# *Laboratory Exercises: 3D Nonlinear Multi-hazard RTHS of a Tall Building*

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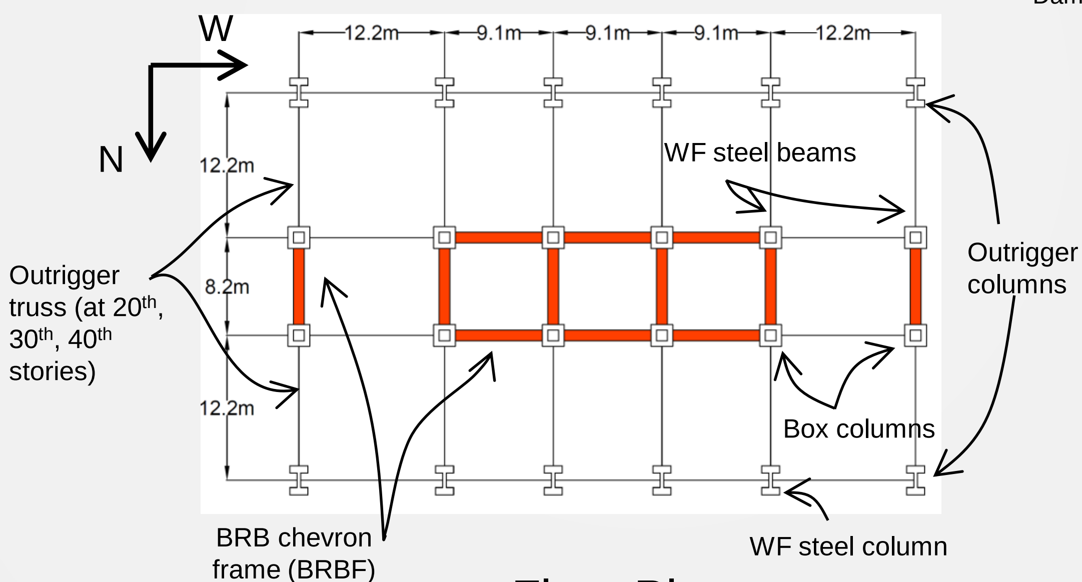
# Presentation

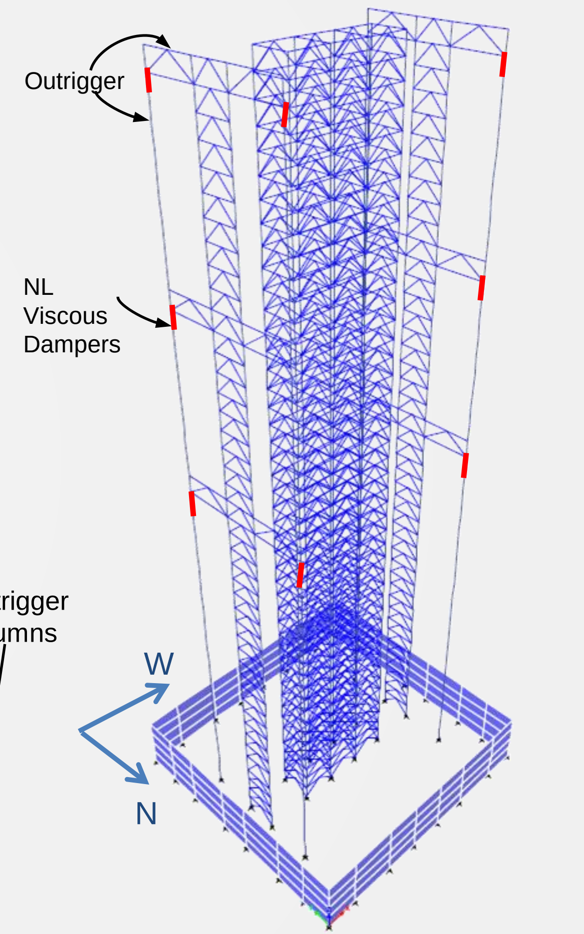
- Description of prototype 40 story tall building
- Multi-natural hazard description
- Real time hybrid simulation with online model updating
- Laboratory demonstration

