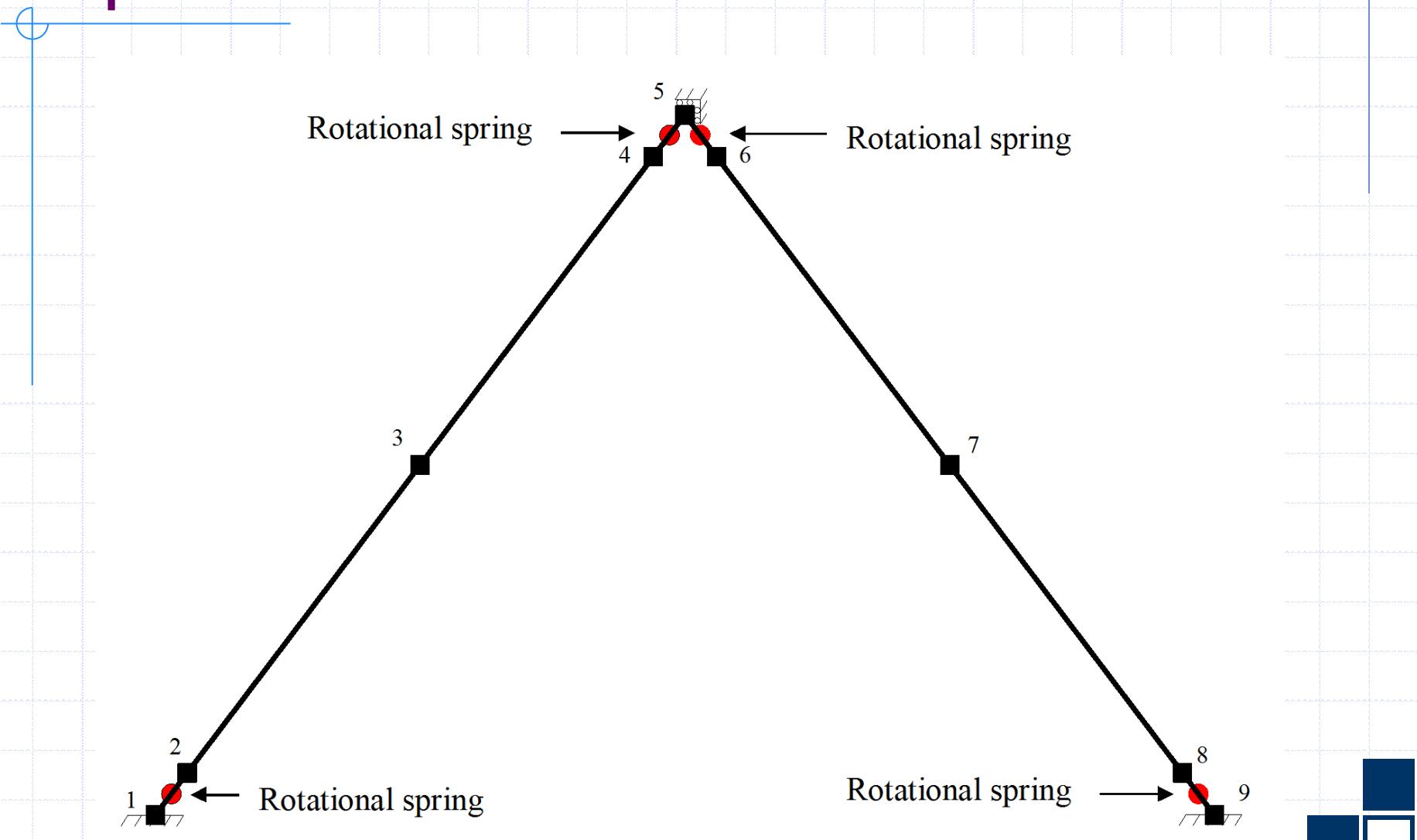
Close Up View of the Braces



More Photos



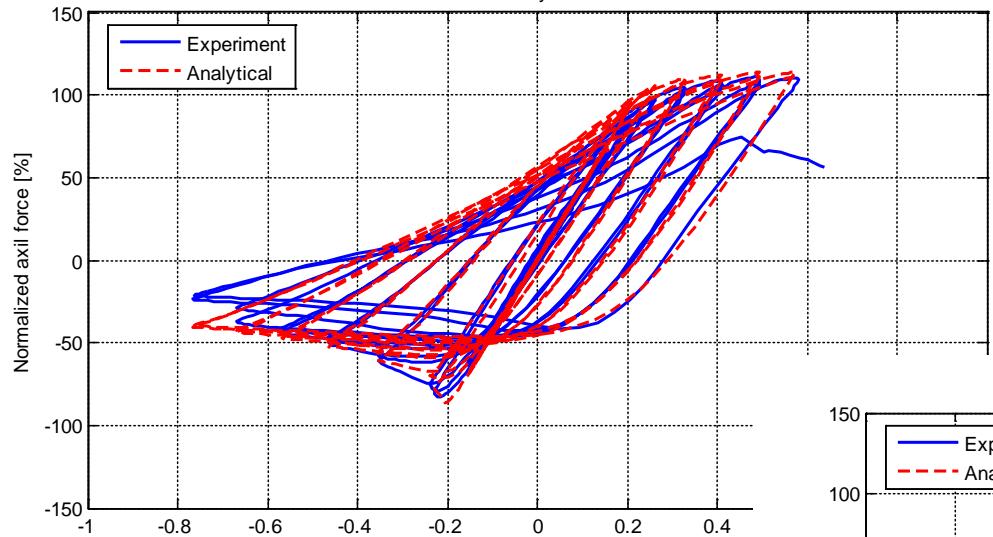
OpenSees Model



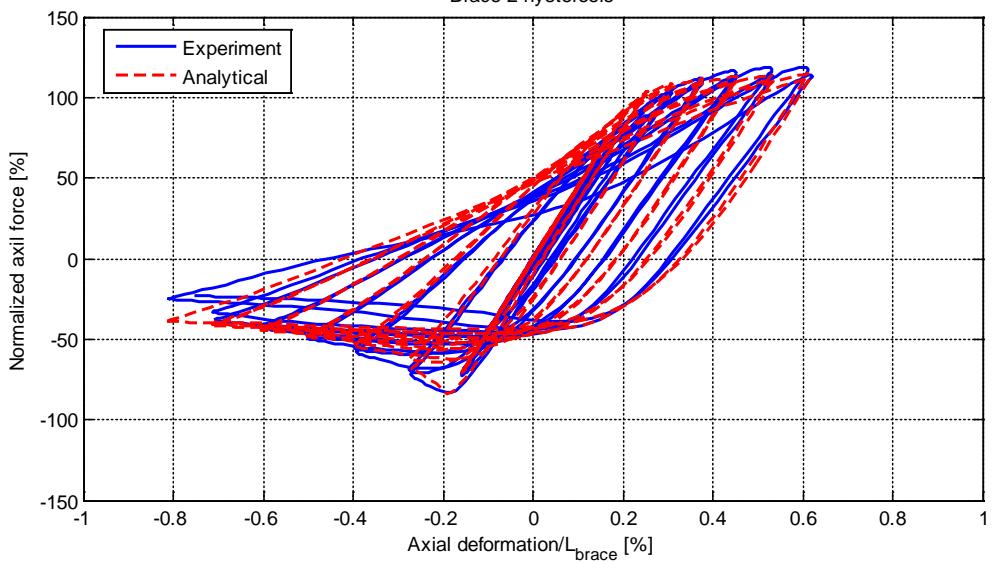
Brace Hysteresis



Brace 1 hysteresis



Brace 2 hysteresis

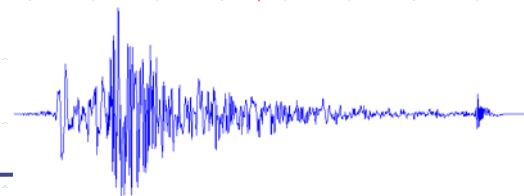
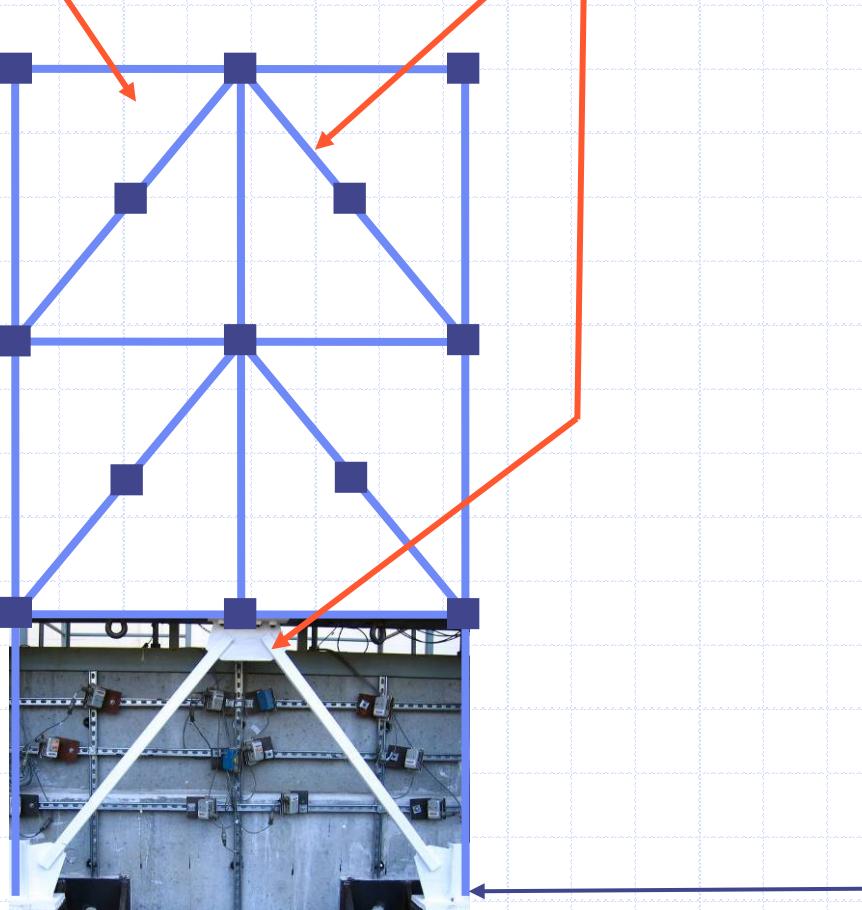


Scope of the Test

- ◆ Analytical simulation of the brace
 - Modeling the analytical brace using OpenSees
- ◆ Quasi-Static testing of the brace
 - Component testing of the brace sub-assembly
- ◆ Hybrid simulation of the frame
 - Analytical model + experimental sub-assembly

Equations of Motion

$$M \ddot{u}_n + C \dot{u}_n + \text{Pr}(u_n, \dot{u}_n) = -M_1 \ddot{u}_{g,n}$$



Solution Algorithm

◆ Newmark integration method

- $u_{n+1} = u_n + h \dot{u}_n + h^2 \left(\left(\frac{1}{2} - \beta \right) \ddot{u}_n + \beta \ddot{u}_{n+1} \right)$
- $\dot{u}_{n+1} = \dot{u}_n + h \left((1 - \gamma) \ddot{u}_n + \gamma \ddot{u}_{n+1} \right)$

γ and β are constant coefficients

When $\gamma = 1/2$ and $\beta = 1/4$ (average acceleration method)

When $\gamma = 1/2$ and $\beta = 1/6$ (linear acceleration method)

Solution Algorithm

◆ Newmark integration method

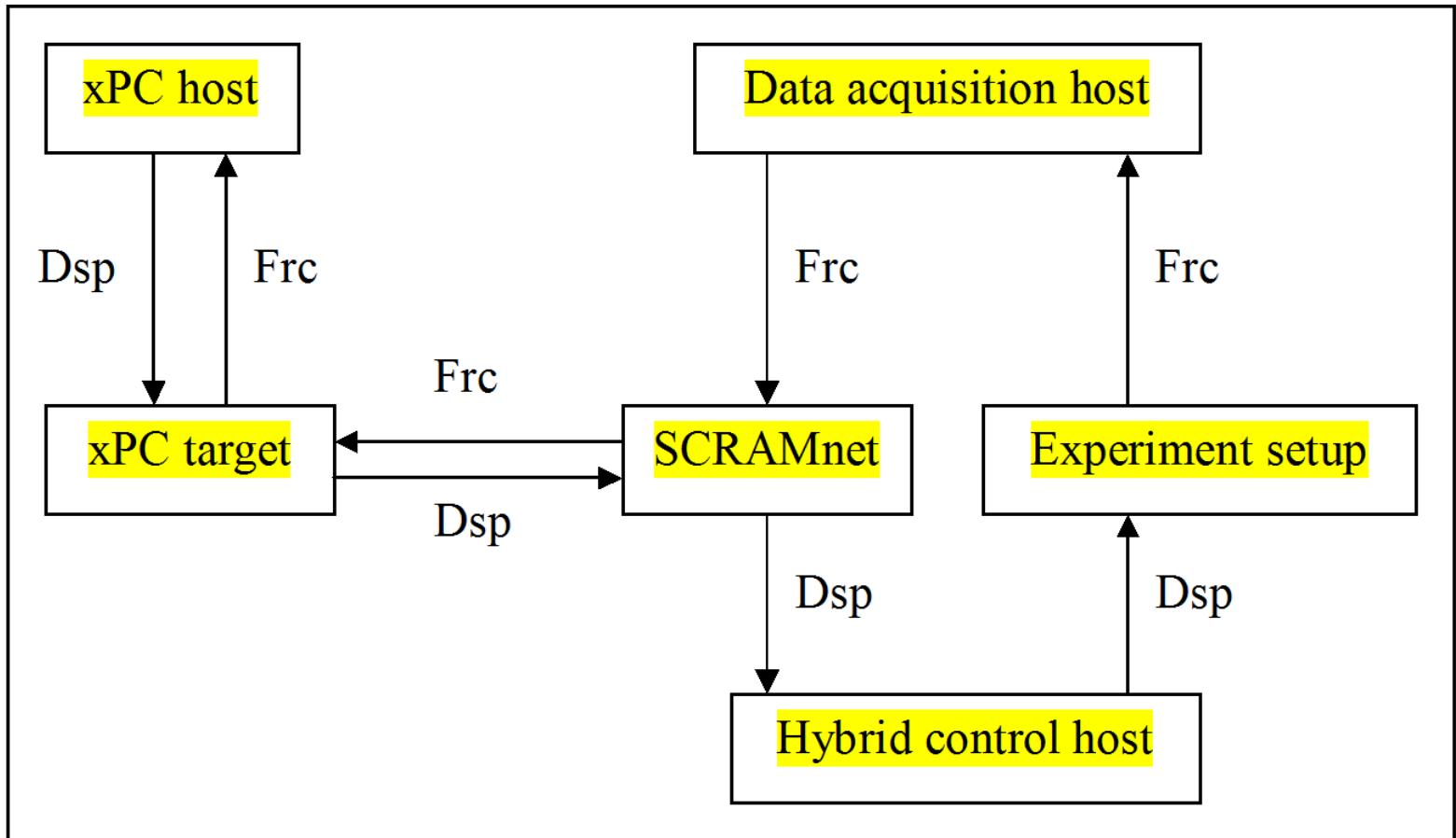
$$M \ddot{u}_{n+1} + C \dot{u}_{n+1} + \text{Pr}(u_{n+1}, \dot{u}_{n+1}) = -M \tau \ddot{u}_{g,n+1}$$

$$F(u) = M \left(\frac{1}{\beta h^2} (u - u_n) - \frac{1}{\beta h} \dot{u}_n - \left(\frac{1}{2\beta} - 1 \right) \ddot{u}_n \right)$$

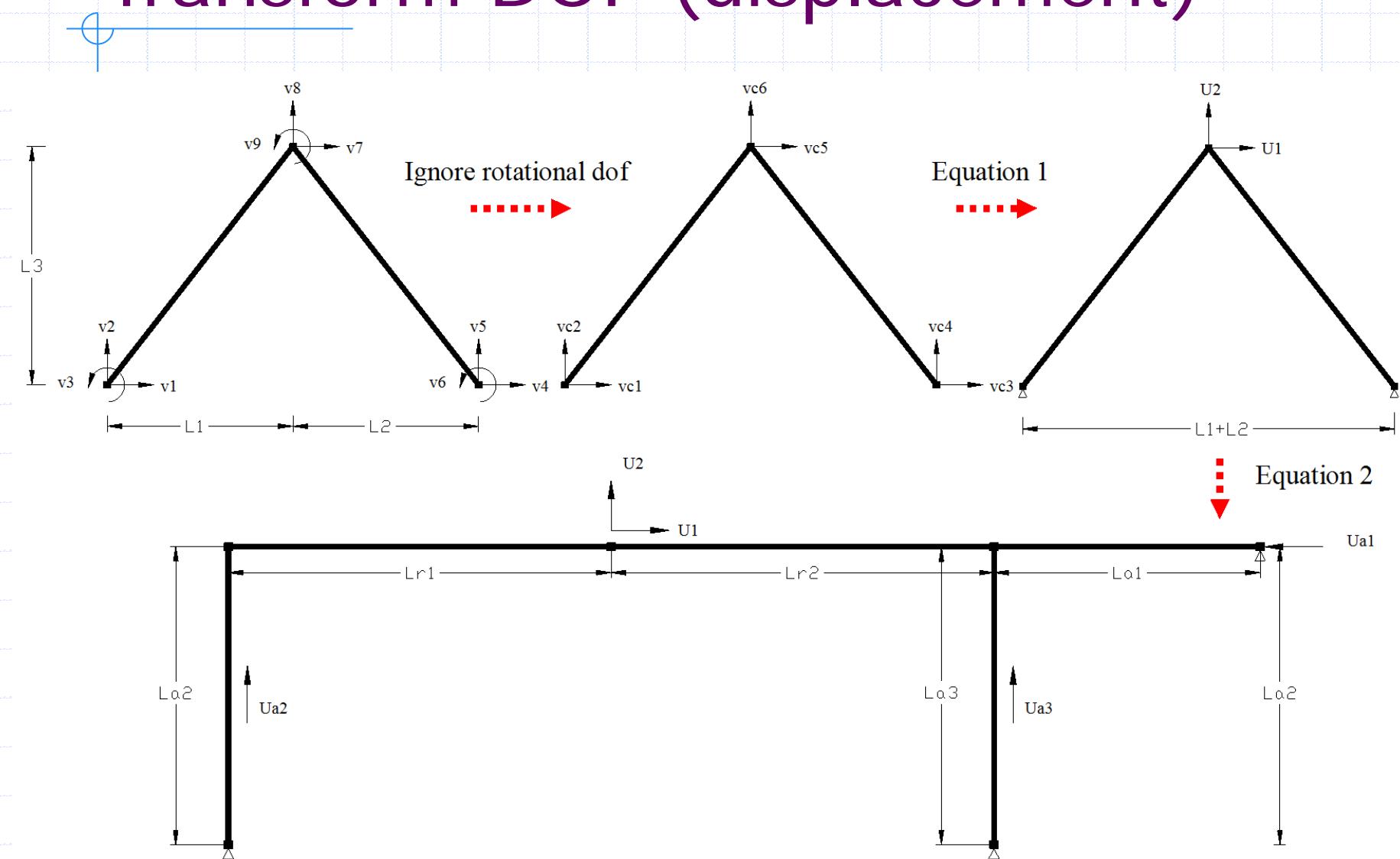
$$+ C \left(\frac{\gamma}{\beta h} (u - u_n) - \left(\frac{\gamma}{\beta} - 1 \right) \dot{u}_n - h \left(\frac{\gamma}{2\beta} - 1 \right) \ddot{u}_n \right)$$

$$+ \text{Pr}(u, u_n, \dot{u}_n, \ddot{u}_n) - P_{n+1} = 0$$

Experimental Testing Architecture



Transform DOF (displacement)

