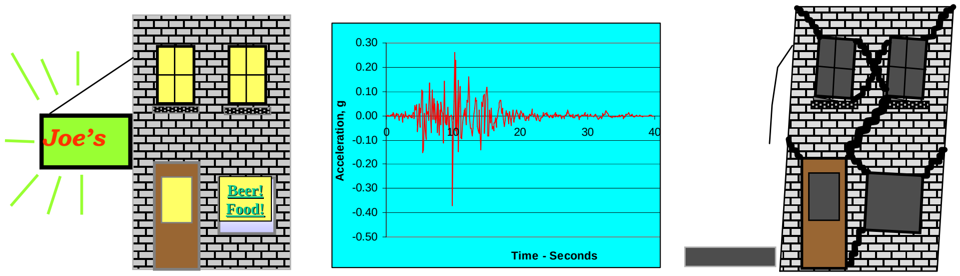
PERFORMANCE-BASED ENGINEERING



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This topic was prepared by James Harris, J. R. Harris & Company, Denver, Colorado, drawing liberally on resources from Ron Hamburger of Simpson Gumpertz & Heger, San Francisco, California, and Finley Charney of Virginia Tech, Blacksburg. Ron Hamburger has led a significant project to further develop performance-based earthquake 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 approaches are not easy; therefore, in the short run, they are not economical. In the long run, they can produce significant economies through more appropriate allocation of resources.

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

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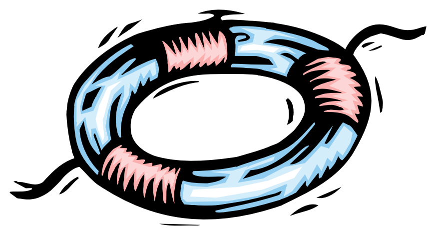
Basically a table of contents for the presentation. Part 2, the focus on earthquake engineering, is the longer portion. It is important to recognize that there is a real and relatively recent precedent that is not based in earthquake engineering.

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.



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A few fundamental examples:

1. Structures used for human occupancy shall provide an environment safe from structural failure due to loads generated by that occupancy.
2. Structures used for human occupancy shall provide safety against structural failure due to environmental loads of wind, snow, rain, ice, earthquake.
3. Structures used to support office occupancies shall not transmit annoying vibrations created by foot traffic.

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 . . ."

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A classic ancestor of building regulations. Very much a performance requirement with a penalty clause. Today, the penalties are far different. For example, the Olive View Medical Center was brand new when destroyed by the 1971 earthquake; yet, the engineer of record was not slain, jailed, or put out of business as a result. In fact, the design met the codes of the day, and the engineer was considered for design of the replacement facility. An argument can be made that codes today protect the engineer.

Two Opposite Poles

- Performance:

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

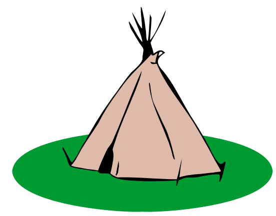
- Prescriptive:

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

Both types of rules are needed. Performance allows the better mousetrap. Prescriptive allows economy to be reproduced. Continuing with rules for conventional wood framed dwellings, the rules for double top plates, minimum header sides, etc. Are all based upon "normal" spans and the weakest available materials.

Why Prescriptive?

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



“If it isn’t broken, don’t fix it.”

Not only is design more economical, construction can be more economical. And quality assurance (QA) is not only much more economical, the reliability of QA is probably higher.

To a very real extent, our society depends on such economy.

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.

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Our earthquake design standards have proven very vulnerable to the third factor cited.

There are also instances in which the first item has been a real restraint: many engineers designing dwellings of light wood framing strongly resisted the change in the prescriptive assumption that all wood diaphragm structures should be analyzed as flexible diaphragms, primarily because they were comfortable with existing practice.

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

Fundamental questions include:

1. How safe is safe enough?
2. How much vibration is too much?
3. How do you measure?
4. How do you predict in advance?

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

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At this point we will make a brief examination of the development of performance standards at the National Bureau of Standards (NBS but now NIST, the National Institute of Standards and Technology) roughly 30 years ago. Most of the work at NBS was being done for other federal agencies, including HUD, GSA, and ERDA (now DOE).

Significant parallel efforts were under way in western Europe at the same time.

NBS Format

R	• A set of performance requirements
C	• A set of quantitative performance criteria for each performance requirement
E **C**	• One evaluation procedure for each performance criterion
	• A commentary if appropriate

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Translating the nonquantitative performance requirement into quantitative (measurable) performance criteria is a key step that requires great care. It will often change with time whereas performance requirements should change much less frequently. Nevertheless, even performance requirements do change with time; the Americans with Disabilities Act is a good example of how society can decide to create a performance requirement that simply was not a design requirement a quarter of a century earlier.

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.

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Consider floor surface. For housing, the old standard was a "double" wood floor (rough board subfloor plus tongue and groove finish board); it was being replaced by a single layer of plywood. How strong and stiff did it need to be? NBS resorted to physical testing for the fundamental evaluation procedure for innovating housing.

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

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Three overall criteria, but only one has specific evaluation procedures. It is the classic strength requirement in which strength is evaluated in a load and resistance factor approach as shown partially in following slides.