# 3D Nonlinear Multi-hazard RTHS of a Tall Building

- 40-story (+4 basement) BRBF building in Los Angeles designed by SGH[1] for PEER Tall Building Initiative case studies – BRBFs with Outriggers
- Objectives of study
  - Improve performance using nonlinear fluid viscous dampers with outriggers
  - Assess performance of structure under multi-hazards using RTHS
- Extend MKR-$\alpha$ integration algorithm and ATS actuator control to wind natural hazard
- Online model updating – explicit-based NL Maxwell model




Floor Plan



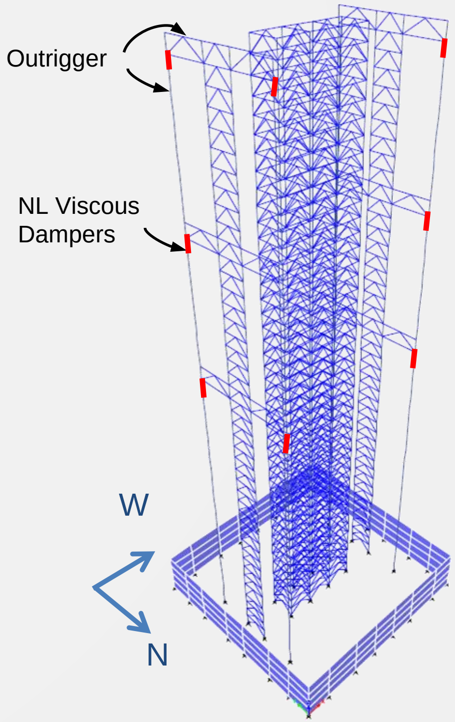

[1] Moehle et al., PEER 2011/05

Al-Subaihawi, S., Kolay, C., Thomas Marullo, Ricles, J. M. and S. E. Quiel, “Assessment of Wind-Induced Vibration Mitigation in a Tall Building with Damped Outriggers Using Real-time Hybrid Simulations,” *Engineering Structures*, submitted for preparation, 2019.

Kolay, C., Al-Subaihawi, S., Thomas Marullo, Ricles, J. M. and S. E. Quiel, “Multi-Hazard Real-Time Hybrid Simulation of a Tall Building with Damped Outriggers,” *International Journal of Lifecycle Performance Engineering*, submitted for preparation, 2019.

# Multi-Hazard 3-D Nonlinear RTHS of Tall Building – EQ & Wind

- Bidirectional EQ ground motions
  - ➢ 1989 Loma Prieta EQ – Saratoga Aloha Ave Station scaled to MCE (2500 year return period) hazard level
- Bidirectional wind loading
  - ➢ Wind speed of 110 mph, 700 MRI
  - ➢ Exposure B



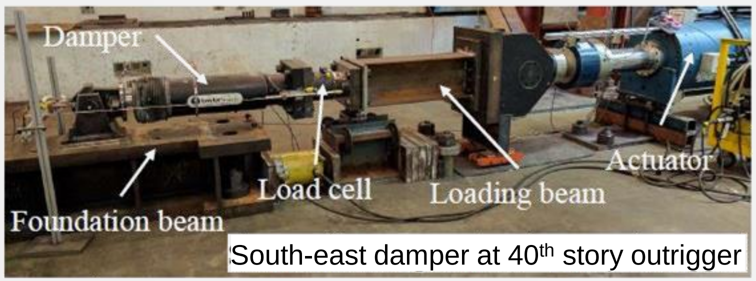
# RTHS Configuration

- Use of:
  - Explicit MKR-$\alpha$ Integration Algorithm
  - Explicit Force-based Nonlinear Fiber Element – Analytical Substructure
  - Adaptive Time Series Compensator for Actuator Control
  - Online Model Updating (OMU) – explicit-based NL Maxwell model

