

### Collapse Simulation of RC Frame Buildings

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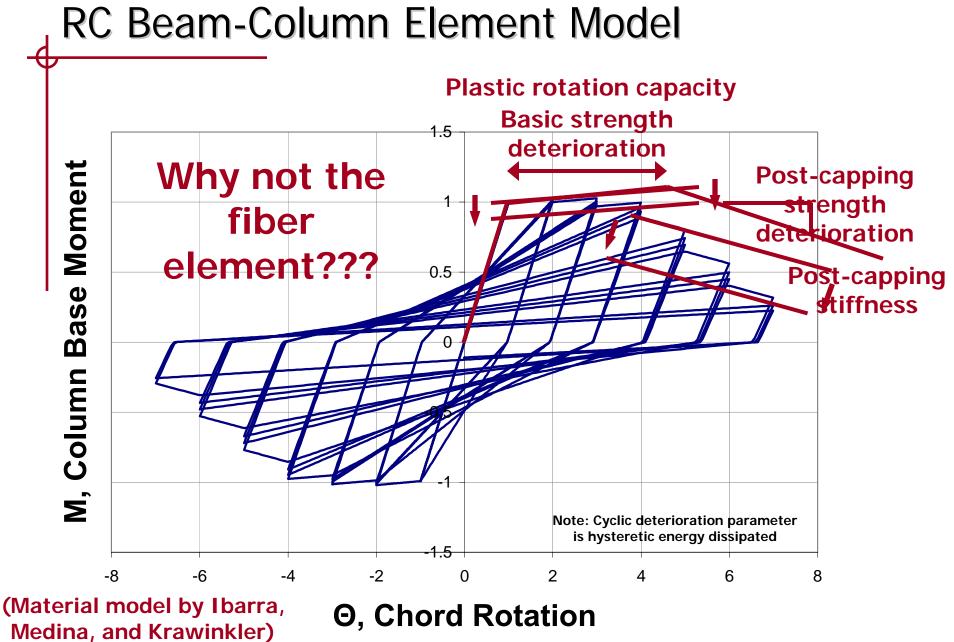


