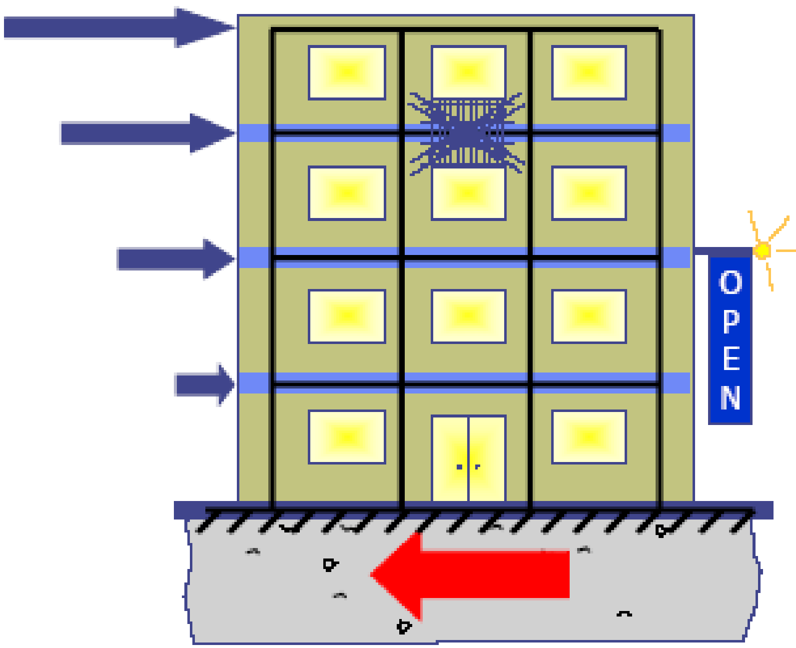
Performance-Based Seismic Design

Outline

- General concepts of PBD

- FEMA-350 in building design: Step-by Step
  1. Performance definition
  2. Evaluation approach
  3. Analysis
  4. Mathematical modeling
  5. Acceptance criteria

