

# Structural Analysis for Performance-Based Earthquake Engineering

- Basic modeling concepts
- Nonlinear static pushover analysis
- Nonlinear dynamic response history analysis
- Incremental nonlinear dynamic analysis
- Probabilistic approaches

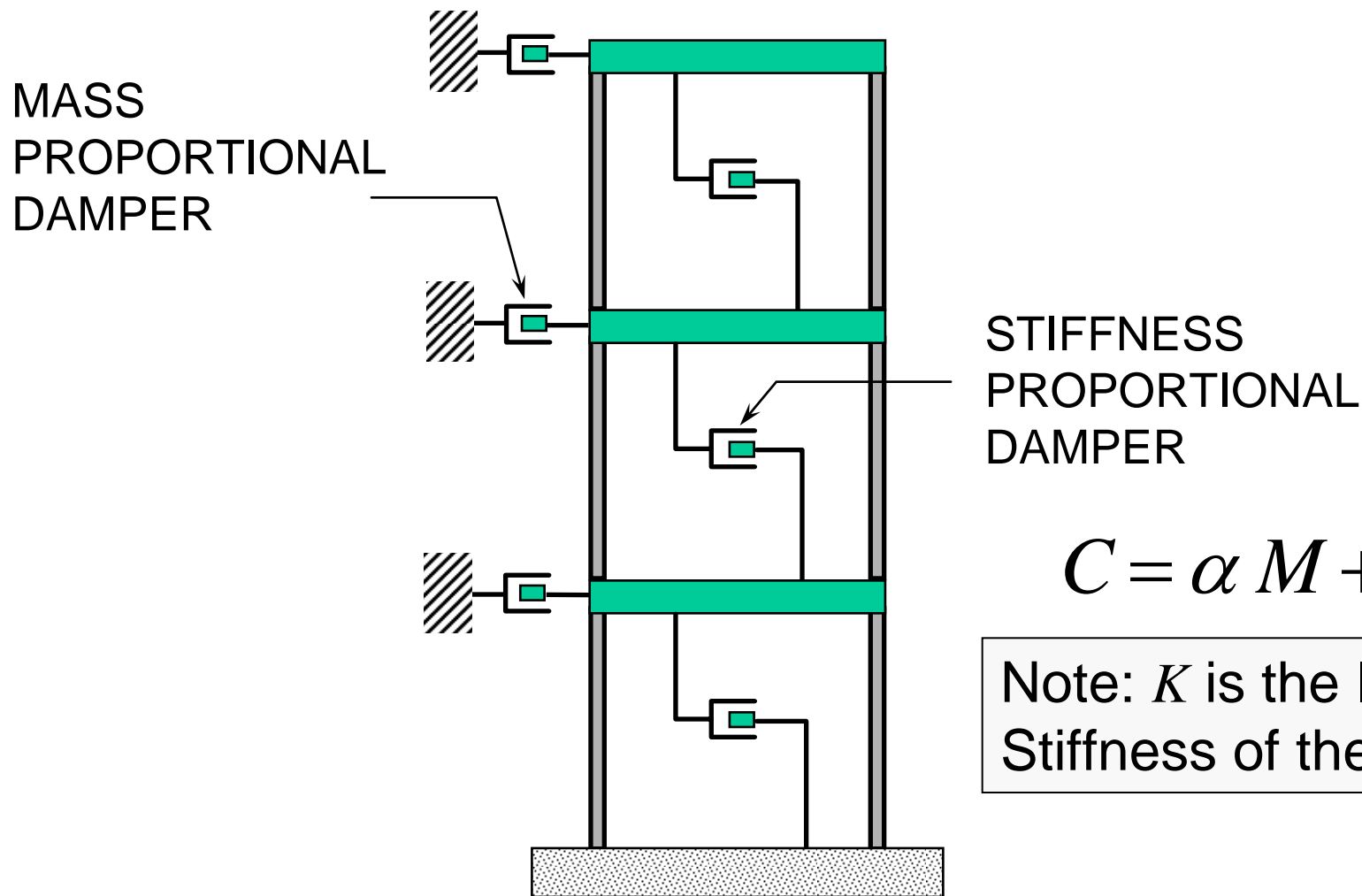
# Nonlinear Dynamic Response History Analysis

Principal Advantage: **All** problems with pushover analysis are eliminated. However, new problems may arise.

Main Concerns in Nonlinear Dynamic Analysis:

- 1) Modeling of hysteretic behavior
- 2) Modeling inherent damping
- 3) Selection and scaling of ground motions
- 4) Interpretation of results
- 5) Results may be very sensitive to seemingly minor perturbations

# Modeling Inherent Damping Using Rayleigh Proportional Damping



$$C = \alpha M + \beta K$$

Note:  $K$  is the INITIAL  
Stiffness of the system

# Rayleigh Proportional Damping

Select Damping value in two modes,  $\xi_k$  and  $\xi_n$

Compute Coefficients  $\alpha$  and  $\beta$ :

$$\begin{Bmatrix} \alpha \\ \beta \end{Bmatrix} = 2 \frac{\omega_k \omega_n}{\omega_n^2 - \omega_k^2} \begin{bmatrix} \omega_n & -\omega_k \\ -1/\omega_n & 1/\omega_k \end{bmatrix} \begin{Bmatrix} \xi_k \\ \xi_n \end{Bmatrix}$$

Form Damping Matrix  $C = \alpha M + \beta K$

# Rayleigh Proportional Damping (Example)

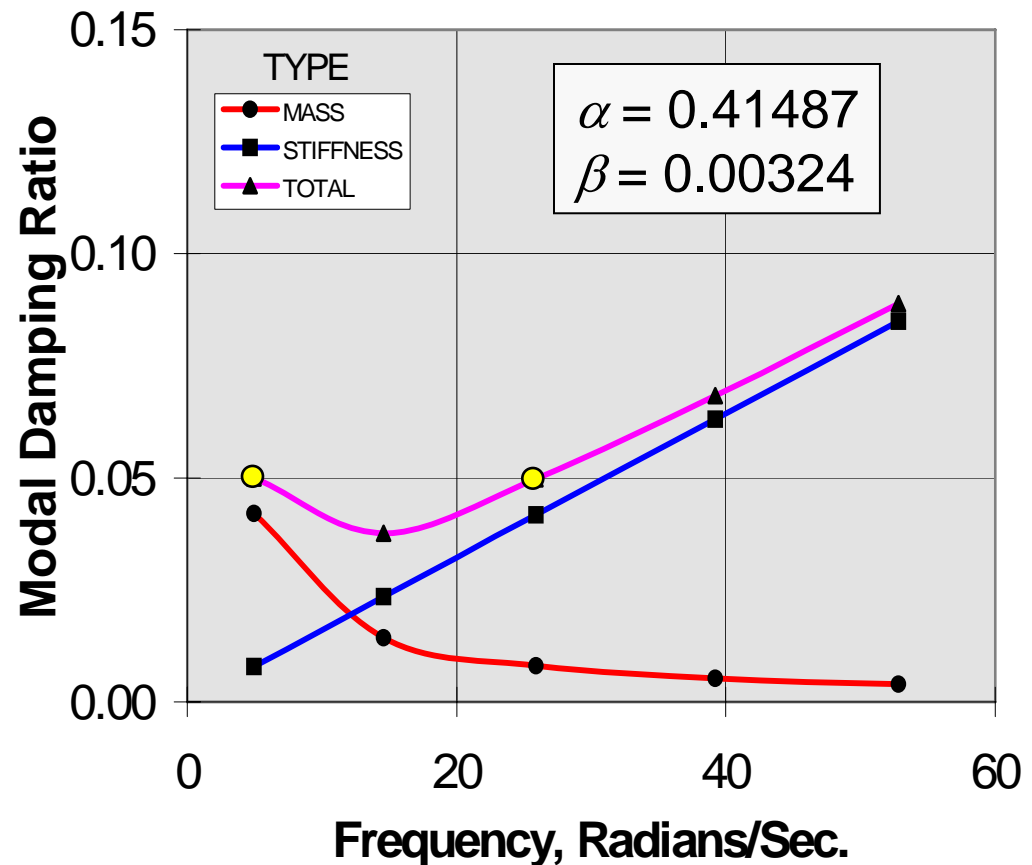
5% Critical in Modes 1 and 3

Damping in any other Mode  $m$ :

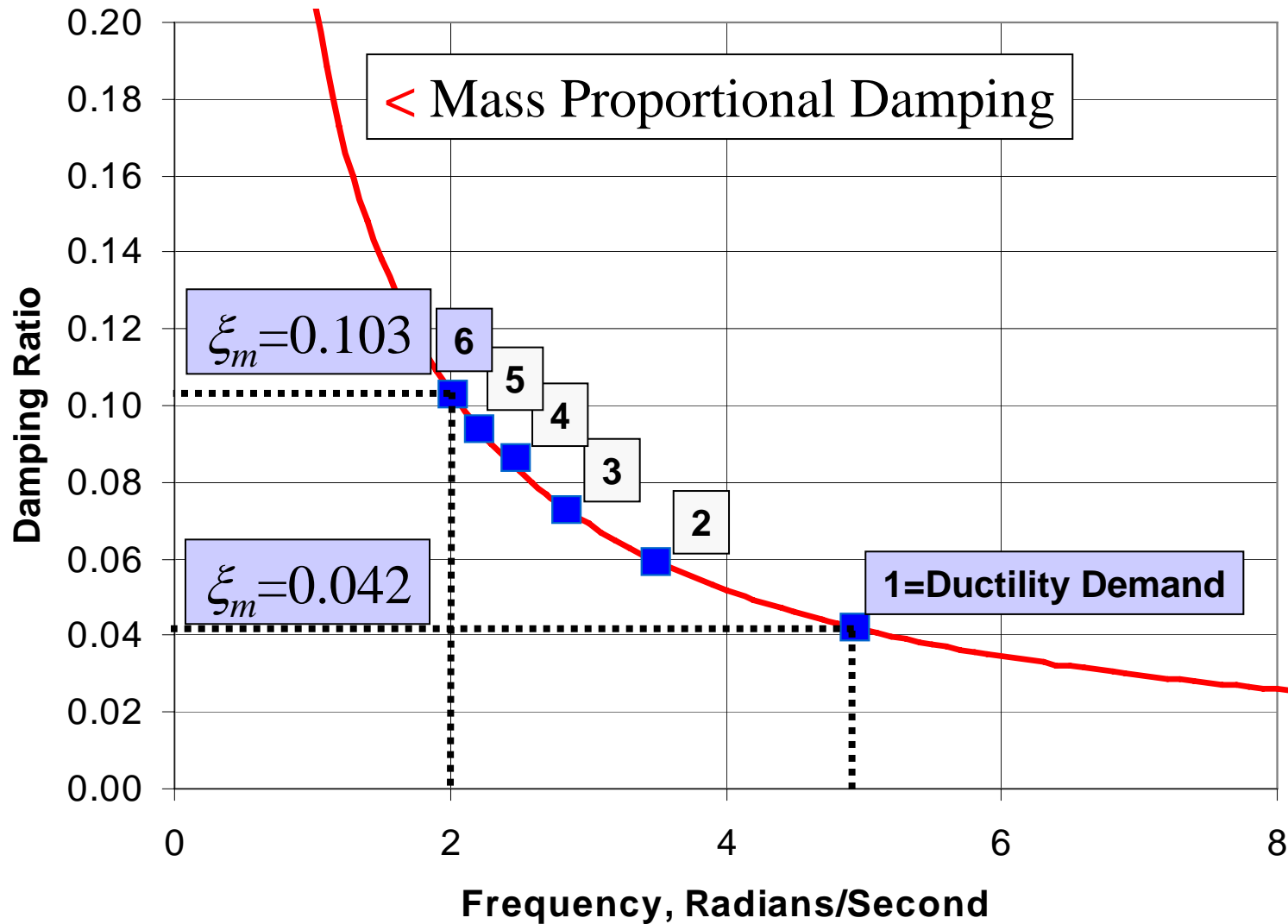
$$\xi_m = 0.5 \left[ \frac{1}{\omega_m} \quad \omega_m \right] \begin{Bmatrix} \alpha \\ \beta \end{Bmatrix}$$

Structural Frequencies

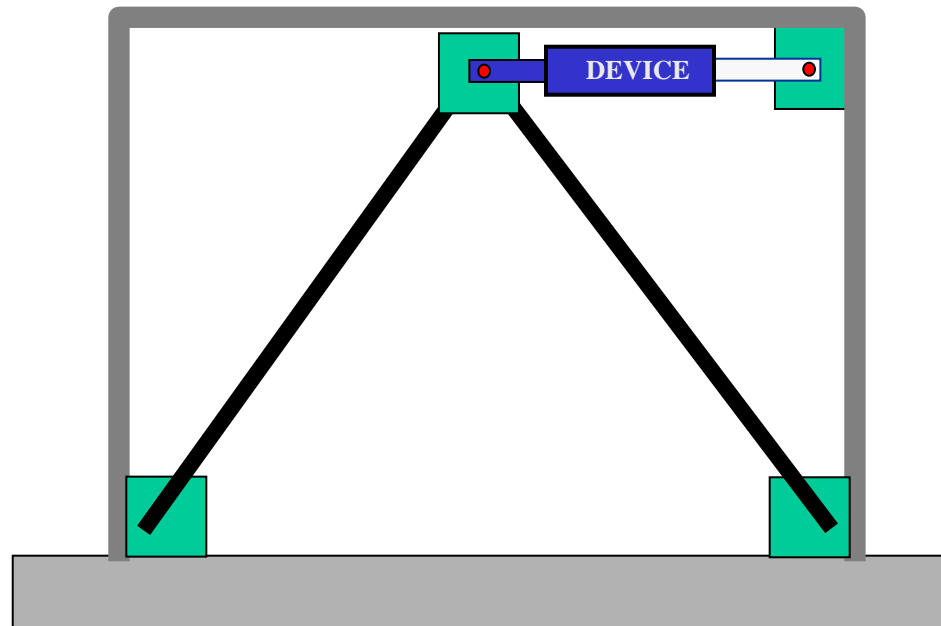
Mode	$\omega$
<b>1</b>	<b>4.94</b>
2	14.6
<b>3</b>	<b>25.9</b>
4	39.2
5	52.8



# Loss of stiffness, frequency shift, and higher mass proportional damping

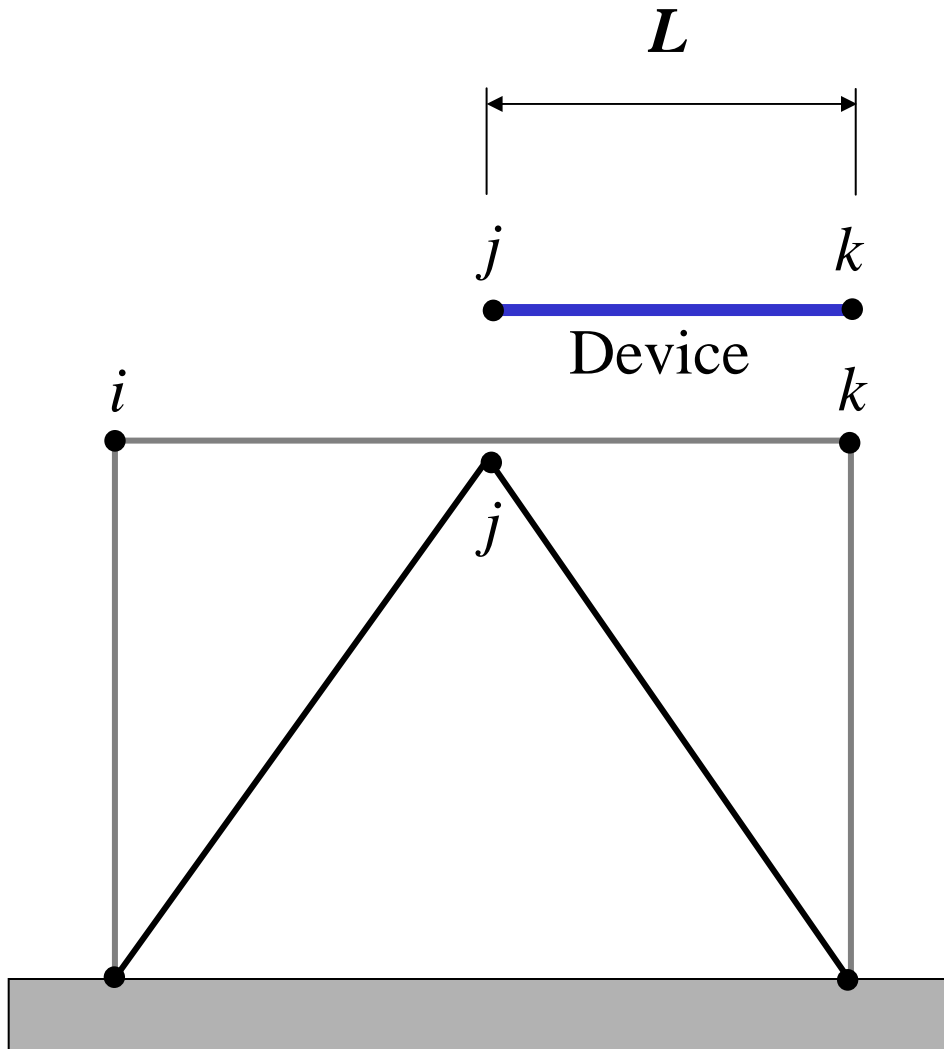


# Modeling Linear Viscous Dampers in DRAIN



**Note: Nonlinear Damping is NOT Available in DRAIN.**

# Modeling Linear Viscous Dampers in DRAIN



Use element stiffness proportional damping.

$$K_{Damper} = \frac{AE}{L}$$

$$C_{Damper} = \beta K_{Damper}$$

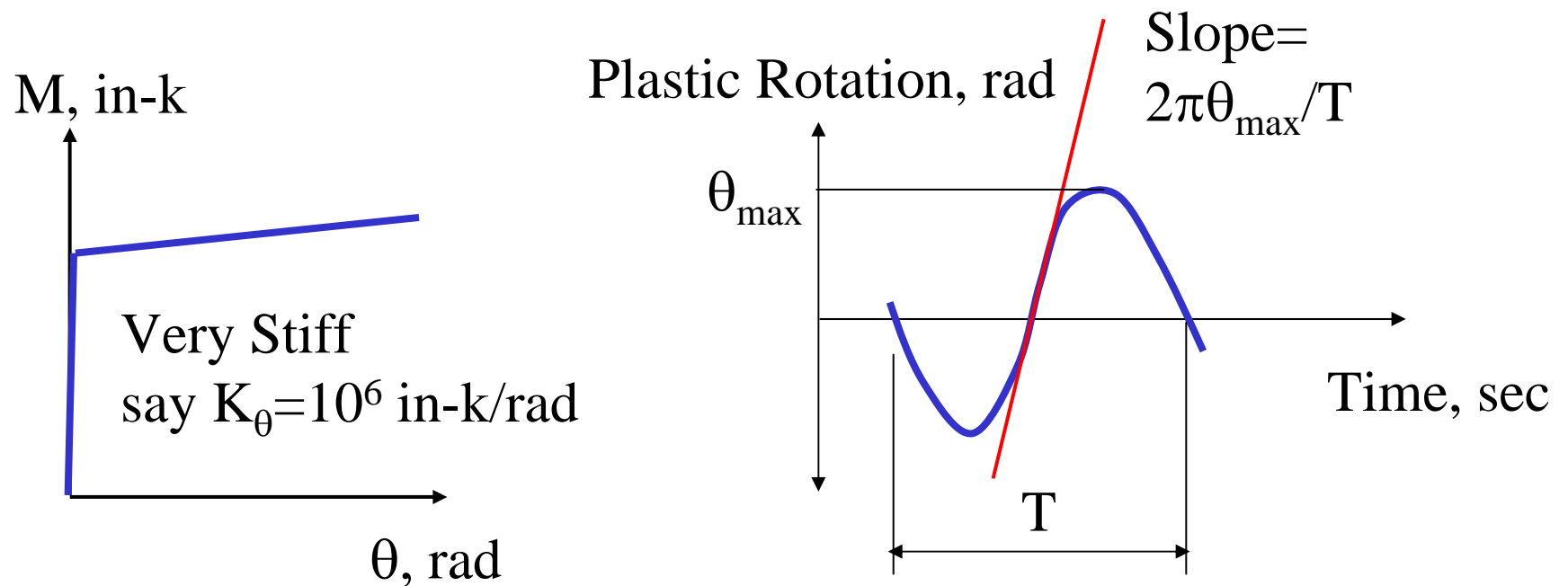
For low damper stiffness:  
Set  $A=L$ ,  $E=0.01$