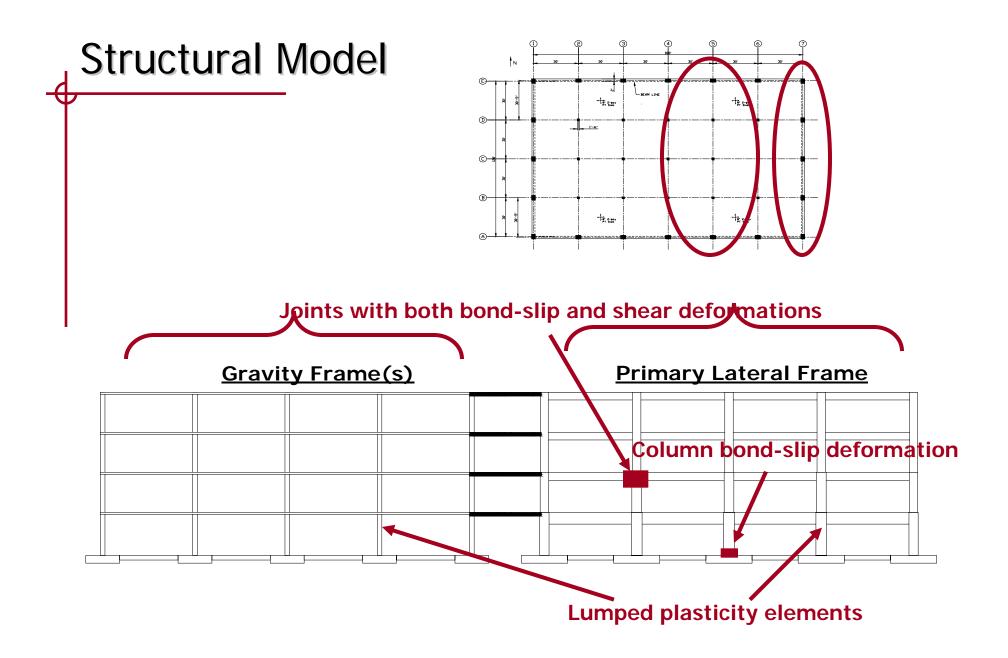
# Outline

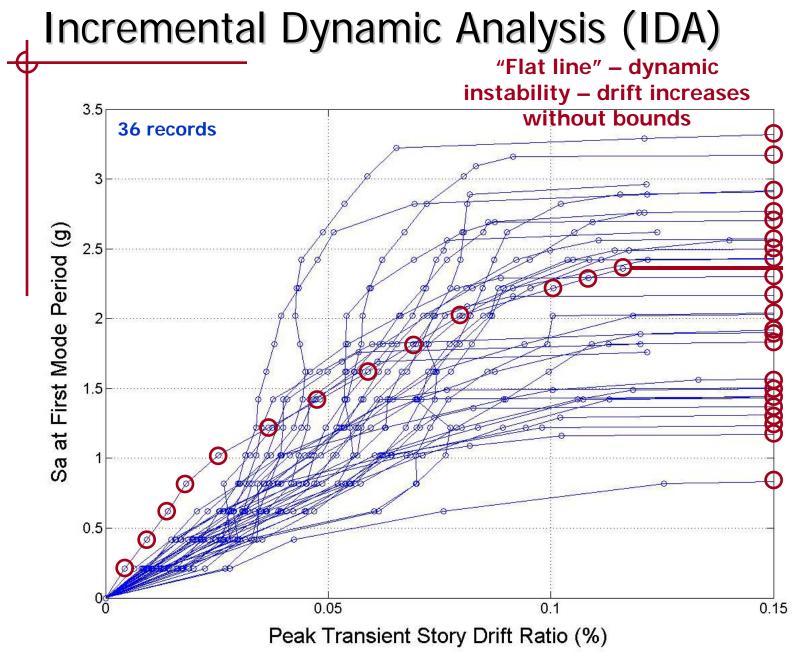
- ⇒ Research Overview
  - → Purpose
  - ⇒ Reinforced-Concrete Beam-Column element model
  - ⇒ Structural model and collapse prediction method
- ➡ Collapse Analysis Method and Tools:
  - ⇒ Calibration of RC Beam-Column element model
  - ➡ Program for Automated OpenSees Model Generation
  - ➡ Matlab algorithms
- ⇒ Numerical Considerations:
  - ⇒ Solution algorithm
  - ➡ Treatment of singularity and non-convergence
  - ➡ Problem with sparse mass matrix
- ➡ Summary

# Purpose of Research

- ➡ Predict the collapse safety of new code-conforming RC frame buildings (60 buildings designed by 2003 IBC)
- Use these predictions to inform design and Code provisions
- ⇒ Develop the data and tools necessary for:
  - ⇒ the collapse predictions to be reliable/defensible
  - others to be able to do collapse analysis with reasonable effort







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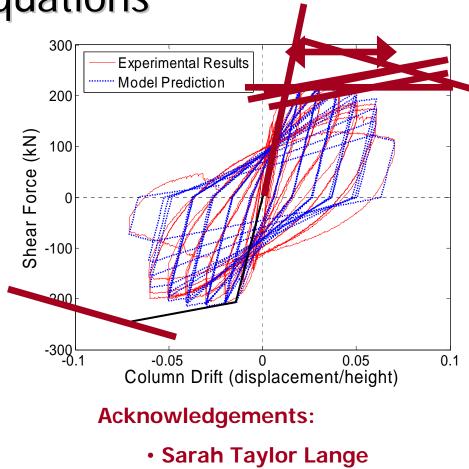
## **Empirical Predictive Equations**

Model calibrated to 255 flexurally dominated test from PEER Structural Performance Database (Berry and Eberhard)

Calibration done using a "brute force" approach; Lignos and Krawinkler are developing a more automated approach.

