Experience with Nonlinear Seismic Analysis of Buildings

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Philosophy of my computer simulation research

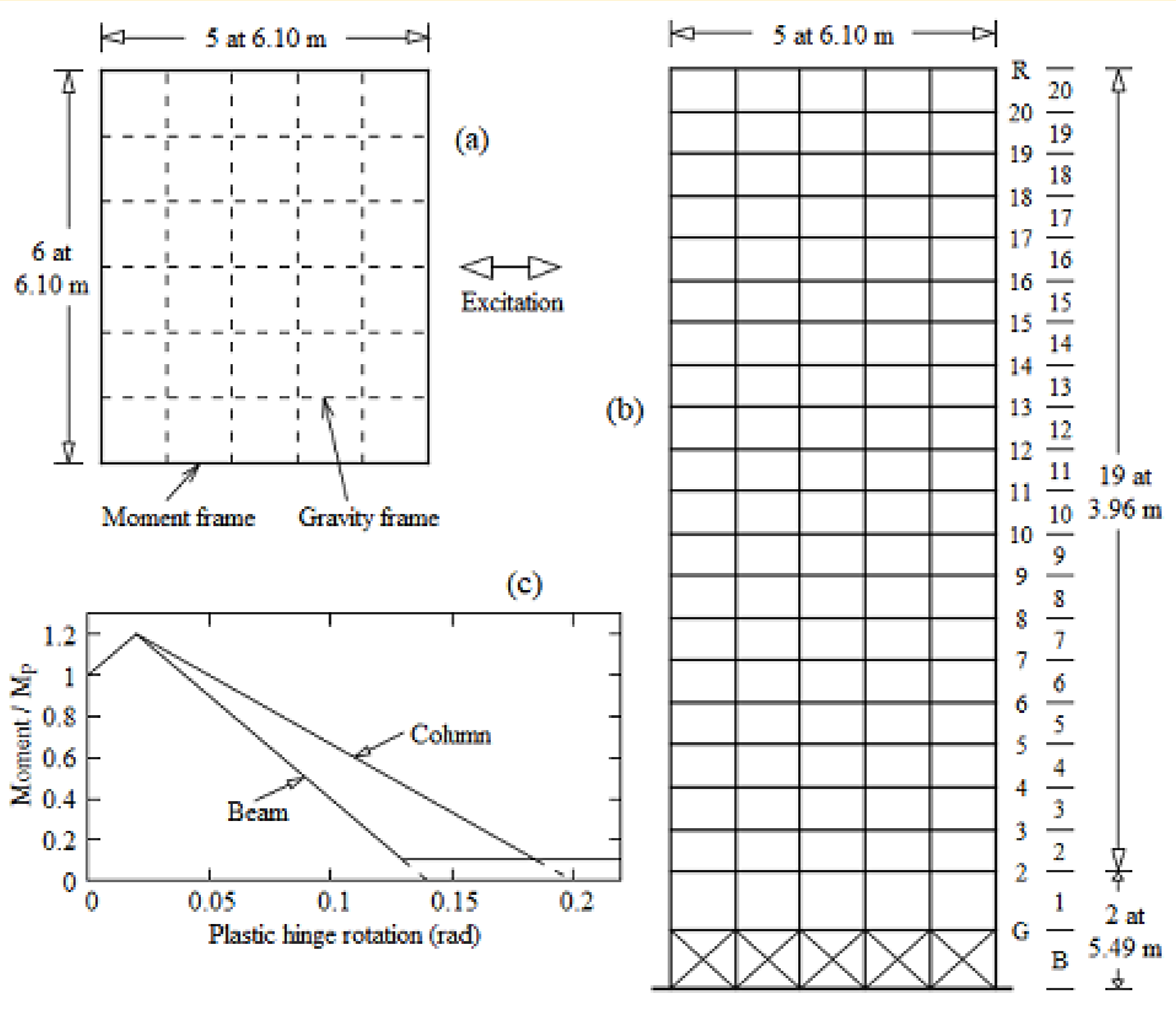
I write and use my own special purpose software:

- More flexible
- Runs fast
- Only my own bugs to worry about
- Avoid dealing with poor documentation

Program features for moment-frame buildings

- 2d-analysis of planar frames
- Beam/column elements with implicit plastic hinges (hardening/softening behavior, axial-bending strength interaction, shear deformations)
- Full geometric nonlinearity
- Panel zone elements (finite size, shear nonlinearity)
- Diaphragm springs
- Implicit time integration with iterations
- Seven damping schemes

Example 20-story building (SAC post-Northridge design for LA)



Features of analysis

- Both moment and gravity frames explicitly modelled
- 3-element beams to model cover plated end segments
- 2-element columns at splice locations
- 1722 degrees of freedom
- Strong ground motion causing beam plastic hinge rotations > 6%
- 2500 time steps at $\Delta t = 0.01$ seconds
- Dell laptop with Intel i7-6700HQ 2.60GHz processor

