Real-time Hybrid Simulation (RTHS): Background, Theory, and Implementation

James Ricles
NHERI Lehigh Director

Outline of Presentation

- RTHS Background
- RTHS Developments/Implementation at NHERI Lehigh
- Multi-hazard Example Application

RTHS Background

- Combines experimental and analytical substructures
  - Experimental substructure(s)
    - Not well understood and modeled analytically
    - Full scale component can be easily accommodated
    - Rate dependent devices (e.g., dampers, base-isolators) can be tested
  - Analytical substructure(s)
    - Well understood and modeled numerically
    - Various substructures possible for a given expt. substructure
    - Damage can accumulate (not a problem) provided it can be modeled

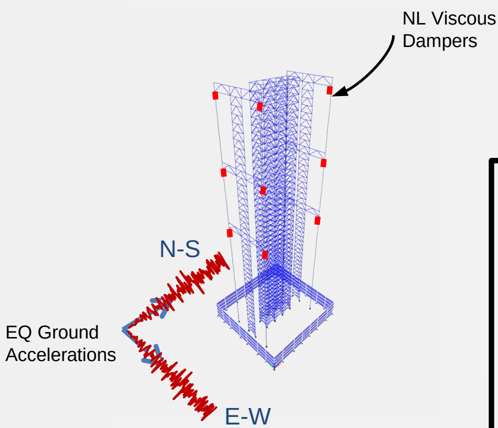
Overall Concept of Real-time Hybrid Simulation: Structural System Subject to Multi-Natural Hazards

NSF CMMI: Semi-Active Controlled Cladding Panels for Multi-Hazard Resilient Buildings

- S. Laflamme (Iowa State), J. Ricles (Lehigh University), S. Quiel (Lehigh University)

Structural System

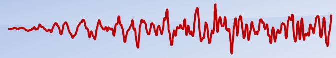
40-Story Building with Outriggers and Supplemental Dampers



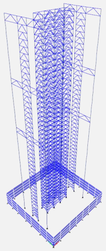
Wind Tunnel Tests NHERI@FIU
Wind Load Determination

Hybrid Earthquake Simulation Experiments

Real-time input EQ ground acceleration



Analytical substructure



(Modeled in the computer)

Cmd Displ $\mathbf{X}^a_{i+1}$

Restoring Force $\mathbf{R}^a_{i+1}$

Simulation Coordinator

$$\mathbf{M}\ddot{\mathbf{X}}_{i+1} + \mathbf{C}\dot{\mathbf{X}}_{i+1} + \mathbf{R}^a_{i+1} + \mathbf{R}^e_{i+1} = \mathbf{F}^a_{i+1}$$

Integrates Eqns of Motion

Real-time structural response

Cmd Displ $\mathbf{X}^e_{i+1}$

Restoring Force $\mathbf{R}^e_{i+1}$

Experimental substructure (dampers)

(Modeled in lab)

Why Real-Time Hybrid Simulation?

- **Enables cost-effective large-scale dynamic tests**
  - ➢ Low experimental cost compared to a full shake table test
  - ➢ Various analytical substructures can be used for a given experimental substructure, enabling extensive and comprehensive experimental studies
  - ➢ Meets the need of the natural hazards engineering community of providing experimental validation of concepts for natural hazards mitigation
- **Accounts for rate-dependency of physical specimens**
  - ➢ Rate-dependent structures (frictional devices, dampers, base-isolators, tuned mass damper, etc.) can be investigated with RTHS

  ➔ not possible with conventional, slow hybrid simulation

RTHS: Implementation issues and challenges

Simulation coordinator

- ❑ Numerical integration algorithm
  - Accurate
  - Explicit
  - Unconditionally stable
  - Dissipative

Preferred

- ❑ Fast communication

Analytical substructure

- ❑ Fast and accurate state determination procedure for complex structures

Experimental substructure

- ❑ Large capacity hydraulic system and dynamic actuators required
- ❑ Actuator kinematic compensation
- ❑ Robust control of dynamic actuators for large-scale structures

RTHS: Implementation issues and challenges

Simulation coordinator

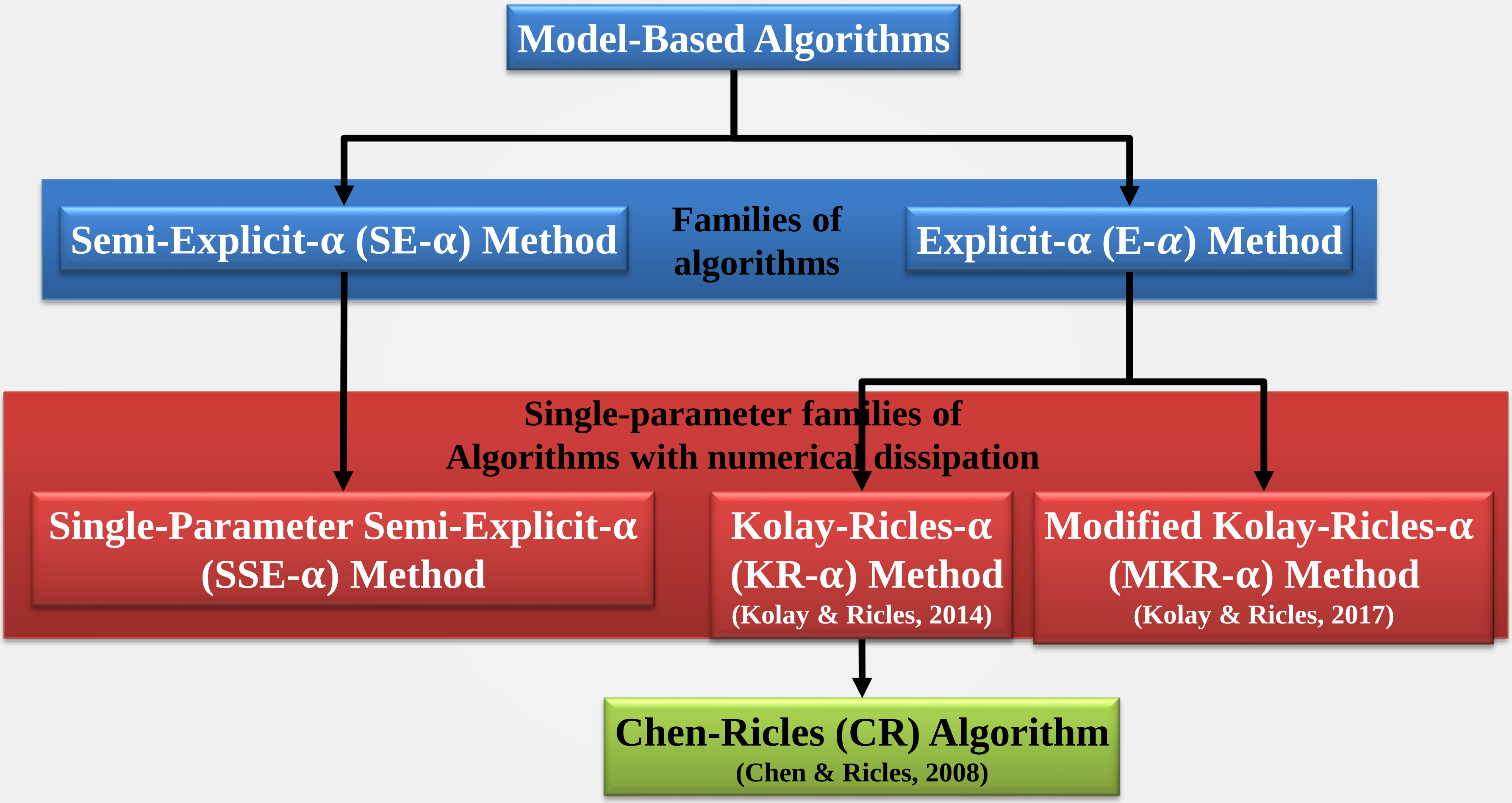
- ❑ Numerical integration algorithm
  - Accurate
  - Explicit
  - Unconditionally stable
  - Dissipative
- ❑ Fast communication

NHERI Lehigh Solutions

- Various explicit model-based algorithms
- RTMD real-time integrated control architecture

Model-based explicit algorithms for RTHS

NHERI Lehigh Solutions to RTHS Challenges



Kolay, C., & Ricles, J. M. (2015). Assessment of explicit and semi-explicit classes of model-based algorithms for direct integration in structural dynamics. *International Journal for Numerical Methods in Engineering*. doi:10.1002/nme.5153

Numerical Integration Algorithms

Explicit Modified KR-α (MKR-α) Method

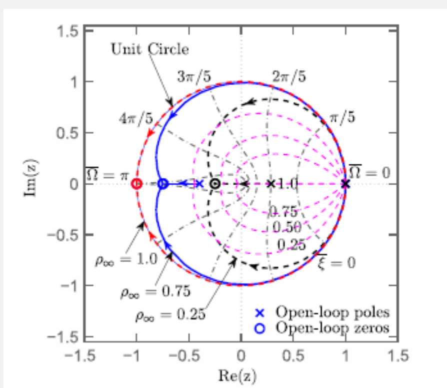
- Explicit Integration of Equations of Motion
- Unconditionally Stable
- One parameter (ρ_∞) algorithm
- Controlled Numerical Damping – eliminate spurious high frequency noise

$\boldsymbol{\alpha_1}$, $\boldsymbol{\alpha_2}$, and $\boldsymbol{\alpha_3}$: model-based integration parameters

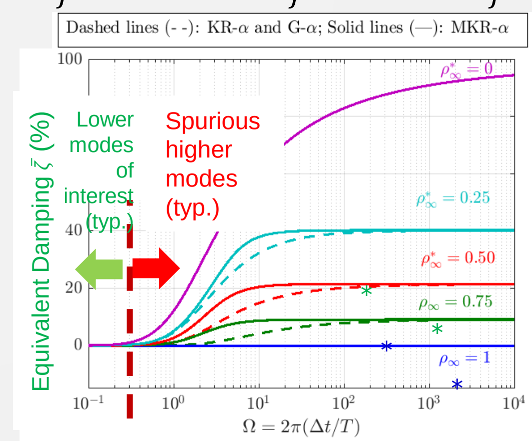
Velocity update: $$\dot{\mathbf{X}}_{n+1} = \dot{\mathbf{X}}_n + \Delta t \boldsymbol{\alpha}_1 \ddot{\mathbf{X}}_n$$

Displacement update: $$\mathbf{X}_{n+1} = \mathbf{X}_n + \Delta t \dot{\mathbf{X}}_n + \Delta t^2 \boldsymbol{\alpha}_2 \ddot{\mathbf{X}}_n$$

Weighted equations of motion: $$\mathbf{M}\widehat{\ddot{\mathbf{X}}}_{n+1} + \mathbf{C}\dot{\mathbf{X}}_{n+1-\alpha_f} + \mathbf{K}\mathbf{X}_{n+1-\alpha_f} = \mathbf{F}_{n+1-\alpha_f}$$