Model Parameters to be Predicted:

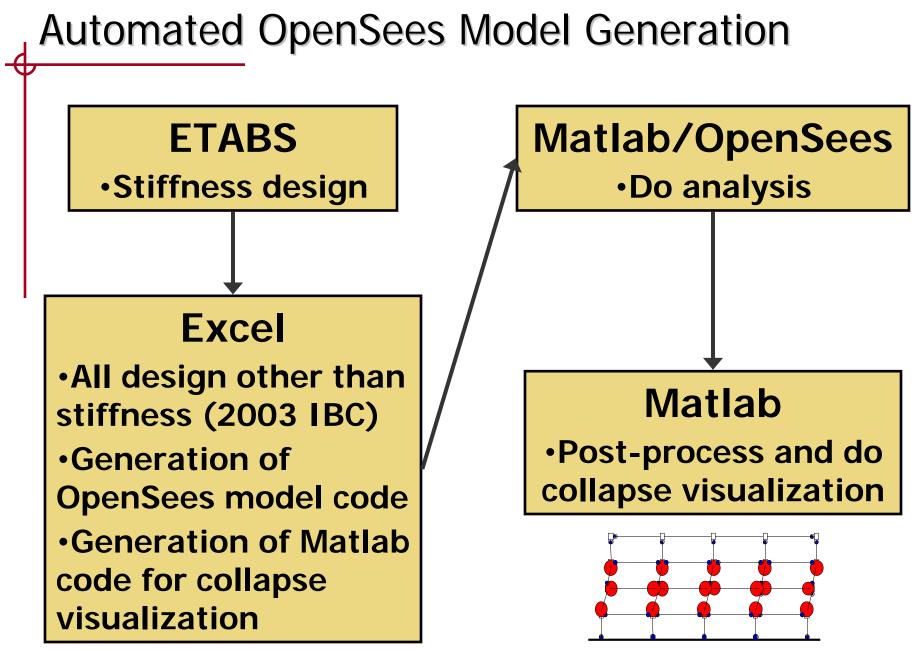
- Strength (easiest)
- Initial stiffness
- Post-yield stiffness
- Plastic rotation capacity
- Negative post-cap slope
- Cyclic deterioration rate



Abbie Liel

$$\theta_{cap,pl} = 0.12(1+0.56a_{sl})(0.16)^{\nu}(0.02+40\rho_{sh})^{0.43}(0.54)^{0.01c_{un}sf'c}(0.66)^{(1s_n)}(2.27)^{100\rho}$$

[Mean and uncertainty both quantified] 8



### Automated OpenSees Model Generation

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### **Overview of Matlab Collapse Algorithm**

- ➡ Matlab drives the collapse analysis
  - Automated: Matlab runs analysis, does post-processing, and runs parameter studies when needed
  - Matlab writes a .Tcl file to tell OpenSees what to do, then Matlab executes OpenSees with the following command:
    - "!openSees RunSingleCollapseSensitivityAnalysisMATLAB.tcl"
- After OpenSees analysis, Matlab processes the results, then runs remaining analyses to find collapse point
- With Matlab, it is easier to handle numerical difficulties such as singularity and non-convergence

# Outline

- ➡ Research Overview
  - ⇒ Purpose
  - ➡ Reinforced-Concrete Beam-Column element model
  - ⇒ Structural model and collapse prediction method
- ⇒ Collapse Analysis Method and Tools:
  - ⇒ Calibration of RC Beam-Column element model
  - ⇒ Excel Program for Automated OpenSees Model Generation
  - ⇒ Matlab algorithms
- ⇒ Numerical Considerations:
  - ▷ Dynamic solution algorithm
  - ➡ Treatment of singularity
  - ⇒ Problem with sparse mass matrix
- ⇒ Summary

# **Dynamic Solution Algorithm**

- The solution algorithm was a large part of this work and we spent a lot of time refining it.
- ⇒ "Try Everything" Approach (more details at end of presentation):
  - ⇒ If Non-Converged:
    - ⇒ Try all solution algorithms (NewtonLineSearch, Newton, Newton –initial, Krylov Newton)
  - ⇒ If Still Non-Converged:
    - ➡ Repeatedly reduce time step
  - ⇒ If Still Non-Converged:
    - ⇒ Repeatedly reduce tolerance
  - ⇒ If Still Non-Converged:
    - ⇒ STOP ANALYSIS and report non-convergence (non-convergence does not mean collapse!!!!)
  - ➡ Else
    - ⇒ Output the convergence tolerance achieved (user decides if acceptable)
    - ➡ Check for collapse (based on an interstory drift limit)
    - ⇒ Check for singularity

