Laboratory Exercises: RTHS of a Tall Building Subject to Multi-Natural Hazards

Safwan Al-Subaihawi
Graduate Research Assistant
Lehigh University

Outline

- Description of prototype 40-story tall building
- Real-time hybrid simulation studies
- Real time hybrid simulation with online model updating (OMU) of nonlinear viscous dampers
- Laboratory demonstration

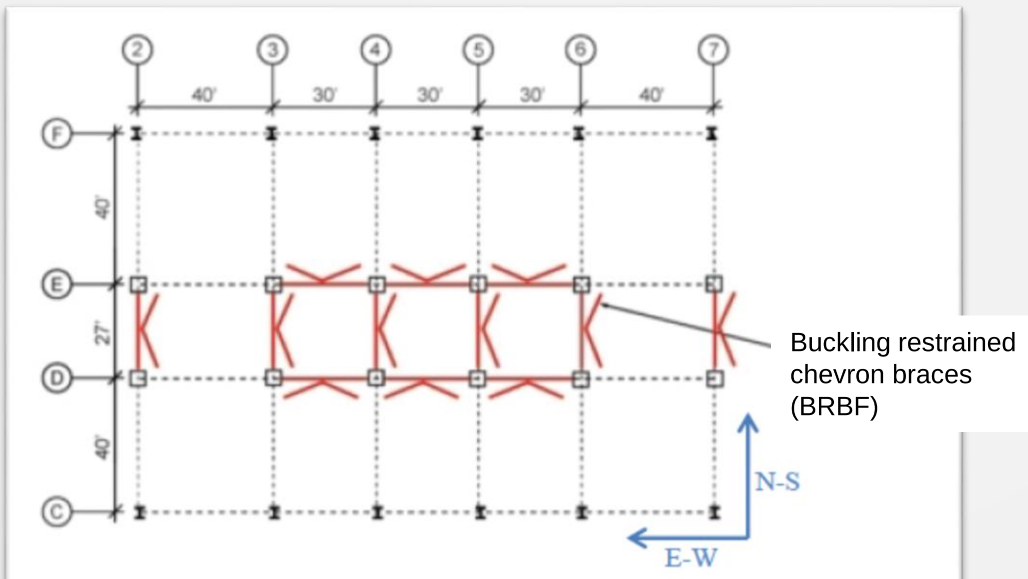
Outline

- Description of prototype 40-story tall building
- Real-time hybrid simulation studies
- Real time hybrid simulation with online model updating (OMU) of nonlinear viscous dampers
- Laboratory demonstration

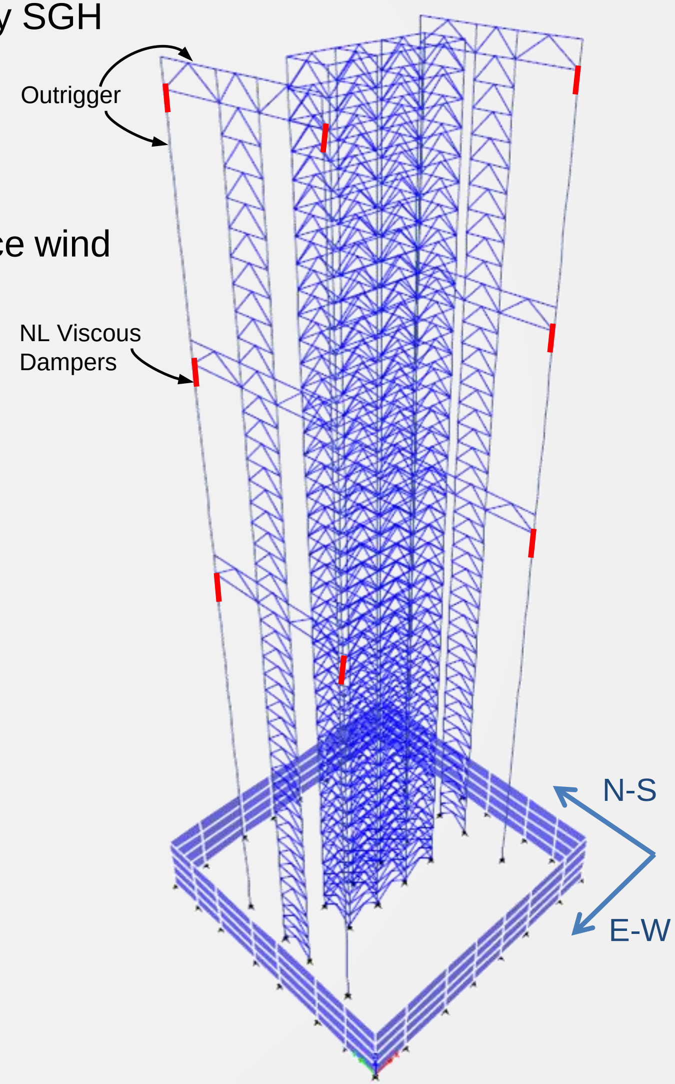
Tall Building Study

Prototype Building

- 40-story (+4 basement) BRBF building in Los Angeles designed by SGH for PEER Tall Building Initiative case studies
- Mean roof height = 544.5 ft. (166 m)
- Original design omitted dampers
- Lehigh added Non-linear viscous dampers to outriggers to enhance wind and earthquake performance of building



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



Ref.: Moehle et al., *Case Studies of the Seismic Performance of Tall Buildings Designed by Alternative Means - Task 12 Report for the Tall Buildings Initiative* PEER Rpt 2011/05

Prototype Building Design Criteria

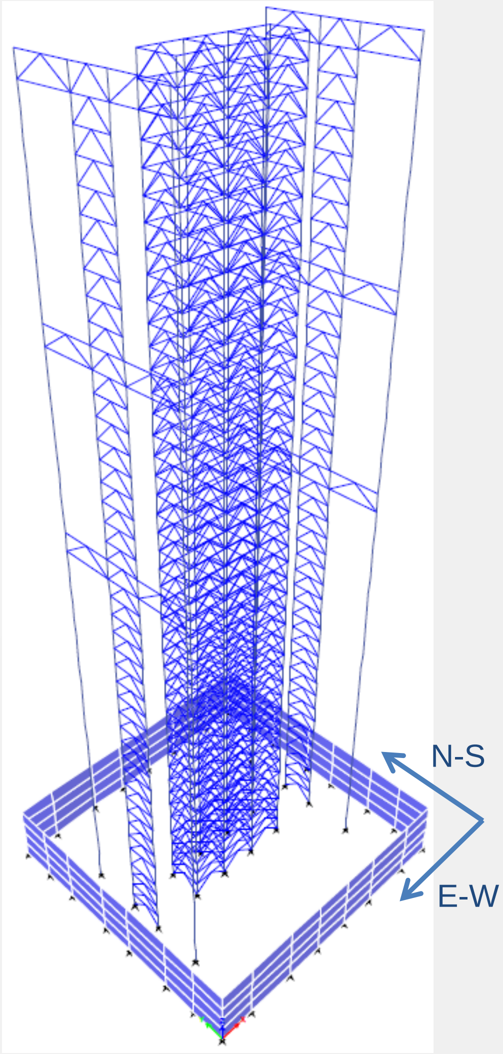
Design criteria without supplemental dampers

Table 2 – Wind Design Criteria

Parameter	Value
Basic Wind Speed, 3 sec. gust (V)	85 mph
Basic Wind Speed, 3 sec gust (V), for serviceability wind demands based on a 10 year mean recurrence interval	67 mph
Exposure	B
Occupancy Category	II
Importance Factor (I_w)	1.0
Topographic Factor (K_{zt})	1.0
Exposure Classification	Enclosed

Table 7 – Seismic Performance Objectives

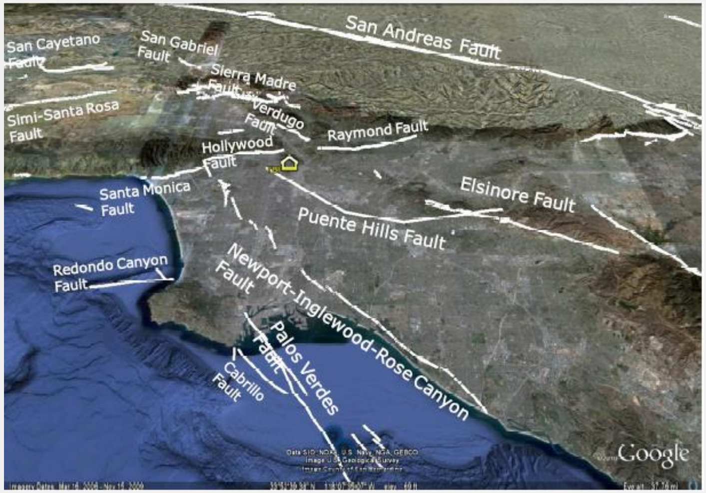
Level of Earthquake	Earthquake Performance Objectives
Frequent/Service : 43 year return period, 2.5% damping (SLE43)	Serviceability: Drift limited to 0.5%. Demand capacity ratio for buckling restrained braces not to exceed 1.5.
Maximum Considered Earthquake (MCE): As defined by ASCE 7-05, Section 21.2, 2.5% damping.	Collapse Prevention: Extensive structural damage, repairs are required and may not be economically feasible. Drift limited to 3%



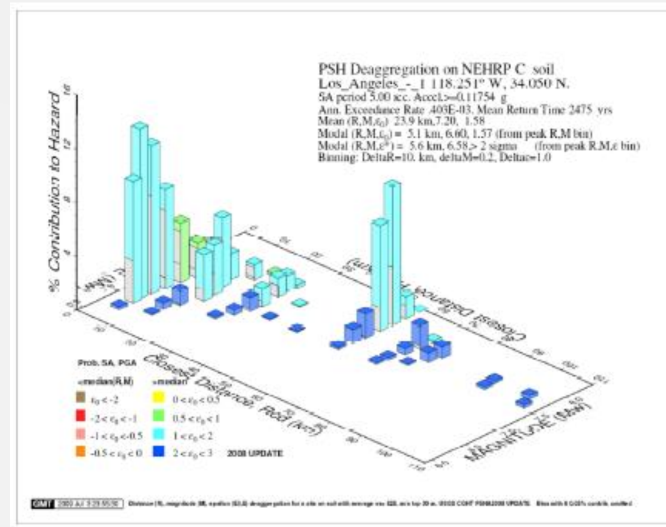
3-D view of the building. Image courtesy of Dutta and Hamburger (2010)

(after Moehle et al. 2011)

Prototype Building Seismicity



Location of Building in Southern California

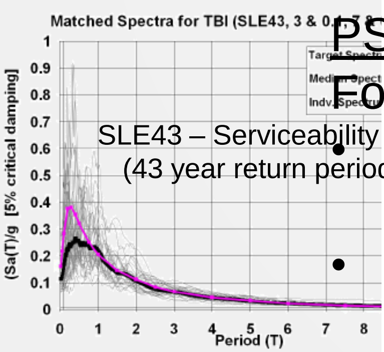


PSHA deaggregation, 2475-year return period at 5 sec. (Moehle et al. 2011)

PSHA

For long periods, hazard dominated by two types of events:

- A relatively large magnitude small distance event (e.g., M = 6.6, R = 5 km, ε = 1.5), or
- An extremely large magnitude long distance event (e.g., M = 8, R = 60 km, and ε = 2.5).



