### 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

Groups	2:35 – 3:15 PM	3:15 – 4:00 PM
1-RED	Control Room – A121	A104
2-BLUE	A104	Control Room – A121

Back of your name tag has a group label and color







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# **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  $C_D = 773 \ kN. \left(\frac{s}{m}\right)^{\alpha}$  and  $\alpha = 0.4$
- Operating temperature: -6.7°C to +54.4°C (+20°F to +130°F



### Full-Scale Nonlinear Viscous Dampers Characterization testing



### **Procedure for Damper Characterization**







# **Input Displacement and Test Matrix**



Numbers in the cells are max velocities in mm/s (in/s)

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# **Actuator Hydraulic Power Curve**









# **Nonlinear Maxwell Damper Model**

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



Model parameters:  $K_D$ ,  $C_D$ , and  $\alpha$ 

Total damper deformation:  $u_D = u_k + u_c$ Total damper velocity:  $\dot{u}_D = \dot{u}_k + \dot{u}_c$ Damper force:

$$f_D = f_K = K_D u_k \Longrightarrow \dot{u}_K = \frac{\dot{f}_D}{K_D}$$

 $f_D$ 

$$= f_C = C_D sgn(\dot{u}_C) |\dot{u}_C|^{\alpha} \Longrightarrow \dot{u}_C = \left| \frac{f_D}{C_D} \right|^{\frac{1}{\alpha}} sgn(f_D)$$





# **Solution of nonlinear ODE**

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



Simulink model for solution of the nonlinear ODE

Solver: variable-step Dormand-Prince solver (ode45) which belongs to 5<sup>th</sup> 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

$$F^{obj}(K_D, C_D, \alpha) = \sqrt{\frac{\sum_{n=1}^{N} (f_{D_n}^e - f_{D_n}^p)^2}{\sum_{n=1}^{N} (f_{D_n}^e)^2}}$$

- >  $f_D^e$  and  $f_D^p$  are experimental and predicted damper forces, respectively
- $\succ$  N is the total number of samples

# **Measured vs Model Prediction**

#### **Characterization testing**



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### **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



2 #7

Steel Reinforcement Ratio, ρ

\* Column confining zones measure 22" from the face of the beams and 33" from the base of the column



# **Building Description - Properties**

	Floor Mass					
Flo	oor	Mass (kip-sec²/in)				
		(	0.239			
	2	(	0.238			
Modal Properties						
Mode	Period (sec)		Inherent Damping			
1	0.43		0.03			
2	(	0.12	0.03			





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# **RTHS Overview**



Kolay, C. "Parametrically Dissipative Explicit Direct Integration Algorithms for Computational and Experimental Structural Dynamics". Ph.D. Dissertation. Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, USA, 2016

# **RTHS configuration**



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# Analytical Substructure -Fiber Material Properties

#### Concrete properties

Member	Prop	Columns	1 <sup>st</sup> story beams	2 <sup>nd</sup> story beams	Cover
	K <sub>c</sub> f'c	5156psi	4360psi	4474psi	-
Confined concrete	εο	0.002	0.002	0.002	-
	0.2K <sub>c</sub> ťc	1030psi	872psi	895psi	-
	٤ <sub>u</sub>	0.045	0.015	0.002	-
	f'c	4768psi	4240psi	4203psi	4000psi
Unconfined concrete	ε <sub>o</sub>	0.002	0.002	0.002	0.002
	0.2f'c	953psi	848psi	841psi	805psi
	ε <sub>u</sub>	0.027	0.014	0.009	0.004



#### Modified Kent-Park Model



#### Modified Kent-Park Model – Cyclic Behavior





# **Analytical Substructure -Fiber Material Properties**

#### Steel properties



# **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**

Parameter	Values
Ground Motion (scaled to MCE) <ul> <li>Far Field</li> </ul> Near Field	1994 Northridge EQ, Canyon Country Recording Station, Component - RSN960_NORTHR_LOS270 1999 Kocaeli, Turkey EQ, Yarimca Station, Component - RSN1176_KOCAELI_YPT150 H2
<ul> <li>Steel Reinforcement Ratio, ρ</li> <li>Columns</li> <li>1<sup>st</sup> Floor Beams</li> <li>Roof Beams</li> <li>Location of Damper</li> <li>Numerical Damping, ρ<sub>∞</sub></li> <li><sup>(1)</sup> Original value of longitudinal rein</li> </ul>	0.0277 <sup>(1)</sup> or 0.0166 <sup>(2)</sup> 0.0062 <sup>(1)</sup> or 0.0047 <sup>(2)</sup> 0.0058 <sup>(1)</sup> or 0.0043 <sup>(2)</sup> $1^{st}$ or 2 <sup>nd</sup> Floor 0.25 or 0.0
<sup>(2)</sup> Reduced value of longitudinal re	einforcement (75% of original)

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## **As-built Response**

#### Floor Lateral Displacement Time History





# **As-built Response**

#### Summary of the floor drift

	Peak story drift (far field)		Peak story drift (near field)		
Steel ratio	1 <sup>st</sup> story (%)	2 <sup>nd</sup> story (%)	1 <sup>st</sup> story (%)	2 <sup>nd</sup> story (%)	
Original	1.78	2.85	5.10	5.75	
Reduced	2.69	4.49	10.12	11.28	



# **As-built Response – Far Field EQ**

#### Moment-Curvature Hysteretic Response at Ends of Members

#### Far Field EQ

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#### Near Field EQ





### **RTHS: Retrofit Response – Far Field EQ**

#### Floor displacement time history





### **RTHS: Retrofit Response – Near Field EQ**

#### Floor displacement time history





# **RTHS: Retrofit Response**

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

#### Far Field EQ

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#### Near Field EQ





# **RTHS: Retrofit Response**

#### Moment-Curvature Hysteretic Response at Ends of Members, Damper at 2<sup>nd</sup> Story

#### Far Field EQ

#### Near Field EQ











### **RTHS: Retrofit Response – Far Field EQ**

#### Damper Response





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- Large-scale nonlinear viscous damper characterization test
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- Room A104 Computer Stations for Lehigh HybridFEM 5.0
  - Various input configuration and hazard loading files for MATLAB
  - PDF Manual is in the folder

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- 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)
- Bulding 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.





- 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







#### Cantilever subjected to step load









- Reconfigurable "Fun" Model
- Column is modeled using linear elastic beam-column element
- GenerateColumnModel.m
- Column10\_Wind\_Nodes.tcl
- EQ or Wind forcing function file

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# **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