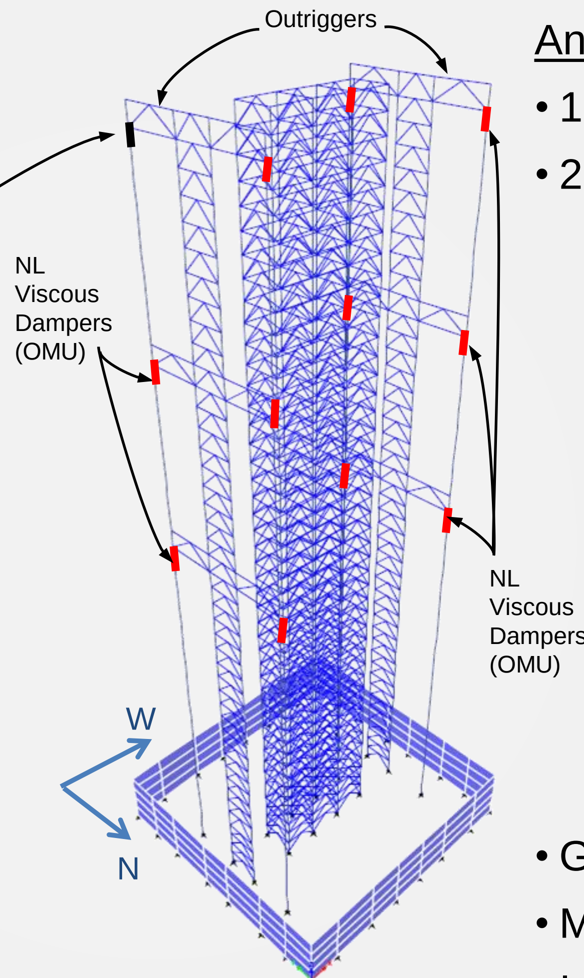
**MKR-α parameter and ATS coefficients**

| Natural Hazard | Time Step, Δt (sec) | $\rho_\infty$ | ATS Coefficients | | | Comments |
|---|---|---|---|---|---|---|
| | | | $a_{0k}$ | $a_{1k}$ | $a_{2k}$ | |
| Wind | $\frac{11}{1024}$ | 0.5 | Fixed | Adaptive | Fixed | Wind: static component with dynamic gusts - 1st mode linear response |
| EQ | $\frac{11}{1024}$ | 0.50 | Adaptive | Adaptive | Adaptive | EQ: Multi-mode non-linear response |

# RTHS Substructures




Experimental Substructure – NL Fluid Viscous Damper




Analytical Substructure

Analytical Sub. Key features:

- 1317 Nodes
- 2974 Elements
  - 2411 Nonlinear Explicit Force-based fiber elements
  - 11 Nonlinear Explicit Maxwell Elements[1] with real-time model updating (dampers placed in each outrigger at 20th, 30th, & 40th floors)
  - 552 Nonlinear truss elements
- Geometric nonlinearities
- Mass
- Inherent damping of building