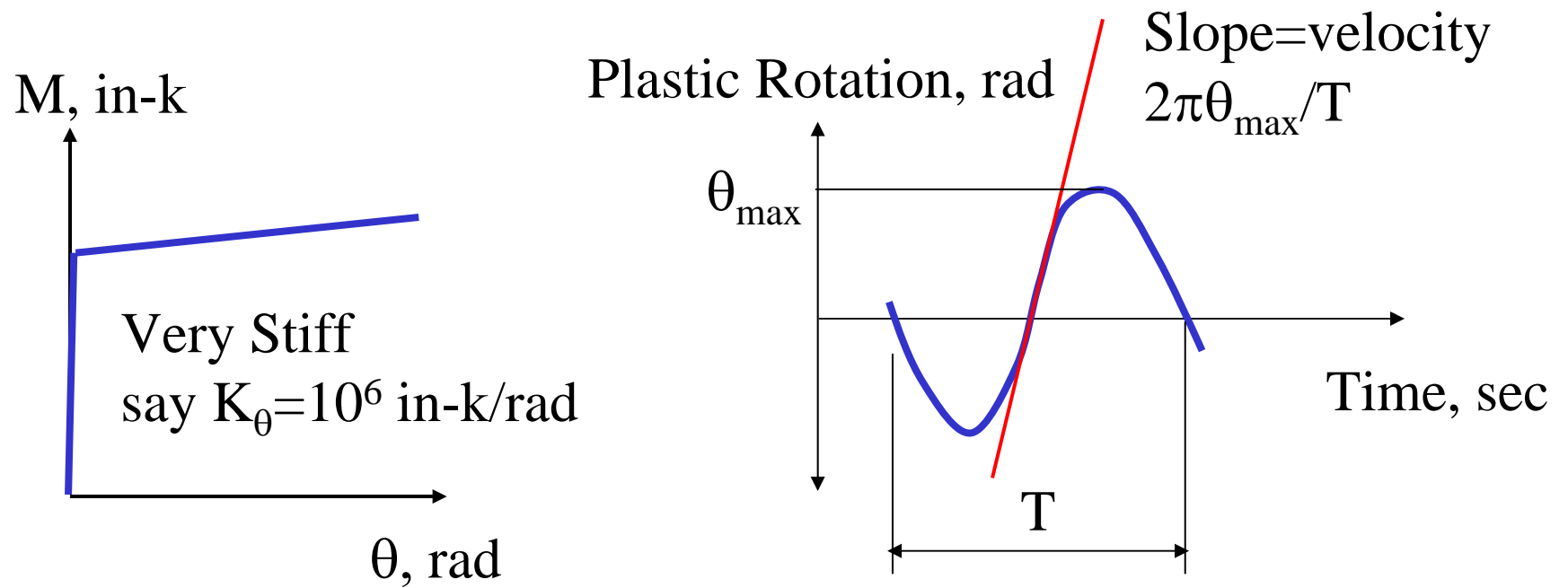
use  $\beta = C_{Damper}/0.01$



# Caution Regarding Stiffness Proportional Damping

**NEVER** use stiffness proportional damping in association with ANY elements that have artificially high stiffness and that may yield.





$$\text{Viscous Moment in Hinge} = K_{\theta}\beta (2\pi\theta_{\max}/T)$$

$$\text{Assume } \theta_{\max} = .03 \text{ rad, } T=1.0 \text{ sec, } \beta=0.004$$

$$M=10^6(0.004)(2\pi(.03)/1.0)=7540 \text{ in-k}$$

# NEHRP Ground Motion Selection

- Ground motions must have magnitude, fault mechanism, and fault distance consistent with the site and must be representative of the maximum considered ground motion
- Where the required number of motions are not available simulated motions (or modified motions) may be used

*(Parenthesis by F. Charney)*

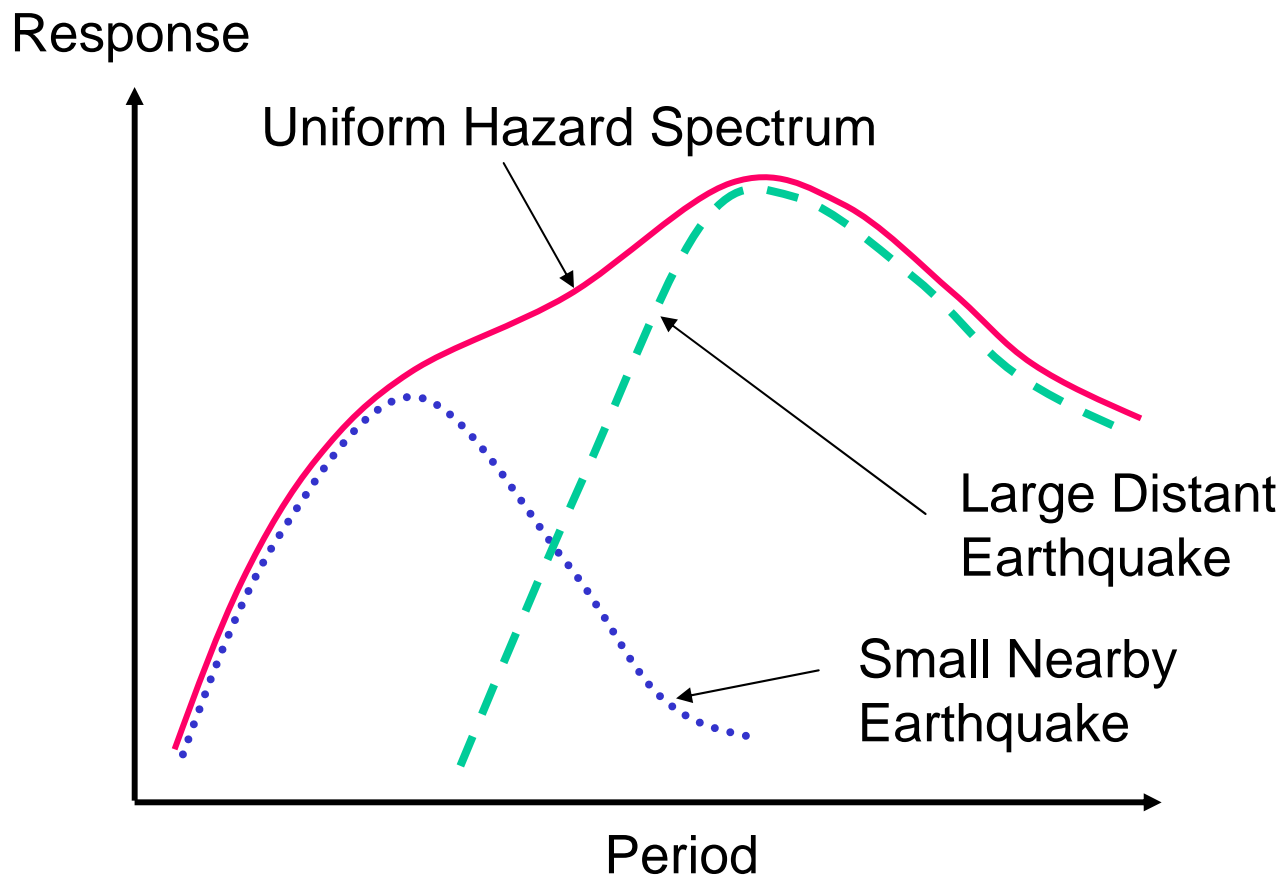
How many records should be used?

Where does one get the records?

How can the records be modified to match site conditions?

# Use of Simulated Ground Motions

Simulated records should **NOT** be used if they have been created on the basis of spectrum matching where the target spectrum is a uniform hazard spectrum.



# Use of Simulated Ground Motions

## Reference:

“On the use of Design Spectrum Compatible Time Histories”,  
by Farzad Naeim and Marshall Lew, Earthquake Spectra,  
Volume 11, No.1.

“Frequency domain scaled Design Spectrum Compatible Time Histories (DSCTH) are based on an erroneous understanding of the role of design spectra and can suffer from a multitude of major problems. They may represent velocities, displacements, and high energy content which are very unreliable. The authors urge extreme caution in the use of DSCTH in the design of earthquake resistant structures.”

# PEER Ground Motion Search Engine

**PEER Strong Motion Database**

[Introduction](#) [Browse](#) [Search](#) [Documentation](#) [Providers](#) [Credits](#)

**1: Search earthquake or station characteristics and peak values**

Earthquake: Any

Mechanism: Strike slip

Magnitude (Range): 6 - 7  ML  M  MS  Any

Distance (km): 50 - 100  Closest  Hypocentral  Projection of fault plane (JB distance)  Any

Site Classification: USGS: B 360 - 750 m/s

Geomatrix: B Shallow (stiff) soil

Taiwan CWB: Any

Mapped Local Geology: Any

Instrument Housing: Any

Data Source: Any

PGA (g): - Range 0.001 ... 2.086

PGV (cm/sec): - Range 0.1 ... 263.1

PGD (cm): - Range 0.01 ... 430.00

**2: Search response spectra**

Maximum Pseudo Acceleration (g): 2

PEER Strong Motion Plotter

PAA (g)

<http://peer.berkeley.edu/smcat/search.html>

# NONLIN Ground Motion Tools (EQTOOLS)

**GROUND MOTION TOOLS (Version 1.00)**

File Site Response Attenuation Transformation Window Help

**SEARCH EARTHQUAKE RECORDS**

Earthquake: Cape Mendocino 1992/04/25 18:06

Component: Horizontal (maximum PGA)

Mechanism: Reverse Normal

**Magnitude OR Peak Ground Acceleration (PGA)**

Magnitude (Range) 7.1 -   M  ML  MS  Other

PGA (g) 0.178 -  Range (0.001... 2.086)

Distance (Kilometers) 44.60 -   Closest  Hypocentral  Projection of Fault Plane

Site Classification (USGS) B

Data Source CDMG California Division of Mines and Geology

Search Restore Clear

Sort Options  Alphabetic  PGA  Magnitude  Distance

Searched Earthquakes **PGA: 0.178g ; Duration: 43.98 sec**

Cape Mendocino 1992/04/25 18:06, 4/25/1992 6:06:00 PM, 89E
Cape Mendocino 1992/04/25 18:06, 4/25/1992 6:06:00 PM, 89A
Cape Mendocino 1992/04/25 18:06, 4/25/1992 6:06:00 PM, 894
Cape Mendocino 1992/04/25 18:06, 4/25/1992 6:06:00 PM, 893
Cape Mendocino 1992/04/25 18:06, 4/25/1992 6:06:00 PM, 89C
Cape Mendocino 1992/04/25 18:06, 4/25/1992 6:06:00 PM, 89E
Cape Mendocino 1992/04/25 18:06, 4/25/1992 6:06:00 PM, 89E
Cape Mendocino 1992/04/25 18:06, 4/25/1992 6:06:00 PM, 89E
Cape Mendocino 1992/04/25 18:06, 4/25/1992 6:06:00 PM, 89E
Imperial Valley 1979/10/15 23:16, 10/15/1979 11:16:00 PM, 660
Imperial Valley 1979/10/15 23:16, 10/15/1979 11:16:00 PM, 286
Imperial Valley 1979/10/15 23:16, 10/15/1979 11:16:00 PM, 660
Imperial Valley 1979/10/15 23:16, 10/15/1979 11:16:00 PM, 505

Earthquakes for Study

Imperial Valley 1979/10/15 23:16, 10/15/1979 11:16:00 PM, 5051 P
Imperial Valley 1979/10/15 23:16, 10/15/1979 11:16:00 PM, 5051 P
Imperial Valley 1979/10/15 23:16, 10/15/1979 11:16:00 PM, 286 Su
Imperial Valley 1979/10/15 23:16, 10/15/1979 11:16:00 PM, 286 Su

Plot all records for study

Delete Record Clear List



# Uniform Hazard Spectrum Coordinates

Lat/Lon Lookup Output! - Microsoft Internet Explorer

Address <http://eqint.cr.usgs.gov/eq/cgi-bin/find-ll-1.cgi>

**USGS**  
Earthquake Hazards Program - National Seismic Hazard Mapping Project

The ground motion values for the requested point:  
LOCATION 37.13 Lat. -80.25 Long.  
DISTANCE TO  
NEAREST GRID POINT 5.55267024317058 kms  
NEAREST GRID POINT 37.10000 Lat.  
-80.30000 Long.  
Probabilistic ground motion values, in %g, at the Nearest Grid point are:

	10%PE in 50 yr	5%PE in 50 yr	2%PE in 50 yr
PGA	5.152937	9.119151	18.00517
0.2 sec SA	11.61050	18.64848	35.15003
0.3 sec SA	9.297289	15.16745	26.59287
1.0 sec SA	3.981873	6.260873	10.83363

-----

The program has detected a zero latitude and has assumed the end of valid input data.

PROJECT INFO: [Home Page](#)  
SEISMIC HAZARD: [Hazard by Lat/Lon](#)

<http://eqint.cr.usgs.gov/eq/html/lookup.shtml>






# Ground Motion Generator

USGS-National Seismic Hazard Mapping Project - Interactive Deaggregations - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Address http://eqint1.cr.usgs.gov/eq/html/deaggint.shtml





WEB SITE CONTENTS Go! RELATED SITES Go!

### INTERACTIVE DEAGGREGATIONS

On this page you may select a return time, SA frequency, specify a latitude and longitude and request seismograms. Links to the following information will be returned:

- A plot of deaggregated distance, magnitude and ground-motion uncertainty for the specified parameters (gif, pdf, ps).
- An ascii text file of the hazard matrices, containing, but not limited to, the frequency selected.
- A geographic deaggregation plot may also be specified (for designated frequencies only - see below). This is in addition to the plot mentioned above.
- An ascii text file and graph of the seismograms for the modal or mean event (if requested).

 **README** is a page containing information on how the deaggregation is done and about the input parameters to the program. It will increase your likelihood of success with this site if you read it first. [Stochastic Seismograms](#) and [What is Epsilon?](#) are articles which discuss the theory behind the seismograms.

 On some browsers you have to click on a pre-selected item in a list to deselect it. If you select an item without doing this you will have two items on the list selected and you will get a broken icon instead of a plot!

<p><b>Site name:</b> <i>Used for plot labeling purposes only</i> underscore ( _ ), comma ( , ) and alphanumeric characters only, <b>no blanks (they will be replaced with an underscore),</b> name length &lt;= 16 characters.</p> <p>Blacksburg</p>	<p><b>Select location of interest in latitude/longitude:</b> Specify in decimal degrees, use " - " to specify western longitudes. <b>Continous US:</b> latitude 25 to 49 degrees, longitude -125 to -65 degrees, only. <b>Alaska:</b> latitude 51 to 71 degrees, longitude -171 to -130 degrees, only. <b>Hawaii:</b> latitude 18 to 23 degrees, longitude -161 to -154 degrees, only.</p> <p>Latitude: 37.13 Longitude: -80.25</p>
<p><b>Return time:</b> <b>PE</b> = probability of exceedance Select one!</p> <p>1% PE in 50 years 2% PE in 50 years 5% PE in 50 years 10% PE in 50 yrs</p>	<p><b>SA frequency:</b> <b>SA</b> = Spectral Acceleration, <b>PGA</b> = peak ground acceleration. 0.5hz, 2.0hz and 10hz are not available for Hawaii.</p> <p>0.5 hz 1.0 hz 2.0 hz 3.33 hz</p>
<p><b>Geographic Deaggregation:</b> This is only available for the following SA frequencies: pga, 1.0 hz, 3.33 hz and 5.0 hz. Not available for Alaska or Hawaii.</p> <p><input type="radio"/> Yes <input checked="" type="radio"/> No</p>	<p><b>Seismograms:</b> Do you want seismograms for the <b>Modal or Mean</b> event?</p> <p><input type="radio"/> Yes, Modal <input checked="" type="radio"/> Yes, Mean <input type="radio"/> No</p>

It may take several minutes to generate the plot(s) and do file conversions  
!!! BE PATIENT !!!

GENERATE PLOT(S) and DATA

These maps are generated using THE GENERIC  
<http://gmt.soest.hawaii.edu/>

## http://eqint1.cr.usgs.gov/eq/html/deaggint.shtml

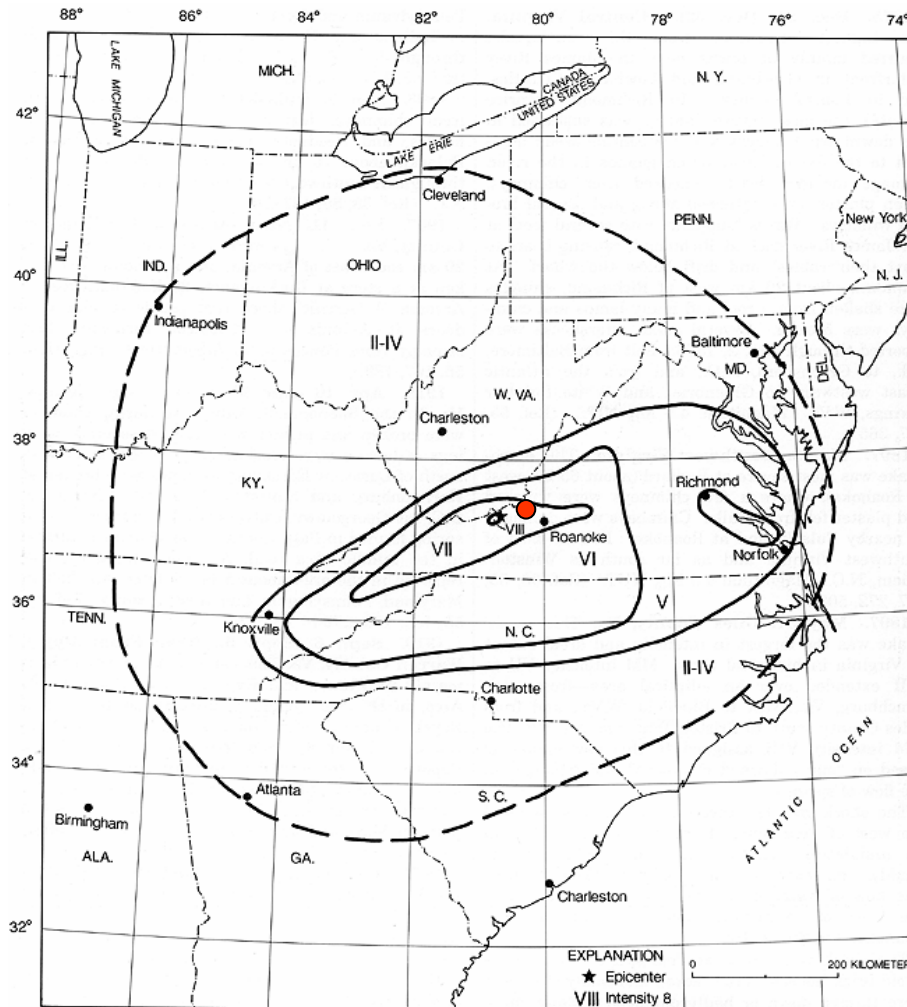


FEMA

Topics in Performance-Based Earthquake Engineering

Advanced Analysis 15 – 5c - 17

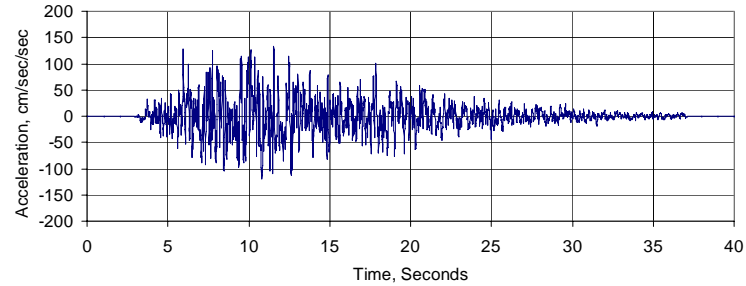
# Isoseismal Map for the Giles County, Virginia, Earthquake of May 31, 1897.



