Performance-Based Earthquake Engineering

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EERI 2005 Distinguished Lecture

Contributors

- PEER
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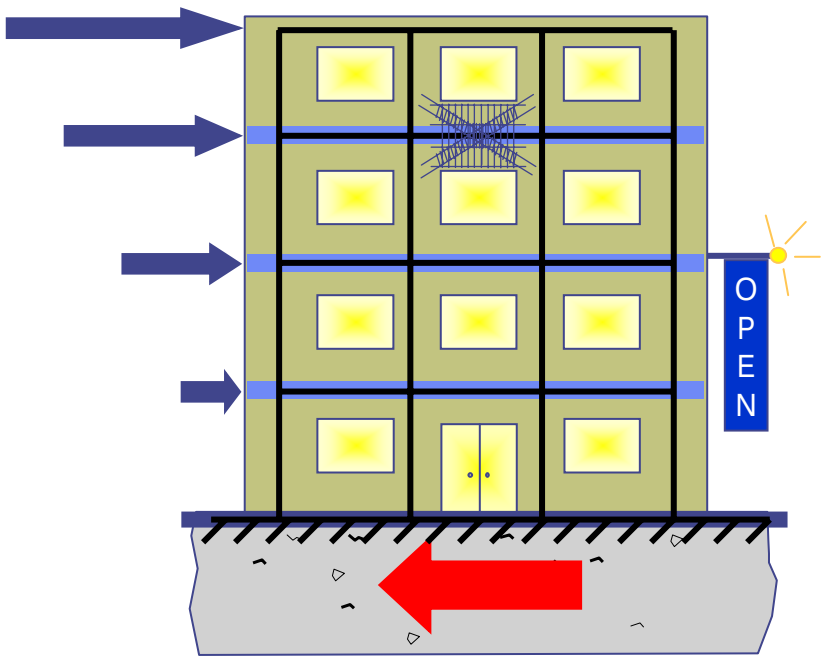
- Example building
  - ATC 58 Project Team Participants: Robert Bachman, Craig Comartin, Ron Hamburger, Gee Hecksher, Andrew Whittaker
  - Rutherford & Chekene; Simpson Gumpertz & Heger
  - Armen der Kiureghian, Kevin Mackie, Boza Stojadinovic, Tony Yang

Performance-based engineering

Design for the achievement of specified results rather than adherence to particular technologies or prescribed means. *(after May 2004)*

If a builder build a house for some one, and does not construct it properly, and the house which he built fall in and kill its owner, then that builder shall be put to death. *(after Hammurabi 1780 BC)*

Prescriptive design approach

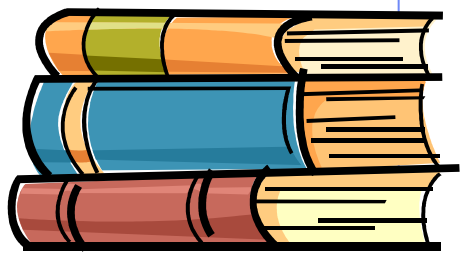


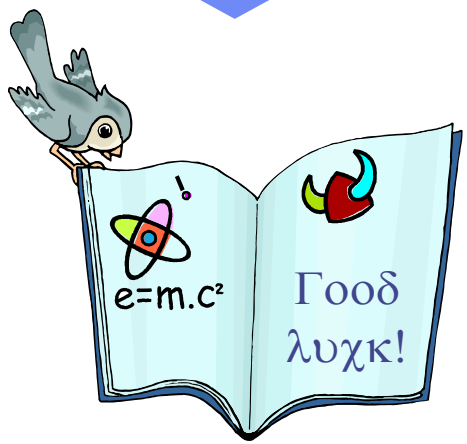
$$V = \frac{CI}{R} W$$

- Linear analysis model
- Prescribed strength
- Prescriptive details
- Shortcomings:
  - focus on aesthetics, functionality during normal service, and up front costs
  - emphasis on satisfying criteria, with performance as an undefined byproduct of design

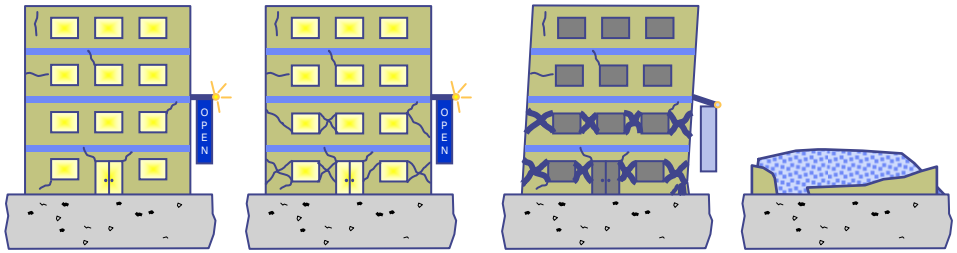
Why shift to a performance basis?

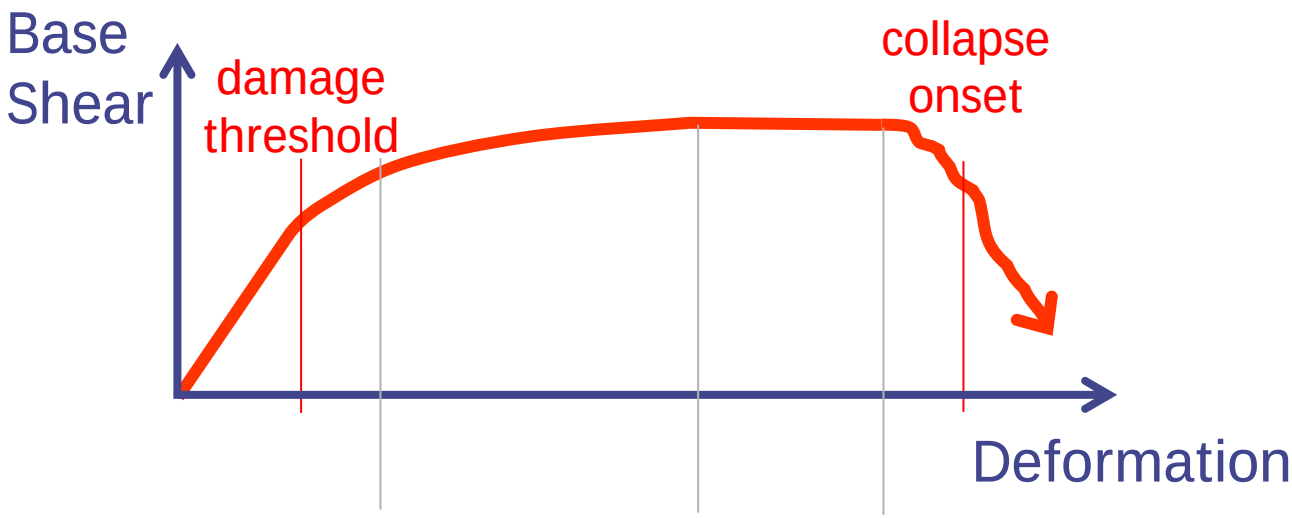
- Reduce code complexity
- Allow intent of building regulations to be understood
  - improve design outcomes
  - promote innovation with materials, systems, design approaches
- Allow design to be tailored to individual buildings and uses
- Reduce cost of facilities
- Easier export of products and expertise





Performance-based design approach





IO	LS	CP	Performance Levels
Infrequent	Rare	Very rare	Frequency of Design Ground Shaking Level

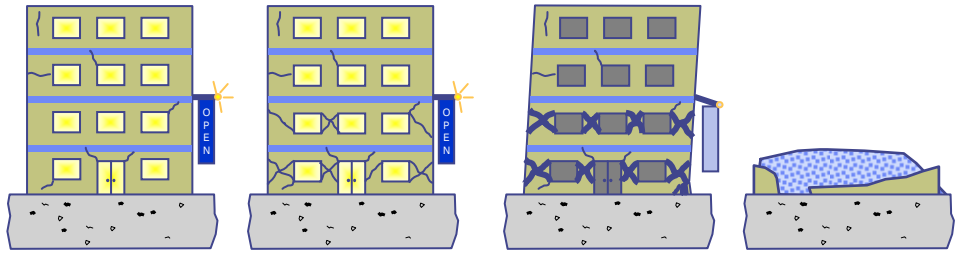
Three styles of decision-making

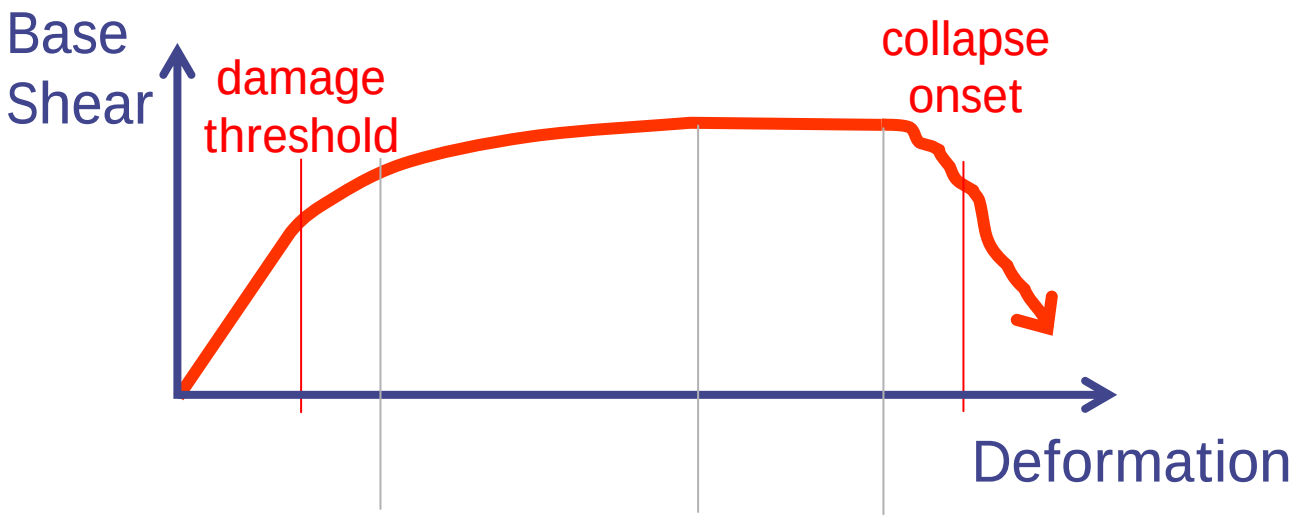
Prescriptive design
focus on up-front costs