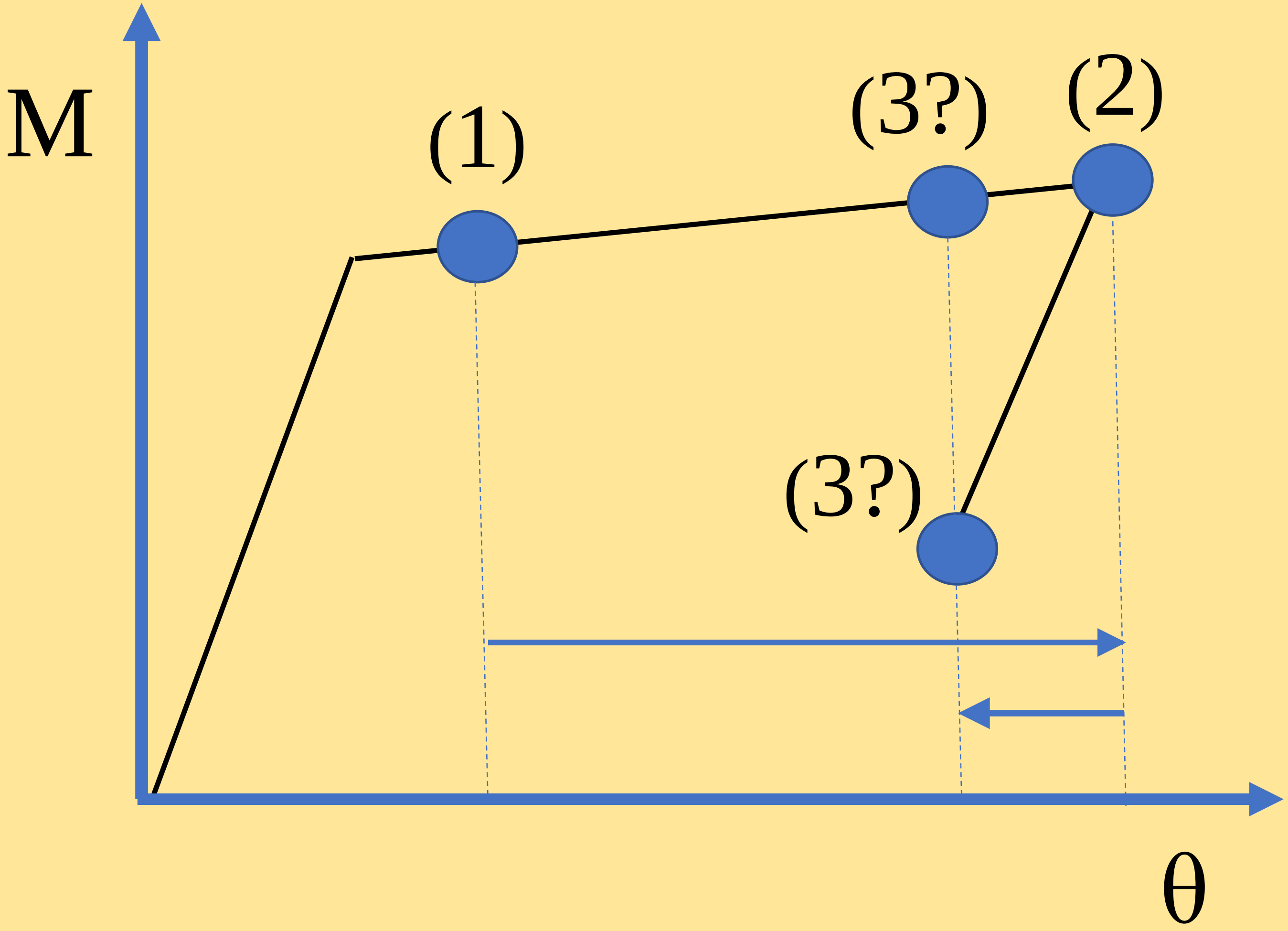
Run time: 37 CPU seconds

Efficiency: solving equation of motion

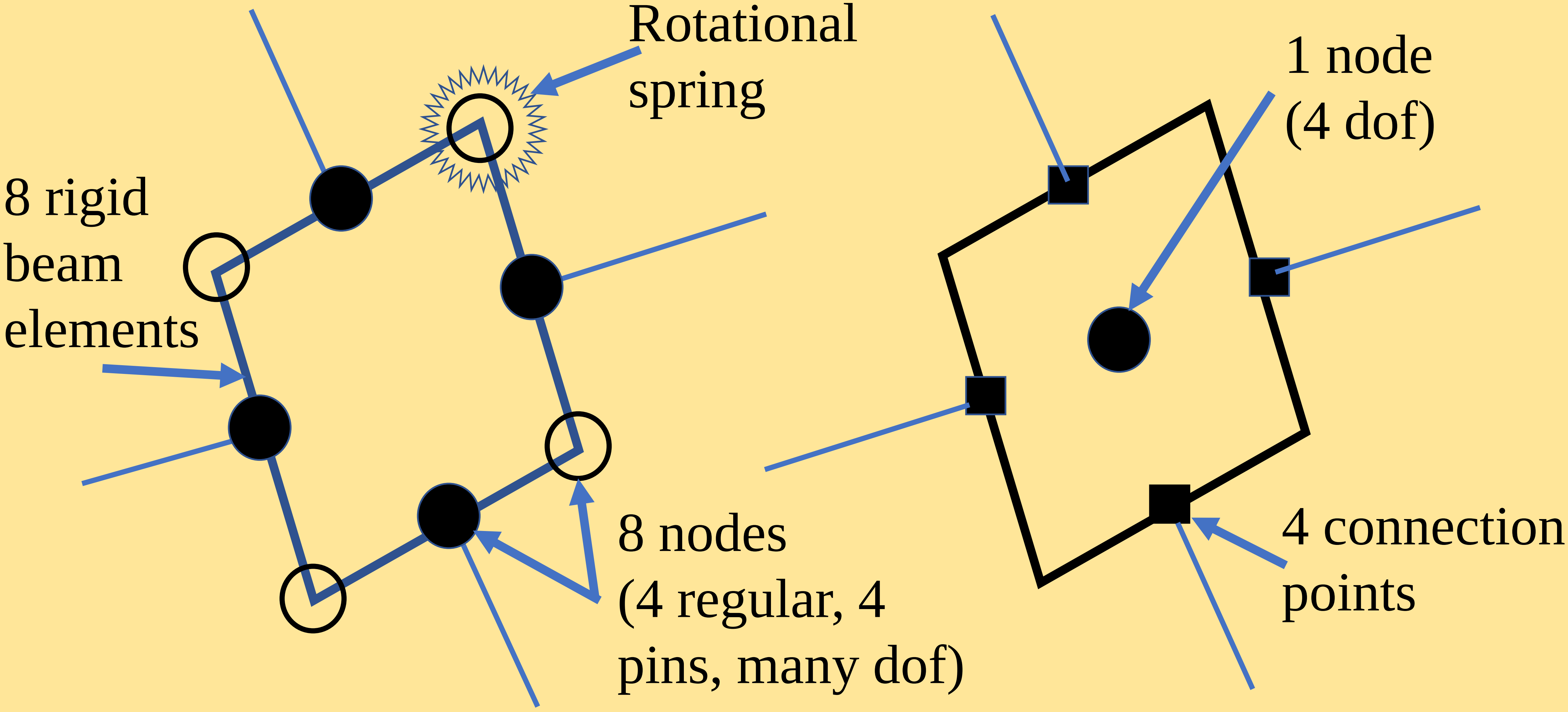
$$[M]\left\{\ddot{a}^{(j+1)}(t+\Delta t)\right\}+[C]\left\{\dot{a}^{(j+1)}(t+\Delta t)\right\}+\left[K_I^{(j)}\right]\left\{\Delta a^{(j)}\right\}$$

