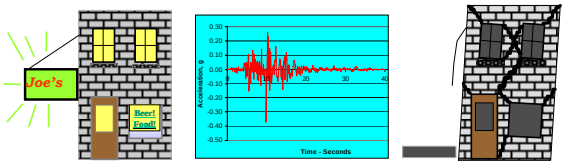
PERFORMANCE-BASED ENGINEERING



Performance Approach

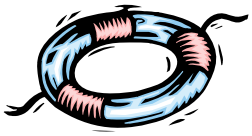
- The fundamental reason for the creation of a structure is placed at the forefront.
- Innovation is permitted, even encouraged.
- Characterization, measurement, and prediction of performance are fundamental concepts.

Performance-Based Structural Engineering

- Historical review
- Motivation
- Communications
- *ICC Performance Code*
- Modern trends in earthquake engineering
  - Performance levels
  - Global v local evaluation
  - Primary and secondary
  - Uncertainty

Performance Requirement

- A qualitative statement of a human need, usually in the form of an attribute that some physical entity, process, or person should possess.



Early Performance Requirement

- From the Code of Hammurabi (circa 1700 BCE):

  "If a builder has built a house for a man and his work is not strong and if the house he has built falls in and kills the householder, the builder shall be slain . . ."

Two Opposite Poles

- Performance:

  An acceptable level of protection against structural failure under extreme load shall be provided.

- Prescriptive:

  ½" diameter bolts spaced no more than 6 feet on center shall anchor the wood sill of an exterior wall to the foundation.

Why Prescriptive?

- Simple to design and check.
- Simple can be economical.
- No need to "re-invent the wheel" on every new project.

What Is Wrong with Prescriptive?

- Loss of rationale leads to loss of ability to change.
- Loss of innovation leads to loss of economy.
- Loss of rationale can lead to loss of compliance.

What's Wrong with Performance Standards?

- Quantitative criteria:
  - Sometimes difficult to develop
  - Often difficult to achieve consensus
- Evaluation procedures:
  - Measurement is the key – it is essential to find a way to measure (analytically or experimentally) a meaningful quantity

Early Performance Standards at NBS (now NIST)

- 1969: Performance concept and its application
- 1970: Criteria for Operation Breakthrough
- 1971: PBS performance criteria for office buildings
- 1975: Interim performance criteria for solar
- 1977: Performance criteria resource document for innovative housing

NBS Format

R • A set of performance requirements

C • A set of quantitative performance criteria for each performance requirement

E • One evaluation procedure for each performance criterion

C • A commentary if appropriate

Performance Requirements Circa 1976

1. The structural system shall support all loads expected during its service life without failure.
2. The structure shall support the service loads…without impairing function…or appearance…or causing discomfort.
3. Floor and wall surfaces shall resist service loadings without damage.

Criteria for Requirement 1 (Safety)

1.1 Resistance to ultimate load
Eight items to evaluate
Based on probabilistic reliability

1.2 Resistance to progressive collapse
No real evaluation; mostly commentary

1.3 Resistance to repeated loads
Evaluation focused on physical testing

Evaluations for Resistance to Maximum Load

- Load combinations for additive and counteracting loads
- Computations of load effects
- Foundation settlements
- Factored resistance, mean and variation in resistance
- Ductility

Maximum Loads

$$U = 1.1\,D + 1.45[Q + \Sigma \Psi_i F_i]$$

where:

D = dead load

Q mean maximum variable load (= 1.25L, 1.2S, 1.0H, 0.85W, 1.4E, or 1.0T)

Ψ_i = factor for arbitrary point in time load

F_i = L, S, H, W, E, or T

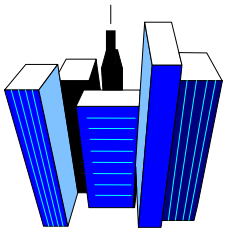
"Partial vs. Pure Performance"

- Specification of the load factors creates a "procedural standard" whereas specification of a reliability level would be more purely "performance"
- Analytical evaluation
- Experimental evaluation ($$$)

Performance-based Design

- Design specifically intended to limit the consequences of one or more perils to defined acceptable levels
- Perils addressed: wind, fire, snow, earthquake, live loads

All Design Is Intended to Achieve Performance . . .