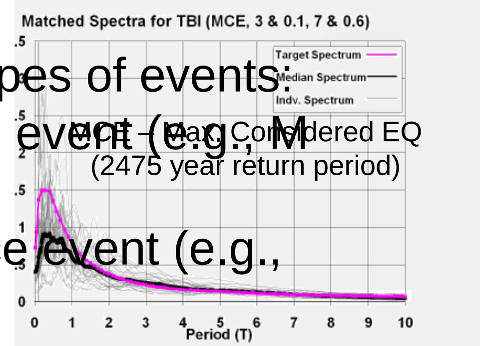
SLE43 – Serviceability EQ (43 year return period)

Figure 2.10 Comparison between the target spectrum, ... ground motion spectra, and median spectr... scaled ground motions for the SLE43 haza...

DBE – Design EQ (475 year return period)

Table 2.1 Seed ground motions used in the spectral matching procedure to match ground motions the design target response spectrum.

Set Number	Earthquake	M_w	Station	R (km)
1	Denali	7.90	Pump Station #9	54.78
2	Loma Prieta	6.93	Saratoga	8.50
3	Northridge	6.69	Sylmar Converter Station	5.35
4	Denali	7.90	Carlo	50.94
5	Chi-Chi	7.62	CHY109	50.53
6	Denali	7.90	Pump Station #8	104.9
7	Landers	7.28	Yermo	23.62



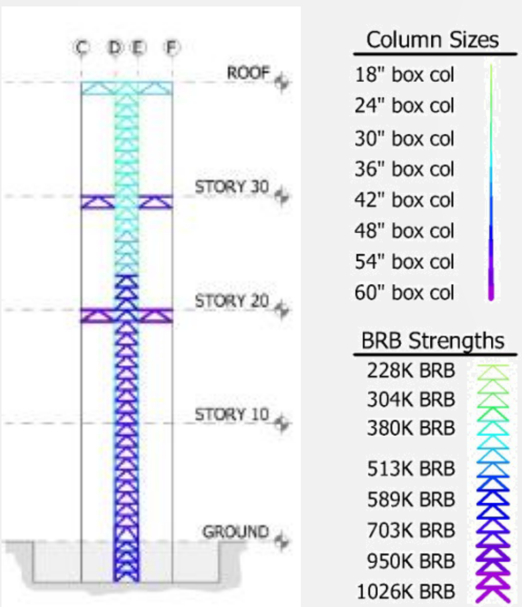
MCE – Max Considered EQ (2475 year return period)

Comparison between the target spectrum, selected and scaled ground motion spectra, and median spectrum of selected and scaled ground motions for the MCE hazard level.

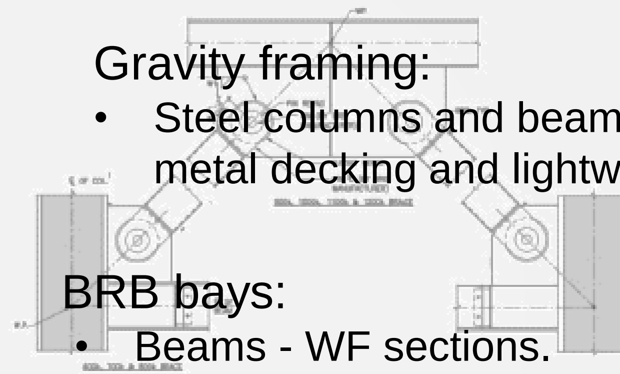
(after Moehle et al. 2011)

Design Detailing

Building (3C) designed used a single central bay of bracing (BRBs) augmented with outrigger trusses spanning three bays at the 20th, 30th, and 40th stories.



Note:
1 Kip = 4.448 kN
1 inch = 25.4 mm



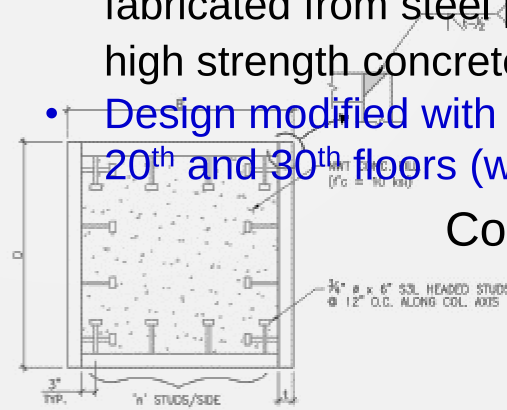
Gravity framing:

- Steel columns and beams with composite metal decking and lightweight concrete fill.

BRB bays:

- Beams - WF sections.
- Composite concrete filled steel box columns, fabricated from steel plates (38 mm to 76 mm), high strength concrete (f_c'=69 MPa).
- Design modified with NL Viscous dampers at 20th and 30th floors (wind)

Buckling Restrained Braces (BRBs)

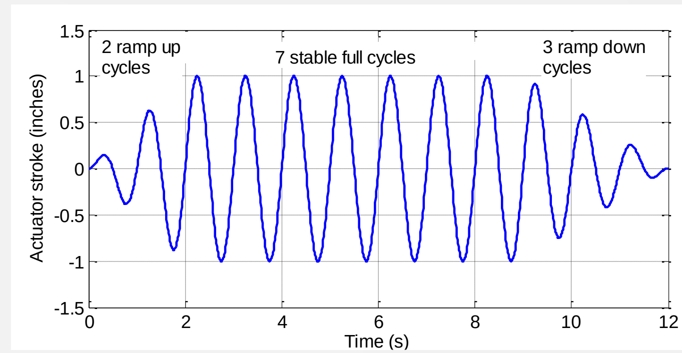


Composite Columns

Nonlinear Viscous Dampers

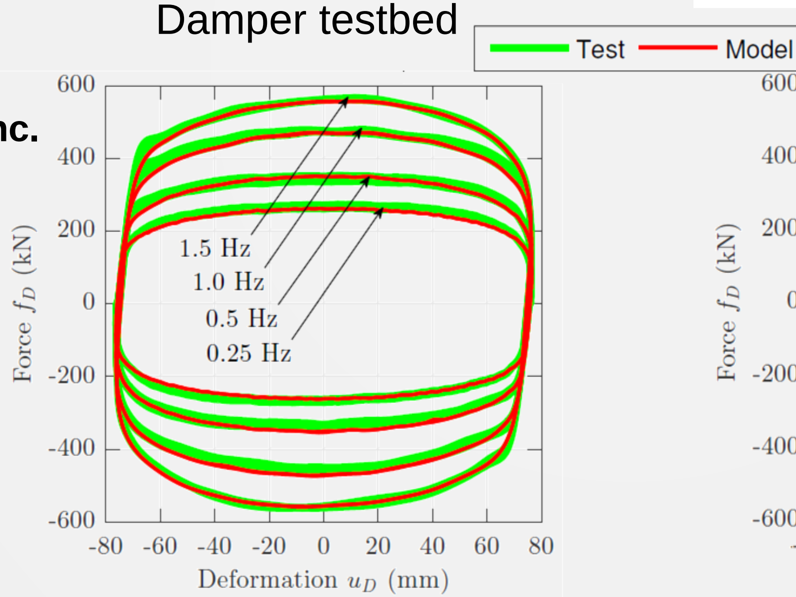
Characterization testing

Damper testbed

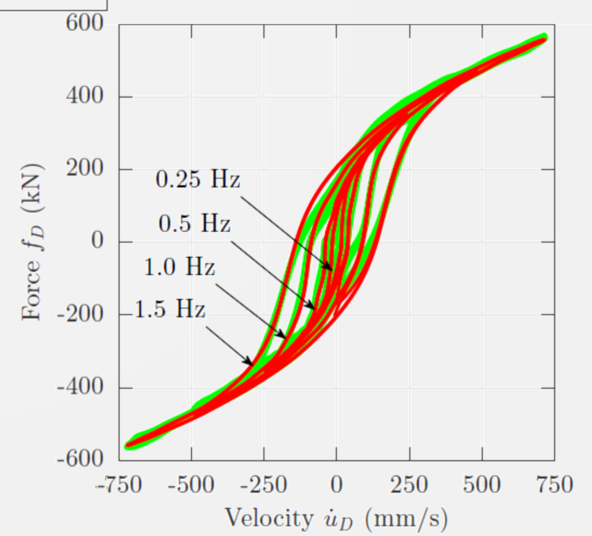


Loading Protocol

600 kN dampers manufactured by Taylor Devices, Inc.



