Seismic Response of Steel MRF Structures with Nonlinear Viscous Dampers from Real-time Hybrid Simulations: Focus on Brace/Connection Flexibility

Prof. Richard Sause,

Prof. James M. Ricles, Dr. Baiping Dong

Advanced Technology for Large Structural Systems (ATLSS) Center
Department of Civil and Environmental Engineering
Lehigh University

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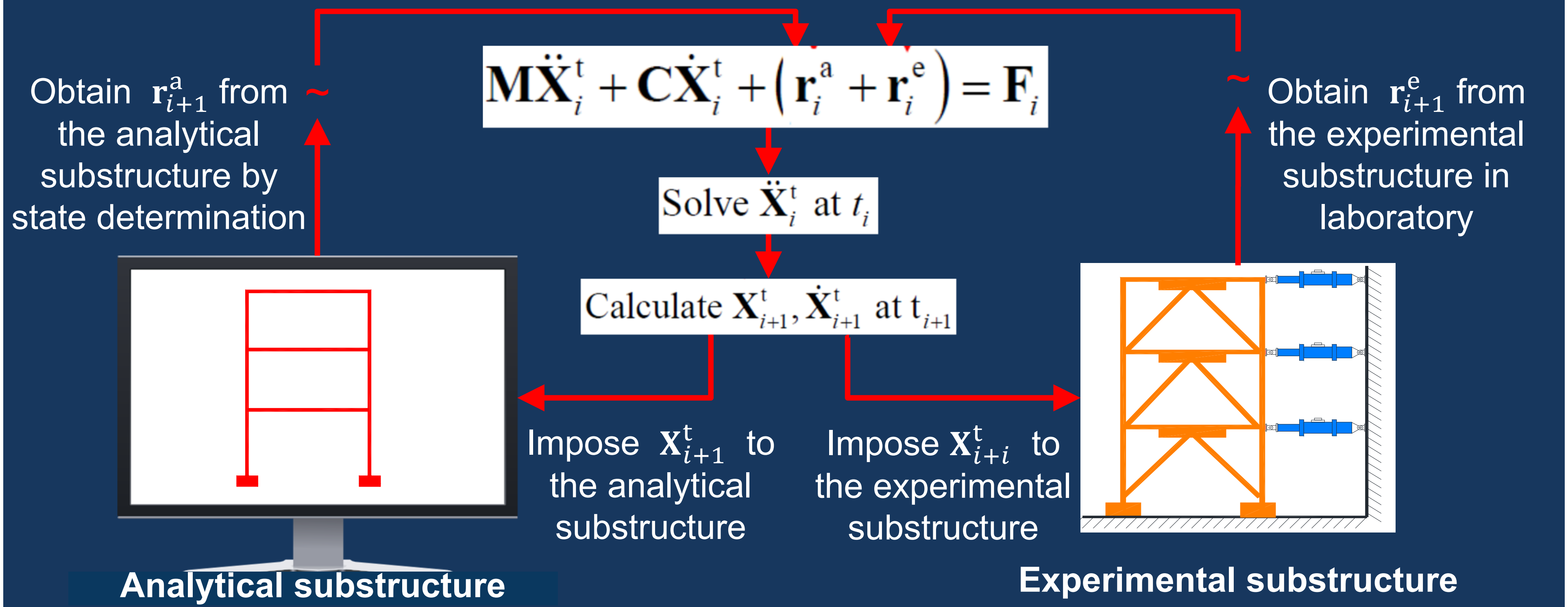
Overview of Real-time Hybrid Simulation (RTHS)

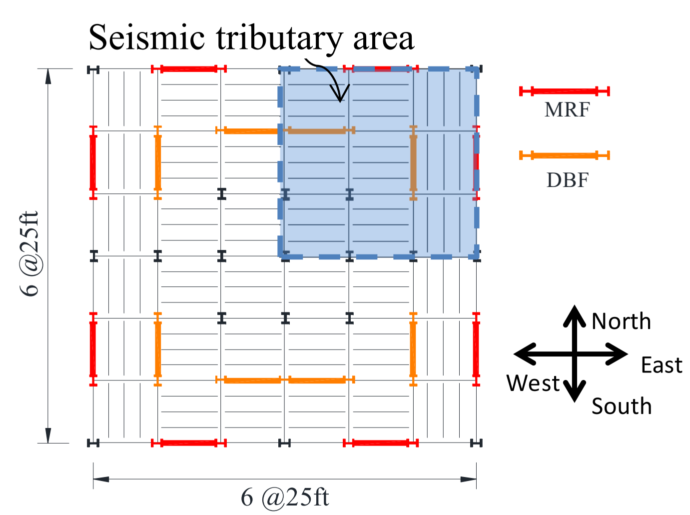
- In RTHS, complete structural system is divided into experimental (physical) and analytical (numerical) substructures
- Target displacements determined from equations of motion and imposed in real time on experimental and analytical substructures
- Restoring forces from experimental and analytical substructures feed back into equations of motion



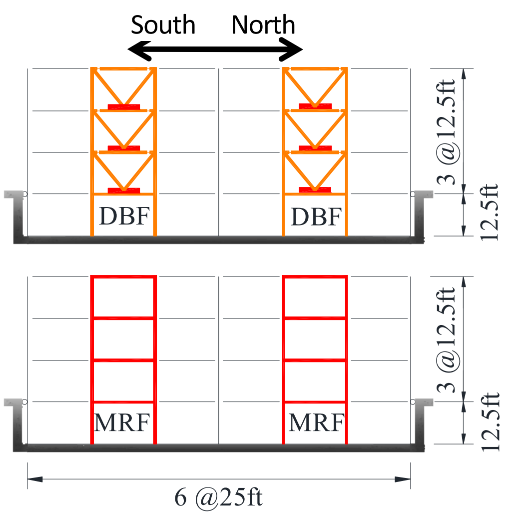
Moment-Resisting Frame (MRF) Building Structure with Nonlinear Viscous Dampers

Prototype building

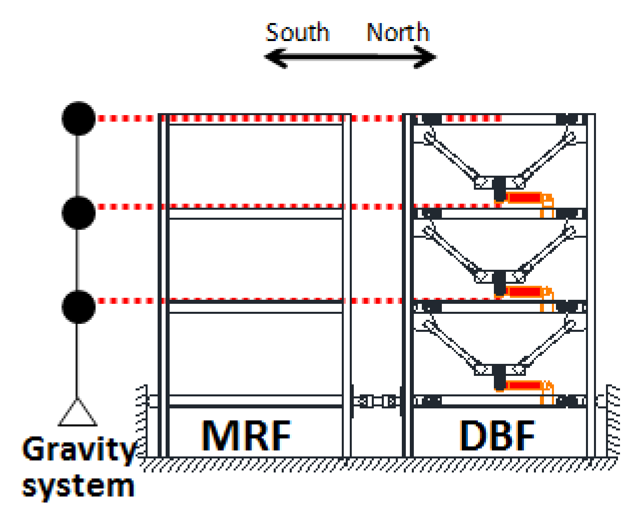
- 3-story, 6-bay by 6-bay office building (Southern California)
- Test structure includes moment resisting frame (MRF), damped brace frame (DBF), gravity load system



Plan view of prototype building



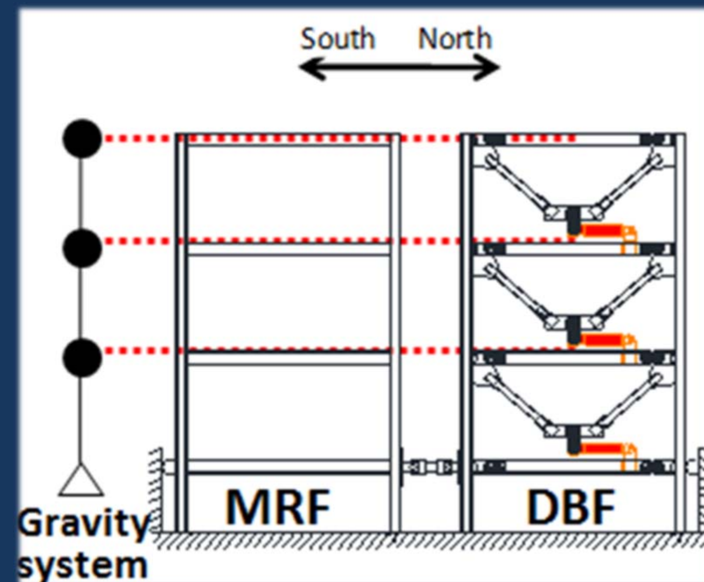
Section view of prototype building



Test structure

Design of MRF Structure with Nonlinear Viscous Dampers: Full Strength MRF

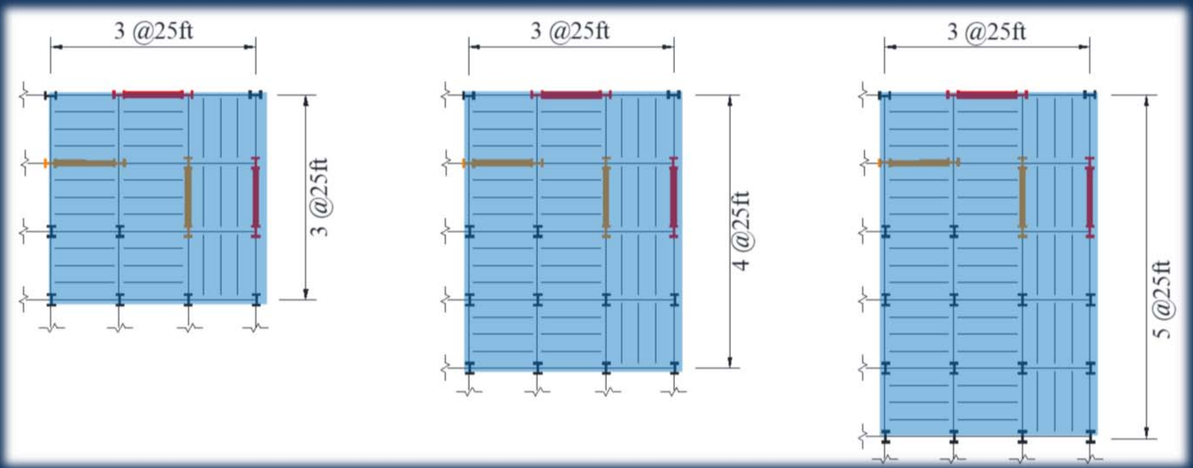
- Design of full strength MRF (D100V)
  - MRF (D100V) is designed to satisfy strength requirement (ASCE 7-10)
  - MRF (D100V) not designed to meet lateral drift requirement in ASCE7-10, lateral drifts are controlled by dampers
- With (3) 600 kN dampers, lateral story drift predicted in design was approx. 1% for design basis earthquake (DBE), with 10% probability of exceedance in 50 yrs
- Damped braced frame (DBF) members designed for maximum forces from dampers



Variations of MRF Building Structures Studied Using RTHS: Reduced Strength MRFs

Use of RTHS 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

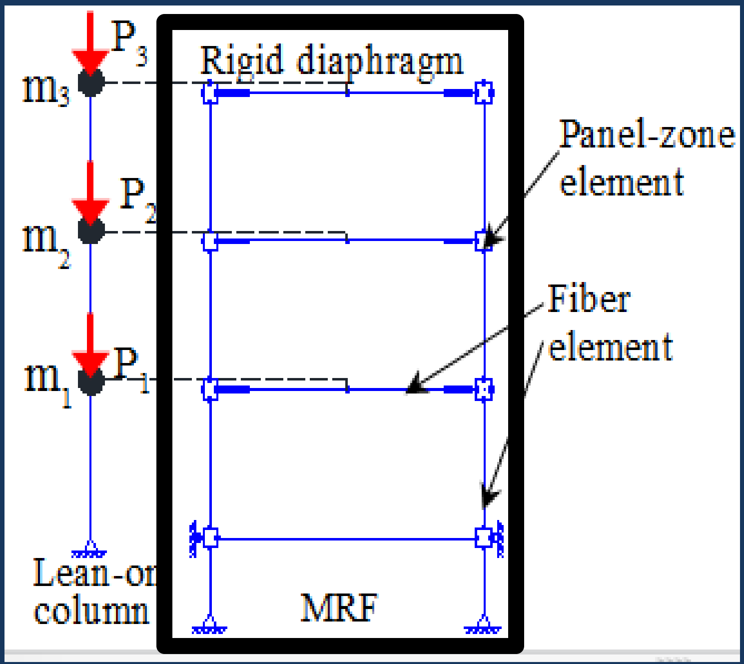
(b) Seismic tributary area for D75V Test Structure

(c) Seismic tributary area for D60V Test Structure

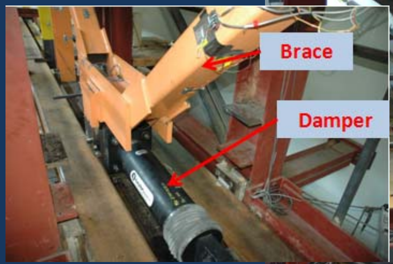
Increase seismic tributary area (mass and gravity system) in analytical substructure for reduced strength MRF building structures

Phase-1 RTHS on MRF Structures with Nonlinear Viscous Dampers

Phase-1 Substructures



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



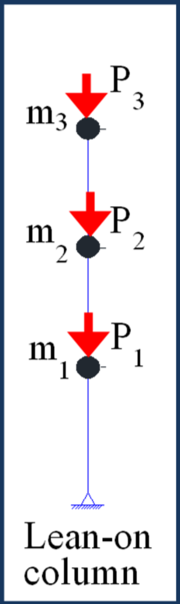
Experimental substructure (0.6-scale DBF)