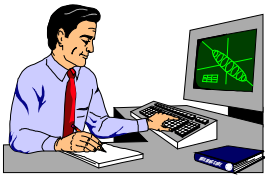


- Protect the public safety by minimizing the chance for:
  - Uncontrolled or inescapable fire
  - Structural collapse
  - Spread of disease
- Limit occupant discomfit by controlling:
  - Noise
  - Vibration
  - Environment

… But Most Building Code Provisions Are Not Performance-based

- Codes typically prescribe design and construction rules:
  - Believed capable of attaining desired performance
  - Largely based on past poor performance

Designers Following These Codes . . .

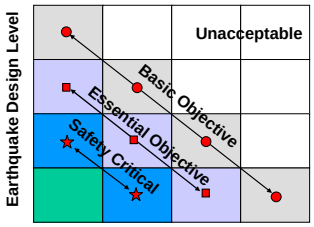


- Learn to follow the rules, but often:
  - Don't know why the rules require certain things.
  - Don't understand the performance intended.
  - Don't know how to adjust the rules to get different performance.

Performance-based Design

- Requires the designer to understand:
  - Intended performance
  - Relationship between design features and performance
- Forces the designer to predict expected performance given a design event

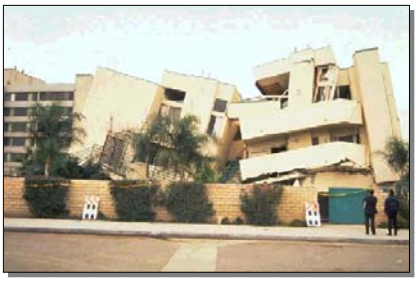
SEAOC's Vision 2000



Motivation for PBE (Structural)

A modern garage at Cal State Northridge.

Motivation for PBE (Structural)



A modern wood-frame residential building on Sherman Way.

Motivation for PBE (Nonstructural)

Veterans Administration Medical Center in Sepulveda.

Motivation for PBE

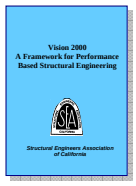
What is wrong with current building codes?

- Only a single performance level is checked.
- Only a single seismic event is applied.
- Linear static or dynamic analysis.
- No local acceptance criteria.

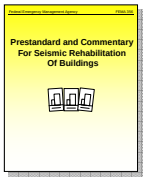
Concepts Incorporated within PBE

- Multiple performance levels are checked.
- Multiple seismic events are applied.
- May utilize nonlinear analysis.
- Detailed local acceptance criteria
  - For structural elements
  - For nonstructural elements

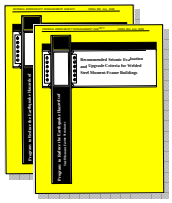
Basic Resource Documents Performance-based Seismic Design



Vision 2000
(new buildings)

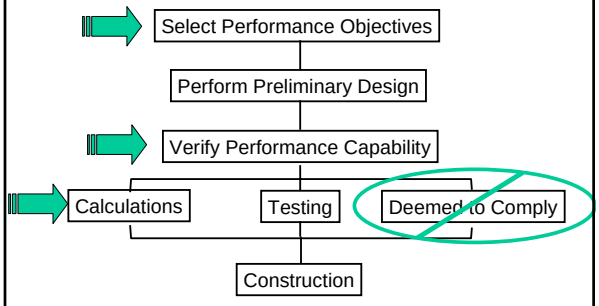


FEMA 356
(existing buildings)



FEMA 350/351
(steel moment frame buildings)

The PBD Process

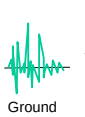


Vision 2000 / FEMA 356 Performance Objectives

Specification of:

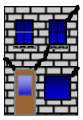
- ***Design Hazard (earthquake ground shaking)***
- ***Acceptable Performance Level (maximum acceptable damage given that shaking occurs)***

Performance Objective =



Ground Motion
x% - 50 years

+



Performance Level

Performance Objectives

- For performance-based design to be successful, the needs of both the client and engineer must be satisfied.