Damper force - deformation



Damper force - velocity

LEHIGH UNIVERSITY · ATLSS · RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE · NSF · DESIGNSAFE-CI A NATURAL HAZARDS ENGINEERING COMMUNITY

Outline

- Description of prototype tall building
- Real-time hybrid simulation studies
- Real time hybrid simulation with online model updating (OMU) of nonlinear viscous dampers
- Laboratory demonstration

Real-time Hybrid Simulation Study of Tall Building Subjected to Multi-Natural Hazards

- Natural Hazards
  - ➢ Earthquake Loading
  - ➢ Wind Loading
- Nonlinear Viscous Dampers at 20th and 30th floors

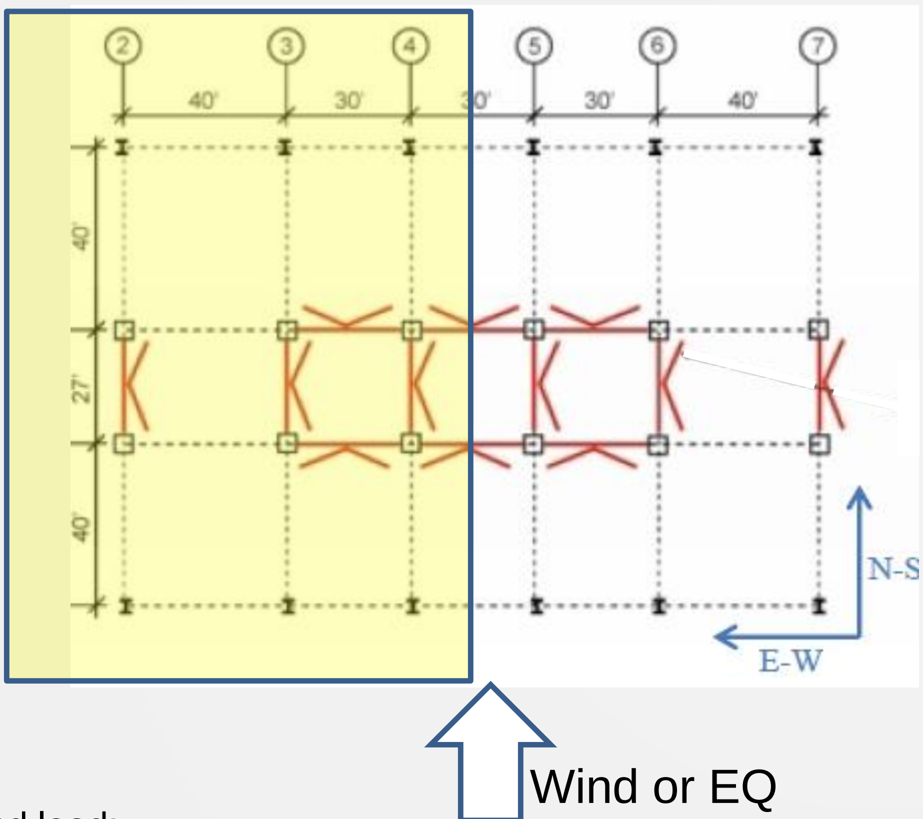
Building Modal Properties

Mode	T (sec)	f (Hz)	ζ_{eq} (%)
1	6.38	0.16	8.3
2	1.71	0.59	10.0
3	0.84	1.19	
4	0.55	1.81	
5	0.41	2.46	
6	0.32	3.12	
7	0.27	3.77	
8	0.22	4.46	
9	0.19	5.15	
10	0.17	5.88	

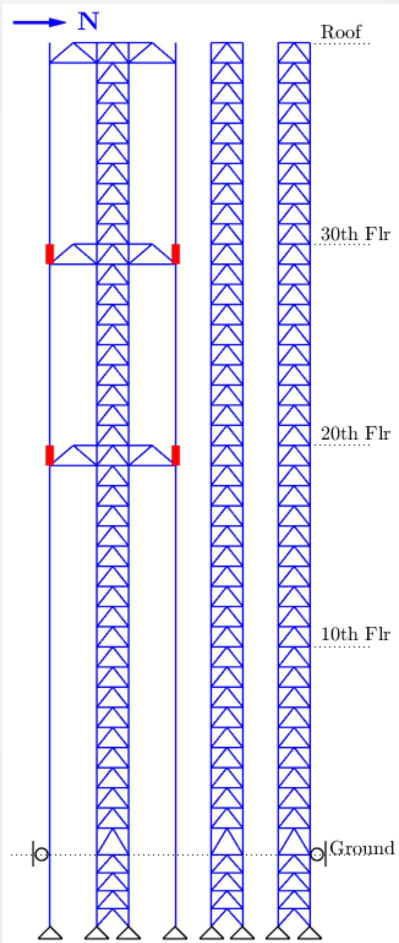
ζ_{eq} : System total damping, half-power bandwidth method

RTHS Configuration

Building Floor Plan



Test Structure Elevation



<u>Wind load</u>:

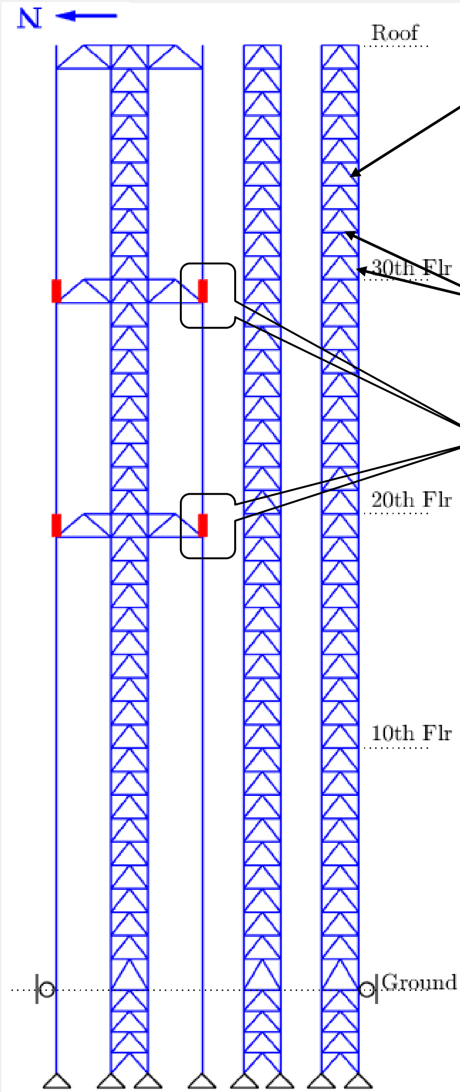
- Tokyo Polytechnic University Wind Tunnel Test database
- Normalized pressure coefficient time histories are converted to full scale forces corresponding to Exposure B and wind speed of 110 mph, 700 year MRI

<u>EQ load</u>:

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

RTHS Substructures

Analytical Substructure

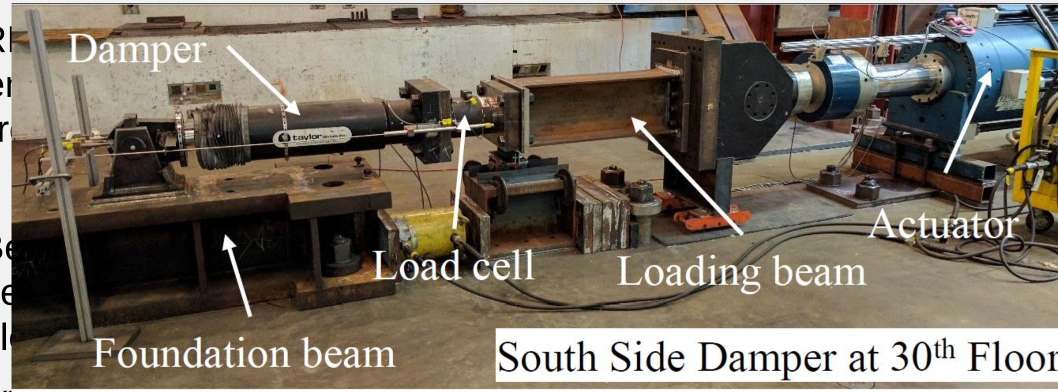


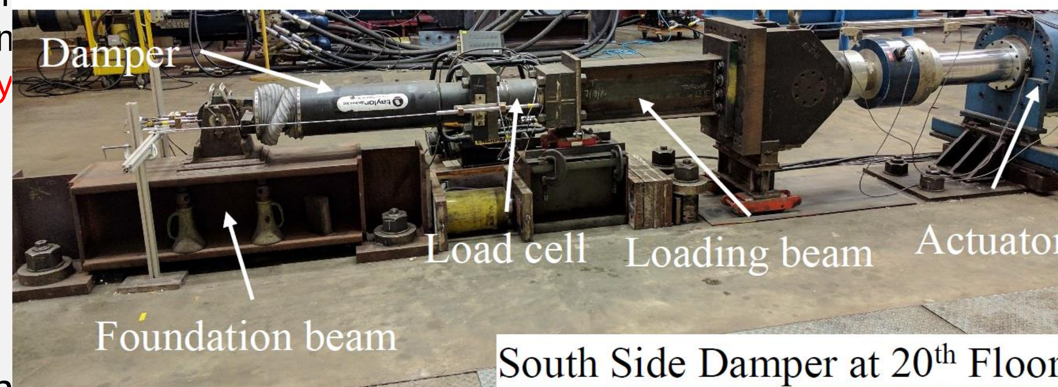
BR
ele
har

Be
be
el

Nor
dan
phy

Experimental Substructures





Analytical Substructure Key features:

- P-Δ effects included
- 780 Nodes
- 996 Elements
- 1590 DOFs

- Mass
- Inherent damping of building

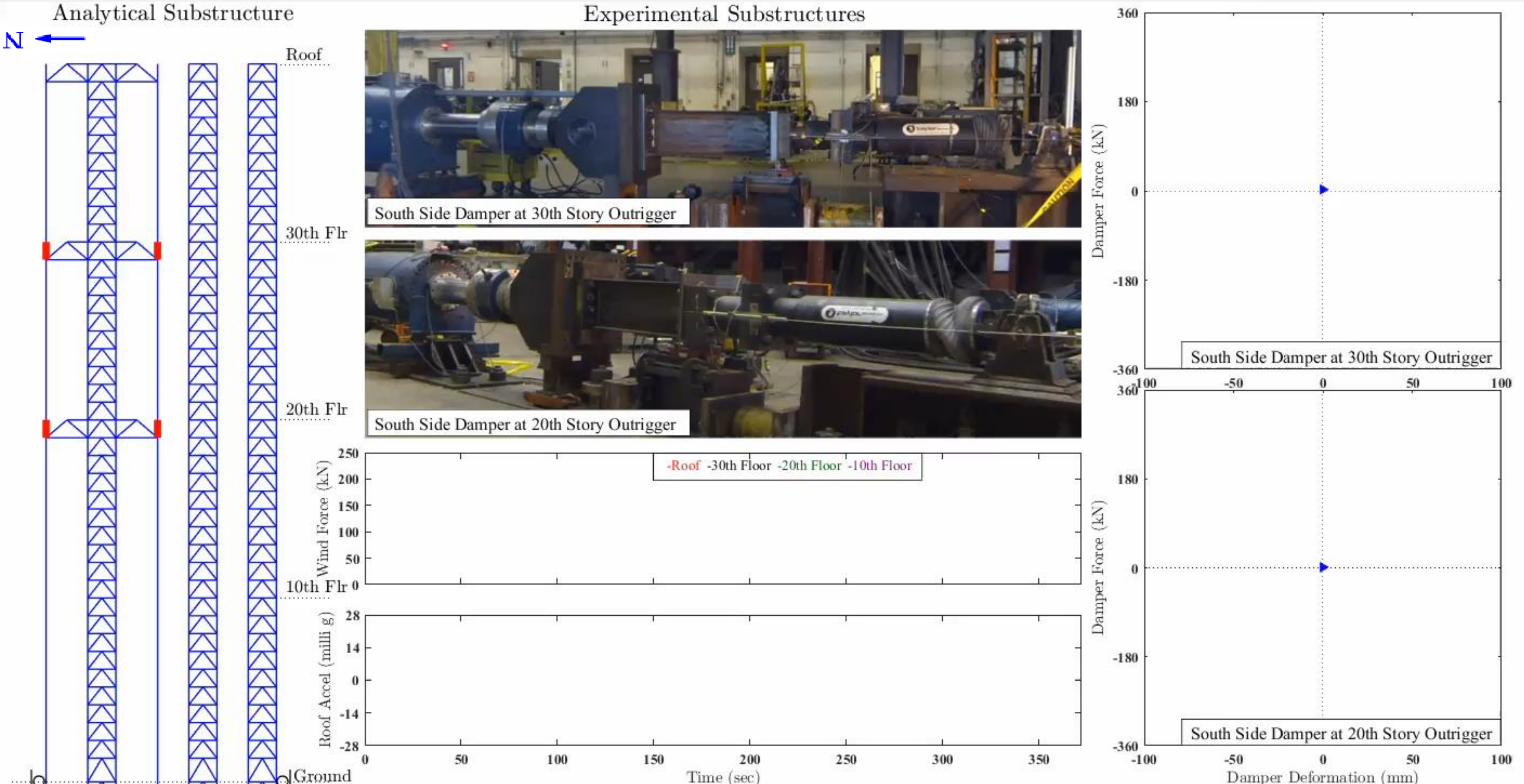
- ρ_∞: 0.866 - Wind
  0.50 - EQ
- Time step for RTHS, Δt=0.006 sec.