$$=\{f(t+\Delta t)\}-\{R^{(j)}(t+\Delta t)\}$$

[K_I} and {R} decisions



Efficiency: panel zones



Modelling problems

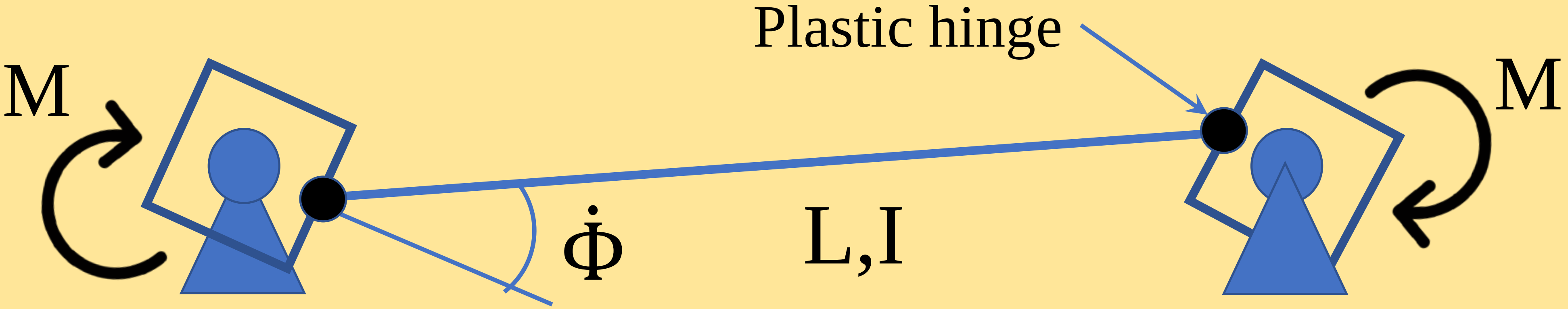
- Diaphragms: tie adjacent frames together, constrain nodes of a floor to move together in horizontal direction
- Plastic hinges: coupling between axial and bending stiffnesses
- Damping: large damping moments with Rayleigh damping in nonlinear analysis

Amplified damping moments when using Rayleigh damping in nonlinear analysis

Two explanations:

- 1980’s – caused by rotational mass, which should be included in an analysis
- 1995 – associated with massless (rotational) degrees of freedom

