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Advanced Simulation for National Hazards Mitigation
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Investigation of Seismic Response of Steel MRF Building Structures with Nonlinear Viscous Dampers Using Real-Time Hybrid Simulation

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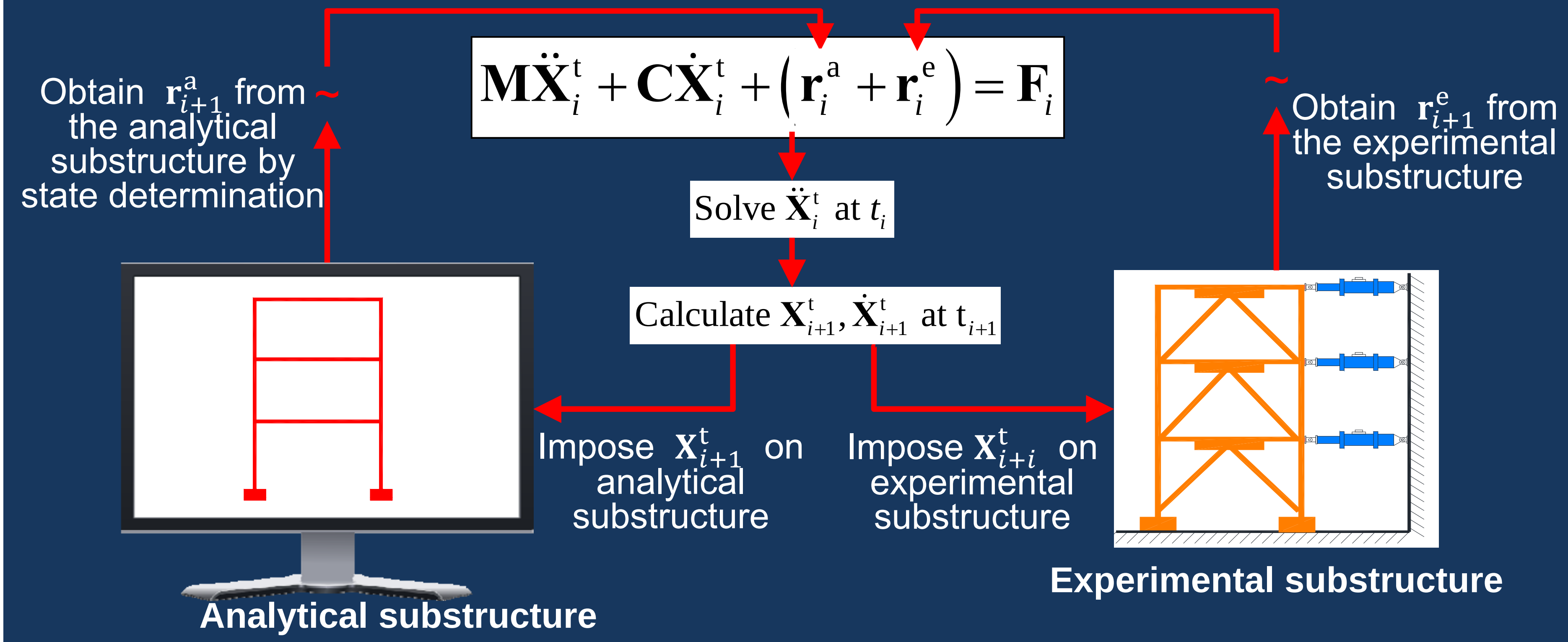
Overview of Real-time Hybrid Simulation

- In a hybrid simulation, a complete structural system is divided into experimental (physical) and analytical (numerical) substructures
- In a “real-time” hybrid simulation (RTHS), the target displacements are determined and imposed on the substructures in “real time”



$$\mathbf{M}\ddot{\mathbf{X}}^{t}_{i} + \mathbf{C}\dot{\mathbf{X}}^{t}_{i} + \left(\mathbf{r}^{a}_{i} + \mathbf{r}^{e}_{i}\right) = \mathbf{F}_{i}$$

Solve $\ddot{\mathbf{X}}^{t}_{i}$ at t_i

Calculate $\mathbf{X}^{t}_{i+1}, \dot{\mathbf{X}}^{t}_{i+1}$ at t_{i+1}

Obtain $\mathbf{r}^{a}_{i+1}$ from the analytical substructure by state determination

Obtain $\mathbf{r}^{e}_{i+1}$ from the experimental substructure

Impose $\mathbf{X}^{t}_{i+1}$ on analytical substructure

Impose $\mathbf{X}^{t}_{i+i}$ on experimental substructure

Analytical substructure

Experimental substructure

Overview of Real-time Hybrid Simulation

- Hybrid simulation is a useful experimental method for investigating seismic response of a complex structural system:
  - Enables part of the system that is poorly understood or difficult to model to be constructed and tested in the laboratory (i.e., as the experimental substructure) at large-scale under simulated seismic conditions
  - Important remaining parts of the system are represented by one or more numerical model(s) (i.e., analytical substructure(s))
- Hybrid simulations of a structural system with rate dependent components (e.g., dampers) in the experimental substructure should be “real-time” hybrid simulations (i.e., RTHS)

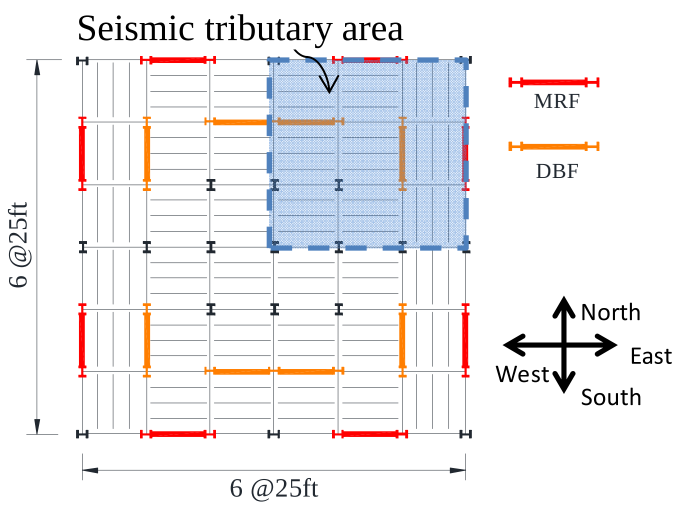
Factors to be considered for successful, accurate, large-scale RTHS

- Possible arrangements of substructures
- Design and resulting dynamic characteristics of test setup
- Accurate real-time integration of equations of motion and state determination of analytical substructure
- Continuous movement of hydraulic actuators (and resulting continuous motion of experimental substructure)
- Appropriate displacement feedback signals to control RTHS
- Adaptive compensation to reduce differences between target and measured displacement responses

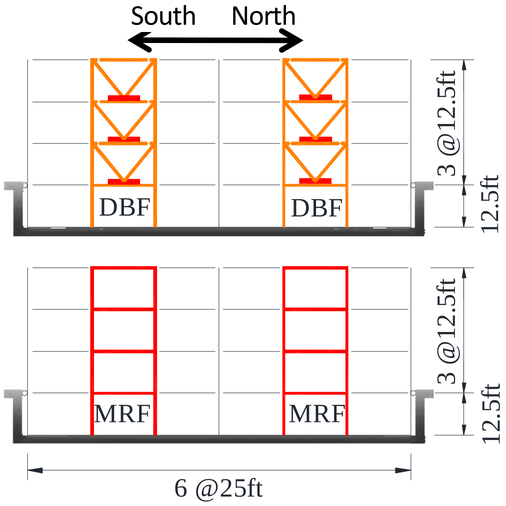
Steel MRF Structure with Nonlinear Viscous Dampers Studied using Large-Scale RTHS

Prototype building (*Dong, Sause, Ricles 2015*)

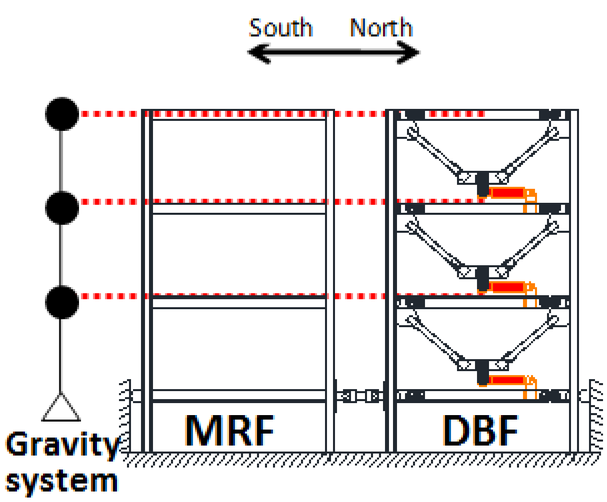
- 3-story, 6-bay by 6-bay office building located in Southern California
- Moment resisting frame (MRF), damped brace frame (DBF), gravity load system, inherent damping of building



