Challenges in Achieving Natural Hazards Mitigation Using Protective Devices

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NHERI Lehigh Researcher Workshop:

Advanced Simulation for Natural Hazards Mitigation & Grand Challenges for Multi-Hazards Engineering

Grand Challenge 2: Protective Systems

Lehigh University
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Challenges in Achieving Natural Hazards Mitigation Using Protective Devices

- Science and technology challenges … … things researchers think about:
    - Advancing the technology: creating new materials, creating new devices, creating new structural systems to better utilize devices …
    - Understanding new and existing devices
    - Understanding response of structural systems with devices
    - Laboratory research: dynamic testing, real-time hybrid simulation, shake table simulations, wind loading simulations …
    - Numerical simulations
    - Performance assessment
- Challenges in practical application … … things researchers ~~may~~ should consider?:
    - Costs and cost trade-offs (cost of design, cost of construction, potential initial cost savings, initial vs. lifecycle costs (including lifecycle costs of damage) …)
    - Safety and perception of safety (if we trade steel and concrete for protective systems)
    - Simplicity of design (effort for design, skills and knowledge needed to design (and who has it), tools needed for design, etc.)… … systems that are easier to design are used more often
    - Policy, codes, standards (e.g., ASCE 7)

Challenges in Achieving Natural Hazards Mitigation Using Protective Devices: Very Broad, Let's Focus a Bit

- This is a "researchers' workshop", so focus on science and technology challenges
- My experience with "protective devices" is mostly on dampers for seismic hazards … … so focus mostly on dampers and seismic hazard
    - This presentation does not include work on seismic base isolation or dampers for wind hazard mitigation
    - Others at this workshop can provide input on these topics
- Since we are at a NHERI facility, the presentation emphasizes laboratory research that can be done using NHERI facilities
    - Some attention to numerical models and using such models to create understanding

Acknowledgements

- Dr. James Ricles, Dr. Le-Wu Lu (deceased), Dr. Robert Michaels, Shannon Sweeney, Ernest Ferro, Dr. Robert Fleischman, Dr. Jose Restrepo (faculty collaborators for various projects)
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- Nonlinear viscous dampers provided by Taylor Devices Inc.
- Compressed elastomer dampers provided by Corey Rubber, Inc. and Penn State Erie

Challenges in Achieving Seismic Hazard Mitigation Using Dampers and Other Devices: Overview of Topics

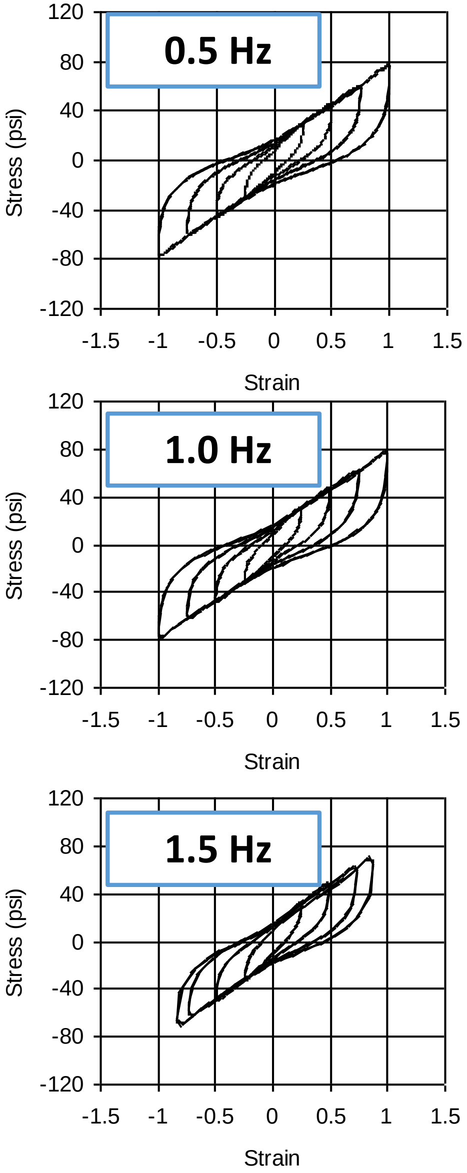
- **Characterization of Devices: Testing and Models**
  - Focus on characterization tests and models of dampers and other devices
- Modeling and Understanding Systems with Dampers
  - Simple models for design and to understand system/damper response
  - Accurate models for numerical simulations
- Response of Systems with Dampers During Hazard Events
  - Real-time hybrid simulations of seismic response of systems with dampers
- Hazard Mitigation Performance of Systems with Dampers
  - Seismic performance of systems with dampers
- Summary of Issues and Thoughts Suggested by Lab Experiences

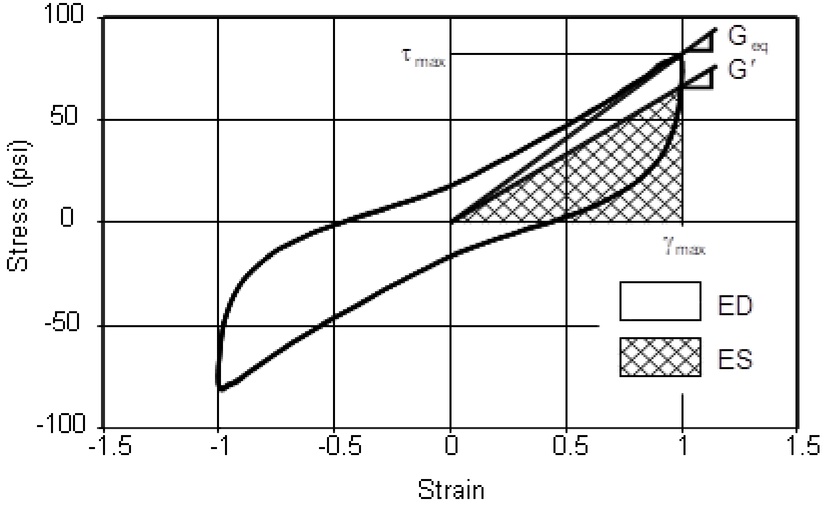
Characterization of Dampers and Other Devices

- Purpose is to investigate force-deformation hysteretic response of device:
  - Is hysteretic response as expected? Should it be improved?
  - Establish sensitivity to deformation amplitude, loading frequency, temperature
  - Establish simple quantities, such as effective stiffness, damping, loss factor
  - Understand physical limits of damper (e.g., when response degrades from exceeding deformation limit)
- And, to develop accurate force-deformation hysteretic response models of devices for nonlinear time-history analyses (numerical simulations) of structural systems with devices:
  - Select mathematical form of model
  - Use system identification techniques to determine model parameters
  - Implement model in numerical simulation software (e.g., OpenSees)
- And, to develop simple models for force-deformation response of devices for understanding response and use in simpler design calculations

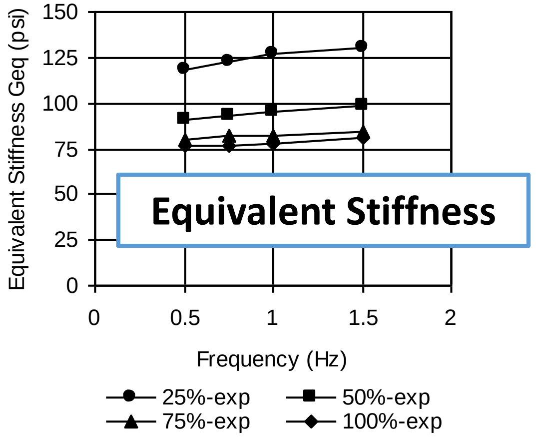
Characterization Tests of Ultra-High Damping Natural Rubber Damper

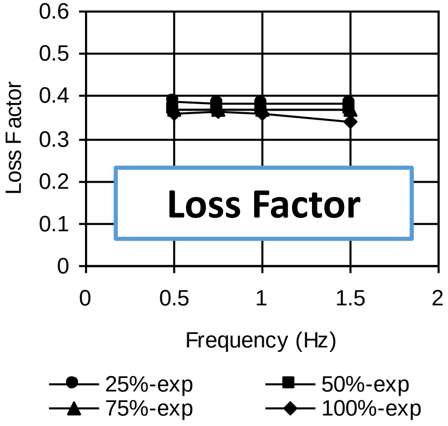
Ultra-High Damping Natural Rubber (UHDNR) damper in test setup





Definition of effective stiffness, energy dissipation (loss factor) for elastomeric or viscoelastic damper

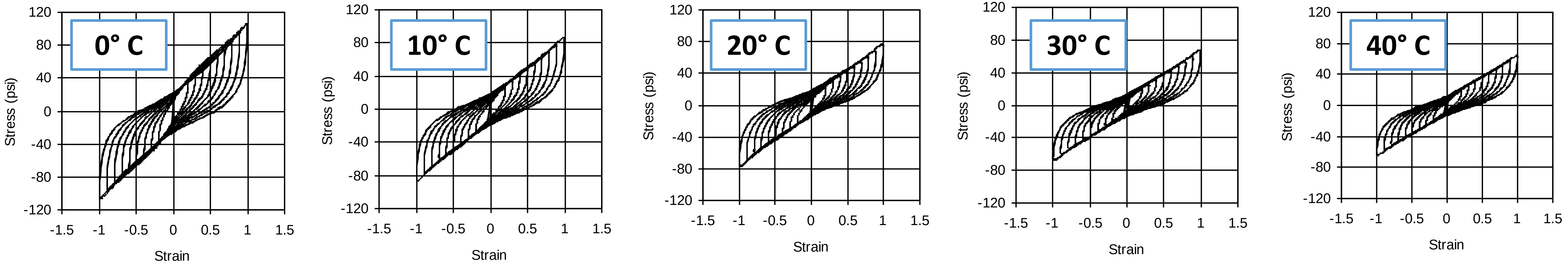




Effective stiffness and loss factor exhibit amplitude dependence, but little frequency dependence

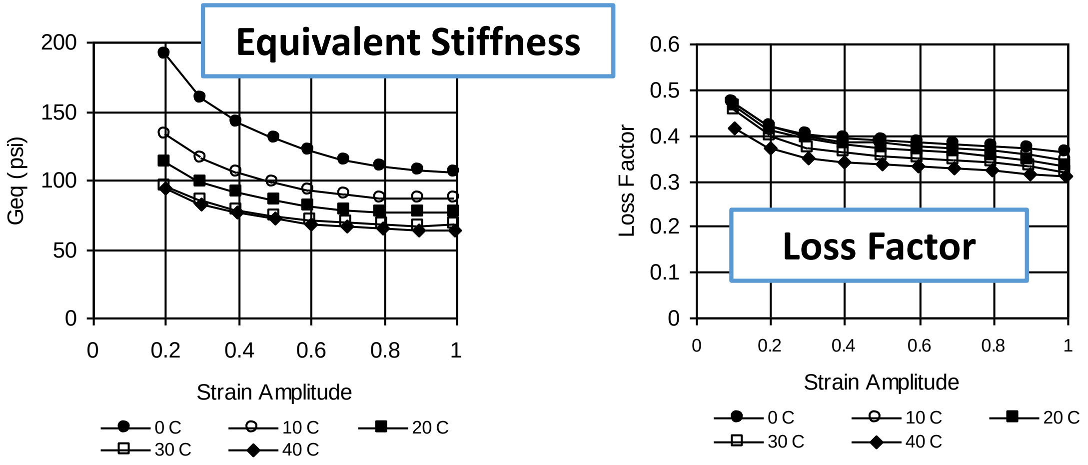
Lee, K.-S., Sause, R., Ricles, J., Ab-Malek, K., and Lu, L.-W., "Nonlinear Rate-Dependent Hysteresis Model for Structural Dampers Made from Ultra High Damping Natural Rubber," *Journal of Rubber Research*, 2004

Characterization Tests of Ultra-High Damping Natural Rubber Damper



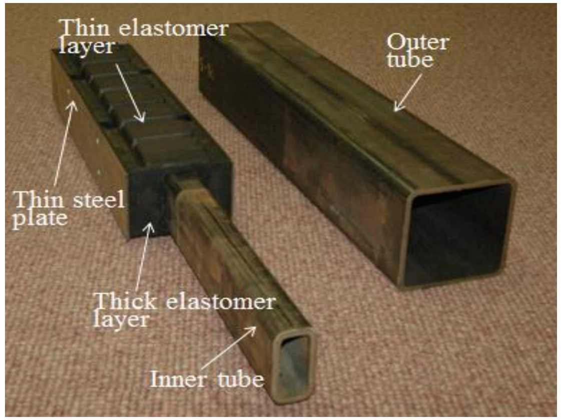
Apparent ambient temperature dependence of UHDNR damper

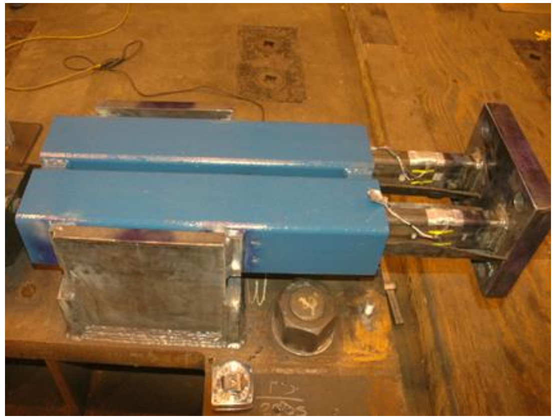
Lee, K.-S., Sause, R., Ricles, J., Ab-Malek, K., and Lu, L.-W., "Nonlinear Rate-Dependent Hysteresis Model for Structural Dampers Made from Ultra High Damping Natural Rubber," *Journal of Rubber Research*, 2004



Ambient temperature and amplitude dependence of UHDNR damper

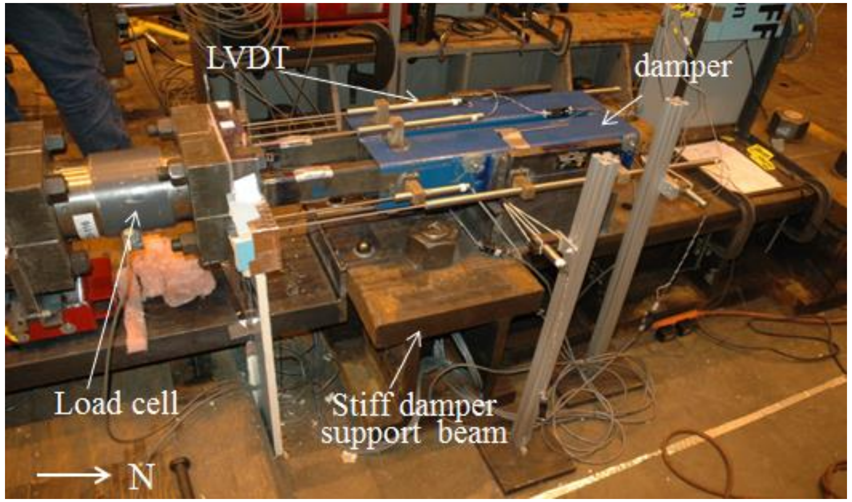
Characterization Tests of Compressed Elastomer Damper



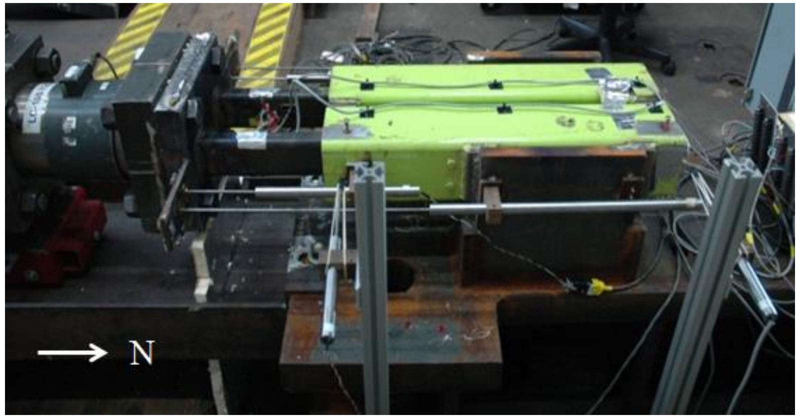


2nd generation compressed elastomer damper

Controlled temperature chamber



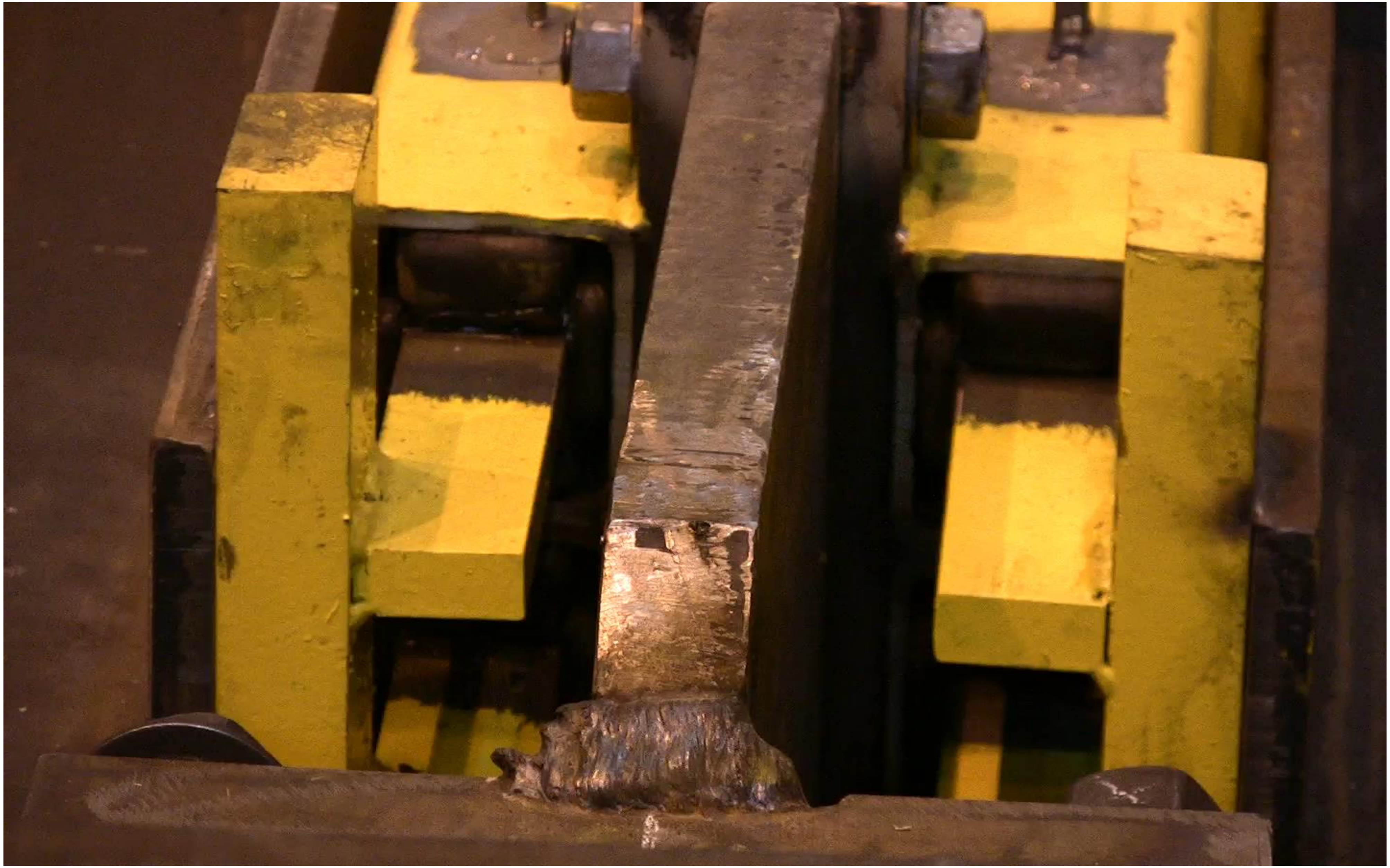
Characterization test setup for 2nd damper



3rd generation damper in test setup

Mahvashmohammadi, A., " Design and Assessment of Supplemental Elastomeric Dampers for Improved Seismic Performance of New Buildings", PhD Dissertation, Lehigh University, 2015.

Characterization Tests of Compressed Elastomer Damper



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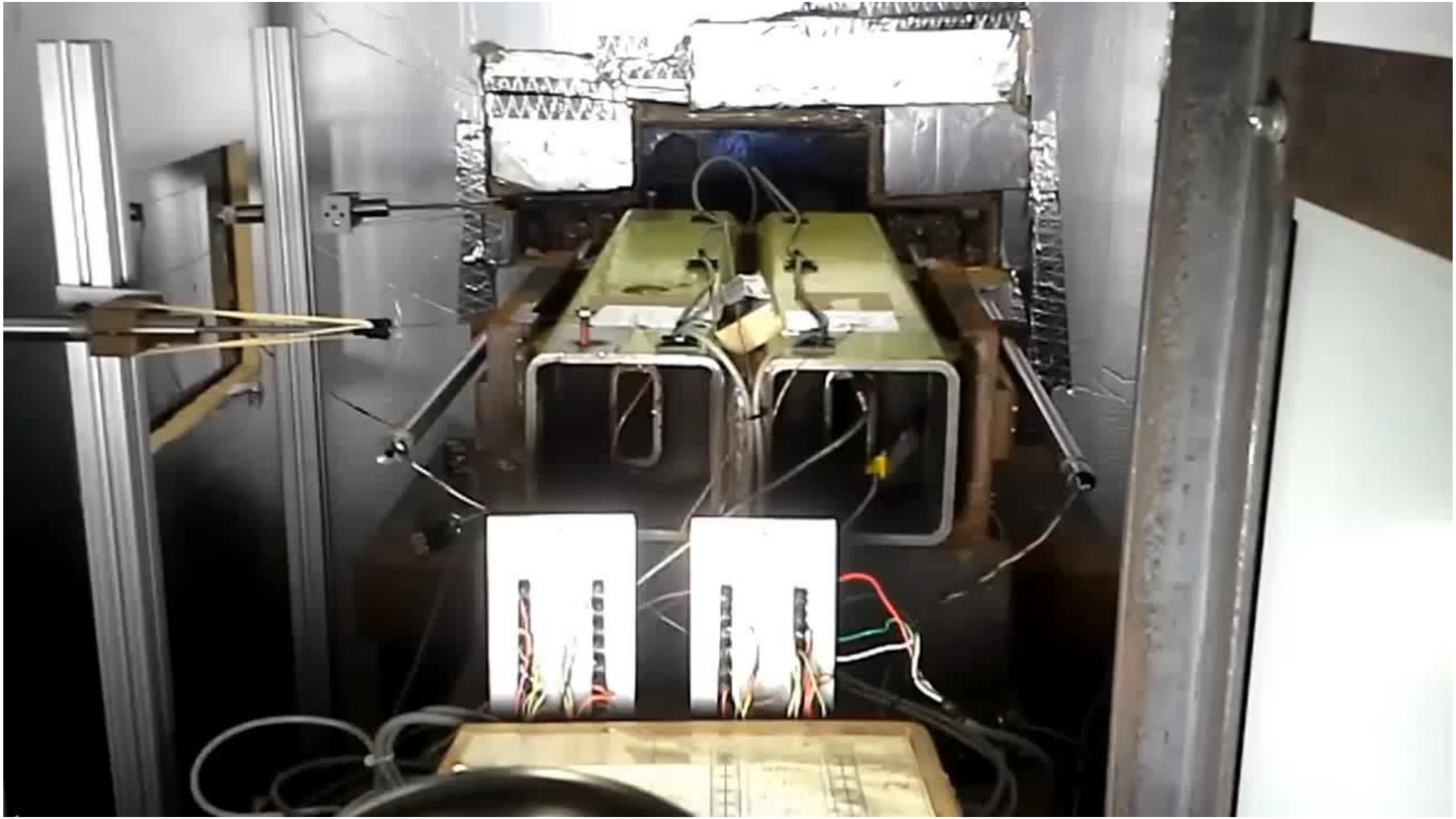
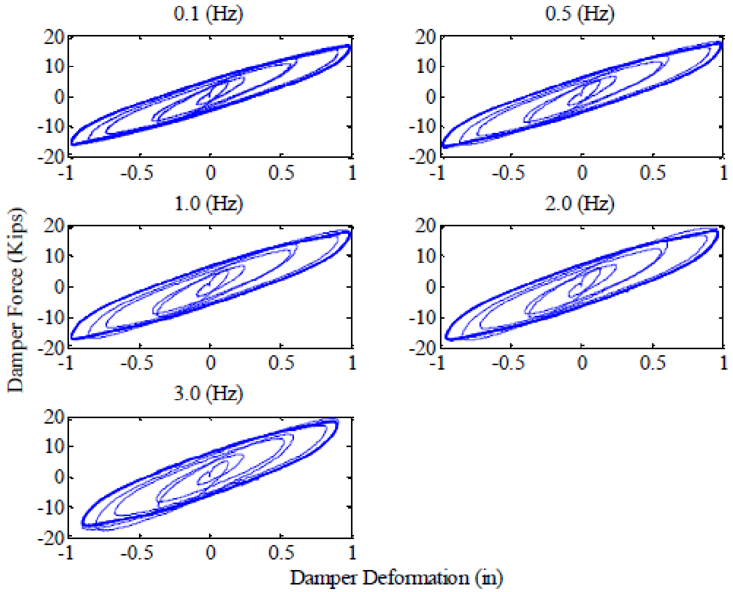
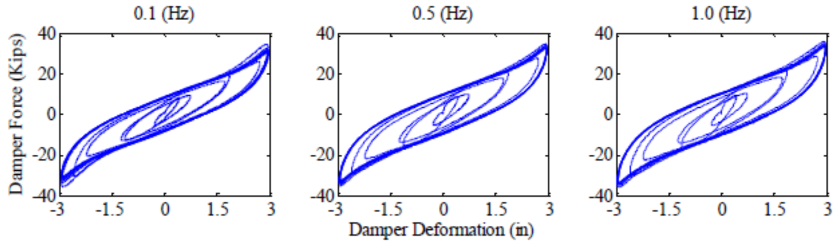


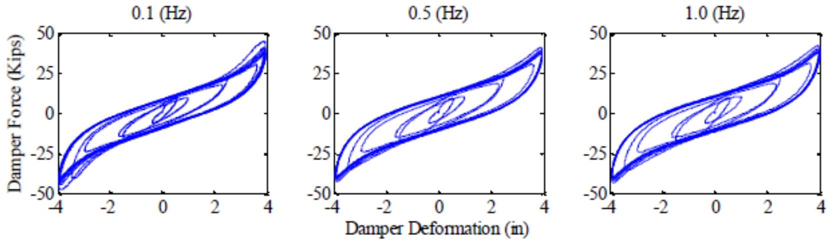
Characterization Tests of Compressed Elastomer Damper



1.0 inch amplitude, 68° F

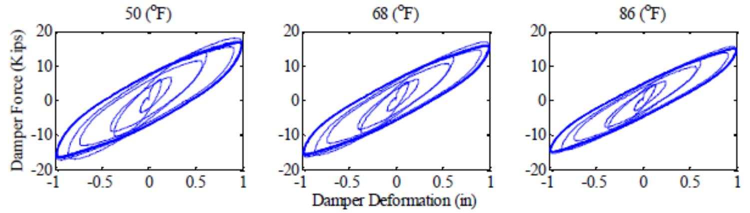


3.0 inch amplitude, 68° F

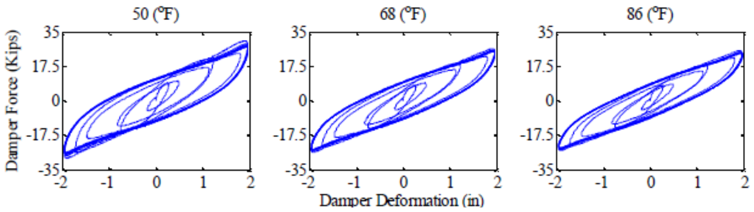


4.0 inch amplitude, 68° F

Deformation amplitude dependence of 2nd generation damper



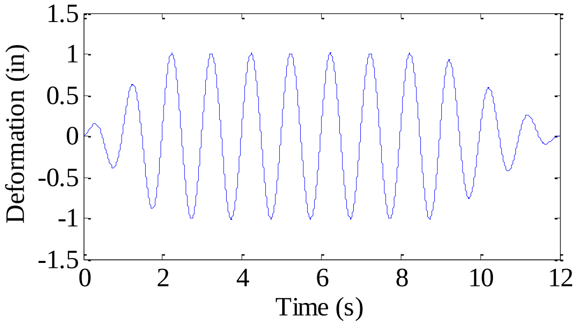
1.0 inch amplitude, 1.0 Hz



2.0 inch amplitude, 1.0 Hz

Temperature dependence of 2nd generation damper

Loading history



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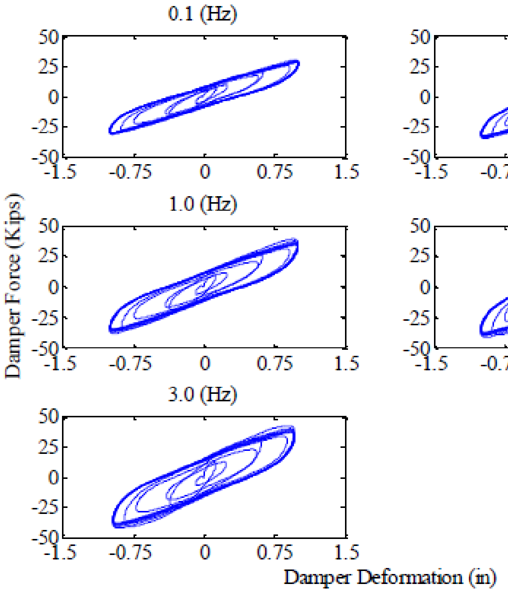
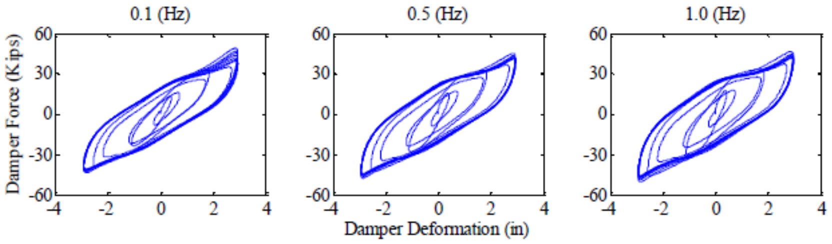
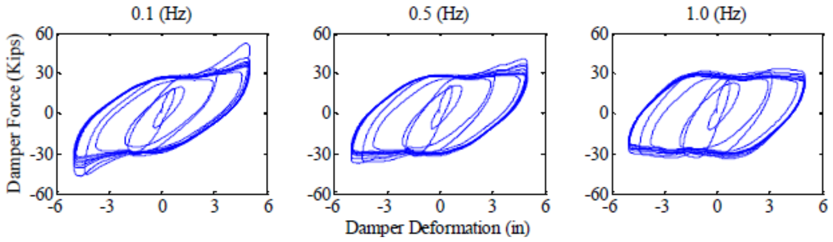
Characterization Tests of Compressed Elastomer Damper



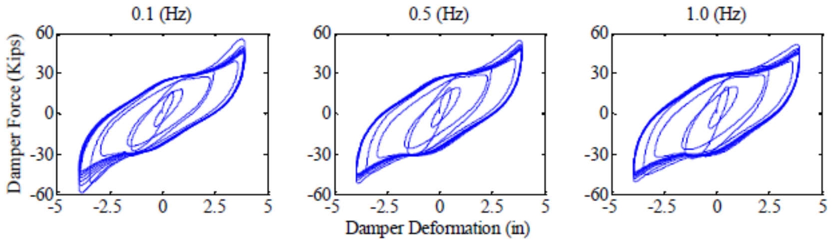
1.0 inch amplitude, 68° F



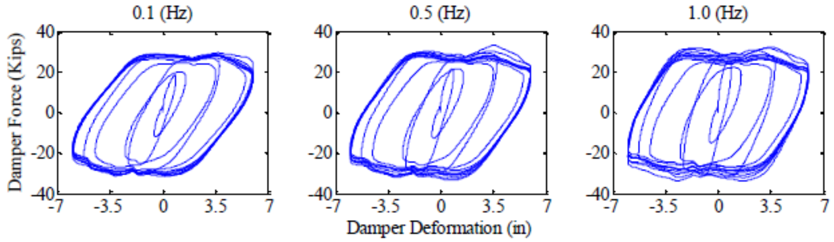
3.0 inch amplitude, 68° F



5.0 inch amplitude, 68° F



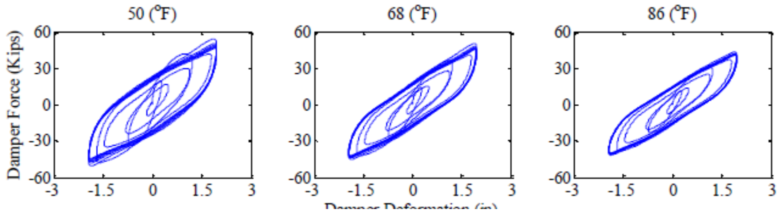
4.0 inch amplitude, 68° F



6.0 inch amplitude, 68° F

Deformation amplitude dependence of 3rd generation damper

Temperature dependence of 3rd generation damper



2.0 inch amplitude, 1.0 Hz

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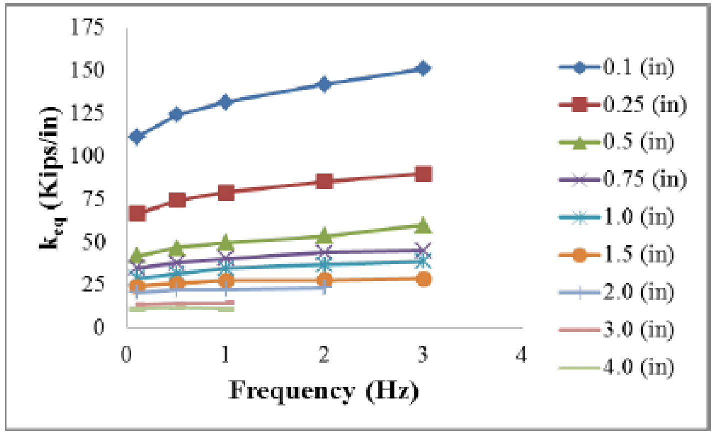
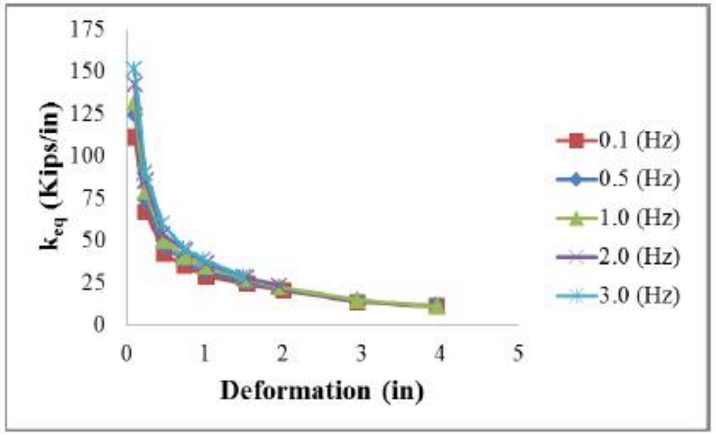
Characterization Tests of Compressed Elastomer Damper