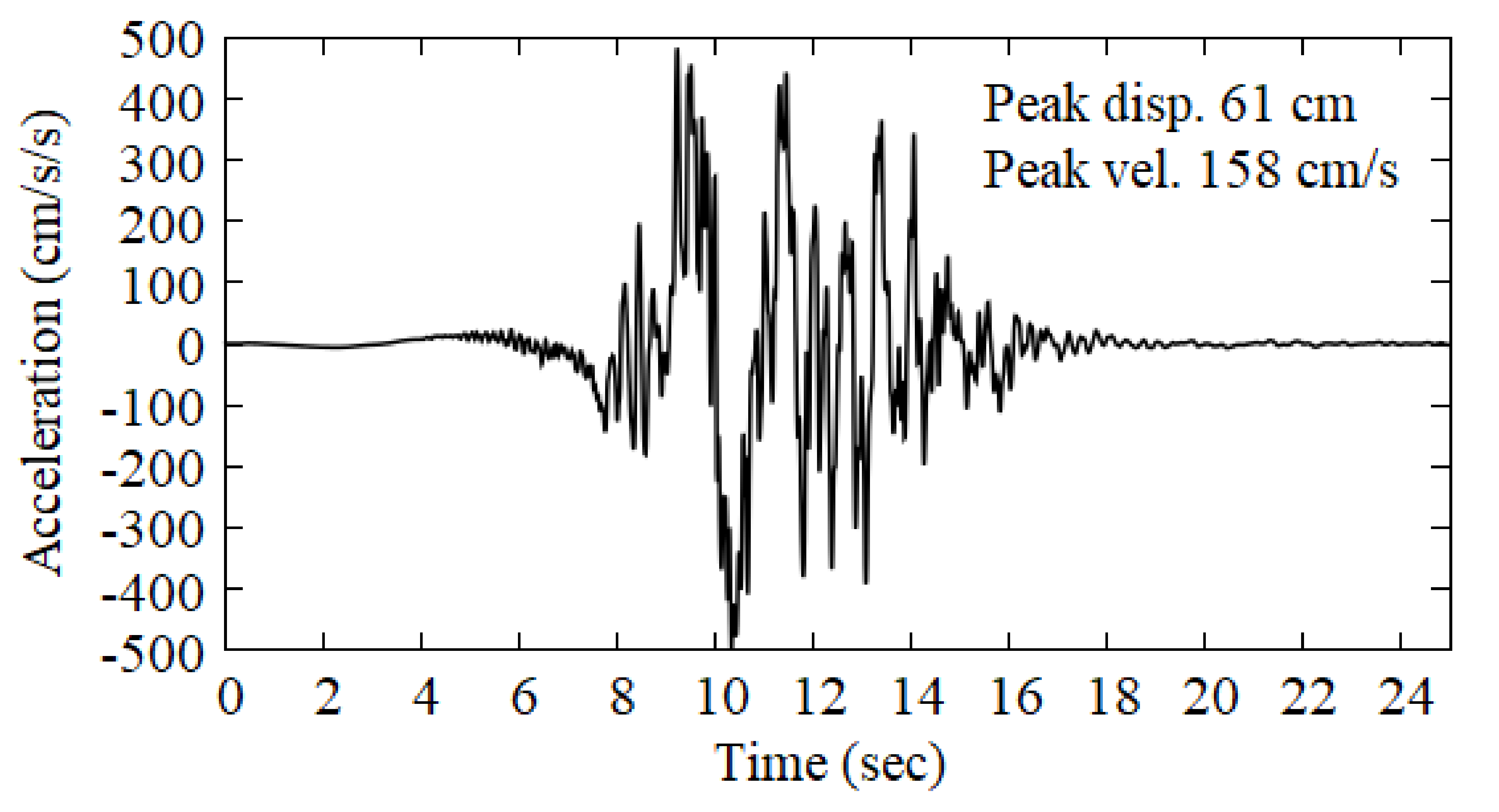
Assessment of damping moments

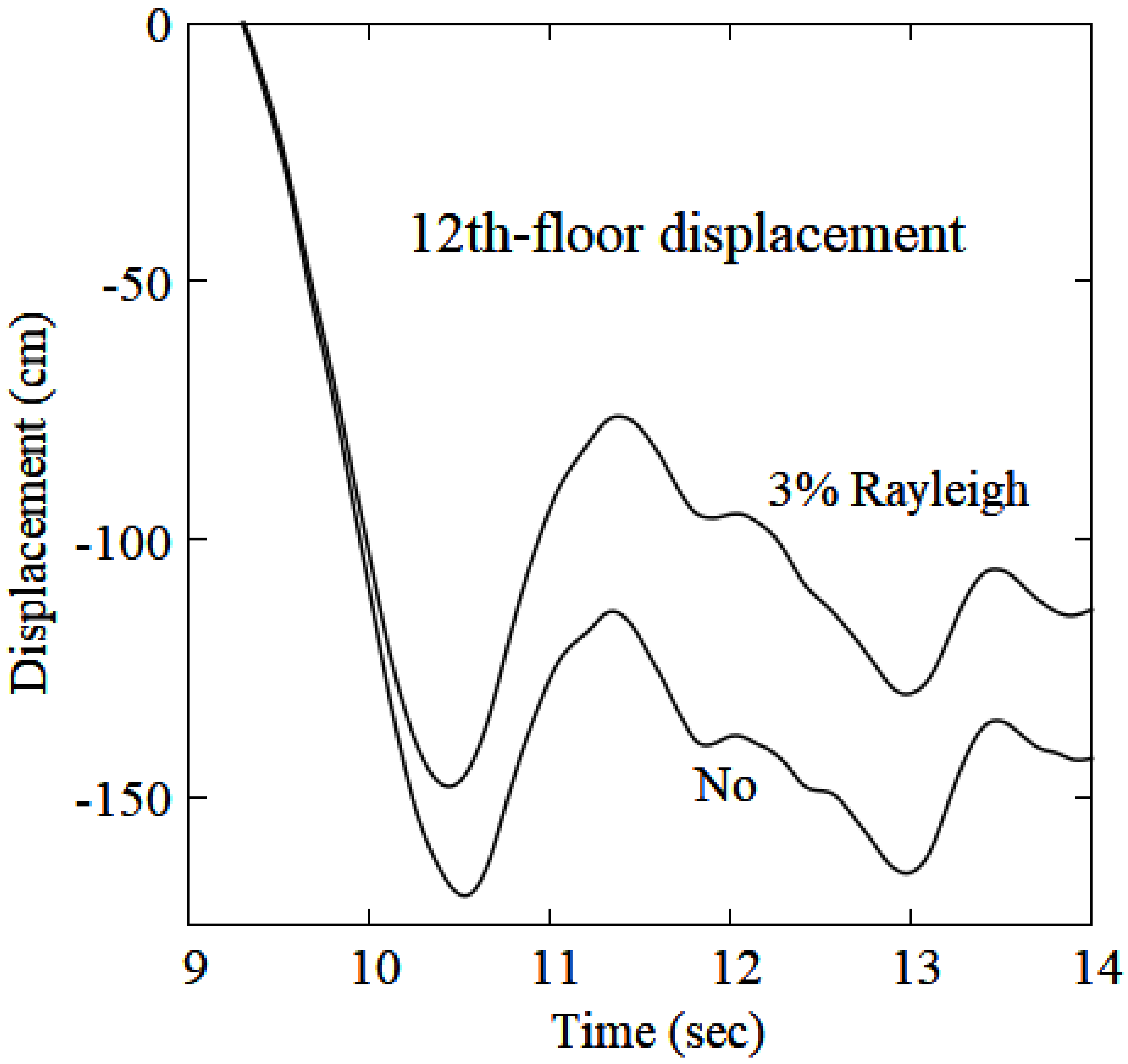


$$M_{ratio} = \frac{M_{Bdamp}}{M_{Bplastic}} = \frac{a_k \frac{6EI}{L} \dot{\Phi}}{\sigma_y Z}$$

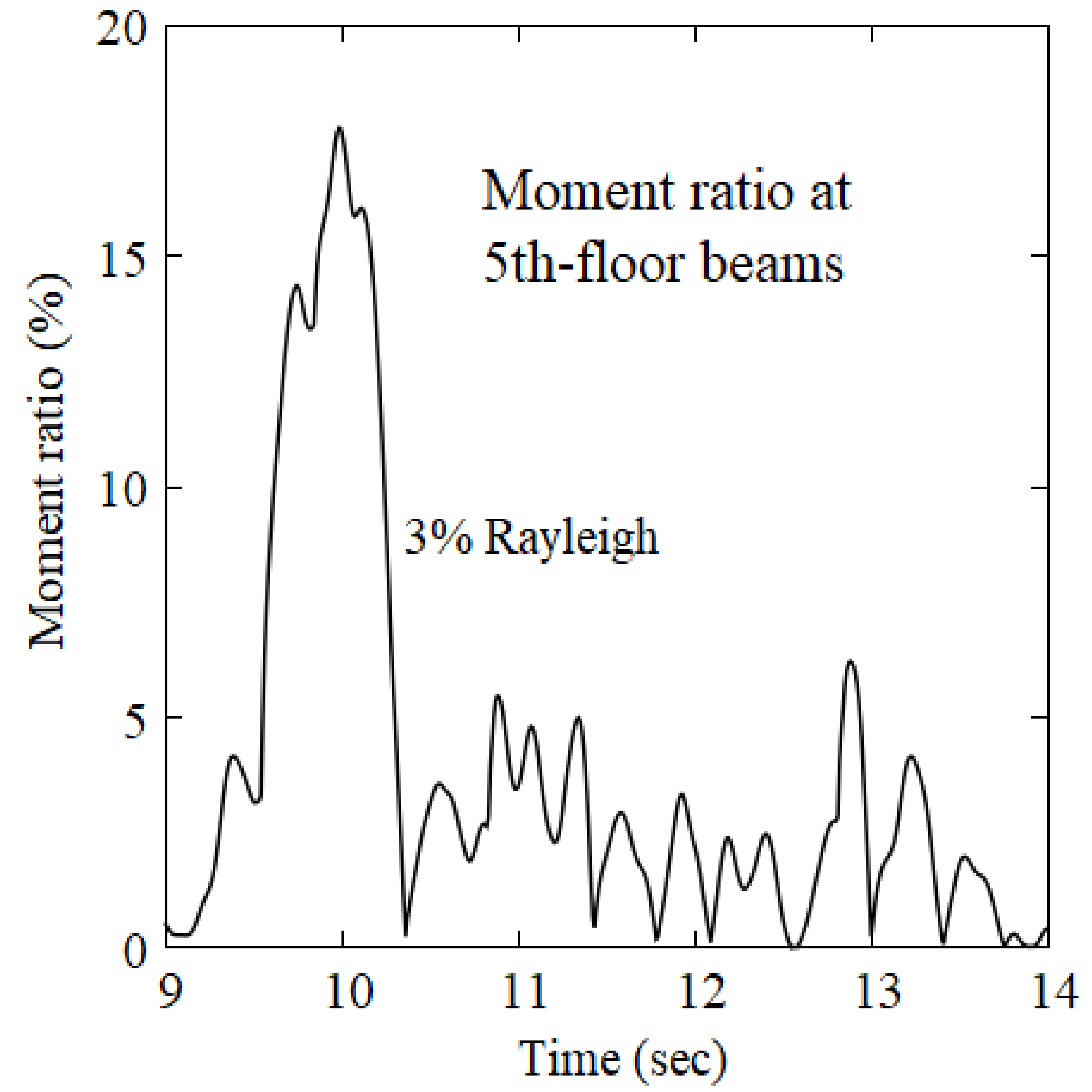
For lower level beams in the 20-story building and 3% damping: $M_{ratio} \approx 0.20$ using $\dot{\Phi} = 0.1$ rad/sec

