State of the Practice of Nonlinear Response History Analysis

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New Technologies Group

Degenkolb Engineers

OpenSees Days - August 16, 2012

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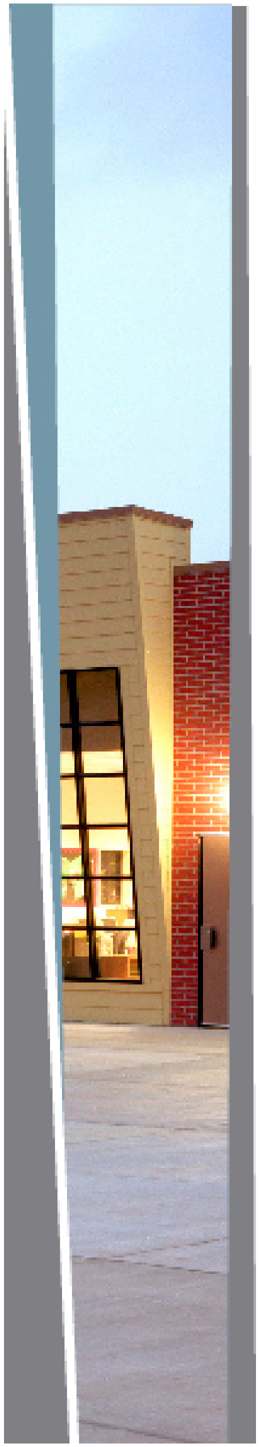

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- Current Activities:
  - Tools for generating ASCE 41 hysteretic properties for Perform 3D, OpenSees, etc
  - Ground Motion Selection and Scaling
  - SFSI: Soil Foundation Structure Interaction Modeling
  - Degenkolb Design Database: Post-Processing and Database Export of Perform 3D results
  - Risk Products: PML/SEL/SUL, EnvISA, Hazus, ShakeCast, Portfolio Loss, etc.
  - NLRHA
  - Component Modeling/Analysis
  - Tall Building / Wind Analysis
  - BIM / Analysis interaction
  - Many other ongoing consulting and research activities

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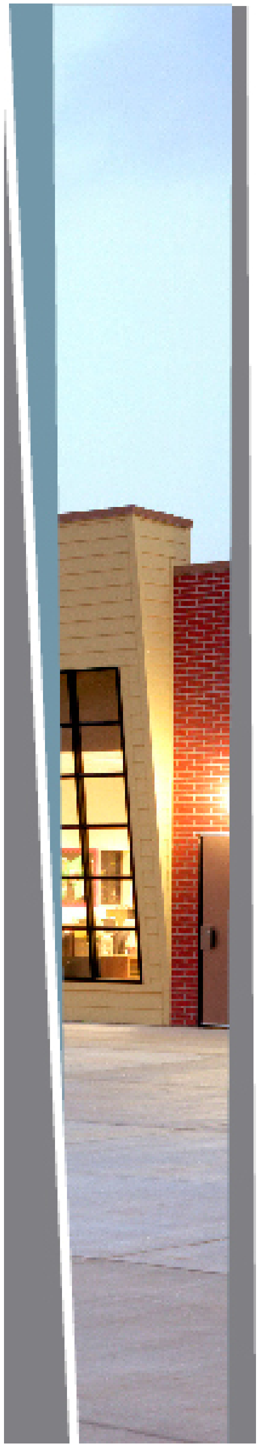
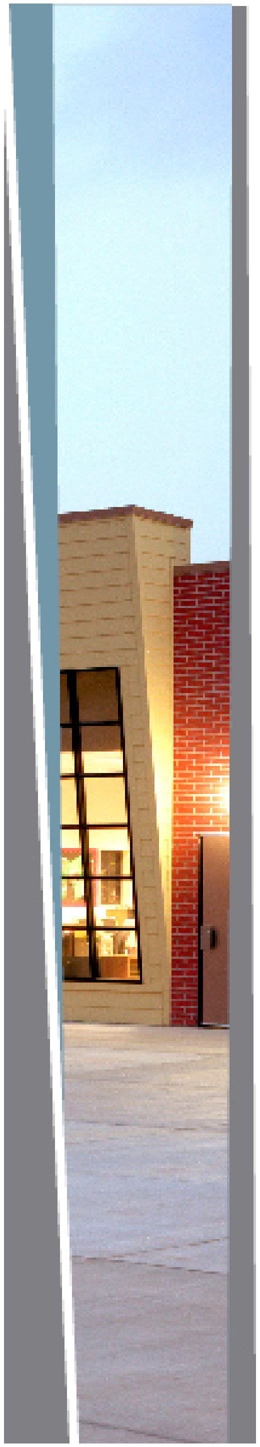


Degenkolb New Technologies Group

- Chris Poland (Group Director)
- Mark Sinclair
- Mahmoud Hachem
- Silvia Mazzoni
- Tim Graf
- 2+ Rotation Engineers
- 3-6 Engineers working on Special Projects
- Summer Interns



Outline

- Why NLRHA?
- NL Analysis at Degenkolb
- Analysis Efficiency & Model Management
- Modeling SFSI in OpenSees
- BuildingTcl
- When to Use NLRHA?
- OpenSees Opportunities and Challenges
- Conclusion

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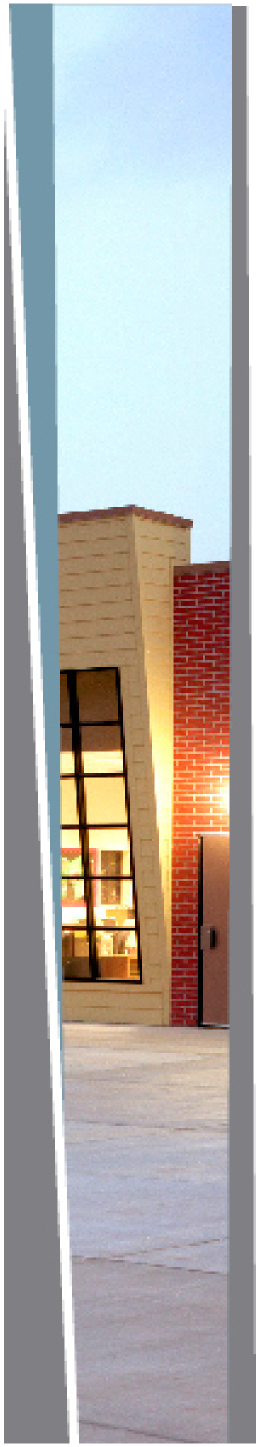

Using Non-linear Response History Analysis (NLRHA) in Design

- Design Process and Goals
- Steps in the Process
- When and Why?
- Examples and Lessons
- Future Directions

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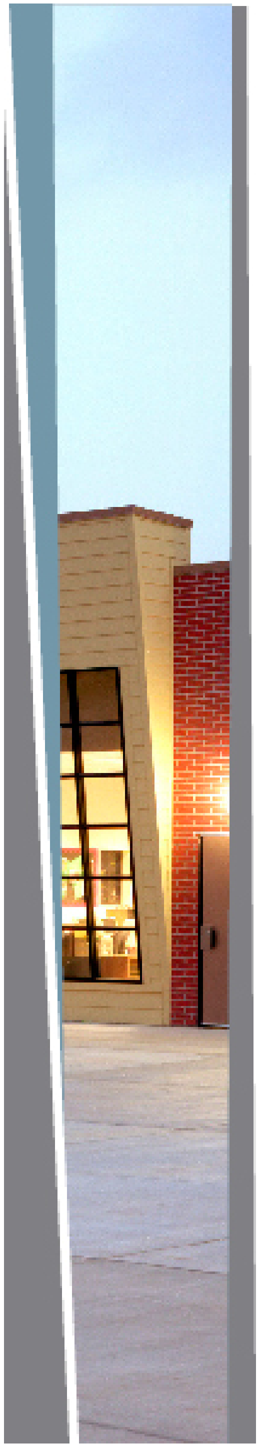
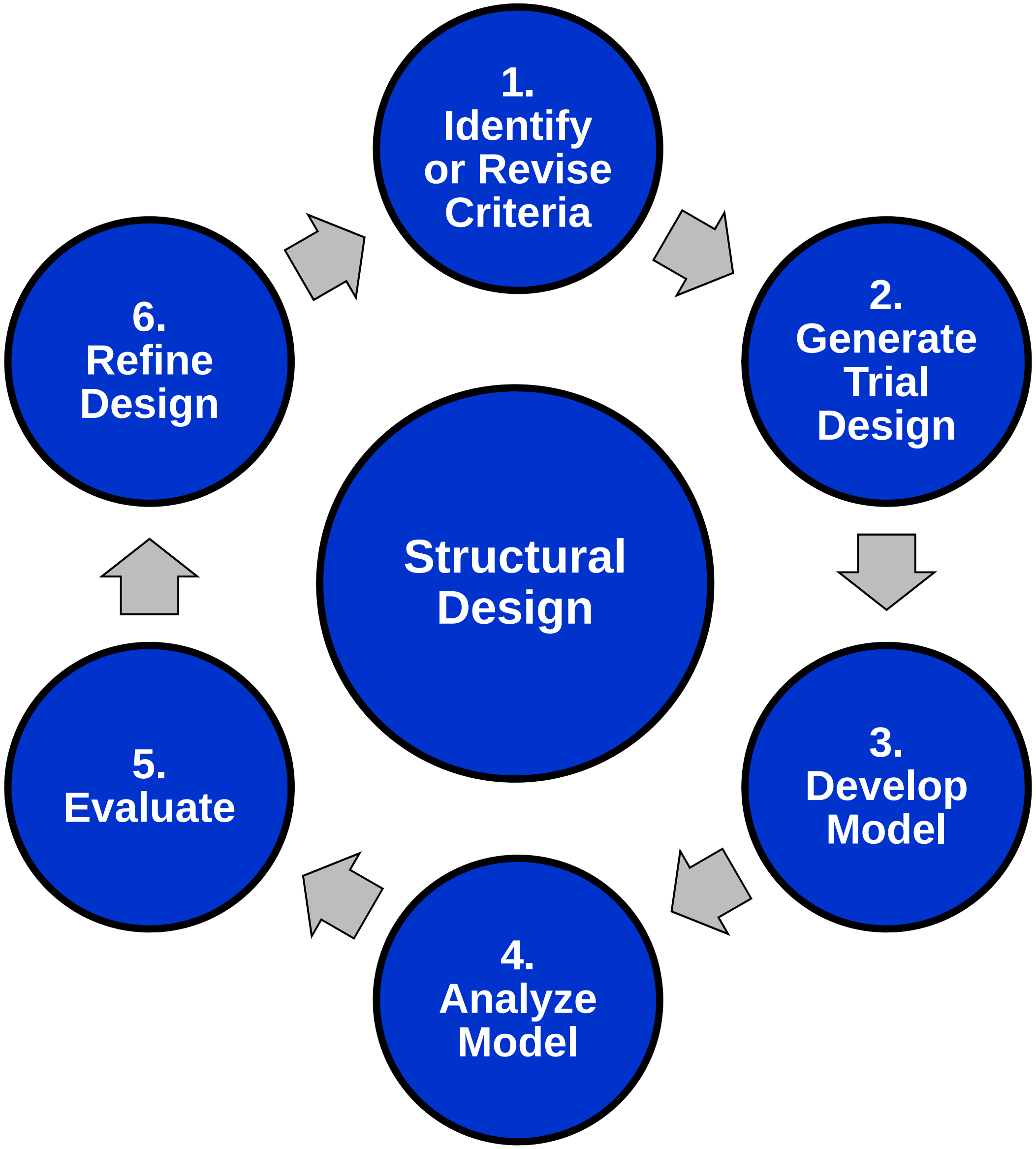


What is design?



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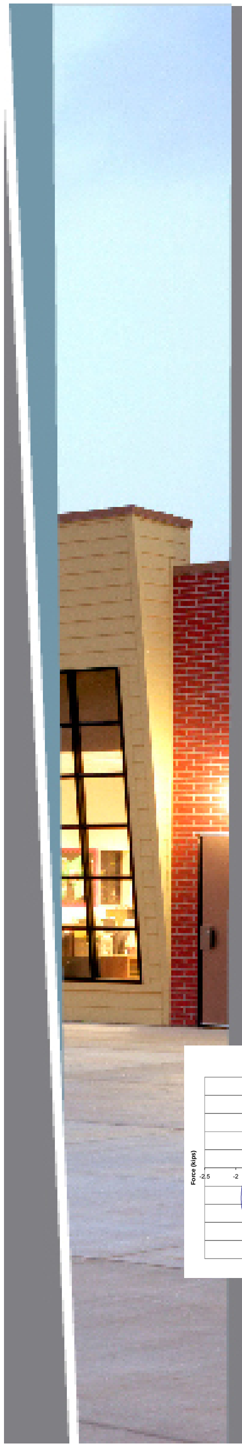
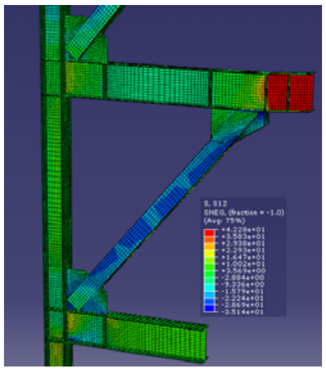
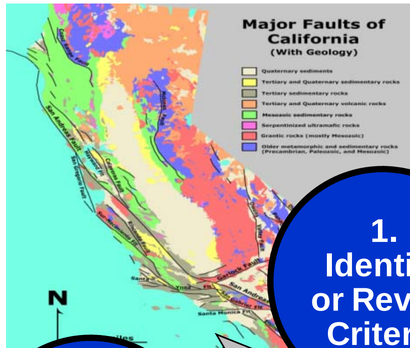
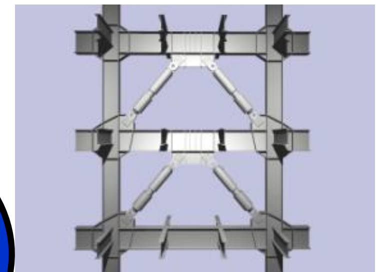
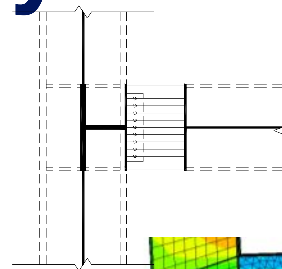
Design using Advanced Analysis

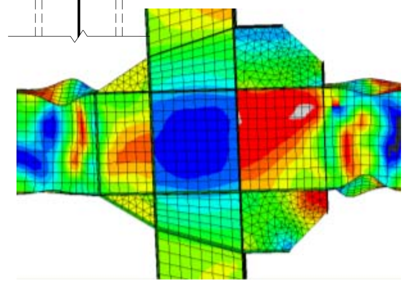


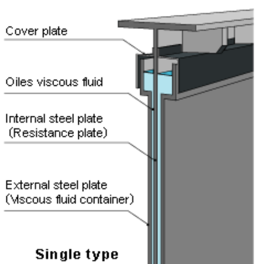






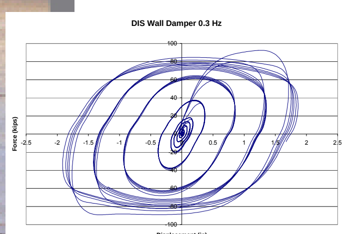


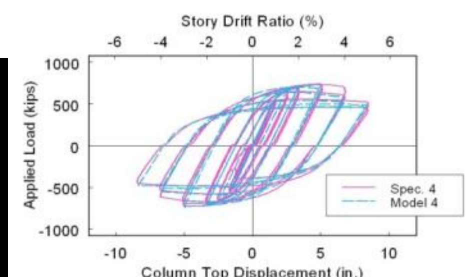


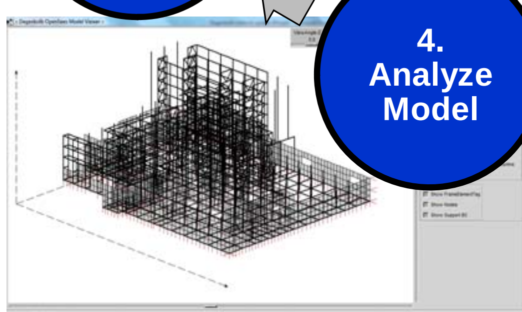


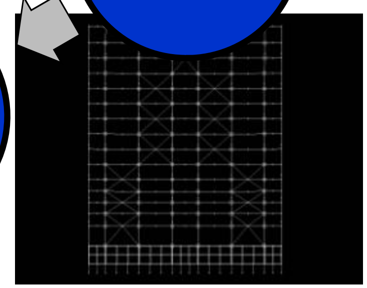
Structural Design

1. Identify or Revise Criteria
2. Generate Trial Design
3. Develop Model
4. Analyze Model
5. Evaluate
6. Refine Design









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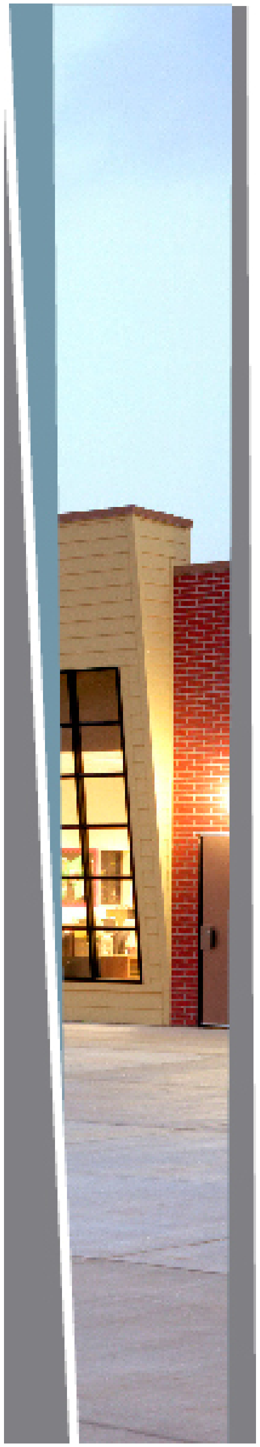

Nonlinear Response History Analysis (NLRHA), Why?

- Improving our prediction of the expected range of structural response by modeling ‘real behavior’.
  - *Reduce the uncertainties that we control.*
  - *Understand those that we cannot.*
  - *Develop our ‘model in the mind’.*

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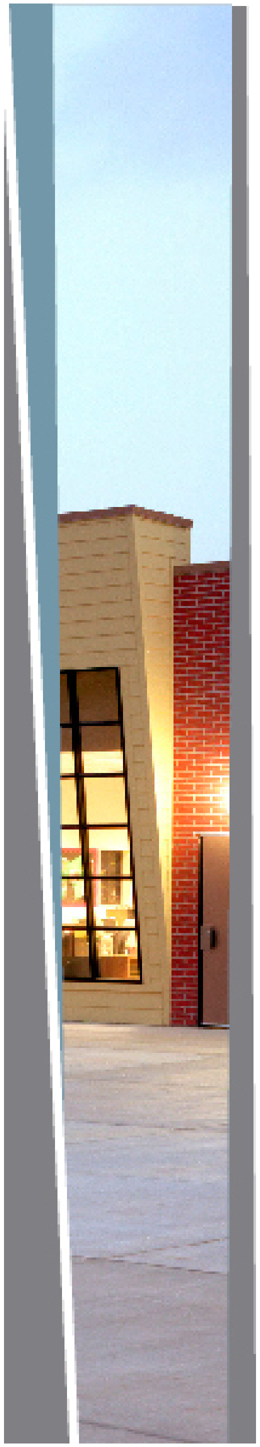
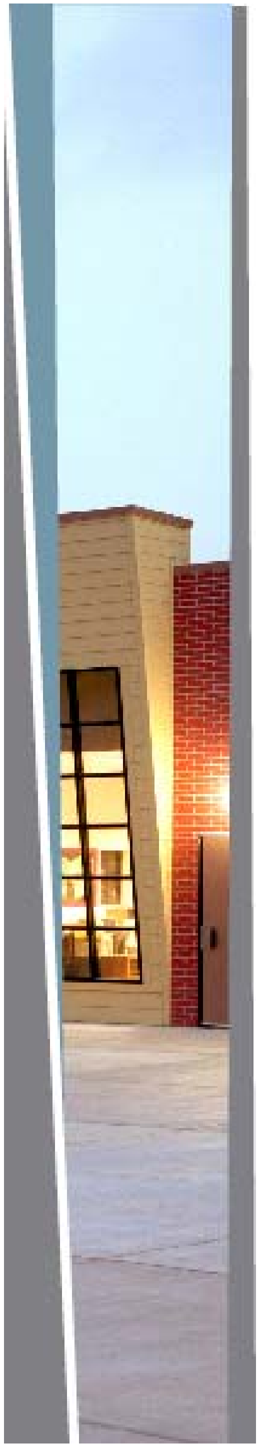
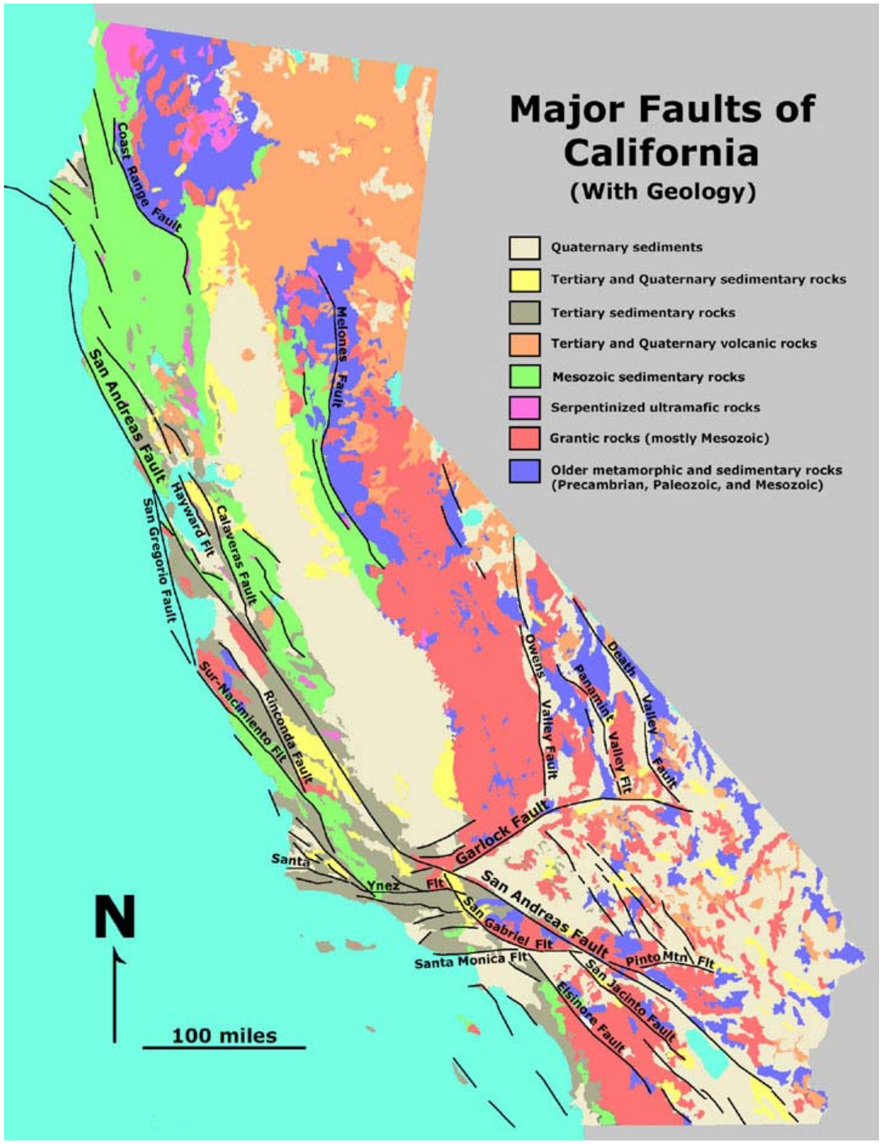


NLRHA: Why?