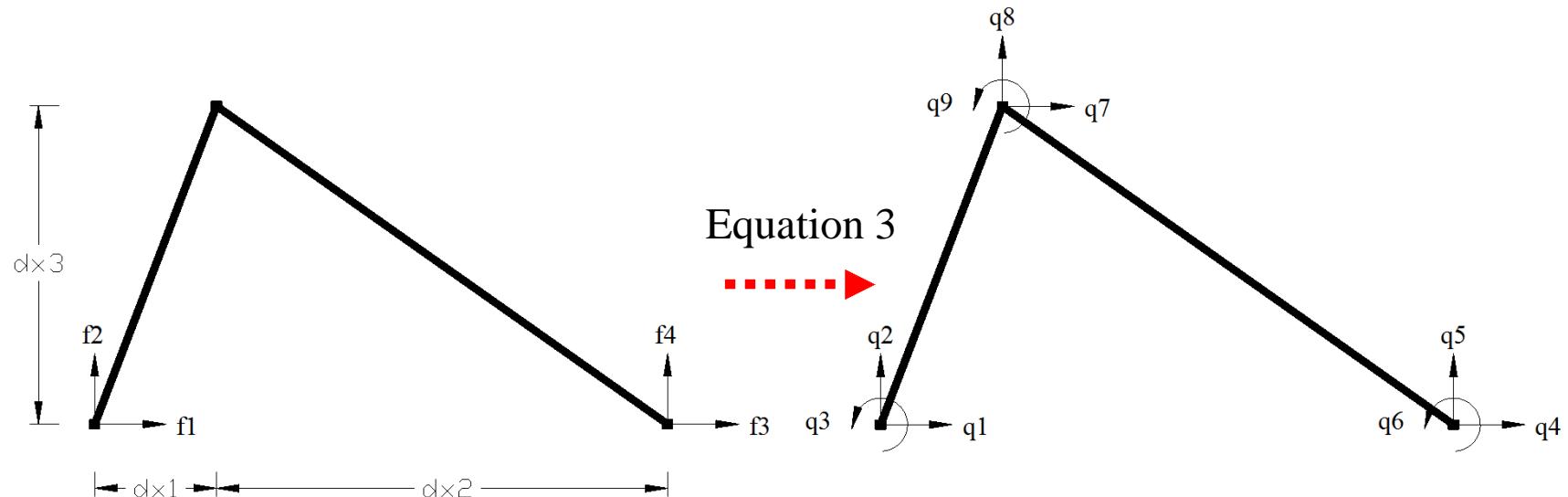


Transform DOF (displacement)

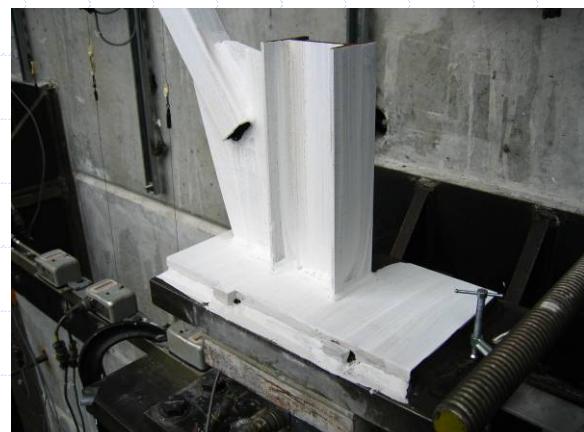
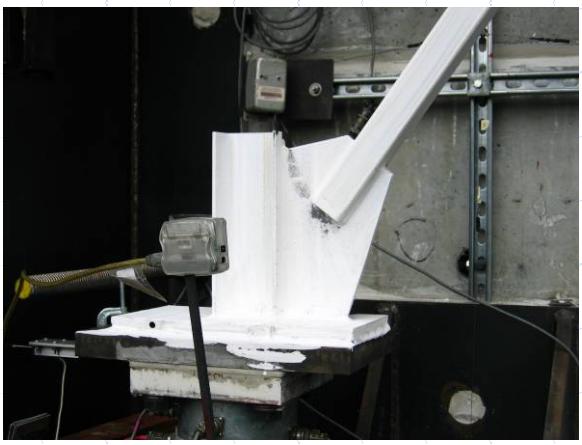
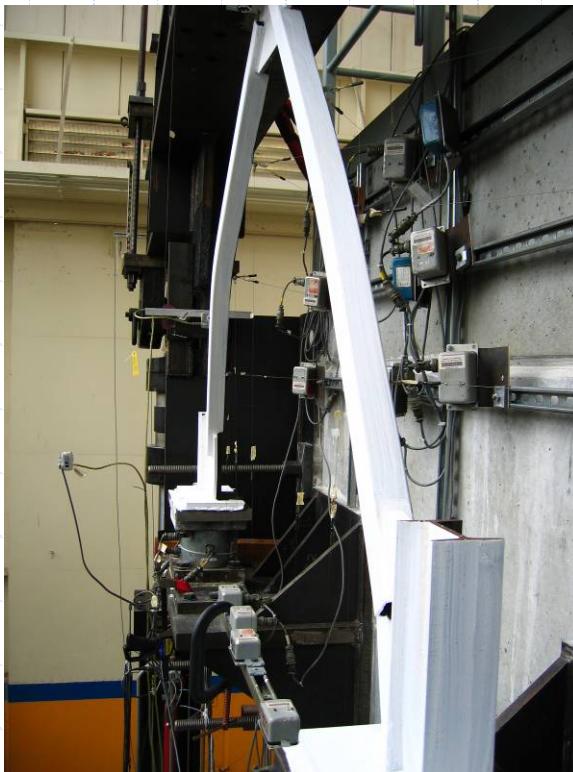


Measured forces

Force feedback to OpenSees

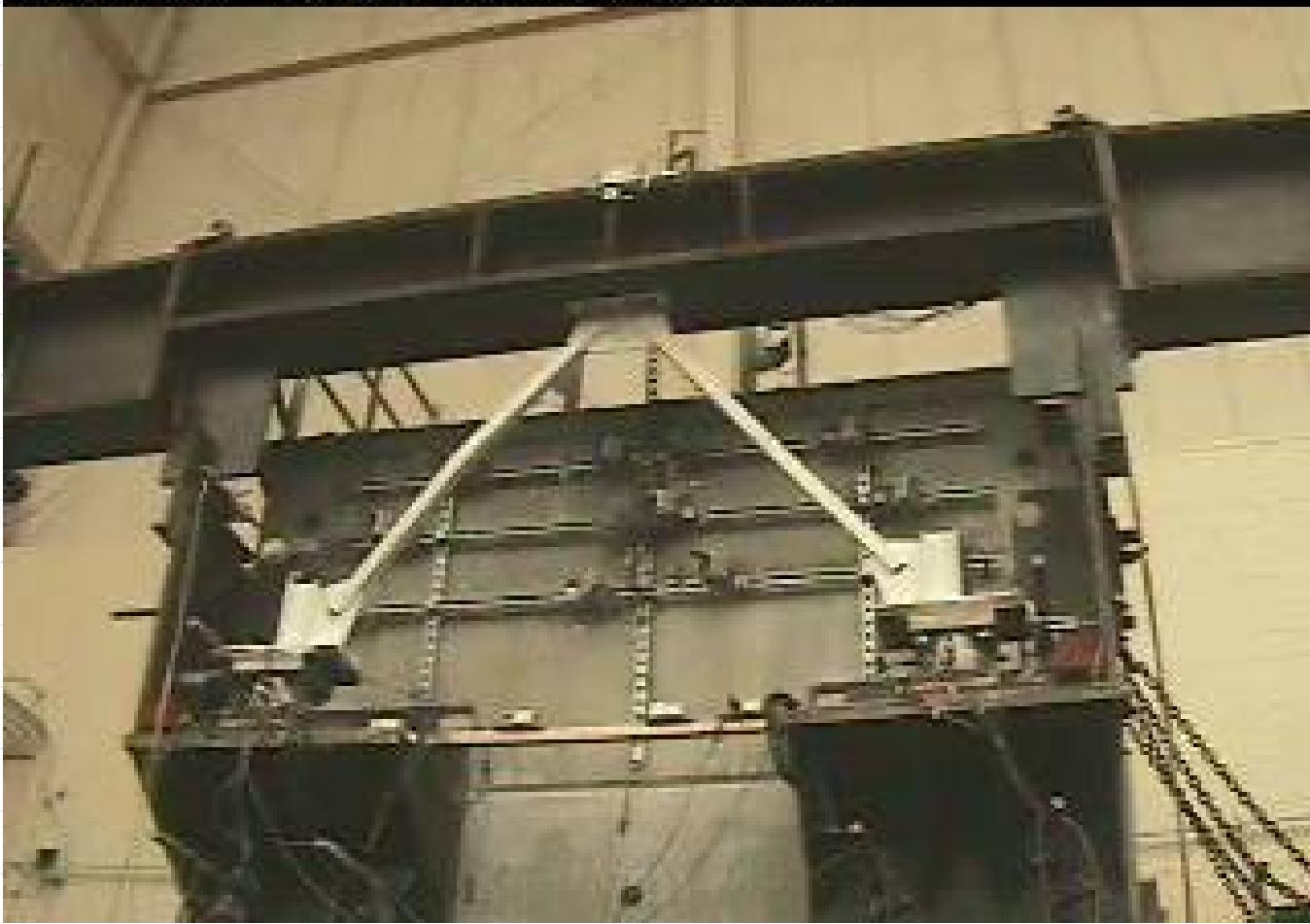


Damaged Specimen (100% LA22YY)

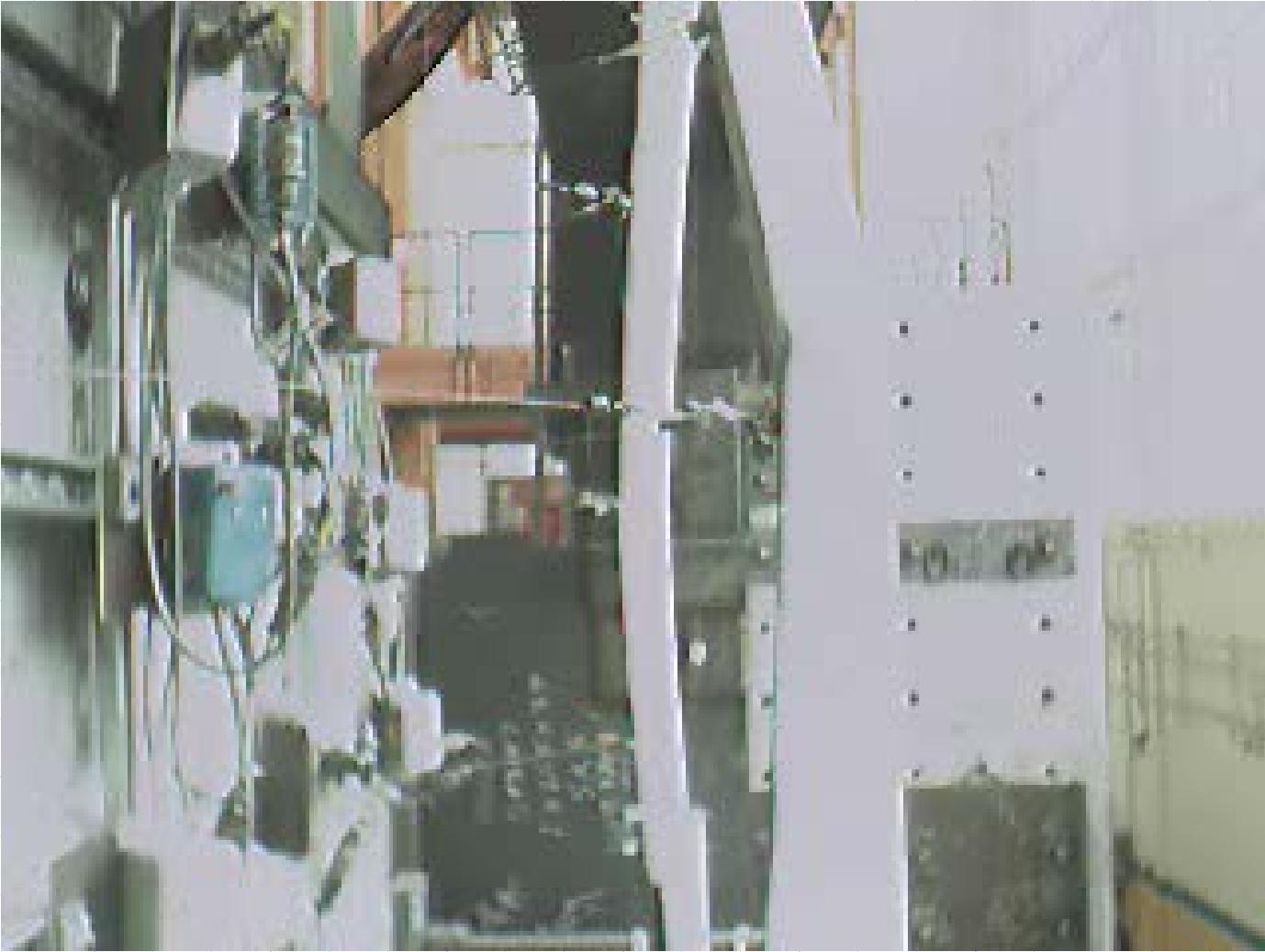


Movie – LA22YY(200%)