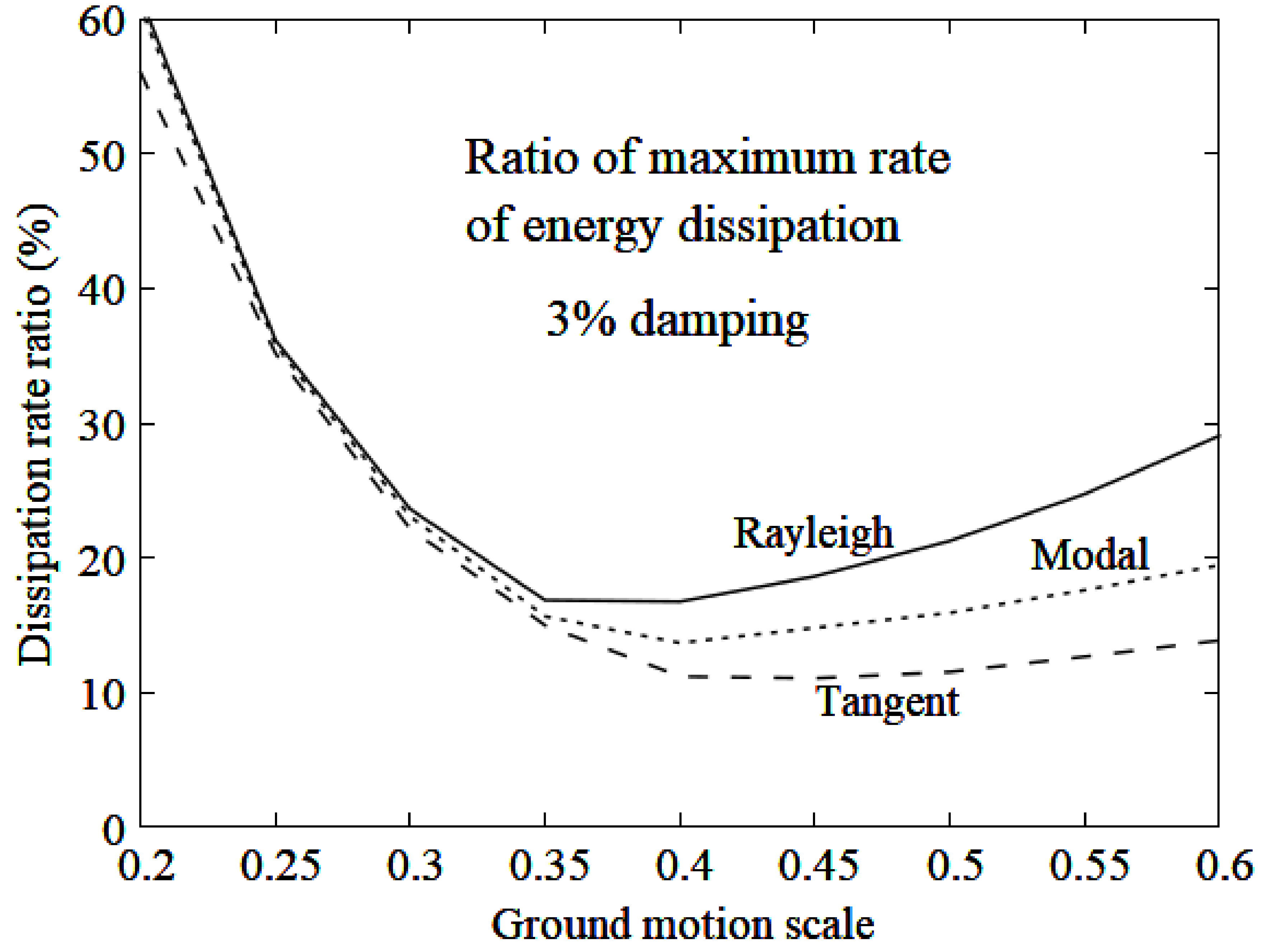
SAC LA35/LA36 Ground Motion (half scale)





12th-floor displacement
3% Rayleigh
No
Displacement (cm)
Time (sec)
0
-50
-100
-150
9
10
11
12
13
14

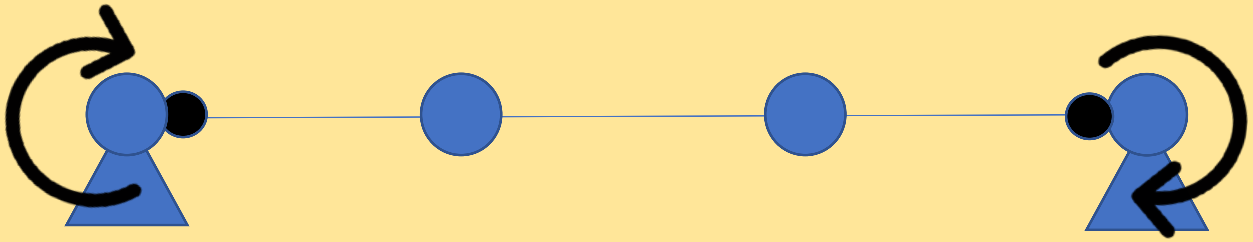

Moment ratio at
5th-floor beams
3% Rayleigh
Moment ratio (%)
Time (sec)
0
5
10
15
20
9
10
11
12
13
14



Ratio of maximum rate
of energy dissipation
3% damping
Rayleigh
Modal
Tangent
Dissipation rate ratio (%)
Ground motion scale
60
50
40
30
20
10
0
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6

Damping: other considerations

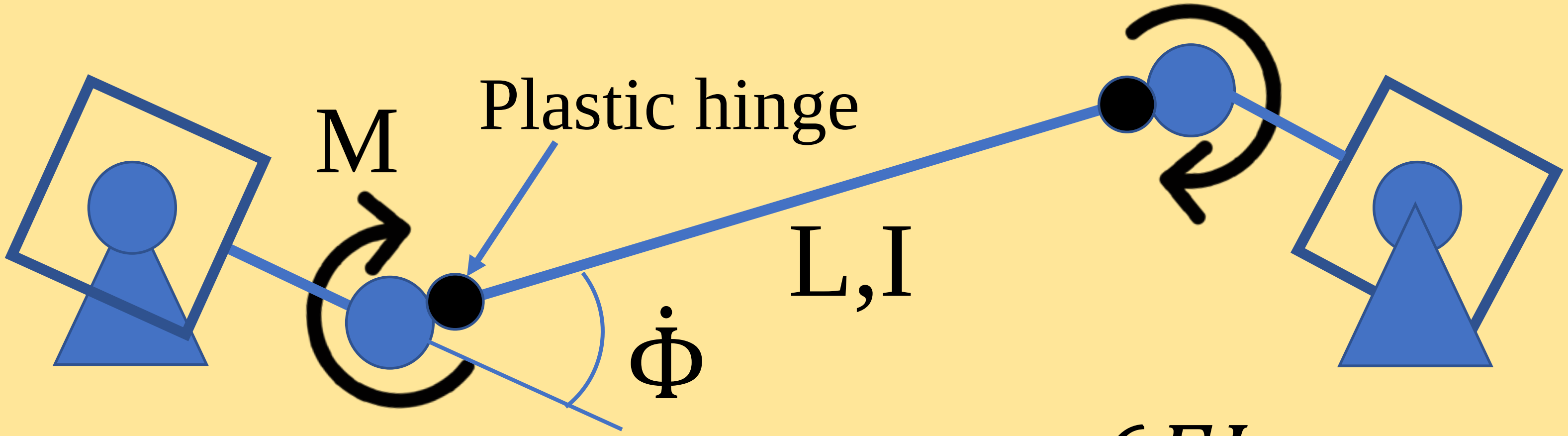
- Interior nodes to capture secondary framing



- Higher damping (5% for concrete buildings)
- Higher stiffness to strength ratio (concrete buildings)
- Braced frames
- Vertical ground motion

Stay active Anil. There are still lots of interesting problems to work on.