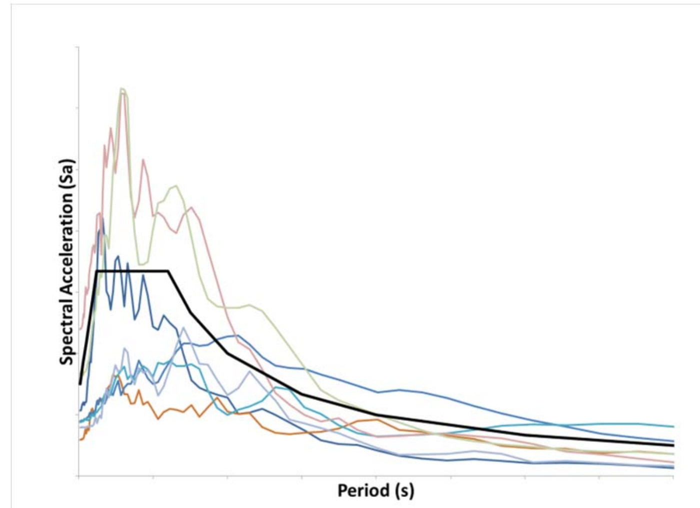
- To better serve our clients…..
  - By exploring solutions outside the code
    - Alternate Means of Compliance (PBEE)
    - New materials, systems, and techniques
  - By reducing structural scope and cost
  - By improving structural & seismic performance for the same or lower scope/cost.
  - By improving post-earthquake outcomes and reducing life-cycle costs.
  - While improving our understanding of structural behavior to make us better Designers



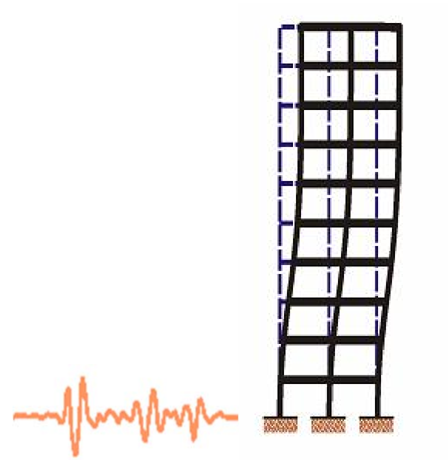
Seismic Hazard & Ground Motions



Source: GeologyCafe.com (Base map modified after the *Geologic Map of California* by Jenning, C.W., 1997, California Dept. of Mines and Geology)



Earthquake Ground Motion Selection and Scaling



Nonlinear Response History Models

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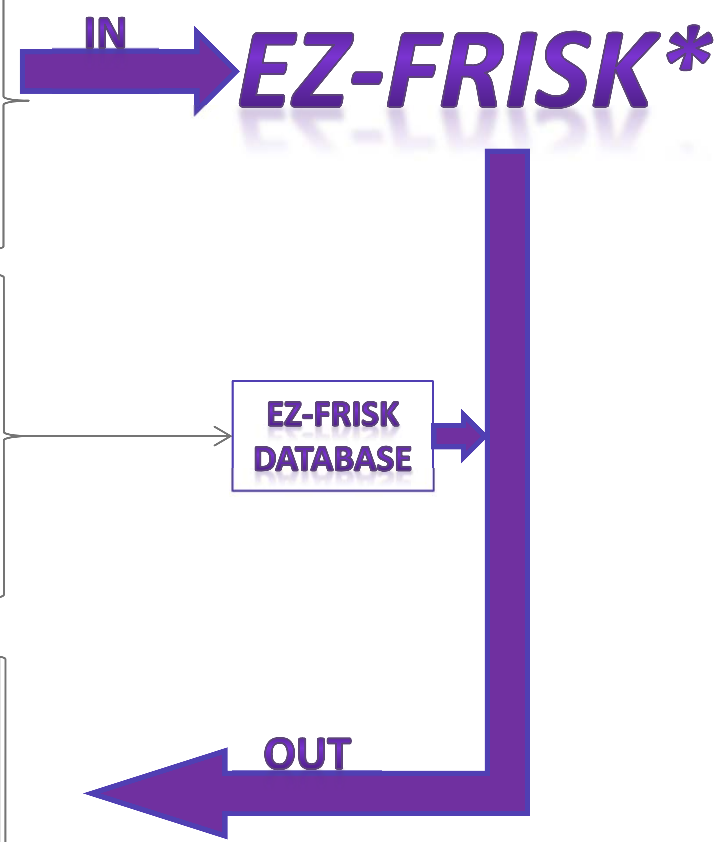
Site-Specific Seismic-Hazard Analysis

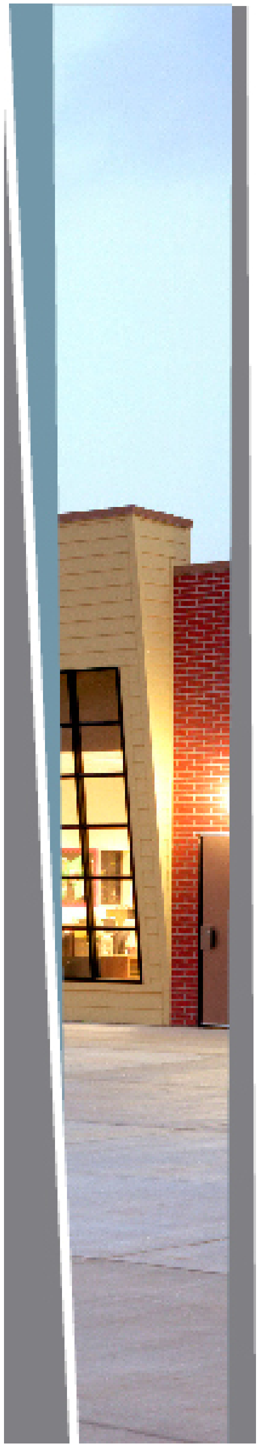
- Site Data
  - Location
  - Soil Profile
    - Average shear-wave velocity in top 100ft: Vs_{30}
    - Depth to Rock
- Regional Seismicity
  - Regional faults
    - Distance & Magnitude
    - Fault Mechanism
- Attenuation Relationships

- Probabilistic Spectra
  - 2% probability of being exceed in 50 years
  - 10% probability of being exceed in 50 years

- Deterministic Spectrum
  - Mean + one standard deviation
  - account for uncertainties associated with near-fault ground motions



* OR YOUR OWN PROGRAM



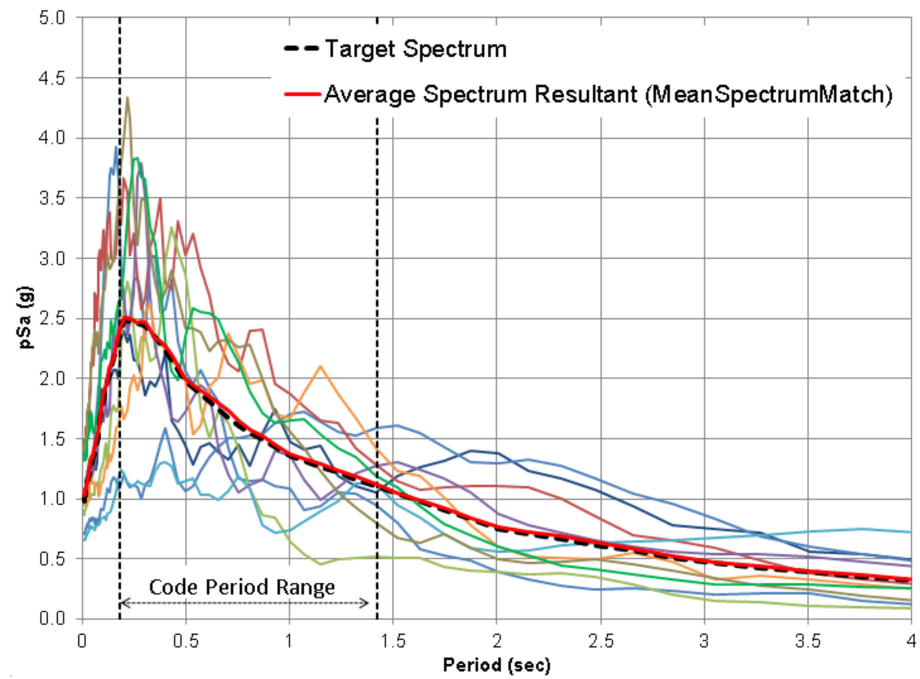
Degenkolb Method

- Mean Spectrum Matching
  - *Developed at Degenkolb Engineers by Mark Sinclair*
  - Addresses the limitations of the other two methods and combines their advantages
  - Addresses what is relevant to the structural engineer
  - Minimal frequency-content modification to ground-motion record
  - Spectral Matching at <u>average</u> level:

    SR_{avg} = Target Spectrum
  - We have used it on several projects
  - Has been reviewed and approved by CGS/OSHPD on a new-hospital design project

Mean Spectrum Matching

- Advantages
  - Maintain
    - All individual characteristics of record (except amplitude)
    - Characteristic period and energy content of record
    - Peaks and valleys in individual spectrum
  - Minimize amplification/effects on higher modes
  - <u>Control</u> variability between records
  - <u>Reduces</u> peaks in spectrum



  – Meet goal of mean response
  – Can set different target spectra for different directions (Fn & Fp in near-field)
  – Can control dispersion in response between records (standard deviation)
- Limitations
  – Less known
  – Implementation is not trivial, but automatable

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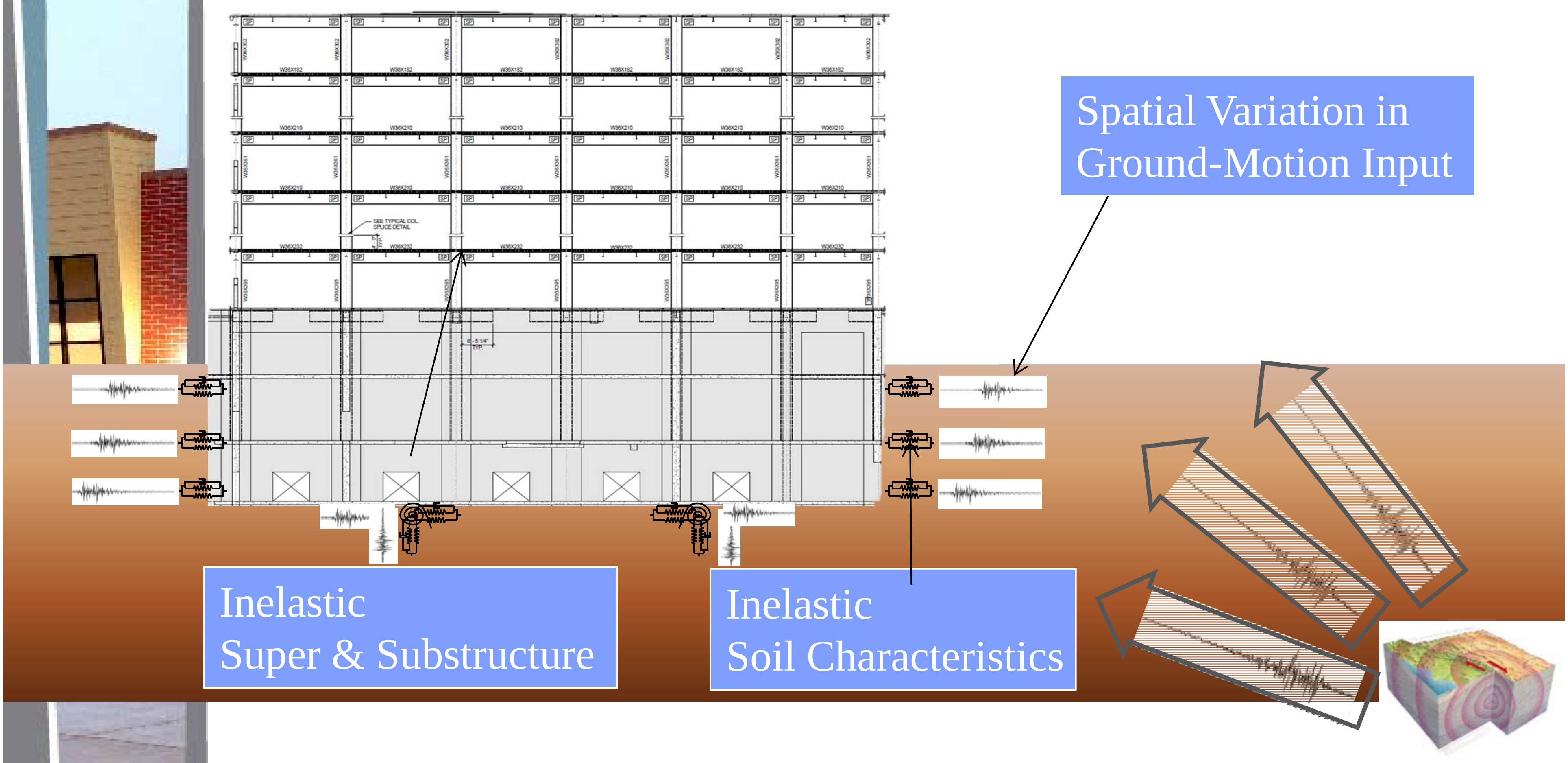
Soil Foundation Structure Interaction



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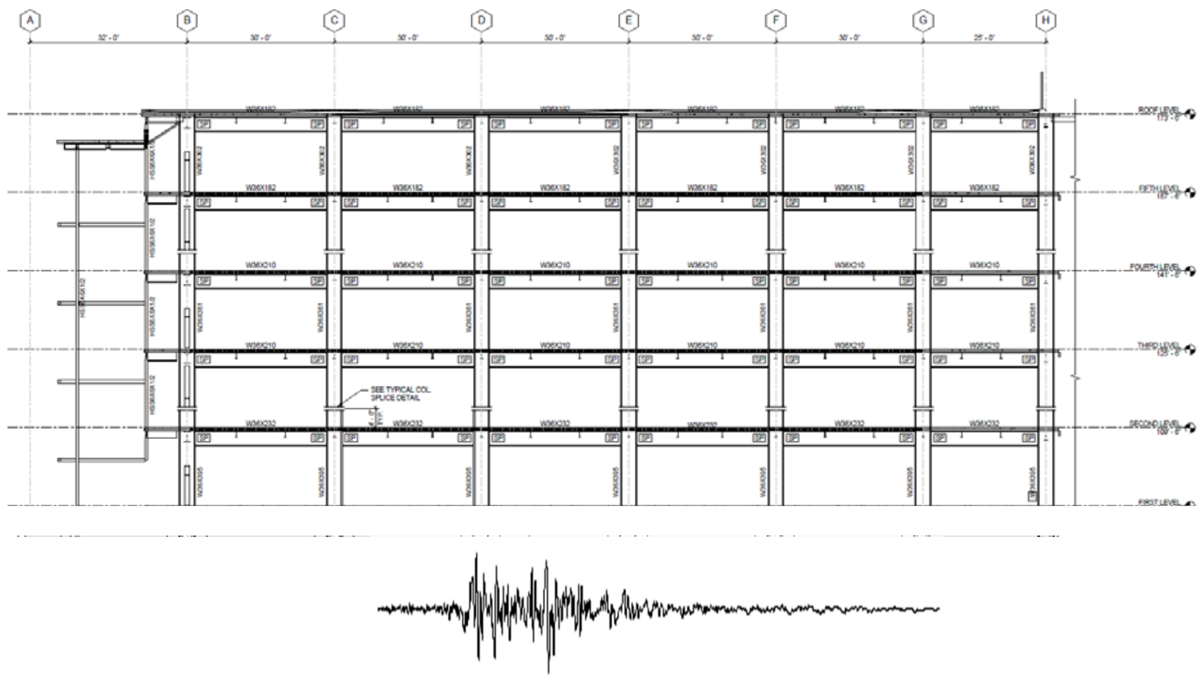
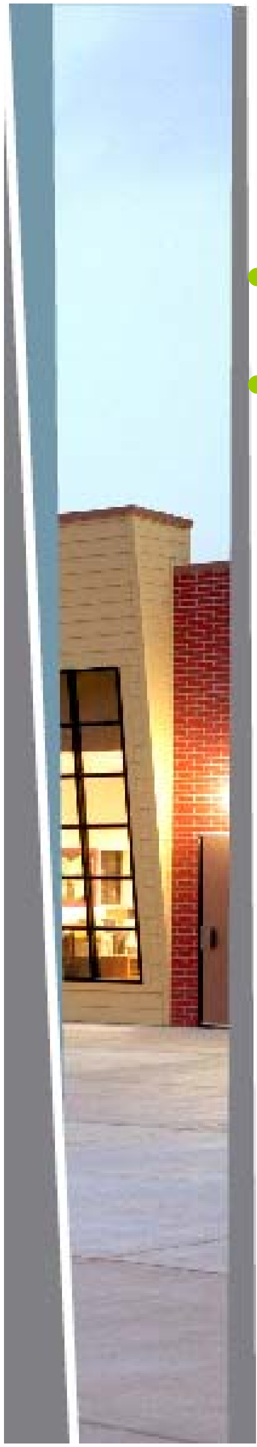
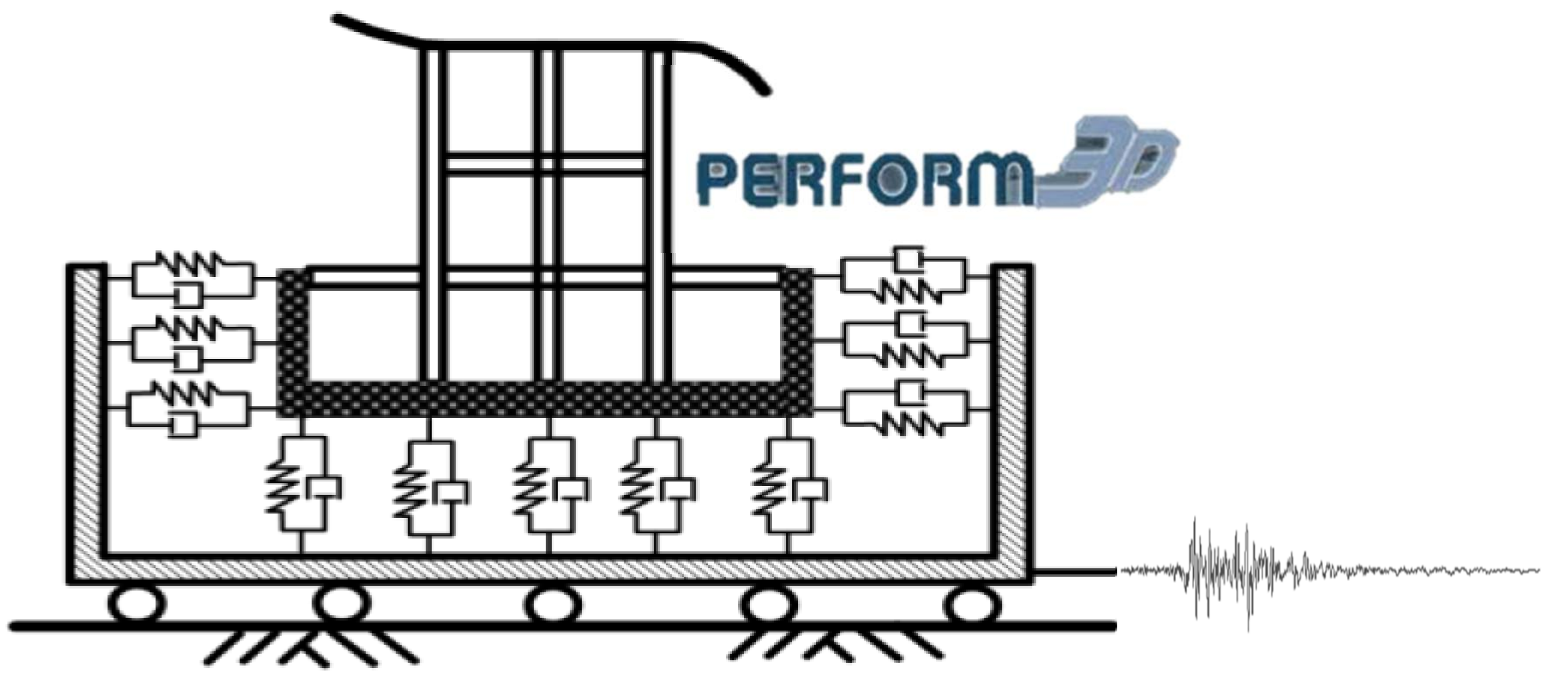
Current State of the Practice:





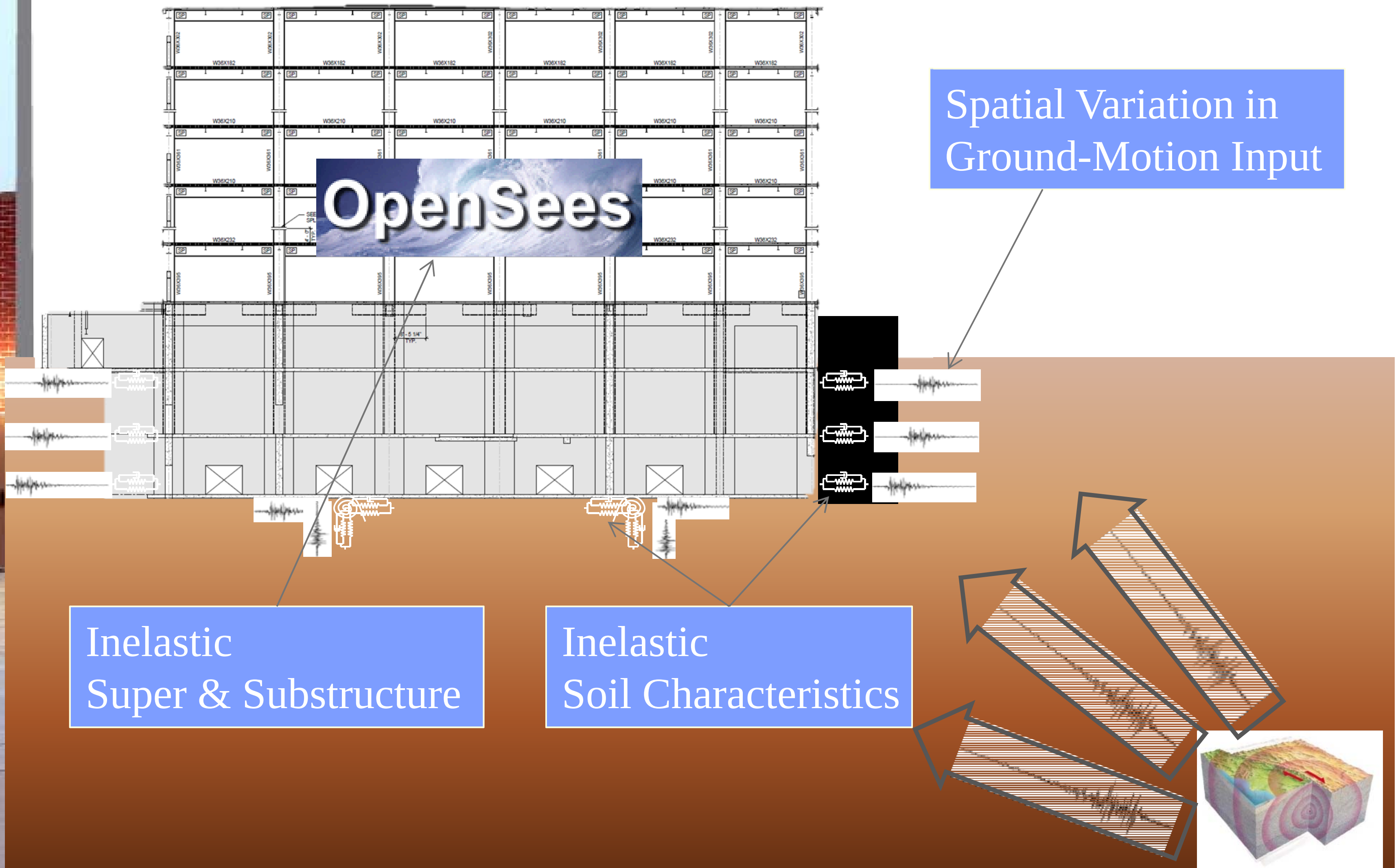
Current Edge of the Practice:

- Uniform-Support Excitation = bathtub model
- Model kinematic effects (spatial variation of ground motions) implicitly

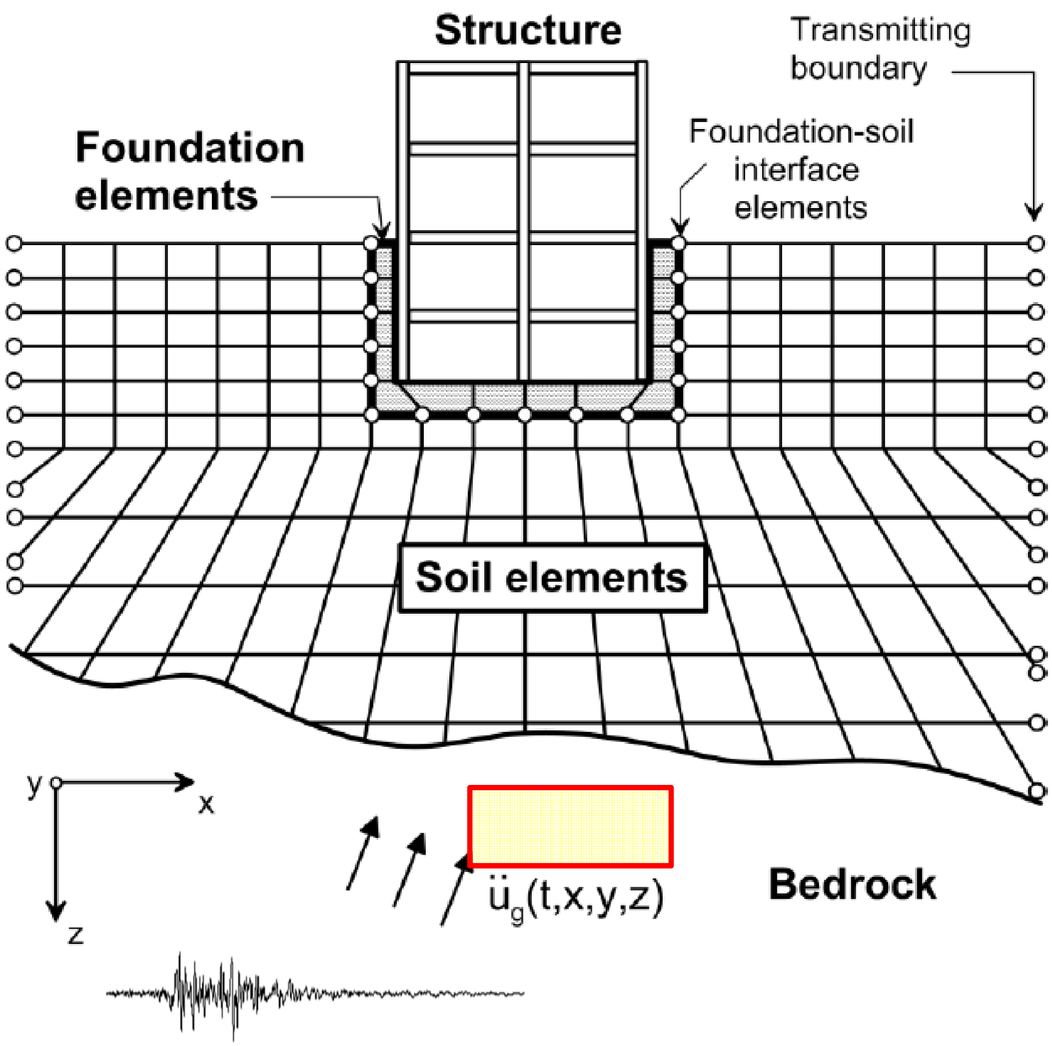


Just Beyond:

- Multi-Support Excitation

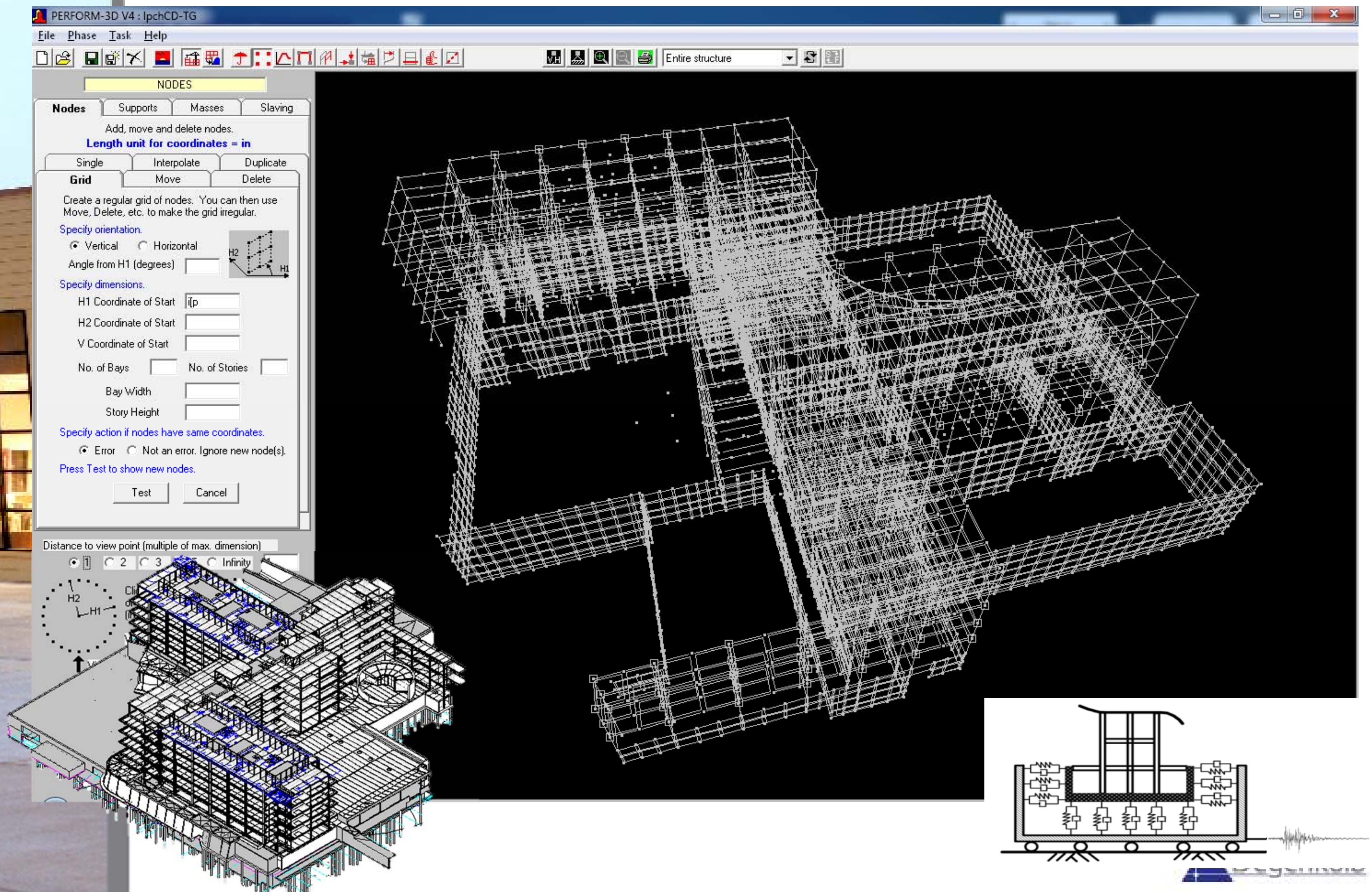


Direct Modeling of System Response

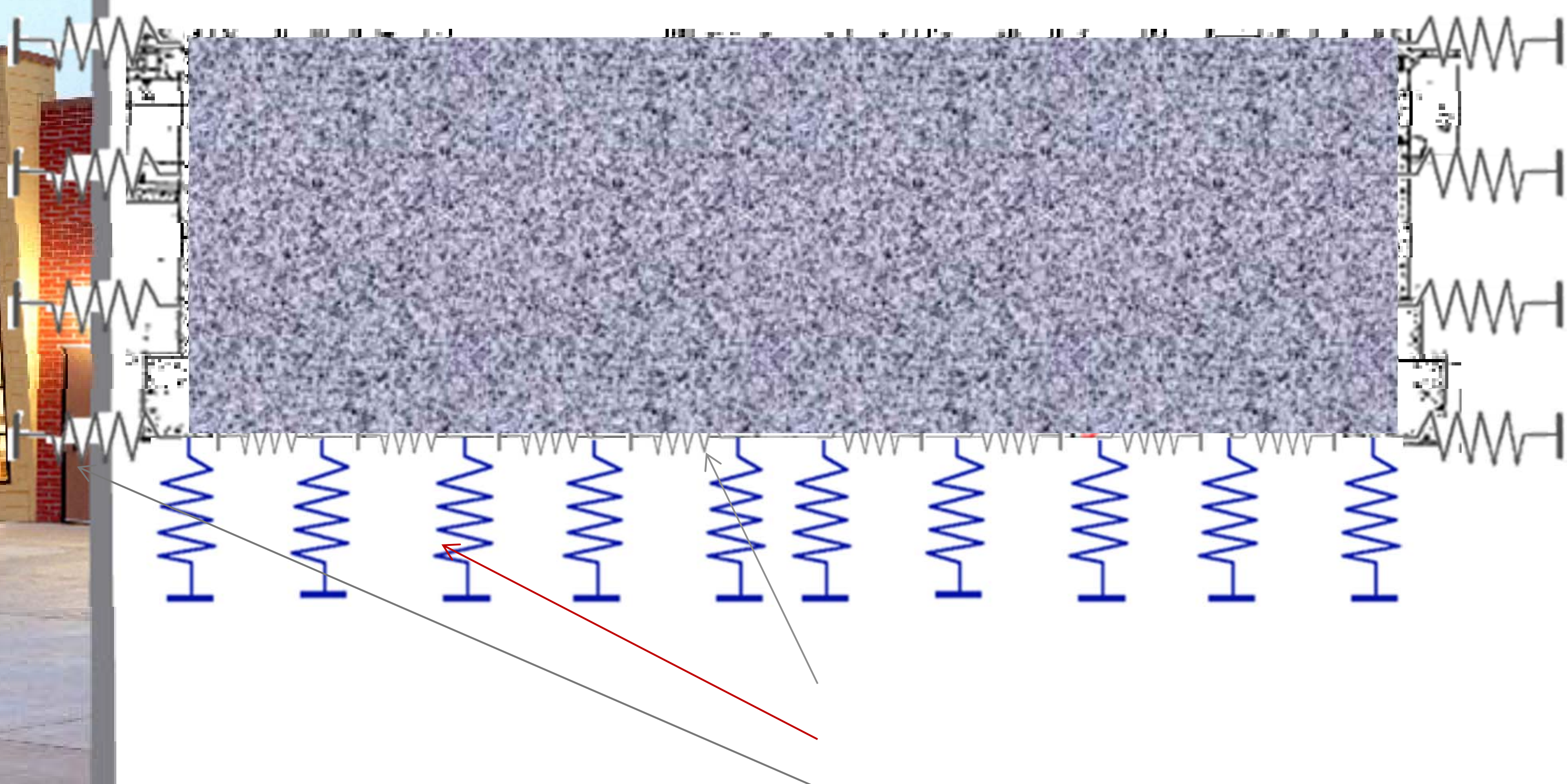


from ATC 83 Project. Task 10, JP Stewart

Perform 3D Model:

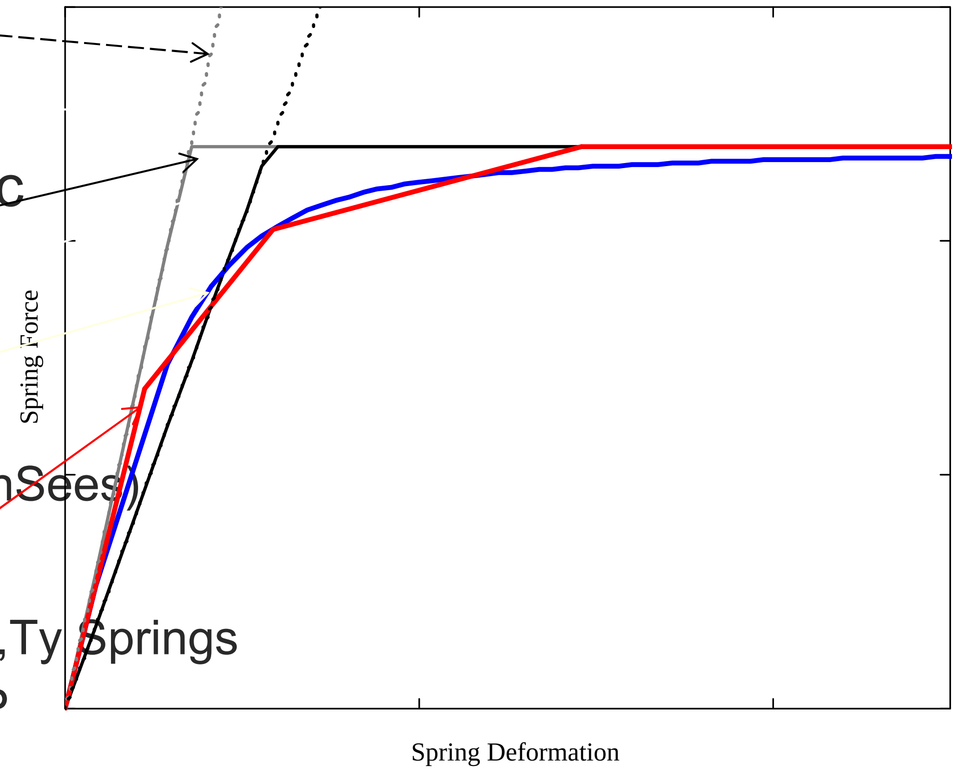


Soil-Spring Characterization Winkler Foundation



Soil Material Models

- Elastic
  - Initial Stiffness
  - Secant Stiffness
- Elastic-Perfectly-Plastic
  - Initial Stiffness
  - Secant Stiffness
- Inelastic Curvilinear
  - Qz,Py,Ty Springs (OpenSees)
- Inelastic Multi-Linear
  - Determined from Qz,Py,Ty Springs
  - Implementable into SAP



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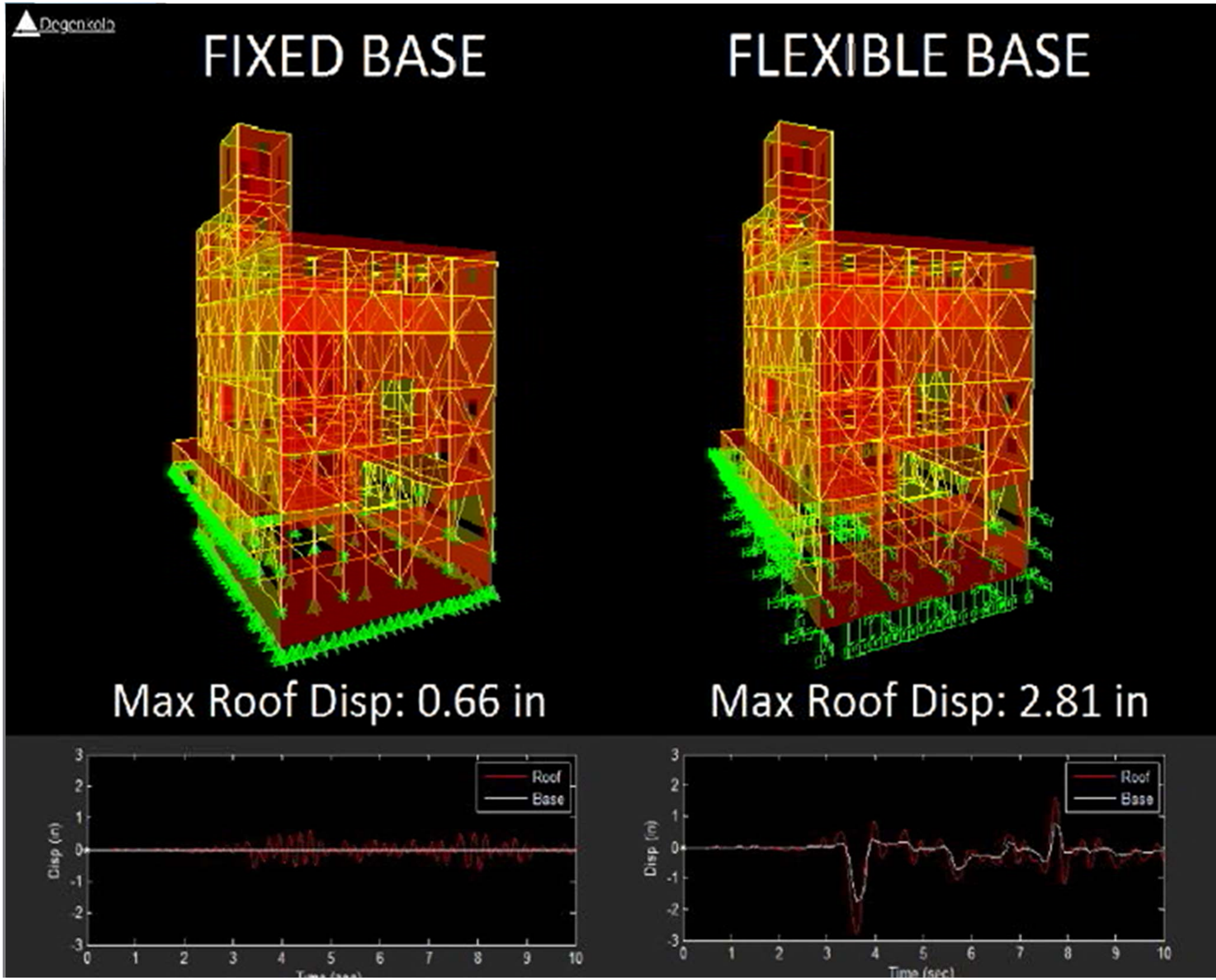
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FIXED BASE
FLEXIBLE BASE
Max Roof Disp: 0.66 in
Max Roof Disp: 2.81 in
Roof
Base
Disp (in)
Roof
Base
Disp (in)

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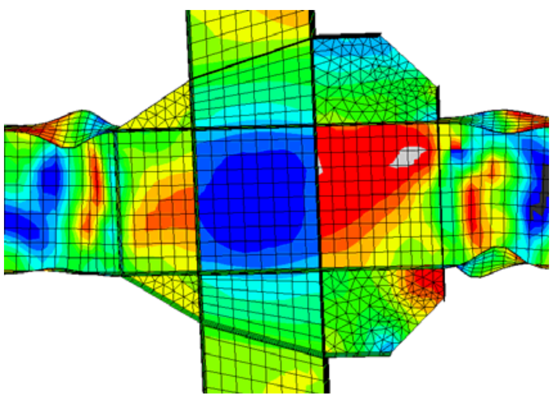
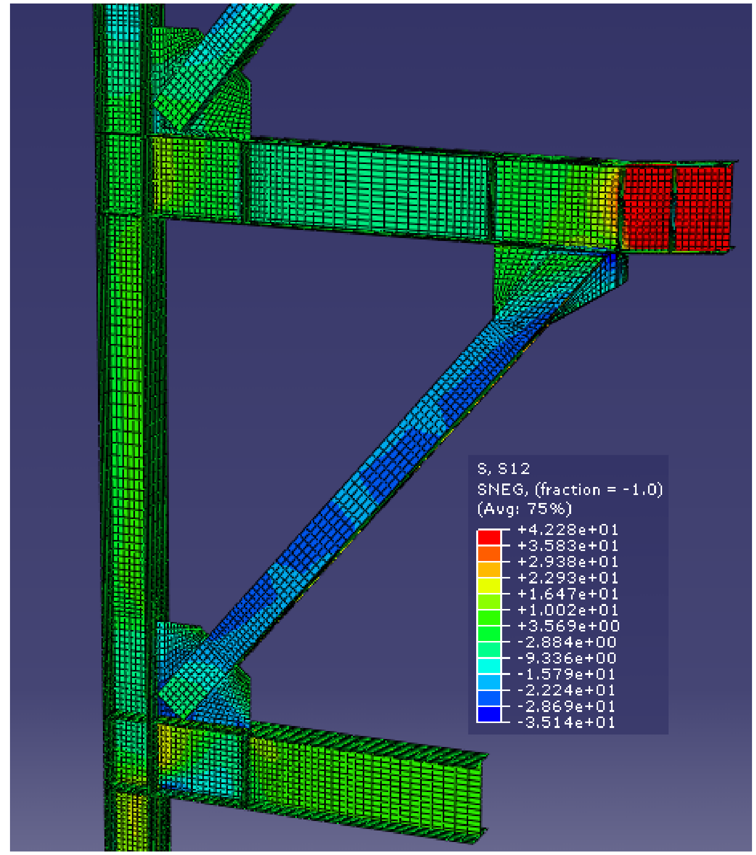
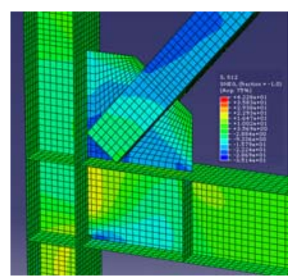
Component Finite Element Analysis

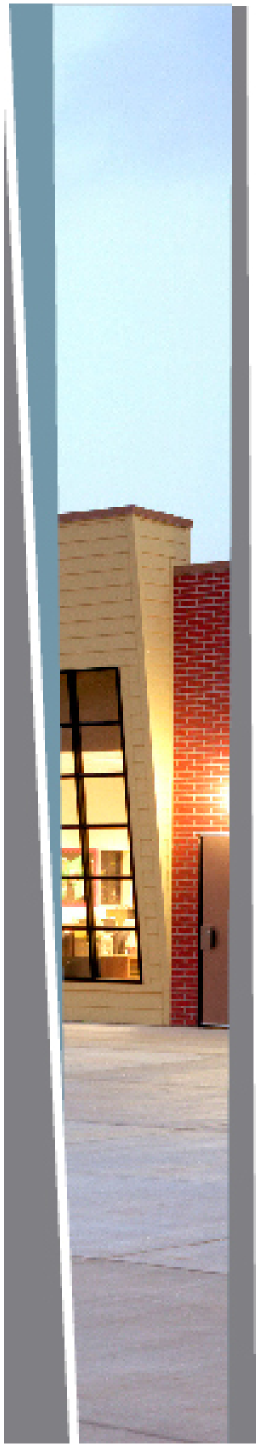
Detailed Component Analysis:

- In support of testing programs, e.g. SMRF Connections
- Evaluate behavior of critical components

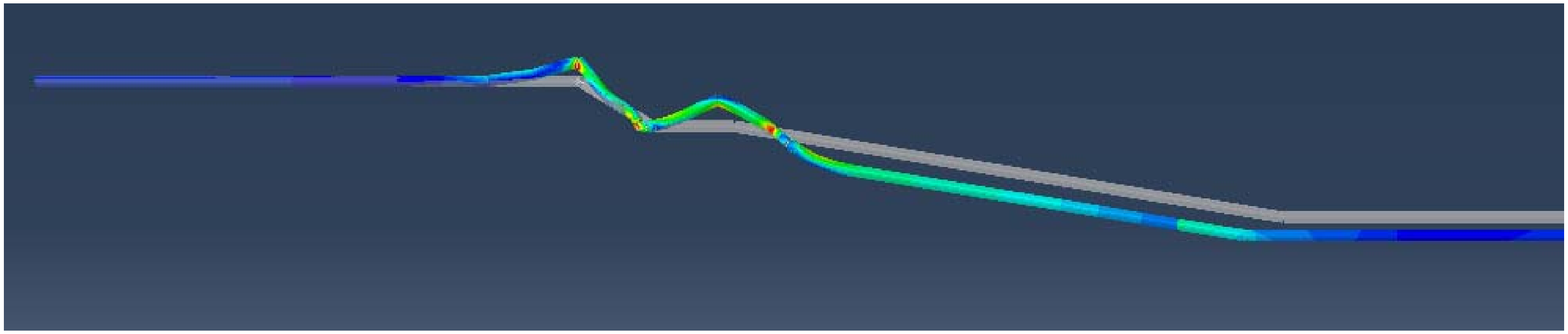




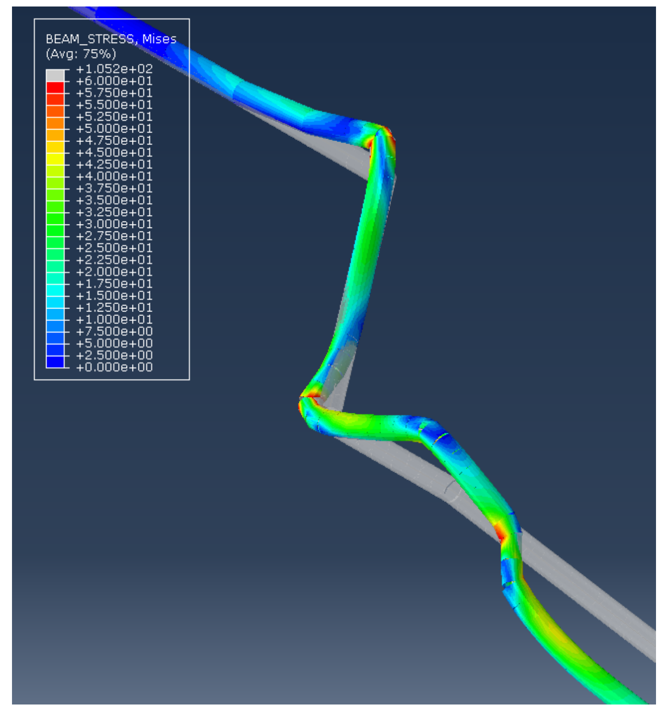




FEA - Pipeline Analysis



- Determination of pipe stresses and strains due to imposed displacement at a fault crossing
- Incorporates:
  - Inelastic pipe properties
  - Inelastic soil properties
  - Internal pipe pressures
  - Varying soil conditions
  - Varying fault locations and offsets



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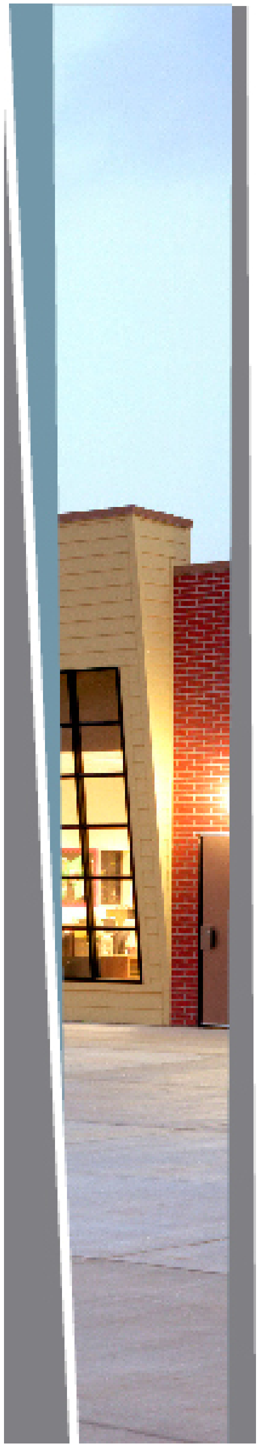
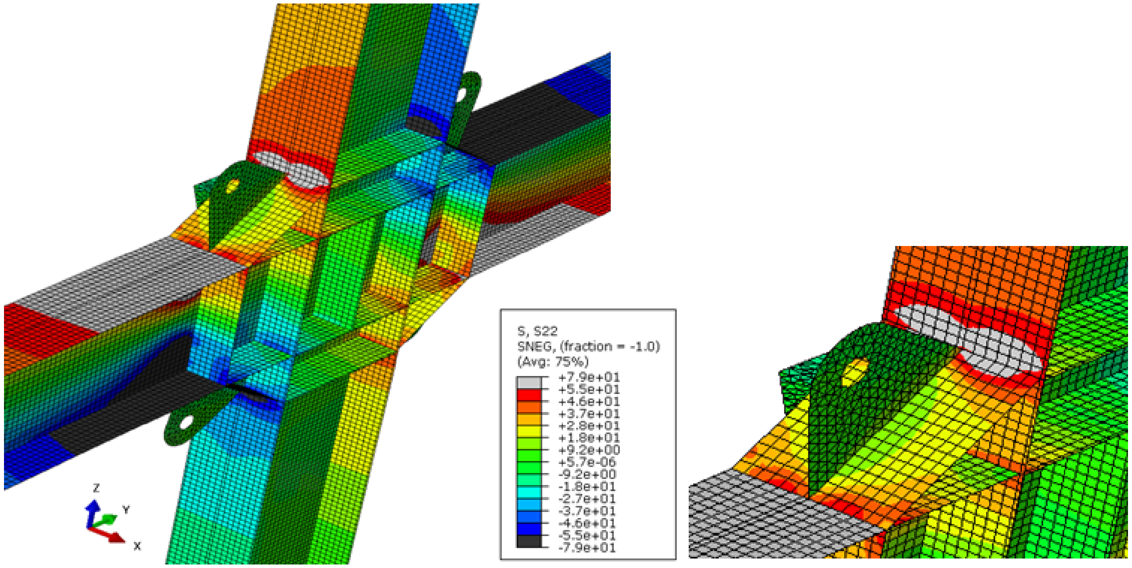
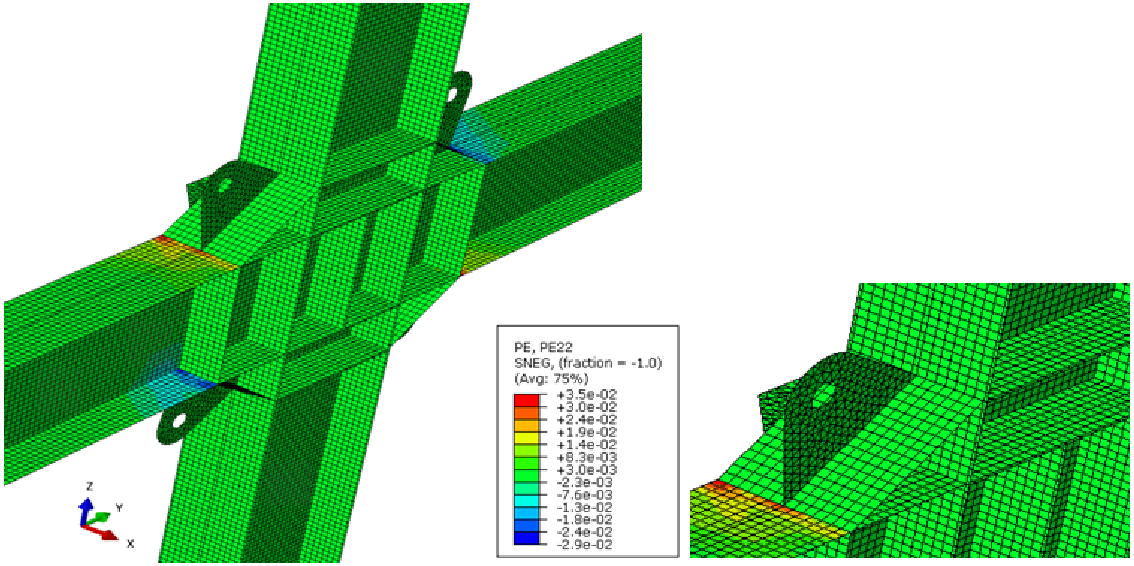
Moment/Brace Haunched Connection