Basic Design Approach

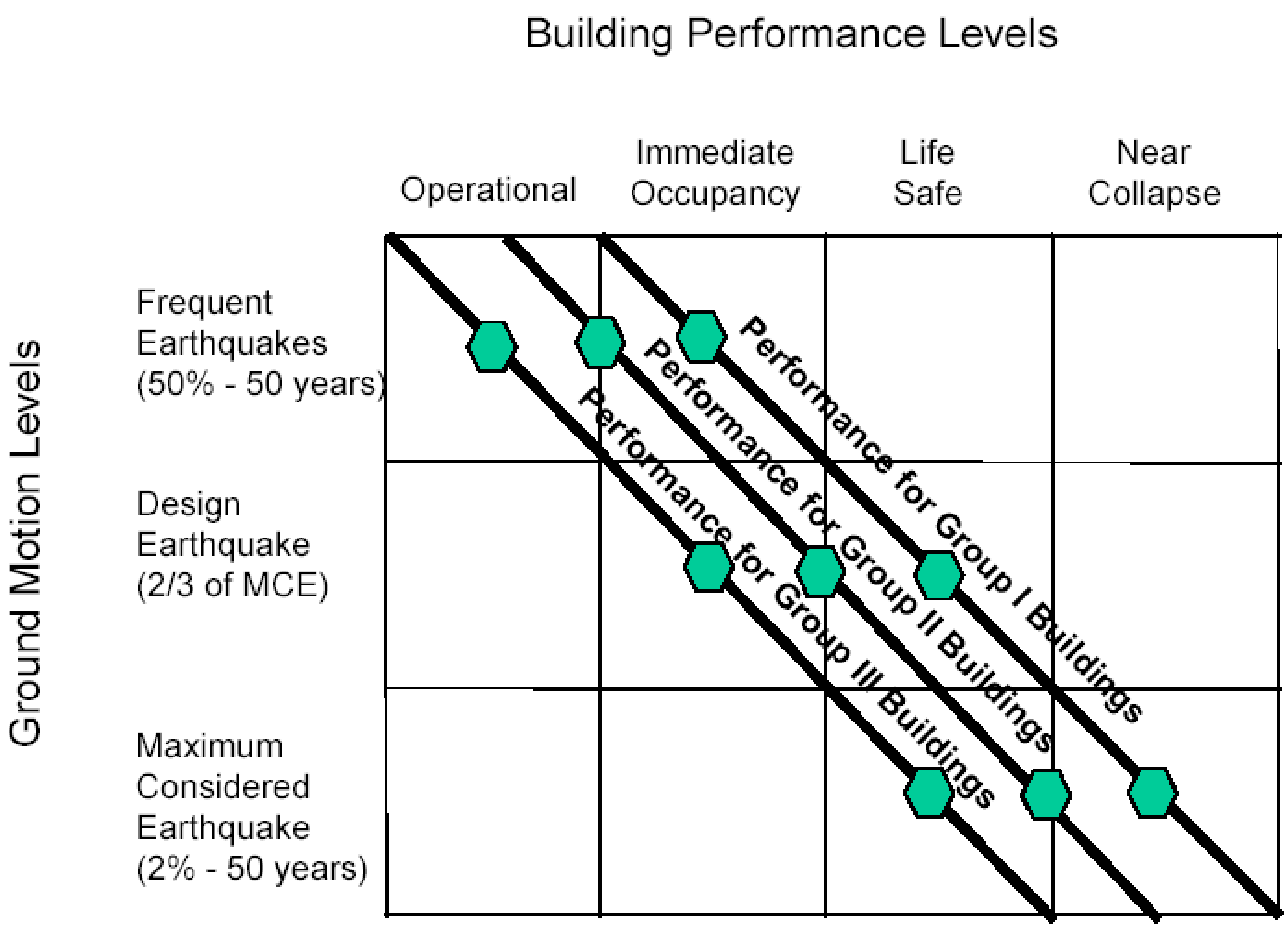


- Prescriptive design
- Prescribed strength
- Prescriptive details.

Basic Design Approach

- Structural system type and frame configuration
- Frame member sizes
- Design force levels
- Perform a structural analysis
- Revise specifications
- Complete the design (detailing requirements)

Expected Performance



Why Performance-Based Design?

- Evaluate the probable seismic performance of steel moment-frame buildings.

- Design steel moment-frame buildings for alternative performance capabilities and also to quantify the ability of a specific design to achieve desired performance objectives.

PB methodology in simple words…

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

PB Methodology

Earthquake professionals quantify seismic risk in terms that are meaningful to the decision makers.

Decision-makers make informed decisions that define a rational course of action for the earthquake professionals.

Applying FEMA-350 in Design
A Step by Step Description

PBSD Steps:

1. Performance definition
2. Evaluation approach
3. Analysis
4. Mathematical modeling
5. Acceptance criteria

I. Performance Definition

A Performance Objective has two components:

- Hazard Level
- Performance Level (limiting damage state)

Association of a performance level (damage state) to a hazard level is called a *performance-objective*.

Hazard Level

- Characterized by a hazard curve, which indicates the probability that a given value of a ground motion parameter, for example peak ground acceleration, will be exceeded over a certain period of time.
- For example:
  - 2% POE in 50 years or 2500 years return period
  - 50% POE in 50 years or 100 years return period

Performance Level

Performance levels are discrete damage states selected among all possible damage states that a building could experience as a result of earthquake response.

- For example:
  - Collapse Prevention (CP)
  - Immediate Occupancy (IO)

Performance Level

Table 4-2 Structural Performance Levels

	Structural Performance Levels	
Elements	**Collapse Prevention**	**Immediate Occupancy**
Girder	Extensive distortion; local yielding and buckling. A few girders may experience partial fractures	Minor local yielding and buckling at a few places.
Column	Moderate distortion; some columns experience yielding. Some local buckling of flanges	No observable damage or distortion
Beam-Column Connections	Many fractures with some connections experiencing near total loss of capacity	Less than 10% of connections fractured on any one floor; minor yielding at other connections
Panel Zone	Extensive distortion	Minor distortion
Column Splice	No fractures	No yielding
Base Plate	Extensive yielding of anchor bolts and base plate	No observable damage or distortion
Interstory Drift	Large permanent	Less than 1% permanent

Performance Objective

- The design need to provide *Collapse Prevention* or better performance for earthquake hazards with *2% probability of exceedance in 50 years*

But….what about uncertainties???

Uncertainties

- Behavior and response of the structure
- Accuracy of analysis procedures
- Ground motions

Therefore the performance objective is expressed in terms of confidence levels.