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

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These are very brief descriptions of the particular evaluation procedures. One load combination is shown following. The other procedures are somewhat simpler statements.

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

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This LRFD format is quite similar to AASHTO's in which there is a factor times a sum of factored loads. Compare with current 1.2 D + 1.6 L + 0.5 S …

The concept that the maximum load effect from a set of variable loads can be evaluated by taking one of the variable loads at its expected maximum (the 1.45 times Q) plus the arbitrary point in time value for all the other variable load, then repeating the exercise by rotating through the variable loads, with each one being in the Q position once . . . this know as Turkstra's rule. It is much simpler than evaluating the total probability of joint occurence of variable loads.

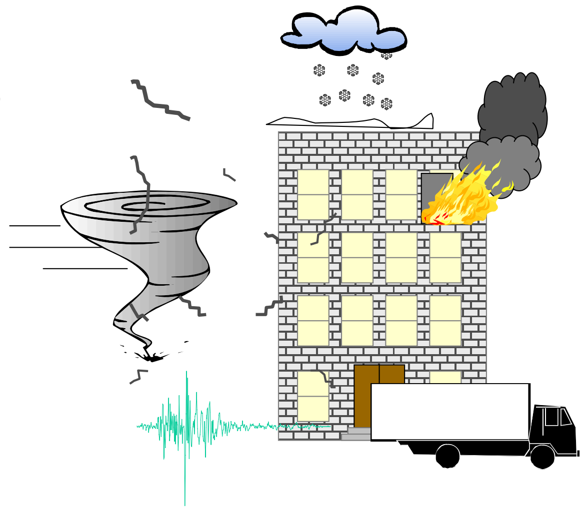
"Partial vs. Pure Performance"

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

How safe is safe enough defined by either a probability of failure less than 0.001 per year or by a factored strength exceeding a factored load? The probability is not computed directly in the factored load approach. Direct computation of probability of failure in practice is difficult due to a lack of statistical information. Probabilistic approaches are good tools for consensus committees to evaluate the "how safe" question. When it is used on an individual project, a peer review team is suggested.

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



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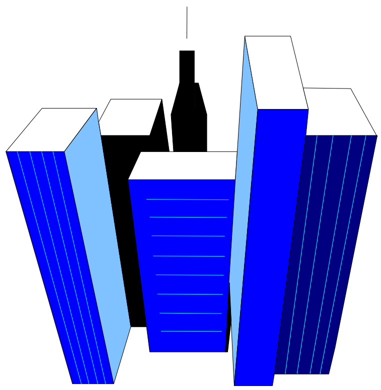
This is not meant to imply that a building designed under performance concepts for one hazard needs to be designed under performance concepts for all hazards, only that design must consider at least all these hazards.

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

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This could be rephrased as (1) protect public safety and health and (2) provide functional serviceability. Of course there are other societal goals, such as:

1. Controlling the economic impact of large scale natural disasters,
2. Reducing barriers to the disabled, and
3. Avoiding the uncontrolled release of toxic materials.

… 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

Structural provisions of building codes tend to be a mix of prescriptive rules for construction (for “conventional” wood framing) and detailed procedures for structural analysis and design.

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.

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Such refinement in procedure can lead to the situation that Alexis de Tocqueville described as a characteristic of China in his book *Democracy in America*. Paraphrasing:

The nation was absorbed in productive industry, but science itself no longer existed, which led to a strange immobility in the minds of the people. The Chinese followed in the track of their forefathers, but had forgotten the reasons by which the latter had been guided. They still used the formula without asking for its meaning. They lost the power of change...

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

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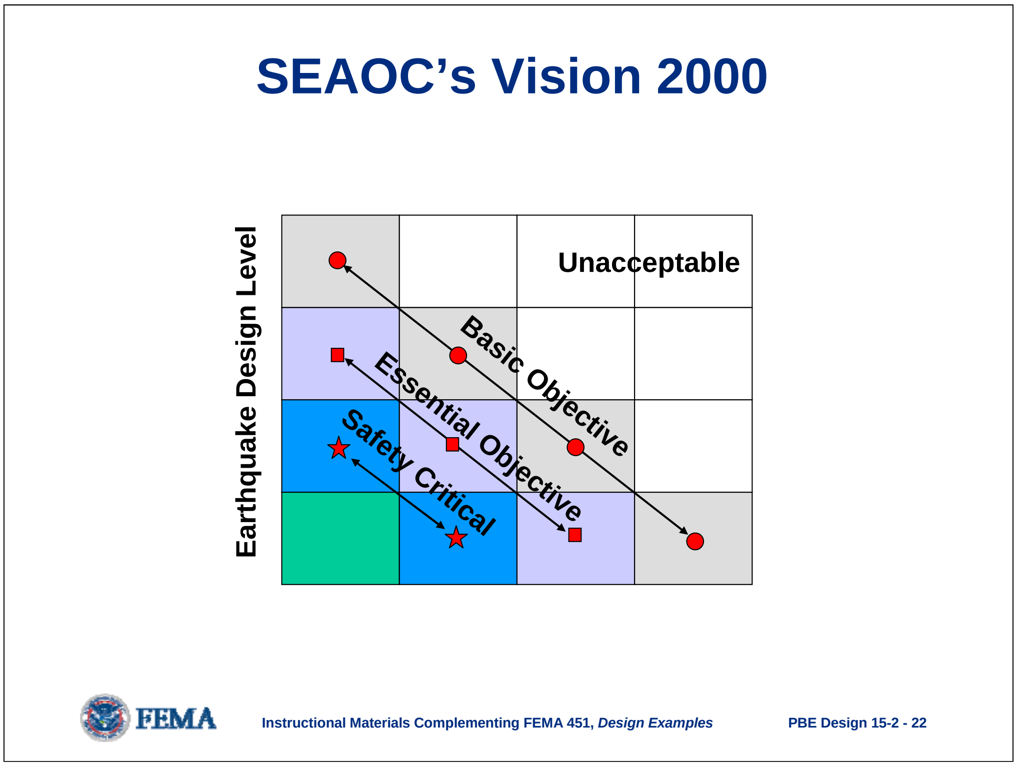
The understanding does not come easy. Our educational system for structural engineers does not deliver it, and it is not developed naturally in practice. Tools to predict performance, assuming significant inelastic response in a dynamic event, are in their infancy.