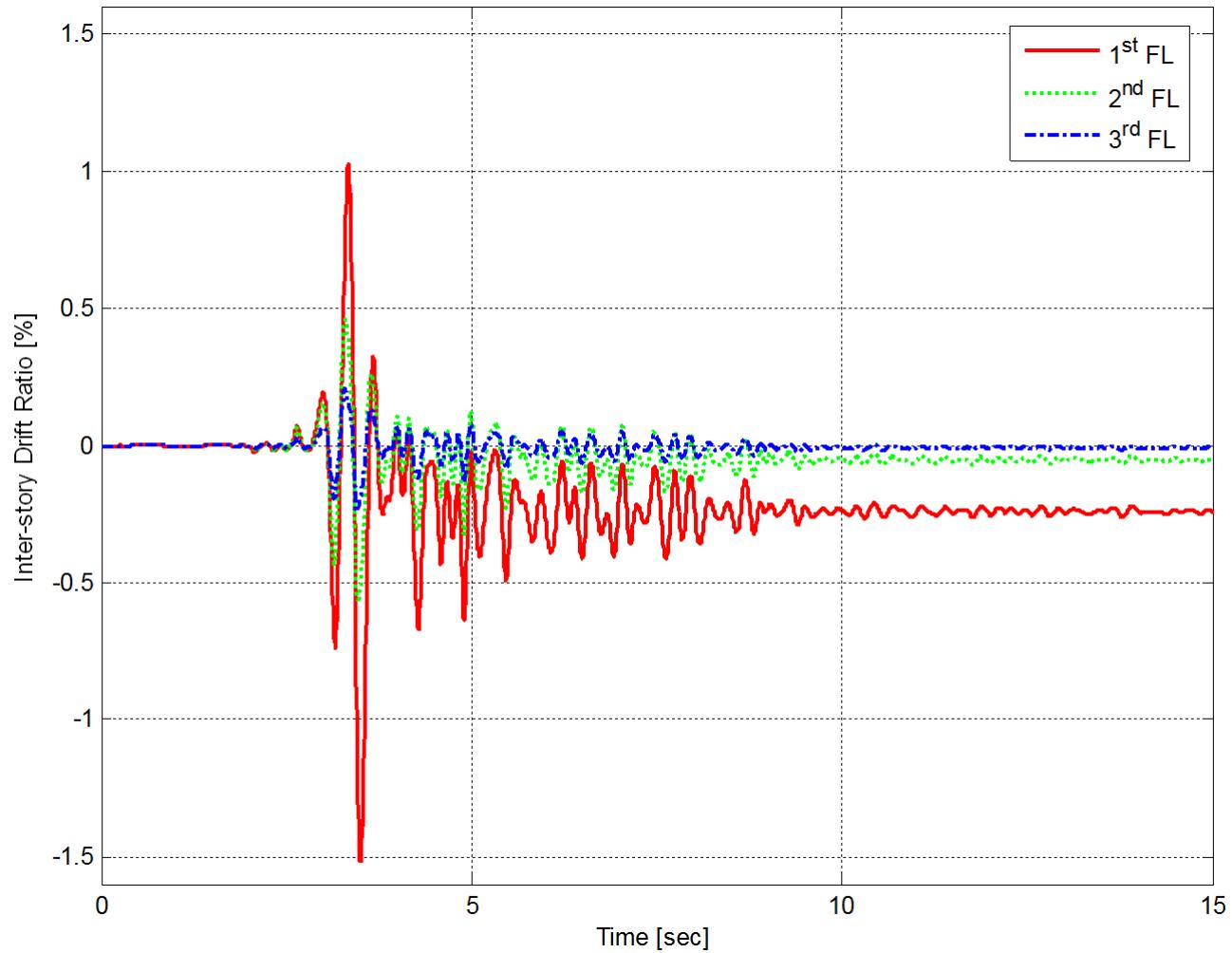
NEES Lab Thu Jun 16 14:35:00 2005



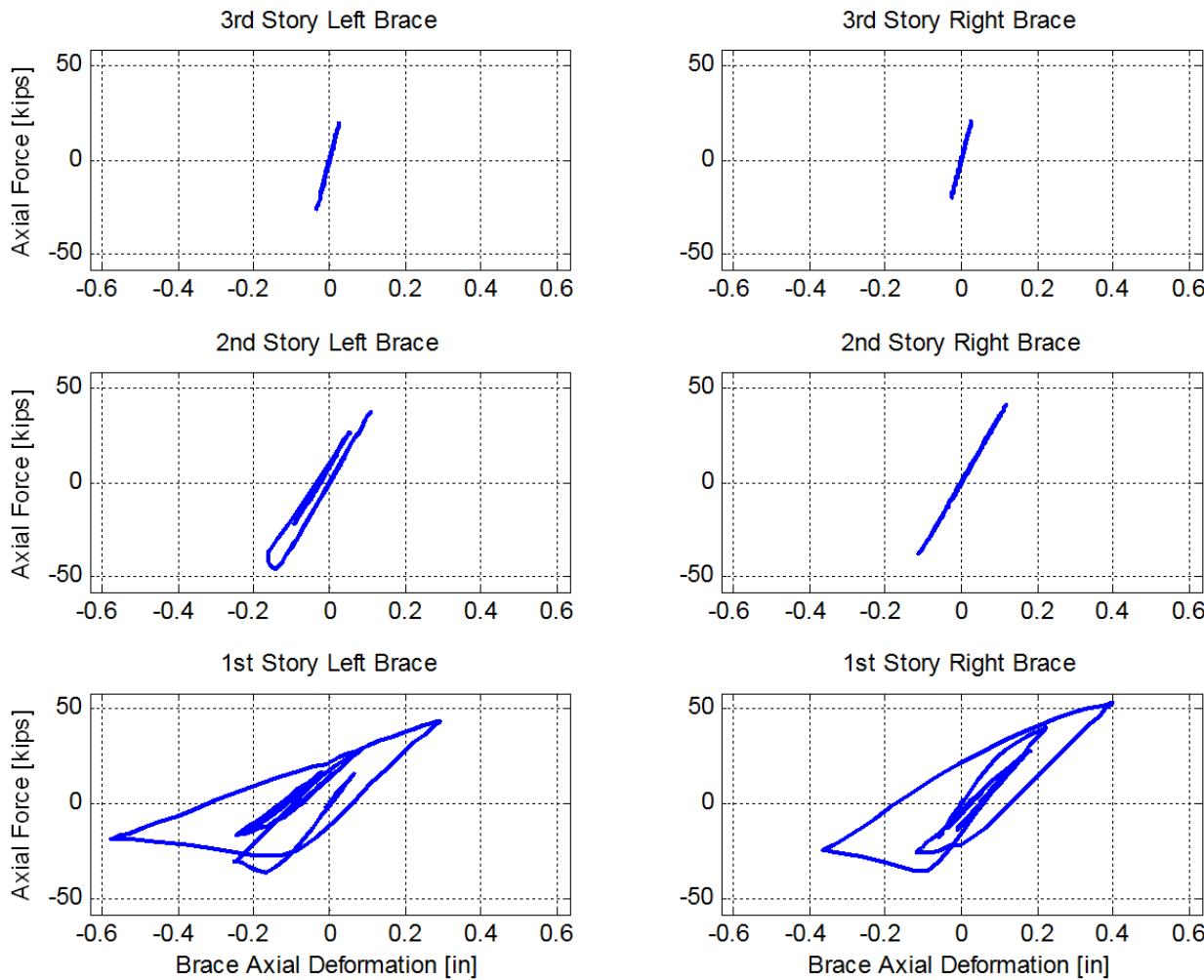
Movie – Out Of Plane Buckling



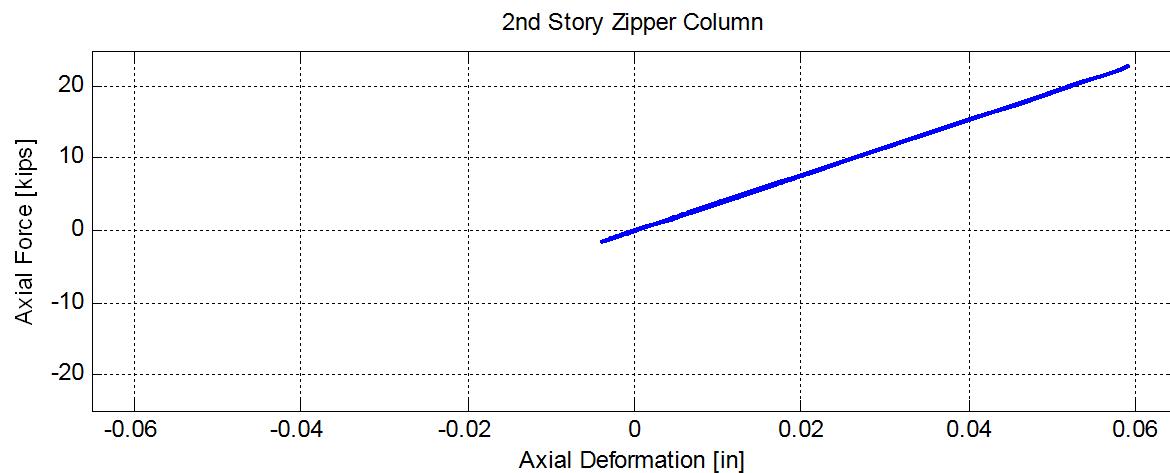
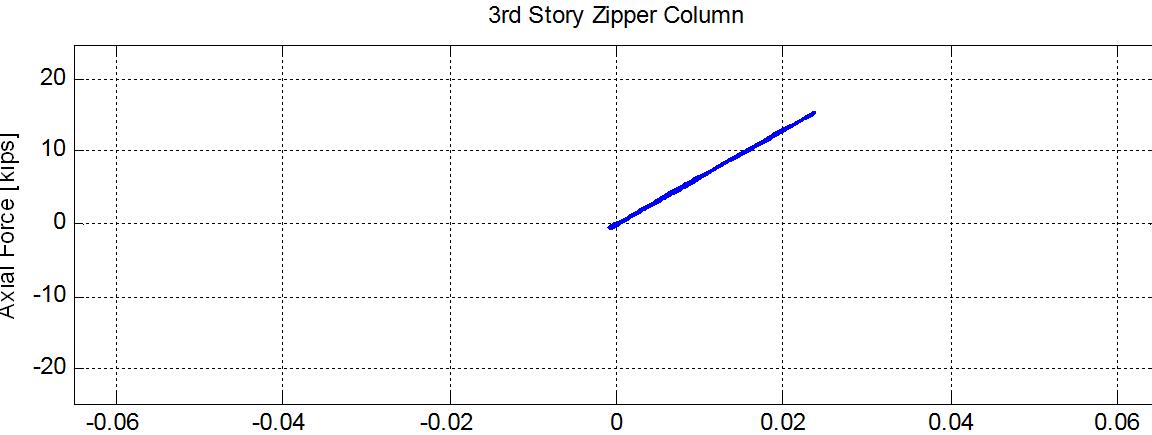
Hybrid Simulation Results



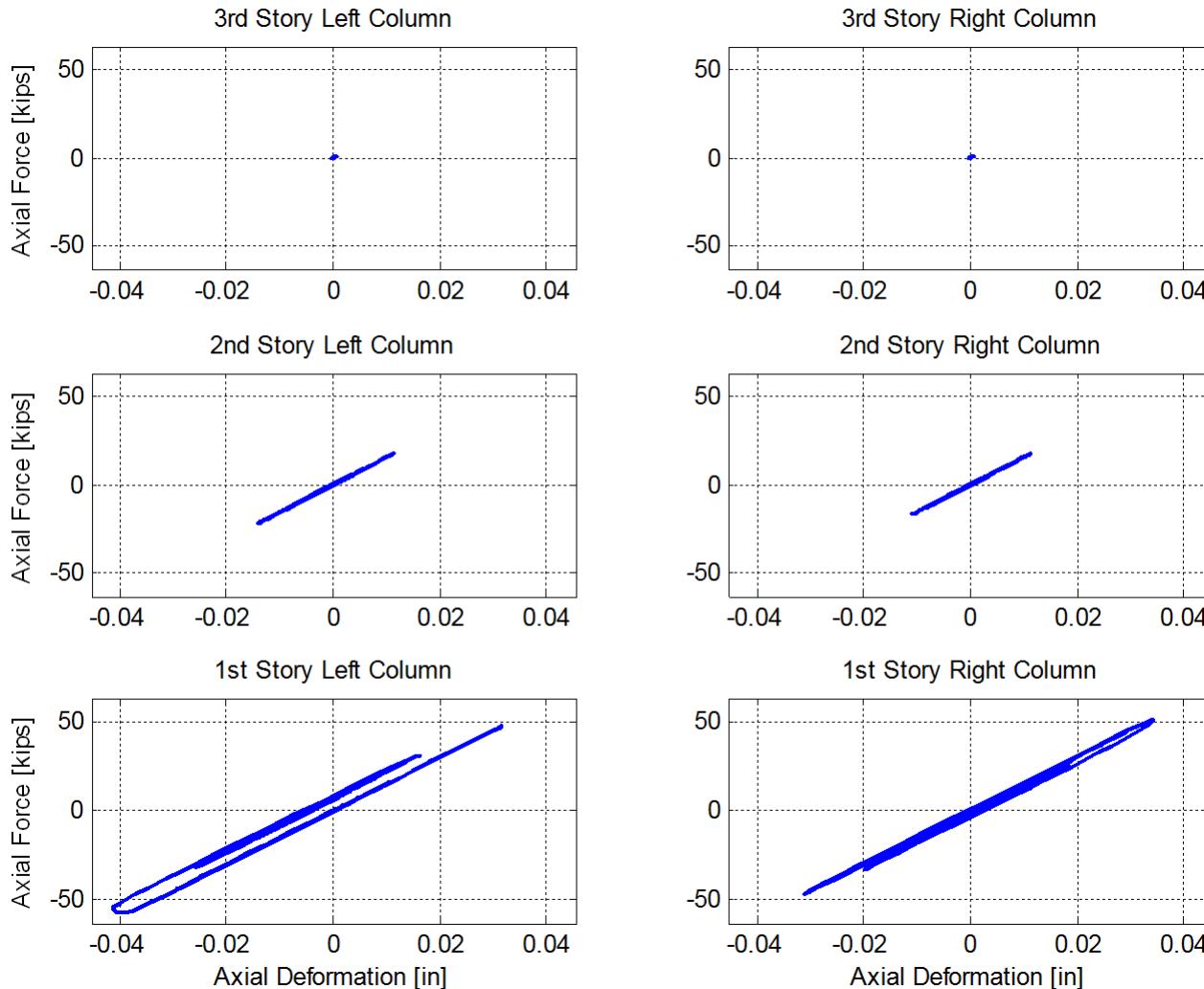
Hybrid Simulation Results



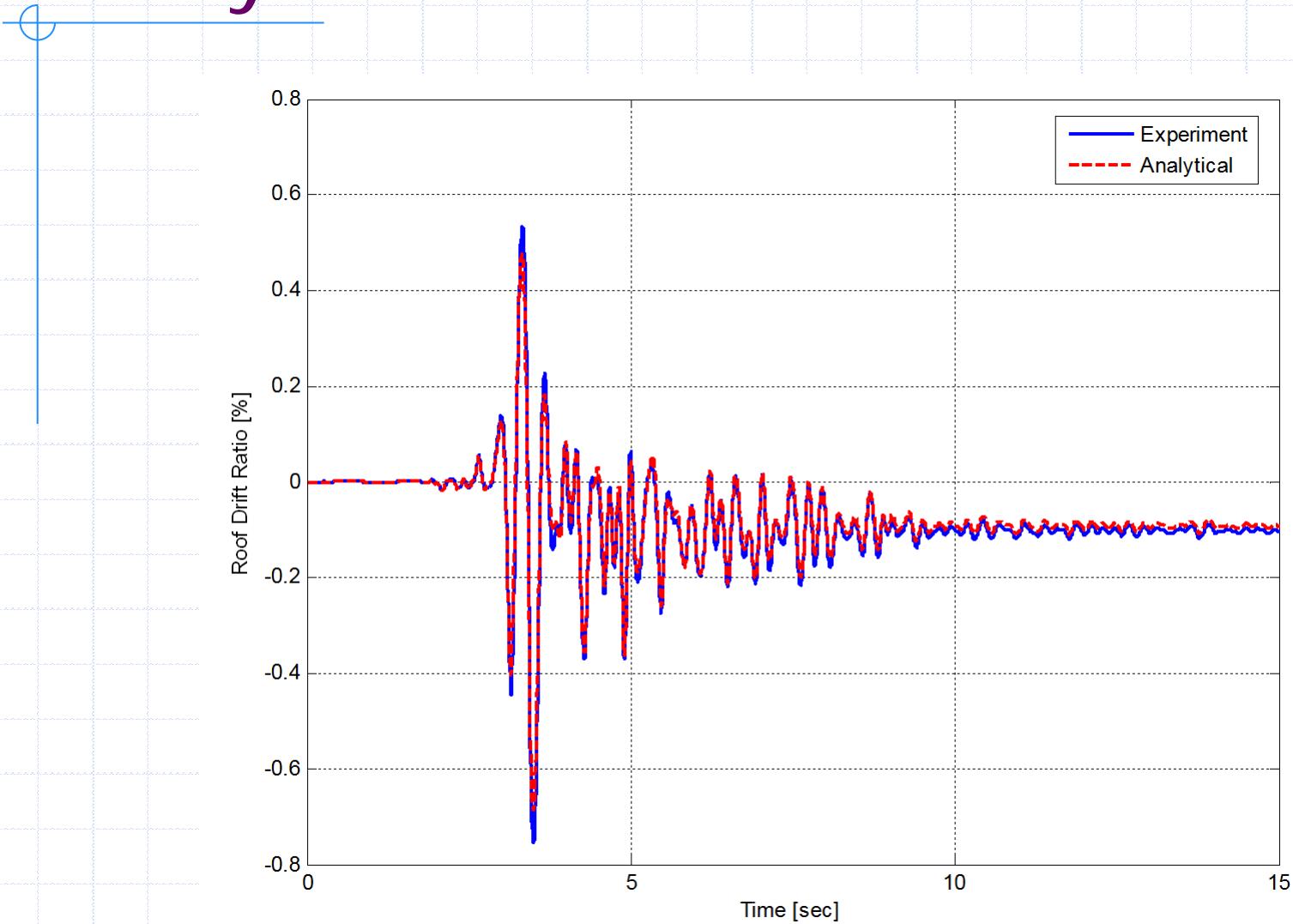
Hybrid Simulation Results



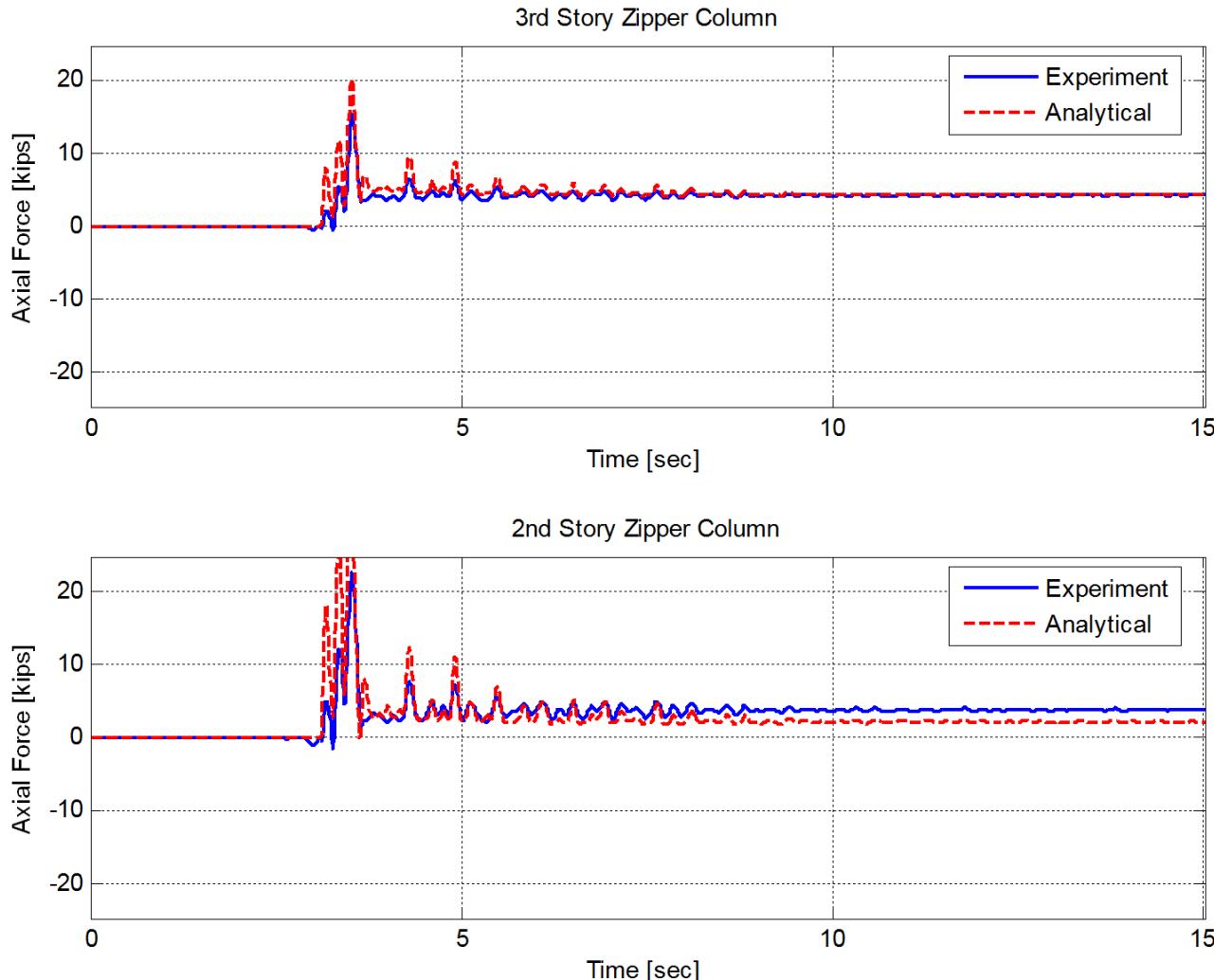
Hybrid Simulation Results



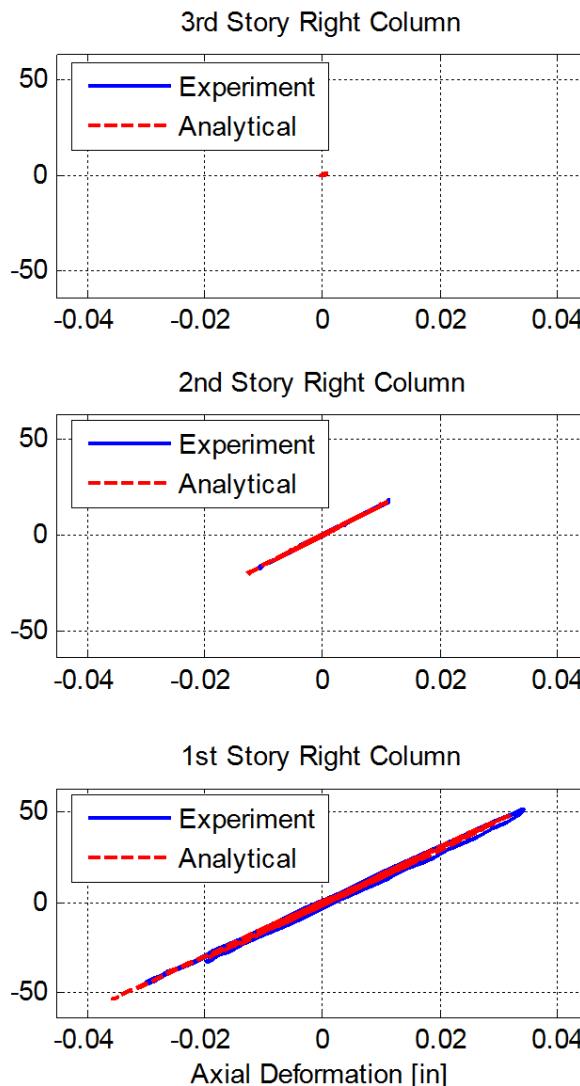
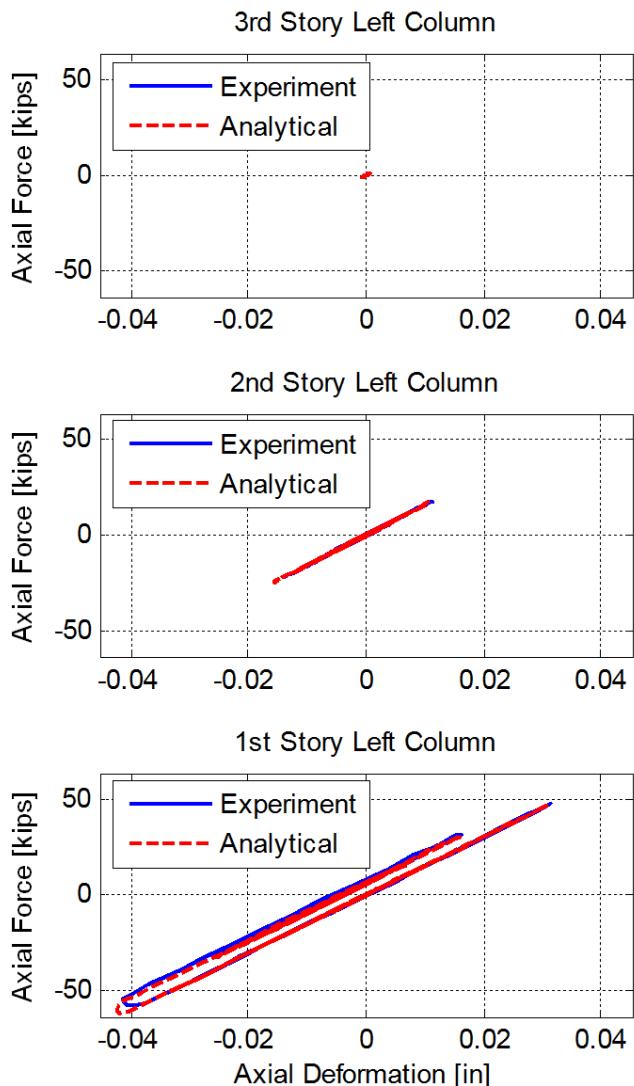
Analytical Verification