Performance Objective

Therefore a performance objective for a design should more correctly be stated as:

- *A certain level of confidence (i.e. 95%)* that the structure will provide *Collapse Prevention* or better performance for earthquake hazards with *2% probability of exceedance in 50 years*

PBSD Steps:

- ✓ Performance definition
2. Evaluation approach
3. Analysis
4. Mathematical modeling
5. Acceptance criteria

II. Evaluation

- The structural analysis is used to predict the value of various structural response parameters:
  - Interstory drift:
  - Axial force
- Predicted demands are adjusted by two factors:
  - Analytical uncertainty factor, γa
  - Demand variability factor, γ
- Structural capacities are adjusted by resistant factors, ϕ
- Level of confidence is calculated based on the ratio of factored demand to factored capacity.

PBSD Steps:

- ✓ Performance definition
- ✓ Evaluation approach

3. Analysis
4. Mathematical modeling
5. Acceptance criteria

III. Analysis Method

1. Linear static procedure
2. Linear dynamic procedure
3. Nonlinear static procedure
4. Nonlinear dynamic procedure

III. Analysis Method

Table 4-3 Analysis Procedure Selection Criteria

Structural Characteristics				Analytical Procedure			
Performance Level	Fundamental Period, T	Regularity	Ratio of Column to Beam Strength	Linear Static	Linear Dynamic	Nonlinear Static	Nonlinear Dynamic
Immediate Occupancy	$T \leq 3.5T_s$[1]	Regular or Irregular	Any Condition	Permitted	Permitted	Permitted	Permitted
	$T > 3.5\ T_s$[1]	Regular or Irregular	Any Conditions	Not Permitted	Permitted	Not Permitted	Permitted
Collapse Prevention	$T \leq 3.5T_s$[1]	Regular[2]	Strong Column[3]	Permitted	Permitted	Permitted	Permitted
			Weak Column[3]	Not Permitted	Not Permitted	Permitted	Permitted
		Irregular[2]	Any Conditions	Not Permitted	Not Permitted	Permitted	Permitted
	$T > 3.5T_s$	Regular	Strong Column[3]	Not Permitted	Permitted	Not Permitted	Permitted
			Weak Column[3]	Not Permitted	Not Permitted	Not Permitted	Permitted
		Irregular[2]	Any Conditions	Not Permitted	Not Permitted	Not Permitted	Permitted

Notes:

1. T_s is the period at which the response spectrum transitions from a domain of constant response acceleration (the plateau of the response spectrum curve) to one of constant spectral velocity. Refer to *FEMA-273* or *FEMA-302* for more information.
2. Conditions of regularity are as defined in *FEMA-273*. These conditions are significantly different from those defined in *FEMA-302*.
3. A structure qualifies as having a strong column condition if at every floor level, the quantity $\Sigma M_{prc} / \Sigma M_{prb}$ is greater than 1.0, where ΣM_{prc} and ΣM_{prb} are the sum of the expected plastic moment strengths of the columns and beams, respectively, that participate in the moment-resisting framing in a given direction of structural response.

Linear Static Procedure

- It is an equivalent lateral force technique
- Has inherently more uncertainty because it accounts less accurately the dynamic characteristics of the structures
- Applied lateral forces follow a pattern that resembles the distribution of inertial forces in a regular structure responding linearly to the ground excitations
- It is assumed that the structure's response is dominated by the fundamental mode

LSP Steps

- Calculate the fundamental period for each of the two orthogonal directions, from:
  - Eigenvalue analysis of the mathematical model
    $\left(\underline{K} - \omega_n^2 \underline{M}\right)\varphi_n = 0$
  - Apoximate period formula (4-1): $T = C_t h_n^{0.8}$

- Calculate Pseudo Lateral Load for each of the two orthogonal directions, from:

$$V = C_1 C_2 C_3 S_a W$$

C_1

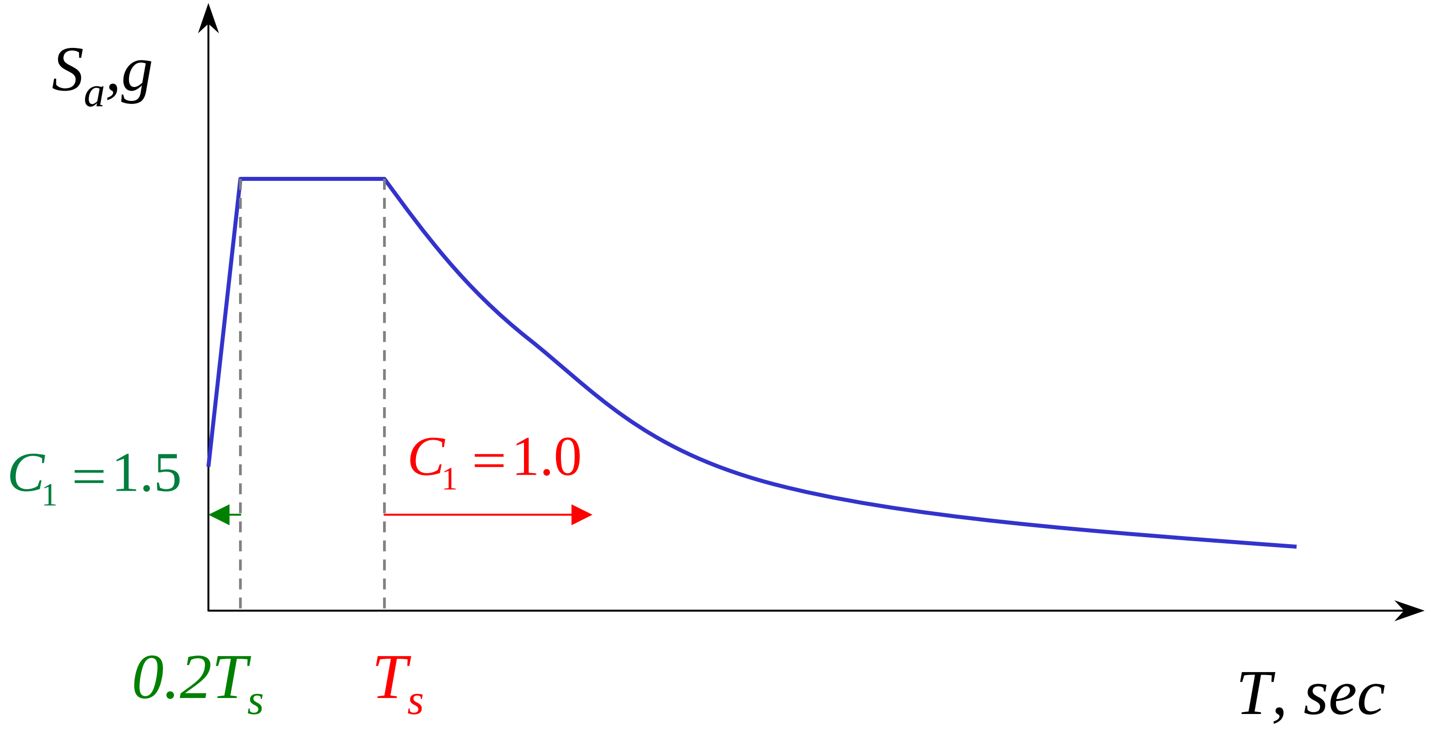
A modification factor to relate expected maximum inelastic displacements to displacements calculated for linear elastic response:

shear capacity substituted for V_y. Alternatively, C_1 may be taken as having a value of 1.0 when the fundamental period T of the building response is greater than T_s and shall be taken as having a value of 1.5 when the fundamental period of the structure is equal to or less than T_0. Linear interpolation shall be used to calculate C_1 for intermediate values of T.

T_0 = period at which the acceleration response spectrum for the site reaches its peak value, as indicated in *FEMA-302*. It may be taken as $0.2T_s$.

T_s = the characteristic period of the response spectrum, defined as the period associated with the transition from the constant spectral response acceleration segment of the spectrum to the constant spectral response velocity segment of the spectrum, as defined in *FEMA-302*.

C_1



C_2

- A modification factor to represent the effect of hysteretic pinching on the maximum displacement response, for steel moment frames:

$$C_2 = 1.0$$

C_3

- A modification factor to represent increased dynamic displacements due to P-delta effects and stiffness degradation:

Table 4-4 Modification Factor C_3 for the Linear Static Procedure

Performance Level	C_3
Immediate Occupancy	1.0
Collapse Prevention	
Connections meeting the criteria for Special Moment Frame structures in accordance with Chapter 3	1.2
Connections meeting the criteria for Ordinary Moment Frame structures in accordance with Chapter 3	1.4

Base Shear- $V = C_1 C_2 C_3 S_a W$

- S_a: *Response spectrum acceleration at the fundamental period and damping ratio of the building in the direction under consideration, for the hazard level corresponding to the performance objective being evaluated (I.e., probability of exceedance.)*
- W: *Total dead load and anticipated live load*

Nonlinear Dynamic Procedure

Response calculations are carried out using nonlinear response-history analysis

An estimate of median response parameter of interest will be obtained by performing the analyses over a set of minimum seven pairs of strong ground motion records