Stability: Root-Loci

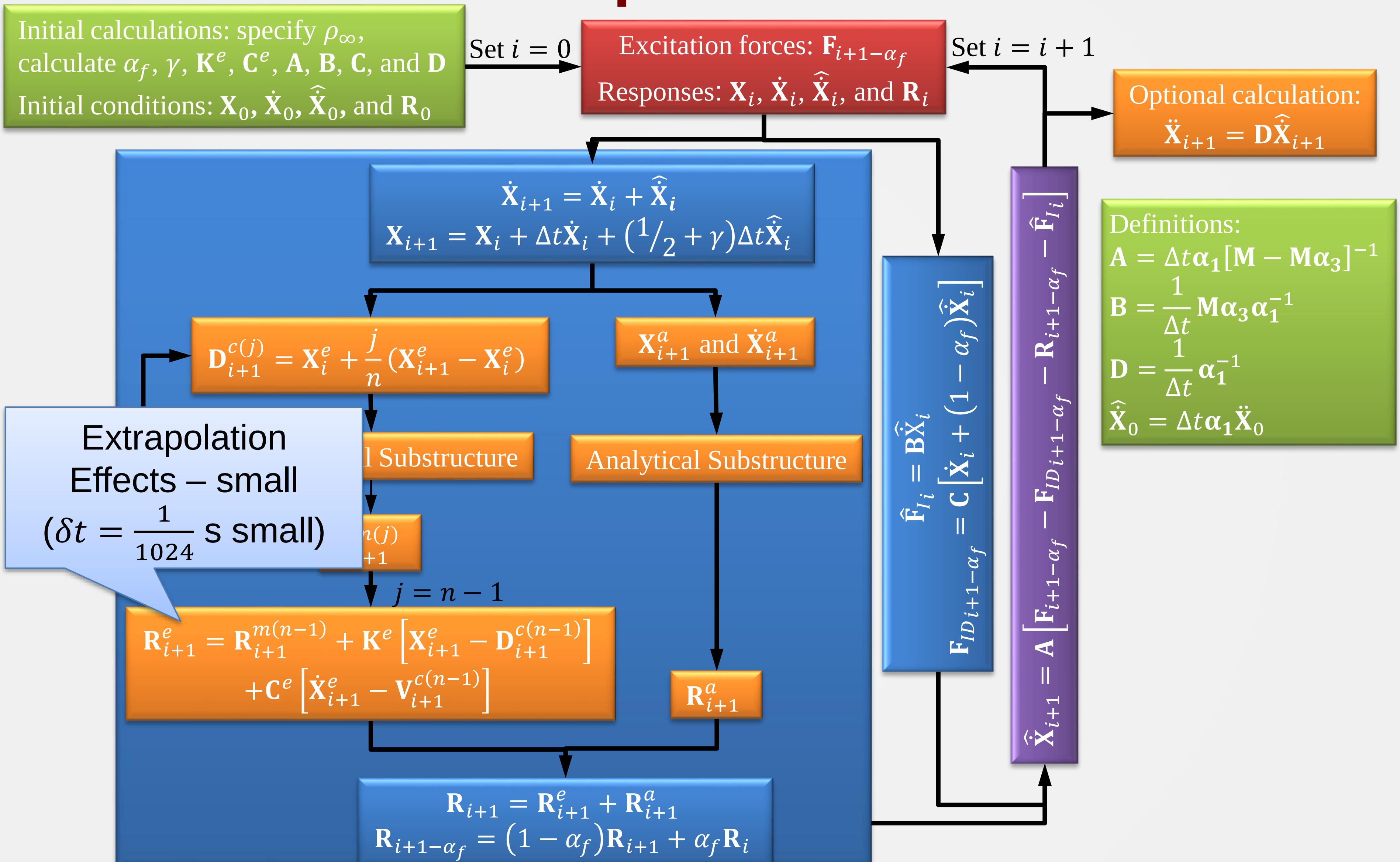


Controlled Numerical Damping

Kolay, C., and J.M. Ricles (2014). Development of a family of unconditionally stable explicit direct integration algorithms with controllable numerical energy dissipation. *Earthquake Engineering and Structural Dynamics*, 43(9), 1361–1380. http://doi.org/10.1002/eqe.2401

Kolay, C., and J.M. Ricles (2017) “Improved Explicit Integration Algorithms for Structural Dynamic Analysis with Unconditional Stability and Controller Numerical Dissipation,” *Journal of Earthquake Engineering*, http://dx.doi.org/10.1080/13632469.2017.1326423.

KR-α Method: Implementation for RTHS

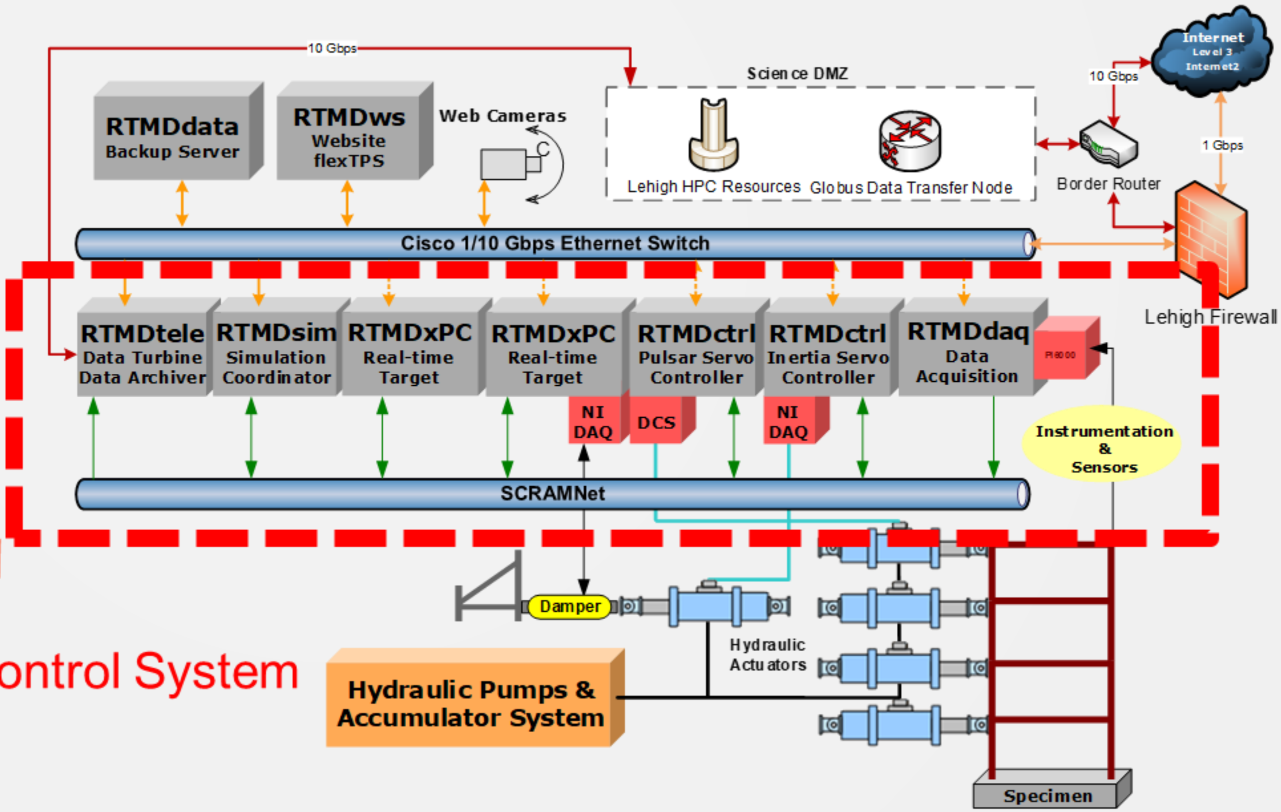


Kolay, C., Ricles, J., Marullo, T., Mahvashmohammadi, A., and Sause, R.. (2015). Implementation and application of the unconditionally stable explicit parametrically dissipative KR-α method for real-time hybrid simulation. *Earthquake Engineering & Structural Dynamics*. 44, 735-755, doi:10.1002/eqe.2484.

RTMD Real-time Integrated Control Architecture

NHERI Lehigh Solutions to RTHS Challenges

- Multiple real-time workstations with real-time communication (SCRAMNet)
- Synchronized control commands with simulation data, DAQ, and camera triggers to enable real time simulations and telepresence



Real-Time
Integrated Control System

RTHS: Implementation issues and challenges

Analytical substructure

- Fast and accurate state determination procedure

NHERI Lehigh Solutions

- Explicit force-based fiber elements
- HybridFEM

Fiber Element State Determination

FE Modeling of Analytical Substructure

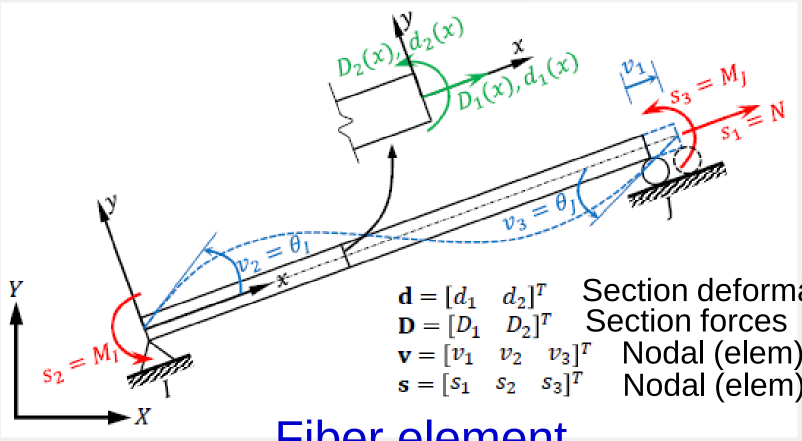
Displacement-based fiber elements

- ❑ Curvature varies linearly
  - ➢ Requires many elements per structural member to model nonlinear response
  - ➢ Increases number of DOFs
- ❑ State determination is straight forward

Force-based fiber elements

- ❑ Equilibrium is strictly enforced
  - ✓ Material nonlinearity can be modeled using a single element per structural member
  - ✓ Reduces number of DOFs
- ❑ Requires iterations at the element level

Jeopardizes explicit integration



$\mathbf{d} = [d_1 \quad d_2]^T$ Section deformations

$\mathbf{D} = [D_1 \quad D_2]^T$ Section forces

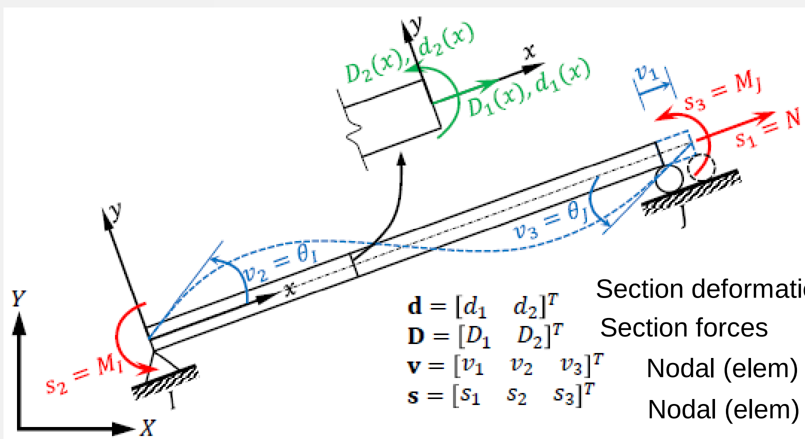
$\mathbf{v} = [v_1 \quad v_2 \quad v_3]^T$ Nodal (elem) deformations

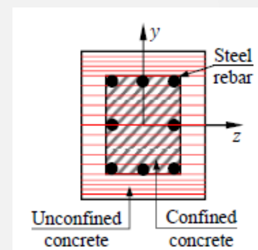
$\mathbf{s} = [s_1 \quad s_2 \quad s_3]^T$ Nodal (elem) forces

Fiber element

Explicit-formulated Force-Based Fiber Element

- Used with explicit integration algorithm
- Material nonlinearity
- Reduced DOFs in system modeling
- Fixed number of iterations during state determination with carry-over and correction of unbalanced section forces in next time step