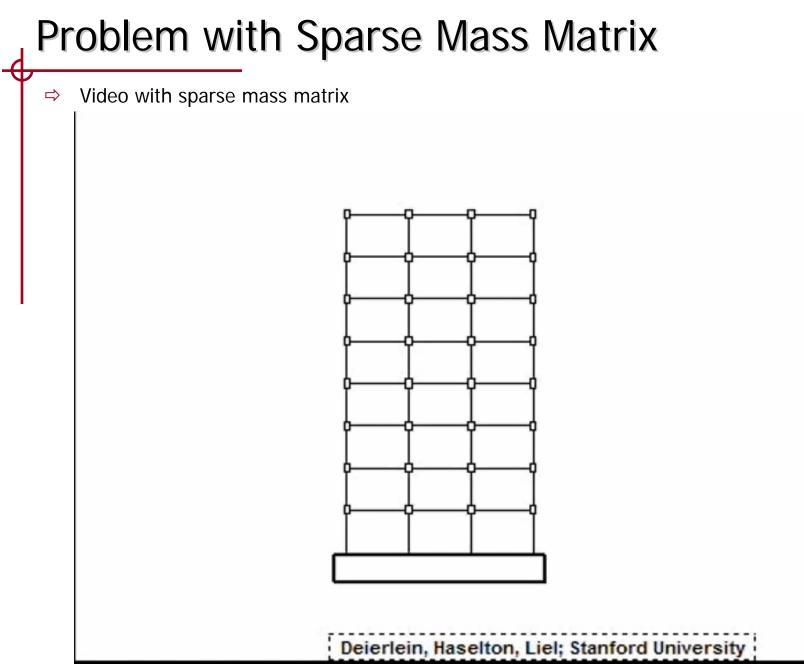
# Treatment of Singularity

- Singularity is a huge problem for collapse analysis. Singularity causes the current version of opensees.exe to have a runtime error (we need to fix this).
- How do we know that the solution went singular? We get any of the following in some (not all) of our nodal recorders:
  - $\Rightarrow$  #QNAN, or #IND, or a huge displacement (disp > 100000.0)
- ⇒ Code to check for singularity: See reference slides at end of presentation
- ⇒ What do we do if the solution goes singular?
  - ➡ OpenSees stops analysis (to avoid run-time error) and reports the singularity back to Matlab
  - ⇒ Matlab throws away the results from the singular analysis
  - ⇒ Matlab then *slightly* alters the Sa level of the earthquake and reruns the analysis
  - Matlab continues these slight alterations to Sa until we get an analysis with either full convergence or collapse (without any singularity)

Problem with Sparse Mass Matrix

⇒ When doing collapse analyses, the dynamic "stiffness" matrix becomes ill-conditioned.

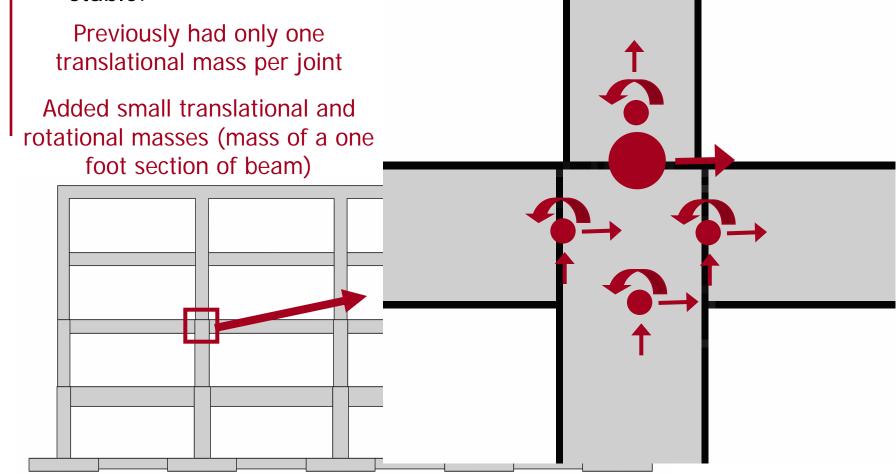
- This can cause the solution to have problems even when it "converges" and does not have singularity problems.
- ⇒We can fix this by adding small terms to the mass matrix.