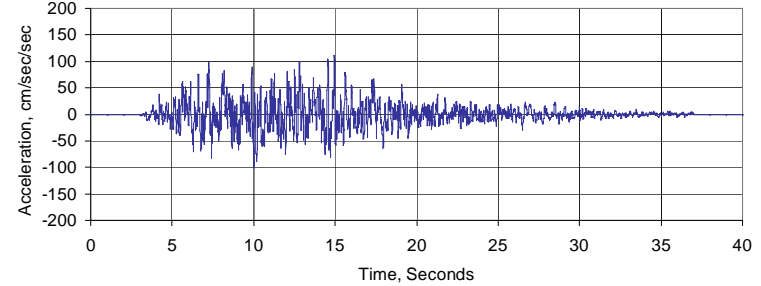
● Blacksburg  
N 37.1  
W -80.25

# Blacksburg 2%-50 Ground Motions from USGS Web Site

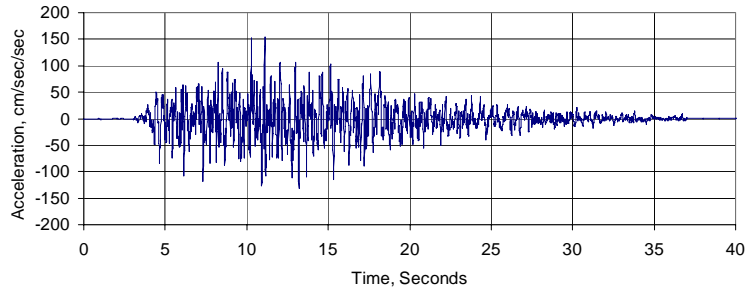
MOTION 1



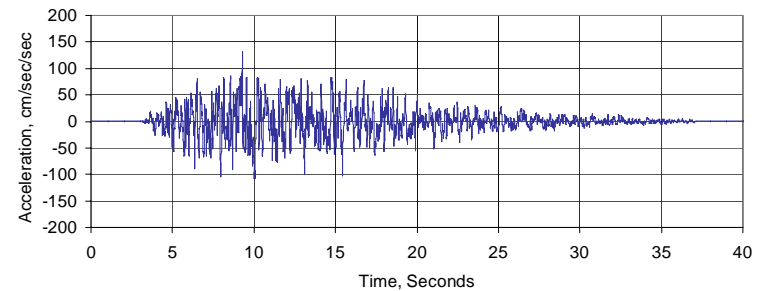
MOTION 4



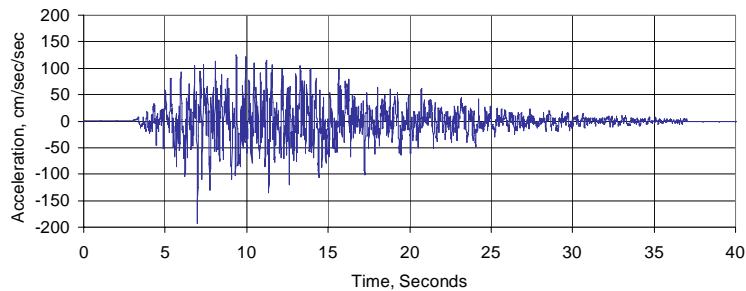
MOTION 2



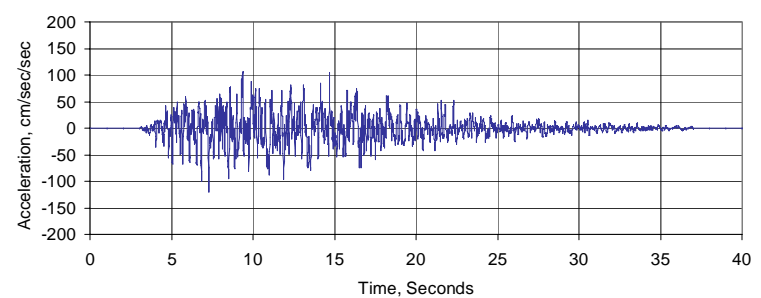
MOTION 5



MOTION 3

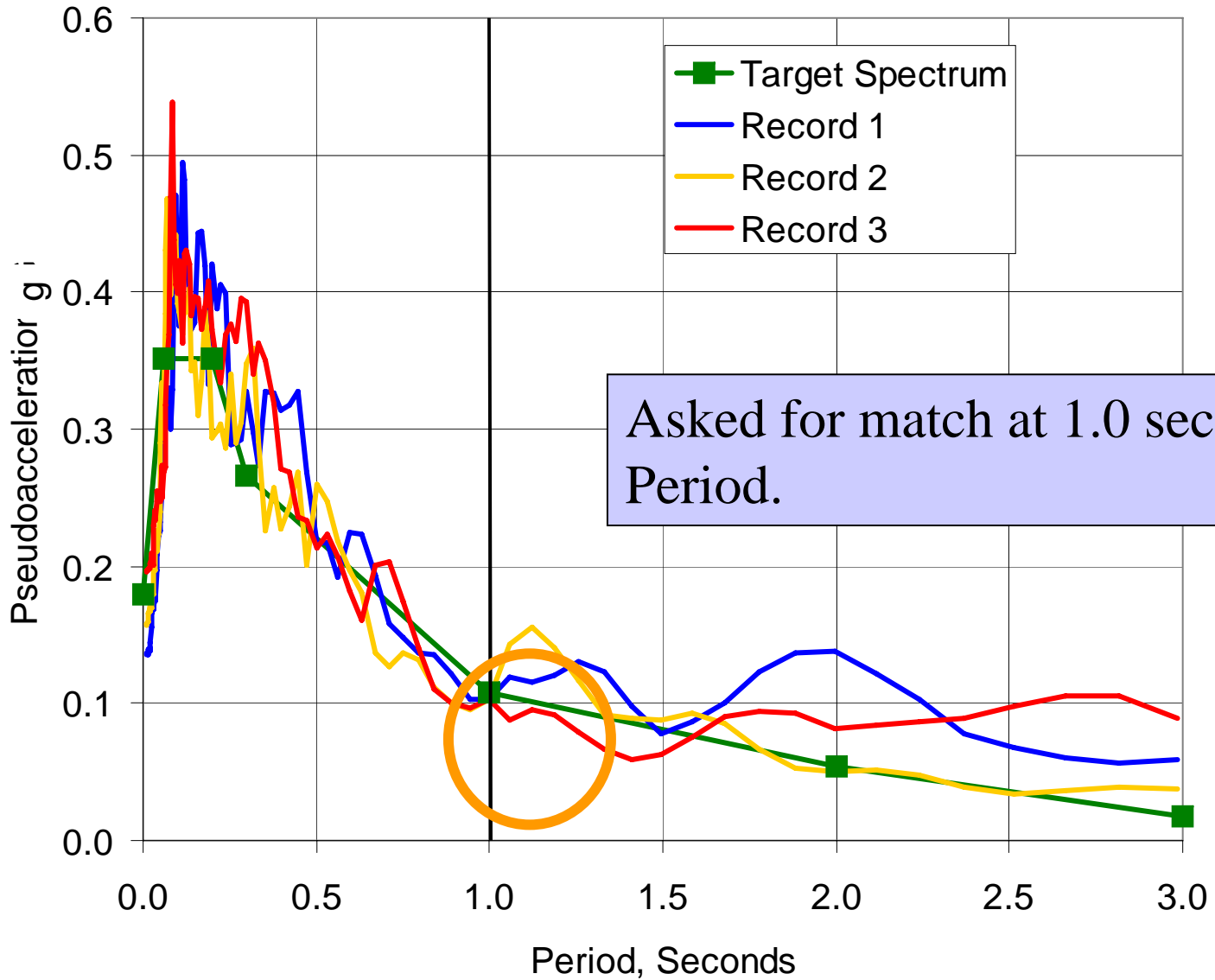


MOTION 6

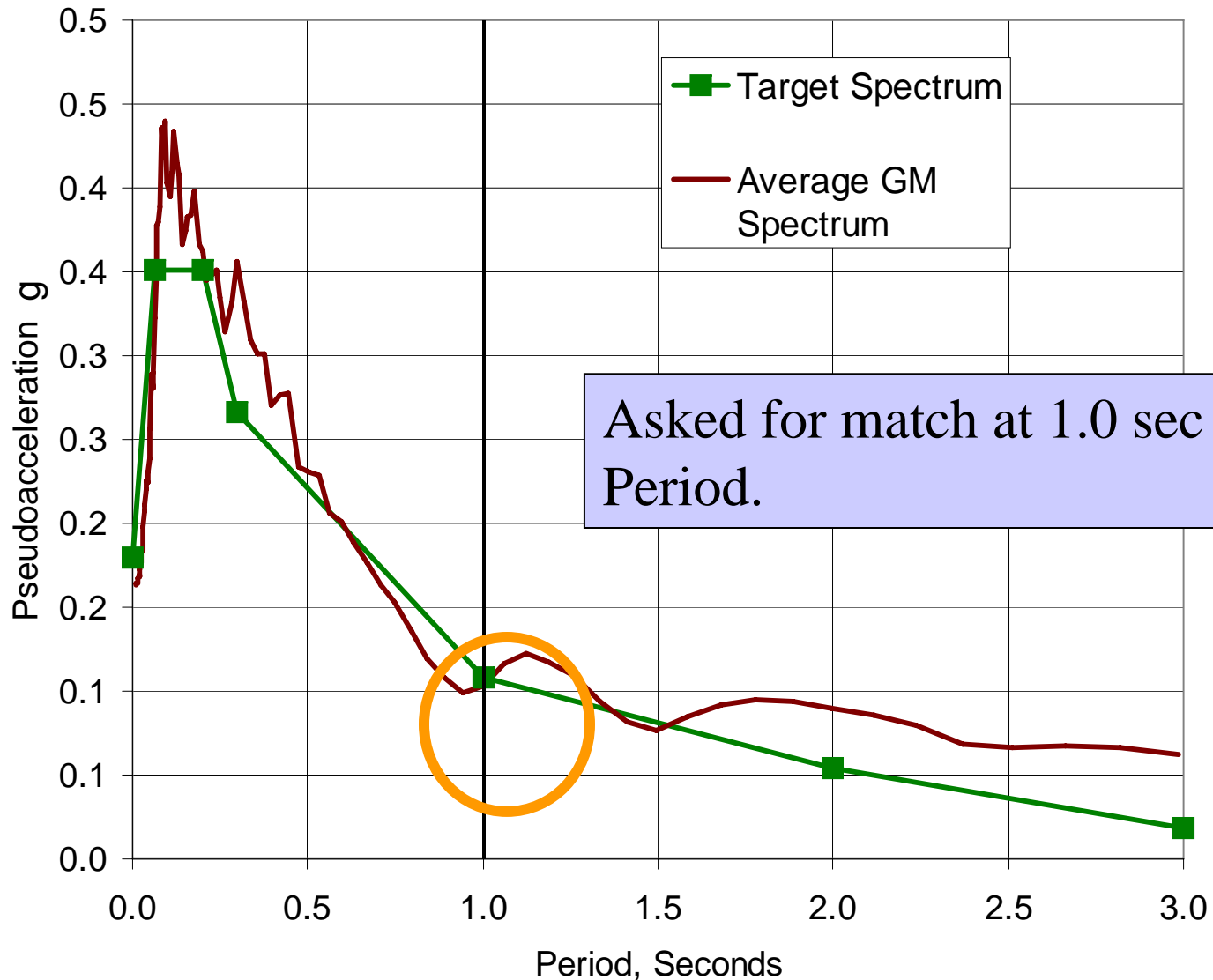


FEMA

# USGS Ground Motion Spectra and Target Spectrum



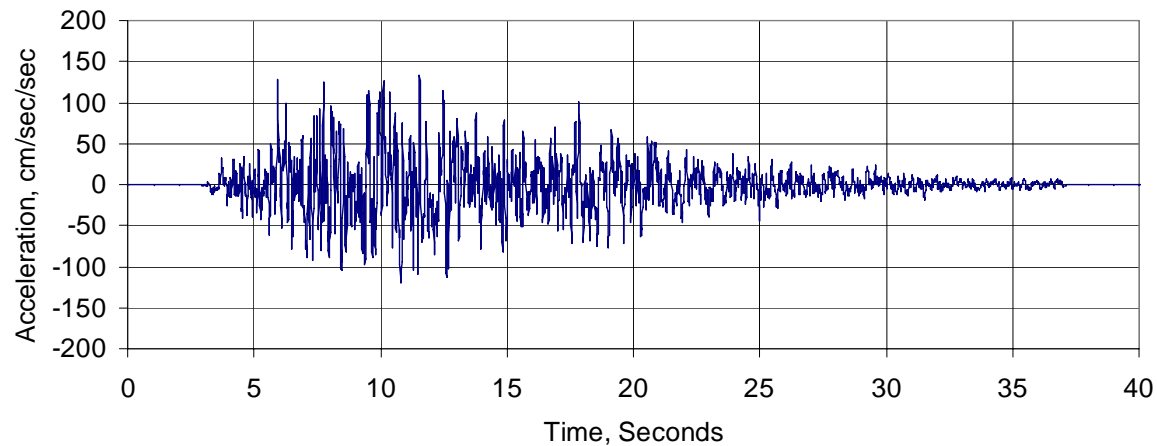
# Average USGS Ground Motion Spectrum and Target Spectrum



# Ground Modification Modifications

1. Scale a given record to a higher or lower acceleration (e.g to produce a record that represents a certain hazard level)
2. Modify a record for distance
3. Modify a record for site classification (usually from hard rock to softer soil)
4. Modify a record for fault orientation