Assessment of damping moments



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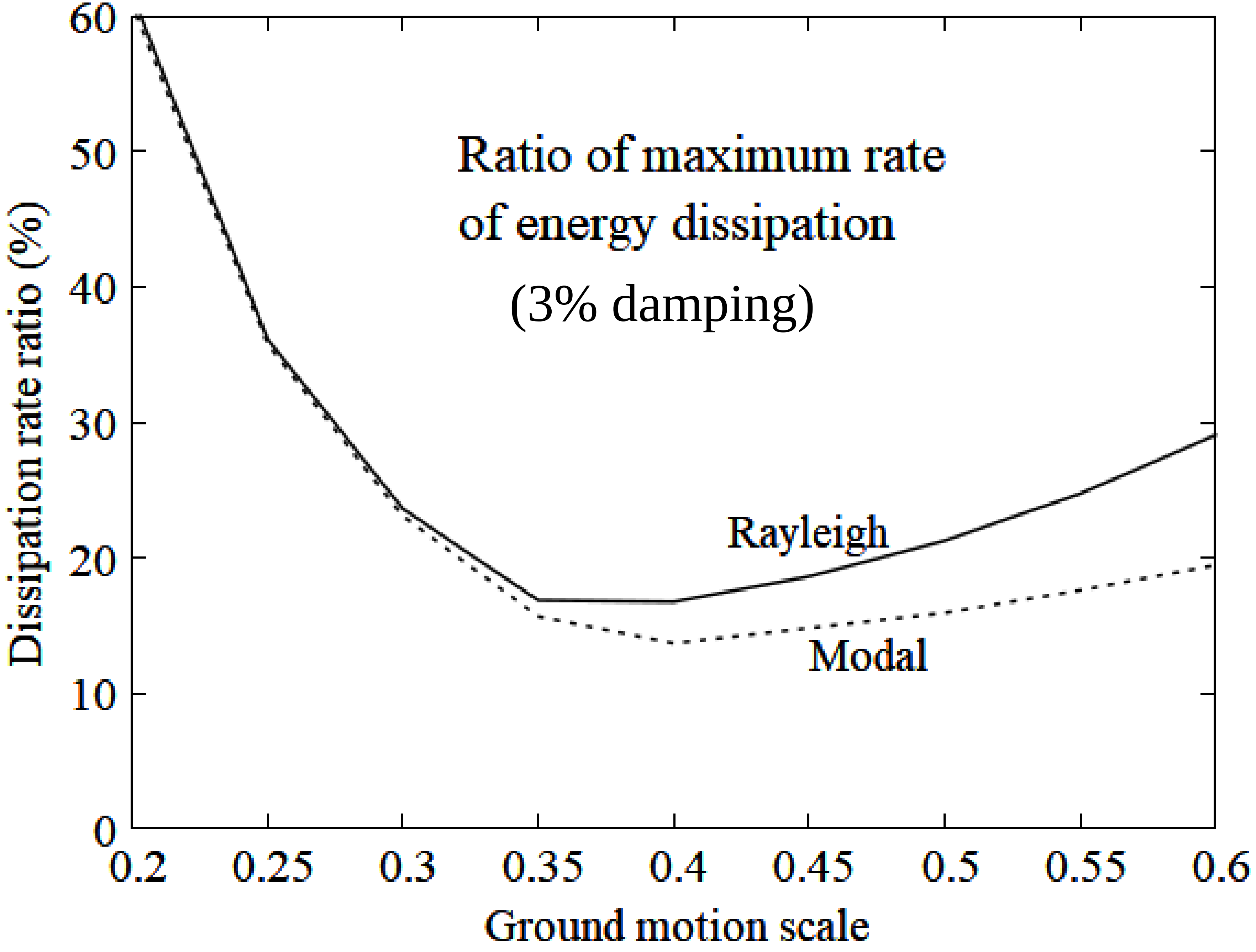