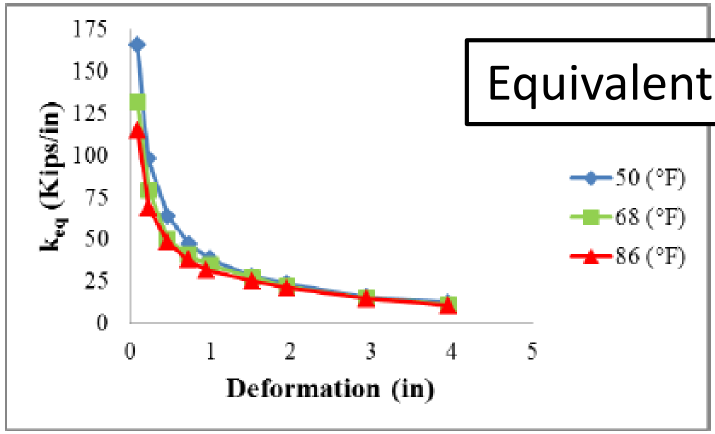
Simple parameters for 3rd generation damper from characterization tests as function of deformation amplitude, frequency, temperature



(a) Equivalent stiffness

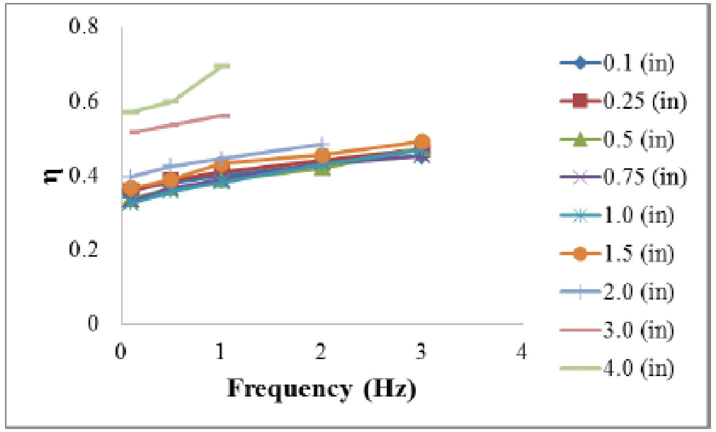


(a) Equivalent stiffness

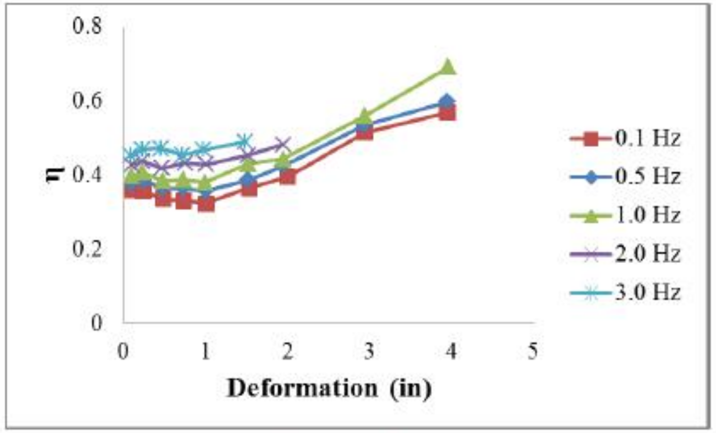


(a) Equivalent stiffness

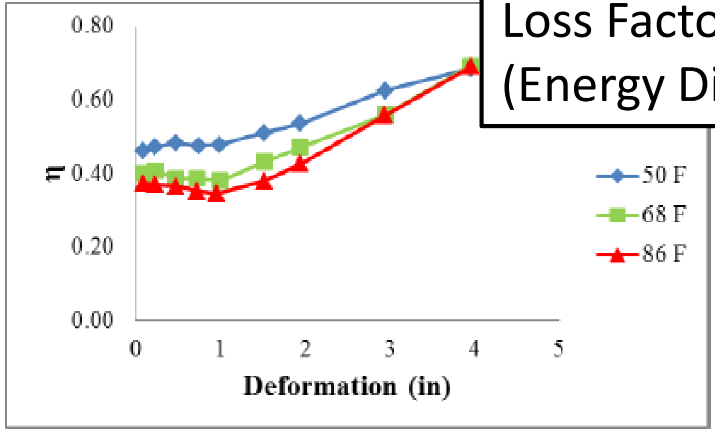
Equivalent Stiffness



(b) Loss factor



(b) Loss factor

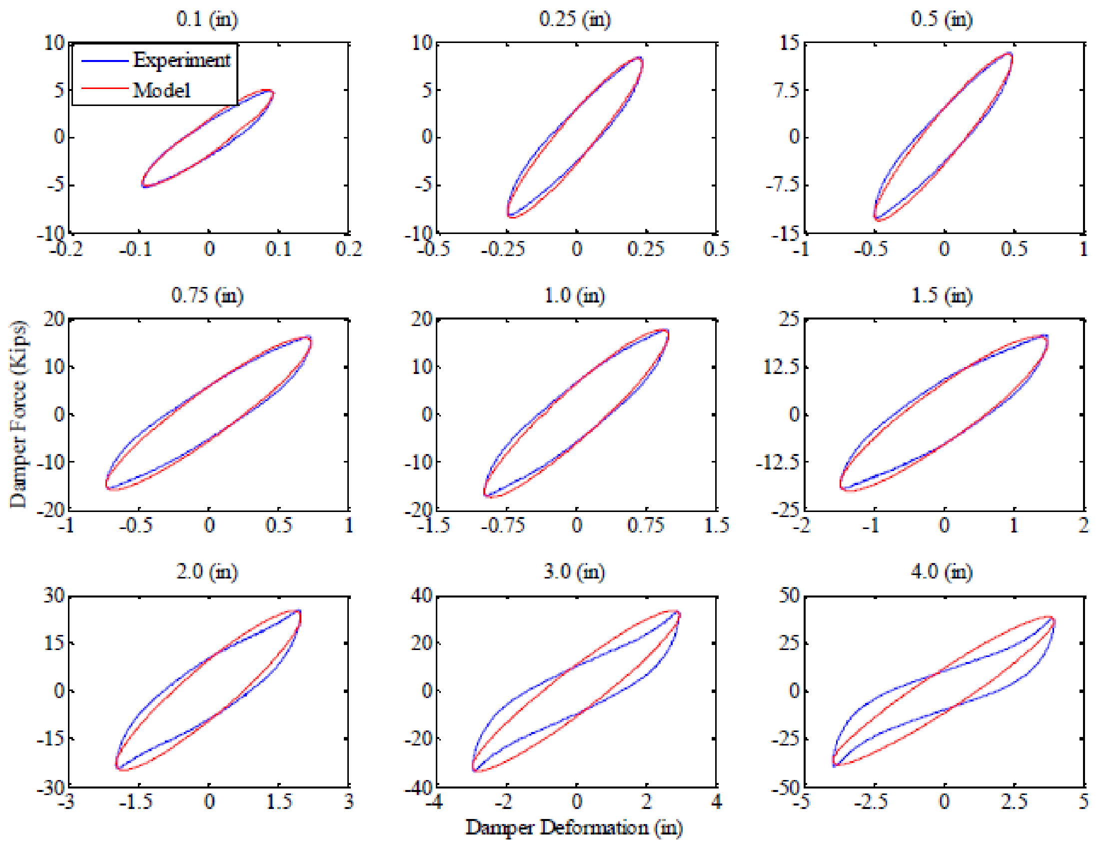


(b) Loss factor

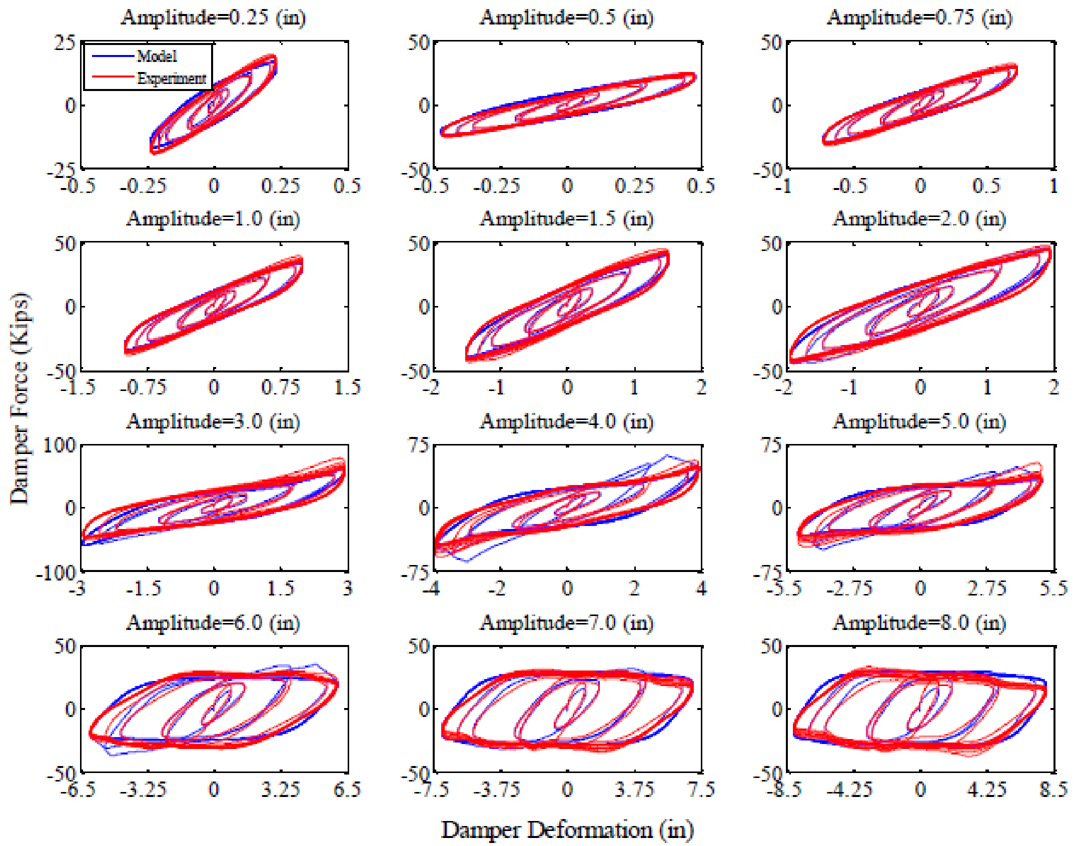
Loss Factor (Energy Dissipation)

Characterization Tests of Compressed Elastomer Damper

Models for 2nd and 3rd generation dampers based on characterization tests



Simple Viscoelastic Hysteretic Force-Deformation Response for 2nd Gen. Damper Based on Equivalent Stiffness and Loss Factor for Seismic Design Calculations

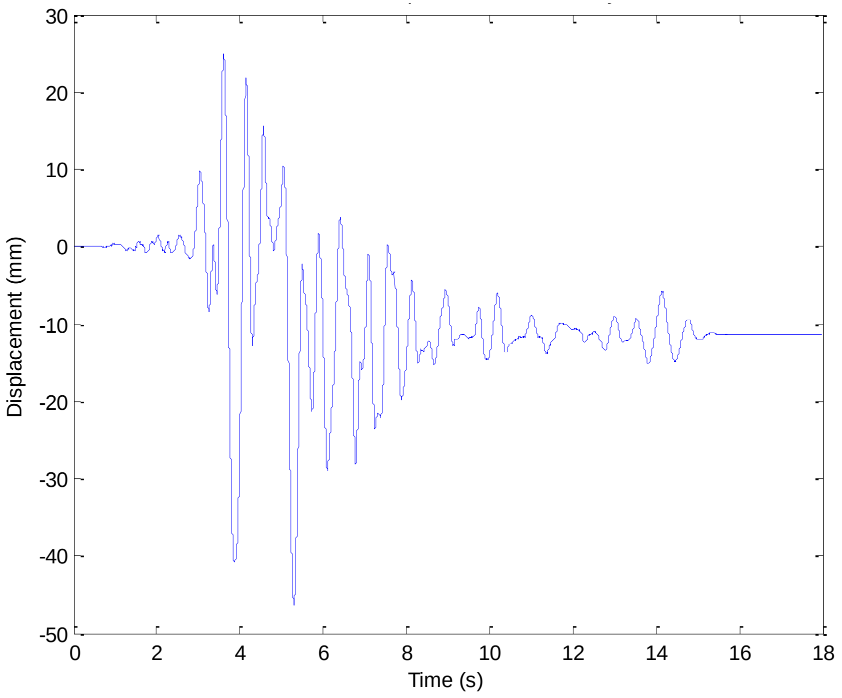


Numerical Model of Hysteretic Force-Deformation Response of 3rd Gen. Damper for Numerical Simulations of Building Seismic Response

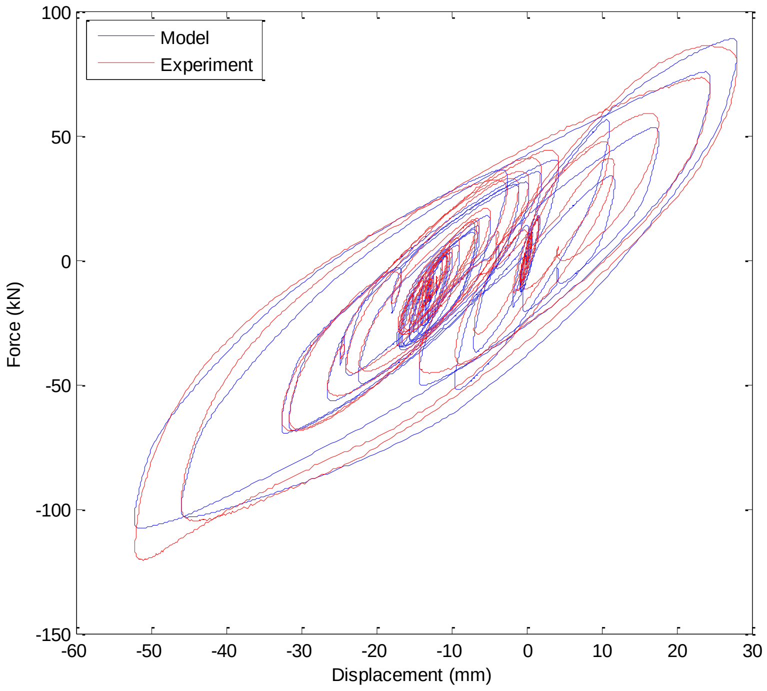
Characterization Tests of Compressed Elastomer Damper

Response of model for predefined deformation history corresponding to response of damper in building under Maximum Considered Earthquake (MCE ~2500 year return period) ground motion

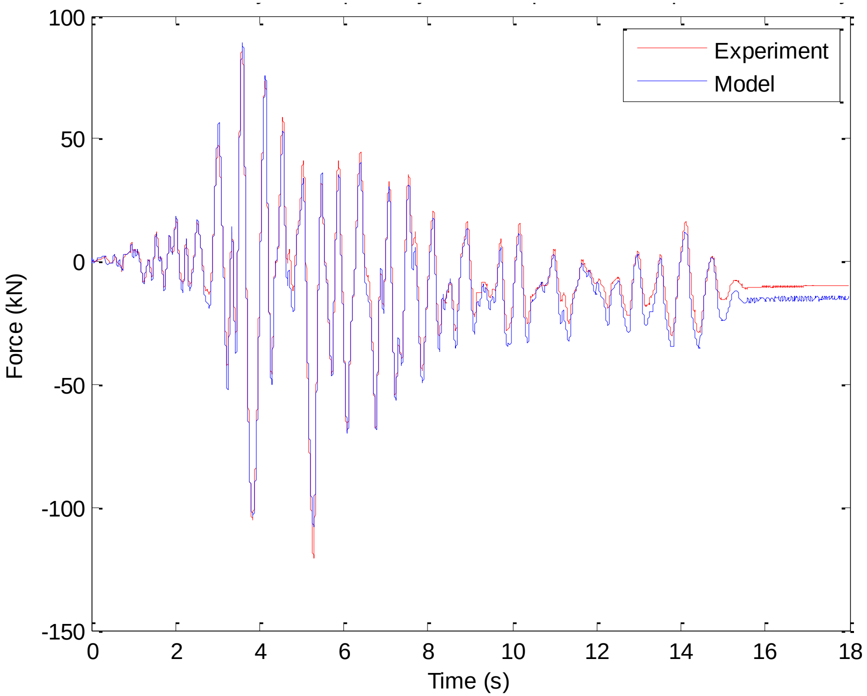
Predefined Deformation History



Force-Deformation Response



Force Response History



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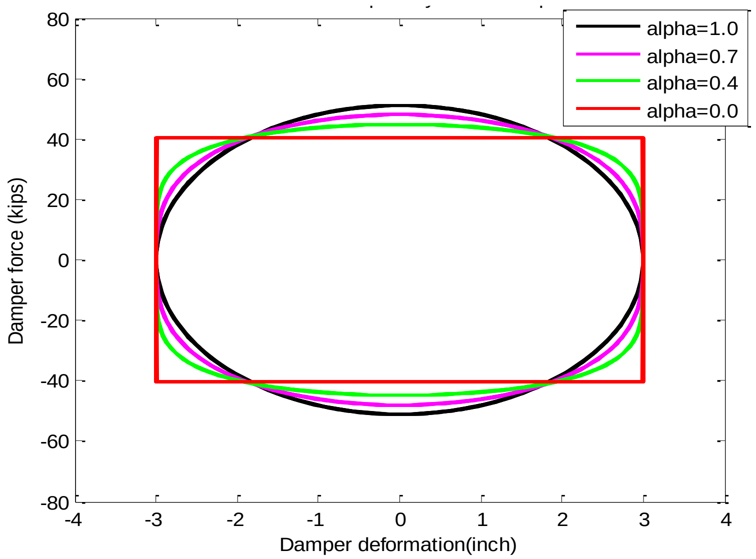
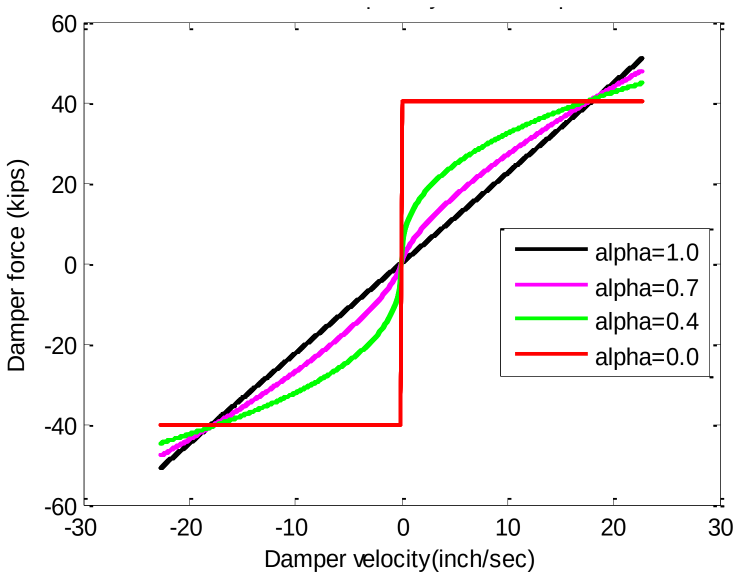
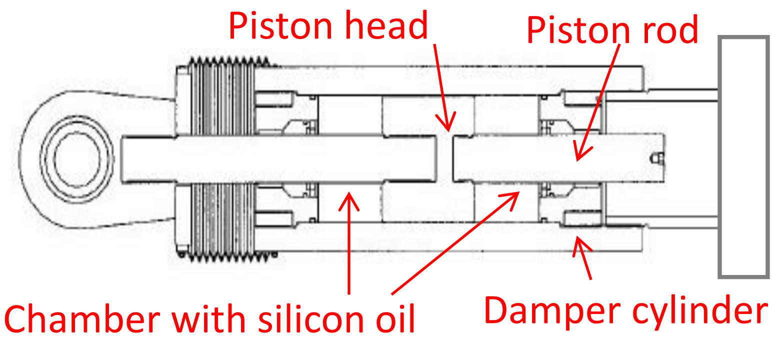
Characterization Tests of Nonlinear Viscous Damper

Nonlinear Viscous Damper







Theory for typical model

$$f_d = C_\alpha \, (v)^\alpha$$

f_d = damper force

C_α = damping coefficient

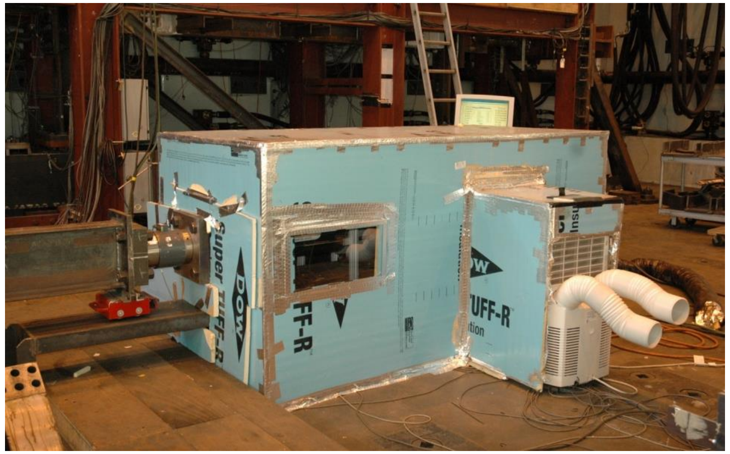
v = damper relative velocity (deformation rate)

α = exponent, $0 < \alpha < 1$ nonlinear viscous, $\alpha = 1$, linear viscous

Dong, B., "Large-scale experimental, numerical, and design studies of steel MRF structures with nonlinear viscous dampers under seismic loading", PhD Dissertation, Lehigh University, 2015.

Characterization Tests of Nonlinear Viscous Damper

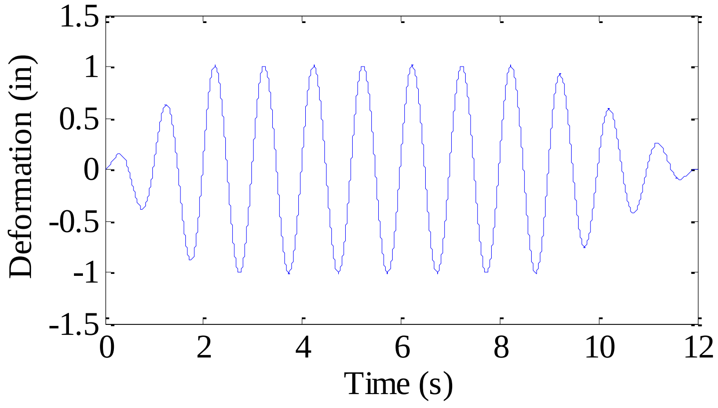
Characterization test setup



Controlled temperature chamber

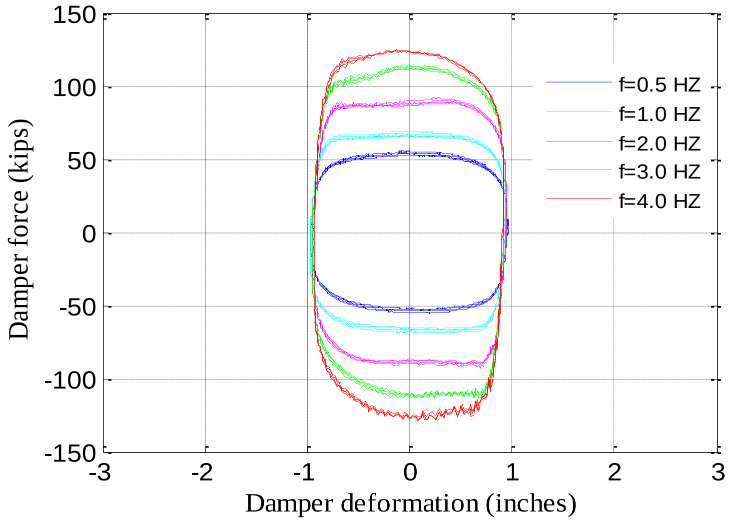
Characterization test matrix

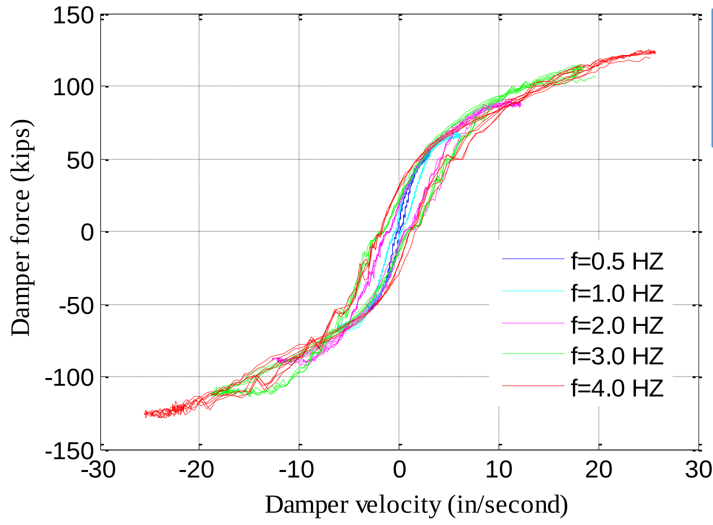
Frequency(Hz)	Displacement amplitude(inch)									
	0.5	0.75	1	1.25	1.5	1.75	2	2.5	3	4
0.25	X	X	X	X	X	X	X	X	X	X
0.5	X	X	X	X	X	X	X	X	X	X
0.75	X	X	X	X	X	X	X	X	X	X
1	X	X	X	X	X	X	X	X	X	X
1.25	X	X	X	X	X	X	X	X	X	X
1.5	X	X	X	X	X	X	X	X	X	
2	X	X	X	X	X	X	X	X		
3	X	X	X	X	X	X				
4	X	X	X	X						



Loading history

Characterization Tests of Nonlinear Viscous Damper

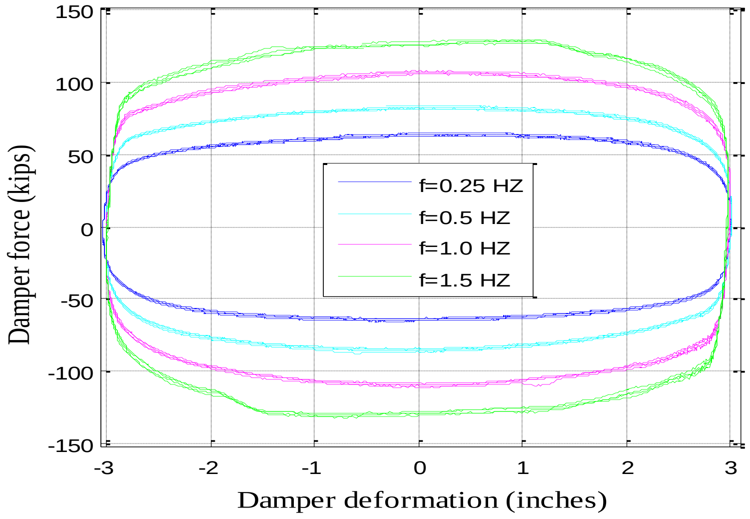


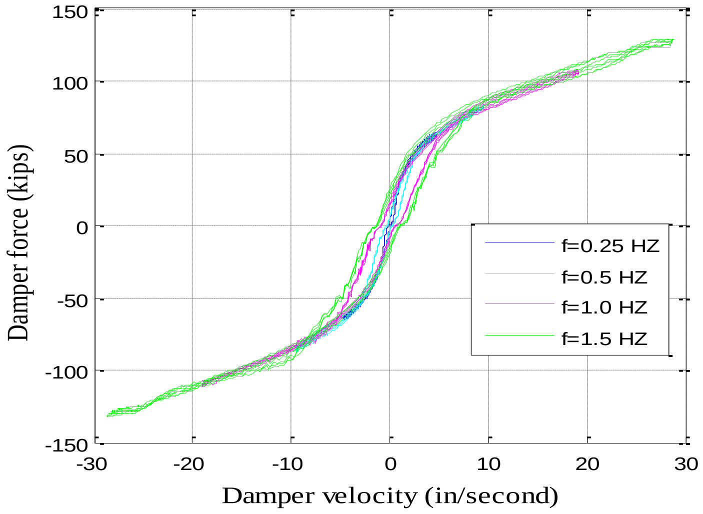


1 inch deformation amplitude

Expected frequency and amplitude dependence of nonlinear viscous damper

3 inch deformation amplitude

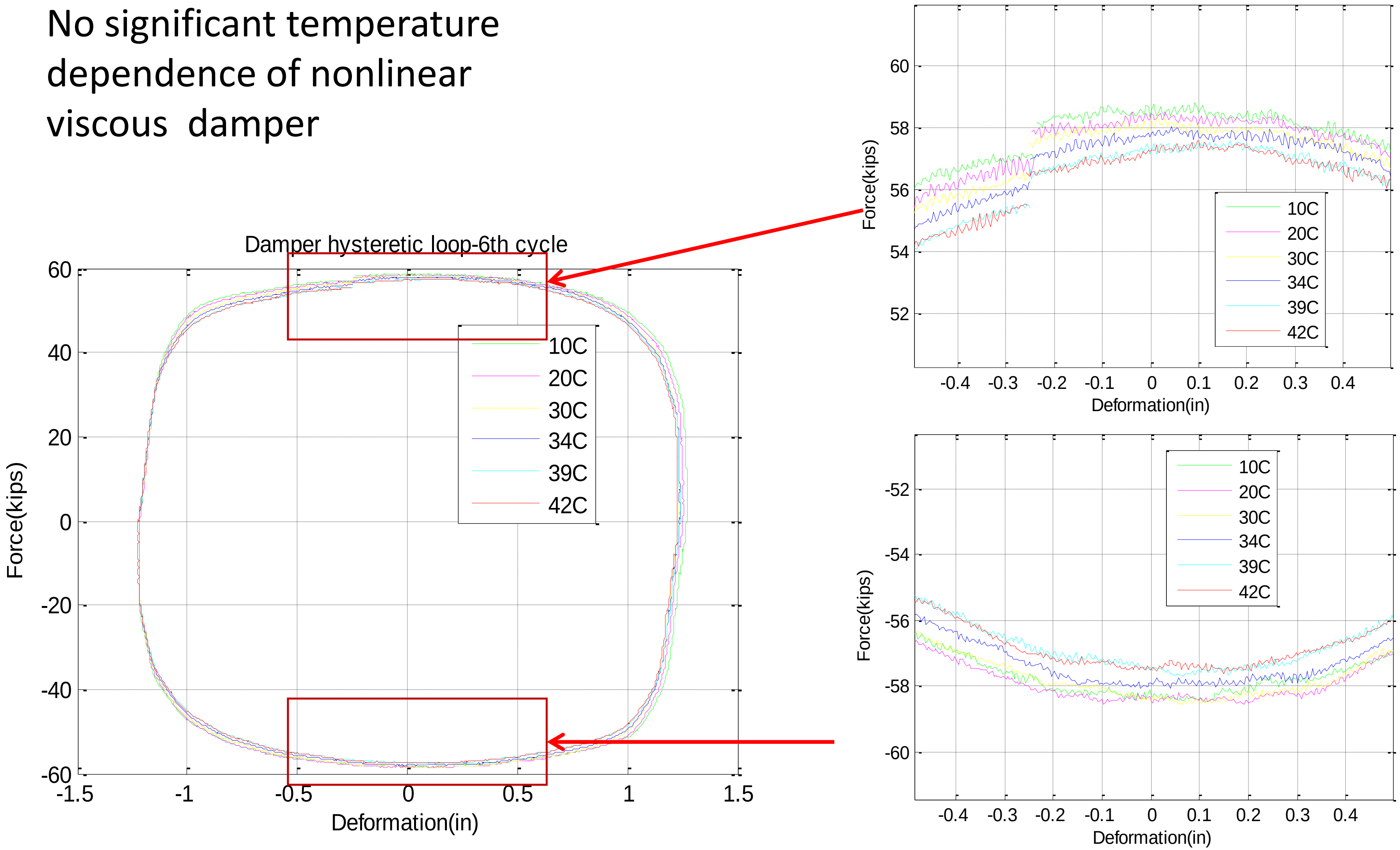




Dong, B., “Large-scale experimental, numerical, and design studies of steel MRF structures with nonlinear viscous dampers under seismic loading”, PhD Dissertation, Lehigh University, 2015.