(a) Flexural Stress Contours



(b) Plastic Flexural Strain Contours

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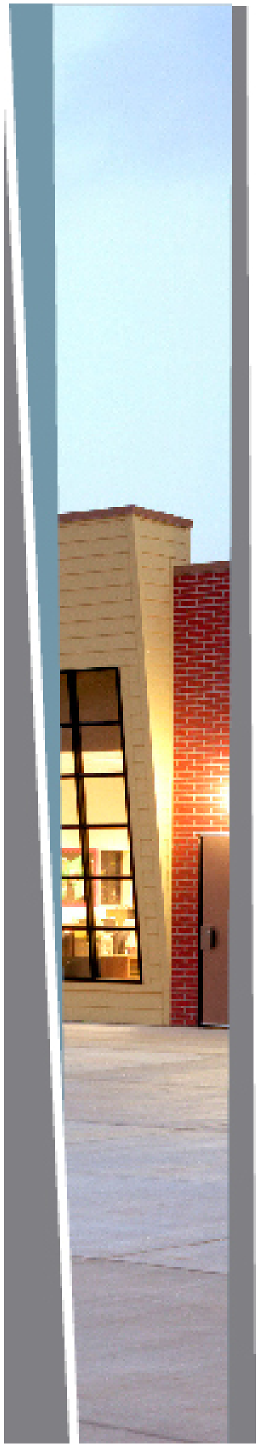
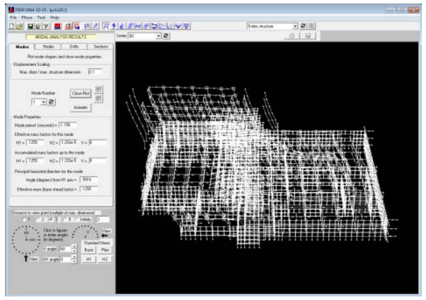
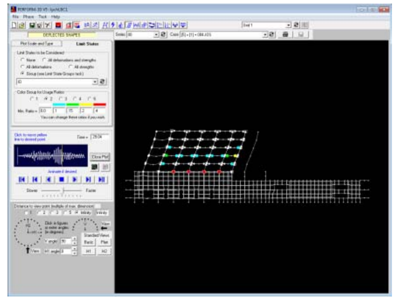
NRH Analyses

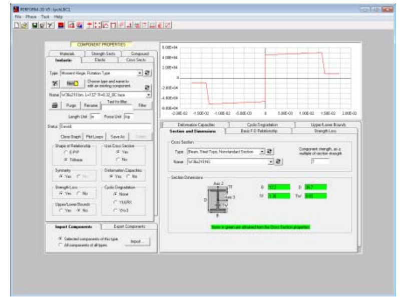
- Typical Analysis
  - 160 records (10 GM's x 16 cases)
  - On average 16 hours each record = over 100 days end-to-end
- Typical suite can generate up to 2 TB of data
  - Includes displacements, drifts, member forces, hinge rotations, energy dissipation, etc. for every single time step
- Can be labor intensive to reduce data to only a few important results per element



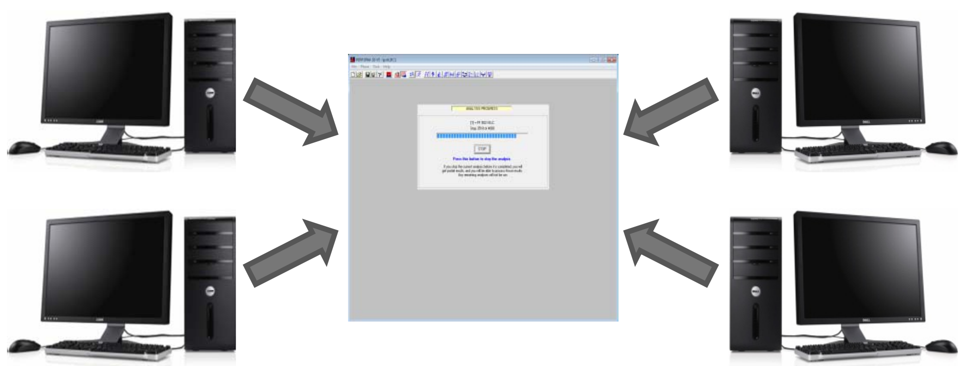
Model Efficiency



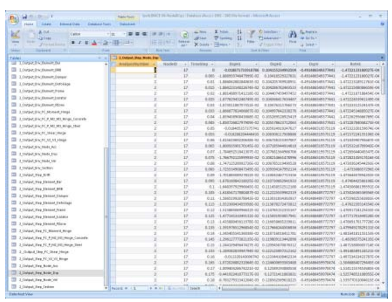


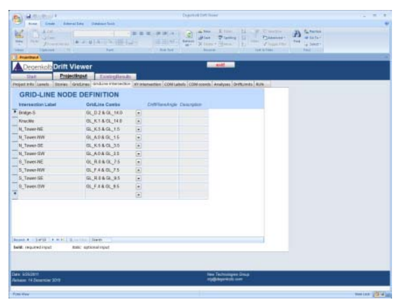


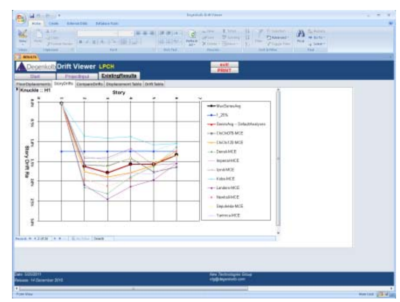
Rapid Model Generation Tools



Multimachine Analysis



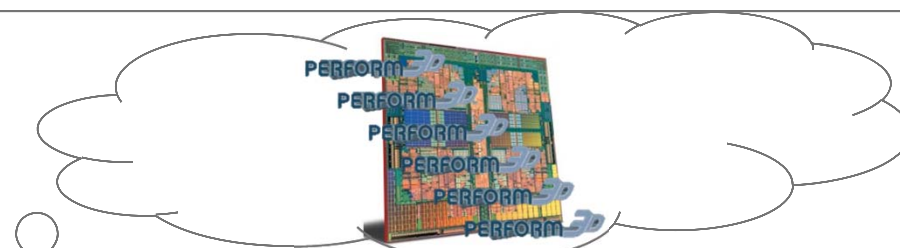




Database Post-Processing

State of the Edge of the practice:

- Discovering limitations
  - Software was developed for serial machines



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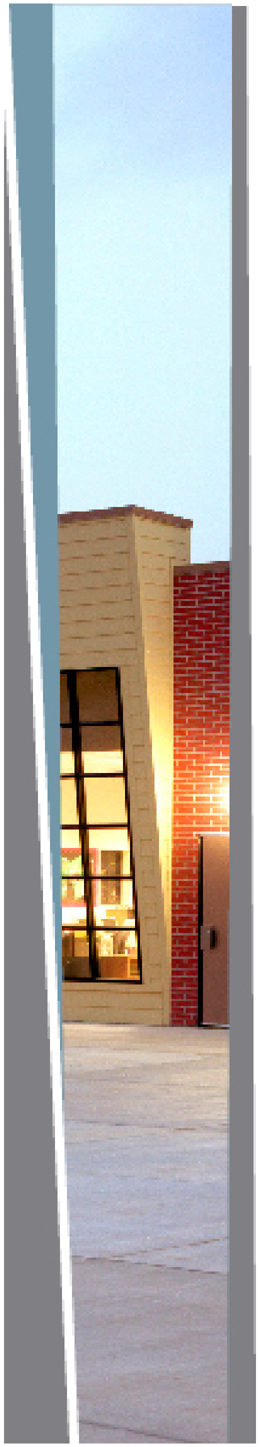

Hardware Efficiencies

- Multi-Core 64 bit Processor
- Virtual Analysis Machines
  - Adjustable allocation of resources
  - Software only utilizes one core per instance, multiple instances on multiple cores machines allows for parallel analyses
- Multi-Machine Analysis

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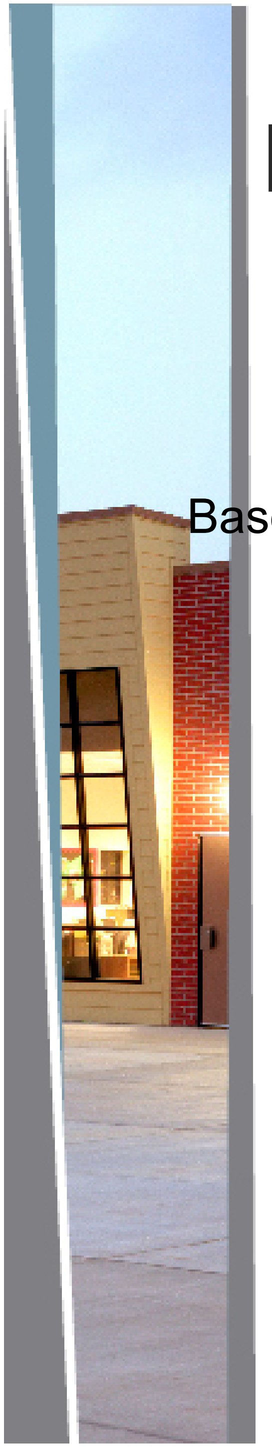
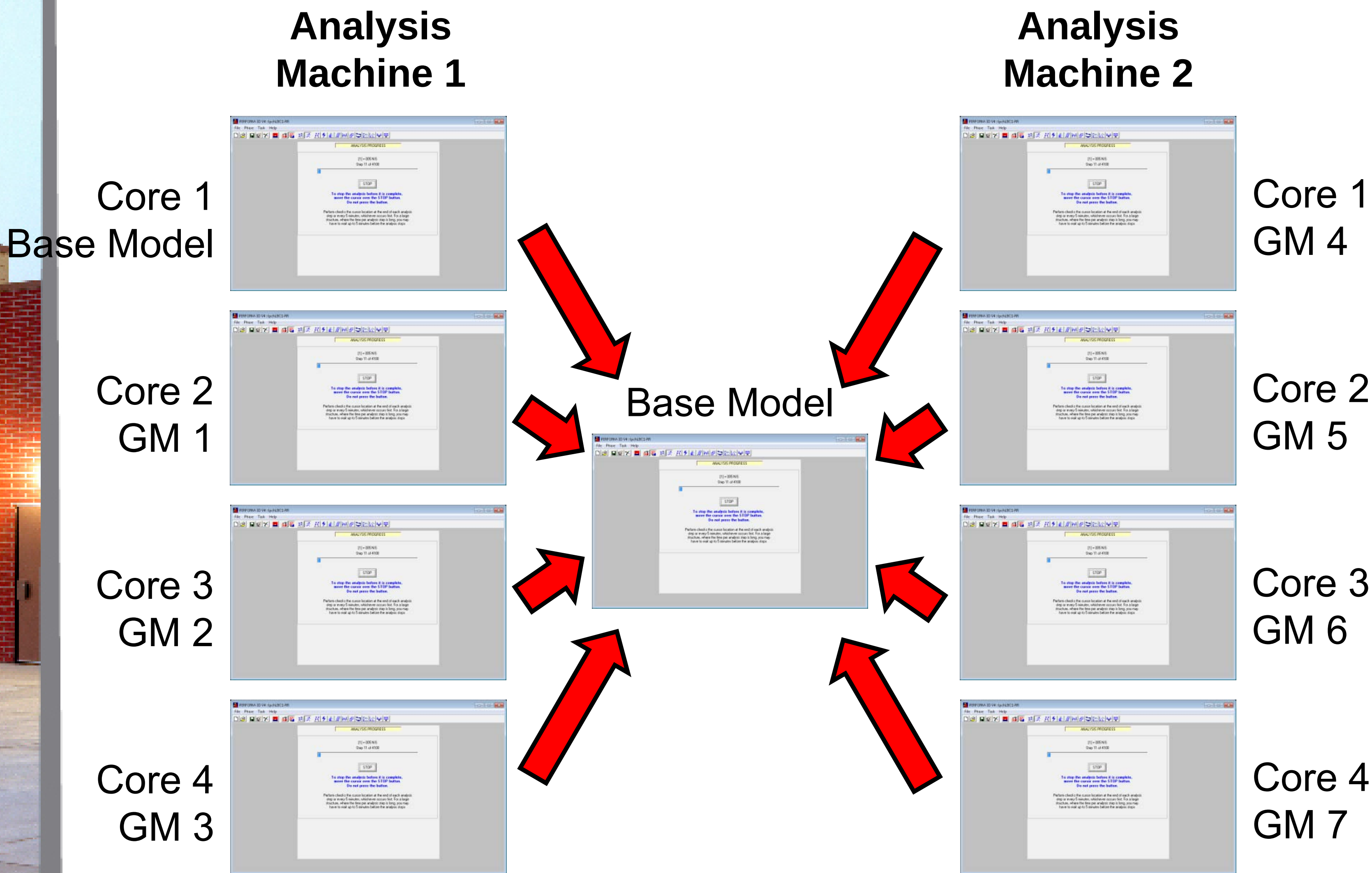


Multi-Machine Analysis



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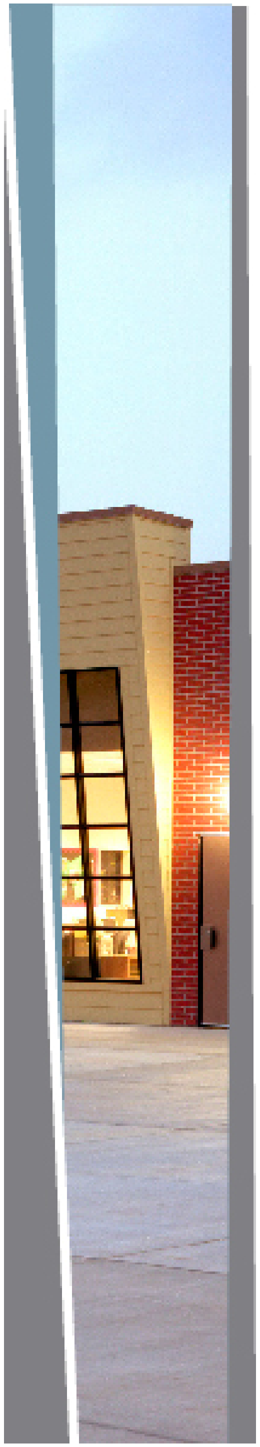
Multi-Machine Analysis

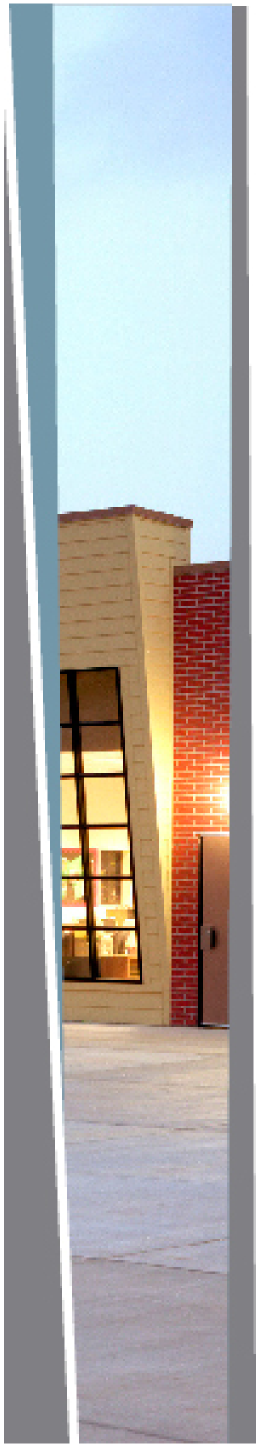
- DE Level Analysis
  - 10 Ground Motion pairs (avg 16 hrs each)
  - x 4 (Eccentric mass cases)
  - x 2 (rotated ground motions)
  - x 2 (Upper & lower bound soil properties)
  - = 160 records

- Run simultaneously runtime reduced from 100s of days to length of 5 ground motion (2-3 days)

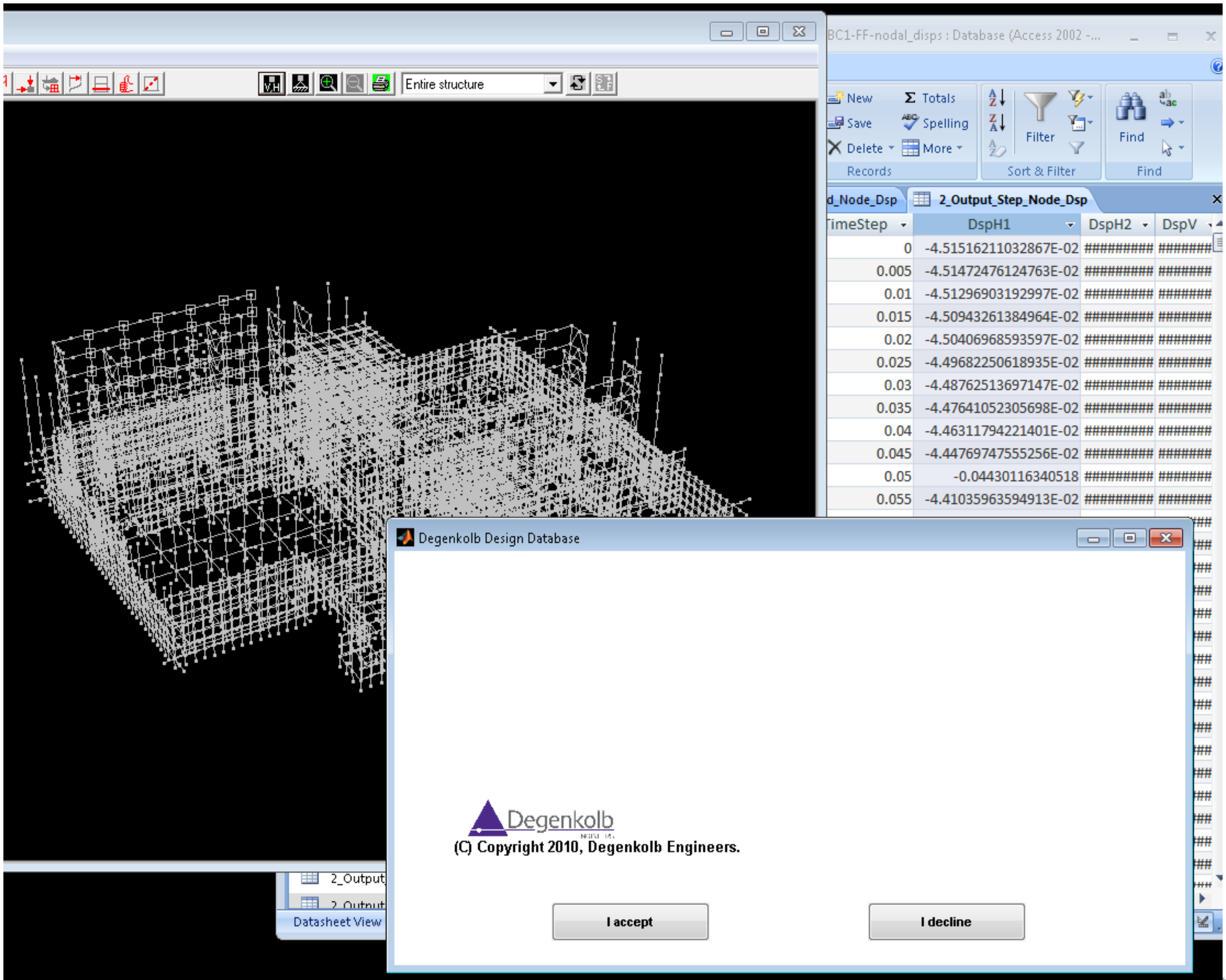


Software Efficiencies

- Degenkolb Design Database
  - Software developed for Degenkolb
  - Accesses PERFORM binary result files directly
  - Output to text files or database files

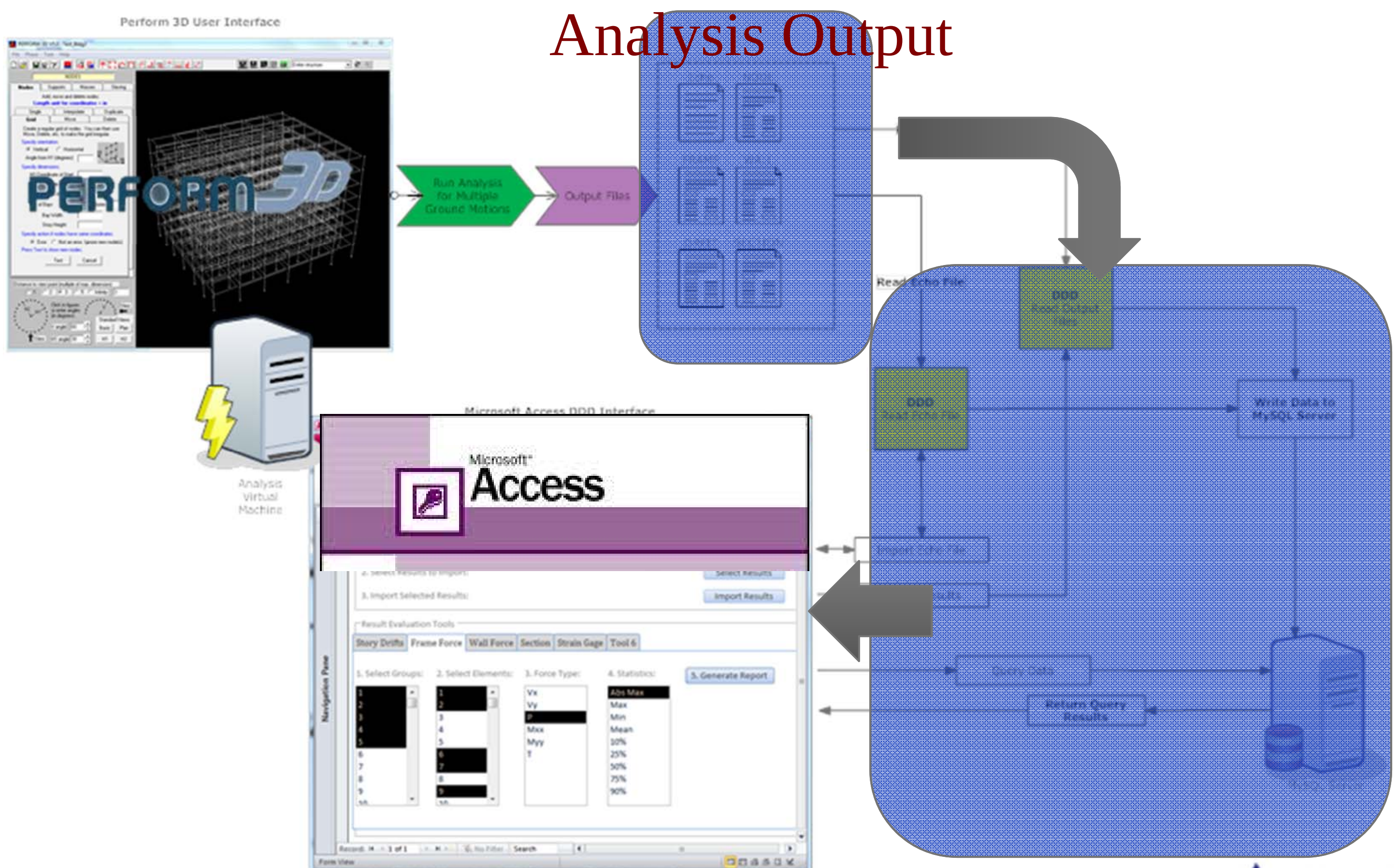


Degenkolb Design Database

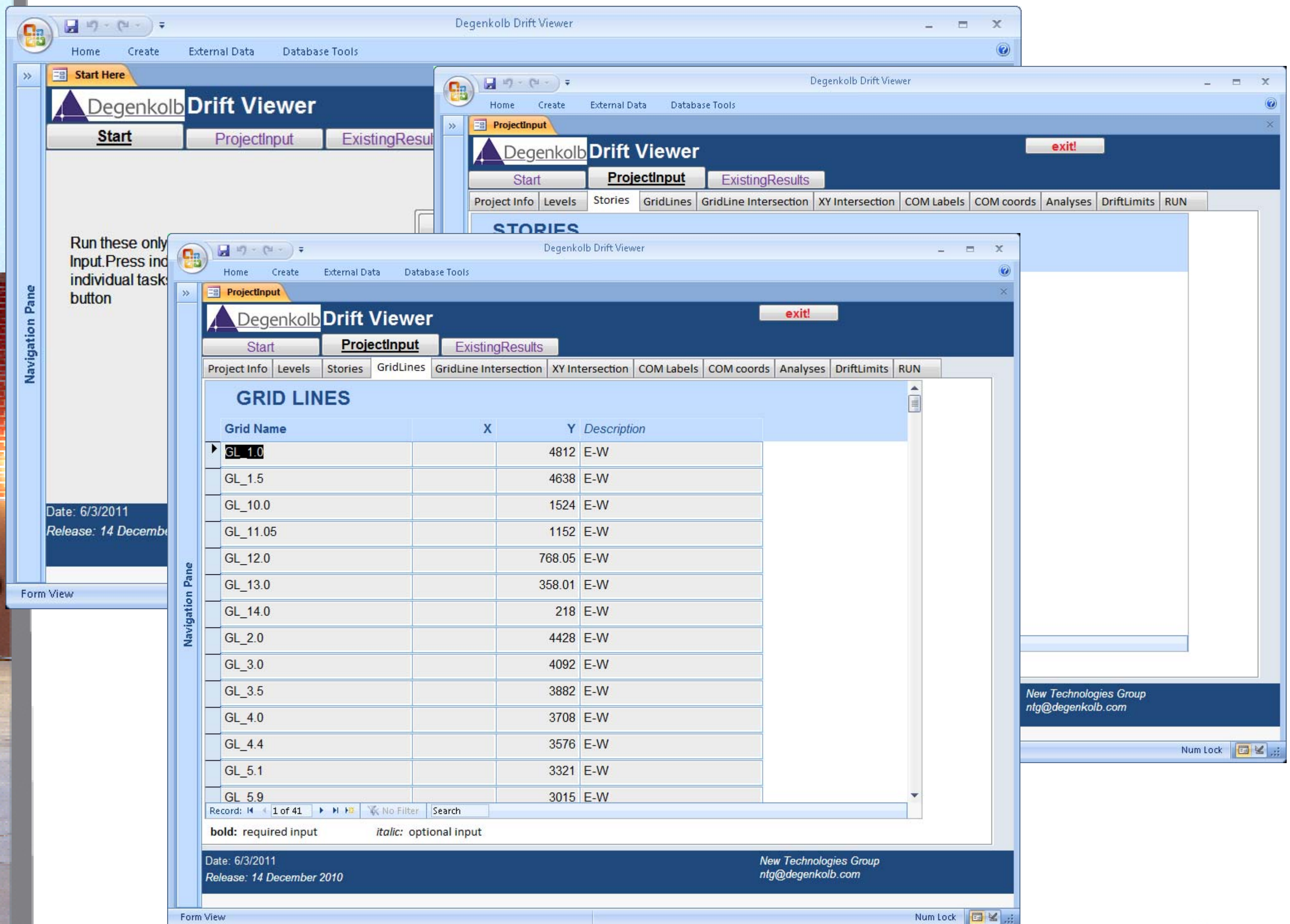


State of the Edge of the practice:

- Discovering limitations
  - Post-processing is proprietary and cumbersome

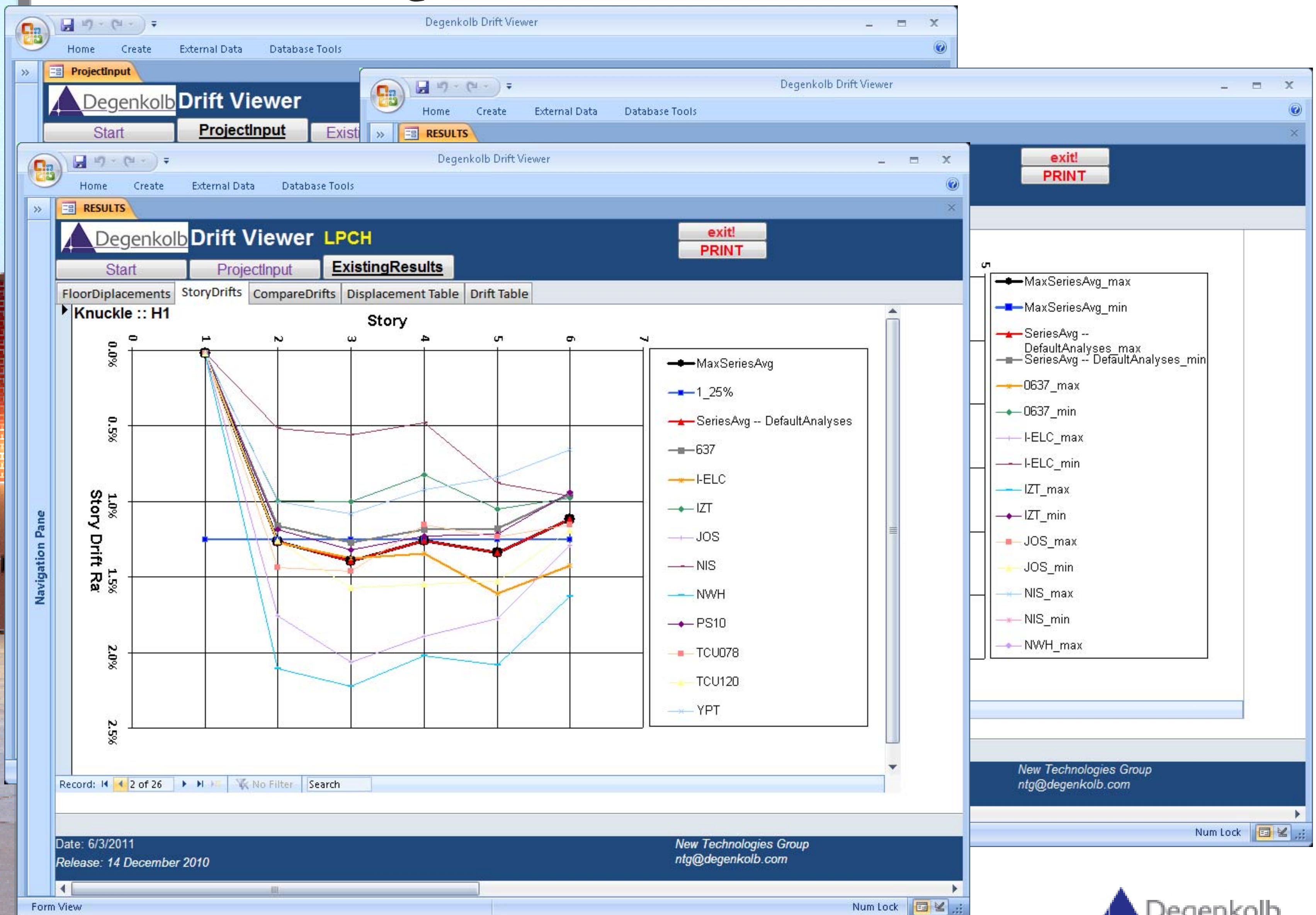


Database Queries - Drift

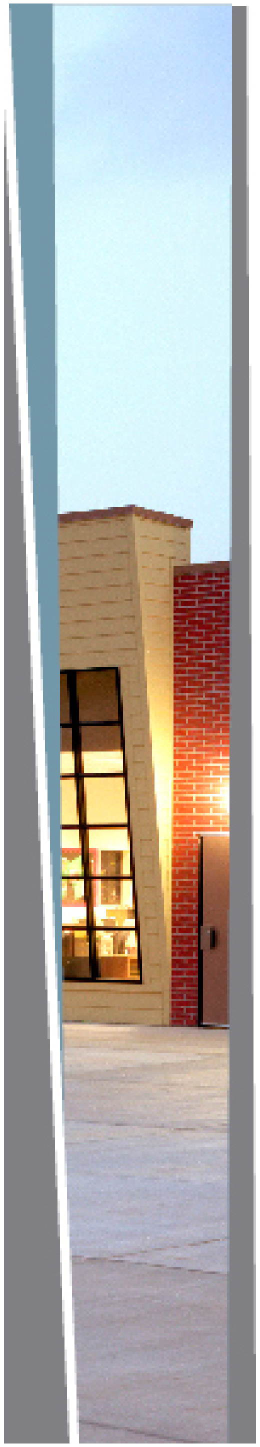


Degenkolb

Database Queries - Drift



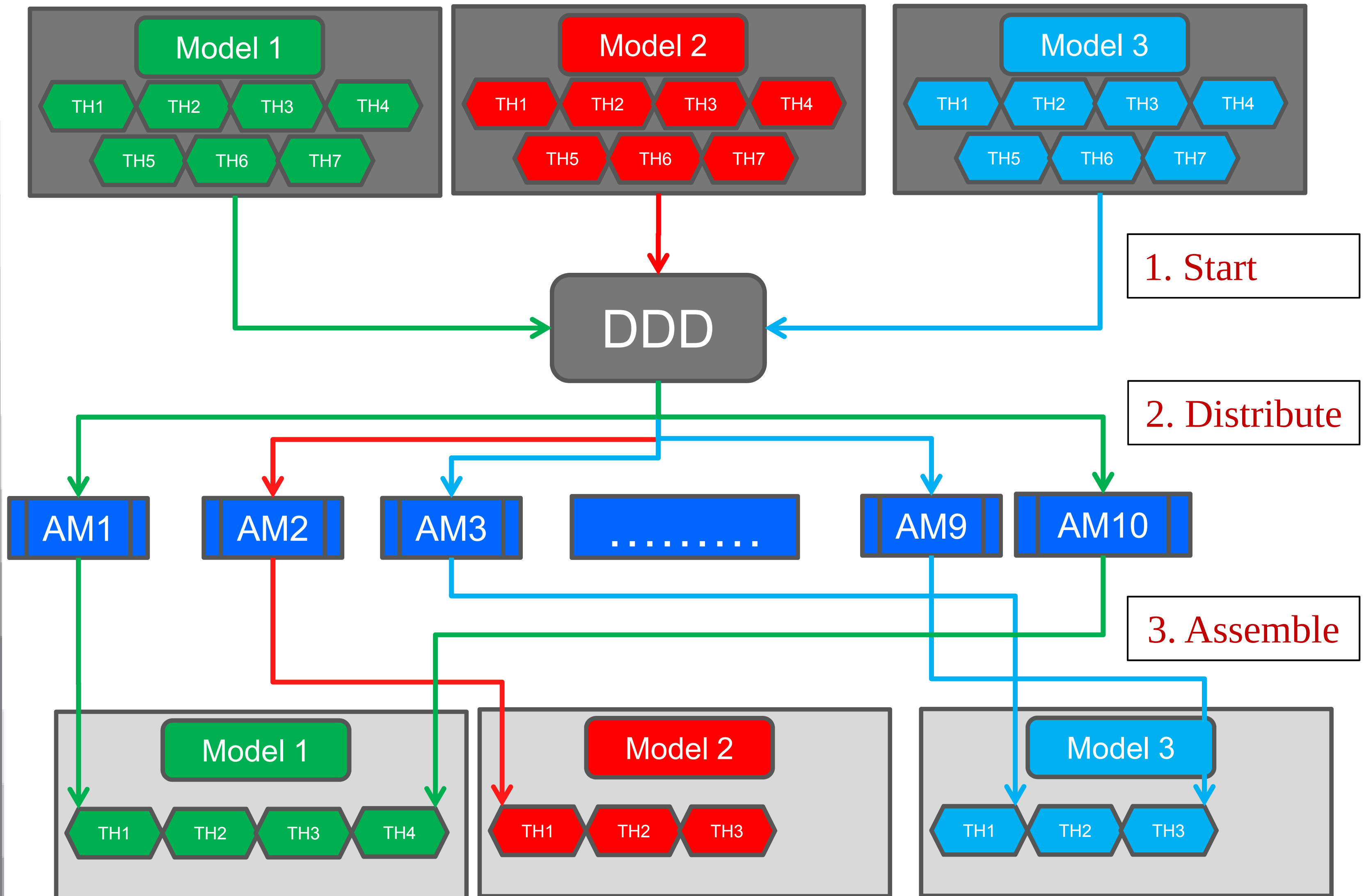
Degenkolb



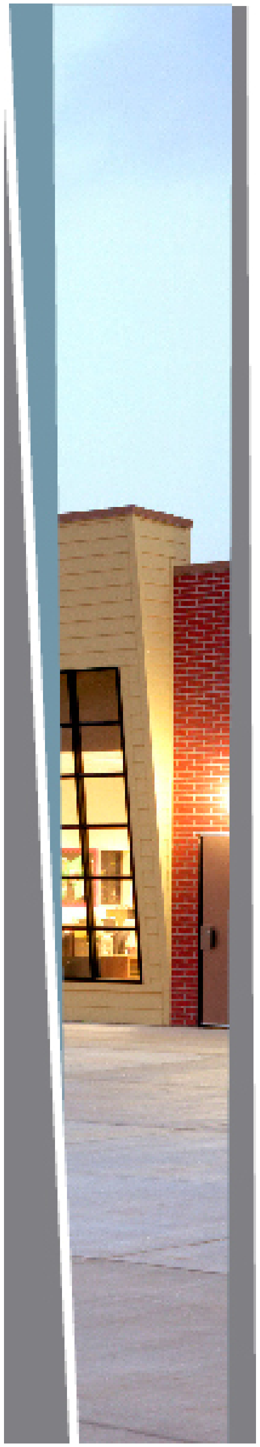
Model Management

- Why the need?
  - Quality Control - Repetitive tasks invite human error
  - Speed
- Software to automate the multi-machine analysis
  - Calls on multiple models
  - Distribute models to available Virtual Analysis Machines.
  - Database can query across results from different models to assemble (envelope/average) results as required.

Analysis Management/Automation



Degenkolb



Model Management

- Model Exchange Tool
  - Intermediate repository of structural model information
  - Allows the conversion of model data from one finite element software to another.
  - Should be able to convert to and from several applications including
    - ETABS,
    - SAP2000,
    - Perform3D,
    - OpenSees,
    - and BIM…

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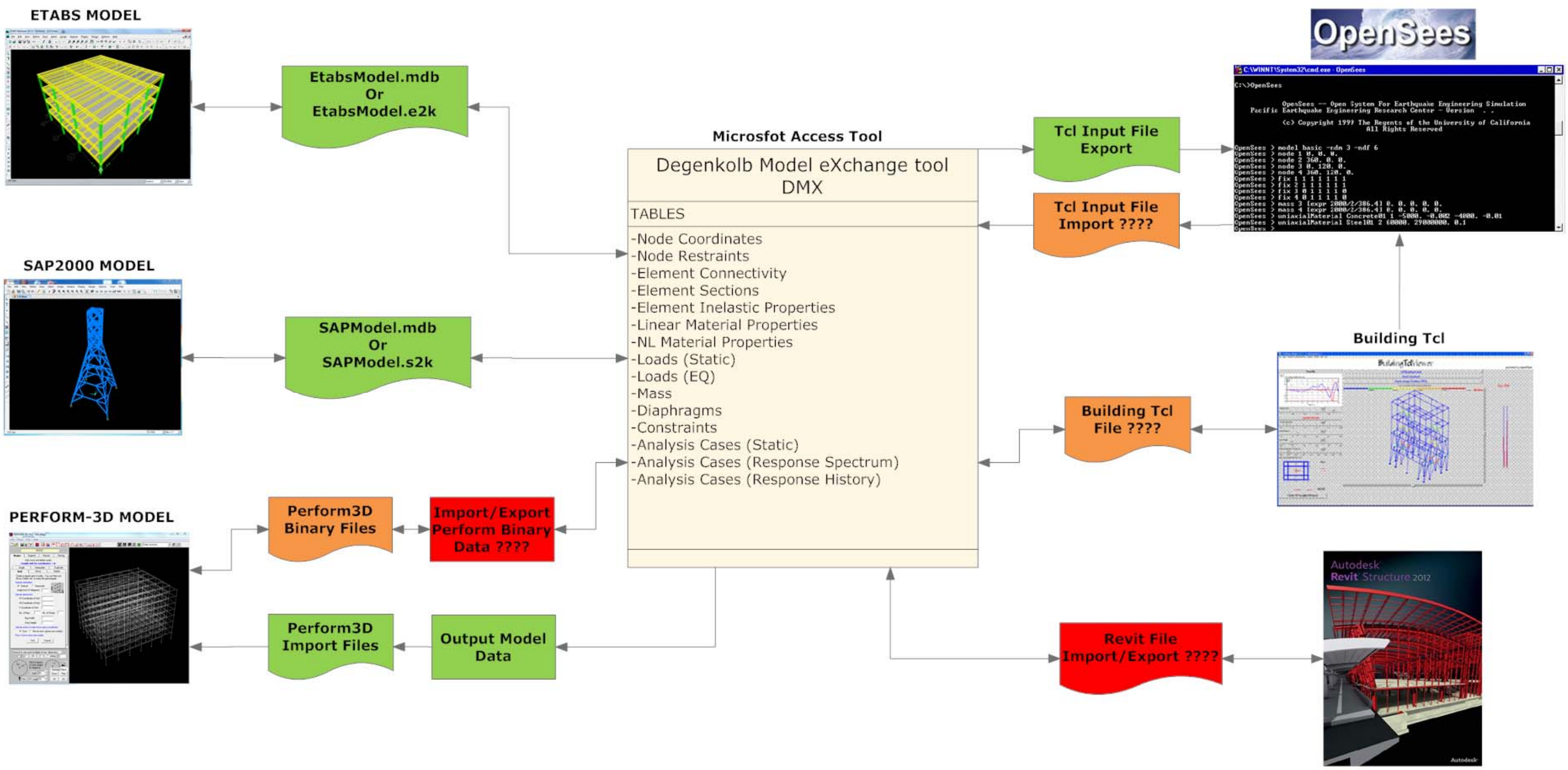
Model Management



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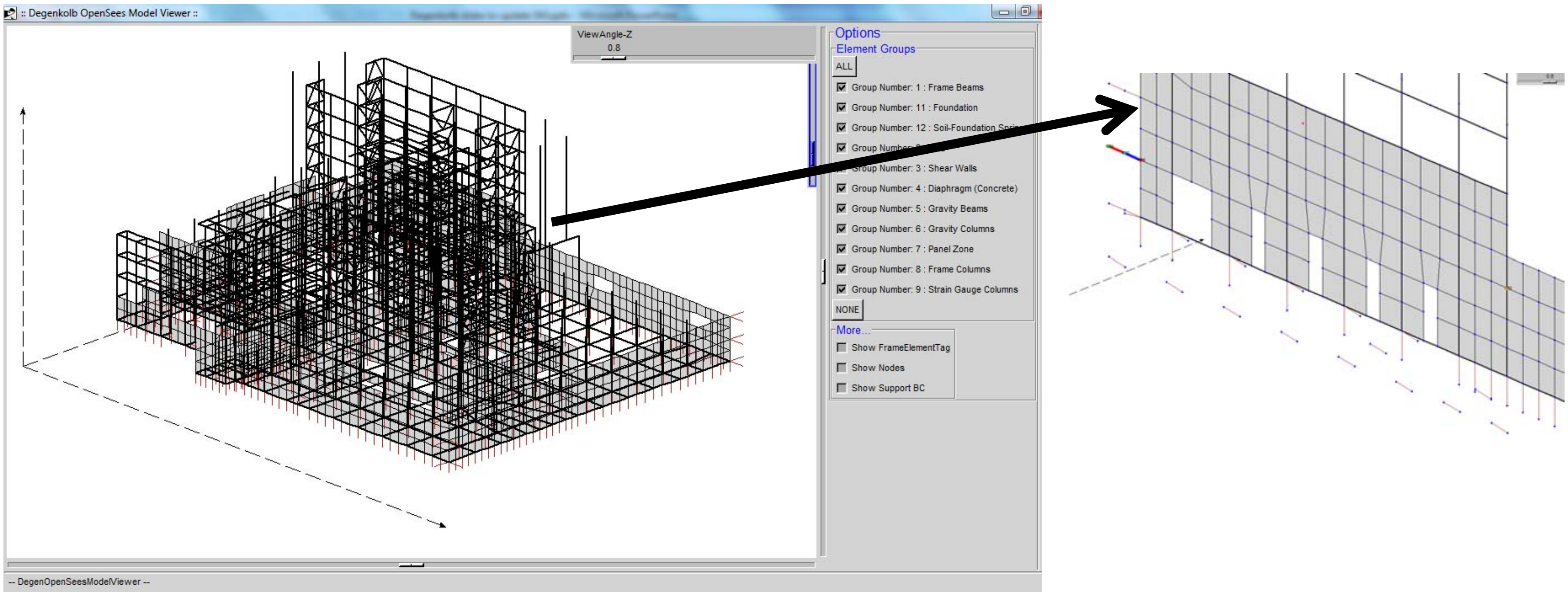
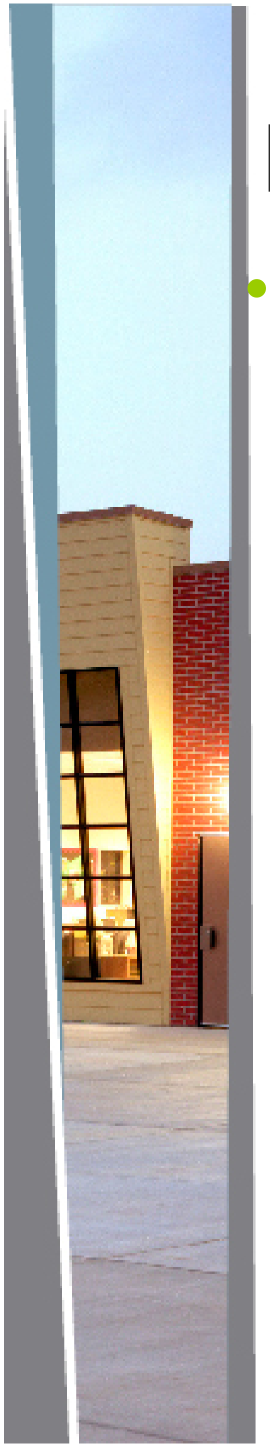
OpenSees Modeling Capability



Research Involvement:

- Next generation structural analysis software
- Past involvement with OpenSees Development Team
- Close collaboration with researchers



Model Conversion

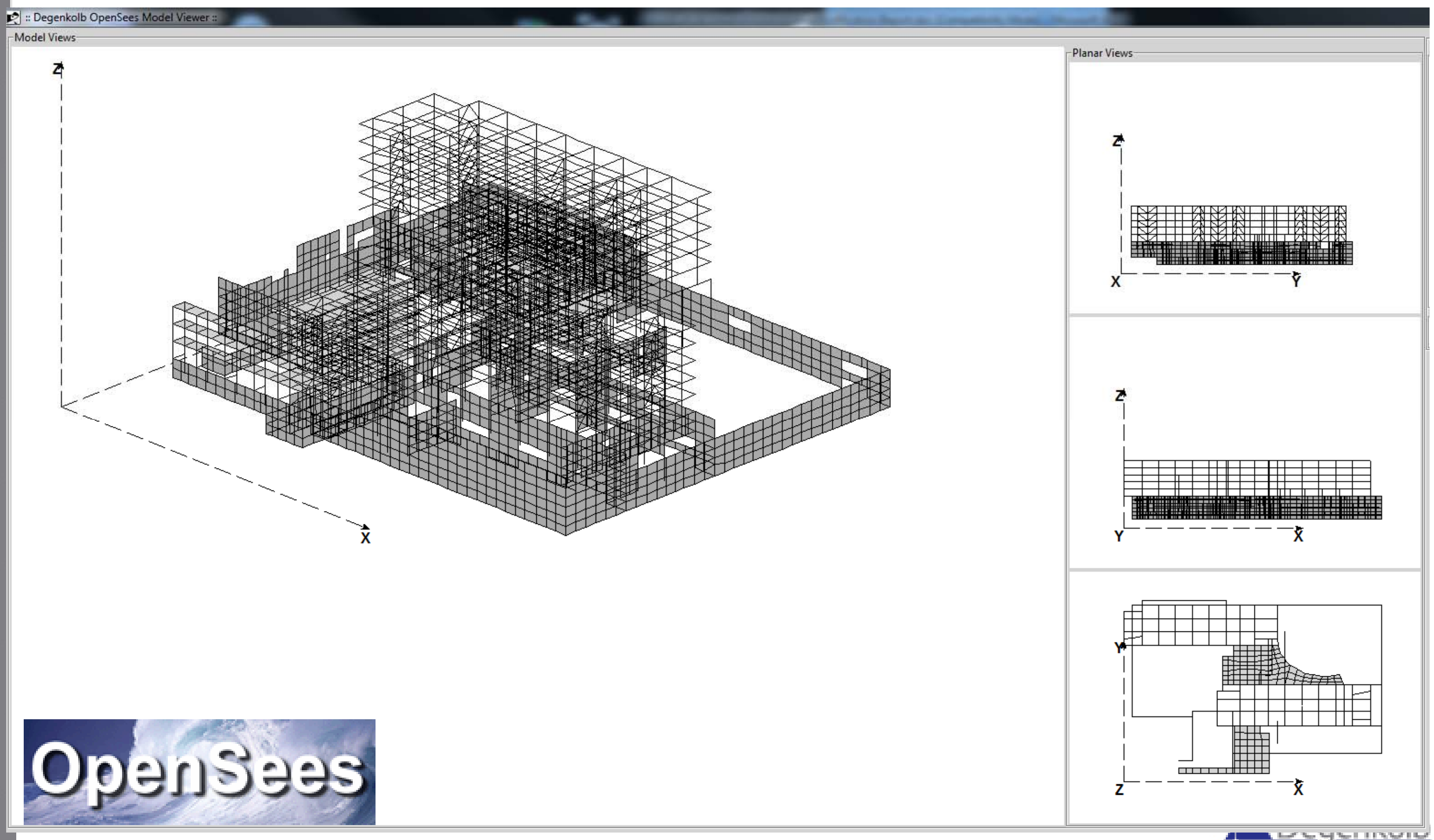
- Automated extraction of Perform Model into OpenSees

```
set thisDataList $HeaderStartList
set GroupData ""
for {set LineCounter 1} {$LineCounter<[expr $NskipStart-4]} {incr LineCounter} {
   set thisLine [lindex $thisDataList $LineCounter]
   if {[llength $thisLine]>0} {
      lappend GroupData $thisLine
   }
}; # end for LineCounter
set NMaxLines [expr [llength $thisDataList] -1];     # the -1 is to remove the last blank line
set ElementInputList ""
for {set LineCounter $NskipStart} {$LineCounter<$NMaxLines} {incr LineCounter $NlinesPerElt} {
   set ElemTag [lindex [lindex $thisDataList $LineCounter] 0]
   set thisEltData ""
   for {set ii 1} {$ii<=$NlinesPerElt} {incr ii} {
      set thisLine [lindex $thisDataList [expr $LineCounter+$ii-1]]
      if {$ElementType=="FRAM" && $ii==1} {
         set elt7 [lindex $thisLine 7]
         if {[catch {set tt [expr 3.*$elt7]}]!=1} {
            set thisLine [linsert $thisLine 7 Null]
            set thisLine [linsert $thisLine 7 Null]
         }
         set elt8 [lindex $thisLine 8]
         if {[catch {set tt [expr 3.*$elt8]}]!=1} {
            set thisLine [linsert $thisLine 8 Null]
         }
      }
      lappend thisEltData $thisLine
   }; # end for ii
```

