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

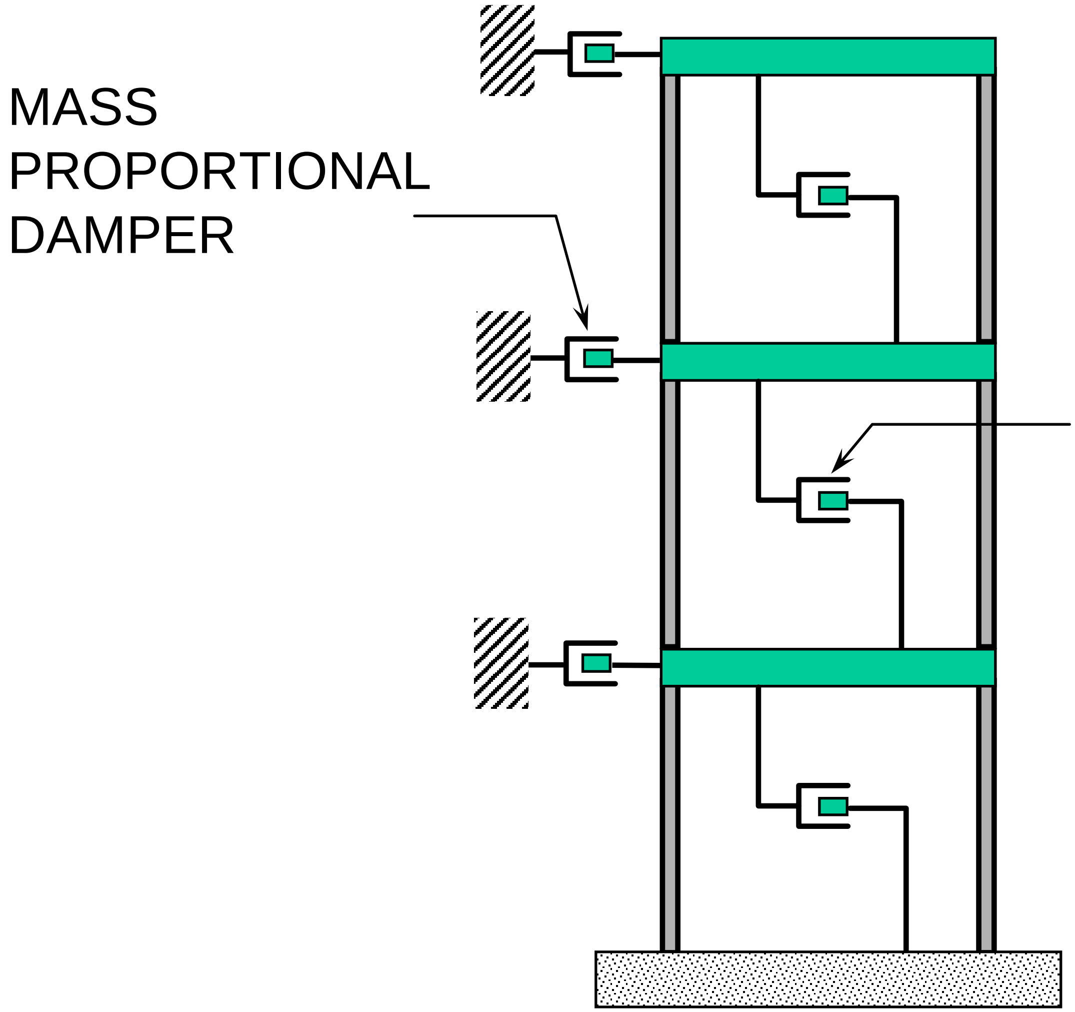
Nonlinear Dynamic Response History Analysis

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, ξ_k and ξ_n

Compute Coefficients α and β:

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

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

Rayleigh Proportional Damping (Example)

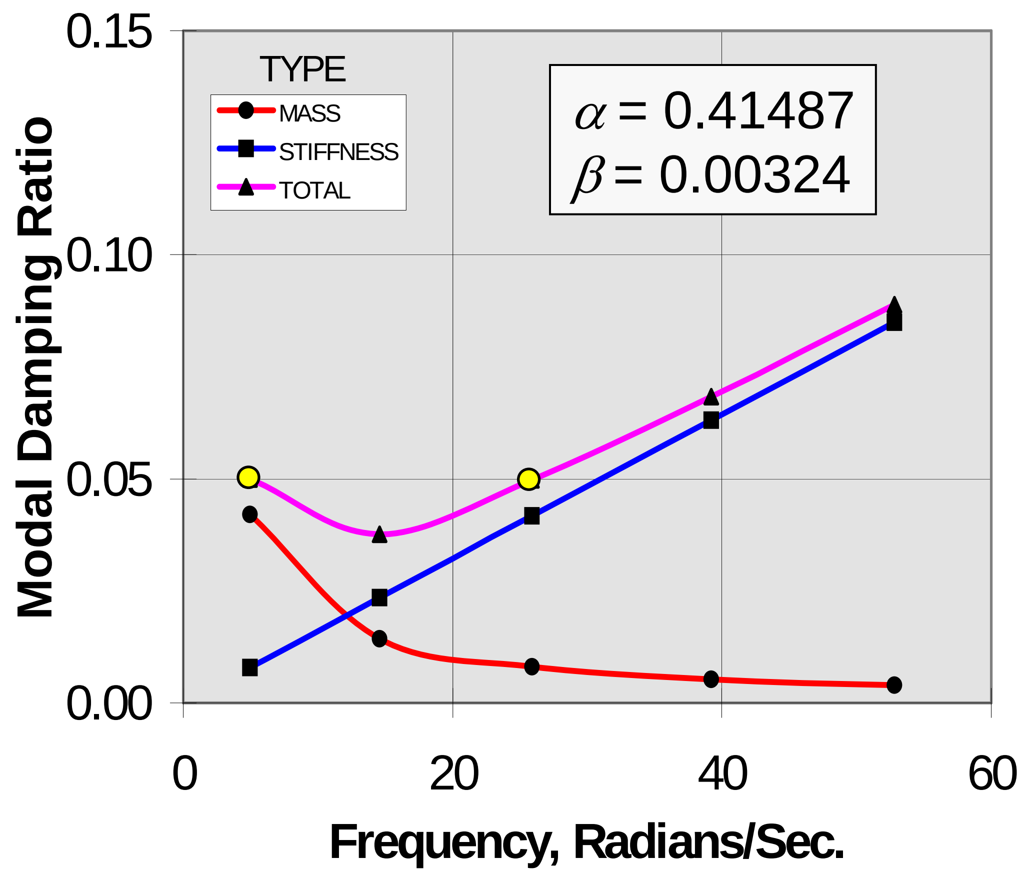
5% Critical in Modes 1 and 3

Damping in any other Mode m:

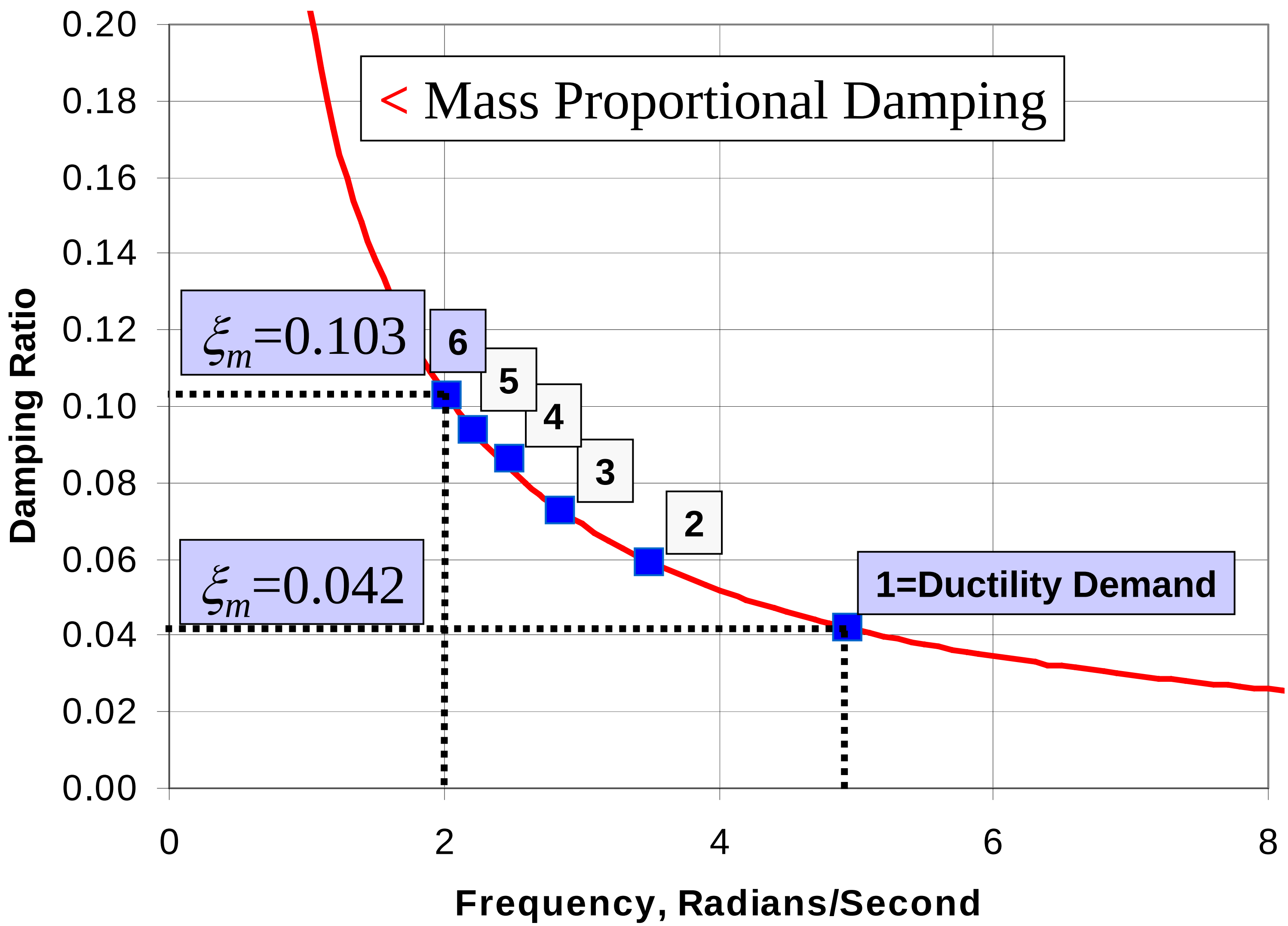
$$\xi_m = 0.5\begin{bmatrix} \frac{1}{\omega_m} & \omega_m \end{bmatrix}\begin{Bmatrix} \alpha \\ \beta \end{Bmatrix}$$

Structural Frequencies

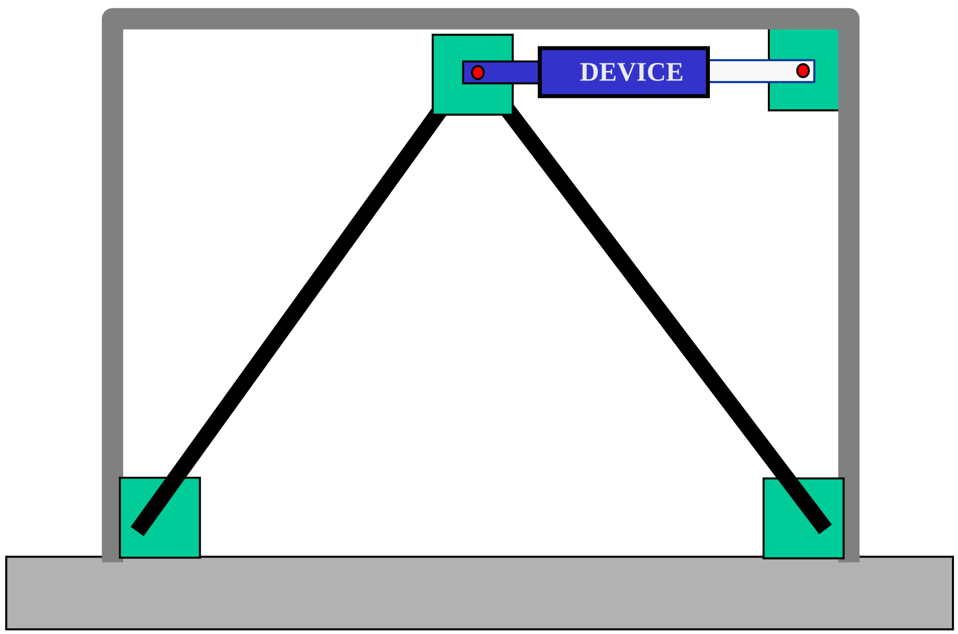
Mode	ω
1	**4.94**
2	14.6
3	**25.9**
4	39.2
5	52.8



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

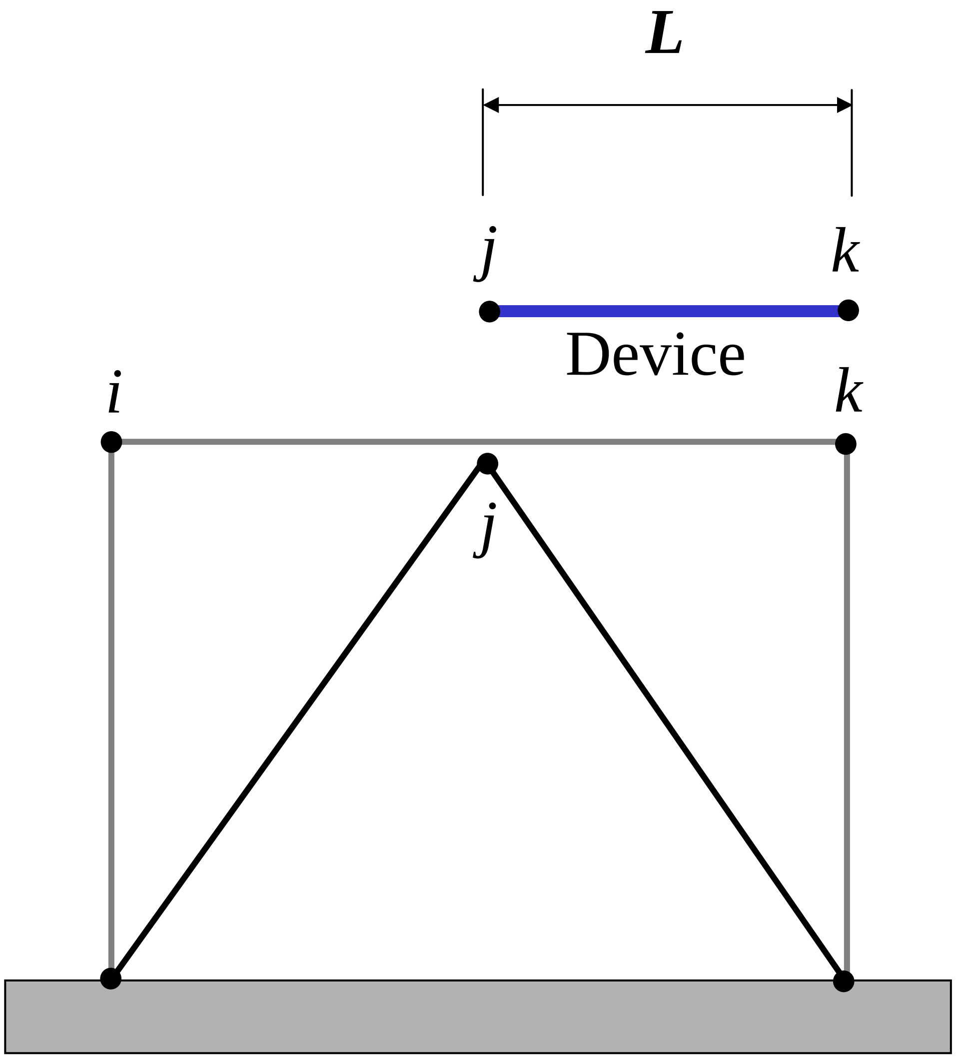


Modeling Linear Viscous Dampers in DRAIN



Note: Nonlinear Damping is NOT Available in DRAIN.

Modeling Linear Viscous Dampers in DRAIN



Use element stiffness proportional damping.