Response of Building under Wind Loading

- Building subjected to 700 year mean recurrence interval (MRI) wind storm
- Response quantities of interest:
  - Dampers
  - Floor displacements and accelerations
  - Members

Wind RTHS: Exposure B, 110 mph Wind Speed

110 mph = 177 km/hr



Real-time Hybrid Simulation of a Wind Excited Tall Building

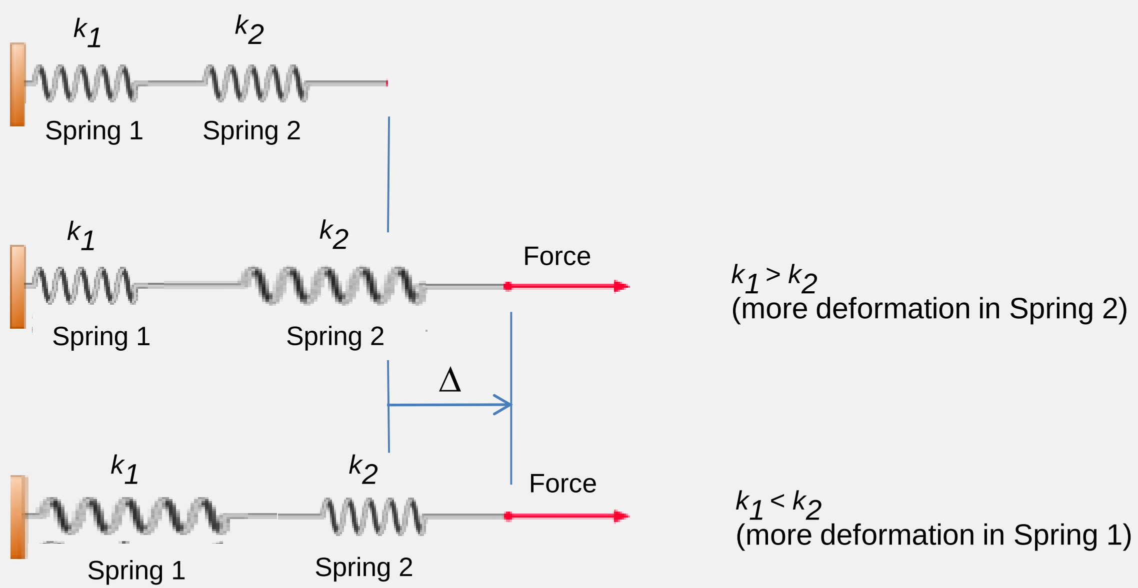
Wind Speed = 110 mph (MRI 700 years)

Illustration of Effects of Member Stiffness in Damper Force Load Path

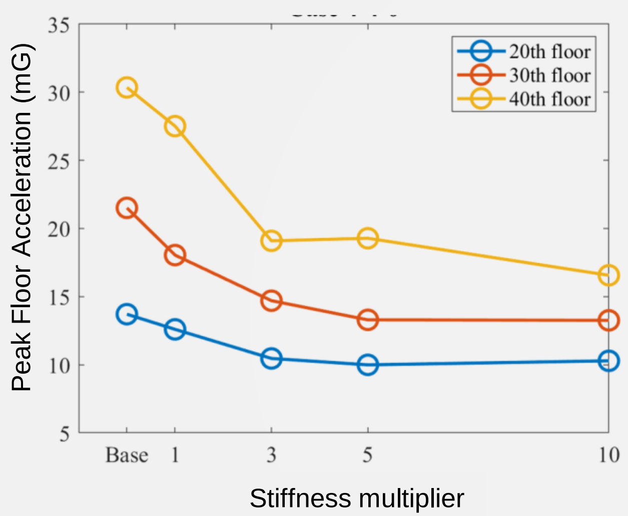
To develop damper velocity (and therefore make dampers efficient):

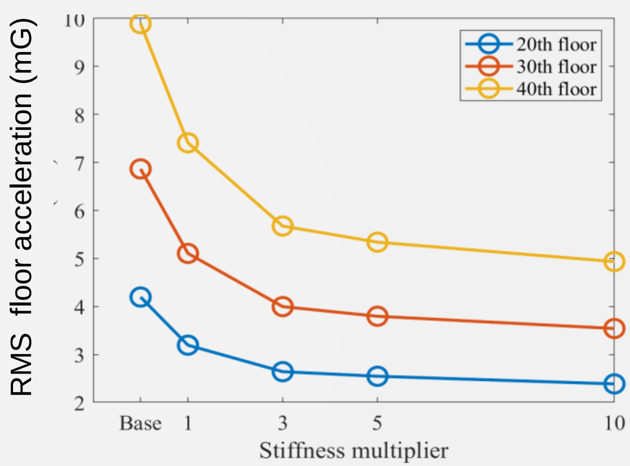
- Members in damper load path must have adequate stiffness
- Equivalent damper stiffness cannot be too large relative to members in load path.

Two springs in series analogy



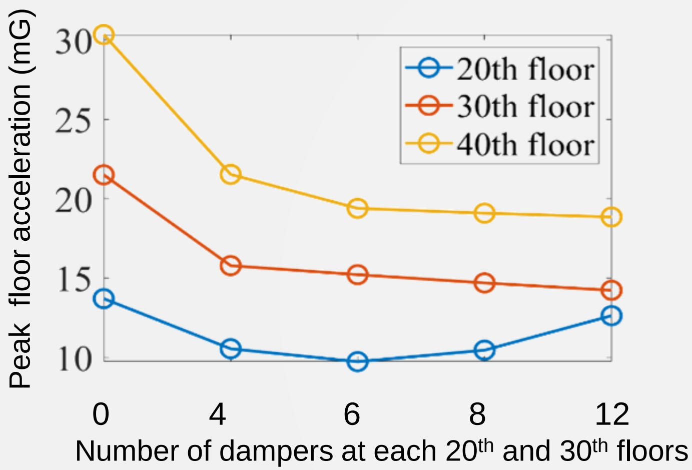
Member Stiffness in Damper Force Load Path – 700 Year MRI Wind

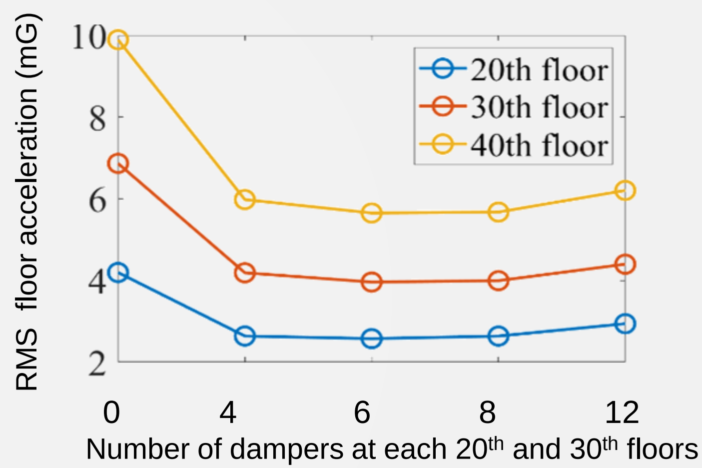




- Outrigger truss members’ and columns’ axial stiffness increased using stiffness multiplier in analytical substructure
- A larger member’s stiffness results in an increase in the deformations being concentrated in the dampers
- Inefficient to increase stiffness multiplier beyond value of 3.0

Effect of Number of Supplemental Dampers - 700 Year MRI Wind





- Increasing the number of dampers beyond a certain number in the outrigger reduces further the velocity in the dampers, making them less effective.
- Not efficient to use more than four – 600 kN dampers.