Performance design
optimized performance

Investment-based design
consideration of trade-offs

Performance measures for decision-making





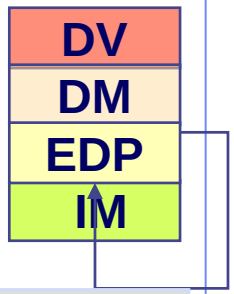
0 25% 50% 100% $, % replacement

0.0 0.0001 0.001 0.01 0.25 Casualty rate

0 1 7 30 180 Downtime, days

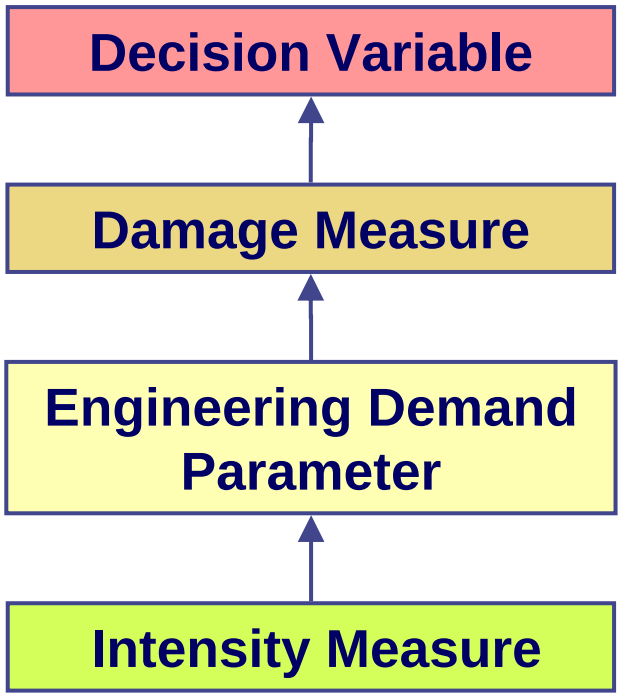
Holmes, 2001

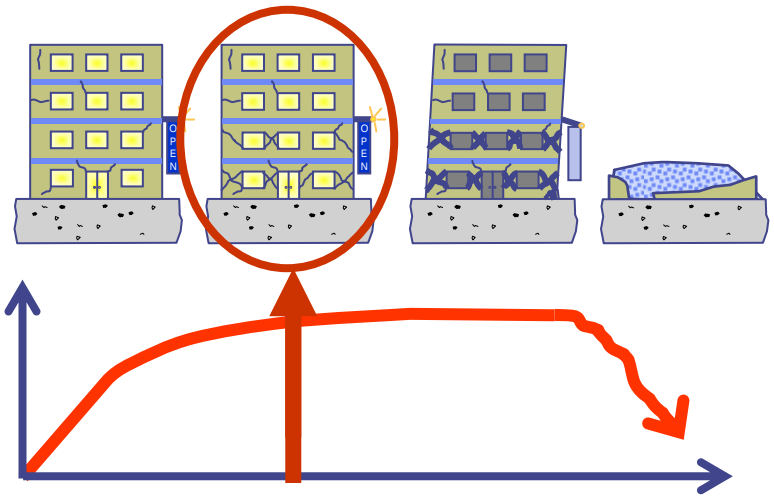
Framework for PBEE

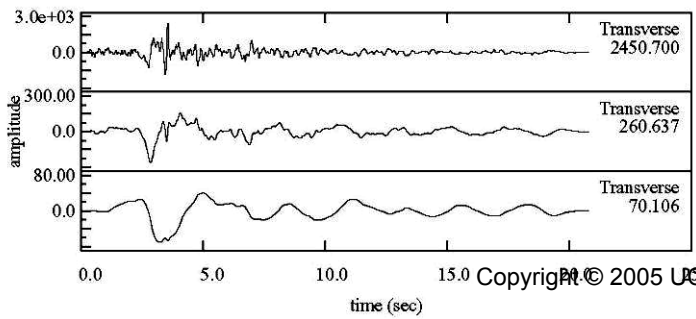


$$v(DV) = \iiint G\langle DV \mid DM \rangle \mid dG\langle DM \mid EDP \rangle \mid dG\langle EDP \mid IM \rangle \mid d\lambda(IM)$$

Loss Functions | **Fragility Functions** | **Response Simulations** | **PSHA**



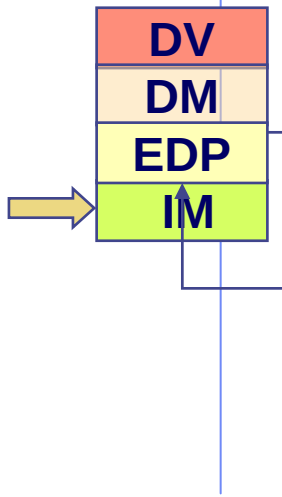


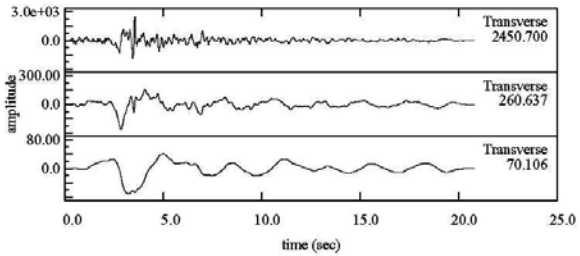


A PBEE implementation challenge

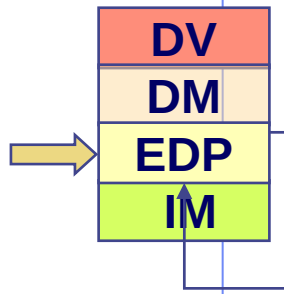
To conduct a PBEE study on a real building using real earthquake professionals and a realistic budget and timeframe.

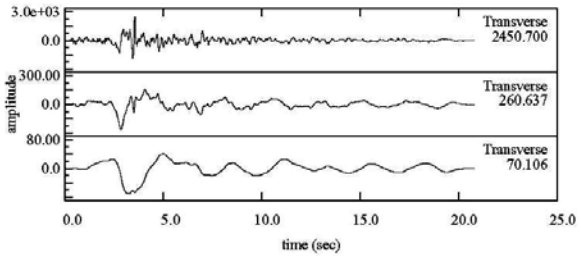
Conceptual damage calculation

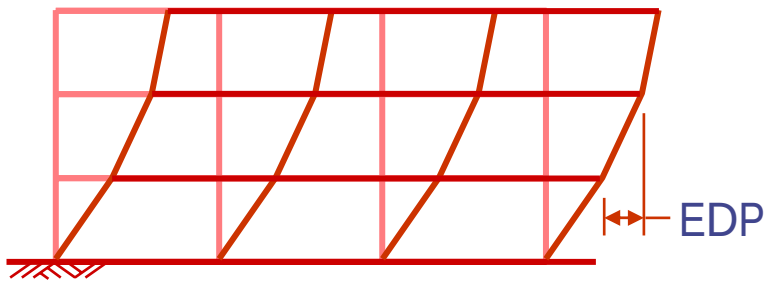




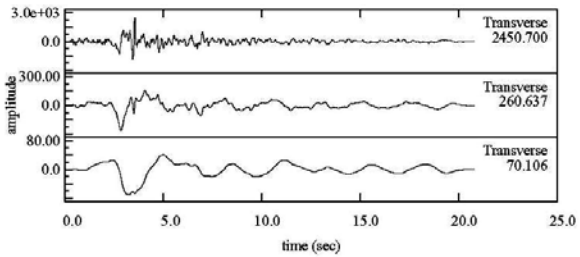
Conceptual damage calculation

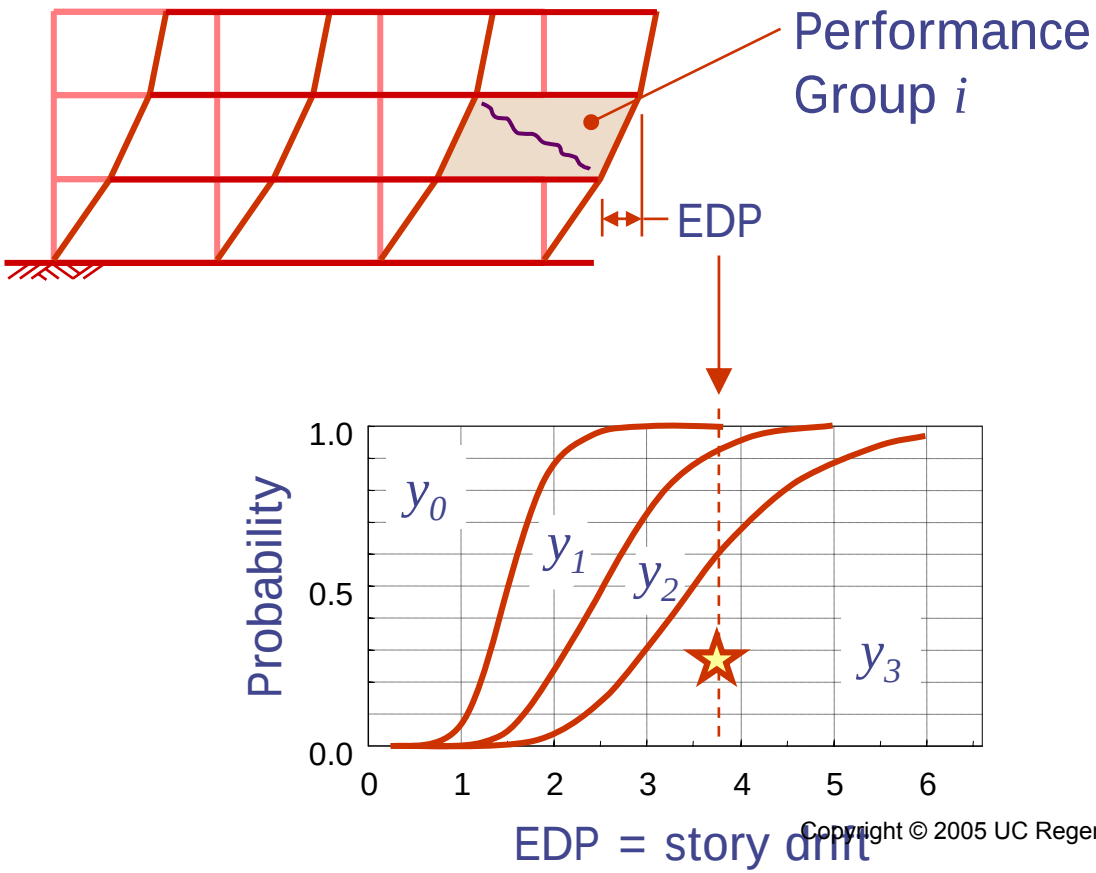




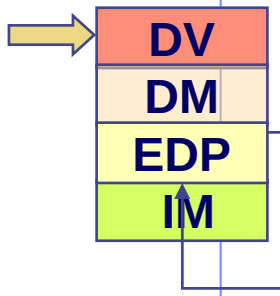


Conceptual damage calculation





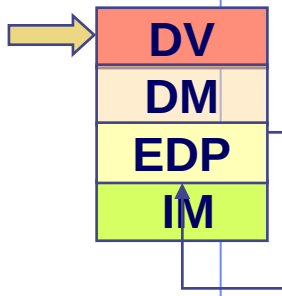
Conceptual repair quantities calculation



Performance Group *i*

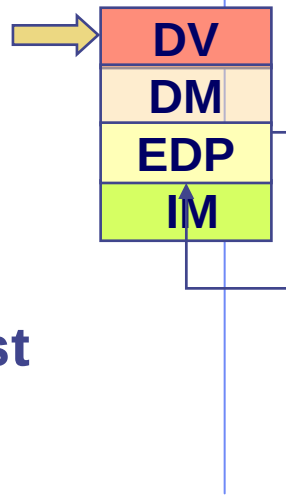
Damage state	Quantities					
	concrete	steel	wallboard	paint	electrical	...
y_0	0	0	0	0	0	
y_1	0	0	0	100	0	
y_2	0	0	100	1000	0	
y_3	0	0	10,000	10,000	0	

Conceptual repair quantities calculation



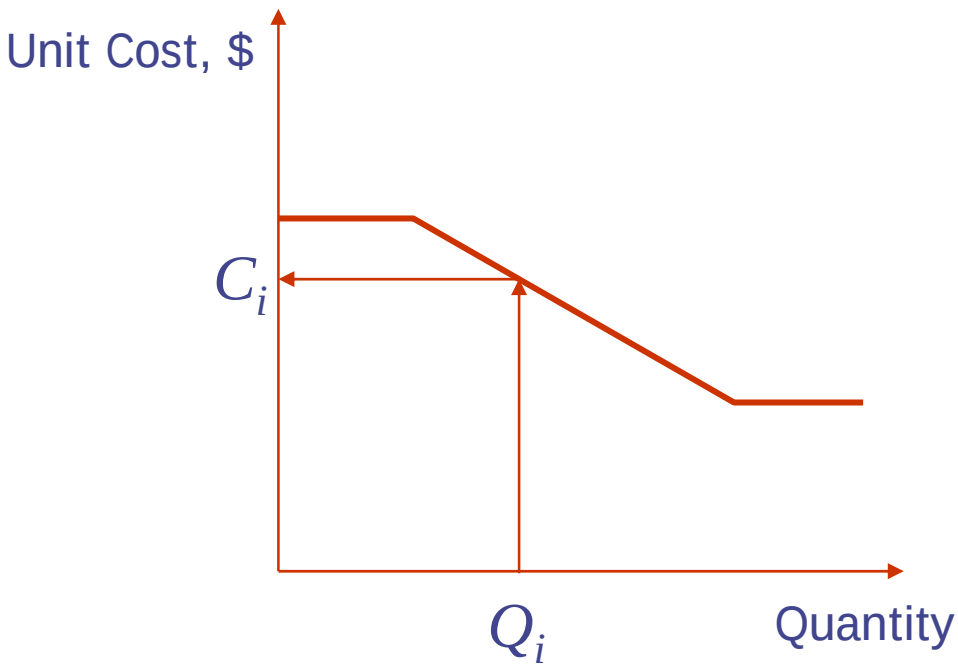
All Performance Groups

Performance group	Quantities, Q_i					
	concrete	steel	wallboard	paint	electrical	...
1	0	0	10,000	10,000	0	
2	0	0	100	1000	0	
3	20	15	0	0	0	
…	0	0	0	0	60	
TOTALS	20	15	10,100	11,000	60	