Characterization Tests of Nonlinear Viscous Damper

No significant temperature dependence of nonlinear viscous damper



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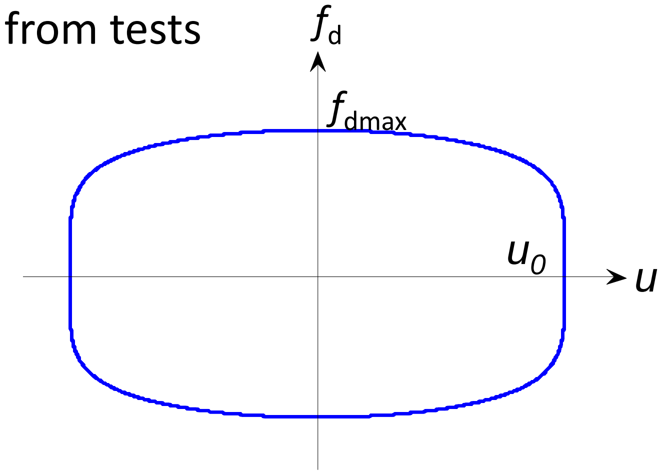
Characterization Tests of Nonlinear Viscous Damper

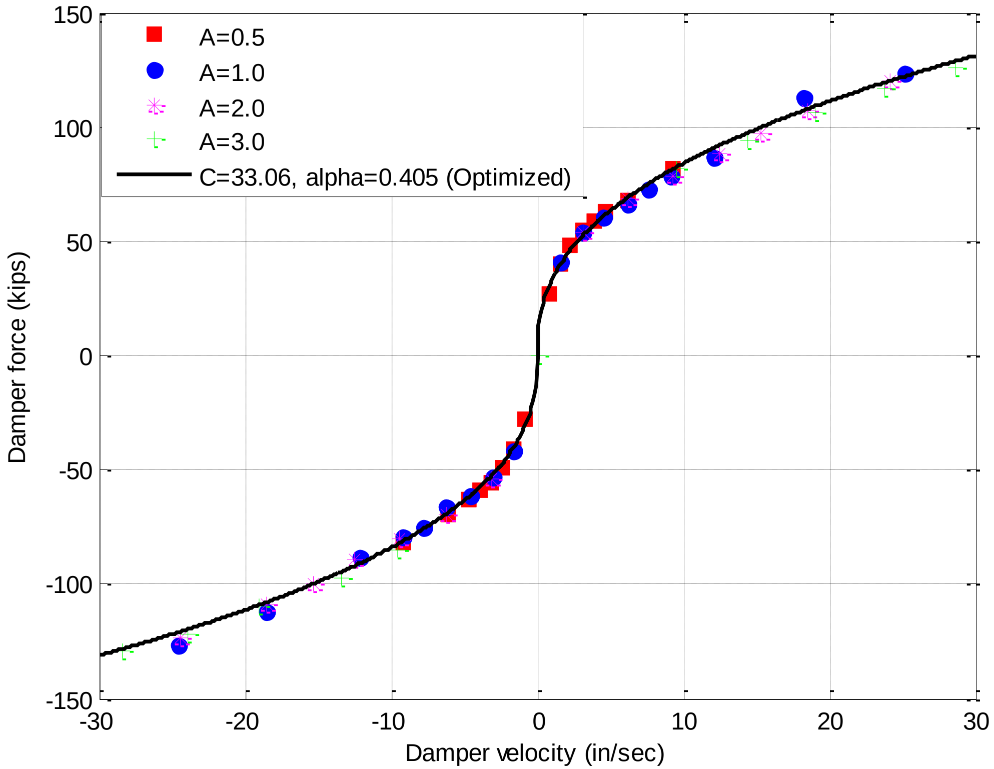
Nonlinear model $f_d = C_\alpha (v)^\alpha$

Identification of parameters (C_α, α)

Identified from average peak damper force and corresponding velocity from tests



$$f_{d\max} = C_\alpha \cdot (\dot{u}_0)^\alpha$$



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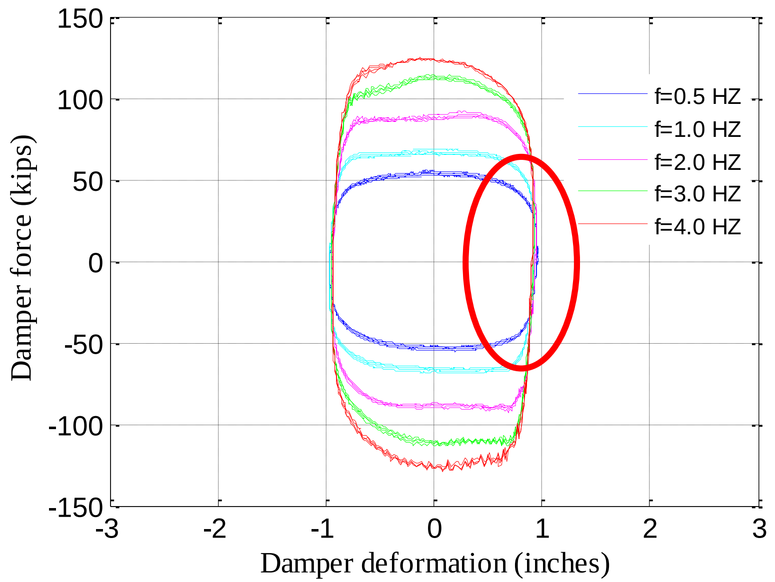
Characterization Tests of Nonlinear Viscous Damper

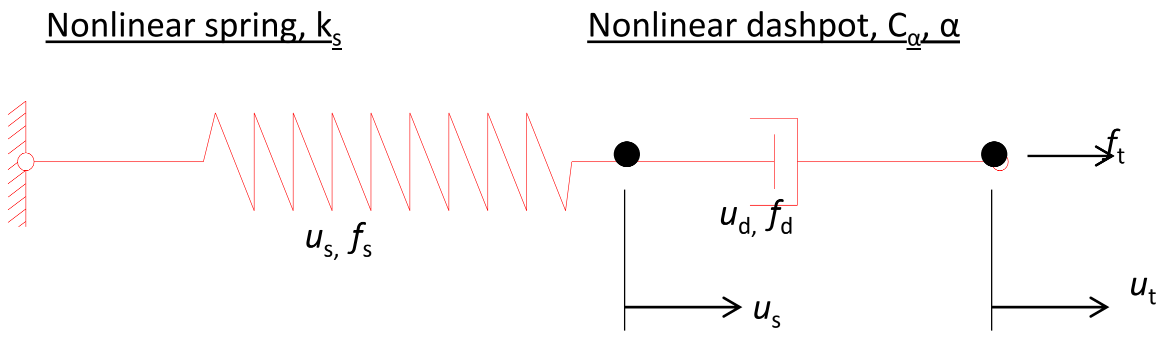
Interesting Variations from Expected Response from Simple Model

Nonlinear viscous damper force-deformation response is not entirely viscous

Clevis connection introduces nonlinearity to non-viscous response



Nonlinear Maxwell Model



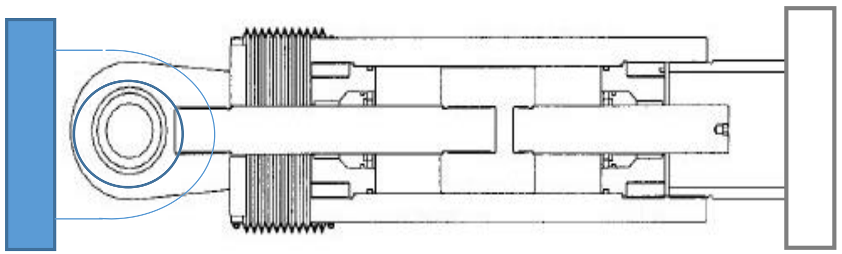
u_t = damper total deformation

u_s = spring deformation

u_d = dashpot deformation

$$u_t = u_s + u_d$$

$$f_t = f_s + f_d$$



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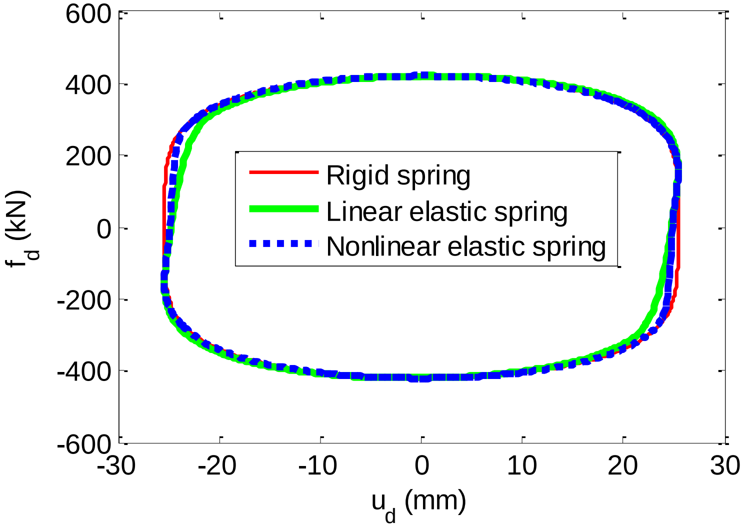
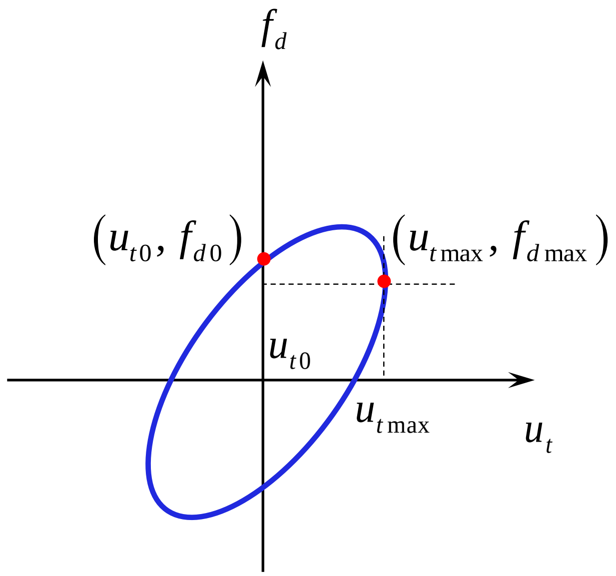
Characterization Tests of Nonlinear Viscous Damper

Identification of parameter for nonlinear spring (k_s)

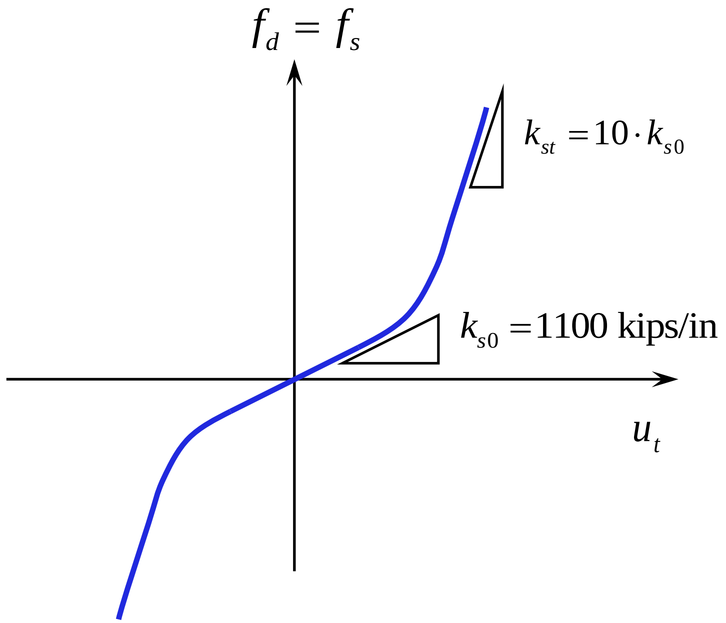
Identified from peak damper force and corresponding velocity from tests





$$k_s = \frac{f_{d0} \cdot \omega}{\left(f_{d\max} / C_\alpha \right)^{1/\alpha}}$$

ω is loading frequency of sinusoidal displacement u_t=A·sin(wt)



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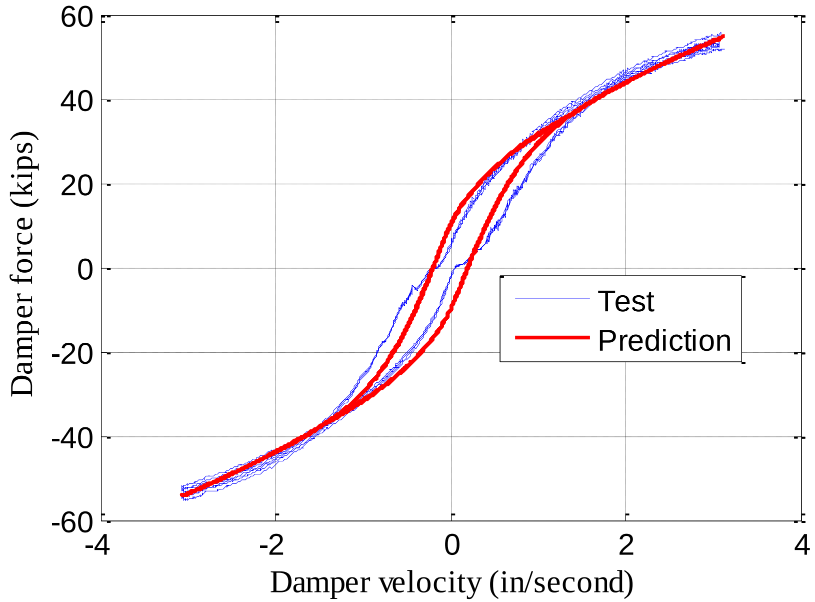
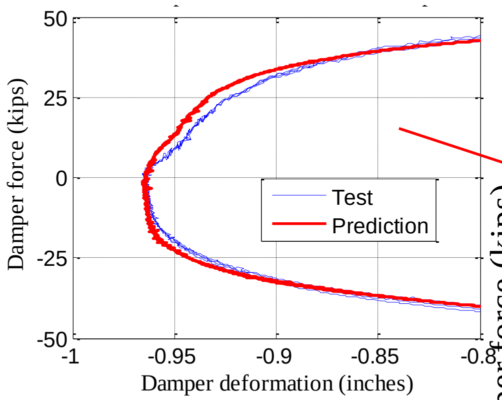
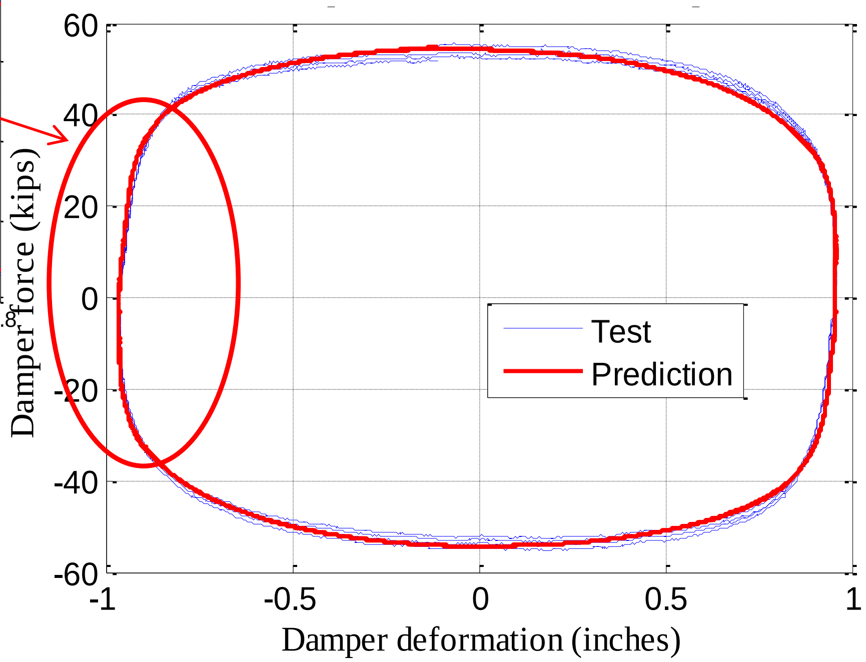
Characterization Tests of Nonlinear Viscous Damper

Nonlinear Maxwell Model





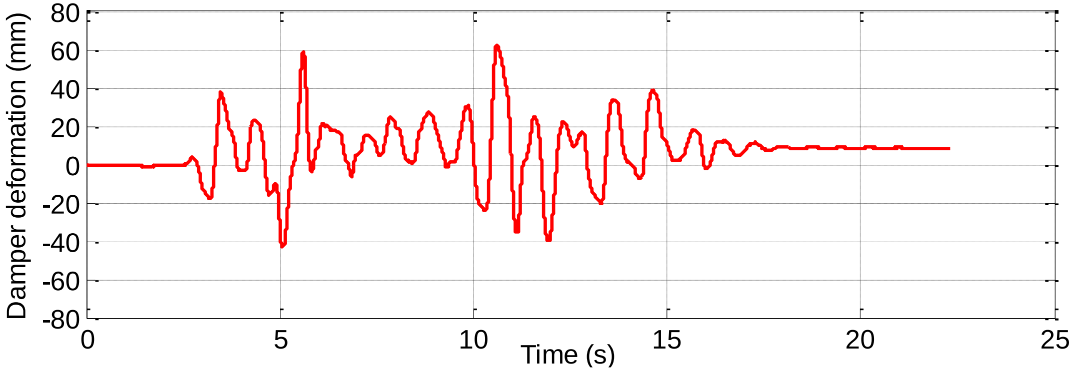


Dong, B., “Large-scale experimental, numerical, and design studies of steel MRF structures with nonlinear viscous dampers under seismic loading”, PhD Dissertation, Lehigh University, 2015.

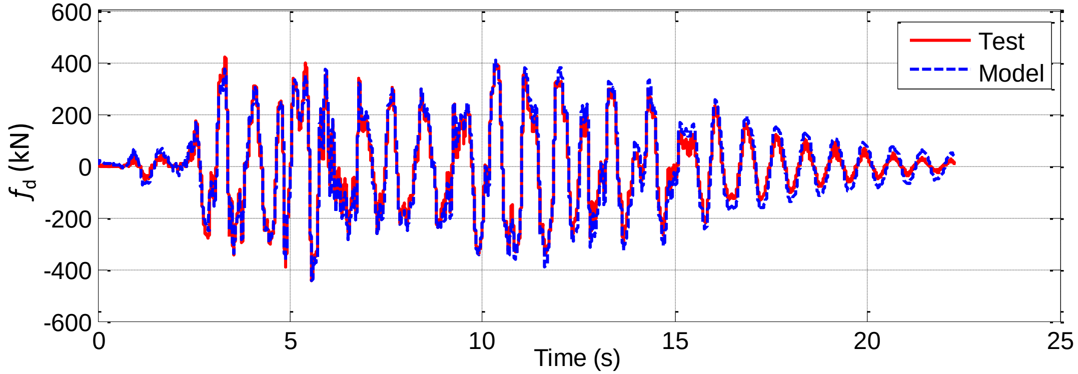
Characterization Tests of Nonlinear Viscous Damper

Response of model for predefined deformation history corresponding to response of damper in building under Maximum Considered Earthquake (MCE ~2500 year return period) ground motion

Predefined Deformation History



Force Response History



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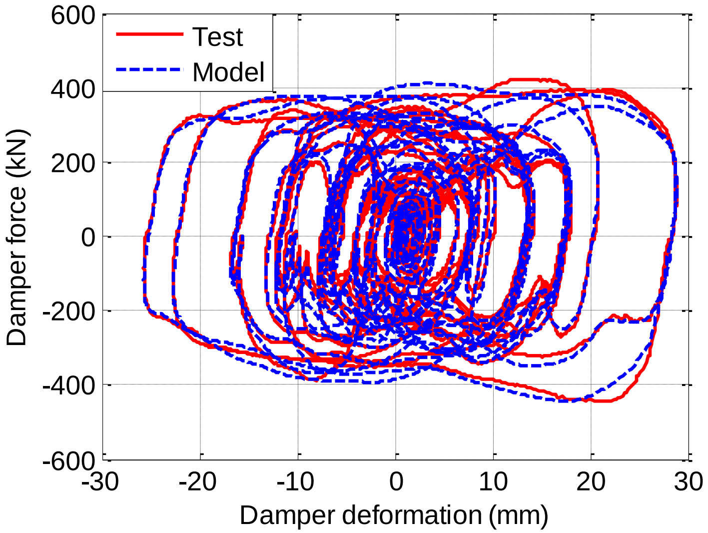
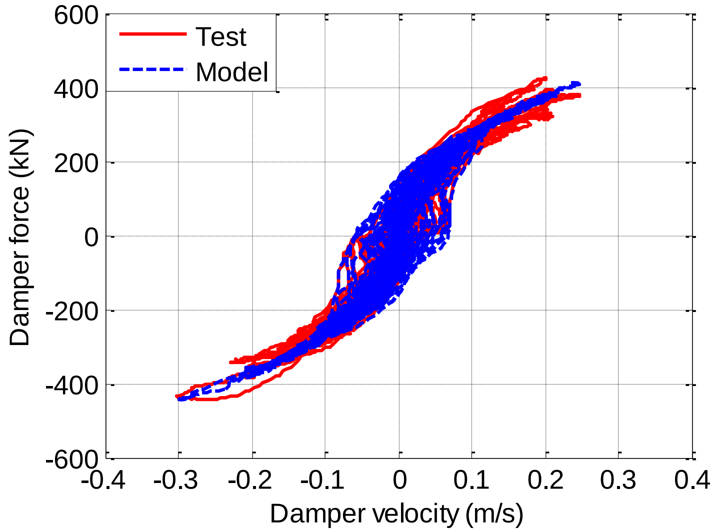
Force-Deformation Response

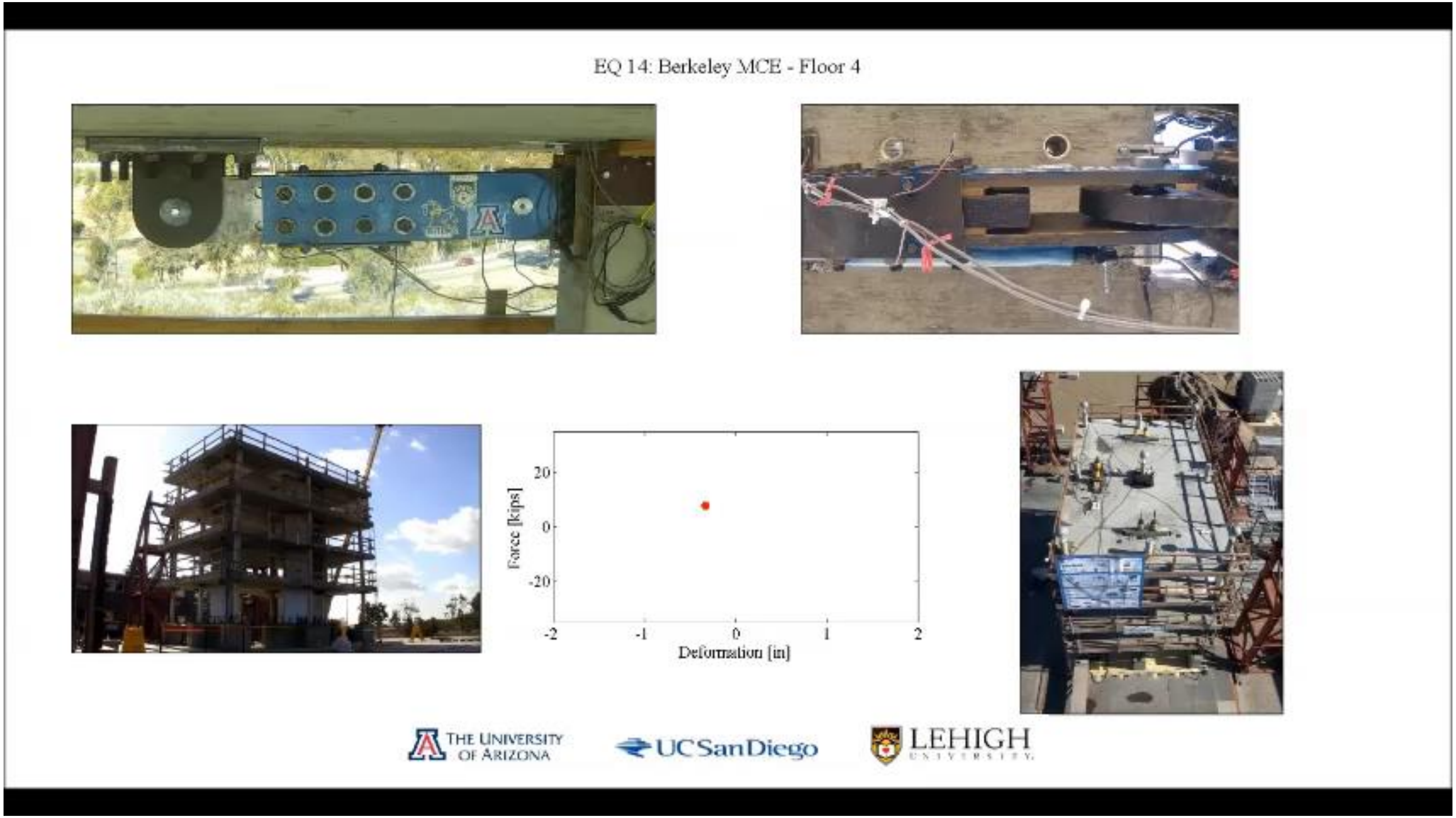


Force-Velocity Response



Characterization of Force-Limiting Friction Device for Floors

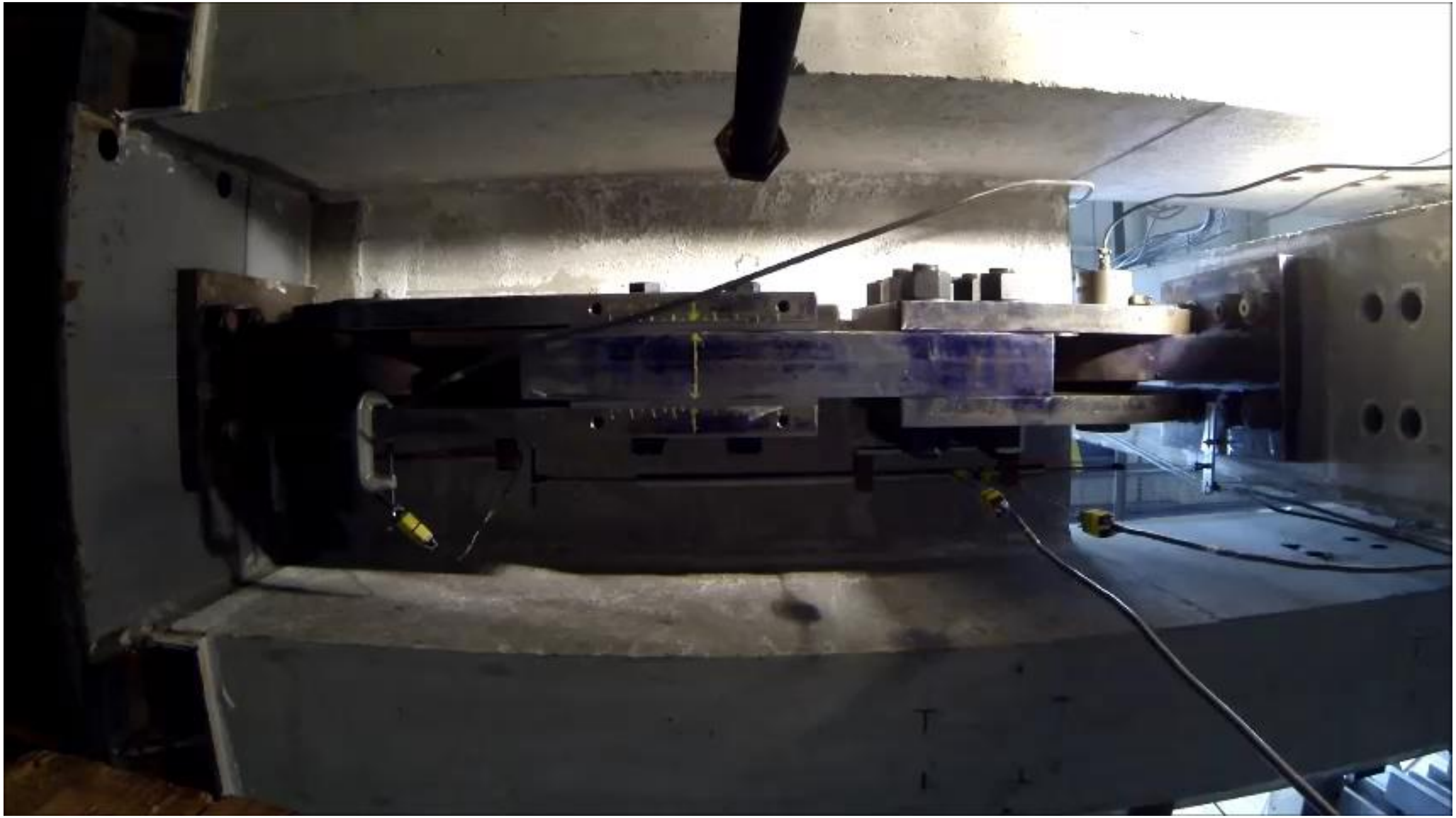
Half-Scale 4-story Precast Rocking Shear Wall Structure Tested at UCSD



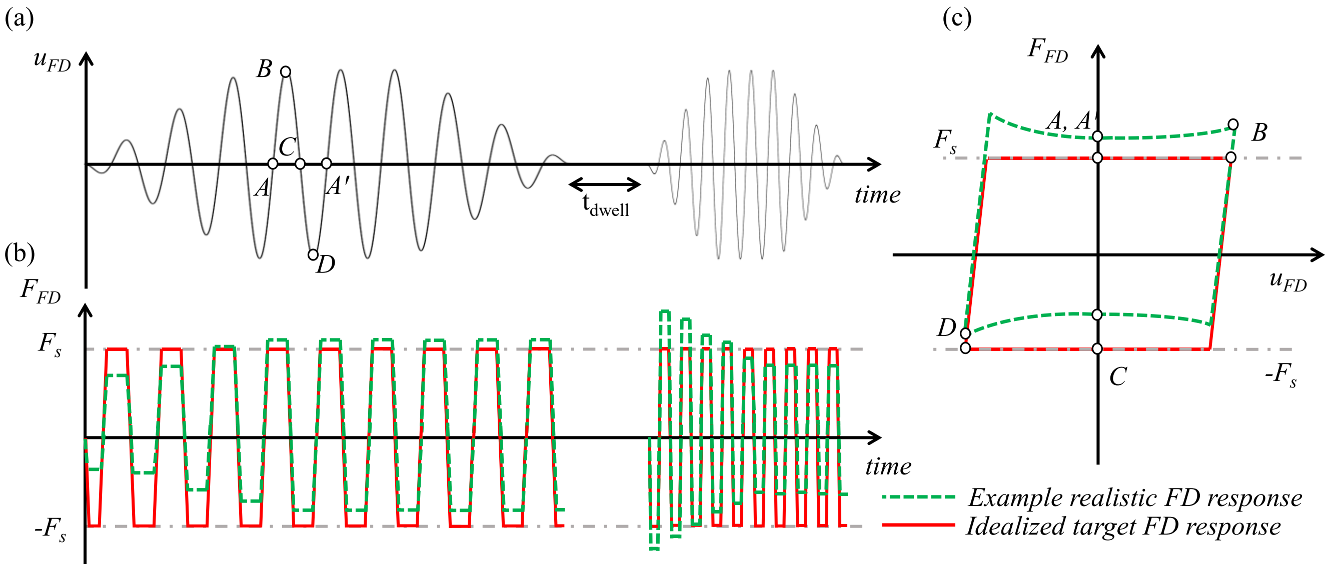
Zhang, Z., Fleischman, R., Restrepo, J., Nema, A., Zhang, D., Guerrini G. Shakya, U., Tsampras, G., and Sause, R., "Shake Table Test Performance of an Inertial Force-Limiting Floor Anchorage System," Journal of Earthquake Engineering and Structural Dynamics 2018

Characterization of Force-Limiting Friction Device for Floors

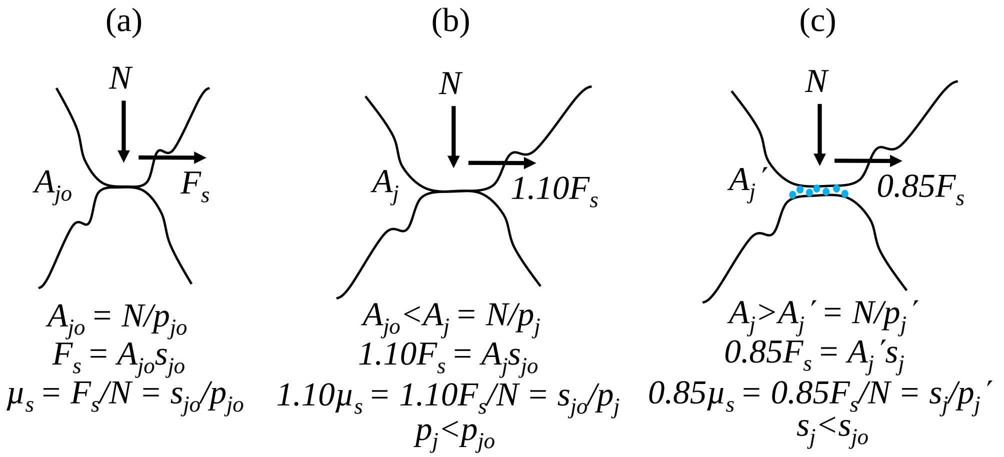
Tsampras, G., Sause, R., Fleischman, R.B., and Restrepo, J.I., "Experimental Study of Deformable Connection Consisting of Friction Device and Rubber Bearings to Connect Floor System to Lateral Force Resisting System," Journal of Earthquake Engineering and Structural Dynamics, 2018