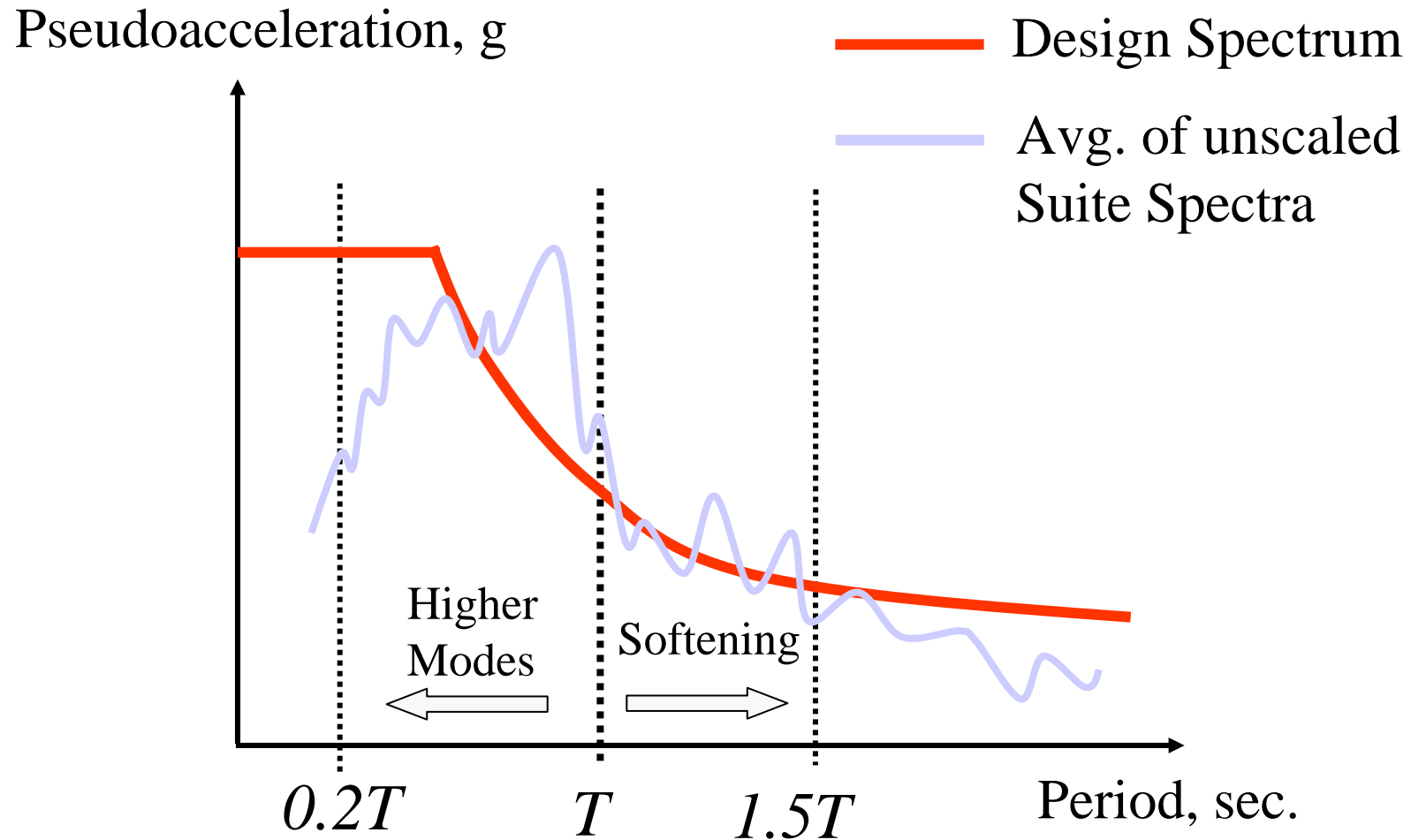
MOTION 1



# NEHRP Ground Motion Scaling (2-D Analysis)

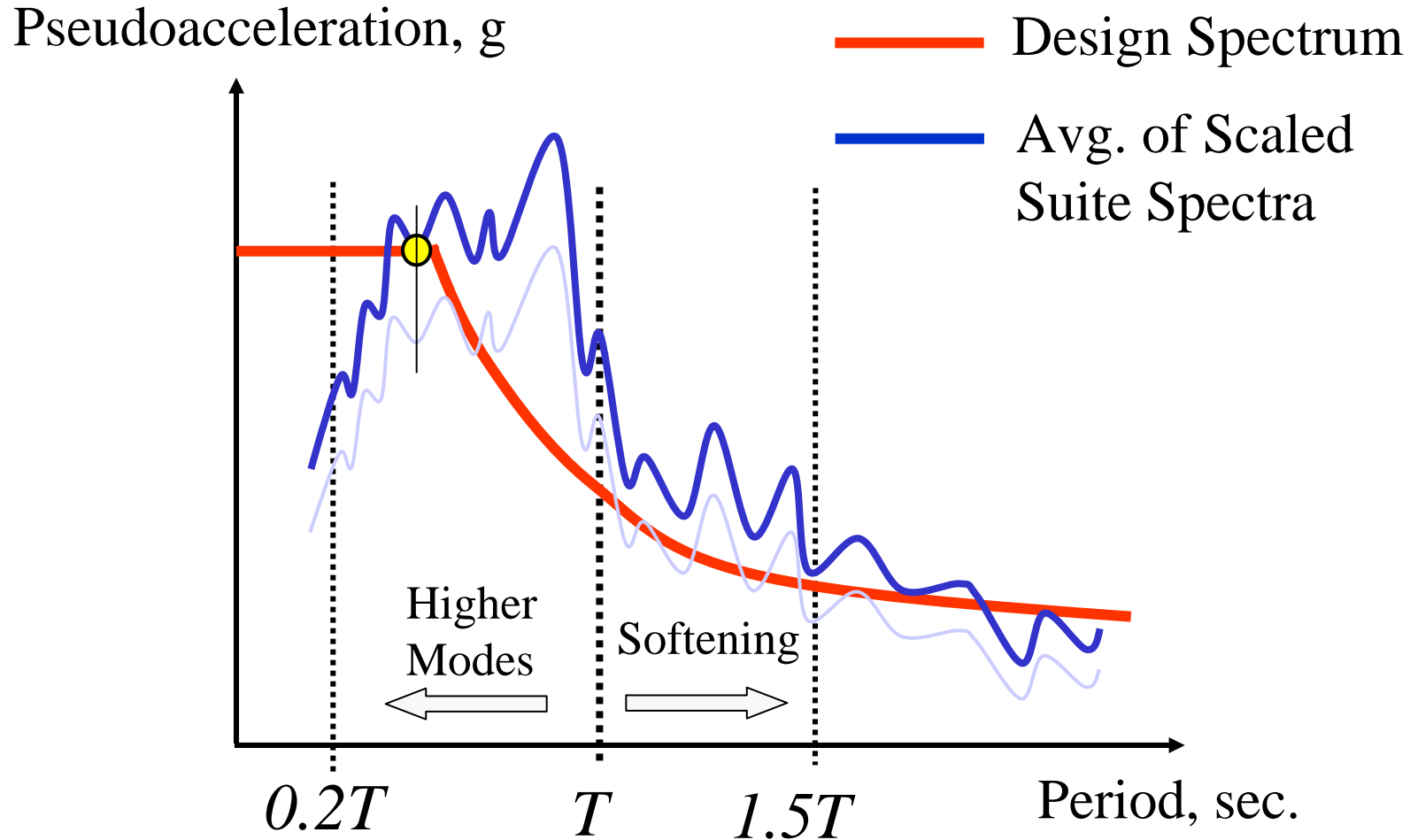
Ground motions must be scaled such that the average value of the 5% damped response spectra of the suite of motions is not less than the design response spectrum in the period range  $0.2T$  to  $1.5T$ , where  $T$  is the fundamental period of the structure.

# NEHRP Scaling for 2-D Analysis





# NEHRP Scaling for 2-D Analysis



# NEHRP Ground Motion Selection and Scaling (3-D Analysis)

1. The Square Root of the Sum of the Squares of the 5% damped spectra of each motion pair (N-S and E-W components) is constructed.
2. Each pair of motions should be scaled such that the average of the SRSS spectra of all component pairs is not less than 1.3 times the the 5% damped design spectrum in the period range 0.2 to 1.5 T.

# Potential Problems with NEHRP Scaling

- A degree of freedom exists in selection of individual motion scale factors, thus different analysts may scale the same suite differently.
- The scaling approach seems overly weighted towards higher modes.
- The scaling approach seems to be excessively conservative when compared to other recommendations (e.g. Shome and Cornell)

# How Many Records to Use?

## *NEHRP Recommended Provisions:*

- 5.6.2 A suite of not less than three motions shall be used
- 5.6.3 If at least seven ground motions are used evaluation may be based on the average responses from the different analyses. If less than seven motions are used the evaluation must be based on the maximum value obtained from all analyses.

# Normalization and Scaling Accelerograms For Nonlinear Analysis

Nilesh Shome and Allin Cornell  
6<sup>th</sup> U.S. Conference on Earthquake Engineering  
Seattle, Washington, September, 1997



# Ground Motion Scaling for Nonlinear Analysis

(Shome and Cornell)

## ***Bin:***

A suite of ground motions with similar source, distance, and magnitude.

## ***Bin Normalization:***

Adjusting individual bin records to the same “intensity”

## ***Bin Scaling:***

Adjusting records from one bin (say a lower magnitude) to the intensity of the records from a different (usually higher) intensity bin.

# Normalization Procedures

(Shome and Cornell)

- Normalize to PGA (NOT RECOMMENDED)
- Normalize to a Single Frequency at low damping (e.g. 2%)
- Normalize to a Single Frequency at a higher damping (e.g 5% to 20%) (RECOMMENDED)
- Normalize over a Range of Frequencies

# How Many Records to Use?

(Shome and Cornell)

For records normalized to first mode spectral acceleration it may typically require about **4 to 6 records** to obtain about a one sigma (plus or minus 10 to 15 percent) confidence band.



# Can records from a low intensity bin be scaled to represent higher intensity earthquakes?

(Shome and Cornell)

When the records are scaled from one intensity level to a higher intensity there is a mild dependency of scaling on computed ductility demand. The median ductility demand may vary 10 to 20 percent for one unit change in magnitude. *The effect of scaling on nonlinear hysteretic energy demand is more significant.*

# Recommendations (Charney):

- 1) Use a minimum of seven ground motions
- 2) If near-field effects are possible for the site a separate set of analyses should be performed using only near field motions
- 3) Try to use motions that are magnitude compatible with the design earthquake
- 4) Scale the earthquakes such that they match the target spectrum at the structure's initial (undamaged) natural frequency and at a damping of at least 5% critical.

# Ground Modification Modifications

1. **Scale a given record to a higher or lower acceleration (e.g to produce a record that represents a certain hazard level)**
2. Modify a record for distance (SRL Attenuation Issue)
3. Modify a record for site classification, usually from hard rock to softer soil. (WAVES by Hart and Wilson)
4. Modify a record for fault orientation (Somerville, et al)

See Also: *Ground Motion Evaluation Procedures for Performance Based Design*, by J.P. Stewart, et al, PEER Report 2001/09

# Damage Prediction

Performance based design requires a quantification of the damage that might be incurred in a structure.

The “damage index” must be calibrated such that it may predict and quantify damage at all performance levels.

While inter-story drift and inelastic component deformation may be useful measures of damage, a key characteristic of response is missing... the effect of the duration of ground motion on damage.

A number of different damage measures have been proposed which are dependent on duration.

# Damage Prediction

Park and Ang (1985)

$$DI_{PA} = \frac{u_{max}}{u_{cap}} + \lambda \frac{E_H}{u_{cap} F_y}$$

$u_{max}$  = maximum attained deformation

$u_{cap}$  = monotonic deformation capacity

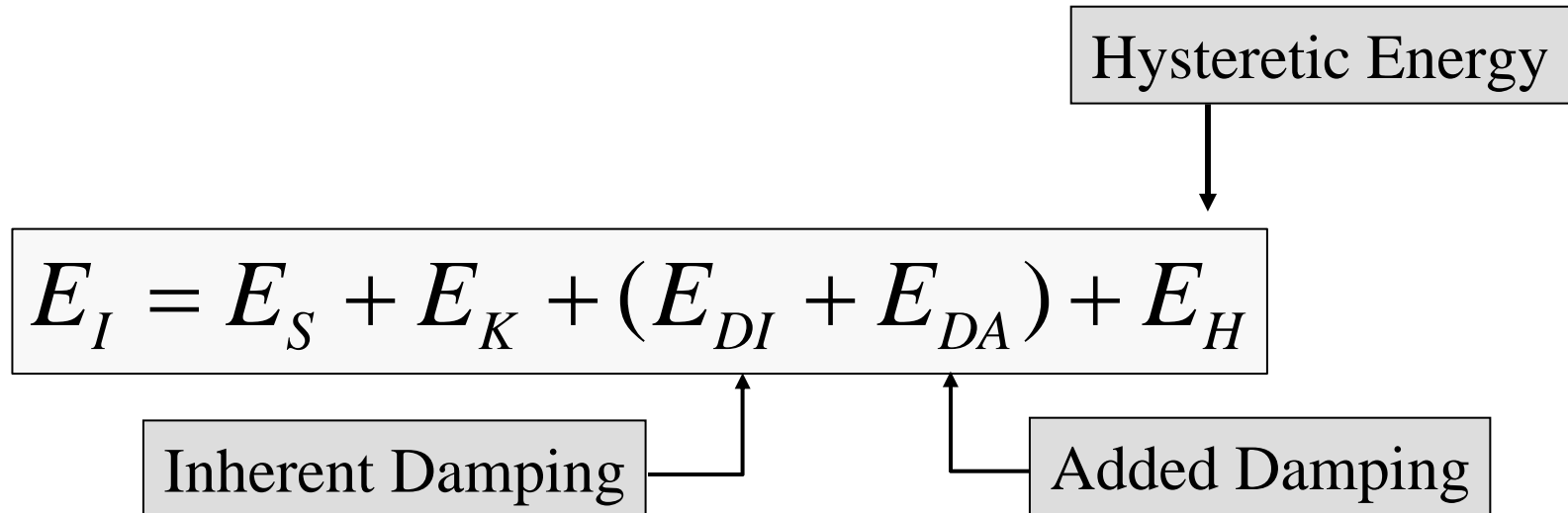
$E_H$  = hysteretic energy dissipated

$F_y$  = monotonic yield strength

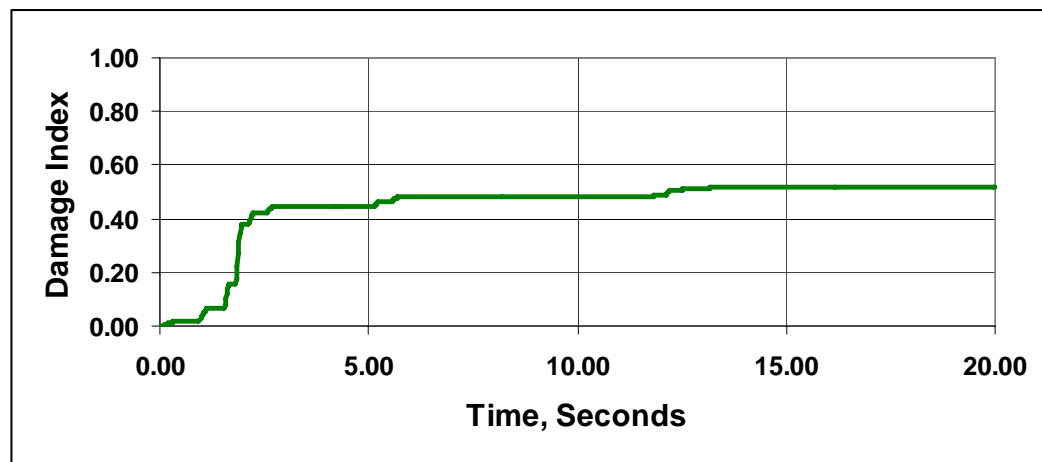
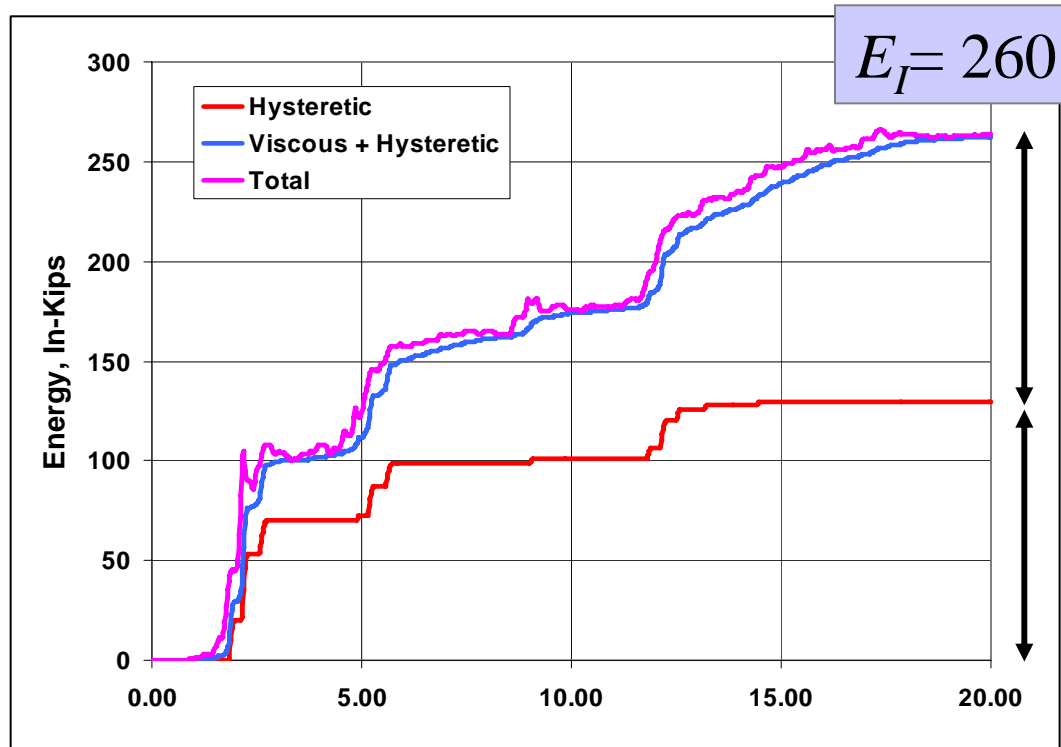
$\lambda$  = calibration factor