Details of Analytical Substructure

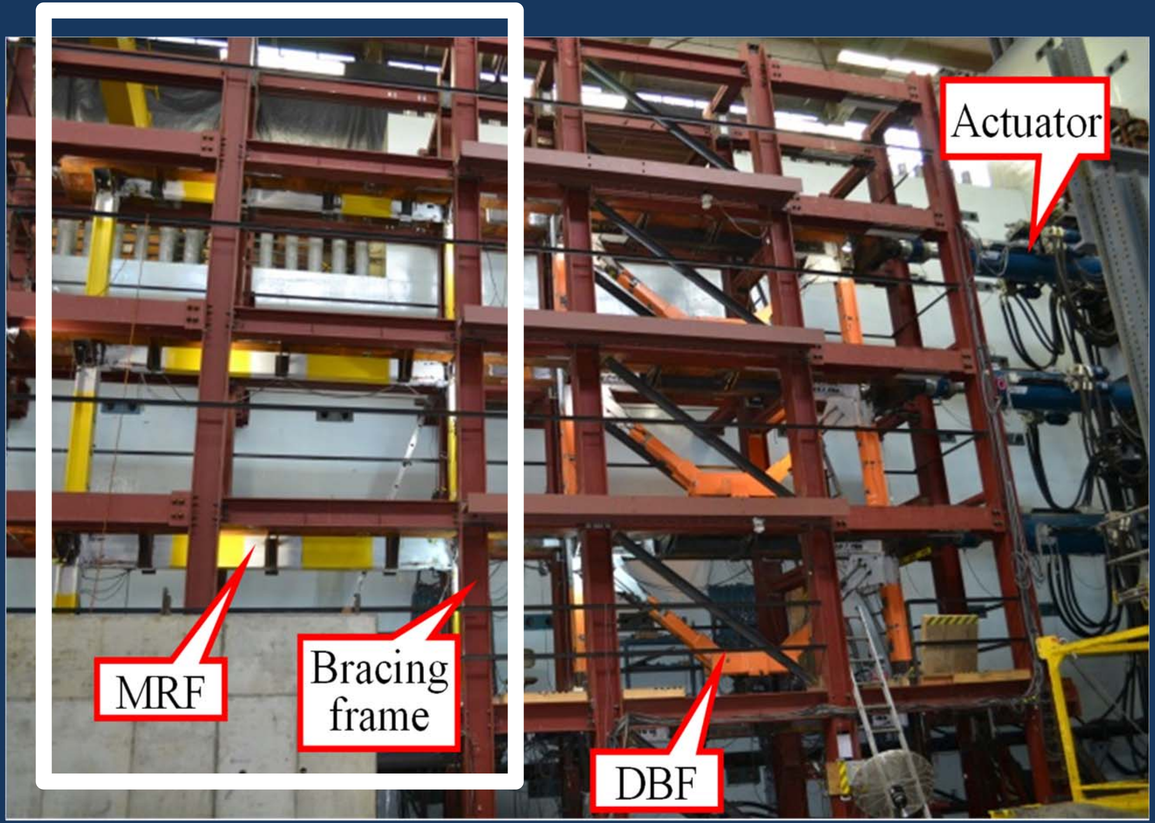
- Analytical substructure has 296 DOFs and 91 elements
- Nonlinear fiber element for beams, columns, and RBS
- Panel zone element for panel zone of beam-column connection
- Elastic beam-column element for the lean-on column
- P-delta effects included in the analytical substructure

Phase-2 RTHS on MRF Structures with Nonlinear Viscous Dampers

Phase-2 Substructures



Analytical substructure (mass, gravity system, inherent damping)

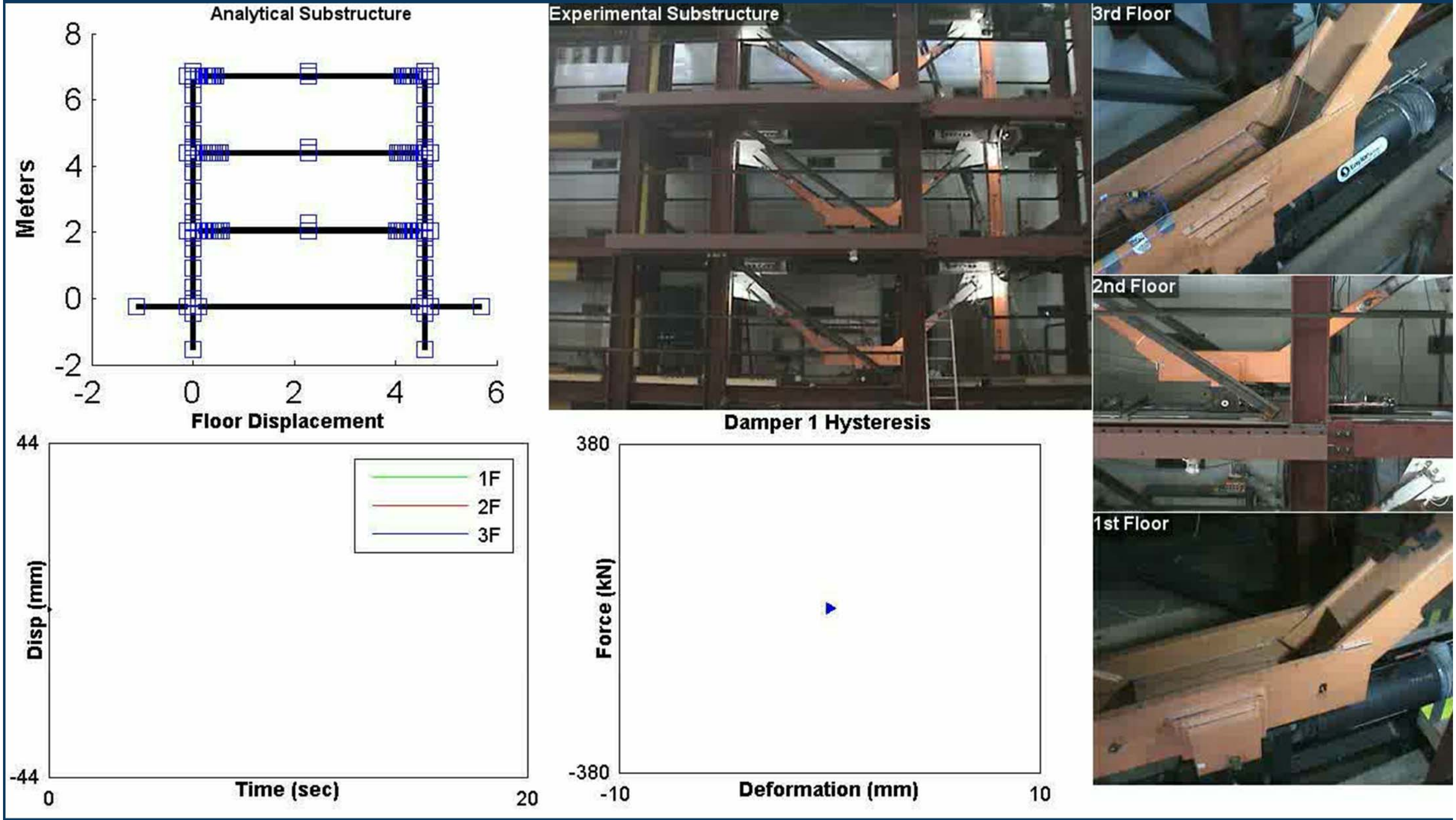


Experimental substructure (0.6-scale MRF and DBF)

Details of Analytical Substructure

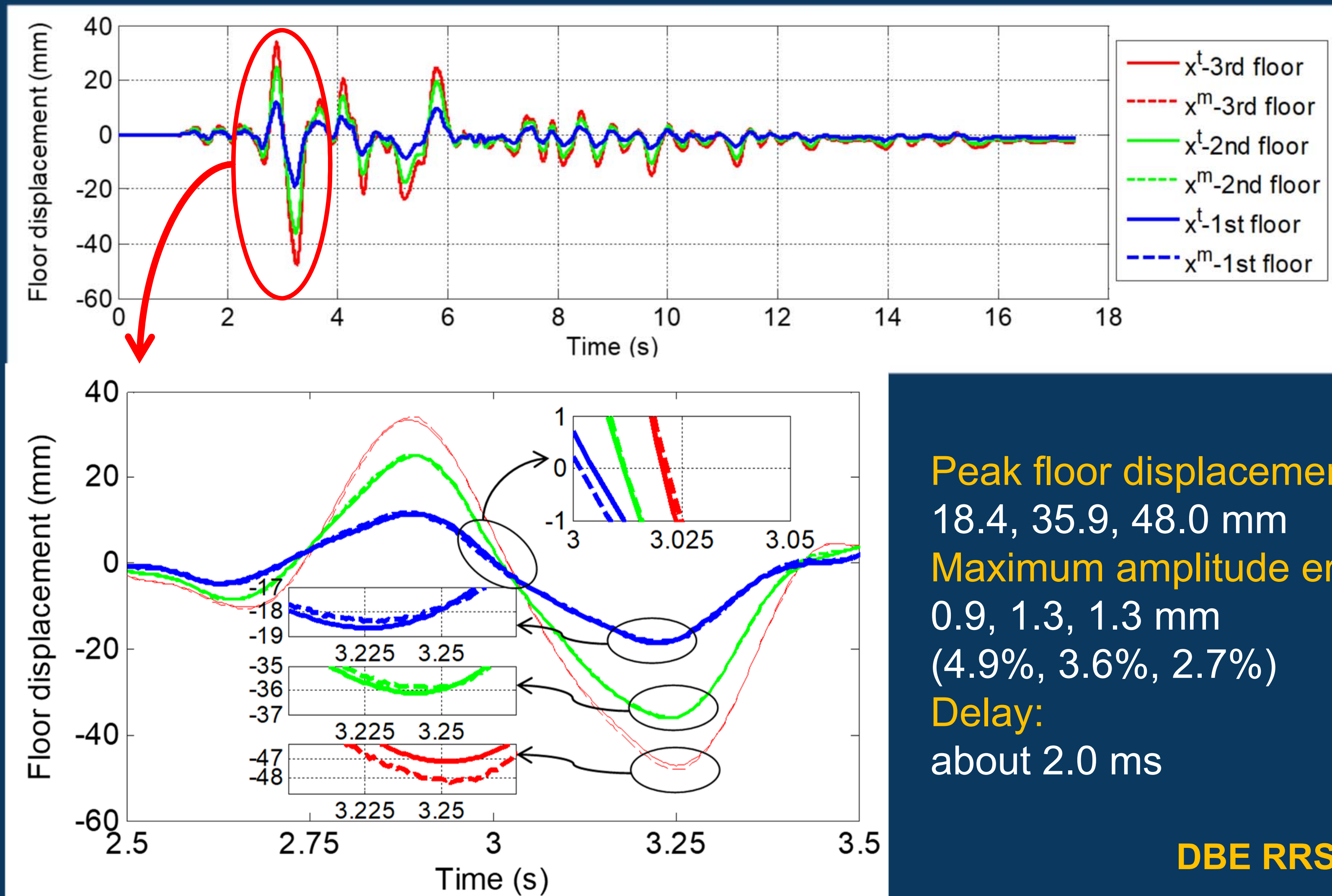
- The analytical substructure has 10 DOFs and 3 elements
- Elastic beam-column element for the lean-on column
- P-delta effects included in the analytical substructure

Phase-1 RTHS on MRF Structure with Nonlinear Viscous Dampers



Phase-1 RTHS Results Evaluation: Design Basis Earthquake (DBE) Level

10% probability of exceedance in 50 years

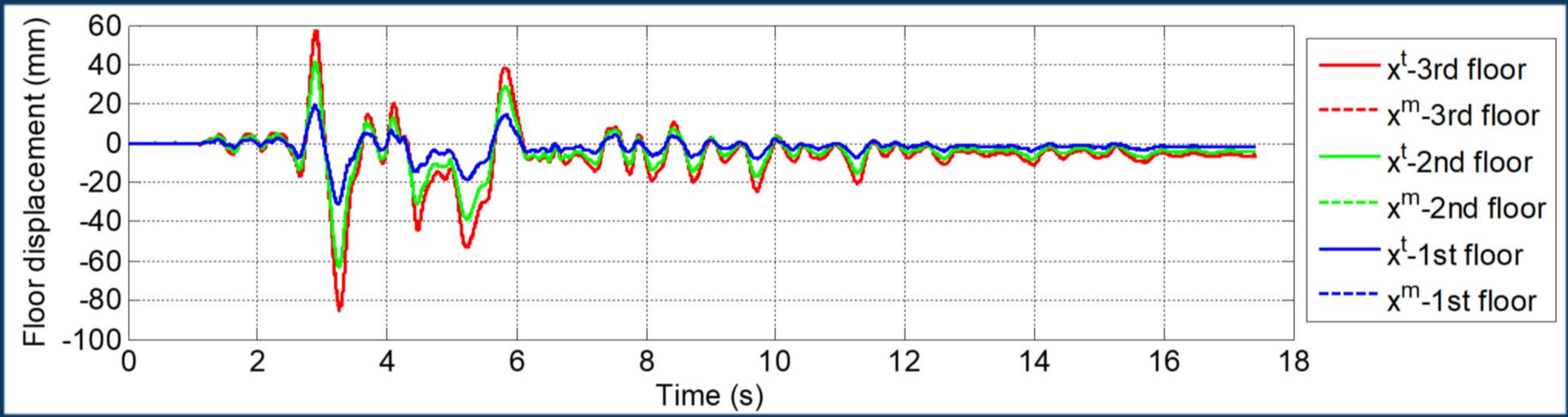


Peak floor displacement:
18.4, 35.9, 48.0 mm
Maximum amplitude error:
0.9, 1.3, 1.3 mm
(4.9%, 3.6%, 2.7%)
Delay:
about 2.0 ms

