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

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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

Characterization Tests of Ultra-High Damping Natural Rubber Damper

Apparent ambient temperature dependence of UHDNR damper


Ambient temperature and amplitude dependence of UHDNR damper
Characterization Tests of Compressed Elastomer Damper

2\textsuperscript{nd} generation compressed elastomer damper

Controlled temperature chamber

Characterization test setup for 2\textsuperscript{nd} damper

3\textsuperscript{rd} generation damper in test setup

Characterization Tests of Compressed Elastomer Damper
Characterization Tests of Compressed Elastomer Damper
Characterization Tests of Compressed Elastomer Damper

Deformation amplitude dependence of 2nd generation damper

1.0 inch amplitude, 68° F
2.0 inch amplitude, 1.0 Hz
3.0 inch amplitude, 68° F
4.0 inch amplitude, 68° F

Temperature dependence of 2nd generation damper

1.0 inch amplitude, 1.0 Hz

Loading history

Characterization Tests of Compressed Elastomer Damper

Deformation amplitude dependence of 3rd generation damper

- 1.0 inch amplitude, 68° F
- 2.0 inch amplitude, 1.0 Hz
- 3.0 inch amplitude, 68° F
- 4.0 inch amplitude, 68° F
- 5.0 inch amplitude, 68° F
- 6.0 inch amplitude, 68° F

Temperature dependence of 3rd generation damper

Characterization Tests of Compressed Elastomer Damper

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

Equivalent Stiffness

Loss Factor (Energy Dissipation)
Characterization Tests of Compressed Elastomer Damper

Models for 2\textsuperscript{nd} and 3\textsuperscript{rd} generation dampers based on characterization tests

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

Numerical Model of Hysteretic Force-Deformation Response of 3\textsuperscript{rd} 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

Characterization Tests of Nonlinear Viscous Damper

Nonlinear Viscous Damper

Chamber with silicon oil

Piston head

Piston rod

Damper cylinder

Theory for typical model

\[ f_d = C_\alpha (v)^\alpha \]

- \( f_d \) = damper force
- \( C_\alpha \) = damping coefficient
- \( v \) = damper relative velocity (deformation rate)
- \( \alpha \) = exponent, \( 0 < \alpha < 1 \) nonlinear viscous, \( \alpha = 1 \), linear viscous

Characterization Tests of Nonlinear Viscous Damper

Characterization test matrix

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>0.25</th>
<th>0.5</th>
<th>0.75</th>
<th>1</th>
<th>1.25</th>
<th>1.5</th>
<th>1.75</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
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</tr>
</tbody>
</table>

Controlled temperature chamber

Loading history
Characterization Tests of Nonlinear Viscous Damper

Characterization Tests of Nonlinear Viscous Damper

No significant temperature dependence of nonlinear viscous damper

Characterization Tests of Nonlinear Viscous Damper

Nonlinear model

\[ f_d = C_\alpha (v)^\alpha \]

Identification of parameters \((C_\alpha, \alpha)\)

Identified from average peak damper force and corresponding velocity from tests

\[ f_d \]

\[ f_{d_{\text{max}}}=C_\alpha \cdot (\dot{u}_0)^\alpha \]

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

Nonlinear spring, $k_s$

Nonlinear dashpot, $C\alpha$

$u_t = \text{damper total deformation}$

$u_s = \text{spring deformation}$

$u_d = \text{dashpot deformation}$

$f_t = f_s + f_d$

Characterization Tests of Nonlinear Viscous Damper

Identification of parameter for nonlinear spring ($k_s$)

Identified from peak damper force and corresponding velocity from tests

\[ k_s = \frac{f_{d0} \cdot \omega}{(f_{d_{\text{max}}}/C_\alpha)^{1/\alpha}} \]

\( \omega \) is loading frequency of sinusoidal displacement \( u_t = A \cdot \sin(\omega t) \)

Characterization Tests of Nonlinear Viscous Damper

Nonlinear Maxwell Model

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

Characterization of Force-Limiting Friction Device for Floors

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

Characterization of Force-Limiting Friction Device for Floors

Characterization of Force-Limiting Friction Device for Floors

Interesting Variations from Expected Response from Simple Model

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

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.

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

Models for MRF System with Elastomeric Damper

Simple models for design calculations and understanding system response

Viscoelastic model for damper

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)

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

Accurate numerical model for elastomeric damper

1.0 Hz, 20°C

Experimental
Analytical

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

Results from simple models for design

Period of MRF building decreases as damper stiffness increases

Equivalent damping of MRF building increases/decreases as damper stiffness increases

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

\[ \beta = \frac{k'_d}{k_o} \]

\( k'_d \) = damper stiffness

\( k_o \) = MRF story stiffness

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

Models for Nonlinear Viscous Damper

Simple Model

\[ f_d = C_\alpha (v)^\alpha \]

Nonlinear Maxwell Model

Nonlinear spring, \( k_s \)

\[ u_s, f_s \]