Conceptual repair cost calculation

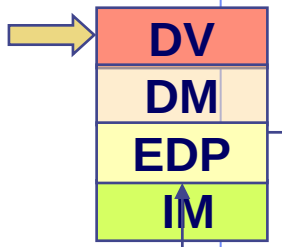
Quantity *i* (e.g., running feet of wallboard partition)



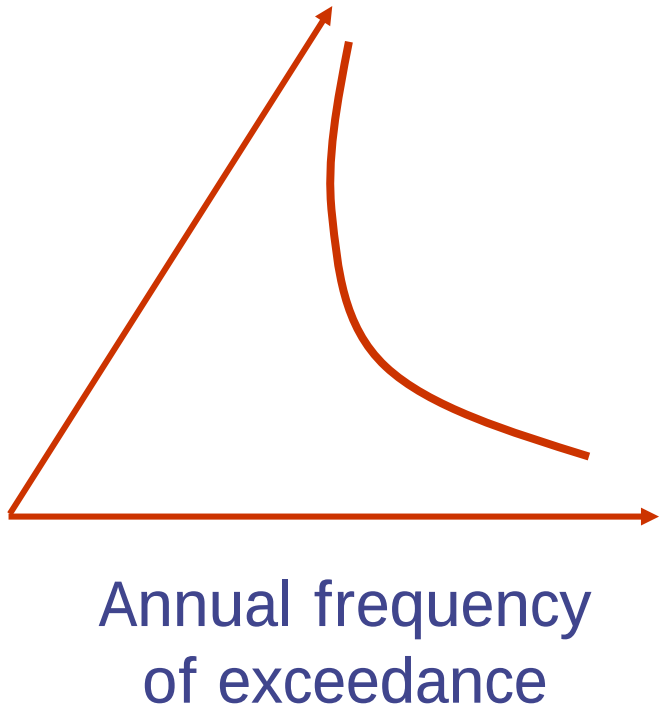
Total repair cost

Total cost = $\Sigma C_i Q_i$

(plus contractor's OH and profit (~12%) and general project costs (design, admin etc, at 20-50%).



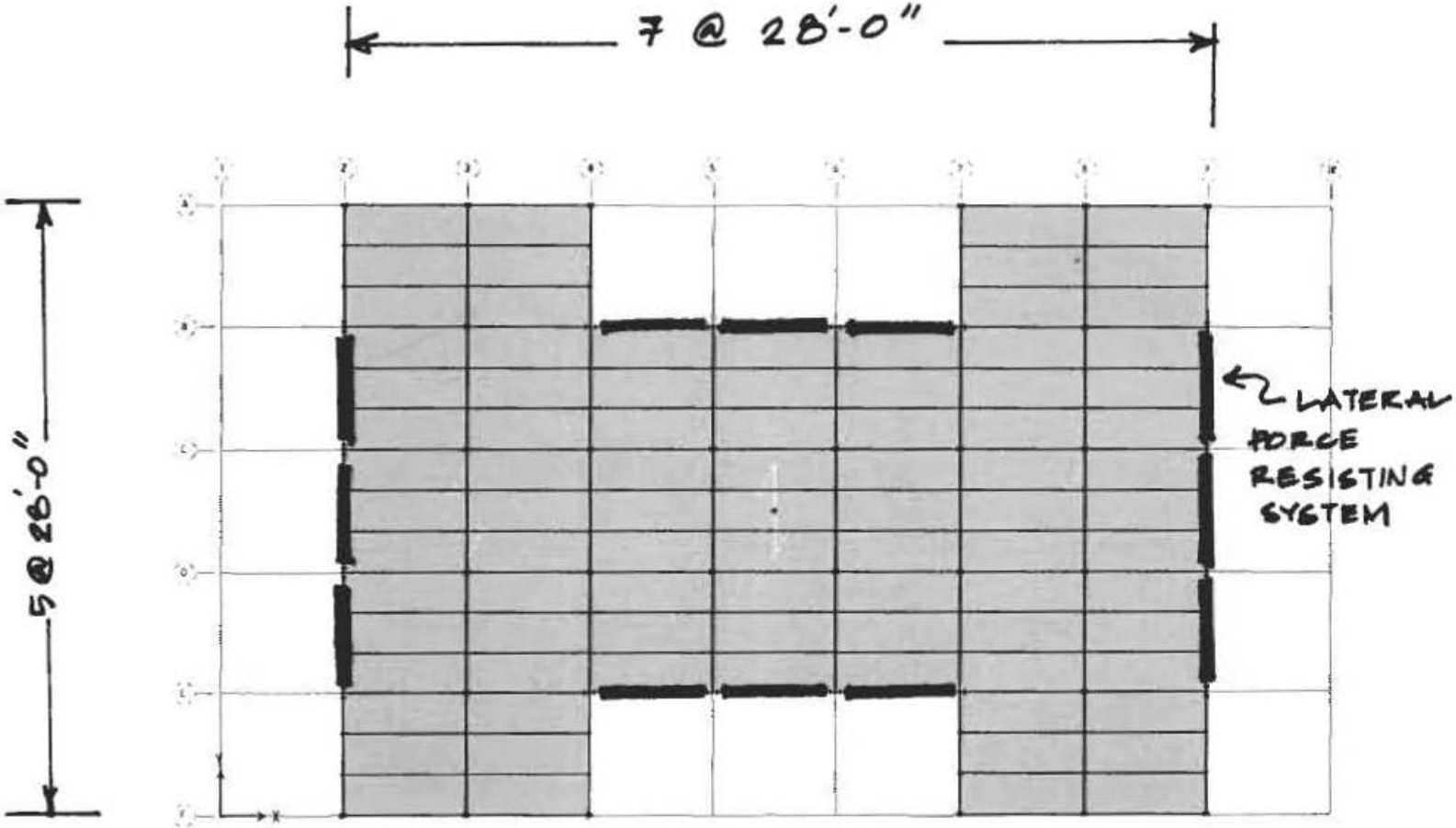
Conceptual repair cost calculation



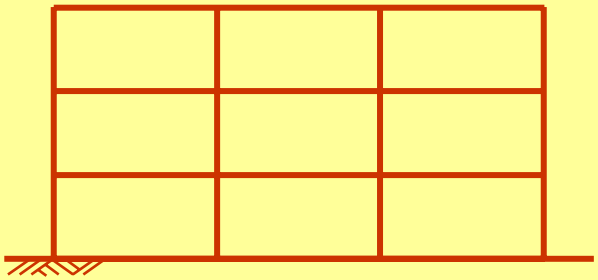
A PBEE implementation challenge

To conduct a PBEE study on a real building using real earthquake professionals and a realistic budget and timeframe.