See Reference List for  
Additional Info on Damage Measures

# Energy Balance



# Energy and Damage Histories, 5% Damping

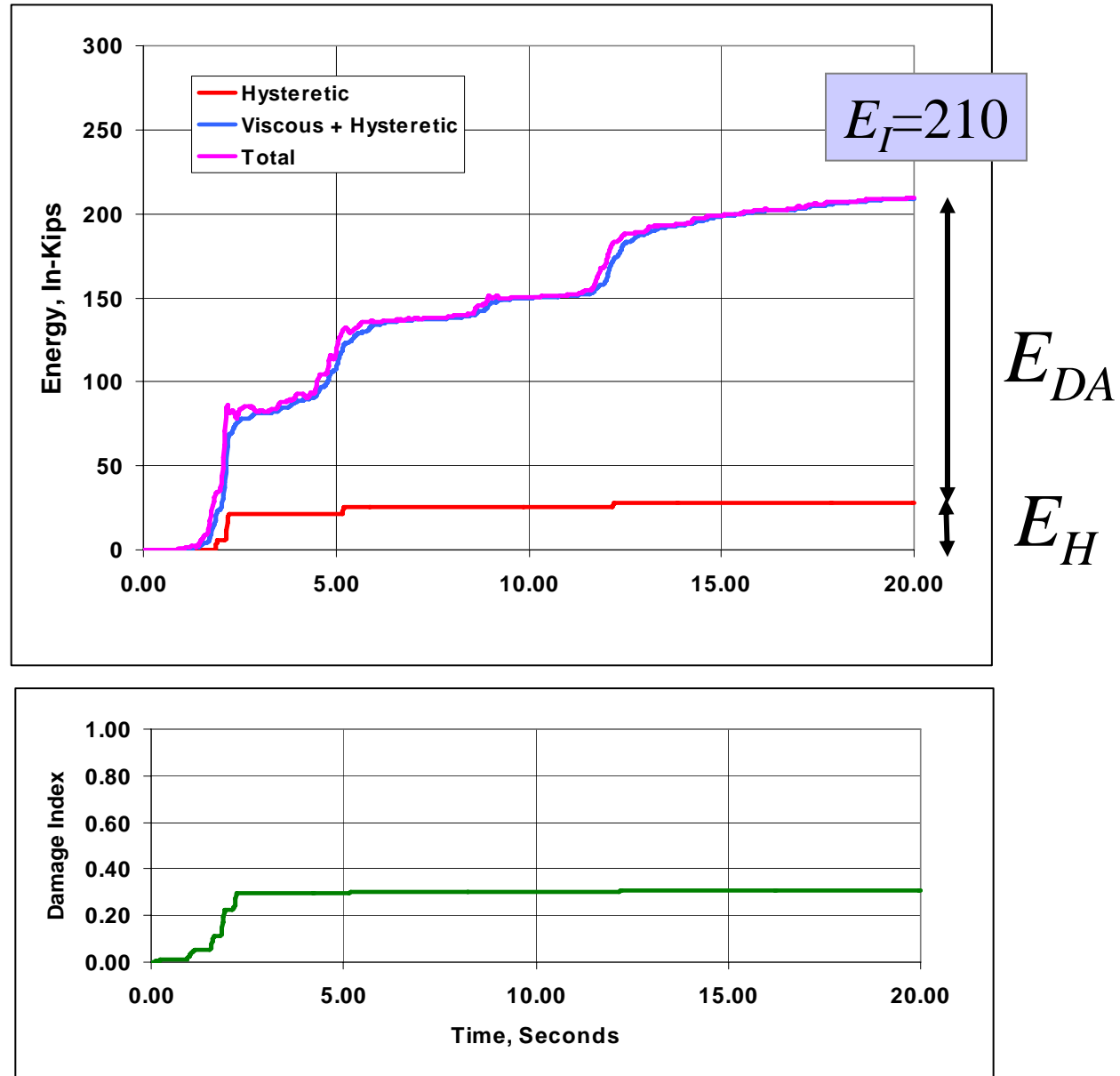


$E_{DA}$

$E_H$

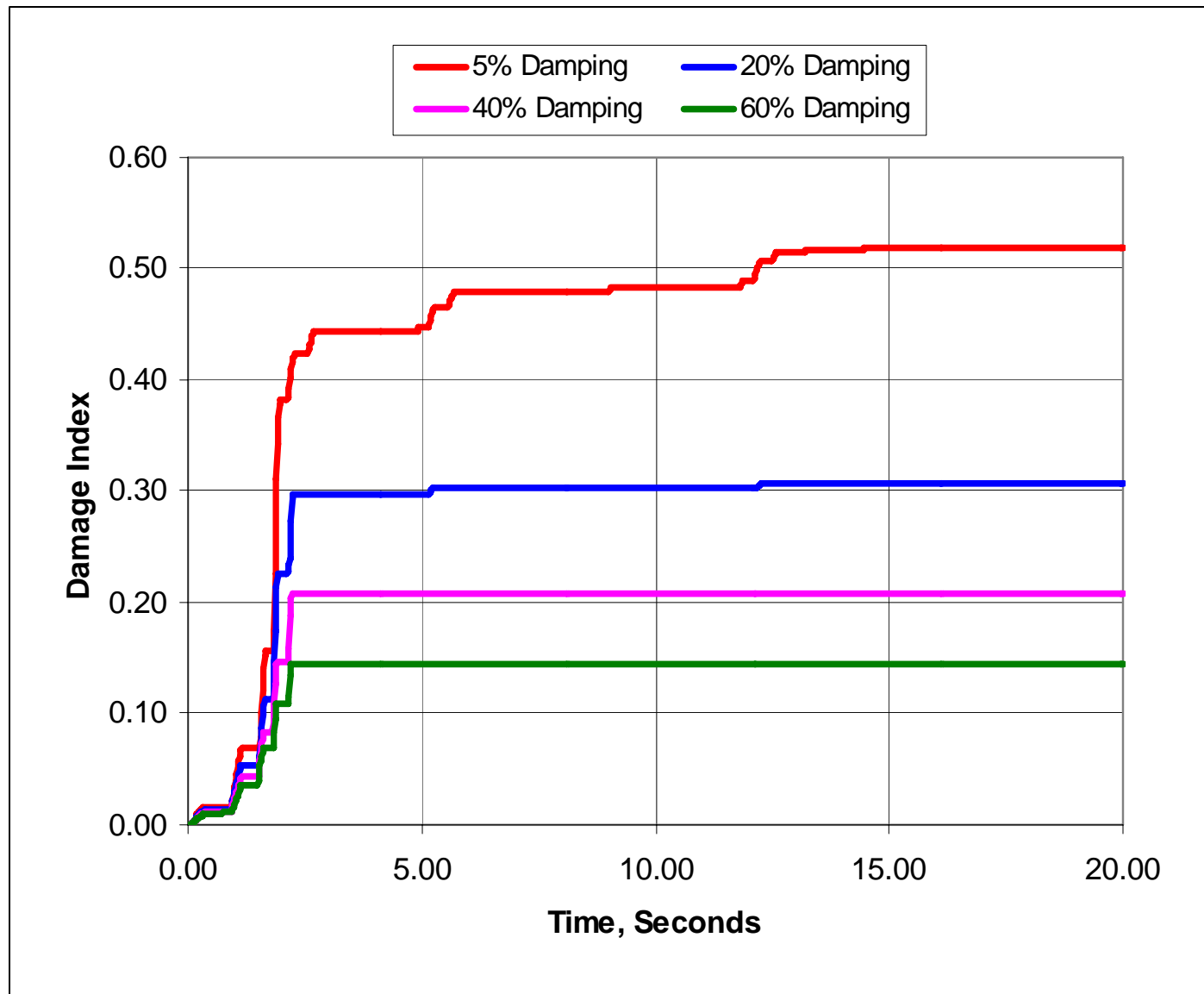
*Analysis performed on NONLIN*

# Energy and Damage Histories, 20% Damping





# Reduction in Damage with Increased Damping



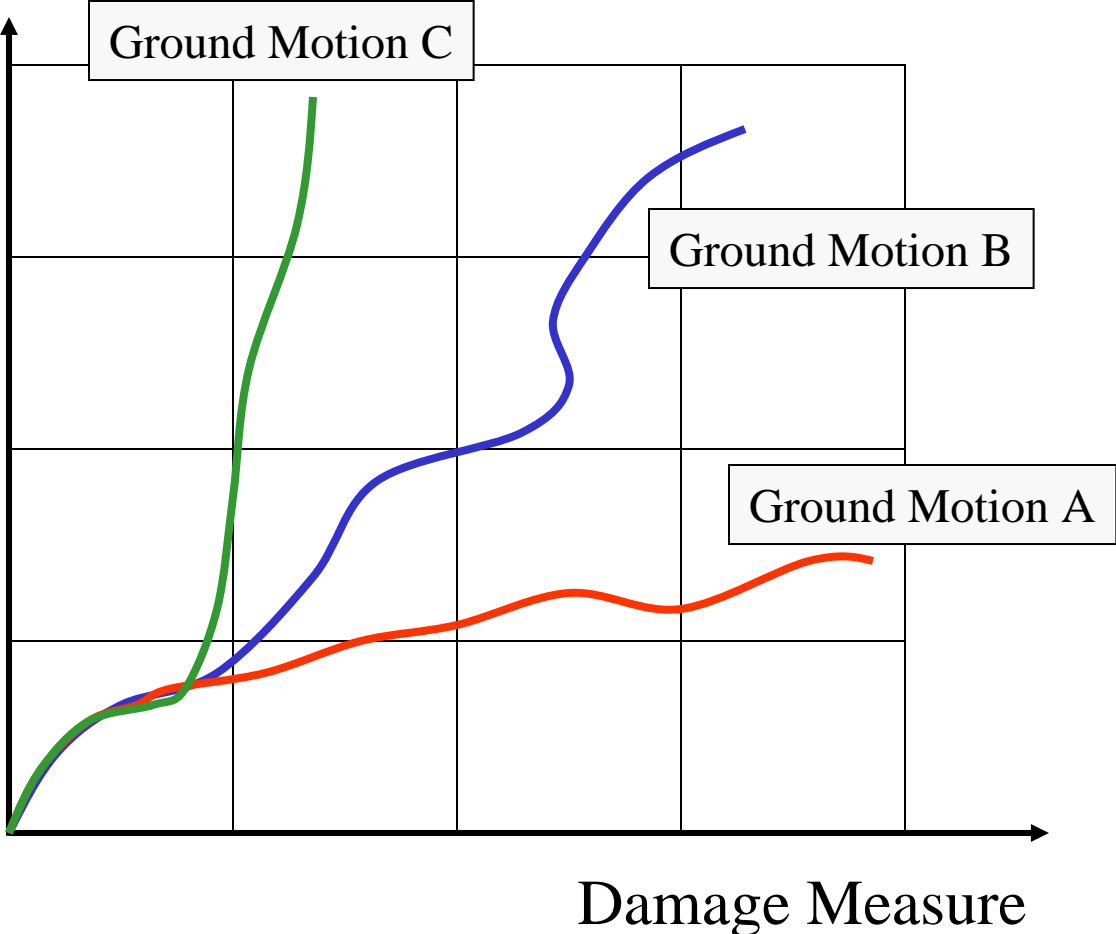
# Incremental Nonlinear Dynamic Analysis

*Seismic Performance, Capacity, and Reliability of  
Structures as Seen Through  
Incremental Dynamic Analysis*

Ph.D. Dissertation of Dimitros Vamvatsikos,  
Department of Civil and Environmental Engineering  
Stanford University  
July 2002.

# Incremental Nonlinear Dynamic Analysis

Ground Motion Intensity Measure

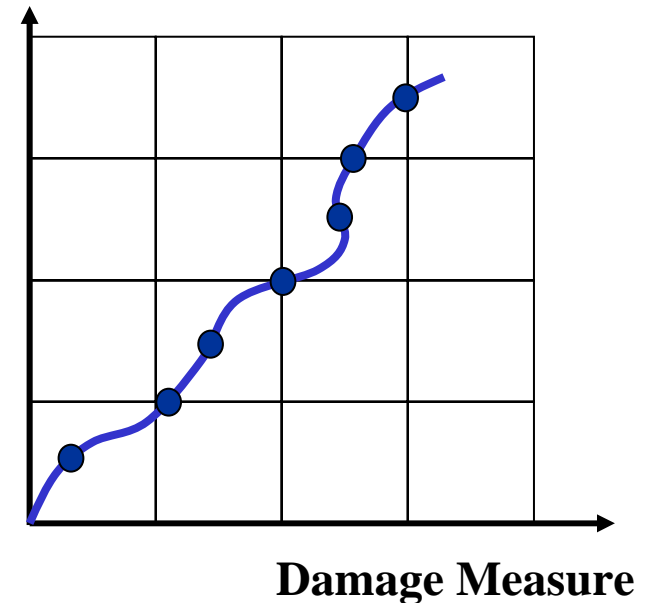


# Incremental Nonlinear Dynamic Analysis

An *IDA study* is produced by subjecting a single structure to a series of time history analyses, where each subsequent analysis uses a higher ground motion intensity.

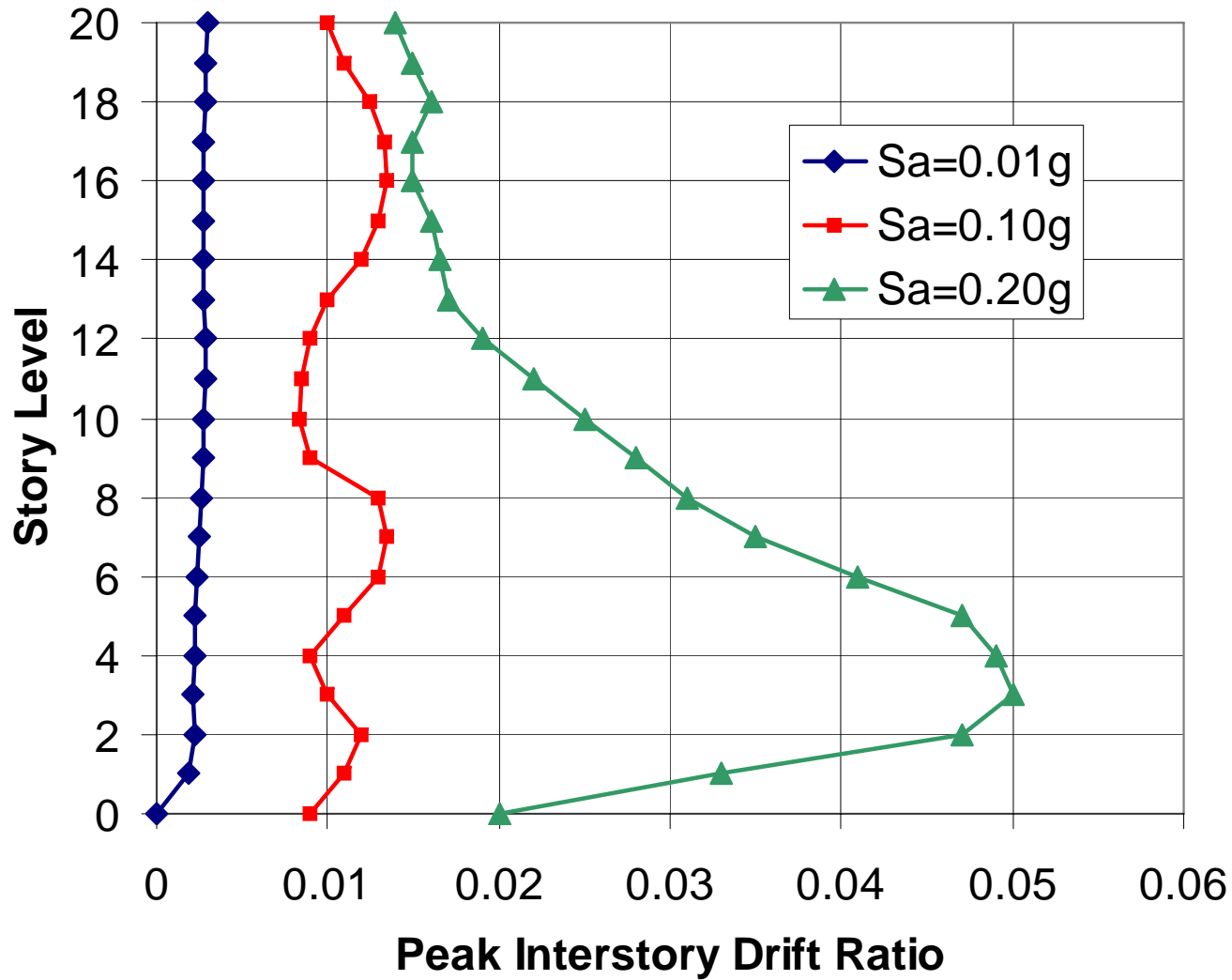
An *IDA Curve* is a plot of a damage measure (DM) versus the ground motion intensity (IM) at which it occurred.

Intensity Measure



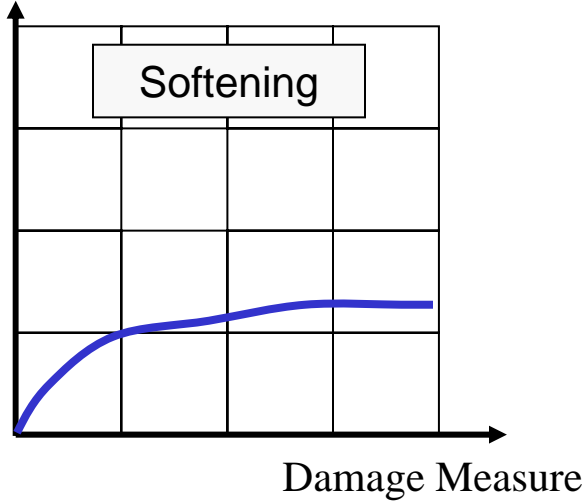
# IDA Results for a Particular Ground Motion

(after Vamvatsikos and Cornell)

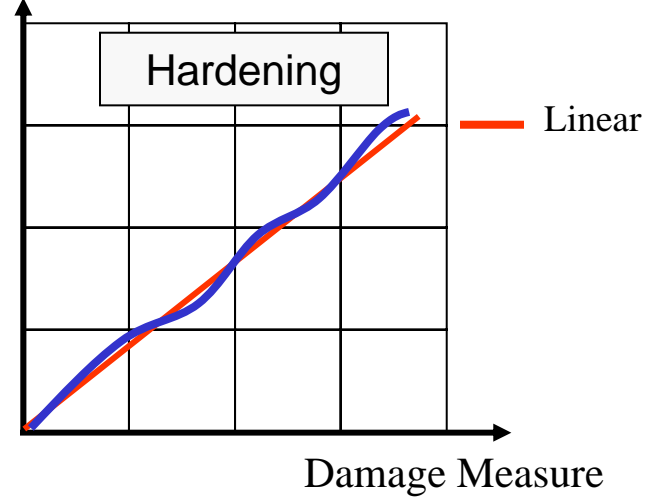


# Typical IDA Curve Characteristics

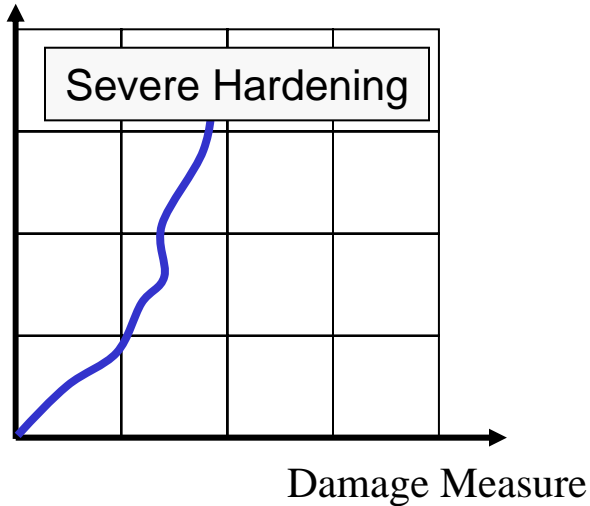
Intensity Measure



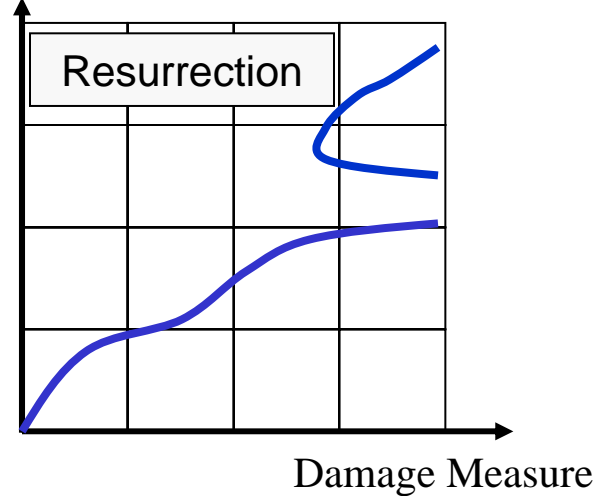
Intensity Measure



Intensity Measure

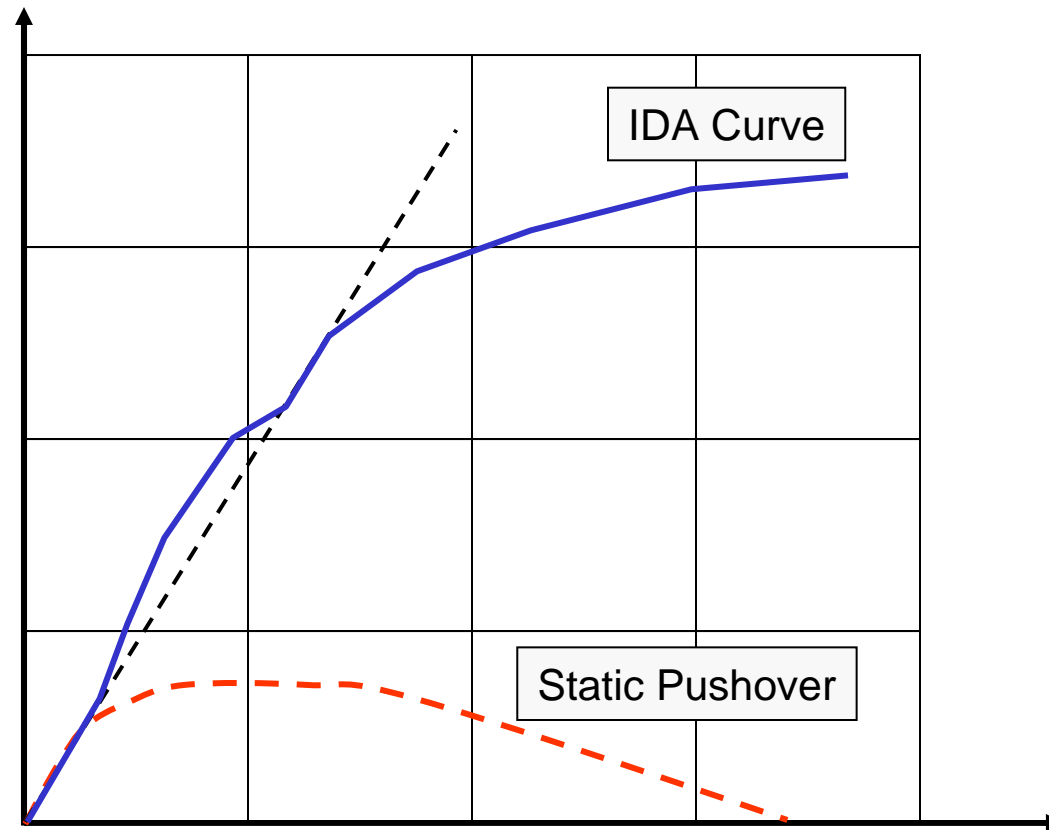


Intensity Measure



# Typical IDA Curve Characteristics

Intensity Measure

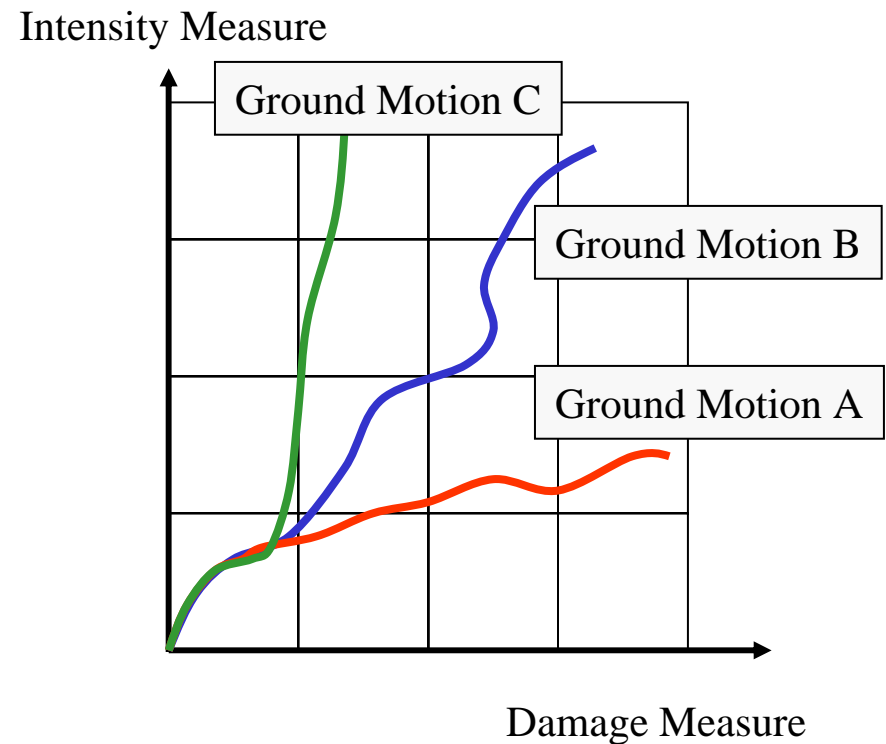


Damage Measure

# Incremental Nonlinear Dynamic Analysis (using Multiple Ground Motions)

Usually, a study compares the response of the structure to a suite of ground motions.