DBE RRS318

Phase-1 RTHS Results Evaluation: Maximum Considered Earthquake (MCE) Level

2% probability of exceedance in 50 years



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

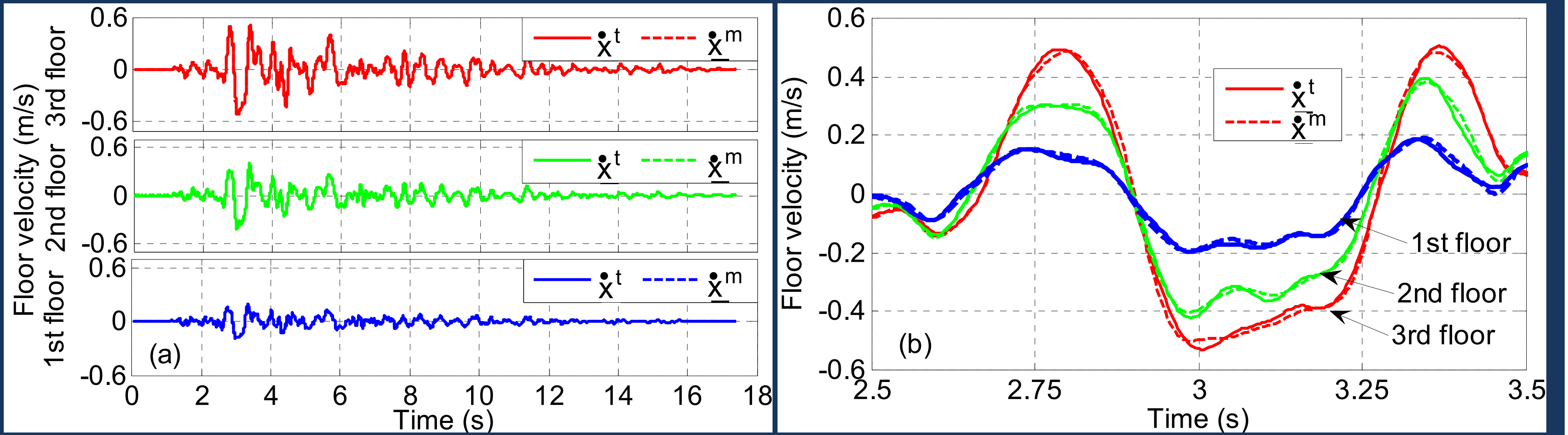
MCE RRS318

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; 44(12)

Phase-1 RTHS Results Evaluation: Maximum Considered Earthquake (MCE) Level

2% probability of exceedance in 50 years

Floor velocity response



Peak velocity: 0.198, 0.422, 0.531 m/s

Maximum difference: 0.005, 0.007, 0.009m/s (2.5%, 1.7%, 1.7%)

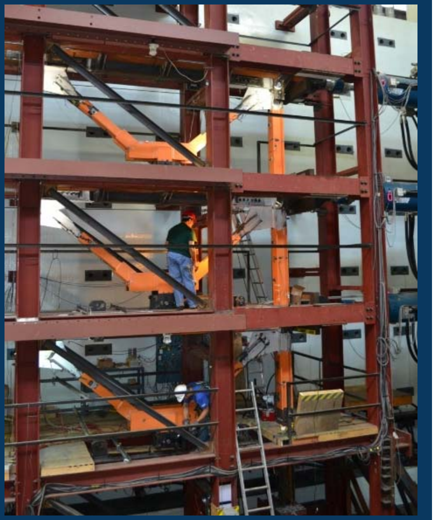
MCE RRS318

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; 44(12)

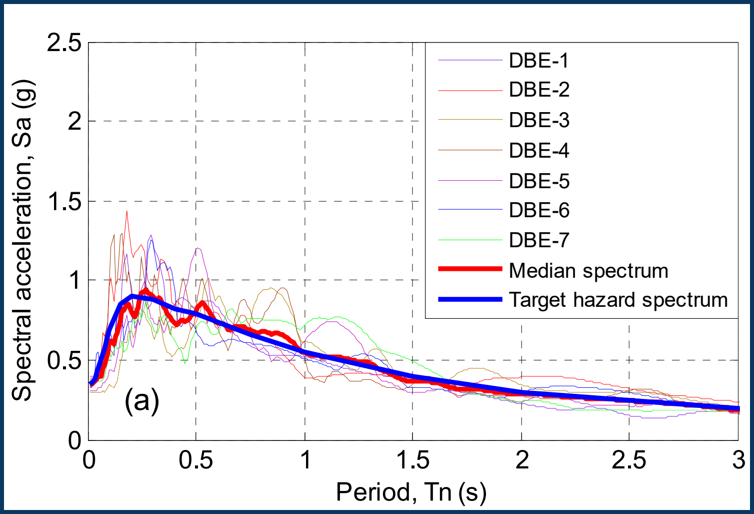
Advantage of Phase-1 RTHS

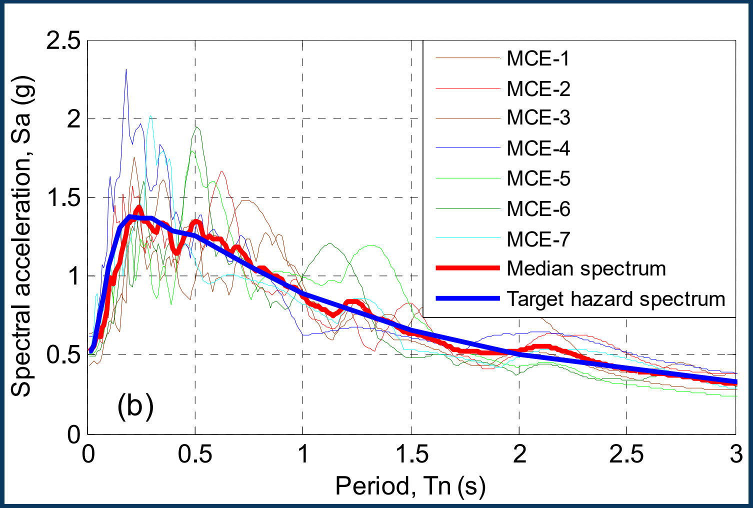
Phase-1 RTHS: damage is confined to MRF in analytical substructure (new for each RTHS); experimental substructure (DBF with dampers) is undamaged by DBE and MCE level input

Therefore, ensemble of ground motion records was used for Phase-1 RTHS; account for record-to-record variability



Experimental substructure (DBF)





Response spectra for ground motions (a) DBE level; (b) MCE level

Statistical Evaluation of Lateral Story Drift Response from Phase-1 RTHS: Full Strength D100V MRF Test Structure

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**	**0.76**	**0.53**
DBE PBD prediction	**0.76**	**0.81**	**0.64**

DBE level RTHS:

- 10% probability of exceedance in 50 yrs
- Mean maximum lateral story drift: **0.69%, <u>0.76%</u>, and 0.53%** for the 1st, 2nd, and 3rd story

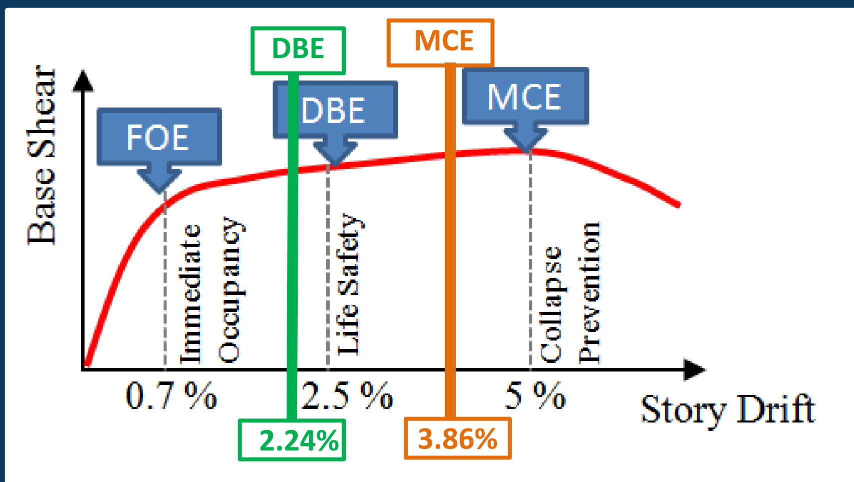
Ground Motion No.	Story drift (%)		
	1st story	2nd story	3rd story
MCE-1	1.25	1.48	1.09
MCE-2	1.10	1.29	0.88
MCE-3	1.18	1.34	1.03
MCE-4	1.09	1.35	1.02
MCE-5	1.27	1.39	0.98
MCE-6	1.07	1.24	0.91
MCE-7	1.32	1.44	1.00
MCE Mean	**1.20**	**1.38**	**1.00**
MCE PBD prediction	**1.33**	**1.41**	**1.12**

MCE level RTHS:

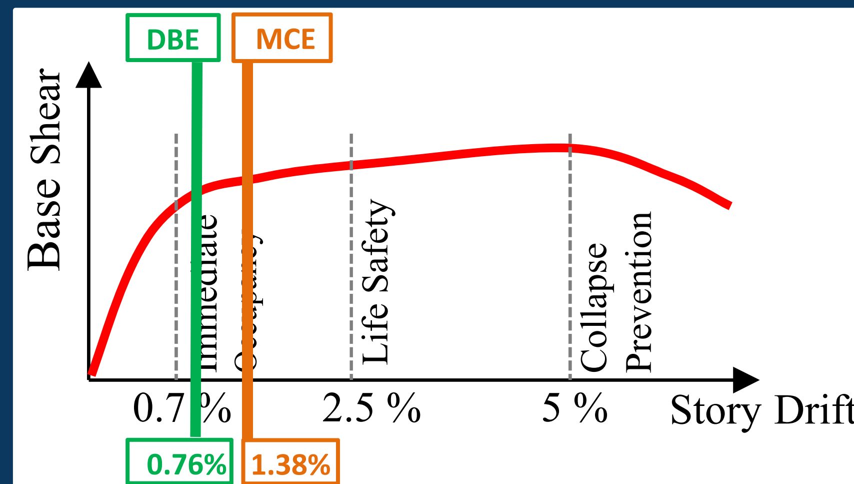
- 2% probability of exceedance in 50 yrs
- Mean maximum lateral story drift: **1.20%, <u>1.38%</u>, and 1.00%** for the 1st, 2nd, and 3rd story

Performance of MRF Structures with Nonlinear Viscous Dampers from Phase-1 RTHS: Full Strength D100V MRF Test Structure

D100V (without dampers)



D100V (with dampers)

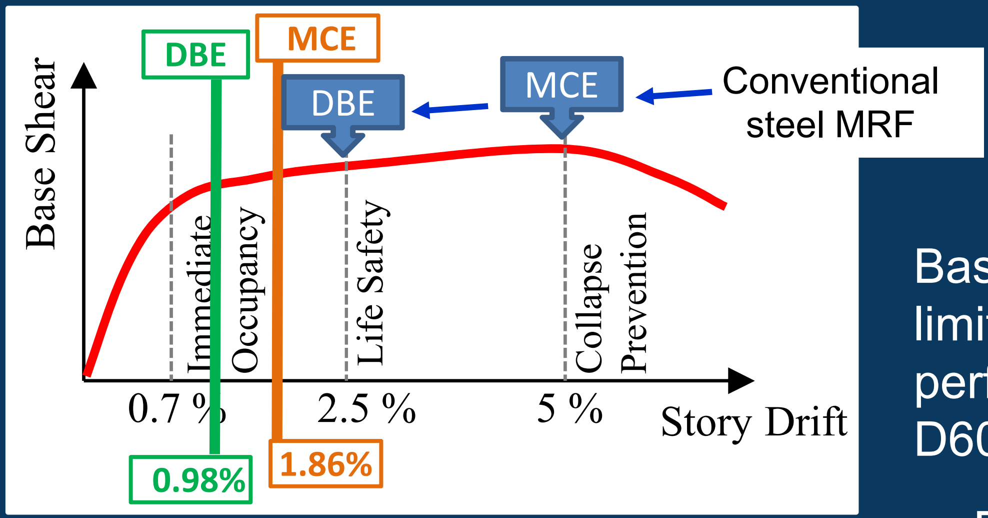


D100V MRF with dampers

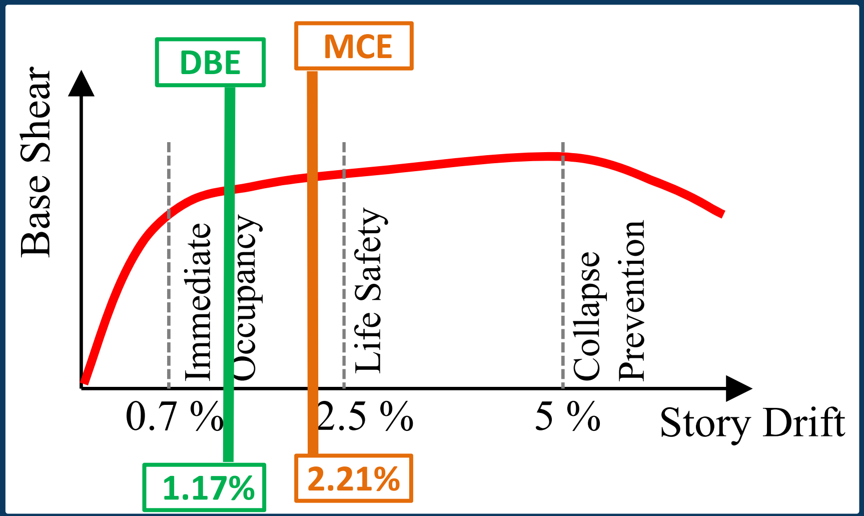
- Based on lateral story drift limits in ASCE/SEI 41-06, performance of D100V with dampers:
  - Close to “Immediate Occupancy” for DBE
  - Between “Immediate Occupancy” and “Life Safety” for MCE

Performance of MRF Structures with Nonlinear Viscous Dampers from Phase-1 RTHS: Reduced Strength D75V and D60V MRF Test Structures

D75V (with dampers)



D60V (with dampers)