Horizontal axis: performance degrades step by step to the right.

Vertical axis: size of earthquake increases as you step down.

This is a refinement of the commentary to the old SEAOC *Blue Book*. A building designed according to the recommendations will be expected to survive minor earthquakes with little, if any, damage; moderate earthquakes with some nonstructural and structural damage; and major earthquakes with significant damage. *(This is a paraphrase, not a quote.)*

Motivation for PBE (Structural)

A modern garage at Cal State Northridge.

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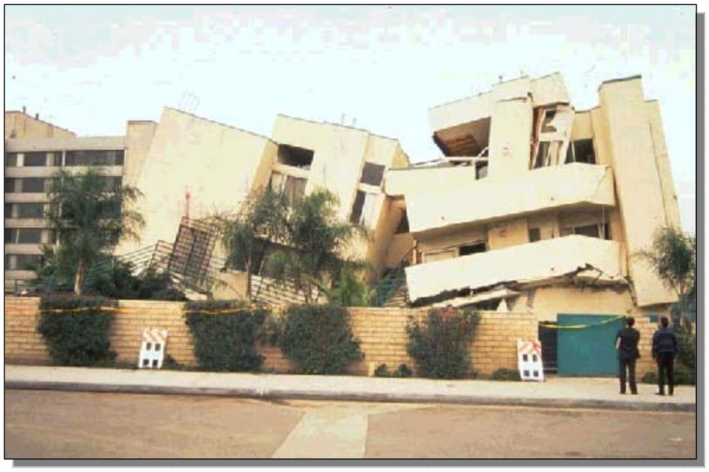
The structure collapsed in an earthquake that would not be considered to be as large as appropriate for structural collapse (i.e., less than the *NEHRP Recommended Provisions* MCE earthquake ground motion). The gravity load system included precast columns on a grid of about 18 ft by 50 ft with corbels that supported precast prestressed rectangular beams that, in turn, supported a cast-in-place post-tensioned slab. The lateral system included the slab as a diaphragm and the exterior "special" moment frames of concrete. The interior columns failed, probably due to shear generated by drifts large enough to cause the interior beams and columns to act as a frame. The exterior frame demonstrates that concrete can indeed exhibit ductility.

Motivation for PBE (Structural)



A modern wood-frame residential building on Sherman Way.

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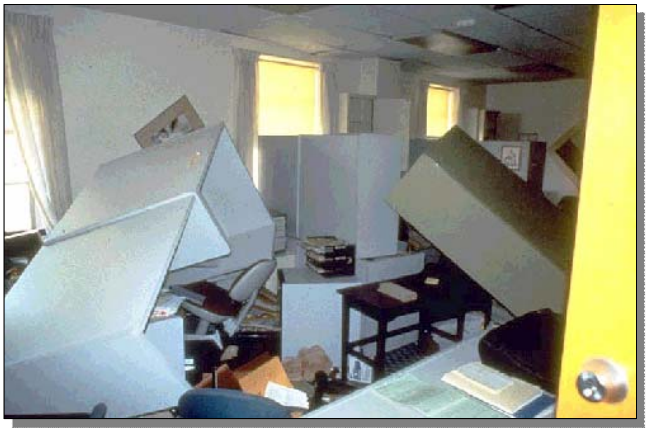
The Northridge earthquake -- parking below lacked enough braced walls.

Motivation for PBE (Nonstructural)



Veterans Administration Medical Center in Sepulveda.

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Nonstructural damage required the facility to close temporarily.

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.

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Code conforming designs have wide variations in real performance, particularly in terms of economic damage.

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

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Examples of performance and event levels combined for a building with "ordinary" occupancies:

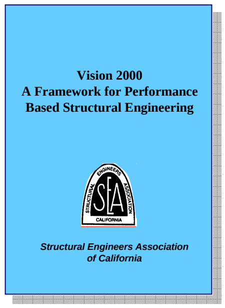
• No collapse in maximum considered ground motion (2500 year MRI)

• Life safe performance (no falling hazards) in design ground motion (500 year MRI)

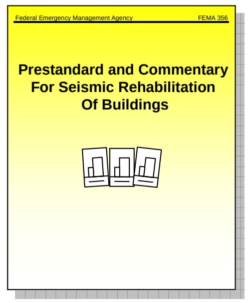
Another example could be immediate reoccupancy for an "essential facility" in the design ground motion.