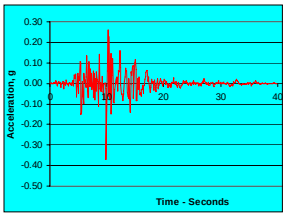
Engineer --
Hazard must be quantifiable and performance must be quantifiable

Performance Objectives

- For performance-based design to be successful, both the client and engineer must be satisfied

Owner --
Hazard must be understandable and performance must be understandable and useful

Hazard



The intensity and characteristics of ground shaking that design is developed to resist.

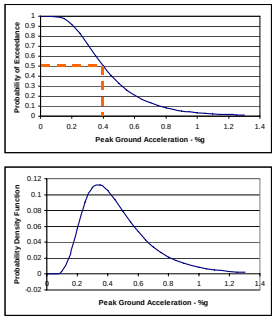
Hazard

- Two methods of expression:
  - Deterministic
    - Magnitude “x” earthquake on “y” fault
  - Probabilistic
    - “x” % probability of exceedance in “y” years for design event

Deterministic Hazards

- Easy to understand but . . .

  there is considerable uncertainty as to how strong the motion from such an event actually is.

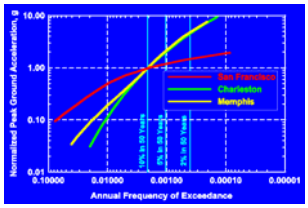


Probabilistic Hazards

- Need to move clients to “probabilistic” mind set.
- Commonly used for other considerations such as:
  - Probable occupancy rates,
  - Probable cost of construction, and
  - Probable return on investment.

Probabilistic Hazards

- Low intensity shaking occurs frequently.
- Moderate intensity shaking occurs occasionally.
- Severe shaking occurs rarely.



Probabilistic Hazards

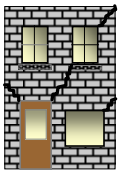
- Probability of exceedance for design event:
  - 10%/50 years
    (500 year mean return) traditionally taken as hazard for "life safety protection"
  - 2%/50 years
    (2,500 year mean return) traditionally taken as hazard for collapse avoidance
  - Hazard for economic loss protection can be taken at any level based on cost-benefit considerations.

Earthquake Hazard Levels (FEMA 273)

Probability	MRI	Frequency
50%-50 Year	72 Years	Frequent
20%-50 Year	225 Years	Occasional
10%-50 Year (BSE-1)	474 Years	Rare
2%-50 Year* (BSE-2)	2475 Years	Very Rare

*NEHRP Maximum Considered Earthquake.

Performance Level



The permissible amount of damage, given that design hazards are experienced.

ICC Performance Code

- "Allows user to systematically achieve various solutions."
- "Prescriptive code deemed to be acceptable."
- "Procedure to address the alternate materials and methods clause of code."
- Commentary highly recommended.

ICC Performance Code

- "Committee envisions limited code changes in the future, except that "acceptable methods" will be an evolving process.

ICC Performance Code

- "Purpose -- To provide appropriate health, safety, welfare, and social and economic value, while promoting innovative, flexible and responsive solutions."
- "Intent -- A structure that will withstand loads associated with normal use and of the severity associated the location…."