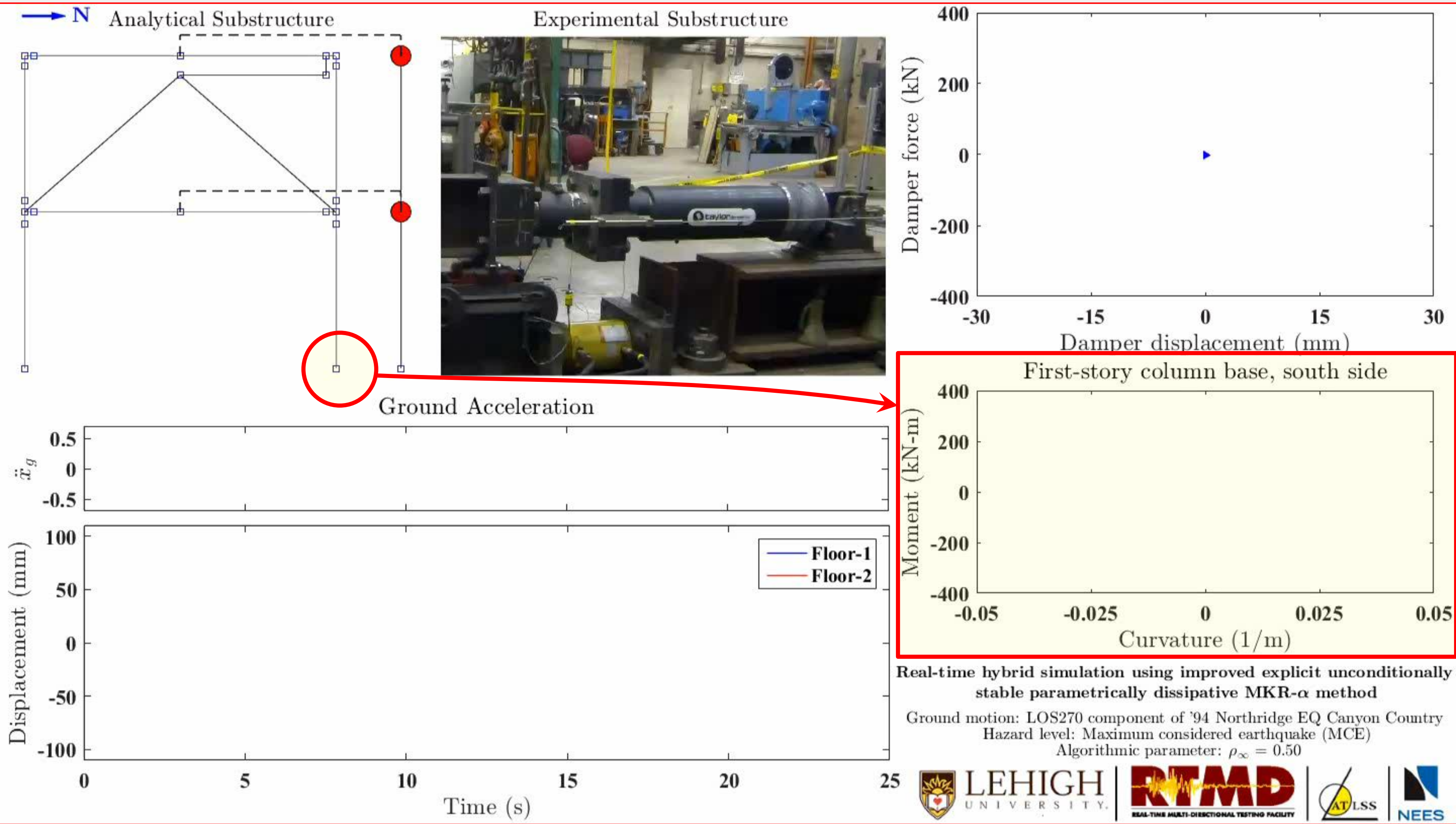




Fiber element

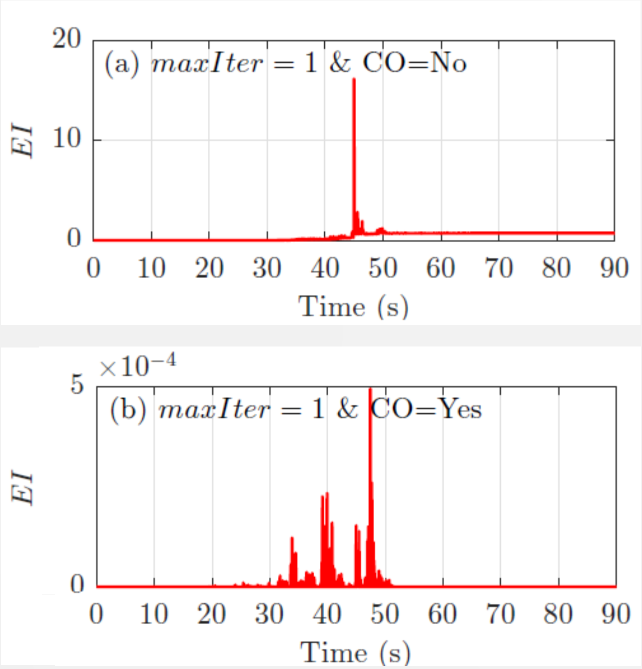
Kolay, C. and J.M. Ricles, (2018). Force-Based Frame Element Implementation for Real-Time Hybrid Simulation Using Explicit Direct Integration Algorithms. *Journal of Structural Engineering*, http://dx.doi.org/10.1080/13632469.2017.1326423.

RTHS of RC Structure: Fiber Element Real-time State-Determination

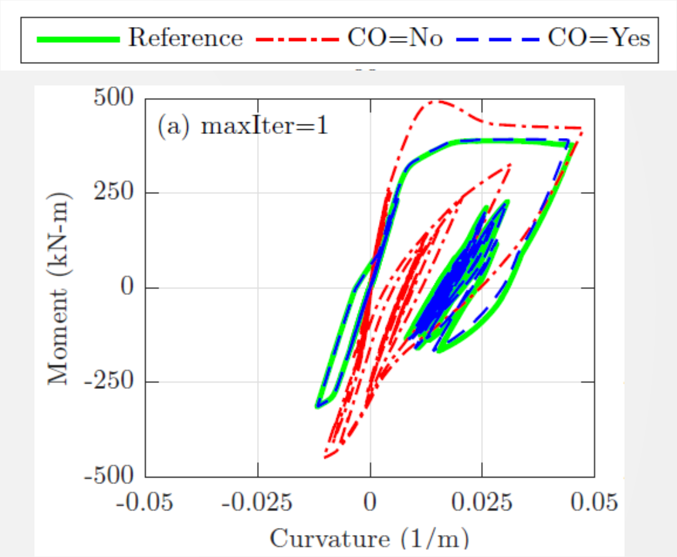


Explicit-formulated Force-Based Fiber Element

- Results



Energy Increment (EI) Error



Moment Curvature Response – 1st story RC column (CO: Carry over unbalanced section forces)

Note: Reference = Newmark Constant Acceleration Method

Kolay, C. and J.M. Ricles, (2018). Force-Based Frame Element Implementation for Real-Time Hybrid Simulation Using Explicit Direct Integration Algorithms. *Journal of Structural Engineering*, http://dx.doi.org/10.1080/13632469.2017.1326423.

Lehigh HybridFEM

NHERI Lehigh Solutions to RTHS Challenges

- MATLAB and SIMULINK based computational modeling and simulation coordinator software for dynamic time history analysis and real-time hybrid simulation of inelastic-framed structures
- Run Modes
  - MATLAB script for numerical simulation
  - SIMULINK modeling for Real-Time Hybrid simulation with experimental elements via xPCs, and hydraulics-off for training and validation of user algorithms.
- User's Manual for training

Karavasilis, T. L., Seo, C.-Y., & Ricles, J. M. (2012). *HybridFEM: A program for dynamic time history analysis and real-time hybrid simulation* (ATLSS Report). *ATLSS Report* (Vol. 08–09). Bethlehem, PA.

Lehigh HybridFEM

Configuration Options:

- Coordinate system of nodes
- Boundary, constraint and restraint conditions
- Elements
  - Elastic beam-column
  - Elastic spring
  - Inelastic beam-column stress resultant element
  - Non-linear spring
  - Non-linear truss element
  - Displacement-based NL beam-column fiber element
  - Force-based NL beam-column fiber element
  - Zero-length
  - 2D NL planar panel zone
  - Elastic beam-column element with geometric stiffness
- Geometric nonlinearities
- Steel wide flange sections (link to AISC shapes Database)
- Reinforced concrete sections
- Structural mass & inherent damping properties
- Adaptable integration methods

- Materials
  - Elastic
  - Bilinear elasto-plastic
  - Hysteretic
  - Bouc-Wen
  - Trilinear
  - Stiffness degrading
  - Concrete
  - Steel

RTHS: Implementation issues and challenges

Experimental substructure

- Large capacity hydraulic system and dynamic actuators required
- Actuator kinematic compensation
- Robust control of dynamic actuators for large-scale structures

NHERI Lehigh Solutions

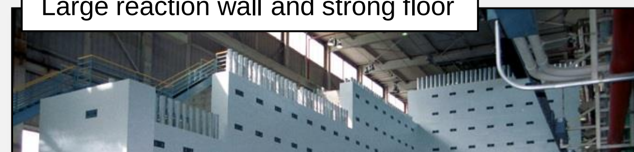
- Large hydraulic power supply system
- 5 large capacity dynamic actuators
- Development of actuator kinematic compensation
- Servo hydraulic actuator control: Adaptive Time Series Compensator (ATS)

Large Capacity Hydraulic System and Dynamic Actuators

NHERI Lehigh Solutions to RTHS Challenges

- Lehigh has unique equipment with large hydraulic power, facilitating large-scale real-time hybrid simulation

Large reaction wall and strong floor

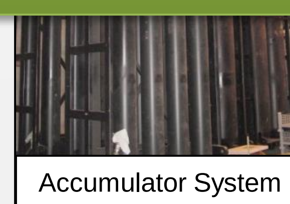


Large-force capacity dynamic actuators

Maximum load capacity
- 2 actuators: 517 kips (2,300kN)
- 3 actuators: 382 kips (1,700kN)

Stroke
- +/- 20 in (+/- 500mm)

Maximum velocity
- 45 in/s (1,140mm/sec) for 382 kip actuators
- 33 in/s (840mm/sec) for 517 kip actuators



Accumulator System

DAQ System

Large Capacity Hydraulic System and Dynamic Actuators

NHERI Lehigh Solutions to RTHS Challenges

- Lehigh has unique equipment with large hydraulic power, facilitating large-scale real-time hybrid simulation

Large reaction wall and strong floor

Large-force capacity dynamic actuators

- Enables a large-scale RTHS of a structure under strong ground motions (i.e., Kobe earthquake, Japan)
- Collapse simulation of a building structure was conducted under extreme earthquake ground motions (beyond MCE level)

Accumulator System

DAQ System

Actuator Kinematic Compensation

- Develop kinematic compensation scheme and implementation for RTHS (Mercan et al. 2009)
  - Kinematic correction of command displacements for multi-directional actuator motions
  - Robust, avoiding accumulation of error over multiple time steps; suited for RTHS
  - Exact solution for planar motions

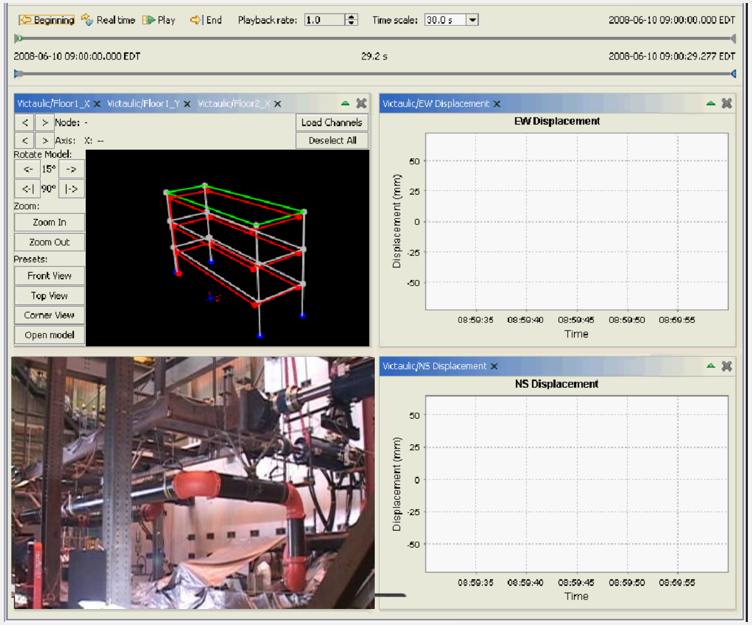
$$(M_i SNxL_{new}, M_i SNyL_{new}) = (-LMa_{inew}\sin(\Theta_2 + \phi_i), LMa_{inew}\cos(\Theta_2 + \phi_i))$$

$$\Theta_2 = \arcsin\left[\frac{LMb_{inew}}{yF_i/\cos\phi_i}\sin\Theta_3\right]$$

$$\Theta_3 = \arccos\left[\frac{LMa_{inew}^{\;2} + LMb_{inew}^{\;2} - (yF_i/\cos\phi_i)^2}{2LMa_{inew}LMb_{inew}}\right]$$

$$(SPN^m x_{new}, SPN^m y_{new}) = (M_1 SN^m x_{new} - \left|\overrightarrow{VM}_1\right|\cos(\Theta M_{1,0} + d^m SPN\Theta), M_1 SN^m y_{new} - \left|\overrightarrow{VM}_1\right|\sin(\Theta M_{1,0} + d^m SPN\Theta))$$

Mercan, O, Ricles, J.M., Sause, R, and M. Marullo, “Kinematic Transformations in Planar Multi-directional Pseudo-Dynamic Testing,” *Earthquake Engineering and Structural Dynamics*, Vol. 38(9), pp. 1093-1119, 2009.