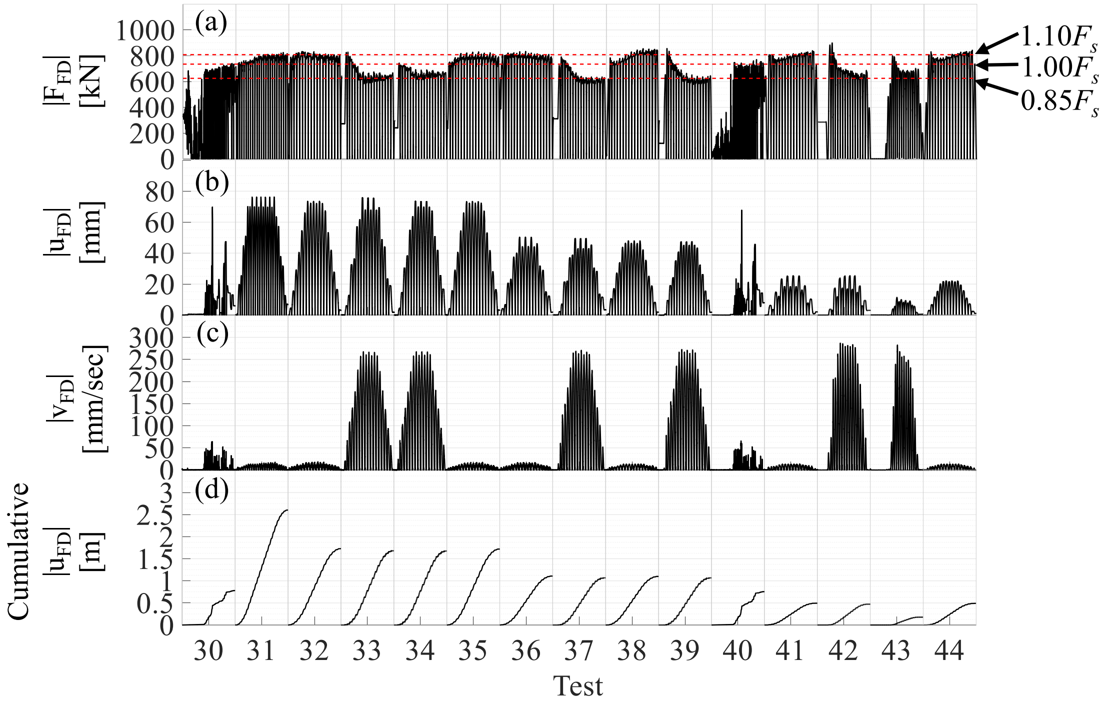


Characterization of Force-Limiting Friction Device for Floors



Interesting Variations from Expected Response from Simple Model





Tsampras, G., Sause, R., Fleischman, R.B., and Restrepo, J.I., "Experimental Study of Deformable Connection Consisting of Friction Device and Rubber Bearings to Connect Floor System to Lateral Force Resisting System," Journal of Earthquake Engineering and Structural Dynamics, 2018

Characterization of Dampers and Other Devices

- Use characterization tests to validate or improve force-deformation response of devices
- Establish sensitivity to deformation amplitude, loading frequency, temperature
- Determine parameters for simple force-deformation response models (e.g., for design)
- Understand physical limits of devices (when do they degrade or fail?)
- Develop accurate force-deformation hysteretic response models for nonlinear time-history analyses (numerical simulations)
- Use variations in force-deformation response from simple models to understand detailed behavior of devices… …pay attention to details of differences
- Much easier to understand these variations from simple device tests (rather than tests of systems with devices)

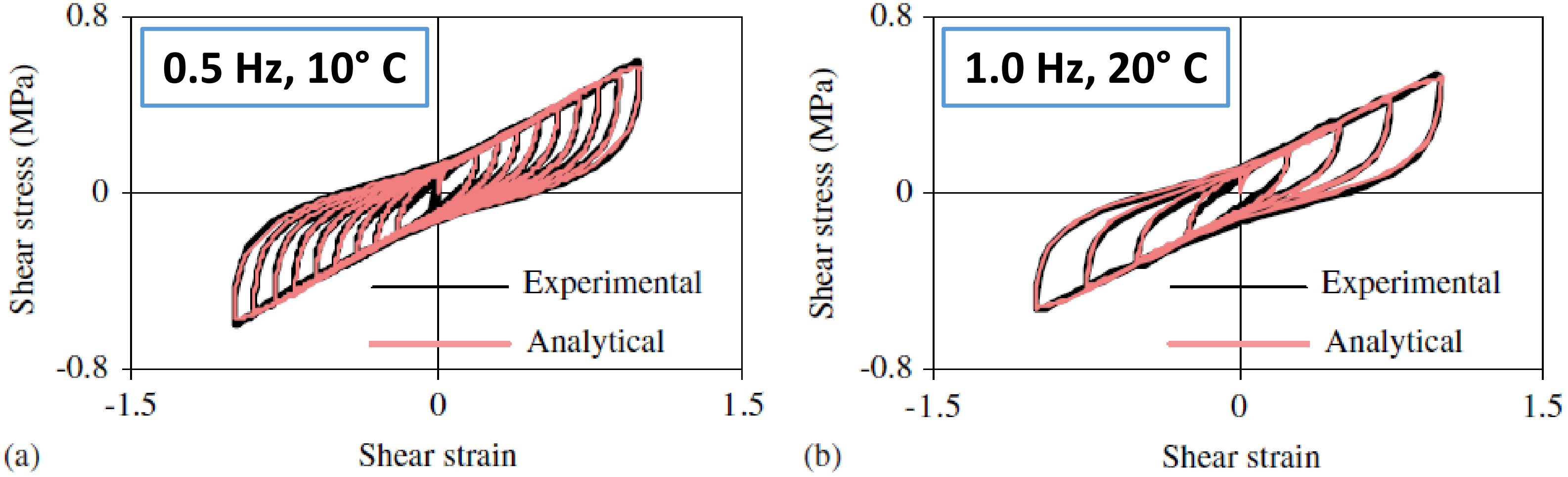
Challenges in Achieving Seismic Hazard Mitigation Using Dampers and Other Devices: Overview of Topics

- Characterization of Devices: Testing and Models
  - Focus on characterization tests and models of dampers and other devices
- **Modeling and Understanding Systems with Dampers**
  - Simple models for design and to understand system/damper response
  - Accurate models for numerical simulations
- Response of Systems with Dampers During Hazard Events
  - Real-time hybrid simulations of seismic response of systems with dampers
- Hazard Mitigation Performance of Systems with Dampers
  - Seismic performance of systems with dampers
- Summary of Issues and Thoughts Suggested by Lab Experiences

Modeling and Understanding of Systems with Dampers

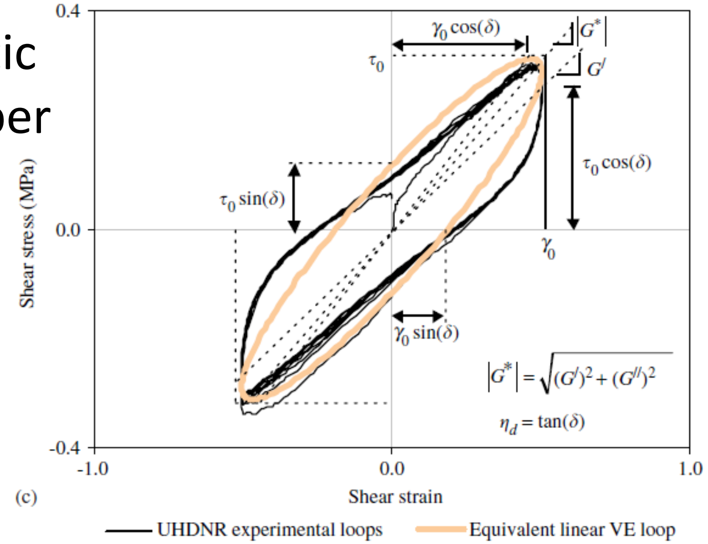
- Purpose is to understand how dampers and other devices interact with structural system
- In this presentation, focus on MRF systems with added dampers
  - There is a need for new systems to better utilize dampers, but use MRF to understand a simpler system first
- Modeling of system with dampers:
  - Simple models for design calculations
  - Accurate models for nonlinear time-history analyses (numerical simulations)
- Investigate response of system with dampers:
  - Estimate effective stiffness, period, damping of system with dampers
  - Effect of flexibility within force path of dampers – “brace stiffness”
  - Effect of dampers on overall system stiffness and period

Models for Elastomeric Damper



Characterization test data and accurate numerical model for elastomeric damper

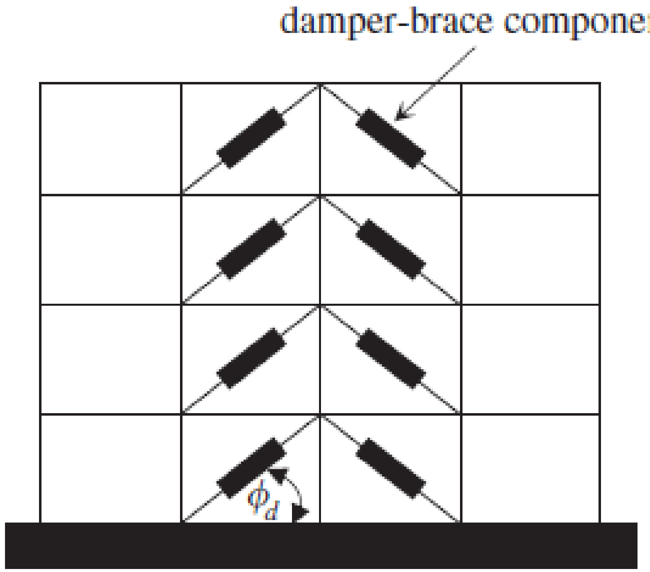
Simple equivalent viscoelastic model for elastomeric damper



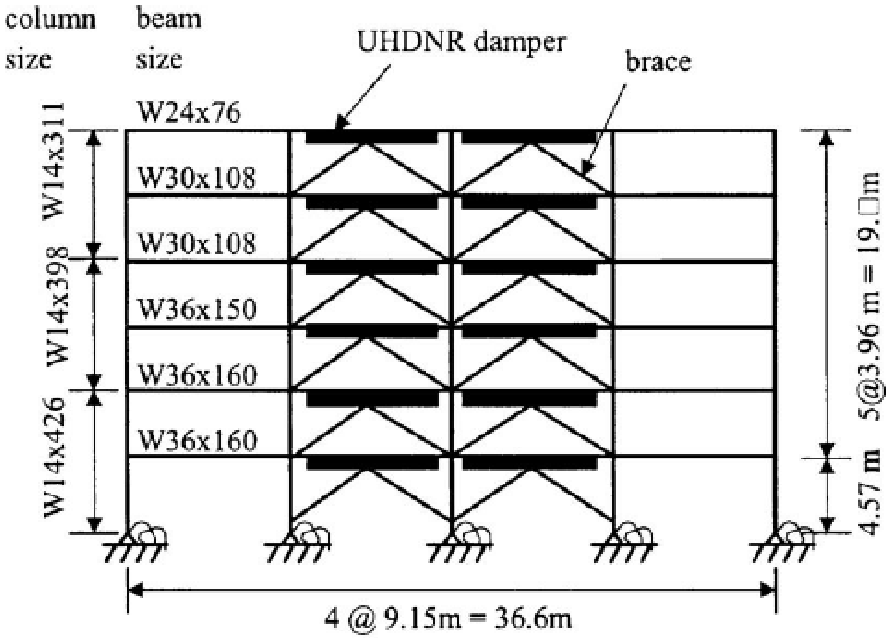
Lee, K.-S., Fan, C.-P., Sause, R., and Ricles, J., "Simplified Design Procedure for Frame Buildings with Viscoelastic or Elastomeric Dampers," Journal of Earthquake Engineering and Structural Dynamics, 2005.

Models for MRF System with Elastomeric Damper

Important to note that dampers do not extend from floor-to-floor without elastic components that are in series with dampers. Essential that elastic components (“bracing”) are included in models



(a)



(a) Steel MRF building

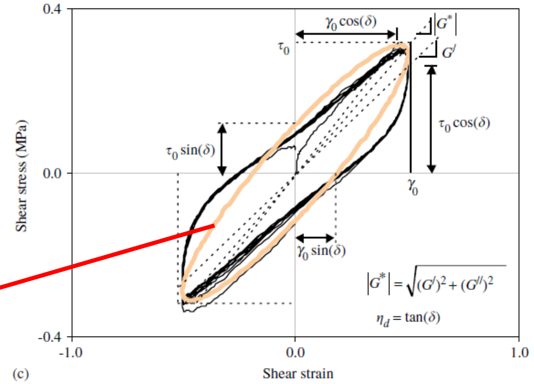
Simplified MRF system model with damper and brace modeled together as damper-brace component

Accurate model for MRF system with elastomeric dampers including model for bracing and accurate model for dampers

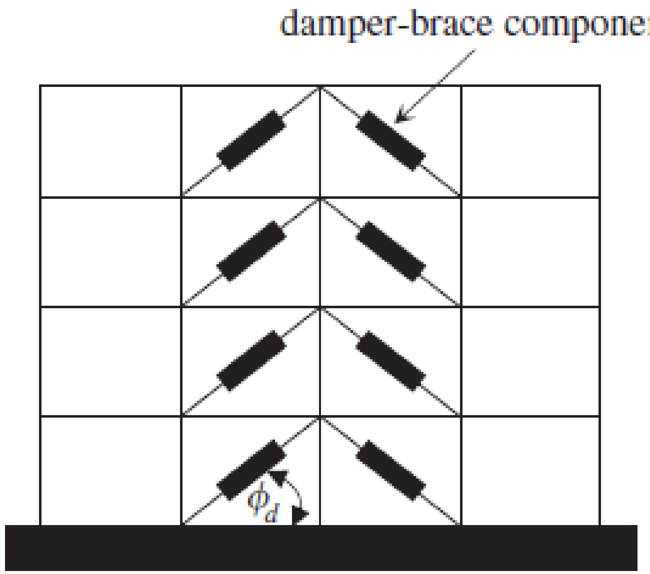
Lee, K.-S., Fan, C.-P., Sause, R., and Ricles, J., "Simplified Design Procedure for Frame Buildings with Viscoelastic or Elastomeric Dampers," Journal of Earthquake Engineering and Structural Dynamics, 2005.

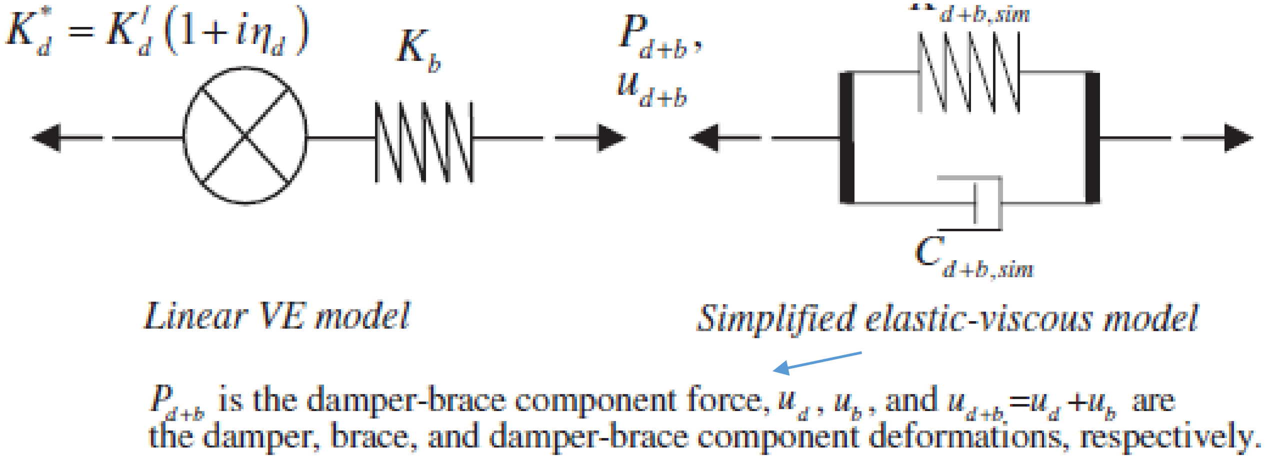
Models for MRF System with Elastomeric Damper

Simple models for design calculations and understanding system response



Viscoelastic model for damper





(a) (b)

Simplified MRF system model with damper and brace modeled together as damper-brace component

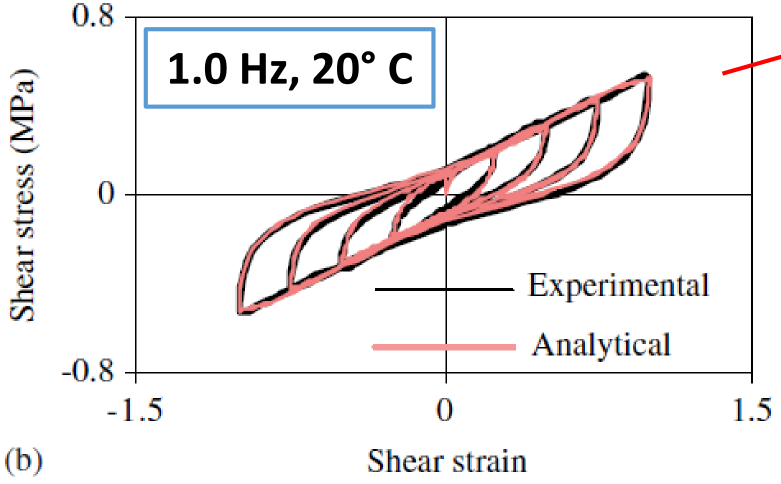
Possible models for damper-brace component: linear viscoelastic model; elastic-viscous (parallel model)

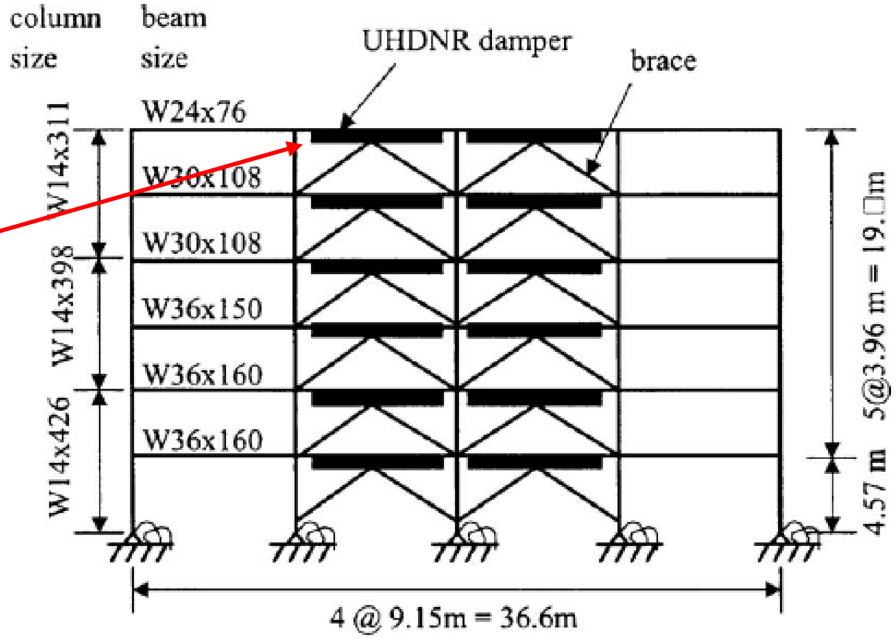
Lee, K.-S., Fan, C.-P., Sause, R., and Ricles, J., "Simplified Design Procedure for Frame Buildings with Viscoelastic or Elastomeric Dampers," Journal of Earthquake Engineering and Structural Dynamics, 2005.

Models for MRF System with Elastomeric Damper

Accurate models for nonlinear time-history analyses (numerical simulations)

Accurate numerical model for elastomeric damper





(a) Steel MRF building

Accurate model for MRF system with elastomeric dampers including model for bracing and accurate model for dampers

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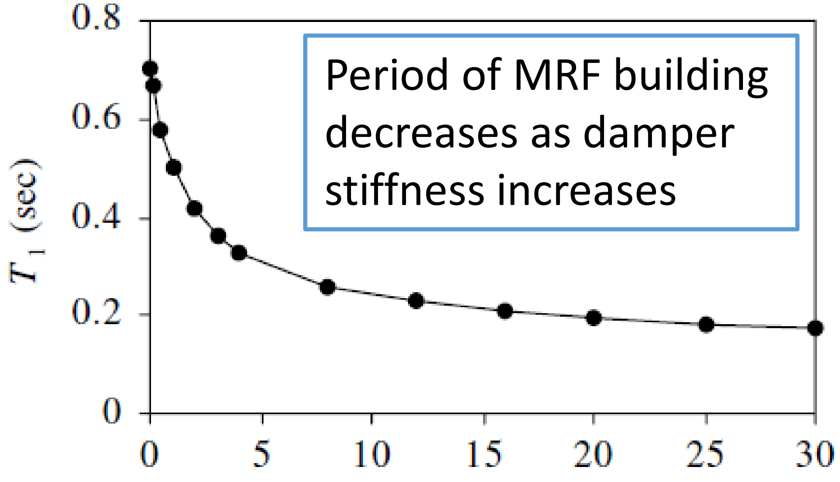
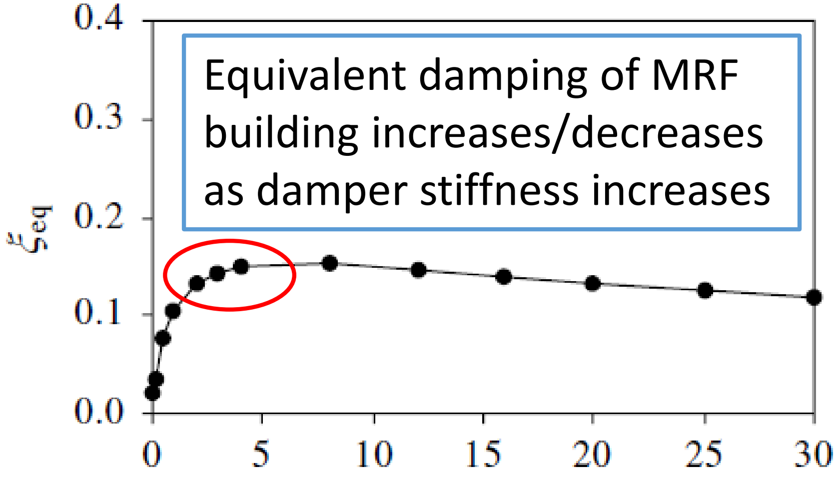
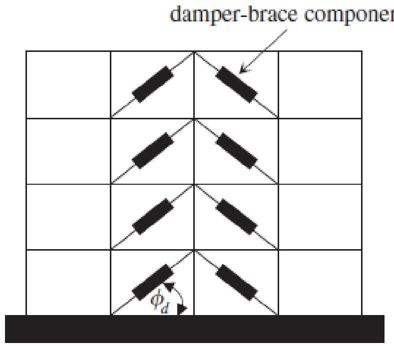
Models for MRF System with Elastomeric Damper

Results from simple models for design





Results suggest an optimal size (stiffness) of elastomeric (or viscoelastic) damper, considering period reduction and equivalent damping



β →

β →

Increasing size of damper, expressed as increasing ratio of damper stiffness to MRF story stiffness

$$\beta = {k'_d}/{k_o}$$

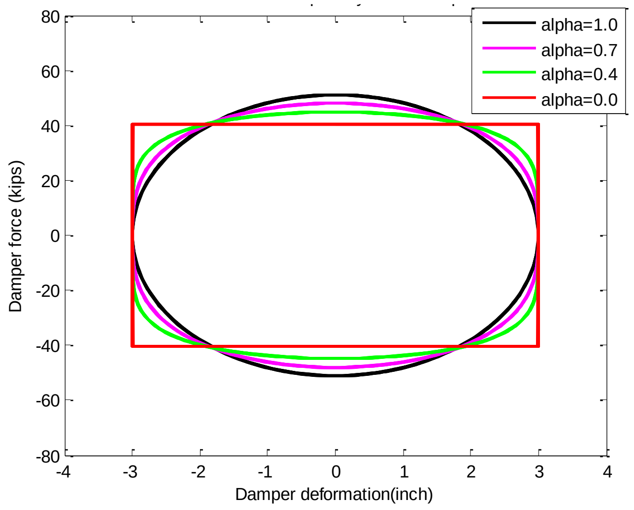
k'_d = damper stiffness
k_o = MRF story stiffness

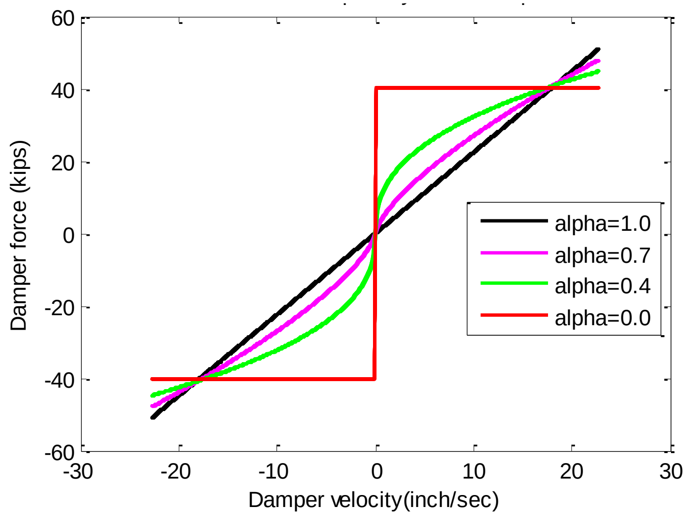
Lee, K.-S., Fan, C.-P., Sause, R., and Ricles, J., "Simplified Design Procedure for Frame Buildings with Viscoelastic or Elastomeric Dampers," Journal of Earthquake Engineering and Structural Dynamics, 2005.

Models for Nonlinear Viscous Damper

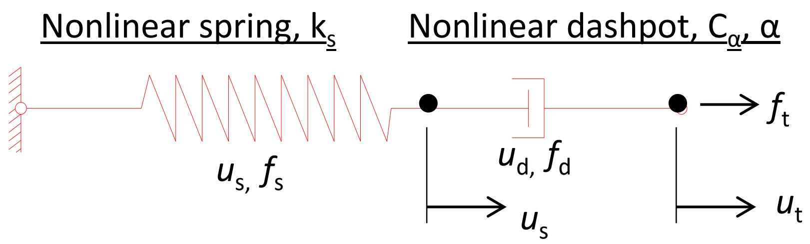
Simple Model

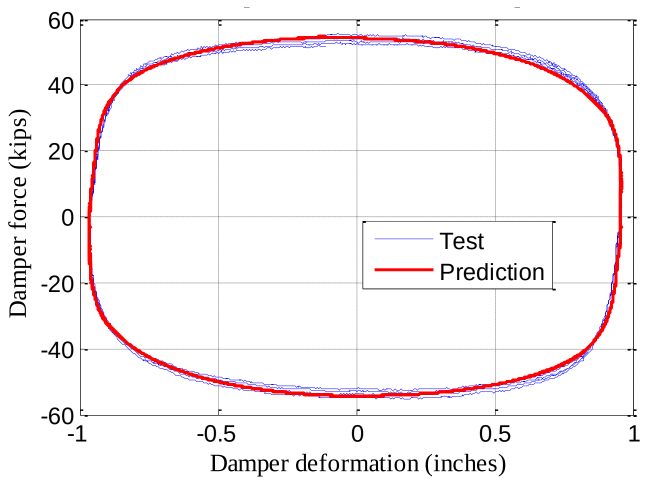
$$f_d = C_\alpha (v)^\alpha$$

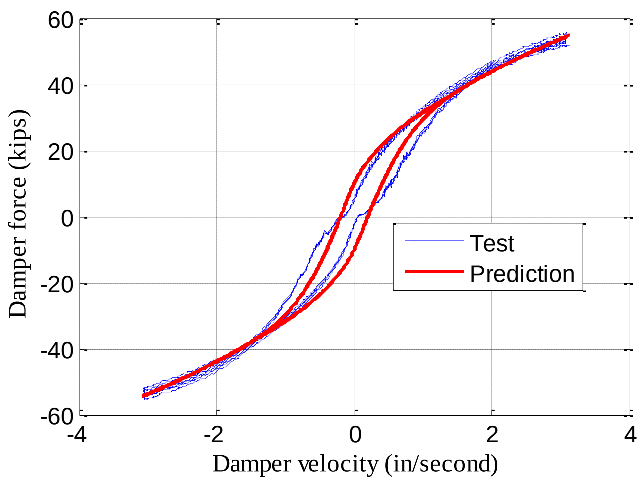




Nonlinear Maxwell Model



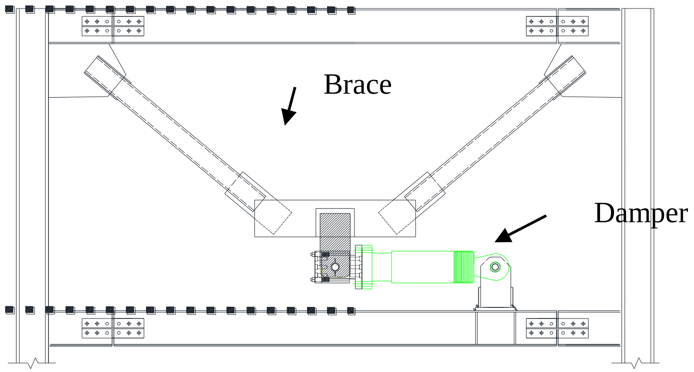


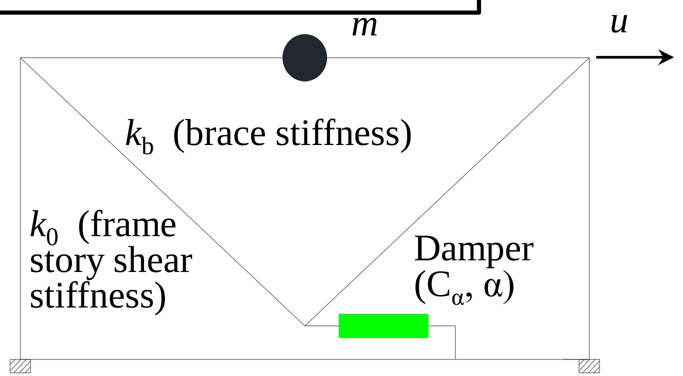


Models for MRF System with Nonlinear Viscous Damper

Simple models for design calculations and understanding system response

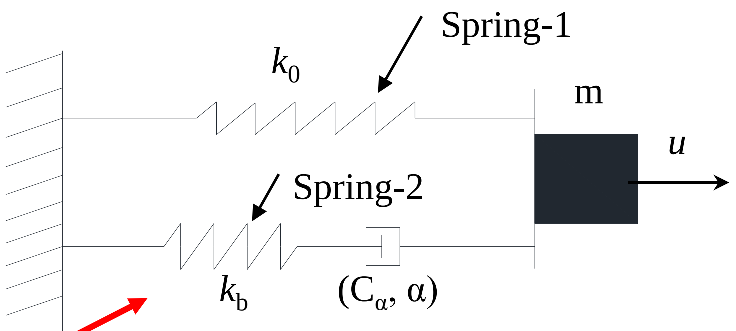
Single story treated as SDOF





Define "brace" stiffness k_b which includes all flexibility in damper force path from mass to mass (or fixed restraint):

- Flexibility of brace
- Axial flexibility of beams and columns
- Flexibility due to eccentricity of damper force
- Flexibility in the damper-brace connection
- Flexibility in the damper-beam connection



Model of SDOF system

damper-brace component

Dong, B., "Large-scale experimental, numerical, and design studies of steel MRF structures with nonlinear viscous dampers under seismic loading", PhD Dissertation, Lehigh University, 2015.