ICC: Administrative Provisions

- Functional statements:
  - Design professional qualifications
  - Design documents required for review
  - Construction compliance to be verified
  - Maintenance of performance-based design over life of building

ICC Administrative Provisions

"Performance" requirements

- Building owner responsibilities
- Design professional qualifications
- Special expert responsibilities
- Documentation
  - Concept report and design reports
  - O & M manual

ICC Use Groups

Basis for assignment:

- Function
- Risks to users

Risk factors:

- Nature of hazard
- Number of people
- Length of time occupied
- Sleep facility
- Familiarity
- Vulnerable groups
- Relationships

ICC Performance Groups

Performance Group	Description
I	Low hazard to humans
II	Normal buildings
III	Hazardous contents
IV	Essential facilities

ICC Design Performance (Damage) Levels

"Size" of event	Perf. Group I	Perf. Group II	Perf. Group III	Perf. Group IV
V. Large (v.rare)	Severe	Severe	High	Mod
Large (rare)	Severe	High	Mod	Mild
Medium	High	Mod	Mild	Mild
Small (frequent)	Mod	Mild	Mild	Mild

Mild Damage Level

- No structural damage; safe to occupy
- Necessary nonstructural is operational
- Minimal number of minor injuries
- Minimal damage to contents

Moderate Damage Level

- Structural damage, but repairable; delay in reoccupancy
- Necessary nonstructural operational
- Locally significant injuries but low likelihood of death
- Moderate cost of damage
- Minimal risk from hazardous materials

High Damage Level

- Significant structural damage, but no large falling debris; repair possible but long-term
- Necessary nonstructural damaged significantly
- Injury and death possible but moderate numbers
- Hazardous materials release locally

Severe Damage Level

- Substantial structural damage, but collapse is avoided; repair may be infeasible
- Necessary nonstructural not functional
- Likely single life loss; moderate probability of multiple lives lost
- Damage may “total” the building
- Hazardous materials release requires relocation

MRI for Environmental Loads

Event Size	Flood	Wind	Snow	Ice	Earth-quake
Small	20 **100**	50	25	25	25
Medium	50 **500**	75	30	50	72
Large	100 **SS**	100	50	100	475
V. large	500 **SS**	125	100	200	2475

ICC Performance Code Appendices

A. Use classification related to main code
B. Worksheet for assignment to performance groups
C. Individually substantiated design method
D. Qualification characteristics
E. Use of computer models

Performance-Based Structural Engineering

- Historical review
- Motivation
- Communications
- *ICC Performance Code*
- Modern trends in earthquake engineering
  - Performance levels
  - Global v local evaluation
  - Primary and secondary
  - Uncertainty

Performance-Based Earthquake Engineering

Two driving factors:

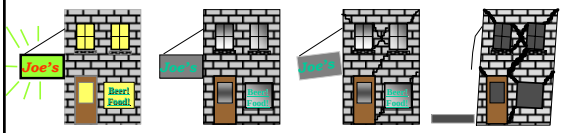
- High cost of upgrading existing structures now considered unsafe
  - Requires more exacting assessment
- High cost of damage and associated impacts from structural performance in earthquakes
  - Higher performance criteria

Performance Levels

Engineer --
amount of yielding, buckling, cracking, permanent deformation that structure experiences

Owner --
Will the building be safe?
Can I use the building after the earthquake?
How much will repair cost?
How long will it take to repair?

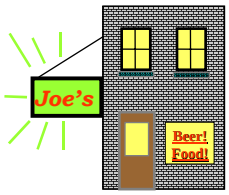
"Standard" Structural Performance Levels



Operational | *Immediate Occupancy* | *Life Safety* | *Collapse Prevention*

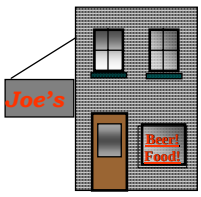
0% — *Damage or Loss* — 99%

Operational Level



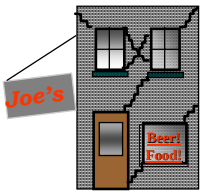
- Negligible structural and nonstructural damage
- Occupants are safe during event
- Utilities are available
- Facility is available for immediate re-use (some cleanup required)
- Loss < 5% of replacement value

