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

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

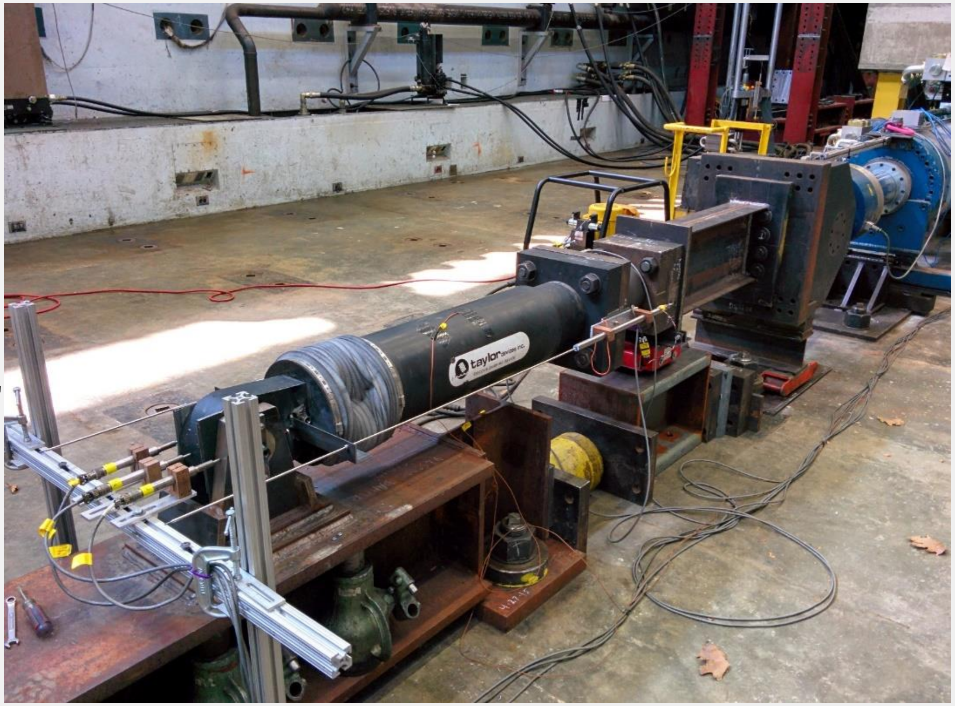
Damper Characterization Test

Nonlinear fluid viscous damper

- Make: Taylor Devices Inc.
- Nominal force capacity 600 kN
- Max stroke ± 125 mm
- Theoretical force-velocity:

$$f_D = C_D sgn(\dot{u}_D)|\dot{u}_D|^{\alpha}$$

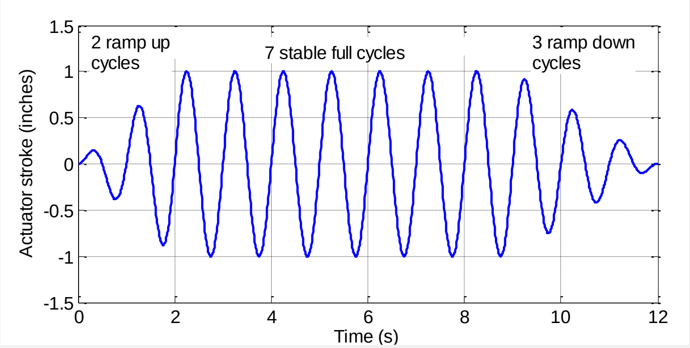
- Manufacturer provided $C_D = 773\,kN.\left(\frac{s}{m}\right)^{\alpha}$ and $\alpha = 0.4$
- Operating temperature: $-6.7°C$ to $+54.4°C$ ($+20°F$ to $+130°F$)



Full-Scale Nonlinear Viscous Dampers

Characterization testing

Damper testbed



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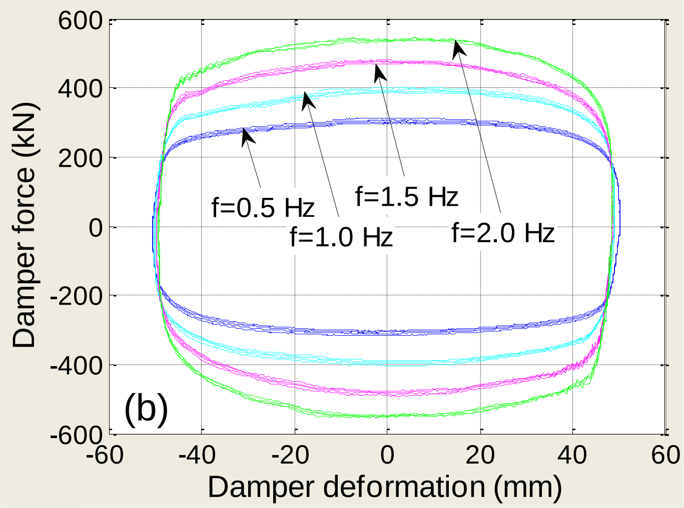
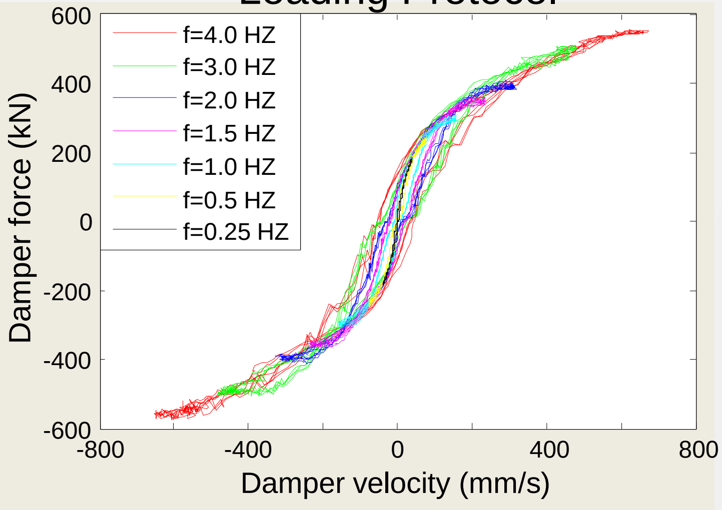


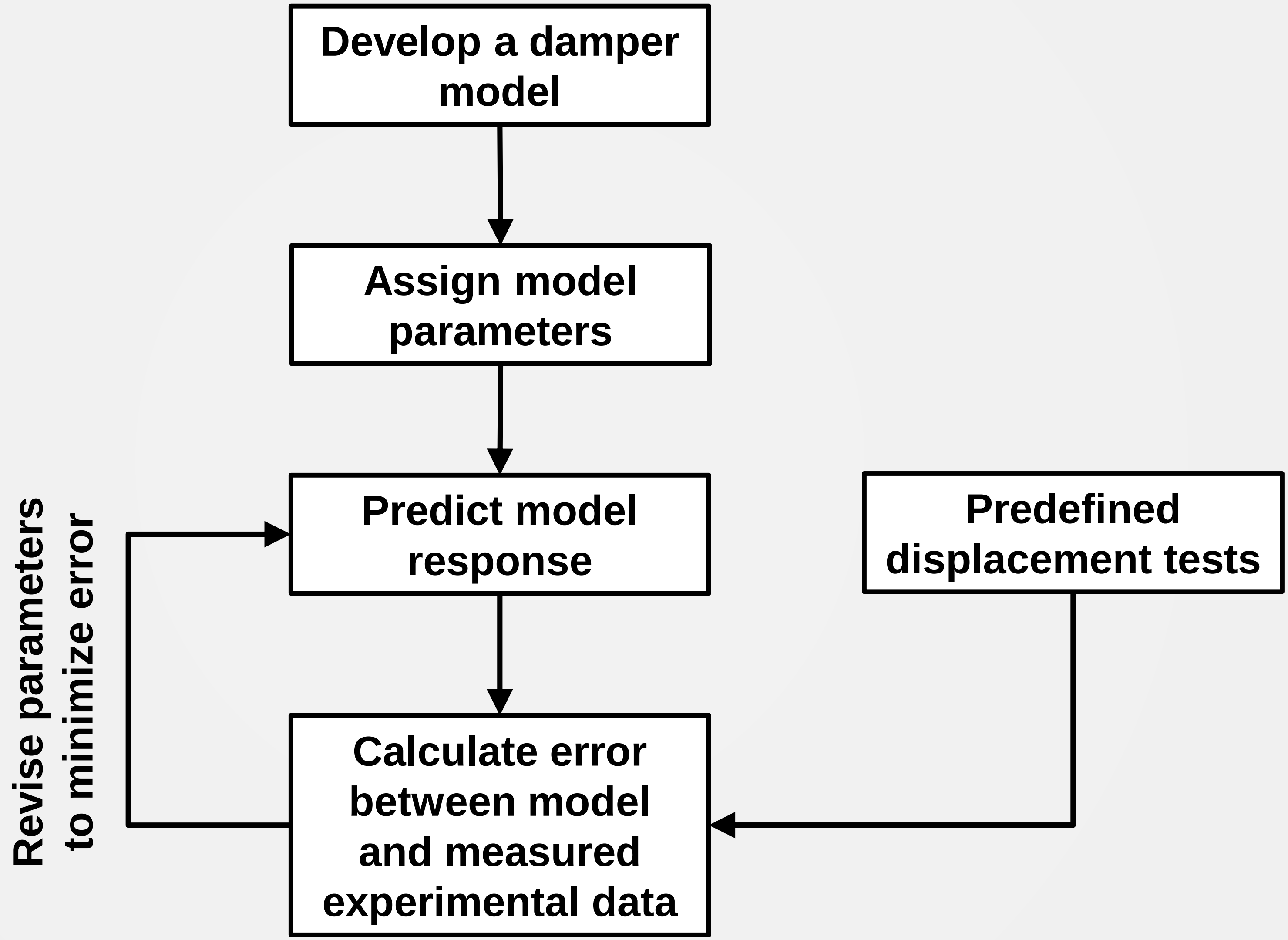
Damper force - deformation



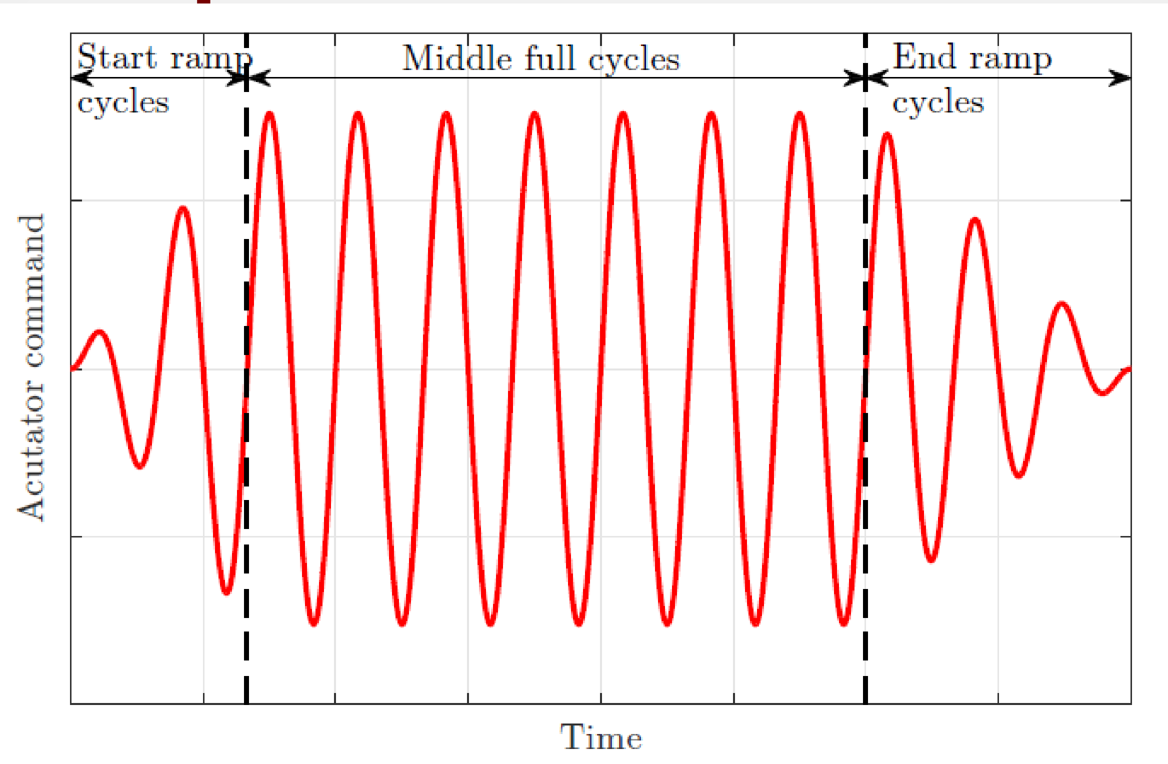
Damper force - velocity

LEHIGH UNIVERSITY ATLSS RTMD REAL-TIME MULTI-DIRECTIONAL SIMULATION NATURAL HAZARDS ENGINEERING RESEARCH INFRASTRUCTURE NSF DESIGNSAFE-CI A NATURAL HAZARDS ENGINEERING COMMUNITY

Procedure for Damper Characterization



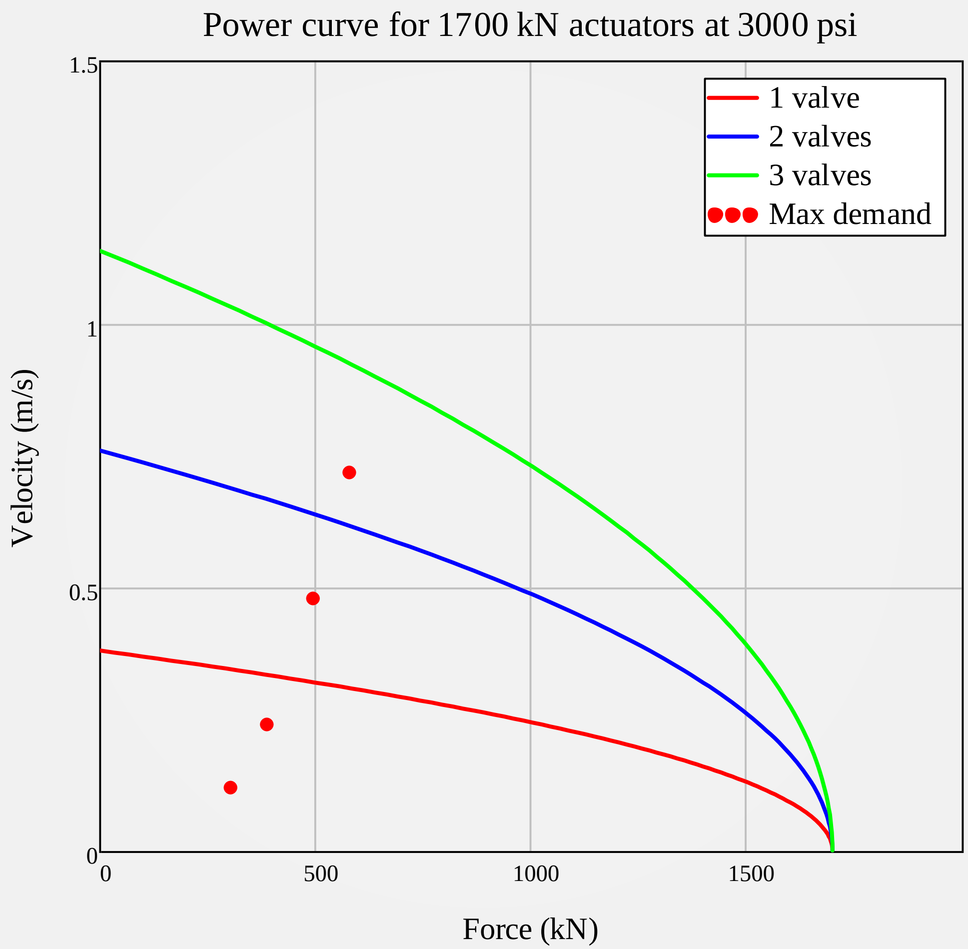
Input Displacement and Test Matrix



Amplitude mm (in.)	Frequency (Hz)			
	0.25	0.50	1.0	1.5
76.2 (3.0)	119.7 (4.7)	239.4 (9.4)	478.8 (18.9)	718.2 (28.3)