The detailed local acceptance criteria indicate element-by-element checking, rather than an overall system *R* factor such as is used in the conventional design of new buildings.

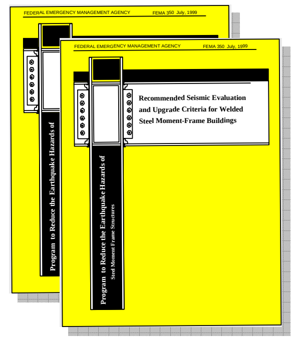
Basic Resource Documents
Performance-based Seismic Design



Vision 2000
(new buildings)

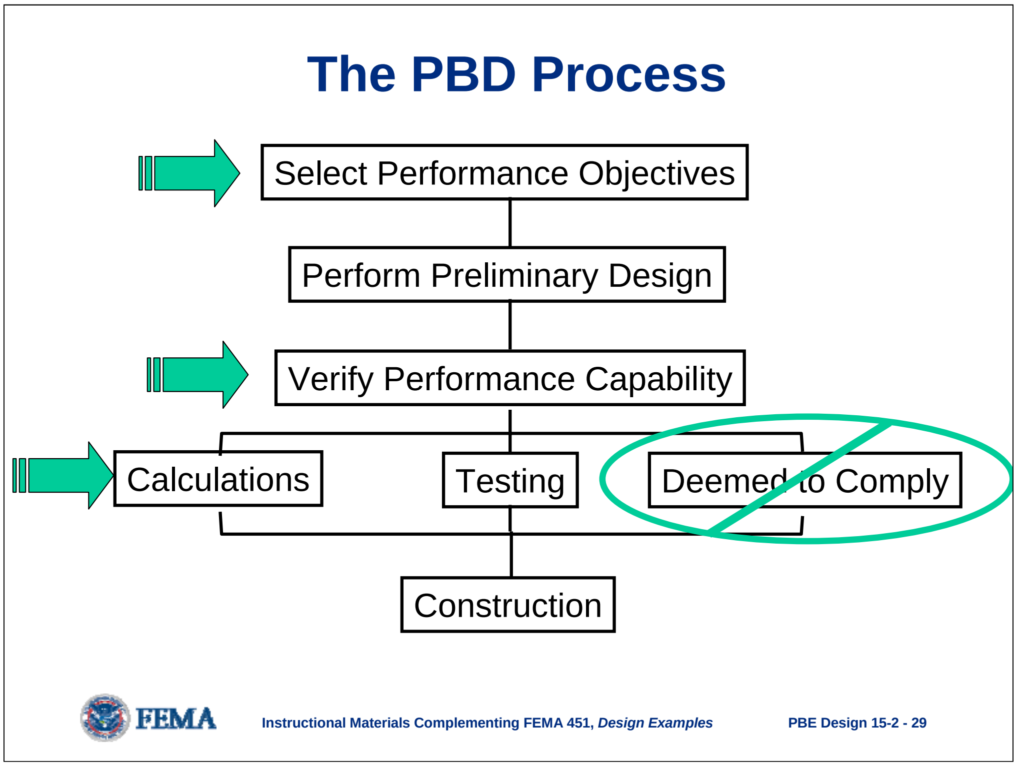


FEMA 356
(existing buildings)



FEMA 350/351
(steel moment frame buildings)

Vision 2000 was written by 1995. It set forth a form that recognized that different levels of performance are necessary for different types of buildings, especially where control of economic loss was necessary. The next step was FEMA 273 for the rehabilitation of existing buildings; FEMA 356 is the second edition of this document. The high expense of rehabilitation of existing buildings drove a need for increased economy. The SAC project developed a significant improvement in quantitative prediction of performance.



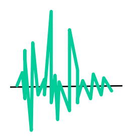
The focus in this topic is on analytical methods to predict/verify performance.

Vision 2000 / FEMA 356 Performance Objectives

Specification of:

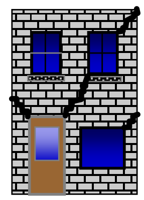
- ***Design Hazard (earthquake ground shaking)***
- ***Acceptable Performance Level (maximum acceptable damage given that shaking occurs)***

Performance Objective =



Ground Motion
x% - 50 years

\+



Performance Level

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The basic statement is essentially deterministic: given a certain level of ground motion (generally selected on a probabilistic basis), then a certain deterministic performance level was to be achieved.

Performance Objectives

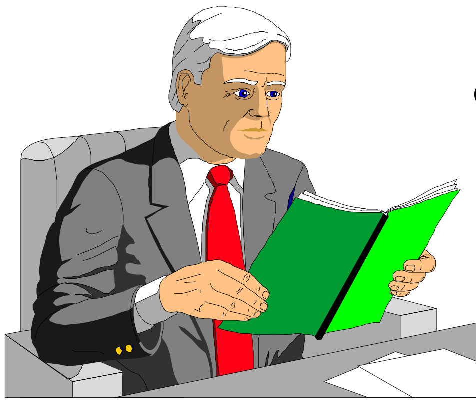
- For performance-based design to be successful, the needs of both the client and engineer must be satisfied.