Immediate Occupancy Level



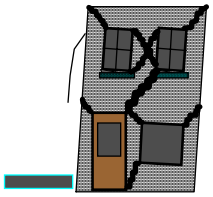
- Negligible structural damage
- Occupants safe during event
- Minor nonstructural damage
- Building is safe to occupy but may not function
- Limited interruption of operations
- Losses < 15%

Life Safety Level



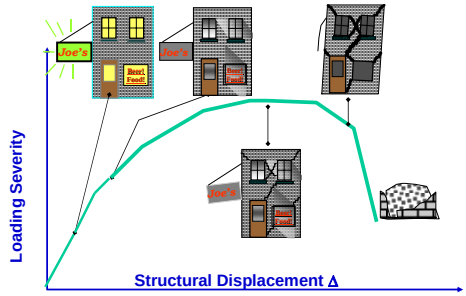
- Significant structural damage
- Some injuries may occur
- Extensive nonstructural damage
- Building not safe for reoccupancy until repaired
- Losses < 30%

Collapse Prevention Level

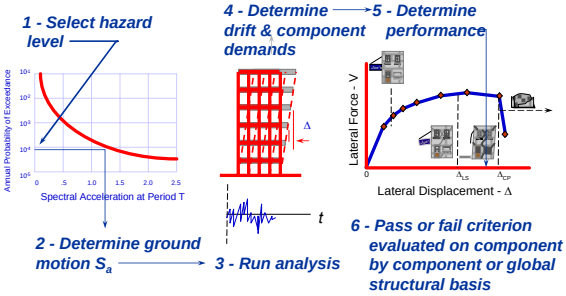


- Extensive (near complete) structural and nonstructural damage
- Significant potential for injury but not wide scale loss of life
- Extended loss of use
- Repair may not be practical
- Loss >> 30%

Global Response and Performance



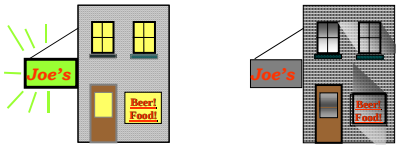
Evaluation Approach



What Type of Analysis?

- The answer depends on:
  - What performance level you are hoping to achieve.
  - The configuration of the structure.
  - How accurate you need to be.
- A wide range of choices are available.

Superior Performance Levels



- Behavior will be essentially elastic
  - Regular structures with short periods
    - Linear static procedures are fine
  - Regular structures with long periods and all irregular structures - linear dynamic procedures are better
    - Response spectra accurate enough

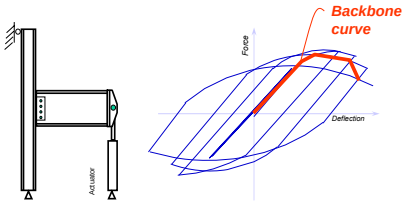
Poorer Performance Levels

- Inelastic behavior is significant (elastic analyses are the wrong approach!)
  - Structures dominated by first mode response
    - Pushover analysis may be adequate
  - Structures with significant higher mode response
    - Nonlinear time history necessary

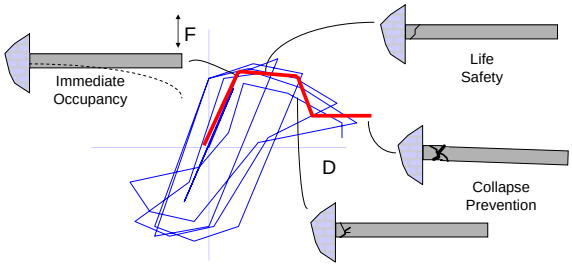
Judging Performance Acceptability

- Acceptance criteria are indicators of whether the predicted performance is adequate
  - Local (component-based)
  - Global (overall structure-based)