RTHS Results: Floor RMS Lateral Accelerations –700 Year MRI Wind

Floor	RMS Acceleration (mG)		Peak Acceleration (mG)	
	No Dampers	With Dampers	No Dampers	With Dampers
20	4.2	2.5	13.9	9.8
30	6.9	3.9	22.1	14.8
40	9.9	5.6	30.1	19.0

6 dampers added to outriggers at 20th and 30th floors:

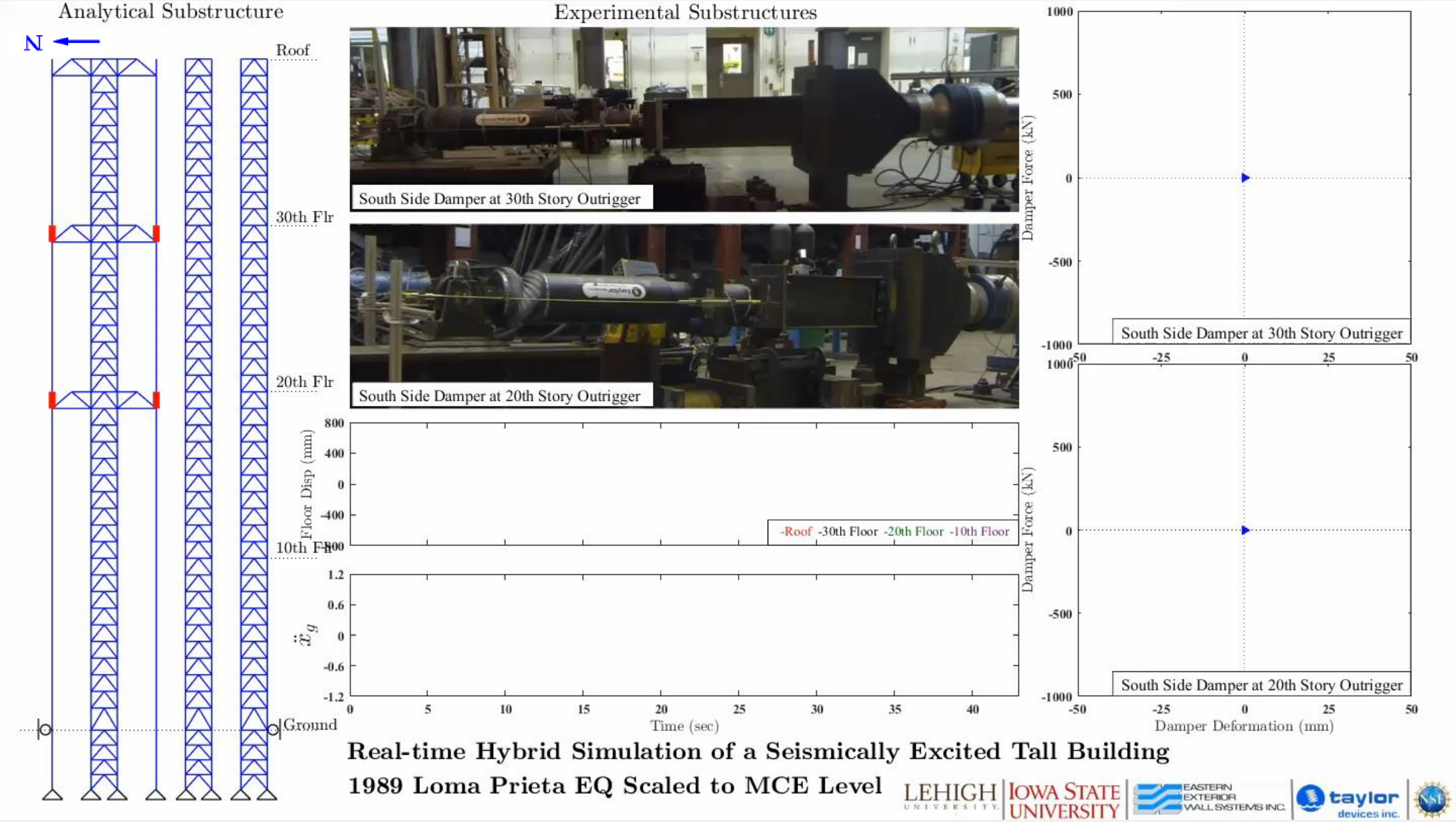
- RMS Acceleration: 43% to 48% reduction
- Peak Acceleration: 29% to 37% reduction

Response of Building under Earthquake Loading

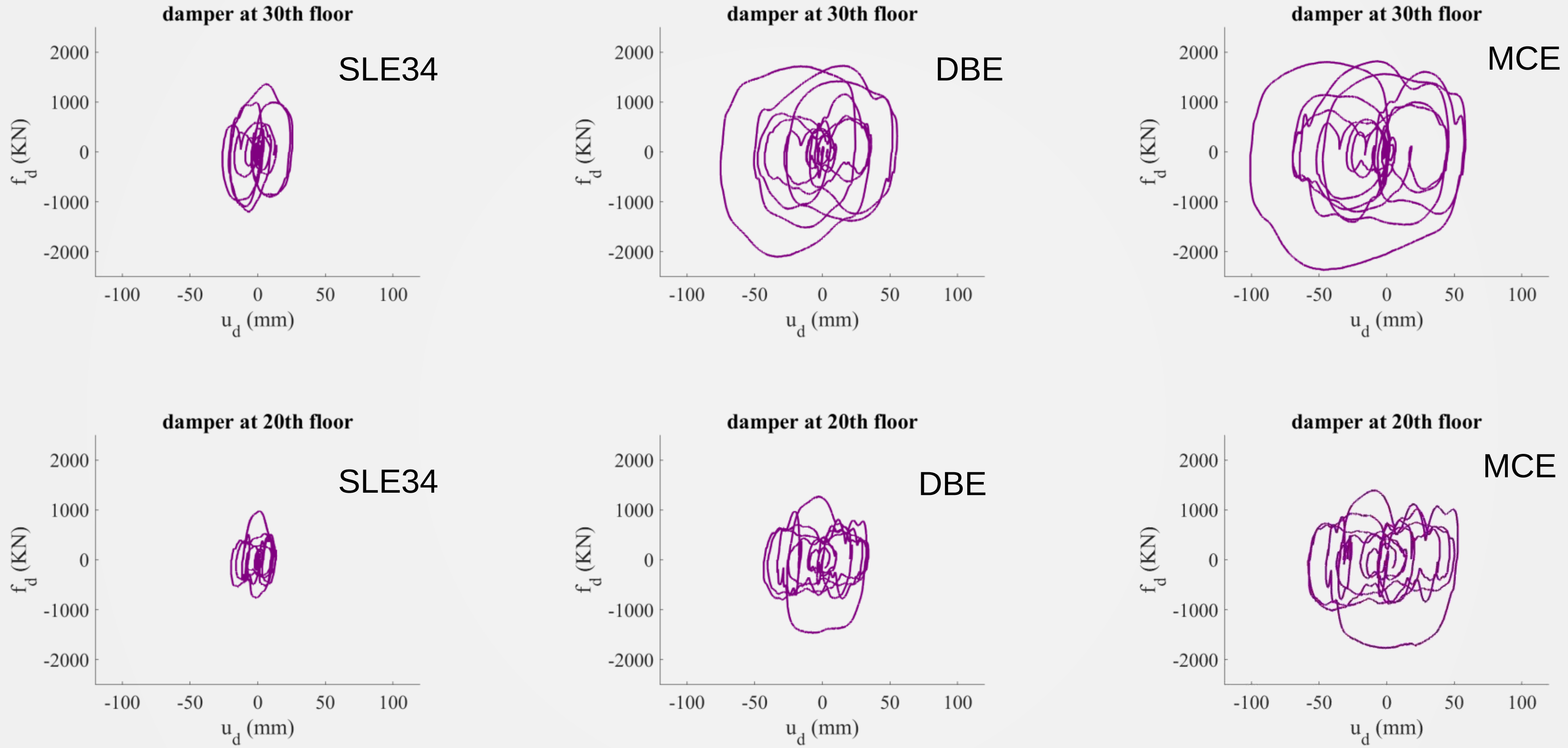
- Building subjected to different hazard levels
  - Serviceability earthquake – 43 year return period (SLE43)
  - Design basis earthquake - 475 year return period (DBE)
  - Maximum considered earthquake – 2475 year return period (MCE)
- Effects of ground motion record-to-record variability considered
  - Ensemble of ground motions selected and appropriately scaled to hazard level
  - Statistics of Response determined
- Response quantities of interest:
  - Members
  - Story Drift
  - Floor Accelerations
  - Dampers

RTHS: 1989 Loma Prieta EQ Scaled to MCE

MCE: 2475 return period EQ

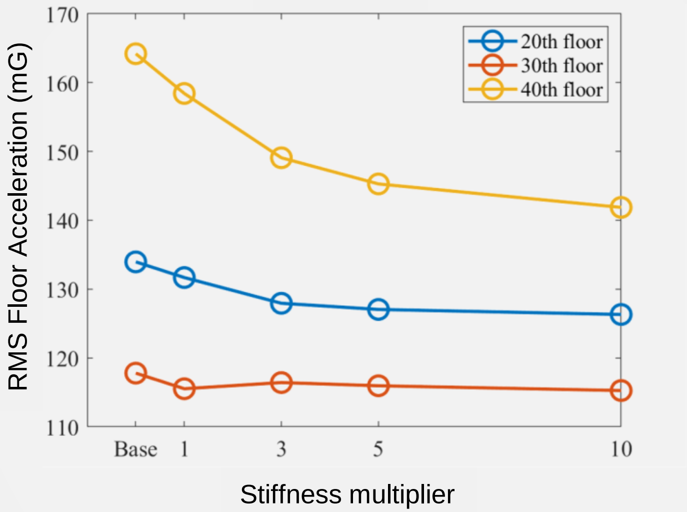


RTHS Results: Damper Force-Displacement, Loma Prieta EQ



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

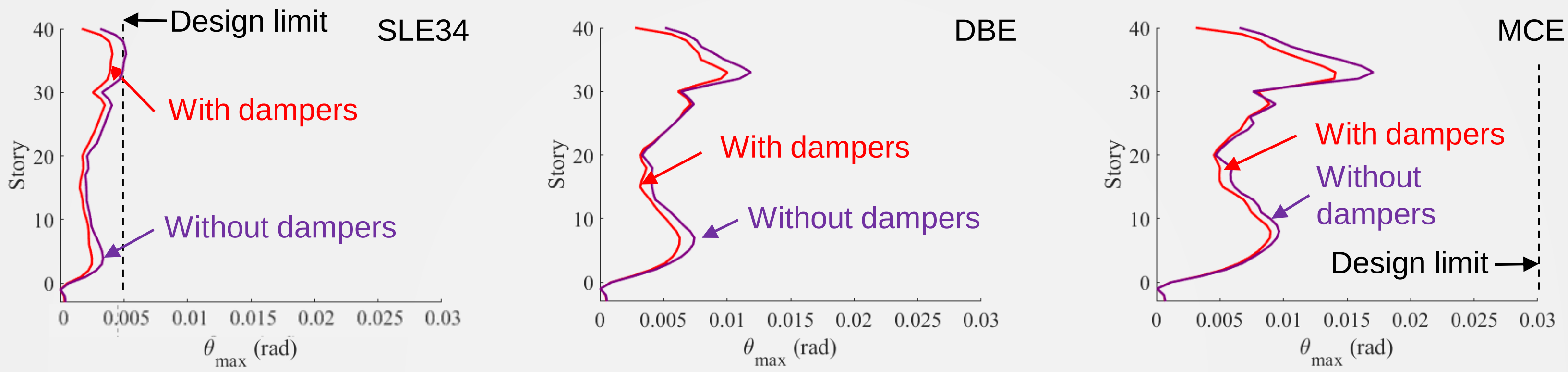
Member Stiffness in Damper Force Load Path - Loma Prieta EQ scaled to MCE