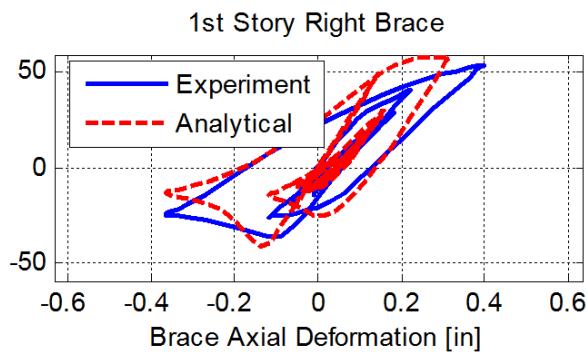
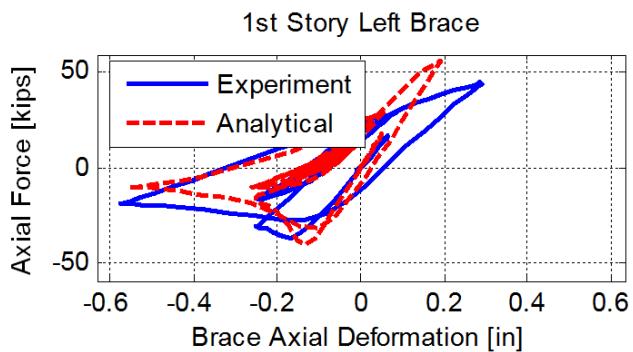
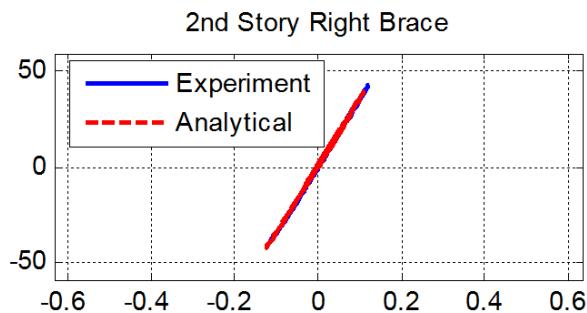
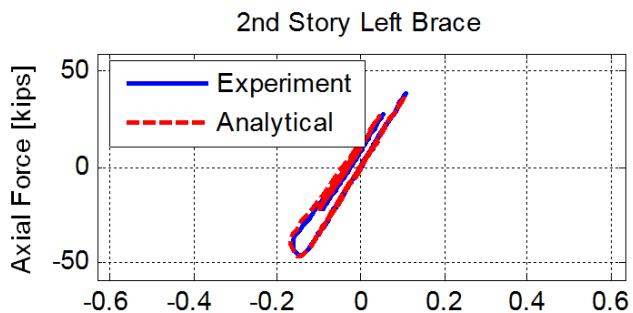
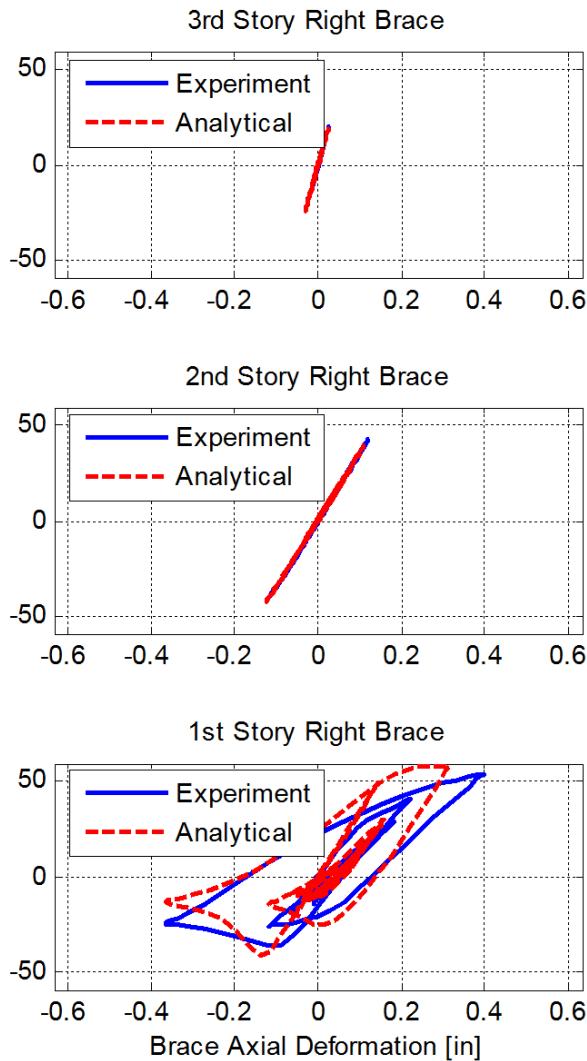
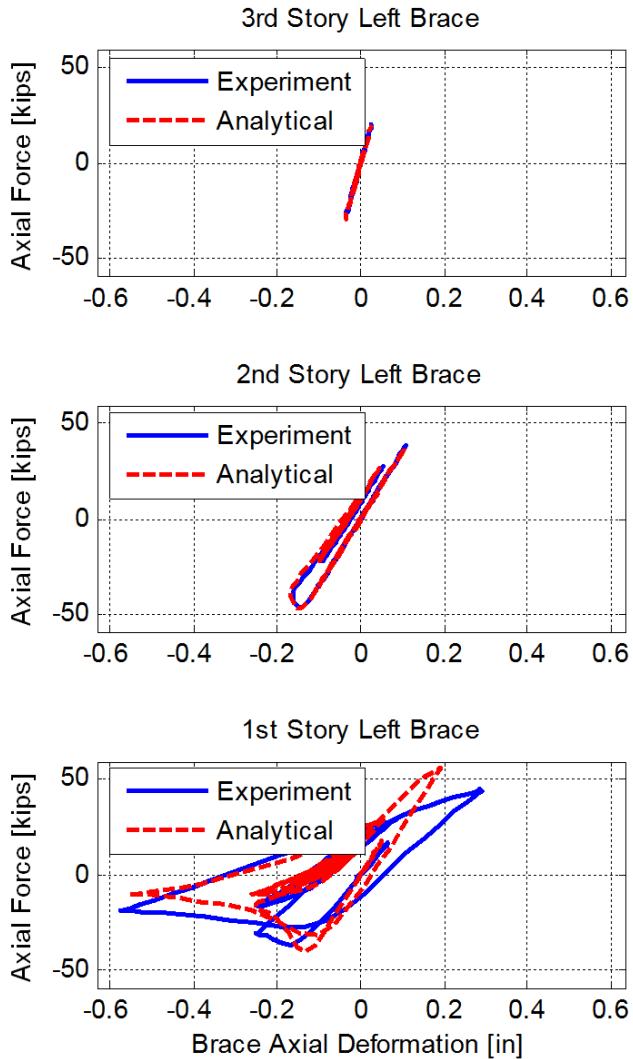
OpenSees Verification



OpenSees Verification



OpenSees Verification



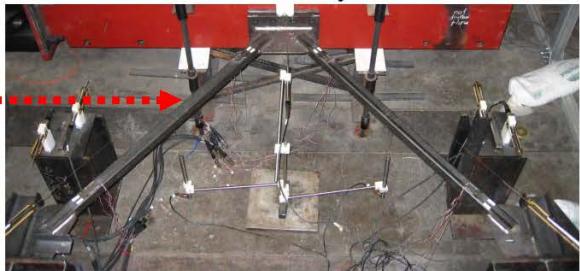
Distributed Hybrid Simulation



University of California at Berkeley



Colorado University Boulder



Summary

- ◆ System evaluation of the suspended zipper frame
- ◆ Analytical simulation of the brace
 - Modeling the analytical brace using OpenSees
- ◆ Quasi-Static testing of the brace
 - Component testing of the brace sub-assembly
- ◆ Hybrid simulation test
 - Analytical model + experimental sub-assembly

Conclusion

◆ Results of the hybrid simulation

- Excellent match between the hybrid simulation results and analytical simulation.
- Good analytical brace model and experimental testing.
- Solution algorithm and experimental testing architecture works.

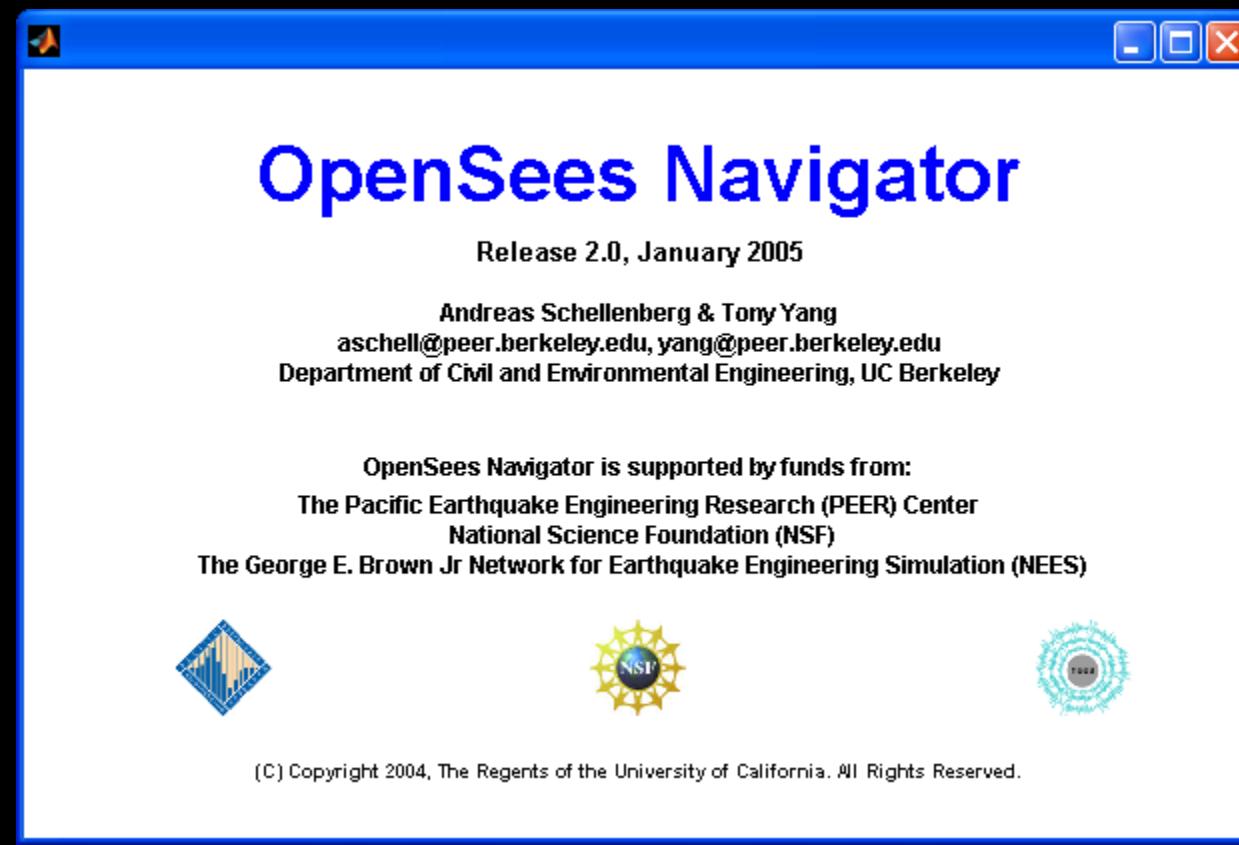


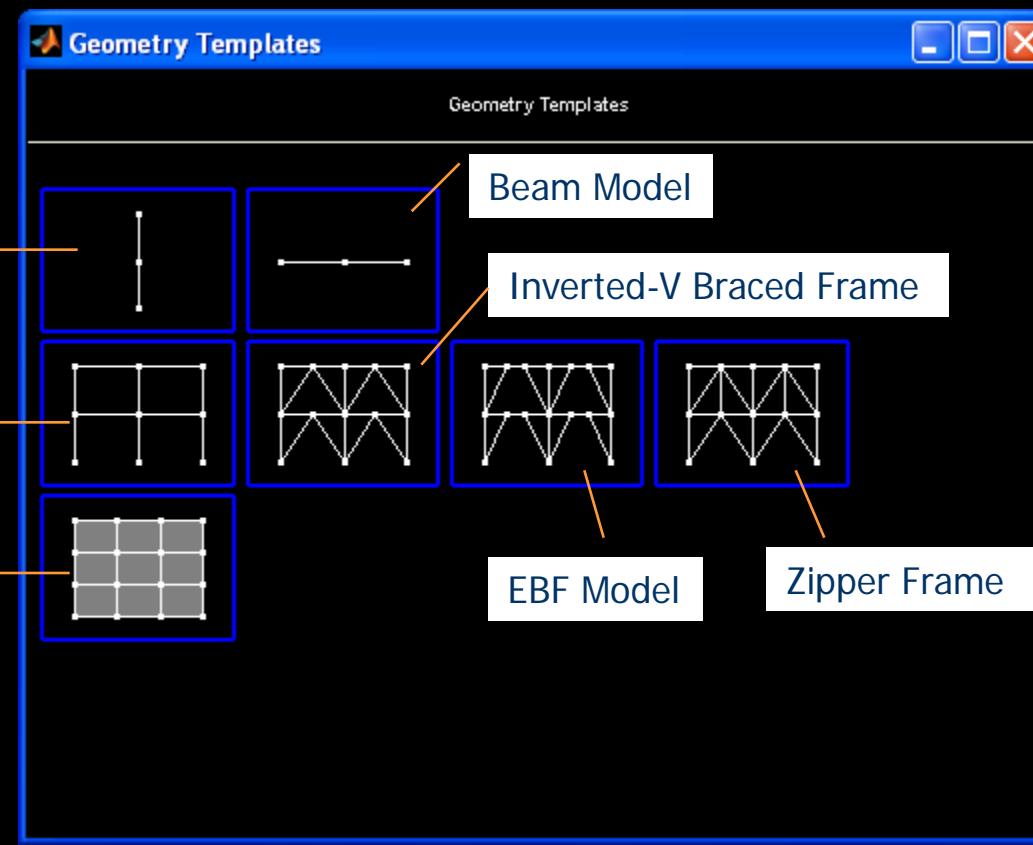
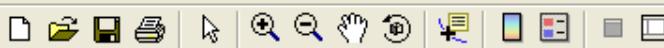
Conclusion cont.

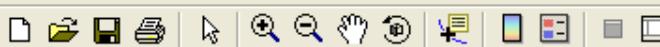
- ◆ Application of hybrid simulation test
 - Can be used to test multiple sub-assemblies.
 - Larger and more complex structural system.
 - More extreme loading.

Conclusion cont.

- ◆ Behavior of the suspended zipper frame
 - Behave as intended.
 - Many redundancies.
 - Brace buckled of out plane.
 - Zipper column effective transferring. unbalanced load.
 - Inter-story drift ratio & permanent story drifts.
 - Rotates the beam. Need to be braced.
 - Axial forces in columns to the support.







Define Zipper Frame Geometry

Define Zipper Frame Geometry	
Dimension (ndm) :	2d
Number of Stories (NOS) :	3
Number of Bays (NOB) :	1
Story Height (SH) :	52
Bay Width (BW) :	80
Boundary Condition (BC) :	pinned
Brace Bay Config (BraceBay) :	BraceBay
Num Segments in Col (NSC) :	1
Num Segments in Beam (NSB) :	1
Num Segments in Brace (NSBR) :	2
Num Segments in Z-Col (NSZC) :	1
Brace Offset (BraceOffset) :	None



Assign BraceBay

Brace Bay Locations

Add

Bay 1 :

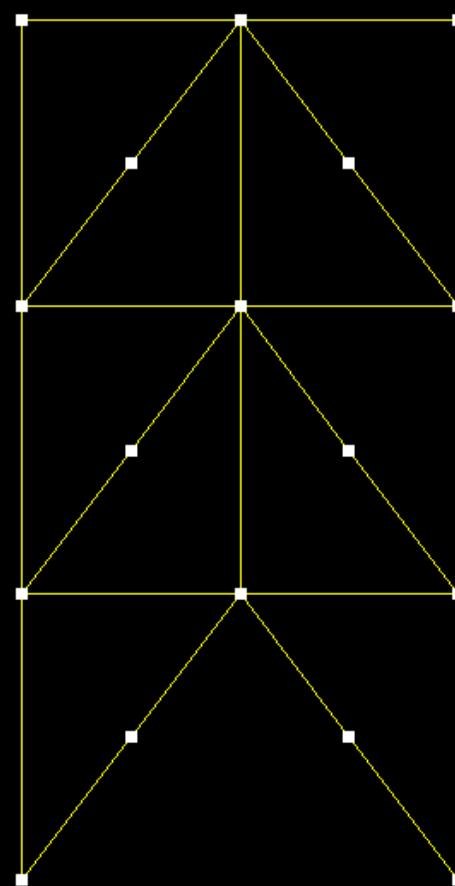
Story 3 :

Story 2 :

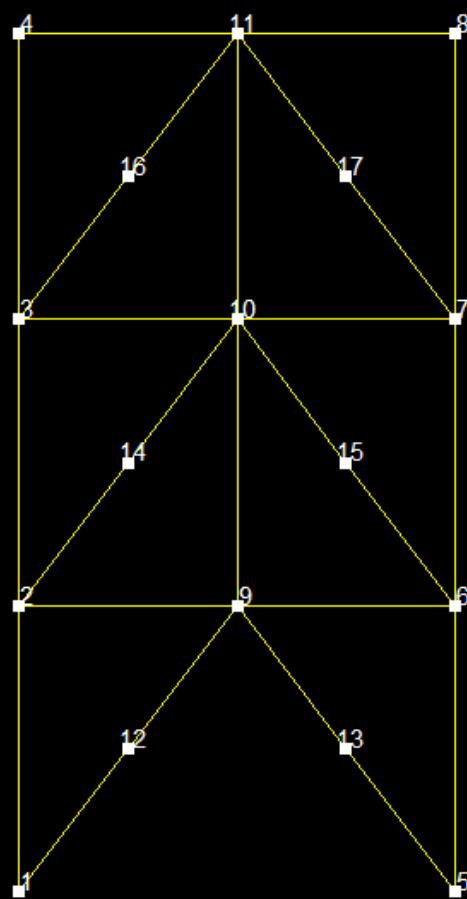
Story 1 :