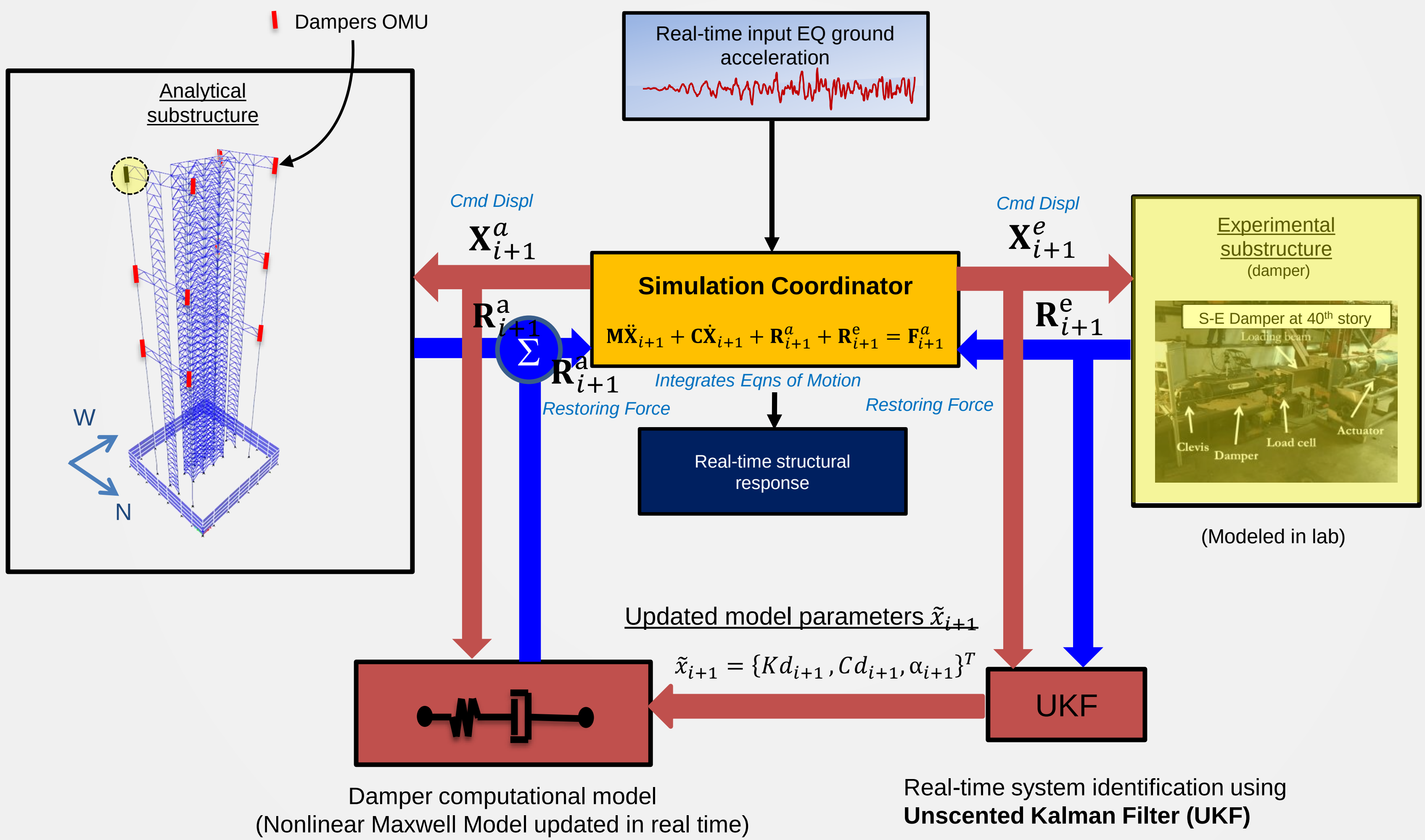
[1] Al-Subaihawi, S. (2020). *Real-time Hybrid Simulation of Complex Structural Systems Subject to Multi-Hazards*. PhD Dissertation, CEE Dept., Lehigh University.

# Real-time Hybrid Simulation with Online Model Updating – Unscented Kalman Filter (UKF)

- Real-time Model Updating
  - 40th story @ S-E corner: damper modeled physically
  - Remaining 11 dampers at 20th, 30th, and 40th stories modeled numerically with real-time model updating
    - Use real-time model updating via Unscented Kalman Filter (UFK) to numerically model the 11 dampers
    - Development of explicit, non-iterative Nonlinear Maxwell Damper Model for real-time hybrid simulation
    - Development of methodology to tune and implement the UKF for real-time identification of nonlinear viscous dampers

Al-Subaihawi, S. (2020). *Real-time Hybrid Simulation of Complex Structural Systems Subject to Multi-Hazards*. PhD Dissertation, CEE Dept., Lehigh University.

# Real-time Hybrid Simulation with Online Model Updating – Unscented Kalman Filter (UKF)



# 3-D RTHS Results: Roof RMS Lateral Accelerations
## East to West 110 mph, 700 Year MRI Wind

RMS Roof Accelerations (mG)

| Floor | No Dampers | | With Dampers | |
|---|---|---|---|---|
| | EW | NS | EW | NS |
| 40 | 7.0 | 31.5 | 6.9 | 16.2 |

Peak Roof Accelerations (mG)

| Floor | No Dampers | | With Dampers | |
|---|---|---|---|---|
| | EW | NS | EW | NS |
| 40 | 28.8 | 90.3 | 25.8 | 59.0 |

Dampers added to outriggers at 20th, 30th, and 40th stories:

- RMS Acceleration: 2% reduction in EW, 49% reduction in NS
- Peak Acceleration: 10% reduction in EW, 35% reduction in NS

Note: Outrigger frames are in NS direction

# 3-D RTHS Results: BRB Maximum Ductility
## 1989 Loma Prieta EQ Scaled to MCE

BRB Maximum Ductility Demand ($\Delta_b^{max}/\Delta_y$)

| Story | No Dampers | | With Dampers | |
|---|---|---|---|---|
| | EW | NS | EW | NS |
| 1 | 3.2 | 3.0 | 3.2 | 2.1 |