Multi-directional Real-time Hybrid Simulation

Servo Hydraulic Actuator Control

Sources of Nonlinearity in Real-Time Hybrid Simulation

- Nonlinear servo-valve dynamics
- Nonlinear actuator fluid dynamics
- Test specimen material and geometric nonlinearities
- Slop, misalignment, deformations in test setup

Can lead to variable amplitude error and time delay in servo-hydraulic system that does not enable the target displacement of the experimental substructure to be achieved

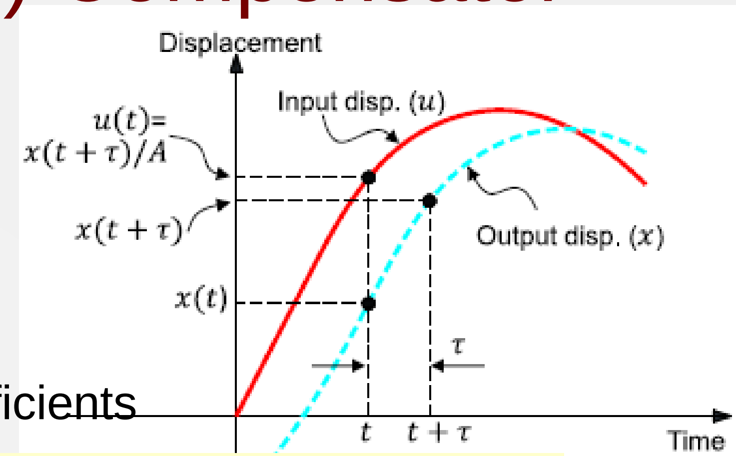
Effect of time delay on real-time hybrid simulation

- Inaccurate structural response
- Delayed restoring force adds energy into the system (negative damping)
- Can cause the instability of simulation

➔ *important to negate the time delay effect in real-time hybrid simulation*

Adaptive Time Series (ATS) Compensator

2nd order ATS compensator



$$u_k^c = a_{0k} x_k^t + a_{jk} \dot{x}_k^t + a_{2k} \ddot{x}_k^t$$

u_k^c: compensated input displacement into actuator

x_k^t: target **specimen** displacement a_{jk}: adaptive coefficients

Adaptive coefficients are optimally updated to minimize the error between the specimen target and measured displacements using the **least squares** method

$$\mathbf{A} = \left(\mathbf{X}_\mathbf{m}^\mathbf{T} \mathbf{X}_\mathbf{m}\right)^{-1} \mathbf{X}_\mathbf{m}^\mathbf{T} \mathbf{U}_\mathbf{c}$$

$$\mathbf{A} = \left[a_{0k}\, a_{1k} \cdots a_{nk}\right]^T \qquad \mathbf{X}_\mathbf{m} = \left[\mathbf{x}^\mathbf{m}\; \dot{\mathbf{x}}^\mathbf{m} \cdots \frac{d^n}{dt^n}\left(\mathbf{x}^\mathbf{m}\right)\right]^T$$

$$\mathbf{x}^\mathbf{m} = \left[x_{k-1}^m\, x_{k-2}^m \cdots x_{k-q}^m\right]^T$$ (Output (measured) specimen displacement history)

$$\mathbf{U}_\mathbf{c} = \left[u_{k-1}^c\, u_{k-2}^c \cdots u_{k-q}^m\right]^T$$ (Input actuator displacement history)

Chae, Y., Kazemibidokhti, K., and Ricles, J.M. (2013). “Adaptive time series compensator for delay compensation of servo-hydraulic actuator systems for real-time hybrid simulation”, *Earthquake Engineering and Structural Dynamics*, DOI: 10.1002/ eqe.2294.

Adaptive Time Series (ATS) Compensator

Unique features of ATS compensator

- No user-defined adaptive gains ➔ applicable for large-scale structures susceptible to damage (i.e., concrete structures)
- Negates both variable time delay and variable amplitude error response
- Time delay and amplitude response factor can be easily estimated from the identified values of the coefficients
- Use specimen feedback

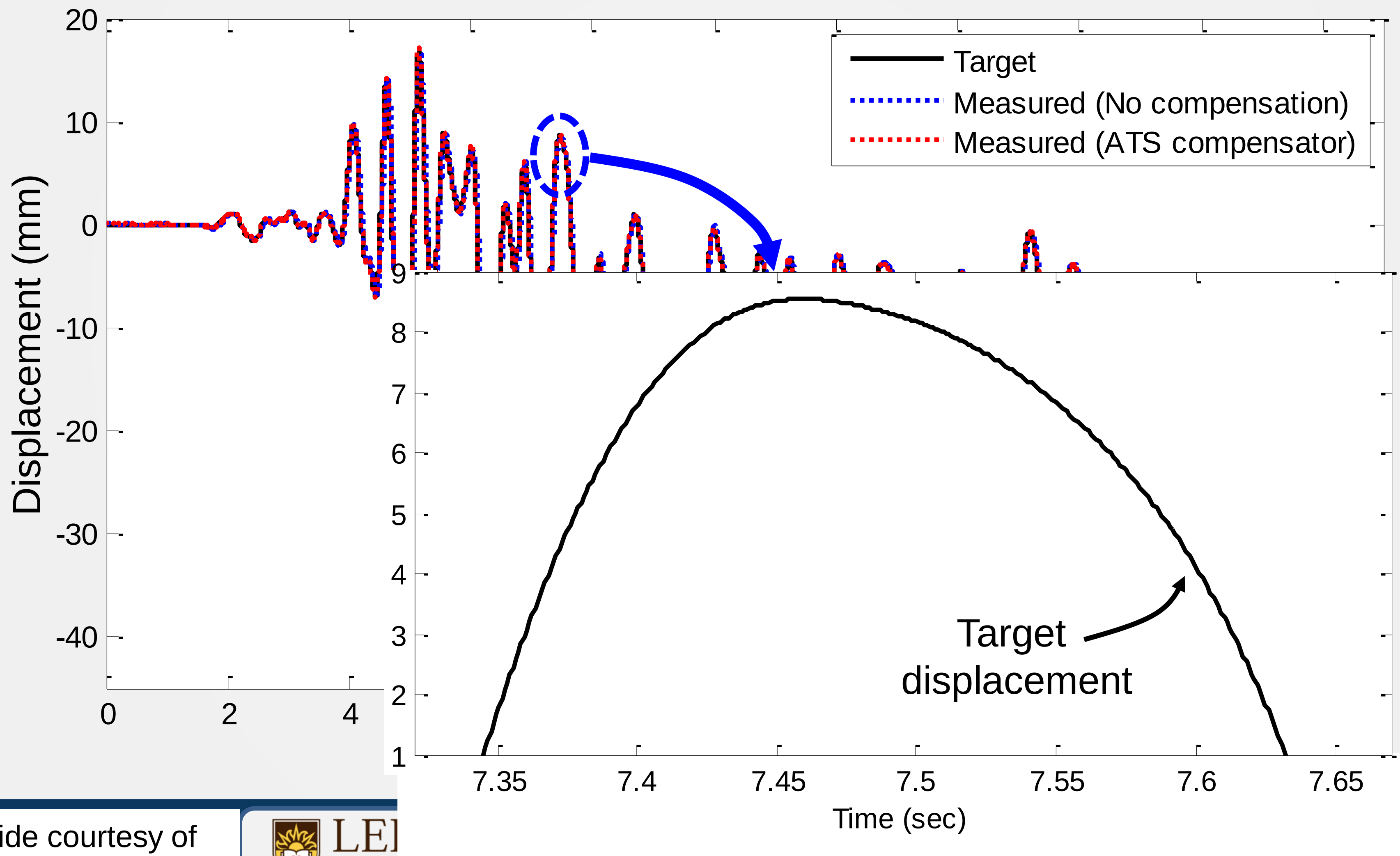
Amplitude error: $$A = \frac{1}{a_{0k}}$$

Time delay: $$t = \frac{a_{1k}}{a_{0k}}$$

Adaptive Time Series (ATS) Compensator

- Performance of ATS compensator -

Predefined EQ displacement test (maximum amplitude=40mm)

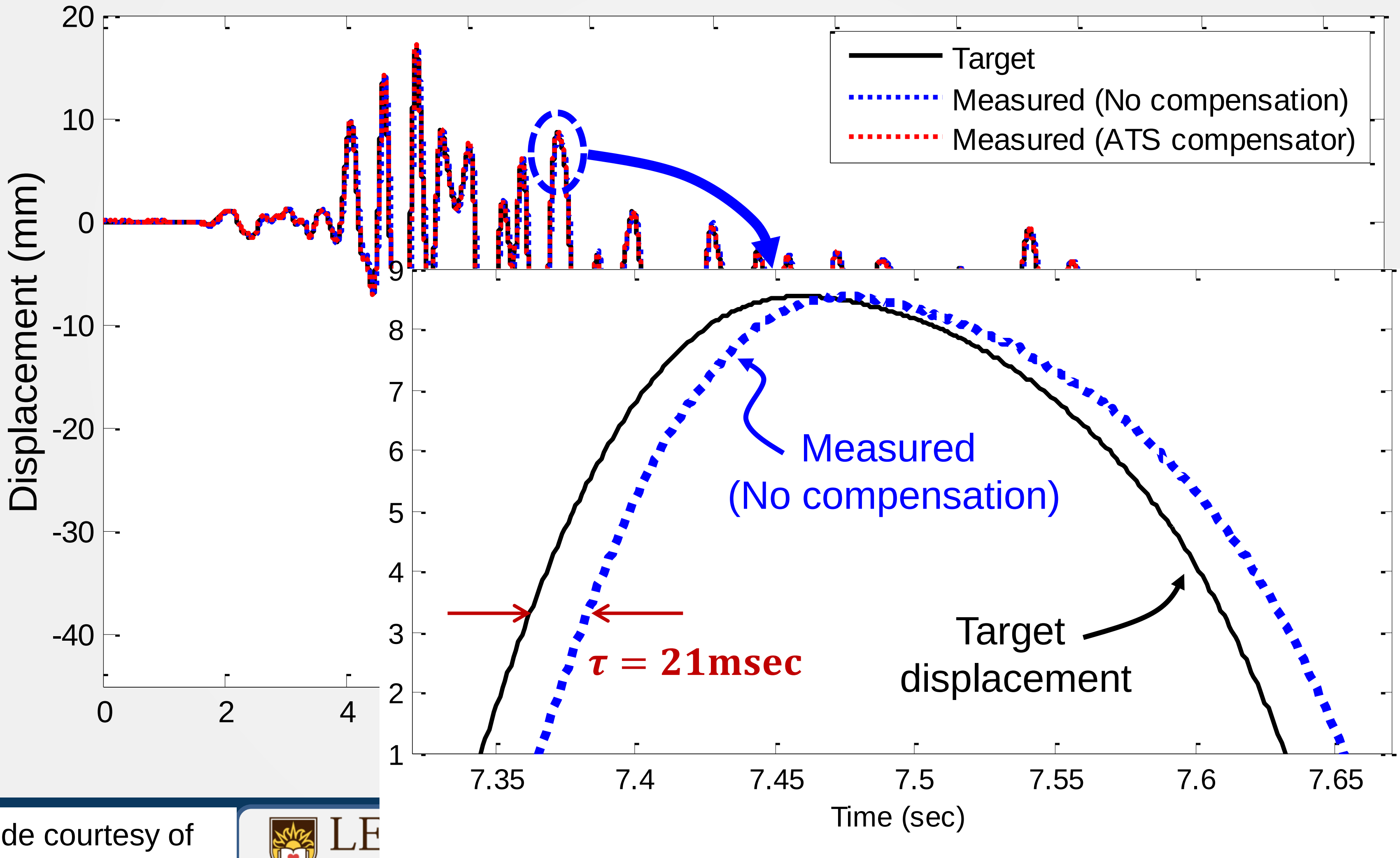


Slide courtesy of
Yunbyeong Chae

Adaptive Time Series (ATS) Compensator

- Performance of ATS compensator -

Predefined EQ displacement test (maximum amplitude=40mm)



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Adaptive Time Series (ATS) Compensator