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

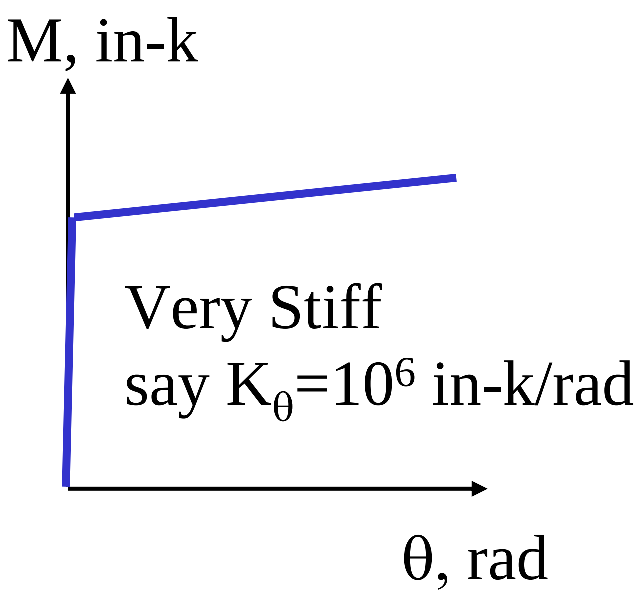
$$C_{Damper} = \beta K_{Damper}$$

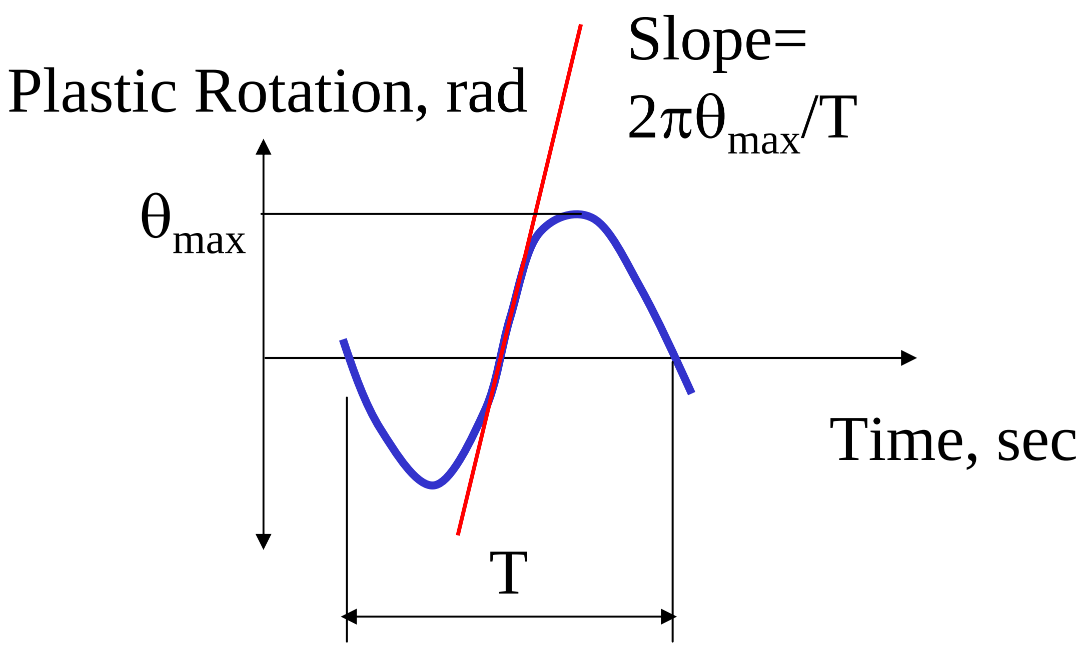
For low damper stiffness:
Set $A=L$, $E=0.01$

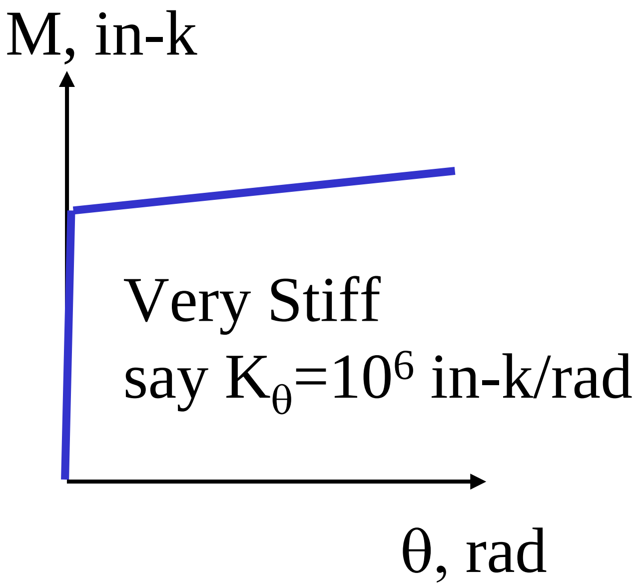
use $\beta = C_{Damper}/0.01$

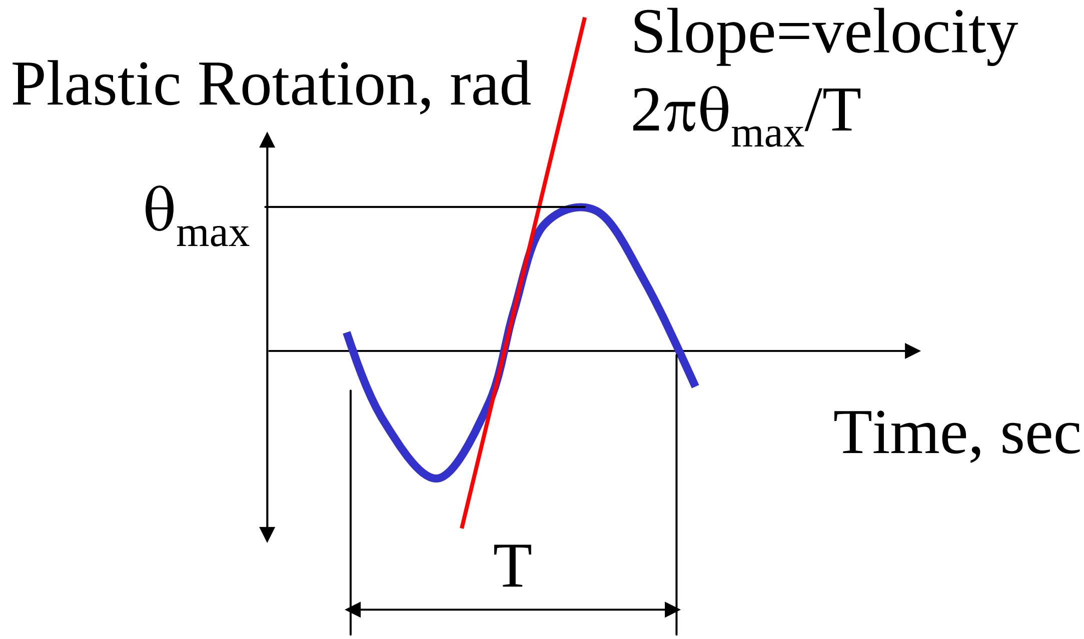
Caution Regarding Stiffness Proportional Damping

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









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

Assume θ_{max} = .03 rad, T=1.0 sec, β=0.004

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

NEHRP Ground Motion Selection

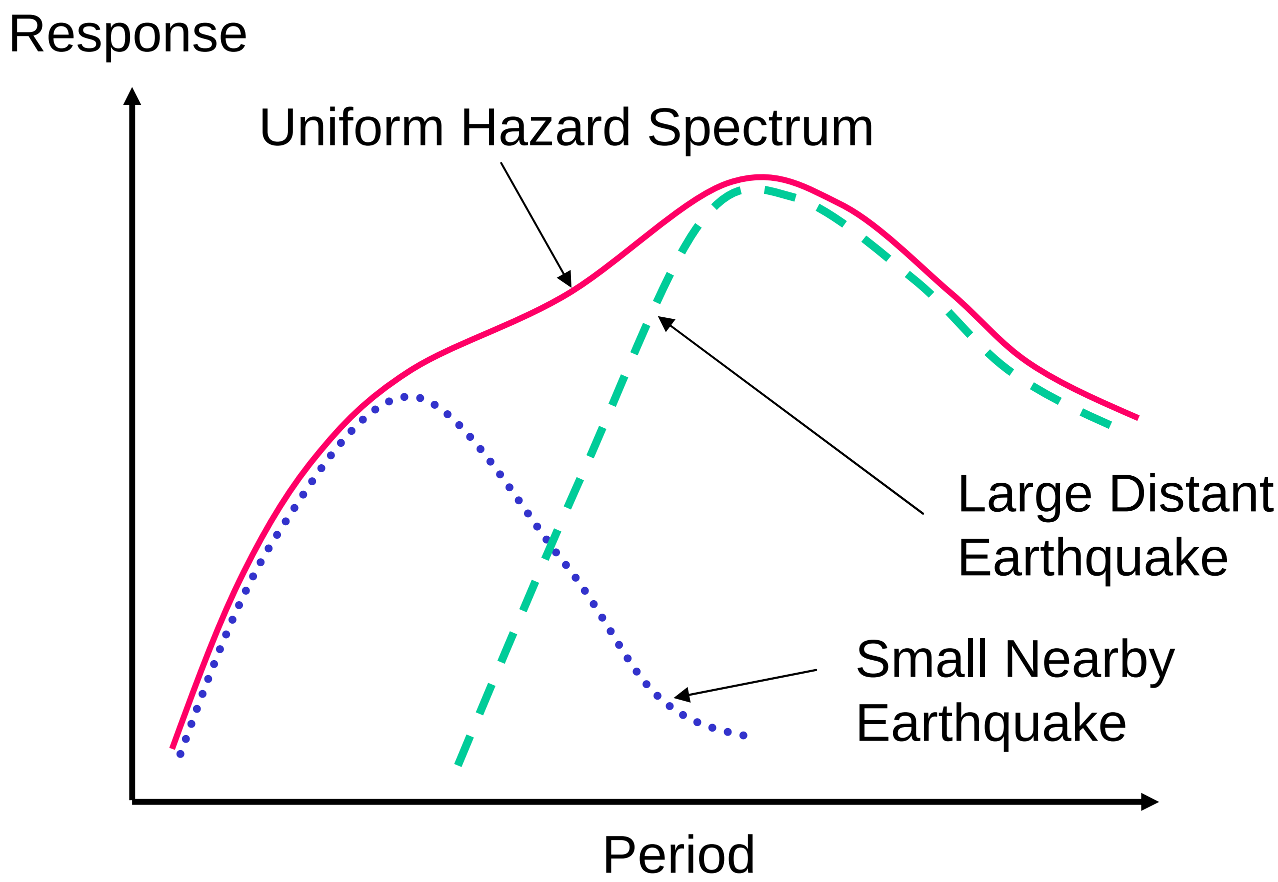
- Ground motions must have magnitude, fault mechanism, and fault distance consistent with the site and must be representative of the maximum considered ground motion
- Where the required number of motions are not available simulated motions (or modified motions) may be used

(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.



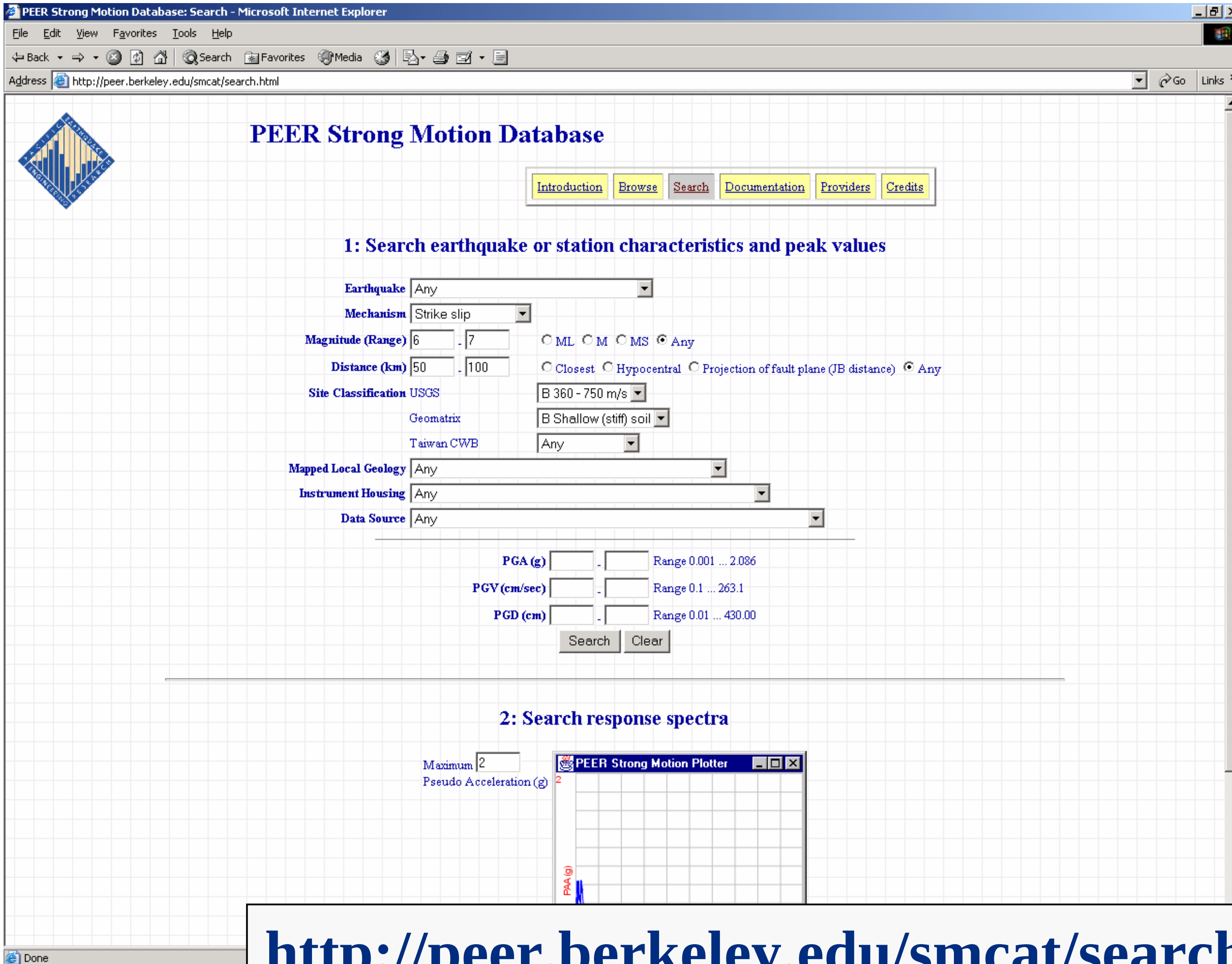
Use of Simulated Ground Motions

Reference:

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

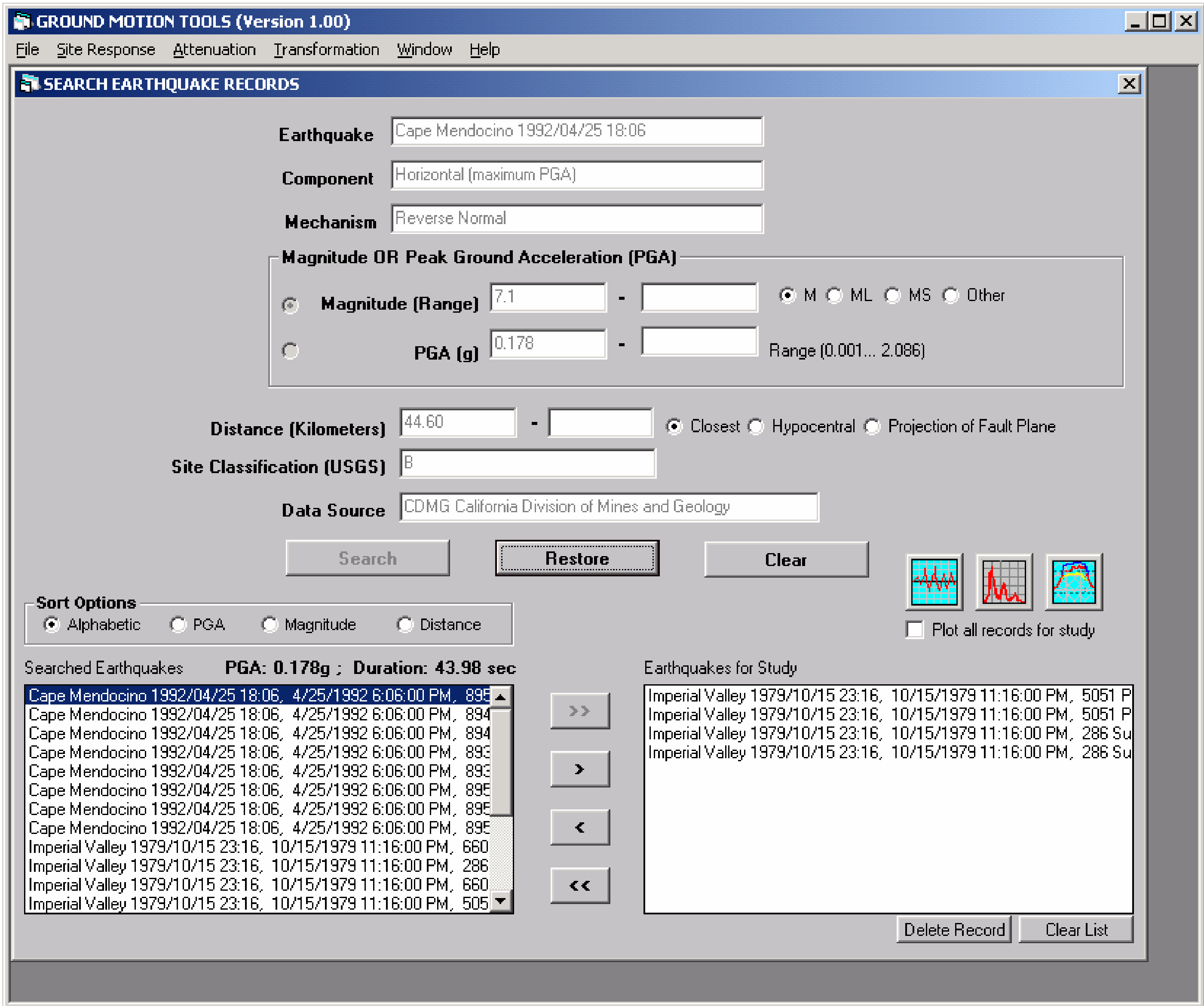
"Frequency domain scaled Design Spectrum Compatible Time Histories (DSCTH) are based on an erroneous understanding of the role of design spectra and can suffer from a multitude of major problems. They may represent velocities, displacements, and high energy content which are very unreliable. The authors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

PEER Ground Motion Search Engine

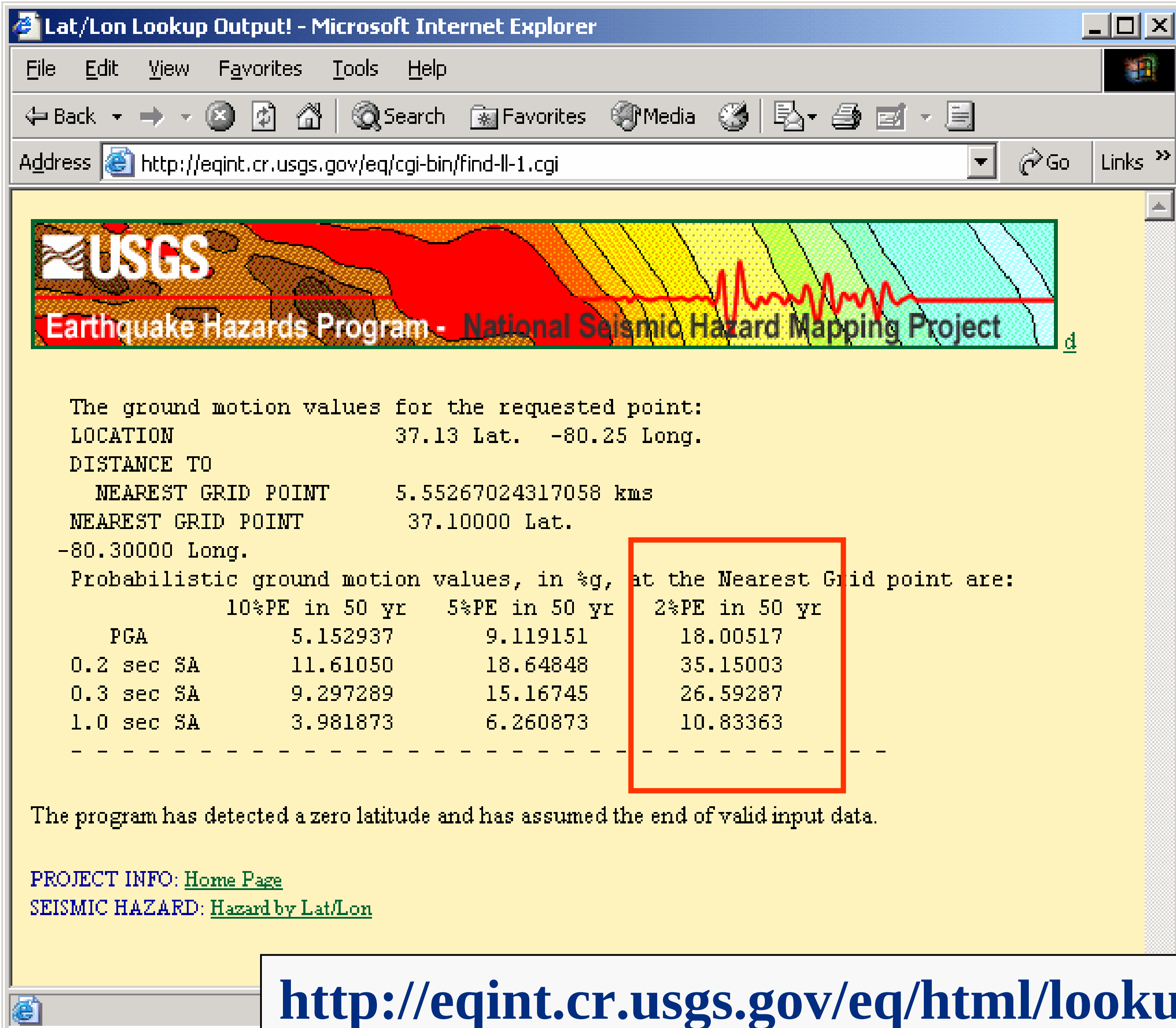


http://peer.berkeley.edu/smcat/search.html

NONLIN Ground Motion Tools (EQTOOLS)