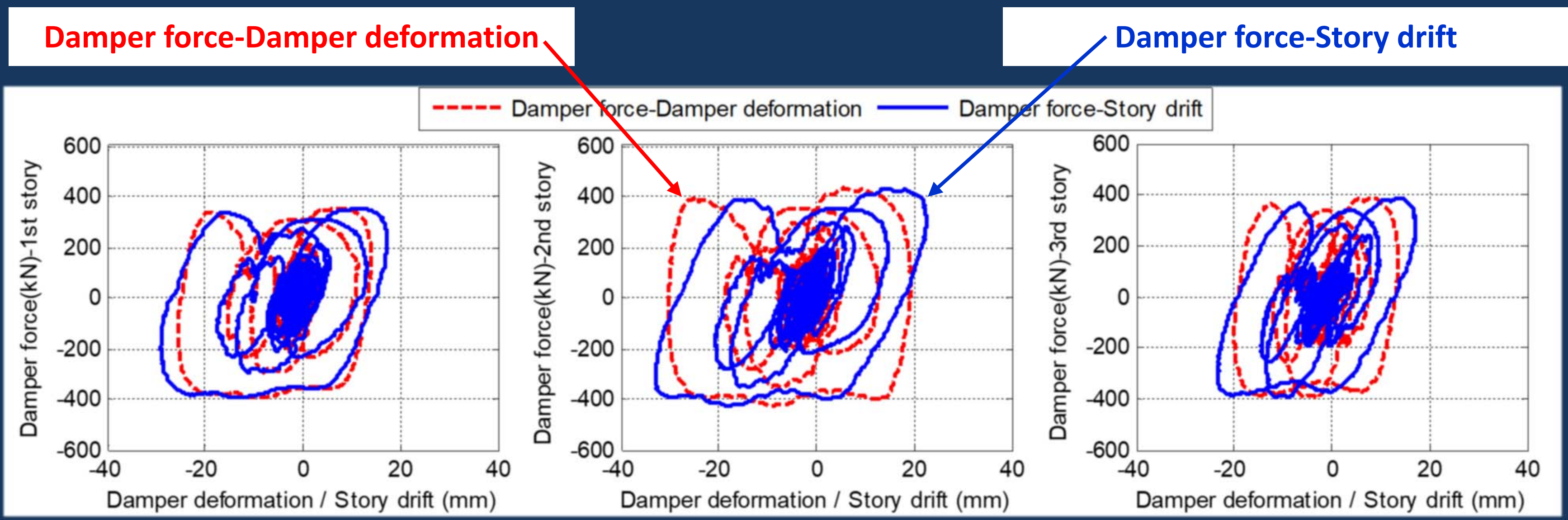


Based on lateral story drift limits in ASCE/SEI 41-06, performance of D75 and D60V with dampers is:

- Between “Immediate Occupancy” and “Life Safety” for DBE and MCE
- Significantly better than conventional steel MRF

Response of MRF Structures with Nonlinear Viscous Dampers from Phase-1 RTHS: Full Strength D100V MRF Test Structure

In-phase behavior of damper force with story drift



Deformations of DBF members/connections adjacent to dampers cause differences between damper deformation and story drift (so-called "brace flexibility" effect)

<u>Damper forces are partially in-phase with elastic forces</u>

As a result, system of dampers and bracing adds stiffness to DBF

MCE RRS318

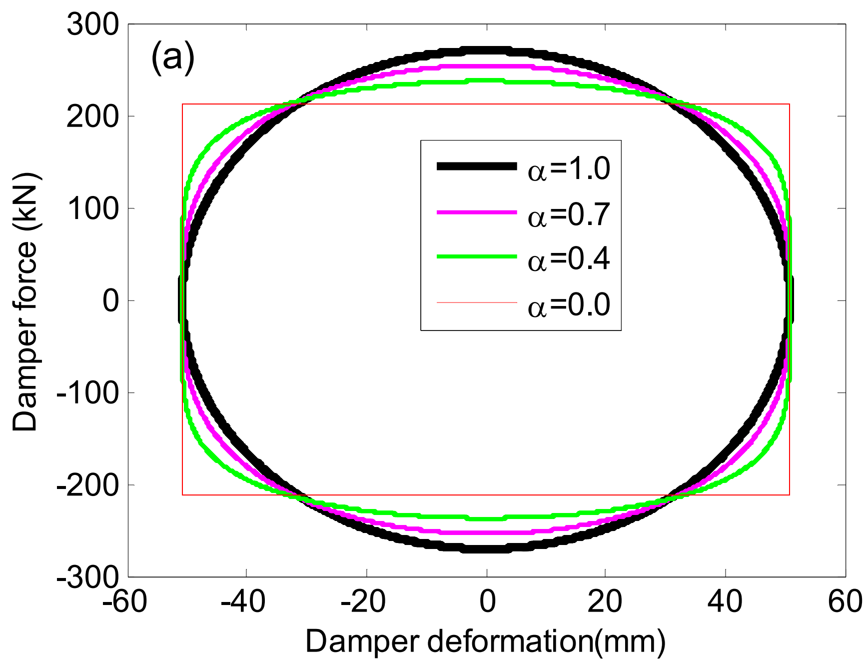
Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," *Journal of Structural Engineering*, 2016; 142(6)

Nonlinear Viscous Damper Response

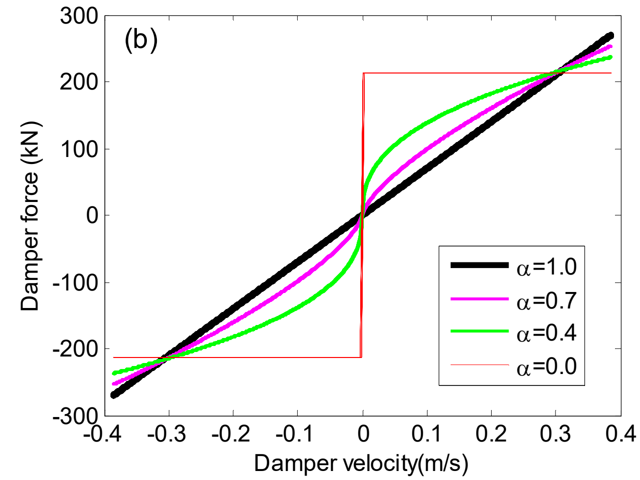
Theoretical nonlinear viscous damper hysteresis

$$f_d(t) = C_\alpha \mathrm{sgn}(\dot{u}_d(t))|\dot{u}_d(t)|^\alpha$$

$f_d(t)$ -damper force;
$\dot{u}_d(t)$ - damper relative velocity;
$\mathrm{sgn}(\dot{u}_d(t))$ -polarity of damper velocity;
C_α -damping coefficient;
α -velocity exponent.



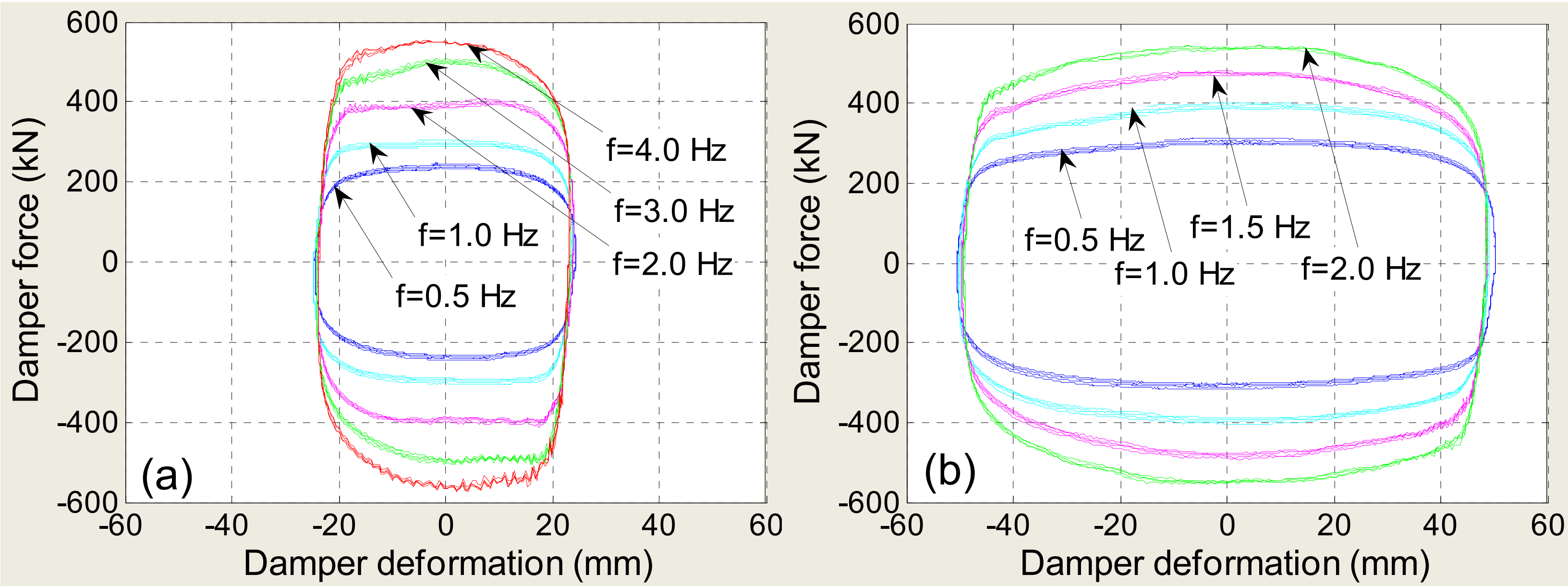
Force-deformation response



Force-relative velocity response

Nonlinear Viscous Damper Response

Experimental nonlinear viscous damper hysteresis

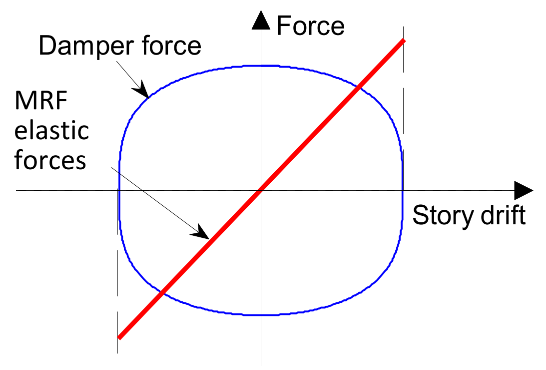


Damper force versus deformation response from characterization tests

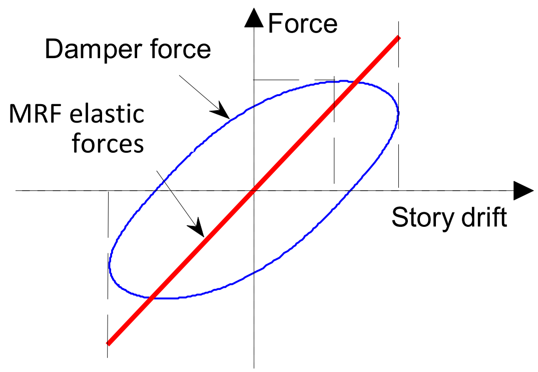
(C_α=696 kN-s/m and α=0.44)

Response of MRF Structures with Nonlinear Viscous Dampers from Phase-1 RTHS: Full Strength D100V MRF Test Structure

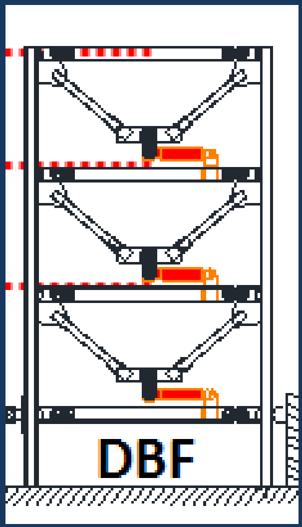
In-phase behavior of damper force with story drift



Theoretical (intended) damper force-story drift hysteresis



Actual damper force-story drift hysteresis with flexibility of adjacent members



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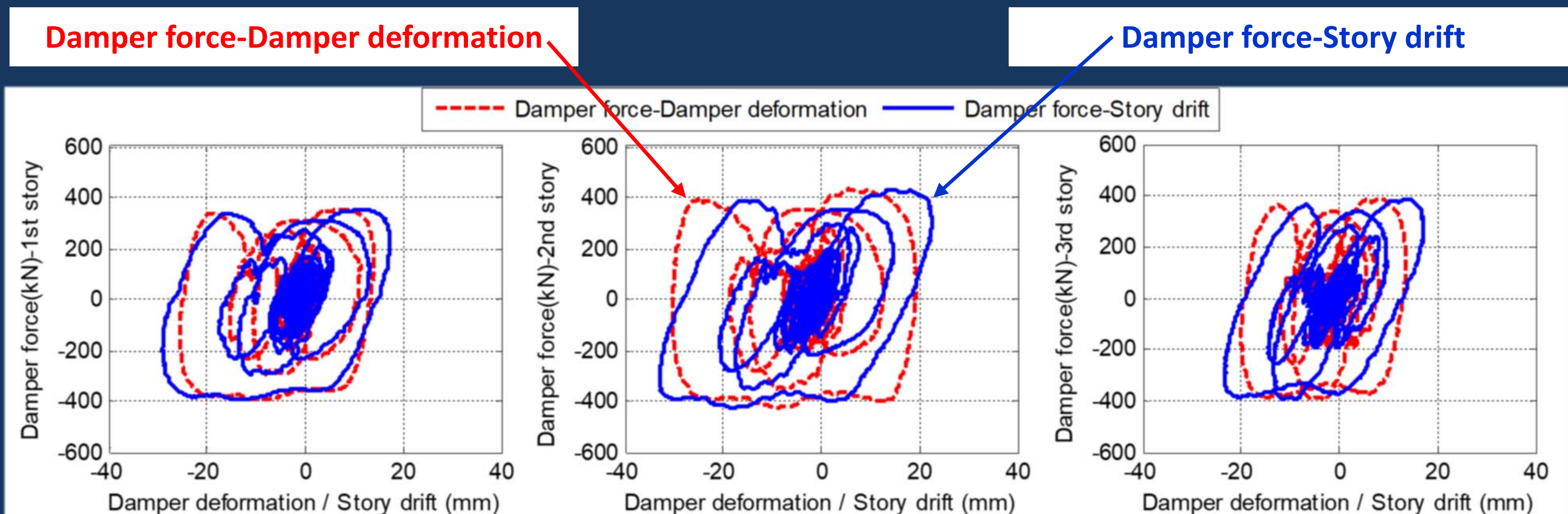
Response of MRF Structures with Nonlinear Viscous Dampers from Phase-1 RTHS: Full Strength D100V MRF Test Structure