Degenkolb

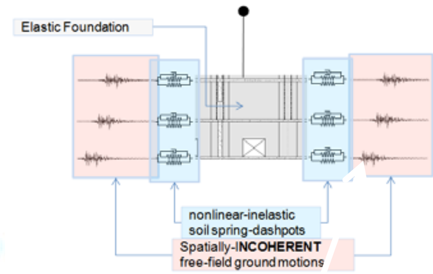
OpenSees Model

- Apply multi-support excitation with spatial variation of ground motion



Frequency Dependent Windowing: A Non-Stationary Method for Simulating Spatially Variable Earthquake Ground Motions

Timothy D. Ancheta,[a)] Jonathan P. Stewart,[b)] and Norman A. Abrahamson,[c)]



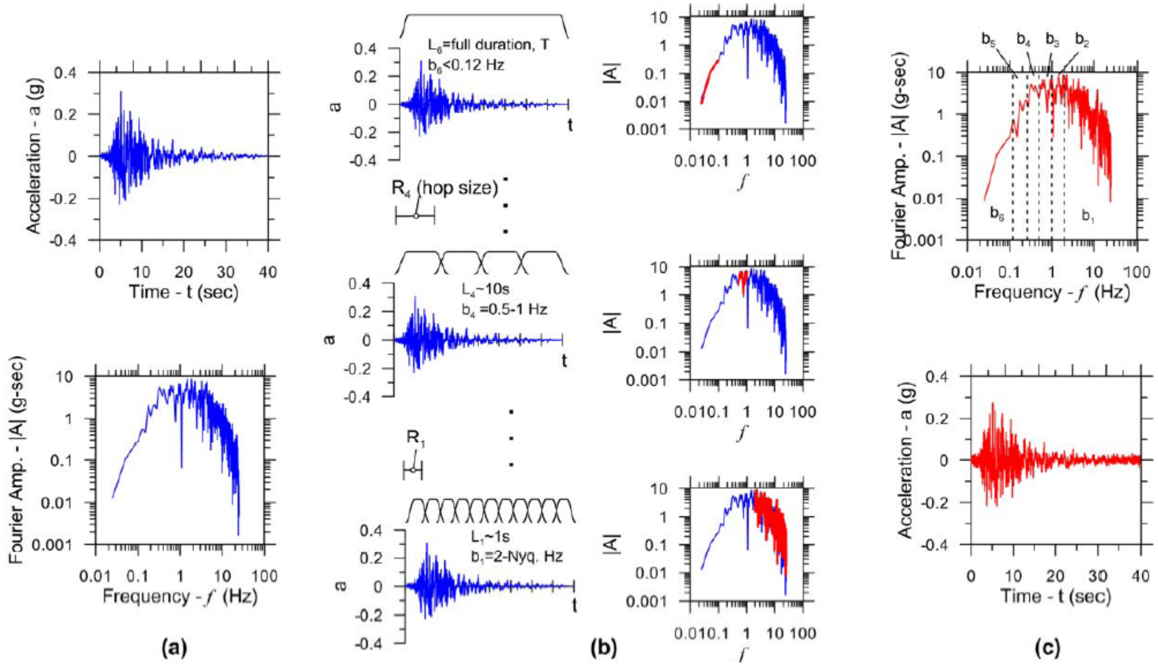


Figure 5. Schematic of the multiple short-time window simulation procedure in Abrahamson (1992b, 1993). (a) seed ground motion and its Fourier amplitude spectrum; (b) six series of multiple time segments and their corresponding frequency modifications shown in red; (c) recombined modified Fourier spectra and inversed simulated time series

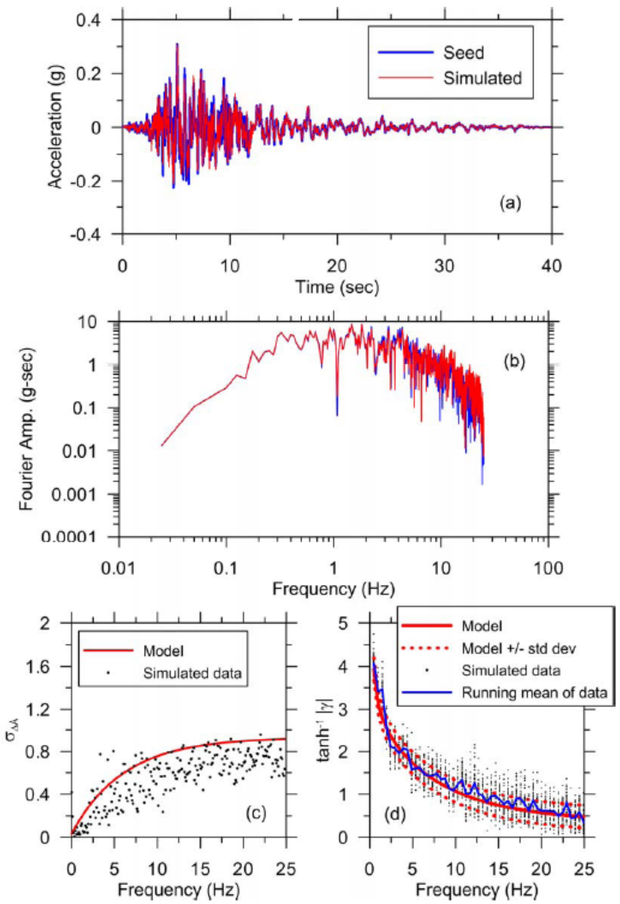


Figure 13. Evaluation of simulated motions developed using final FDW simulation procedure. (a) seed and simulated time series; (b) seed and simulated Fourier amplitude spectra; (c) comparison of $\sigma_{\Delta A}$ calculated from 40 realizations and model; (d) comparison of $|\gamma|$ calculated from realizations and model.

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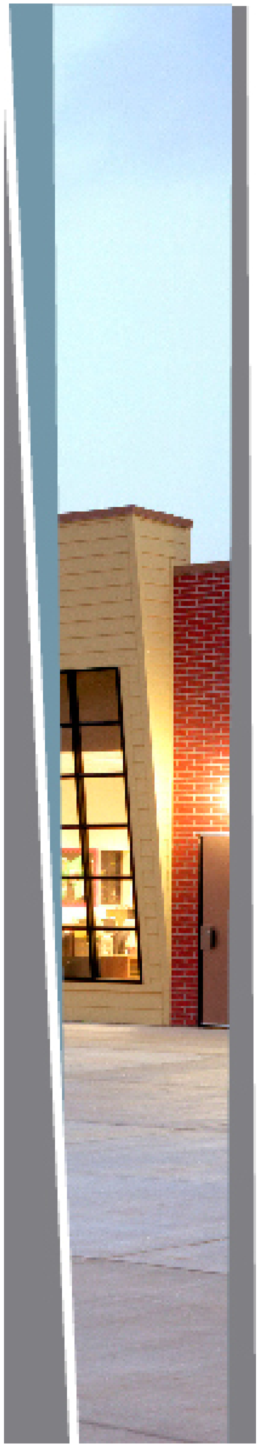


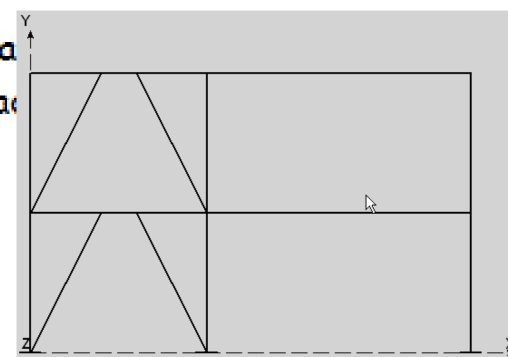
Continued Improvement of BuildingTcl & BuildingTclViewer

BuildingTcl

Degenkolb

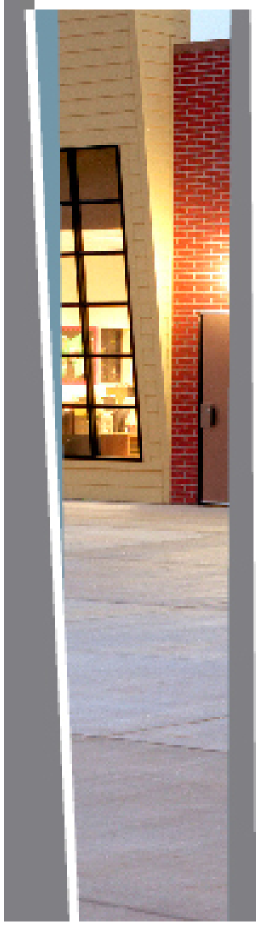
Model Input -- elevation

```
addModelData ModelLabel RCTestFrame2Story2BayBbraced
addModelData ModelDescription "RC MRF, 2-Story, 2-Bay"
addModelData ModelTypeLabel Elevation
addModelData -Geometry Height 16*\$ft StoryRange "1 2"
addModelData -Geometry Width 20*\$ft Bay 1
addModelData -Geometry Width 30*\$ft Bay 2
addModelData -Columns  SectionLabel ColumnSection ColumnLineRange "1 3" StoryRange "1 2" Orient Rotated
addModelData -Beams  SectionLabel ColumnSection BayRange "1 2" FloorRange "2 3"
addModelData -ChevronBraces SectionLabel W12x16 BayRange "1 1" Story "1 2"  Eccentricity 4.*\$ft
addModelData SupportBC fix
addModelData OutOfPlaneSupportBC fix
addModelData RigidFloor Off
addModelData JointOffsetsSwitch on
addModelData TributaryWidth 5.*\$ft
addModelData -GravityLoad LoadLabel DL1  FloorRange "2 3" DistributedLoa
addModelData -GravityLoad LoadLabel LL1  FloorRange "2 3" DistributedLoad
addModel
```



RC Sections

```
addSectionData SectionLabel Beamtomodelfoundation;
addSectionData SectionModelLabel RectangularElastic;
addSectionData E 3600e6*\$ksi
addSectionData B 600*\$in
addSectionData H 480*\$in
```



```
# ELEMENT SECTION ------------------------------------------
addSectionData SectionLabel 30x30RCRectFiber
addSectionData SectionDescription "Square Rectangular RC Section"
addSectionData SectionModelLabel RCRectFiber;
addSectionData H 30*$in;
addSectionData B 30*$in;
addSectionData NBarBot 6;                 # number of bottom longitud
addSectionData NBarTop 6;                 # number of top longitudinal
addSectionData NBarInt 6;                 # total number of intermedic
addSectionData BarSizeBot #9;
addSectionData BarSizeTop #9;
addSectionData BarSizeInt #9;
addSectionData CoverBot 2.6*$in;
addSectionData CoverTop 2.6*$in;
addSectionData CoverInt 2.6*$in;
addSectionData CoreMaterialLabel 4ksiConfinedConcrete;
addSectionData CoverMaterialLabel 4ksiUnconfinedConcrete;
addSectionData ReinforcementMaterialLabel 60ksiReinforcingSteel;
addSection
```

Lateral Loads

```
addLoadData LoadLabel StaticPushover;
addLoadData LoadTypeLabel LateralPushover;
addLoadData DMax 1*\$in;
addLoadData ControlNodeFloor top;
addLoad
```

```
addLoadData LoadLabel EQ2D;
addLoadData LoadTypeLabel UniformEQ2D;
addLoadData GMfactor \$g;
addLoadData GMdirectory "GMfiles";
addLoadData FileType "PEER";
addLoadData GMfilenameX "H-E01140.AT2";
addLoadData GMscaleX 1.;
addLoadData GMfilenameZ "H-E12140.AT2";
addLoadData GMscaleZ 1.;
addLoad
```

```
addLoadData LoadLabel EQ;
addLoadData LoadTypeLabel UniformEQ;
addLoadData GMfactor \$g;
addLoadData GMdirectory "GMfiles";
addLoadData FileType "PEER";
addLoadData GMfilename "H-E12140.at2";
addLoadData GMdirection X;
addLoadData GMscale 1.;
addLoad
```

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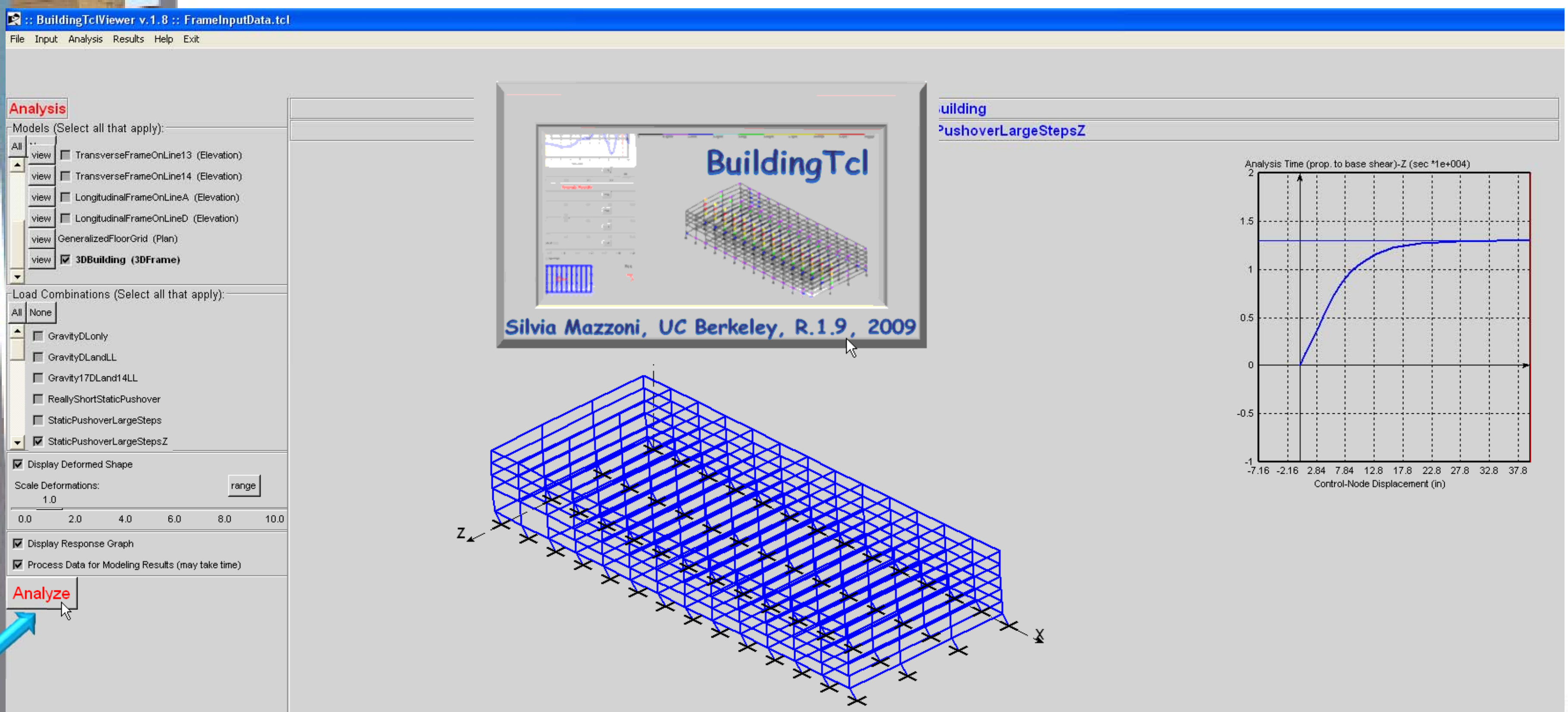
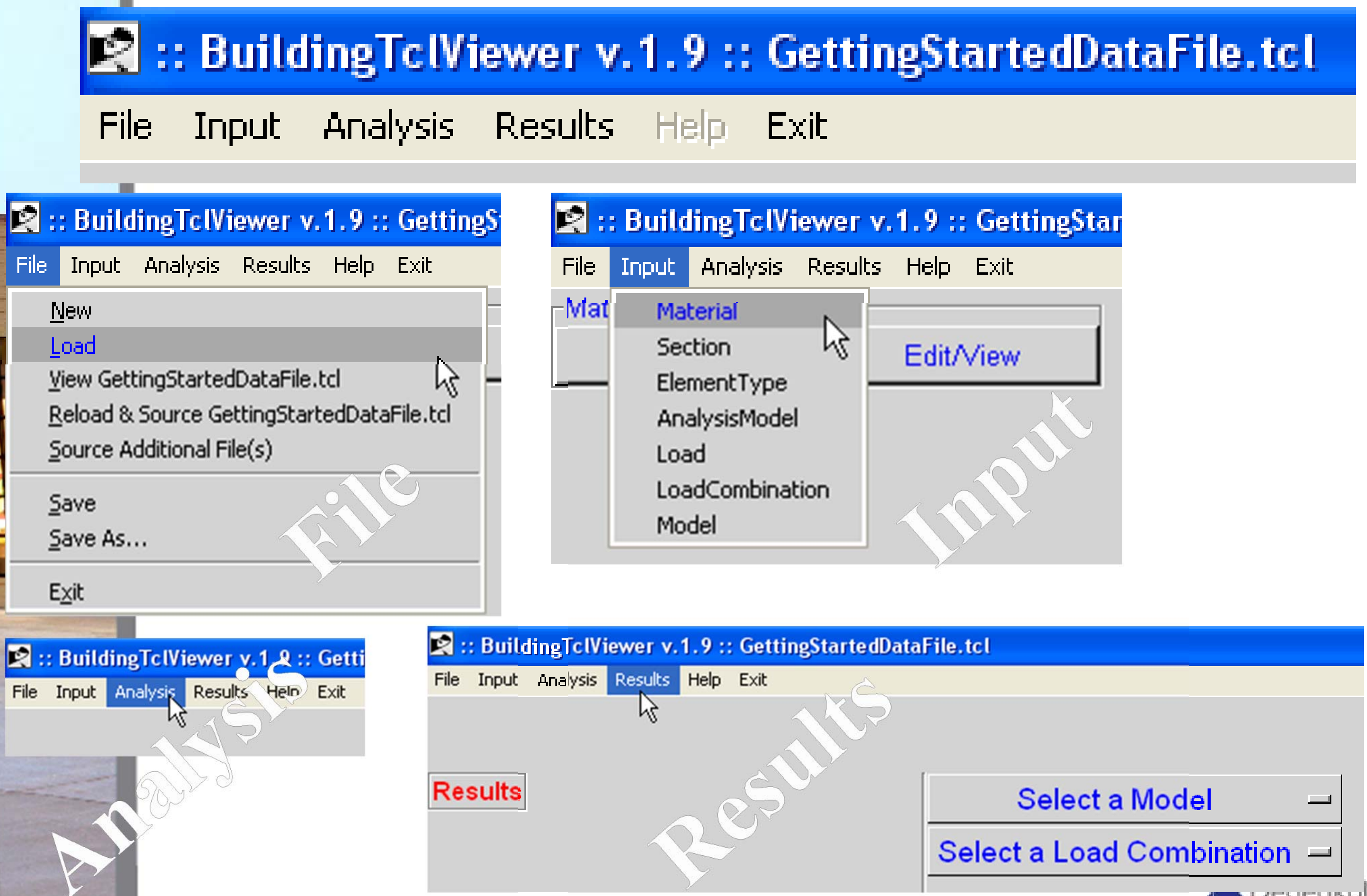
BuildingTclViewer

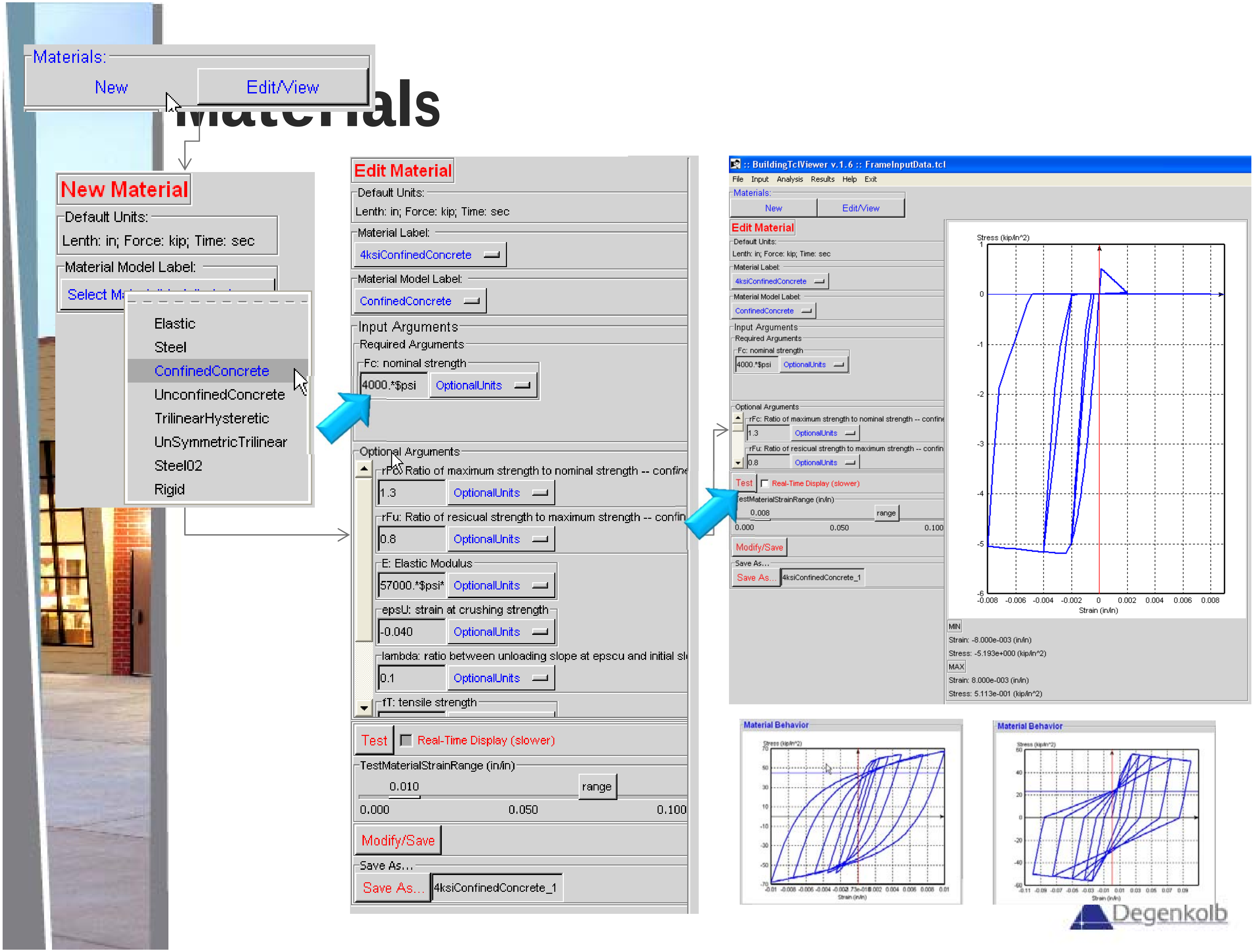
- Pr
- Pr
- Vi
- Sa



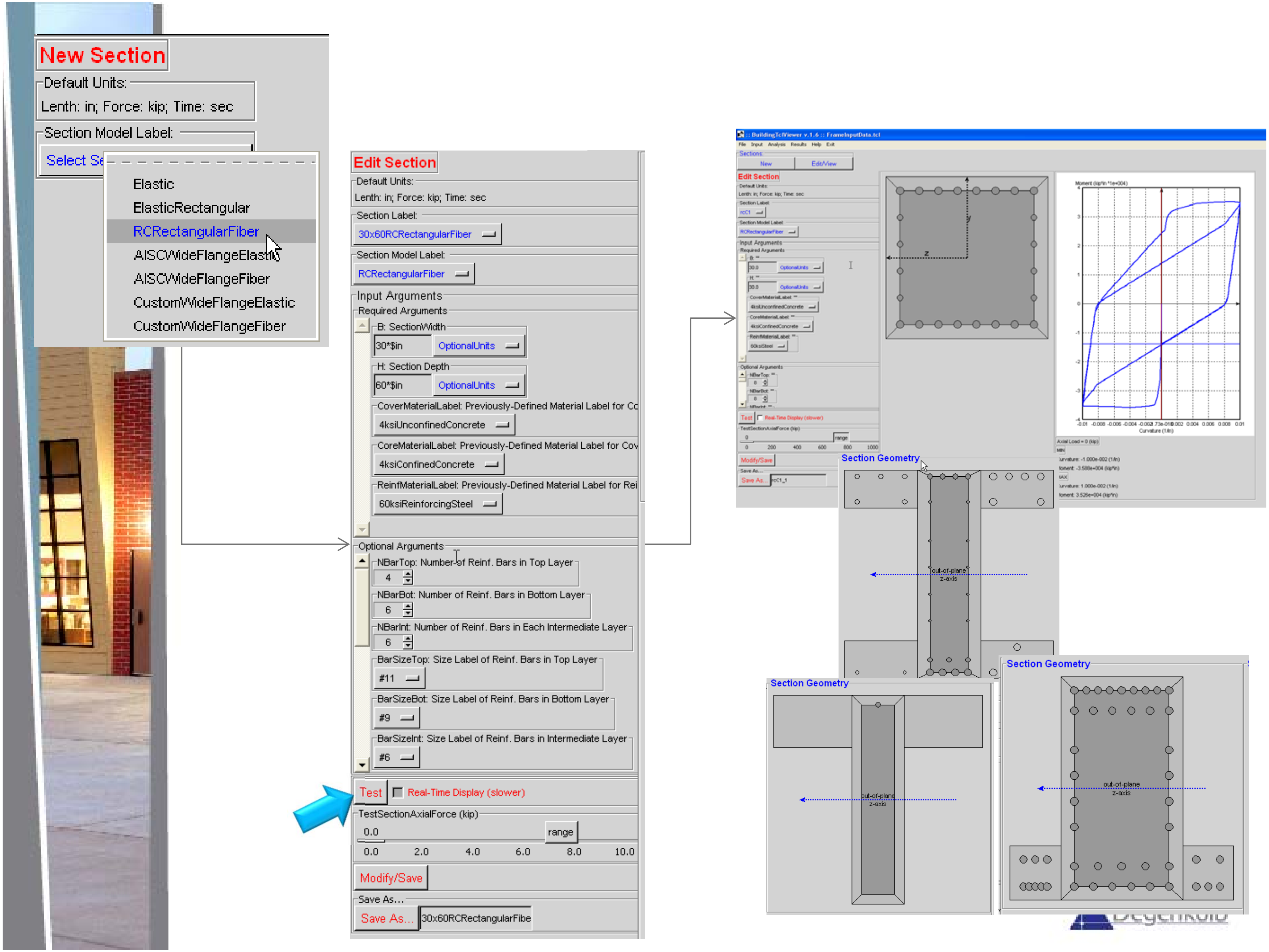
Menus


:: BuildingTclViewer v.1.9 :: GettingStartedDataFile.tcl
File Input Analysis Results Help Exit
New
Load
View GettingStartedDataFile.tcl
Reload & Source GettingStartedDataFile.tcl
Source Additional File(s)
Save
Save As...
Exit
File
Material
Section
ElementType
AnalysisModel
Load
LoadCombination
Model
Edit/View
Input
Analysis
Results
Select a Model
Select a Load Combination
Results