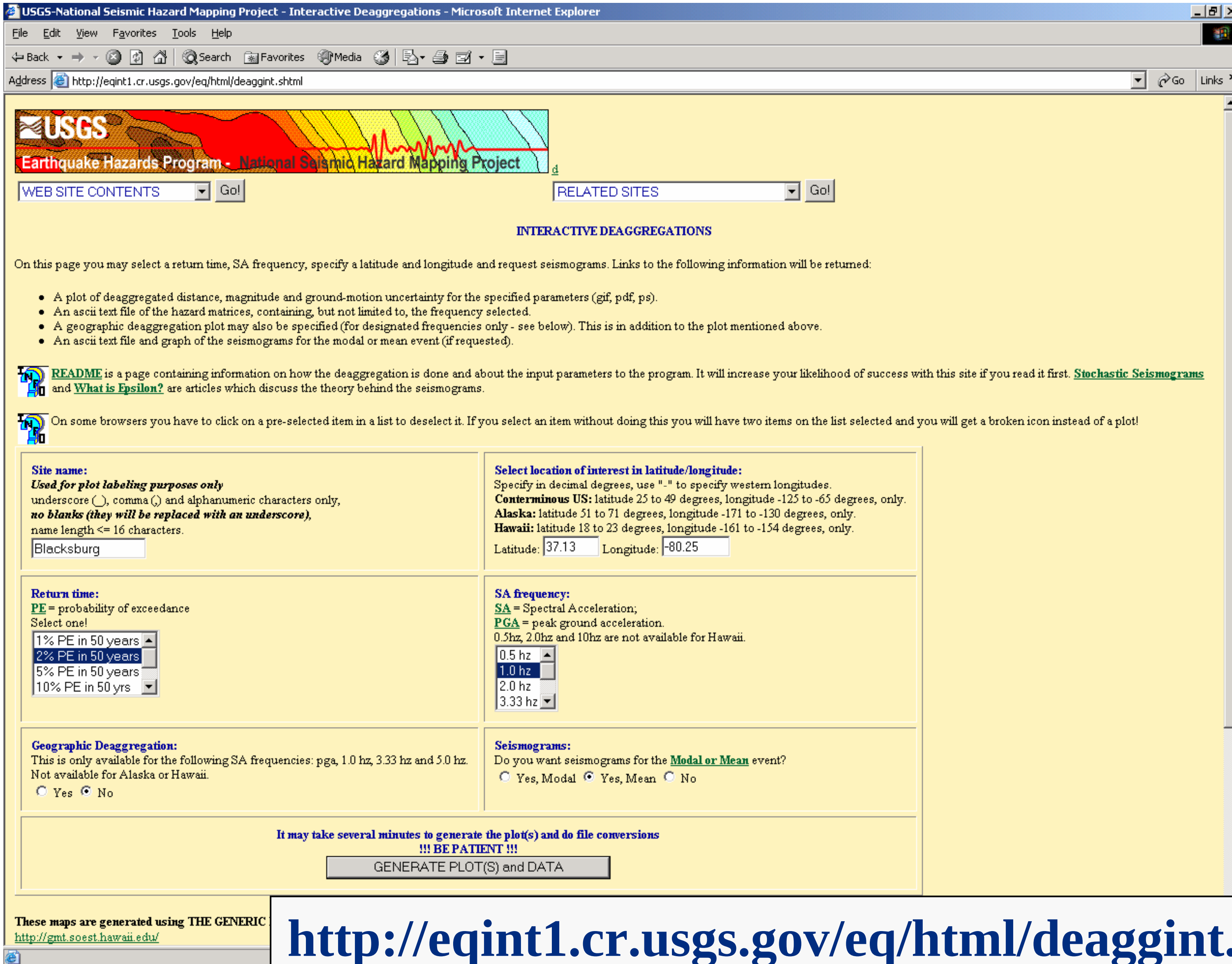


Uniform Hazard Spectrum Coordinates



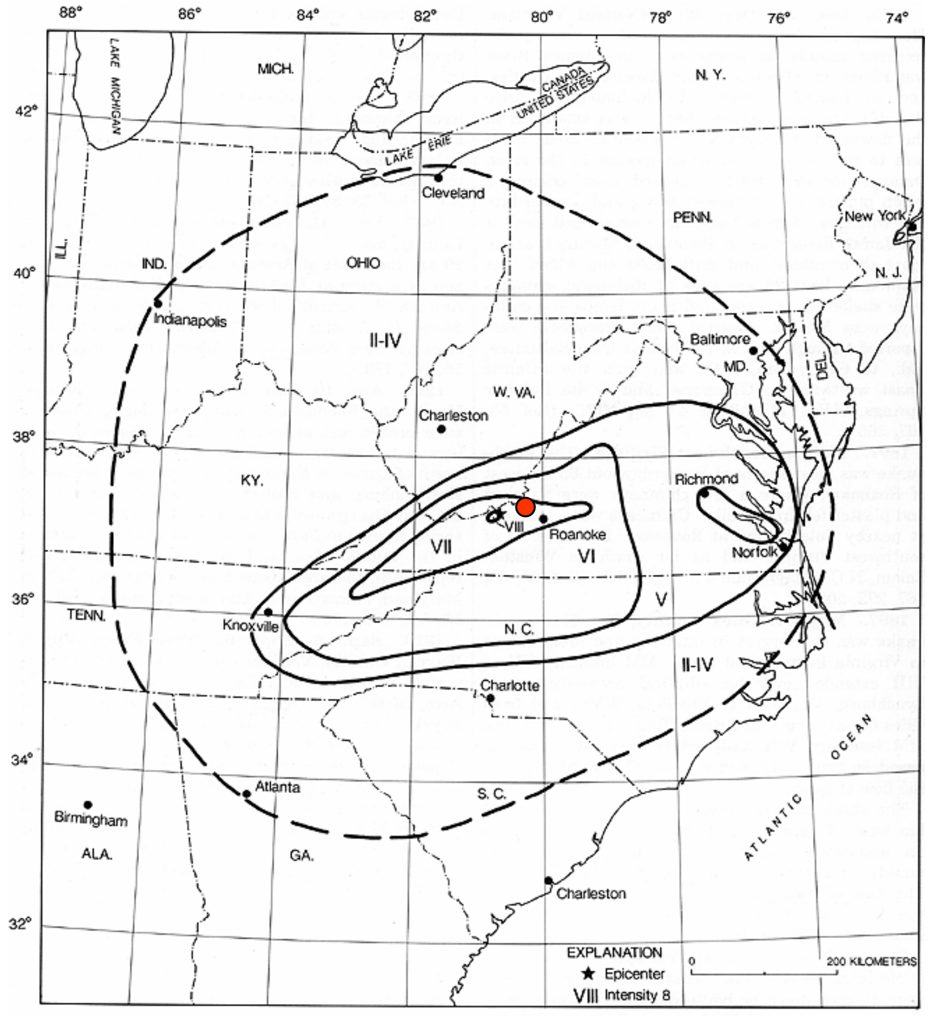
http://eqint.cr.usgs.gov/eq/html/lookup.shtml

Ground Motion Generator



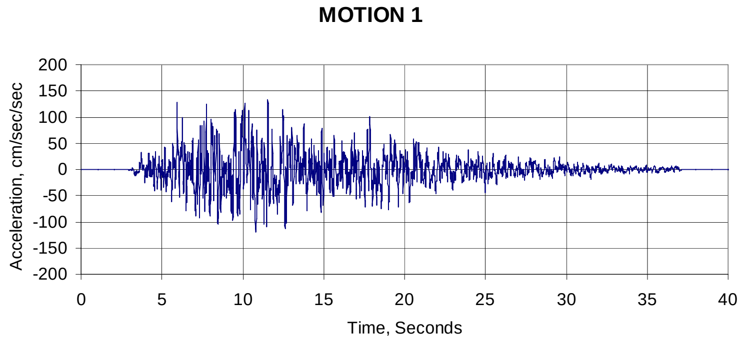
http://eqint1.cr.usgs.gov/eq/html/deaggint.shtml

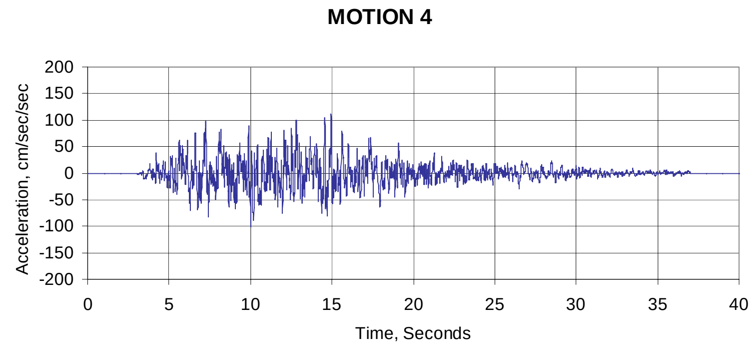
Isoseismal Map for the Giles County, Virginia, Earthquake of May 31, 1897.

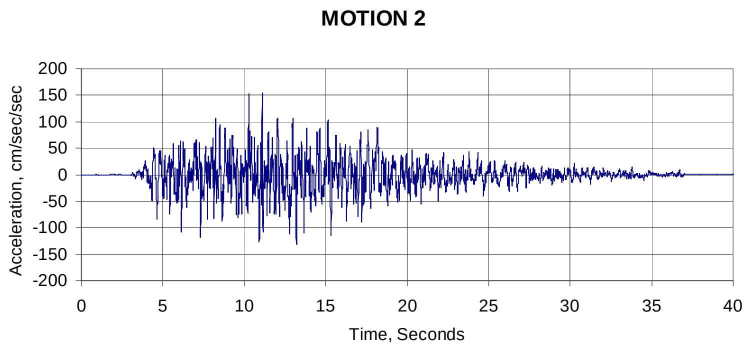


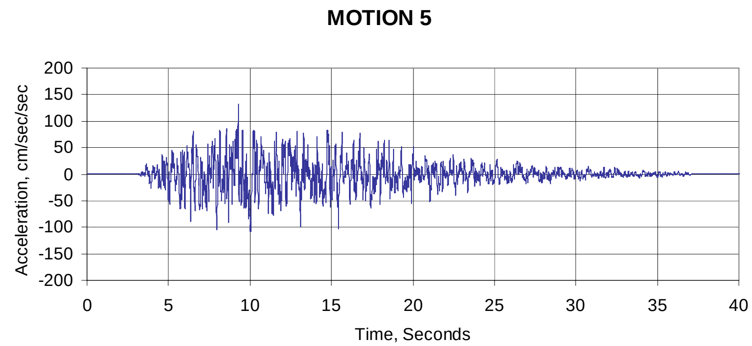
● Blacksburg
N 37.1
W -80.25

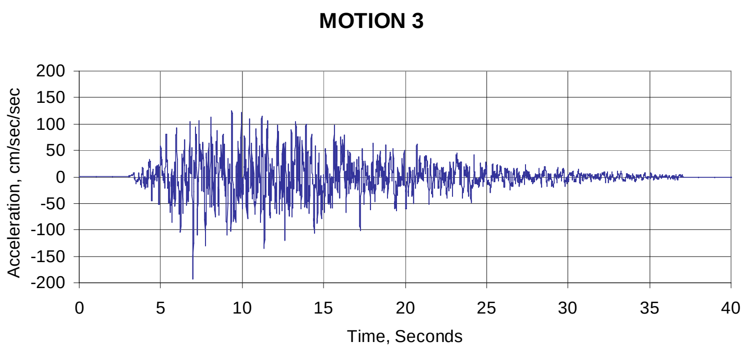
Blacksburg 2%-50 Ground Motions from USGS Web Site