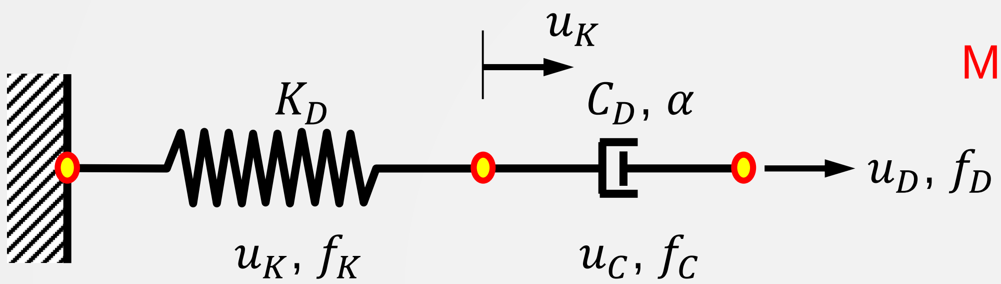
Numbers in the cells are max velocities in mm/s (in/s)

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 α

Total damper deformation: $u_D = u_k + u_c$

Total damper velocity: $\dot{u}_D = \dot{u}_k + \dot{u}_c$

Damper force:

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

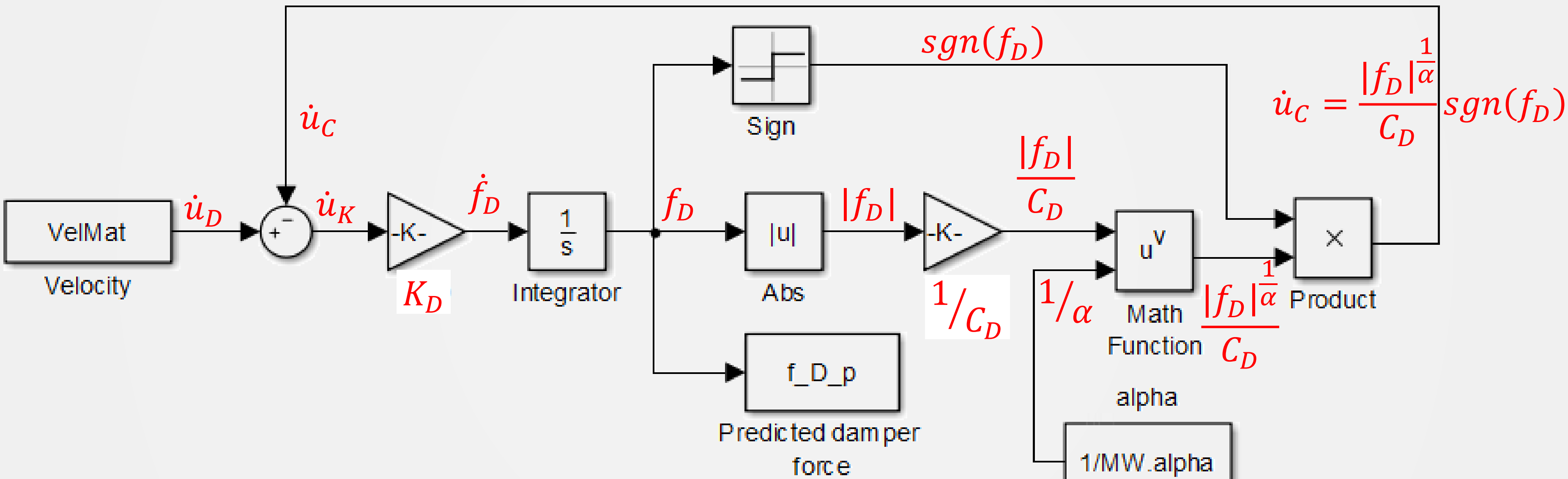
$$f_D = f_C = C_D sgn(\dot{u}_C)|\dot{u}_C|^{\alpha} \Longrightarrow \dot{u}_C = \left|\frac{f_D}{C_D}\right|^{\frac{1}{\alpha}} sgn(f_D)$$

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



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

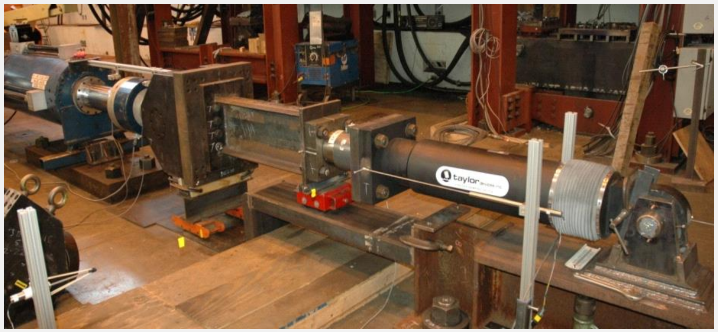
- Identify K_D, C_D, and α so that the error between the model prediction and experimental data are minimized
- We use particle swarm optimization (PSO) algorithm (Kennedy and Eberhart, 1995; Ye and Wang, 2007; Chae, 2011)
  - The algorithm in Matlab script is available for users
- Objective function: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

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

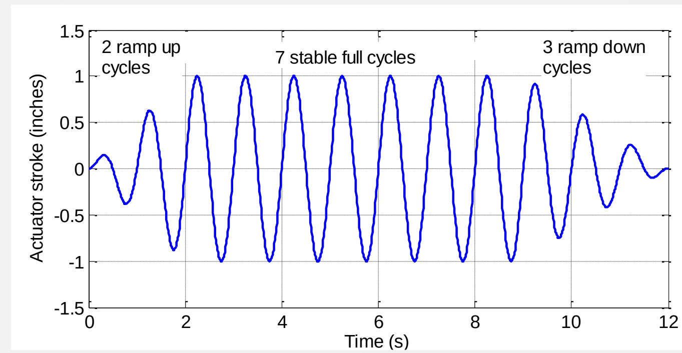
  - f_D^e and f_D^p are experimental and predicted damper forces, respectively
  - N is the total number of samples

Measured vs Model Prediction

Characterization testing



Damper testbed



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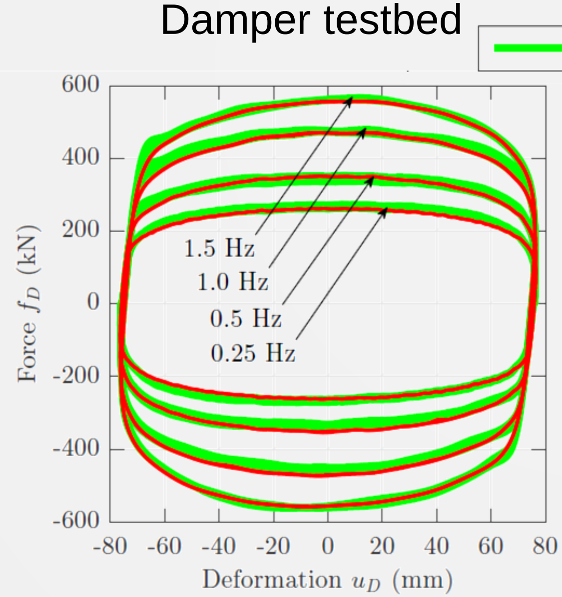
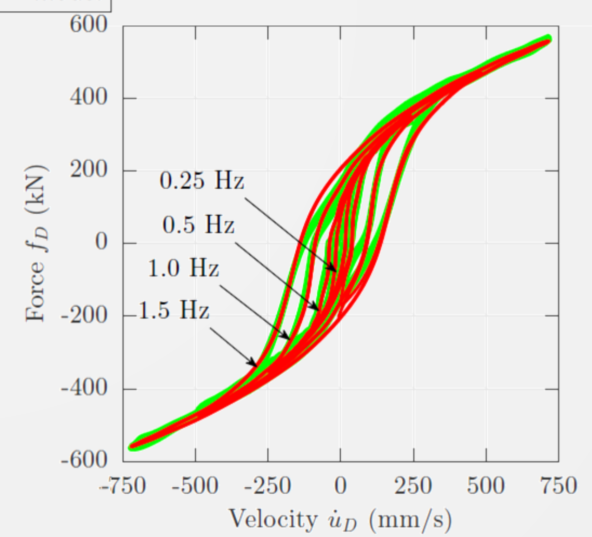


Damper force - deformation



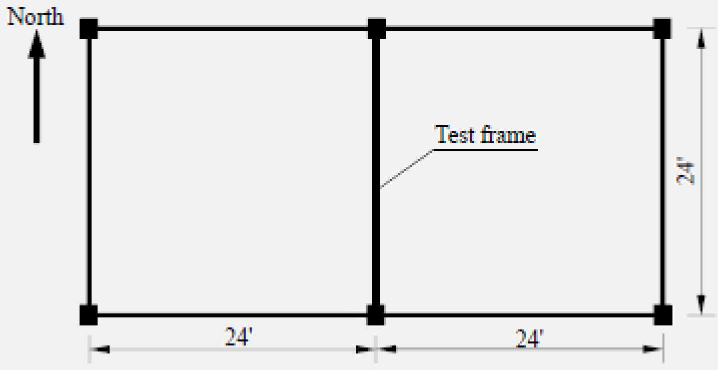
Damper force - velocity

Outline

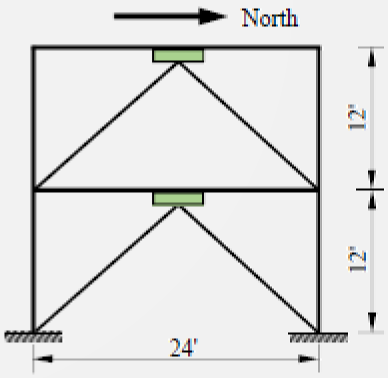
- Large-scale nonlinear viscous damper characterization test
- RTHS of a RC building with nonlinear viscous damper
- Numerical simulations using HybridFEM to experience the various features

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



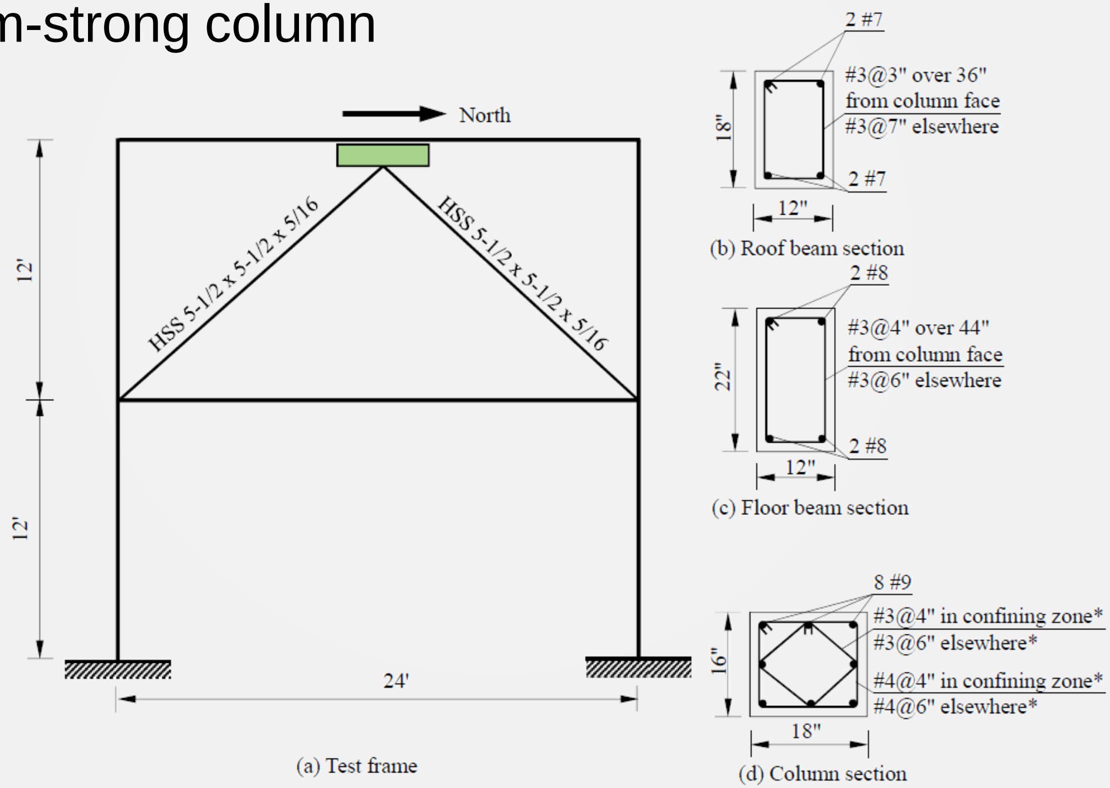
(a) Floor plan



(b) Elevation view

Building Description - Details

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



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

<u>Steel Reinforcement Ratio, ρ</u>

0.0058

0.0062

0.0277

Building Description - Properties

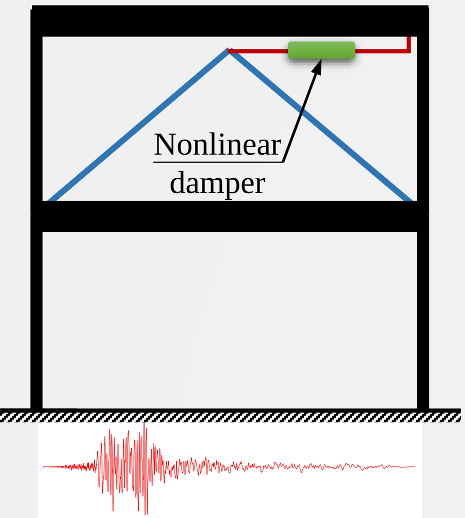
Floor Mass

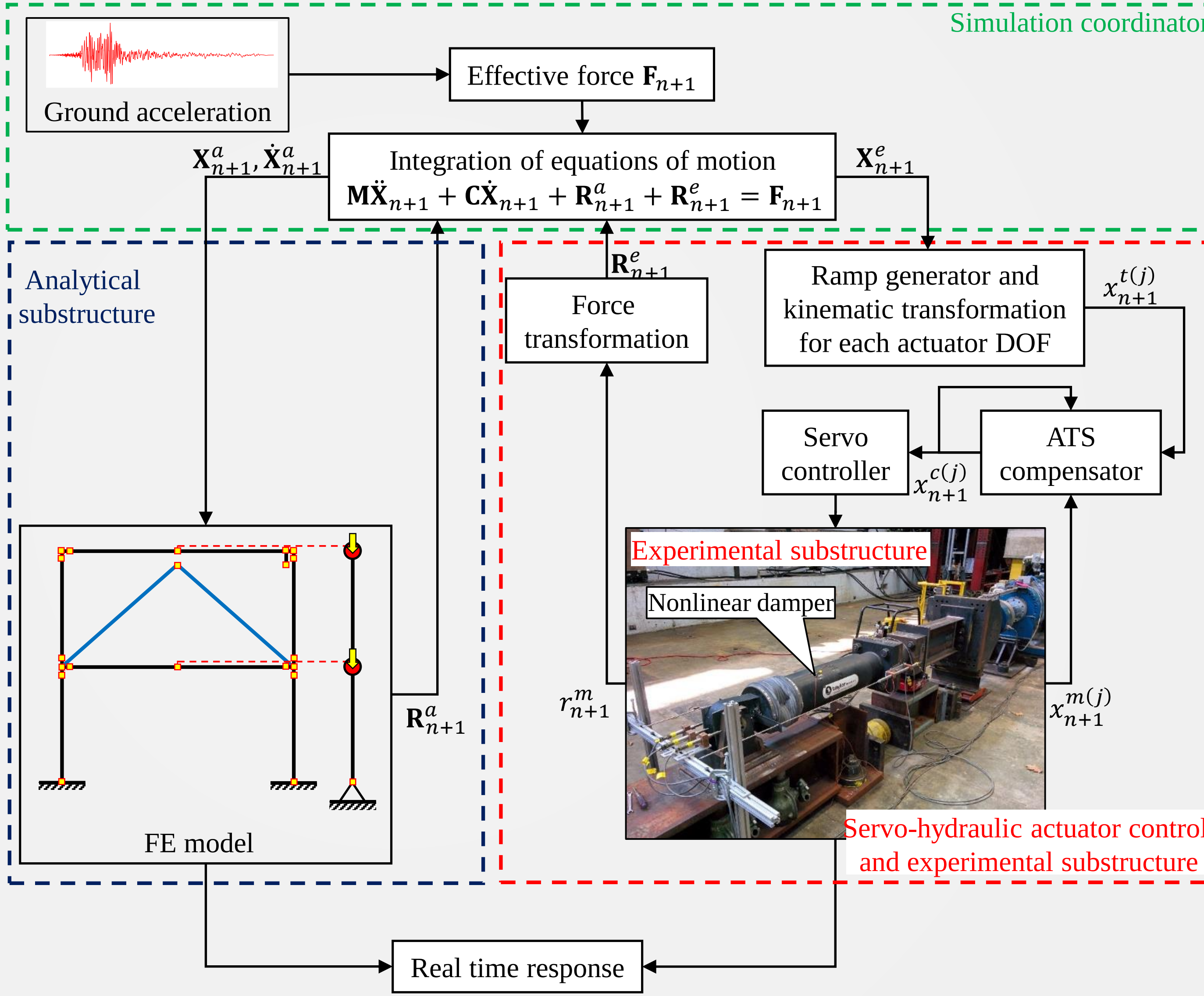
Floor	Mass (kip-sec^2/in)
1	0.239
2	0.238