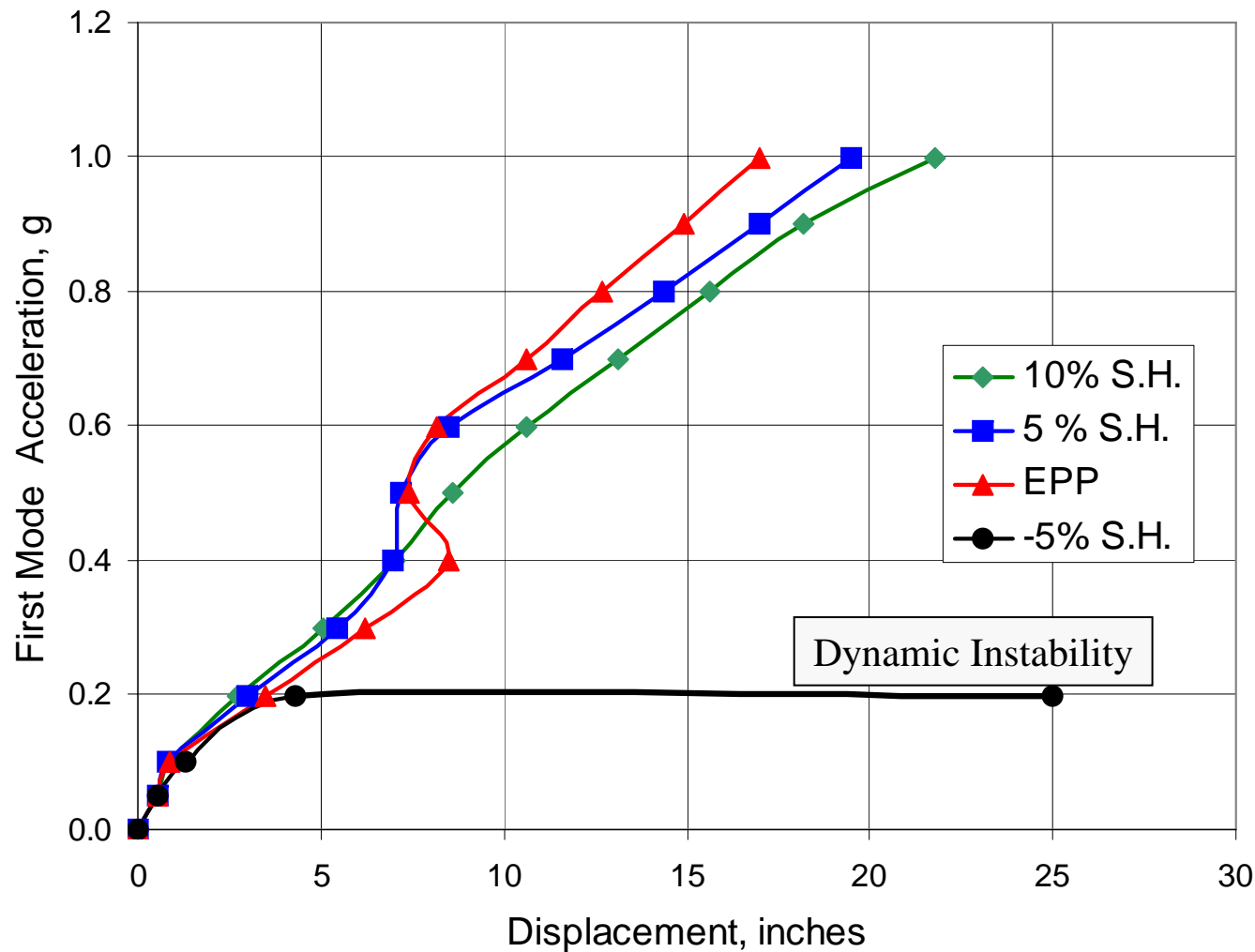
An IDA study may also be used to assess the effect of a design change (or uncertainty) on the response of a structure to a particular ground motion.





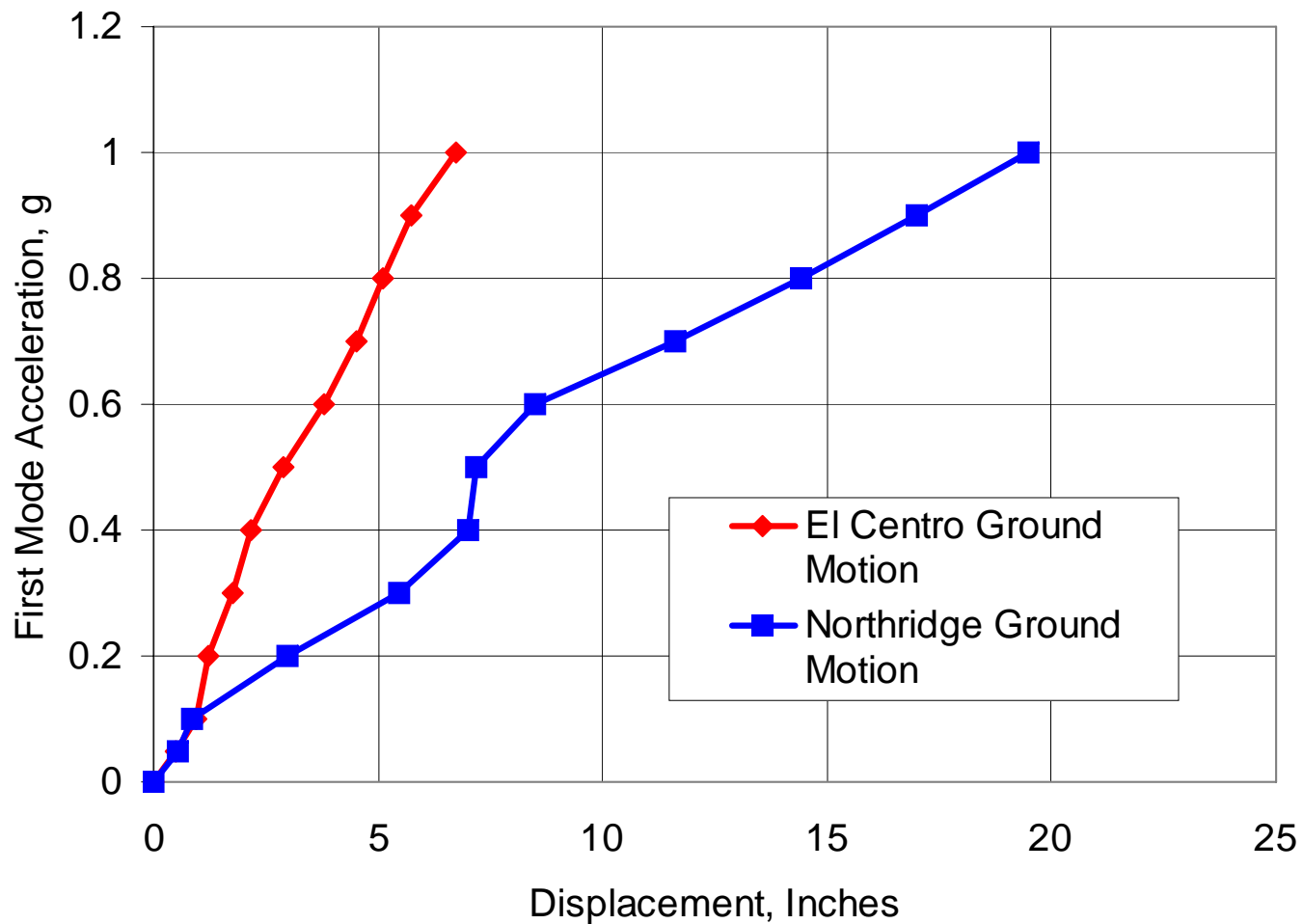
# IDA Curves to Investigate Sensitivity of SDOF System Response to Strain Hardening Ratio

Analyzed on NONLIN Using Northridge (Slymar) Ground Motion.