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

Engineers are most comfortable with quantitative decision making. Some clients will be comfortable with quantified probabilities, others will not. Many people will want deterministic assurance. This is a communications minefield.

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

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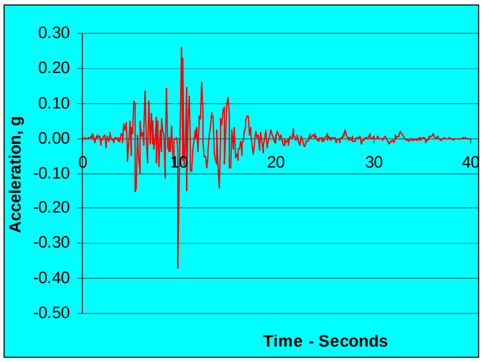
Nonengineers will not necessarily be satisfied with the conventional quantities of engineering decision making

Hazard

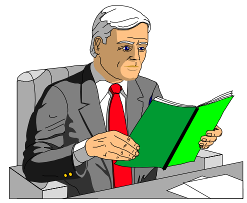


The intensity and characteristics of ground shaking that design is developed to resist.

Topics 15-3 and 15-4 focus on selection of appropriate descriptions of the ground shaking hazard.

Hazard

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



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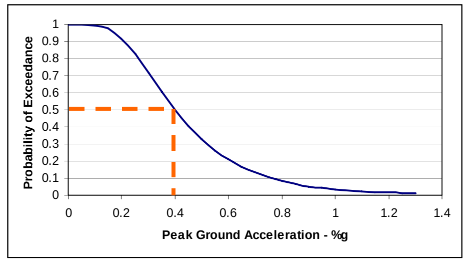
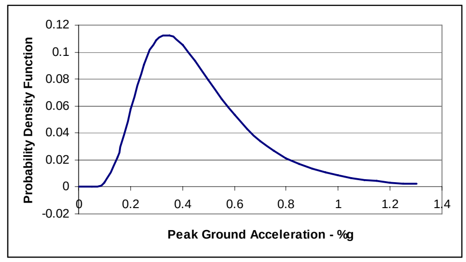
Nonengineers may think they understand a lot when “magnitude” is used, but engineers must be careful for it will not be clear just what the nonengineers actually perceive about magnitude. Attenuation and site effects are certainly not well understood.

Deterministic Hazards

- Easy to understand but . . .

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





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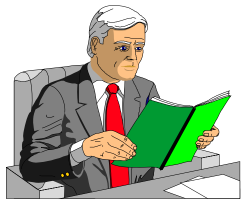
Median probability on the upper graph is mode of the lognormal distribution.

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.

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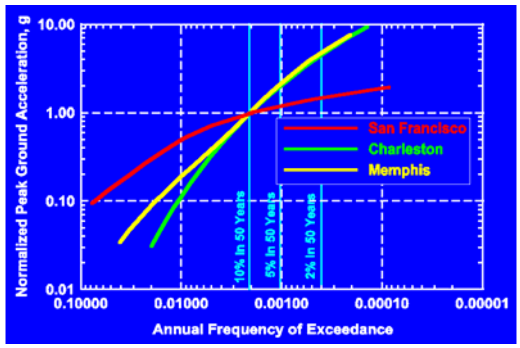
Client may be more amenable to probabilistic estimates than engineers imagine.

Probabilistic Hazards

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



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Note that the curves on this chart are normalized to a design point at a 10% probability of exceedance in 50 years. The significance is that the actual peak ground acceleration at the design point is not 1.0g for any of the three locations. It is accurate that the ground motions at more remote probabilities are a larger multiple of the design point for Memphis than for San Francisco. In fact the predicted ground motions in Memphis do exceed those for San Francisco, but the annual frequency of occurrence at which this occurs is between 0.001 and 0.0001.

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.

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Note that appropriately round numbers are used here for the mean return interval. Engineers have a bad habit of going to extreme precision.

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.

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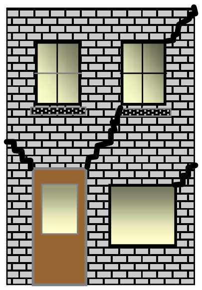
The first, third, and fourth lines have been used or advocated for various purposes. The 20% in 50 years has not been used much. Note the unjustified precision in MRI, which is a direct computation based on the Poisson assumption of earthquake occurrence.

Performance Level



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

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Engineers are not well trained to think of damage levels; our education focuses on computation of specific strength limit states that are usually idealized states (e.g., the plastic moment capacity of a steel beam or the maximum bending moment capacity of a concrete beam) without much focus on the formation of buckles in beam flanges or cracks in the concrete beam let alone on how badly cracked a masonry façade will be when the structural drift goes to a certain level.

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.