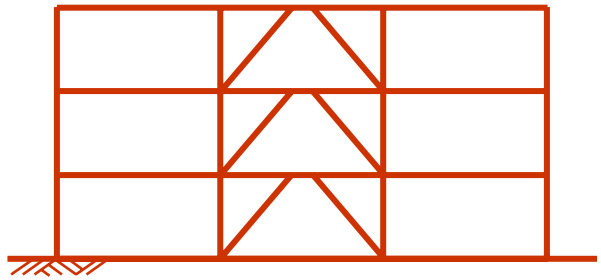
Simplified building plan



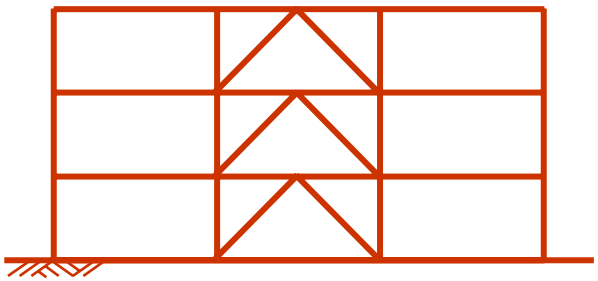
Lateral-force-resisting systems



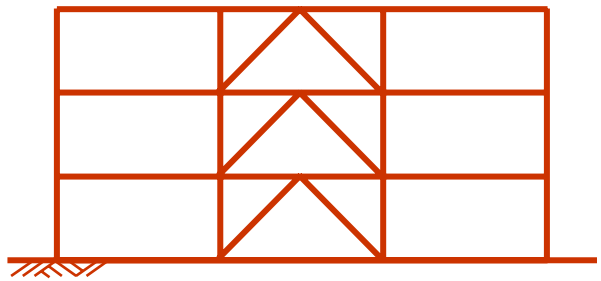
(a) Special moment frame



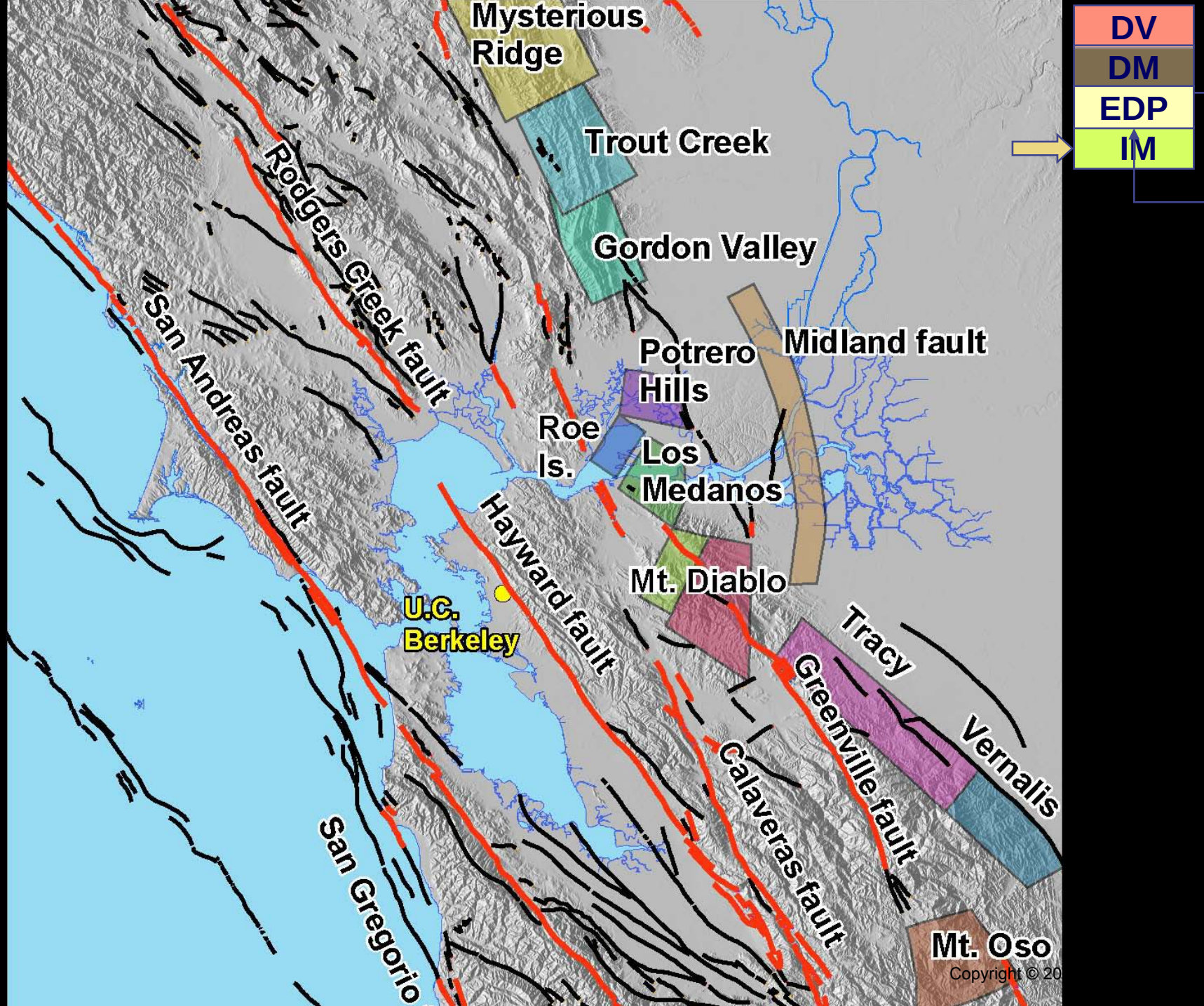
(b) Eccentric braced frame



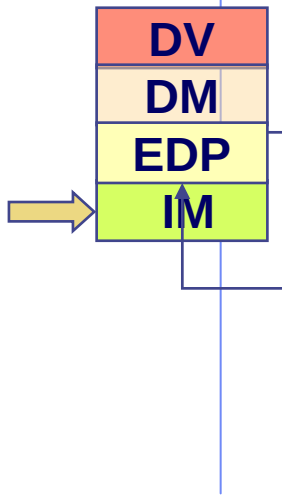
(c) Special concentric braced frame

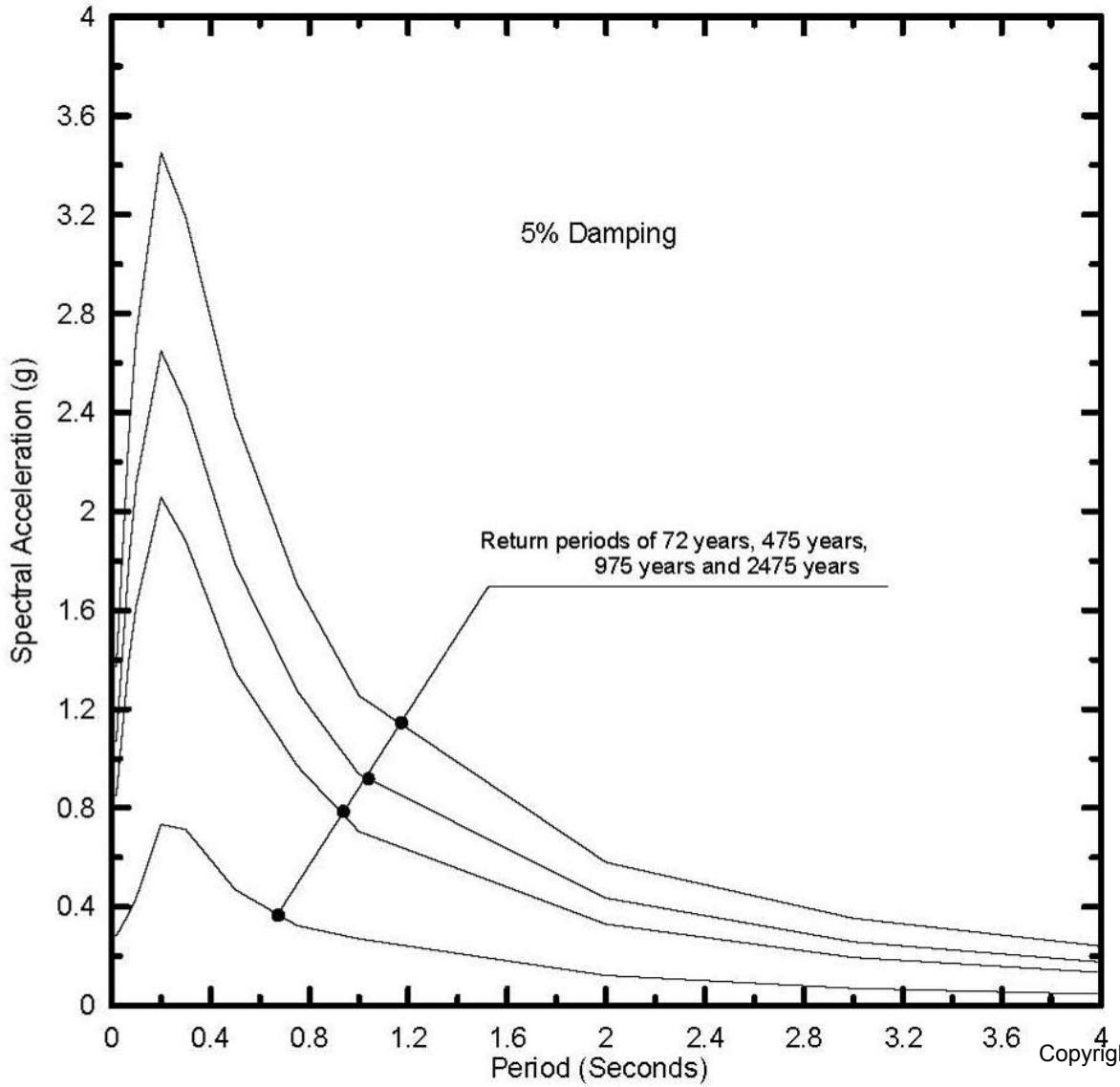


(d) Buckling-restrained braced frame

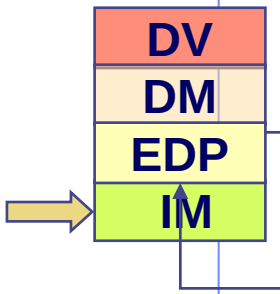


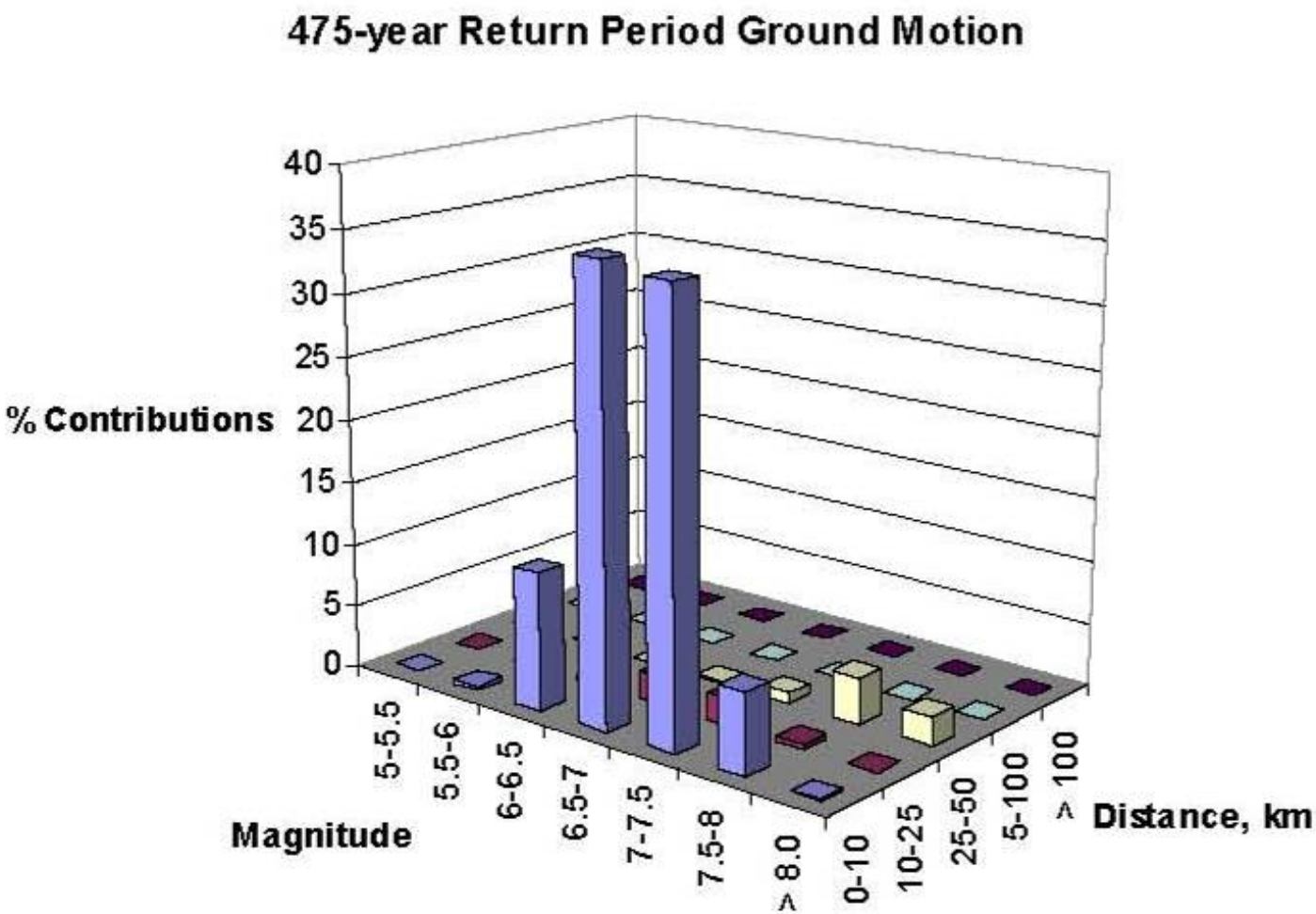
Equal-hazard spectra with average fault rupture directivity effects