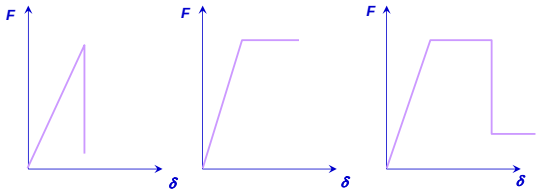
Local Response and Performance



Local (Component-based) Acceptance Criteria



Component Backbones and Acceptance Criteria

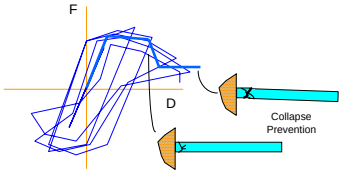


Brittle Behavior (Force Controlled)

Ductile Behavior (Deformation Controlled)

Disadvantages Associated with Local Acceptance Criteria

- The "weakest" or "most highly damageable" element controls the structure's performance.
- The effect on global stability is difficult to judge.

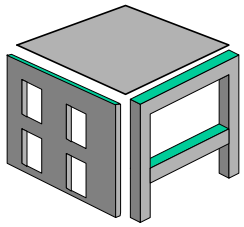


Building Configuration

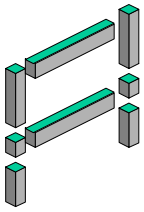
- Hierarchy of "parts" that comprise a building:
  - Elements
  - Components
  - Actions

Elements

- Horizontal or vertical subassemblies that comprise a structure:
  - Braced frame
  - Moment frame
  - Shear wall
  - Diaphragm



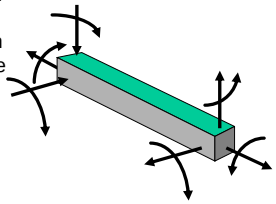
Components



- Individual members that comprise an element:
  - Beam
  - Column
  - Joint
  - Brace
  - Pier
  - Footing
  - Damper

Actions

- Independent degrees of freedom associated with a component, each with an associated force and deformation:
  - Axial force - elongation
  - Moment - rotation
  - Torsional moment - twist



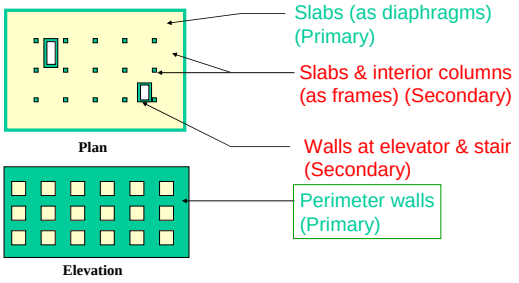
Primary and Secondary Parts

- Primary Elements:
  - Any element (component) {action} required to provide the building's basic lateral resistance.
    - Similar to the concept of a "*participating*" element in the building code.
- Secondary:
  - Any element (component) {action} that is not required to provide the building's basic lateral resistance.
    - May "*participate*" but is not required to do so.

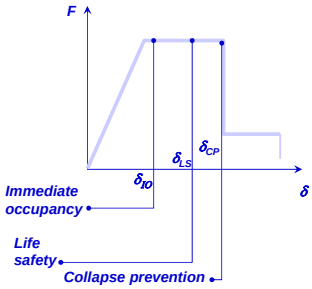
Primary and Secondary

- Permits engineer to utilize judgment in determining whether a building meets the intended performance levels.
  - Secondary elements are permitted to experience more damage than primary elements.
  - Acceptance criteria for secondary elements are more permissive than for primary elements.