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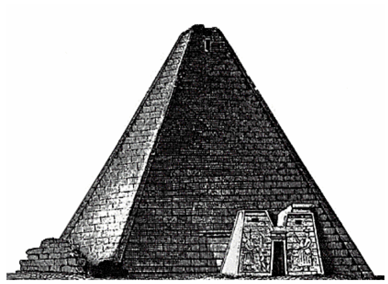
The ICC Performance Code follows the tradition from the earlier work on general structural performance. Much of it focuses on design for fire safety. The following slides briefly review the general structure and the structural performance criteria.

ICC Performance Code

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



The concept is that societal needs change less rapidly than technological solutions. Some recent trends, such as the Americans with Disabilities Act and mandated energy conservation, belie that notion.

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….”

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The purpose is an overriding performance requirement.

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

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Procedures for verification are more important for innovative design. The dots at the bottom indicate that there are more administrative functional statements than shown here.

ICC Administrative Provisions

"Performance" requirements

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

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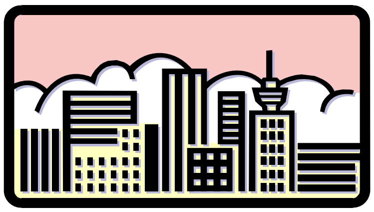
Owners may be obligated to maintain new technologies. Although much of this is aimed at fire prevention and control, there are also structural technologies that could require maintenance over the life of the structure (e.g., some types of dampers and isolators). As technologies become more sophisticated, more division of expertise is natural.

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

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Different hazards could logically result in different occupancy classes.

ICC Performance Groups

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

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This classification is very similar to that in ASCE 7

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

FEMA

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"Severe" means that the performance level accepts severe damage. Damage levels are explained more on following slides; size of event will also be discussed in more detail. Ordinary buildings are Group II.

Mild Damage Level

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

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ICC's definition of structural performance levels.

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

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Hazmat is shorthand for release of 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

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This damage level is close to the safety limit state for conventional probabilistic load and resistance factor design.

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

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This is the current basis for earthquake-resistant design under the “maximum considered earthquake ground motion.”

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

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MRI = mean recurrence interval.

SS = site-specific study (note that the values for flood loads in the final draft are in black whereas the values in the actual published document are in red.

The values for wind and snow are really not consistent with existing practice and should not be used in the opinion of the author.

The values for earthquake are 72 = 50% in 50 years; 475 = 10% in 50 years; 2475 = 2% in 50 years.

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

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The appendices are a key feature of the document. In addition, there is a "Users Guide," which is very much like a commentary – very few model codes include a commentary but the guidance is needed here.

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

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Repeat of the table of contents for this topic. The remainder of the presentation will focus more specifically on earthquake engineering.

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

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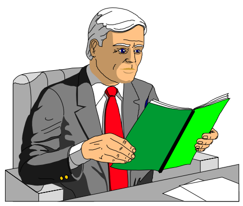
This has been alluded to previously but is emphasized here.

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?

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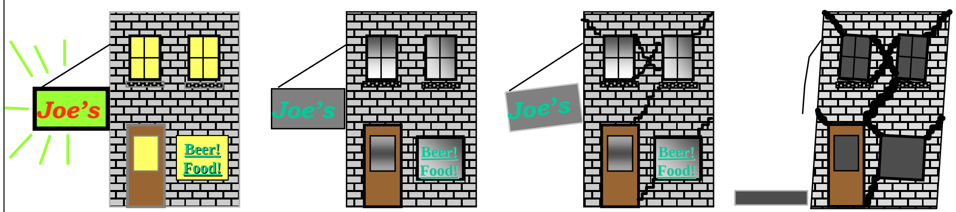
Notice the contrast in issues and values for decision making.

“Standard” Structural Performance Levels

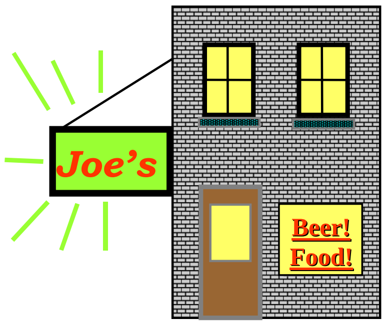


Operational | *Immediate Occupancy* | *Life Safety* | *Collapse Prevention*

0% — *Damage or Loss* — 99%

These four categories are the currently favored standard levels; each will be described in more detail.

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

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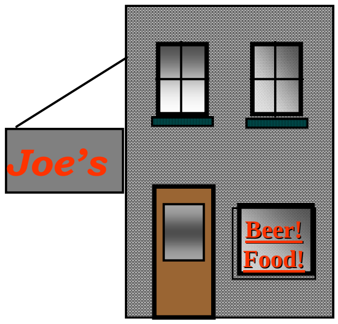
You can walk in immediately after the earthquake with no perceptible concern for structural safety or for any incipient collapse hazards; there is electric power for lights and to keep the beer cold; there is water to prepare food and gas to cook it, and the sewer system functions to carry away waste. For an office building, communications systems will be in order. The losses will probably be even smaller than 5% and will be mostly confined to fragile contents. Note that many of the key issues here are out of the design control of the structural engineer, specifically the functioning of the external utility systems.