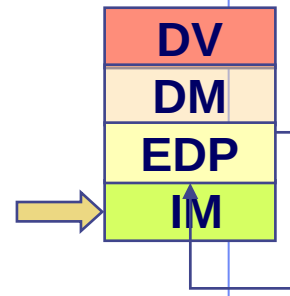


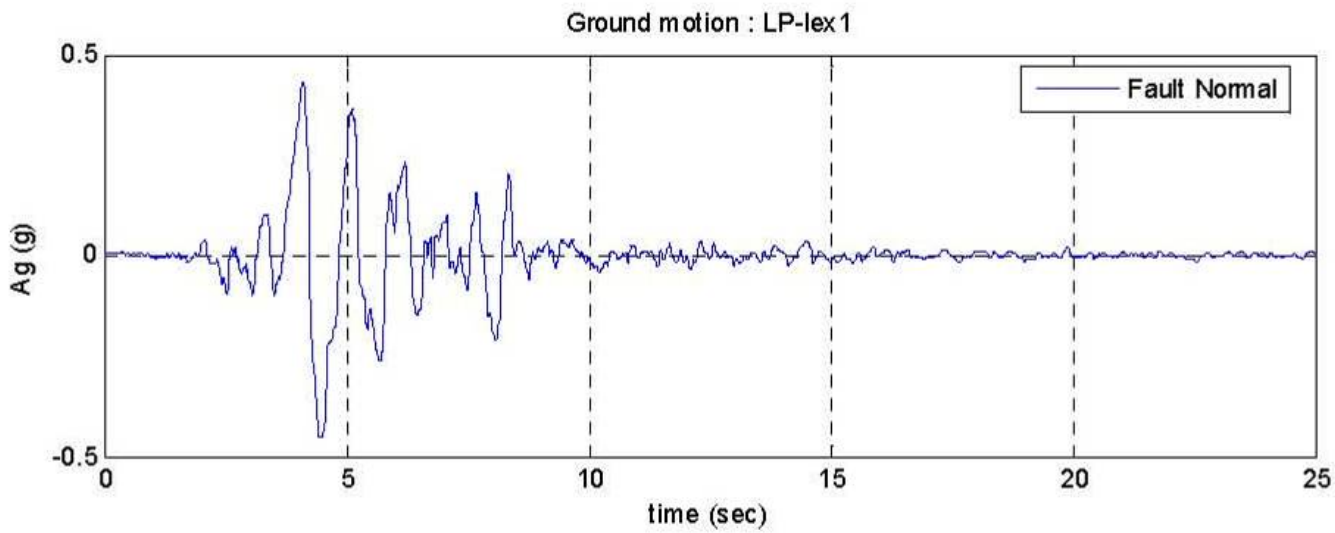
1-second spectral accelerations

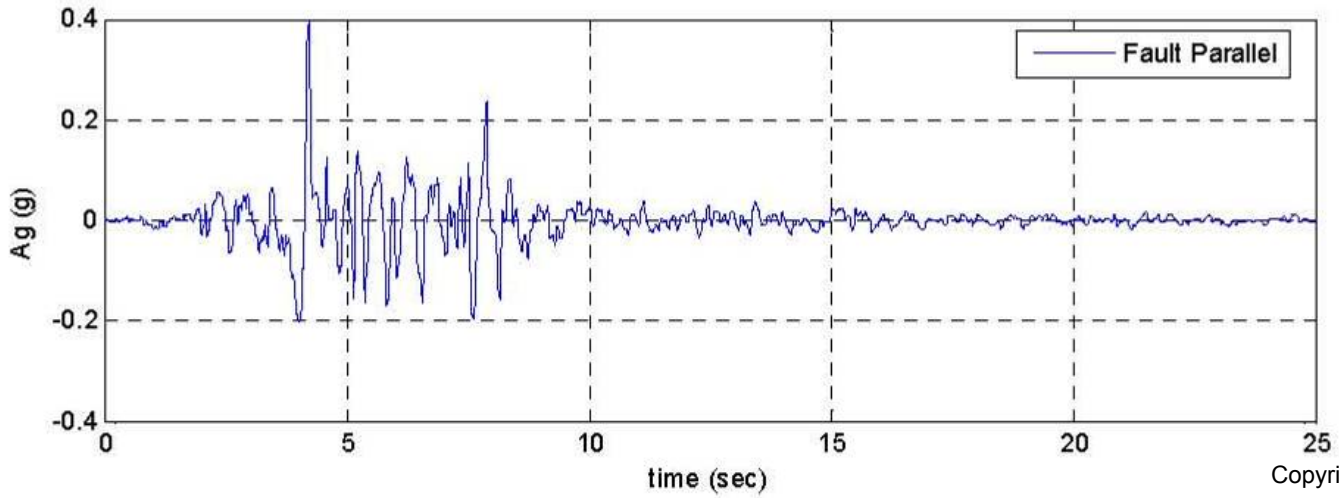




Suites of ground motions

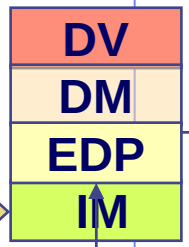


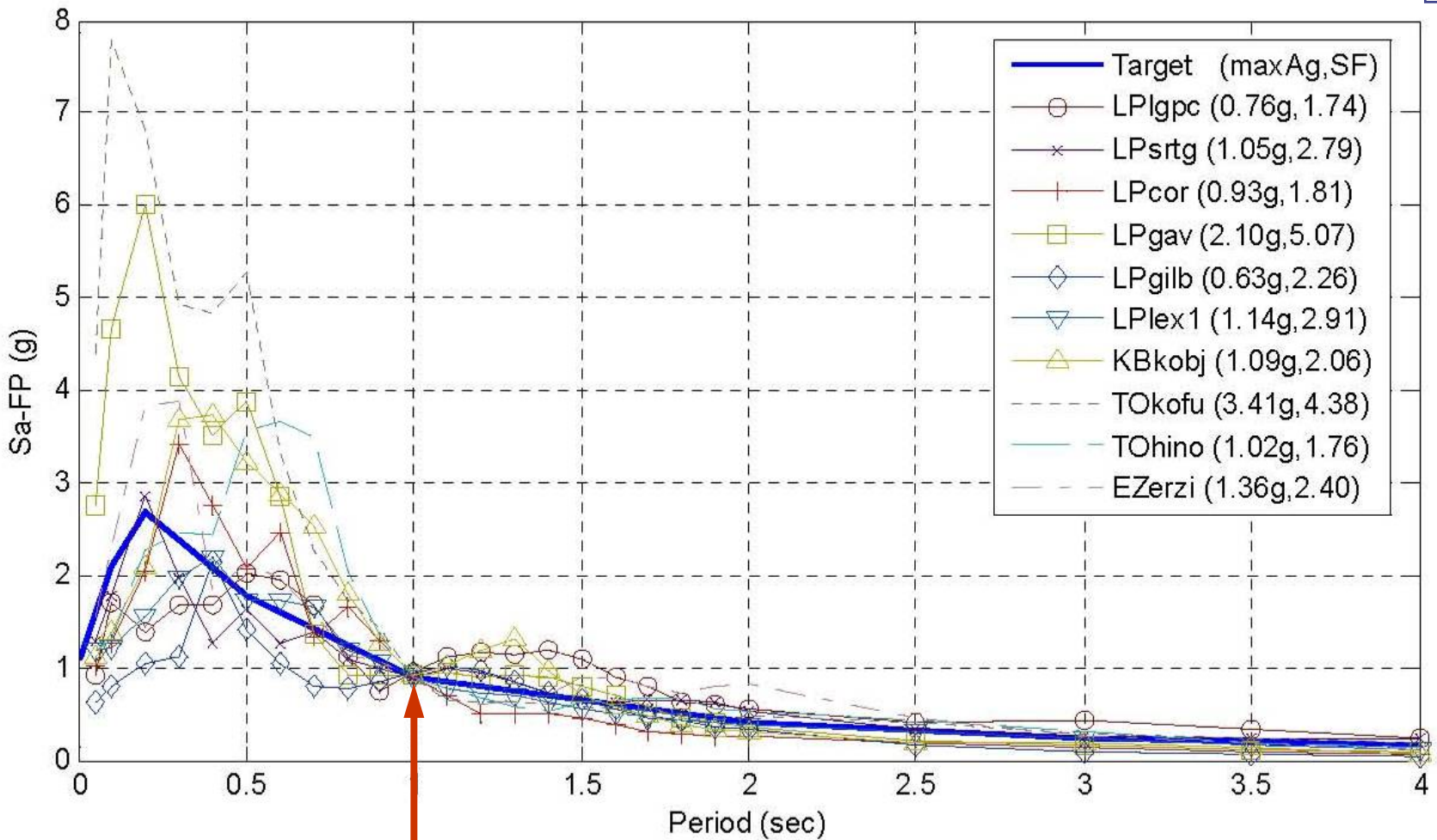




URS

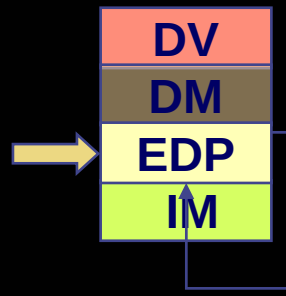
Ground motion scaling procedure

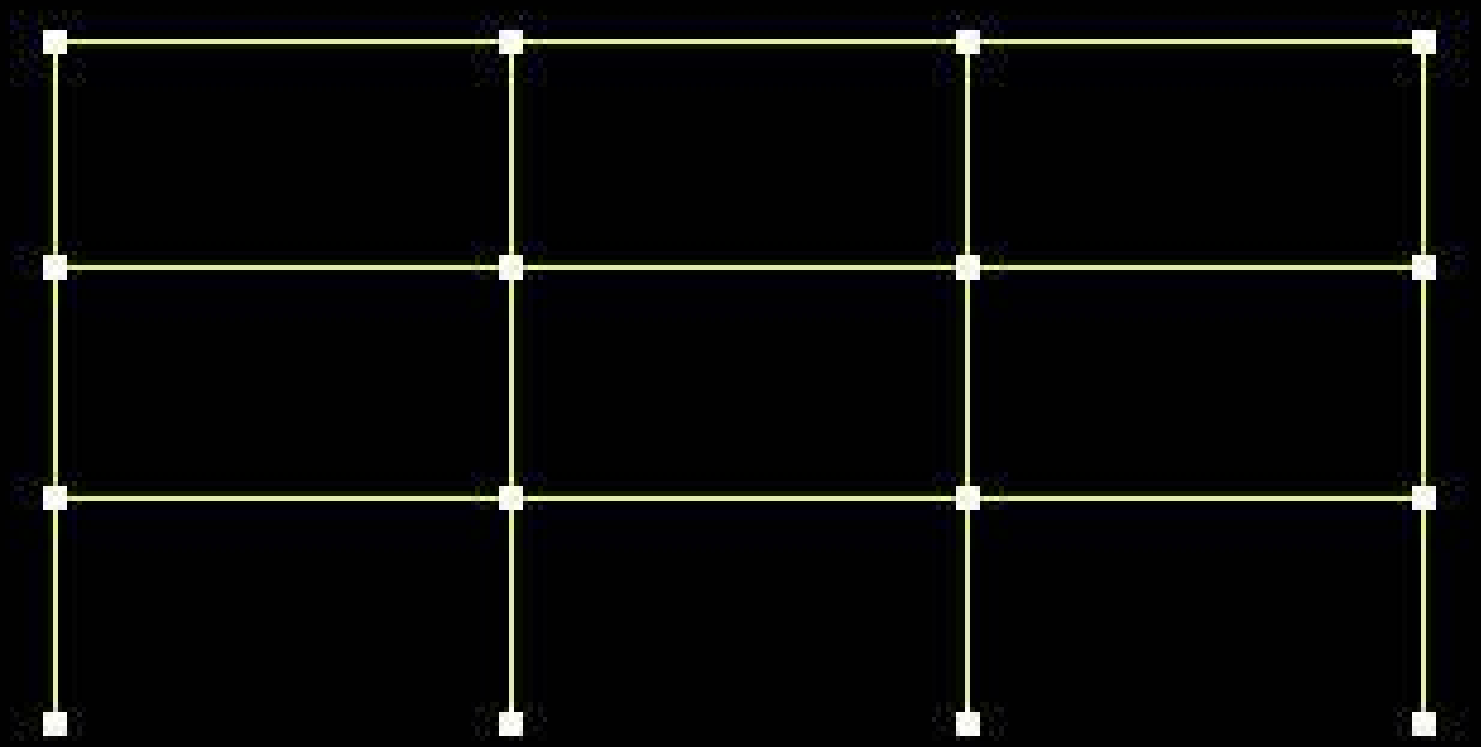


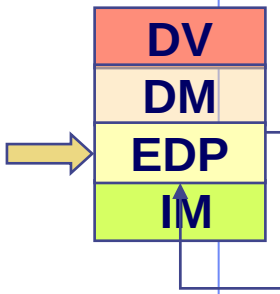


Scaled to $S_{a,T1}$

Nonlinear dynamic analysis







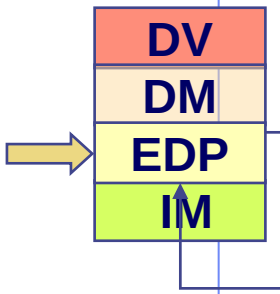
Summary of responses

Seismic hazard level: 10% in 50 years

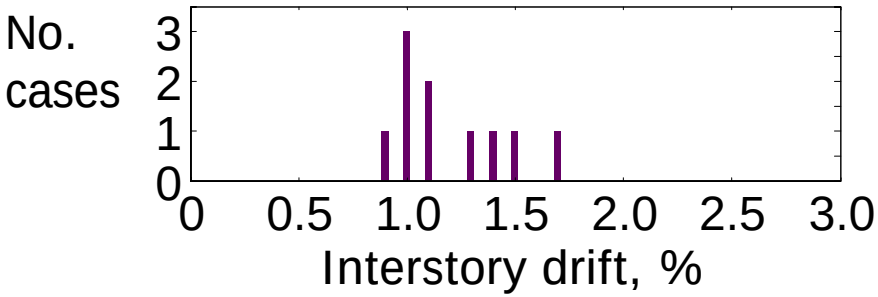
Filename	$\Delta u_{1,max}$	$\Delta u_{2,max}$	$\Delta u_{3,max}$	$\Delta u_{R,max}$	$\Delta u_{1,res}$	$\Delta u_{2,res}$	$\Delta u_{3,res}$	$\Delta u_{R,res}$	$V_{2,max}$	$V_{3,max}$	$V_{r,max}$	$A_{2,max}$	$A_{3,max}$	$A_{r,max}$
	%	%	%	%	%	%	%	%	in/sec	in/sec	in/sec	g	g	g
LPlgpcFN1050	1.40	1.83	1.79	1.62	0.53	0.51	0.45	0.50	12.85	26.99	40.88	1.02	0.65	0.64
LPlgpcFP1050	1.07	1.69	2.22	1.55	0.04	0.15	0.19	0.13	12.90	24.64	37.94	0.89	0.62	0.60
LPsrtgFN1050	1.31	1.47	1.63	1.22	0.19	0.23	0.26	0.22	16.53	27.94	39.09	0.94	0.99	0.64
LPsrtgFP1050	1.48	2.25	2.58	1.98	0.68	0.80	0.82	0.77	17.08	30.10	45.97	1.46	0.90	0.64
LPcorFN1050	1.53	2.56	3.10	2.35	0.64	0.78	0.80	0.74	23.04	37.05	55.16	0.97	1.01	0.85
LPcorFP1050	1.21	1.53	3.07	1.41	0.16	0.10	0.31	0.01	33.67	35.55	63.04	1.55	1.36	0.94
LPgavFN1050	1.84	1.89	2.79	1.67	0.59	0.65	0.77	0.67	31.42	50.46	47.56	1.64	1.45	1.04
LPgavFP1050	1.71	2.26	2.67	1.68	0.67	0.63	0.70	0.67	31.87	43.90	60.88	2.00	1.32	1.01
LPgilbFN1050	2.14	2.63	2.94	2.42	0.40	0.48	0.49	0.46	15.98	29.68	50.78	0.77	0.74	0.72
LPgilbFP1050	1.22	1.49	1.87	1.29	0.15	0.06	0.02	0.06	11.66	25.87	49.43	0.60	0.49	0.58
