Hands-on Laboratory Exercises: RTHS; HybridFEM Numerical Sims

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Outline

• Large-scale nonlinear viscous damper characterization test
• RTHS of a RC building with nonlinear viscous damper
• Numerical simulations using HybridFEM to experience the various features
Groups

<table>
<thead>
<tr>
<th>Groups</th>
<th>2:35 – 3:15 PM</th>
<th>3:15 – 4:00 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-RED</td>
<td>Control Room – A121</td>
<td>A104</td>
</tr>
<tr>
<td>2-BLUE</td>
<td>A104</td>
<td>Control Room – A121</td>
</tr>
</tbody>
</table>

Back of your name tag has a group label and color
Outline

• Large-scale nonlinear viscous damper characterization test
  • RTHS of a RC building with nonlinear viscous damper
  • Numerical simulations using HybridFEM to experience the various features
Damper Characterization Test

Nonlinear fluid viscous damper

- Make: Taylor Devices Inc.
- Nominal force capacity 600 kN
- Max stroke ±125 mm
- Theoretical force-velocity:
  \[ f_D = C_D sgn(\dot{u}_D) |\dot{u}_D|^{\alpha} \]
- Manufacturer provided
  \[ C_D = 773 \, kN \cdot \left( \frac{s}{m} \right)^{\alpha} \] and \( \alpha = 0.4 \)
- Operating temperature:
  \(-6.7^\circ C \) to \(+54.4^\circ C \) (+20°F to +130°F)
Full-Scale Nonlinear Viscous Dampers

Characterization testing

Damper testbed

Loading Protocol

Damper force - deformation

Damper force - velocity
Procedure for Damper Characterization

1. Develop a damper model
2. Assign model parameters
3. Predict model response
4. Calculate error between model and measured experimental data
5. Revise parameters to minimize error
6. Predefined displacement tests
### Input Displacement and Test Matrix

![Graph showing input displacement and test matrix](image)

<table>
<thead>
<tr>
<th>Amplitude mm (in.)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>76.2 (3.0)</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>119.7 (4.7)</td>
</tr>
<tr>
<td>239.4 (9.4)</td>
<td>1.0</td>
</tr>
<tr>
<td>478.8 (18.9)</td>
<td>1.5</td>
</tr>
<tr>
<td>718.2 (28.3)</td>
<td></td>
</tr>
</tbody>
</table>

Numbers in the cells are max velocities in mm/s (in/s)
Actuator Hydraulic Power Curve

Power curve for 1700 kN actuators at 3000 psi

- 1 valve
- 2 valves
- 3 valves
- Max demand

Force (kN) vs. Velocity (m/s)
Nonlinear Maxwell Damper Model

- Damper shows strong frequency dependent behavior
- Usually modeled using a nonlinear Maxwell model

\[
\begin{align*}
K_D & \quad u_K \\
C_D, \alpha & \quad u_C, f_C \\
u_D, f_D
\end{align*}
\]

Total damper deformation: \( u_D = u_k + u_c \)
Total damper velocity: \( \dot{u}_D = \dot{u}_k + \dot{u}_c \)
Damper force:
\[
f_D = f_K = K_D u_k \Rightarrow \dot{u}_K = \frac{f_D}{K_D}
\]
\[
f_D = f_C = C_D sgn(\dot{u}_C)|\dot{u}_C|^\alpha \Rightarrow \dot{u}_C = \left| \frac{f_D}{C_D} \right|^\frac{1}{\alpha} sgn(f_D)
\]

Governing equation (nonlinear ODE)
\[
\dot{f}_D + K_D \left| \frac{f_D}{C_D} \right|^{\frac{1}{\alpha}} sgn(f_D) = K_D \dot{u}_D
\]
Solution of nonlinear ODE

Governing equation (nonlinear ODE): \( \dot{f}_D + K_D \left| \frac{f_D}{C_D} \right|^{\frac{1}{\alpha}} \text{sgn}(f_D) = K_D \dot{u}_D \)

Simulink model for solution of the nonlinear ODE

Solver: variable-step Dormand-Prince solver (ode45) which belongs to 5th order Runga-Kutta family
Determination of Model Parameters