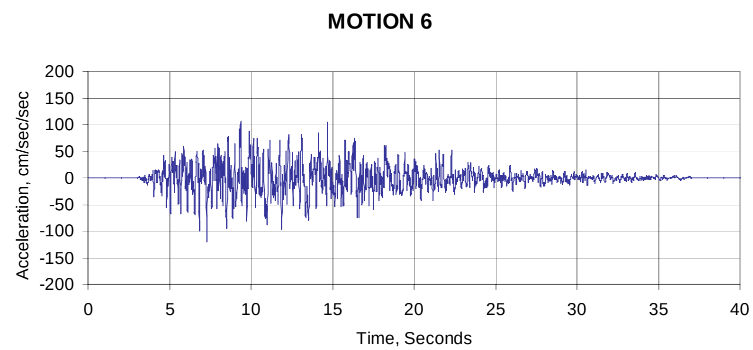




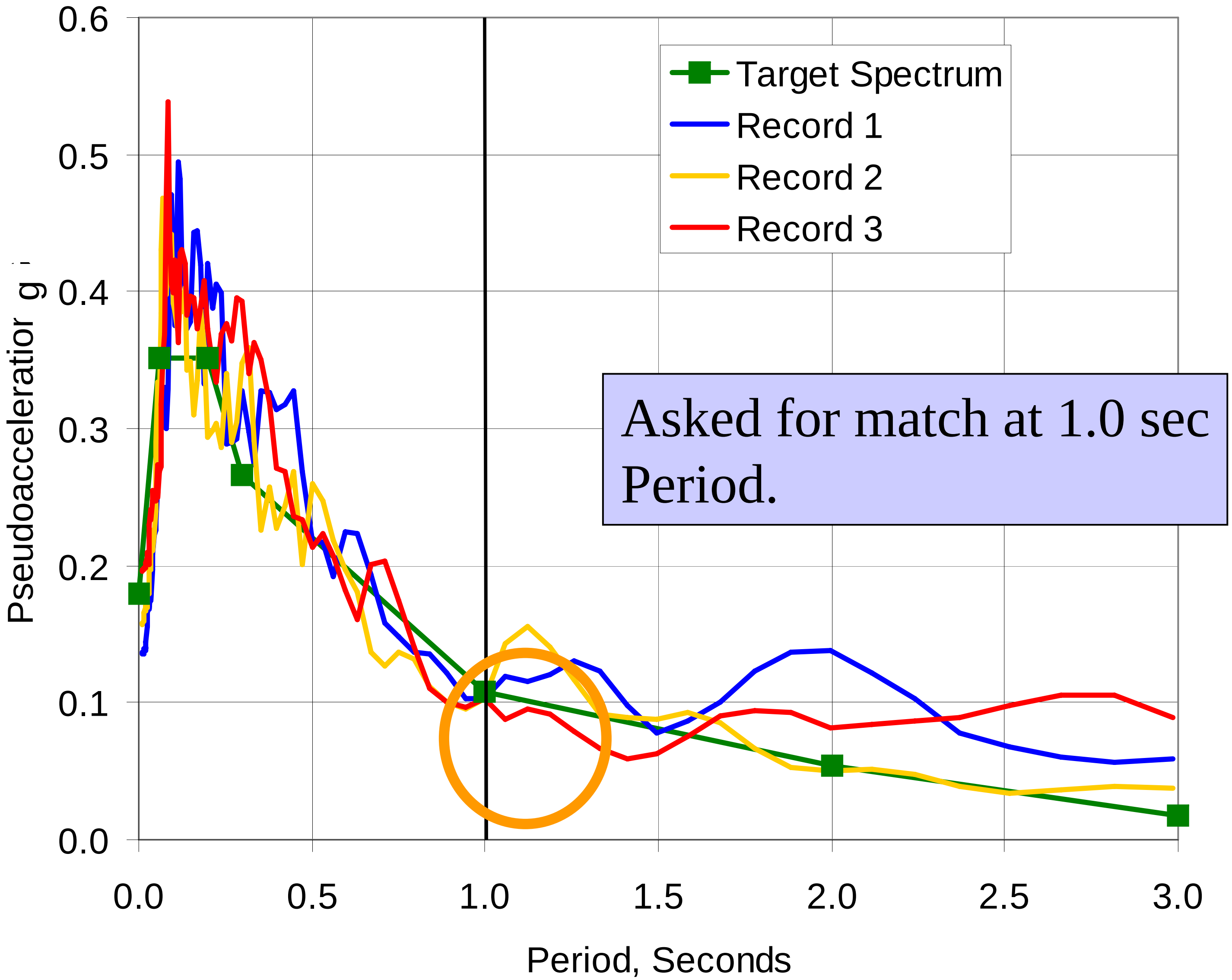




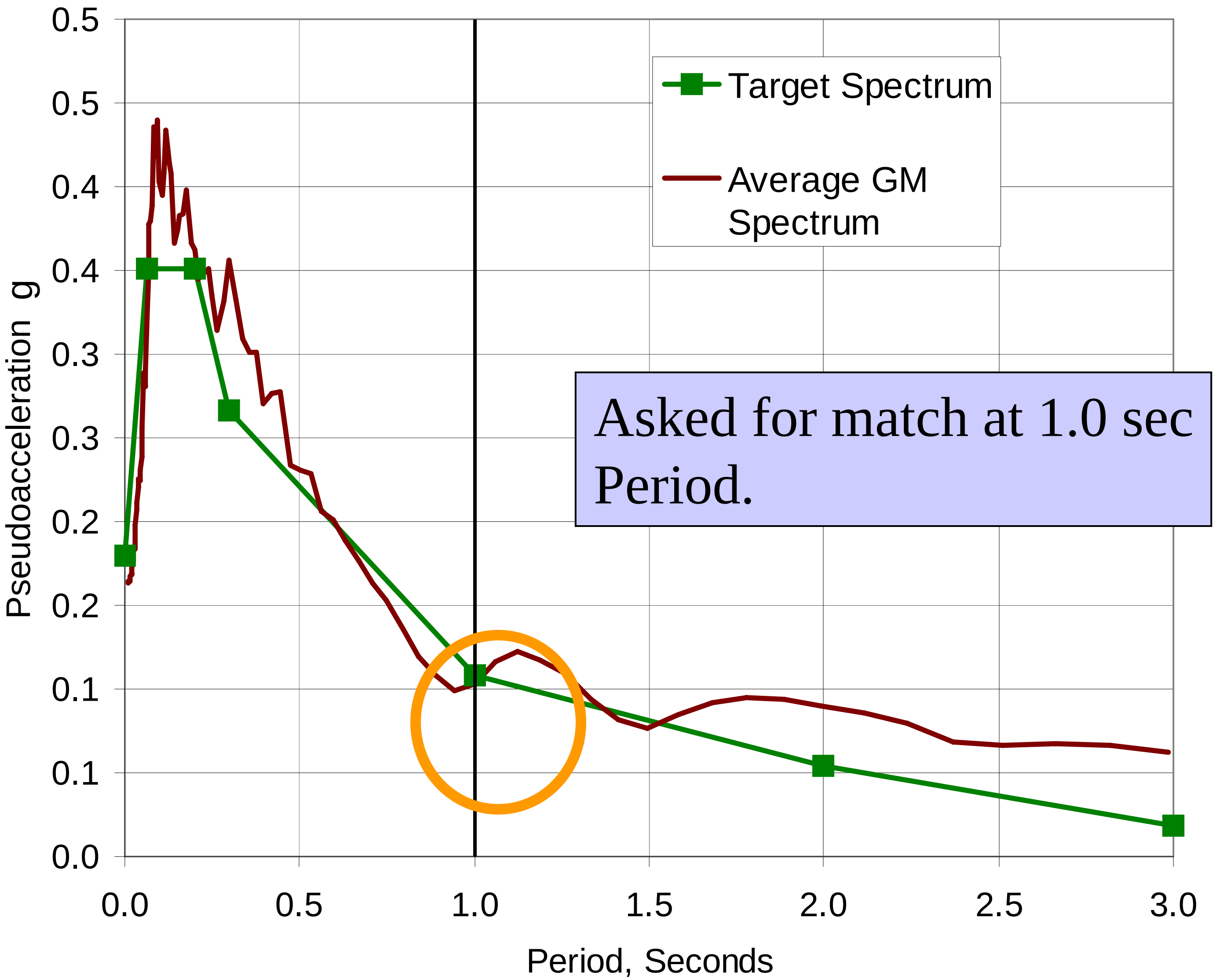




USGS Ground Motion Spectra and Target Spectrum

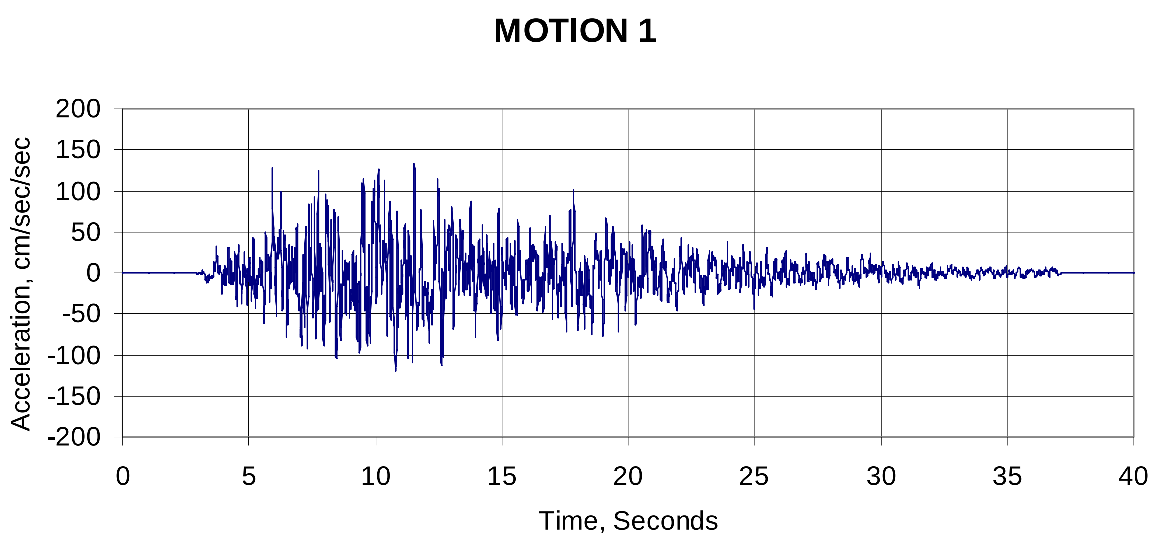


Average USGS Ground Motion Spectrum and Target Spectrum



Ground Modification Modifications

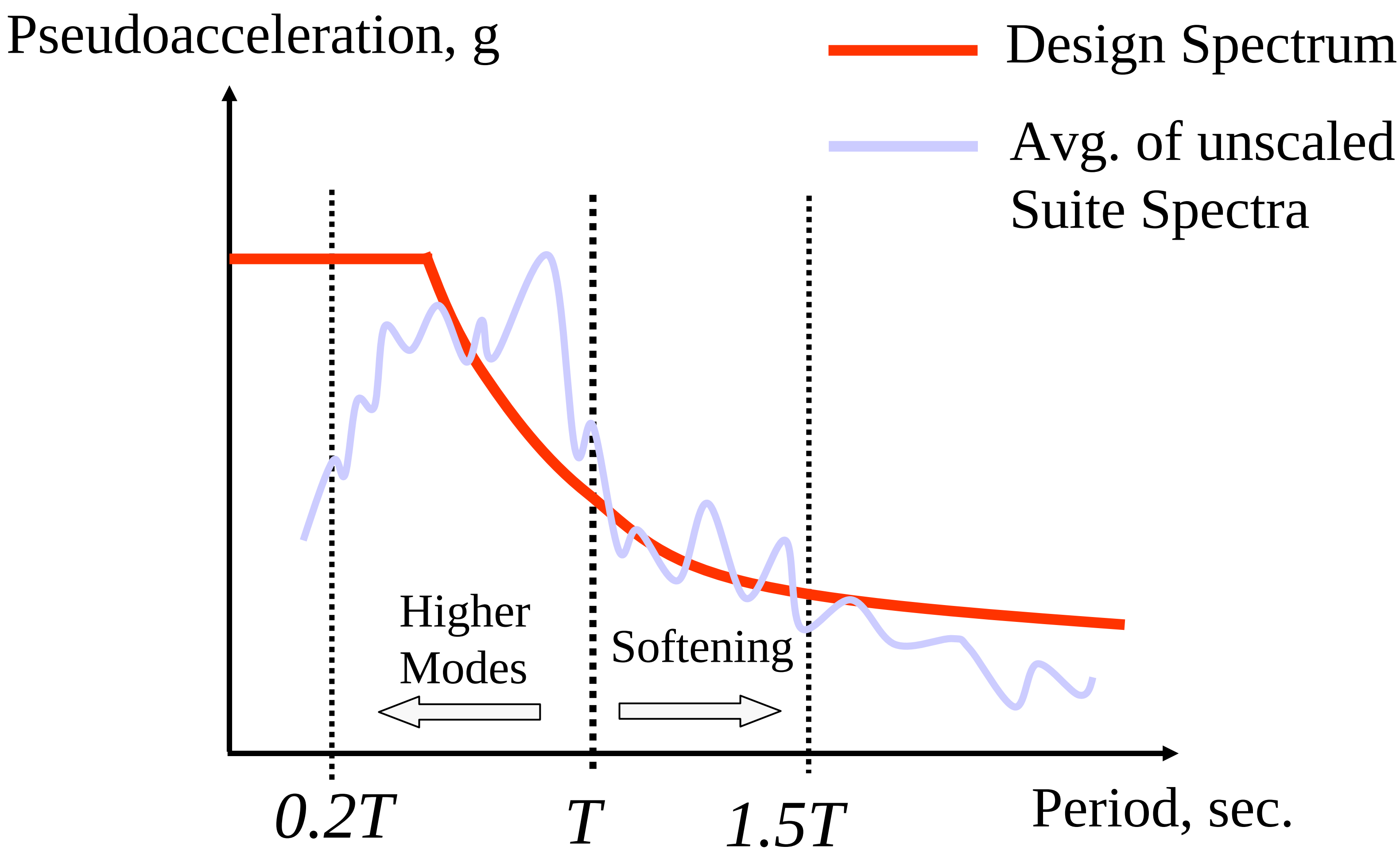
1. **Scale a given record to a higher or lower acceleration (e.g to produce a record that represents a certain hazard level)**
2. Modify a record for distance
3. Modify a record for site classification (usually from hard rock to softer soil)
4. Modify a record for fault orientation



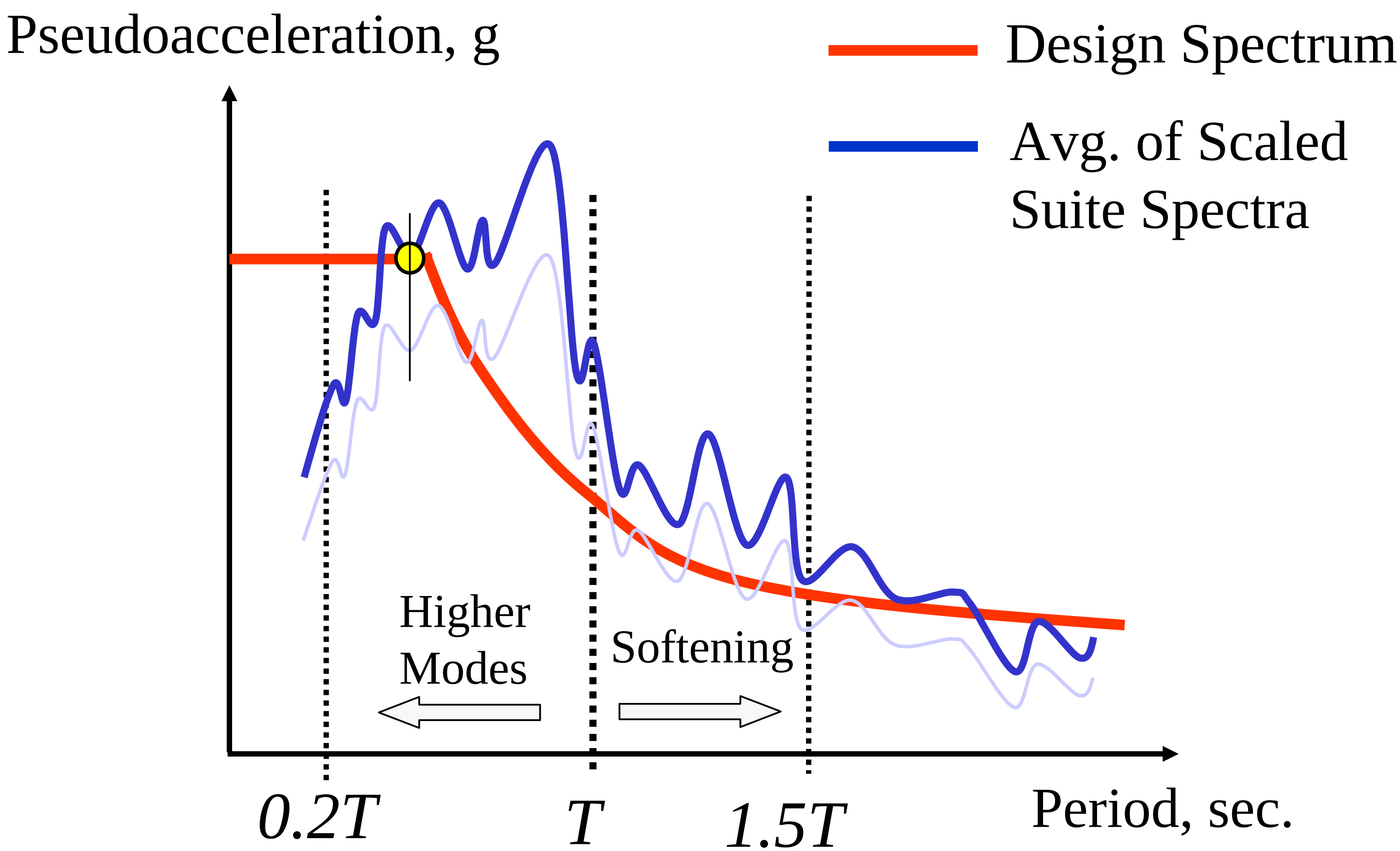
NEHRP Ground Motion Scaling
(2-D Analysis)

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 0.2*T* to 1.5*T*, 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
6th 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