Primary & Secondary



Performance Evaluation Primary Components

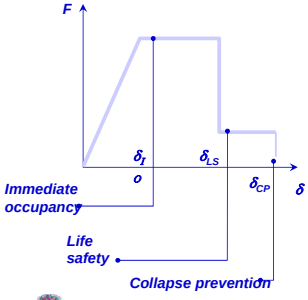


δ_{IO} - based on appearance of damage

δ_{CP} - based on loss of lateral load resisting capacity

δ_{LS} - 75 % δ_{CP}

Performance Evaluation Secondary Components



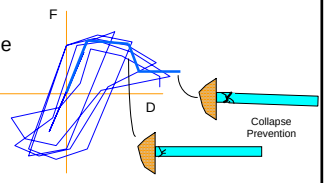
δ_{IO} - based on appearance of damage

δ_{CP} - based on complete failure of element

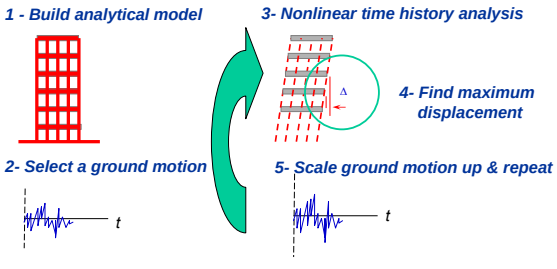
δ_{LS} - 75% δ_{CP}

Disadvantages Associated with Local Acceptance Criteria

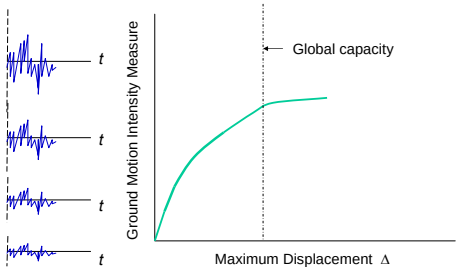
- The "weakest" or "most highly damageable" element controls the structure's performance
- The effect on global stability is difficult to judge



Incremental Dynamic Analysis
Determining Capacity Limited by Global Stability



Incremental Dynamic Analysis
Determining Capacity Limited by Global Stability

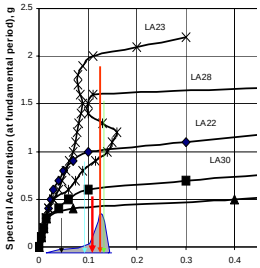


Perception of a Guarantee

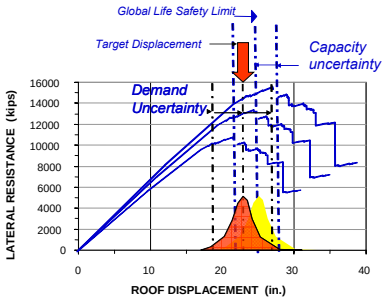
How Could This Happen?

- Loading that will occur in the future is uncertain.
- Actual strength of materials and quality of construction is variable.
- Neither the real demands nor the capacity of the structure to resist these demands can be perfectly defined.

Ground Motion and Capacity are Uncertain and Variable



Capacity, Demand, and Performance Prediction



Performance Objective Redefined

- Vision 2000 / FEMA 273/356:
  - Damage will not exceed desired level, given that ground motion of specified probability is experienced.
- SAC Approach:
  - Total probability of damage exceeding a desired level, will not exceed a specified amount, given our understanding of site hazards.
    - Confidence level associated with achieving this performance is defined.

Performance Objectives Redefined

I am highly / moderately / not very confident

that there is less than x% chance in 50 years

that damage will be worse than Immediate occupancy / Collapse prevention

Total Probability of Damage Exceeding Specified Level

$$P(Damage > PerLev) = \int P\left|D > C\right|GM\left|P\left(GM\right)\right.$$

D = demand (drift, or force) = b (GM) - random variable β_D

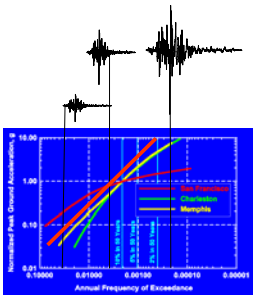
C = capacity (function of drift or force) - random variable β_C

ln(GM) = kln(PE)