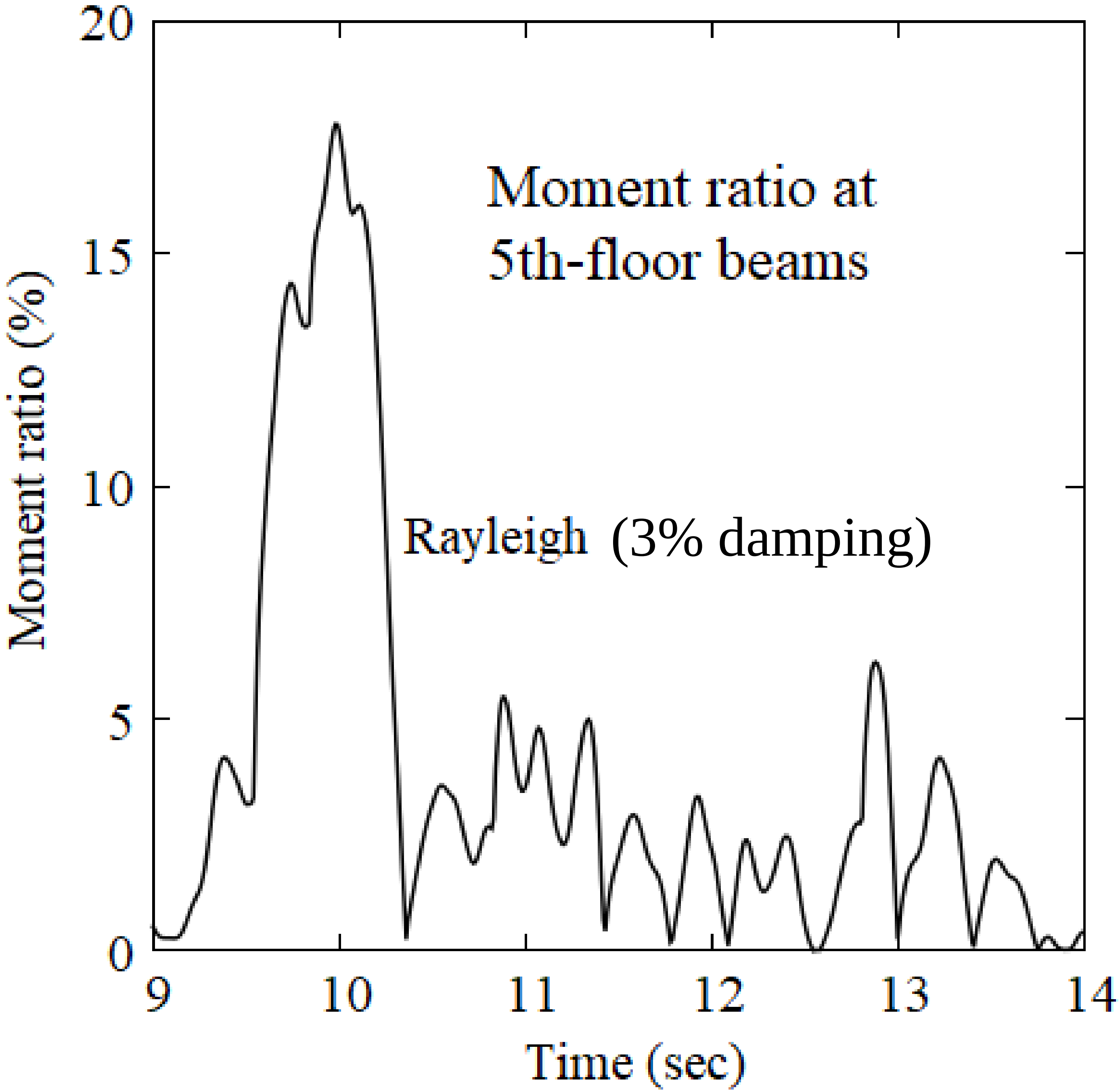
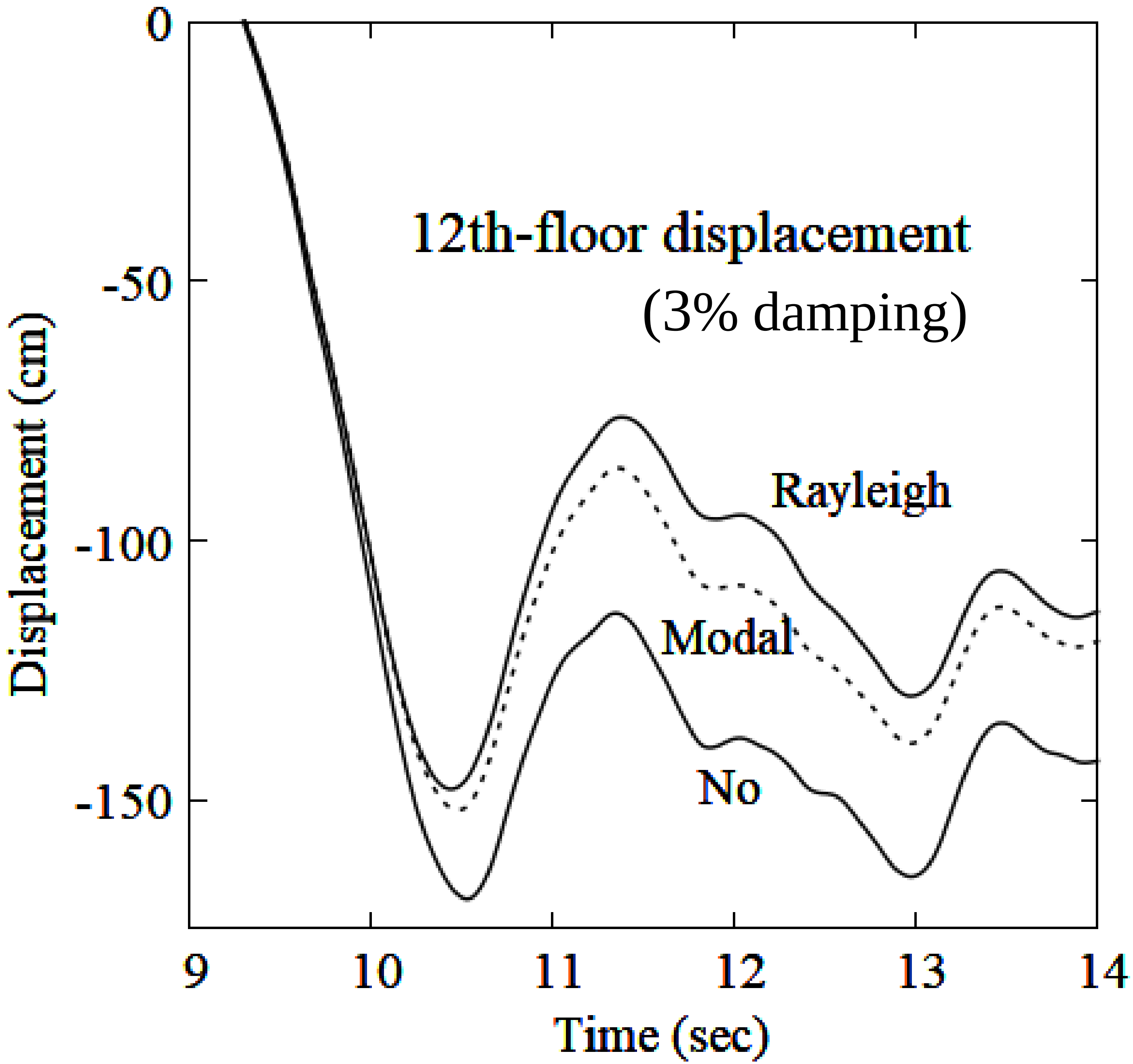
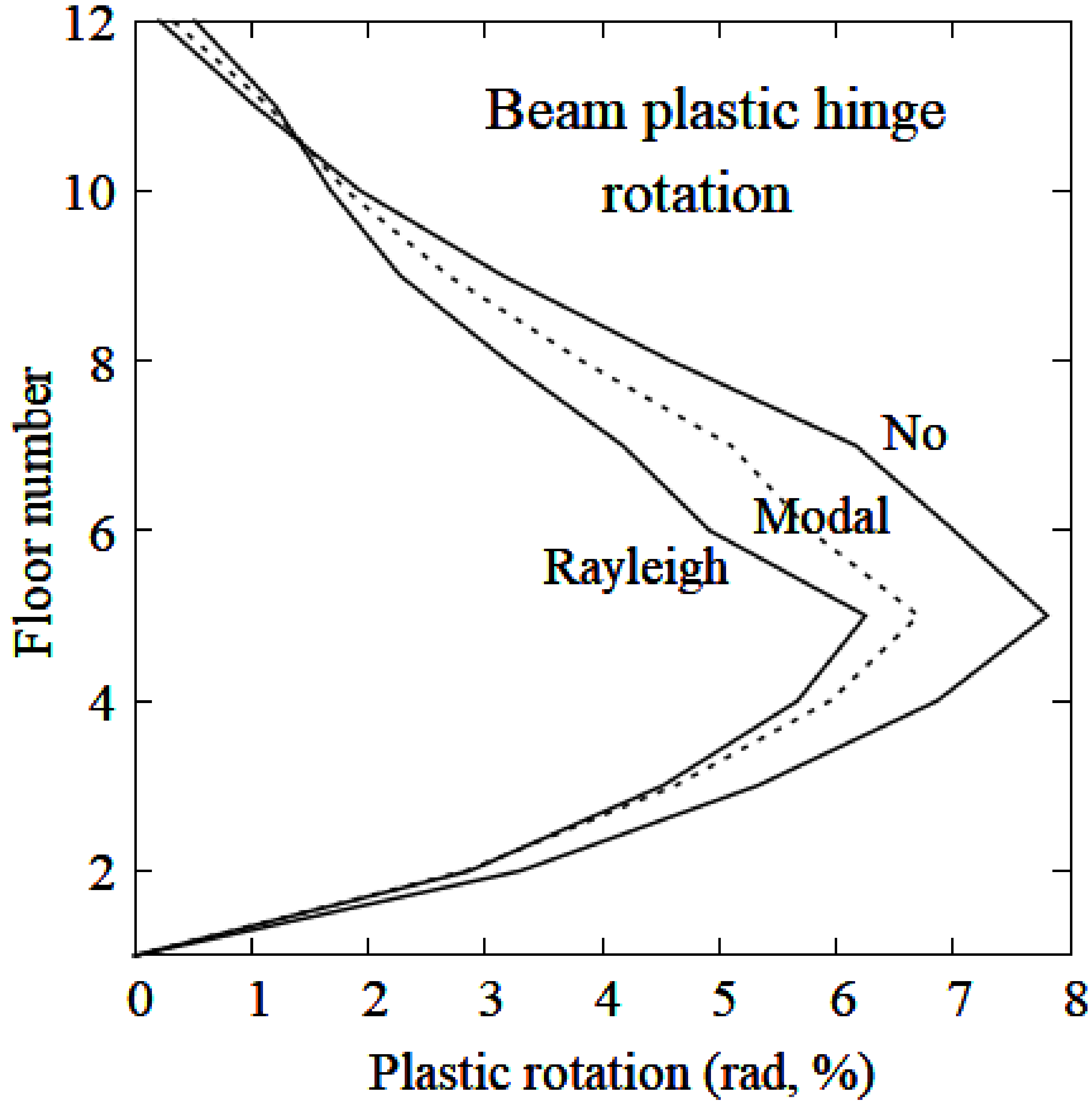