Modal Properties

Mode	Period (sec)	Inherent Damping
1	0.43	0.03
2	0.12	0.03

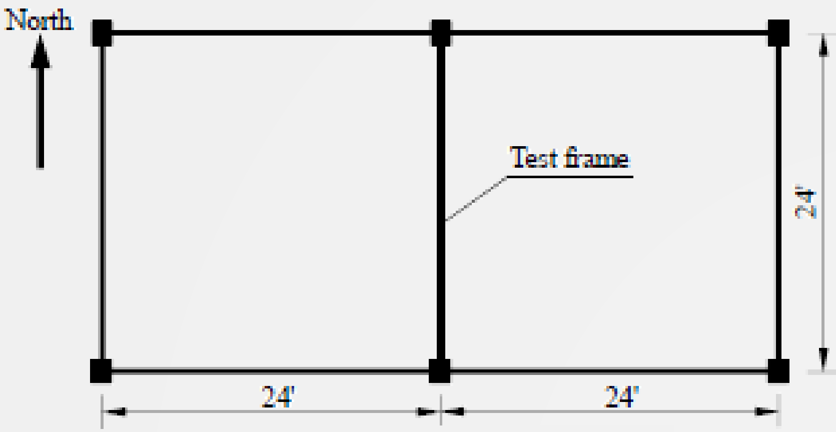
RTHS Overview



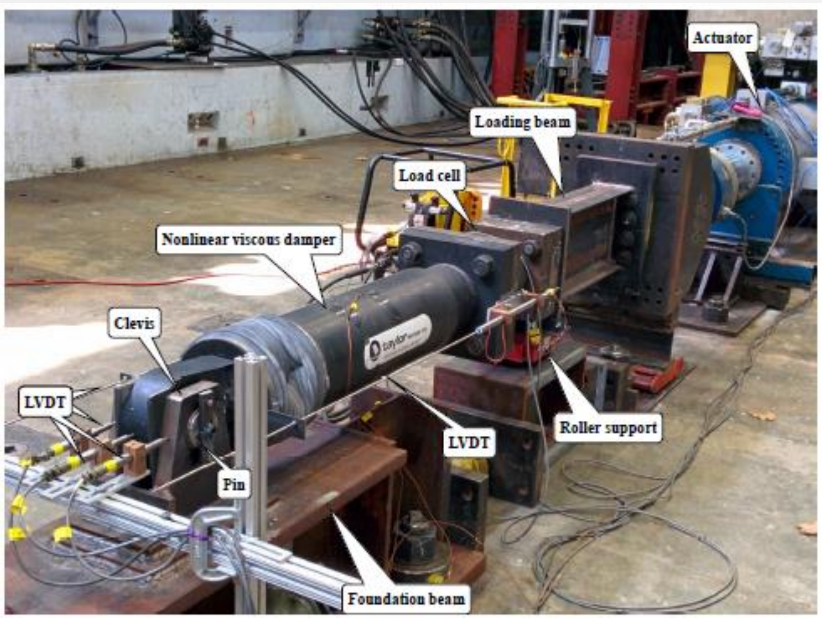


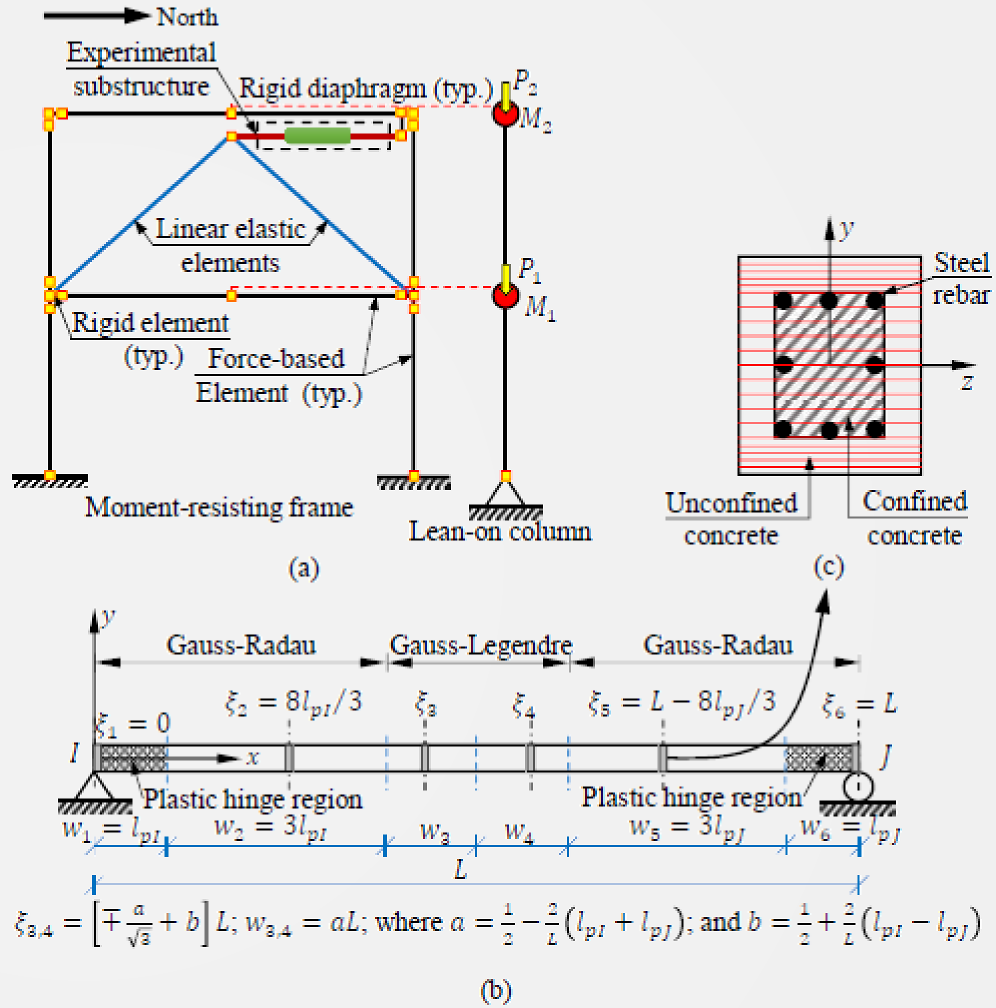
Kolay, C. “Parametrically Dissipative Explicit Direct Integration Algorithms for Computational and Experimental Structural Dynamics”. Ph.D. Dissertation. Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, USA, 2016

RTHS configuration



Prototype floor plan



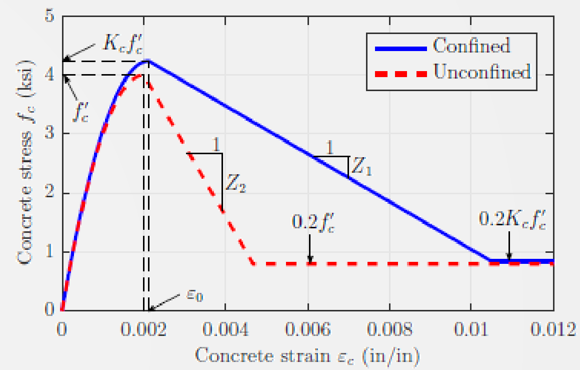


- EQ record scaled to MCE hazard level
- Time step: $\Delta t = \frac{3}{1024}$ s

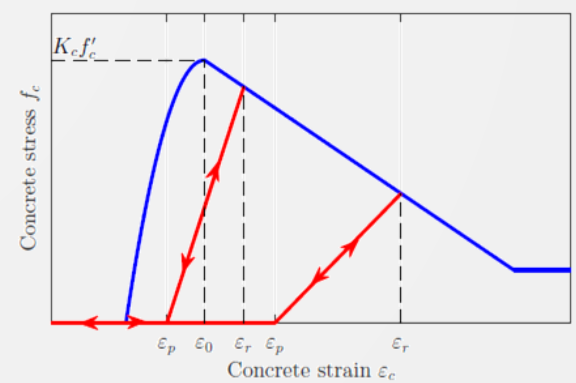
Analytical Substructure - Fiber Material Properties

➢ Concrete properties

Member	Prop	Columns	1st story beams	2nd story beams	Cover
Confined concrete	K_cf'c	5156psi	4360psi	4474psi	-
	ε_o	0.002	0.002	0.002	-
	0.2K_cf'c	1030psi	872psi	895psi	-
	ε_u	0.045	0.015	0.002	-
Unconfined concrete	f'c	4768psi	4240psi	4203psi	4000psi
	ε_o	0.002	0.002	0.002	0.002
	0.2f'c	953psi	848psi	841psi	805psi
	ε_u	0.027	0.014	0.009	0.004



Modified Kent-Park Model

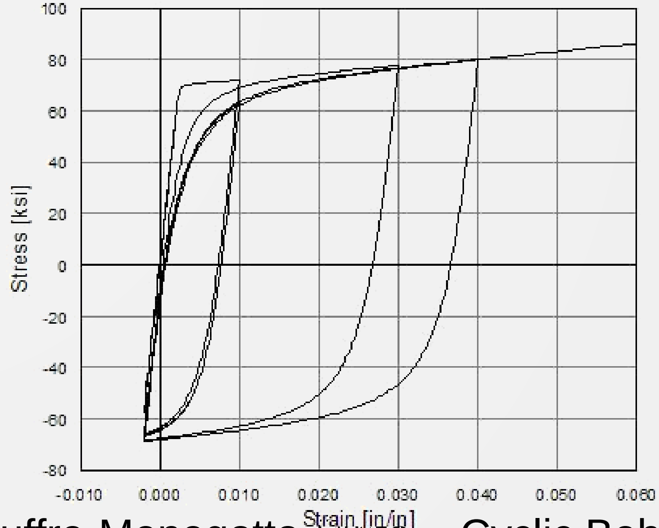


Modified Kent-Park Model – Cyclic Behavior

Analytical Substructure - Fiber Material Properties

- Steel properties

Yield stress (ksi)	Modulus of elasticity (ksi)	Strain hardening ratio	Ro	cR1	cR2	a1	a2	a3	a4	sigInit
60	29000	0.01	15	0.925	0.15	-0.05	1	0	1	0



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-α method (parameter ρ_∞)
  - ➢ Model-based integration parameters ($\boldsymbol{\alpha}_1$, $\boldsymbol{\alpha}_2$, $\boldsymbol{\alpha}_3$) determined from characterization test data
- ATS Compensator for adaptive time delay and amplitude compensation

Parameters to Consider for RTHS

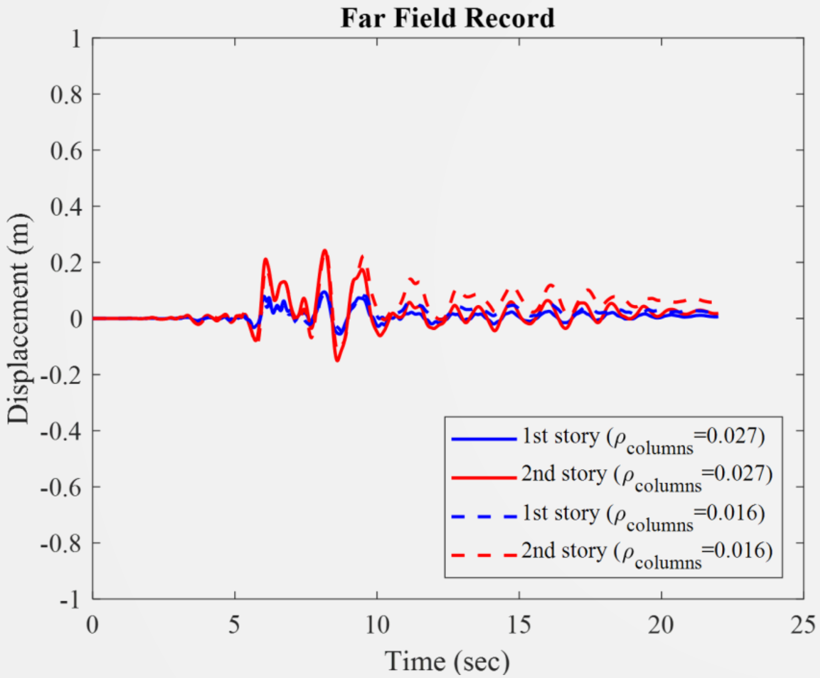
Parameter	Values
Ground Motion (scaled to MCE)	
• Far Field	1994 Northridge EQ, Canyon Country Recording Station, Component - RSN960_NORTHR_LOS270
• Near Field	1999 Kocaeli, Turkey EQ, Yarimca Station, Component - RSN1176_KOCAELI_YPT150 H2
Steel Reinforcement Ratio, ρ	
• Columns	$0.0277^{(1)}$ or $0.0166^{(2)}$
• 1^{st} Floor Beams	$0.0062^{(1)}$ or $0.0047^{(2)}$
• Roof Beams	$0.0058^{(1)}$ or $0.0043^{(2)}$
Location of Damper	1^{st} or 2^{nd} Floor
Numerical Damping, ρ_∞	0.25 or 0.0

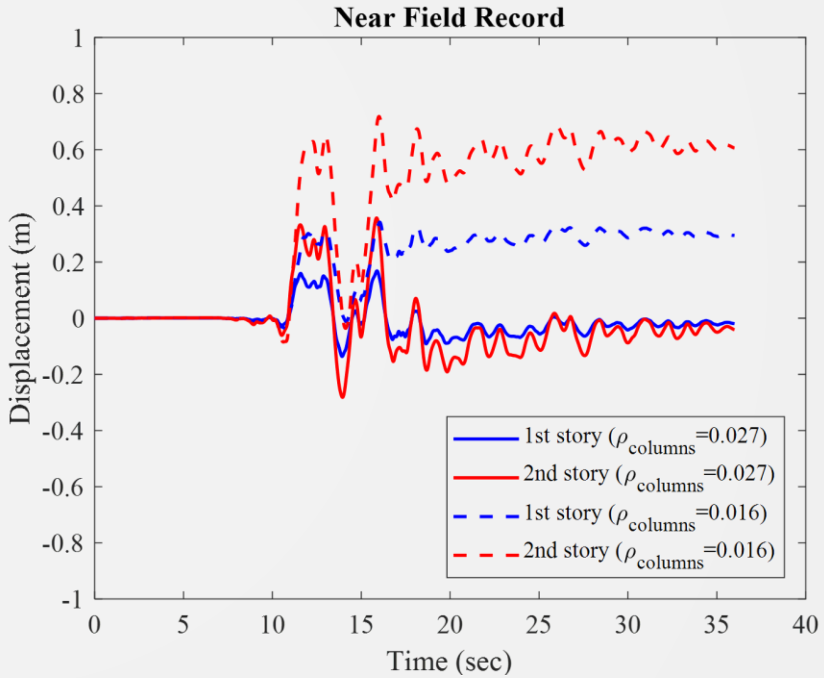
(1) Original value of longitudinal reinforcement