Plan view of prototype building



Section view of prototype building

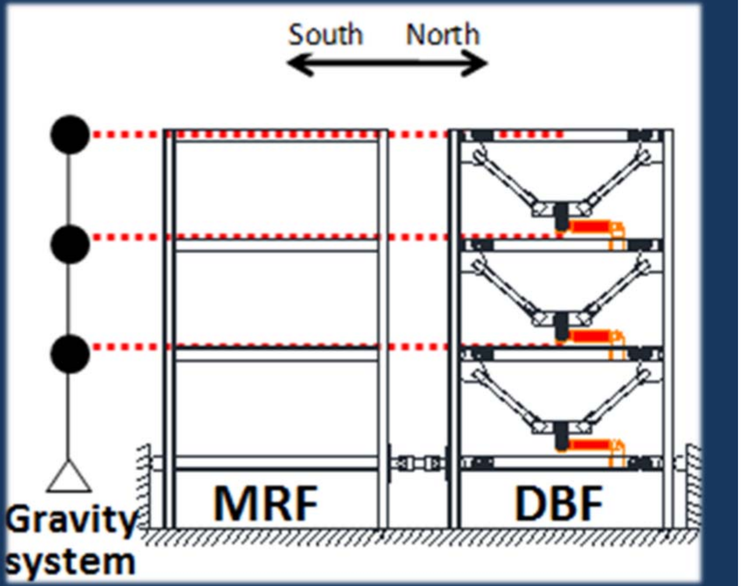


Test structure

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): 2035-2055 (DOI: 10.1002/eqe.2572)

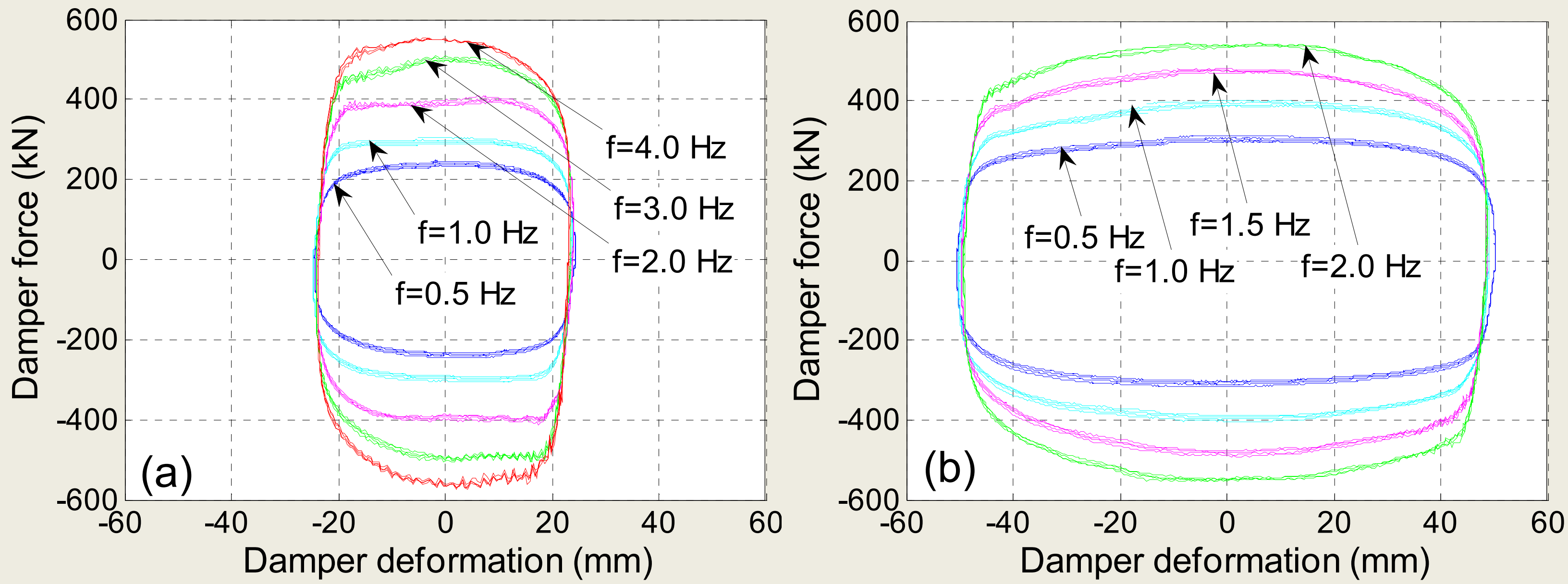
Design of Steel MRF Structure with Nonlinear Viscous Dampers

- Design of prototype building (MRF,DBF)
  - MRF is designed to satisfy strength requirement of ASCE 7-10
  - MRF is not designed to meet drift requirement of ASCE7-10, story drifts will be controlled by dampers in DBF
  - DBF is designed to remain elastic under the design basis earthquake (DBE)
- Maximum story drift of 0.85% and 1.5% was initially estimated for prototype building with three 600 kN dampers (C_α=696 kN-s/m and α=0.44) under DBE and MCE, respectively



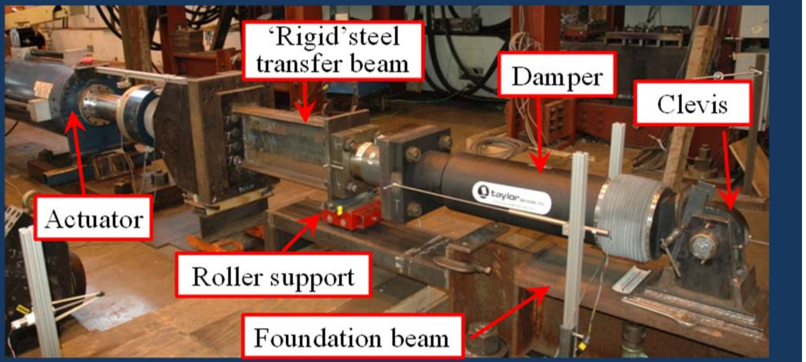
Dong, B., Sause, R., and Ricles, J.M. Accurate real-time hybrid earthquake simulations on large-scale MDOF steel structure with nonlinear viscous dampers. *Earthquake Engineering and Structural Dynamics*, 2015, 44(12): 2035-2055 (DOI: 10.1002/eqe.2572)

Nonlinear Viscous Dampers



Damper force versus deformation response from characterization tests conducted using damper test bed

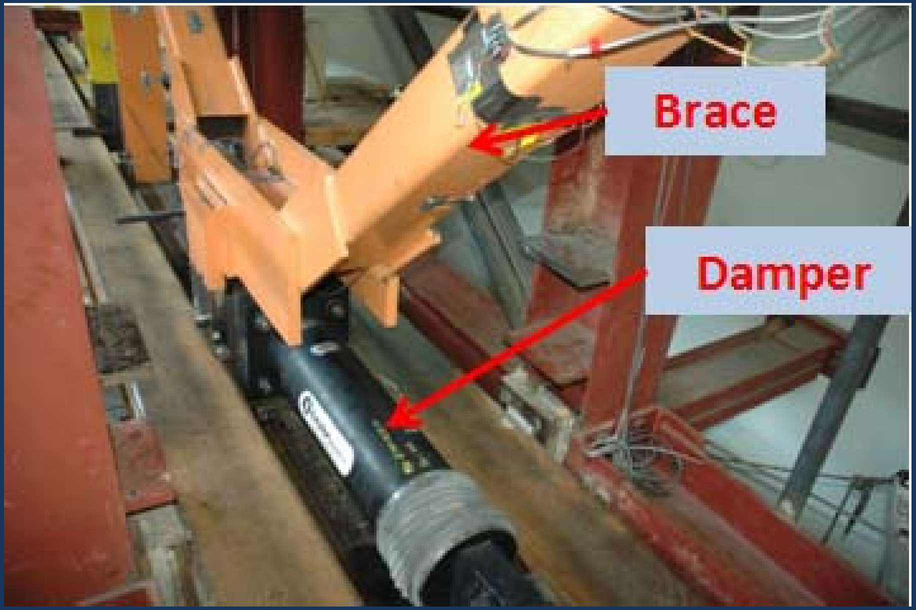
Rate-dependent response, so hybrid earthquake simulations should be real-time