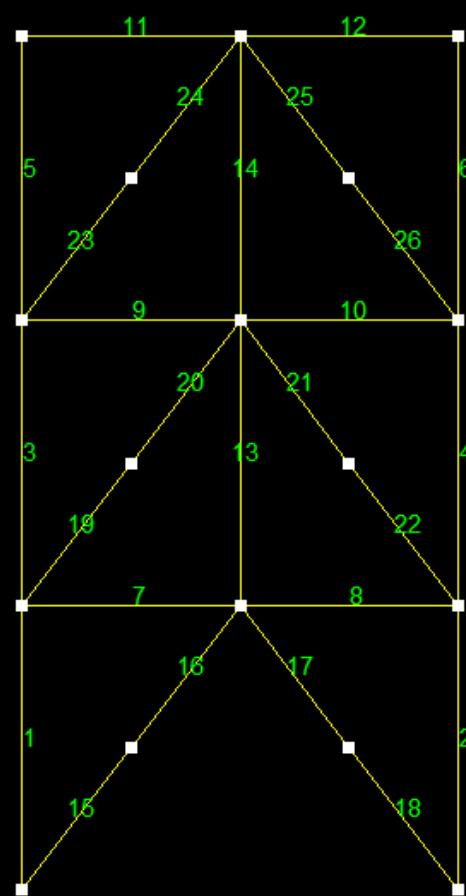
File Edit View Define Assign Analyze Display Output Design Help | MATLAB Menu



zipper frame geometry has been generated successfully



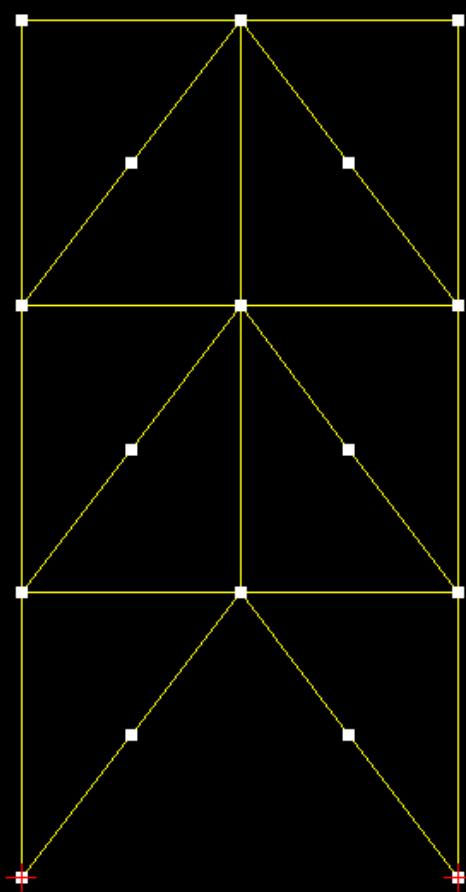
zipper frame geometry has been generated successfully



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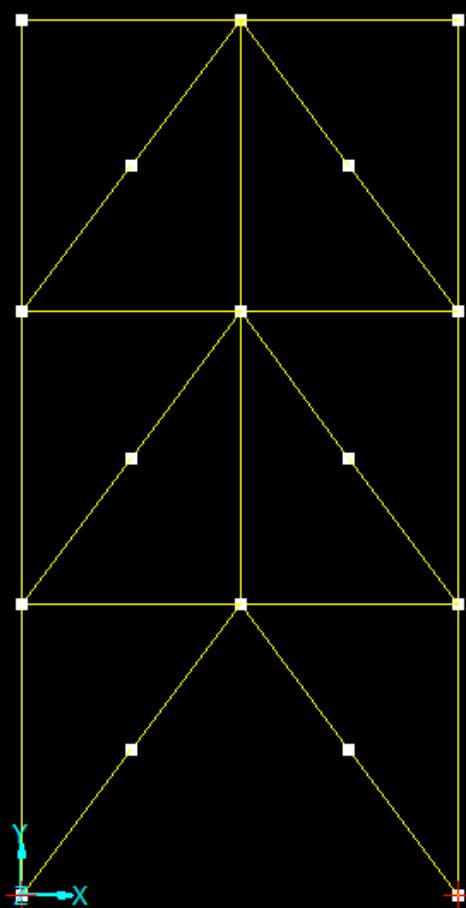
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zipper frame geometry has been generated successfully



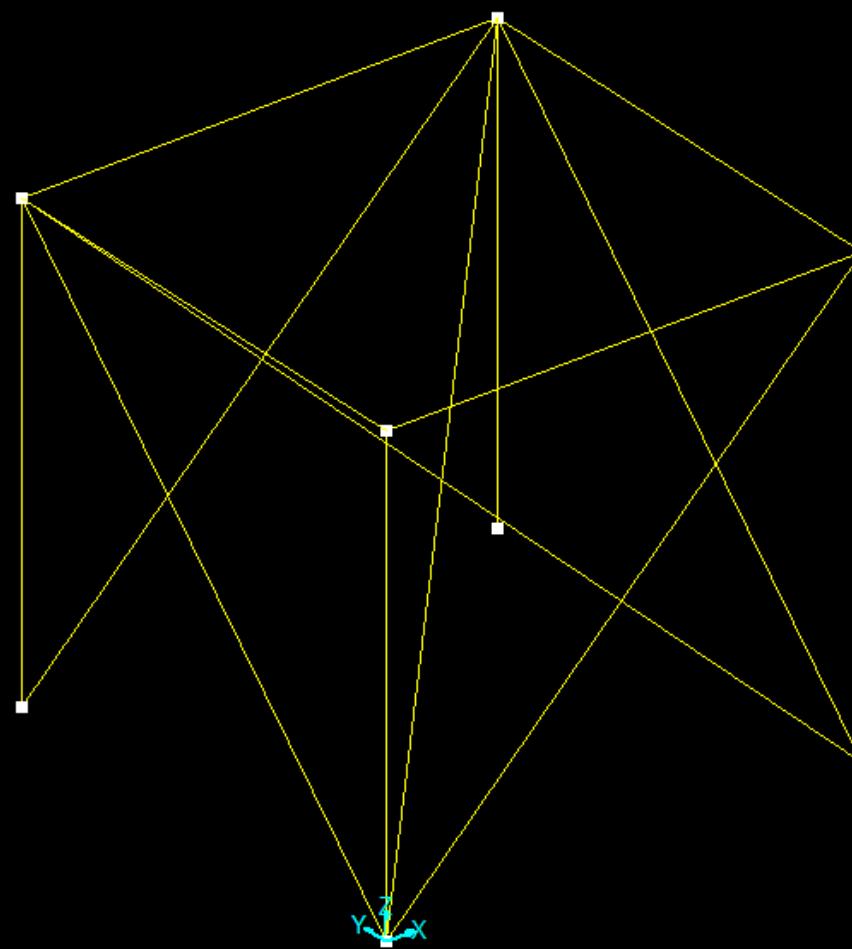
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zipper frame geometry has been generated successfully



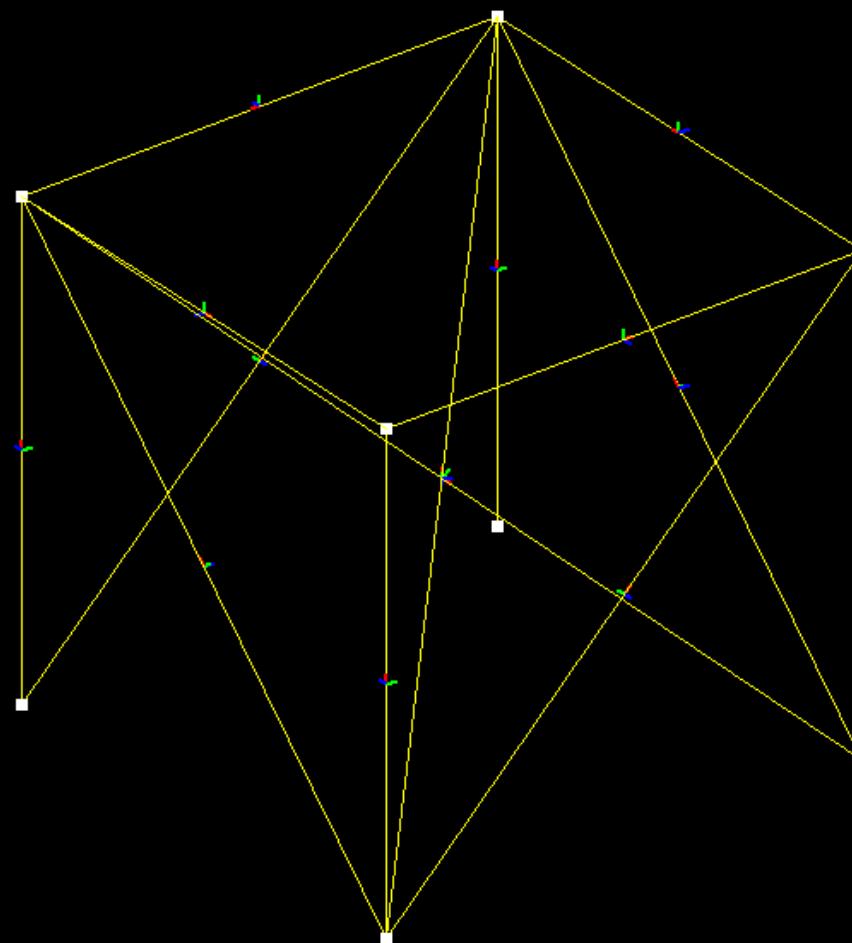
File Edit View Define Assign Analyze Display Output Design Help | MATLAB Menu



zipper frame geometry has been generated successfully



File Edit View Define Assign Analyze Display Output Design Help | MATLAB Menu



zipper frame geometry has been generated successfully

OpenSees Navigator

Define Material:

◆ Uniaxial Materials:

- Steel01/Steel02
- EPP/Elastic/Hysteretic
- Hardening Material
- Concrete01/Concrete02/Concrete03
-

◆ nD Materials:

- Elastic Isotropic
- Plane Stress
-

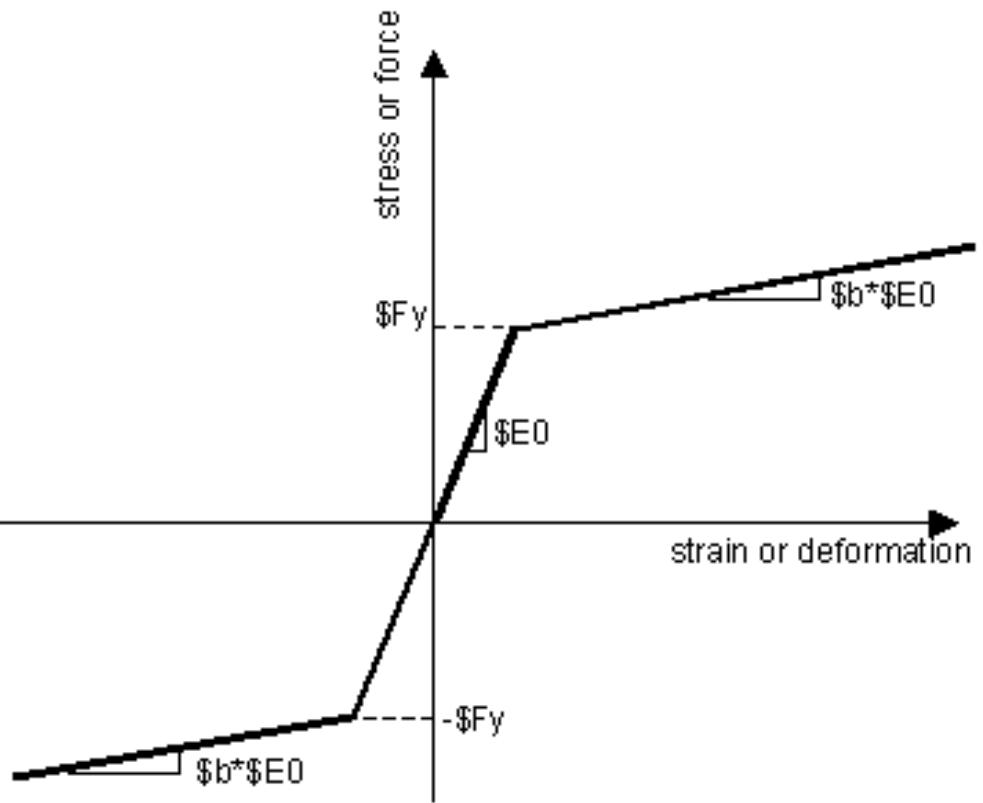
OpenSees Navigator

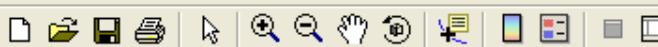
Define Uniaxial Material:

◆ Steel01

- $F_y = 50 \text{ ksi}$
- $E = 29000 \text{ ksi}$
- $b = 0.05$

Name : A50

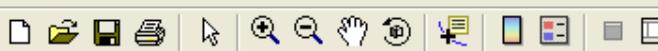


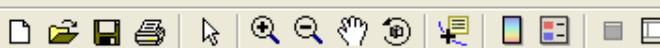


Define Steel01 Material

Define Steel01 Material

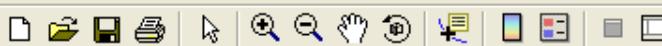
Material Name :	A50	Add
Yield Stress (Fy) :	50	
Modulus of Elasticity (E) :	29000	
Hardening Ratio (b) :	0.05	
<i>Optional Parameters :</i>		
Iso Hardening Parameter (a1) :	0.0	
Iso Hardening Parameter (a2) :	1.0	
Iso Hardening Parameter (a3) :	0.0	
Iso Hardening Parameter (a4) :	1.0	





Define AISC Patch

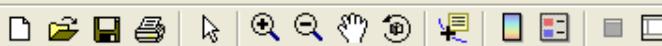
Patch Name :	AISC_Patch	Add
Material Type :	A50	
AISC Section Name :	W24X68	
Number of Fibers along dw (nfdw) :	10	
Number of Fibers along tw (nftw) :	1	
Number of Fibers along bf (nfbf) :	10	
Number of Fibers along tf (nftf) :	1	
<i>Optional Arguments :</i>		
Counter-Clockwise Rot (Theta) :	0.	



Define Fiber Section

Define Fiber Section

Section Name :	<input type="text" value="1st Fl Beam"/>	Add
Add Fiber :	<input type="text" value="Fiber"/>	
Modify Fiber :	<input type="text"/>	
Delete Fiber :	<input type="text"/>	
Add Patch :	<input type="text" value="Quadrilateral"/>	
Modify Patch :	<input type="text" value="AISC_Patch"/>	
Delete Patch :	<input type="text" value="AISC_Patch"/>	
Add Layer :	<input type="text" value="Straight"/>	
Modify Layer :	<input type="text"/>	
Delete Layer :	<input type="text"/>	



Define Section - X

Define Section

Add Section :

Modify Section :

Delete Section :



OpenSees Navigator

Define Element:

◆ Line Element:

- Truss
- Elastic Beam Column
- Nonlinear Beam Column
- Zero Length Element
-

◆ Solid Element:

- Quad
- Shell
-

Define Force Beam Column Element

 Define ForceBeamColumn Element

Define ForceBeamColumn Element

Element Name :	Column	Add
Number Intergration Points (NIP) :	5	
Section Type :	Column	
<i>Optional Arguments :</i>		
Mass Density (massDens) :	0.	
Maximum Iterations (maxIters) :	10	
Tolerance (tol) :	1E-8	

Define Elastic Beam Column Element

Define ElasticBeamColumn Element

Element Name :	EColumn	Add
Modulus of Elasticity (E) :	29000	Database
Cross-Sectional Area (A) :	13.3	
Moment of Inertia (Iz) :	248	

Select Section from Database

Database :	AISC	Select
Section Name :	W10X45	
Direction :	strong	

OpenSees Navigator

Define:

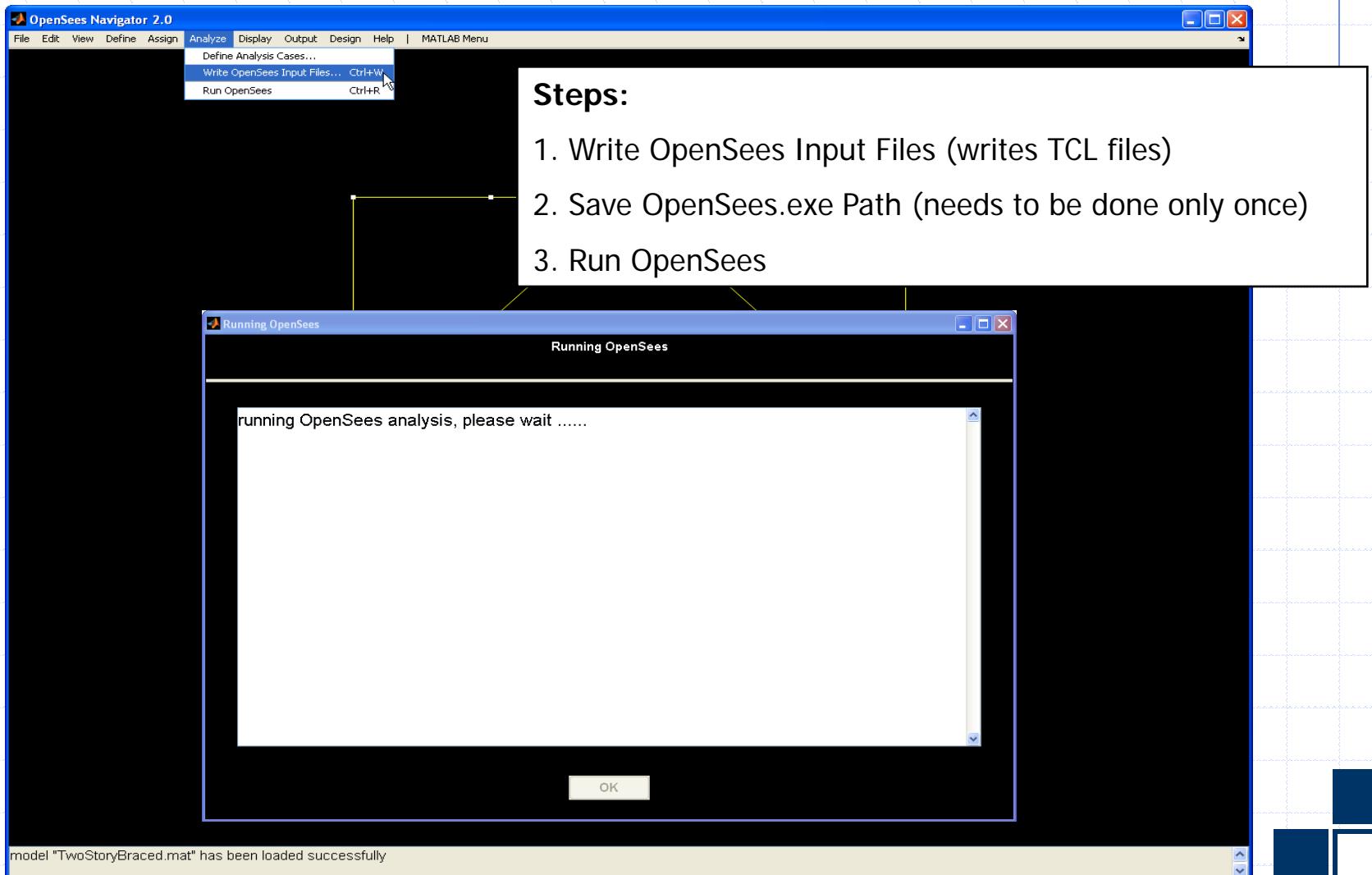
- ◆ Geometry
- ◆ Material
- ◆ Section
- ◆ Element
- ◆ Loading
- ◆ Recorder
- ◆ Analysis Option