λ = calibration factor

See Reference List for Additional Info on Damage Measures

Energy Balance

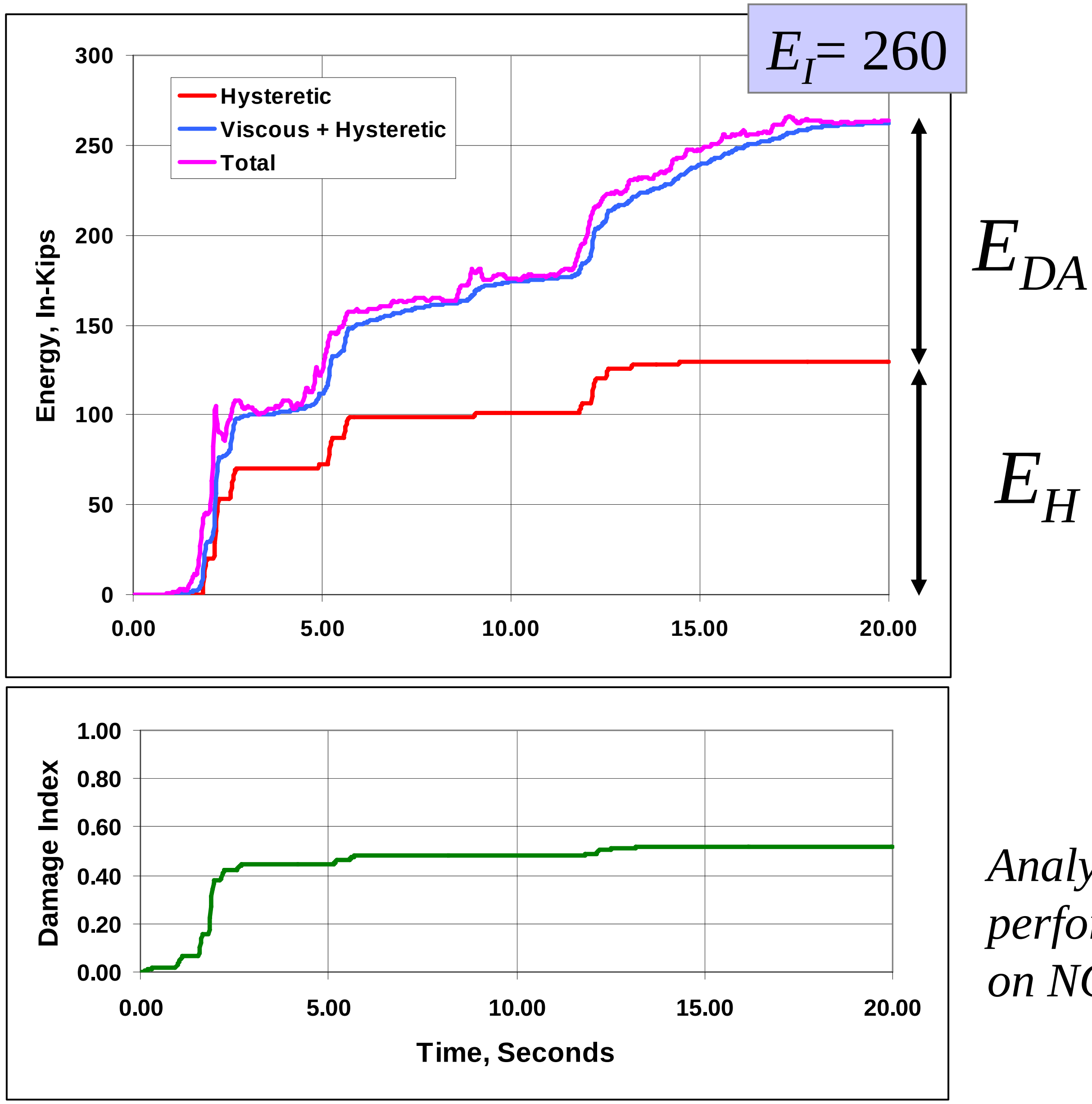
Hysteretic Energy

$$E_I = E_S + E_K + (E_{DI} + E_{DA}) + E_H$$

Inherent Damping

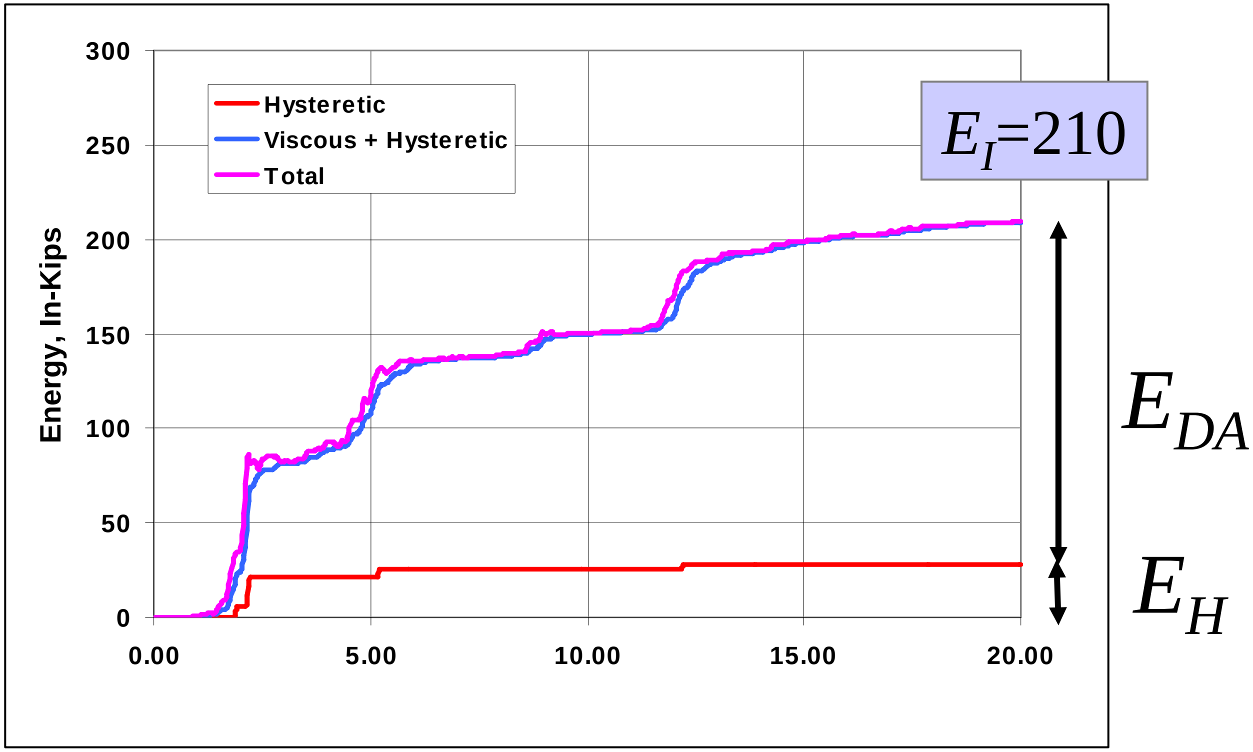
Added Damping

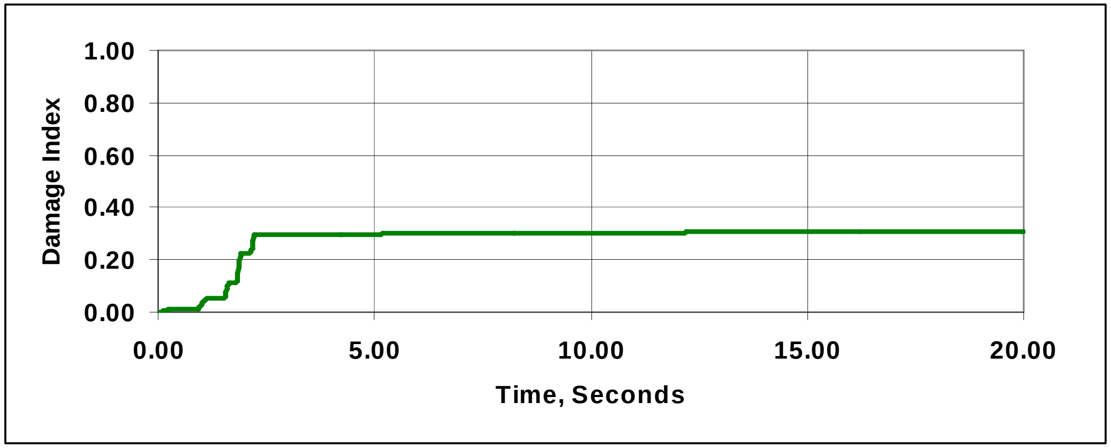
Energy and Damage Histories, 5% Damping



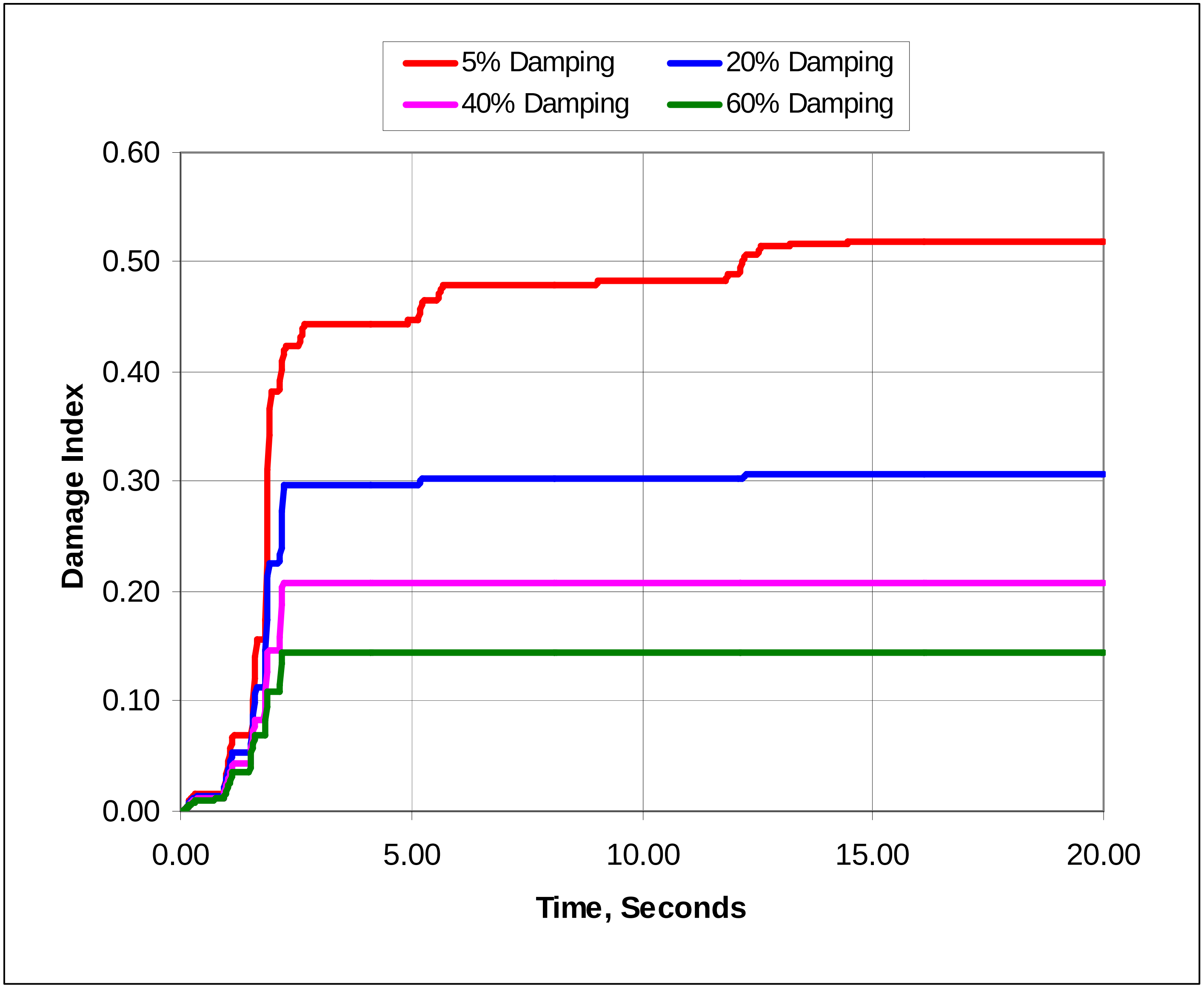
Analysis performed on NONLIN

Energy and Damage Histories, 20% Damping





Reduction in Damage with Increased Damping

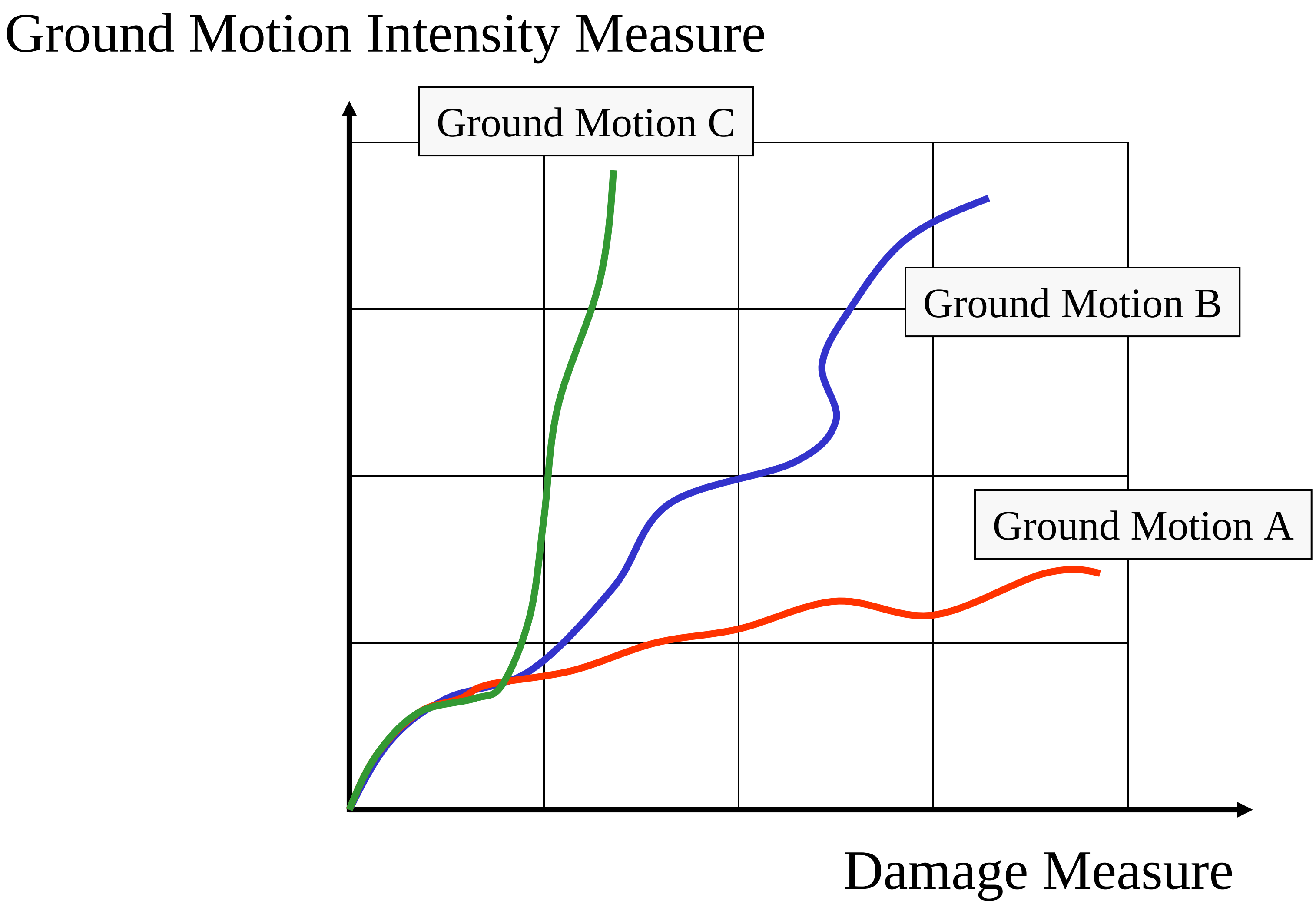


Incremental Nonlinear Dynamic Analysis

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

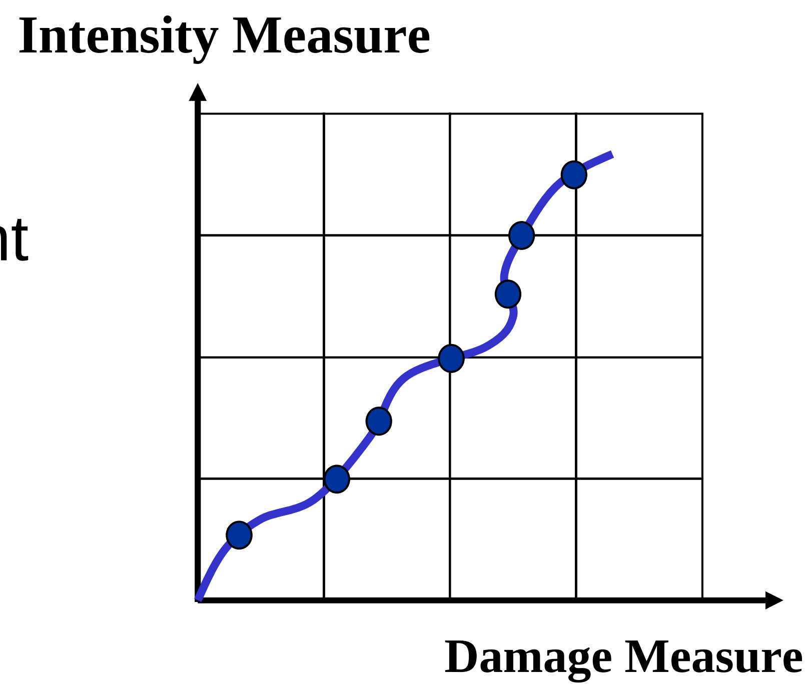
Ph.D. Dissertation of Dimitros Vamvatsikos,
Department of Civil and Environmental Engineering
Stanford University
July 2002.

Incremental Nonlinear Dynamic Analysis



Incremental Nonlinear Dynamic Analysis

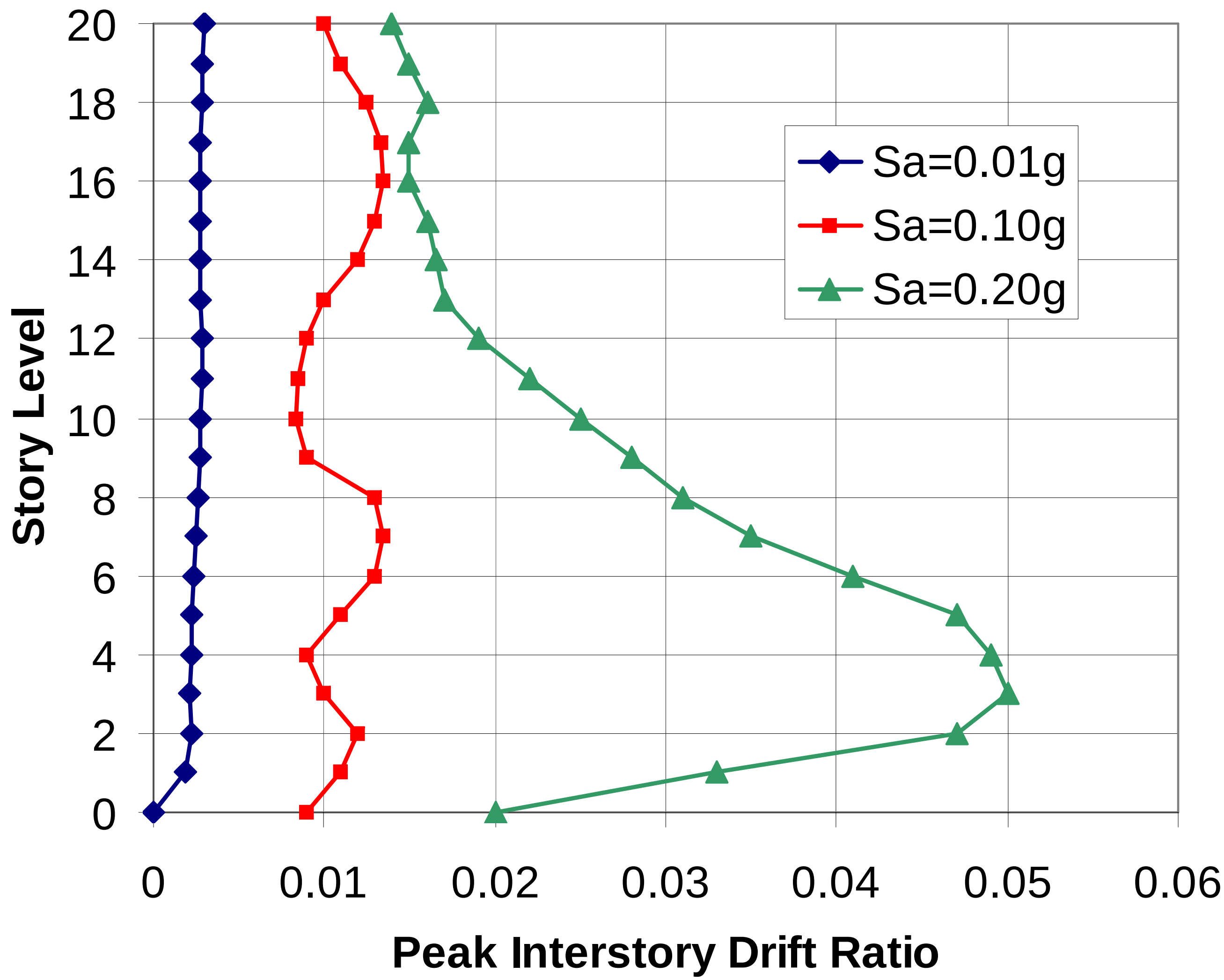
An *IDA study* is produced by subjecting a single structure to a series of time history analyses, where each subsequent analysis uses a higher ground motion intensity.



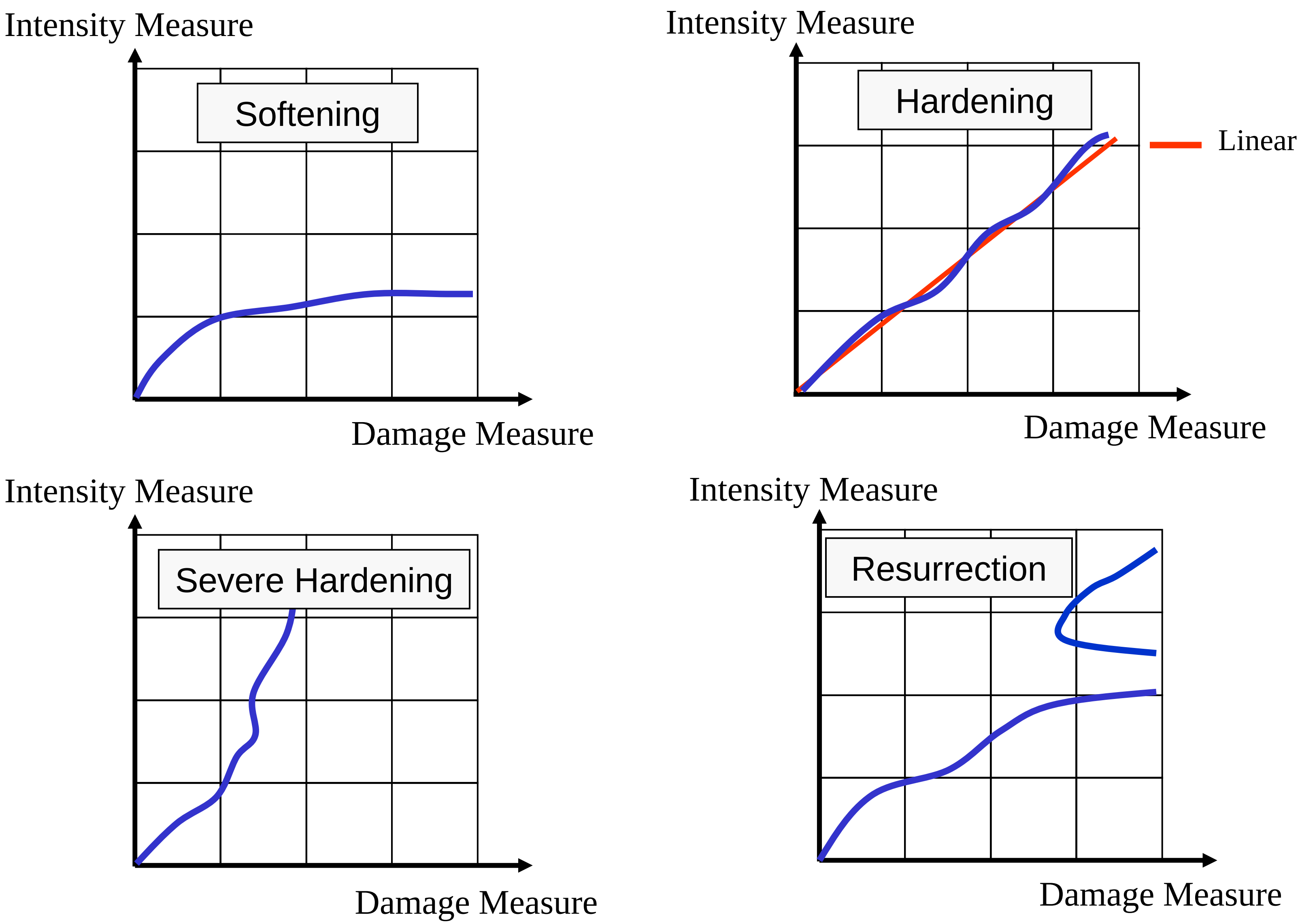
An *IDA Curve* is a plot of a damage measure (DM) versus the ground motion intensity (IM) at which it occurred.