- Identify $K_D$, $C_D$, and $\alpha$ so that the error between the model prediction and experimental data are minimized
- We use particle swarm optimization (PSO) algorithm (Kennedy and Eberhart, 1995; Ye and Wang, 2007; Chae, 2011)
  - The algorithm in Matlab script is available for users
- Objective function: Normalized root mean square error

$$F_{obj}^{K_D, C_D, \alpha} = \sqrt{\frac{\Sigma_{n=1}^{N} (f_{Dn}^e - f_{Dn}^p)^2}{\Sigma_{n=1}^{N} (f_{Dn}^e)^2}}$$

- $f_{Dn}^e$ and $f_{Dn}^p$ are experimental and predicted damper forces, respectively
- $N$ is the total number of samples
Measured vs Model Prediction

Characterization testing

Damper testbed

Loading Protocol

Damper force - deformation

Damper force - velocity

2 ramp up cycles
7 stable full cycles
3 ramp down cycles
Outline

• Large-scale nonlinear viscous damper characterization test

• RTHS of a RC building with nonlinear viscous damper

• Numerical simulations using HybridFEM to experience the various features
Building Description – Location and Layout

- Retail store located in Los Angeles
- Assumed to be on stiff soil
- Spectral accelerations $S_{DS}$ and $S_{D1}$ are 1.0 and 0.6, respectively
- Building is designed based on the ASCE-10 and ACI 318 Code
Building Description - Details

- Nominal concrete compressive strength of 4 ksi
- Nominal reinforcement strength of 60 ksi
- Seismic reinforcement detailing
- Weak beam-strong column

Steel Reinforcement Ratio, $p$

- 0.0058
- 0.0062
- 0.0277
# Building Description - Properties

<table>
<thead>
<tr>
<th>Floor</th>
<th>Floor Mass (kip-sec²/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.239</td>
</tr>
<tr>
<td>2</td>
<td>0.238</td>
</tr>
</tbody>
</table>

## Modal Properties

<table>
<thead>
<tr>
<th>Mode</th>
<th>Period (sec)</th>
<th>Inherent Damping</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.43</td>
<td>0.03</td>
</tr>
<tr>
<td>2</td>
<td>0.12</td>
<td>0.03</td>
</tr>
</tbody>
</table>
RTHS Overview

**Integration of equations of motion**

\[
M\ddot{X}_{n+1} + C\dot{X}_{n+1} + R^a_{n+1} + R^e_{n+1} = F_{n+1}
\]

**Effective force**

\[
F_{n+1} = X^e_{n+1}
\]

**Ground acceleration**

**Analytical substructure**

**FE model**

**Servo-hydraulic actuator control**

**Experimental substructure**

**Nonlinear damper**

**Simulation coordinator**

**Ramp generator and kinematic transformation for each actuator DOF**

**ATS compensator**

**Servo controller**

**Real time response**

---

RTHS configuration

Prototype floor plan

- EQ record scaled to MCE hazard level
- Time step: $\Delta t = \frac{3}{1024}$ s
## Analytical Substructure - Fiber Material Properties

### Concrete properties

<table>
<thead>
<tr>
<th>Member</th>
<th>Prop</th>
<th>Columns</th>
<th>1(^{\text{st}}) story beams</th>
<th>2(^{\text{nd}}) story beams</th>
<th>Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confined concrete</td>
<td>$K_c f'_c$</td>
<td>5156psi</td>
<td>4360psi</td>
<td>4474psi</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_o$</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$0.2K_c f'_c$</td>
<td>1030psi</td>
<td>872psi</td>
<td>895psi</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_u$</td>
<td>0.045</td>
<td>0.015</td>
<td>0.002</td>
<td>-</td>
</tr>
<tr>
<td>Unconfined concrete</td>
<td>$f'_c$</td>
<td>4768psi</td>
<td>4240psi</td>
<td>4203psi</td>
<td>4000psi</td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_o$</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>$0.2f'_c$</td>
<td>953psi</td>
<td>848psi</td>
<td>841psi</td>
<td>805psi</td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_u$</td>
<td>0.027</td>
<td>0.014</td>
<td>0.009</td>
<td>0.004</td>
</tr>
</tbody>
</table>

![Modified Kent-Park Model](image)

Modified Kent-Park Model – Cyclic Behavior
Analytical Substructure - Fiber Material Properties