Large-scale nonlinear viscous damper characterization tests in damper testbed

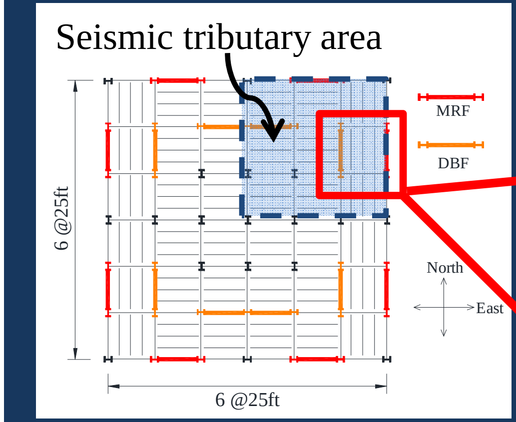
Goals for Large-Scale RTHS on Steel MRF Structure with Nonlinear Viscous Dampers

- Experimentally investigate nonlinear viscous damper response within frame structure
- Generate data for evaluating design procedures and numerical models for structures with nonlinear viscous dampers

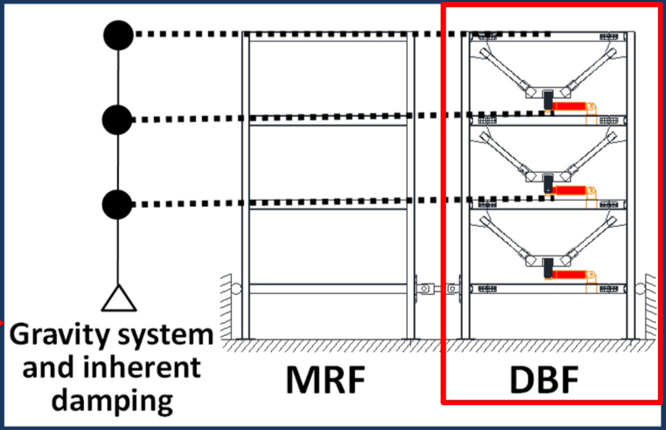


Large-Scale RTHS on Steel MRF Structure with Nonlinear Viscous Dampers: Substructures

Two different arrangements of substructures were used in two phases of RTHS at 0.6 scale



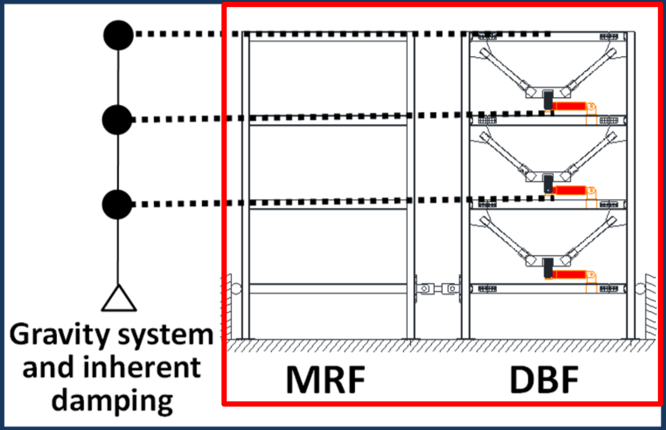
Prototype Building



RTHS Phase-1

Experimental substructure:
- **DBF**

Analytical substructure:
- **MRF**
- **Mass**
- **Gravity system**
- **Building inherent damping**



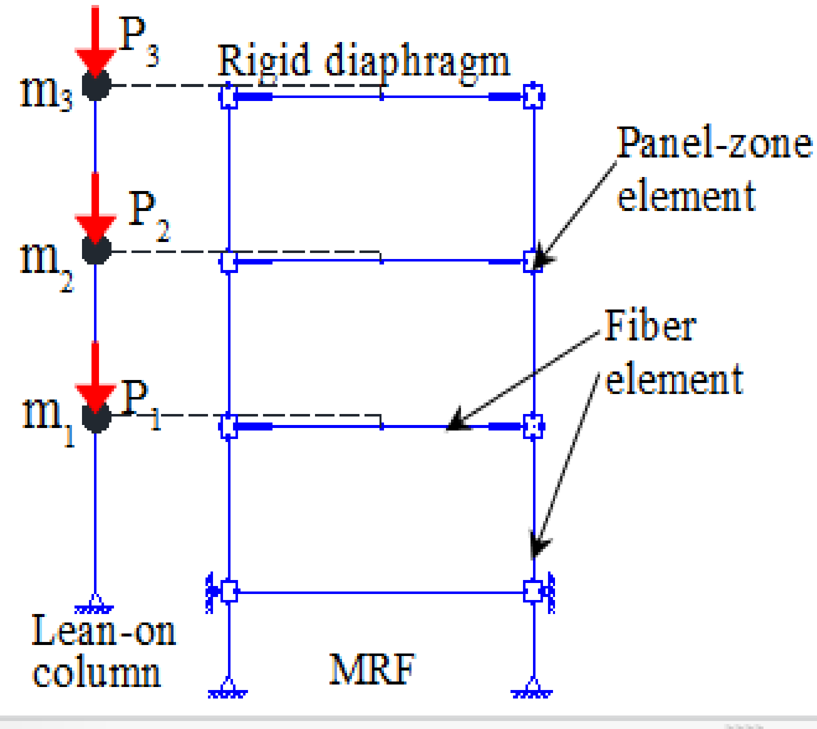
RTHS Phase-2

Experimental substructure:
- **DBF**
- **MRF**

Analytical substructure:
- **Mass**
- **Gravity system**
- **Building inherent damping**

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): 2035-2055 (DOI: 10.1002/eqe.2572)

Large-Scale RTHS on Steel MRF Structure with Nonlinear Viscous Dampers: Phase-1 Substructures



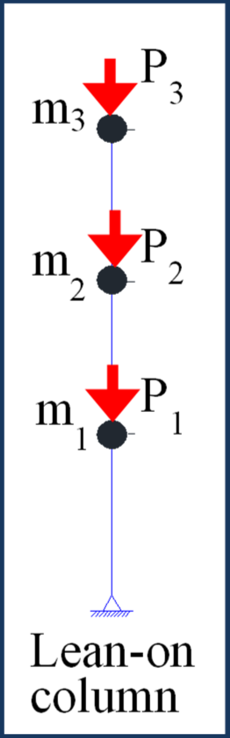
Analytical substructure
(MRF, mass, gravity system, inherent damping)

Experimental substructure
(0.6-scale DBF)

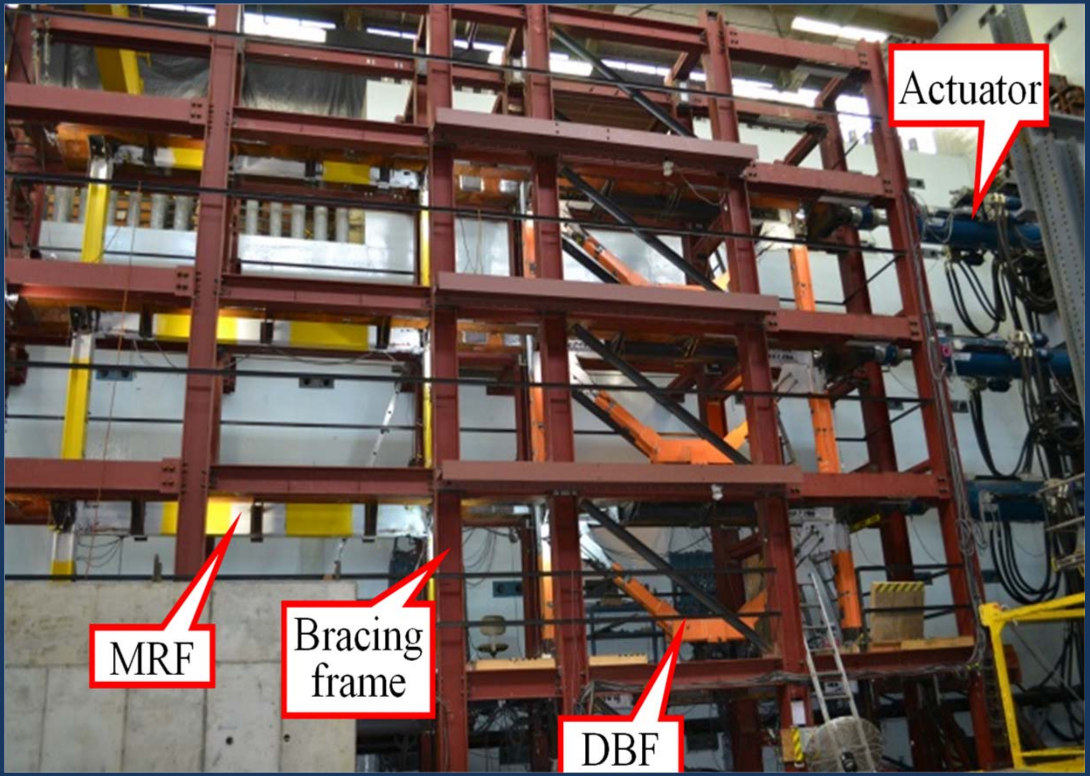
Real-time state determination

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

Large-Scale RTHS on Steel MRF Structure with Nonlinear Viscous Dampers: Phase-2 Substructures