IDA Results for a Particular Ground Motion

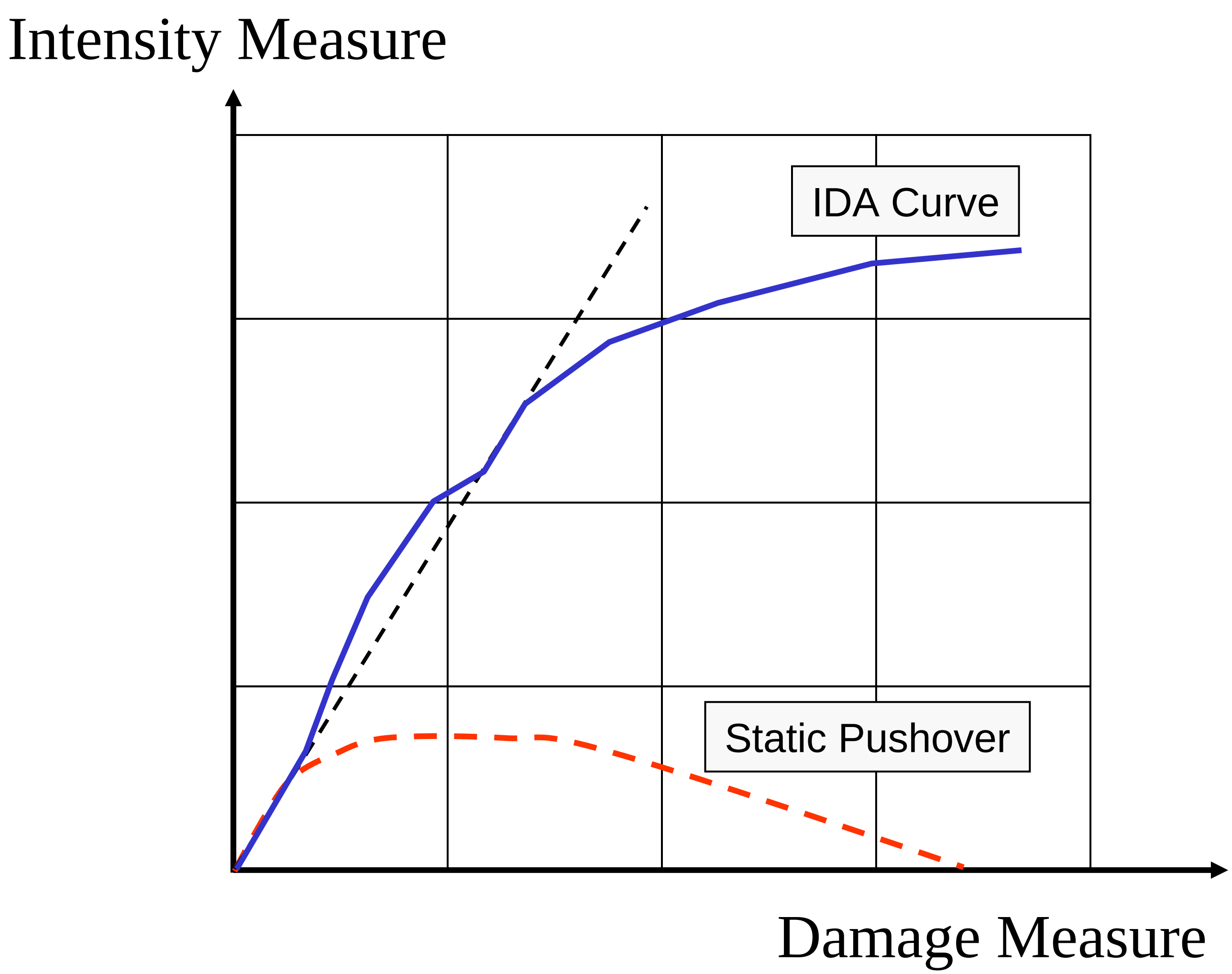
(after Vamvatsikos and Cornell)



Typical IDA Curve Characteristics



Typical IDA Curve Characteristics

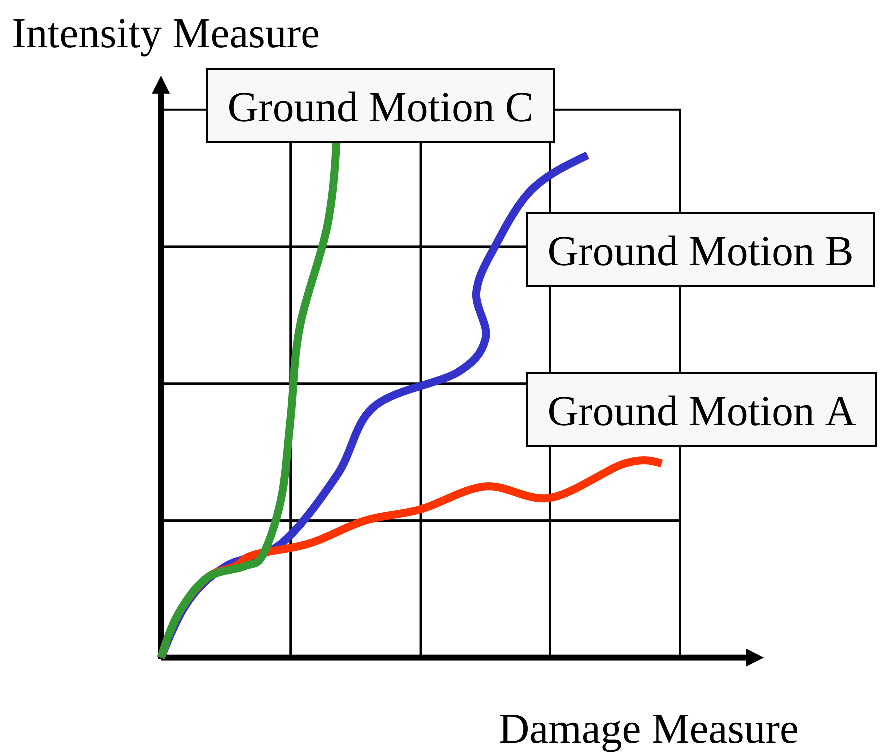


Incremental Nonlinear Dynamic Analysis

(using Multiple Ground Motions)

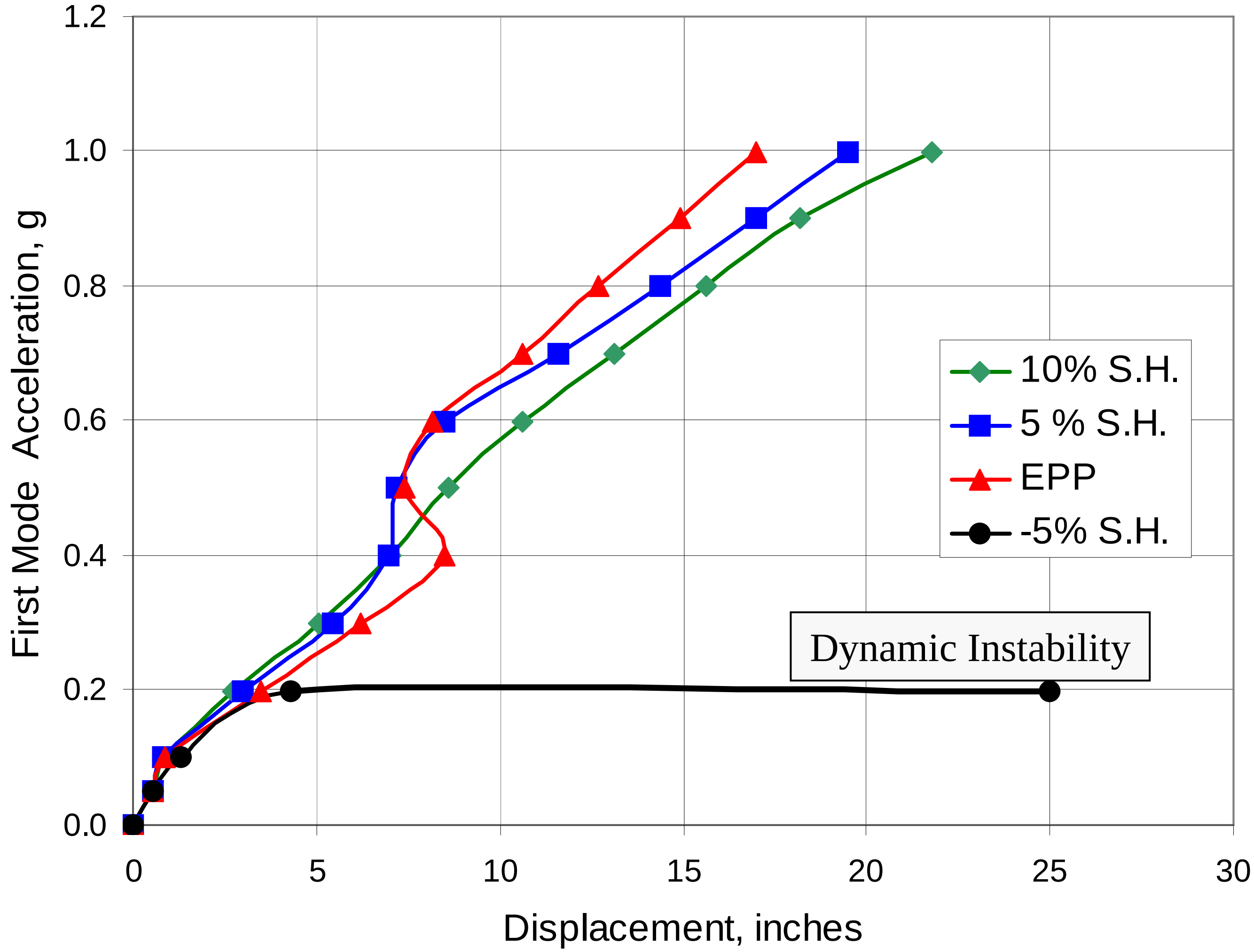
Usually, a study compares the response of the structure to a suite of ground motions.

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.



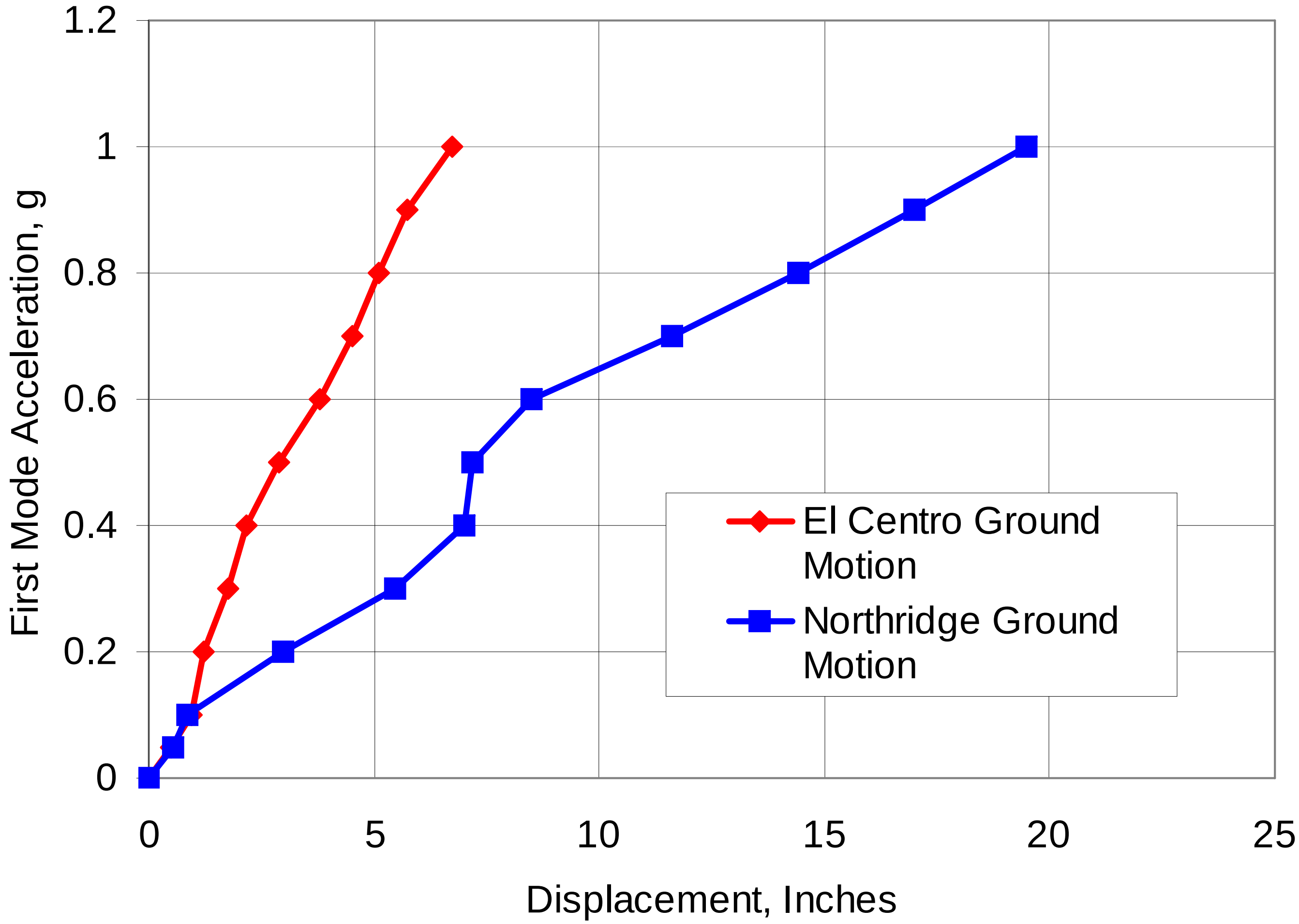
IDA Curves to Investigate Sensitivity of SDOF System Response to Strain Hardening Ratio

Analyzed on NONLIN Using Northridge (Slymar) Ground Motion.

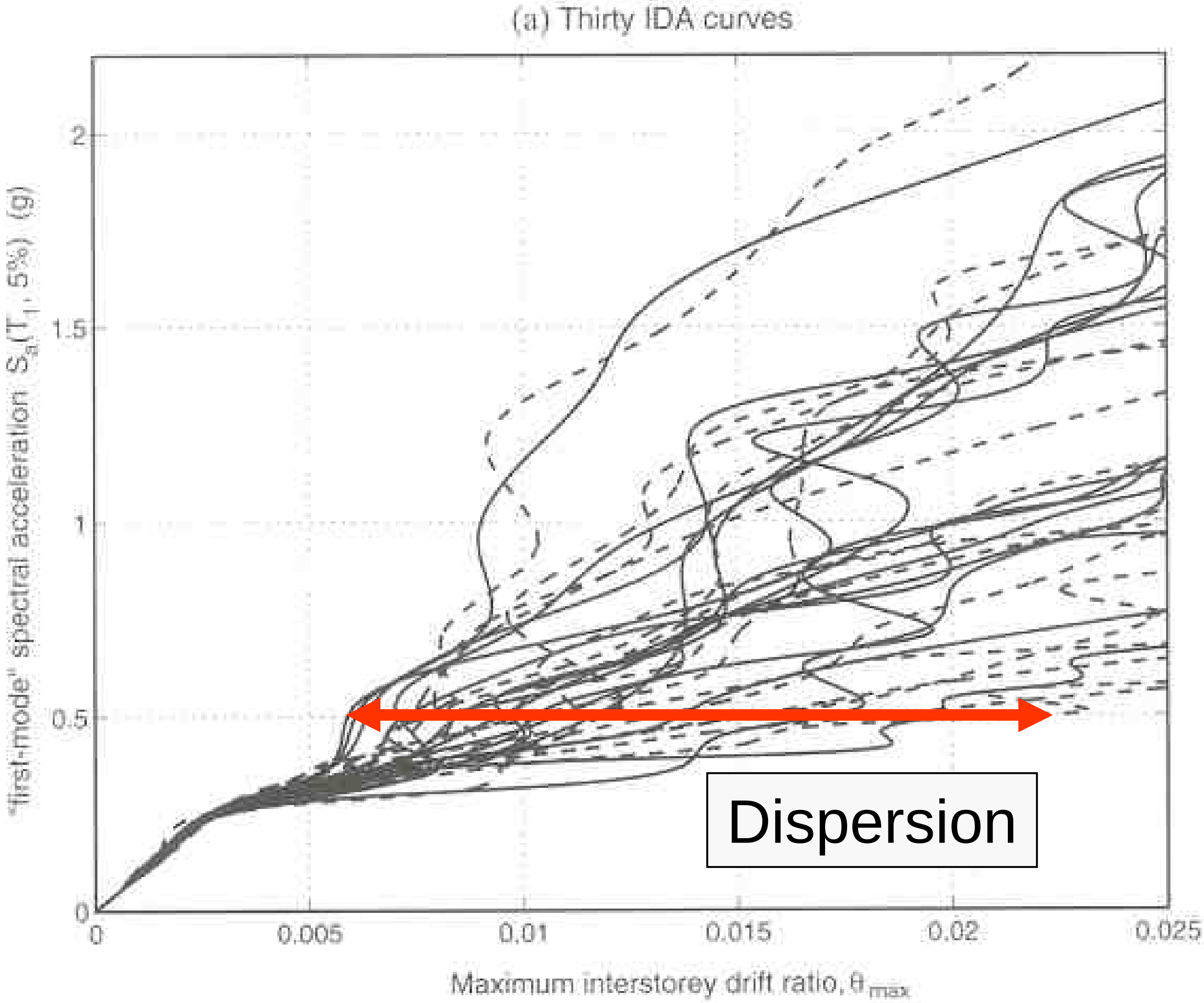


IDA Curves to Investigate Sensitivity of SDOF System Response to Choice of Ground Motion