(2) Reduced value of longitudinal reinforcement (75% of original)

As-built Response

Floor Lateral Displacement Time History





As-built Response

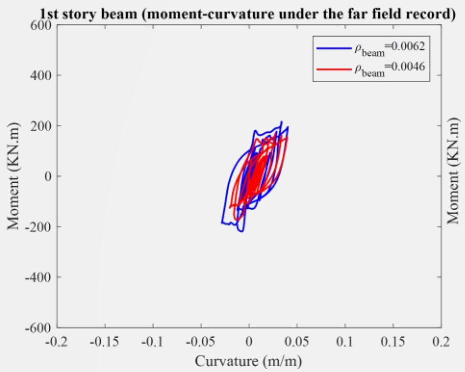
Summary of the floor drift

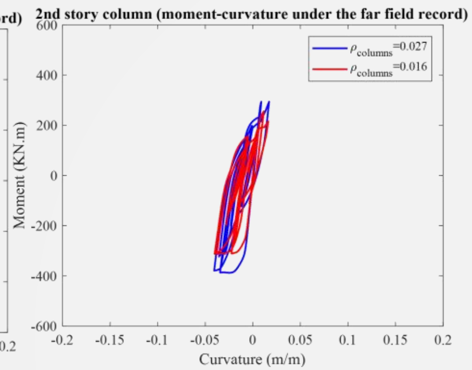
Steel ratio	Peak story drift (far field) 1st story (%)	2nd story (%)	Peak story drift (near field) 1st story (%)	2nd story (%)
Original	1.78	2.85	5.10	5.75
Reduced	2.69	4.49	10.12	11.28

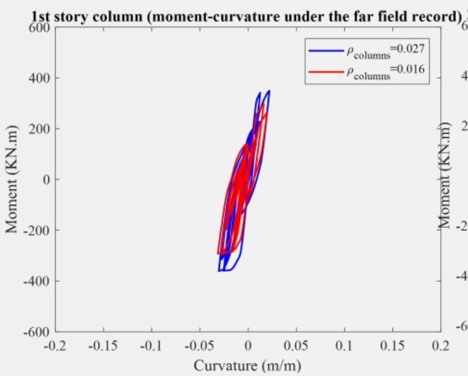
As-built Response – Far Field EQ

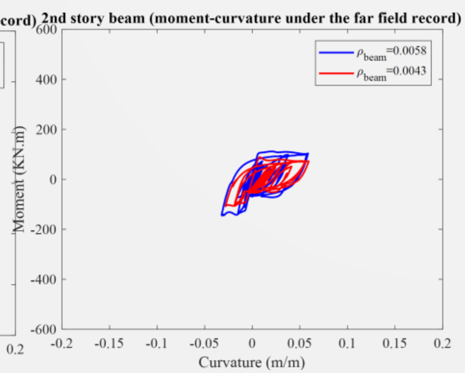
Moment-Curvature Hysteretic Response at Ends of Members

Far Field EQ

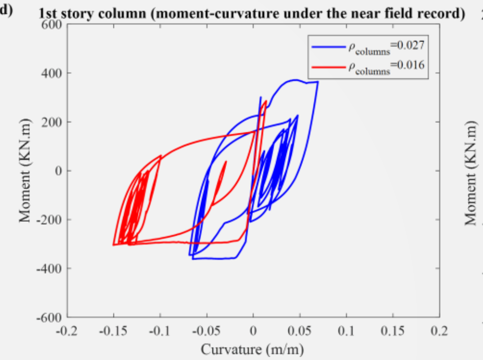


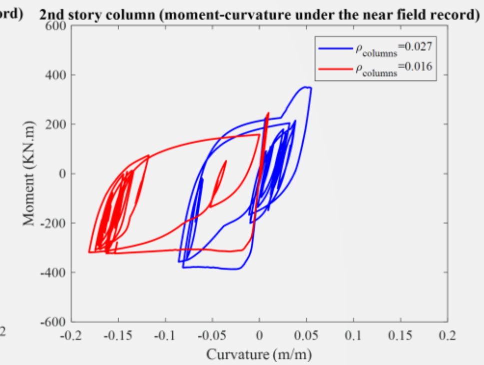


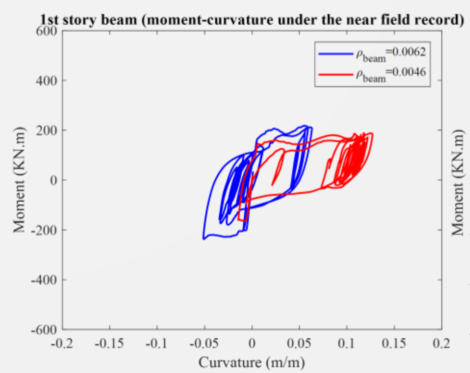


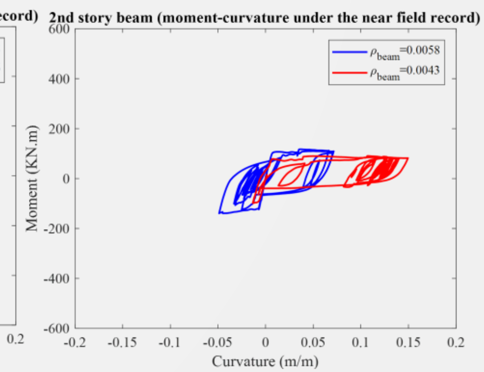


Near Field EQ



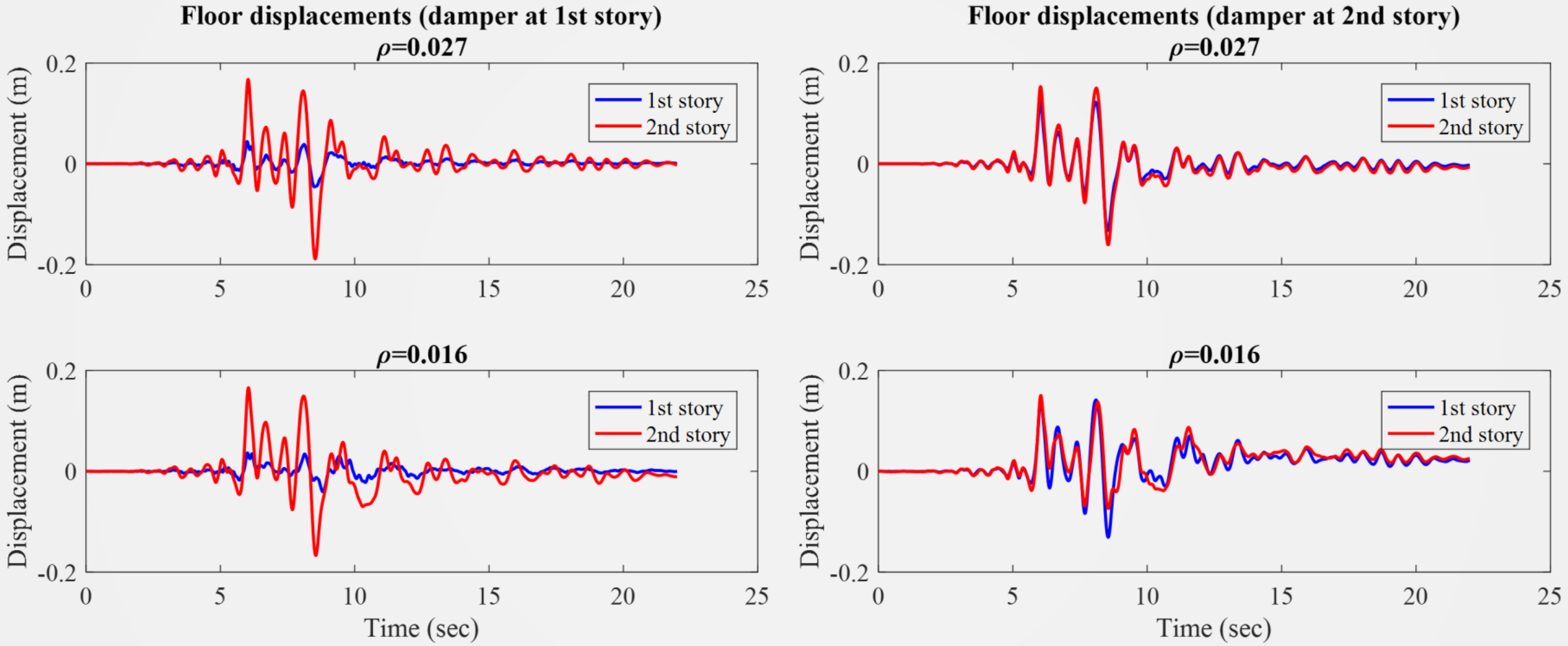






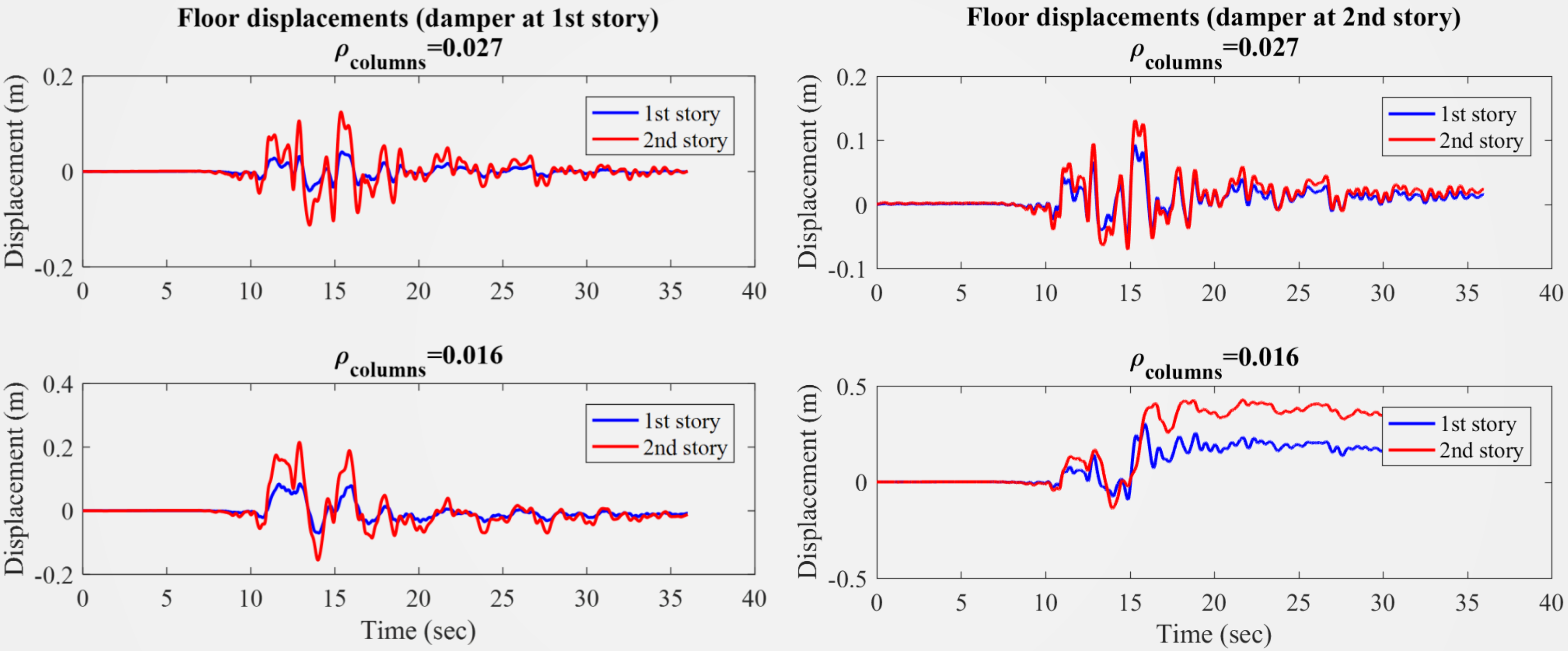
RTHS: Retrofit Response – Far Field EQ

Floor displacement time history



RTHS: Retrofit Response – Near Field EQ

Floor displacement time history

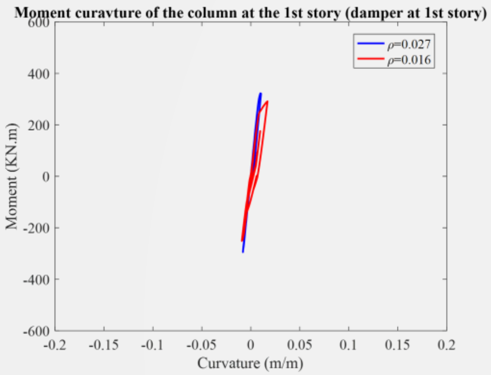


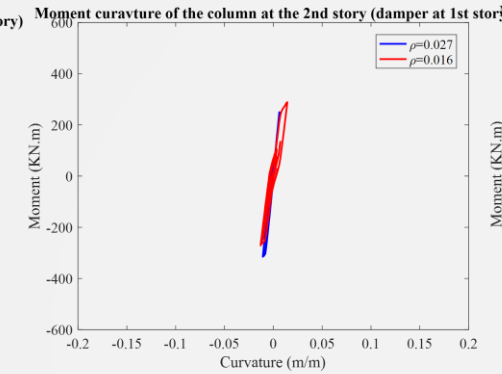
RTHS: Retrofit Response

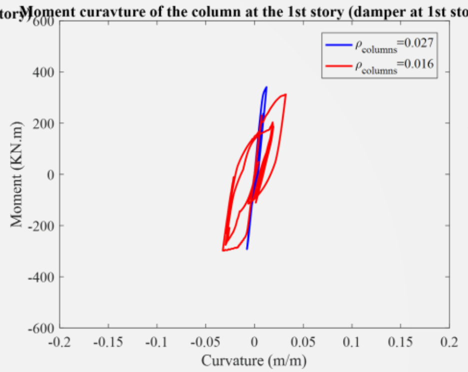
Moment-Curvature Hysteretic Response at Ends of Members, Damper at 1st Story