The mathematical model of the building structures should incorporate the inelastic material and nonlinear geometric behavior

PBSD Steps:

- ✓ Performance definition
- ✓ Evaluation approach
- ✓ Analysis

4. Mathematical modeling
5. Acceptance criteria

IV. Mathematical Modeling

1. Frame configuration
2. Connection modeling
    - Fully-restrained (FR)
    - Partially-restrained (PR)
    - Simple shear tab
    - Panel zone stiffness
3. Horizontal torsion
4. Foundation
5. Diaphragms
6. P-Delta effects
7. Multidimensional excitation effects
8. Vertical ground motion

PBSD Steps:

- ✓ Performance definition
- ✓ Evaluation approach
- ✓ Analysis
- ✓ Mathematical modeling

5. Acceptance criteria

V. Acceptance Criteria

Acceptability of building performance should be evaluated by determining a level of confidence in the building's ability to meet the desired performance objective(s).

1. Factored-Demand-to-Capacity Ratio
   - For interstory drift
   - For column axial load
   - For column splice tension
2. Confidence-level computations

V. Acceptance Criteria

Table 4-7 Recommended Minimum Confidence Levels

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

Factored-Demand-to-Capacity Ratio

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

D = the median estimate of demand from the structural analysis,

C = the median structural capacity for the performance parameter under consideration,

γ = the demand variability factor,

γ_a = the analysis uncertainty factor, and

φ = the capacity factor

Analysis Uncertainty Factor

Table 4-8 Interstory Drift Angle Analysis Uncertainty Factors γ_a

Analysis Procedure	LSP		LDP		NSP		NDP	
System Characteristic	I.O.[1]	C.P.[2]	I.O.[1]	C.P.[2]	I.O.[1]	C.P.[2]	I.O.[1]	C.P.[2]
Special Moment Frames								
Low Rise (<4 stories)	0.94	0.70	1.03	0.83	1.13	0.89	1.02	1.03
Mid Rise (4-12 stories)	1.15	0.97	1.14	1.25	1.45	0.99	1.02	1.06
High Rise (> 12 stories)	1.12	1.21	1.21	1.14	1.36	0.95	1.04	1.10
Ordinary Moment Frames								
Low Rise (<4 stories)	0.79	0.98	1.04	1.32	0.95	1.31	1.02	1.03
Mid Rise (4-12 stories)	0.85	1.14	1.10	1.53	1.11	1.42	1.02	1.06
High Rise (> 12 stories)	0.80	0.85	1.39	1.38	1.36	1.53	1.04	1.10

Notes: 1. I.O. = Immediate Occupancy Performance Level
2. C.P. = Collapse Prevention Performance Level

Demand Variability Factor

Table 4-9 Interstory Drift Angle Demand Variability Factors γ

Building Height	γ	
	Immediate Occupancy (I.O.)	Collapse Prevention (C.P.)
Special Moment Frame		
Low Rise (1 - 3 stories)	1.5	1.3
Mid Rise (4 - 12 stories)	1.4	1.2
High Rise (> 12 stories)	1.4	1.5
Ordinary Moment Frame		
Low Rise (1 - 3 stories)	1.4	1.4
Mid Rise (4 - 12 stories)	1.3	1.5
High Rise (> 12 stories)	1.6	1.8

Structural Capacity and Capacity Factor

Table 4-10 Global Interstory Drift Angle Capacity C and Resistance Factors ϕ for Regular SMF and OMF Buildings

Building Height	Performance Level			
	Immediate Occupancy		Collapse Prevention	
	Interstory Drift Angle Capacity *C*	Resistance Factor ϕ	Interstory Drift Angle Capacity *C*	Resistance Factor ϕ
Special Moment Frames (SMF)				
Low Rise (3 stories or less)	0.02	1.0	0.10	0.90
Mid Rise (4 – 12 stories)	0.02	1.0	0.10	0.85
High Rise (> 12 stories)	0.02	1.0	0.085	0.75
Ordinary Moment Frames (OMF)				
Low Rise (3 stories or less)	0.01	1.0	0.10	0.85
Mid Rise (4 – 12 stories)	0.01	0.9	0.08	0.70
High Rise (> 12 stories)	0.01	0.85	0.06	0.60