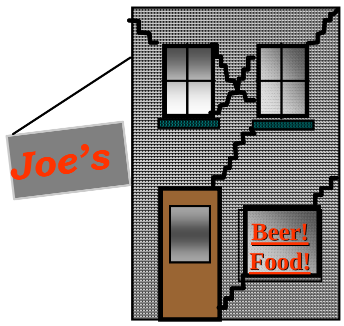
Immediate Occupancy Level



- 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%

The primary difference between operational and immediate (re)occupancy is the performance of external utility systems. In other words, the structural performance is essentially the same. This is a "green tag" building.

Life Safety Level



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

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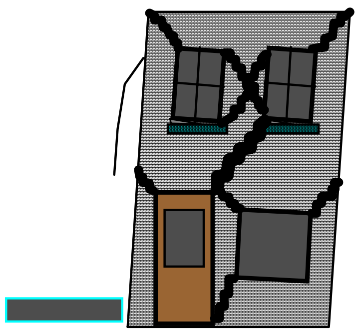
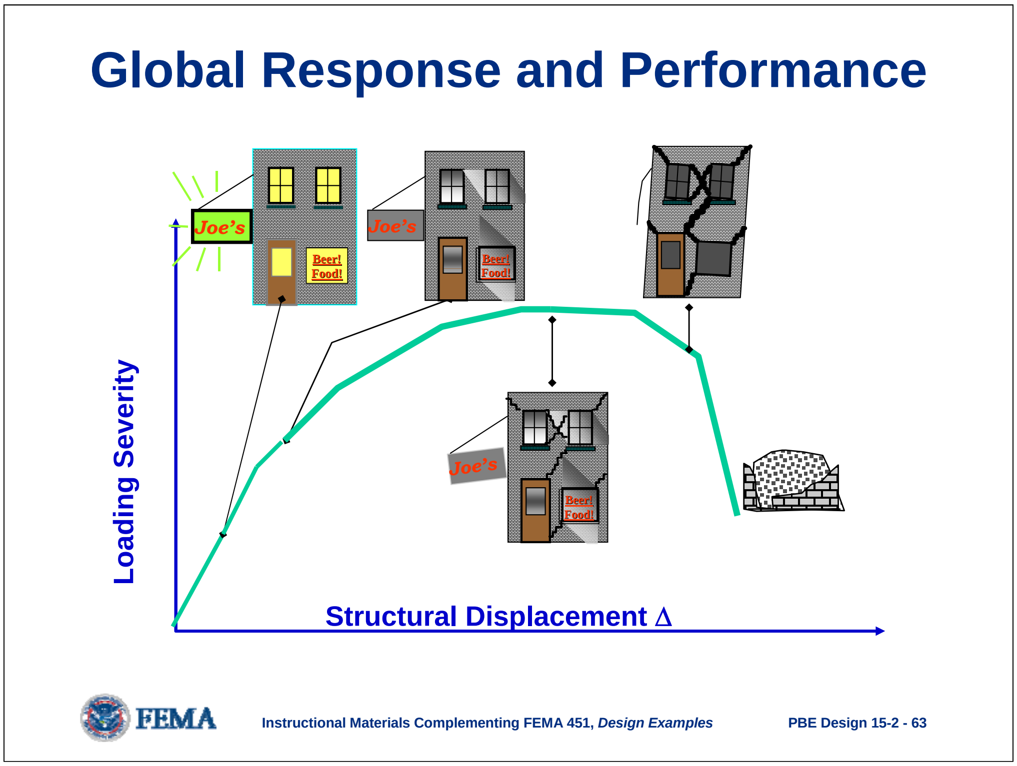
In conventional jargon, this is a “yellow tag” building. It is not a given that the utilities would not function. The key issue here is that the structural safety, or perhaps life safety provided by necessary nonstructural systems, is compromised.