- **Steel properties**

<table>
<thead>
<tr>
<th>Yield stress (ksi)</th>
<th>Modulus of elasticity (ksi)</th>
<th>Strain hardening ratio</th>
<th>Ro</th>
<th>cR1</th>
<th>cR2</th>
<th>a1</th>
<th>a2</th>
<th>a3</th>
<th>a4</th>
<th>sigInit</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>29000</td>
<td>0.01</td>
<td>15</td>
<td>0.925</td>
<td>0.15</td>
<td>-0.05</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Giuffre-Menegotto-Pinto – Cyclic Behavior
RTHS Configuration

- Analytical substructure modeled using force-based elements for beams and columns with fixed number of iterations, and linear elastic elements for diagonal bracing
- Fiber elements: Mass and tangent stiffness proportional damping
- Elastic elements: Rayleigh proportional damping
- Time step: $\Delta t = \frac{3}{1024}$ s
- MKR-\(\alpha\) method (parameter $\rho_\infty$)
  - Model-based integration parameters ($\alpha_1$, $\alpha_2$, $\alpha_3$) determined from characterization test data
- ATS Compensator for adaptive time delay and amplitude compensation
## Parameters to Consider for RTHS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground Motion (scaled to MCE)</td>
<td>1994 Northridge EQ, Canyon Country Recording Station, Component - RSN960_NORTHR_LOS270 1999 Kocaeli, Turkey EQ, Yarimca Station, Component - RSN1176_KOCAELI_YPT150 H2</td>
</tr>
<tr>
<td>• Far Field</td>
<td></td>
</tr>
<tr>
<td>• Near Field</td>
<td></td>
</tr>
</tbody>
</table>
| Steel Reinforcement Ratio, \( \rho \)       | 0.0277 \(^{(1)}\) or 0.0166 \(^{(2)}\)  
0.0062 \(^{(1)}\) or 0.0047 \(^{(2)}\)  
0.0058 \(^{(1)}\) or 0.0043 \(^{(2)}\)  |
| • Columns                                     |                                                                        |
| • 1\(^{st}\) Floor Beams                     |                                                                        |
| • Roof Beams                                  |                                                                        |
| Location of Damper                            | 1\(^{st}\) or 2\(^{nd}\) Floor                                       |
| Numerical Damping, \( \rho_\infty \)         | 0.25 or 0.0                                                            |

\(^{(1)}\) Original value of longitudinal reinforcement  
\(^{(2)}\) Reduced value of longitudinal reinforcement (75% of original)
As-built Response

Floor Lateral Displacement Time History

Far Field Record

Near Field Record
## Summary of the floor drift

<table>
<thead>
<tr>
<th>Steel ratio</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; story (%)</th>
<th>2&lt;sup&gt;nd&lt;/sup&gt; story (%)</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; story (%)</th>
<th>2&lt;sup&gt;nd&lt;/sup&gt; story (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>1.78</td>
<td>2.85</td>
<td>5.10</td>
<td>5.75</td>
</tr>
<tr>
<td>Reduced</td>
<td>2.69</td>
<td>4.49</td>
<td>10.12</td>
<td>11.28</td>
</tr>
</tbody>
</table>
As-built Response – Far Field EQ

Moment-Curvature Hysteretic Response at Ends of Members

Far Field EQ

Near Field EQ
RTHS: Retrofit Response – Far Field EQ

Floor displacement time history

Floor displacements (damper at 1st story) $\rho=0.027$

Floor displacements (damper at 2nd story) $\rho=0.027$

Floor displacements $\rho=0.016$

Displacement (m)

Time (sec)
RTHS: Retrofit Response – Near Field EQ

Floor displacement time history

Floor displacements (damper at 1st story) $\rho_{\text{columns}} = 0.027$

Floor displacements (damper at 2nd story) $\rho_{\text{columns}} = 0.027$

Floor displacements (damper at 1st story) $\rho_{\text{columns}} = 0.016$

Floor displacements (damper at 2nd story) $\rho_{\text{columns}} = 0.016$
RTHS: Retrofit Response