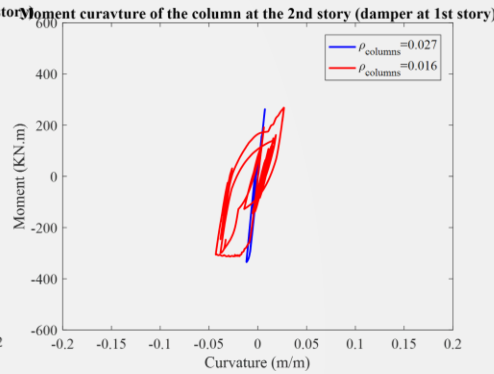
Far Field EQ

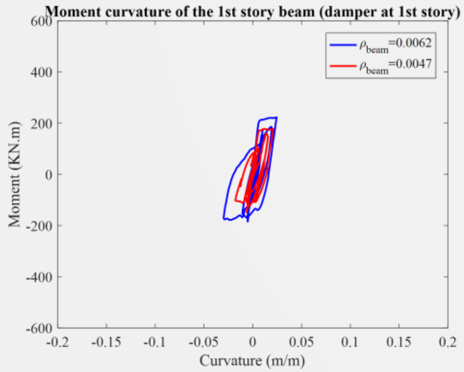
Near Field EQ

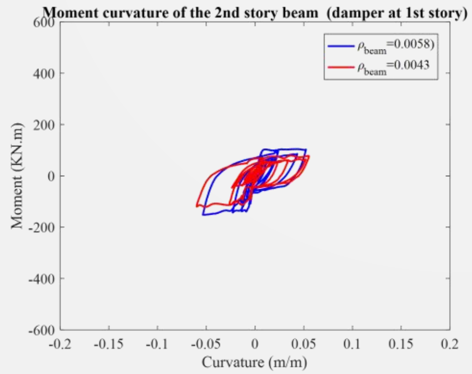


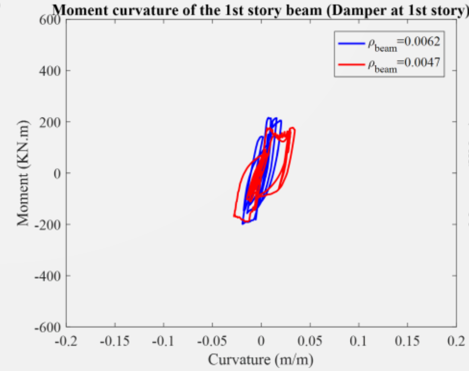


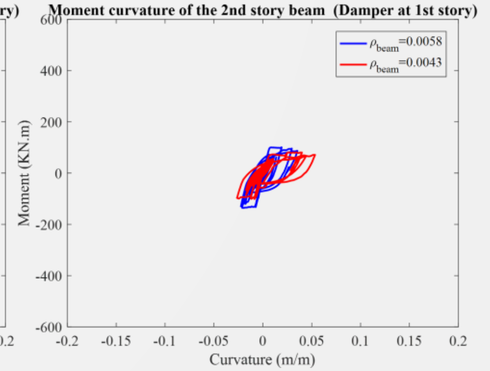










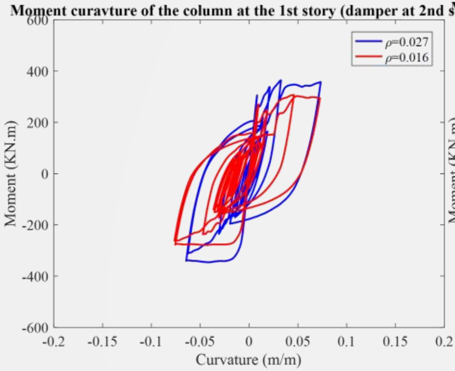


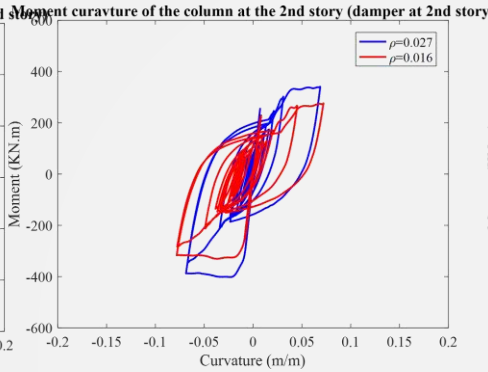
RTHS: Retrofit Response

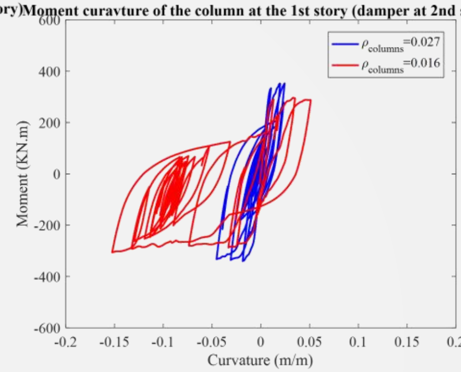
Moment-Curvature Hysteretic Response at Ends of Members, Damper at 2nd Story

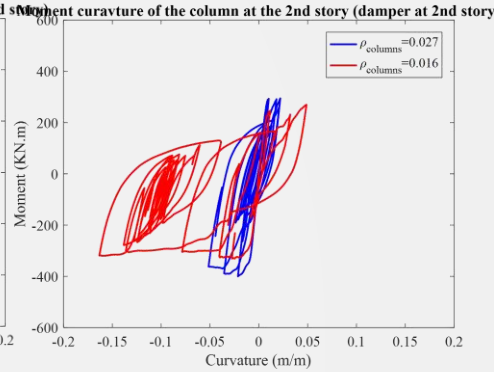
Far Field EQ

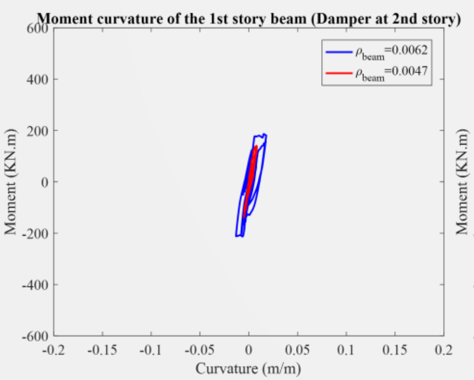
Near Field EQ

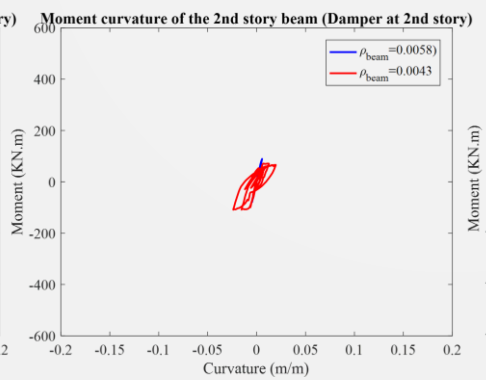


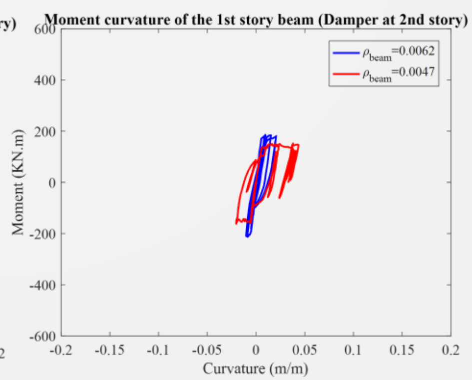


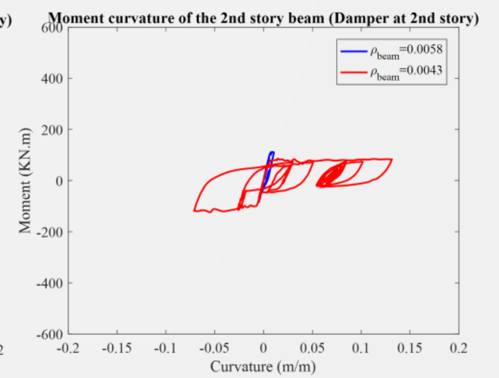






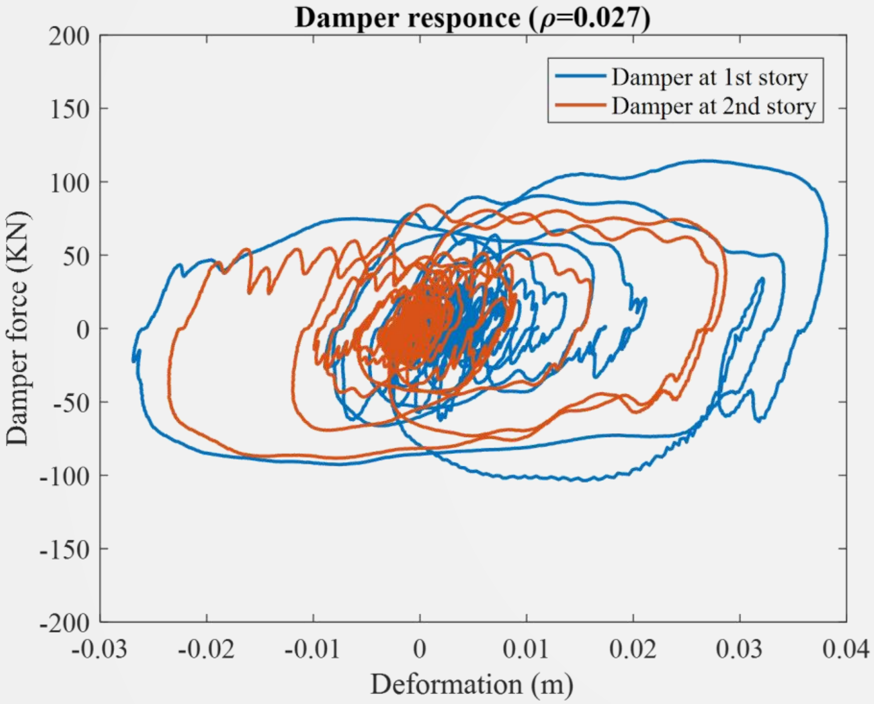


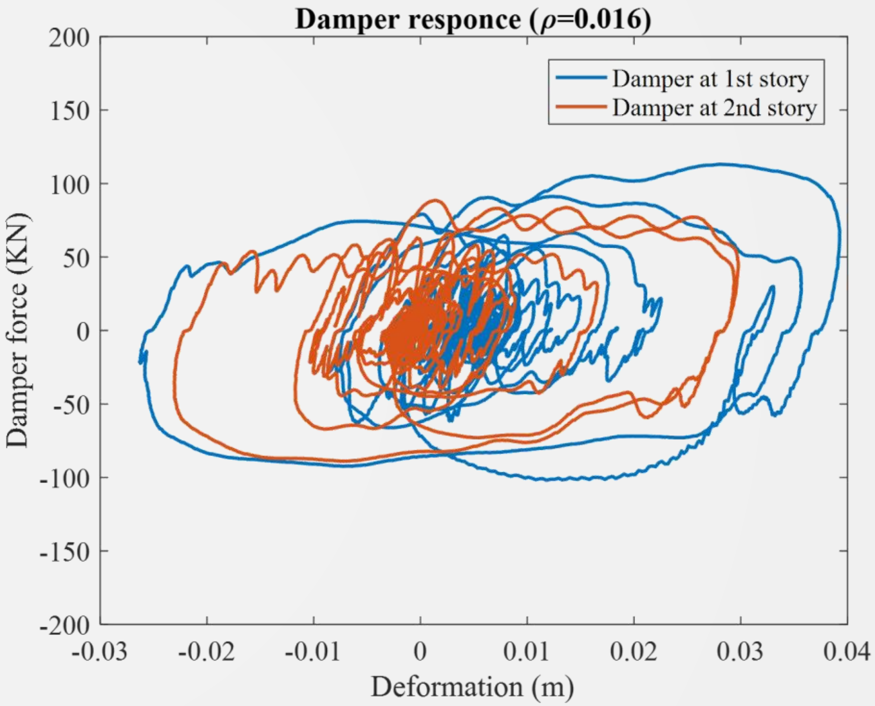




RTHS: Retrofit Response – Far Field EQ

Damper Response





Outline

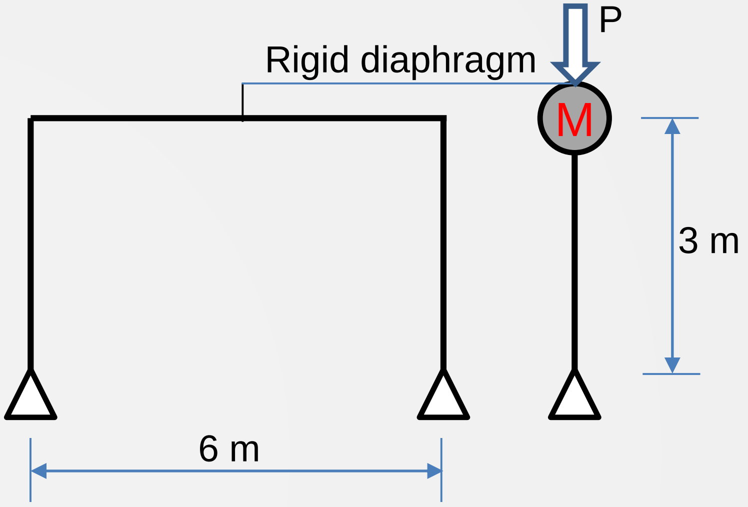
- Large-scale nonlinear viscous damper characterization test
- RTHS of a RC building with nonlinear viscous damper
- Numerical simulations using HybridFEM to experience the various features

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)
  - 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.

Numerical Simulation Exercise

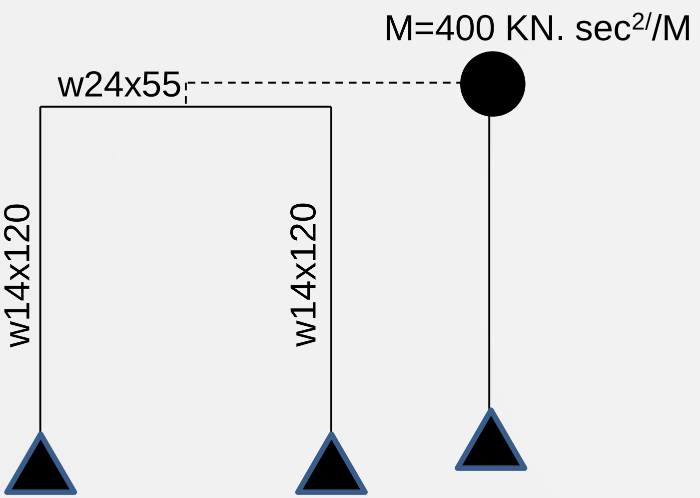
- All beam column elements are modeled using displacement-based fiber elements
- Lean-on column is modeled using linear elastic beam-column elements
- $P - \Delta$ effects are included
- Various integration algorithms can be used
- Input file, Model_Building.tcl
- In the input file, any line preceded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

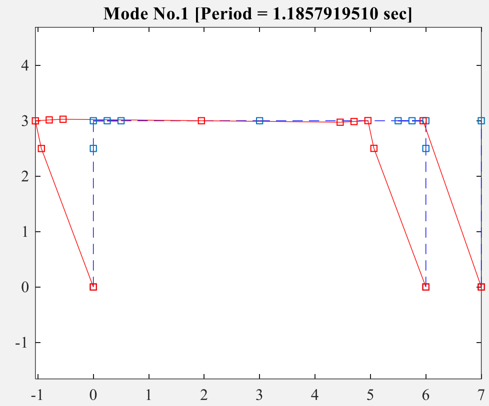


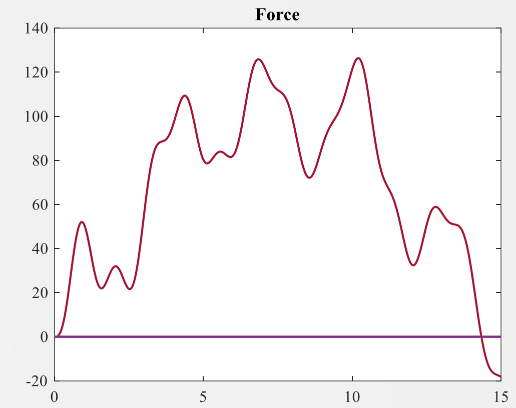
<u>1-Story, 1-Bay Structure</u>
Columns: W14x120
Beam: W24x55
Lean-on column:
A = 0.0976 m^2
I = 7.1254×10^{-4} m^4