Analytical substructure (mass, gravity system, inherent damping)



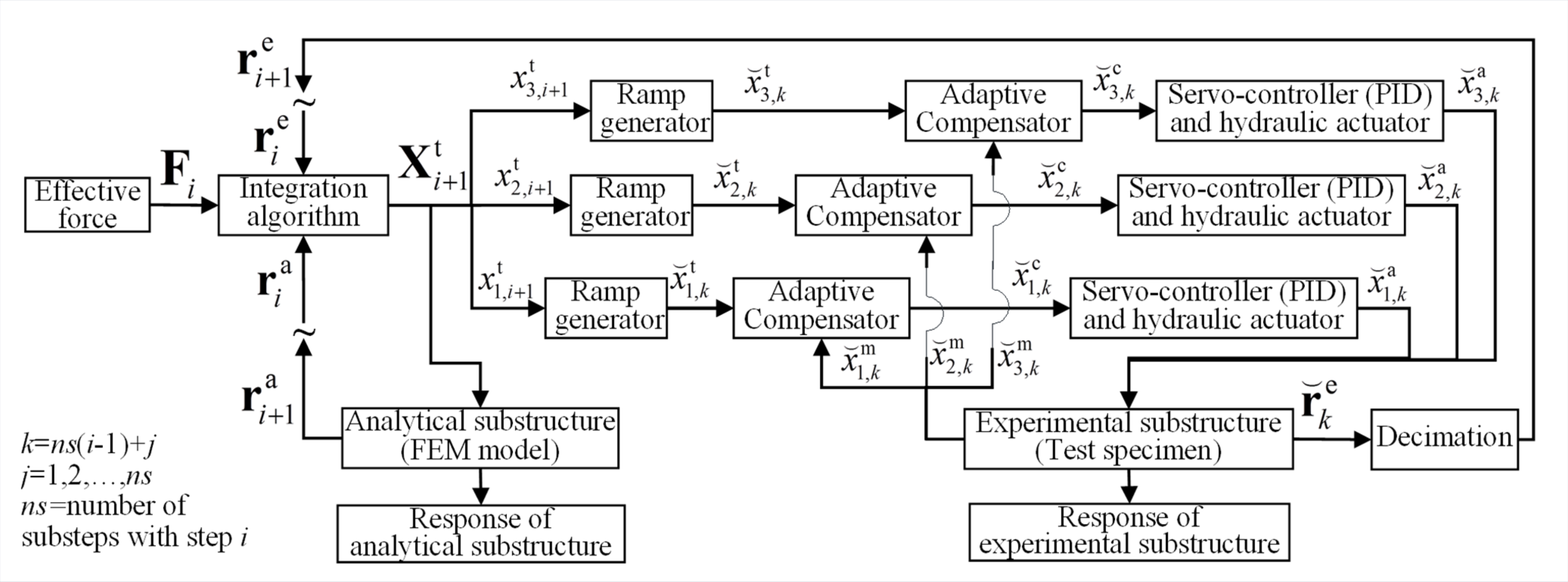
Experimental substructure (0.6-scale MRF and DBF)

<u>Real-time state determination</u>

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

Large-Scale RTHS on Steel MRF Structure with Nonlinear Viscous Dampers: Procedure

Schematic of procedure for RTHS



$k=ns(i\text{-}1)+j$

$j=1,2,\ldots,ns$

ns=number of substeps with step i

Within step *i*

Large-Scale RTHS on Steel MRF Structure with Nonlinear Viscous Dampers: Procedure

Integration Algorithm: Integration of equations of motion

Explicit CR integration algorithm (*Chen, Ricles, Marullo, Mercan 2009*)

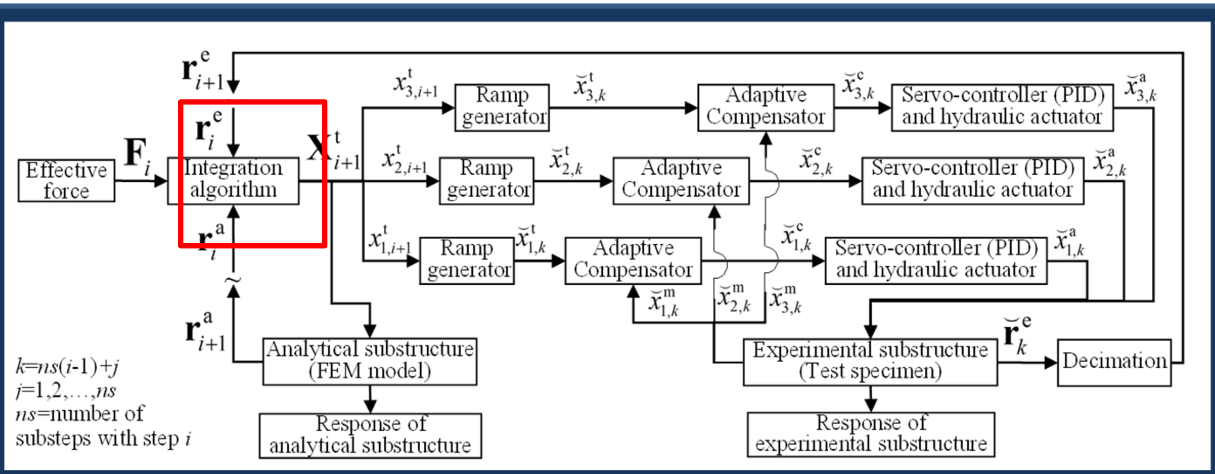
Calculate $\mathbf{X}^{t}_{i+1}$ at $t_{i+1} = (i+1)\cdot\Delta t$:

$$\dot{\mathbf{X}}^{t}_{i+1} = \dot{\mathbf{X}}^{t}_{i} + \Delta t \cdot \boldsymbol{\alpha}_1 \cdot \ddot{\mathbf{X}}^{t}_{i}$$

$$\mathbf{X}^{t}_{i+1} = \mathbf{X}^{t}_{i} + \Delta t \cdot \dot{\mathbf{X}}^{t}_{i} + \Delta t^2 \cdot \boldsymbol{\alpha}_2 \cdot \ddot{\mathbf{X}}^{t}_{i}$$

$\boldsymbol{\alpha}_1, \boldsymbol{\alpha}_2$ – matrices of integration parameters

$$\boldsymbol{\alpha}_1 = \boldsymbol{\alpha}_2 = 4\mathbf{M}\cdot(4\mathbf{M} + 2\Delta t \cdot \mathbf{C} + \Delta t^2 \cdot \mathbf{K})^{-1}$$



Chen C, Ricles J.M, Marullo T.M, and Mercan O. Real-time hybrid testing using the unconditionally stable explicit CR integration algorithm. *Earthquake Engineering & Structural Dynamics*, 2009, 38(1): 23-44

Large-Scale RTHS on Steel MRF Structure with Nonlinear Viscous Dampers: Procedure

Ramp generator: Continuous movement of actuators

Interpolation of displacements to account for difference in time increment between integration time step (Δt) and controller time interval (δt).

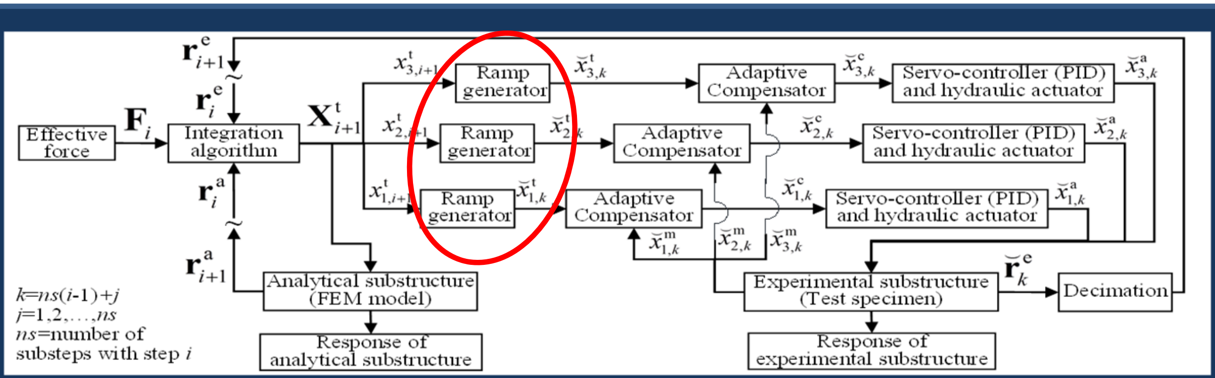
$$\breve{x}^{\mathrm{t}}_{n,k} = \frac{j}{ns} \cdot (x^{\mathrm{t}}_{n,i+1} - x^{\mathrm{t}}_{n,i}) + x^{\mathrm{t}}_{n,i} \qquad (j = 1, 2, \ldots ns)$$

ns – number of substeps, ns=4;

j – substep index of the ramp generator, ranges from 1 to ns;

$x^{\mathrm{t}}_{n,i+1}$ and $x^{\mathrm{t}}_{n,i}$ – target displacements for DOF n at $t_{\mathrm{i+1}}$ and t_{i};

$\breve{x}^{\mathrm{t}}_{n,k}$ – target displacement discretized at δt for the j^{th} substep within step i.