Assign:

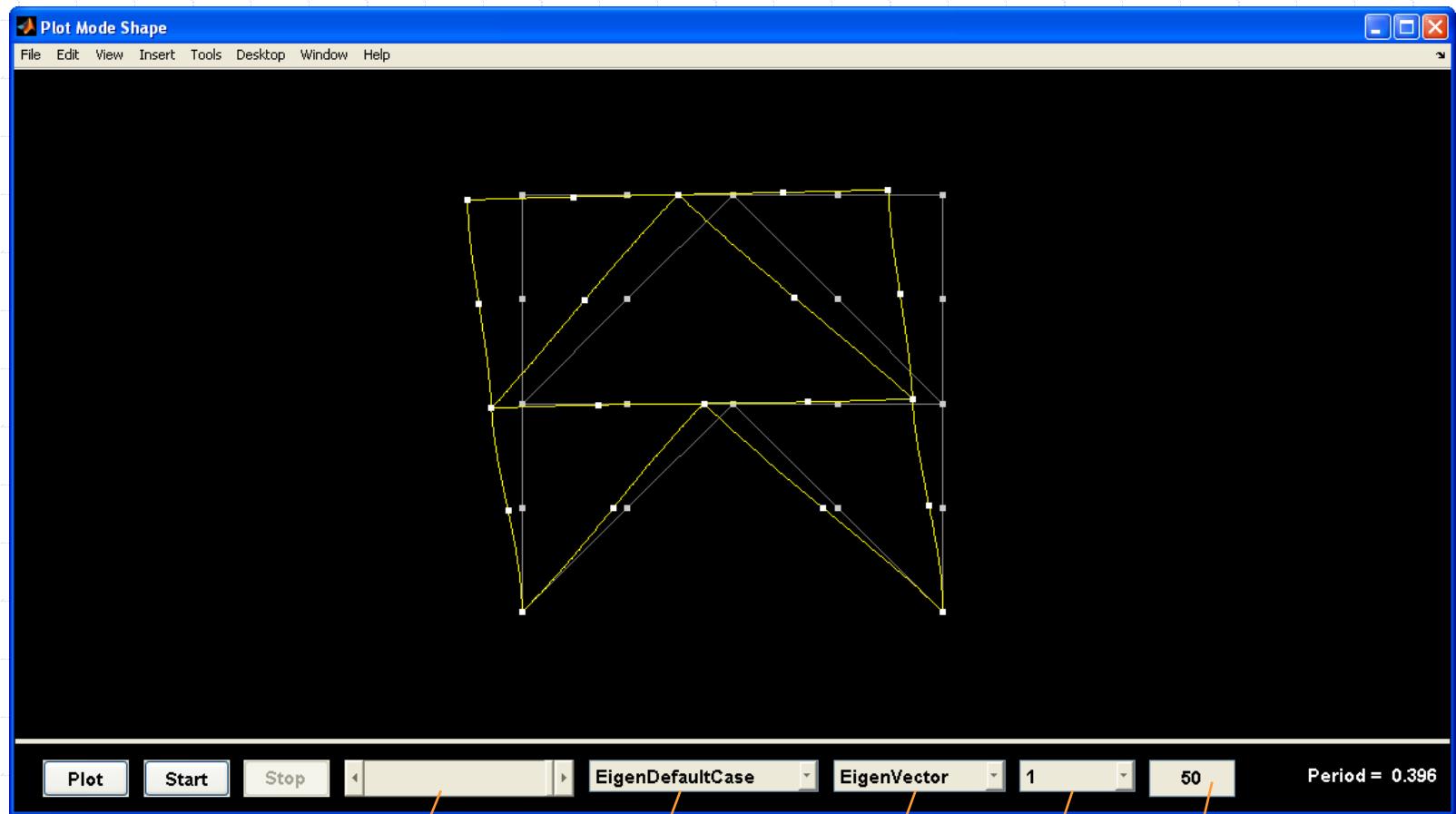
- ◆ Element
- ◆ Loading



To Run OpenSees



Mode Shape: 1st Mode



Animation Speed

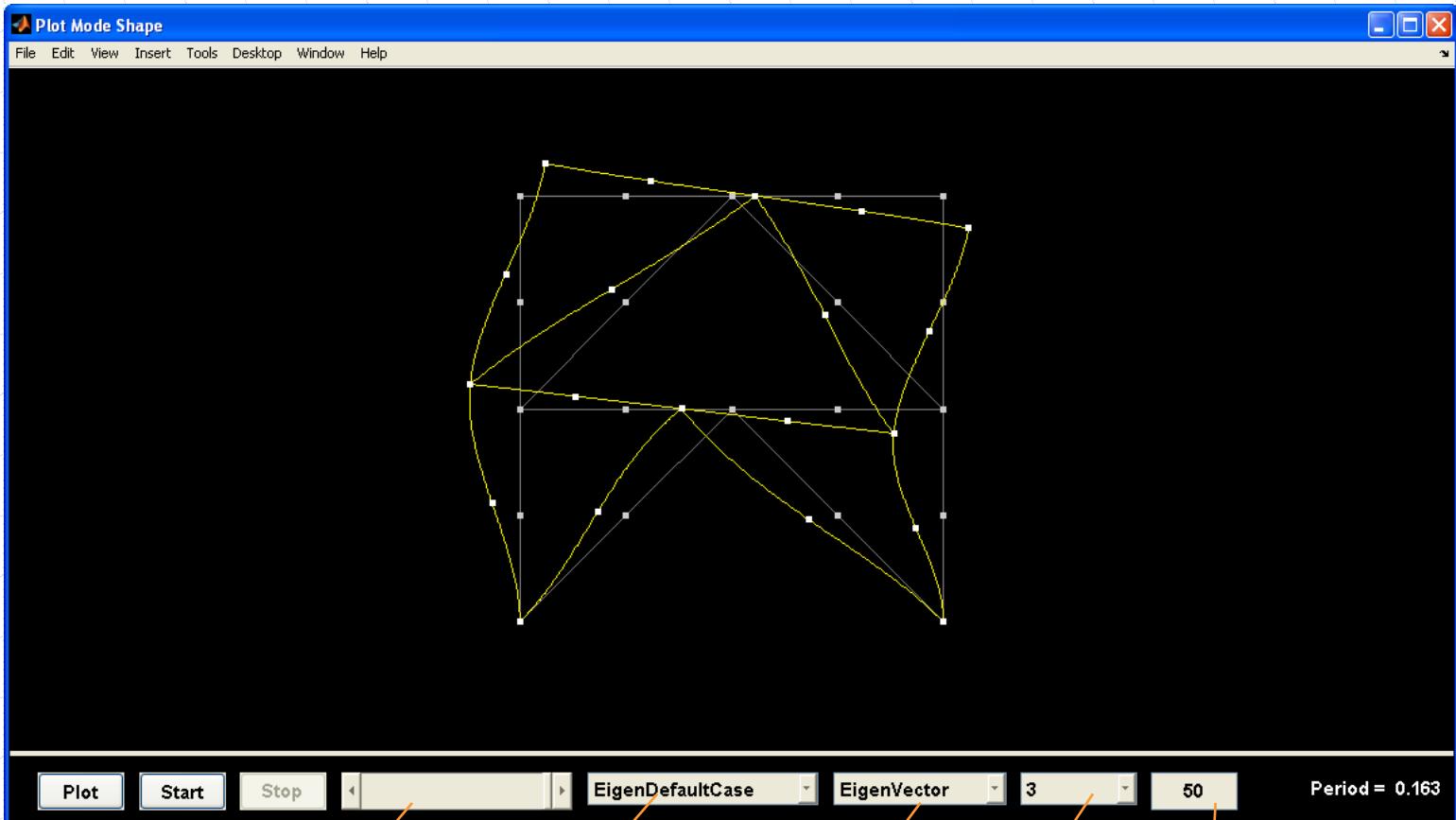
AnalysisCase

Recorder

Mode

Magnification

Mode Shape: 3rd Mode



Animation Speed

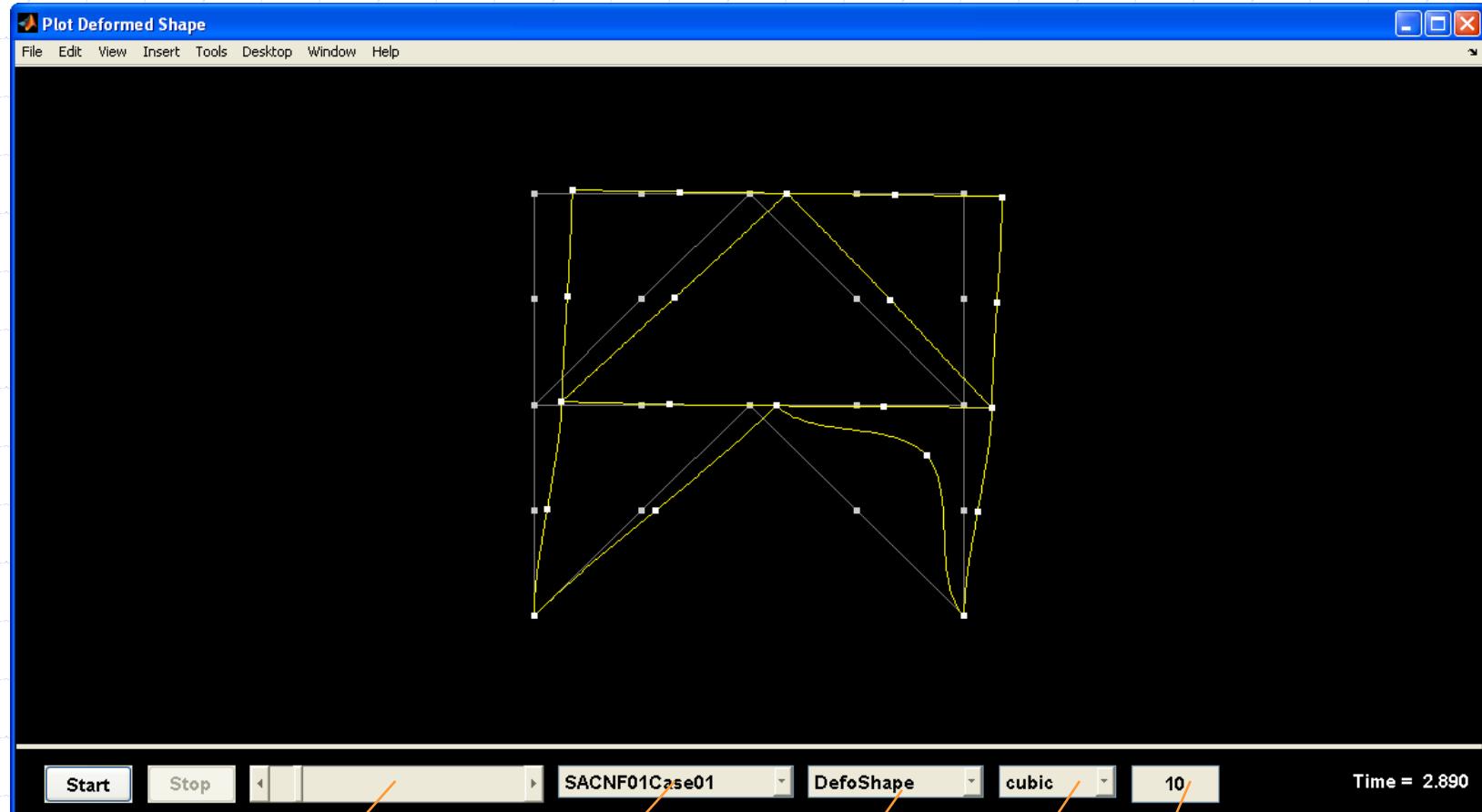
AnalysisCase

Recorder

Mode

Magnification

Deformed Shape



Time Step

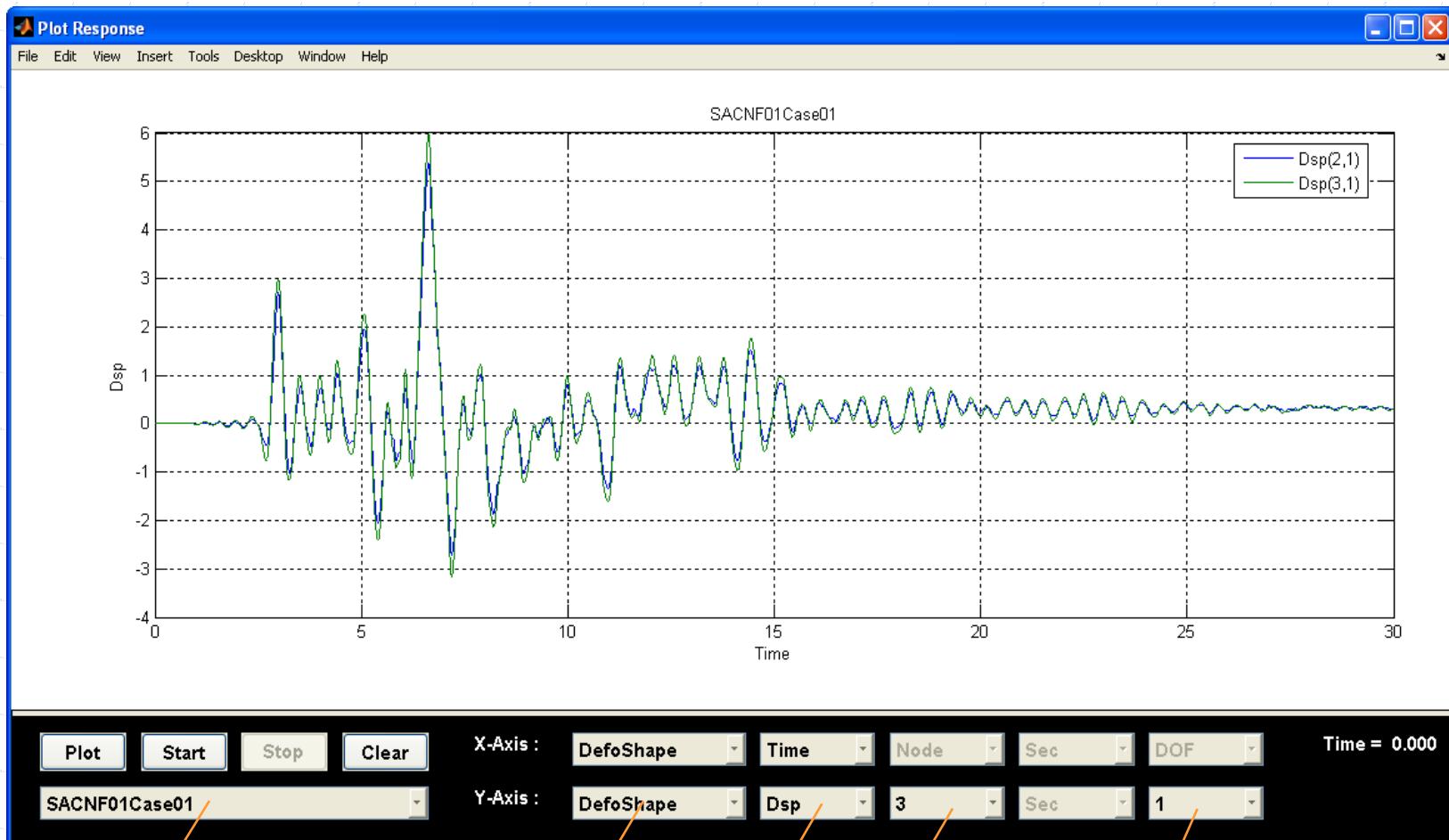
AnalysisCase

Recorder

Order

Magnification

Response



AnalysisCase

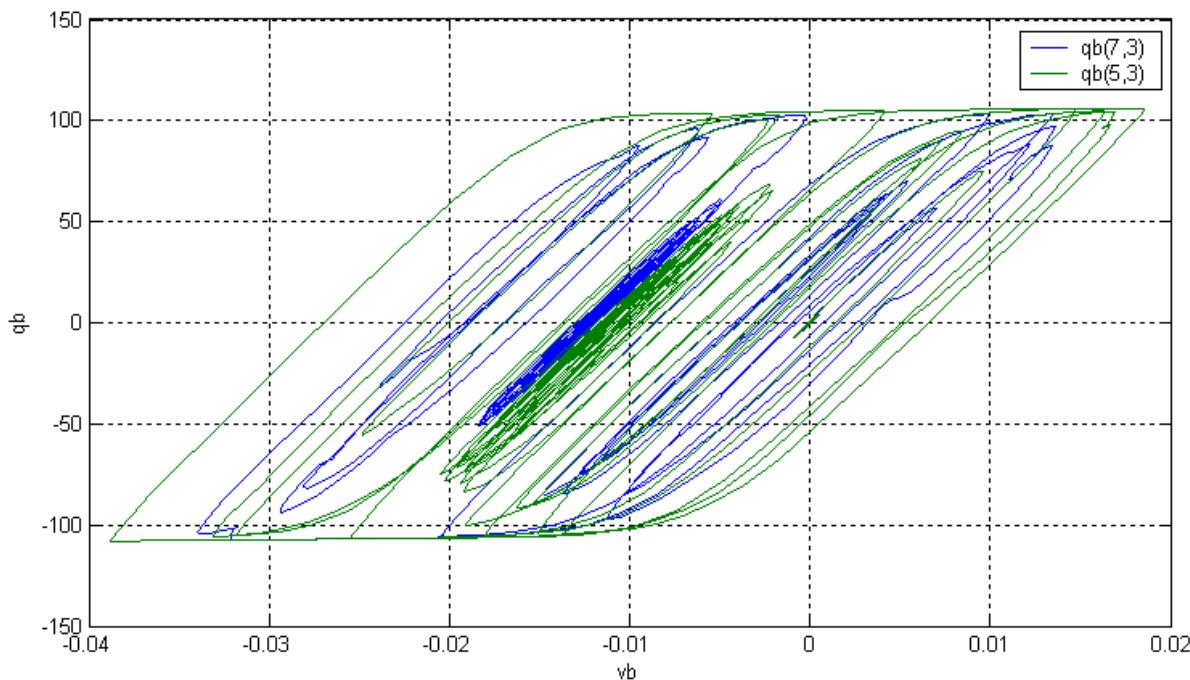
Recorder

Parameter

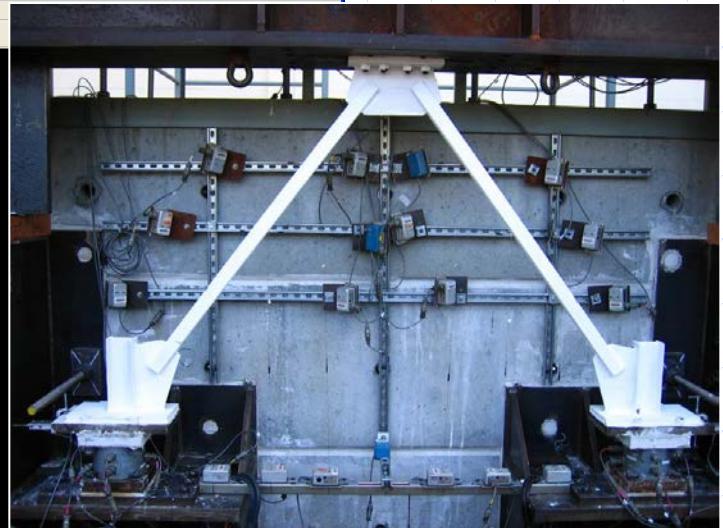
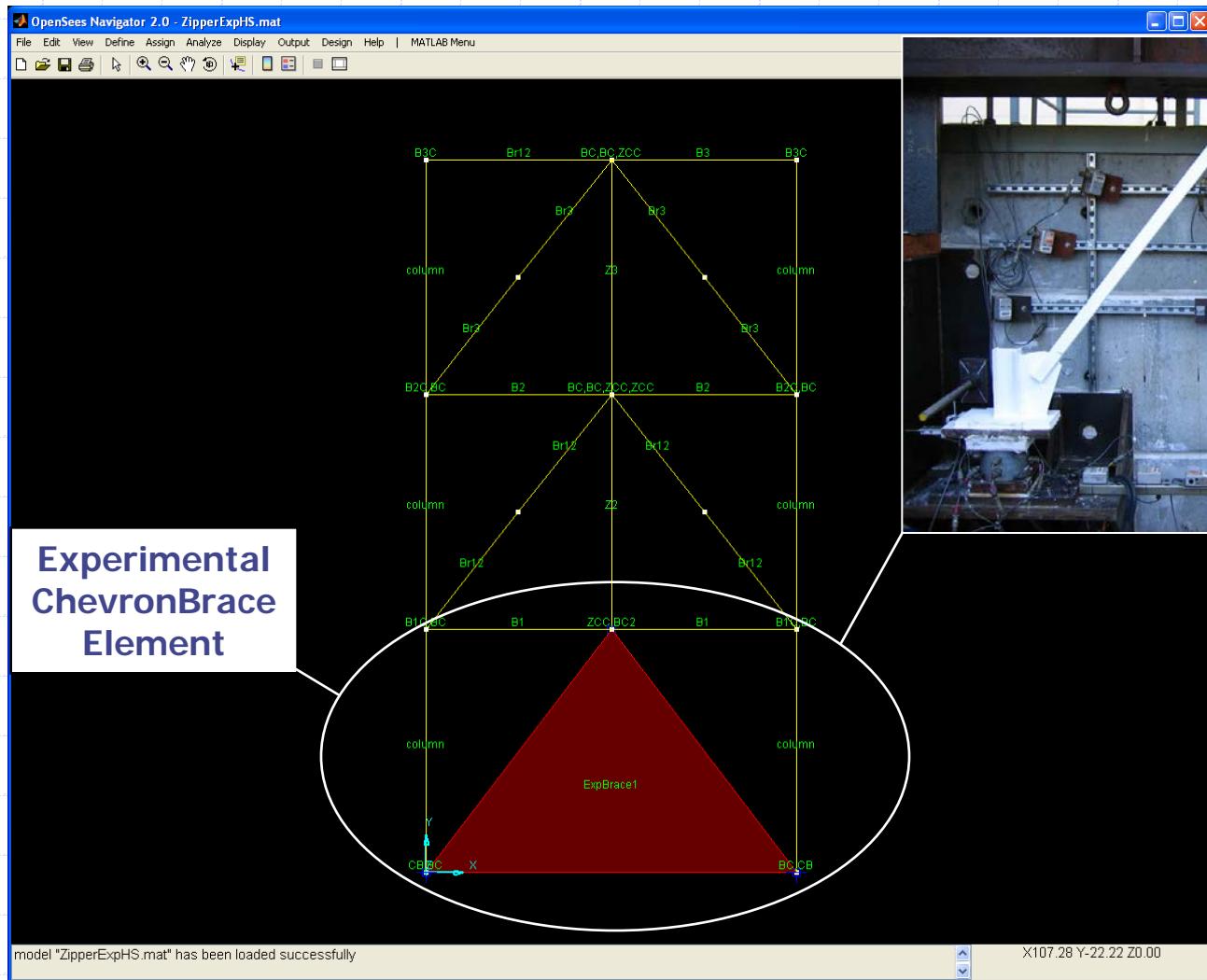
Node/Elem

Hysteresis Loops

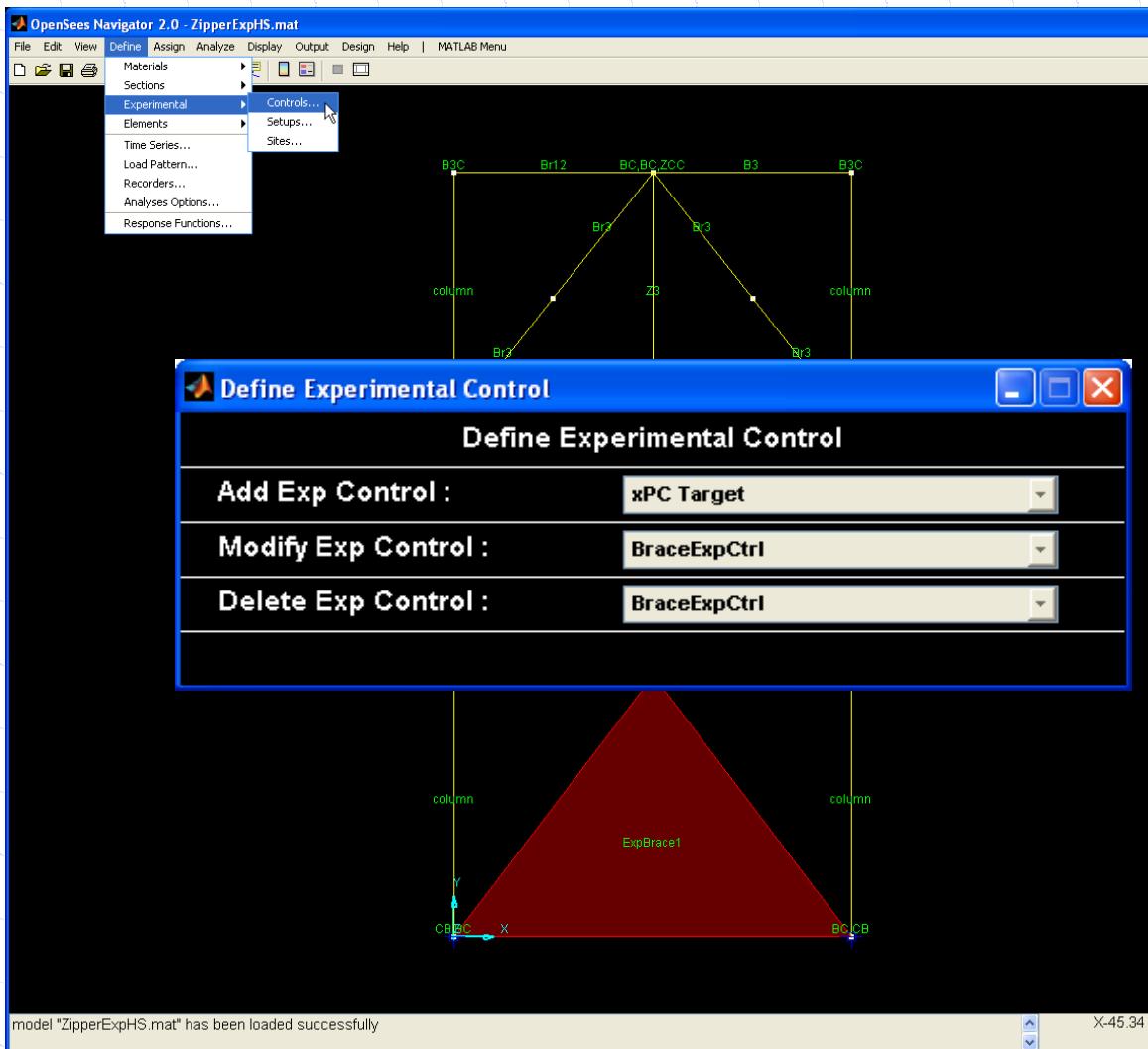
Nonlinear Dynamic Analysis



Hybrid Simulation Example



Define Experimental Control

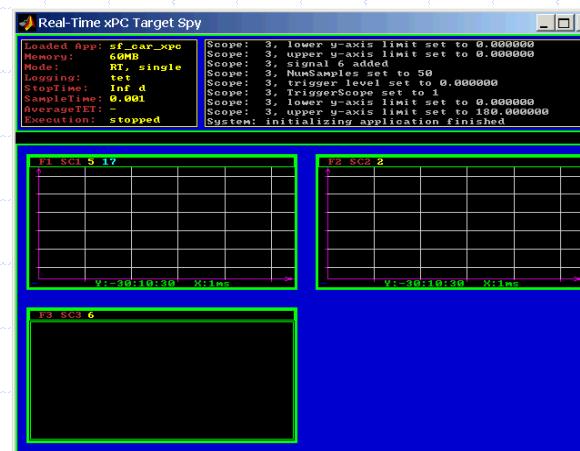
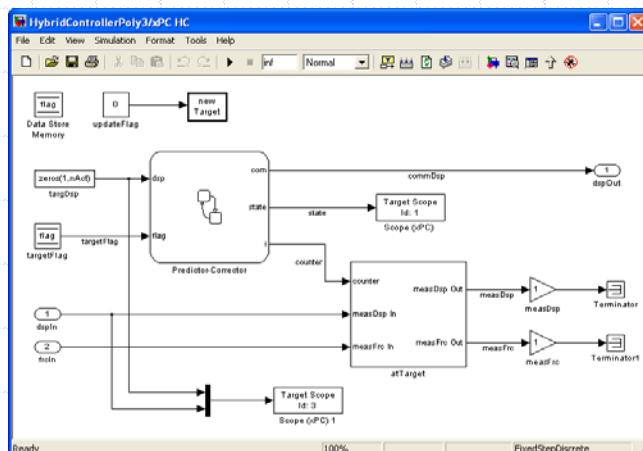


Templates:
-dSpace 1104
-xPC Target
(-SCRAMNET 150)
-BeamColumnSim
-ChevronBraceSim

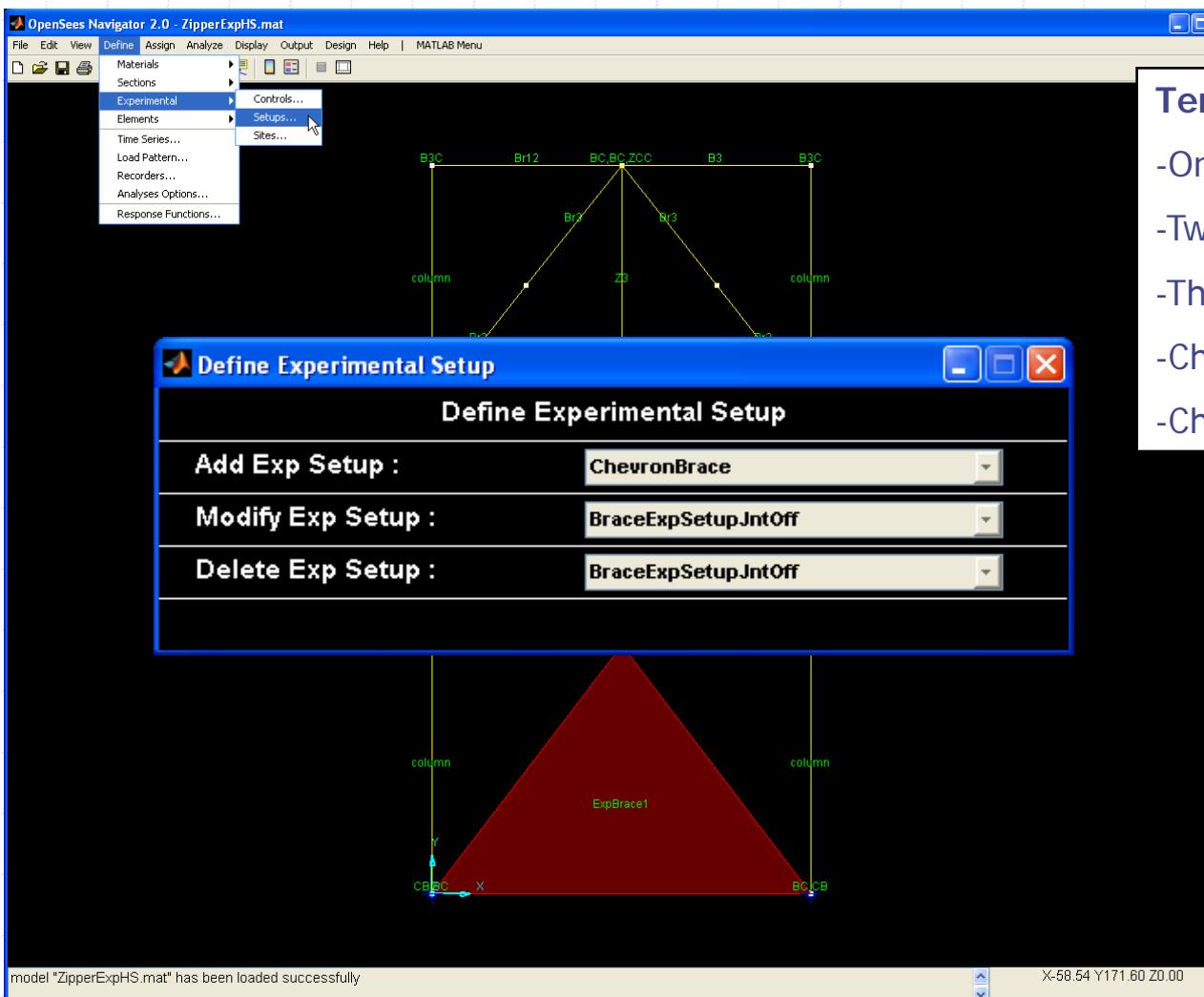
Define ExpControl: xPC Target

Define xPC Target Control

Control Name :	BraceExpCtrlXPC	Add
Number of Controls (numCtrl) :	3	
Number of DAQs (numDaq) :	6	