Dampers added to outriggers at 20th, 30th, and 40th stories:

- BRB ductility demand: Minimal reduction in EW, 30% reduction in NS

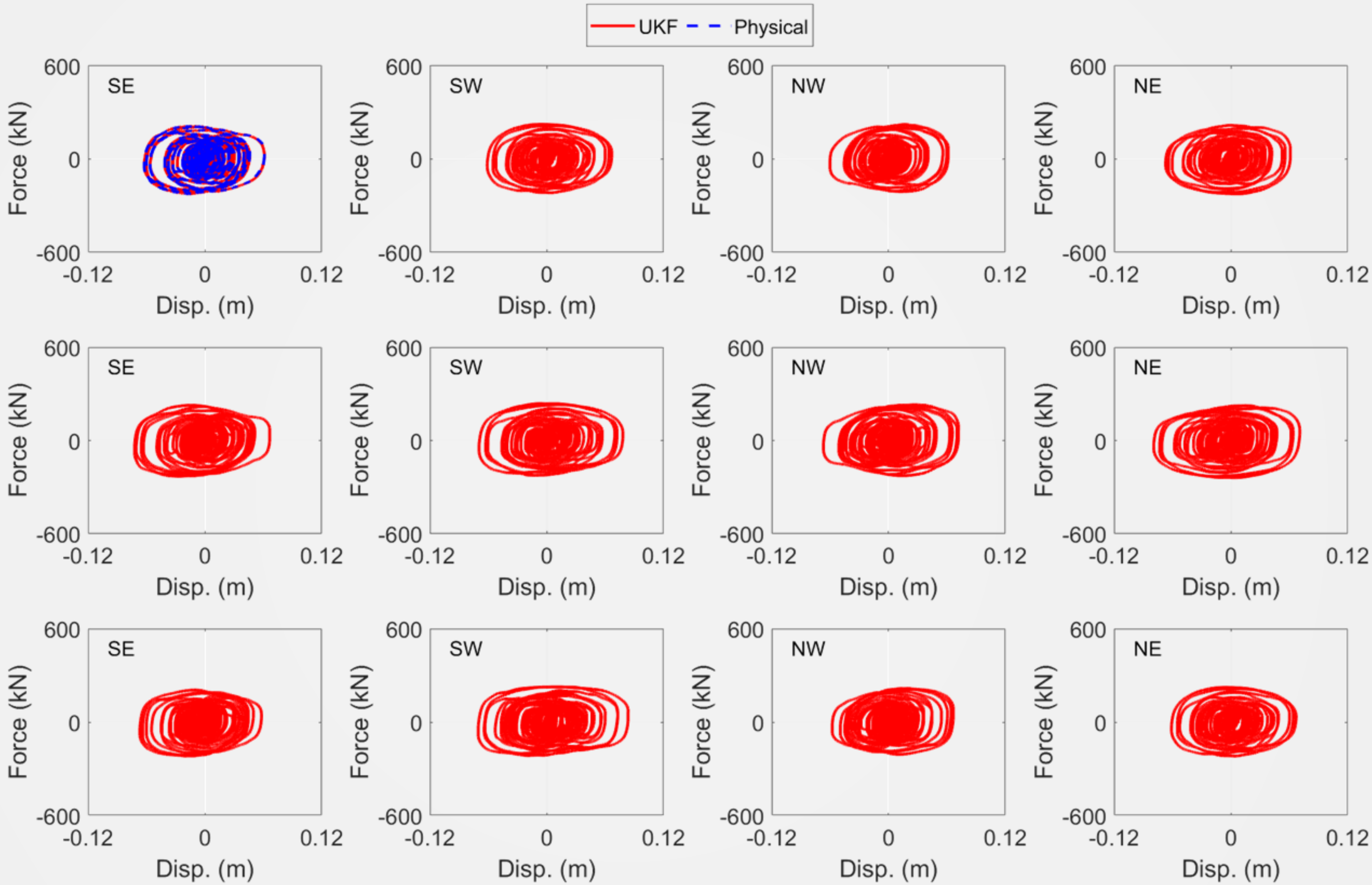
  Note: Outrigger frames are in NS direction