Large-Scale RTHS on Steel MRF Structure with Nonlinear Viscous Dampers: Procedure

Compensator: Reduce potential errors between target displacement and actual displacment due to dynamic characteristics of servo-hydraulic controller, actuators, test fixture and experimental substructure

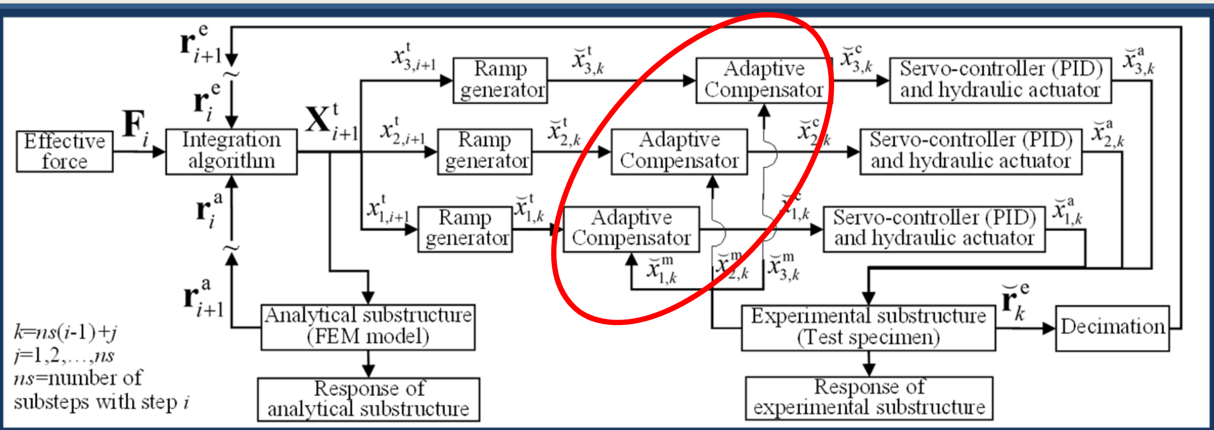
<u>Adaptive ATS compensator</u> (*Chae, Kazemibidokhti, Ricles 2013*)

$$\breve{x}^{\mathrm{c}}_{n,k} = a_{0k}\cdot\breve{x}^{\mathrm{t}}_{n,k} + a_{1k}\cdot\dot{\breve{x}}^{\mathrm{t}}_{n,k} + a_{2k}\cdot\ddot{\breve{x}}^{\mathrm{t}}_{n,k}$$

$x^{\mathrm{c}}_{n,k}$ – compensated command displacement of n^{th} floor to actuator at $t_k = k\cdot\delta_t$;

$x^{\mathrm{t}}_{n,k}, \dot{x}^{\mathrm{t}}_{n,k}, \ddot{x}^{\mathrm{t}}_{n,k}$ – target displacement, velocity, and acceleration of n^{th} floor at t_k;

a_{0k}, a_{1k}, a_{2k} – compensator coefficients at t_k.



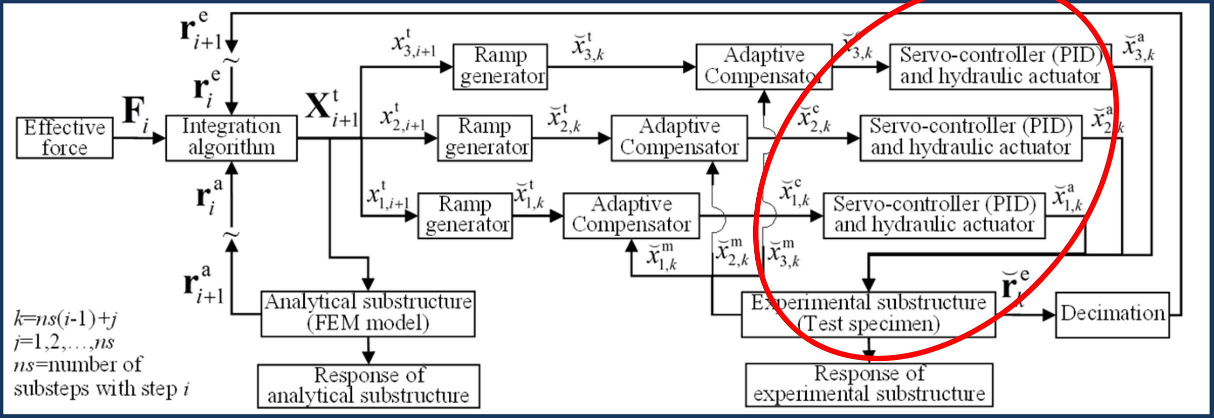
Chae Y, Kazemibidokhti K, and Ricles J.M. Adaptive time series compensator for delay compensation of servo-hydraulic actuator systems for real-time hybrid simulation. *Earthquake Engineering and Structural Dynamics*, 2013, 42(11): 1697-1715

Large-Scale RTHS on Steel MRF Structure with Nonlinear Viscous Dampers: Procedure

Use measured displacements from experimental substructure as feedback for RTHS control (*Dong, Sause, Ricles 2015*)

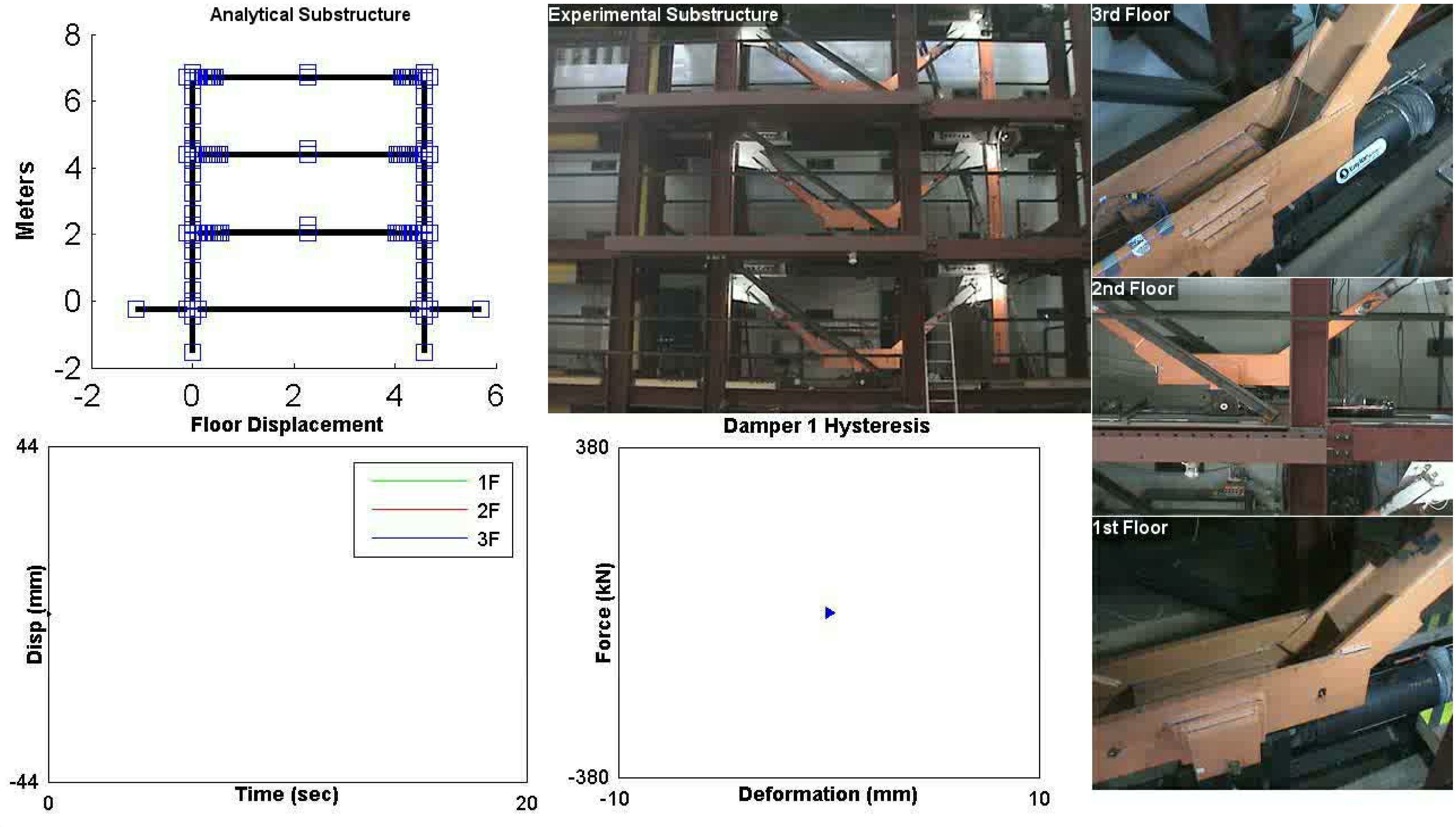
Enables target displacements to be imposed accurately on experimental substructure