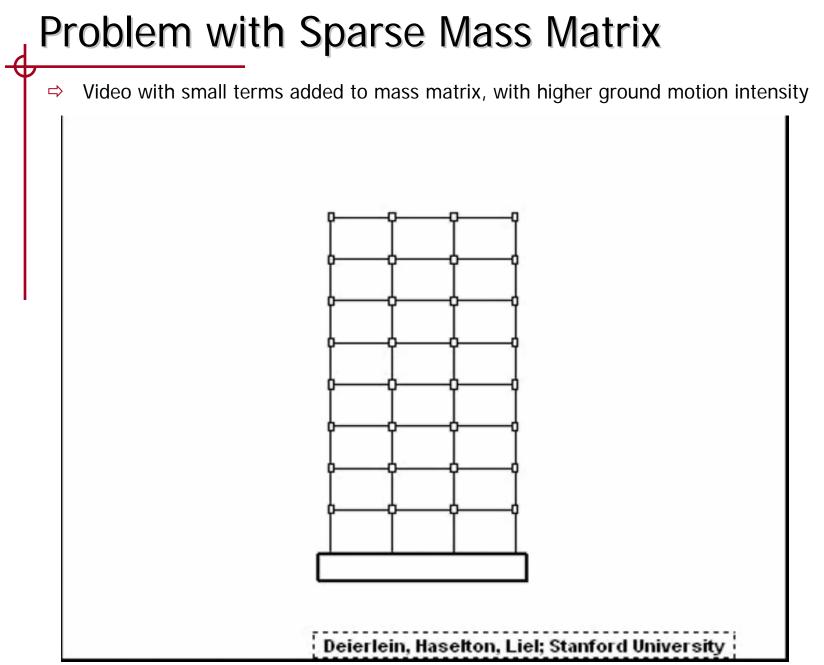


**OpenSees Developers Symposium – August 16, 2006** 

## Problem with Sparse Mass Matrix

Adding small masses to populate mass matrix and make solution more stable.





# Summary

- ➡ It is easy and extremely useful for Matlab to run OpenSees
- ⇒ For collapse analyses, numerical issues are a large problem
- Using Tcl and OpenSees commands, we can identify these numerical problems and "get around them" in order to get analysis results that are reliable
- ➡ Tools Developed (available shortly)
  - ⇒ Calibrated model for RC beam-columns (PEER report available shortly)
  - ⇒ Excel program for automated model generation (available as soon as papers are out)
  - ⇒ Matlab program to run and post-process analysis (available shortly)
- ⇒ A book that I have found *extremely* useful for programming in Tcl:
  - "Practical Programming in Tcl and Tk", Fourth Edition, by Brent B. Welch and Ken Jones



### Reference: Calib. of Beam-Column Model

$$\begin{split} & \frac{EI_{y}}{EI_{g}} = -0.07 + 0.59 \left[ \frac{P}{A_{g} f_{c}} \right] + 0.07 \left[ \frac{L_{s}}{H} \right] \\ & 0.2 \le \frac{EI_{y}}{EI_{g}} \le 0.6 \\ & \frac{EI_{stf}}{EI_{g}} = -0.02 + 0.98 \left[ \frac{P}{A_{g} f_{c}} \right] + 0.09 \left[ \frac{L_{s}}{H} \right] \\ & 0.35 \le \frac{EI_{stf}}{EI_{g}} \le 0.8 \\ & \frac{M_{c}}{M_{c}} / M_{y} = (1.25)(0.89)^{v} (0.91)^{0.01c_{units}f'_{c}} \\ & \frac{M_{c}}{M_{c}} / M_{y} = (1.25)(0.89)^{v} (0.91)^{0.01c_{units}f'_{c}} \\ & \frac{M_{c}}{M_{c}} / M_{y} = (1.25)(0.31)^{v} (0.02 + 40\rho_{sh})^{0.43} (0.54)^{0.01c_{units}f'_{c}} (0.66)^{0.1s_{n}} (2.27)^{10.0\rho} \\ & \frac{M_{c}}{M_{c}} = (0.76)(0.031)^{v} (0.02 + 40\rho_{sh})^{1.02} \le 0.10 \\ & \frac{M_{c}}{M_{c}} - (1.27.2)(0.19)^{v} (0.24)^{s/d} (0.595)^{v_{p}} / V_{n} (4.25)^{\rho} sh, eff \end{split}$$