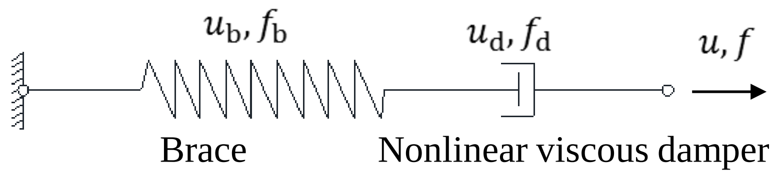
Models for MRF System with Nonlinear Viscous Damper

Simple models for design calculations and understanding system response

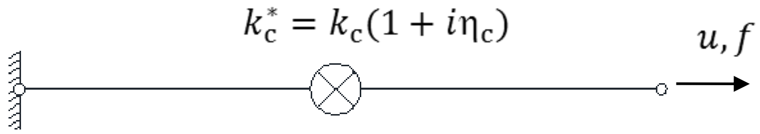
Sequence of models for equivalent linearization of damper-brace component

Equivalent linearization of damper-brace component

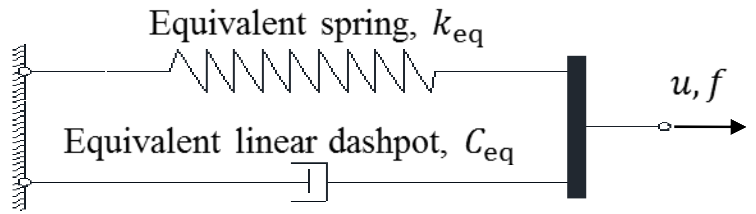
(a) Damper-brace component



(b) Equivalent viscoelastic model



(c) Equivalent elastic-viscous model



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Models for MRF System with Nonlinear Viscous Damper

Simple models for design calculations and understanding system response

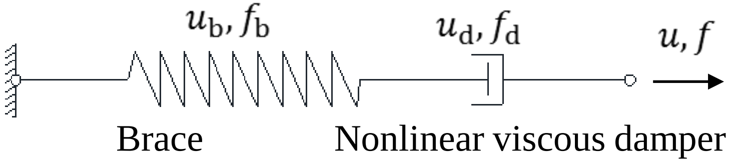
Damper-brace component stiffness

$$f_{\mathrm{d}}(i\omega) = iC_{\alpha}\omega^{\alpha}(u_{\mathrm{d}}(i\omega))^{\alpha}$$

Damper stiffness in frequency domain:

$$\boxed{k_{\mathrm{d}}(i\omega) = iC_{\alpha}\omega^{\alpha}(u_{\mathrm{d}}(i\omega))^{\alpha-1}}$$

$$f_{\mathrm{d}}(i\omega) = k_{\mathrm{d}}(i\omega)\cdot u_{\mathrm{d}}(i\omega)$$



(a) Damper-brace component

Combined stiffness for damper-brace component:

$$k_{\mathrm{c}}^{*}(i\omega) = \frac{1}{\dfrac{1}{k_{\mathrm{b}}} + \dfrac{1}{k_{\mathrm{d}}(i\omega)}}$$

$$= \frac{\left(C_{\alpha}\omega^{\alpha}(u_{\mathrm{d}}(i\omega))^{\alpha-1}\right)^2}{\left(C_{\alpha}\omega^{\alpha}(u_{\mathrm{d}}(i\omega))^{\alpha-1}\right)^2 + (k_{\mathrm{b}})^2} k_{\mathrm{b}} + i\frac{\left(C_{\alpha}\omega^{\alpha}(u_{\mathrm{d}}(i\omega))^{\alpha-1}\right)}{\left(C_{\alpha}\omega^{\alpha}(u_{\mathrm{d}}(i\omega))^{\alpha-1}\right)^2 + (k_{\mathrm{b}})^2} k_{\mathrm{b}}^2$$

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Models for MRF System with Nonlinear Viscous Damper

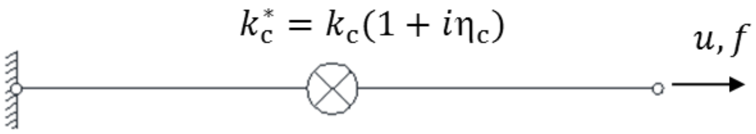
Simple models for design calculations and understanding system response

Equivalent viscoelastic model of damper-brace component

$$k_c^*(i\omega) = k_c(i\omega)\left(1 + i\eta_c(i\omega)\right)$$

$$k_c(i\omega) = \frac{\left(C_\alpha \omega^\alpha (u_d(i\omega))^{\alpha-1}\right)^2}{\left(C_\alpha \omega^\alpha (u_d(i\omega))^{\alpha-1}\right)^2 + (k_b)^2} k_b$$

$$\eta_c(i\omega) = \frac{k_b}{C_\alpha \omega^\alpha (u_d(i\omega))^{\alpha-1}}$$



(b) Equivalent viscoelastic model

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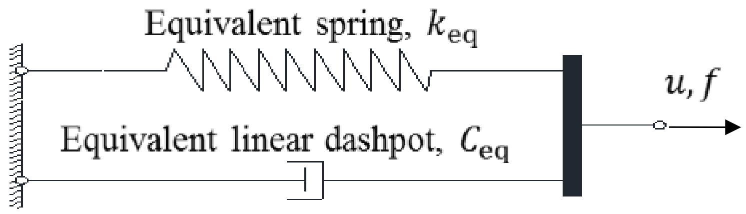
Models for MRF System with Nonlinear Viscous Damper

Simple models for design calculations and understanding system response

Equivalent linear elastic-viscous model for damper-brace component

Equivalent frequency-dependent linear spring stiffness for damper-brace component

$$k_{\mathrm{eq}} = k_{\mathrm{c}}(i\omega_{\mathrm{s}}) = \frac{\left(C_\alpha \omega_{\mathrm{s}}^{\alpha} (u_{\mathrm{ds}})^{\alpha-1}\right)^2}{\left(C_\alpha \omega_{\mathrm{s}}^{\alpha} (u_{\mathrm{ds}})^{\alpha-1}\right)^2 + (k_{\mathrm{b}})^2} k_{\mathrm{b}}$$



(c) Equivalent linear elastic-viscous model

Equivalent frequency-dependent linear dashpot dissipates same energy at given frequency

$$C_{\mathrm{eq}} = \frac{k_{\mathrm{c}}(i\omega_{\mathrm{s}})\eta_{\mathrm{c}}(i\omega_{\mathrm{s}})}{\omega_{\mathrm{s}}} = \frac{C_\alpha \omega_{\mathrm{s}}^{\alpha-1} (u_{\mathrm{ds}})^{\alpha-1}}{\left(C_\alpha \omega_{\mathrm{s}}^{\alpha} (u_{\mathrm{ds}})^{\alpha-1}\right)^2 + (k_{\mathrm{b}})^2} k_{\mathrm{b}}^2$$

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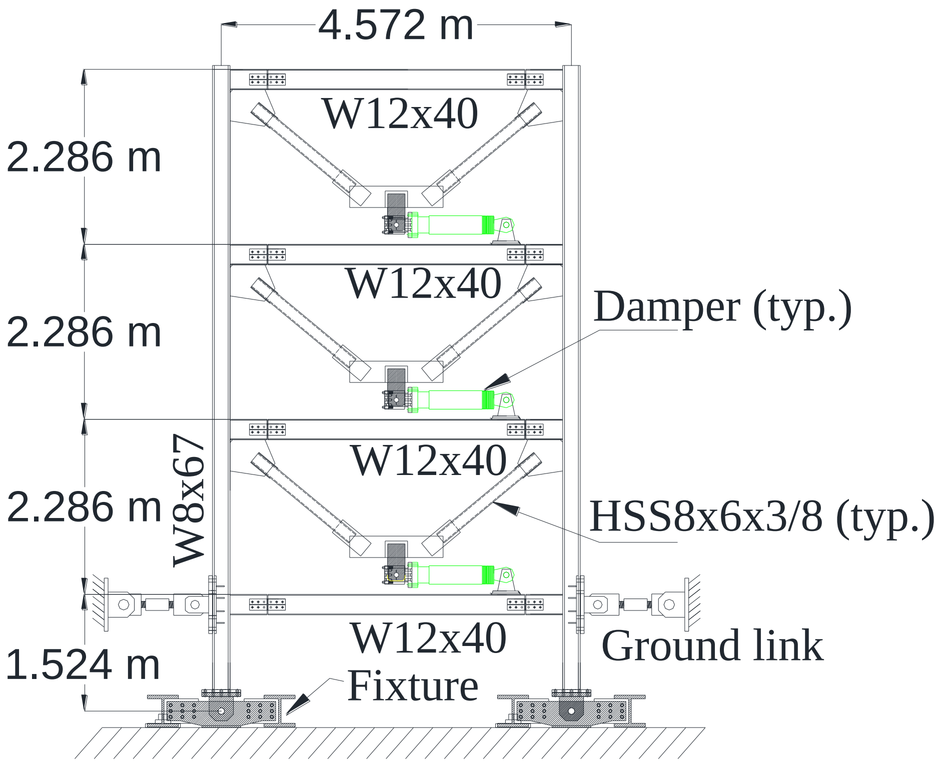
Models for MRF System with Nonlinear Viscous Damper

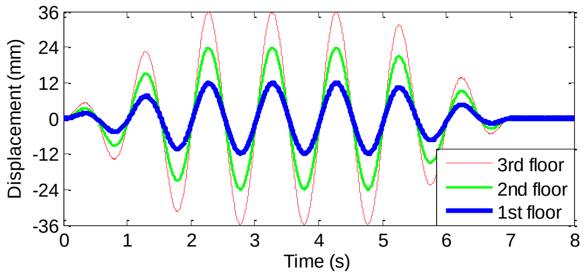
Simple models for design calculations and understanding system response

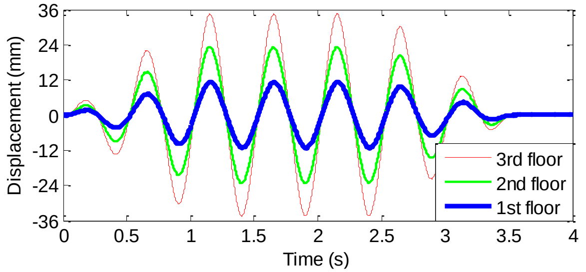
Validation of equivalent linear elastic-viscous model for damper-brace component

Test structure with nonlinear viscous dampers



Harmonic loading tests with predefined floor displacements





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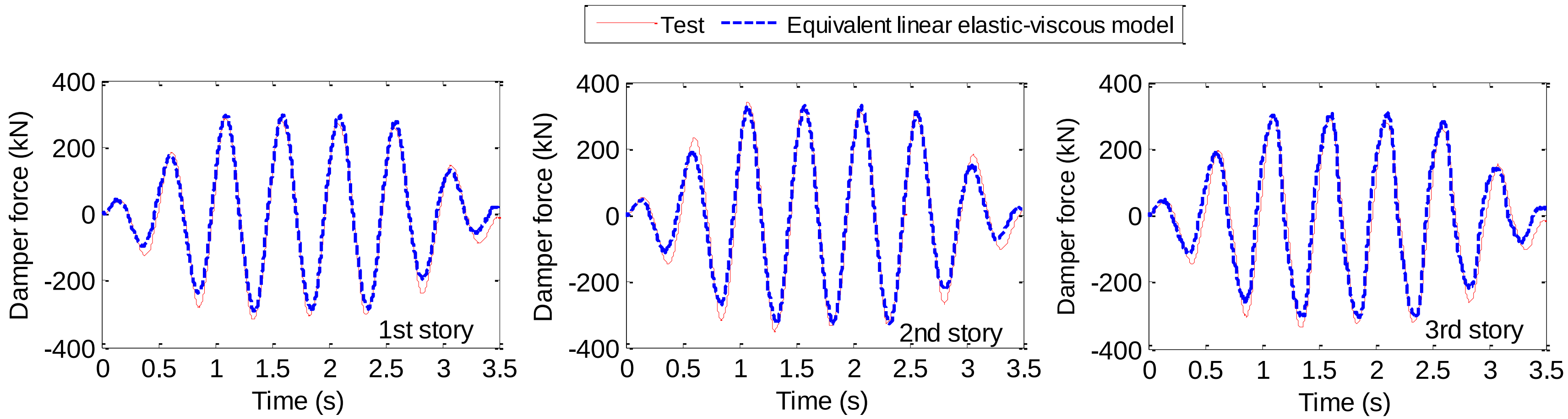
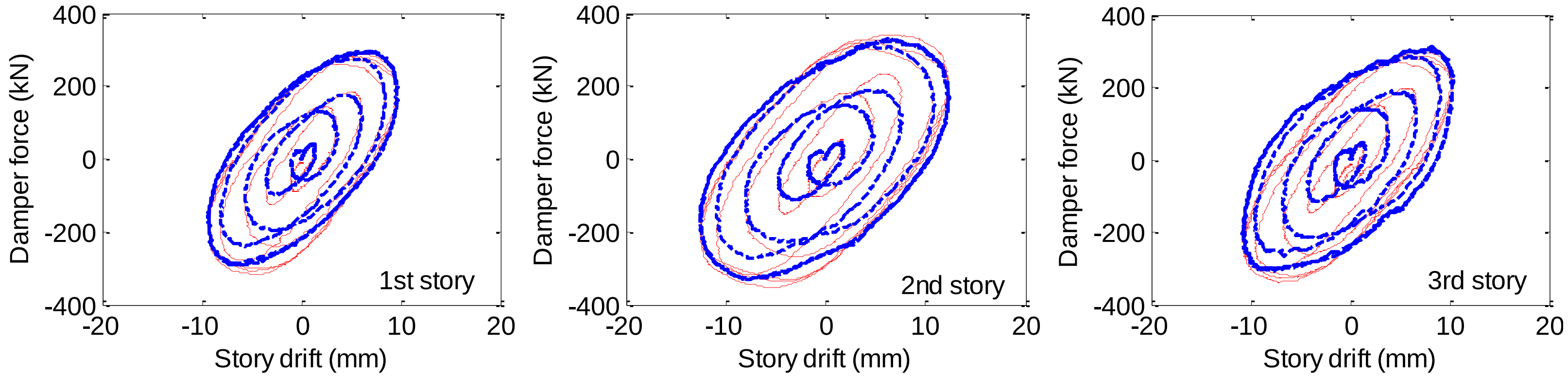
Models for MRF System with Nonlinear Viscous Damper

Simple models for design calculations and understanding system response

Validation of equivalent linear elastic-viscous model for damper-brace component



Comparison of damper force time histories



Comparison of damper force-story drift hysteresis behavior

Dong, B., "Large-scale experimental, numerical, and design studies of steel MRF structures with nonlinear viscous dampers under seismic loading", PhD Dissertation, Lehigh University, 2015.

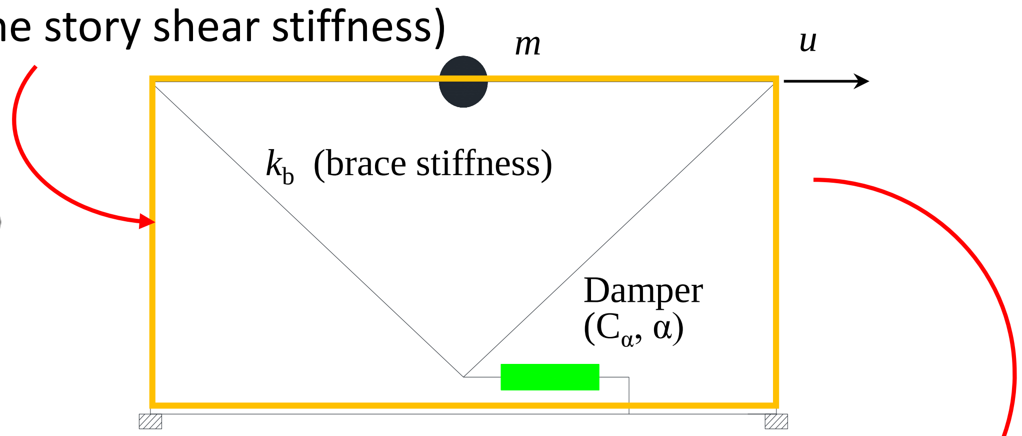
Models for MRF System with Nonlinear Viscous Damper

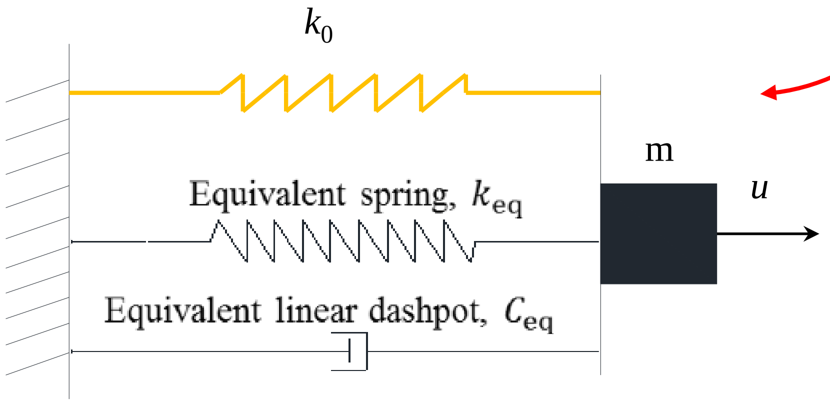
Simple models for design calculations and understanding system response

Combined system model using equivalent linear elastic-viscous model for damper-brace component

$$k_{\text{eff}} = k_0 + k_{\text{eq}}$$
$$= k_0 + \frac{\left(C_\alpha \omega_s^\alpha (u_{\text{ds}})^{\alpha-1}\right)^2}{\left(C_\alpha \omega_s^\alpha (u_{\text{ds}})^{\alpha-1}\right)^2 + (k_b)^2} k_b$$

$$\xi_{\text{eff}} = \frac{C_{\text{eq}}}{2m\omega_{\text{eff}}} = \frac{\eta_c}{2} \frac{k_{\text{eq}}}{k_{\text{eff}}} \frac{\omega_{\text{eff}}}{\omega_s}$$





Effective stiffness and damping of combined system by combining equivalent linear elastic-viscous model of damper-brace component with linear story shear stiffness of frame (k_0)

Dong, B., “Large-scale experimental, numerical, and design studies of steel MRF structures with nonlinear viscous dampers under seismic loading”, PhD Dissertation, Lehigh University, 2015.

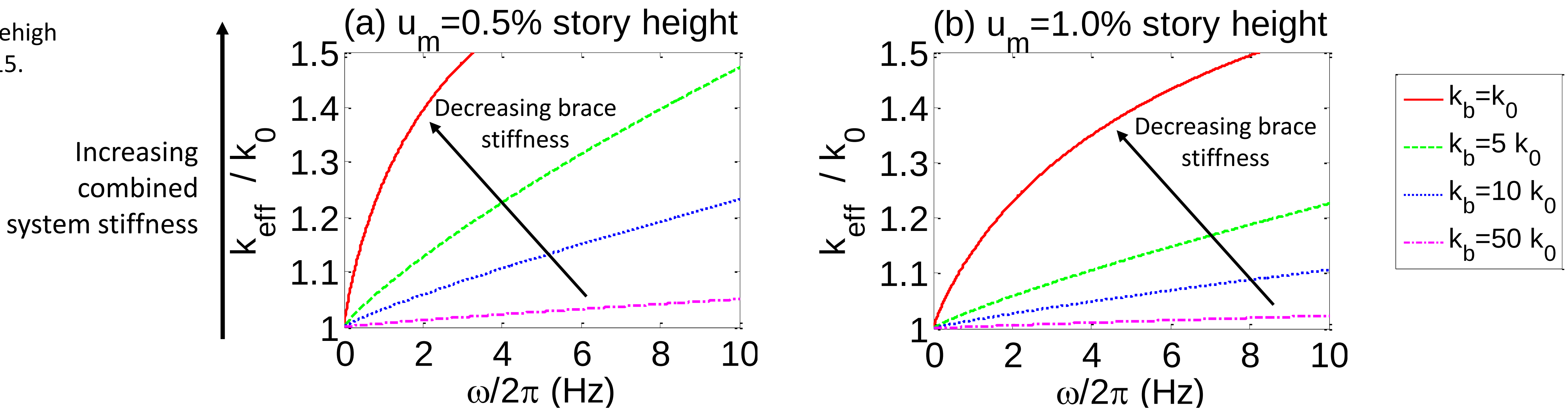
Models for MRF System with Nonlinear Viscous Damper

Simple models for design calculations and understanding system response

Combined system model using equivalent linear elastic-viscous model for damper-brace component

Dong, B., "Large-scale experimental, numerical, and design studies of steel MRF structures with nonlinear viscous dampers under seismic loading", PhD Dissertation, Lehigh University, 2015.

- Normalized stiffness of MRF with damper-brace component k_{eff}/k_0 <u>increases with decreased brace stiffness</u> and increases with increased loading frequency
- For rigid bracing (i.e., $k_b/k_0 \rightarrow \infty$), k_{eff}/k_0 is approximately 1.0, so combined system stiffness is only the story shear stiffness
- k_{eff}/k_0 decreases with increasing story drift amplitude



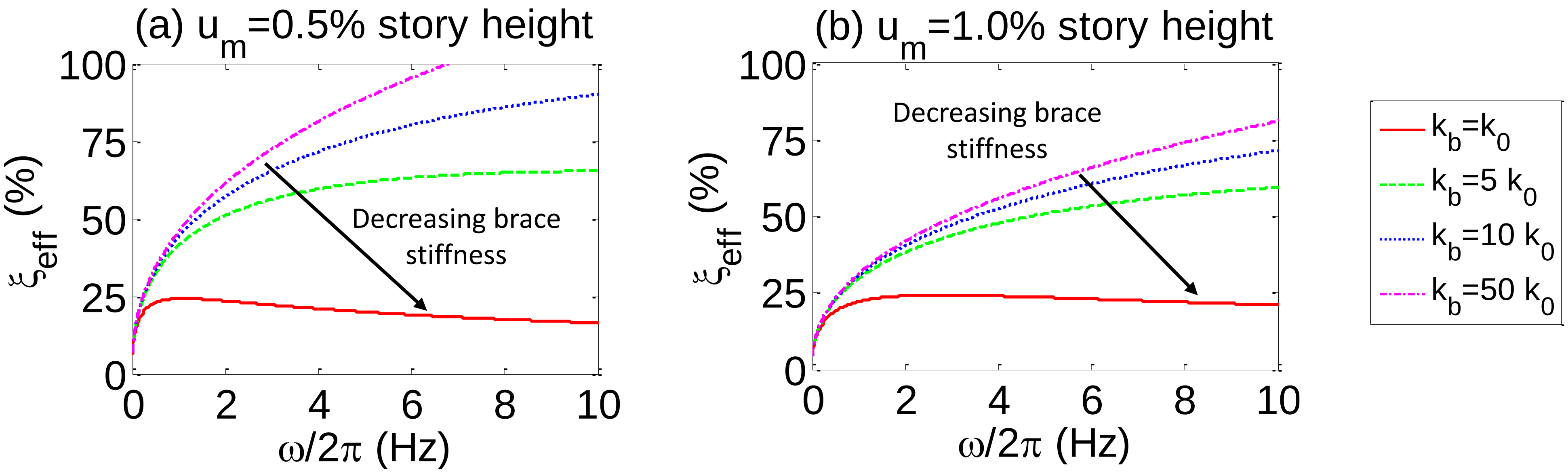
Models for MRF System with Nonlinear Viscous Damper

Simple models for design calculations and understanding system response

Combined system model using equivalent linear elastic-viscous model for damper-brace component

- Effect of brace stiffness on effective damping of system ξ_{eff} increases with increasing frequency;
- Effect of brace stiffness on effective damping of system ξ_{eff} decreases with increasing story drift amplitude.

Dong, B., "Large-scale experimental, numerical, and design studies of steel MRF structures with nonlinear viscous dampers under seismic loading", PhD Dissertation, Lehigh University, 2015.



Modeling and Understanding of MRF System with Dampers

- Simple models of dampers within MRF system used to understand effective stiffness, period, and damping of combined system
- Elastomeric (and viscoelastic) dampers have quantifiable stiffness (often amplitude-dependent and frequency-dependent), and comparing damper stiffness with MRF story stiffness suggests appropriate damper size in preliminary seismic design
- Equivalent linearized models of nonlinear viscous damper-brace component within an MRF are useful to understand effective stiffness and damping of combined system, and for preliminary seismic design
- Effects of elastic flexibility of bracing that transmits damper forces are considered in damper-brace component model; modeling this flexibility is critical, since viscous damper in series with non-rigid bracing (damper-brace component) is actually viscoelastic
- Equivalent linear elastic-viscous model for damper-brace component was validated using test results for MRF with dampers in laboratory under predefined harmonic displacement histories
- Analytical results show that more flexible bracing (decreasing brace stiffness) within damper force path actually increases the stiffness of the structure and decreases the equivalent damping ratio

Challenges in Achieving Seismic Hazard Mitigation Using Dampers and Other Devices: Overview of Topics

- Characterization of Devices: Testing and Models
  - Focus on characterization tests and models of dampers and other devices
- Modeling and Understanding Systems with Dampers
  - Simple models for design and to understand system/damper response
  - Accurate models for numerical simulations
- **Response of Systems with Dampers During Hazard Events**
  - Real-time hybrid simulations of seismic response of systems with dampers
- Hazard Mitigation Performance of Systems with Dampers
  - Seismic performance of systems with dampers
- Summary of Issues and Thoughts Suggested by Lab Experiences

Response of Systems with Dampers During Seismic Hazard Events

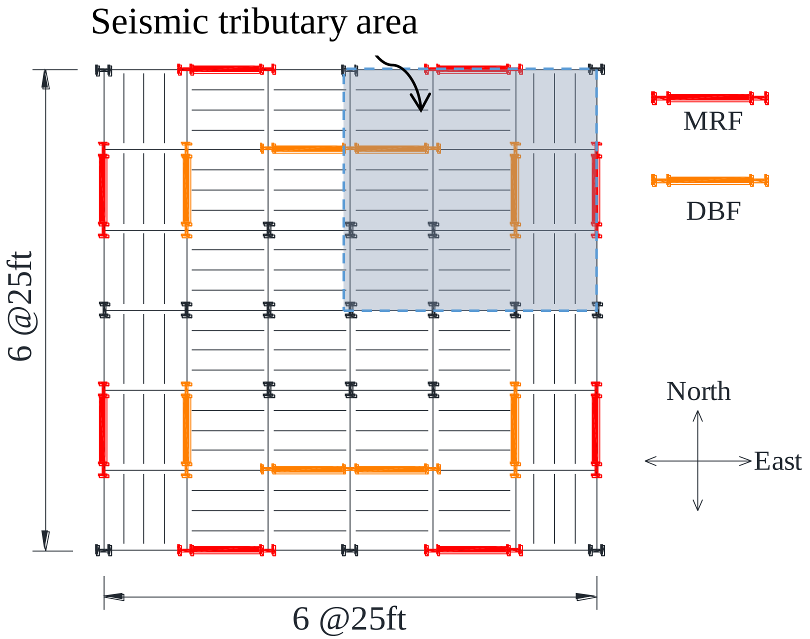
- Purpose is to understand and quantify response of system with dampers (or other devices) under hazard events
- Methods generally include:
  - Numerical simulations using accurate force-deformation hysteretic response models (developed from characterization work)
  - Real-time hybrid simulations
  - Shake table tests
- In this presentation, focus on example study of MRF with nonlinear viscous dampers:
  - Use of real-time hybrid simulations (RTHS, Phase-1 and Phase-2), since at NHERI workshop; numerical simulations were also performed and results available in cited papers
  - Accuracy of RTHS
  - Quantification of response and comparison with expected results
  - Demonstrate the effect of flexibility in force path of dampers, so-called “brace stiffness”

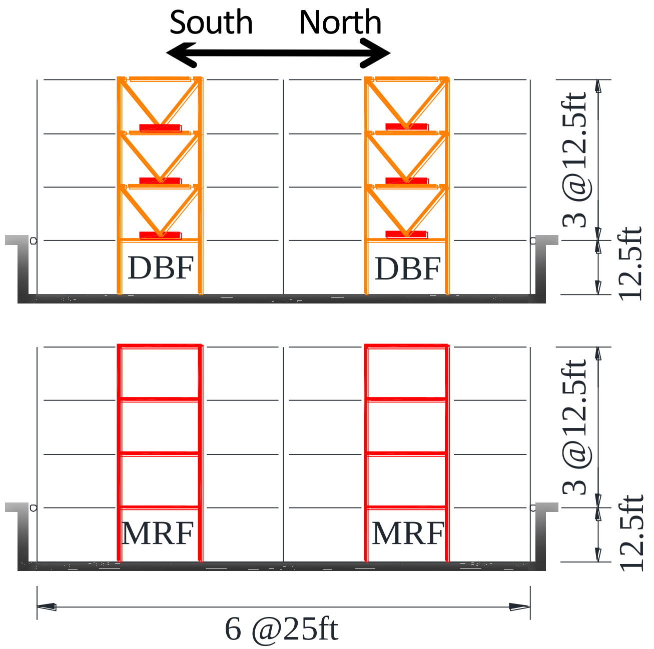
Moment-Resisting Frame Building Structure with Nonlinear Viscous Dampers: Prototype Building

Prototype building

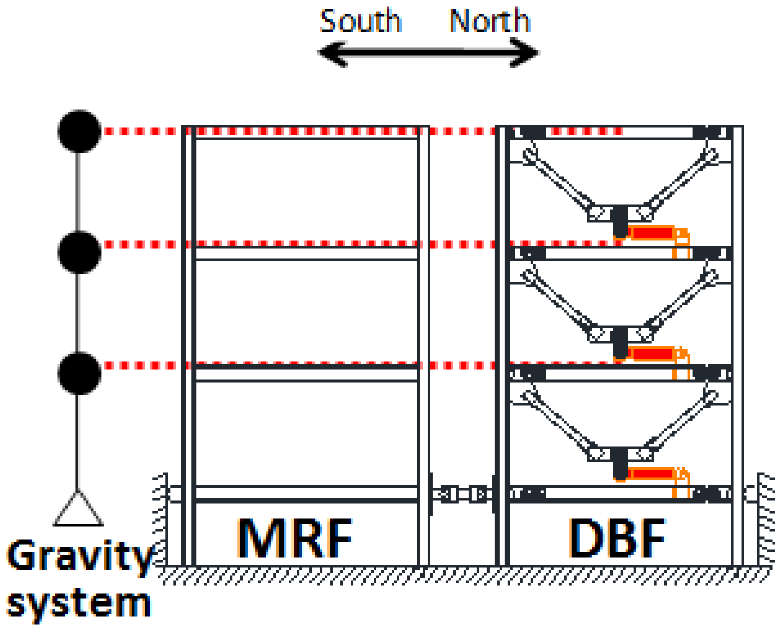
— 3-story, 6-bay by 6-bay office building assumed to be in Southern California

— Moment resisting frame (MRF), damped brace frame (DBF), gravity load system, inherent damping of building





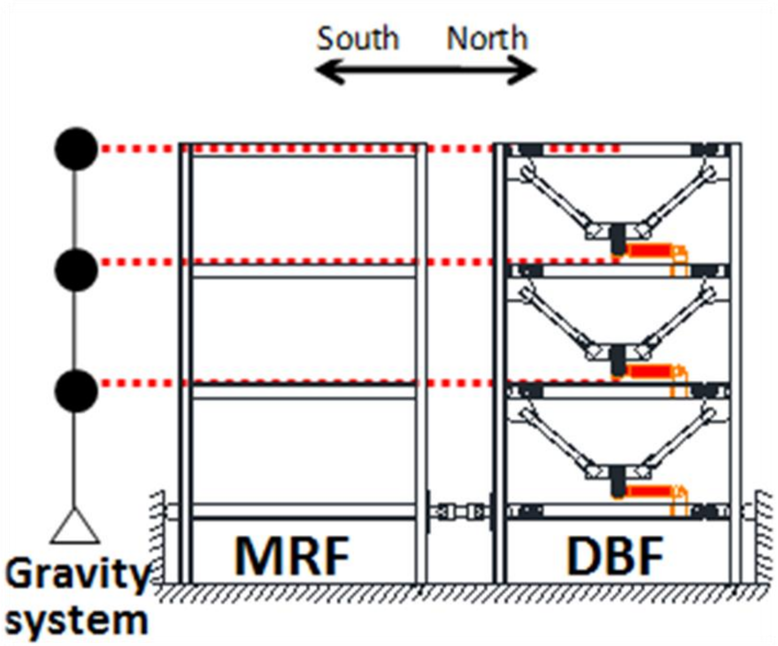
Model for Analysis and Testing



Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Moment-Resisting Frame Building Structure with Nonlinear Viscous Dampers: Full Strength MRF

- Design of prototype building (MRF, DBF)
  - —MRF (D100V) is designed to satisfy strength requirement in ASCE 7-10
  - —MRF is not designed to meet drift requirement in ASCE7-10, story drifts will be controlled by dampers in DBF
  - —DBF is designed to remain elastic under the design basis earthquake (DBE), with 10% probability of exceedance in 50 yrs
- With (3) 600 kN dampers (C_{α} = 696 kN-s/m and α = 0.44) predicted story drift was 0.8% for the DBE, and 1.4% for the maximum considered earthquake (MCE - 2% probability of exceedance in 50 yr)

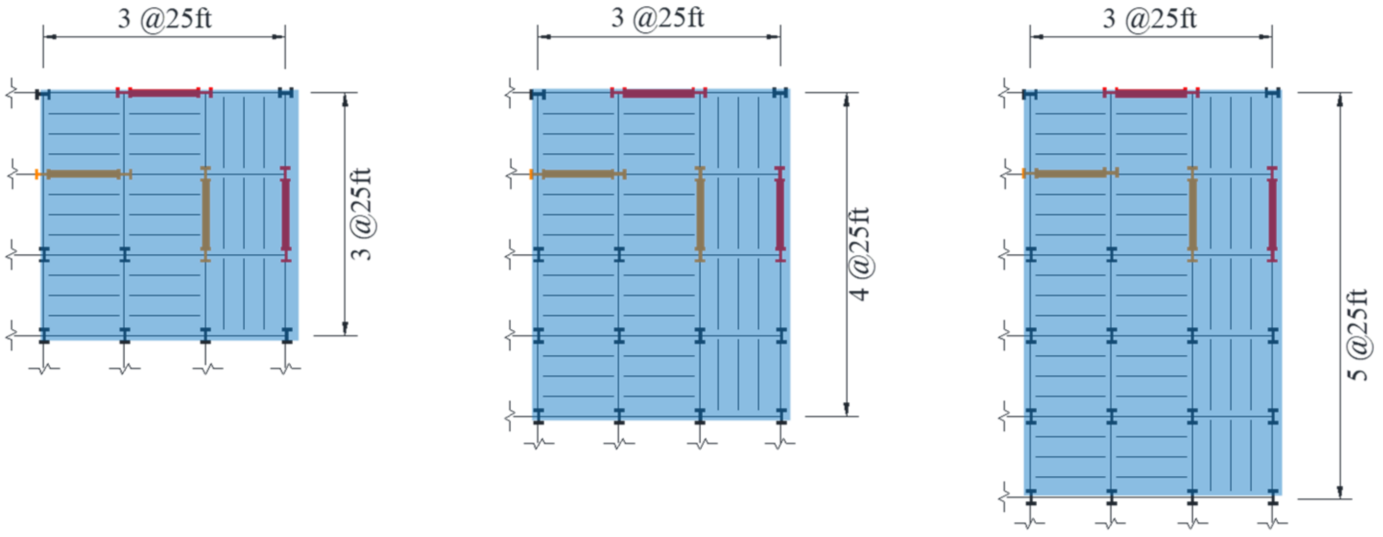


Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Variations of Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers: Reduced Strength MRFs