Uncertainty Coefficient

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

Building Height	Performance Level	
	Immediate Occupancy	Collapse Prevention
Special Moment Frames (SMF)		
Low Rise (3 stories or less)	0.20	0.3
Mid Rise (4 – 12 stories)	0.20	0.4
High Rise (> 12 stories)	0.20	0.5
Ordinary Moment Frames (OMF)		
Low Rise (3 stories or less)	0.20	0.35
Mid Rise (4 – 12 stories)	0.20	0.45
High Rise (> 12 stories)	0.20	0.55

Notes: 1- Value of β_{UT} should be increased by 0.05 for linear static analysis
2- Value of β_{UT} may be reduced by 0.05 for nonlinear dynamic analysis

Confidence Levels

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

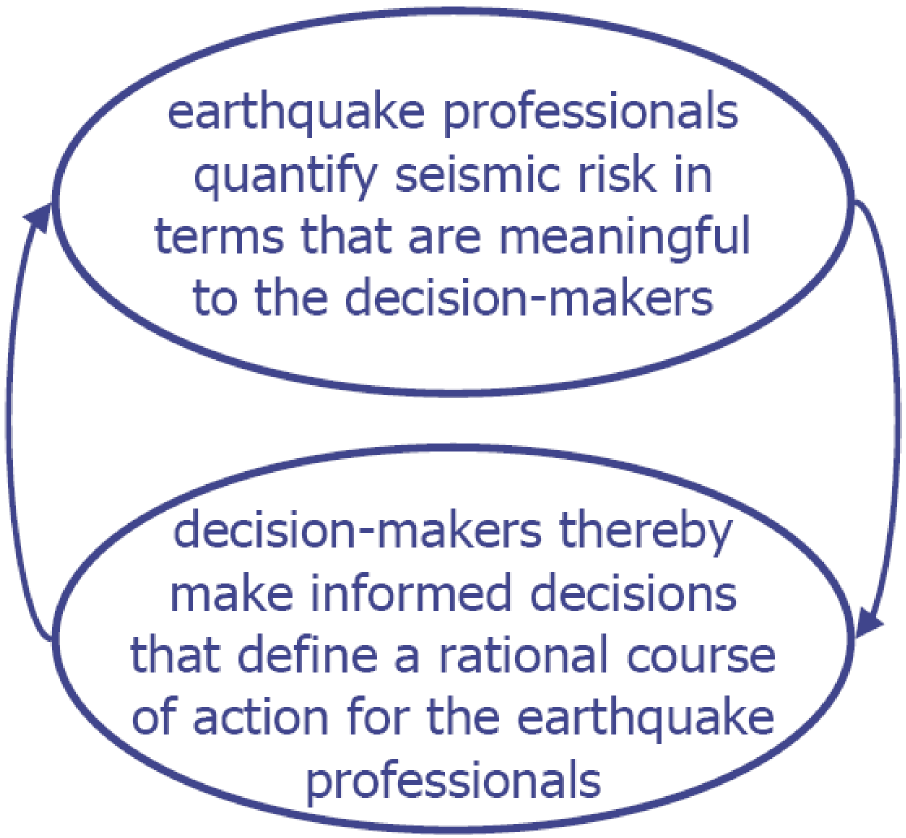
Confidence Level	10	20	30	40	50	60	70	80	90	95	99
β_{UT} = 0.2											
λ	1.37	1.26	1.18	1.12	1.06	1.01	0.96	0.90	0.82	0.76	0.67
β_{UT} = 0.3											
λ	1.68	1.48	1.34	1.23	1.14	1.06	0.98	0.89	0.78	0.70	0.57
β_{UT} = 0.4											
λ	2.12	1.79	1.57	1.40	1.27	1.15	1.03	0.90	0.76	0.66	0.51
β_{UT} = 0.5											
λ	2.76	2.23	1.90	1.65	1.45	1.28	1.12	0.95	0.77	0.64	0.46
β_{UT} = 0.6											
λ	3.70	2.86	2.36	1.99	1.72	1.48	1.25	1.03	0.80	0.64	0.43

