Investigation of Seismic Response of Steel MRF Building Structures with Nonlinear Viscous Dampers Using Real-Time Hybrid Simulation

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Acknowledgements

• Sponsors:
  – The National Science Foundation
    This research was supported by grants from National Science Foundation, Award No. CMS-0936610, in the George E. Brown, Jr. Network for Earthquake Engineering Simulation Research (NEESR) program, and Grant No. CMS-0402490 within the George E. Brown, Jr. Network for Earthquake Engineering Simulation Consortium Operation. Partial support for the development of the test specimen was provided by Award No. CMMI-0830173 in the George E. Brown, Jr. Network for Earthquake Engineering Simulation Research (NEESR) program.
  – Pennsylvania Infrastructure Technology Alliance (Pennsylvania Department of Community and Economic Development)

• NEES@Lehigh Staff: Tommy Marullo, Gary Novak

• Former Ph.D. students:
  – Dr. Yunbyeong Chae, Dr. Cheng Chen, Dr. Oya Mercan

• Nonlinear viscous dampers provided by Taylor Devices, Inc.
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.”

\[ M\ddot{X} + C\dot{X} + (r^a_i + r^e_i) = F_i \]

- Observe \( r^{a}_{i+1} \) from the analytical substructure by state determination.
- Observe \( r^{e}_{i+1} \) from the experimental substructure.
- Calculate \( X^t_{i+1}, \dot{X}^t_{i+1} \) at \( t_{i+1} \).
- Impose \( X^t_{i+1} \) on the analytical substructure.
- Impose \( X^t_{i+1} \) on the experimental substructure.
- Solve \( \ddot{X}^t_i \) at \( t_i \).
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 \((\text{Dong, Sause, Ricles 2015})\)

- 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

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 ($C_\alpha=696 \text{ kN-s/m}$ and $\alpha=0.44$) under DBE and MCE, respectively

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

RTHS Phase-1

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

RTHS Phase-2

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

Seismic tributary area

Prototype Building

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

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.

Experimental substructure
(0.6-scale DBF)
Large-Scale RTHS on Steel MRF Structure with Nonlinear Viscous Dampers: Phase-2 Substructures

Experimental substructure (0.6-scale MRF and DBF)

Analytical substructure (mass, gravity system, inherent damping)

Real-time state determination
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

Within step $i$

$k = n_s(i-1) + j$

$n_s =$ number of substeps with step $i$
Integration Algorithm: Integration of equations of motion

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

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

$$
\dot{X}_{i+1}^t = \dot{X}_i^t + \Delta t \cdot a_1 \cdot \ddot{X}_i^t
$$

$$
X_{i+1}^t = X_i^t + \Delta t \cdot \dot{X}_i^t + \Delta t^2 \cdot a_2 \cdot \ddot{X}_i^t
$$

$\alpha_1, \alpha_2$ – matrices of integration parameters

$\alpha_1 = \alpha_2 = 4M \cdot (4M + 2\Delta t \cdot C + \Delta t^2 \cdot K)^{-1}$

Ramp generator: Continuous movement of actuators

Interpolation of displacements to account for difference in time increment between integration time step ($\Delta t$) and controller time interval ($\delta t$).

\[ \tilde{x}_{n,k}^{t} = \frac{j}{n_s} (x_{n,i+1}^{t} - x_{n,i}^{t}) + x_{n,i}^{t} \quad (j = 1, 2, \ldots n_s) \]

$n_s$ – number of substeps, $n_s=4$;

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

$x_{n,i}^{t}$ and $x_{n,i+1}^{t}$ – target displacements for DOF $n$ at $t_{i+1}$ and $t_i$;

$\tilde{x}_{n,k}^{t}$ – target displacement discretized at $\delta t$ for the $j^{th}$ substep within step $i$. 
Compensator: Reduce potential errors between target displacement and actual displacement due to dynamic characteristics of servo-hydraulic controller, actuators, test fixture and experimental substructure

Adaptive ATS compensator (Chae, Kazemibidokhti, Ricles 2013)

\[
\ddot{x}_{n,k}^c = a_{0k} \cdot \dot{x}_{n,k} + a_{1k} \cdot \ddot{x}_{n,k} + a_{2k} \cdot \dddot{x}_{n,k}
\]