In-phase behavior of damper force with story drift



Deformations of DBF members/connections adjacent to dampers cause differences between damper deformation and story drift (so-called "brace flexibility" effect)

Damper forces are partially in-phase with elastic forces

As a result, system of dampers and bracing adds stiffness to DBF

MCE RRS318

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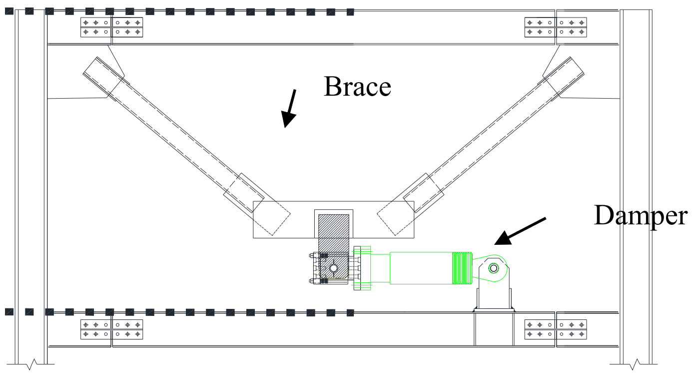
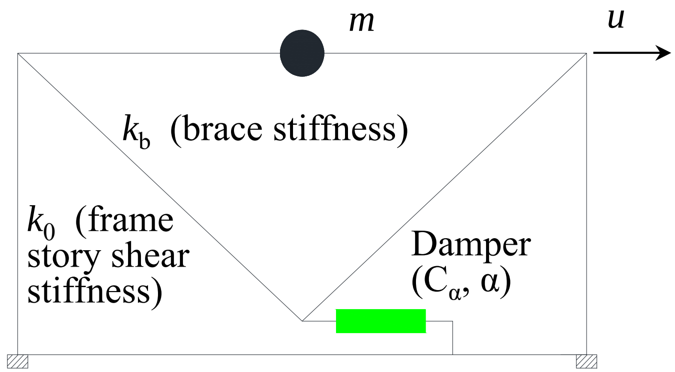
Equivalent Linear Model for Nonlinear Viscous Damper in Steel Frame Considering Bracing Flexibility

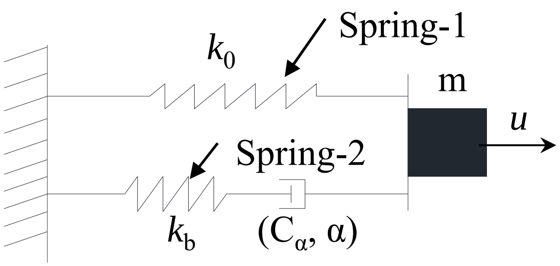
Analysis of single story treated as SDOF





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

Dong, B. "Large-scale Experimental, Numerical, and Design Studies of Steel MRF Structures with Nonlinear Viscous Dampers under Seismic Loading," PhD Dissertation, Lehigh University, Bethlehem, PA.

Dong, B., Sause, R., and Ricles, J.M., "Equivalent Linearized Model of Damper Response for Seismic Design of Steel Structures with Nonlinear Viscous Dampers," 8th International Conference on Behavior of Steel Structures in Seismic Areas (STESSA), Shanghai, China, July 1-3, 2015.

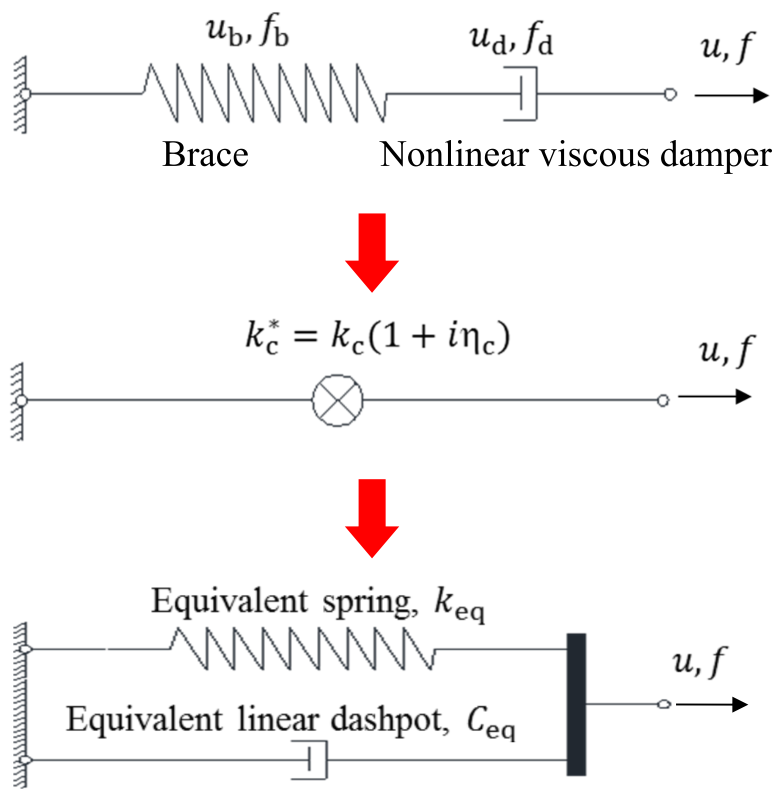
Equivalent Linear Elastic-Viscous Model for Damper-Brace Component

Sequence of models for equivalent linearization

(a) Damper-brace component

(b) Equivalent viscoelastic model

(c) Equivalent elastic-viscous 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, Bethlehem, PA.

Equivalent Linear Elastic-Viscous Model for Damper-Brace Component

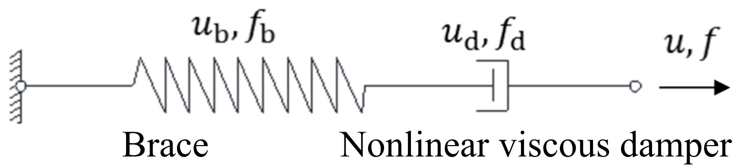
Damper-brace component stiffness in frequency domain

Damper stiffness in frequency domain:

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

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

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



(a) Damper-brace component

Combined stiffness for damper-brace component:

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

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

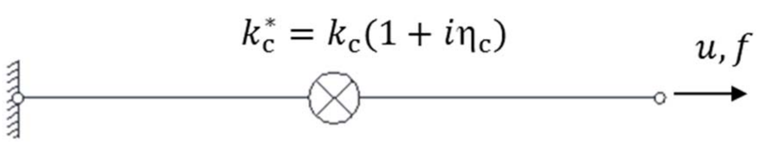
Equivalent Linear Elastic-Viscous Model for Damper-Brace Component

Equivalent viscoelastic model

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

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

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



(b) Equivalent viscoelastic model

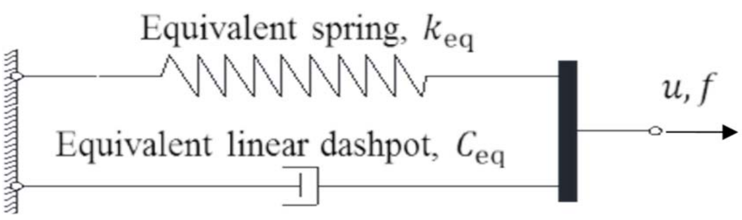
Dong, B. "Large-scale Experimental, Numerical, and Design Studies of Steel MRF Structures with Nonlinear Viscous Dampers under Seismic Loading," PhD Dissertation, Lehigh University, Bethlehem, PA.

Equivalent Linear Elastic-Viscous Model for Damper-Brace Component

Equivalent linear elastic-viscous model

Equivalent linear spring stiffness:

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



(c) Equivalent linear elastic-viscous model

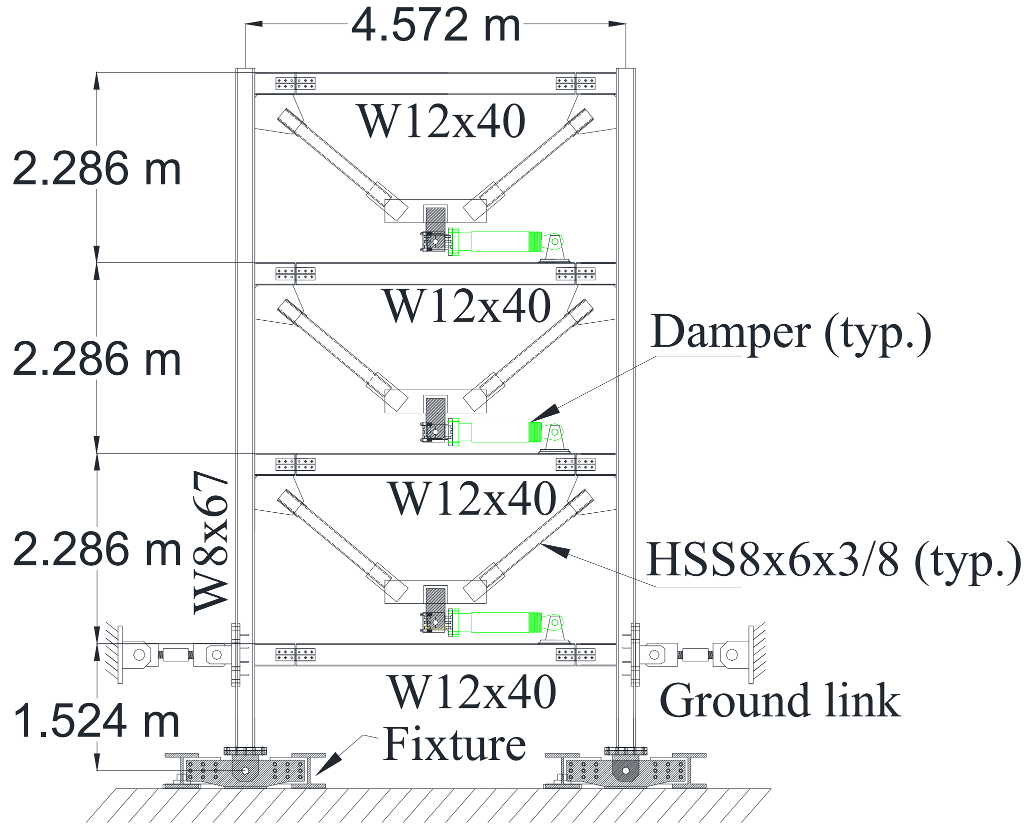
Equivalent linear dashpot dissipates same energy at given frequency:

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

Dong, B. "Large-scale Experimental, Numerical, and Design Studies of Steel MRF Structures with Nonlinear Viscous Dampers under Seismic Loading," PhD Dissertation, Lehigh University, Bethlehem, PA.

Validation of Equivalent Linear Elastic-Viscous Model for Damper-Brace Component

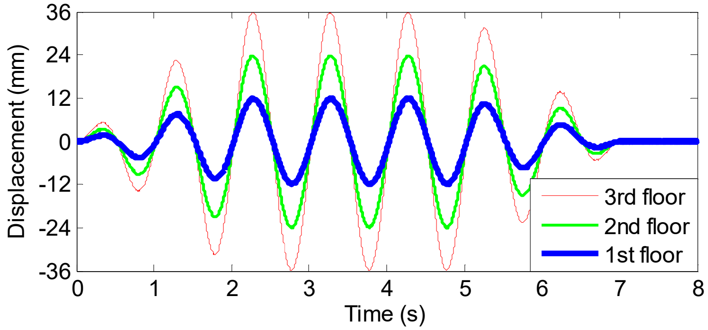
Test structure with nonlinear viscous dampers



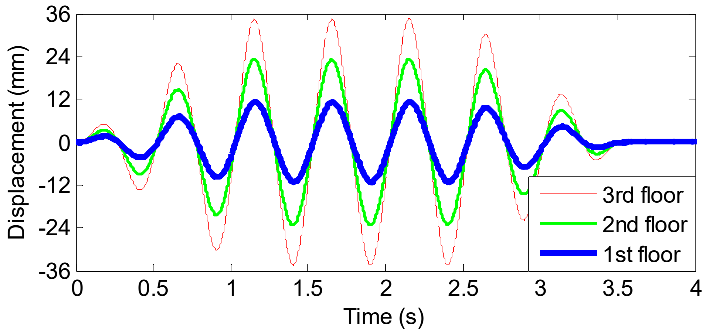
Dong, B. "Large-scale Experimental, Numerical, and Design Studies of Steel MRF Structures with Nonlinear Viscous Dampers under Seismic Loading," PhD Dissertation, Lehigh University, Bethlehem, PA.