LPlex1FN1050	1.26	1.90	1.89	1.68	0.24	0.17	0.11	0.18	9.55	23.89	38.98	0.36	0.40	0.48
LPlex1FP1050	1.66	1.74	2.28	1.57	0.51	0.55	0.59	0.55	15.51	33.38	56.06	1.22	0.99	0.72
KBkobjFN1050	0.77	1.69	2.29	1.55	0.06	0.14	0.19	0.13	13.32	27.07	46.98	0.76	0.72	0.64
KBkobjFP1050	1.43	1.65	2.78	1.57	0.16	0.16	0.25	0.19	26.21	30.46	42.07	1.24	1.26	0.84
TOkofuFN1050	3.15	3.40	4.70	2.79	0.24	0.16	0.03	0.13	62.90	95.60	92.17	4.76	3.00	3.07
TOkofuFP1050	2.06	2.74	4.08	2.38	0.26	0.72	1.03	0.67	45.02	54.25	82.76	3.97	2.34	2.62
TOhinoFN1050	1.38	1.76	2.07	1.54	0.45	0.34	0.21	0.33	12.89	27.83	51.44	0.69	0.58	0.61
TOhinoFP1050	1.61	2.63	3.82	2.43	0.28	0.39	0.46	0.37	22.55	45.14	67.44	0.91	0.82	0.82
EZerziFN1050	1.66	2.23	2.35	1.89	0.70	0.68	0.58	0.65	15.83	27.64	42.55	0.77	0.77	0.61
EZerziFP1050	1.87	2.58	3.31	2.41	0.05	0.05	0.12	0.04	22.94	50.88	54.30	1.49	1.18	0.77

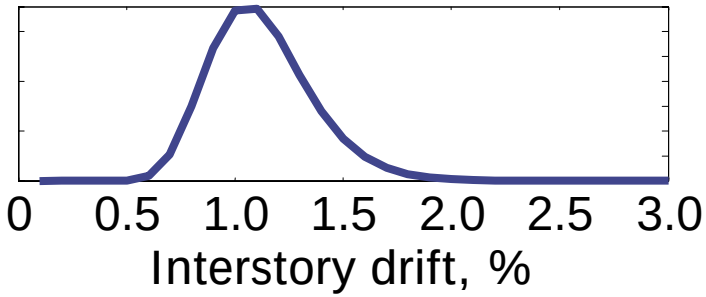
$\Delta u_{i,max}$ = maximum inter-story drift at the ith floor as a ratio of the story height.
$\Delta u_{R,max}$ = maximum roof drift as a ratio of the total building height.
$\Delta u_{i,res}$ = residue inter-story drift at the ith floor as a ratio of the story height.
$\Delta u_{R,res}$ = residue roof drift as a ratio of the total building height.
$V_{i,residue}$ = maximum floor velocity with respect to the ground.
$A_{i,residue}$ = maximum absolute floor acceleration.

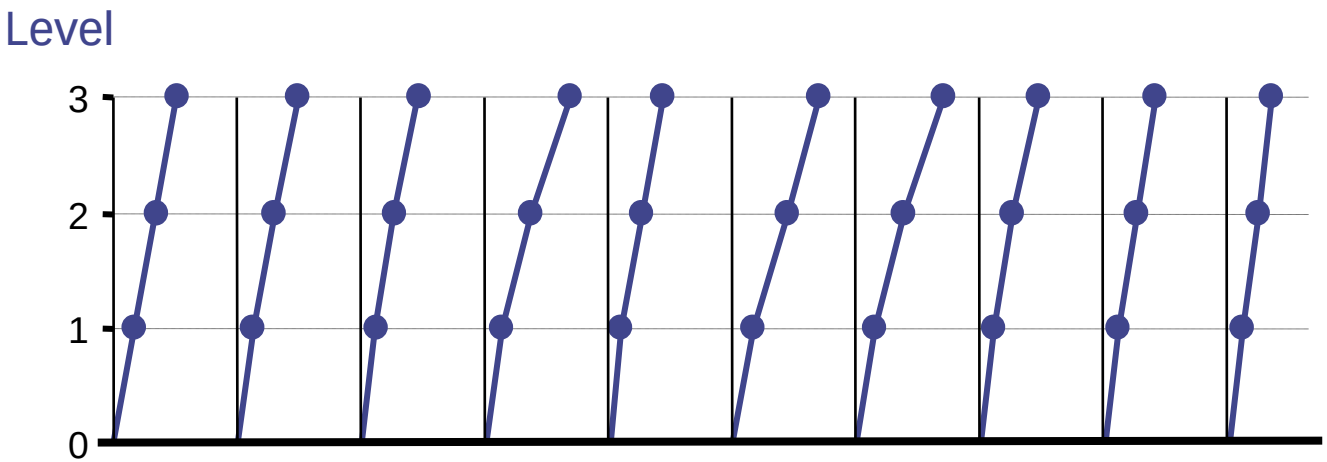
Response simulation



- Lots of nonlinear dynamic analyses
- Simulation of the results

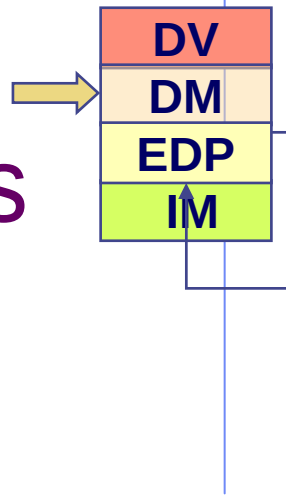


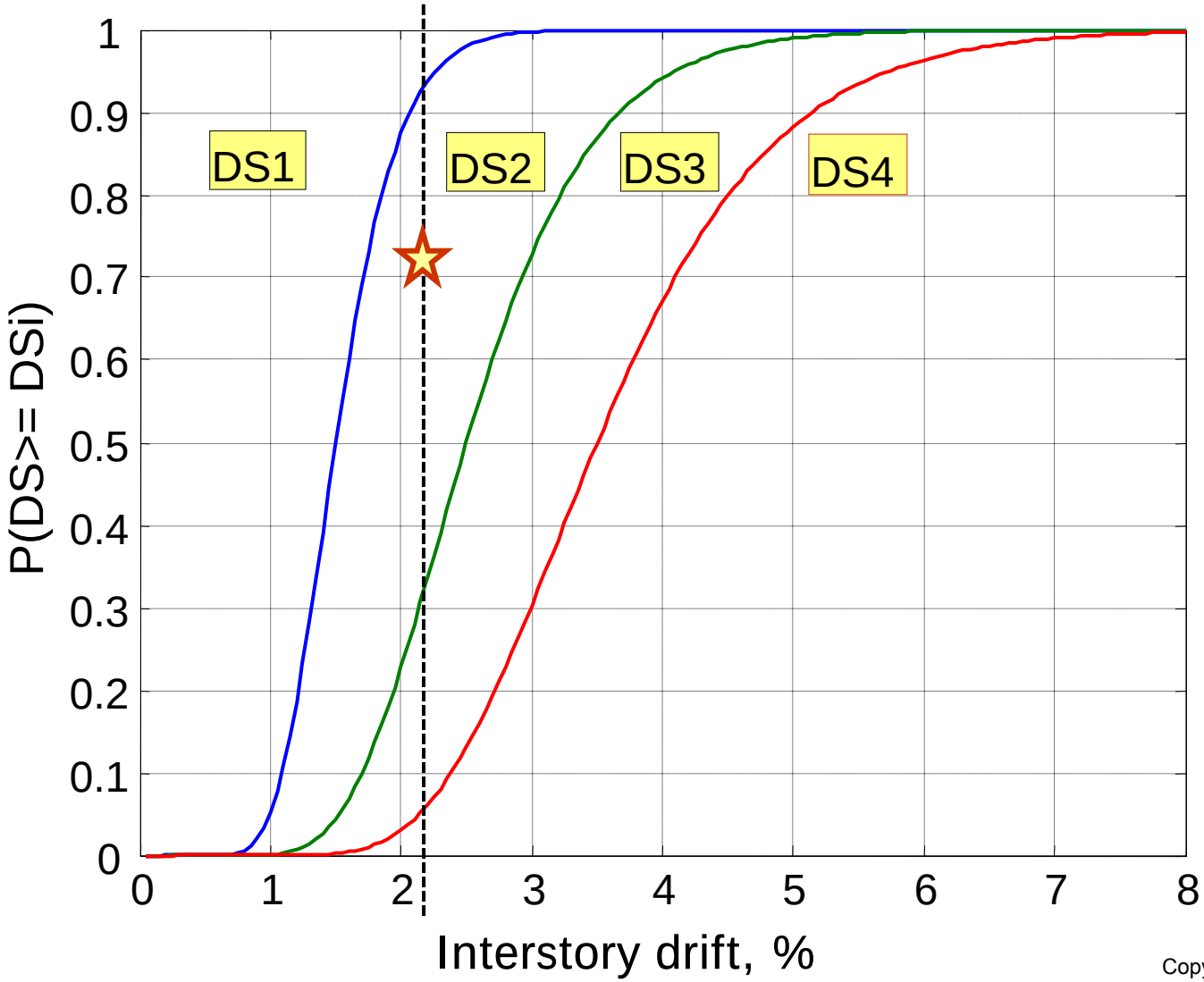




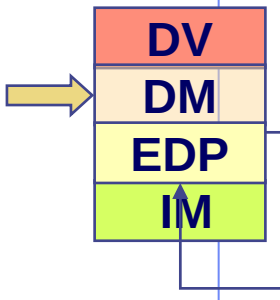
Floor Peak Relative Displacements for 10 EDP Realizations