Using real-time hybrid simulation (RTHS) and numerical simulations enabled parametric studies of MRF building structures with reduced strength MRF designs:

- D100V: MRF designed for 100% of design base shear
- D75V: MRF designed for 75% of design base shear
- D60V: MRF designed for 60% of design base shear



(a) Seismic tributary area for D100V Test Structure

(b) Seismic tributary area for D75V Test Structure

(c) Seismic tributary area for D60V Test Structure

<u>Keep MRF and DBF unchanged</u>

Change mass and gravity system model in numerical simulation model for numerical simulations…

or…

Change mass and gravity system in analytical substructure for RTHS of different MRF building structures

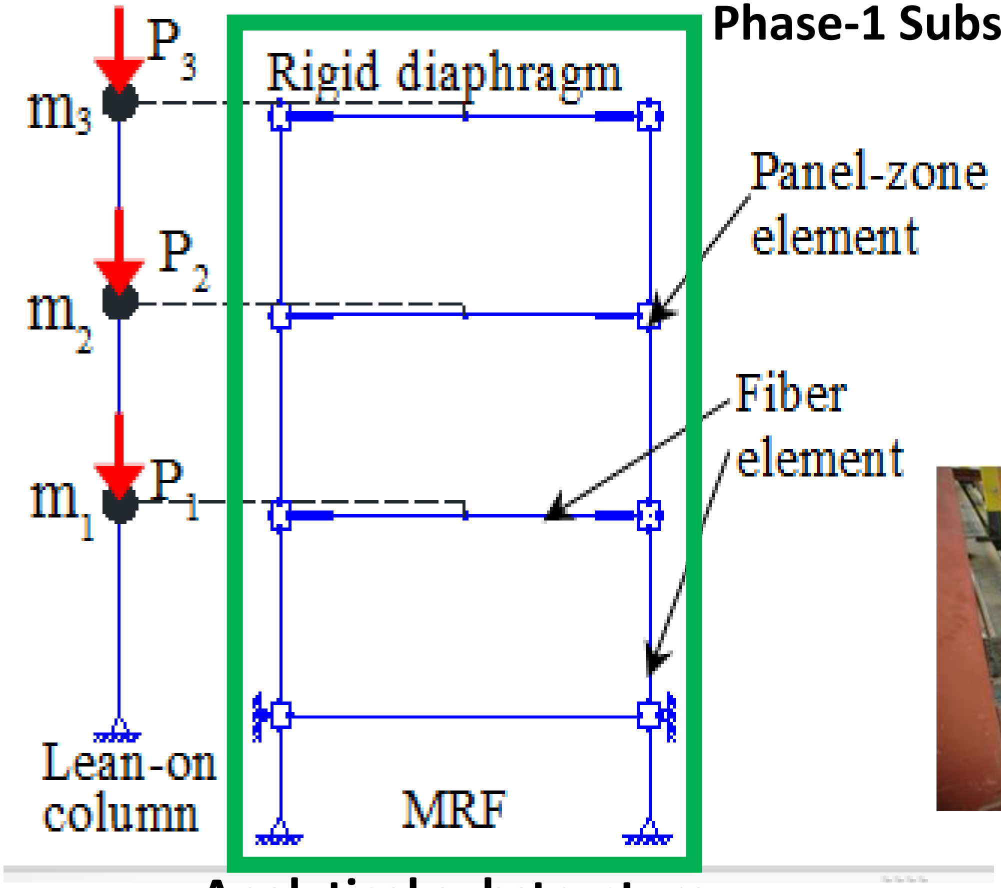
Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Real-Time Hybrid Simulations on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers

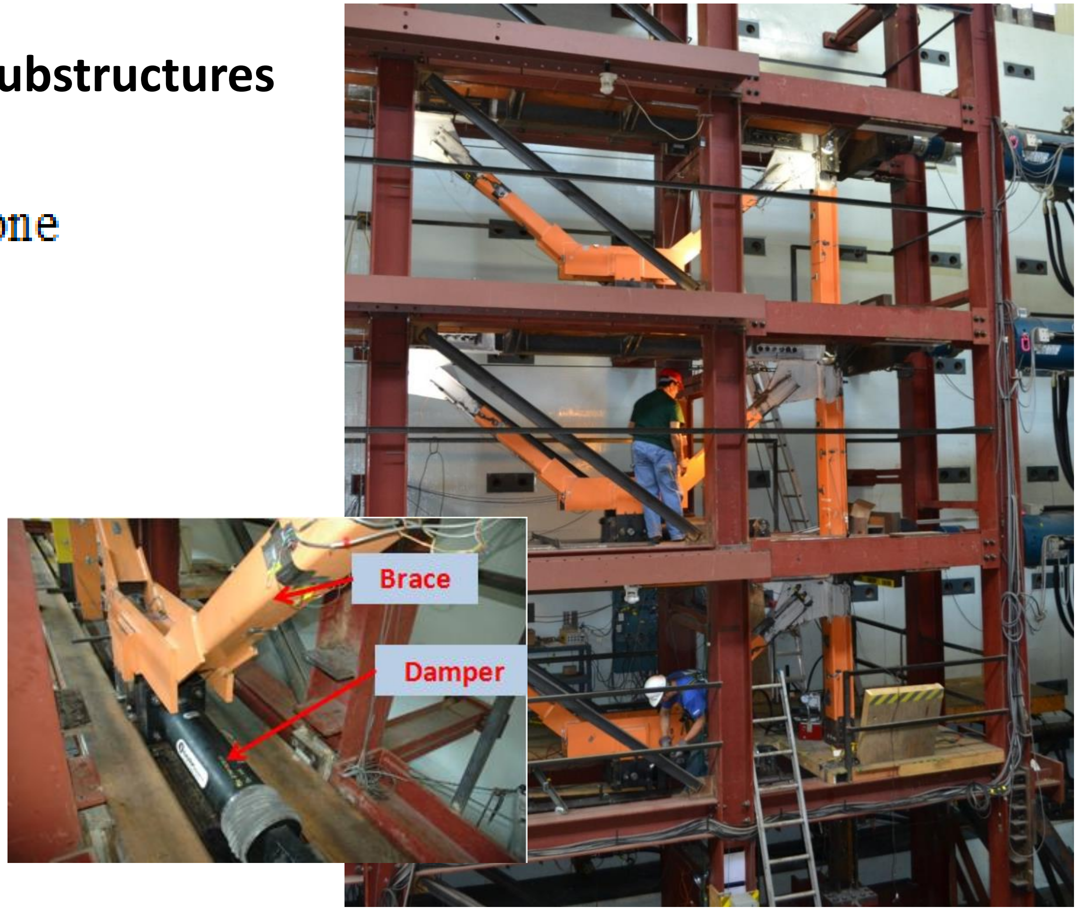
Phase-1 RTHS

Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Phase-1 Substructures



Analytical substructure (MRF, mass, gravity system, inherent damping)



Experimental substructure (0.6-scale DBF)

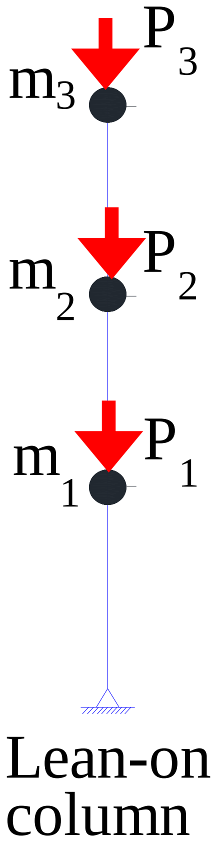
Details of Analytical Substructure

- Analytical substructure has 296 DOFs and 91 elements, with nonlinear fiber element for beams, columns, and RBS
- Panel zone element for panel zone of beam-column connection
- Elastic beam-column element for lean-on column, P-delta effects included in the analytical substructure

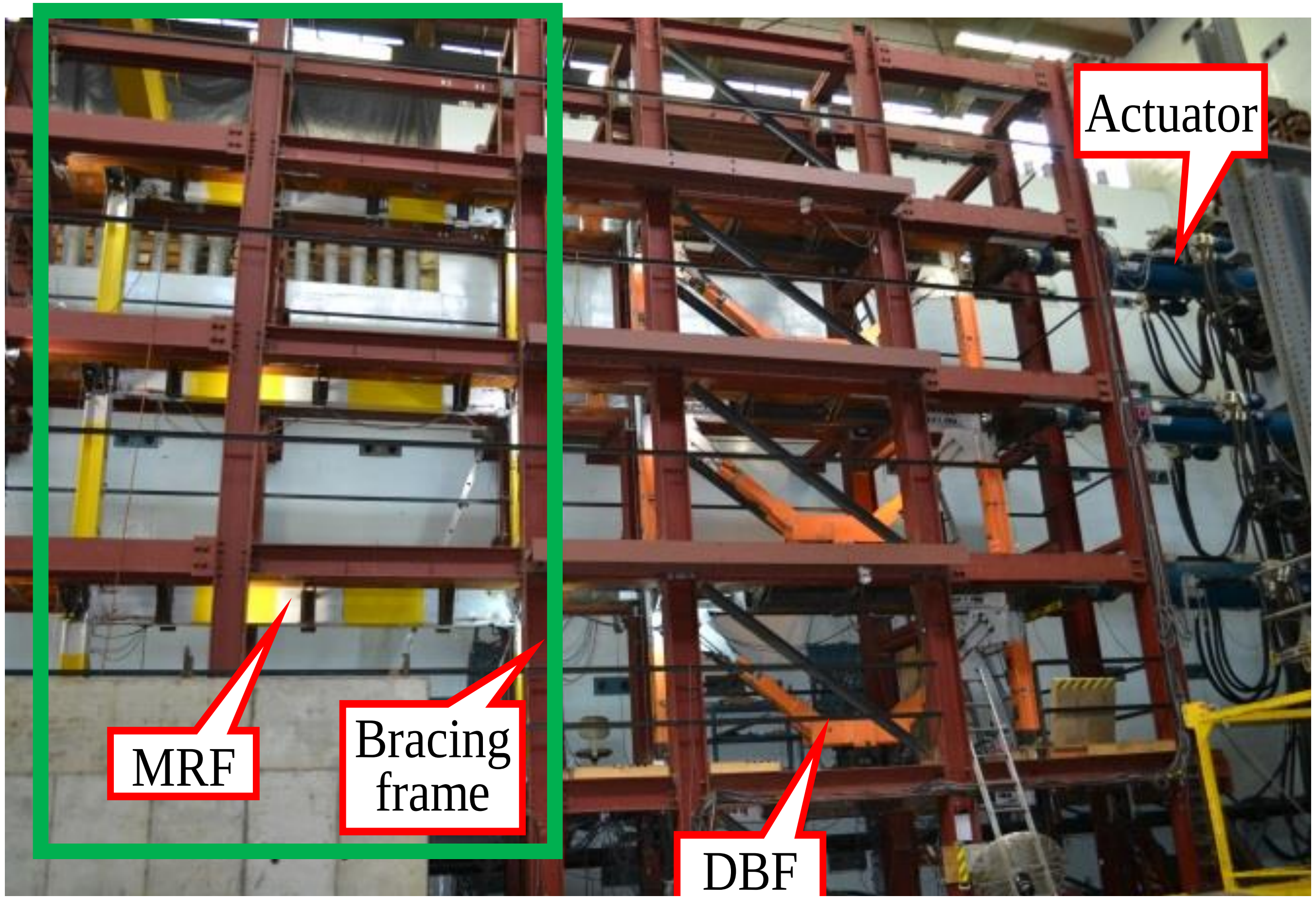
Real-Time Hybrid Simulations on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers

Phase-2 RTHS

Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Damage of Reduced-Strength Steel MRF Structures with Nonlinear Viscous Dampers," Journal of Structural Engineering, 2018



Phase-2 Substructures



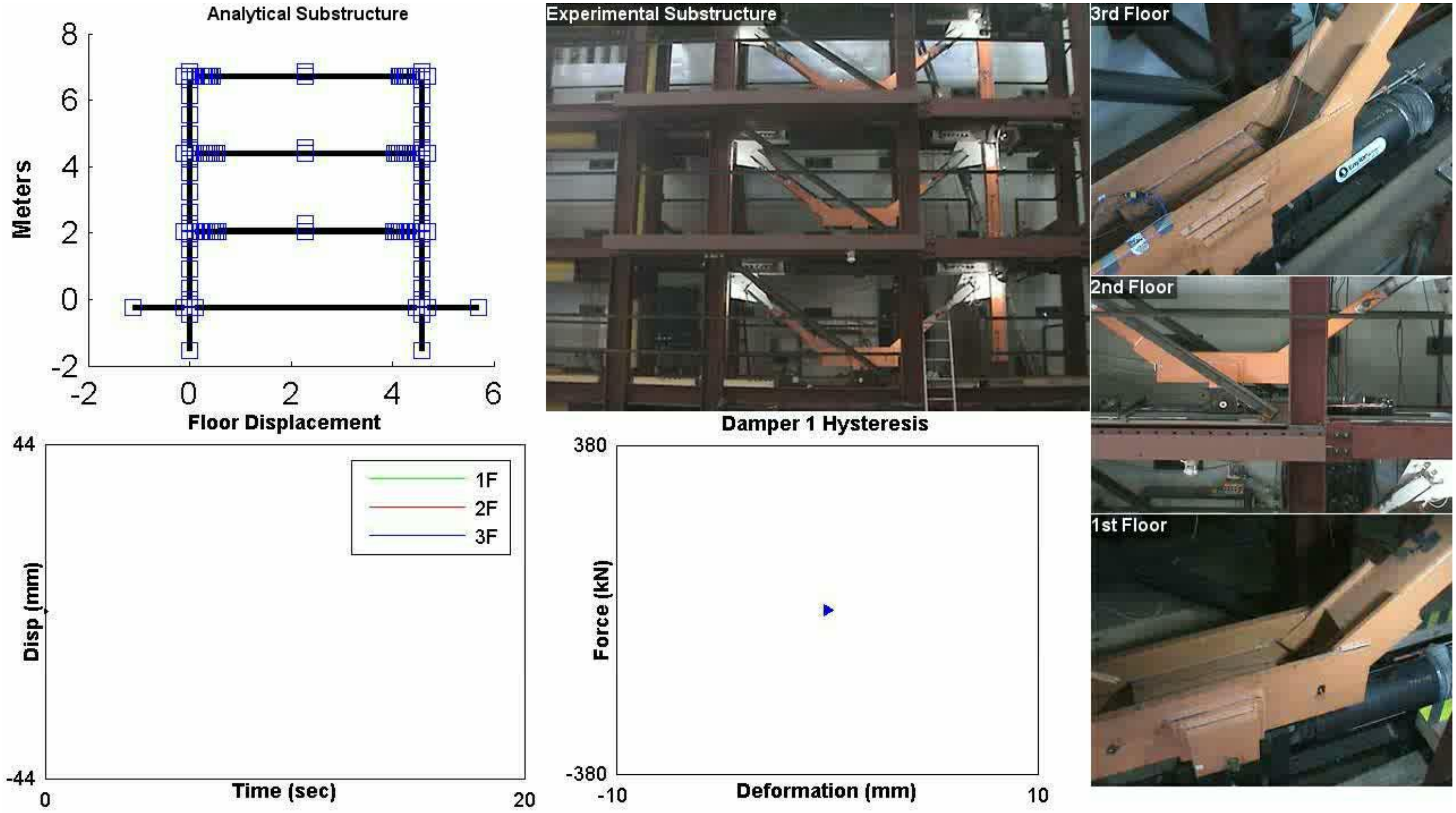
Analytical substructure (Mass, gravity system, inherent damping)

Experimental substructure (0.6-scale DBF)

Details of Analytical Substructure

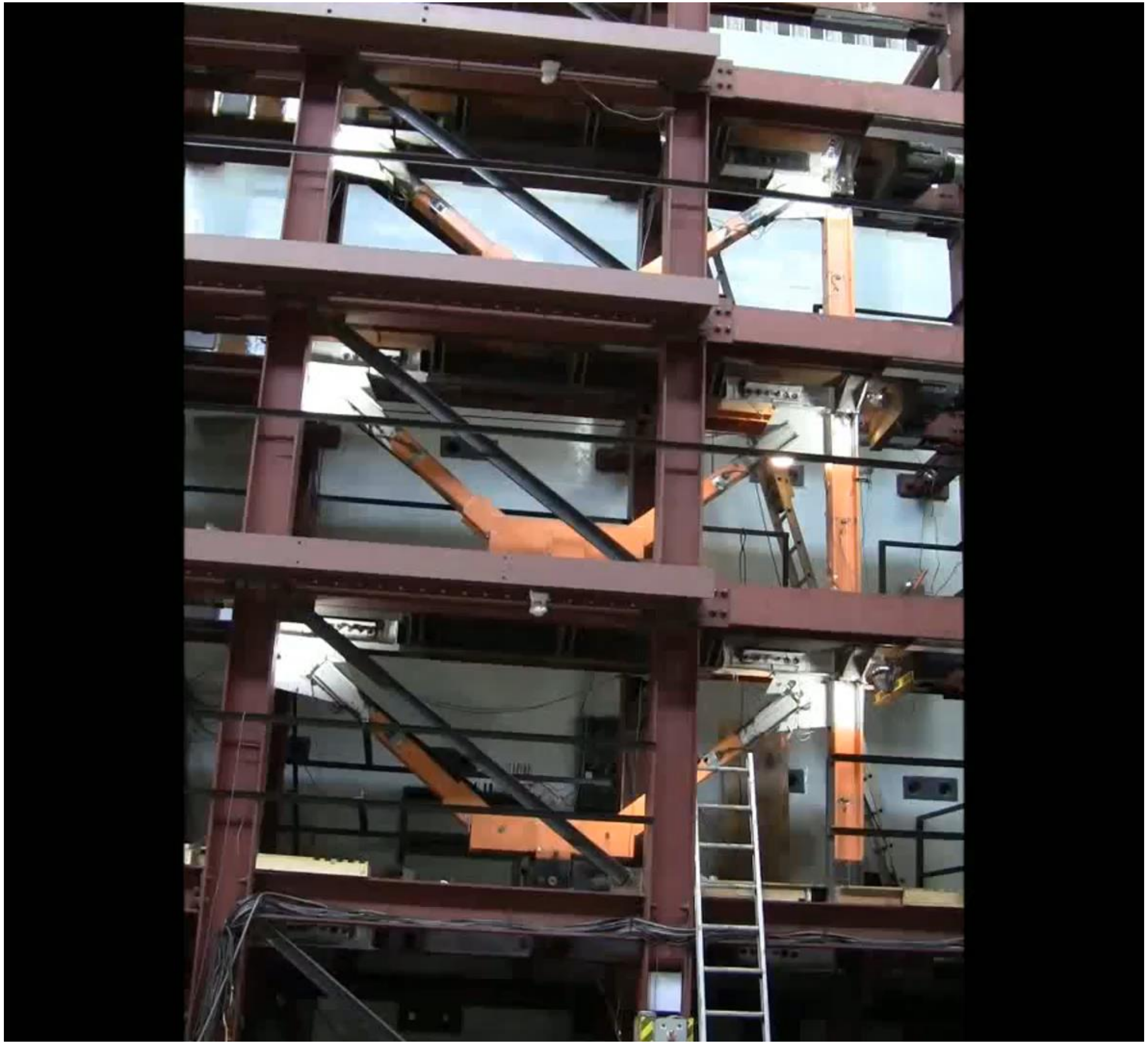
- Analytical substructure has 10 DOFs and 3 elements
- Elastic beam-column element for the lean-on column, P-delta effects included in analytical substructure

Phase 1 Real-Time Hybrid Simulations on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers (DBE)

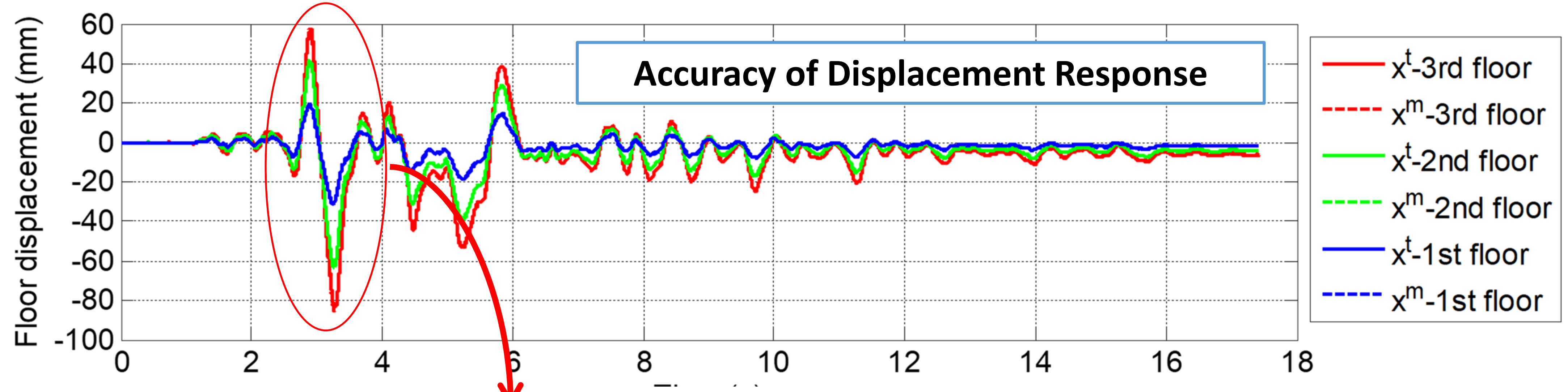


Phase 1 Real-Time Hybrid Simulations on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers (MCE)

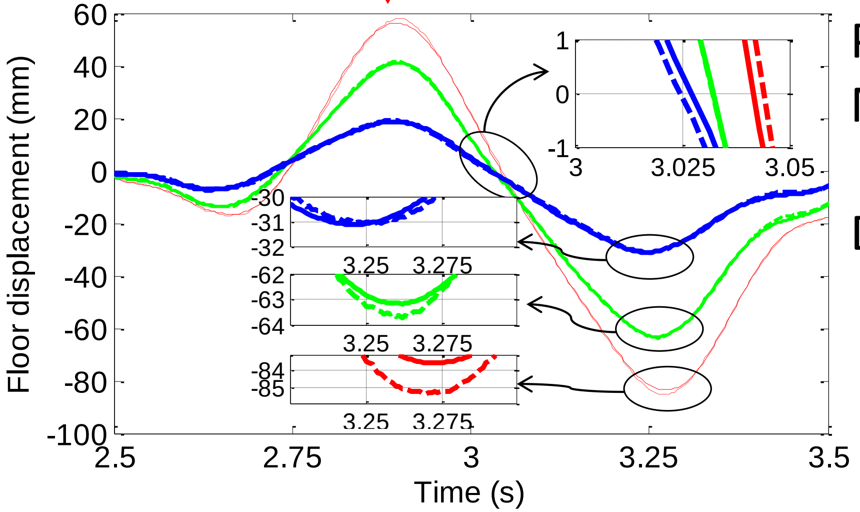
1994 Northridge Earthquake record RRS318 component scaled to MCE Level (2% probability of exceedance (POE) in 50 yr.)



Phase-1 Real-Time Hybrid Simulations on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers: Accuracy



1994 Northridge Earthquake record RRS318 component scaled to MCE Level (2% POE in 50 yr.)



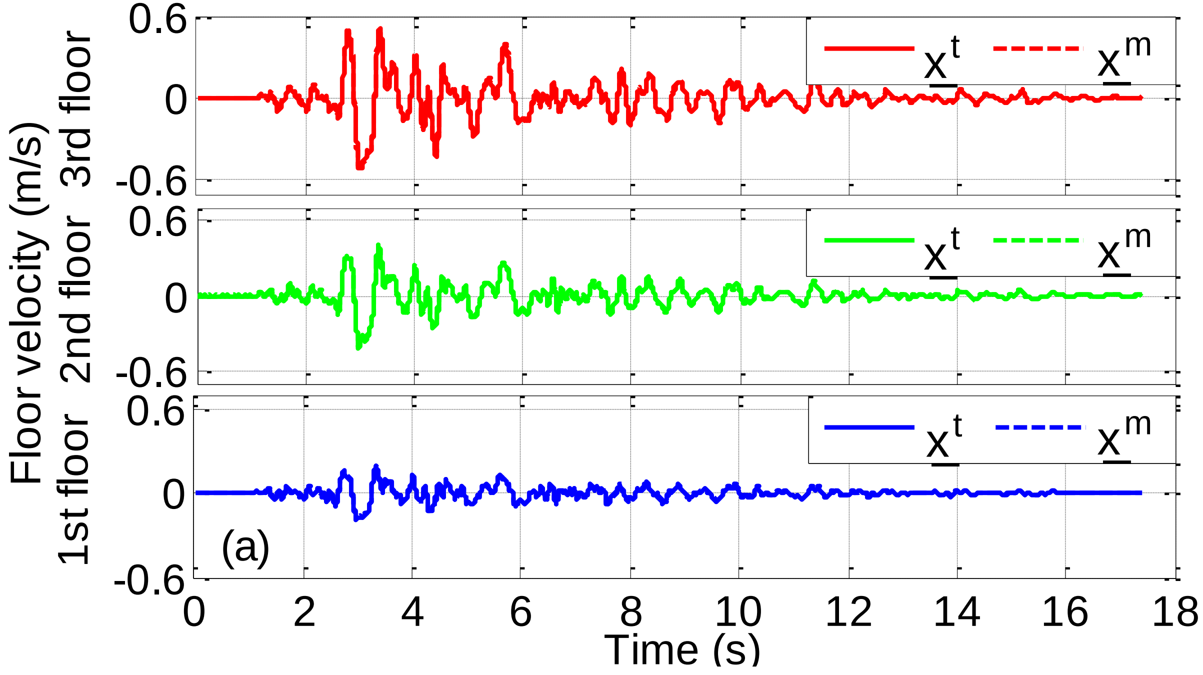
Peak floor displacement: 31.1, 63.7, 85.5 mm

Maximum amplitude error: 1.1, 1.6, 2.0 mm (3.5%, 2.5%, 2.3%)

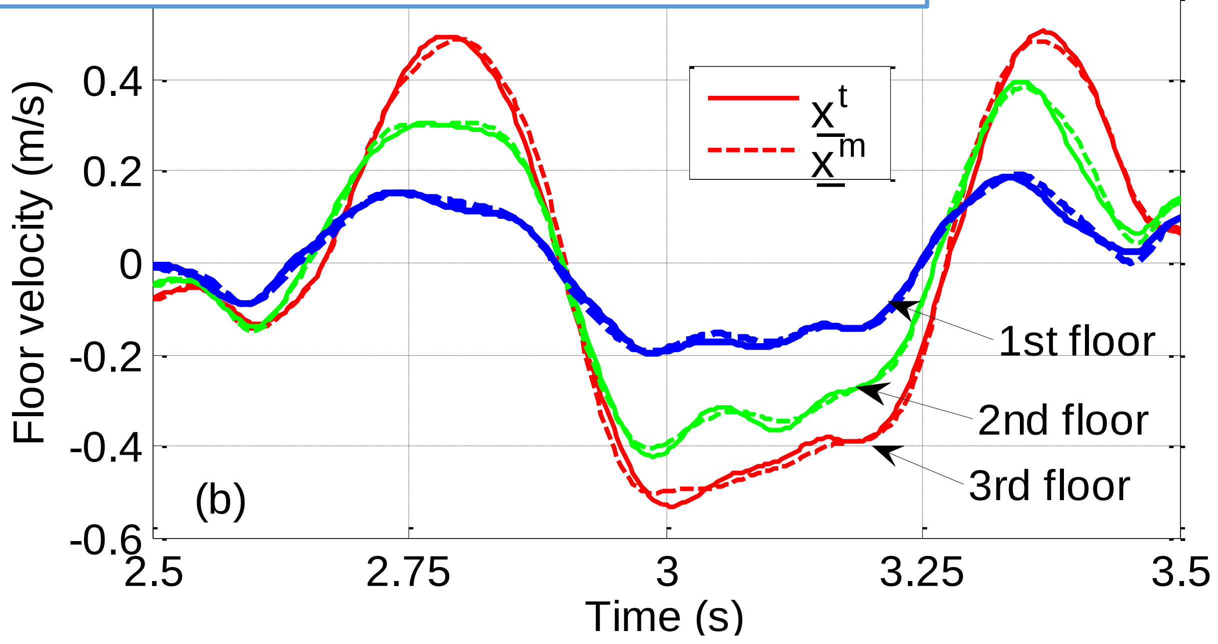
Delay: about 2.0 ms

Dong, B., Sause, R., and Ricles, J.M., "Accurate Real-time Hybrid Earthquake Simulations on Large-Scale MDOF Steel Structure with Nonlinear Viscous Dampers," *Earthquake Engineering and Structural Dynamics*, 2015

Phase-1 Real-Time Hybrid Simulations on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers: Accuracy



Accuracy of Floor Velocity Response



1994 Northridge Earthquake record RRS318 component scaled to MCE Level (2% POE in 50 yr.)

Peak floor velocity:	0.198, 0.422, 0.531 m/s
Maximum difference:	0.005, 0.007, 0.009m/s
	(2.5%, 1.7%, 1.7%)

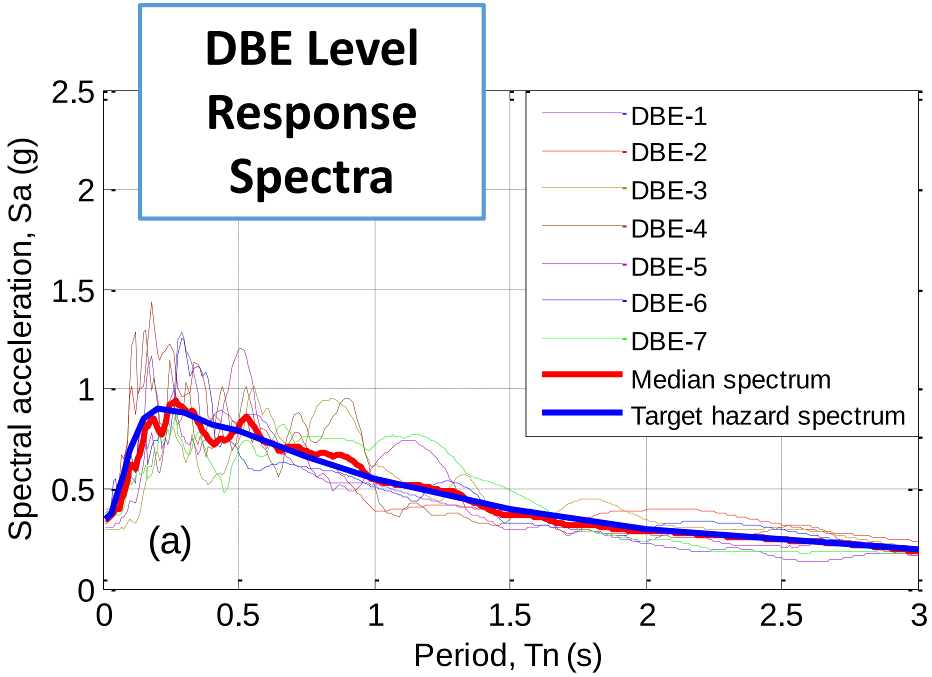
Dong, B., Sause, R., and Ricles, J.M., "Accurate Real-time Hybrid Earthquake Simulations on Large-Scale MDOF Steel Structure with Nonlinear Viscous Dampers," *Earthquake Engineering and Structural Dynamics*, 2015.