Classroom activity…

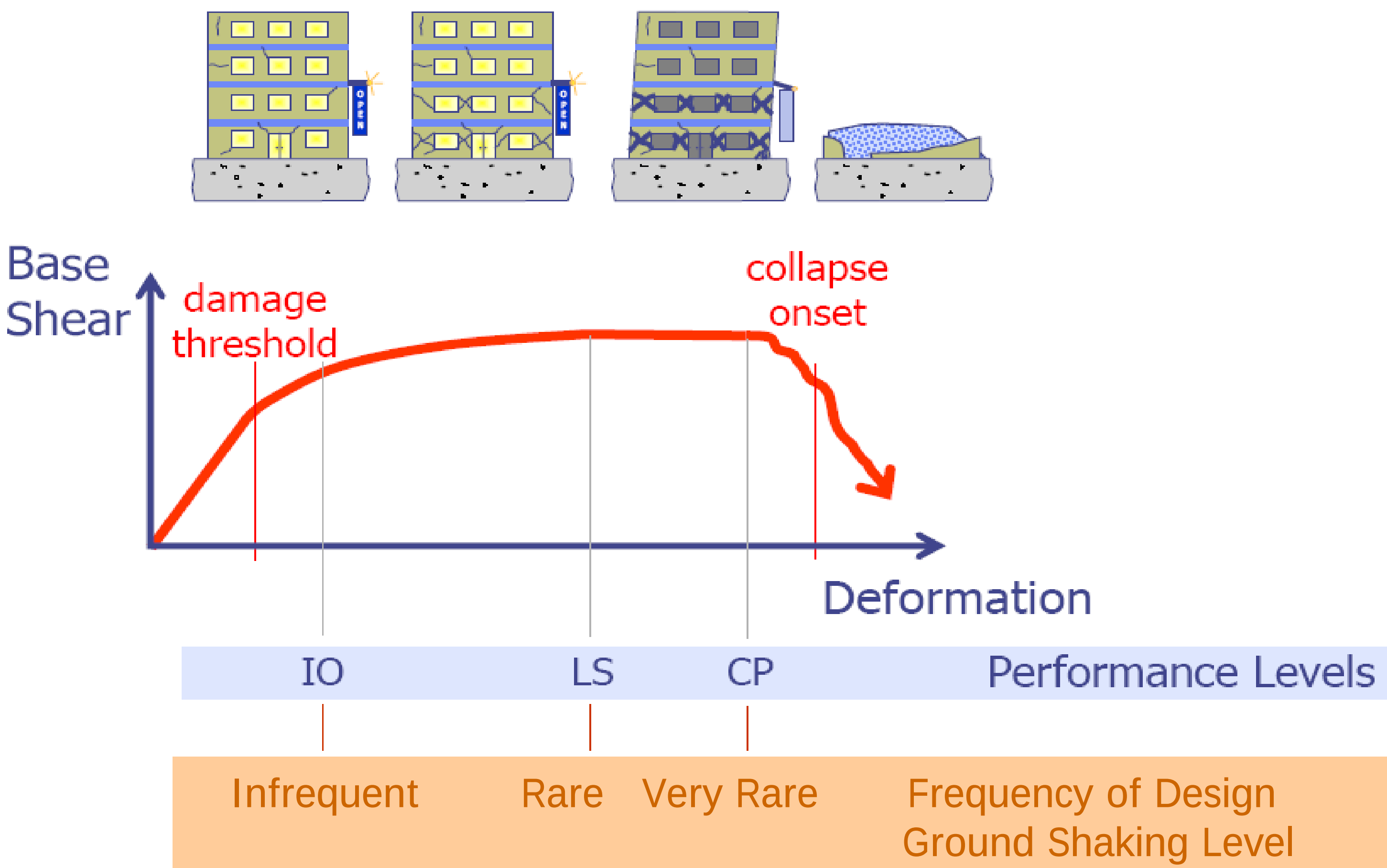
- *Problem 1: Find how much confidence a designer has on his/her design against collapse for a 10-story SMF (with post-Northridge partially retrained connection) that has a median interstory drift demand of 5% under a set of seven earthquake input motion records with 2% probability of exceedance in 50 years? Nonlinear dynamic analysis is used.*