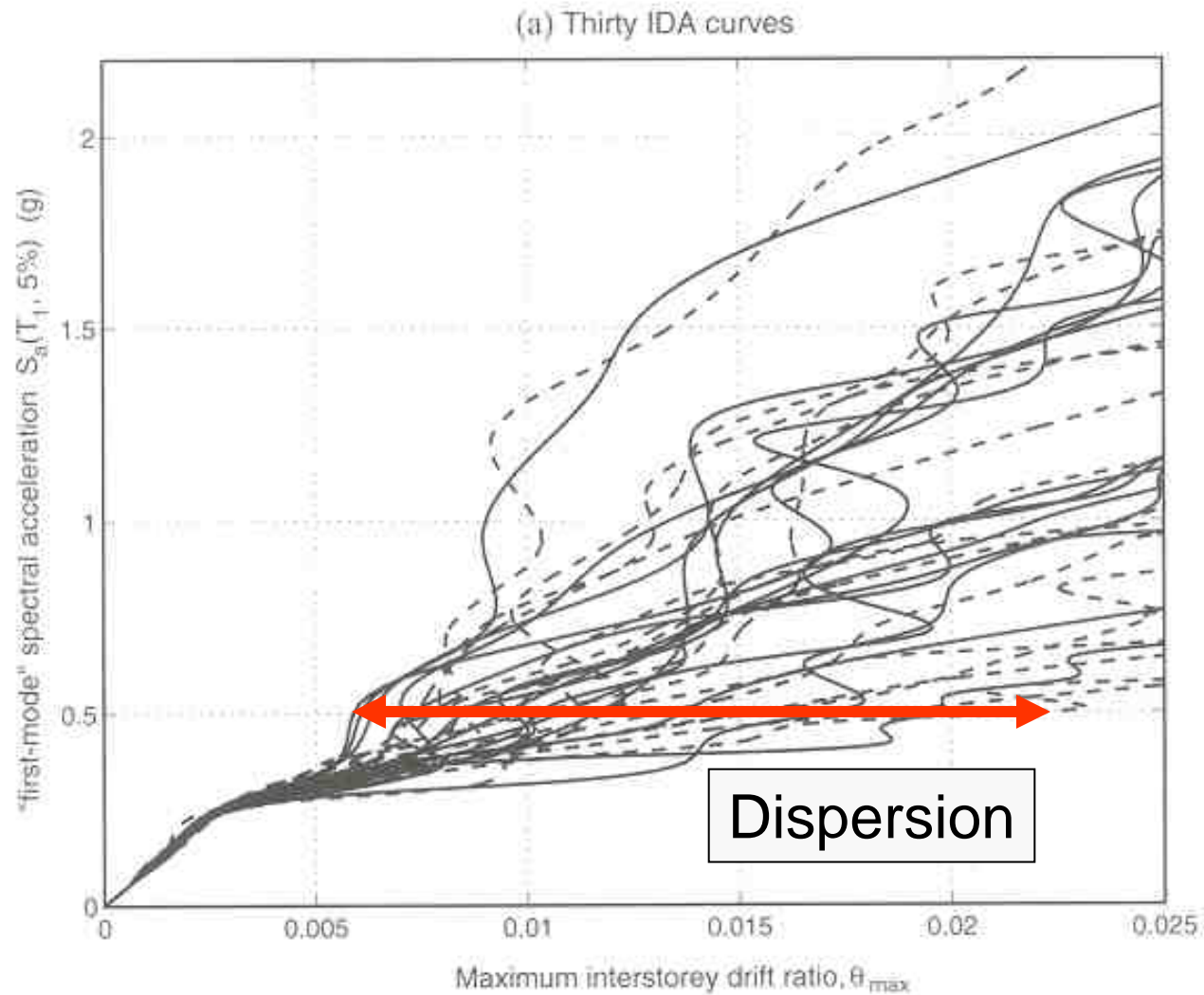


# IDA Curves to Investigate Sensitivity of SDOF System Response to Choice of Ground Motion

2% Damping, 5% Strain Hardening

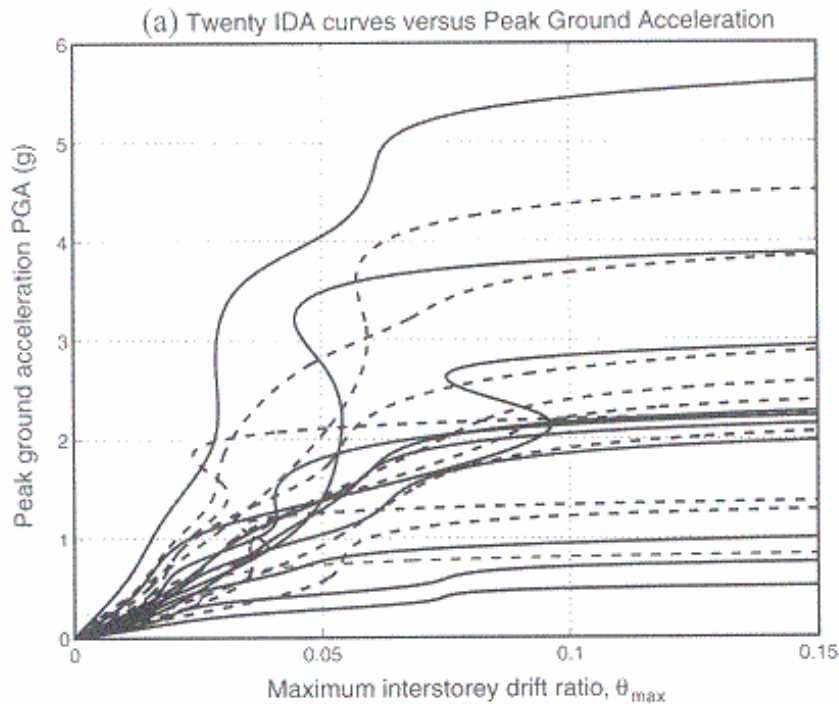


# A Family of IDA Curves of the Same Building Subjected to Thirty Earthquakes

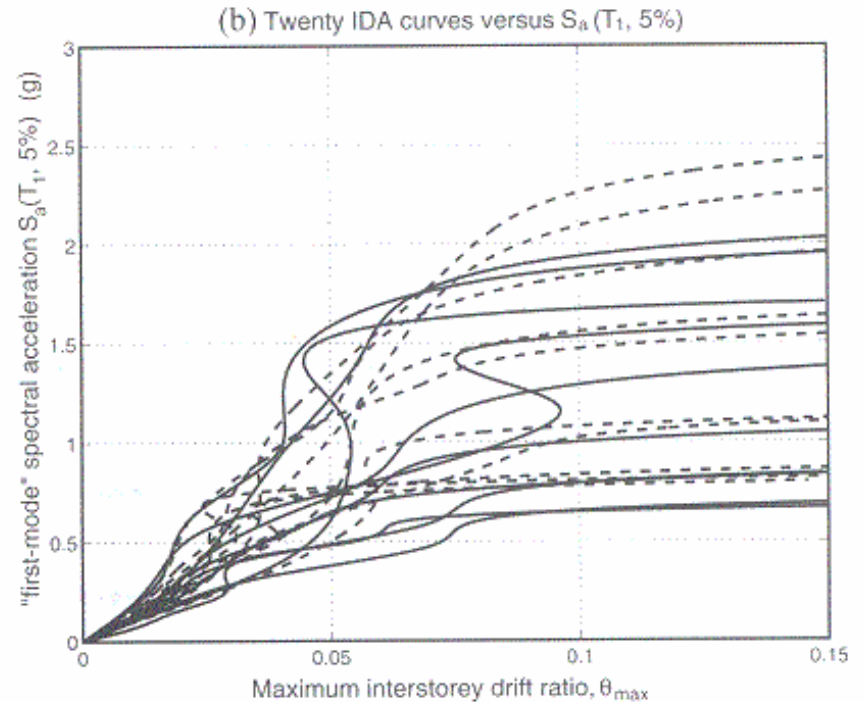


# IDA Curves of the Same Building Subjected to Suite of Earthquakes

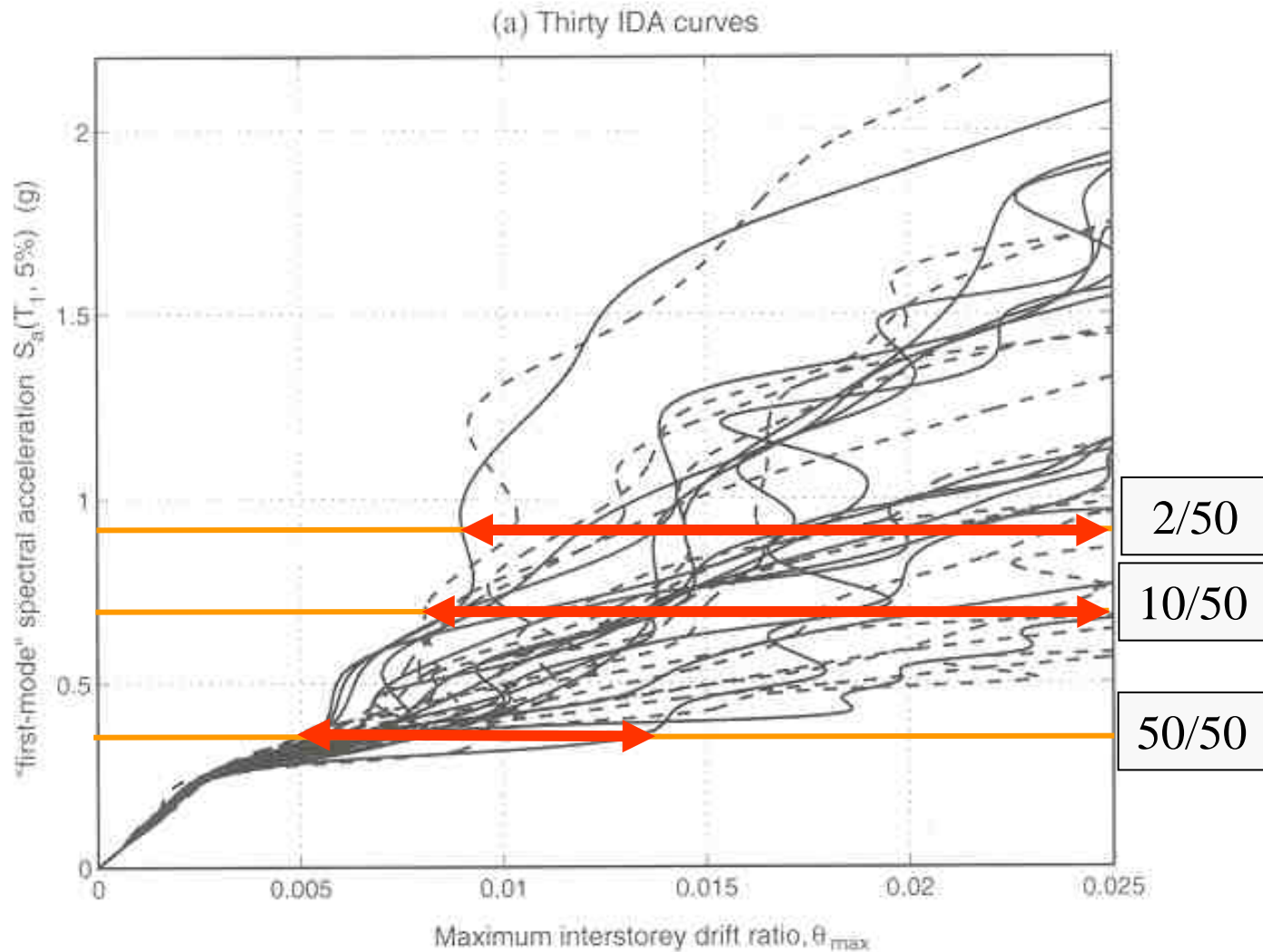
NORMALIZED to PGA



NORMALIZED to SA



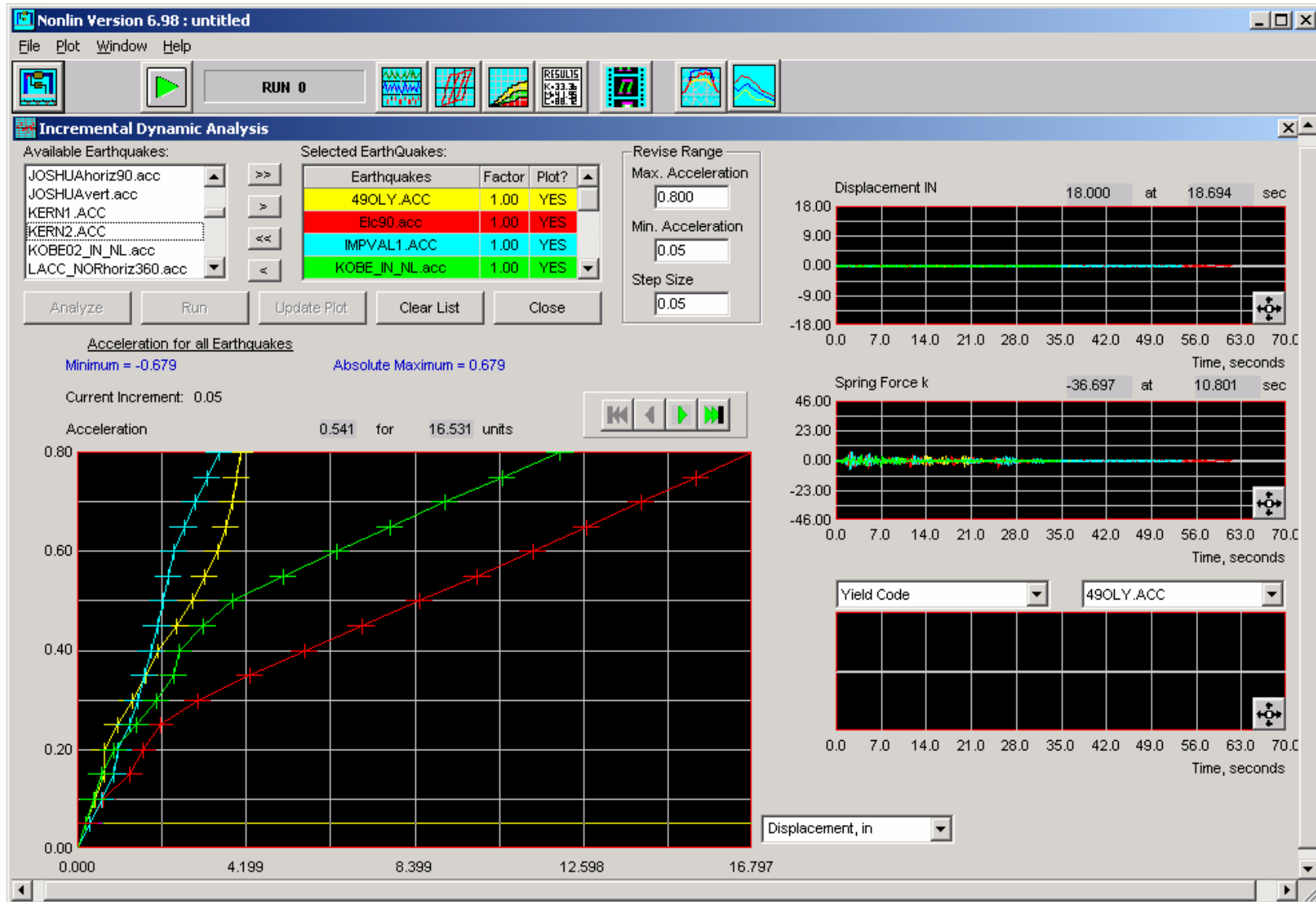
# A Family of IDA Curves of the Same Building Subjected to Thirty Earthquakes



# Incremental Nonlinear Dynamic Analysis

- Use of IDA shows the **EXTREME** sensitivity of damage to ground motion intensity, as well as the **EXTREME** sensitivity of damage to the chosen ground motion.
- Dispersion in multiple ground motion IDA may be reduced by scaling each base ground motion to a target spectral intensity computed at the structure's fundamental frequency of vibration.
- Even with such scaling, it is clear that PBE assessments based on response history analysis is problematic if carried out in a purely deterministic framework. Probabilistic methods must be employed to adequately handle the randomness of the input and the apparent “chaos” in the results.

# NONLIN Version 7 IDA Tool



# Probabilistic Approaches to Performance-Based Engineering

## The Most Daunting Task: Identifying and Quantifying Uncertainties

Demand Side (Ground Motion)

- 1) Magnitude
- 2) Source Mechanism
- 3) Wave Propagation Direction
- 4) Attenuation
- 5) Site Amplification
- 6) Frequency Content
- 7) Duration
- 8) Sequence (foreshocks, aftershocks)

...



# Probabilistic Approaches

## The Most Daunting Task: Identifying and Quantifying Uncertainties

Capacity Side (Soil/Foundation/Structure Behavior)

- 1) Strength
- 2) Stiffness
- 3) Inherent Damping
- 4) Hysteretic Behavior
- 5) Gravity Load
- 6) Built-in Imperfections

...

### Analysis Uncertainties



# PEER's Probabilistic Framing Equation

$$\lambda(DV) = \iint G(DV|DM) |dG(DV|IM)| |d\lambda(IM)|$$

$\lambda(DV)$       Likelihood of exceeding a certain limit state

IM      Intensity Measure

DM      Damage Measure

DV      Decision Variable

# Probabilistic Approaches: FEMA 350

$$P(D > PL) = \int P_{D>PL}(x)h(x)dx$$

$P(D > PL)$  Probability of damage exceeding a performance level in a period of  $t$  years

$P_{D>PL}(x)$  Probability of damage exceeding a performance level given that the ground motion intensity is level  $x$ , as a function of  $x$ .

$h(x)dx$  Probability of experiencing a ground motion intensity of level  $(x)$  to  $(x+dx)$  in a period of  $t$  years

# Probabilistic Approaches: FEMA 350

$$P(D > PL) = \int P_{D>PL}(x)h(x)dx$$

**Simplified Method**

Detailed Method

# Probabilistic Approaches: FEMA 350

$$\lambda = \frac{\gamma \gamma_a D}{\phi C}$$

- $\lambda$  Capacity to Demand Ratio
- $\gamma$  Demand Variability Factor
- $\gamma_a$  Analysis Uncertainty Factor
- $C$  Tabulated Capacity for the Component
- $\phi$  Capacity Resistance Factor
- $D$  Calculated Demand for the Component
- 
- $\beta_{UT}$  Total Coefficient of Variation

# Probabilistic Approaches: FEMA 350

**Table 4-7**  
**Recommended Minimum Confidence Levels**

Behavior	Performance Level	
	Immediate Occupancy	Collapse Prevention
Global Interstory Drift	50%	90%
Local Interstory Drift	50%	50%
Column Compression	50%	90%
Splice Tension	50%	50%

# Probabilistic Approaches: FEMA 350

**Table 4-8**  
**Interstory Drift Angle Analysis Uncertainty Factor  $\gamma_a$**

Analysis Procedure		LSP		LDP		NSP		NDP	
		I.O	C.P.	I.O	C.P.	I.O	C.P.	I.O	C.P.
<b>Special</b>	<b>Low Rise (&lt;4 stories)</b>	0.94	0.70	1.03	0.83	1.13	0.89	1.02	1.03
<b>Special</b>	<b>Mid Rise (4-12 stories)</b>	1.15	0.97	1.14	1.25	1.45	0.99	1.02	1.06
<b>Special</b>	<b>High Rise (&gt; 12 stories)</b>	1.12	1.21	1.21	1.14	1.36	0.95	1.04	1.10
<b>Ordinary</b>	<b>Low Rise (&lt;4 stories)</b>	0.79	0.98	1.04	1.32	0.95	1.31	1.02	1.03
<b>Ordinary</b>	<b>Mid Rise (4-12 stories)</b>	0.85	1.14	1.10	1.53	1.11	1.42	1.02	1.06
<b>Ordinary</b>	<b>High Rise (&gt; 12 stories)</b>	0.80	0.85	1.39	1.38	1.36	1.53	1.04	1.10

# Probabilistic Approaches: FEMA 350

**Table 4-9**  
**Interstory Drift Angle Demand Variability Factor  $\gamma$**

Building Height		$\gamma$	
		I.O.	C.P.
Special	Low Rise (< 4 stories)	1.5	1.3
Special	Mid Rise ( 4-12 stories)	1.4	1.2
Special	High rise (>12 stories)	1.4	1.5
Ordinary	Low Rise (< 4 stories)	1.4	1.4
Ordinary	Mid Rise ( 4-12 stories)	1.3	1.5
Ordinary	High rise (>12 stories)	1.6	1.8



# Probabilistic Approaches: FEMA 350

**Table 4-10**  
**Global Interstory Drift Angle Capacity Factors (C)**  
**and Resistance Factors ( $\phi$ )**

Building Height		I.O.		C.P.	
		C	$\phi$	C	$\phi$
Special	Low Rise (<4 stories)	0.02	1.00	0.10	0.90
Special	Mid Rise (4-12 stories)	0.02	1.00	0.10	0.85
Special	High Rise (> 12 stories)	0.02	1.00	0.09	0.75
Ordinary	Low Rise (<4 stories)	0.01	1.00	0.10	0.85
Ordinary	Mid Rise (4-12 stories)	0.01	0.90	0.08	0.70
Ordinary	High Rise (> 12 stories)	0.01	0.85	0.06	0.60

# Probabilistic Approaches: FEMA 350

**Table 4-11  
Uncertainty Coefficient  $\beta_{UT}$  for Global Interstory Drift  
Evaluation**

Building Height		Perf. Level	
		I.O.	C.P.
<b>Special</b>	<b>Low Rise (&lt; 4 stories)</b>	<b>0.20</b>	<b>0.30</b>
<b>Special</b>	<b>Mid Rise ( 4-12 stories)</b>	<b>0.20</b>	<b>0.40</b>
<b>Special</b>	<b>High rise (&gt;12 stories)</b>	<b>0.20</b>	<b>0.50</b>
<b>Ordinary</b>	<b>Low Rise (&lt; 4 stories)</b>	<b>0.20</b>	<b>0.35</b>
<b>Ordinary</b>	<b>Mid Rise ( 4-12 stories)</b>	<b>0.20</b>	<b>0.45</b>
<b>Ordinary</b>	<b>High rise (&gt;12 stories)</b>	<b>0.20</b>	<b>0.55</b>

# Probabilistic Approaches: FEMA 350

**Table 4-6**  
**Confidence Levels for Various Values of  $\lambda$  and  $\beta_{UT}$**

Confidence Level	10	20	30	40	50	60	70	80	90	95	99
$\lambda$ for $\beta_{UT} = 0.2$	1.37	1.26	1.18	1.12	1.06	1.01	0.96	0.90	0.82	0.76	0.67
$\lambda$ for $\beta_{UT} = 0.3$	1.68	1.48	1.34	1.24	1.14	1.06	0.98	0.89	0.78	0.70	0.57
$\lambda$ for $\beta_{UT} = 0.4$	2.12	1.79	1.57	1.40	1.27	1.15	1.03	0.90	0.76	0.66	0.51
$\lambda$ for $\beta_{UT} = 0.5$	2.76	2.23	1.90	1.65	1.45	1.28	1.12	0.95	0.77	0.64	0.46
$\lambda$ for $\beta_{UT} = 0.6$	3.70	2.86	2.36	1.99	1.72	1.48	1.25	1.03	0.80	0.64	0.43

# Probabilistic Approaches: FEMA 350

## Example Calculations for 4-12 Story Frame (DL is “Allowable” Interstory Drift Limit)

Type	PERF	Analysis	Confidence	$\gamma$	$\gamma_a$	$\phi$	C	$\beta_{UT}$	$\lambda$	DL
SPECIAL	IO	NSP	50%	1.4	1.45	1	0.02	0.2	1.06	0.0104
SPECIAL	IO	NDP	50%	1.4	1.02	1	0.02	0.2	1.06	0.0148
SPECIAL	CP	NSP	90%	1.2	0.99	0.85	0.1	0.4	0.76	0.0544
SPECIAL	CP	NDP	90%	1.2	1.06	0.85	0.1	0.4	0.76	0.0508
ORDINARY	IO	NSP	50%	1.3	1.11	0.9	0.01	0.2	1.06	0.0066
ORDINARY	IO	NDP	90%	1.3	1.02	0.9	0.01	0.2	1.06	0.0072
ORDINARY	CP	NSP	50%	1.5	1.42	0.7	0.08	0.45	0.765	0.0201
ORDINARY	CP	NDP	90%	1.5	1.06	0.7	0.08	0.45	0.765	0.0269

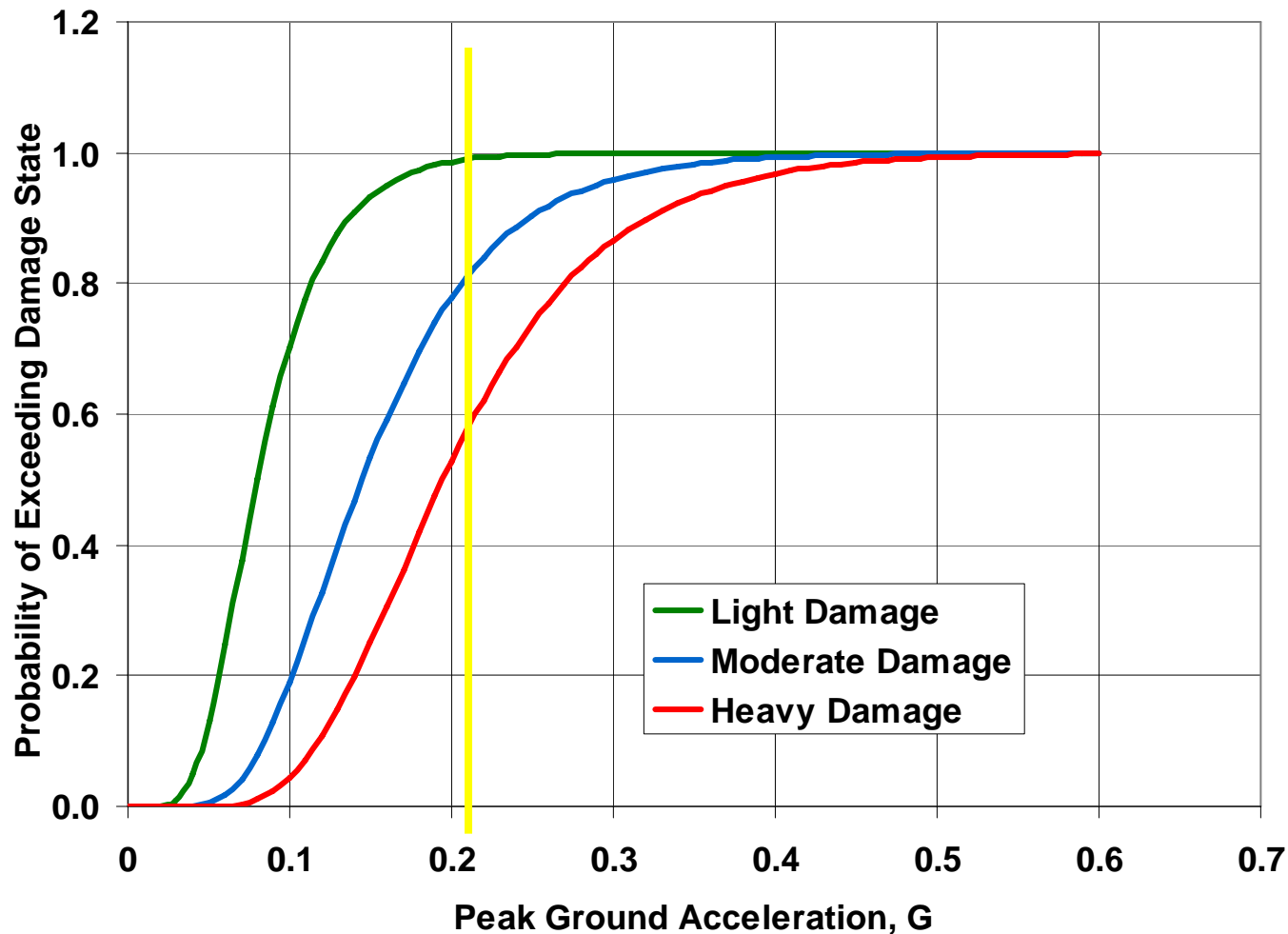
# Problem with FEMA 350 Approach?

Even though the method provides the owner a “Level of Confidence” that a certain performance criteria will be met, the engineer is likely to be bewildered by the arrays of coefficients. Hence, it is difficult for the engineer to obtain a feel for the validity of the results.

Given this, how confident is the engineer with the value of confidence provided?