<u>Accuracy is determined by displacement history of experimental substructure, not by actuator stroke</u>



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): 2035-2055 (DOI: 10.1002/eqe.2572)

Large-Scale RTHS on Steel MRF Structure with Nonlinear Viscous Dampers

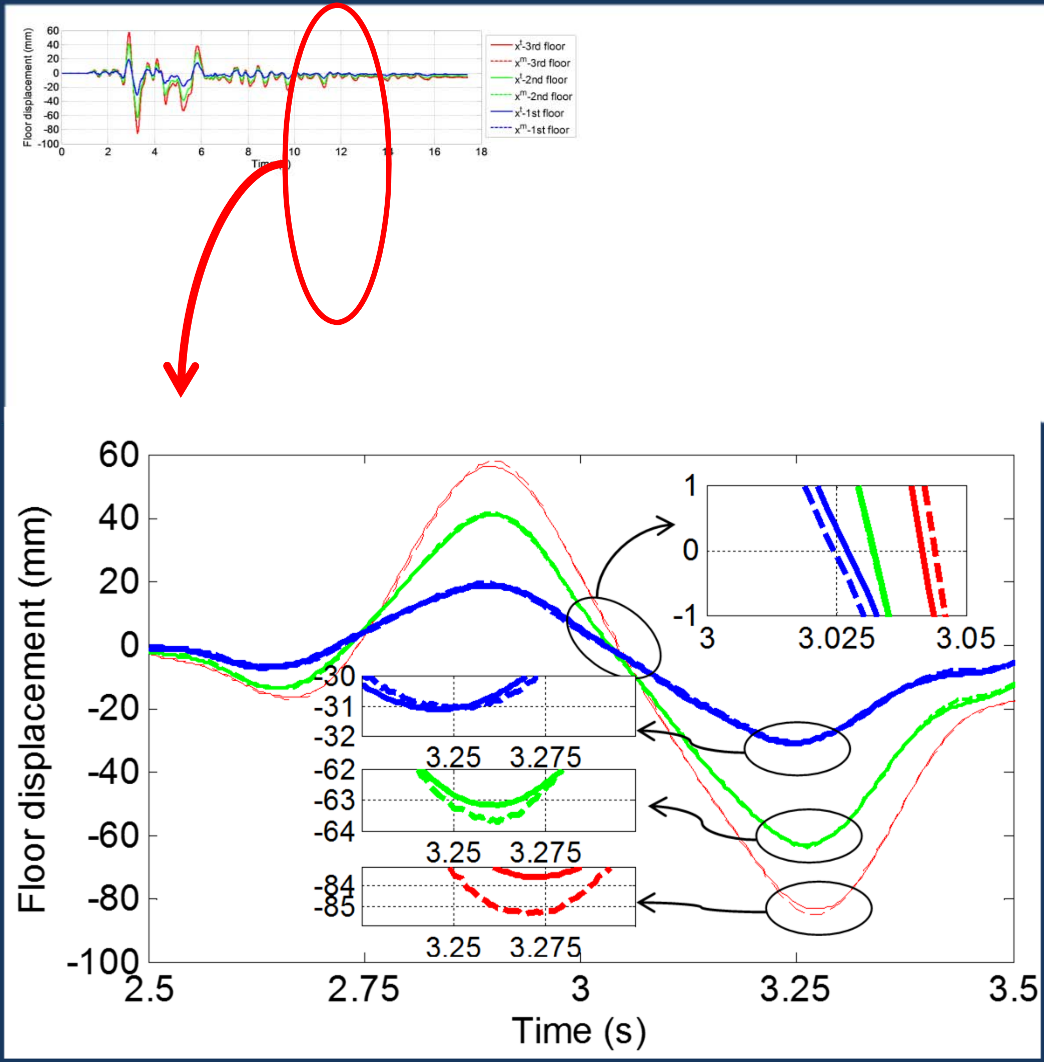


RTHS Phase-1: MCE level 1994 Northridge (RRS318)

MCE ground motion: 2% probability of exceedance in 50 years.

RTHS Phase-1 Results Evaluation

Floor Displacements in MCE level 1994 Northridge (RRS318)



Peak floor displacement:
31.1, 63.7, 85.5 mm

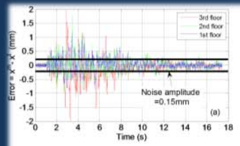
Maximum amplitude error:
1.1, 1.6, 2.0 mm
(3.5%, 2.5%, 2.3%)

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, 44(12): 2035-2055 (DOI: 10.1002/eqe.2572).

RTHS Phase-1 Results Evaluation

Error between x^m and x^t in MCE level 1994 Northridge (RRS318)



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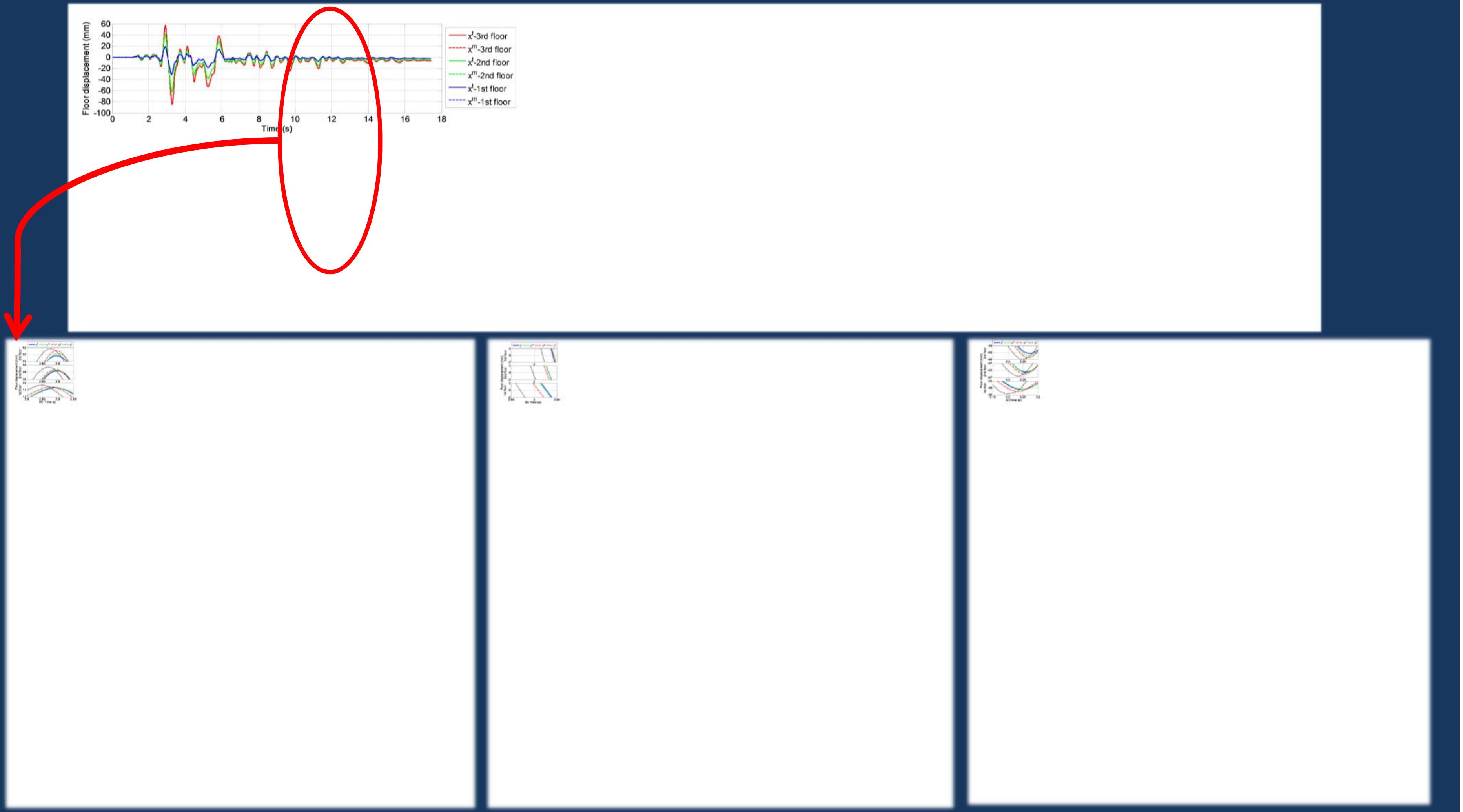
RTHS Phase-1 Results Evaluation