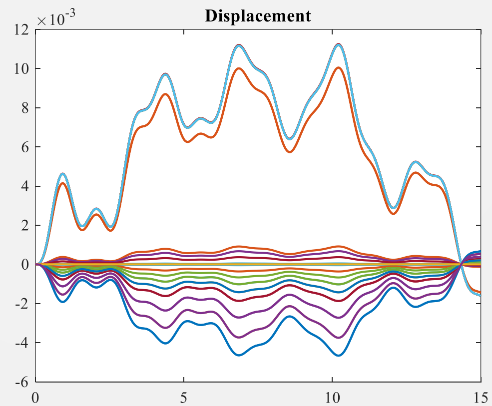
Numerical Simulation Exercise

One story building subjected to wind

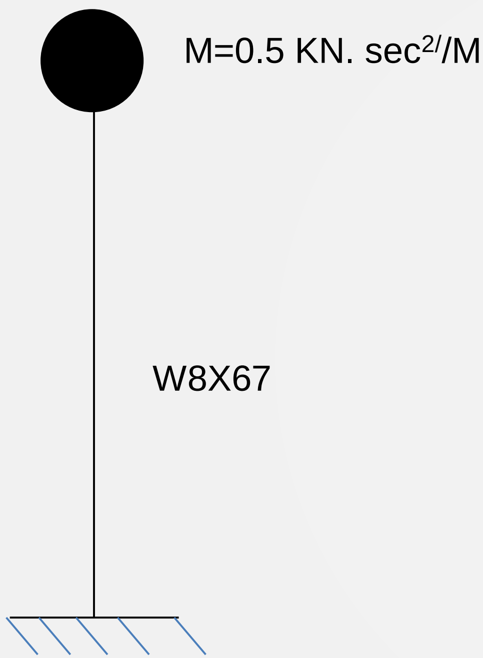




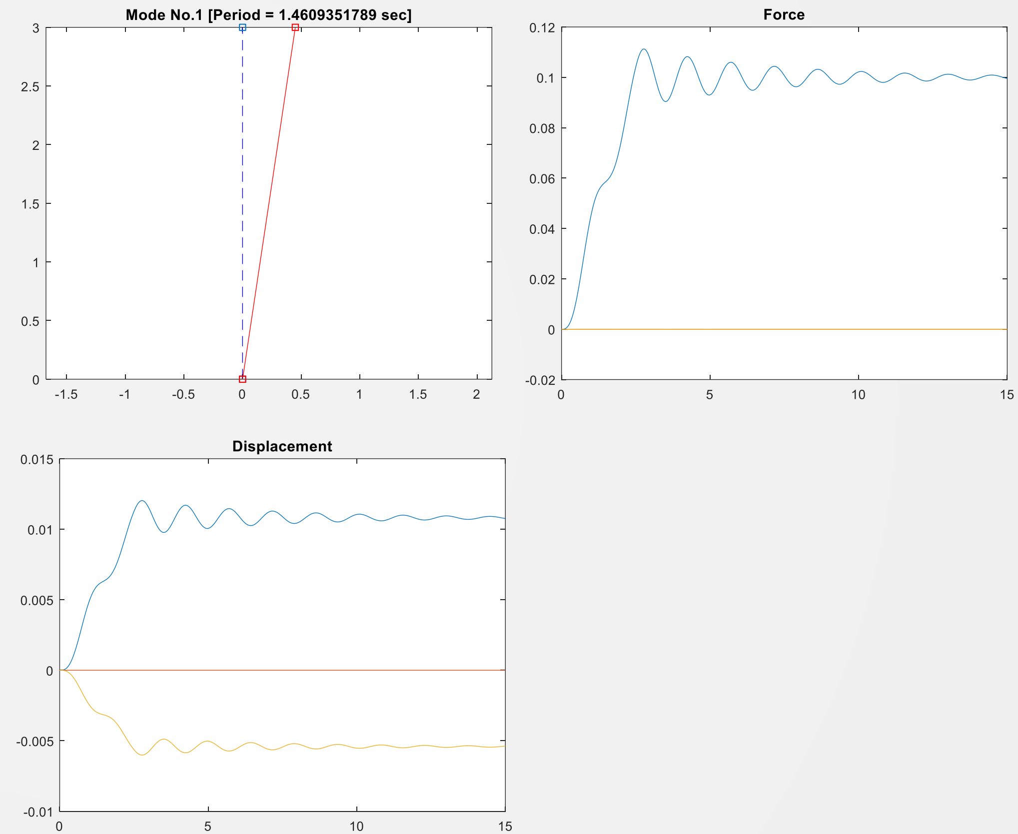




Numerical Simulation Exercise

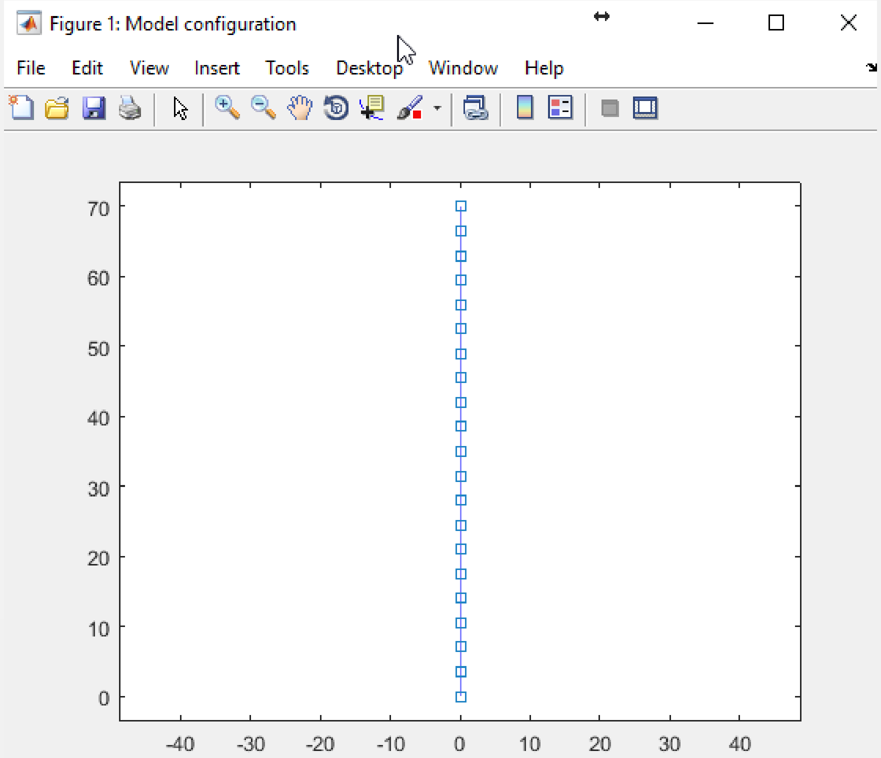


Cantilever subjected to step load

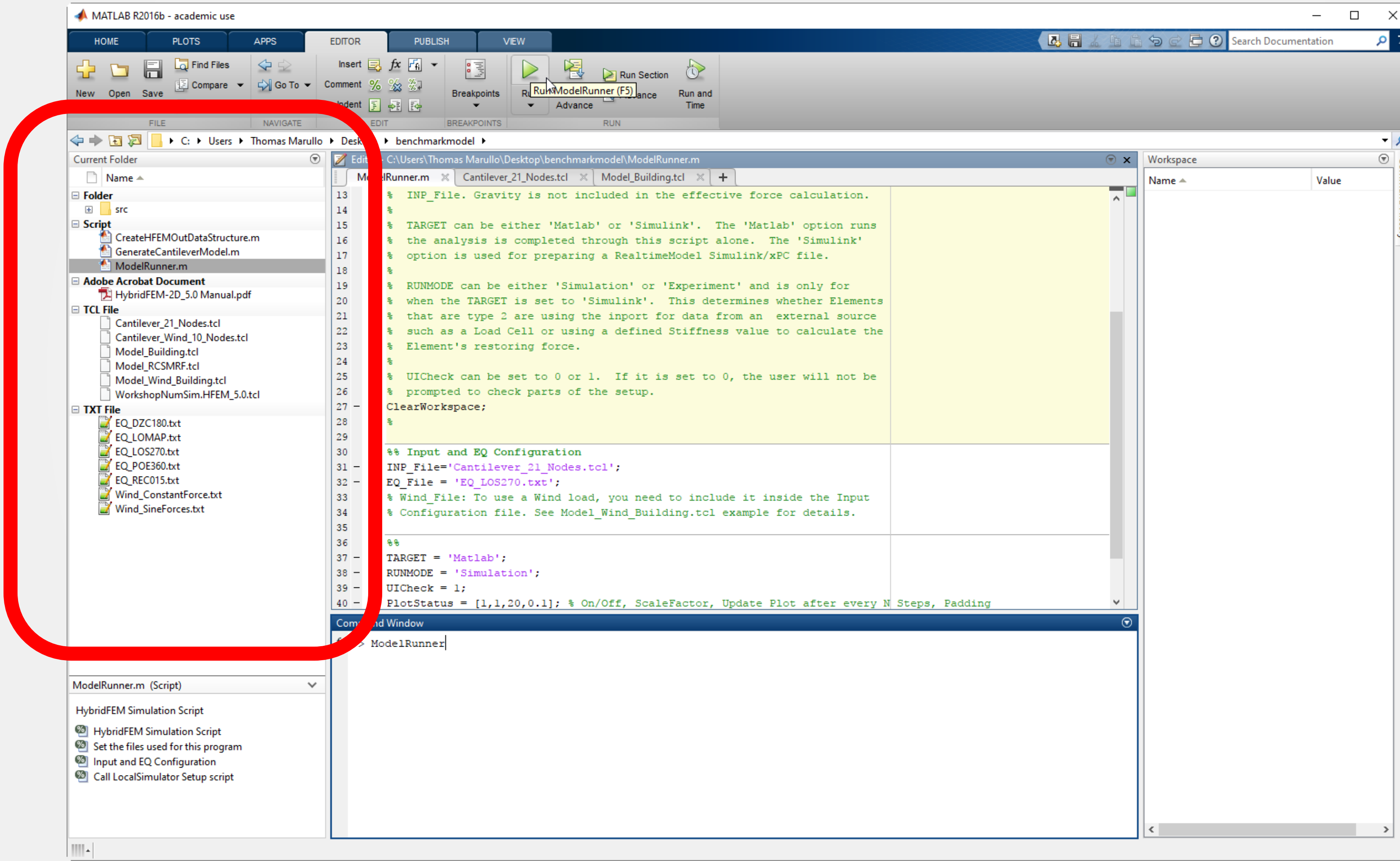


Numerical Simulation Exercise

- 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



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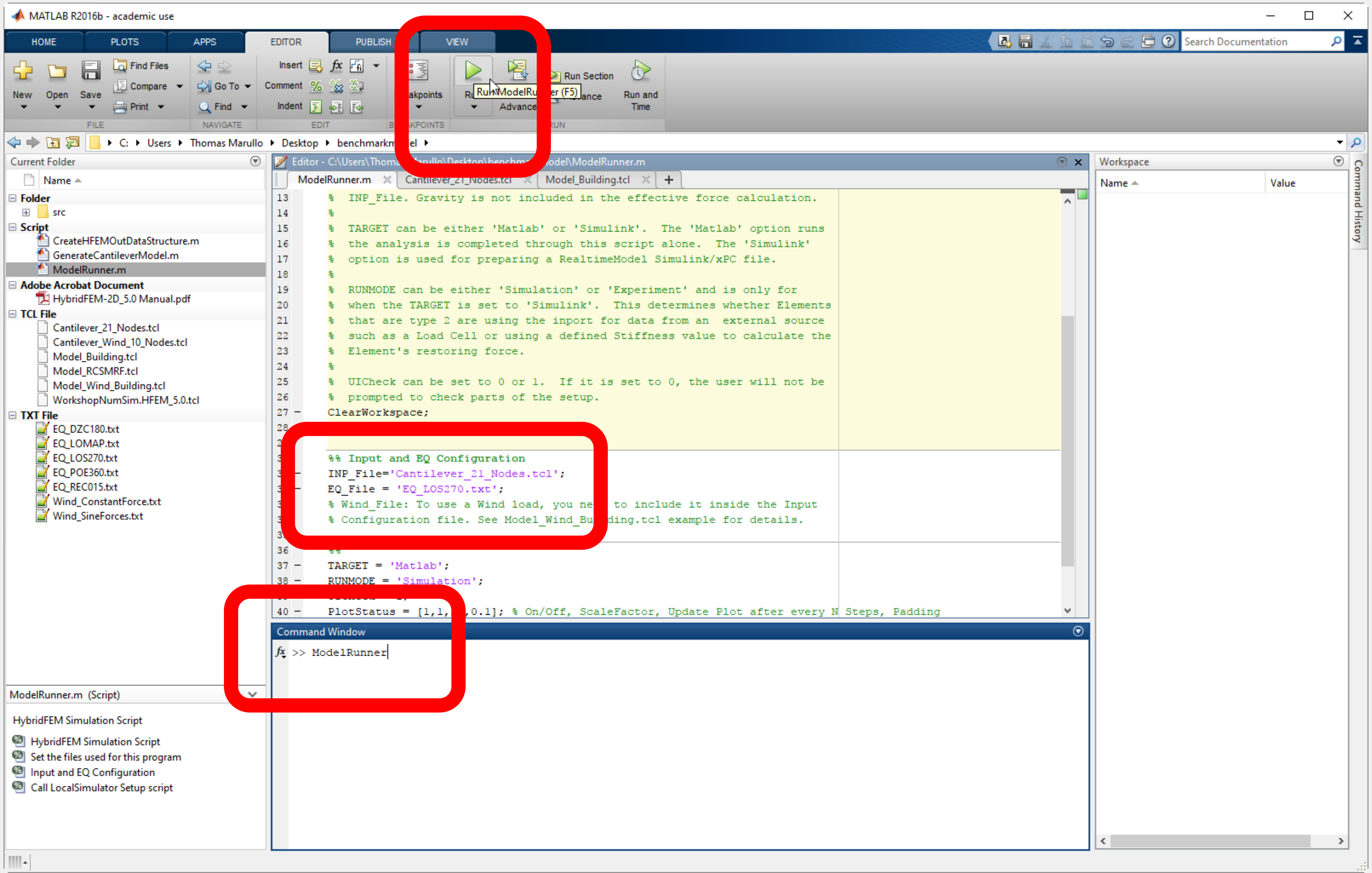

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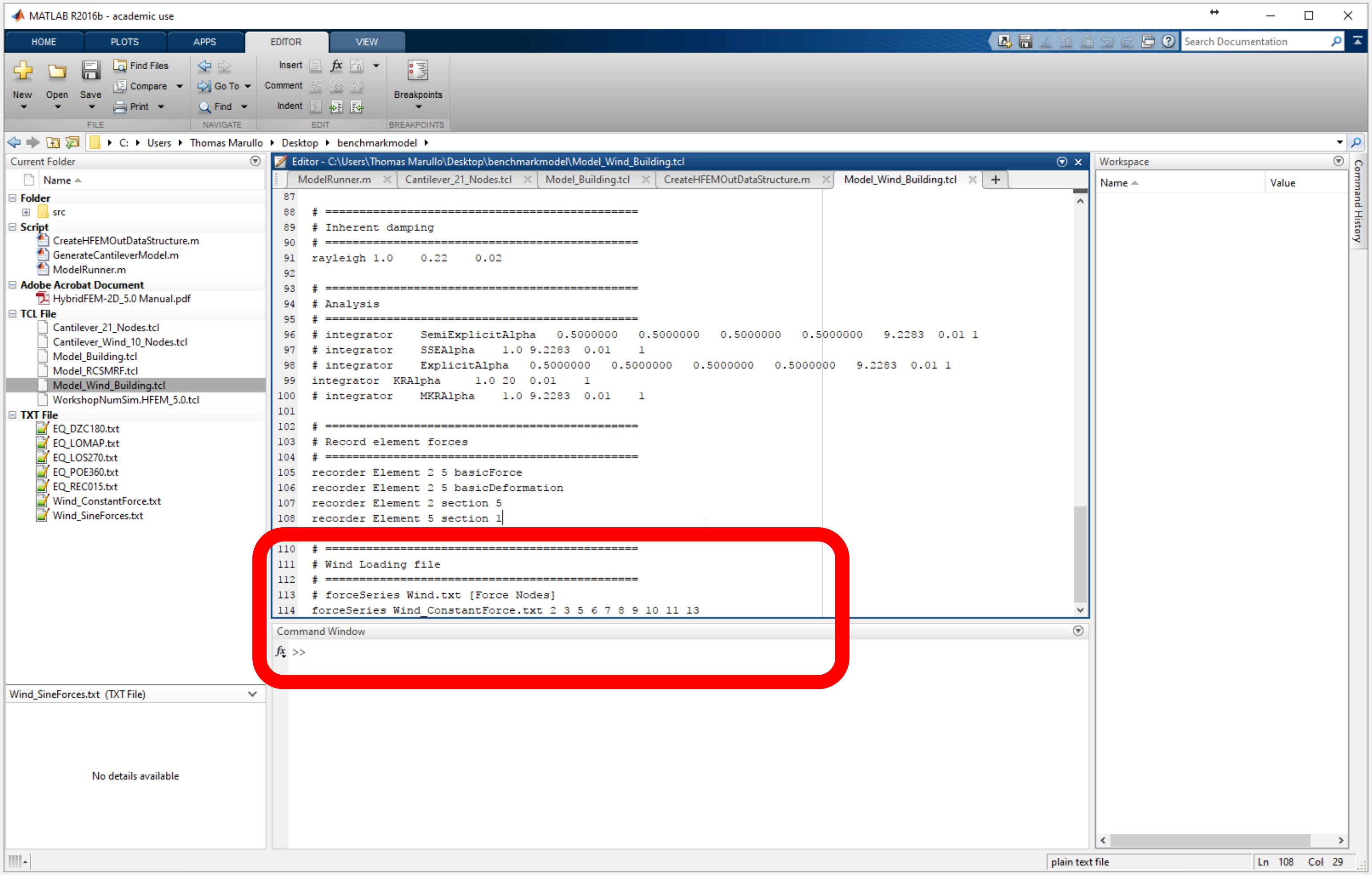