Ratio of maximum rate
of energy dissipation
(3% damping)
Rayleigh
Modal
Dissipation rate ratio (%)
Ground motion scale
0
10
20
30
40
50
60
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6

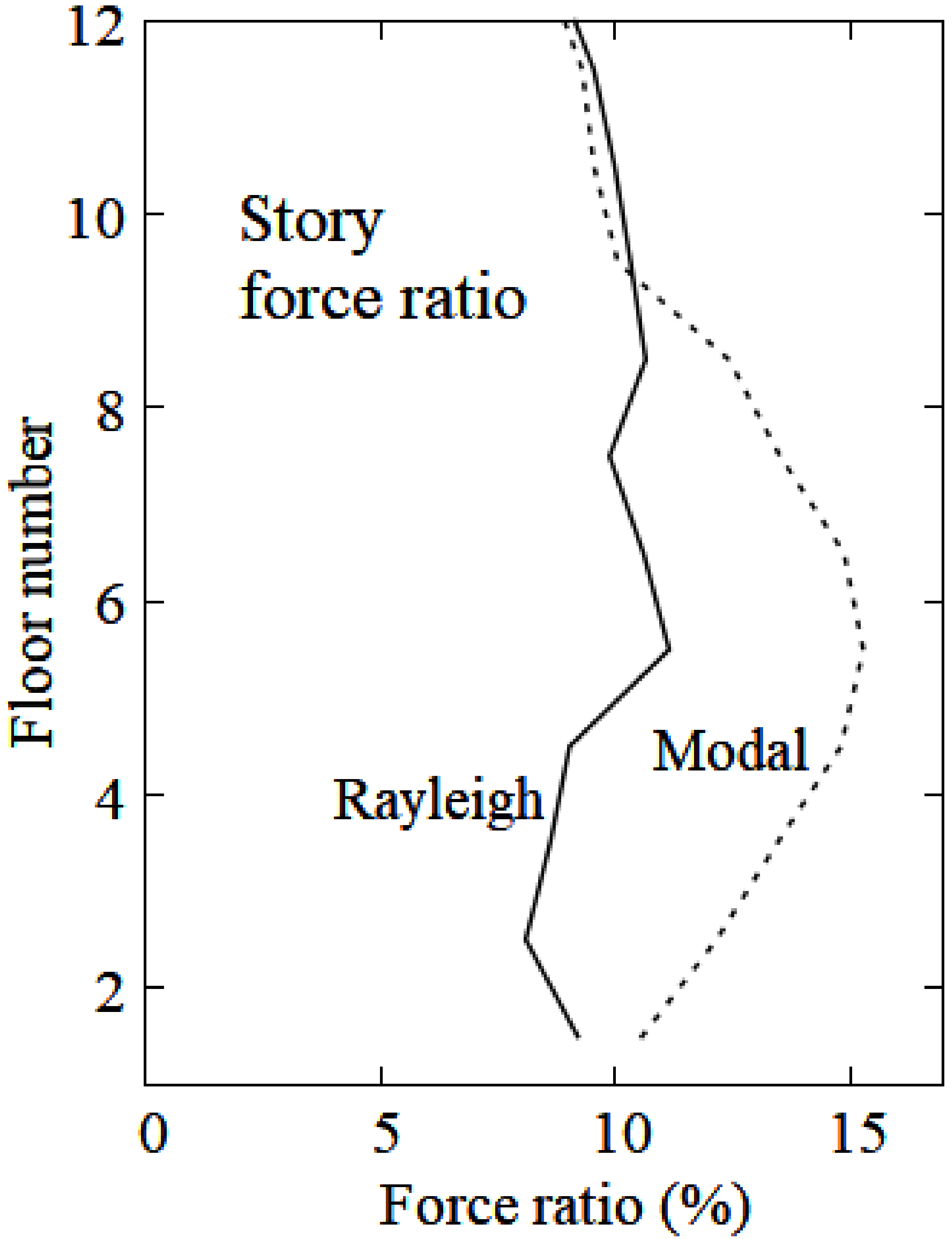


Moment ratio at
5th-floor beams
Rayleigh (3% damping)
Moment ratio (%)
Time (sec)
0
5
10
15
20
9
10
11
12
13
14



12th-floor displacement
(3% damping)
Rayleigh
Modal
No
Displacement (cm)
0
-50
-100
-150
9
10
11
12
13
14
Time (sec)


Beam plastic hinge
rotation
No
Modal
Rayleigh
Floor number
Plastic rotation (rad, %)
0
1
2
3
4
5
6
7
8
2
4
6
8
10
12



Story
force ratio
Modal
Rayleigh
Floor number
Force ratio (%)
0
5
10
15
2
4
6
8
10
12