# Damper Hysteretic Response – 700 MRI Wind

40th Story

30th Story

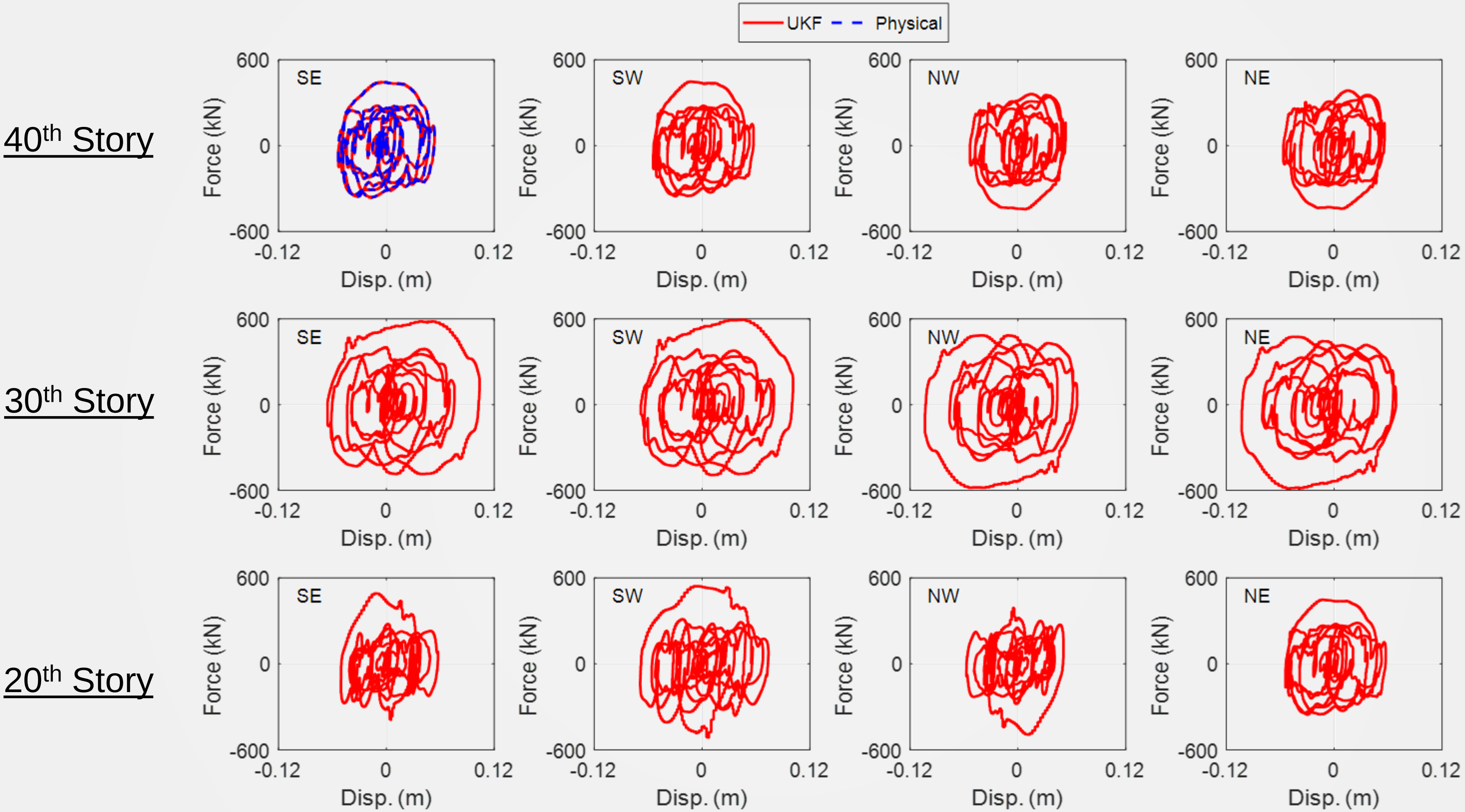
20th Story




40th Story @ SE: Experimental Substructure

All other dampers: Real-time Model Updating is UKF

# Damper Hysteretic Response – EQ MCE Level



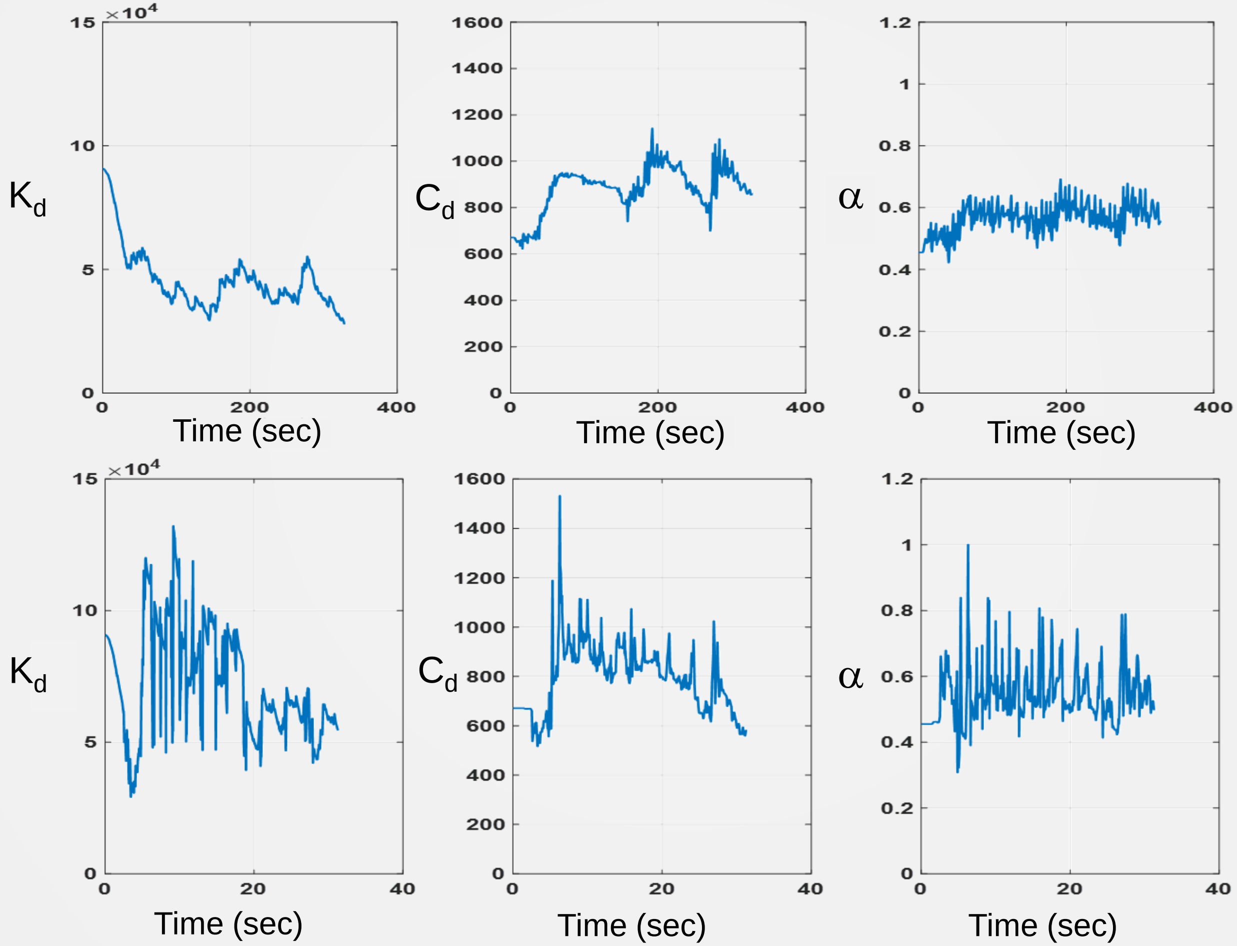

40th Story @ SE: Experimental Substructure

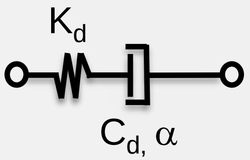
All other dampers: Real-time Model Updating is UKF

# Online Model Updating – UKF
# Variation of Nonlinear Maxwell Model Parameters

Wind

EQ



# Summary and Conclusions

- The application of real-time hybrid simulation to large complex non-linear systems subject to wind and earthquake natural hazards was demonstrated.
- Using dampers, building's performance is improved (accelerations) under wind and (drift, BRB ductility) under EQ loading.

# Acknowledgements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# Thank you