Comparison of x^c, x^a, x^m and x^t in MCE level 1994 Northridge (RRS318)



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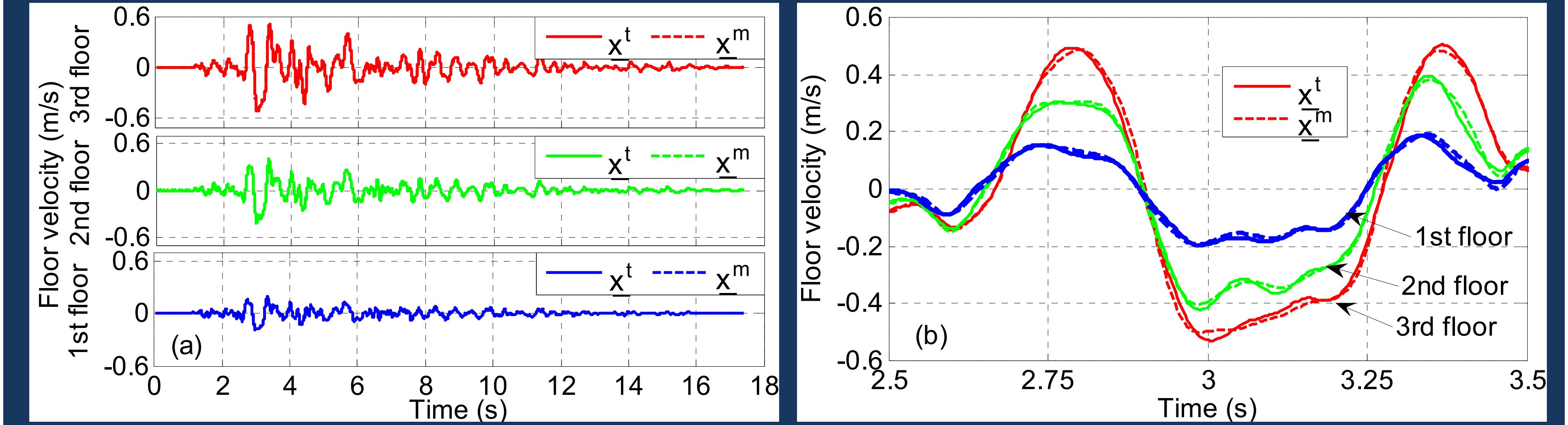
RTHS Phase-1 Results Evaluation

Floor Velocities in MCE level 1994 Northridge (RRS318)



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%)

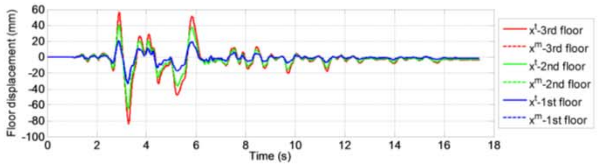
Dong, B., Sause, R., and Ricles, J.M. Accurate real-time hybrid earthquake simulations on large-scale MDOF steel structure with nonlinear viscous dampers. *Earthquake Engineering and Structural Dynamics*, 2015, 44(12): 2035-2055 (DOI: 10.1002/eqe.2572).

RTHS Phase-2: MCE level 1994 Northridge (RRS318)

MCE ground motion: 2% probability of exceedance in 50 years.

RTHS Phase-2 Results Evaluation

Floor Displacements in MCE level 1994 Northridge (RRS318)

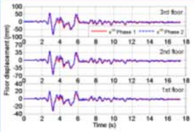


Peak floor displacement:
33.3, 65.4, 83.7 mm
Maximum amplitude error:
1.2, 0.9, 1.9 mm
(3.6%, 1.4%, 2.3%)
Delay:
about 2.0 ms

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, 44(12): 2035-2055 (DOI: 10.1002/eqe.2572).

Comparison of RTHS Phase-1 and Phase-2 Results

Comparison of floor displacements in Phase-1 and Phase-2 MCE level 1994 Northridge (RRS318)



Peak displacement (Phase-1):

31.1, 63.7, 85.5 mm

Maximum difference:

2.1, 1.7, 1.8 mm

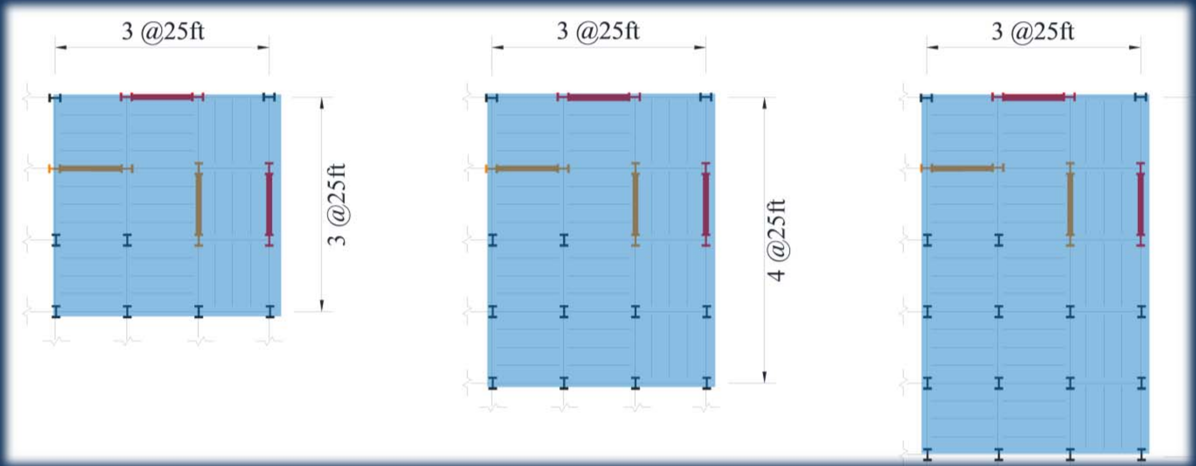
(6.8%, 2.7%, 2.1%)

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): 2035-2055 (DOI: 10.1002/eqe.2572).

Use of RTHS in Earthquake Engineering Research

Parametric study of Prototype Buildings with reduced-strength steel MRF designs in Phase-1 RTHS (*Dong, Sause, Ricles 2016*)

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



(a) Seismic tributary area for D100V prototype building

(b) Seismic tributary area for D75V prototype building

(c) Seismic tributary area for D60V prototype building

Change mass and gravity system properties of analytical substructure to perform RTHS for three different Prototype Buildings

