State of the Practice of Nonlinear Response History Analysis

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Degenkolb New Technologies Group

• 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
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
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
What is design?

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

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

Structural Design
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’.***
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

Major Faults of California
(With Geology)

- Quaternary sediments
- Tertiary and Quaternary sedimentary rocks
- Tertiary sedimentary rocks
- Tertiary and Quaternary volcanic rocks
- Mesozoic sedimentary rocks
- Serpentinitized ultramafic rocks
- Gneissic rocks (mostly Mesozoic)
- Older metamorphic and sedimentary rocks (Precambrian, Paleozoic, and Mesozoic)

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
Site-Specific Seismic-Hazard Analysis

- Site Data
  - Location
  - Soil Profile
    - Average shear-wave velocity in top 100ft: \( V_s_{30} \)
    - 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
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 average level:
    \[ SR_{\text{avg}} = \text{Target Spectrum} \]
• 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
  • Control variability between records
  • Reduces 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
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

Spatial Variation in Ground-Motion Input

Inelastic Super & Substructure

Inelastic Soil Characteristics

OpenSees
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
FIXED BASE

Max Roof Disp: 0.66 in

FLEXIBLE BASE

Max Roof Disp: 2.81 in
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
Moment/Brace Haunched Connection

(a) Flexural Stress Contours

(b) Plastic Flexural Strain Contours
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
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
Multi-Machine Analysis
Multi-Machine Analysis

- DE Level Analysis
  - 10 Ground Motion pairs (avg 16 hrs each)
  - $\times 4$ (Eccentric mass cases)
  - $\times 2$ (rotated ground motions)
  - $\times 2$ (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

Analysis Output
Database Queries - Drift
Database Queries - Drift
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

1. Start
2. Distribute
3. Assemble
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…
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 [index $thisDataList $LineCounter]
  if {([length $thisLine]-0) { lappend GroupData $thisLine }
}
}\; # end for LineCounter
set NMaxLines [expr {length $thisDataList} -1]; # the -1 is to remove the last blank line
set ElementInputList ""
for [set LineCounter $NskipStart] {LineCounter<$NMaxLines} {incr LineCounter $NlinesPerEl} {
  set ElemTag [index [index $thisDataList $LineCounter] 0]
  set thisElpData ""
  for [set ii 1] {$ii<=$NlinesPerEl} {incr ii} {
    set thisLine [index $thisDataList [expr $LineCounter+$ii-1]]
    if {($ElementType=="FRAM" & $ii==1) {
      set elt7 [index $thisLine 7]
      if {[catch {set tt [expr 3.*elt7]}]=1} {
        set thisLine [insert $thisLine 7 Null]
        set thisLine [insert $thisLine 7 Null]
      }
      set elt8 [index $thisLine 8]
      if {[catch {set tt [expr 3.*elt8]}]=1} {
        set thisLine [insert $thisLine 8 Null]
      }
    }
    lappend thisElpData $thisLine
  }
}\; # end for ii
```
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, Jonathan P. Stewart, and Norman A. Abrahamson

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 $\sigma_{\text{ud}}$ calculated from 40 realizations and model; (d) comparison of $\sigma_{\text{ud}}$ calculated from realizations and model
Continued Improvement of BuildingTcl & BuildingTclViewer

BuildingTcl
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" DistributedLoad
addModelData -GravityLoad LoadLabel LL1 FloorRange "2 3" DistributedLoad
addModel
```
RC Sections

# 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 longitudinal
addSectionData NBarTop 6;  # number of top longitudinal
addSectionData NBarInt 6;   # total number of intermediate
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

```csharp
addLoadData LoadLabel StaticPushover;
addLoadData DMax 1*$in;
addLoadData ControlNodeFloor top;
addLoad

addLoadData LoadLabel EQ;
addLoadData LoadTypeLabel UniformEQ;
addLoadData GMfactor \$g;
addLoadData GMdirectory "GMfiles";
addLoadData FileType "PEER";
addLoadData GMfilename "H-E12140.at2";
addLoadData GMScale 1.;
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
```
BuildingTclViewer

- Provide a graphical user interface for BuildingTcl input
- Provide capability of running OpenSees real-time
- Visualization of Input / real-time response / output
- Save graphically-generated input into BuildingTcl script file

BuildingTclViewer v. 3.5 - FramingGravity3D.R

File Input Analysis Results Help Exit

Analysis
Models (Select all that apply):
- Gravity
- Frame
- Gravity/Frame
- Gravity/Shared
- Gravity/Frame/Shared
- Gravity/Frame/Shared/Heavy
- Gravity/Frame/Shared/Heavy/Load
- Gravity/Frame/Shared/Heavy/Load/Gravity
- Frame/Gravity