Conclusions

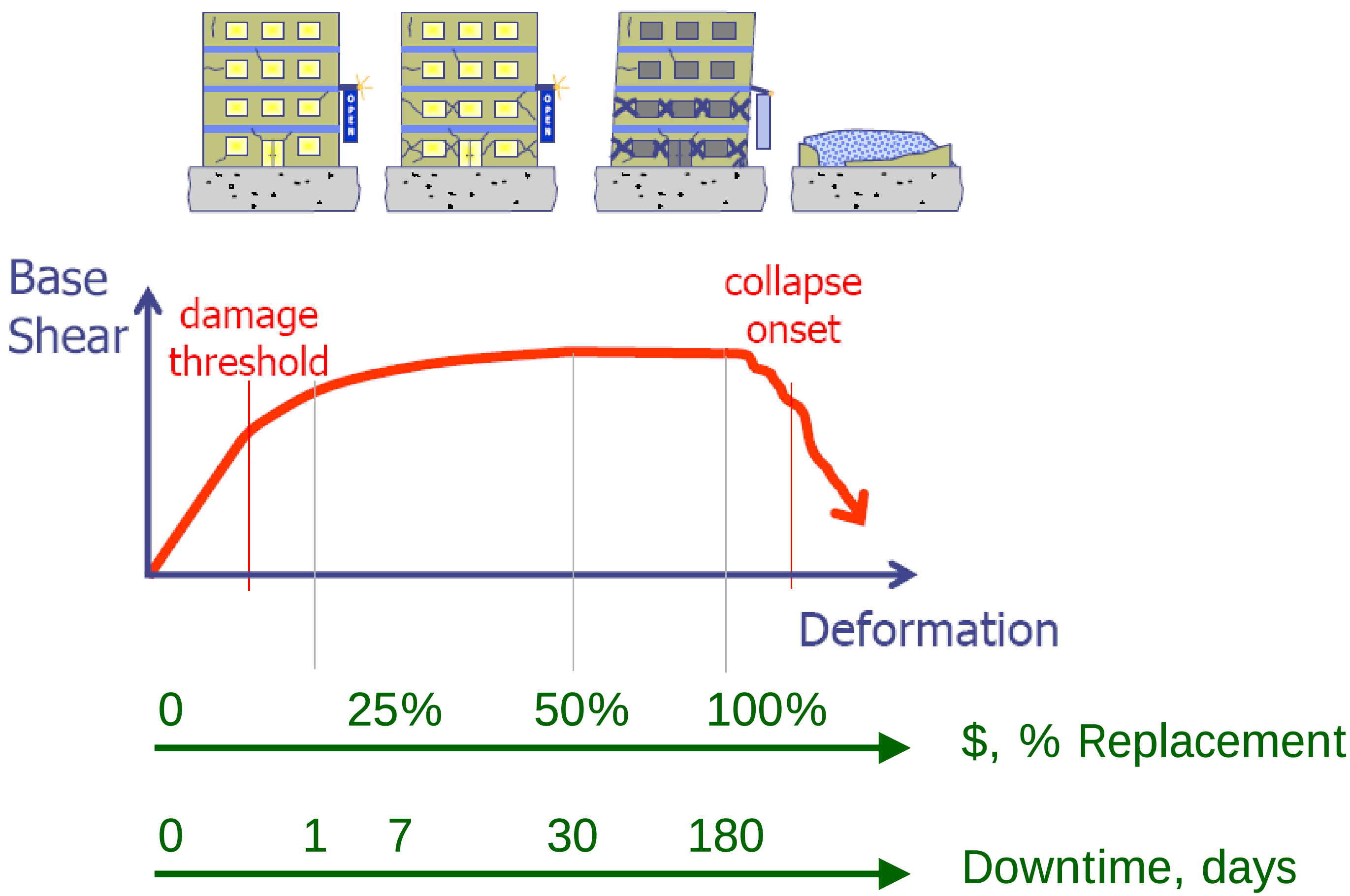
1. PBD can be seen as an approach for managing seismic risk, where by:



Conclusions



Conclusions



Conclusions

2. Simplified analytical performance evaluation methodology. (Chapter 4) Applicable only to well-configured, regular structures.
3. Detailed procedures for performance evaluation. (Appendix A) Applicable to irregular structures.

Conclusions

4. Increased confidence in a building's ability to provide specific performance can be obtained by:

- Providing greater earthquake resistance,
- Reducing some of the uncertainties in the performance evaluation process,
- Using more exact procedures of Appendix A.

Thank you!

Any Questions?

Confidence Levels

$$\lambda = \exp\left\{-\beta_{UT}\left(K_x - \frac{k}{2b}\beta_{UT}\right)\right\}$$

	=	Uncertainty measure equal to the vector sum (SRSS) of the logarithmic standard deviation of the variations in demand and capacity resulting from uncertainty;
k	=	Slope of the hazard curve in ln-ln coordinates at the hazard level of interest;
b	=	Coefficient relating the incremental change in demand to an incremental change in ground motion intensity (usually taken as 1.0).
K_x	=	Standard Gaussian variate associated with the probability of x not being exceeded as a function of the number of standard deviations above or below the mean found in standard probability tables.