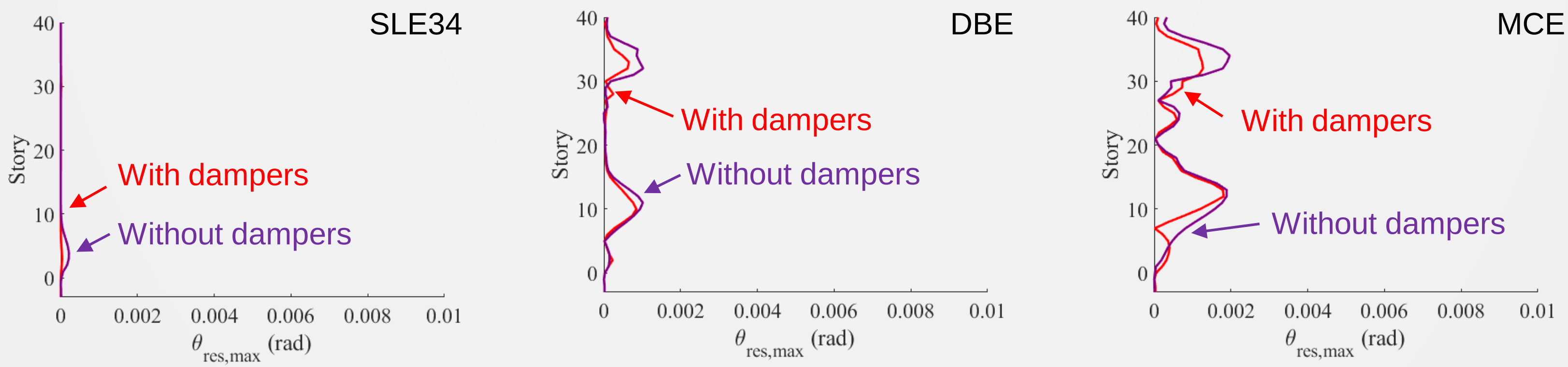
- Outrigger truss members' and columns' axial stiffness increased using stiffness multiplier in analytical substructure
- A larger stiffness of members results in an increase in the deformations being concentrated in the dampers
- Inefficient to increase stiffness multiplier beyond value of 3.0

RTHS Results: Maximum Story and Residual Story Drift - Loma Prieta EQ

Maximum Story Drift



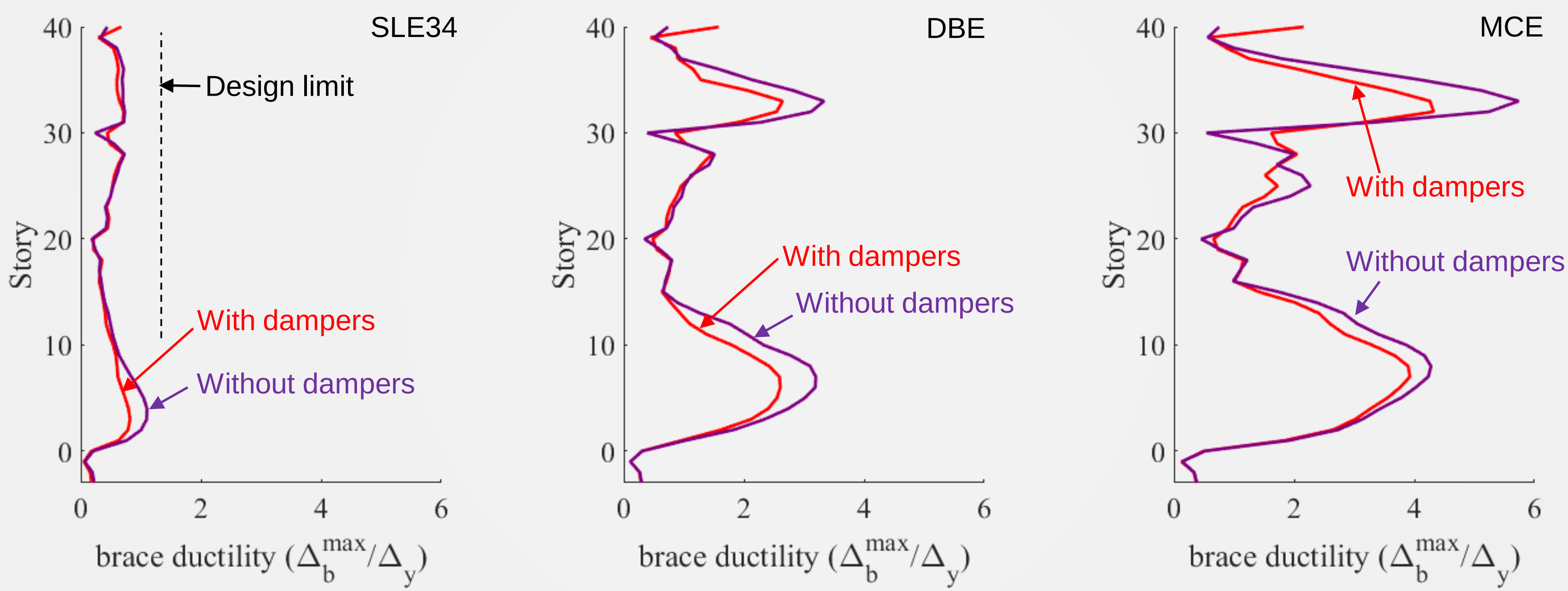
Maximum Residual Story Drift



Stiffness multiplier = 3

Number dampers at 20 and 30th floors = 6

RTHS Results: Maximum Normalized BRB Deformation - Loma Prieta EQ



Stiffness multiplier = 3
Number dampers at 20 and 30th floors = 6

EQ Response Statistics - Median

EQ Hazard	Maximum Story Drift (rad)			Maximum Residual Story Drift (rad)		BRB Maximum Ductility Δ_b^{max}/Δ_y		
	No Dampers	With Dampers	Design Obj	No Dampers	With Dampers	No Dampers	With Dampers	Design Obj
SLE43	0.005	0.004	$\leq$ 0.005	0.000	0.000	0.8	0.7	1.5
DBE	0.012	0.007	-	0.003	0.001	4.7	2.2	-
MCE	0.017	0.011	$\leq$ 0.03	0.006	0.002	5.5	3.4	-

- All configurations meet design objectives
- Dampers improved performance under DBE and MCE by reducing inelastic demand in structure (BRBs)

Stiffness multiplier = 3
Number dampers at 20 and 30^{th} floors = 6

RTHS Summary and Conclusions

- The application of real-time hybrid simulation to large complex systems subject to wind and earthquake natural hazards was illustrated, demonstrating these new advancements.
- Using dampers, building’s performance was demonstrated to be improved (accelerations) under wind and (drift, BRB ductility) under EQ loading.
- The methodologies presented herein will enable real-time large-scale simulations of complex systems to be successfully achieved, leading to new knowledge for hazard mitigation solutions and innovative, resilient hazard-resistant structural concepts.

Outline

- Description of prototype tall building
- Real-time hybrid simulation studies
- Real time hybrid simulation with online model updating (OMU) of nonlinear viscous dampers
- Laboratory demonstration

RTHS OMU Background

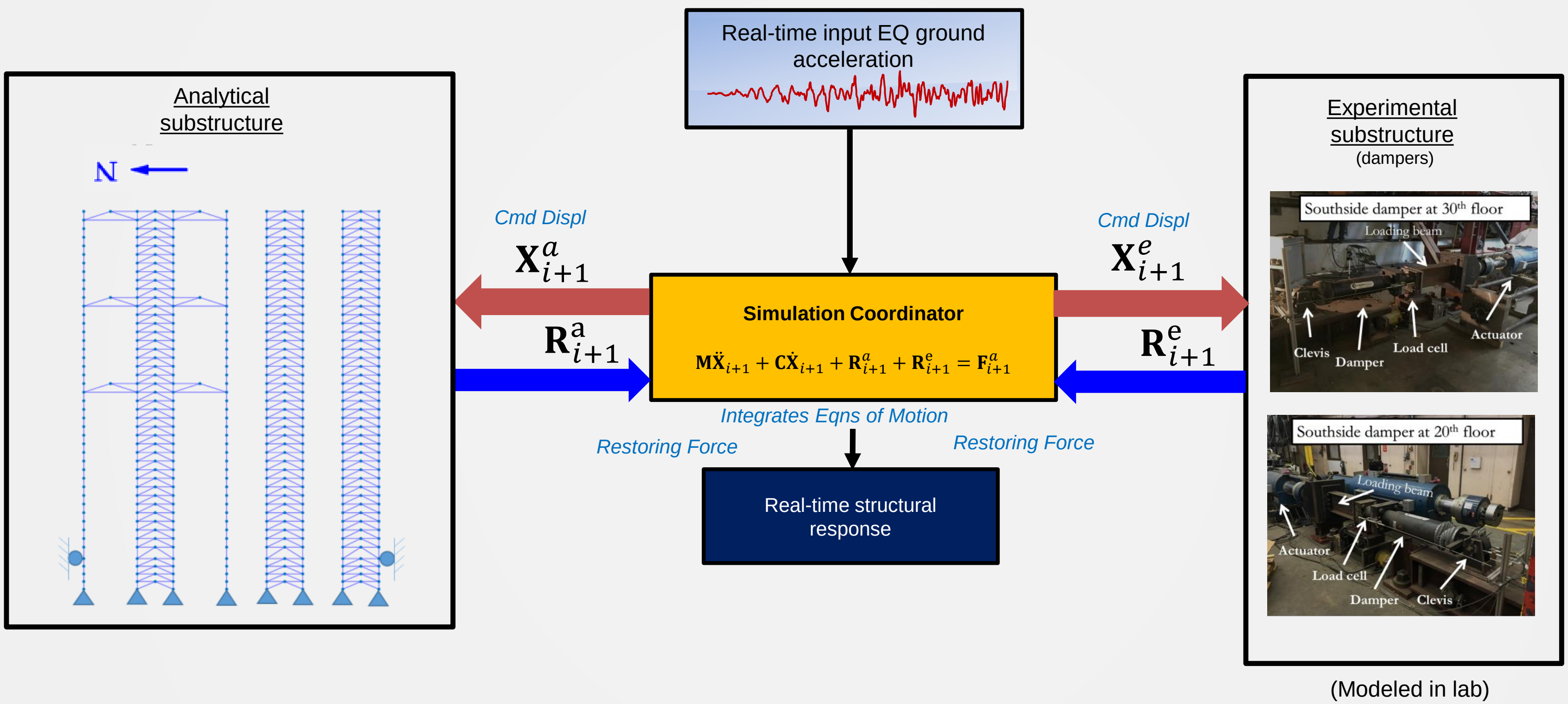
Dynamic testing using real-time hybrid simulation