Materials

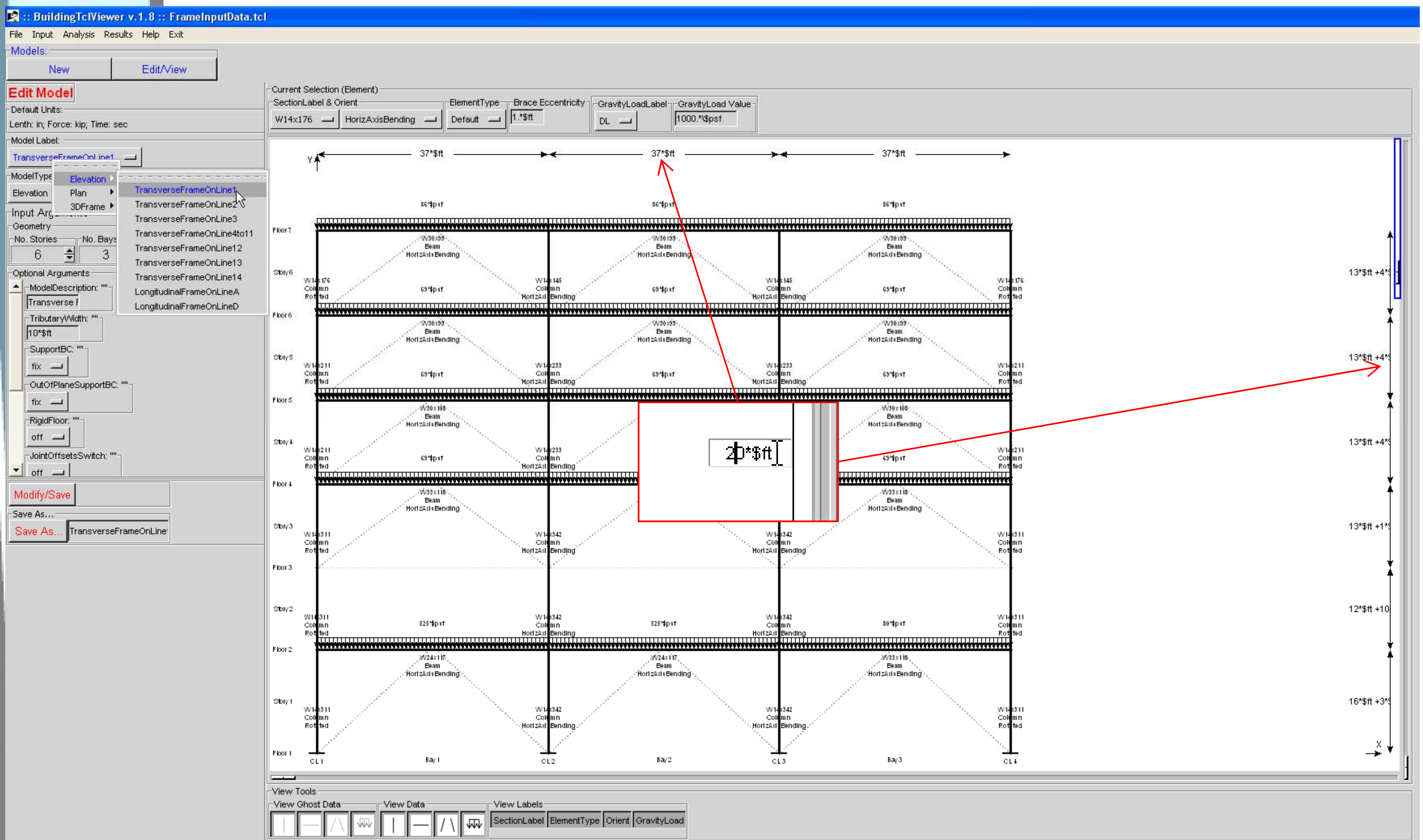


Materials:
New
Edit/View
New Material
Default Units:
Lenth: in; Force: kip; Time: sec
Material Model Label:
Elastic
Steel
ConfinedConcrete
UnconfinedConcrete
TrilinearHysteretic
UnSymmetricTrilinear
Steel02
Rigid
Edit Material
Default Units:
Lenth: in; Force: kip; Time: sec
Material Label:
4ksiConfinedConcrete
Material Model Label:
ConfinedConcrete
Input Arguments
Required Arguments
Fc: nominal strength
4000.*$psi
OptionalUnits
Optional Arguments
rFc: Ratio of maximum strength to nominal strength -- confine
1.3
rFu: Ratio of resicual strength to maximum strength -- confin
0.8
E: Elastic Modulus
57000.*$psi*
epsU: strain at crushing strength
-0.040
lambda: ratio between unloading slope at epscu and initial sl
0.1
fT: tensile strength
Test
Real-Time Display (slower)
TestMaterialStrainRange (in/in)
0.010
range
0.000
0.050
0.100
Modify/Save
Save As...
4ksiConfinedConcrete_1
:: BuildingTclViewer v.1.6 :: FrameInputData.tcl
File Input Analysis Results Help Exit
Stress (kip/in^2)
Strain (in/in)
MIN
Strain: -8.000e-003 (in/in)
Stress: -5.193e+000 (kip/in^2)
MAX
Strain: 8.000e-003 (in/in)
Stress: 5.113e-001 (kip/in^2)
Material Behavior
Material Behavior
Degenkolb



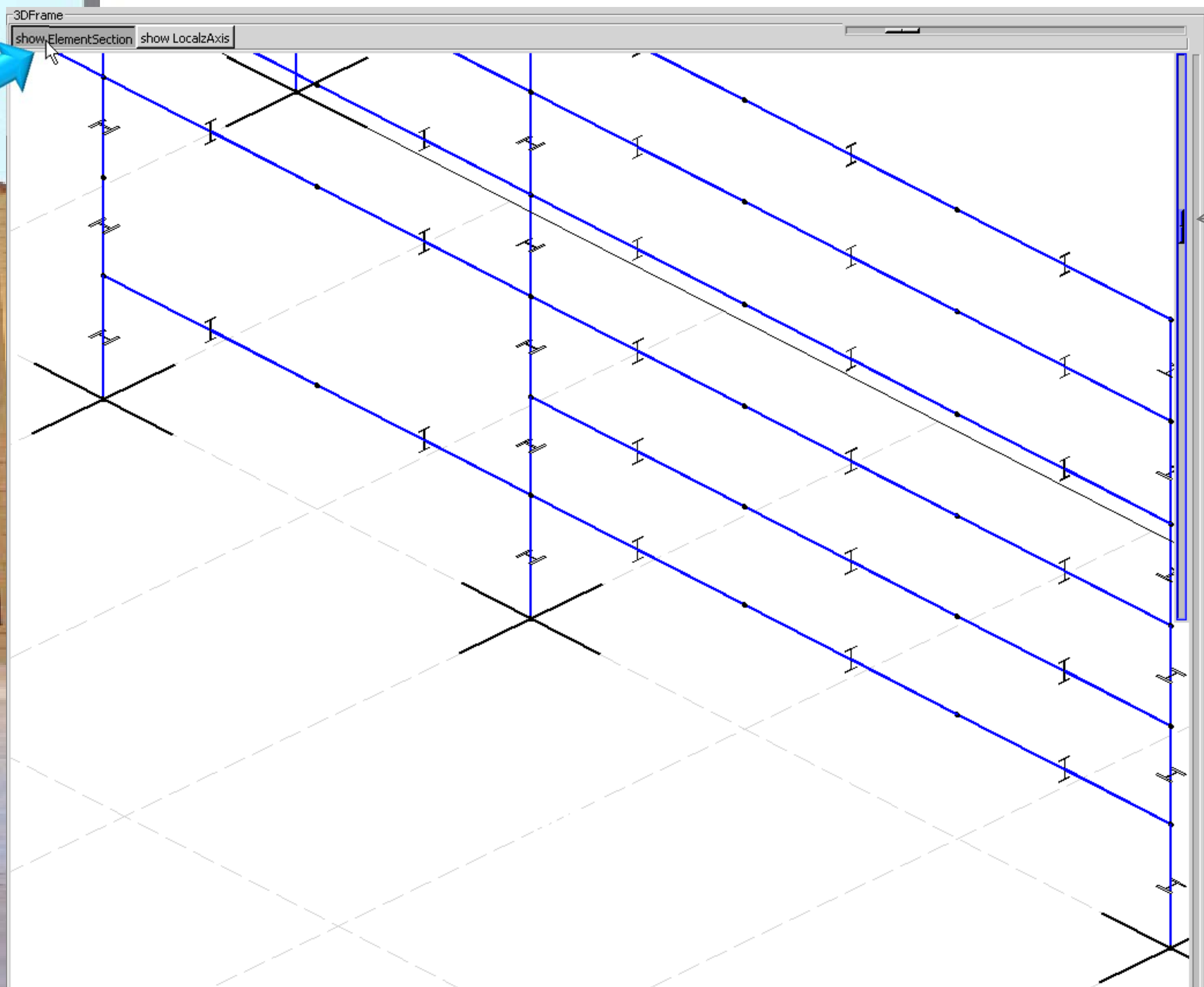
New Section
Default Units:
Lenth: in; Force: kip; Time: sec
Section Model Label:
Elastic
ElasticRectangular
RCRectangularFiber
AISCWideFlangeElastic
AISCWideFlangeFiber
CustomWideFlangeElastic
CustomWideFlangeFiber
Edit Section
Default Units:
Lenth: in; Force: kip; Time: sec
Section Label:
30x60RCRectangularFiber
Section Model Label:
RCRectangularFiber
Input Arguments
Required Arguments
B: SectionWidth
30*$in
OptionalUnits
H: Section Depth
60*$in
OptionalUnits
CoverMaterialLabel: Previously-Defined Material Label for Co
4ksiUnconfinedConcrete
CoreMaterialLabel: Previously-Defined Material Label for Cov
4ksiConfinedConcrete
ReinfMaterialLabel: Previously-Defined Material Label for Rei
60ksiReinforcingSteel
Optional Arguments
NBarTop: Number of Reinf. Bars in Top Layer
4
NBarBot: Number of Reinf. Bars in Bottom Layer
6
NBarInt: Number of Reinf. Bars in Each Intermediate Layer
6
BarSizeTop: Size Label of Reinf. Bars in Top Layer
#11
BarSizeBot: Size Label of Reinf. Bars in Bottom Layer
#9
BarSizeInt: Size Label of Reinf. Bars in Intermediate Layer
#6
Test
Real-Time Display (slower)
TestSectionAxialForce (kip)
0.0
range
0.0 2.0 4.0 6.0 8.0 10.0
Modify/Save
Save As...
Save As...
30x60RCRectangularFibe
Section Geometry
out-of-plane
z-axis
Section Geometry
out-of-plane
z-axis
Section Geometry
out-of-plane
z-axis

Elevation-Model Input



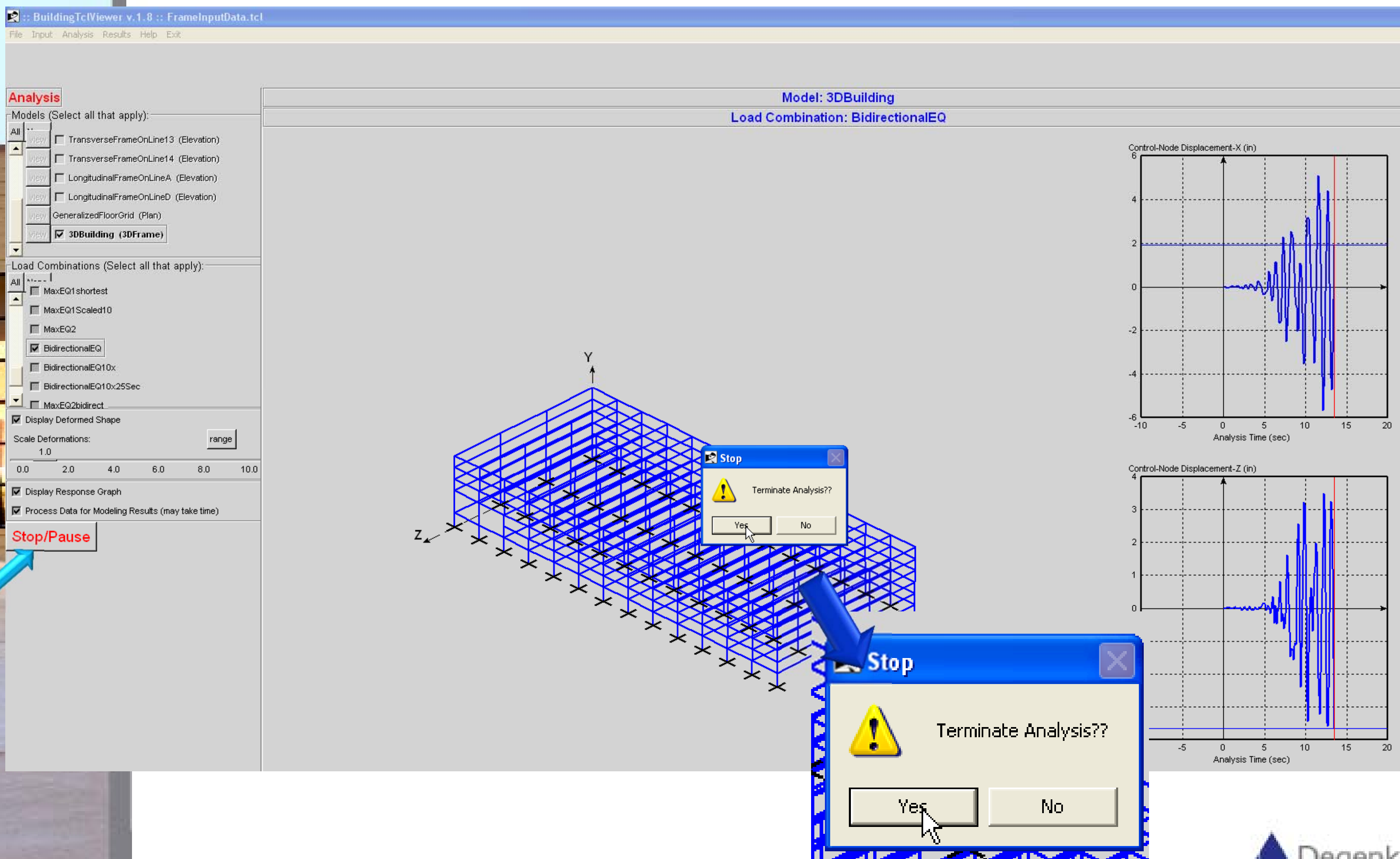
Degenkolb

3DFrame-Model Input
view Element Cross Sections



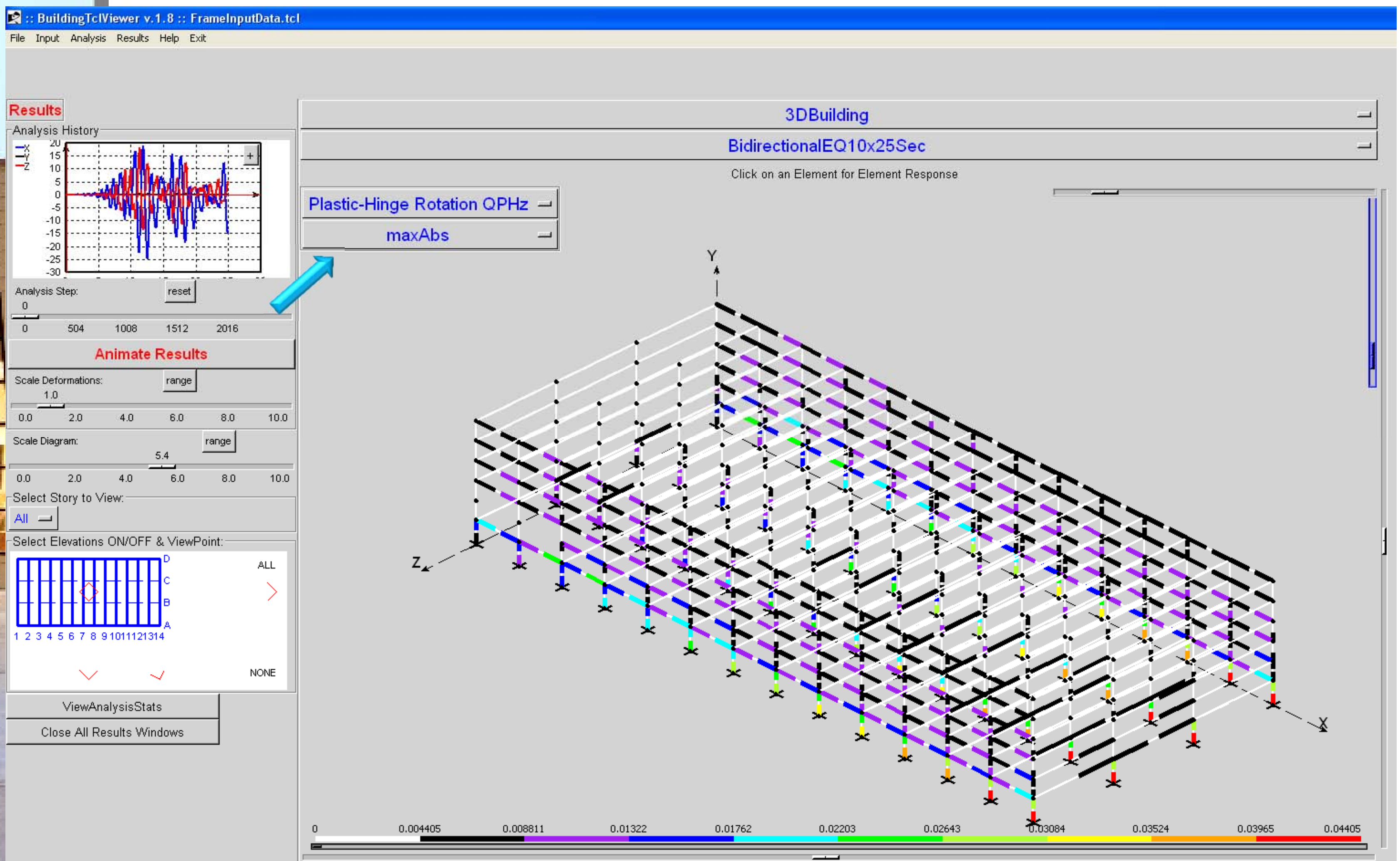
Degenkolb

Real-Time OpenSees Simulation
Real-Time Pause/Stop



Degenkolb

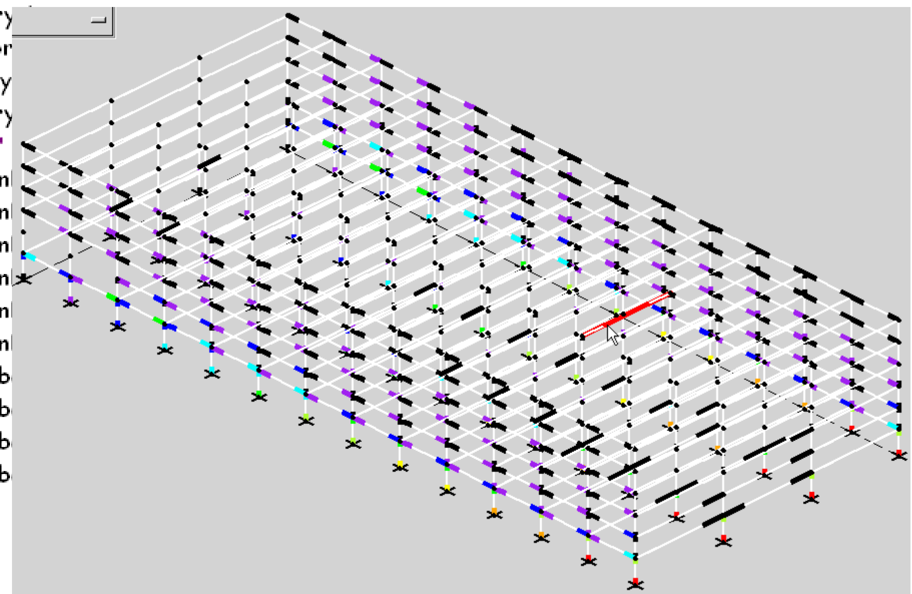
Visualization of Structural Response
envelope values



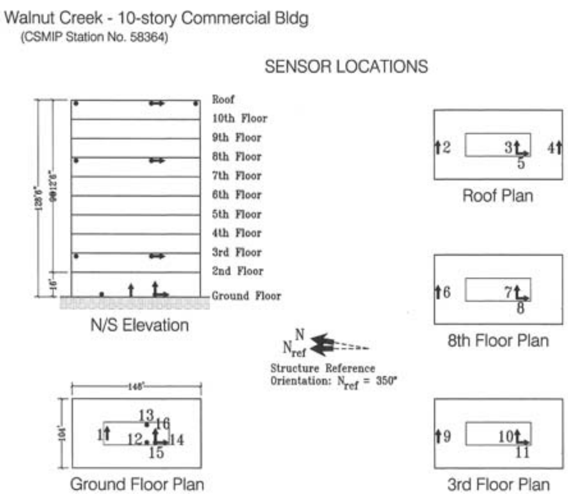
Degenkolb

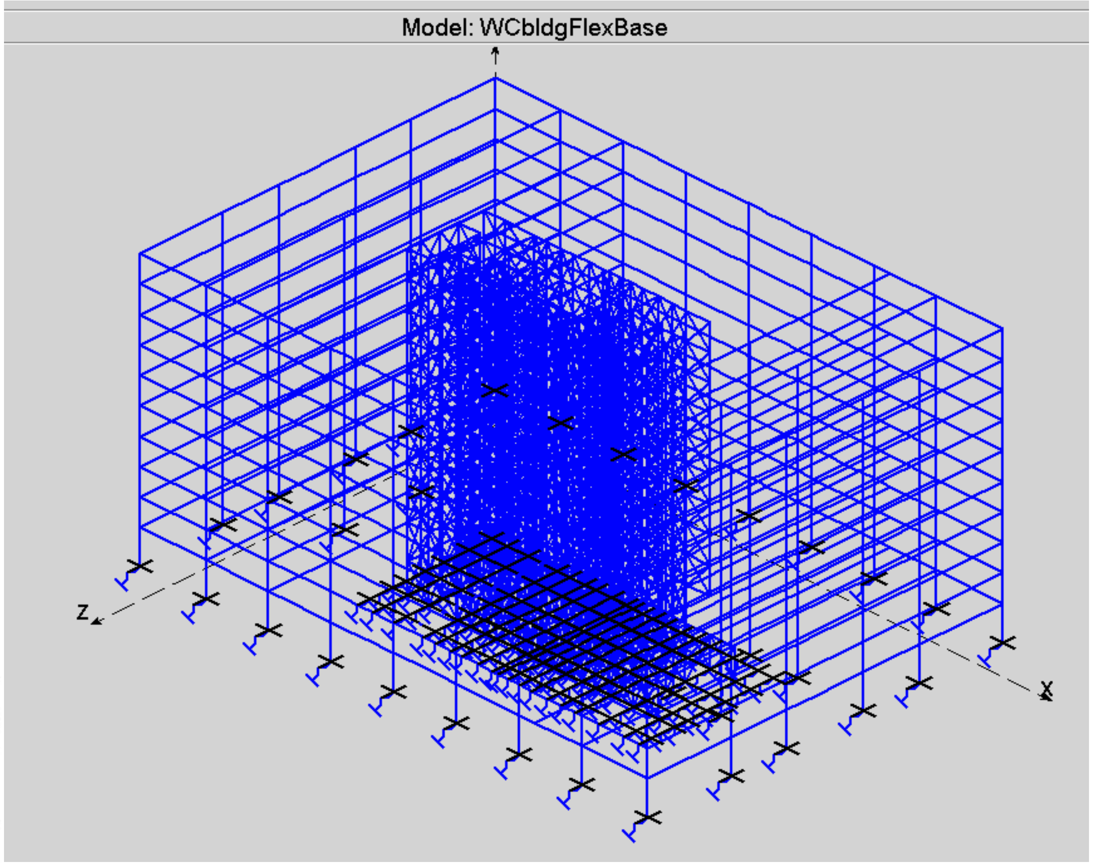
BuildingTcl combines the power of a scripting UI with a GUI

```
# MODELS --------------
addModelData ModelLabel TransverseFrameOnLine1
addModelData ModelDescription "Transverse Frame On Line 1"
addModelData ModelTypeLabel Elevation
addModelData -Geometry Height "16*\$ft +3*\$in" Story
addModelData -Geometry Height "12*\$ft +10*\$in" Stor
addModelData -Geometry Height "13*\$ft +1*\$in" Story
addModelData -Geometry Height "13*\$ft +4*\$in" Story
addModelData -Geometry Width 37*\$ft BayRange "1 3"
addModelData -Columns ElementTypeLabel Column Section
addModelData -Columns ElementTypeLabel Column Section
addModelData -Columns ElementTypeLabel Column Section
addModelData -Columns ElementTypeLabel Column Section
addModelData -Columns ElementTypeLabel Column Section
addModelData -Columns ElementTypeLabel Column Section
addModelData -Beams ElementTypeLabel Beam SectionLab
addModelData -Beams ElementTypeLabel Beam SectionLab
addModelData -Beams ElementTypeLabel Beam SectionLab
addModelData -Beams ElementTypeLabel Beam SectionLab
addModelData SupportBC fix
addModelData JointOffsetsSwitch off
addModelData TributaryWidth 10*\$ft
addModelData -GravityLoad LoadLabel DL Floor 2 Bay "1 2" DistributedLoad 525*\$psf
addModelData -GravityLoad LoadLabel DL Floor 2 Bay 3 DistributedLoad 80*\$psf
addModelData -GravityLoad LoadLabel DL FloorRange "4 6" BayRange "1 3" DistributedLoad 69*\$psf
addModelData -GravityLoad LoadLabel DL Floor 7 BayRange "1 3" DistributedLoad 86*\$psf
addModelData -GravityLoad LoadLabel LL Floor 2 Bay "1 2" DistributedLoad 30*\$psf
addModelData -GravityLoad LoadLabel LL Floor 2 Bay 3 DistributedLoad 80*\$psf
addModelData -GravityLoad LoadLabel LL FloorRange "4 6" BayRange "1 3" DistributedLoad 150*\$psf
addModelData -GravityLoad LoadLabel LL Floor 7 BayRange "1 3" DistributedLoad 20*\$psf
addModel
```