- Performance of ATS compensator -

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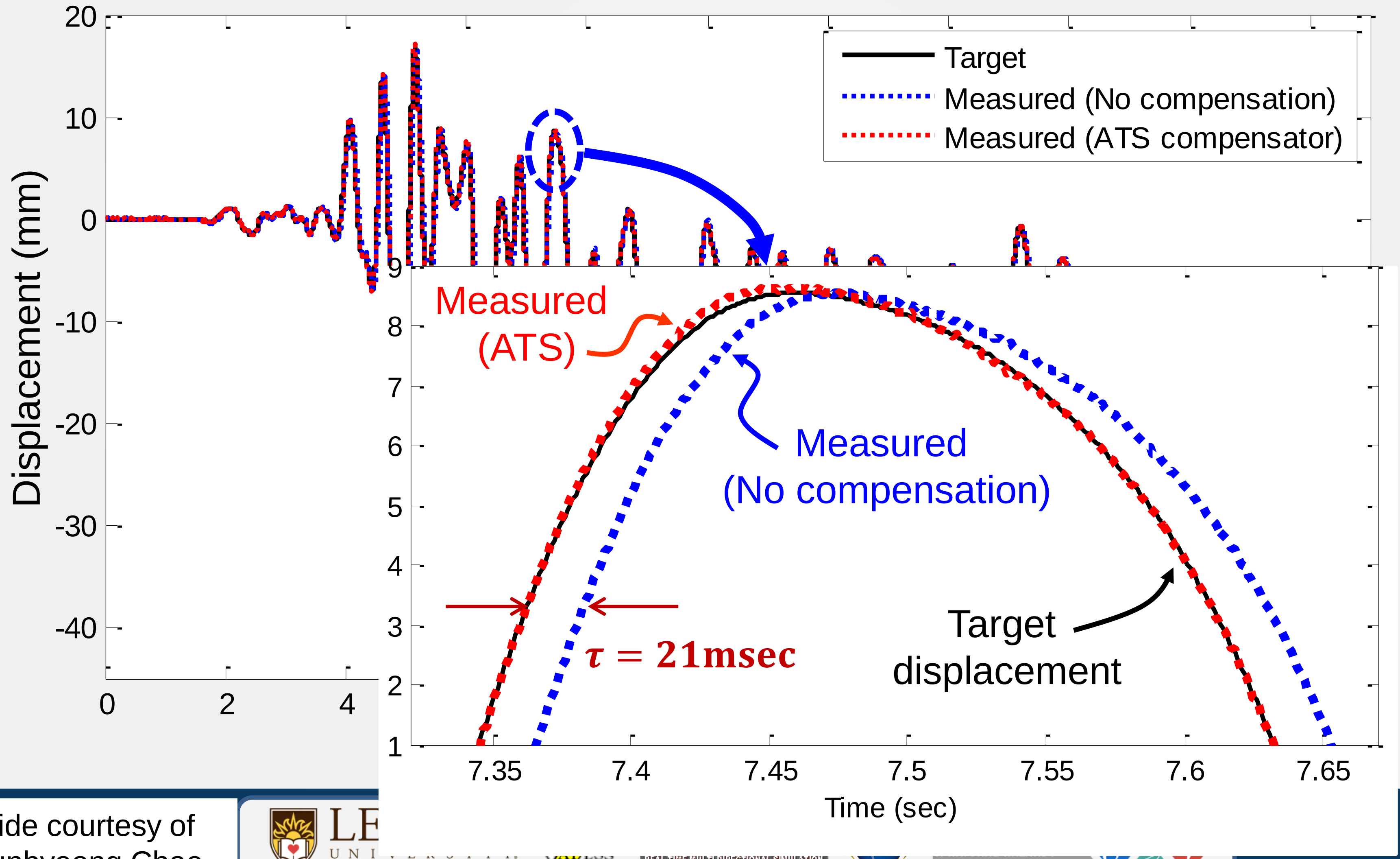
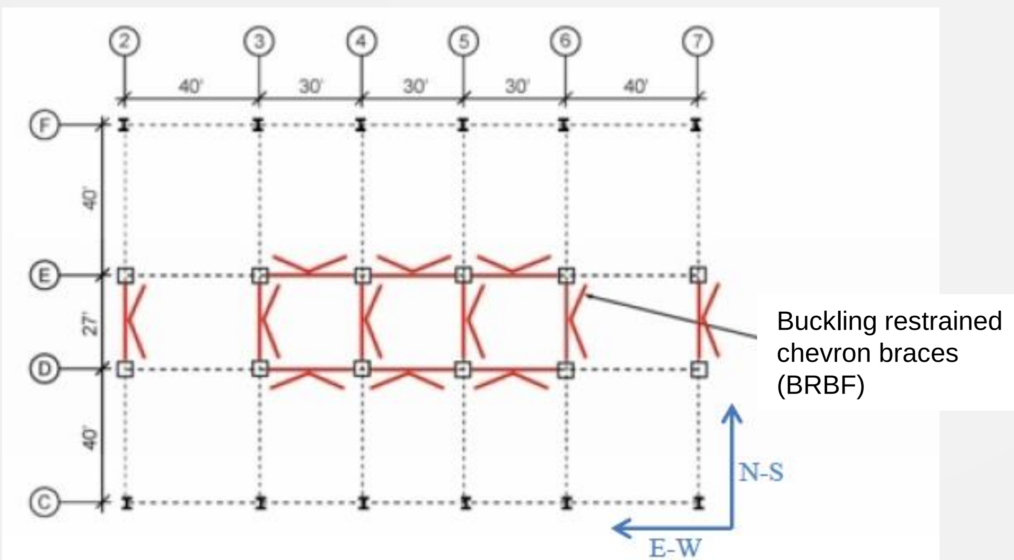


Slide courtesy of
Yunbyeong Chae

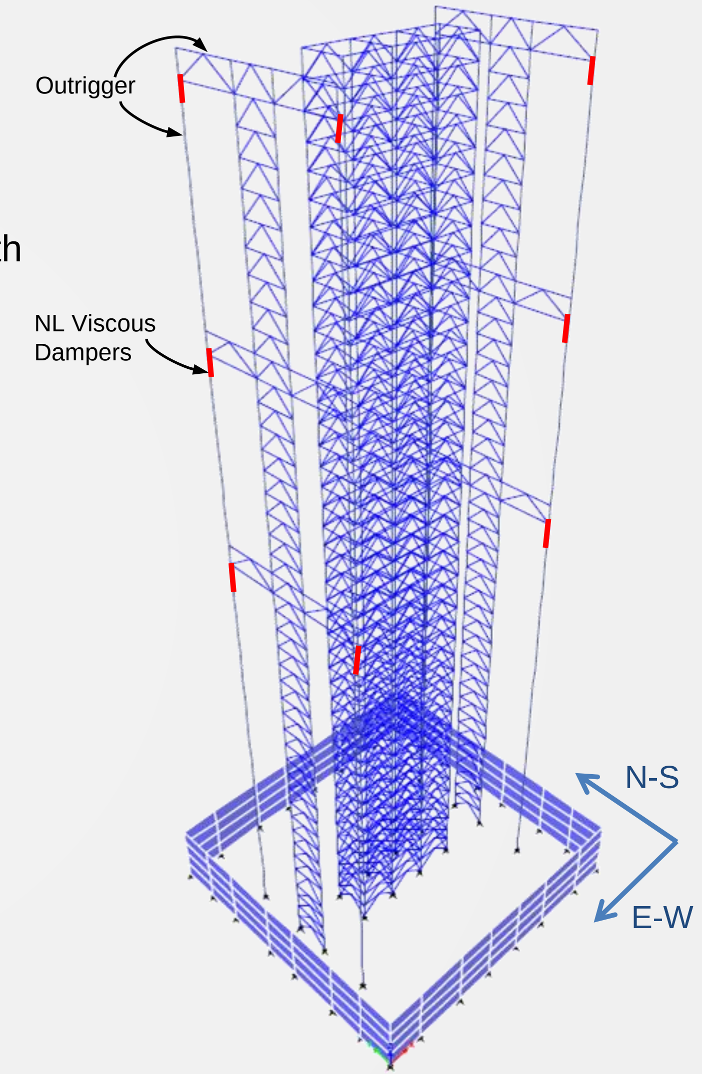
Applications of RTHS to Multi-Hazards

RTHS of a Tall Building

- 40-story (+4 basement) BRBF building in Los Angeles designed by SGH for PEER Tall Building Initiative case studies
- Objectives of study
  - Investigate multi-hazard performance of building outfitted with nonlinear fluid viscous dampers placed in outriggers
  - Assess performance using RTHS
- Extend MKR-α integration algorithm and ATS actuator control to wind natural hazard



Plan for floors that do not include the outriggers. Image courtesy of Dutta and Hamburger (2010)

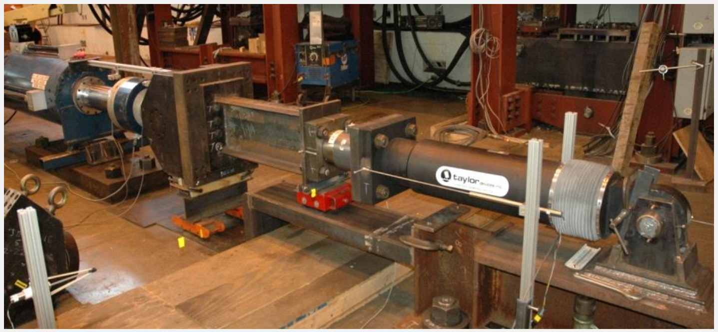


3-D view of the building. Image courtesy of Dutta and Hamburger (2010)