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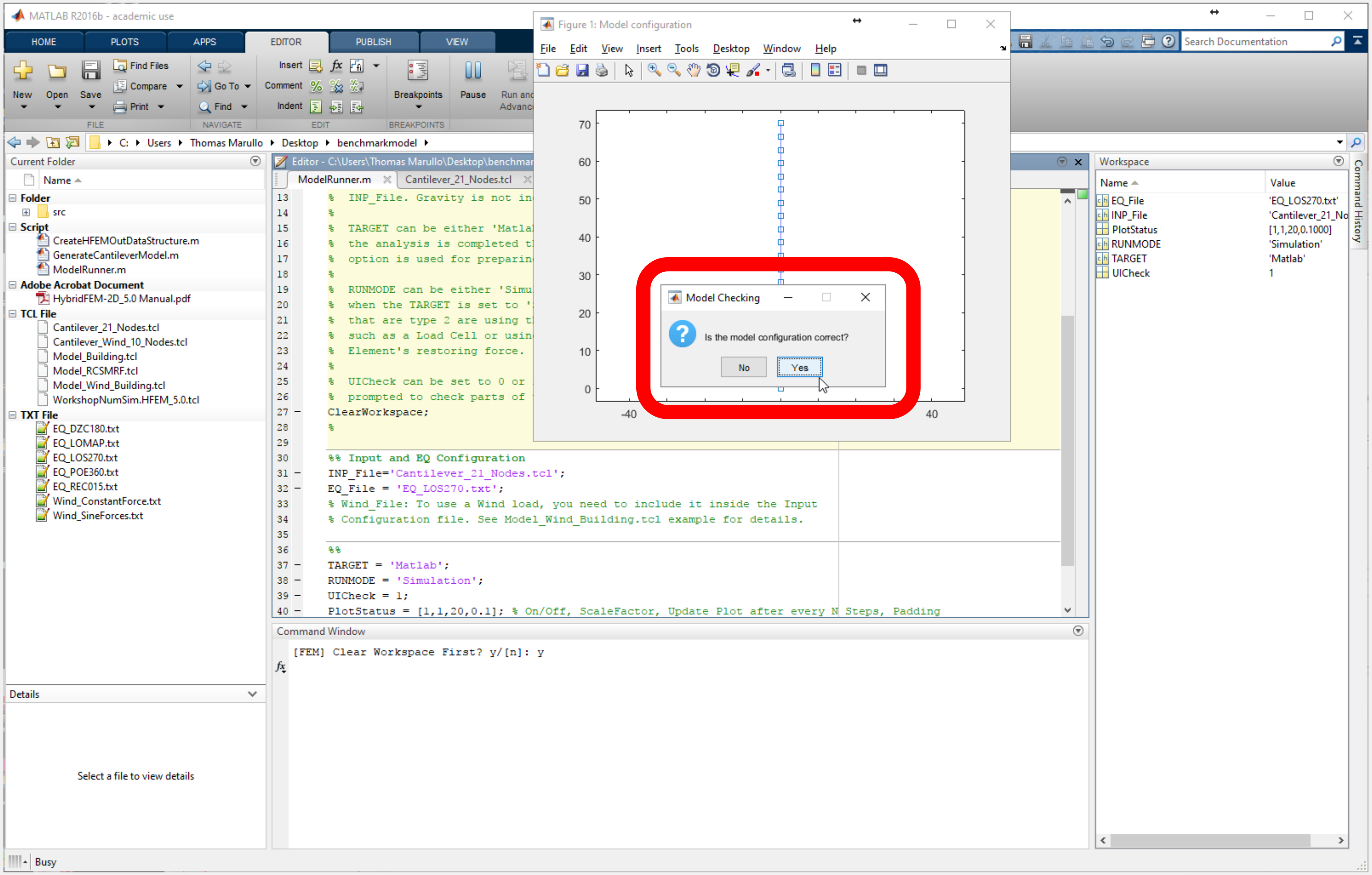

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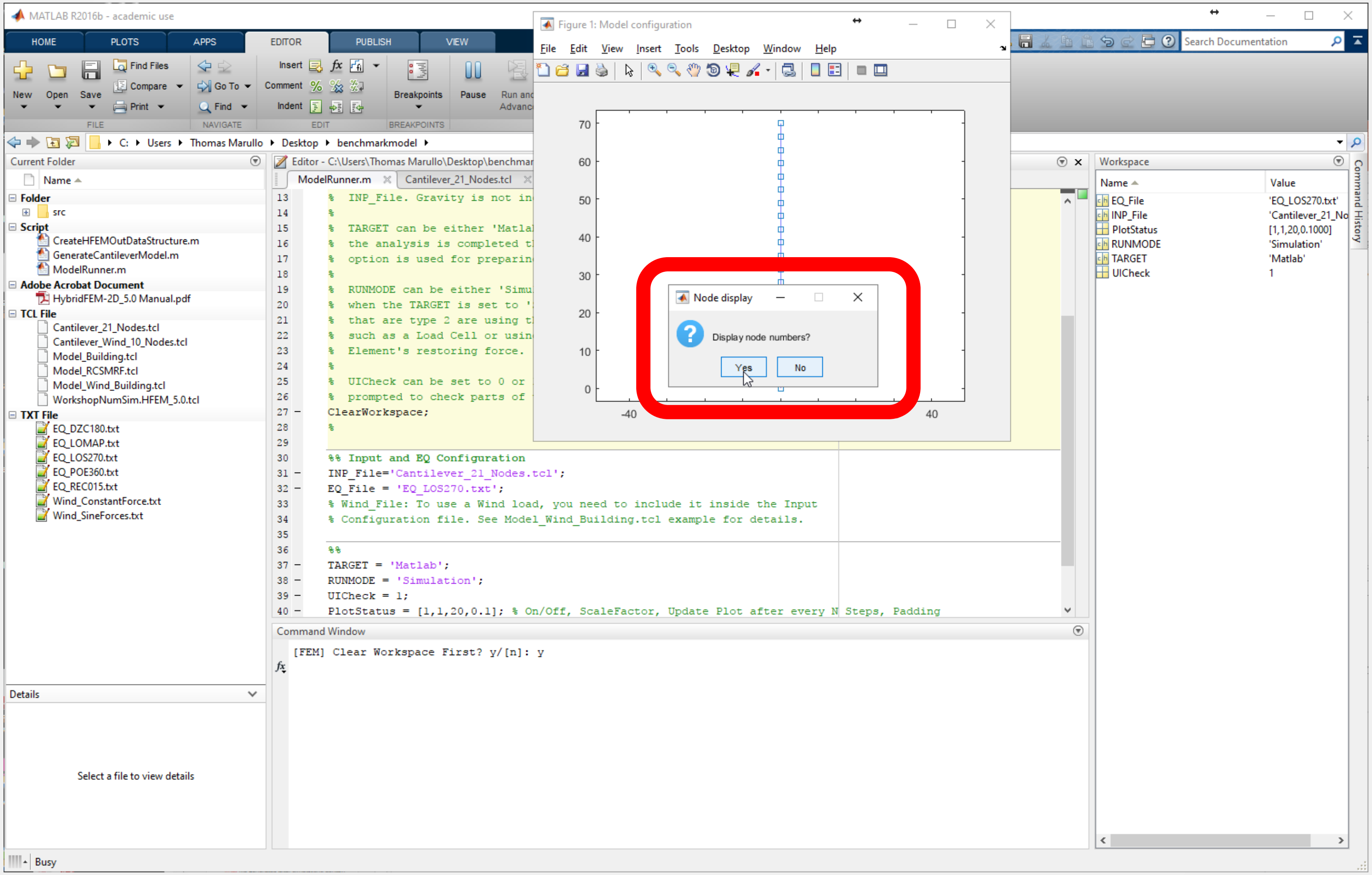

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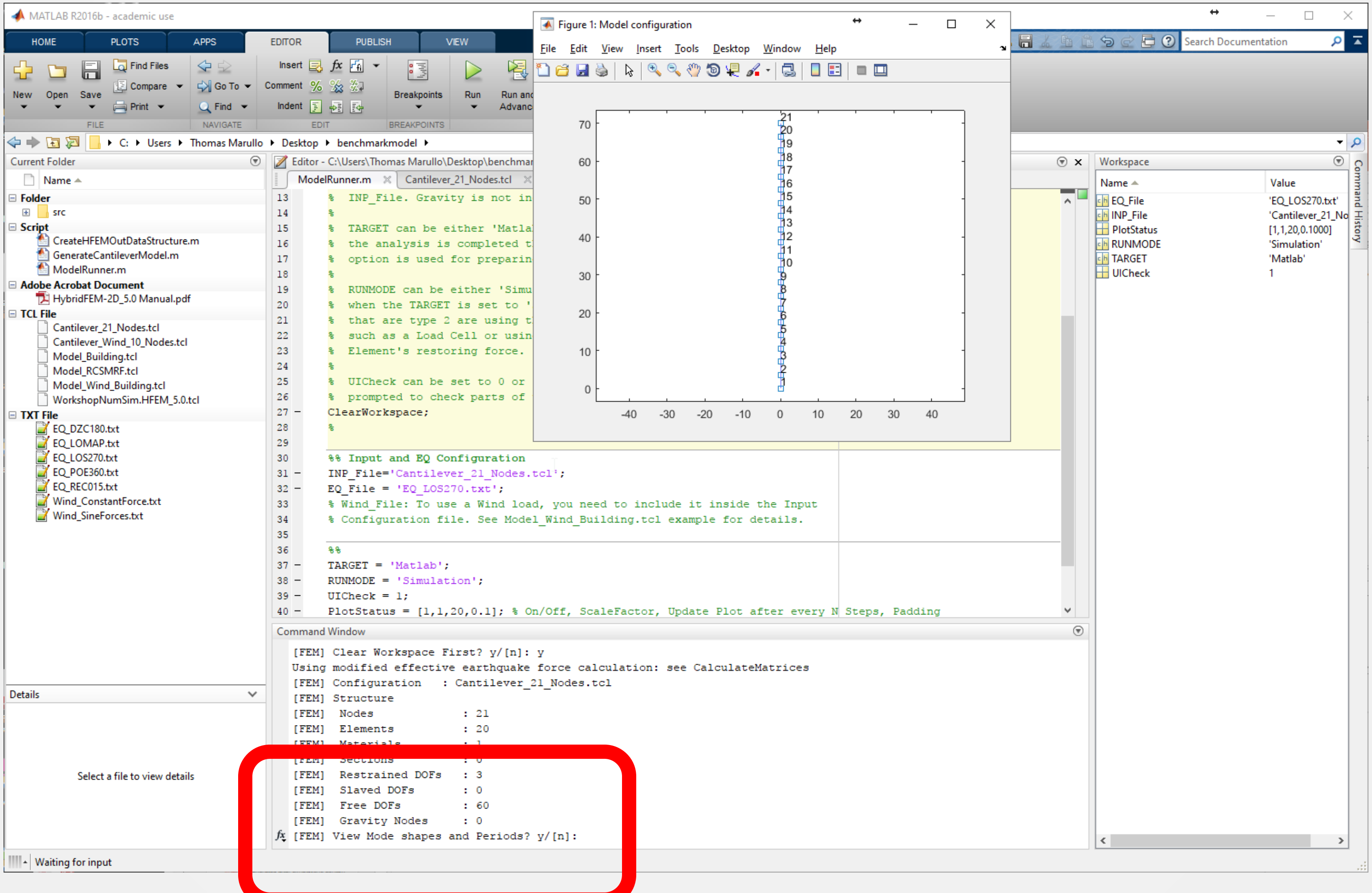
How to Simulate the Model



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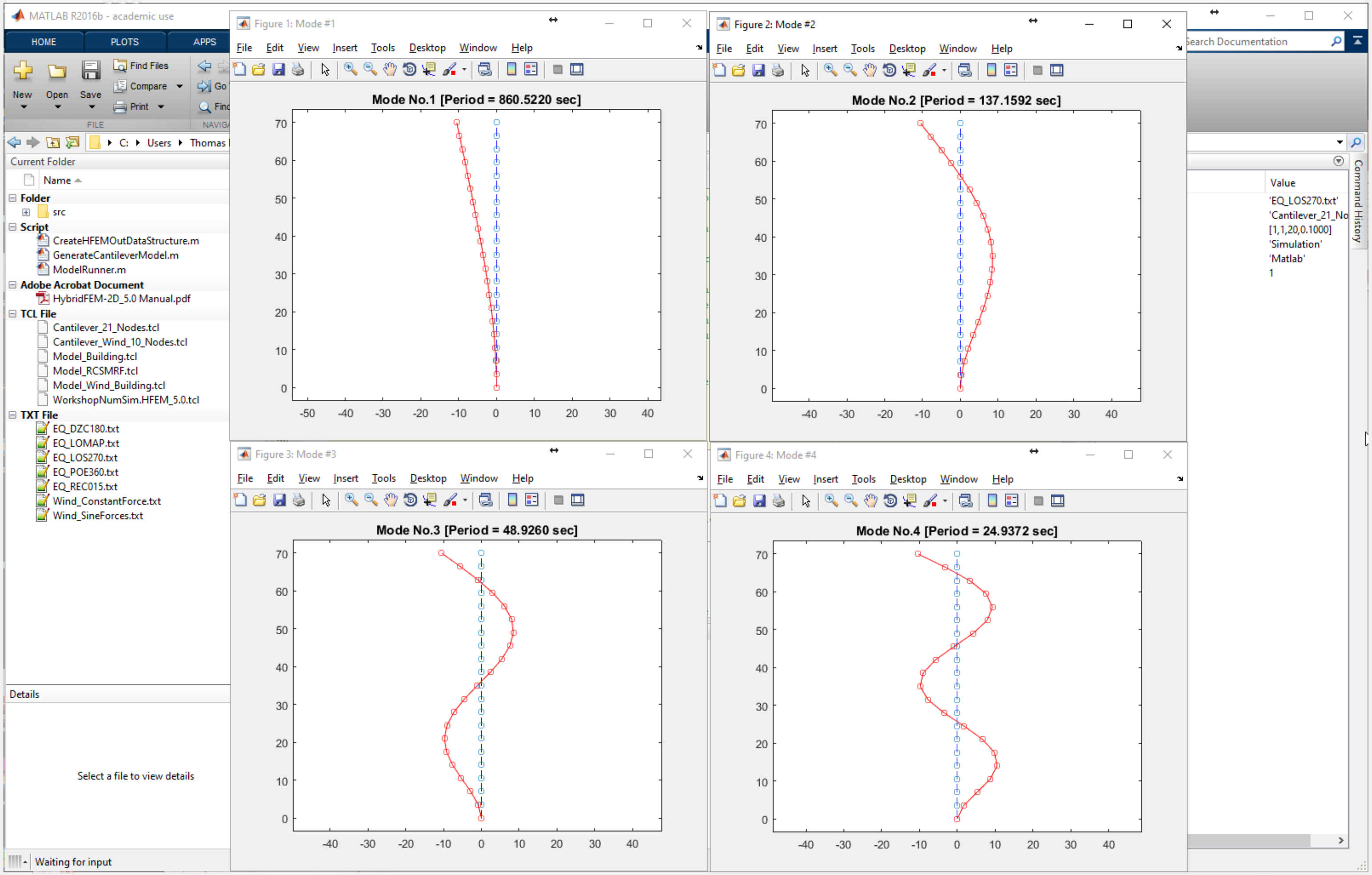