Validation of Equivalent Linear Elastic-Viscous Model for Damper-Brace Component

Harmonic tests with predefined floor displacements



1.0 Hz

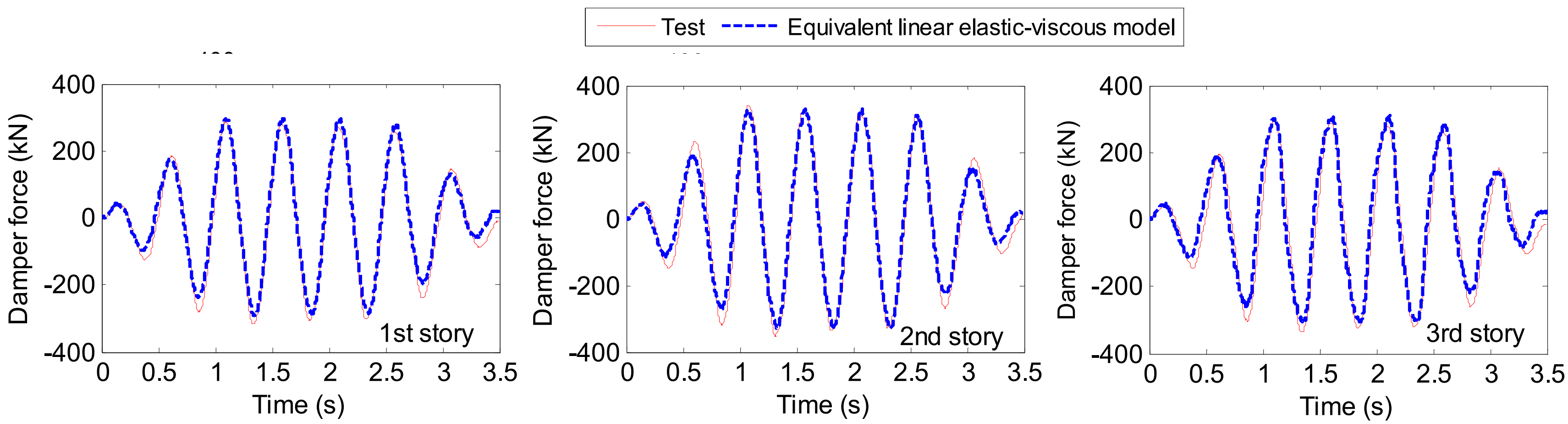


2.0 Hz

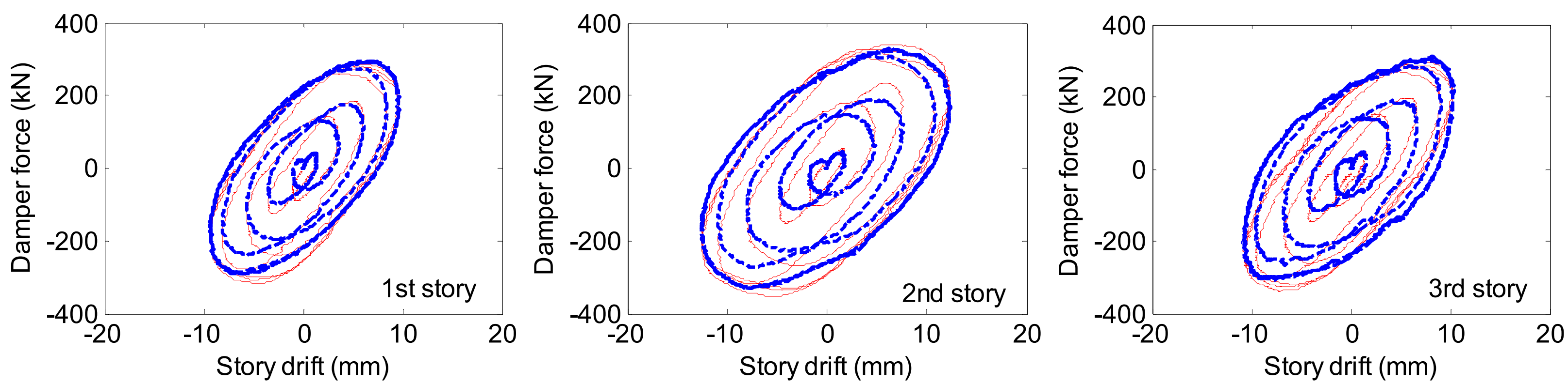
Predefined floor displacement time histories

Validation of Equivalent Linear Elastic-Viscous Model for Damper-Brace Component

Test results at 2.0Hz



Comparison of damper force time histories



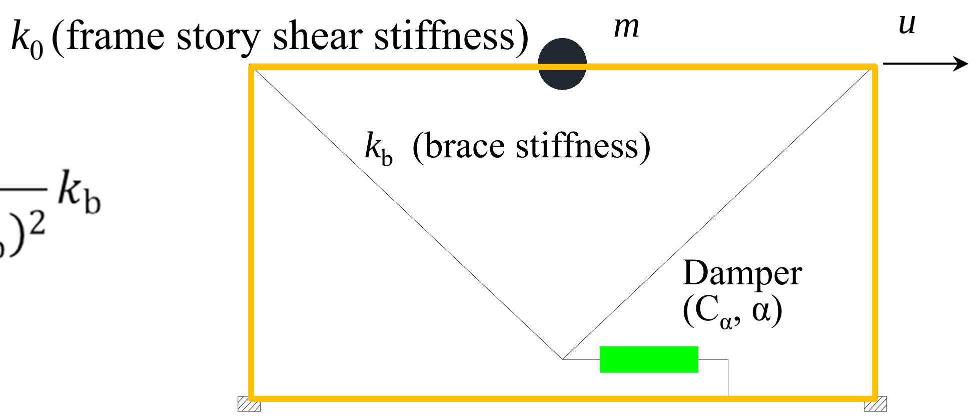
Comparison of damper force-story drift hysteresis behavior

Combined System using Equivalent Linear Elastic-Viscous Model for Damper-Brace Component

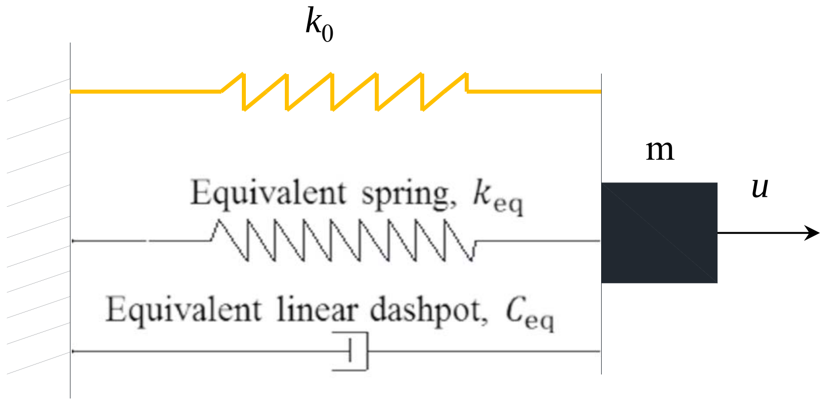
Effective stiffness and damping ratio for combined system of damper-brace component and frame story shear stiffness (k_0)

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

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



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)



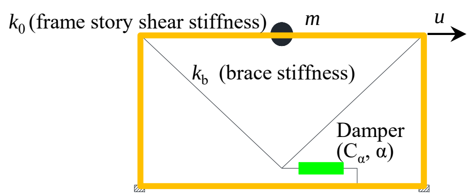
Use of Equivalent Linear Elastic-Viscous Model to Study Effect of Brace Stiffness on Combined System

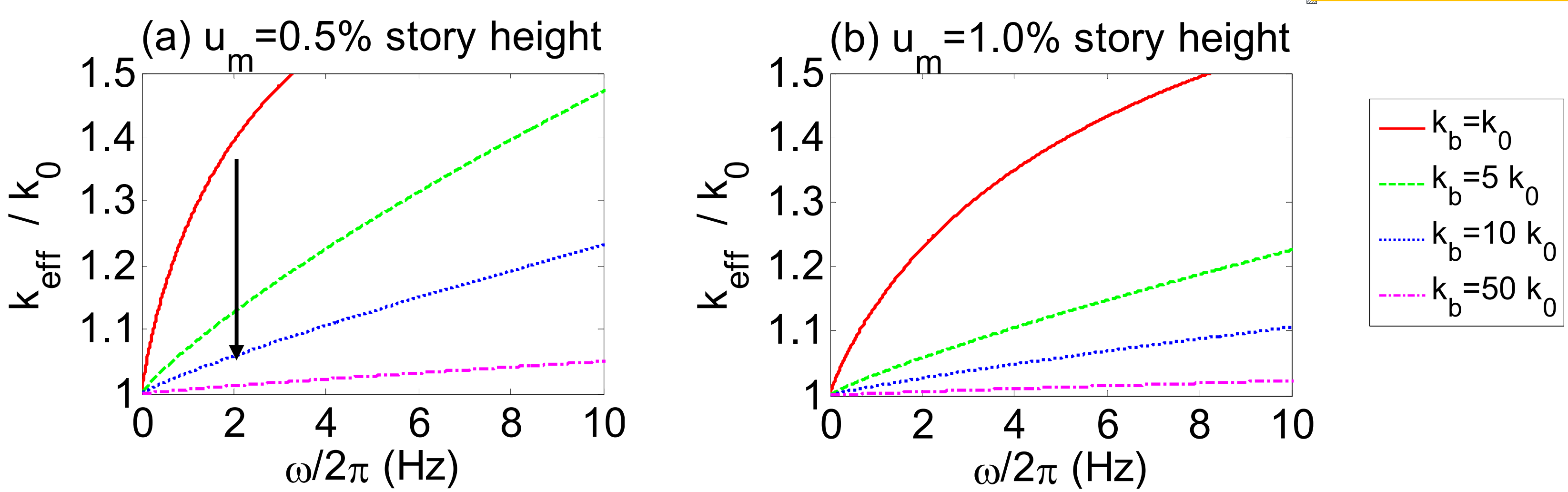
k_{eff}/k_0 decreases (period increases) with increasing brace stiffness;

k_{eff}/k_0 increases with increasing frequency;

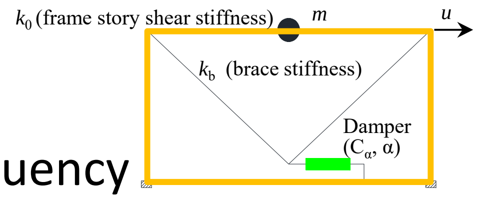
For rigid bracing (i.e., $k_b/k_0 \rightarrow \infty$), k_{eff}/k_0 is approximately 1.0, so combined system stiffness equals story shear stiffness (ideal case, damper force is out-of-phase with story drift);

k_{eff}/k_0 decreases with increasing story drift amplitude.





Use of Equivalent Linear Elastic-Viscous Model to Study Effect of Brace Stiffness on Combined System

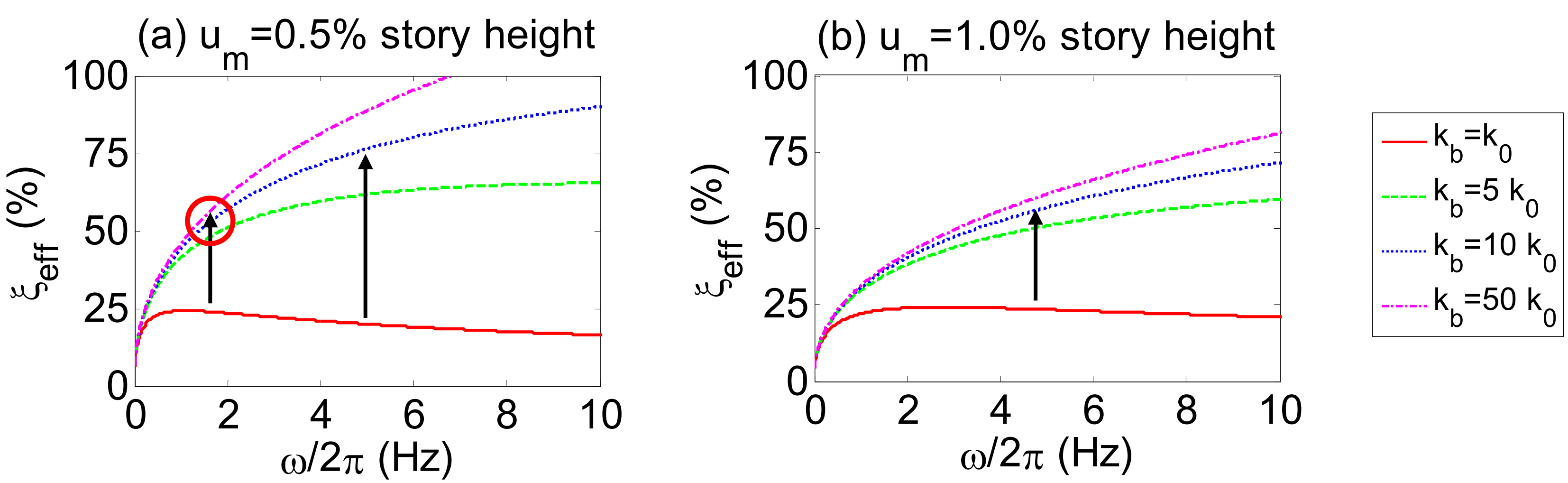


ξ_{eff} increases with increasing brace stiffness

Effect of brace stiffness on ξ_{eff} increases with increasing frequency

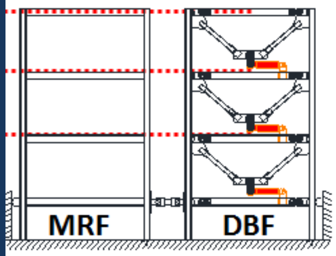
At modest frequency, effect of brace stiffness beyond threshold value is small

Effect of brace stiffness on ξ_{eff} decreases with increasing story drift amplitude.