Soil-Structure Interaction: Base Rocking 10-story RC Frame





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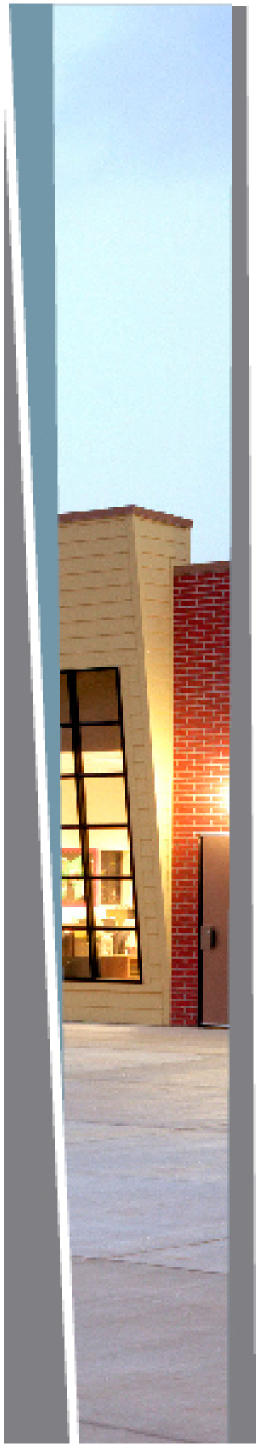
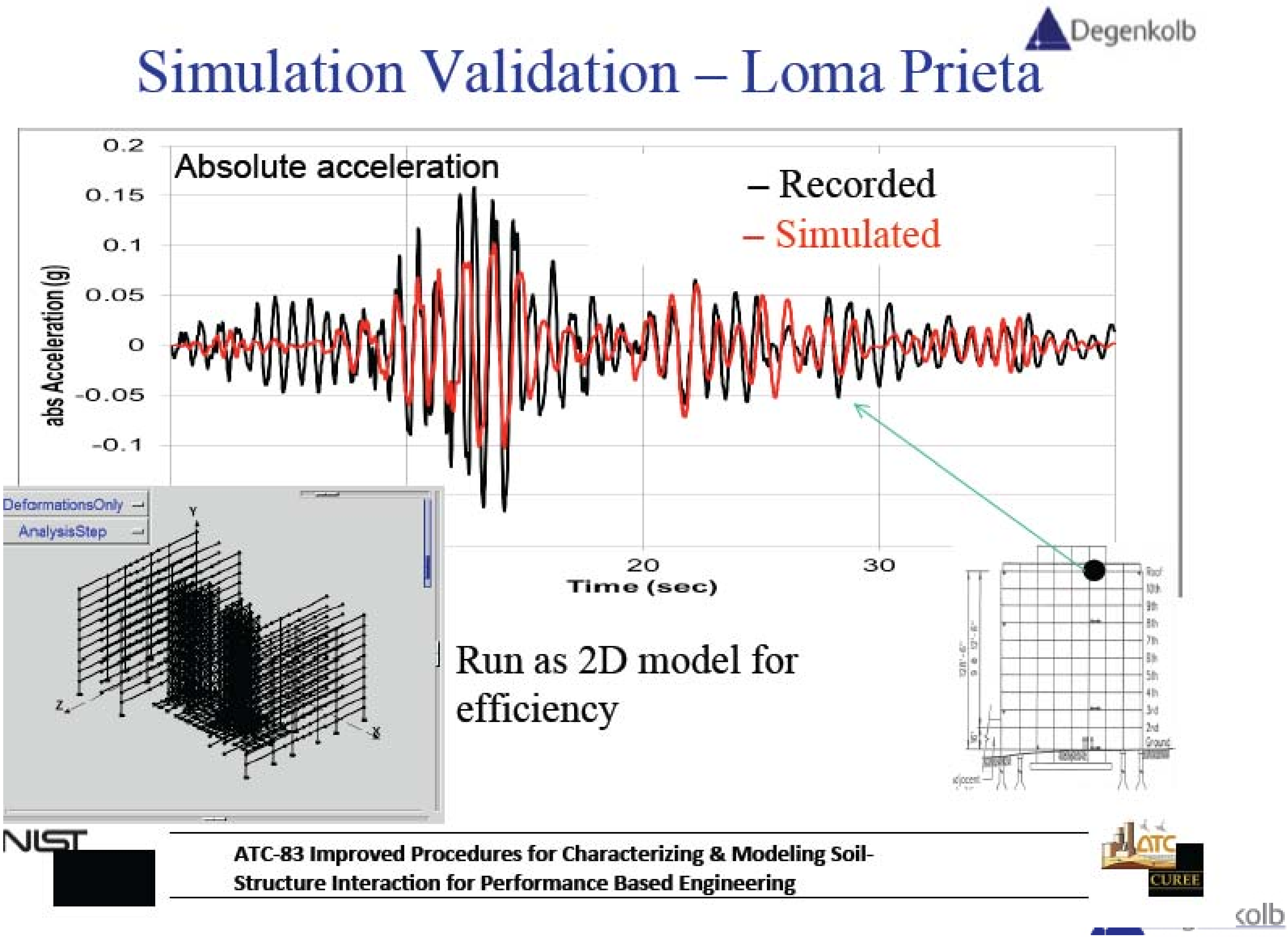
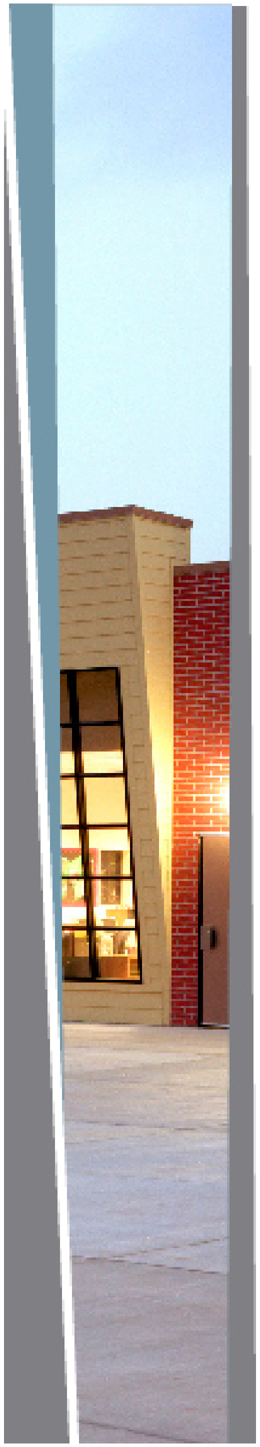


Model Validation

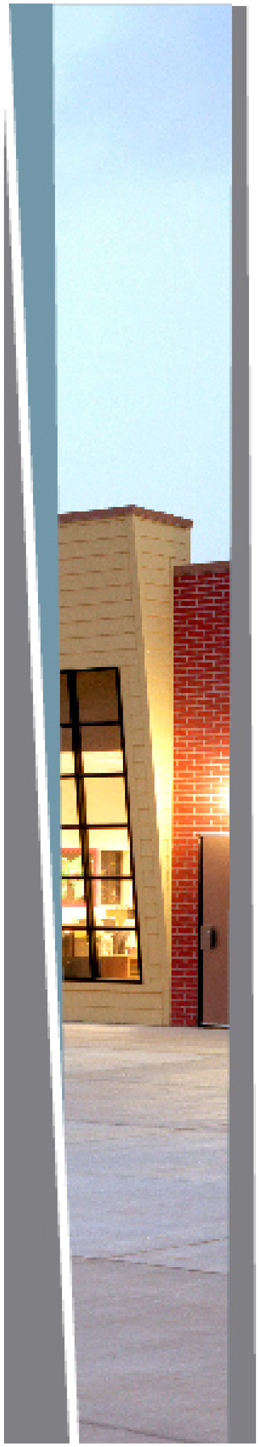




When to go to NLRHA?

- Confirm first that there is a point, and degree of potential advantage:
  - Is it required? e.g. Base Isolation
  - Is it going to produce a better answer?
  - Is it going to justify the increased cost?
  - Should we just fix the problem….?
- Better for some structural systems
  - Where R or m is much smaller than Δlimit / Δy
- When a ‘nonstructural’ project advantage exists (e.g. reduced disruption)

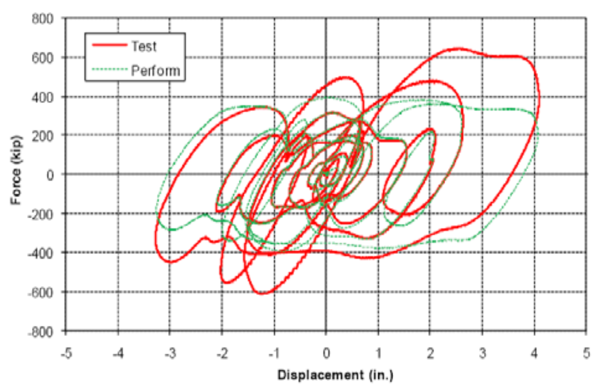
Degenkolb

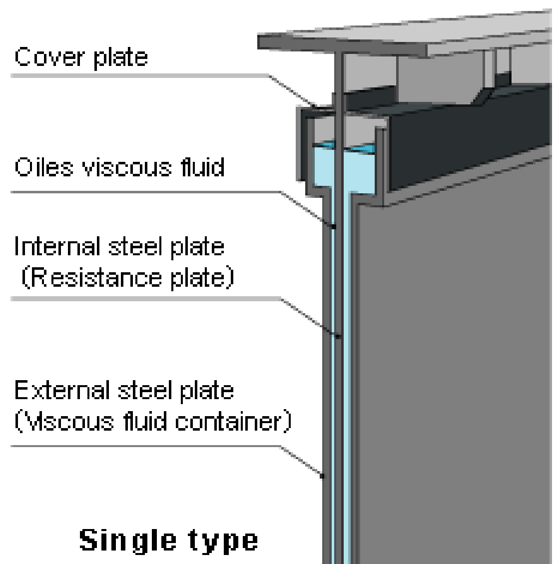


Comparison w/ Code-Based-Design

- Advantages
  - Allowable drift increase (1.25 factor)
  - Can achieve lower Ω_o Factor (1.5 vs. 2.5-3.0)
  - Advantage in ground motion scaling in far-field
  - When taking a code exception
  - Sometimes can use lower mass eccentricity
- Disadvantages
  - Code drifts computed using Cd = 0.7R
  - Podium structures, no easy two-stage analysis

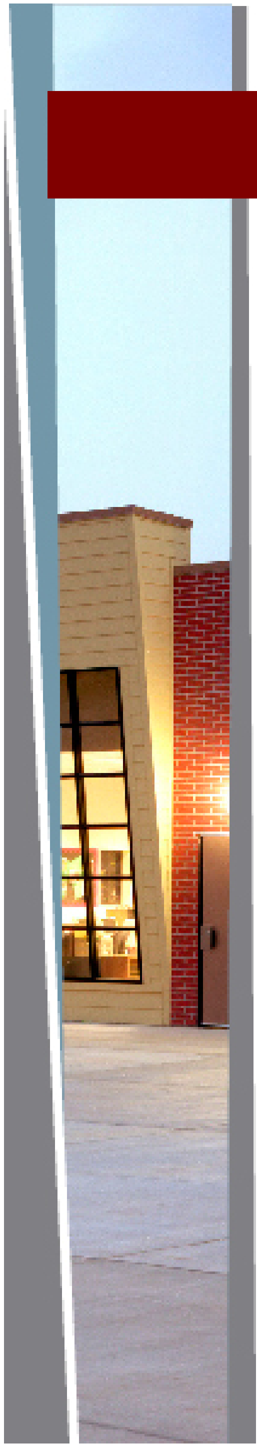
CPMC Cathedral Hill





Single type

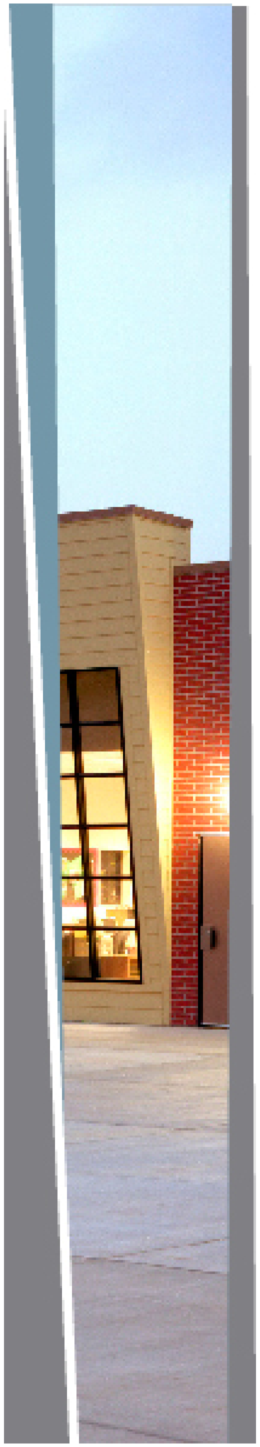
Degenkolb



CPMC Cathedral Hill - Scheme Comparison

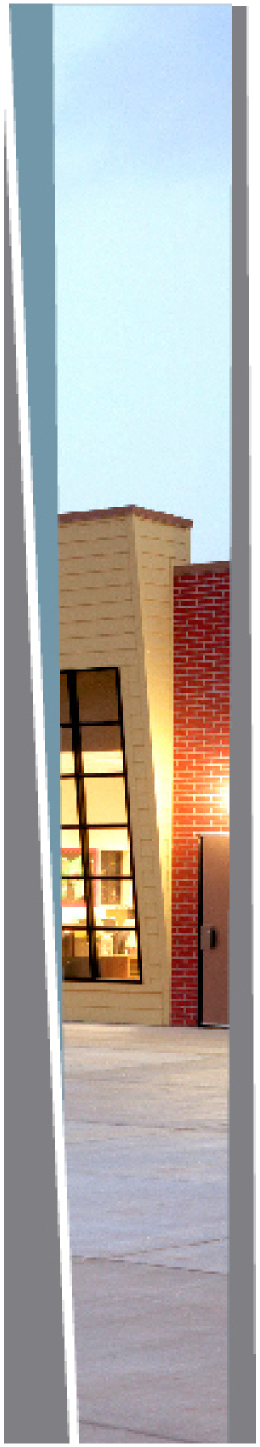
Structural System	Drift	Floor Accel.	Steel Wt. (psf)	Cost Index
Conventional SMRF	1.25%	1.0g -1.5g	36	1.0
Dual System - BRBF+SMRF	1.25%	1.5g -2.0g	27	0.8
Braced Frame with Isolation	0.7%	0.2g -0.3g	28	1.0
SMRF with Dampers	1.25%	0.5g -0.8g	20	0.7

Degenkolb



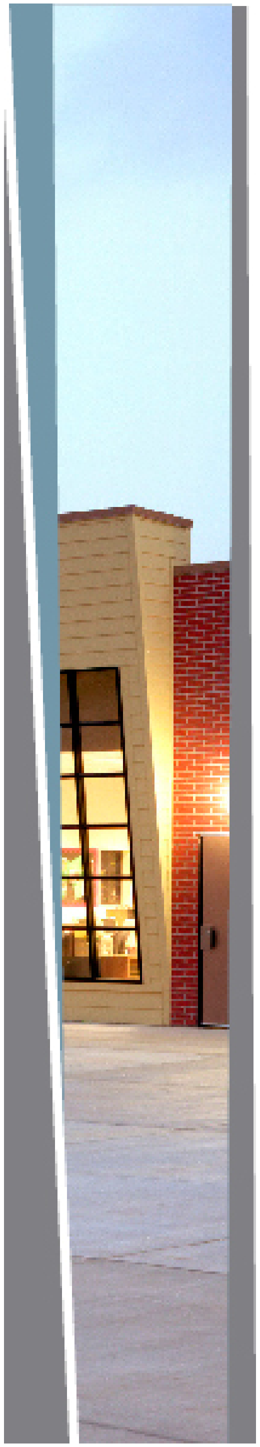
NLRHA: Design Requirements

- No current “code requirements”:
  - In development, BSSC Task Group
  - Usually means an AMoC or “Design Criteria”
  - Make it as brief as possible.
  - Reference other standards where possible, e.g. ASCE-41, Tall Buildings Initiative
  - Avoid finalizing it too early
- Understand review process
  - Local jurisdiction/reviewer experience
  - Consider impact of potential delays



NLRHA: Lessons Learned

- Allow extra time for learning process
  - Spend time with the model, run nightly
- Concrete is much harder than steel
  - Especially at large deformations, e.g. for retrofit, or in podium structures.
- Viscous damping assumptions are important
- Accidental mass eccentricity assumptions are important
- Don’t overstate savings in the beginning
- Can work well IPD and DB environment



NLRHA Future Directions

- Which Software to use?
  - Perform-3D: Future support by CSI?
  - OpenSees: Continued development and funding?
- Overnight run-result cycle
  - Better model management and automation
  - Cloud based computing, multiple runs
  - Explicitly consider dispersion
- Still have limitation on length of single RHA for large models
  - Flexible diaphragm, Fiber models, Walls

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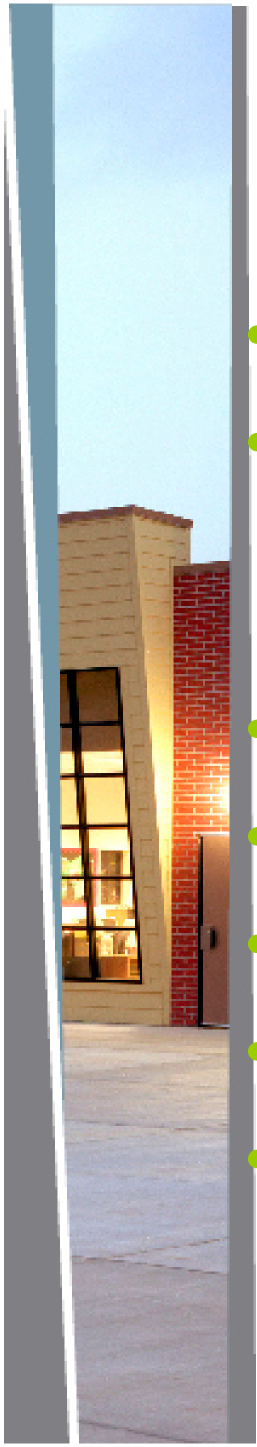
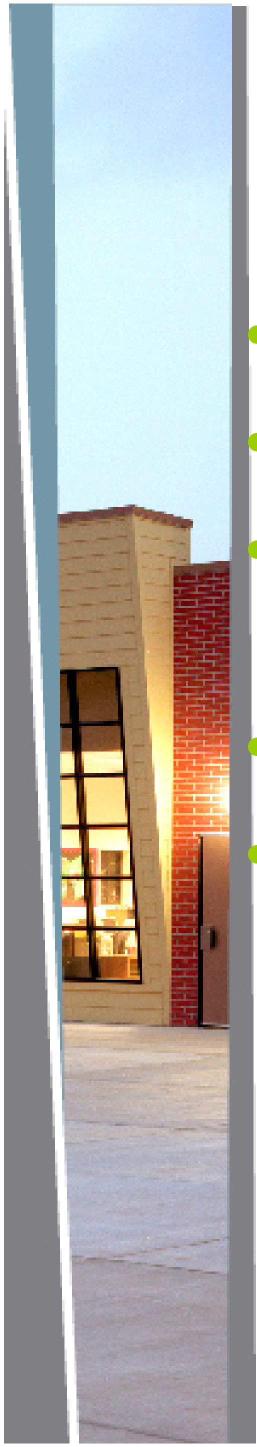


Simulation Needs in the Profession

- Project time is key → Optimize simulation
- Integration with BIM – model management, and synchronizing models between software (OpenSees <-> Revit <-> Etabs)
- Multi-analysis & multi-model management
- Model uncertainties, sensitivities & optimization
- Integration into design tools
- Distributed computing
- Smart solution algorithms



Simulation Needs (cont.)

- Validation & verification of models
- Education of engineers
- Move away from always using lumped-plasticity models
- Data management & visualization
- Direct modeling of systems

OpenSees

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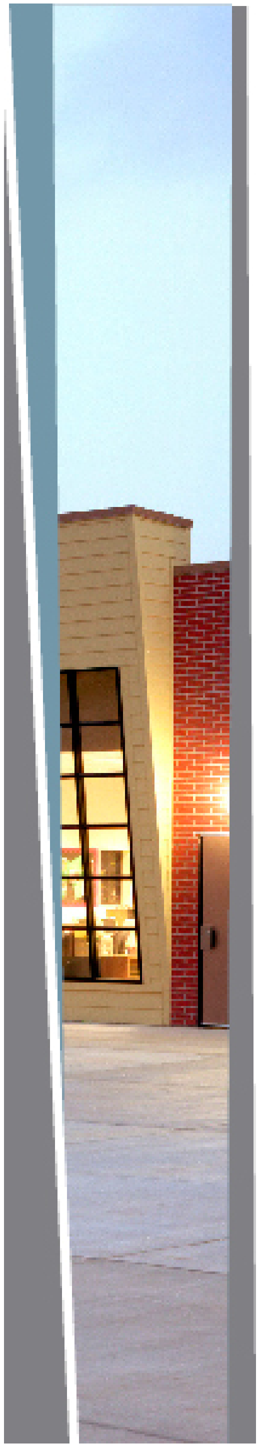
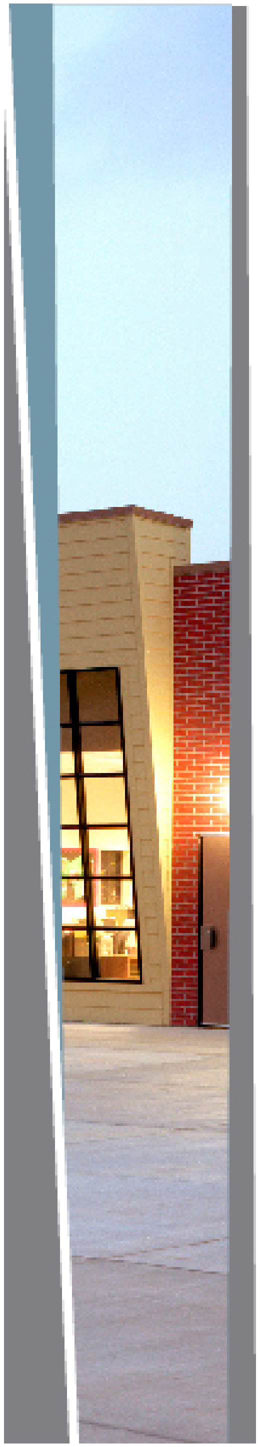


OpenSees Opportunities/Benefits

- Open-Source
- Robust Solvers
- Latest research knowledge/models
- Can add user models/materials
- Multiple-support excitation
- SFSI / Soil modeling
- Parallel / Multi-Machine processing
- Customizable Output / Recorders
- Fiber models



OpenSees Limitations/Challenges

- Open-Source: Stability
- Solvers (Convergence, tuning)
- Latest Research: Model Stability/Robustness
- Lack of robust nonlinear RC wall elements (Promising developments by Prof. Filippou)
- Lack of some basic analysis tools used in design (modal analysis, etc..)
- Visualization / User Interface

QUESTIONS?

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