Predictor-Corrector Type (type) :	Dsp	
xPC Target IP Address (ipAddr) :	192.168.2.20	
xPC Target IP Port (ipPort) :	22222	
Application Name (appName) :	HybridControllerDOD1	Browse
Application Path (appPath) :	TestModels\c&mCode-xPCTarget-STSW	



Define Experimental Setup



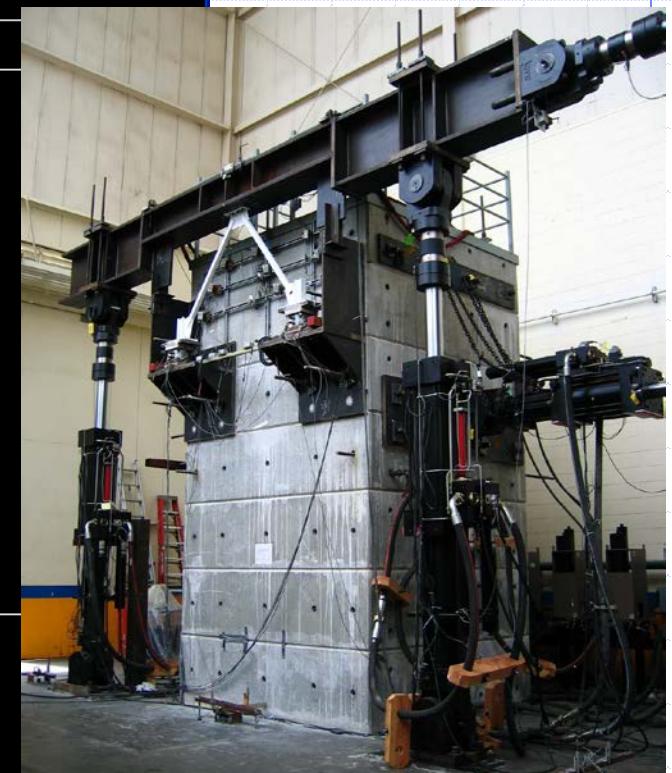
Templates:

- OneActuator
- TwoActuators
- ThreeActuators
- ChevronBrace
- ChevronBraceJntOff

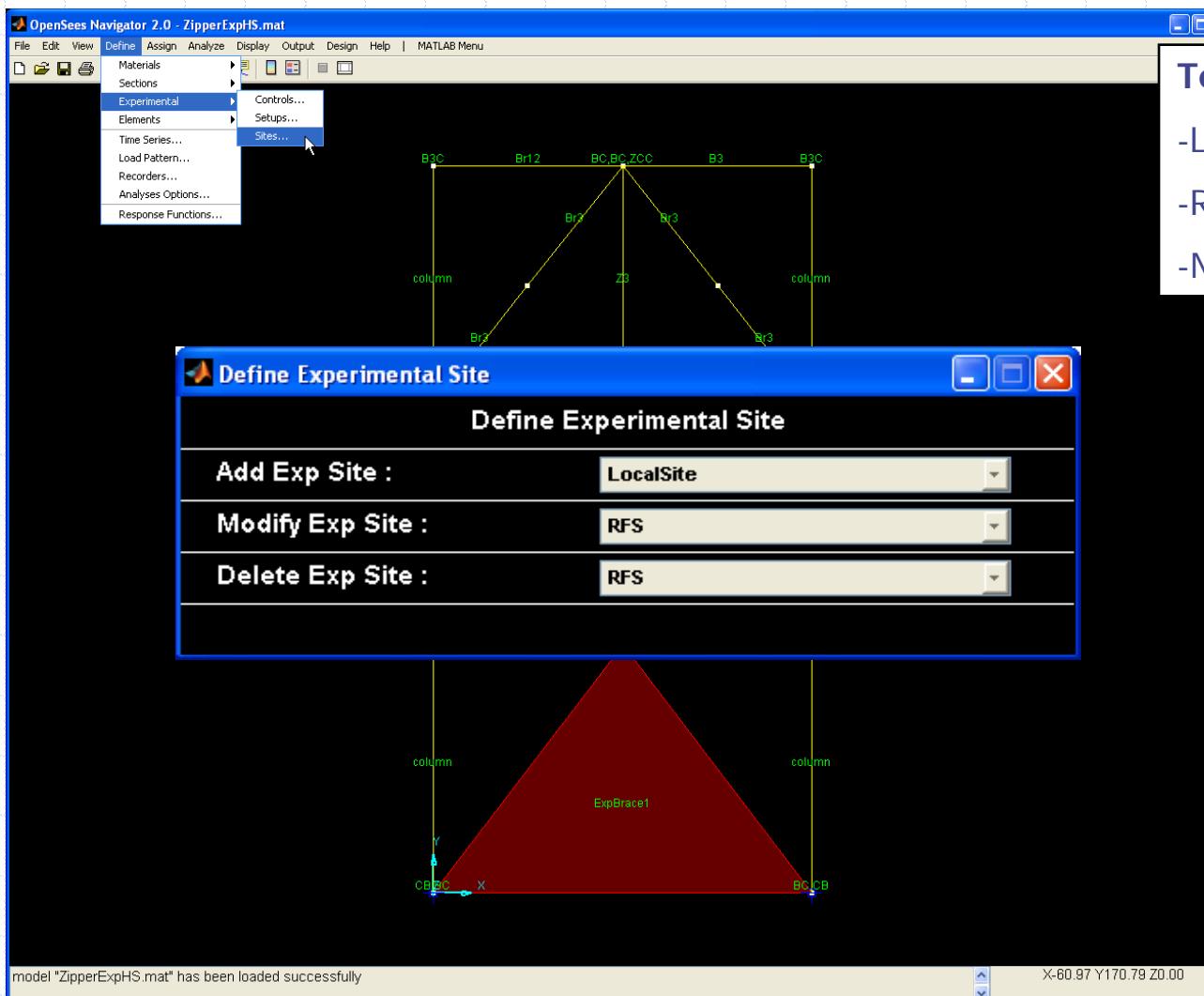
Define ExpSetup: ChevronBrace

Define ChevronBraceJntOff Setup

Setup Name :	BraceExpSetupJntOff
Experimental Control Type :	BraceExpCtrlIXPC
Geometry Type (nlGeomFlag) :	nonlinear, horizontal right
Actuator Length 1 (La1) :	124.5
Actuator Length 2 (La2) :	176.625
Actuator Length 3 (La3) :	176.625
Rigid Link Length 1 (L1) :	53
Rigid Link Length 2 (L2) :	108
Rigid Link Length 3 (L3) :	108
Rigid Link Length 4 (L4) :	53
Rigid Link Length 5 (L5) :	24.625
Rigid Link Length 6 (L6) :	24.625
<i>Optional Parameters :</i>	
Dsp Control Factor (dspCtrlFact) :	[1 1 1]
Vel Control Factor (velCtrlFact) :	[1 1 1]
Acc Control Factor (accCtrlFact) :	[1 1 1]
Dsp Daq Factor (dspDaqFact) :	[1 1 1 1 1 1]
Force Daq Factor (frdDaqFact) :	[1 1 1 1 -1 1]