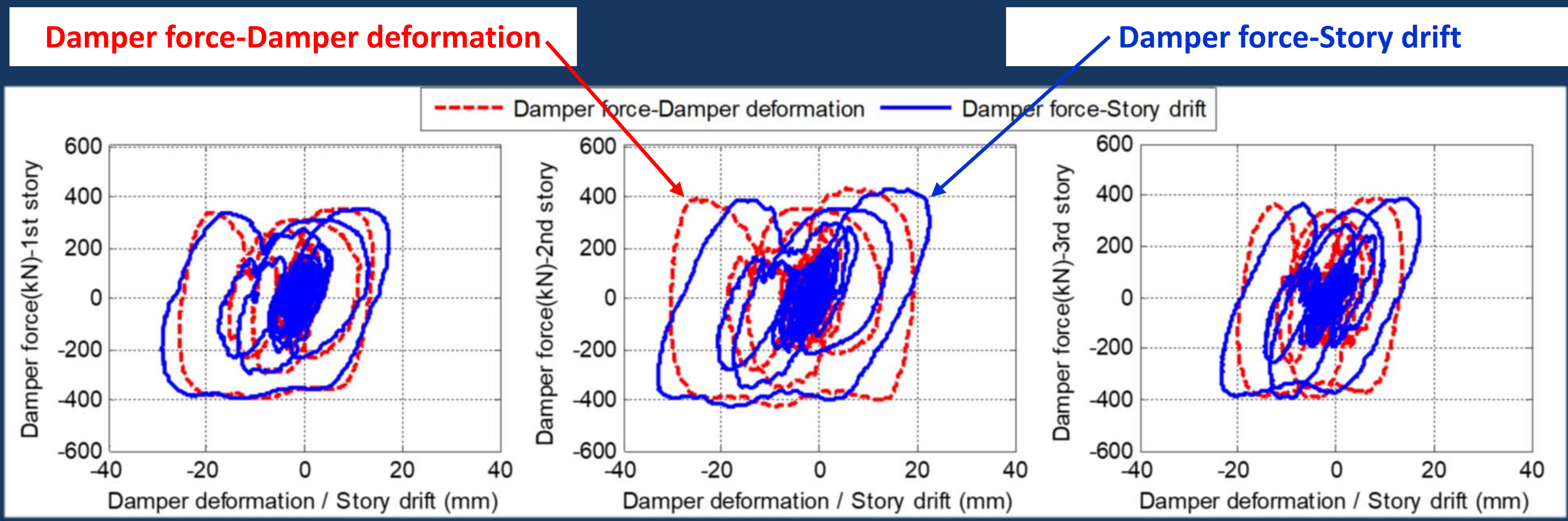


Dong, B. "Large-scale Experimental, Numerical, and Design Studies of Steel MRF Structures with Nonlinear Viscous Dampers under Seismic Loading," PhD Dissertation, Lehigh University, Bethlehem, PA.

Response of MRF Structures with Nonlinear Viscous Dampers from Phase-1 RTHS: Full Strength D100V MRF Test Structure



In-phase behavior of damper force with story drift



Deformations of DBF members/connections adjacent to dampers cause differences between damper deformation and story drift (so-called "brace flexibility")

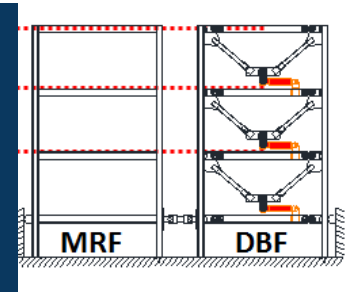
Damper forces are partially in-phase with elastic forces

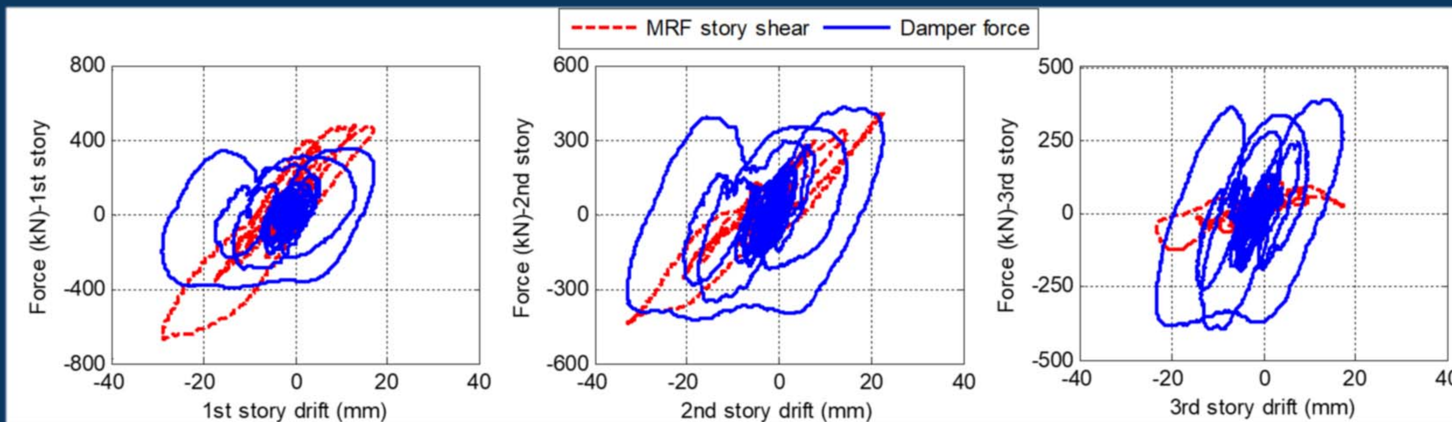
As a result, system of dampers and bracing adds stiffness to DBF

MCE RRS318

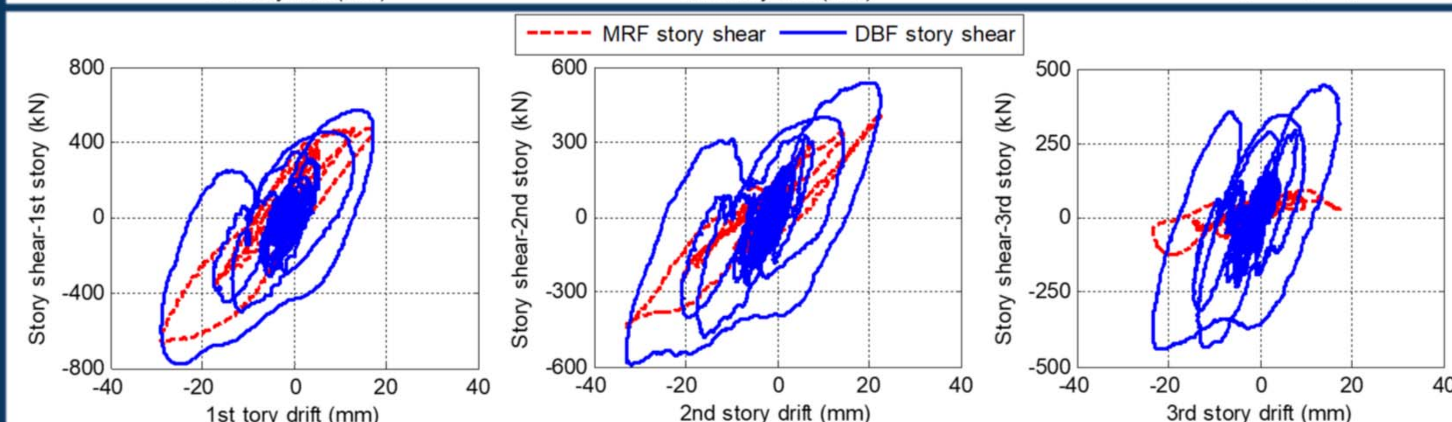
Dong, B., Sause, R., and Ricles, J.M., "Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE," *Journal of Structural Engineering*, 2016; 142(6)

Response of MRF Structures with Nonlinear Viscous Dampers from Phase-1 RTHS: Full Strength D100V MRF Test Structure





MRF story shear and damper force versus story drift



MRF and DBF story shear versus story drift

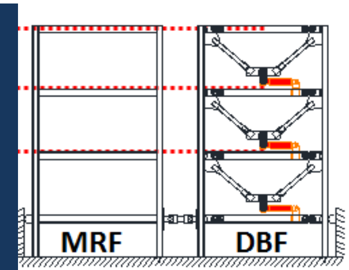
MCE RRS318

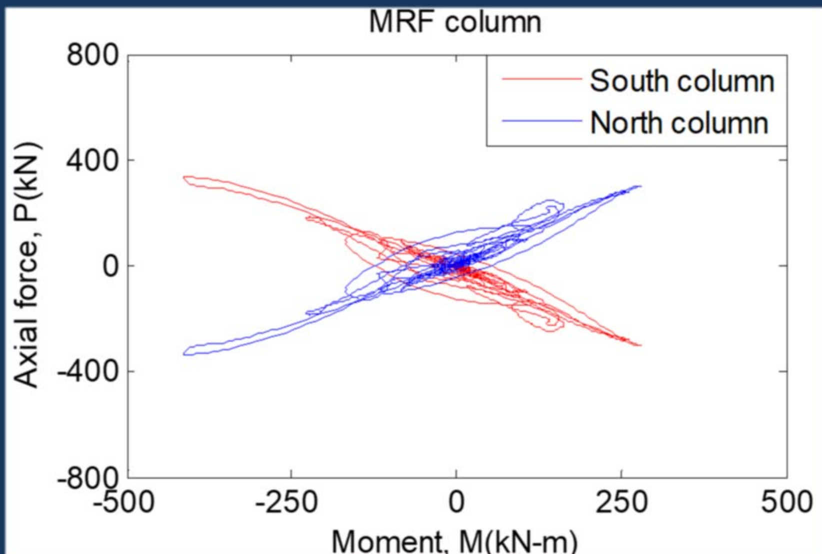
Damper force is partially in-phase with MRF story shear (structure is stiffer, period is shorter)

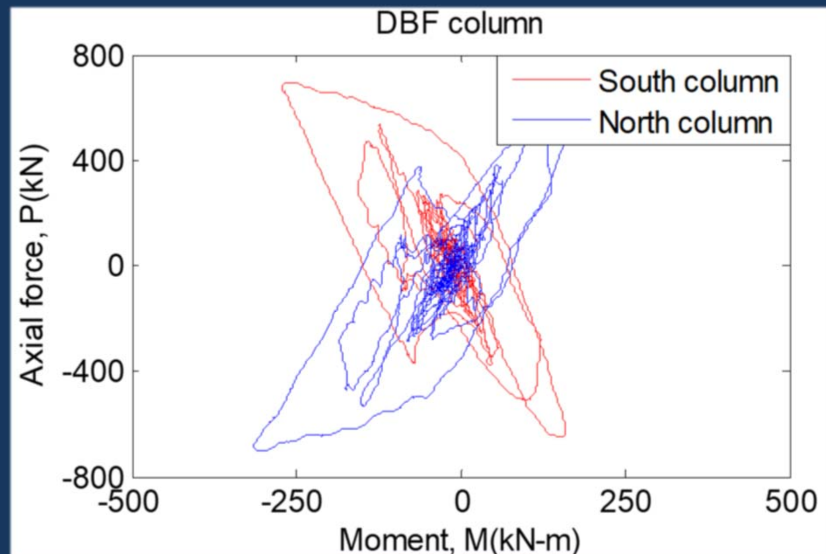
Damper and DBF forces are large at time of peak MRF forces, must consider in design

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; 142(6)

Response of MRF Structures with Nonlinear Viscous Dampers from Phase-1 RTHS: Full Strength D100V MRF Test Structure







Column axial force-moment interaction

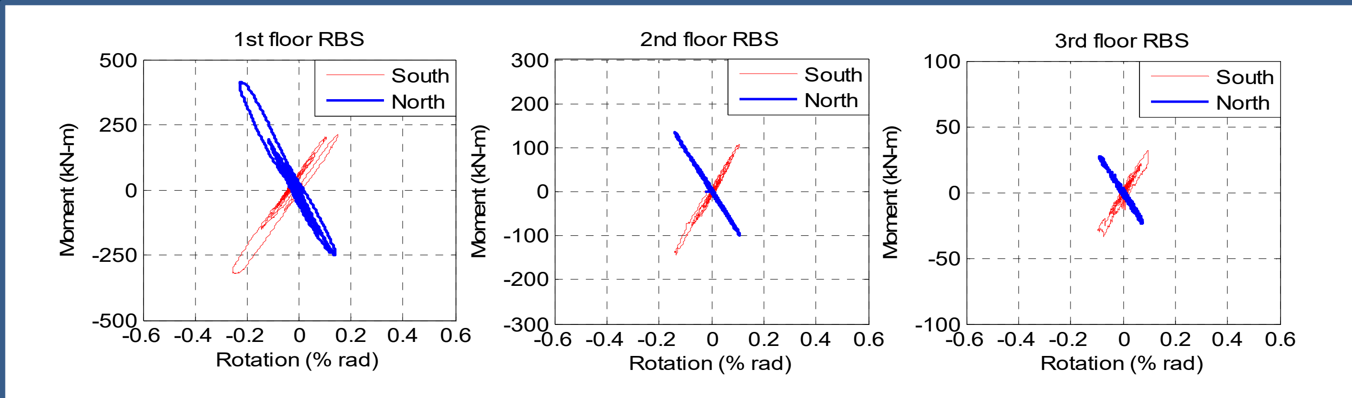
In MRF columns, axial forces and bending moment are in-phase, peak values at same time

In DBF columns, axial forces (controlled by damper forces) are partially in-phase with bending moments (controlled by lateral drift); should be considered in design