- Complex substructures may be difficult to model numerically
- If multiple experimental substructures are needed, all must be present in the lab

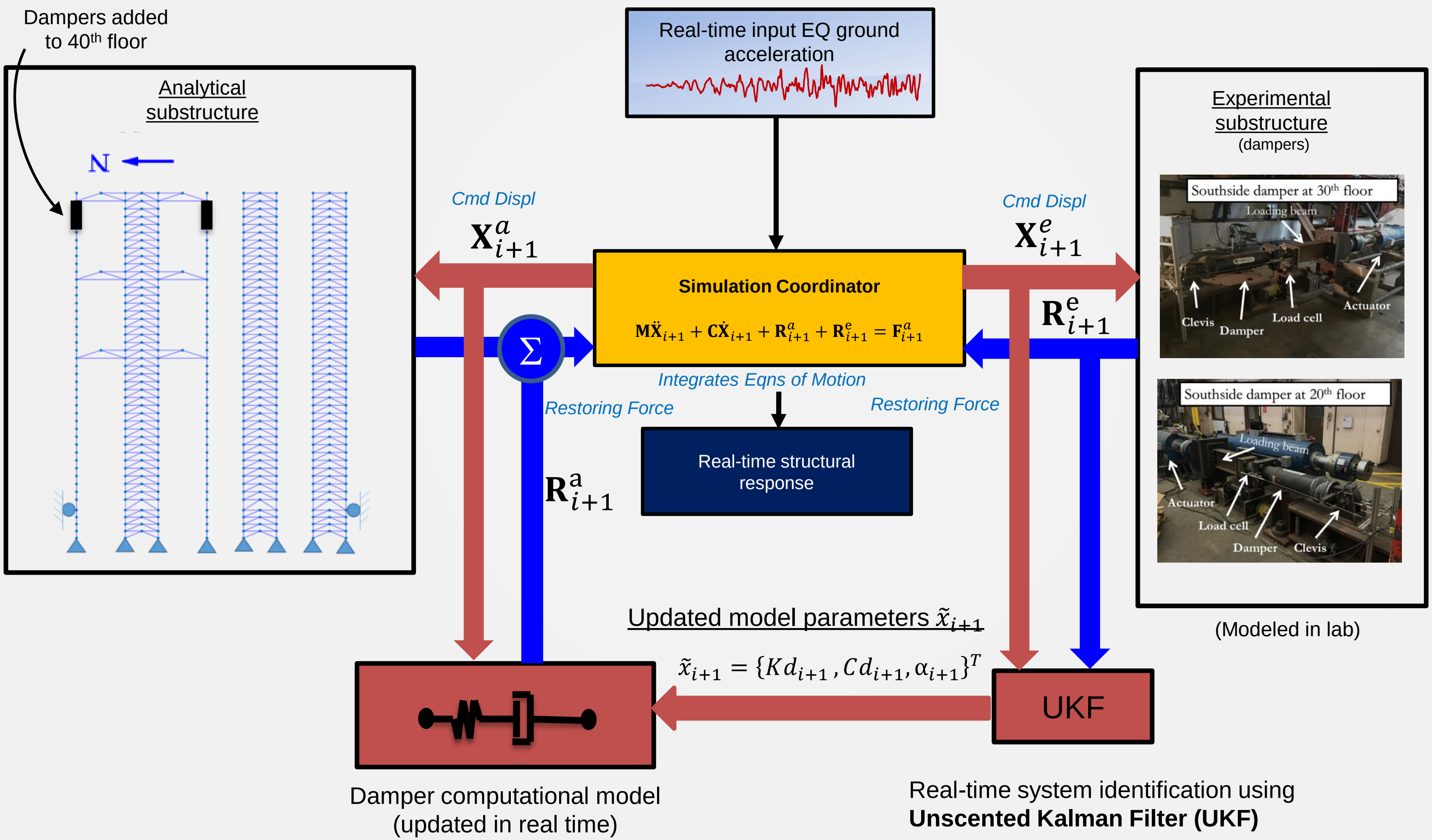
Dynamic testing using real-time hybrid simulation with online model updating

- Reduce the number of experimental substructures required for a hybrid simulation by including some of them as computational model components of the analytical substructure
- Update the component computational model of analytical substructure using information obtained from the experimental substructure of a similar component during the hybrid simulation

Real-time Hybrid Simulation



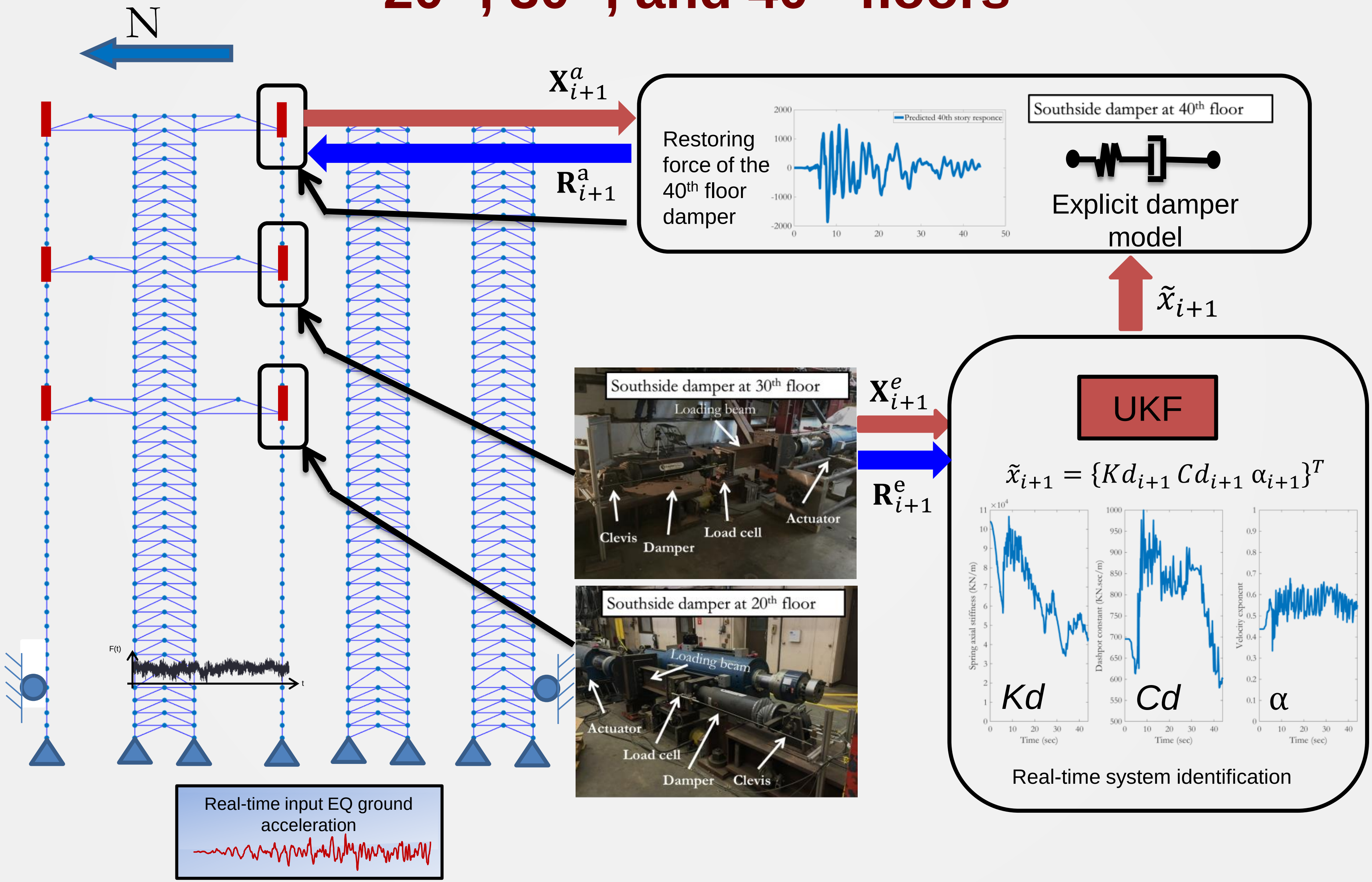
Real-time Hybrid Simulation with Online Model Updating



RTHS OMU Developments at Lehigh University

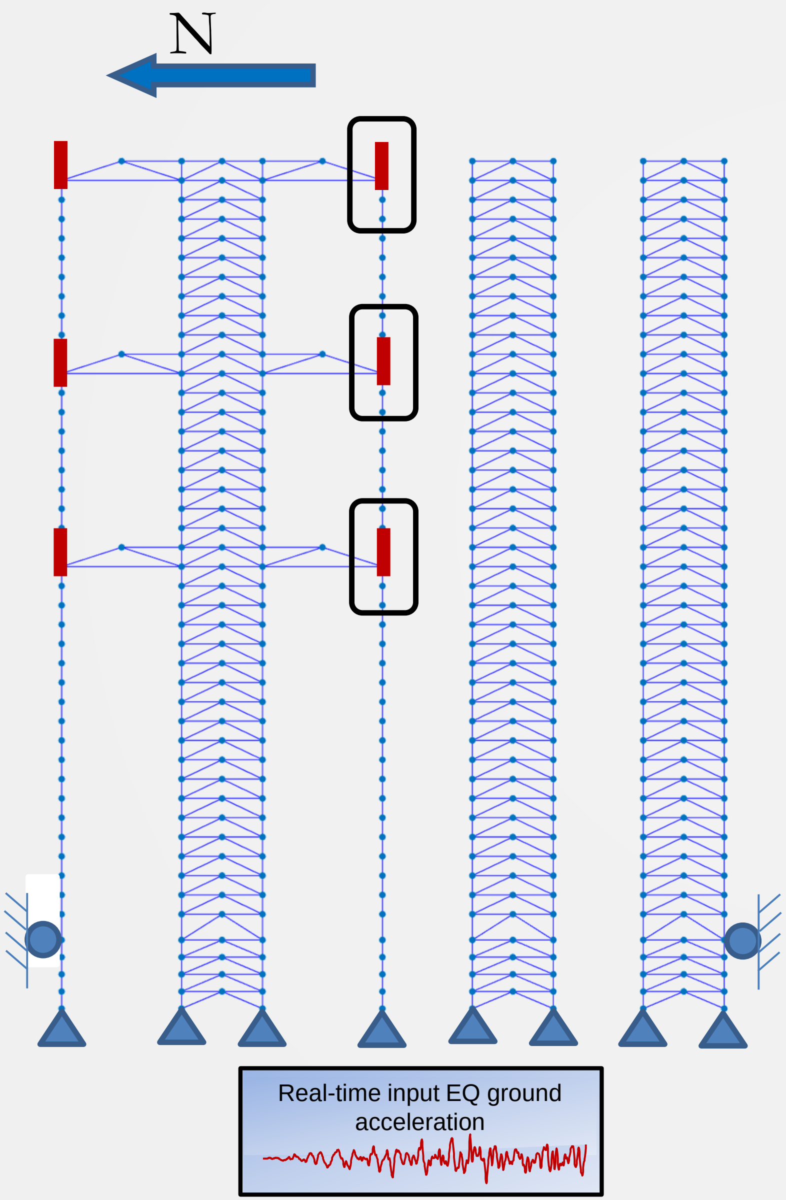
- Development of explicit, non-iterative damper model for real-time hybrid simulation
- Development of methodology to tune and implement the UKF for real-time identification of nonlinear viscous dampers