Moment-Curvature Hysteretic Response at Ends of Members, Damper at 1st Story

Far Field EQ

Near Field EQ
RTHS: Retrofit Response

Moment-Curvature Hysteretic Response at Ends of Members, Damper at 2nd Story

Far Field EQ

Near Field EQ
RTHS: Retrofit Response – Far Field EQ

Damper Response

Damper response ($\rho=0.027$)

- Blue: Damper at 1st story
- Red: Damper at 2nd story

Damper response ($\rho=0.016$)

- Blue: Damper at 1st story
- Red: Damper at 2nd story
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Numerical Simulation Exercise

- Room A104 Computer Stations for Lehigh HybridFEM 5.0
  - Various input configuration and hazard loading files for MATLAB
  - PDF Manual is in the folder
  - You will edit and run the script, `ModelRunner.m` to select input and hazard files
  - **Tcl files** are the input files
  - **Txt files** are the forces (EQ and Wind)
  - Building and Cantilever models
  - `GenerateColumnModel.m` will create an N-story “fun” column model
  - `CreateHFEMOutDataStructure.m` file is a MATLAB script that is automatically executed when you run `ModelRunner.m` and creates a *.mat file that contains all the input/output data
  - Feel free to make any changes in the input file and run it. For example, you can change the mass, gravity load, hazard type and model dimensions.
Numerical Simulation Exercise

- All beam column elements are modeled using displacement-based fiber elements
- Lean-on column is modeled using linear elastic beam-column elements
- $P - \Delta$ effects are included
- Various integration algorithms can be used
- Input file, `Model_Building.tcl`
- In the input file, any line preceded by a “#” is treated as a comment line
- EQ or Wind forcing function file
Numerical Simulation Exercise

One story building subjected to wind

M=400 KN. sec²/M

Mode No.1 [Period = 1.1857919510 sec]

Force

Displacement

$10^{-3}$
Numerical Simulation Exercise

Cantilever subjected to step load

\[ M = 0.5 \text{ KN. sec}^2/\text{M} \]
Numerical Simulation Exercise

- Reconfigurable “Fun” Model
- Column is modeled using linear elastic beam-column element
- GenerateColumnModel.m
- Column10_Wind_Nodes.tcl
- EQ or Wind forcing function file
How to Simulate the Model
How to Simulate the Model

%% Input and EQ Configuration
INF_FILE = 'cantilever_2DNodes.txt';
EQ_FILE = 'EQ_0687004-00471.txt';
Wind_FILE = 'Wind_0687004-00471.txt';
% Wind_FILE: To use a Wind load, you need to include it inside the Input
% Configuration file. See Model_WindRunner.tcl example for details.

TARGET = 'Matlab';
RUNMODE = 'Simulation';

%% Code
% Matlab

figure; % Create a new figure
plot(x, y); % Plot the data
xlabel('X-axis label'); % Set the x-axis label
ylabel('Y-axis label'); % Set the y-axis label
title('Title of the plot'); % Set the title of the plot
grid on; % Display grid lines

% Simulink

%% Code
% Simulink

figure; % Create a new figure
plot(x, y); % Plot the data
xlabel('X-axis label'); % Set the x-axis label
ylabel('Y-axis label'); % Set the y-axis label
title('Title of the plot'); % Set the title of the plot
grid on; % Display grid lines

%% Code
% Text display

figure; % Create a new figure
text(x, y, 'Text display'); % Display text
xlabel('X-axis label'); % Set the x-axis label
ylabel('Y-axis label'); % Set the y-axis label
title('Title of the plot'); % Set the title of the plot
grid on; % Display grid lines

How to Simulate the Model
How to Simulate the Model
How to Simulate the Model

[Image of MATLAB interface with a dialogue box asking if you want to display node numbers]
How to Simulate the Model
How to Simulate the Model
How to Simulate the Model

[MATLAB GUI interface shown with a focus on the ModelRunner.m file and the command window output, highlighting the numerical simulation details]
How to Simulate the Model
How to Simulate the Model
Simulation Results

• By default, the program plots the displacement, velocity, acceleration, and restoring forces at all unrestrained (free) DOFs

• Using CreateHFEMOutDataStructure.m, you can generate Node and Element data to see:
  • Plots of section force deformations
  • Story drifts

• *.mat file generated after simulations contain all the input/output data
Some Example Results
Thank you