

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.



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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.

⇒<u>haselton@stanford.edu</u>