2% Damping, 5% Strain Hardening

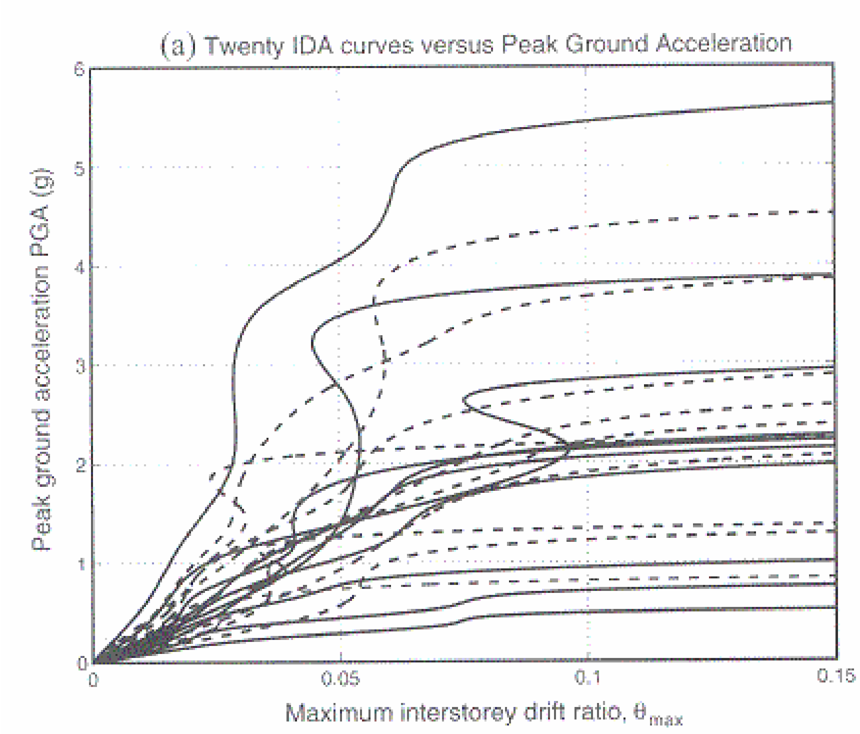


A Family of IDA Curves of the Same Building Subjected to Thirty Earthquakes

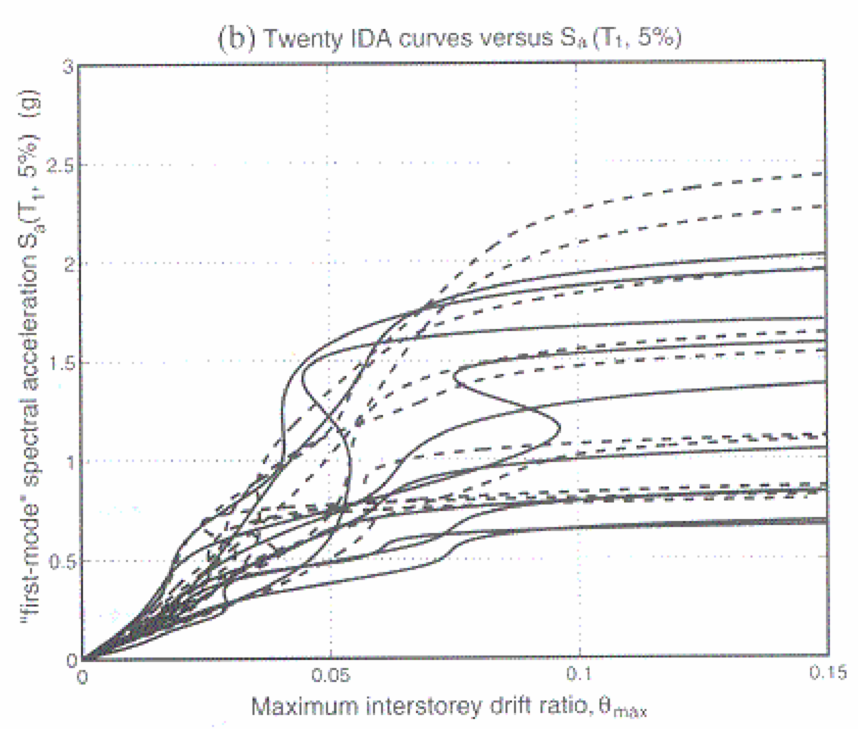


IDA Curves of the Same Building Subjected to Suite of Earthquakes

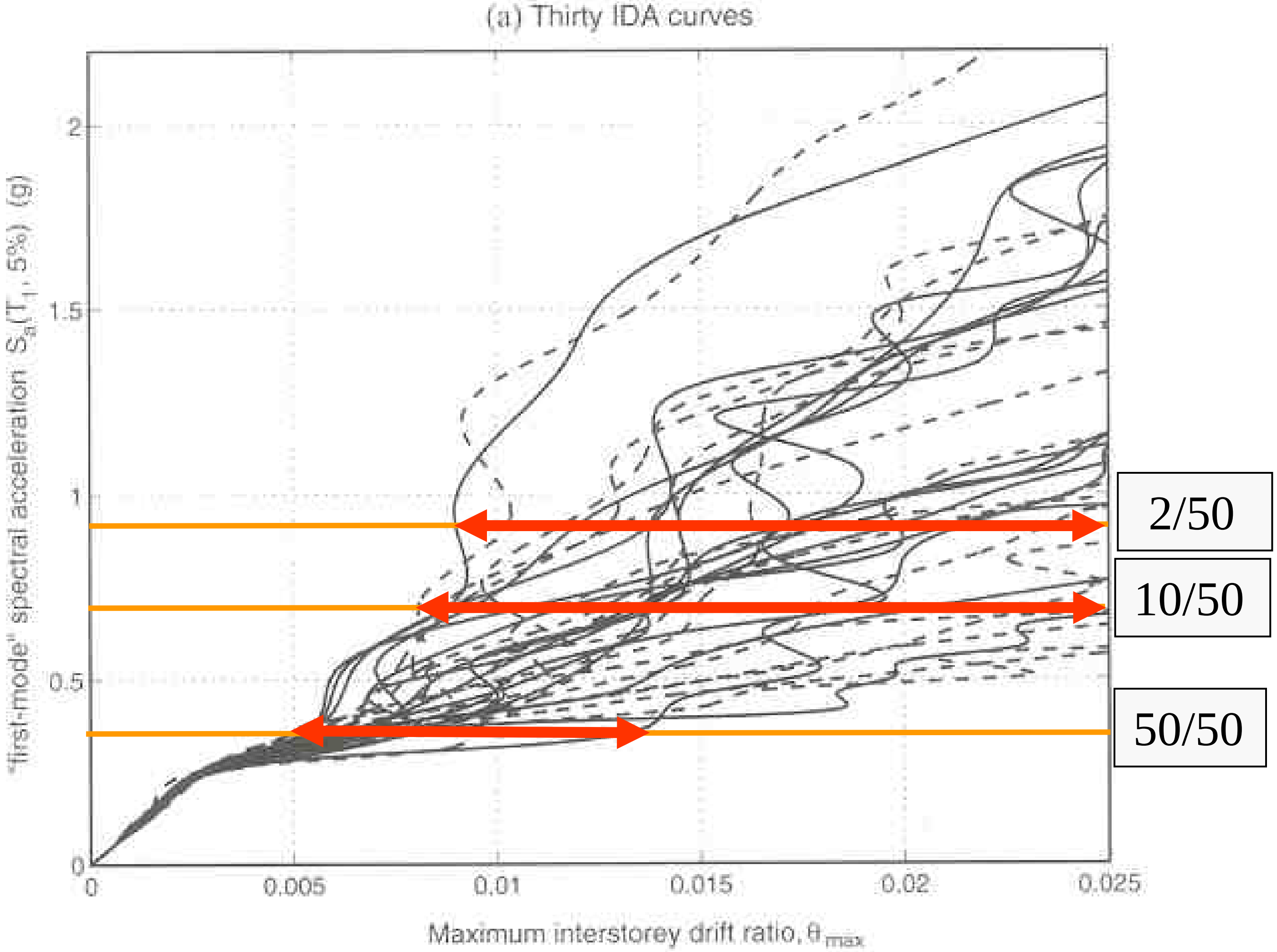
NORMALIZED to PGA



NORMALIZED to SA



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



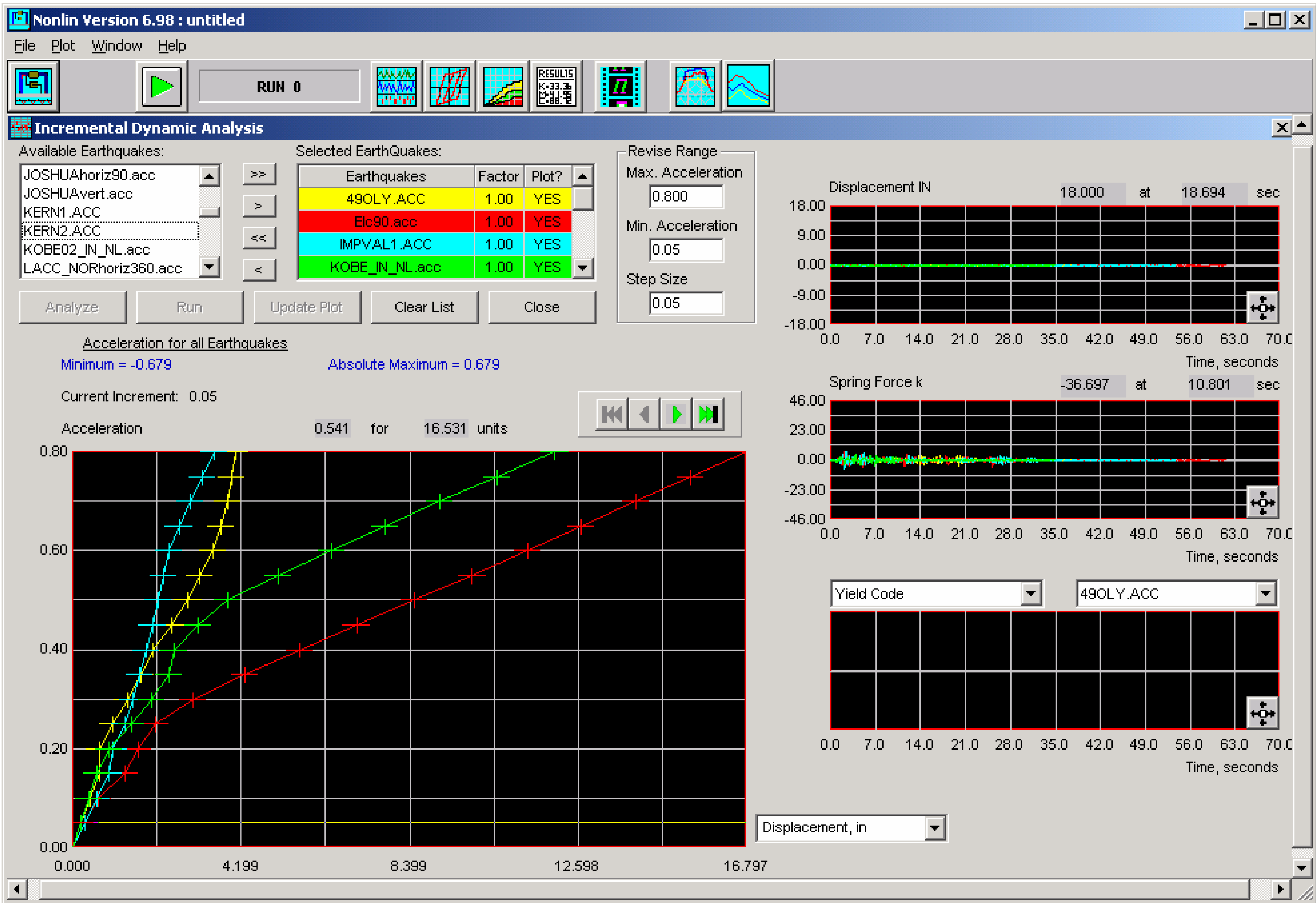
Incremental Nonlinear Dynamic Analysis

- 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

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

λ	Capacity to Demand Ratio
γ	Demand Variability Factor
γ_a	Analysis Uncertainty Factor
C	Tabulated Capacity for the Component
ϕ	Capacity Resistance Factor
D	Calculated Demand for the Component

β_{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 γ_a

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

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Table 4-9
Interstory Drift Angle Demand Variability Factor γ

	Building Height	γ	
		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

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Table 4-10
Global Interstory Drift Angle Capacity Factors (C) and Resistance Factors (ϕ)

	Building Height	I.O.		C.P.	
		C	ϕ	C	ϕ
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

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Table 4-11
Uncertainty Coefficient β_{UT} for Global Interstory Drift Evaluation

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

Probabilistic Approaches: FEMA 350

Table 4-6
Confidence Levels for Various Values of λ and β_{UT}

Confidence Level	10	20	30	40	50	60	70	80	90	95	99
λ for β_{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
λ for β_{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
λ for β_{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
λ for β_{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
λ for β_{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)

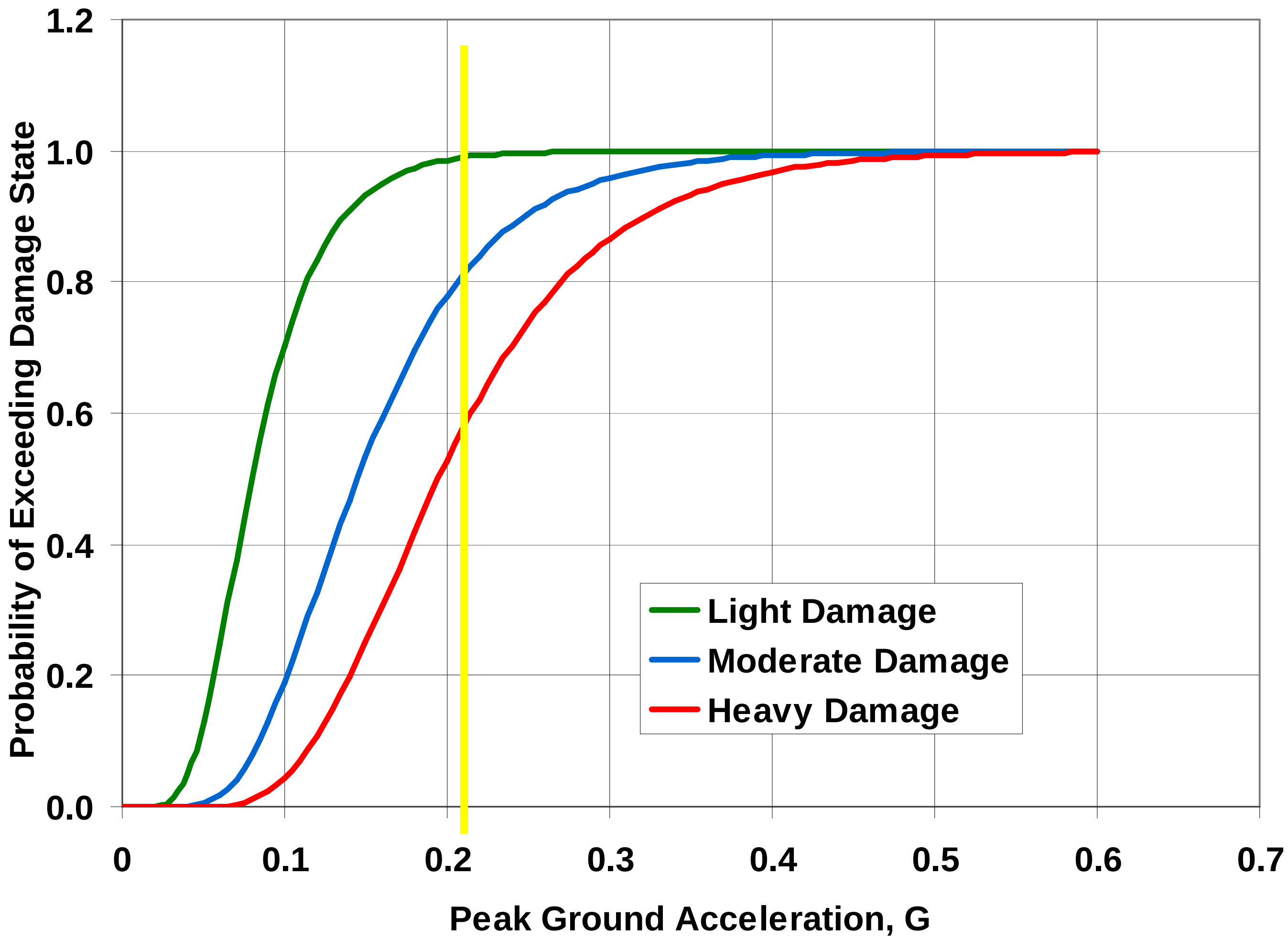
Type	PERF	Analysis	Confidence	γ	γ_a	ϕ	C	β_{UT}	λ	DL
SPECIAL	IO	NSP	50%	1.4	1.45	1	0.02	0.2	1.06	0.0104
SPECIAL	IO	NDP	50%	1.4	1.02	1	0.02	0.2	1.06	0.0148
SPECIAL	CP	NSP	90%	1.2	0.99	0.85	0.1	0.4	0.76	0.0544
SPECIAL	CP	NDP	90%	1.2	1.06	0.85	0.1	0.4	0.76	0.0508
ORDINARY	IO	NSP	50%	1.3	1.11	0.9	0.01	0.2	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?