\(x_{n,k}^c\) – compensated command displacement of \(n^{th}\) floor to actuator at \(t_k = k \cdot \delta_t\);

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

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

Use measured displacements from experimental substructure as feedback for RTHS control \((\text{Dong, Sause, Ricles 2015})\)

Enables target displacements to be imposed accurately on experimental substructure

Accuracy is determined by displacement history of experimental substructure, not by actuator stroke

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

RTHS Phase-1 Results Evaluation

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

RTHS Phase-1 Results Evaluation

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

**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, 0.009 m/s  (2.5%, 1.7%, 1.7%)

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

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

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%)

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

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

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

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

**DBE level RTHS:**
- Mean maximum story drifts: 0.71%, 0.78%, and 0.54% for the 1<sup>st</sup>, 2<sup>nd</sup>, and 3<sup>rd</sup> story
- Negligible residual story drift

<table>
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<th>Story drift (%)</th>
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<td>1st story 2nd story 3rd story</td>
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<tr>
<td>DBE-1</td>
<td>0.68 0.82 0.53</td>
<td>0.009 0.013 0.022</td>
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<td>DBE-2</td>
<td>0.63 0.73 0.52</td>
<td>0.000 0.000 0.000</td>
</tr>
<tr>
<td>DBE-3</td>
<td>0.68 0.76 0.48</td>
<td>0.013 0.017 0.009</td>
</tr>
<tr>
<td>DBE-4</td>
<td>0.79 0.82 0.55</td>
<td>0.031 0.035 0.022</td>
</tr>
<tr>
<td>DBE-5</td>
<td>0.62 0.71 0.49</td>
<td>0.004 0.004 0.009</td>
</tr>
<tr>
<td>DBE-6</td>
<td>0.79 0.80 0.55</td>
<td>0.044 0.044 0.022</td>
</tr>
<tr>
<td>DBE-7</td>
<td>0.71 0.80 0.57</td>
<td>0.013 0.013 0.000</td>
</tr>
<tr>
<td>DBE Mean</td>
<td><strong>0.71</strong> <strong>0.78</strong> <strong>0.54</strong></td>
<td><strong>0.016</strong> <strong>0.018</strong> <strong>0.012</strong></td>
</tr>
<tr>
<td>DBE prediction</td>
<td><strong>0.76</strong> <strong>0.81</strong> <strong>0.64</strong></td>
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**MCE level RTHS:**
- Mean maximum story drifts: 1.18%, 1.37%, and 0.99% for the 1<sup>st</sup>, 2<sup>nd</sup>, and 3<sup>rd</sup> story
- Mean residual story drift : 0.08%, 0.12%, and 0.09% for the 1<sup>st</sup>, 2<sup>nd</sup>, and 3<sup>rd</sup> story

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<td>1.25 1.48 1.09</td>
<td>0.118 0.176 0.137</td>
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<td>1.10 1.29 0.88</td>
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<td>1.27 1.39 0.98</td>
<td>0.091 0.124 0.060</td>
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<td>1.07 1.24 0.91</td>
<td>0.112 0.150 0.104</td>
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Predicted drift is close to mean from RTHS D100V structure
### Use of RTHS in Earthquake Engineering Research: Statistical Evaluation of Response from RTHS

#### DBE level RTHS:
- **Mean maximum story drifts:** 0.71%, 0.78%, and 0.54% for the 1\(^{st}\), 2\(^{nd}\), and 3\(^{rd}\) story
- **Negligible residual story drift**

#### MCE level RTHS:
- **Mean maximum story drifts:** 1.18%, 1.37%, and 0.99% for the 1\(^{st}\), 2\(^{nd}\), and 3\(^{rd}\) story
- **Mean residual story drift:** 0.08%, 0.12%, and 0.09% for the 1\(^{st}\), 2\(^{nd}\), and 3\(^{rd}\) story

Predicted drift is close to mean from RTHS

D100V structure

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DBF flexibility produces differences between damper deformation and story drift

Damper forces are more in-phase with DBF column shear forces

D100V structure
MCE RRS318
Use of RTHS in Earthquake Engineering Research: Steel MRF Structure with Viscous Dampers: Results

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

MRF story shear and damper force versus story drift
MRF and DBF story shear versus story drift

D100V structure
MCE RRS318
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
Selected References


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