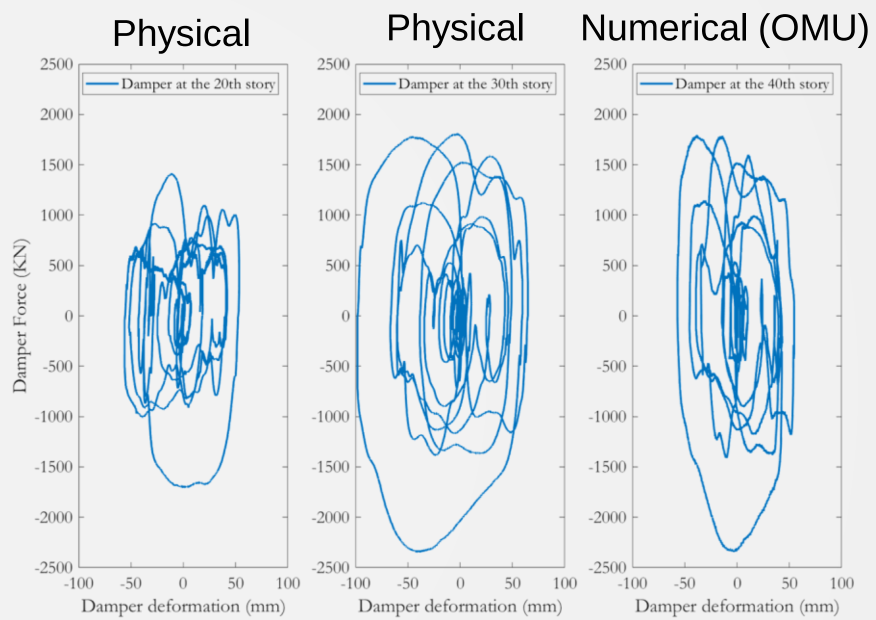
RTHS OMU: 40-story building with dampers at 20th, 30th, and 40th floors



RTHS OMU: 40-story building with dampers at 20th, 30th, and 40th floors

Response under the MCE Loma Prieta EQ

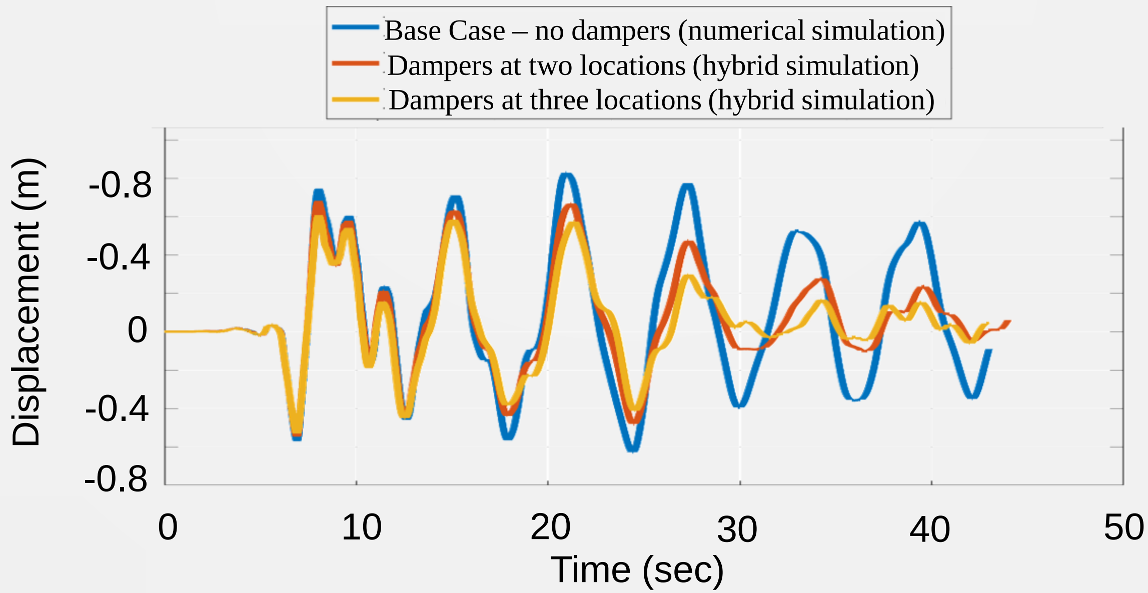




Damper force-deformation hysteretic response

RTHS OMU: 40-story building with dampers at 20th, 30th, and 40th floors Response under the MCE Loma Prieta EQ

Case	Stiffness multiplier	Number of dampers			Roof peak disp (m)	Disp reduction (%)
		20th Flr	30th Flr	40th Flr		
Base – no dampers	1	0	0	0	0.82	-
Dampers at two floors	3	8	8	0	0.68	17
Dampers at three floors	3	8	8	8	0.60	27

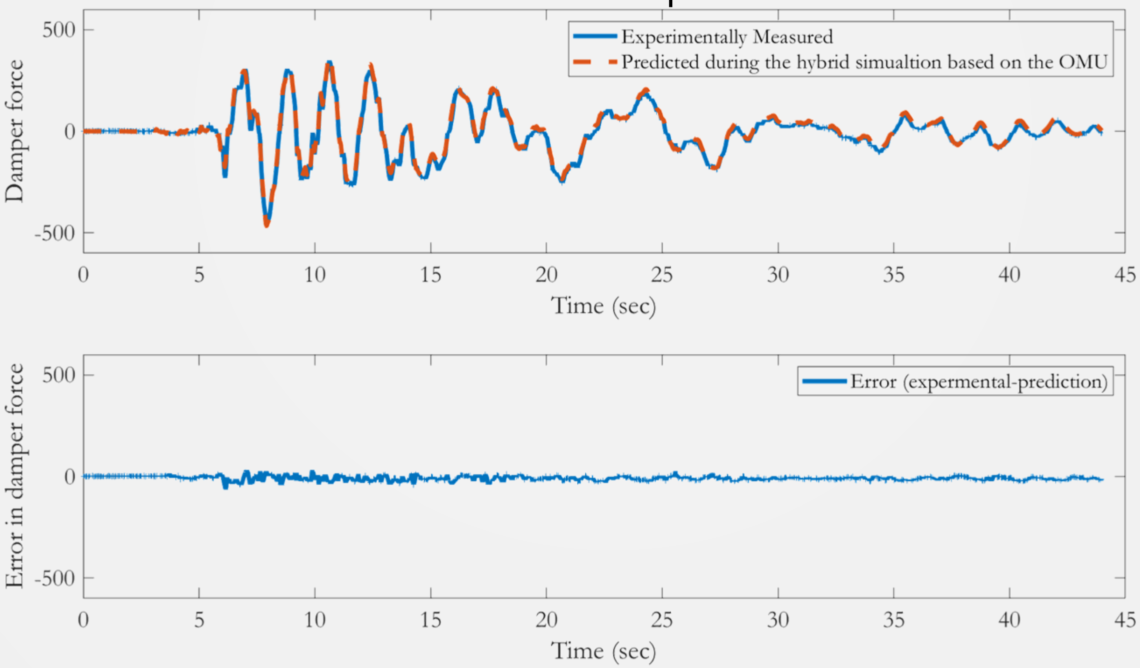


RTHS OMU: 40-story building with dampers at 20th, 30th, and 40th floors

Response under the MCE Loma Prieta EQ

- Displacement history of the damper at the 40th story is applied to the physical damper at the 30th story after the hybrid simulation is completed
- Forces predicted based on the OMU compared to the experimentally measured results
- Good agreement achieved

40th floor damper



Outline

- Description of prototype tall building
- Real-time hybrid simulation studies
- Real time hybrid simulation with online model updating (OMU) of nonlinear viscous dampers
- Laboratory demonstration

Laboratory Demonstration

Test	Hazard	Model	Dampers at 20th story	Dampers at 30th story	Dampers at the 40th story
1	MCE EQ	40 story building	Physical	None	None
2	MCE EQ	40 story building	Physical	OMU	OMU
3	110 mph wind	40 story building	Physical	None	None
4	110 mph wind	40 story building	Physical	OMU	OMU

RTHS Configuration

Parameter	Values
Ground Motion (scaled to MCE)	
• Near Field	1989 Loma Prieta Earthquake, component SN802_LOMAP_STG000
• Integration Algorithm	MKR-α method
• Integration Time step	7/1024 sec
• Numerical damping, ρ_∞	0
• UKF tuning parameters	Measurement noise = 8 KN State variables uncertainty =0.001

Parameter	Values
Storm (110 mph wind speed)	
• Integration Algorithm	MKR-α method
• Integration Time step	7/1024 sec
• Numerical damping, ρ_∞	0
• UKF tuning parameters	Measurement noise = 8 KN State variables uncertainty =0.0001

Acknowledgements

- Research reported in this presentation was performed at the NHERI Lehigh Large-Scale Multi-Directional Hybrid Simulation Experimental Facility
- Supported by the National Science Foundation (NSF) under Awards CMS-0936610 and CMS-1463497
- Financial support for the operation of the NHERI Lehigh Large-Scale Multi-Directional Hybrid Simulation Experimental Facility provided by NSF under Cooperative Agreement No. CMMI-1520765.
- Nonlinear viscous dampers provided by Taylor Devices Inc.

Thank you