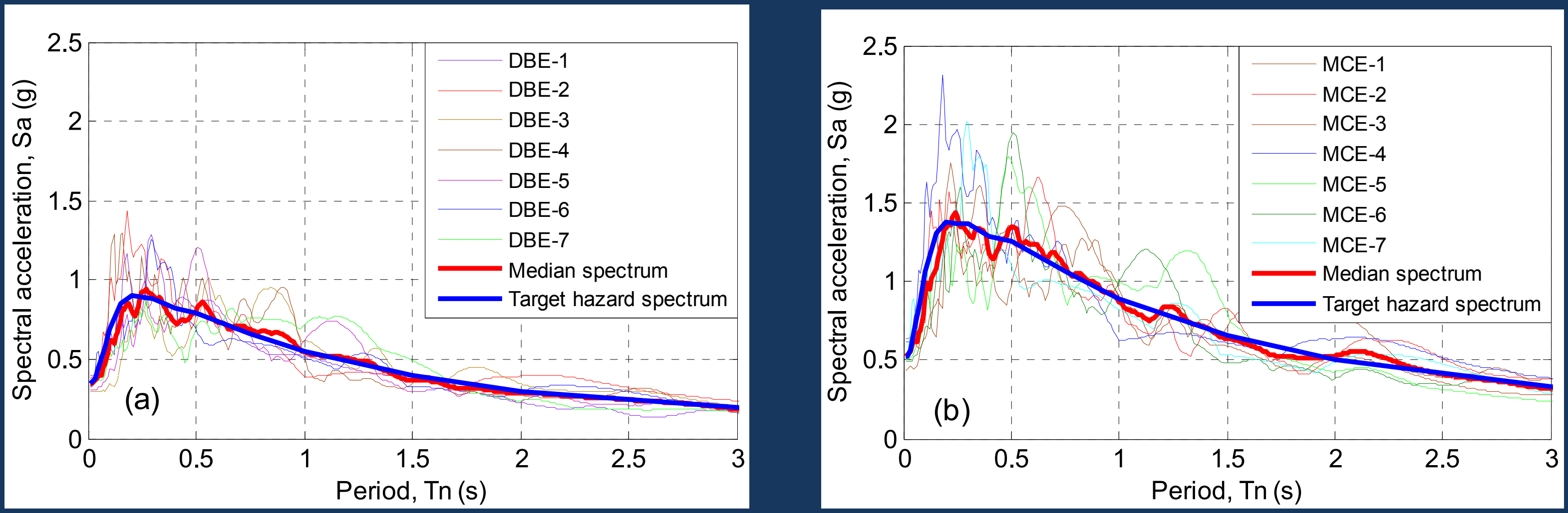
Dong, B., Sause, R., and Ricles, J.M., Seismic Response and Performance of Steel MRF Building with Nonlinear Viscous Dampers under DBE and MCE, *Journal of Structural Engineering*, 2016, 142(6): 04016023-1 – 04016023-16 (DOI: 10.1061/(ASCE)ST.1943-541X.0001482)

Use of RTHS in Earthquake Engineering Research

Phase-1 experimental substructure (DBF with dampers) is undamaged by DBE and MCE input

Damage is confined to MRF within analytical substructure in Phase-1

Therefore, an ensemble of ground motion records can be used as input for Phase-1 RTHS (account for record-to-record variability



Ground motion response spectra (a) DBE level; (b) MCE level

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): 04016023-1 – 04016023-16 (DOI: 10.1061/(ASCE)ST.1943-541X.0001482)

Use of RTHS in Earthquake Engineering Research: Statistical Evaluation of Response from RTHS

Ground Motion No.	Story drift (%)			Residual story drift (%)		
	1st story	2nd story	3rd story	1st story	2nd story	3rd story
DBE-1	0.68	0.82	0.53	0.009	0.013	0.022
DBE-2	0.63	0.73	0.52	0.000	0.000	0.000
DBE-3	0.68	0.76	0.48	0.013	0.017	0.009
DBE-4	0.79	0.82	0.55	0.031	0.035	0.022
DBE-5	0.62	0.71	0.49	0.004	0.004	0.009
DBE-6	0.79	0.80	0.55	0.044	0.044	0.022
DBE-7	0.71	0.80	0.57	0.013	0.013	0.000
DBE Mean	**0.71**	**0.78**	**0.54**	**0.016**	**0.018**	**0.012**
DBE prediction	**0.76**	**0.81**	**0.64**	-	-	-

DBE level RTHS:

- Mean maximum story drifts: 0.71%, 0.78%, and 0.54% for the 1st, 2nd, and 3rd story
- Negligible residual story drift

Ground Motion No.	Story drift (%)			Residual story drift (%)		
	1st story	2nd story	3rd story	1st story	2nd story	3rd story
MCE-1	1.25	1.48	1.09	0.118	0.176	0.137
MCE-2	1.10	1.29	0.88	0.042	0.061	0.035
MCE-3	1.18	1.34	1.03	0.042	0.085	0.076
MCE-4	1.09	1.35	1.02	0.087	0.159	0.131
MCE-5	1.27	1.39	0.98	0.091	0.124	0.060
MCE-6	1.07	1.24	0.91	0.112	0.150	0.104
MCE-7	1.32	1.44	1.00	0.080	0.105	0.079
MCE Mean	**1.18**	**1.37**	**0.99**	**0.082**	**0.123**	**0.089**
MCE prediction	**1.33**	**1.41**	**1.12**	-	-	-

MCE level RTHS:

- Mean maximum story drifts: 1.18%, 1.37%, and 0.99% for the 1st, 2nd, and 3rd story
- Mean residual story drift : 0.08%, 0.12%, and 0.09% for the 1st, 2nd, and 3rd story

Predicted drift is close to mean from RTHS

D100V structure

Use of RTHS in Earthquake Engineering Research: Statistical Evaluation of Response from RTHS

Ground Motion No.	Story drift (%)			Residual story drift (%)		
	1st story	2nd story	3rd story	1st story	2nd story	3rd story
DBE-1	0.68	0.82	0.53	0.009	0.013	0.022
DBE-2	0.63	0.73	0.52	0.000	0.000	0.000
DBE-3	0.68	0.76	0.48	0.013	0.017	0.009
DBE-4	0.79	0.82	0.55	0.031	0.035	0.022
DBE-5	0.62	0.71	0.49	0.004	0.004	0.009
DBE-6	0.79	0.80	0.55	0.044	0.044	0.022
DBE-7	0.71	0.80	0.57	0.013	0.013	0.000
DBE Mean	**0.71**	**0.78**	**0.54**	**0.016**	**0.018**	**0.012**
DBE prediction	**0.76**	**0.81**	**0.64**	**-**	**-**	**-**

DBE level RTHS:

- Mean maximum story drifts: 0.71%, 0.78%, and 0.54% for the 1st, 2nd, and 3rd story
- Negligible residual story drift

Ground Motion No.	Story drift (%)			Residual story drift (%)		
	1st story	2nd story	3rd story	1st story	2nd story	3rd story
MCE-1	1.25	1.48	1.09	0.118	0.176	0.137
MCE-2	1.10	1.29	0.88	0.042	0.061	0.035
MCE-3	1.18	1.34	1.03	0.042	0.085	0.076
MCE-4	1.09	1.35	1.02	0.087	0.159	0.131
MCE-5	1.27	1.39	0.98	0.091	0.124	0.060
MCE-6	1.07	1.24	0.91	0.112	0.150	0.104
MCE-7	1.32	1.44	1.00	0.080	0.105	0.079
MCE Mean	**1.18**	**1.37**	**0.99**	**0.082**	**0.123**	**0.089**
MCE prediction	**1.33**	**1.41**	**1.12**	**-**	**-**	**-**

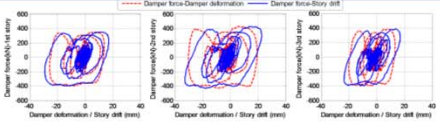
MCE level RTHS:

- Mean maximum story drifts: 1.18%, 1.37%, and 0.99% for the 1st, 2nd, and 3rd story
- Mean residual story drift : 0.08%, 0.12%, and 0.09% for the 1st, 2nd, and 3rd story

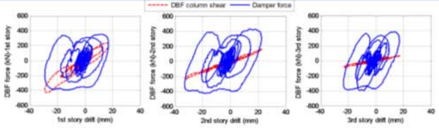
Predicted drift is close to mean from RTHS

D100V structure

Use of RTHS in Earthquake Engineering Research: Steel MRF Structure with Viscous Dampers: Results



Damper force-damper deformation and damper force-story drift



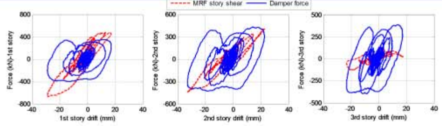
Damper force and DBF column shear versus story drift

DBF flexibility produces differences between damper deformation and story drift

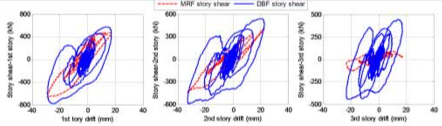
<u>Damper forces are more in-phase with DBF column shear forces</u>

D100V structure
MCE RRS318

Use of RTHS in Earthquake Engineering Research: Steel MRF Structure with Viscous Dampers: Results



MRF story shear and damper force versus story drift



MRF and DBF story shear versus story drift

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

DBF forces large at time of peak MRF forces

D100V structure
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Summary

- Factors for accurate large-scale RTHS:
  - Arrangements of substructures
  - Design and resulting dynamic characteristics of test setup
  - Accurate real-time integration of equations of motion and state determination of analytical substructure
  - Continuous movement of hydraulic actuators
  - Appropriate displacement feedback signals to control RTHS
  - Adaptive compensation to reduce differences between target and measured displacement responses
- Accurate RTHS results were achieved (experimental substructure displacements close to target displacements)
- Use of RTHS in Earthquake Engineering Research:
  - Potential for parametric investigation of large-scale structural systems by varying analytical substructure properties
  - Potential for statistical investigation of structural system response
  - Broad structural response data set under simulated earthquake loading

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Thank you