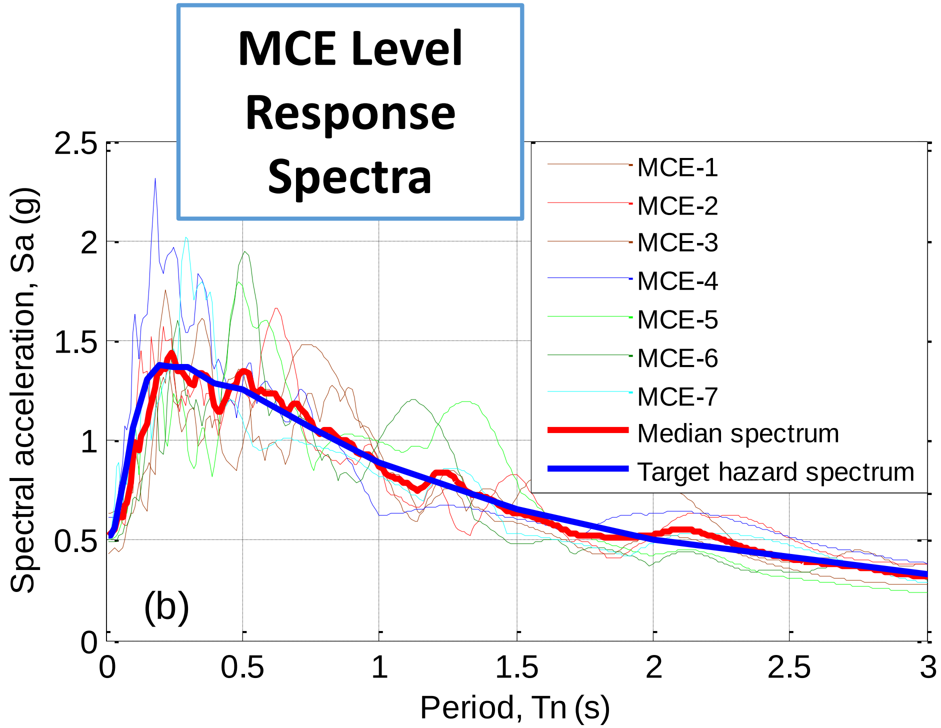
Phase-1 Real-Time Hybrid Simulations on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers

Advantage of Phase-1 RTHS

- Phase-1 experimental substructure (DBF with dampers) is undamaged by DBE and MCE input; damage is confined to MRF within analytical substructure; undamaged MRF for each simulation
- Therefore, an ensemble of ground motion records could be used as input for Phase-1 RTHS to account for record-to-record variability

Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016





Phase-1 Real-Time Hybrid Simulations on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers

Statistical evaluation of lateral story drift response from Phase-1 RTHS

Ground Motion No.	Story drift (%)		
	1st story	2nd story	3rd story
DBE-1	0.68	0.82	0.53
DBE-2	0.63	0.73	0.52
DBE-3	0.68	0.76	0.48
DBE-4	0.79	0.82	0.55
DBE-5	0.62	0.71	0.49
DBE-6	0.79	0.80	0.55
DBE-7	0.71	0.80	0.57
DBE Mean	**0.69**	$\boxed{\textbf{0.76}}$	**0.53**
DBE prediction	**0.76**	**0.81**	**0.64**

DBE (10% POE in 50 yr.) RTHS

- Mean maximum story drifts: 0.69%, $\boxed{0.76\%,}$ 0.53% for 1st, 2nd, 3rd story
- Mean maximum residual story drift: 0.03%

Ground Motion No.	Story drift (%)		
	1st story	2nd story	3rd story
MCE-1	1.25	1.48	1.09
MCE-2	1.10	1.29	0.88
MCE-3	1.18	1.34	1.03
MCE-4	1.09	1.35	1.02
MCE-5	1.27	1.39	0.98
MCE-6	1.07	1.24	0.91
MCE-7	1.32	1.44	1.00
MCE Mean	**1.20**	$\boxed{\textbf{1.38}}$	**1.00**
MCE prediction	**1.33**	**1.41**	**1.12**

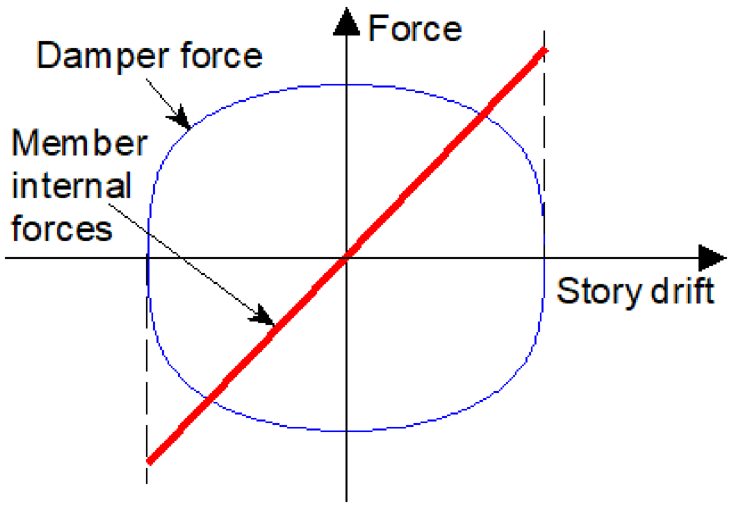
MCE (2% POE in 50 yr.) RTHS

- Mean maximum story drifts: 1.20%, $\boxed{1.38\%,}$ 1.00% for 1st, 2nd, 3rd story
- Mean maximum residual story drift: 0.06%

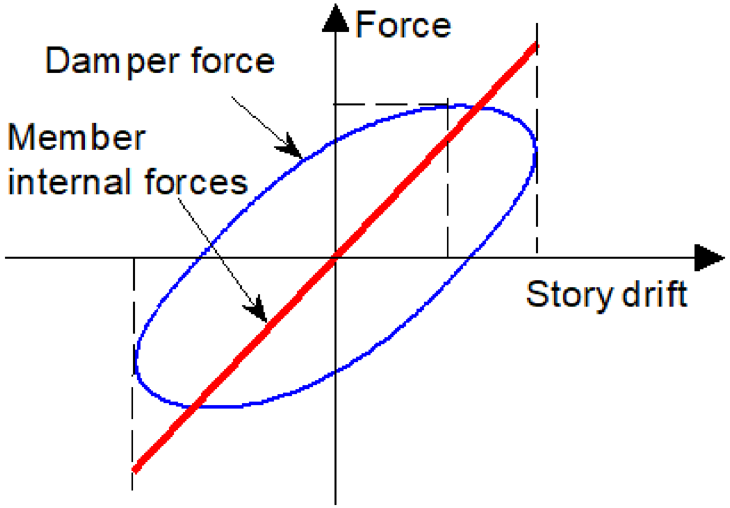
Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Phase-1 Real-Time Hybrid Simulations on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers

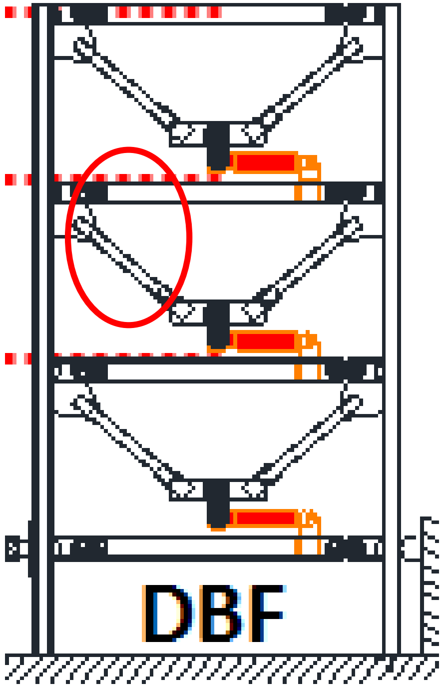
In-phase behavior of damper force with story drift (effect of brace flexibility)



Theoretical damper force-story drift hysteresis



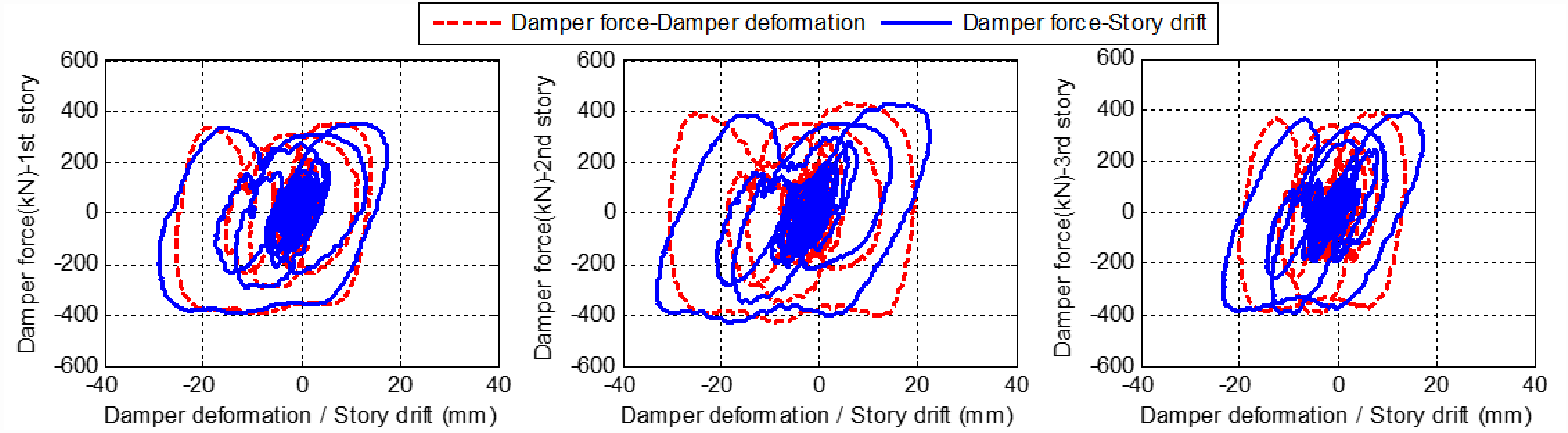
Damper force-story drift hysteresis with flexibility of adjacent members within damper force path



Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

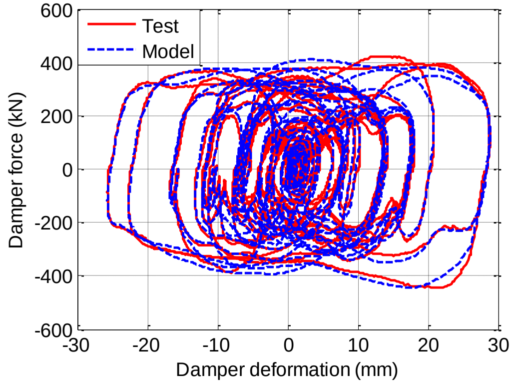
Phase-1 Real-Time Hybrid Simulations on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers

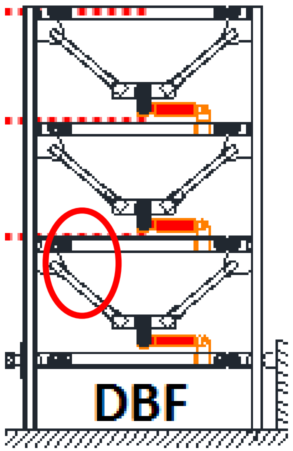
In-phase behavior of damper force with story drift (effect of brace flexibility)



Damper force-damper deformation and damper force-story drift response from RTHS (MCE RRS318)

Damper Force-Deformation Response from Characterization Test





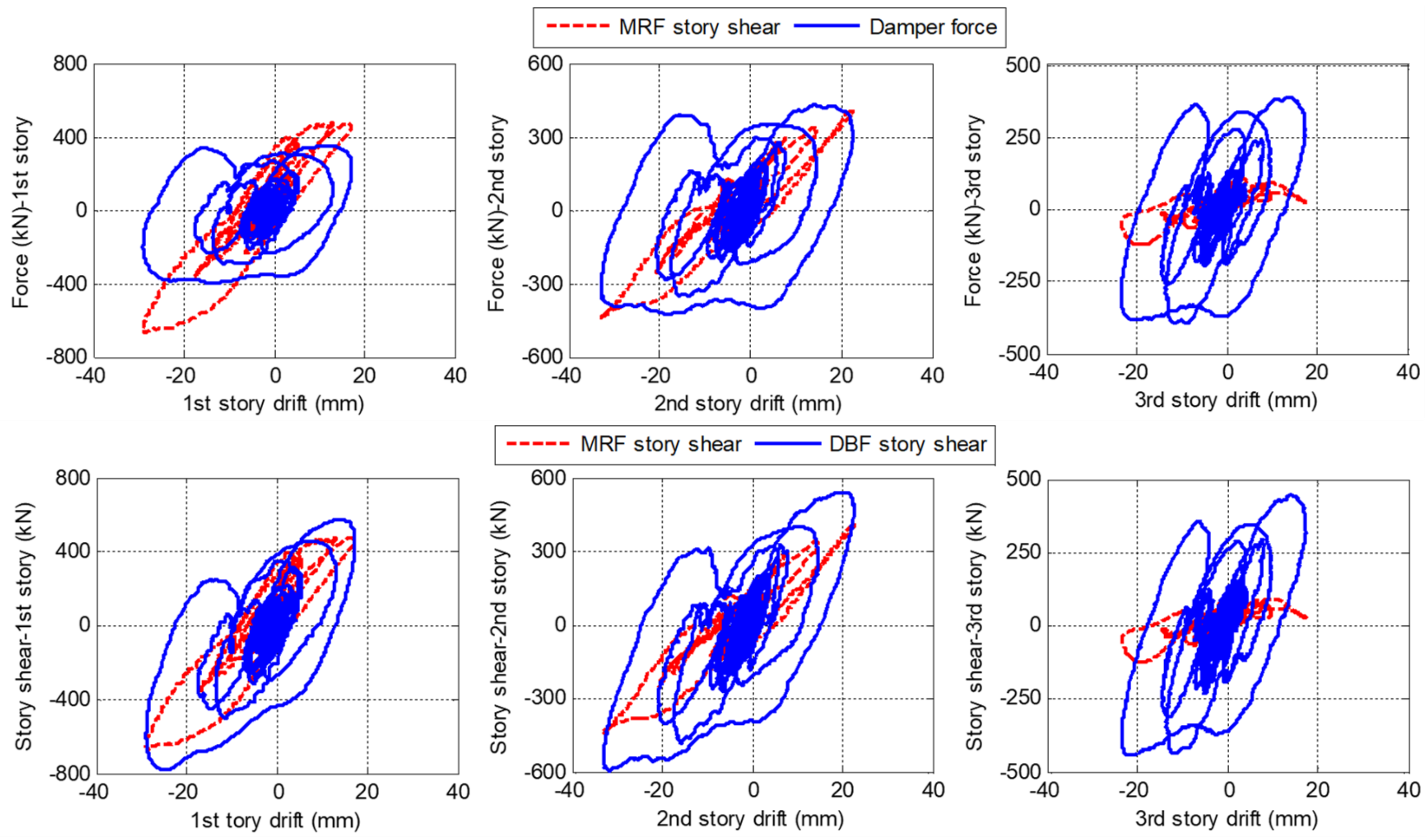
DBF elastic deformation in damper force path (members adjacent to dampers) produces differences between damper deformation and story drift

Resulting damper forces tend to be in-phase with elastic forces

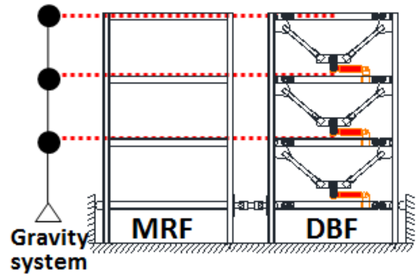
Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Phase-1 Real-Time Hybrid Simulations on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers

In-phase behavior of damper force with story drift (effect of brace flexibility)



MRF story shear and damper force versus story drift response from RTHS (MCE RRS318)



MRF and DBF story shear versus story drift response from RTHS (MCE RRS318)

Damper forces are partly in-phase with MRF story shear (at time of peak MRF story shear, damper force is large)

DBF forces are large at time of peak MRF forces, should be considered in design

Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Response of Systems with Dampers During Seismic Hazard Events

- RTHS can be used to accurately quantify and understand response of system with dampers (or other devices) under seismic hazard events
- Phase-1 RTHS with undamaged MRF (in analytical substructure) and undamaged DBF (in experimental substructure) for each simulation enabled ensemble of ground motions to be used, so record-to-record variability could be included in statistical results
- RTHS results show importance of "brace stiffness" – elastic flexibility in damper force path:
  - Damper forces and DBF story shears are partly in-phase with MRF story shears (at peak MRF story shear, damper force is large)
  - Results are contrary to assumption that viscous damper produces forces out-of-phase with restoring forces from structural members
  - Results should be considered in design, since period, base shear (for foundation design), floor diaphragm forces/accelerations, etc. are influenced by in-phase forces

Challenges in Achieving Seismic Hazard Mitigation Using Dampers and Other Devices: Overview of Topics

- Characterization of Devices: Testing and Models
  - Focus on characterization tests and models of dampers and other devices
- Modeling and Understanding Systems with Dampers
  - Simple models for design and to understand system/damper response
  - Accurate models for numerical simulations
- Response of Systems with Dampers During Hazard Events
  - Real-time hybrid simulations of seismic response of systems with dampers
- **Hazard Mitigation Performance of Systems with Dampers**
  - Seismic performance of systems with dampers
- Summary of Issues and Thoughts Suggested by Lab Experiences

Seismic Hazard Performance of Systems with Dampers

- Purpose is to understand and quantify performance of system with dampers (or other devices) under seismic hazard events
- Methods generally include:
  - Numerical simulations using accurate force-deformation hysteretic response models, for example, Incremental Dynamic Analysis
  - Real-time hybrid simulations
  - Shake table tests
- In this presentation, focus on example study of MRF with nonlinear viscous dampers:
  - Use of RTHS (Phase-1 and Phase-2); numerical simulations were also performed and results available in cited papers
  - Statistics for drift-based assessment of performance from Phase-1 RTHS
  - Results to show the effect of MRF design strength on seismic performance
  - Damage states in MRF from Phase-2 RTHS

Seismic Performance of Moment Resisting Frame with Nonlinear Viscous Dampers Based on Phase-1 Real-Time Hybrid Simulations (RTHS)

Seismic performance of 100V MRF with dampers based on story drift

Ground Motion No.	Story drift (%)		
	1st story	2nd story	3rd story
DBE-1	0.68	0.82	0.53
DBE-2	0.63	0.73	0.52
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DBE prediction	**0.76**	**0.81**	**0.64**

DBE (10% POE in 50 yr.) RTHS

- Mean maximum story drifts: 0.69%, 0.76%, 0.53% for 1st, 2nd, 3rd story
- Mean maximum residual story drift: 0.03%

Ground Motion No.	Story drift (%)		
	1st story	2nd story	3rd story
MCE-1	1.25	1.48	1.09
MCE-2	1.10	1.29	0.88
MCE-3	1.18	1.34	1.03
MCE-4	1.09	1.35	1.02
MCE-5	1.27	1.39	0.98
MCE-6	1.07	1.24	0.91
MCE-7	1.32	1.44	1.00
MCE Mean	**1.20**	**1.38**	**1.00**
MCE prediction	**1.33**	**1.41**	**1.12**

MCE (2% POE in 50 yr.) RTHS

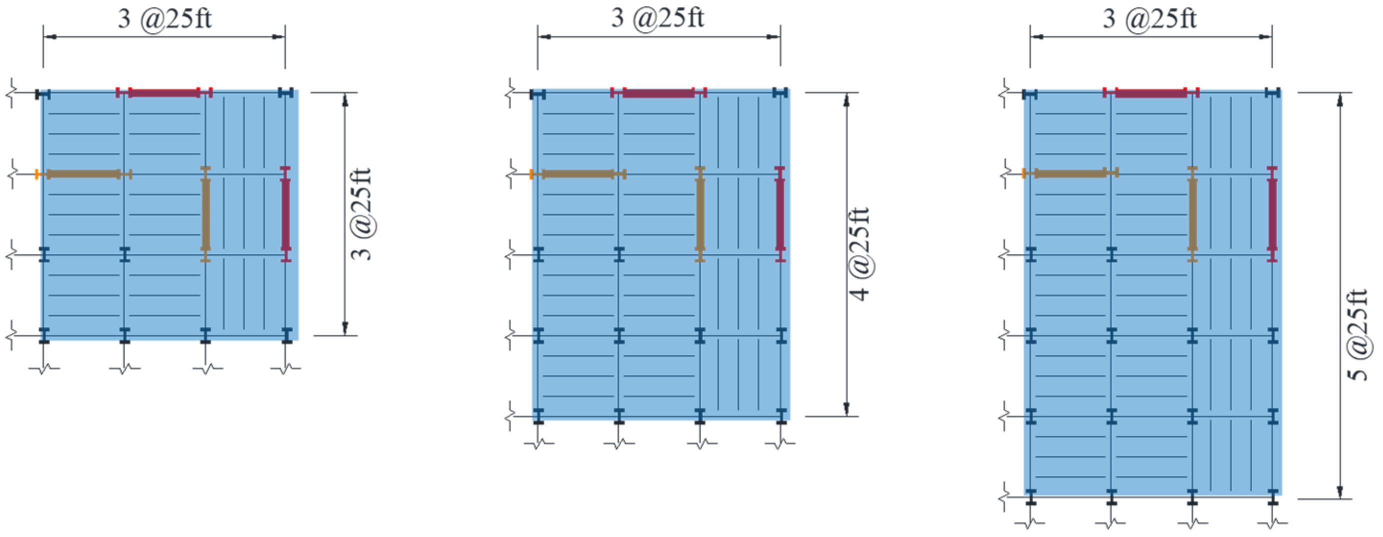
- Mean maximum story drifts: 1.20%, 1.38%, 1.00% for 1st, 2nd, 3rd story
- Mean maximum residual story drift: 0.06%

Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Seismic Performance of Different Versions of Moment Resisting Frame with Nonlinear Viscous Dampers: Reduced Strength MRFs

Using real-time hybrid simulation (RTHS) and numerical simulations enabled parametric studies of MRF building structures with reduced strength MRF designs:

- D100V: MRF designed for 100% of design base shear
- D75V: MRF designed for 75% of design base shear
- D60V: MRF designed for 60% of design base shear



(a) Seismic tributary area for D100V Test Structure

(b) Seismic tributary area for D75V Test Structure

(c) Seismic tributary area for D60V Test Structure

<u>Keep MRF and DBF unchanged</u>

Change mass and gravity system model in numerical simulation model for numerical simulations…

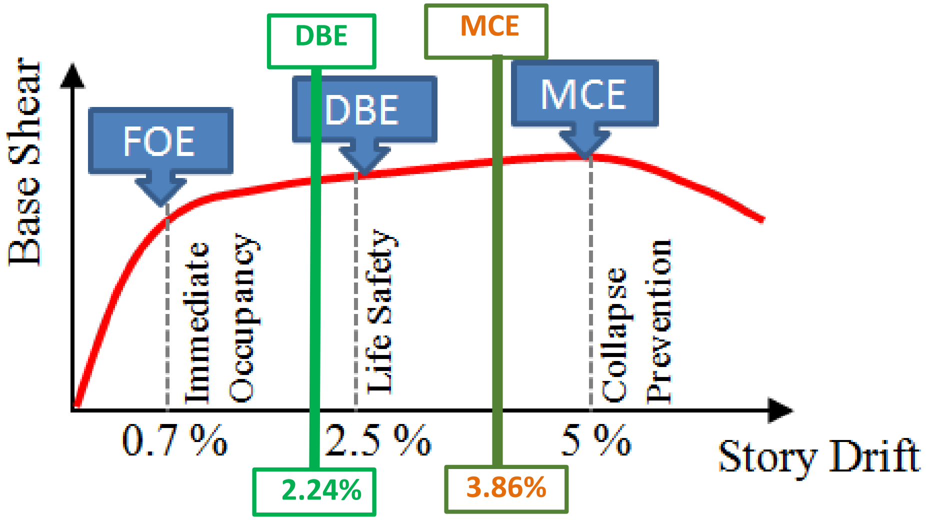
or…

Change mass and gravity system in analytical substructure for RTHS of different MRF building structures

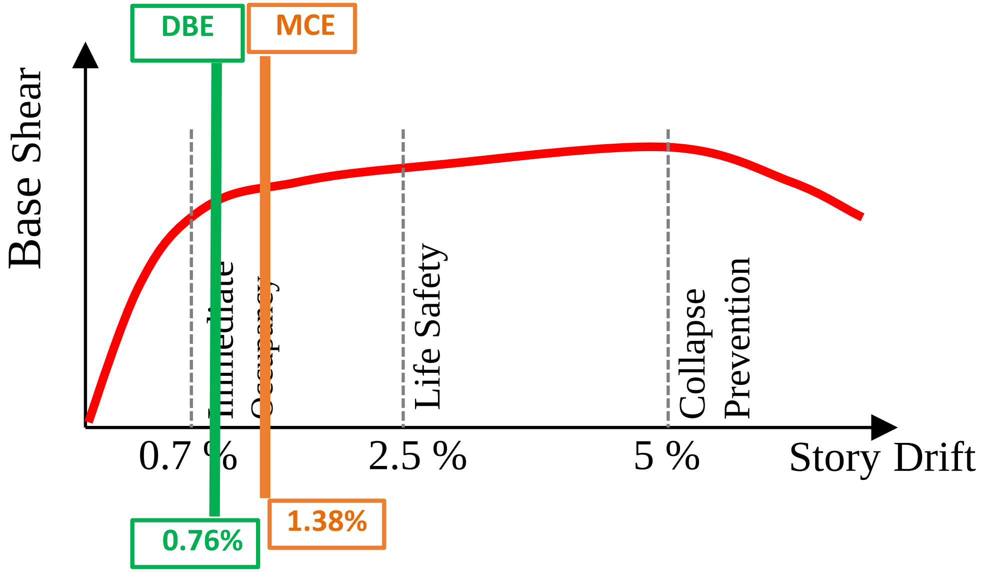
Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Seismic Performance of Moment Resisting Frame with Nonlinear Viscous Dampers Based on Phase-1 RTHS

D100V (without dampers)



D100V (with dampers)

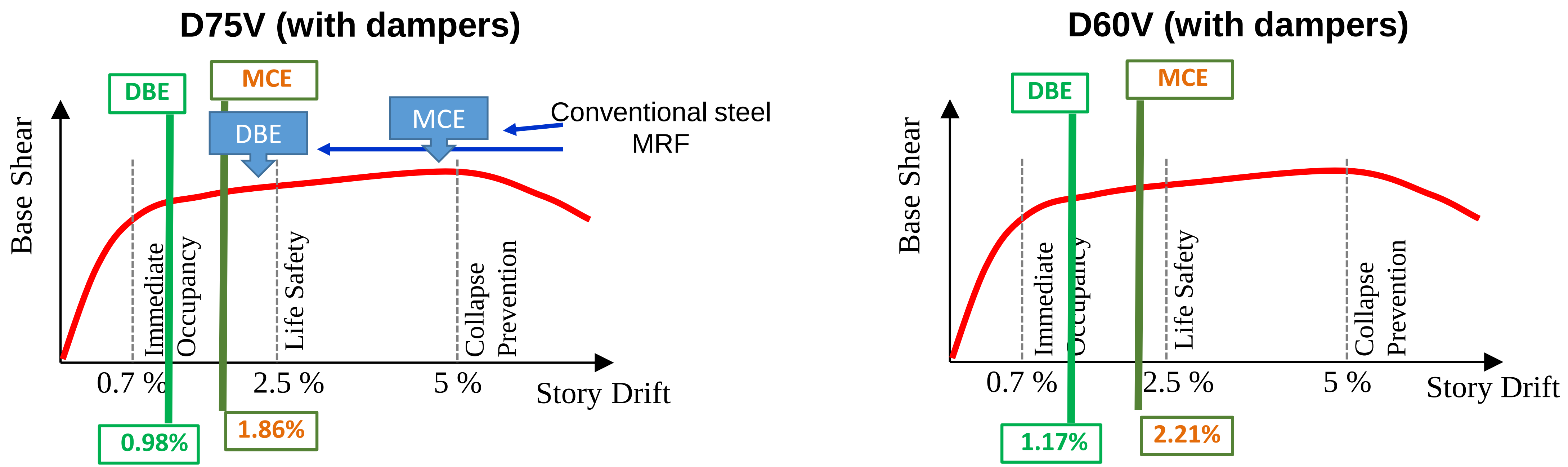


D100V MRF with dampers:

- Test structure remained elastic under DBE, with minor yielding under MCE
- Based on lateral story drift limits in ASCE/SEI 41-06, performance of D100V with dampers:
  - Close to “Immediate Occupancy” for DBE
  - Between “Immediate Occupancy” and “Life Safety” for MCE (small mean max residual drift 0.06%)

Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Seismic Performance of Moment Resisting Frame with Nonlinear Viscous Dampers Based on Phase-1 RTHS: Reduced Strength MRFs

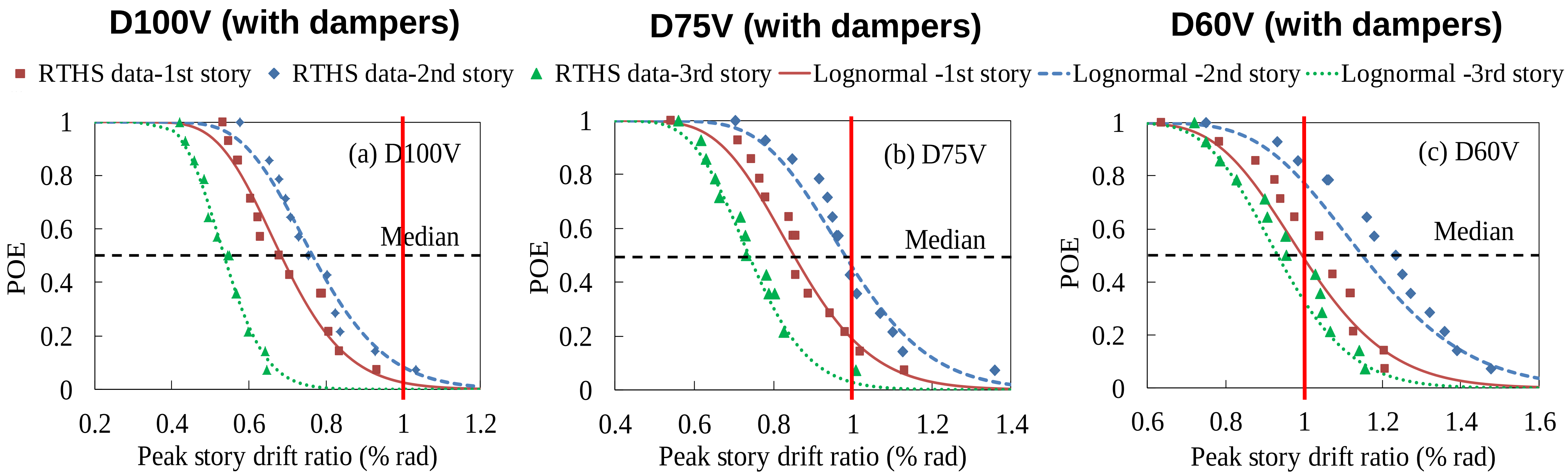


- Based on lateral story drift limits in ASCE/SEI 41-06, performance of D75 and D60V with dampers is:
  - Between “Immediate Occupancy” and “Life Safety” for DBE and MCE
  - Significantly better than conventional steel MRF
- Also consider cost trade-off between cost of conventional MRF and cost of D60V with nonlinear viscous dampers

Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Seismic Performance of Moment Resisting Frame with Nonlinear Viscous Dampers Based on Phase-1 RTHS: Reduced Strength MRFs

Probability of exceedance (POE) for peak story drift ratio (e.g., 1%) under DBE

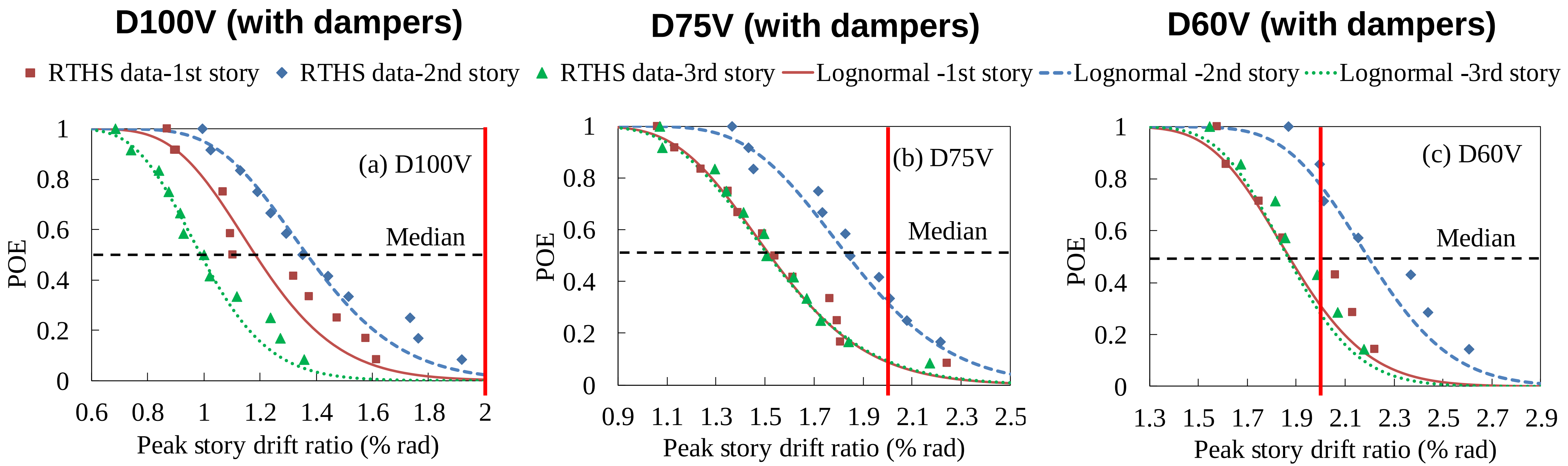


Based on Results from Phase-1 RTHS

Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Seismic Performance of Moment Resisting Frame with Nonlinear Viscous Dampers Based on Phase-1 RTHS: Reduced Strength MRFs