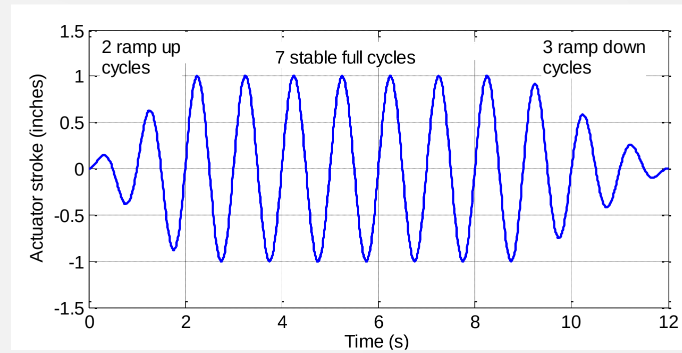
Ref.: Moehle et al., PEER 2011/05

Nonlinear Viscous Dampers

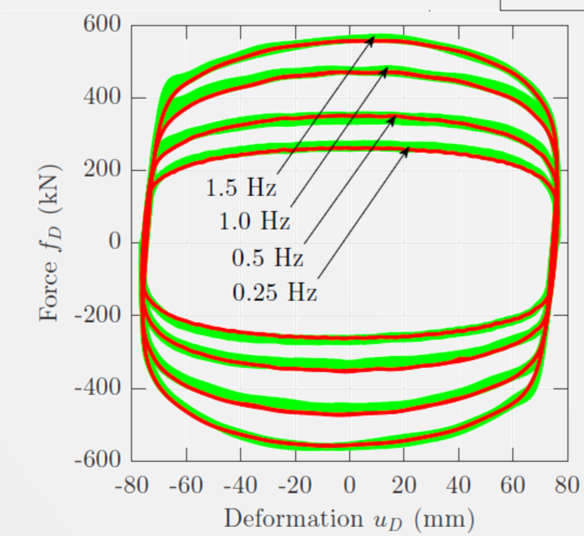
Characterization testing



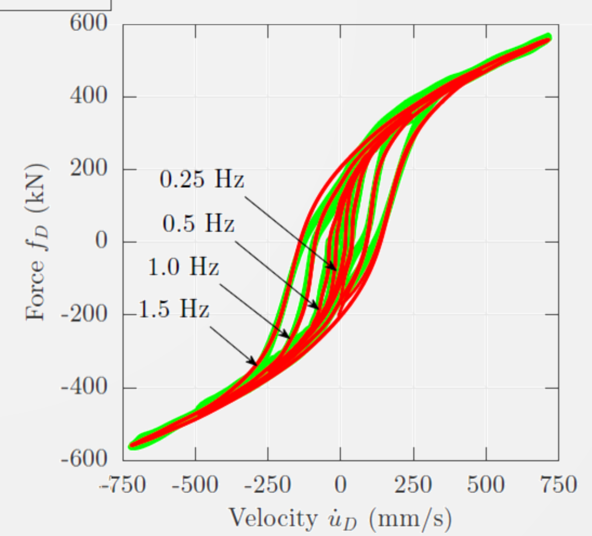
Damper testbed



Loading Protocol



Damper force - deformation



Damper force - velocity

RTHS Configuration

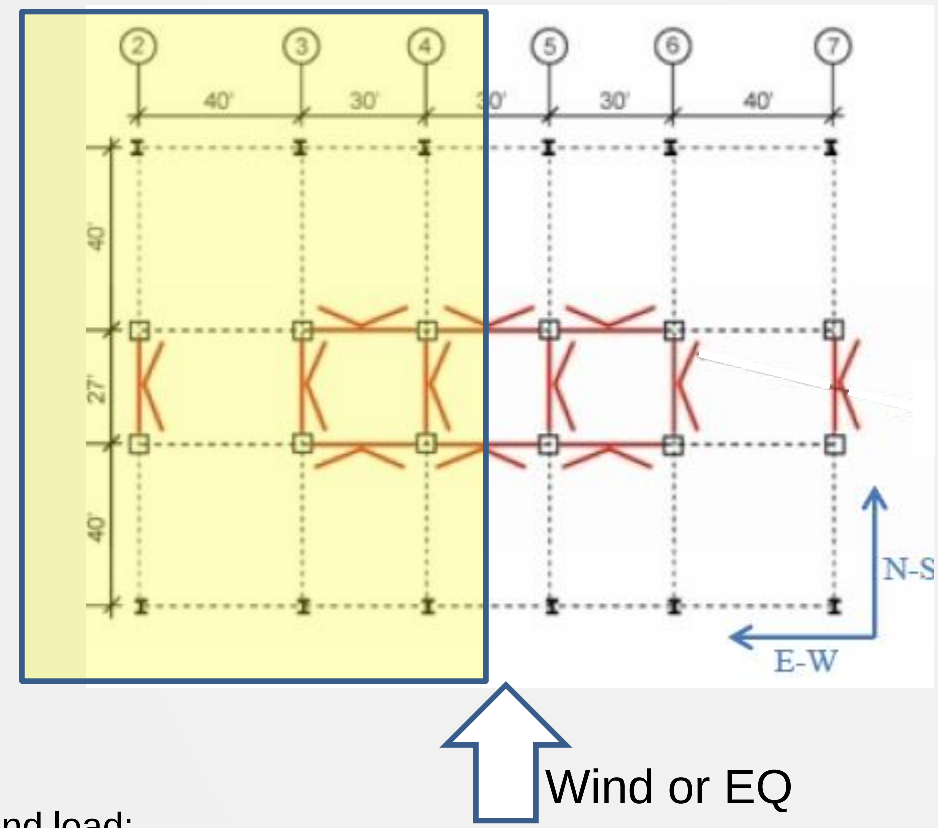
- Use of:
  - Explicit MKR-α Integration Algorithm
  - Explicit Force-based Fiber Element – Analytical Substructure
  - Adaptive Time Series Compensator for Actuator Control

MKR-α parameter and ATS coefficients

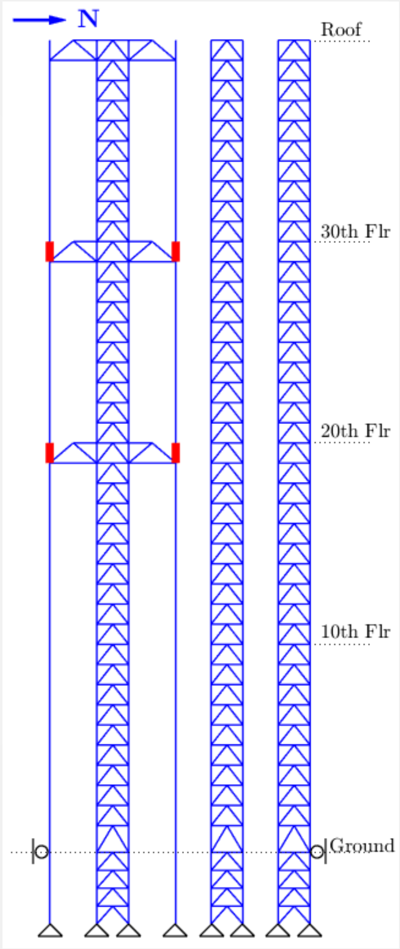
Natural Hazard	Time Step, Δt (sec)	ρ_∞	ATS Coefficients			Comments
			a_{0k}	a_{1k}	a_{2k}	
Wind	$\frac{6}{1024}$	0.866	Fixed	Adaptive	Fixed	Wind: static component with dynamic gusts - 1st mode linear response
EQ	$\frac{6}{1024}$	0.50	Adaptive	Adaptive	Adaptive	EQ: Multi-mode non-linear response

RTHS Configuration

Building Floor Plan



Test Structure Elevation



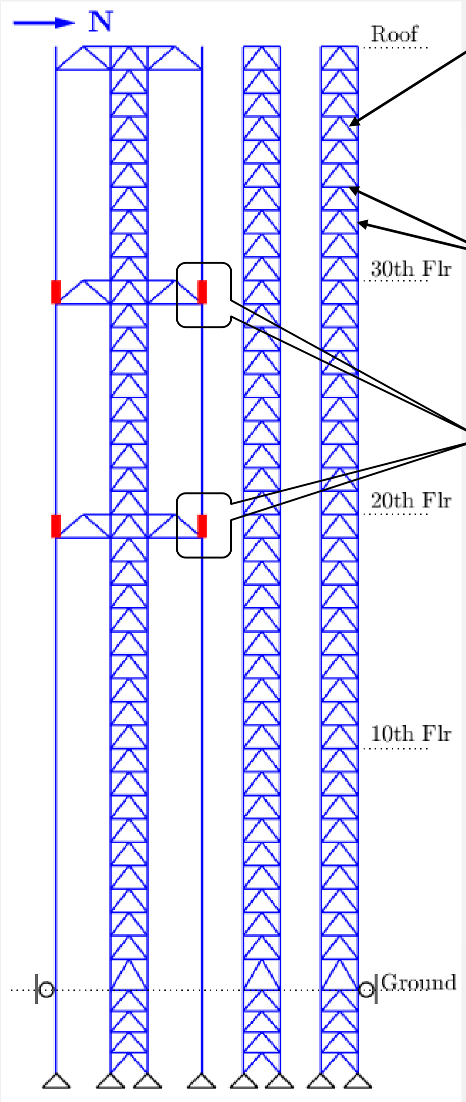
Wind load:

- Tokyo Polytechnic University Wind Tunnel Test database
- Normalized pressure coefficient time histories are converted to full scale forces corresponding to Exposure B and wind speed of 110 mph, 700 year MRI

EQ load:

- 1989 Loma Prieta EQ – Saratoga Aloha Ave Station scaled to SLE, DBE, and MCE (43, 475, 2475 year return periods, respectively) hazard level

RTHS Test Structure



BRB: nonlinear truss element with isotropic hardening

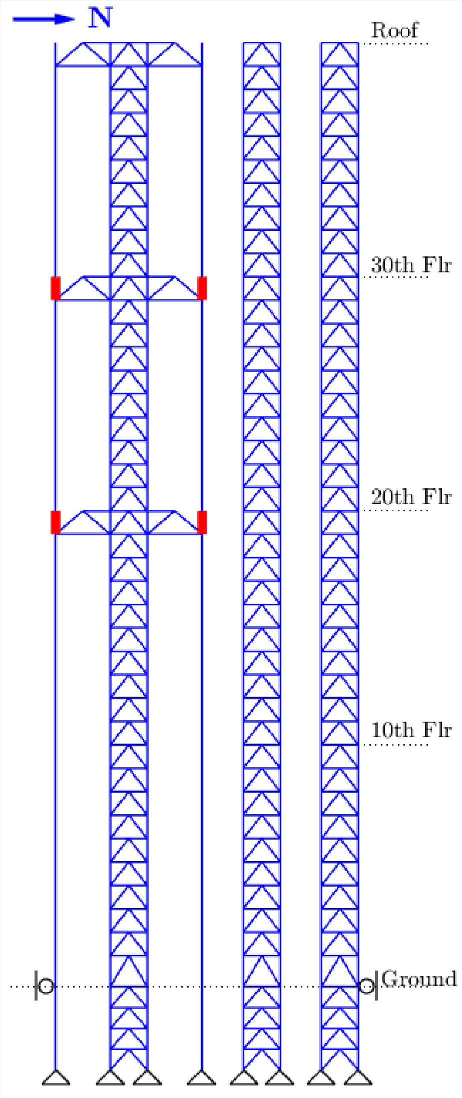
Beams and columns: beam-column fiber element

Nonlinear fluid viscous dampers: Modeled physically

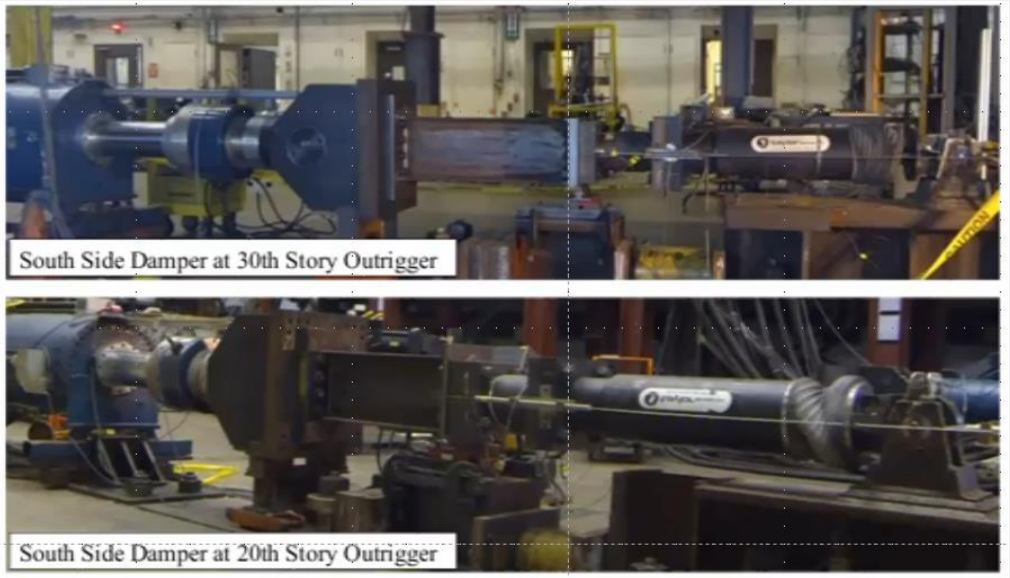
- Mass & inherent damping of building: modeled analytically