Load Combinations (Select all that apply):
- None
- Gravity/Frame
- Gravity/Frame/Gravity
- Gravity/Frame/Gravity/Frame
- Frame/Gravity/Frame
- Frame/Gravity/Frame/Frame
- Frame/Gravity/Frame/Frame/Gravity

Display Deformed Shape
- Scale Deformations: range
- 0.0 2.0 4.0 6.0 8.0 10.0

Display Response Graph
- Process Cells for Modeling Results (only take time)

Analyze

Silvia Mazzoni, UC Berkeley, R.1.9, 2009

Building

ushoveLargeStepsZ

Analytic Time (sec) vs. Load (kN)

Control-Node Displacement (m)
Menus

*New*
*Load*
*View GettingStartedDataFile.tcl*
*Reload & Source GettingStartedDataFile.tcl*
*Source Additional File(s)*
*Save*
*Save As...*
*Exit*

*Material*
*Section*
*ElementType*
*AnalysisModel*
*Load*
*LoadCombination*
*Model*

*Results*
*Select a Model*
*Select a Load Combination*
## New Section

- Default Units:
  - Length: in, Force: kip, Time: sec

### Select Section

- Elastic
- ElasticRectangular
- RCRectangularFiber
- AISC/WideFlangeElastic
- AISC/WideFlangeFiber
- Custom/WideFlangeElastic
- Custom/WideFlangeFiber

### Edit Section

<table>
<thead>
<tr>
<th>Section/Width</th>
<th>B Width</th>
<th>Option/Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section Depth</td>
<td>D Depth</td>
<td>Option/Units</td>
</tr>
</tbody>
</table>

### Input Arguments

#### Required Arguments

- B Width
- D Depth

#### Optional Arguments

- NilR Top: Number of Reinforced Bars in Top Layer
- NilR Bottom: Number of Reinforced Bars in Bottom Layer
- NilR Intermediate: Number of Reinforced Bars in Intermediate Layer

#### Section Geometry

- Section Geometry

### Test

- Real-Time Display (on/off)

#### Test Section/Total Force (kips)

<table>
<thead>
<tr>
<th>Force (kips)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>2.0</td>
</tr>
<tr>
<td>0.0</td>
<td>4.0</td>
</tr>
<tr>
<td>0.0</td>
<td>6.0</td>
</tr>
<tr>
<td>0.0</td>
<td>8.0</td>
</tr>
</tbody>
</table>

### Modify/Save

- Save As...
- Save As: RCRectangularFiber
Elevation-Model Input
3DFrame-Model Input

*view Element Cross Sections*
Real-Time OpenSees Simulation

Real-Time Pause/Stop
Visualization of Structural Response

envelope values
BuildingTcl combines the power of a scripting UI with a GUI
Soil-Structure Interaction: Base Rocking 10-story RC Frame
Model Validation

Simulation Validation – Loma Prieta

Absolute acceleration

– Recorded
– Simulated

Run as 2D model for efficiency

ATC-83 Improved Procedures for Characterizing & Modeling Soil-Structure Interaction for Performance Based Engineering
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)
Comparison w/ Code-Based-Design

- **Advantages**
  - Allowable drift increase (1.25 factor)
  - Can achieve lower $\Omega_0$ 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 $C_d = 0.7R$
  - Podium structures, no easy two-stage analysis
CPMC Cathedral Hill

Cover plate
Oiling viscous fluid
Internal steel plate (Resistance plate)
External steel plate (Viscous fluid container)

Single type
<table>
<thead>
<tr>
<th>Structural System</th>
<th>Drift</th>
<th>Floor Accel.</th>
<th>Steel Wt. (psf)</th>
<th>Cost Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional SMRF</td>
<td>1.25%</td>
<td>1.0g - 1.5g</td>
<td>36</td>
<td>1.0</td>
</tr>
<tr>
<td>Dual System - BRBF+SMRF</td>
<td>1.25%</td>
<td>1.5g - 2.0g</td>
<td>27</td>
<td>0.8</td>
</tr>
<tr>
<td>Braced Frame with Isolation</td>
<td>0.7%</td>
<td>0.2g - 0.3g</td>
<td>28</td>
<td>1.0</td>
</tr>
<tr>
<td>SMRF with Dampers</td>
<td>1.25%</td>
<td>0.5g - 0.8g</td>
<td>20</td>
<td>0.7</td>
</tr>
</tbody>
</table>
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
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
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?