Haselton, C.B., Liel A.B., Taylor Lange S. and G.G. Deierlein, 2006. Beam-Column Element Model Calibrated for Predicting Flexural Response Leading to Global Collapse of RC Frame Buildings, PEER Report 2006, Pacific Engineering Research Center, University of California, Berkeley, California, (in preparation).

# **Reference: Dynamic Solution Algorithm**

# Loop for full earthquake unless we detect collapse or until the system goes singular

```
while { \$eqNotFinished == 1 \&\& \$isCollapsed == 0 \&\& \$isSingular == 0 \} {
```

```
test RelativeNormDispIncr 1.0e-6 10 1; # test testType $tolerance $maxNumIter
<$printFlag>
```

```
algorithm NewtonLineSearch 0.6;
```

```
set ok [analyze 1 $dT]
```

```
if {$ok != 0} {
       algorithm Newton
       set ok [analyze 1 $dT]
}
```

```
if {$ok != 0} {
       algorithm Newton -initial
       set ok [analyze 1 $dT]
}
```

```
if {$ok != 0} {
       algorithm KrylovNewton
       set ok [analyze 1 $dT]
}
```

# Continued on next slide...

This algorithm was built starting from the work of other researchers:

- Frank McKenna
- Paul Cordova

# **Reference: Dynamic Solution Algorithm**

# ...continued from last slide

```
if {$ok != 0} {
       # Repeatedly reduce the time step then the tolerance and try all of the solution
       # algorithms again
}
if {$ok != 0} {
       # STOP ANALYSIS: Give up and let OpenSees return with a convergence error
} else {
       # Output the convergence tolerance achieved for user to decide if that is acceptable
}
# If we get to this line the analysis converged...check for collapse and singularity
if { isCollapsed } { # Stop analysis and report collapse [Details on next slide] }
if { isSingular } { # Stop analysis and report singularity [Details on next slide] }
```

}

# Reference: Treatment of Collapse State

- At each step of the analysis we check collapse based on a predefined drift limit (this collapse definition can easily be altered).
- We stop the analysis if the model collapses (dynamically unstable) or else the solution may become singular (which causes an OpenSees error)
- ➡ Code to check for collapse:

# Get floor displacements from OpenSees at this analysis step set floor2Displ "[nodeDisp \$nodeNumAtFloor2 1]"; ...do for all floors

# Compute story drift ratios for all stories set story2DriftRatio [expr (\$floor3Displ - \$floor2Displ) / [lindex \$floorHeightsLIST 2]] ...do for all stories

```
# Check is collapseDriftLimit is exceeded
if { abs(any story drift) > collapseDriftLimit } {
    set isCollapsed 1; # Stop the analysis at this time step and report collapse to MATLAB
}
```

# **Reference: Treatment of Singularity**

# Code for singularity check

```
# Check for singularity in a single nodal recorder
       set floor2Displ "[nodeDisp $nodeNumAtFloor2 1]"
       # Check recorders for IND or QNAN...
       set checkForQNANFIr2 [string first QNAN $floor2Displ 1];
       set checkForINDFIr2 [string first IND $floor2Displ 1];
       # Check recorder for a huge unreasonable displacement...
       if { $ floor2Displ > 100000.0 } {
                   set isSingular 1; # Set singularity flag
       }
# ...do same checks for many other nodal recorders...
# Set the singularity flag based on IND or QNAN
       if {($checkForQNANFIr2 != -1) || ($checkForINDFIr2 != -1) || ...check other nodes... } {
                   set isSingular 1; # Set singularity flag
       }
# Stop analysis if singular
if { is Singular = = 1 } {
       # Stop the analysis at this time step and report singularity to MATLAB
```

Thank You

⇒Thank you for your attention!

I am a believer in all of us not wasting our time in research, so please contact me if any of this would be useful in your work.

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