Determination of damage states



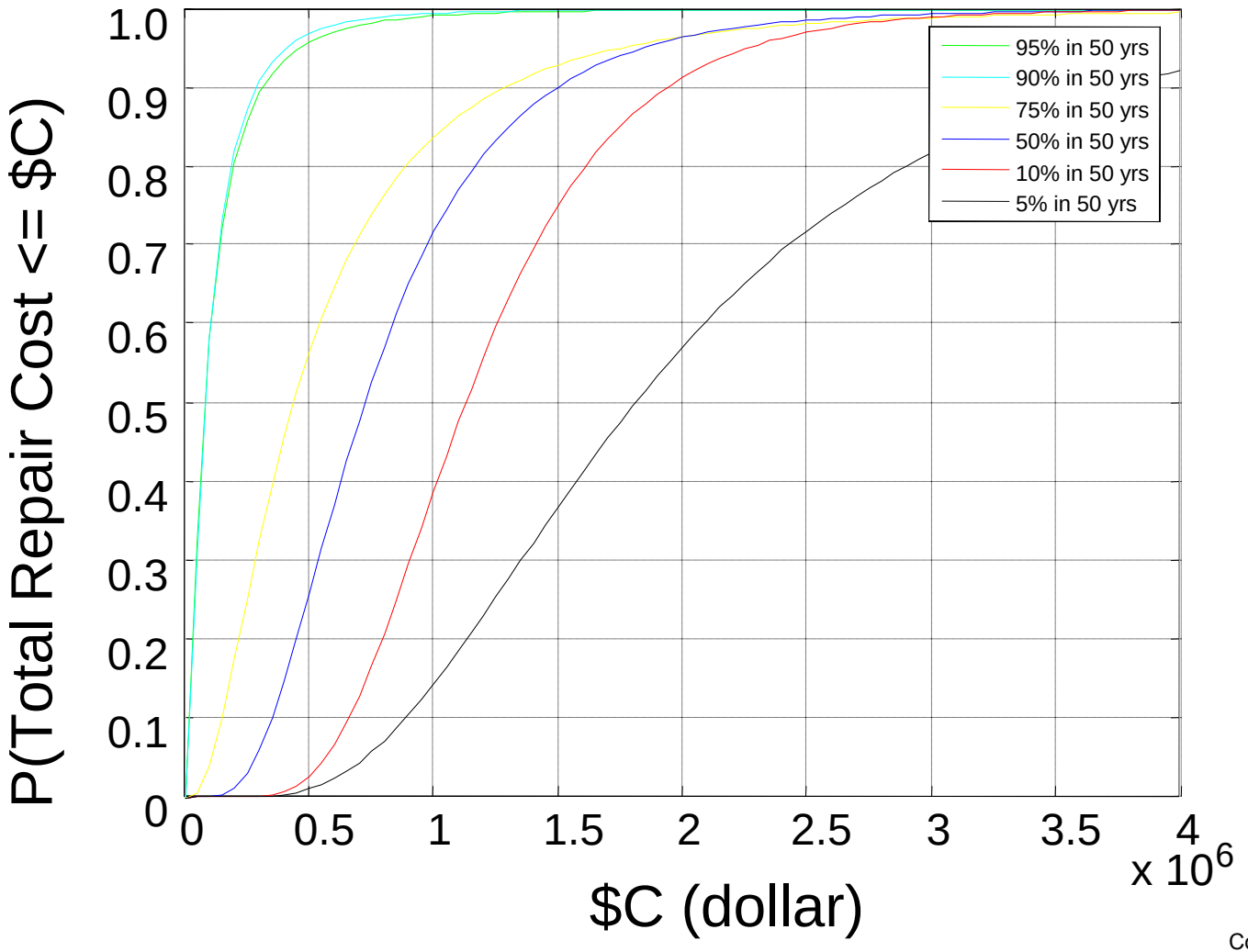


Tables of performance groups, damage states, quantities, and unit costs

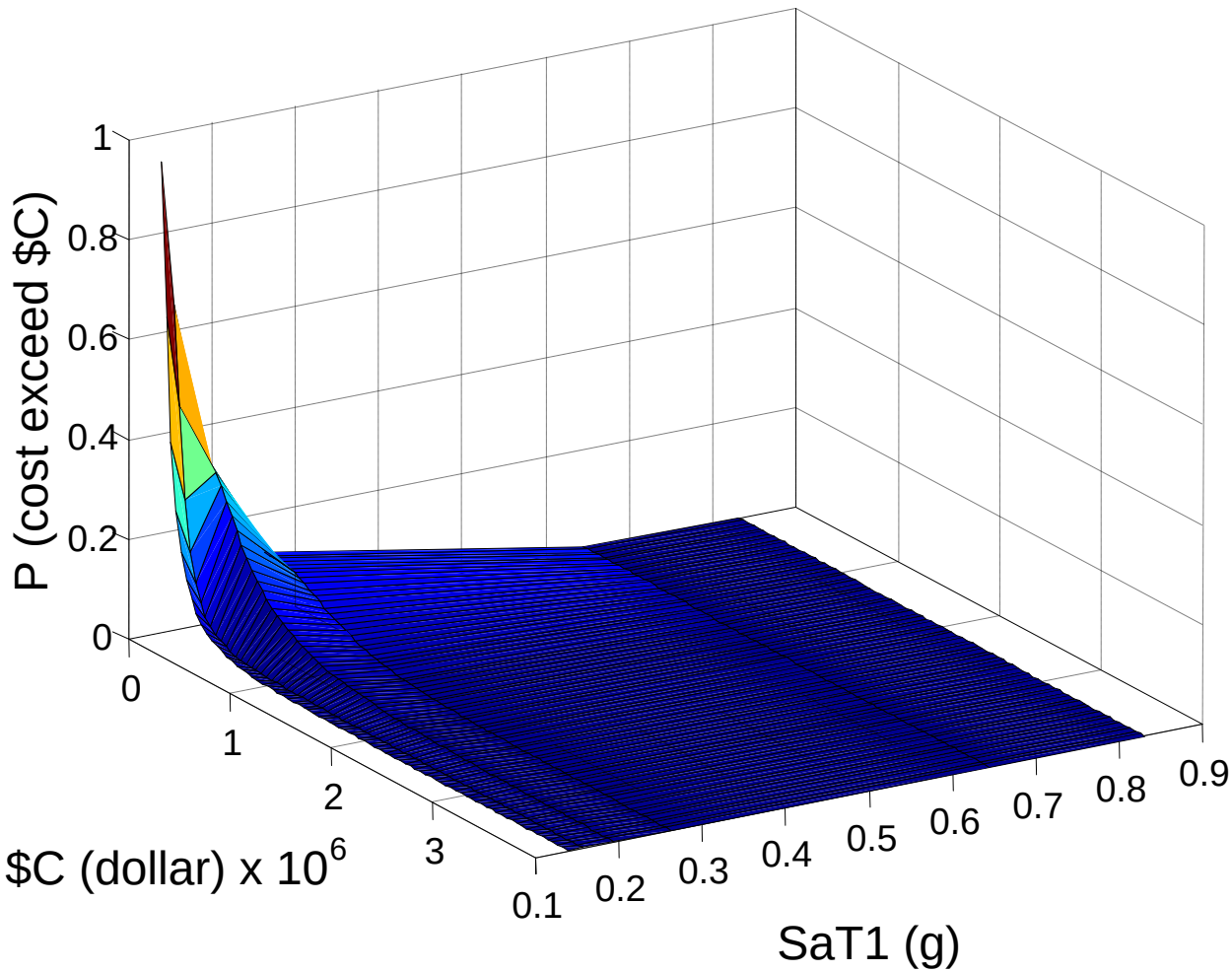


	PG1 - SH12			
	DS1	DS2	DS3	DS4
Finish_protection	0	6000	6000	6000
Ceiling_system_removal	0	2000	3000	5000
Drywall_assembly_removal	0	800	800	6000
Miscellaneous_MEP	0	2	4	6
Remove_exterior_skin	0	0	0	5600
Welding_protection	0	1500	1500	1500
Shore_beams_below_remove	0	0	0	12
Remove_replace_connection	0	0	0	3000
Replace_slab	0	70	70	1600
Miscellaneous_MEP_and_cleanup	0	2	4	6
Wall_framing(studs_drywall_tape_paint)	0	800	800	6000
Replace_exterior_skin(from_salvage)	0	0	0	5600
Ceiling_system	0	2000	3000	5000

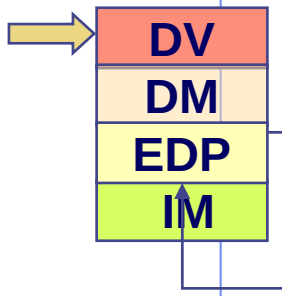
Summary repair costs



Summary repair costs



Various expressions of costs



$1.2M

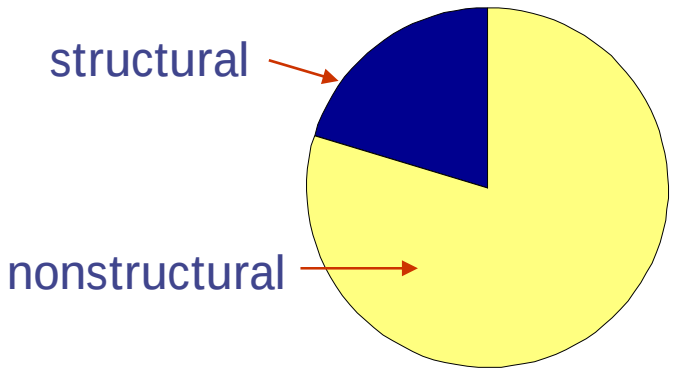
(a) Expected cost for M7 scenario

$2.0M

(b) 90% confidence cost does not exceed threshold for 975-yr return period hazard level

$50,000

(c) Mean cumulative annual total cost of damage



(d) Contributions to total cost for scenario

The language of PBEE

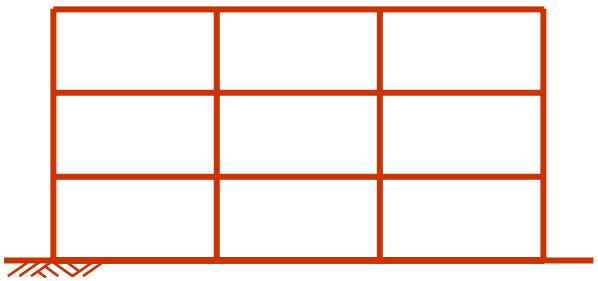
- Recognize the range of stakeholders
  - public versus private
  - large and small firms
  - single facilities versus inventories
  - single versus distributed facilities
  - essential versus nonessential facilities
  - facilities providing lifeline support
- Develop language and measures for specific stakeholder

The language of PBEE

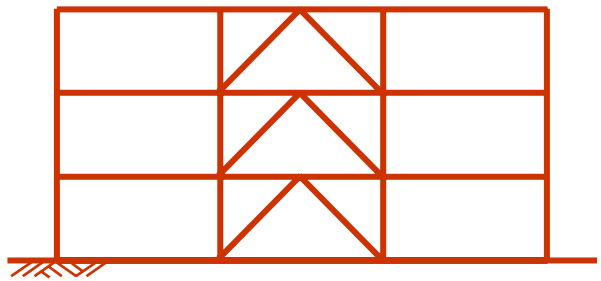
- Expression of seismic hazard
  - mean annual rate of exceedance
  - return period
  - probability of exceedance in 20-50 years
  - scenario that has a reasonable probability of occurring over 20-50 years
- Expression of risk
  - Ranges of losses versus confidence intervals
  - Maximum probable loss
  - Risk of financial ruin

Some uses of PBEE

- Should the owner retrofit a facility to reduce earthquake losses?