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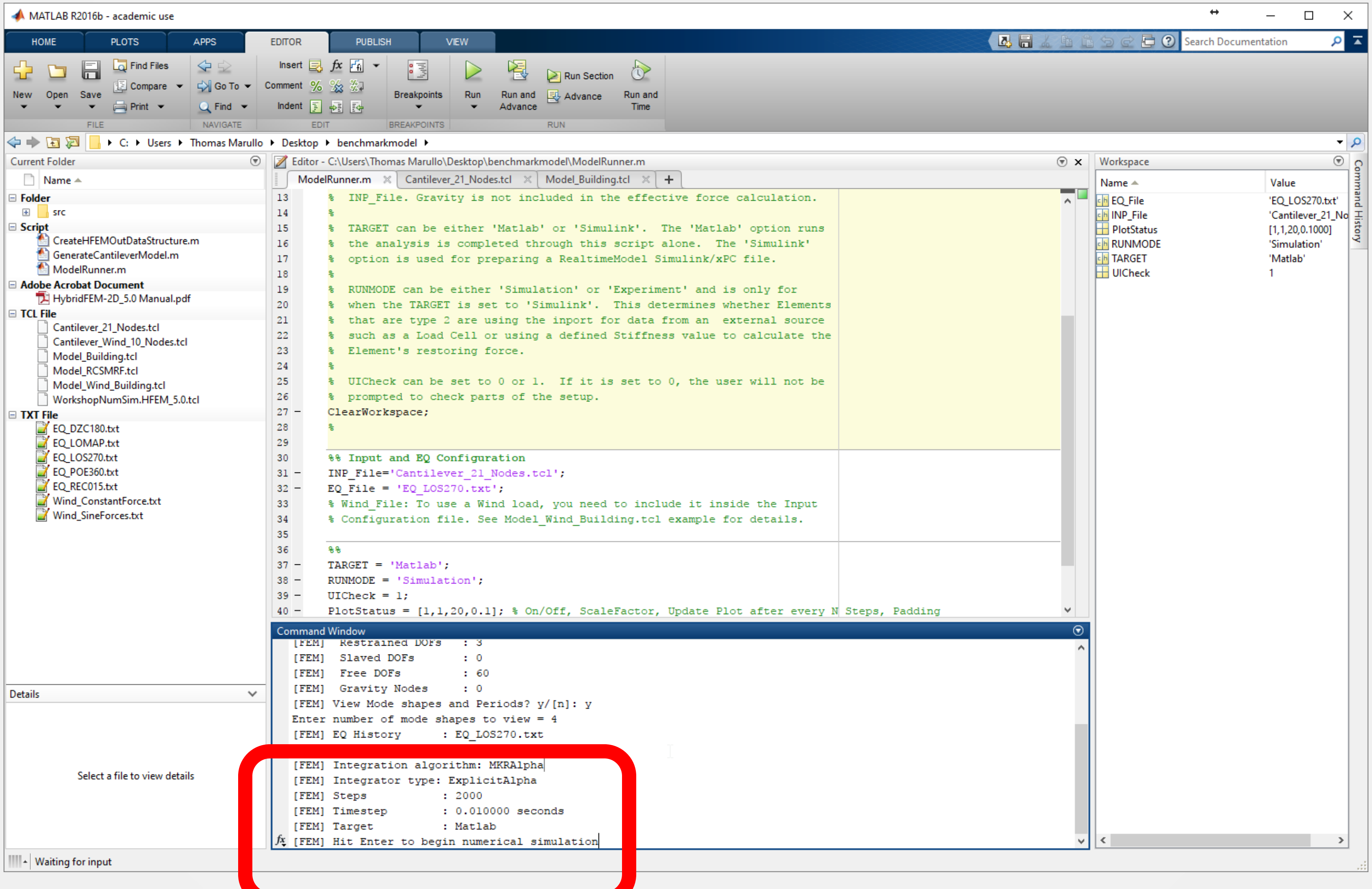

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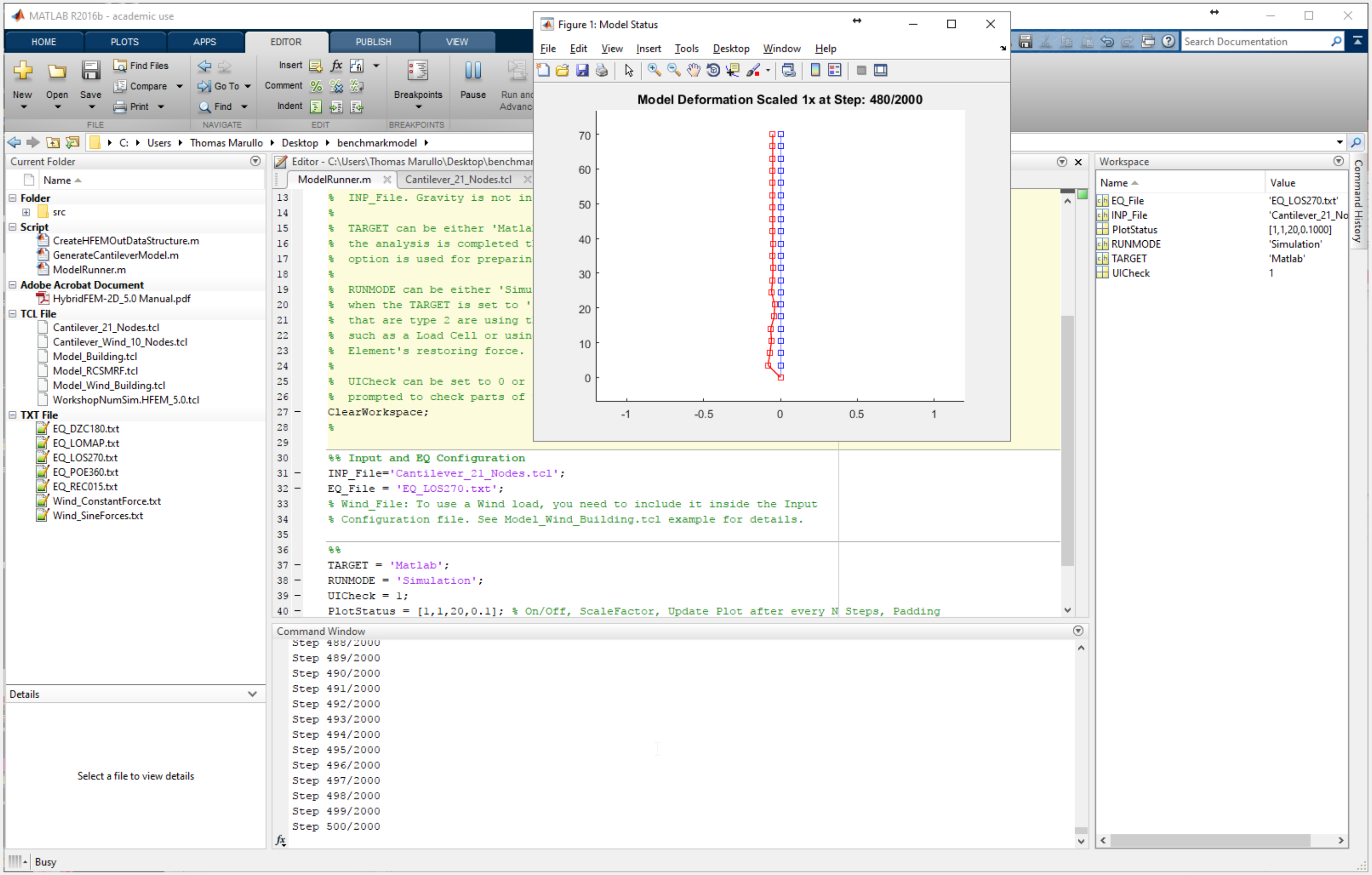

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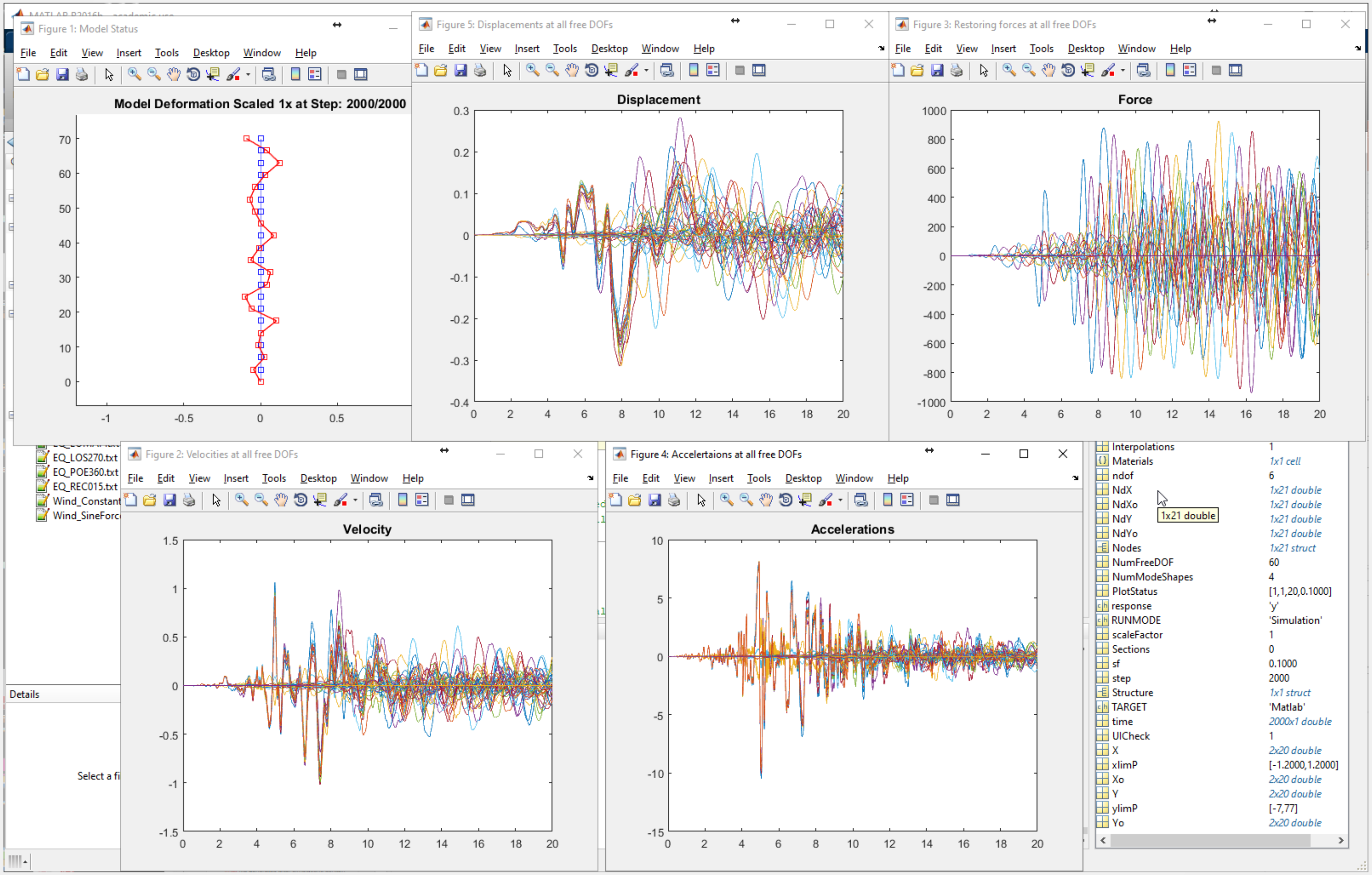
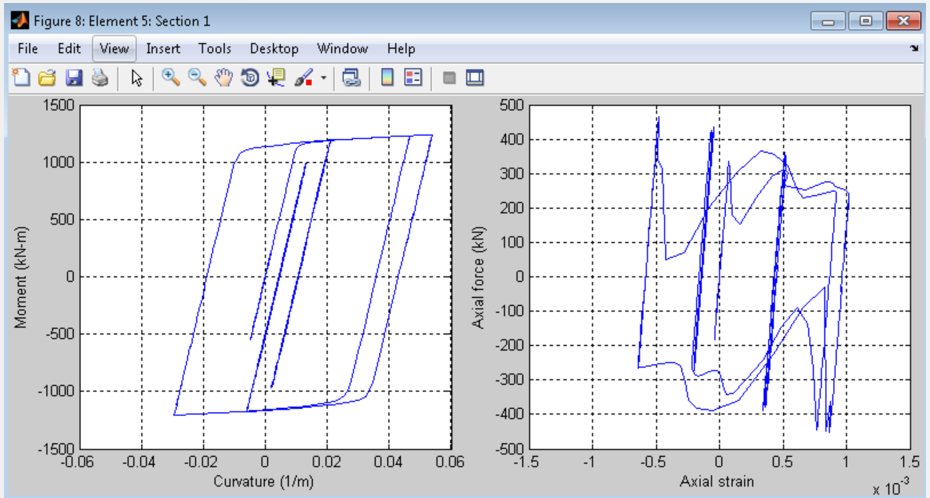
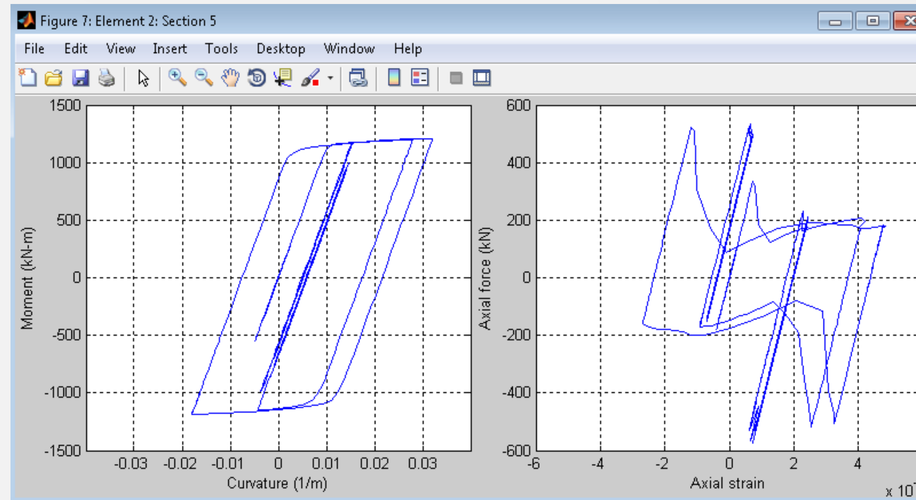


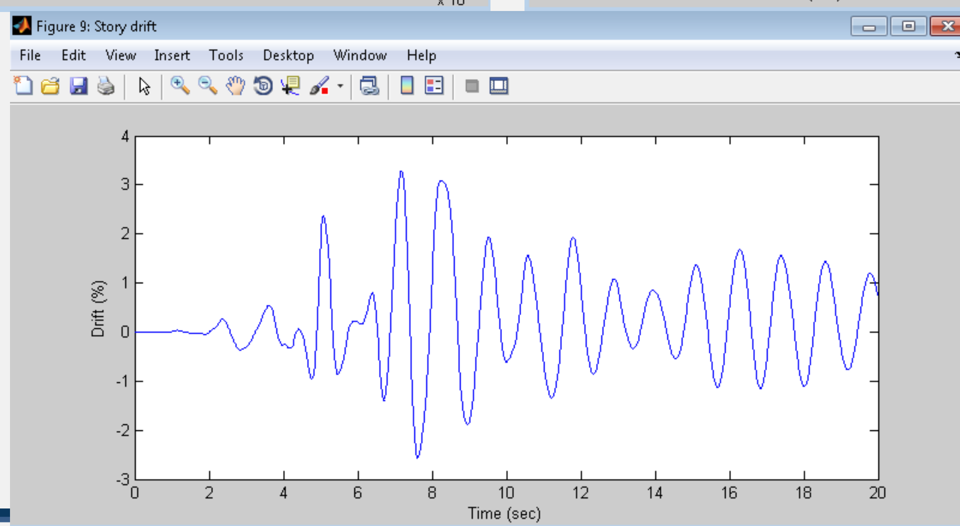
Simulation Results

- 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