Define Experimental Site



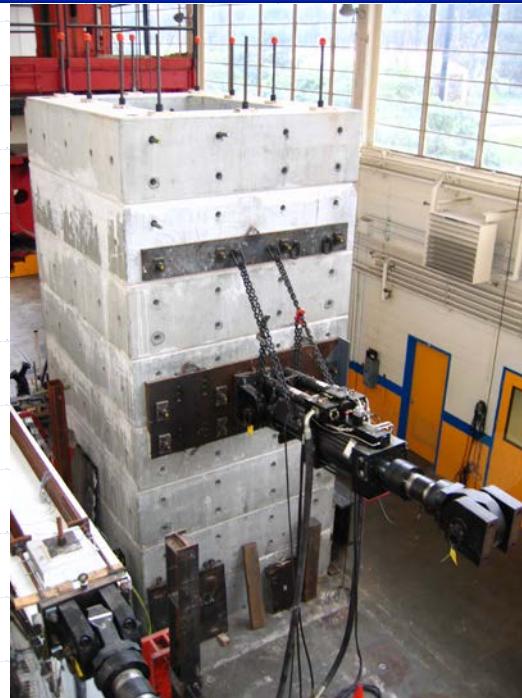
Templates:

- LocalSite
- RemoteSite
- NEESE ExprSite

Define ExpSite: RFS

Define Local Site

Site Name :	RFS	Add
Experimental Setup Type :	BraceExpSetup	



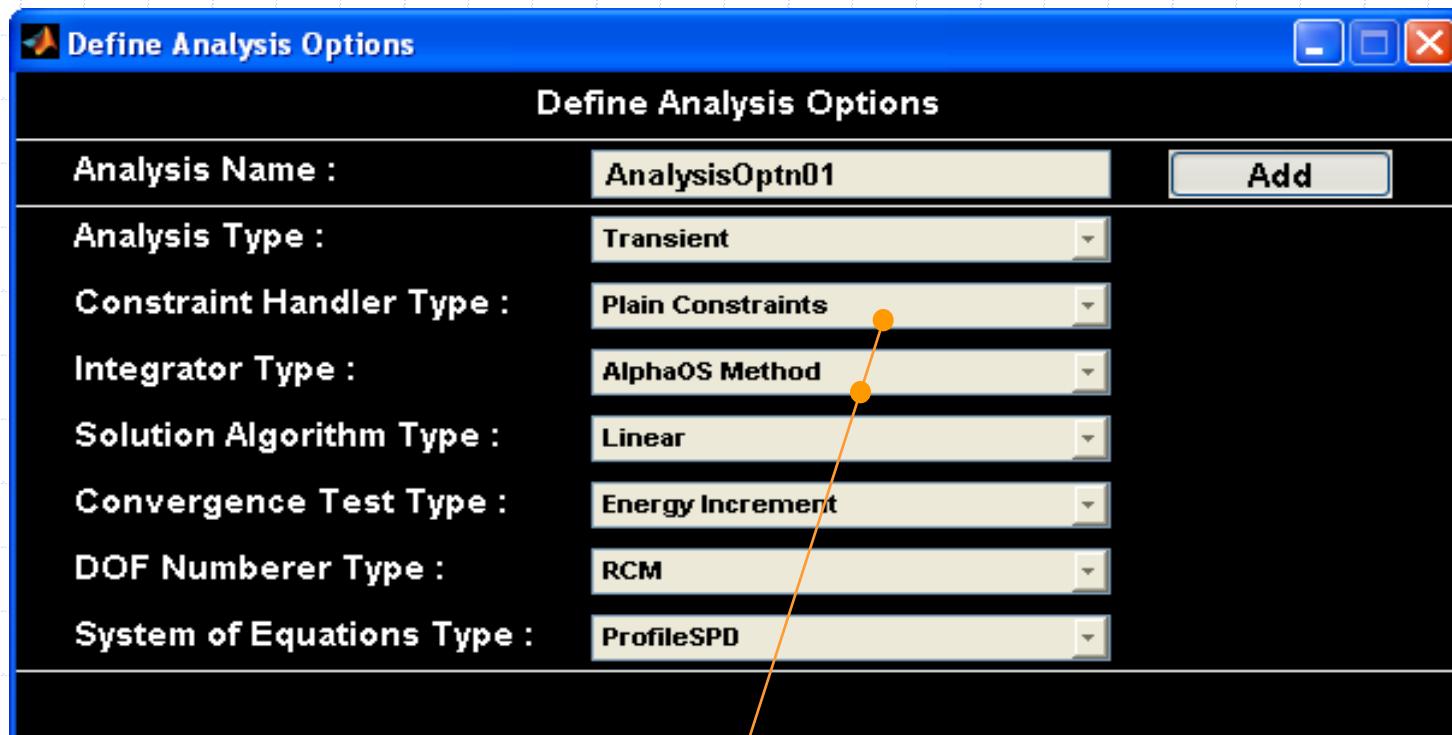
Define ExpElement: ChevronBrace

Define ExpChevronBrace Element

Element Name :	ExpBrace1			Add
Experimental Site Type :	RFS			
Initial Stiffness (initStif) :	250	0	0	
	0	434.4	0	
	0	0	0	
I-Modification (iMod) :	no			
<i>Optional Arguments :</i>				
Mass Density 1 (massDens1) :	0			
Mass Density 2 (massDens2) :	0			



Modify Analysis Options



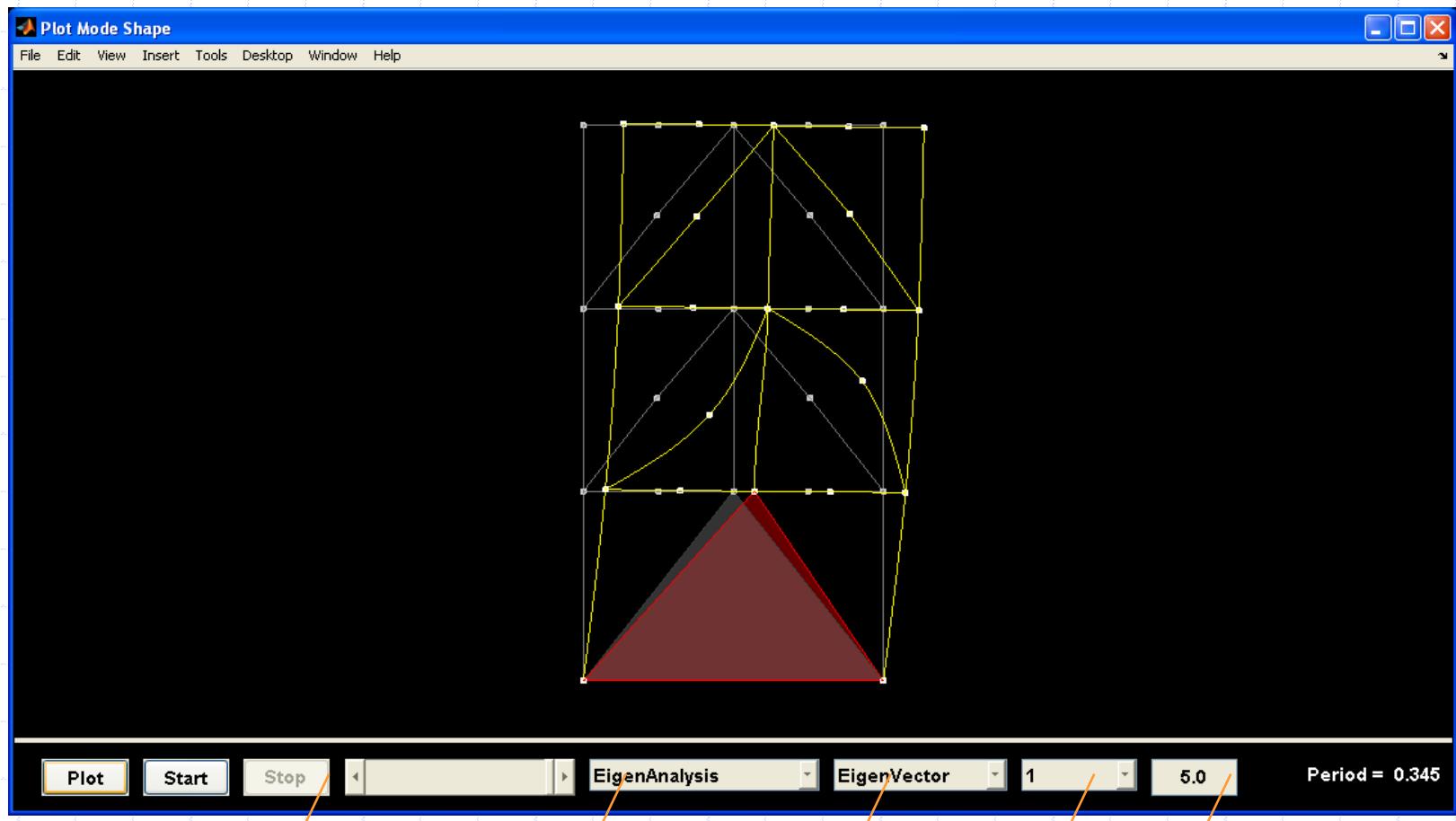
Integrator Type:

Use AlphaOS Method for Hybrid Simulation

Solution Algorithm:

The AlphaOS Method requires a Linear solution algorithm

Mode Shape: 1st Mode



Animation Speed

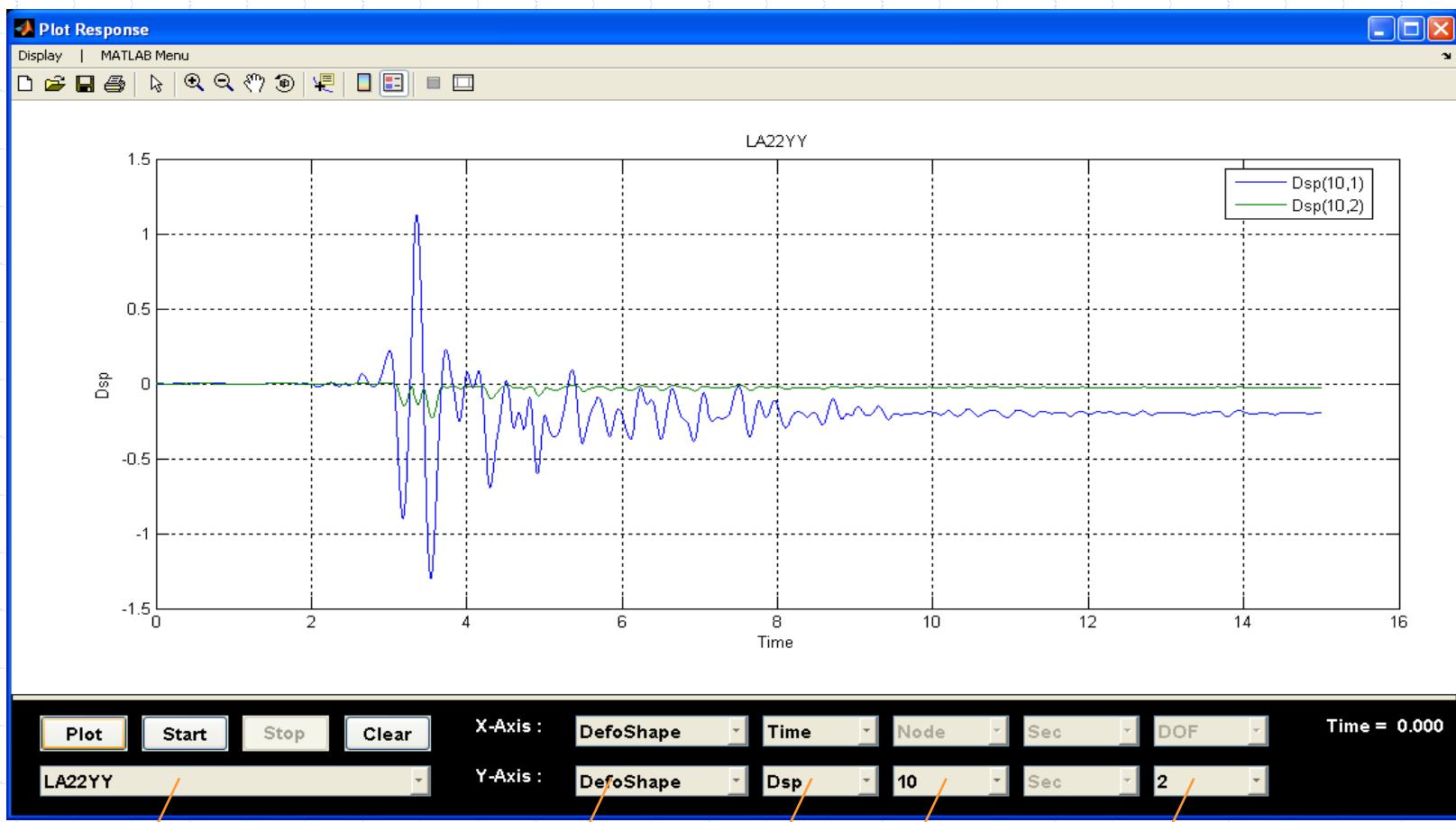
AnalysisCase

Recorder

Mode

Magnification

Response



AnalysisCase

Recorder

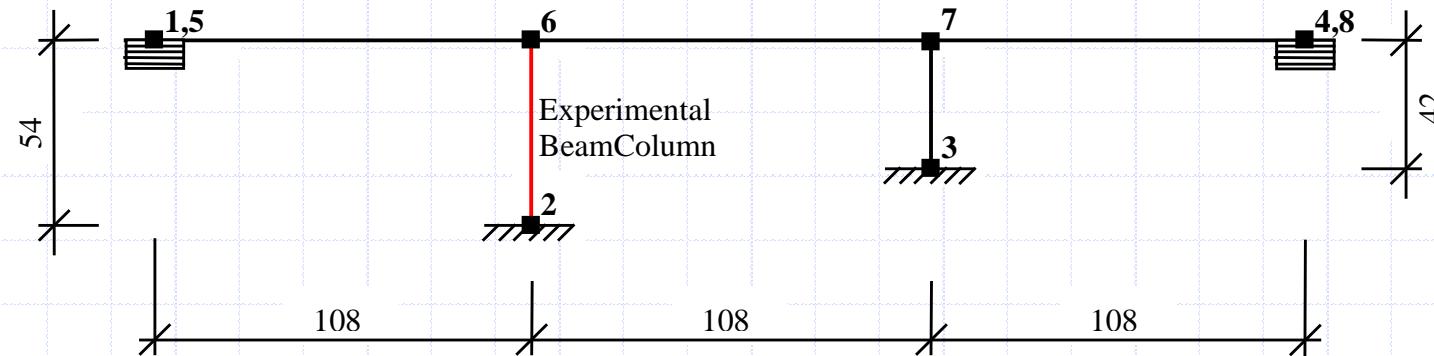
Parameter

Node/Elem

DOF

Application Examples

1) Three-Span-Bridge



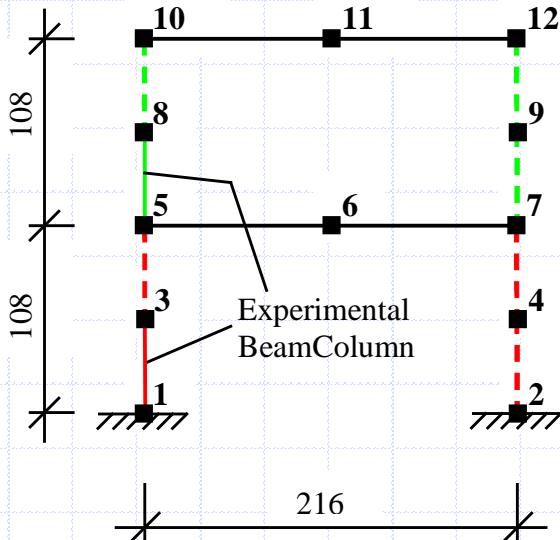
Properties of Model:

- num. DOF = 12 (4 with mass)
- Period: $T_1 = 0.918\text{sec}$
- Damping: $\zeta_1 = 0.02$
- ExpElement: EEBeamColumn2d
- ExpSetup: ESOneActuator
- ExpControl: ECxPCtarget



Application Examples

2) Two-Story-Shear

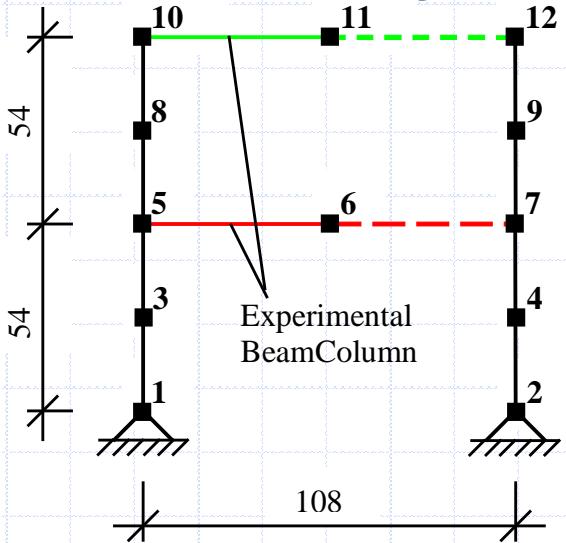


Properties of Model:

- num. DOF = 14 (6 with mass)
- Period: $T_1 = 0.618\text{sec}$
 $T_2 = 0.236\text{sec}$
- Damping: $\zeta_1 = 0.02$
- ExpElements: EEBeamColumn2d
- ExpSetups: ESOneActuator
- ExpControl: ECxPCTarget

Application Examples

3) Two-Story-Frame



Properties of Model:

- num. DOF = 28 (4 with mass)
- Period: $T_1 = 0.473\text{sec}$
 $T_2 = 0.071\text{sec}$
- Damping: $\zeta_1 = 0.02$
- ExpElements: EEBeamColumn2d
- ExpSetups: ESOneActuator
- ExpControl: ECxPCTarget

Conclusion

- ◆ A hybrid simulation test has been conducted.
 - Close match between the analytical and experimental results verifies the applicability of the experiment method.
- ◆ Graphical user interface creates the OpenSees hybrid model and graphically displays results before, during and after a test.
- ◆ Three additional examples of hybrid simulation test presented.

Thank you!

Development and operation of the *nees@berkeley* Equipment Site is sponsored by NSF George E. Brown Jr. NEES grants.

<http://nees.berkeley.edu>

<http://peer.berkeley.edu/~yang/NEESZipper/>

<http://peer.berkeley.edu/OpenSeesNavigator/>



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