Existing structure

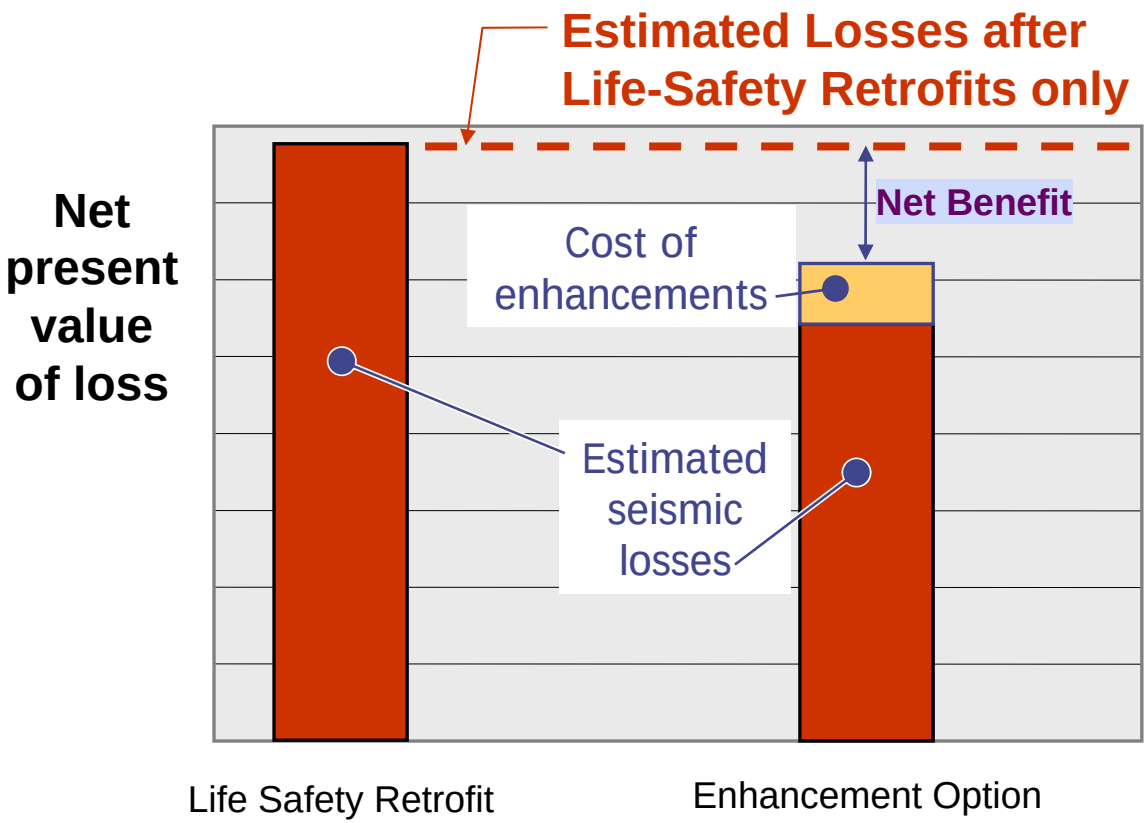


Retrofitted structure

A = net present value of annual losses

B = retrofit cost + net present value of annual losses

Design enhancements beyond life safety



Some uses of PBEE

- Business owner

  90% confidence that my business will not be financially ruined by capital losses exceeding $1M over the next 30 years

Some uses of PBEE

- Essential facilities

  For a hospital....
  10% chance of being unable to accept new patients for more than a week after an earthquake in the next 50 years

Some uses of PBEE

- Improve reliability aspects of FEMA 356

  For standard occupancy building....
  90% confidence that a building will not collapse for ground shaking representative of 2500-year return period hazard level

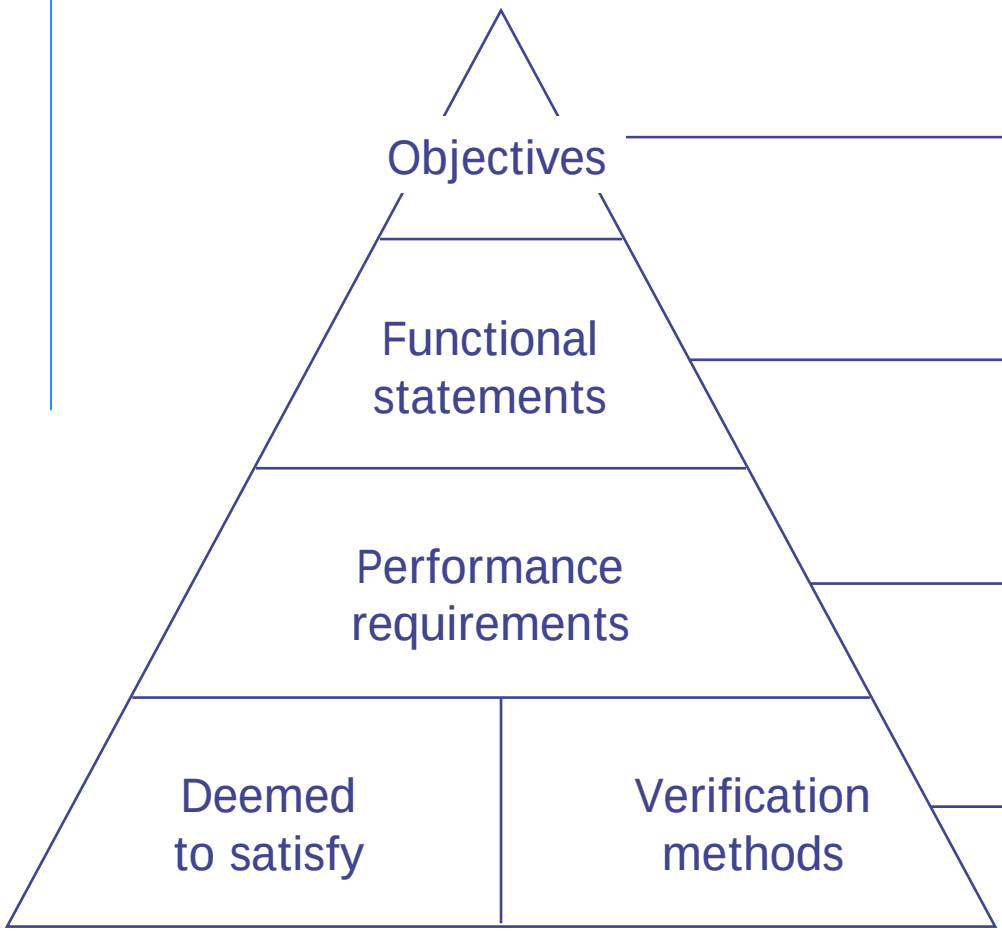
Some uses of PBEE

- Clearer specification of code intent

  For standard occupancy building....
  not more than 0.0002 chance per year of a single life loss (considering the entire hazard)

- and code provisions the better accomplish the intent

A performance code format



Safeguard people from earthquakes

Avoid building collapse

Mean annual rate of one or more lives lost in building collapse = 0.0002

Prescriptive code or recognized PBEE methodology

after Meecham 2005, Australian Building Code 1995

Regulation of PBEE

- Regulation of performance standards not new – US drinking water standard of 1914
- Qualitative versus quantitative approach
  - Qualitative: performance at least equivalent to that obtained using prescriptive code requirements
  - Quantitative: the number of lives lost in a single building for 475year event
- Open question: How tight should controls be to ensure consistency and accountability, versus how much discretion should be granted in promoting flexibility?

PBEE regulations/guidelines

- UBC 1946

  This code …“is dedicated to the development of better building construction and greater safety to the public, through the elimination of needless red tape, favoritism and local politics by uniformity in building laws; to the granting of full justice to all building materials on the fair basis of the true merits of each material; and to the development of a sound economic basis for the future growth of cities through unbiased and equitable dealing with structural design and fire hazards.”

PBEE regulations/guidelines

- UBC 1946
- SEAOC Blue Book - 1967

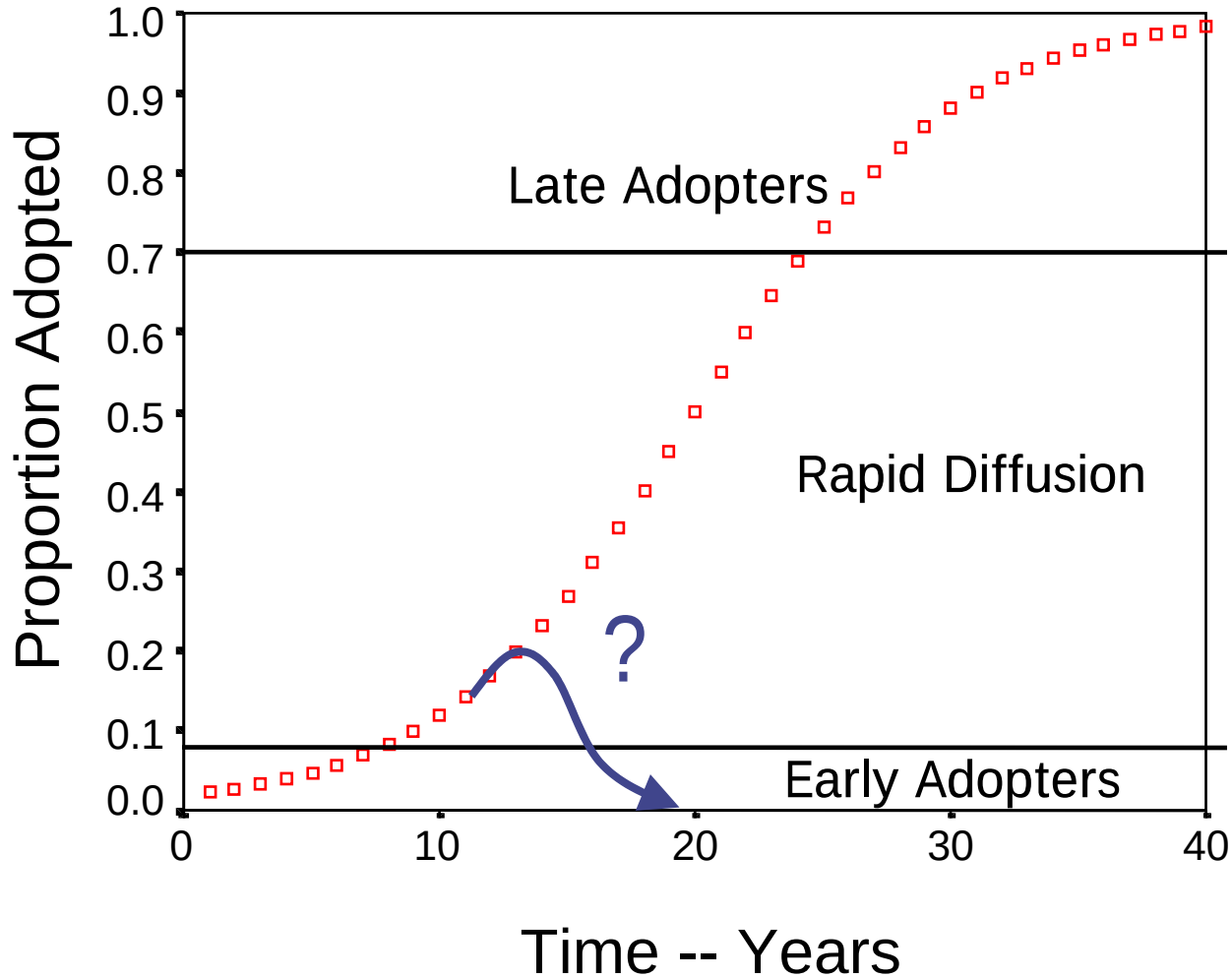
  • Resist minor earthquakes without damage;
  • Resist moderate earthquakes without structural damage, but with some nonstructural damage;
  • Resist major earthquakes … without collapse, but with some structural as well as nonstructural damage.

PBEE regulations/guidelines

- UBC 1946
- SEAOC Blue Book - 1967
- ATC 3-06 - 1978
- FEMA 273/356 - 1997
- SAC (steel moment frames) - 1999
- ATC 58 - ongoing

Pattern of Diffusion of Technological Innovations

(hypothetical example)



May 2002

Adoption of PBEE

- Attributes
  - relative advantage
  - compatibility
  - complexity
  - trialability
  - observability
- Promoting its effective use
  - engaging early adopters
  - FEMA 356, ATC 58, ...

May 2002, after Rogers 1995

Performance-based engineering

Design for the achievement of specified results rather than adherence to particular technologies or prescribed means.

Performance-based earthquake engineering

An approach for managing seismic risk, whereby