RTHS Substructures

Analytical Substructure



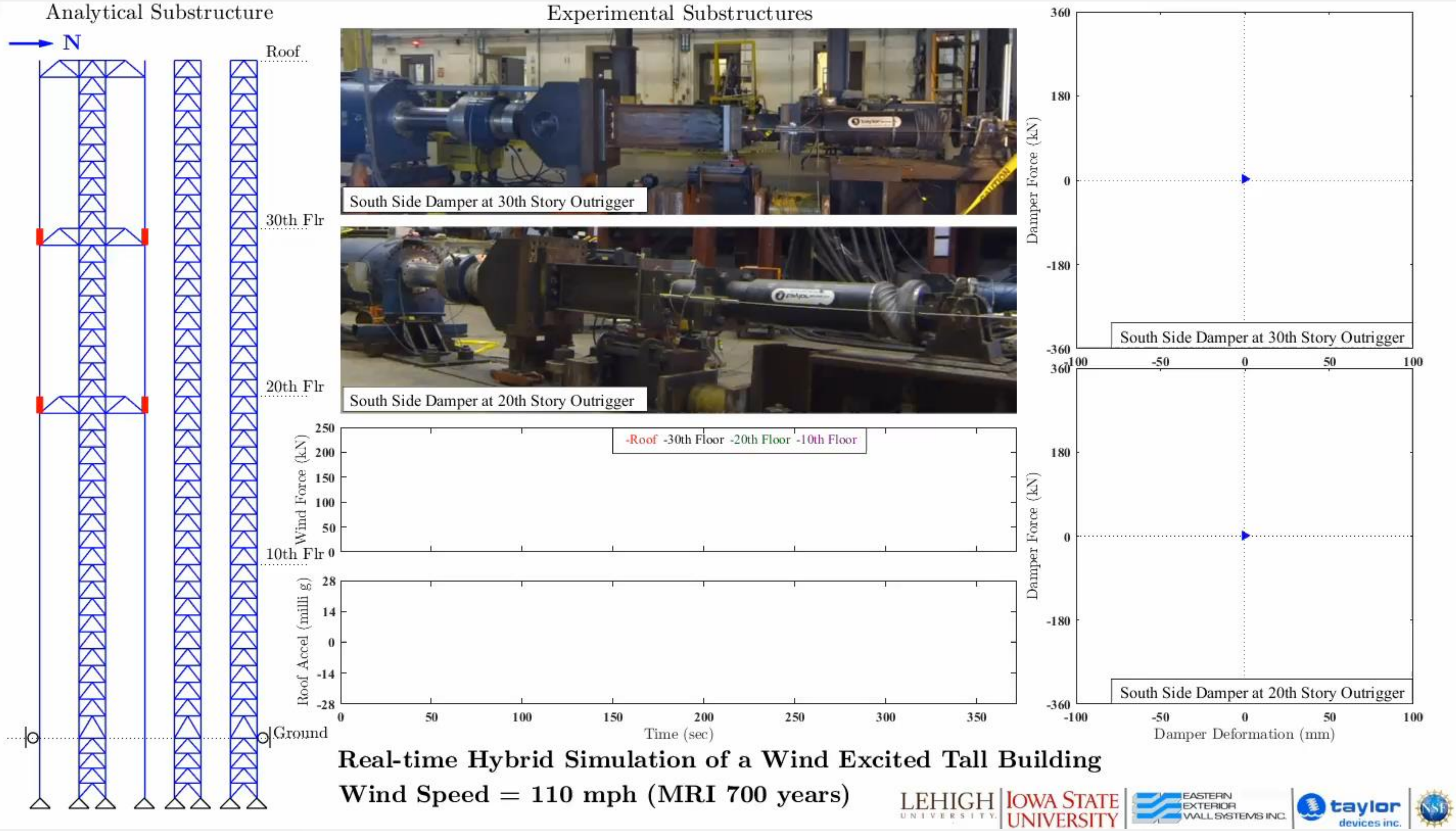
Experimental Substructures



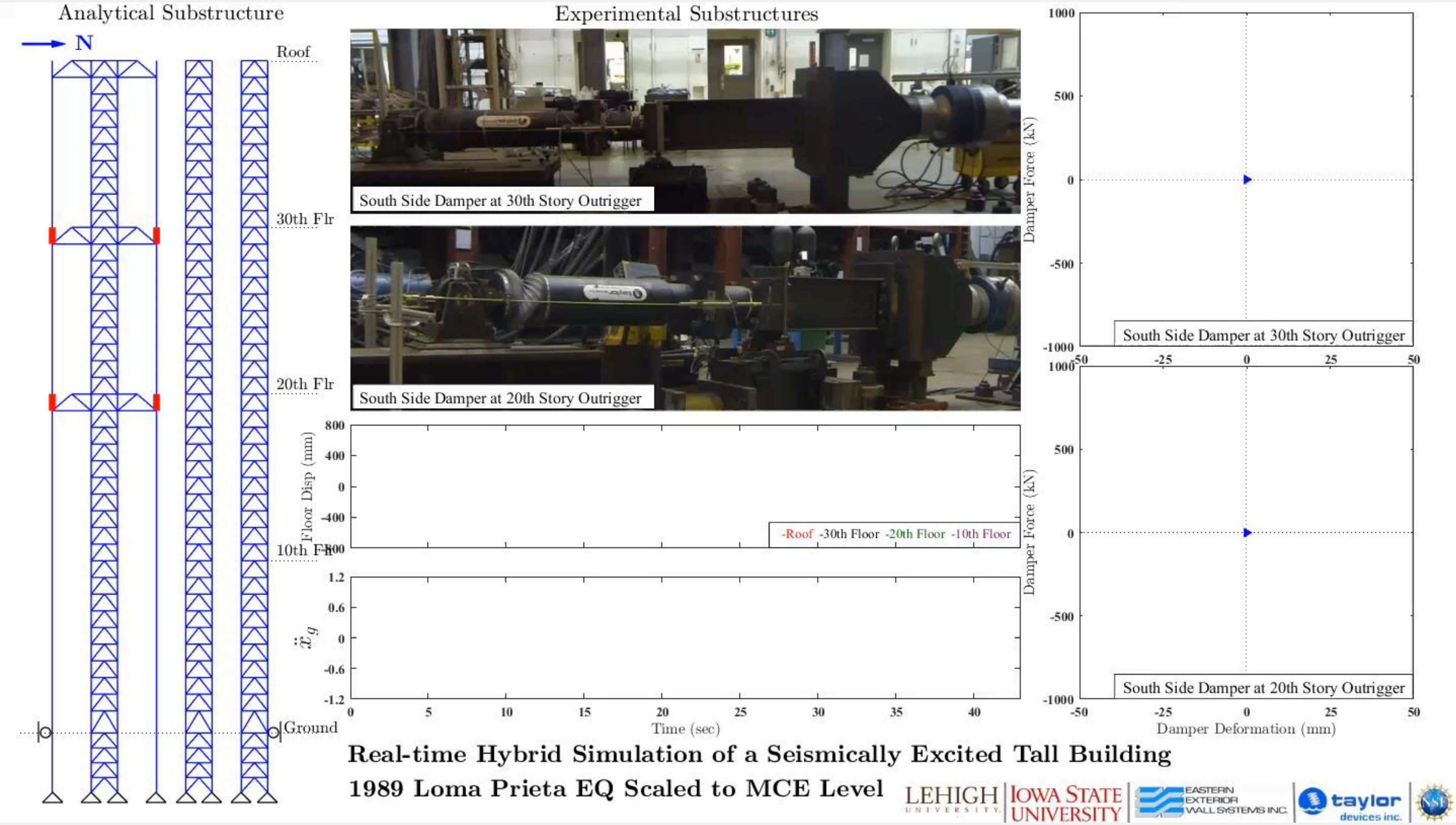
<u>Analytical Substructure Key features</u>:

- P-Δ effects included
- 780 Nodes
- 996 Elements
- 1590 DOFs
- Mass
- Inherent damping of building

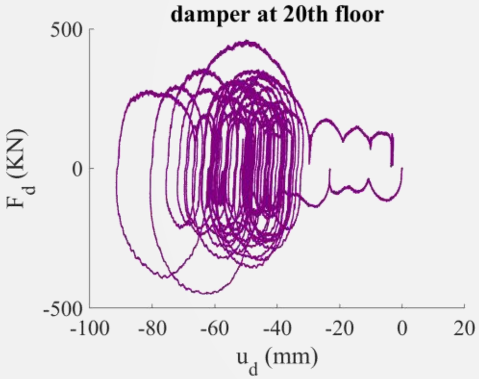
Demonstration of a Typical Wind RTHS

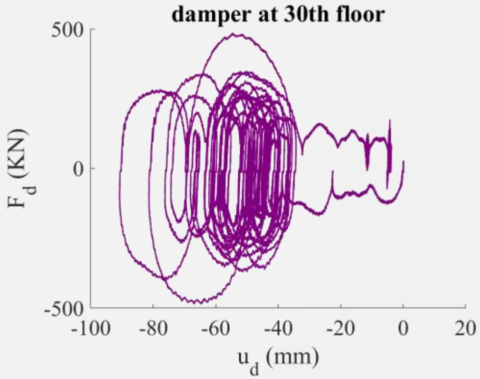


Demonstration of a Typical EQ RTHS



RTHS Results: Damper Force-Displacement Response, 700 Year MRI Wind





- Dampers experienced low velocity, with dynamic gust
  - ➢ Dampers performed similar to linear viscous dampers

RTHS Results: Damper Force-Displacement, Loma Prieta EQ

- Dampers developed appreciable dynamic response
  - ➢ Dampers performed as nonlinear dampers, where force is capped

Actuator Control: Typical Wind RTHS

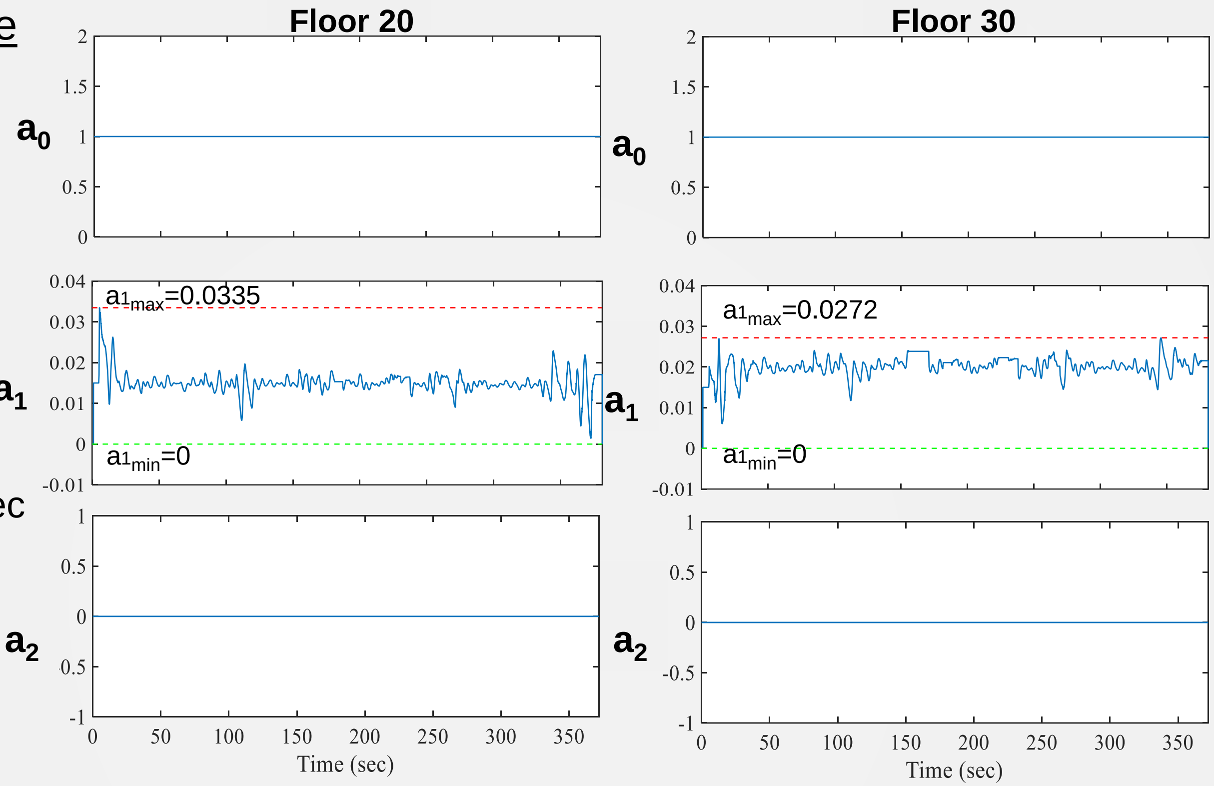
Time History of Adaptive Coefficients

Amplitude Correction

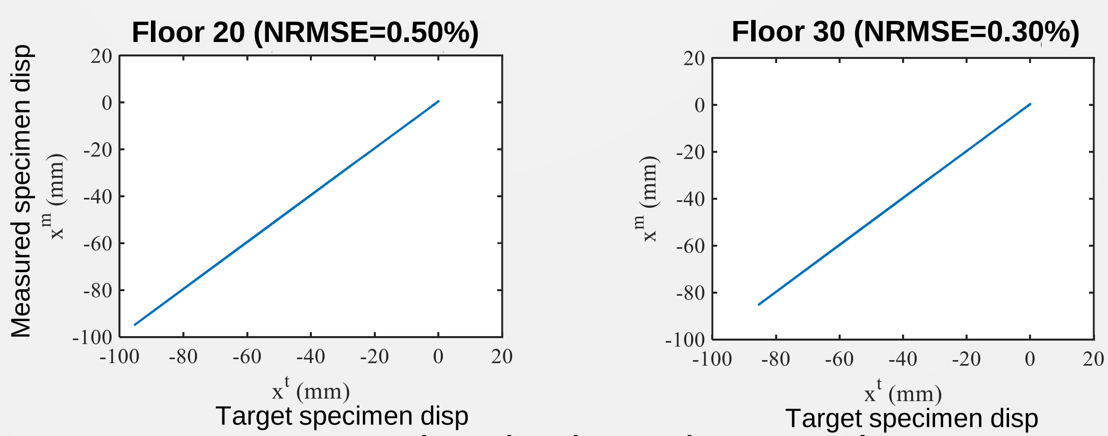
$$A_k^{(j)} \approx \frac{1}{a_{0k}^{(j)}} = 1.0$$

Delay Compensation

$$\tau_k^{(j)} \approx \frac{a_{1k}^{(j)}}{a_{0k}^{(j)}} = 27 \sim 34 \text{ msec}$$