Nonlinear dashpot, \( C_\alpha, \alpha \)

\[ u_d, f_d \]

\[ f_t \]

\[ u_t \]
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

Simple models for design calculations and understanding system response

(a) Damper-brace component

Sequence of models for equivalent linearization of damper-brace component

(b) Equivalent viscoelastic model

(c) Equivalent elastic-viscous model

Models for MRF System with Nonlinear Viscous Damper

Simple models for design calculations and understanding system response

Damper stiffness in frequency domain:

\[ f_d(i\omega) = iC_\alpha \omega^\alpha (u_d(i\omega))^{\alpha-1} \]

\[ k_d(i\omega) = \frac{1}{iC_\alpha \omega^\alpha (u_d(i\omega))^{\alpha-1}} \]

\[ f_d(i\omega) = k_d(i\omega) \cdot u_d(i\omega) \]

Combined stiffness for damper-brace component:

\[ k_c^*(i\omega) = \frac{1}{k_b + k_d(i\omega)} \]

\[ = \frac{(C_\alpha \omega^\alpha (u_d(i\omega))^{\alpha-1})^2}{(C_\alpha \omega^\alpha (u_d(i\omega))^{\alpha-1})^2 + (k_b)^2} k_b + i \frac{(C_\alpha \omega^\alpha (u_d(i\omega))^{\alpha-1})}{(C_\alpha \omega^\alpha (u_d(i\omega))^{\alpha-1})^2 + (k_b)^2} k_b^2 \]

Equivalent viscoelastic model of damper-brace component

Simple models for design calculations and understanding system response

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

\[ k_c(i\omega) = \frac{(C_\alpha \omega^\alpha (u_d(i\omega))^{\alpha-1})^2}{(C_\alpha \omega^\alpha (u_d(i\omega))^{\alpha-1})^2 + (k_b)^2} k_b \]

\[ \eta_c(i\omega) = \frac{k_h}{C_\alpha \omega^\alpha (u_d(i\omega))^{\alpha-1}} \]

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

\[ k_{eq} = k_c(i\omega_s) = \frac{(C_\alpha \omega_s^{\alpha_2}(u_{ds})^{\alpha-1})^2}{(C_\alpha \omega_s^{\alpha_2}(u_{ds})^{\alpha-1})^2 + (k_b)^2} k_b \]

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

\[ C_{eq} = \frac{k_c(i\omega_s)\eta_c(i\omega_s)}{\omega_s} = \frac{C_\alpha \omega_s^{\alpha-1}(u_{ds})^{\alpha-1}}{(C_\alpha \omega_s^{\alpha_2}(u_{ds})^{\alpha-1})^2 + (k_b)^2} k_b^2 \]

(c) Equivalent linear elastic-viscous model

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

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

Models for MRF System with Nonlinear Viscous Damper

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 ($k_0$)

$$k_{\text{eff}} = k_0 + k_{\text{eq}}$$

$$= k_0 + \frac{(C_\alpha \omega_s (u_{ds})^{\alpha-1})^2}{(C_\alpha \omega_s (u_{ds})^{\alpha-1})^2 + (k_b)^2} k_b$$

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

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

- Normalized stiffness of MRF with damper-brace component $k_{eff}/k_0$ increases with decreased brace stiffness 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

(a) $u_m=0.5\%$ story height

(b) $u_m=1.0\%$ story height

Increasing combined system stiffness

Increasing combined system stiffness
Models for MRF System with Nonlinear Viscous Damper

Simple models for design calculations and understanding system response

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

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
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• 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

• 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 ($C_\alpha = 696$ kN-s/m and $\alpha = 0.44$) 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)
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

Keep MRF and DBF unchanged
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

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

Phase-1 RTHS


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

Experimental substructure (0.6-scale DBF)
Real-Time Hybrid Simulations on Moment Resisting Frame Building Structure with Nonlinear Viscous Dampers

Phase-2 RTHS


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.)
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

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 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%)
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

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

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<tr>
<th>Ground Motion No.</th>
<th>Story drift (%)</th>
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<td>1st story</td>
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</table>

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%

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<tr>
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<td>MCE Mean</td>
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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%

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)

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)

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

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

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

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MCE (2% POE in 50 yr.) RTHS
- Mean maximum story drifts: 1.20%, 1.38%, 1.00% for 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> story
- Mean maximum residual story drift: 0.06%

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

Keep MRF and DBF unchanged

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


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

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%)
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

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

Based on Results from Phase-1 RTHS

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

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

Phase-2 RTHS

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.)
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

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


Comparison of Velocity Response

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.)

Provides Validation of Phase-1 RTHS
Seismic Performance of Moment Resisting Frame with Nonlinear Viscous Dampers Based on Phase-2 RTHS: Beam End Damage States for DBE

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

D60 Test Structure for MCE

D60V Test Structure for 1.4 MCE


Beam moment-rotation (incl. RBS) for scaled H-BRA315 18
Seismic Performance of Moment Resisting Frame with Nonlinear Viscous Dampers Based on Phase-2 RTHS: Beam End Damage States for D60V

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

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

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• 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