Probability of exceedance (POE) for peak story drift ratio (e.g., 2%) under MCE



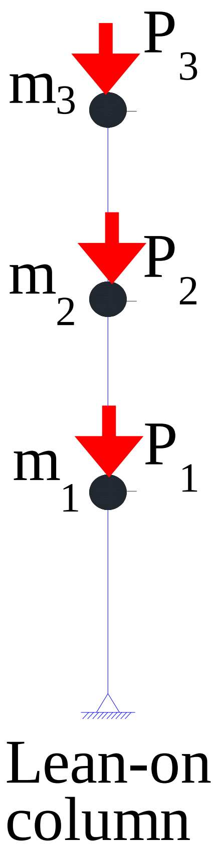
Based on Results from Phase-1 RTHS

Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

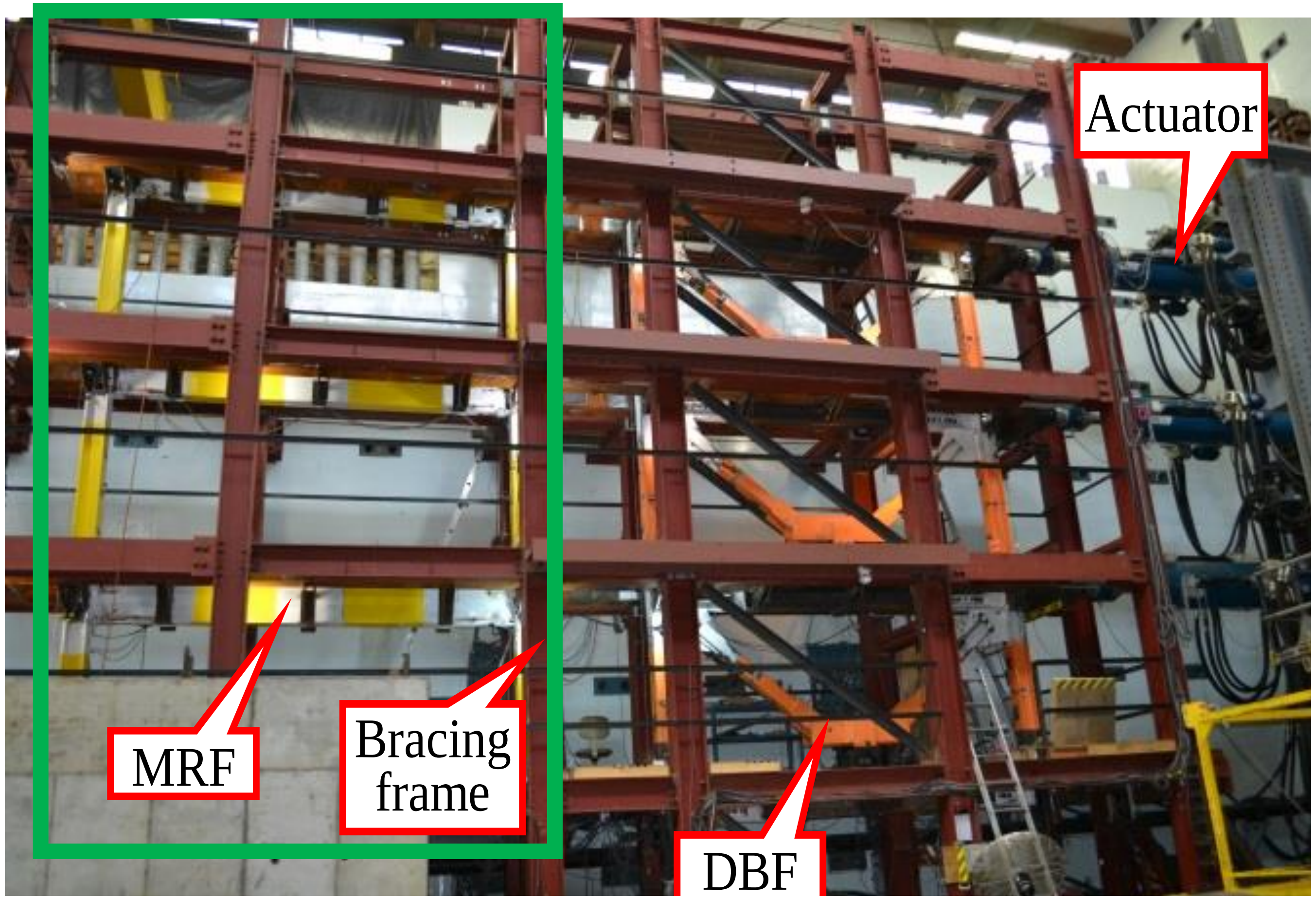
Real-Time Hybrid Simulations on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers

Phase-2 RTHS

Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Damage of Reduced-Strength Steel MRF Structures with Nonlinear Viscous Dampers," Journal of Structural Engineering, 2018



Phase-2 Substructures



Analytical substructure (Mass, gravity system, inherent damping)

Experimental substructure (0.6-scale DBF)

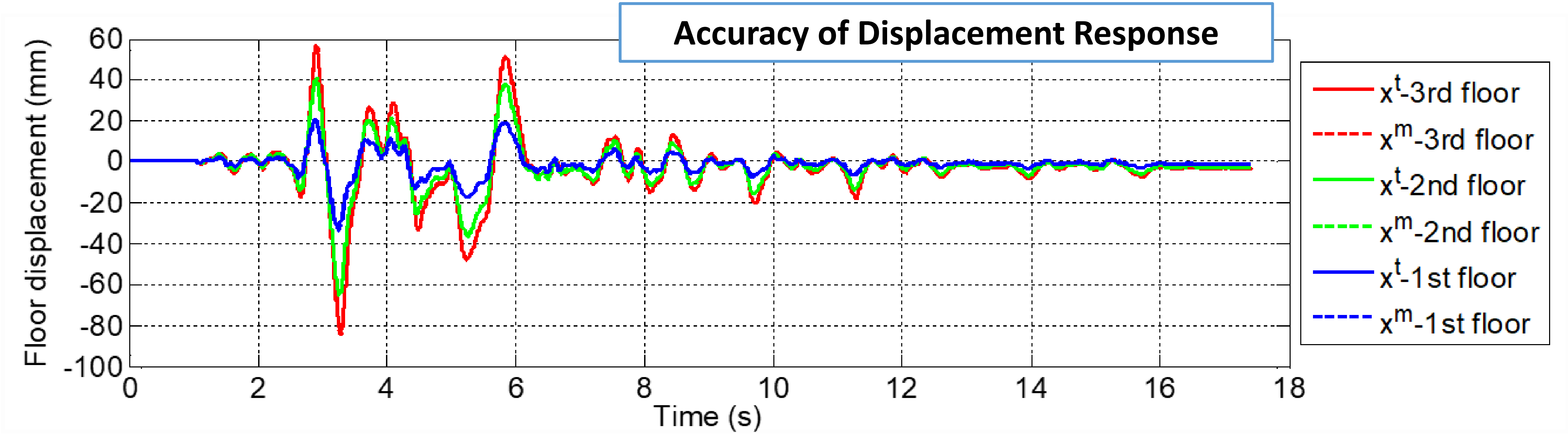
Details of Analytical Substructure

- Analytical substructure has 10 DOFs and 3 elements
- Elastic beam-column element for the lean-on column, P-delta effects included in analytical substructure

Phase 2 Real-Time Hybrid Simulations on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers (MCE)

1994 Northridge Earthquake record RRS318 component scaled to MCE Level (2% POE in 50 yr.)

Phase-2 Real-Time Hybrid Simulations on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers: Accuracy



1994 Northridge Earthquake record RRS318 component scaled to MCE Level (2% POE in 50 yr.)

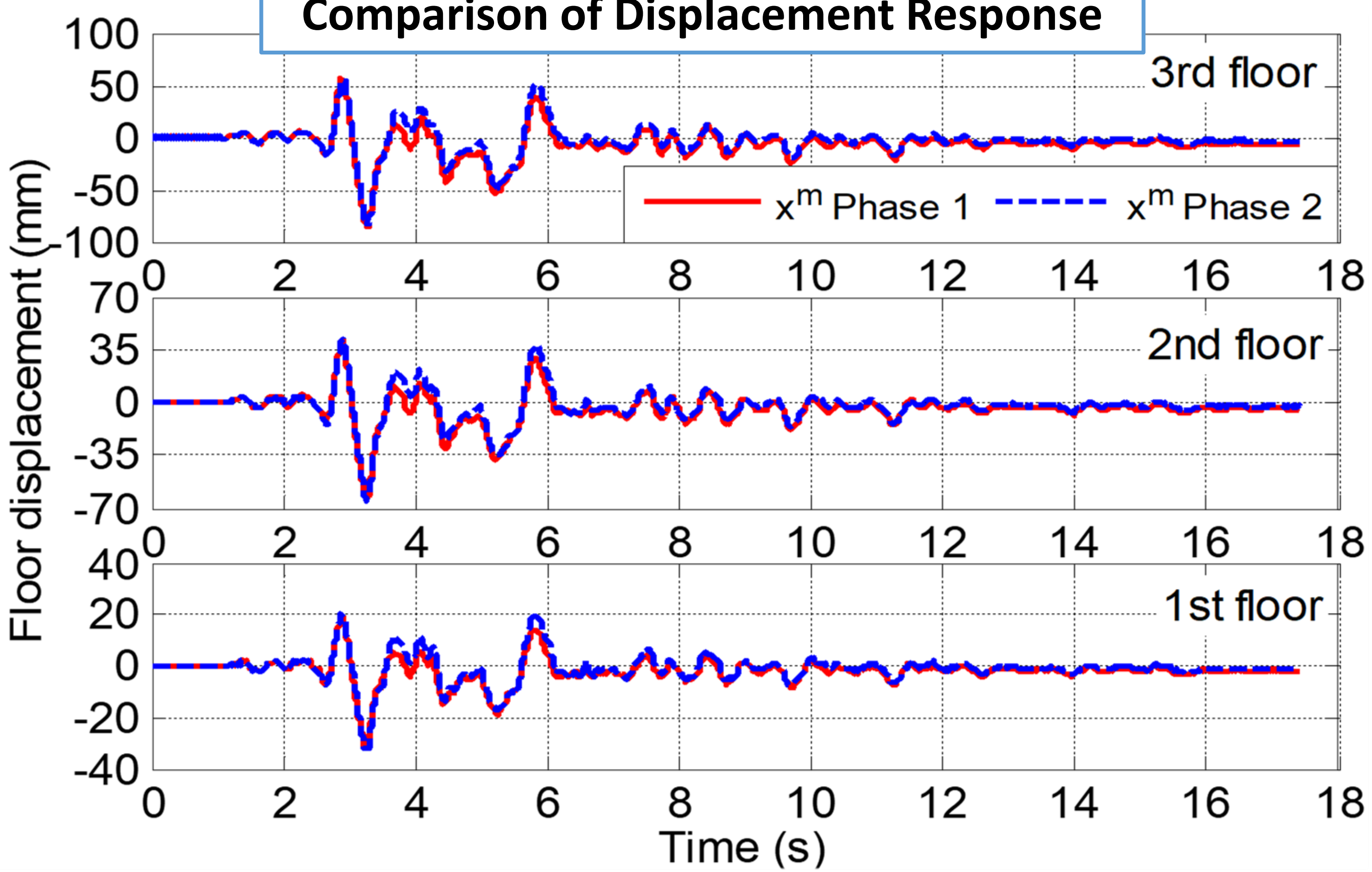
Peak floor displacement: 33.3, 65.4, 83.7 mm
Maximum amplitude error: 1.2, 0.9, 1.9 mm
(3.6%, 1.4%, 2.3%)

Delay: about 2.0 ms

Dong, B., Sause, R., and Ricles, J.M., "Accurate Real-time Hybrid Earthquake Simulations on Large-Scale MDOF Steel Structure with Nonlinear Viscous Dampers," *Earthquake Engineering and Structural Dynamics*, 2015

Comparison of Phase-1 and Phase-2 RTHS on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers

Comparison of Displacement Response



Provides Validation of Phase-1 RTHS

Peak floor displacement (Phase-1):
31.1, 63.7, 85.5 mm

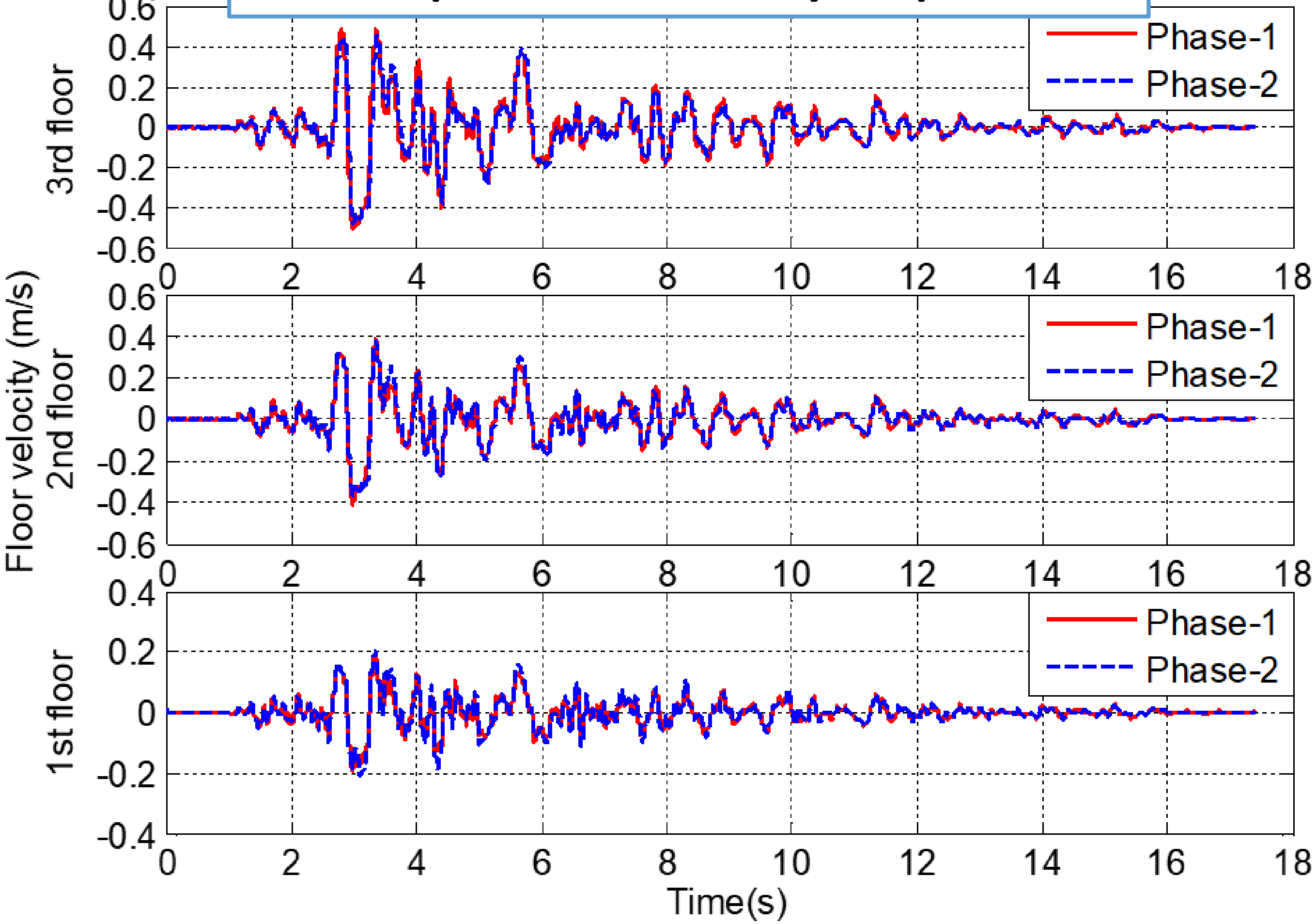
Maximum peak displacement difference:
2.1, 1.7, 1.8 mm
(6.8%, 2.7%, 2.1%)

1994 Northridge Earthquake record RRS318 component scaled to MCE Level (2% POE in 50 yr.)

Dong, B., Sause, R., and Ricles, J.M., "Accurate Real-time Hybrid Earthquake Simulations on Large-Scale MDOF Steel Structure with Nonlinear Viscous Dampers," *Earthquake Engineering and Structural Dynamics*, 2015

Comparison of Phase-1 and Phase-2 RTHS on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers

Comparison of Velocity Response



Provides Validation of Phase-1 RTHS

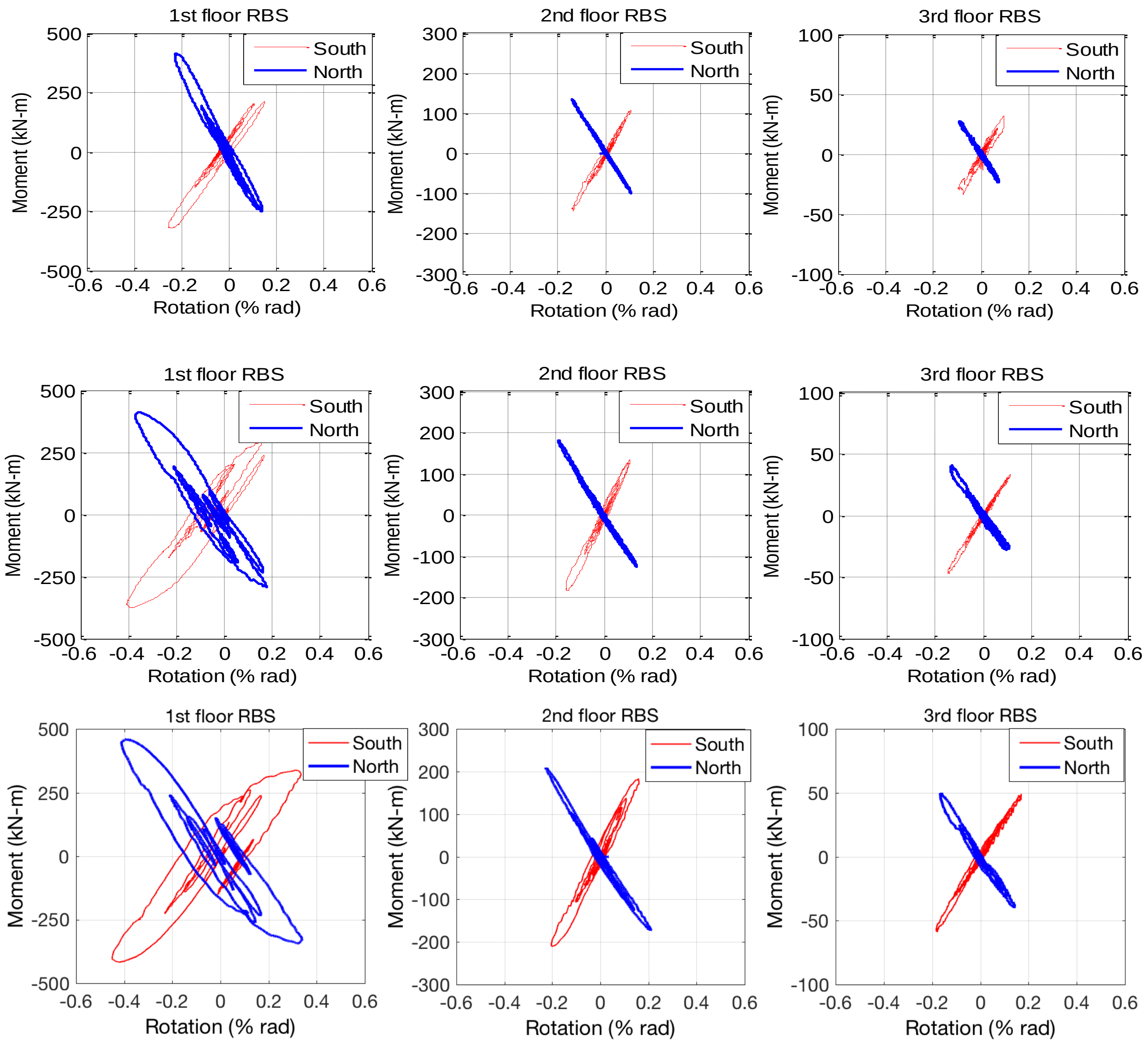
Peak floor velocity (Phase-1):
0.198, 0.422, 0.531 m/s

Maximum peak velocity difference:
0.010, 0.030, 0.035 m/s
(5.1%, 7.1%, 6.6%)

1994 Northridge Earthquake record RRS318 component scaled to MCE Level (2% POE in 50 yr.)

Dong, B., Sause, R., and Ricles, J.M., "Accurate Real-time Hybrid Earthquake Simulations on Large-Scale MDOF Steel Structure with Nonlinear Viscous Dampers," *Earthquake Engineering and Structural Dynamics*, 2015

Seismic Performance of Moment Resisting Frame with Nonlinear Viscous Dampers Based on Phase-2 RTHS: Beam End Damage States for DBE



D100V Test Structure

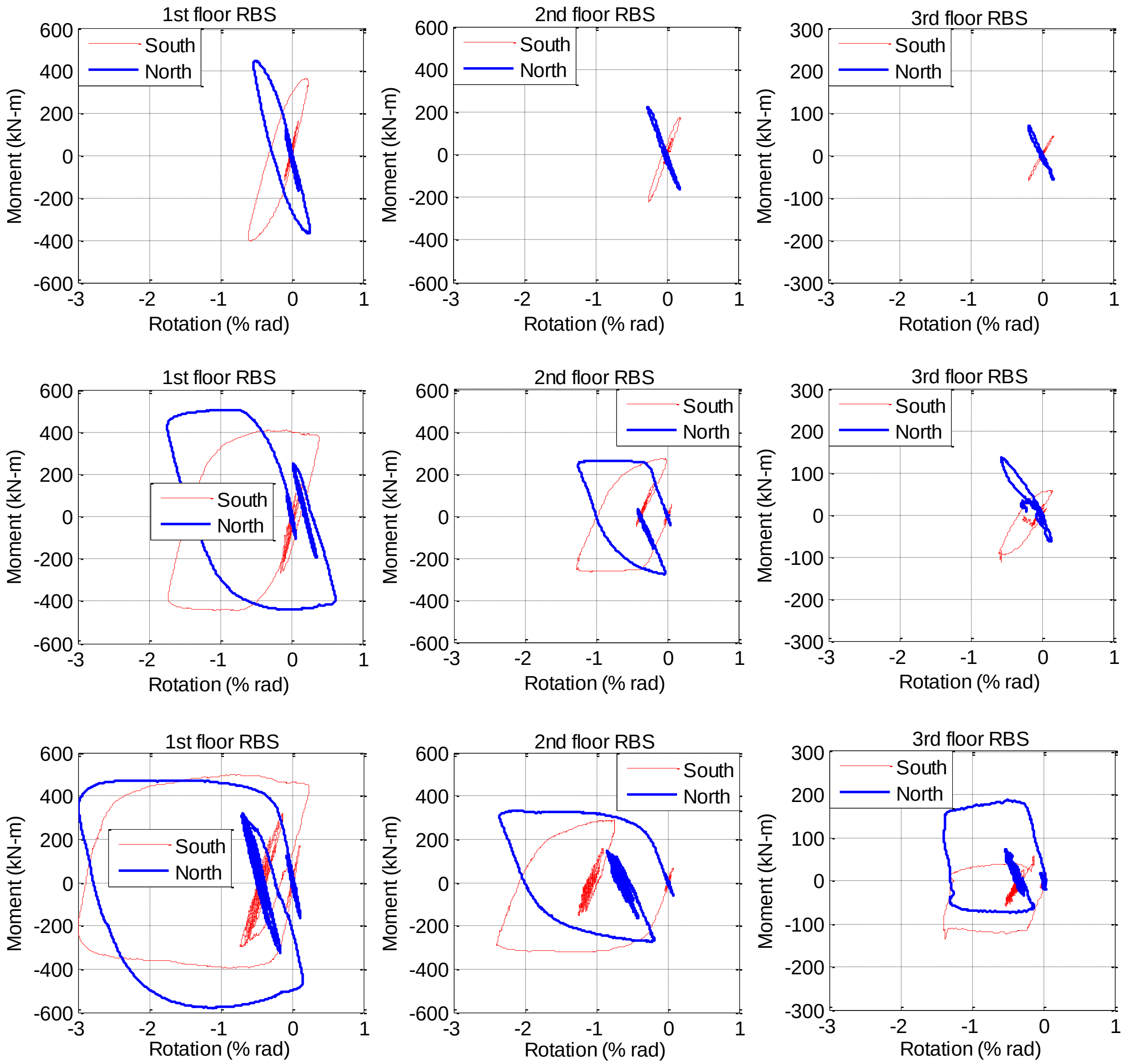
D75V Test Structure

D60V Test Structure

Beam moment-rotation (in RBS) for DBE RRS318

Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Seismic Performance of Moment Resisting Frame with Nonlinear Viscous Dampers Based on Phase-2 RTHS: Beam End Damage States for D60V



D60V Test Structure for DBE

Beam moment-rotation (incl. RBS) for scaled H-BRA315 18

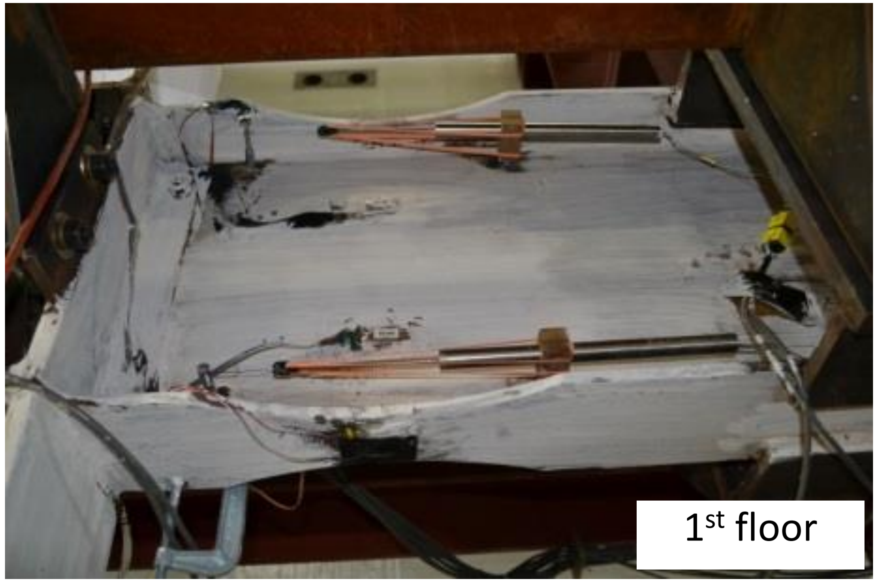
D60 Test Structure for MCE

D60V Test Structure for 1.4 MCE

Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Seismic Performance of Moment Resisting Frame with Nonlinear Viscous Dampers Based on Phase-2 RTHS: Beam End Damage States for D60V

Beam end damage states for scaled H-BRA315 18



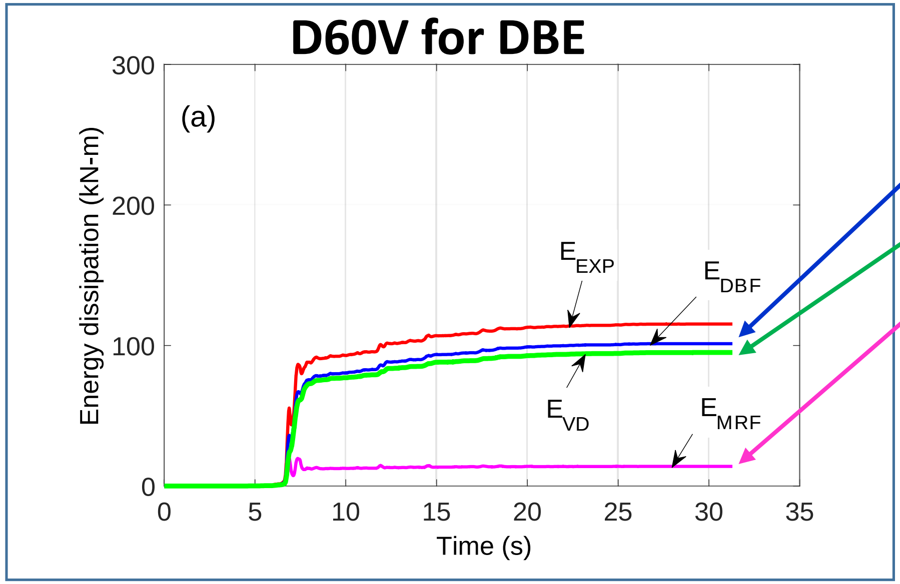
D60V Test Structure for DBE

D60 Test Structure for MCE

D60V Test Structure for 1.4 MCE

Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Seismic Performance of Moment Resisting Frame with Nonlinear Viscous Dampers Based on Phase-2 RTHS: Energy Dissipation in D60V

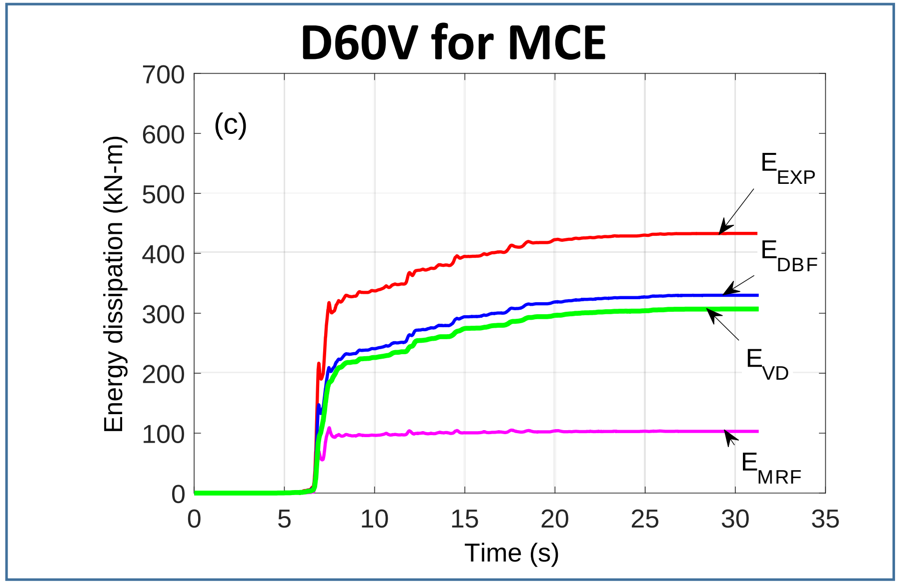


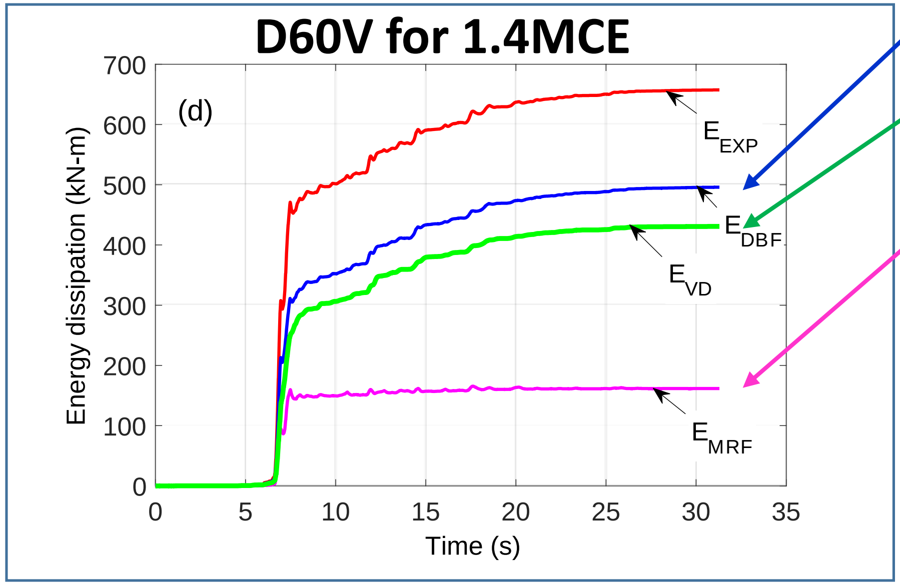
DBF (including dampers)

Dampers

MRF

Energy dissipation for scaled H-BRA315 18





DBF (including dampers)

Dampers

MRF

Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," Journal of Structural Engineering, 2016

Seismic Hazard Performance of Systems with Dampers

- RTHS can be used to quantify seismic performance of system with dampers
- RTHS results show that MRF structures with nonlinear viscous dampers have enhanced performance relative to conventional steel MRF
- D100V MRF with dampers:
  - Elastic under DBE, with minor yielding under MCE
  - Residual drift is negligible
  - Performance is close to “Immediate Occupancy” for DBE, and between “Immediate Occupancy” and “Life Safety” for MCE
- D75 and D60V MRFs with dampers:
  - Performance is between “Immediate Occupancy” and “Life Safety” for DBE and MCE
  - Significantly better performance than conventional steel MRF
- Even D60V had stable beam plastic hinges under 1.4MCE-level ground motion
- Dampers dominate energy dissipation, even for D60V MRF structure under 1.4MCE-level ground motion, when full plastic hinges form in MRF

Challenges in Achieving Seismic Hazard Mitigation Using Dampers and Other Devices: Overview of Topics

- Characterization of Devices: Testing and Models
  - Focus on characterization tests and models of dampers and other devices
- Modeling and Understanding Systems with Dampers
  - Simple models for design and to understand system/damper response
  - Accurate models for numerical simulations
- Response of Systems with Dampers During Hazard Events
  - Real-time hybrid simulations of seismic response of systems with dampers
- Hazard Mitigation Performance of Systems with Dampers
  - Seismic performance of systems with dampers
- **Summary of Issues and Thoughts Suggested by Lab Experiences**

Summary of Issues and Thoughts Suggested by Lab Experiences

- There is an essential need to understand and quantify response (and performance) of systems with protective devices under hazard events – this is essential knowledge for hazard mitigation
- Science and technology of protective devices is still an open research field
  - Potential for new materials and devices
  - Greater potential for structural systems that better utilize devices
- Firm belief in numerical simulations … … but we also see unexpected (based on numerical simulation) results in the lab
- This presentation shows that devices within systems may not respond as anticipated, and interactions with system (e.g., “brace stiffness”) may reduce effectiveness of devices and may alter response of system in unexpected ways

Summary of Issues and Thoughts Suggested by Lab Experiences

- Numerical simulations, RTHS, and shake table simulations are essential tools for studying structural systems with protective devices
- Device characterization testing and related force-deformation models are essential
- Simple force-deformation models for devices provide the framework for understanding and improving devices, for understanding the response of systems with devices, and for system design
- Research projects on systems with protective devices should include:
  - Characterization tests or existing, accurate characterization data for devices
  - Accurate force-deformation models for devices for numerical simulations
  - Simple force-deformation models for devices
  - Numerical simulations, RTHS, and/or shake table tests to understand system response and performance

Challenges in Achieving Natural Hazards Mitigation Using Protective Devices

Comments and Discussion