Time variation of ATS parameters



Synchronization subspace plot

Actuator Control: Typical EQ RTHS

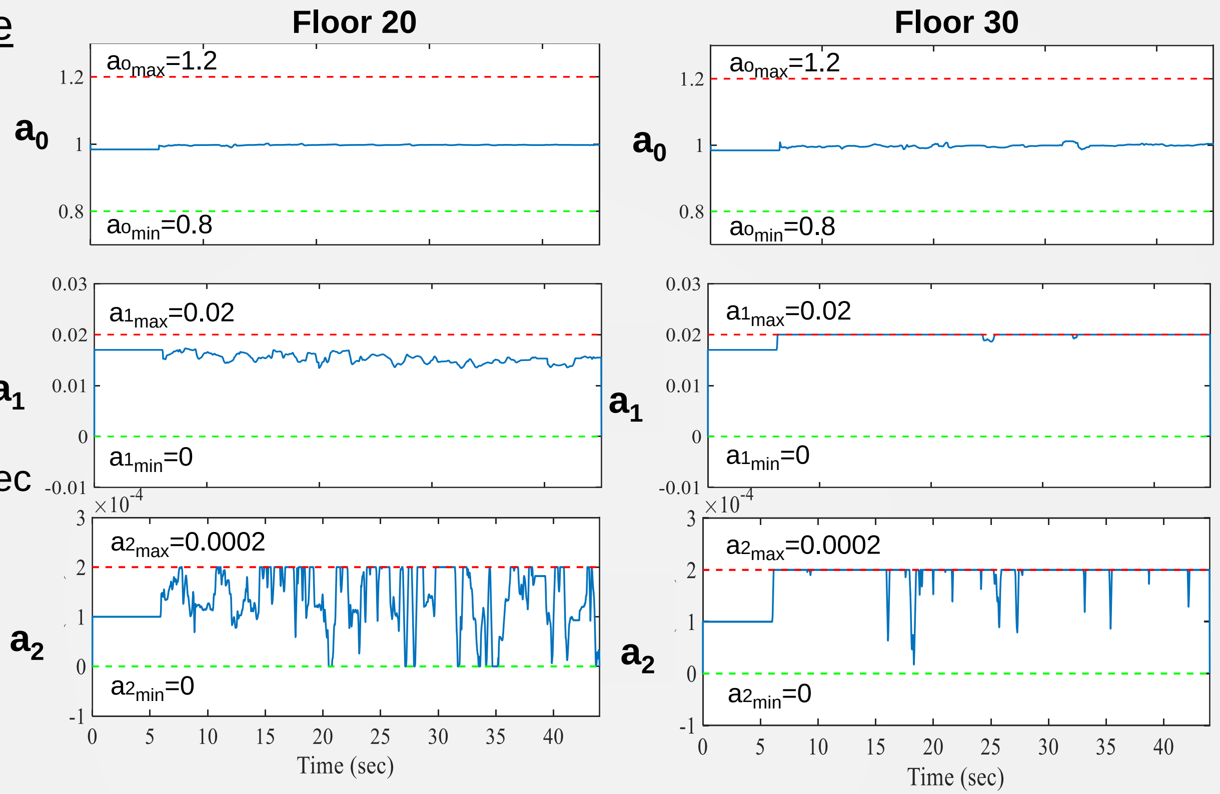
Time History of Adaptive Coefficients

Amplitude Correction

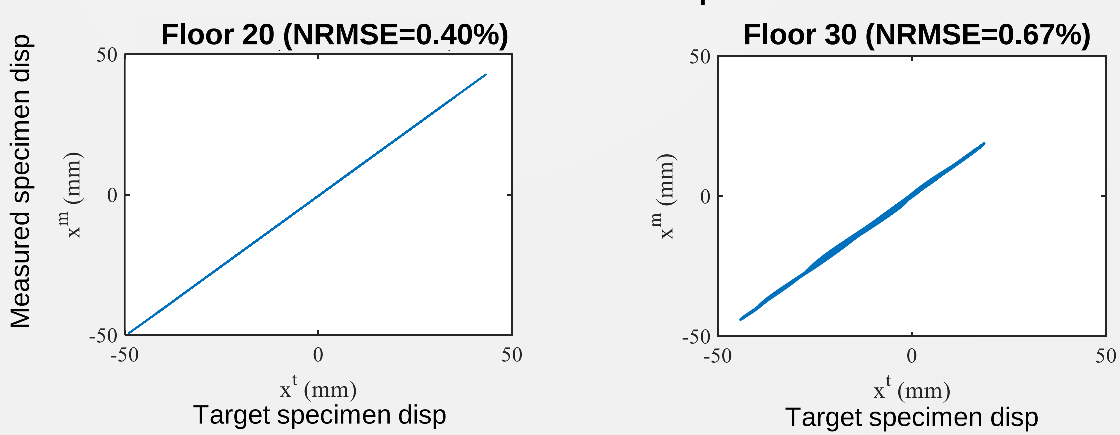
$$A_k^{(j)} \approx \frac{1}{a_{0k}^{(j)}} = 0.99 \sim 1.01$$

Delay Compensation

$$\tau_k^{(j)} \approx \frac{a_{1k}^{(j)}}{a_{0k}^{(j)}} = 15 \sim 20 \text{ msec}$$



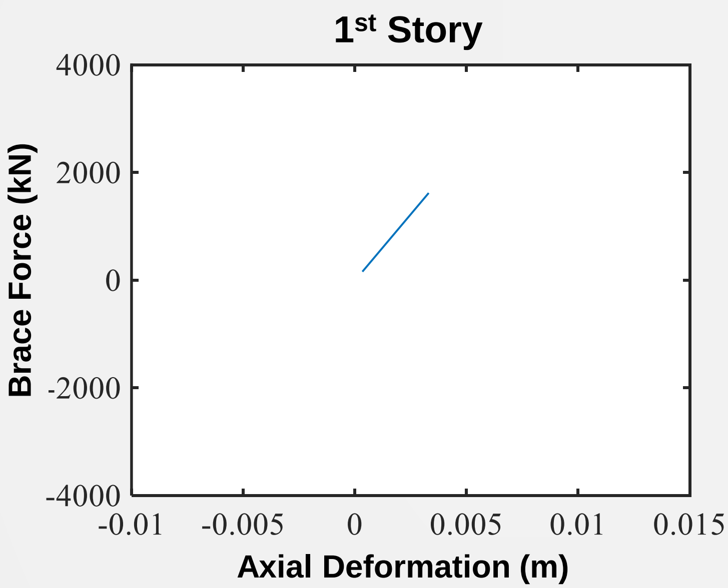
Time variation of ATS parameters



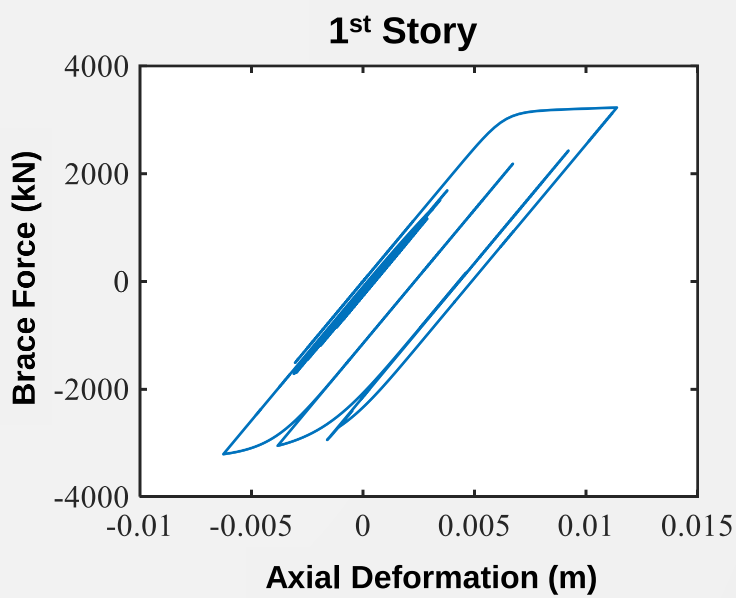
Synchronization subspace plot

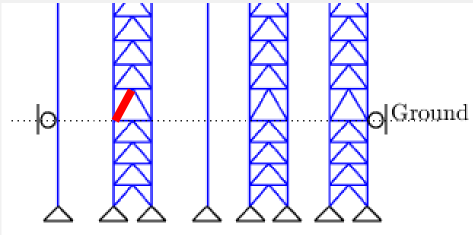
RTHS Analytical Substructure
Buckling Restrained Brace Response

Wind



Earthquake

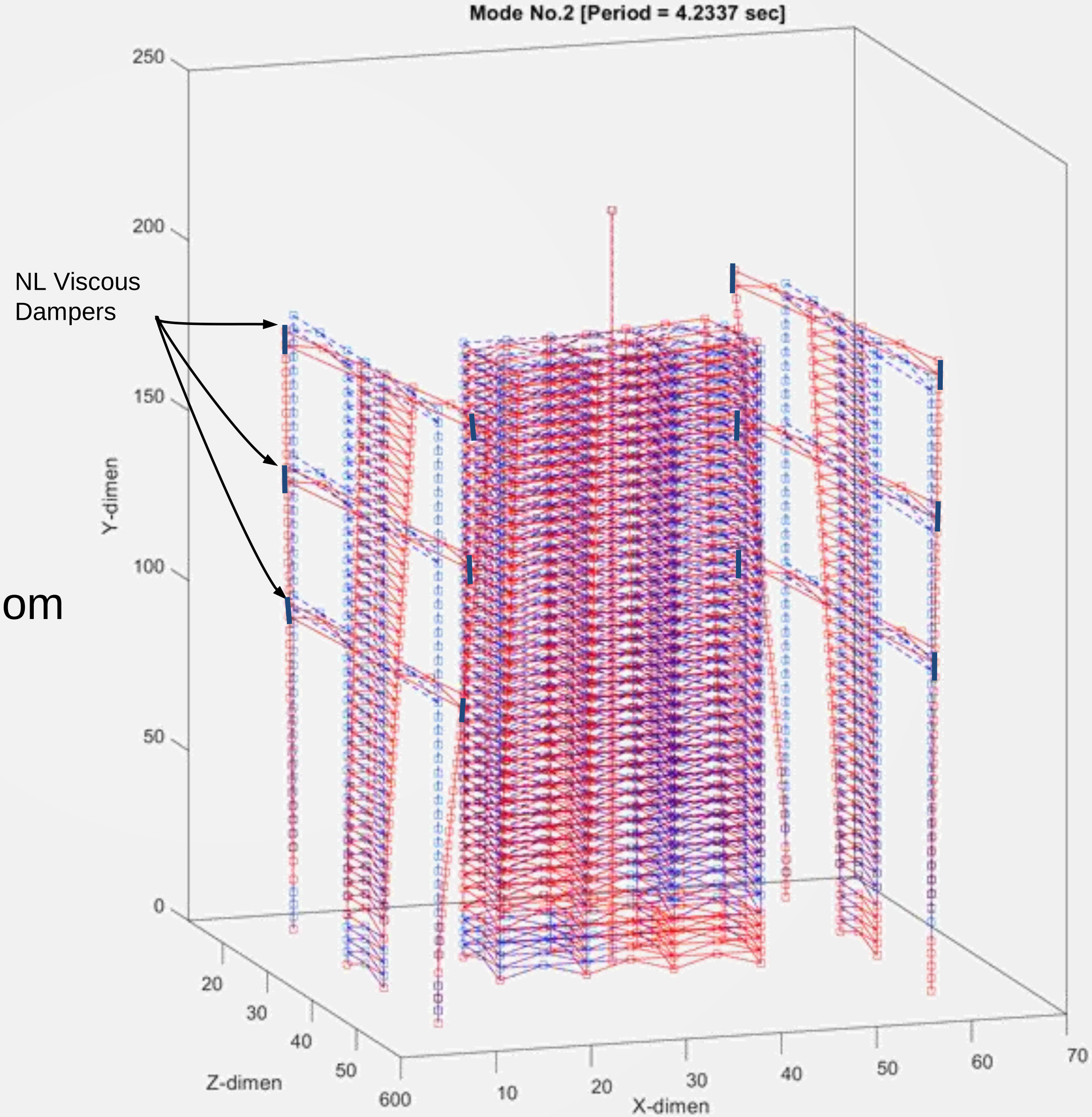




Current Research: Multi-Natural Hazard 3-D Hybrid Simulation

Natural Hazards:
- Earthquake
- Wind (FIU WOW)

Analytical Substructure
- 2920 elements
- 4069 degrees of freedom



Thank you