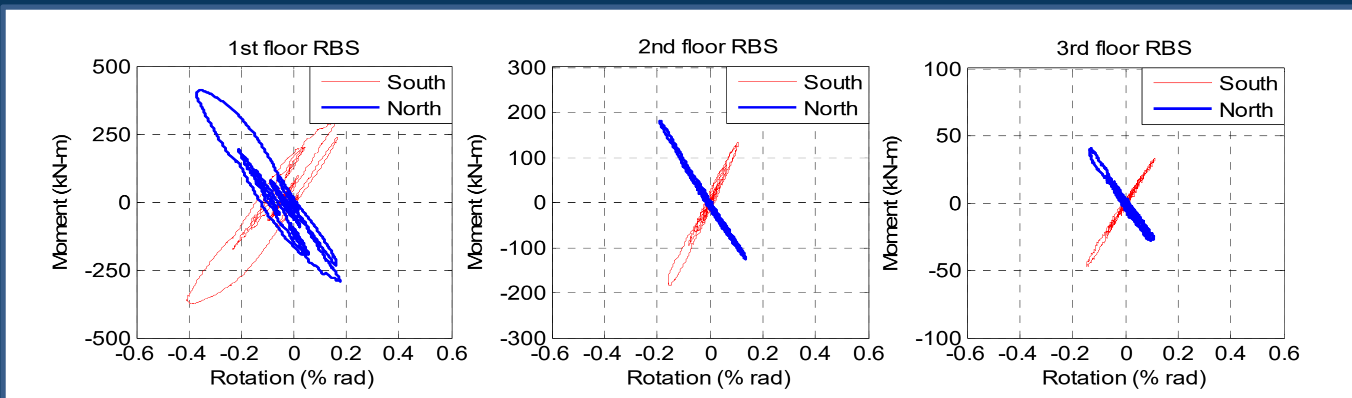
MCE RRS318

Phase-2 RTHS: 1994 Northridge Earthquake
RRS318 component scaled to MCE Level
2% probability of exceedance in 50 years

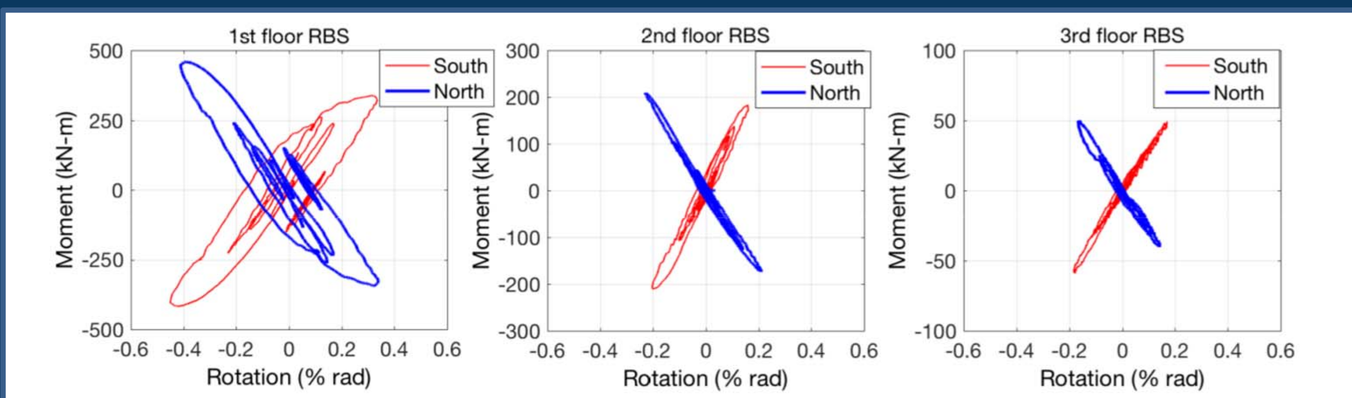
Response of MRF Structures with Nonlinear Viscous Dampers from Phase-2 RTHS: Beam Moment-Rotation for DBE



D100V Test Structure (DBE)



D75V Test Structure (DBE)

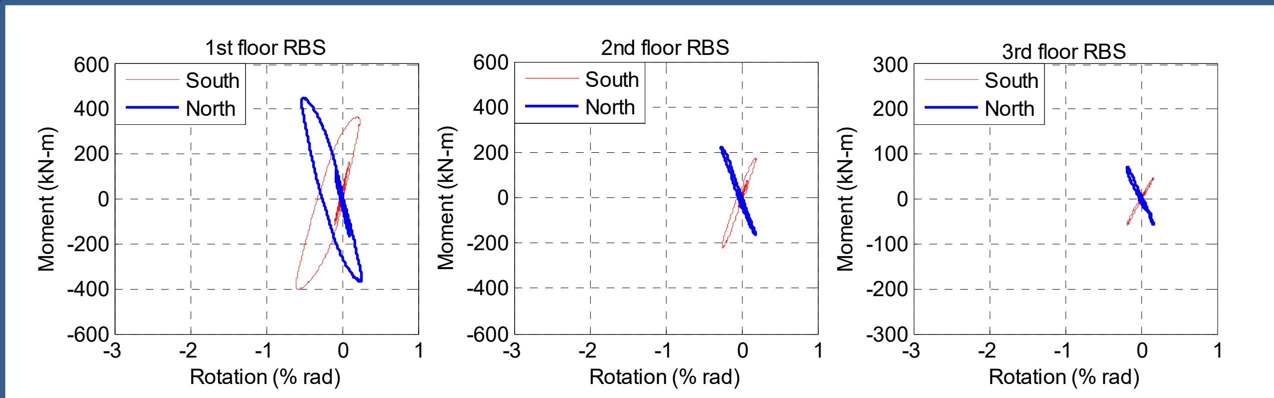


D60V Test Structure (DBE)

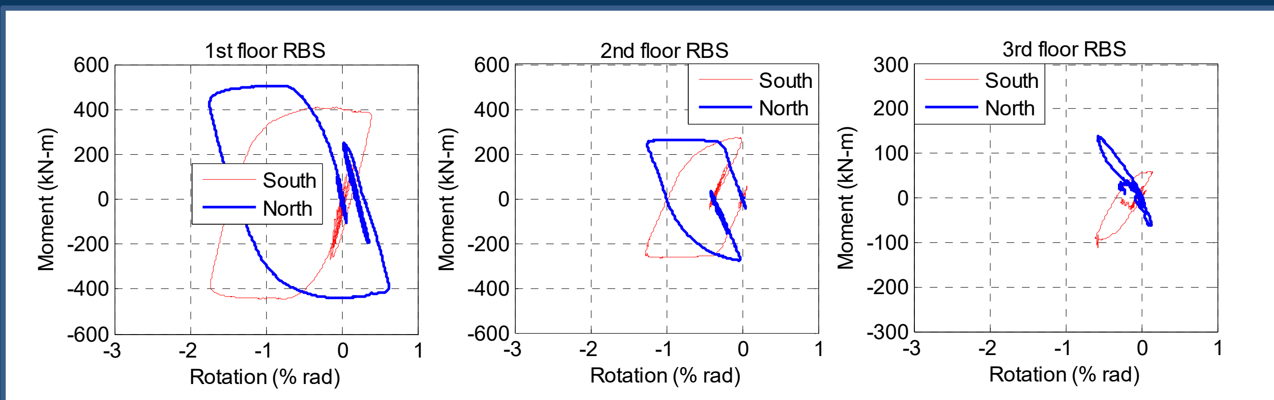
DBE RRS318

Response of MRF Structures with Nonlinear Viscous Dampers from Phase-2 RTHS: Beam Moment-Rotation in D60V

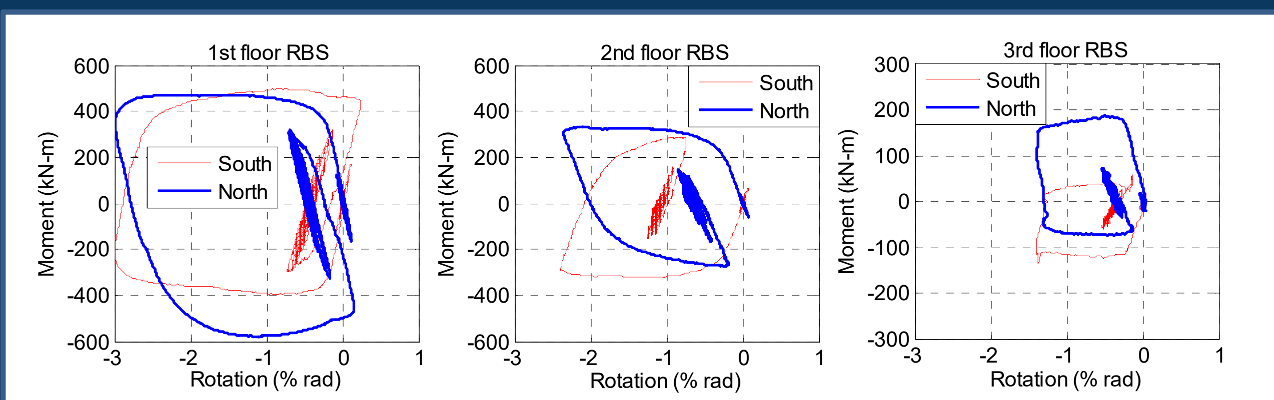
H-BRA315 18



DBE (D60V)



MCE (D60V)



1.4 MCE (D60V)

Response of MRF Structures with Nonlinear Viscous Dampers from Phase-2 RTHS: South Beam Damage in D60V Test Structure

H-BRA315 18

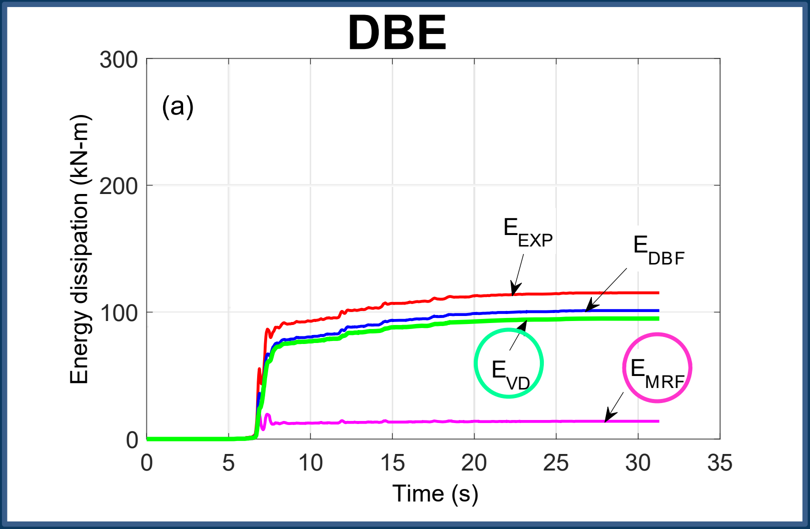
DBE

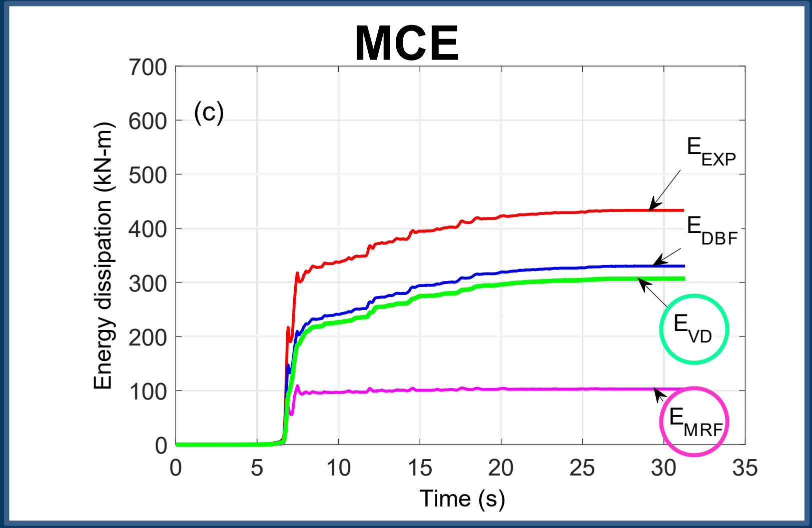
MCE

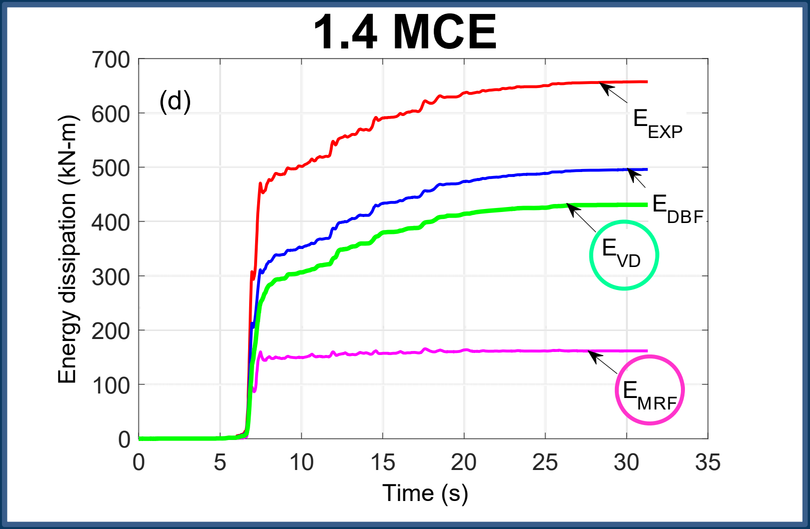
1.4 MCE

Response of MRF Structures with Nonlinear Viscous Dampers from Phase-2 RTHS: Energy Dissipation in D60V Test Structure

H-BRA315 18







Conclusions

MRF structures with nonlinear viscous dampers have enhanced performance relative to conventional MRF:

- D100V MRF with dampers:
  - Elastic under DBE, with minor yielding under MCE
  - Performance is close to "Immediate Occupancy" for DBE, and between "Immediate Occupancy" and "Life Safety" for MCE
- D75 and D60V with dampers:
  - Performance is between "Immediate Occupancy" and "Life Safety" for DBE and MCE
  - Significantly better than conventional steel MRF
  - Little beam damage under DBE and MCE

Damper forces are partially in-phase with MRF story shear (at peak MRF story shear, damper force is large); must be considered in design

Acknowledgements

- Sponsors:
  - U.S. National Science Foundation

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  - Pennsylvania Infrastructure Technology Alliance (Pennsylvania Department of Community and Economic Development)
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Thank you