# Probabilistic Approaches: Fragility Curves Unreinforced Masonry

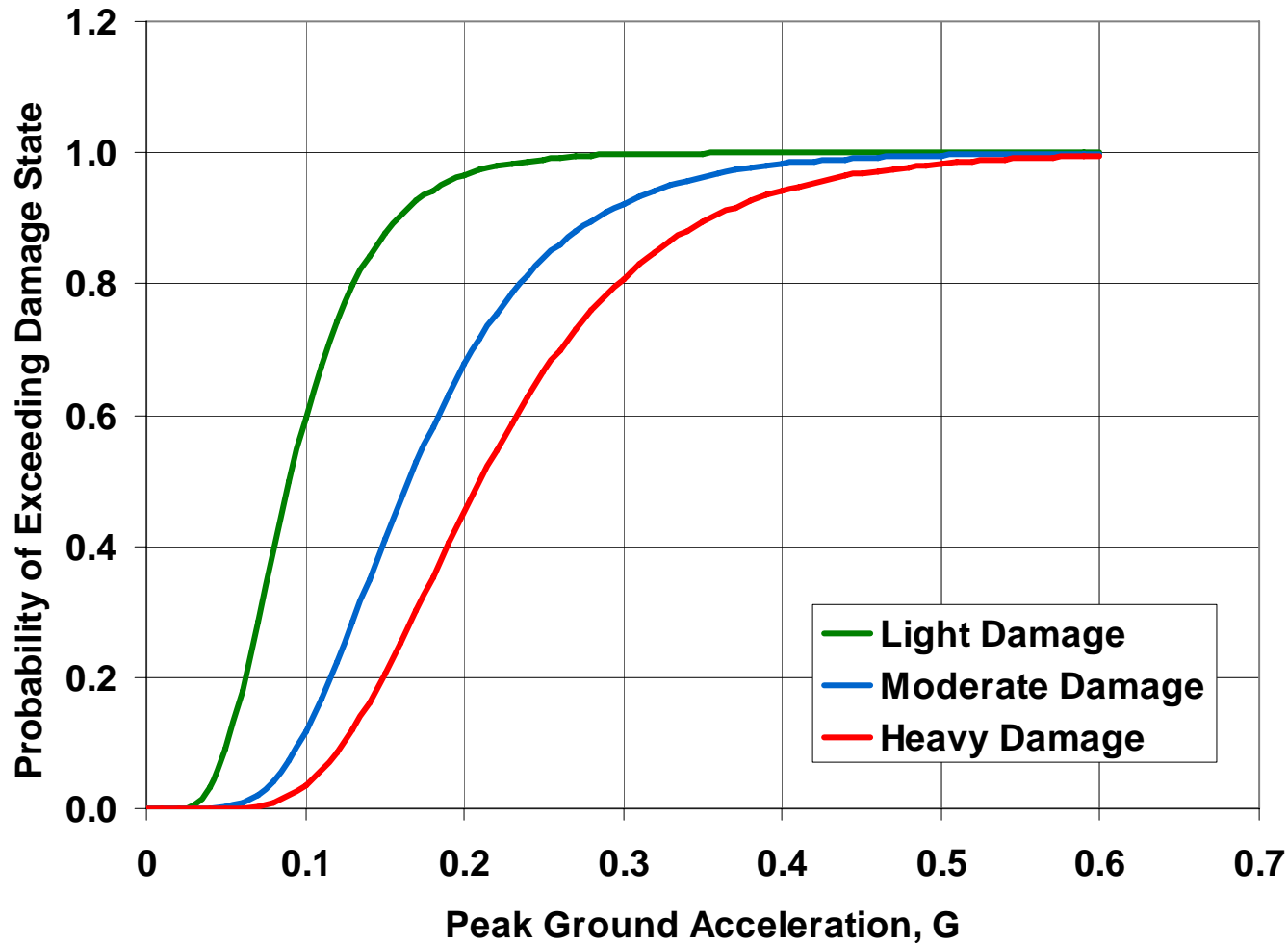


<http://www.ceri.memphis.edu/~hwang/>



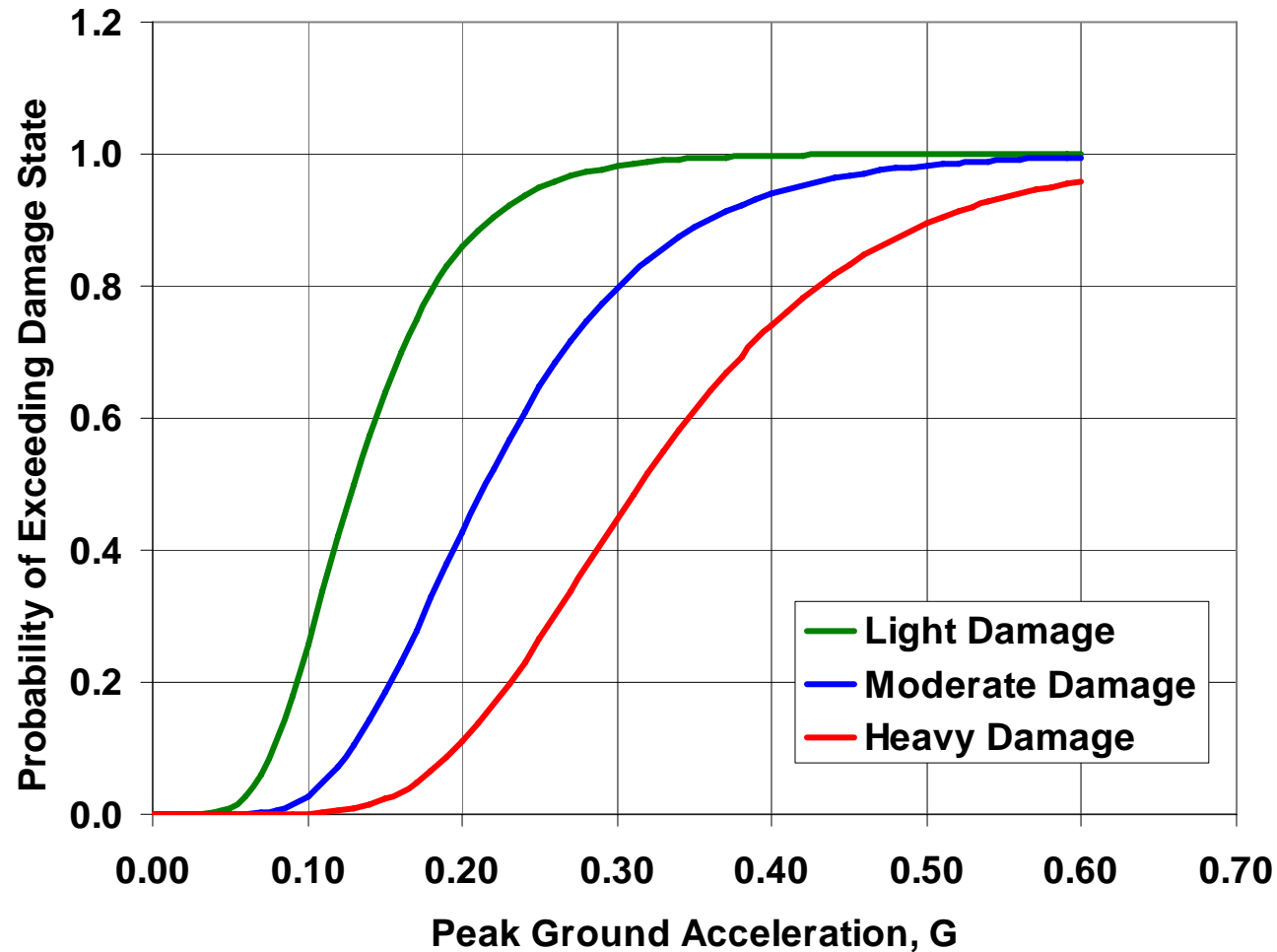
# Probabilistic Approaches: Fragility Curves

## Reinforced Masonry



<http://www.ceri.memphis.edu/~hwang/>

# Probabilistic Approaches: Fragility Curves Reinforced Concrete



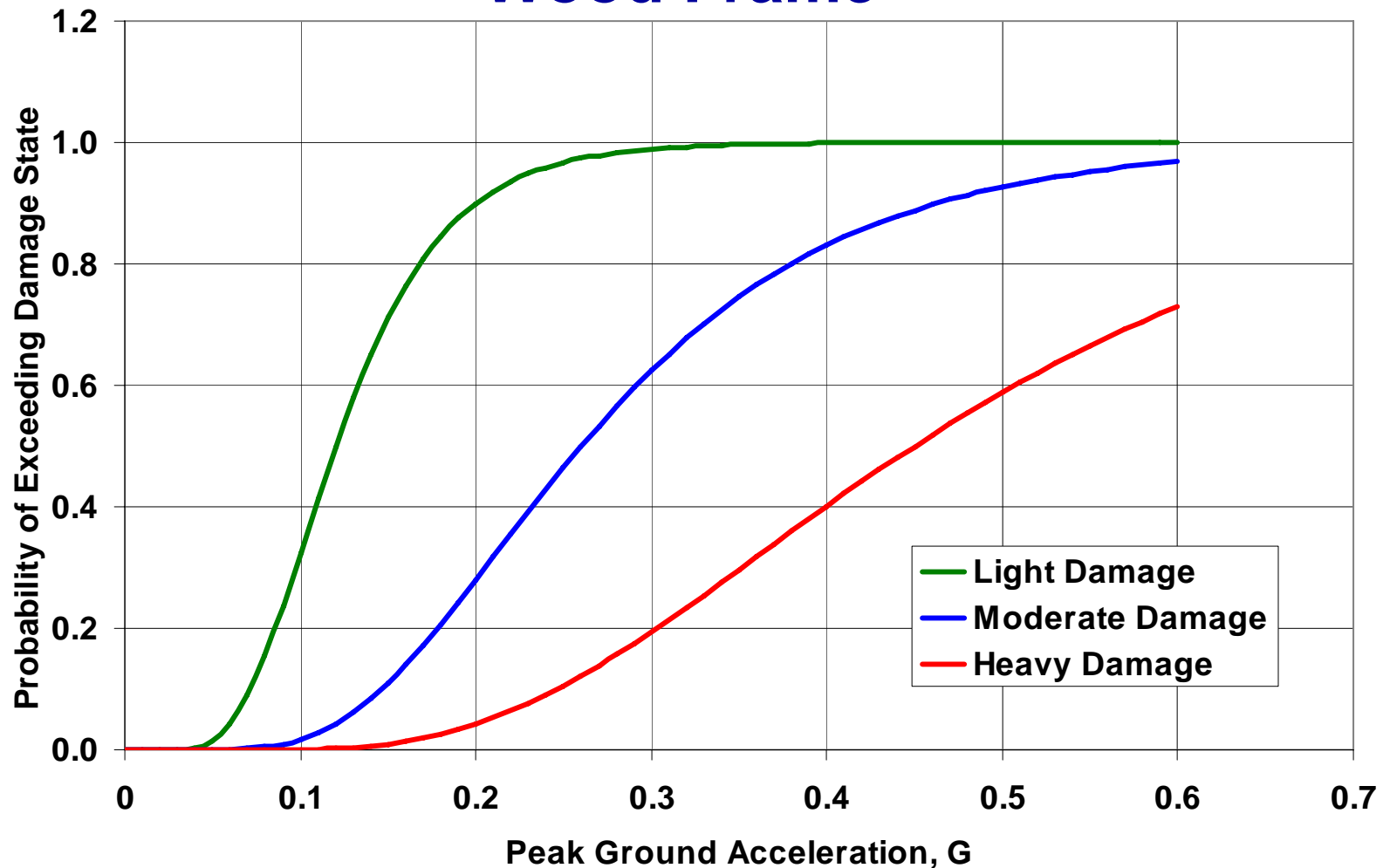
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# Probabilistic Approaches: Fragility Curves

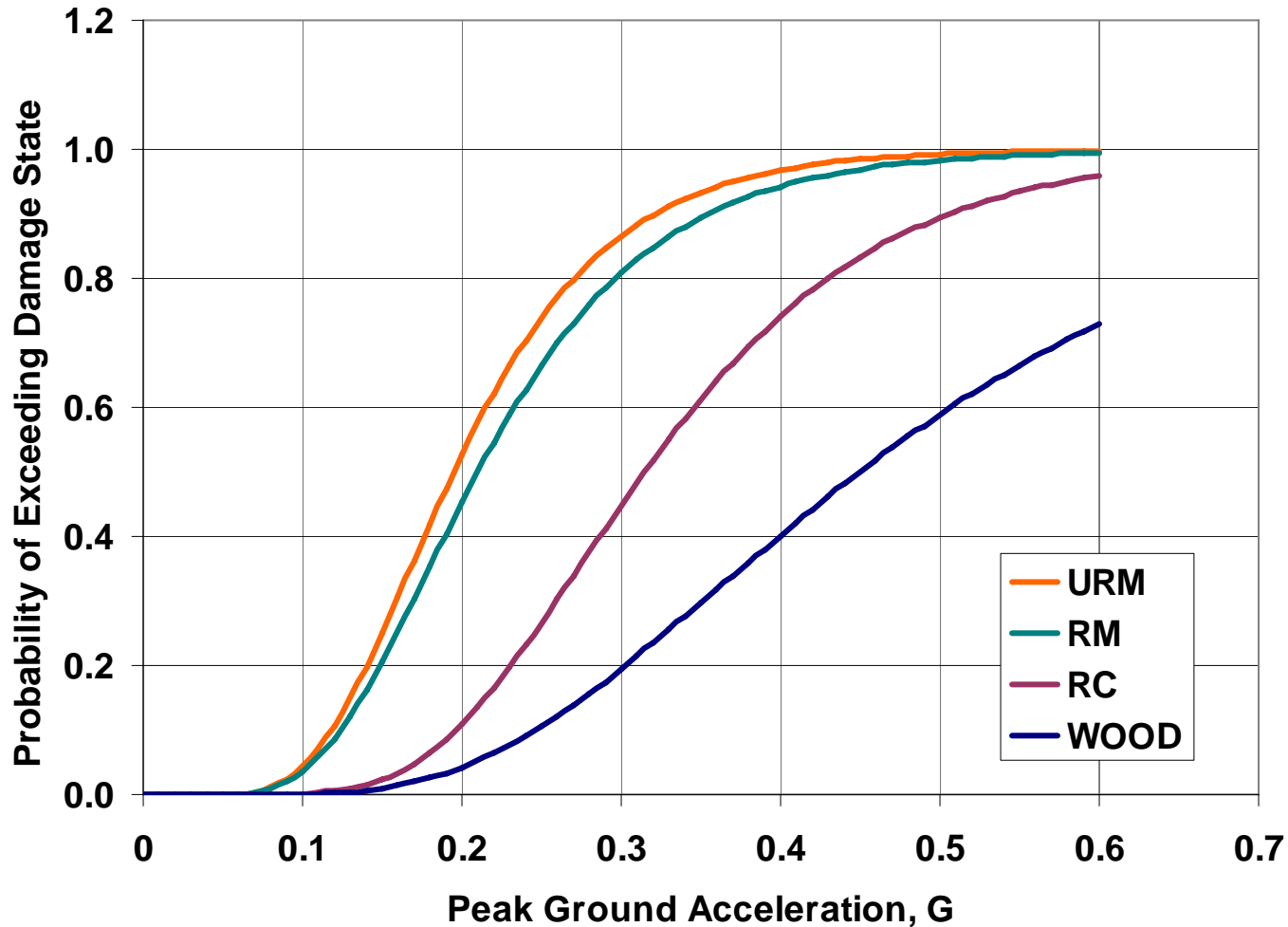
## Wood Frame



<http://www.ceri.memphis.edu/~hwang/>



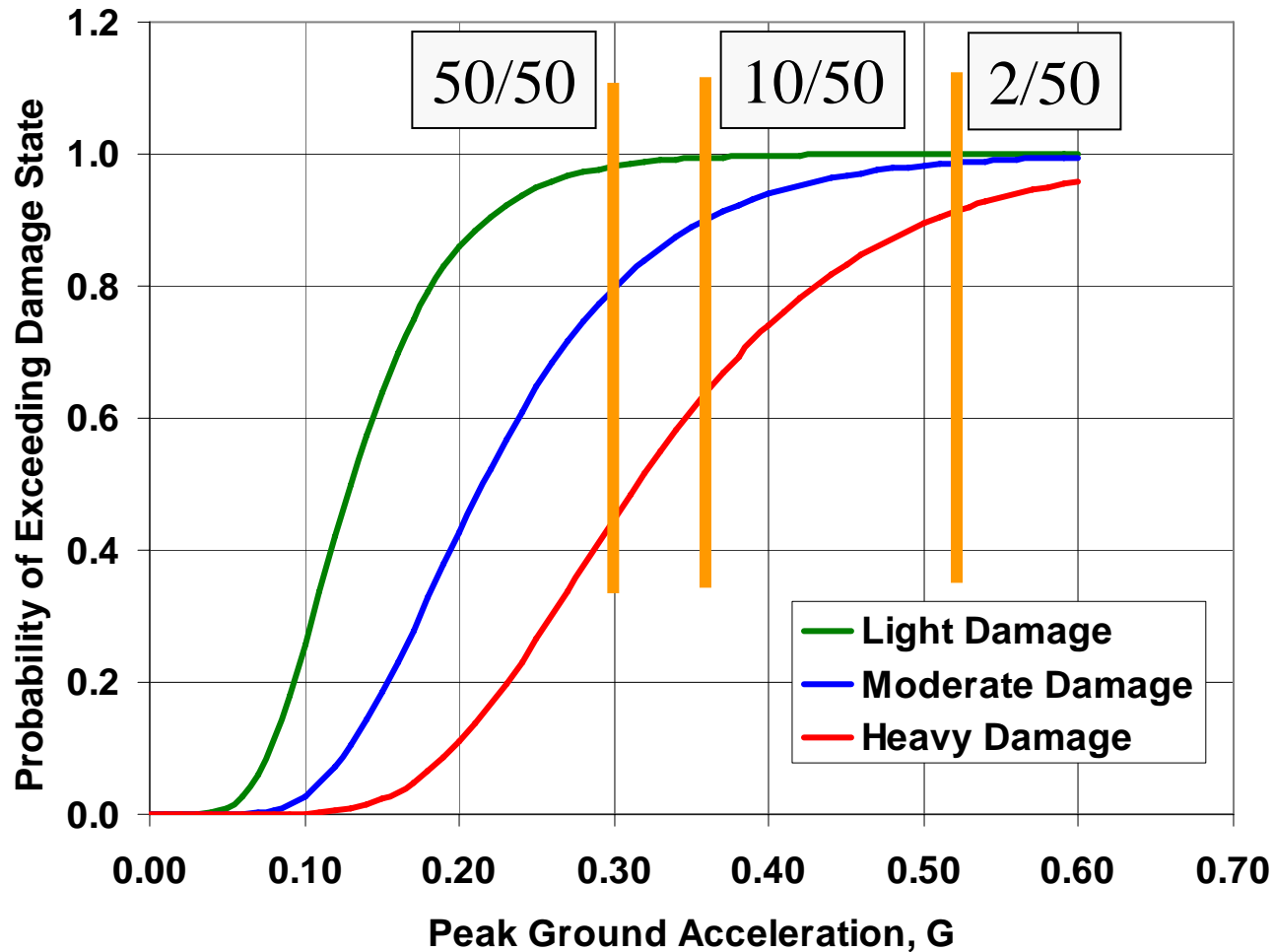
# Probabilistic Approaches: Fragility Curves (Heavy Damage)



<http://www.ceri.memphis.edu/~hwang/>



# Probabilistic Approaches: Fragility Curves Reinforced Concrete



<http://www.ceri.memphis.edu/~hwang/>



# Where are We Headed with Performance Based Engineering?

- **Performance Basis: Minimize Life Cycle Costs**
  - Realistic Damage Measures
  - Realistic Forecasting of Cost of Repairing Damage
  - Realistic Forecasting of Cost of Loss of Use
- **Analysis Procedures**
  - Incremental Nonlinear Dynamic Response History Analysis
  - Sensitivity Analysis (Deterministic)
  - Probabilistic Assessment of Performance
  - Deaggregation of Probabilistic Results (Deterministic)

# What We Need

- Ground motion search, scaling, and modification tools for development of suites for nonlinear dynamic analysis
- Reliable damage measures which (hopefully) minimize dispersion in results
- **Rapid** but reliable methods of analysis, including
  - Multiple Ground Motions [7 motions]
  - Incremental Nonlinear Dynamic Analysis [20 increments]
  - Systematic Sensitivity Analysis [10 uncert. X 8 values ]
  - Deterministic/Probabilistic Assessment Tools
- Big, **Fast** (Parallel Processing) Computers