β_D, β_C defined in terms of random and uncertain components

Load and resistance factors derived as products of integration

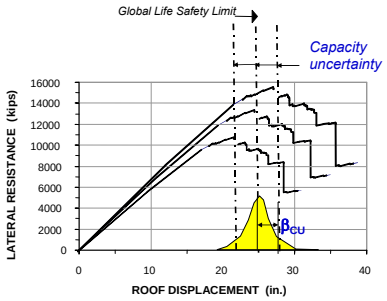
Hazard Level and Load Severity



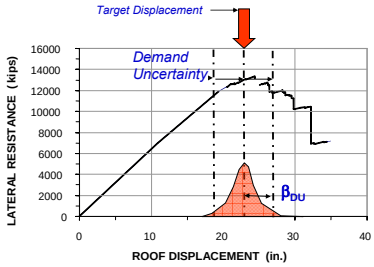
- Minor earthquakes occur frequently.
- Moderate earthquakes occur occasionally.
- Major earthquakes occur rarely.

Mathematically, "*k*" is the slope of the hazard curve and indicates how much more intense motion gets with decreasing probability of exceedance.

Uncertainty in Capacity b_{CU}



Uncertainty in Demand b_{DU}



Demand and Resistance Factor Procedure

- Demand and resistance factors computed as products of integration, functions of hazard, randomness and uncertainty

$$\gamma = e^{\frac{k}{2b}\beta_{DR}^2};\gamma_a = C_B e^{\frac{k}{2b}\beta_{DU}^2};\phi = e^{\frac{-k}{2b}\left(\beta_{CU}^2+\beta_{CR}^2\right)}$$

- Factored demand -- Capacity ratio used to determine confidence of successful performance

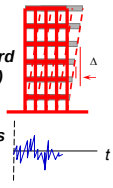
$$\lambda = \frac{\gamma\gamma_a D}{\phi C}$$

- $\lambda = 1$ indicates mean confidence (on order of 60%)
- < 1 indicates higher than mean confidence
- > 1 indicates less than mean confidence

Procedure

1. ***Start with frame design:***
   - ***Configuration***
   - ***Member sizes***
   - ***Connection details***

2. ***Analyze frame :***
   - ***Use ground motion at appropriate hazard level (x% - 50 years)***
   - ***Predict maximum drift, member deformations, forces***



3. ***Correct predicted maximum demands for known inaccuracies in prediction method to obtain median estimate of demand.***

$$\gamma\gamma_a D$$

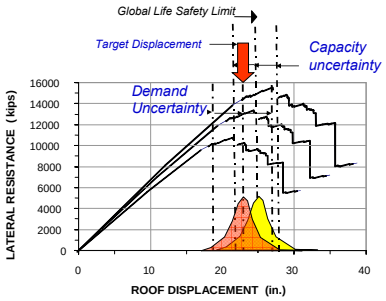
Procedure

4. ***Compute factored demand to capacity ratio (DCR)***

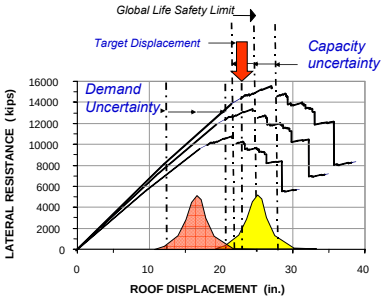
$$\lambda = \frac{\gamma\left(\gamma_a D\right)}{\phi C}$$

Confidence	2%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	98%
λ	3.0	2.6	2.2	1.9	1.6	1.5	1.3	1.2	1.1	0.95	0.8	0.7	0.5

Low Confidence λ > 1



High Confidence λ < 1



Summary

- Performance-based design for earthquake resistance is possible.
  - There is considerable uncertainty associated with prediction of performance.
- LRFD approach developed for steel moment frame buildings allows the engineer to be honest as to confidence that performance may (or may not) be achieved.
- Communication is more complex but less dangerous.
- Extensive work necessary to derive demand and resistance factors for various structural systems for general application.