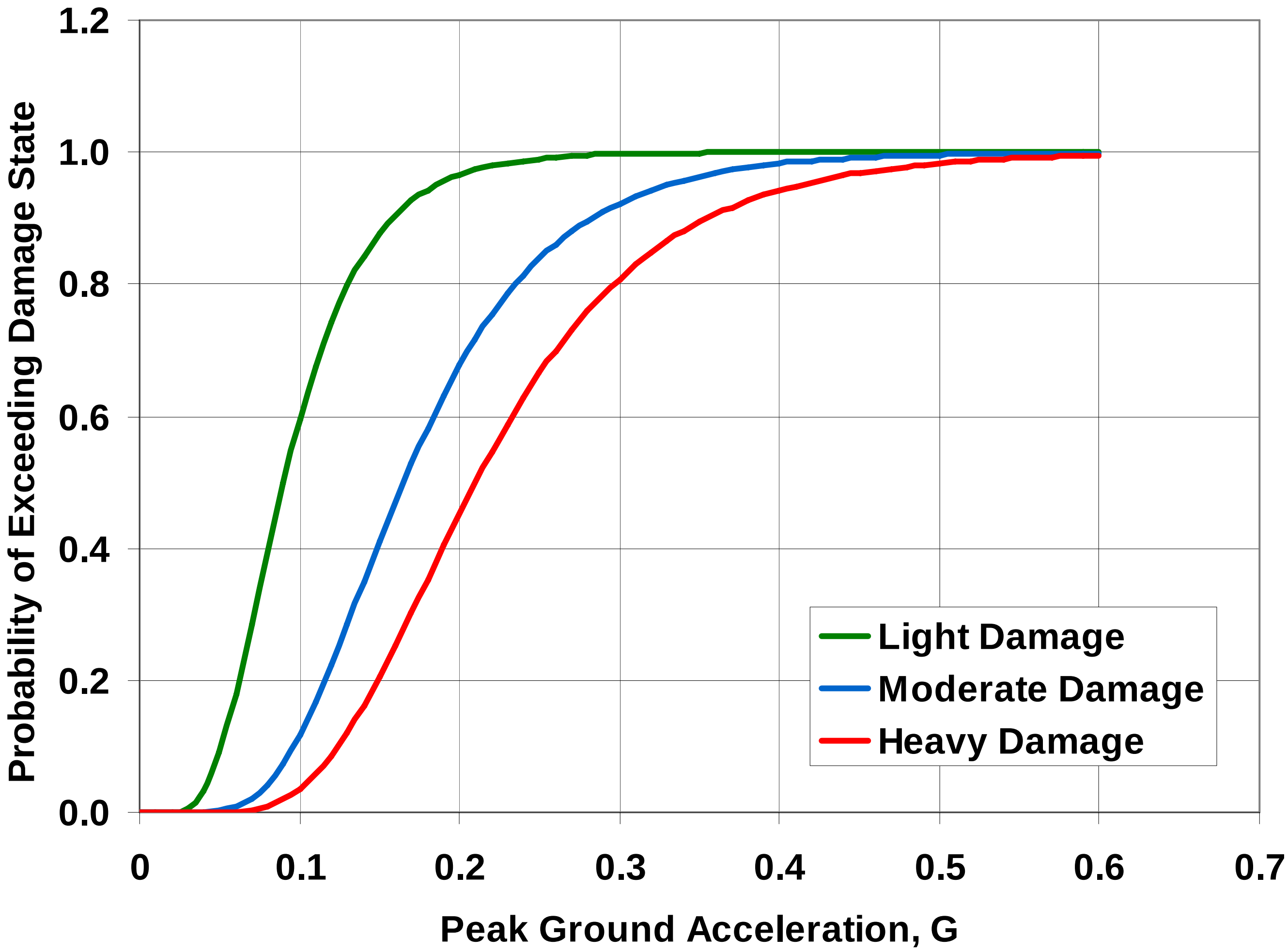
Probabilistic Approaches: Fragility Curves
Unreinforced Masonry



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

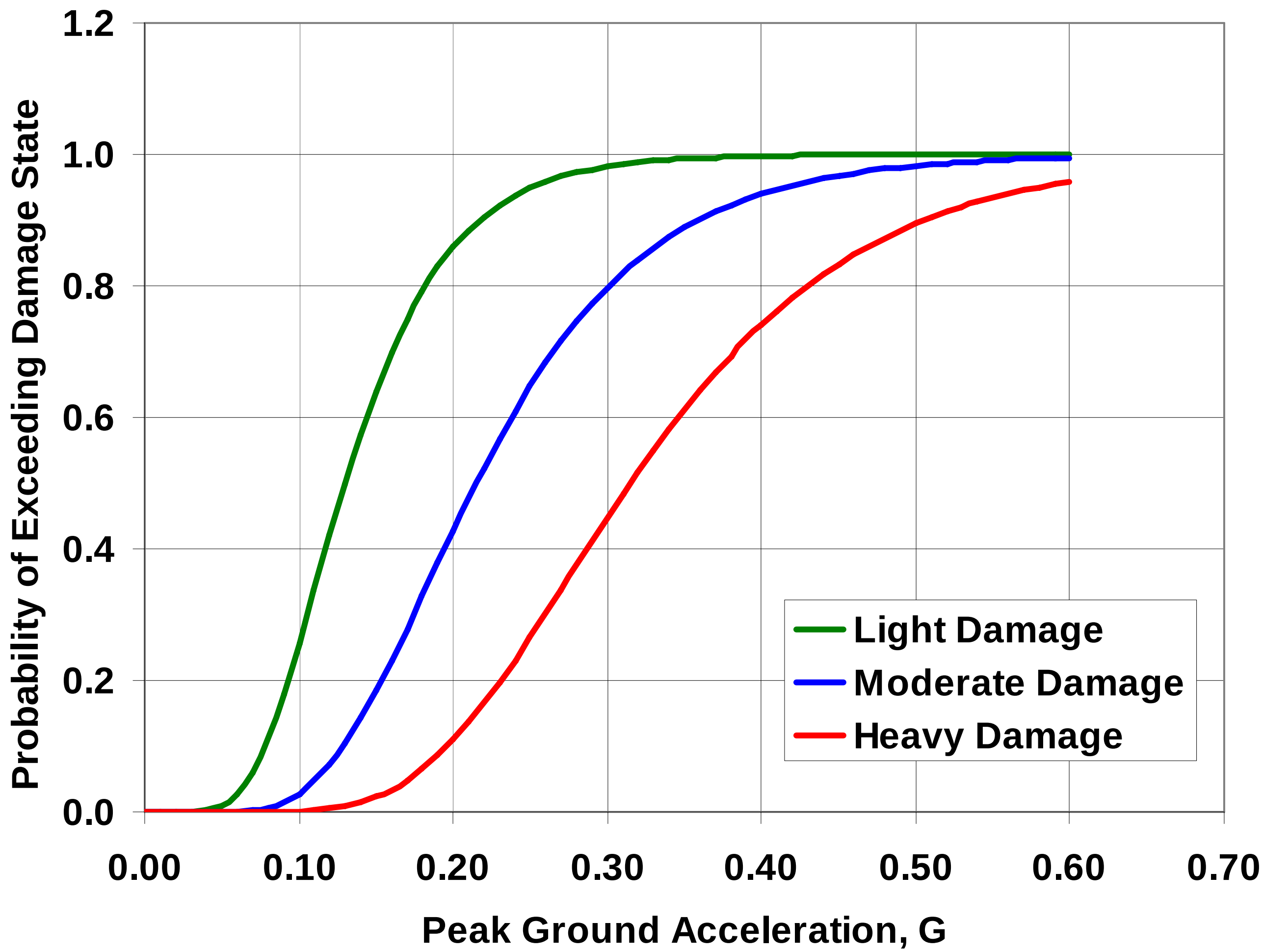
Probabilistic Approaches: Fragility Curves

Reinforced Masonry



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

Probabilistic Approaches: Fragility Curves
Reinforced Concrete



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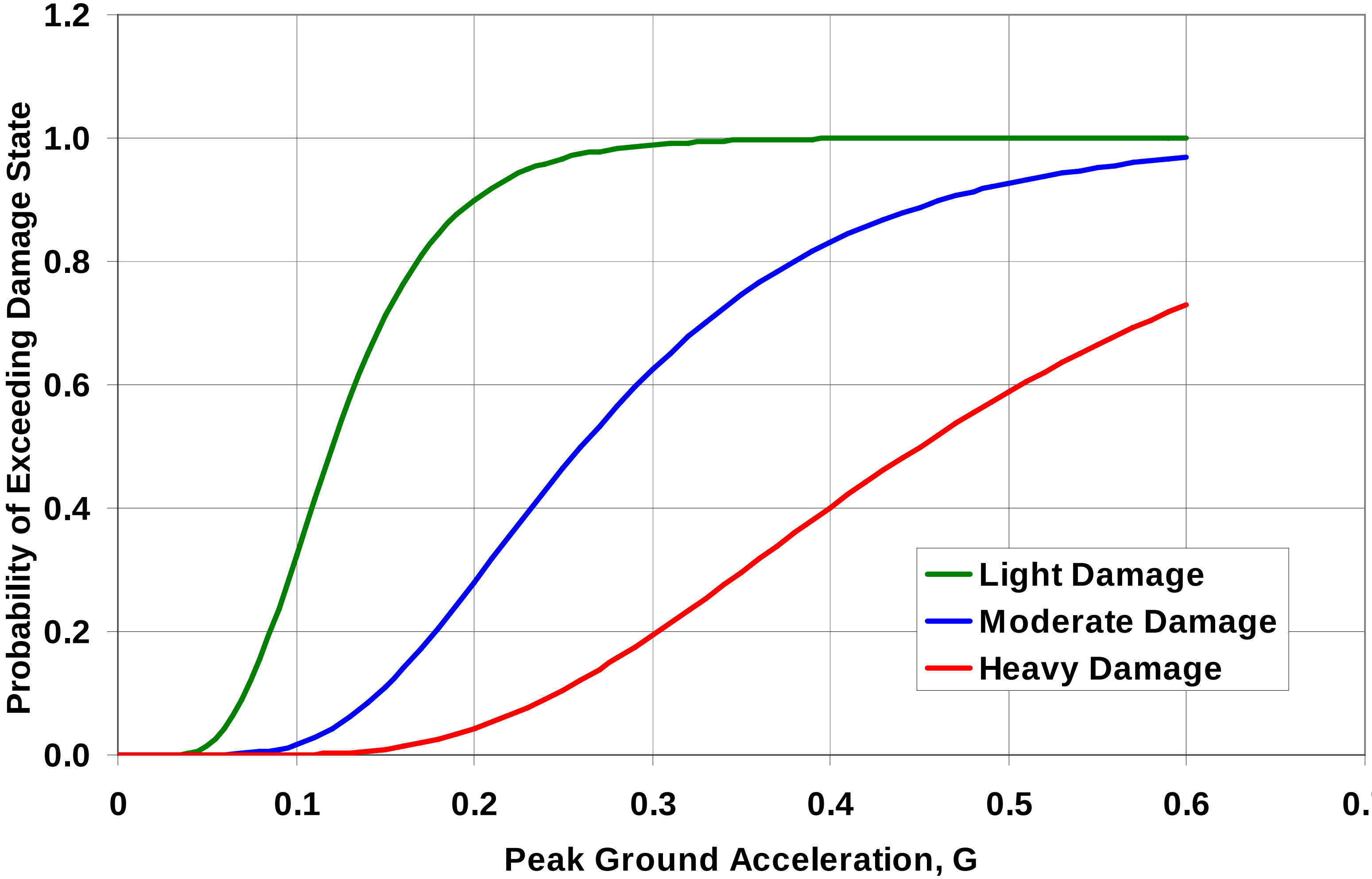
Probabilistic Approaches: Fragility Curves

Wood Frame



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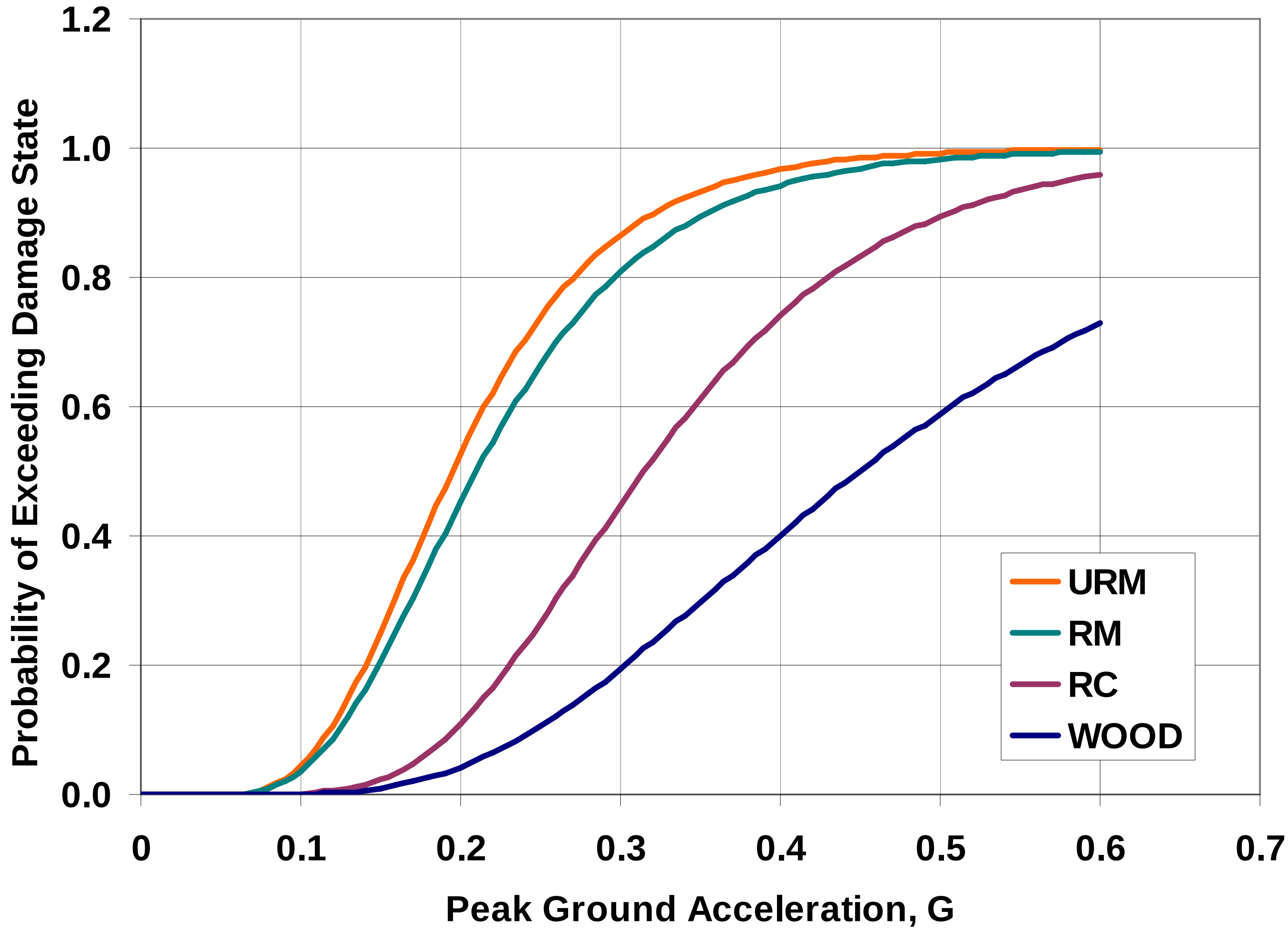
Probabilistic Approaches: Fragility Curves (Heavy Damage)



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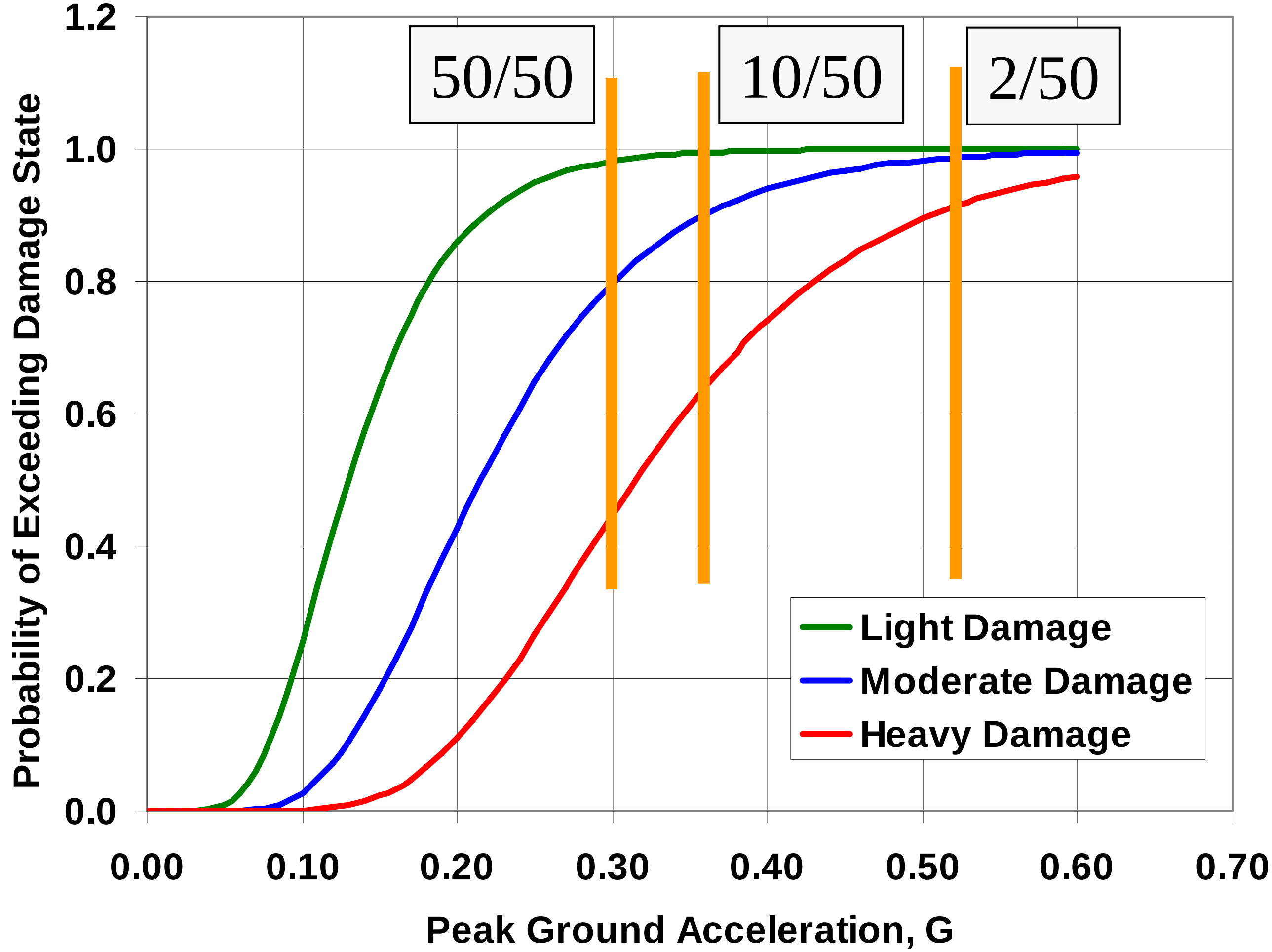
Probabilistic Approaches: Fragility Curves

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