Collapse Prevention Level

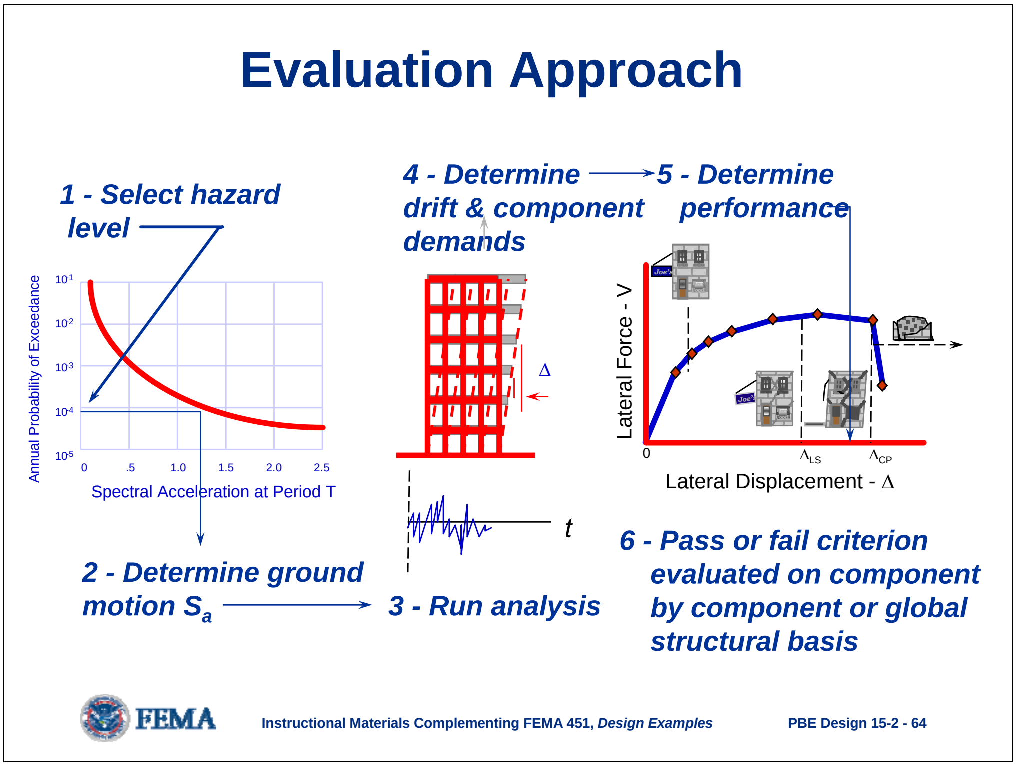


- Extensive (near complete) structural and nonstructural damage
- Significant potential for injury but not wide scale loss of life
- Extended loss of use
- Repair may not be practical
- Loss >> 30%

This near collapse limit state is perhaps more meaningful on a philosophical basis. Accurate prediction of this level of performance is most difficult.



The load *v* displacement curve should not be thought of simply as a monotonic loading process. The earthquake is a dynamic event with several cycles of large displacement.



Note that this procedure does not address performance of external utilities, which means that it cannot deliver any assurance of operational performance.

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.

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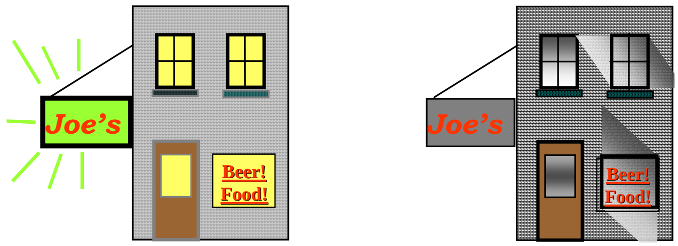
Suggested answers come in following slides; they may not be intuitive.

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

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If you want to limit structural performance to near linear behavior, then linear analysis is adequate and economical.

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

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The great irony: Low budget structures are designed for more damage, which, in reality, should require the most sophisticated, demanding, and expensive engineering design. Dream on!

Judging Performance Acceptability

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

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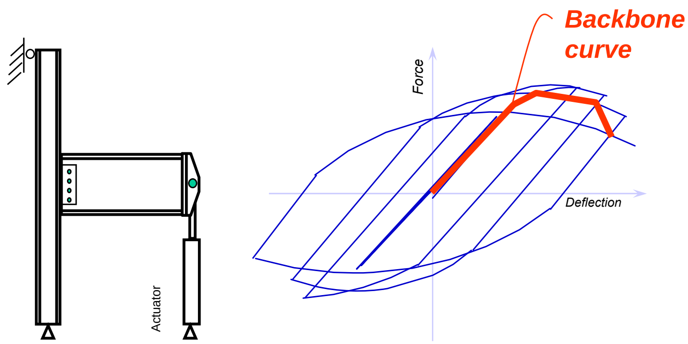
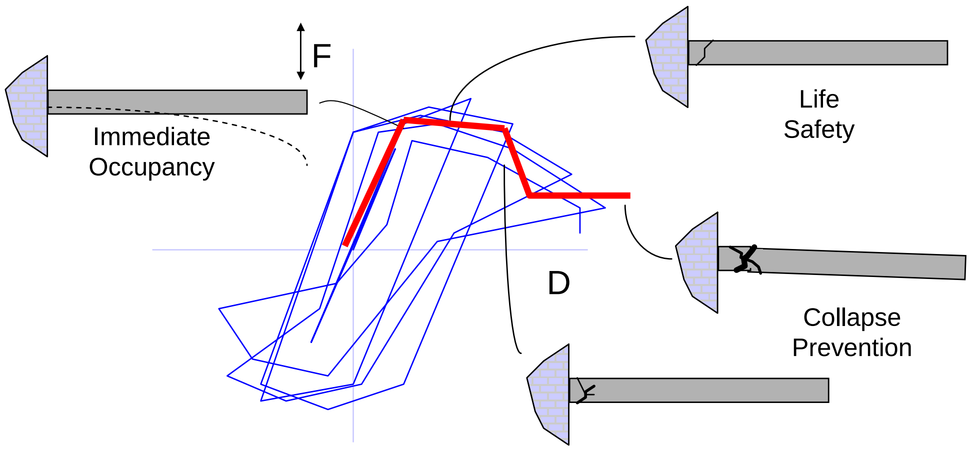
Nonstructural criteria can be added and are necessary for the higher performance levels.

Local Response and Performance



The second cycle backbone curve is taken as a standard technique to capture some aspect of stability in response. There are elements and components where it could be questioned, but the acceptance criteria typically account for strongly degrading behavior with lower limits on ductility.

Local (Component-based) Acceptance Criteria



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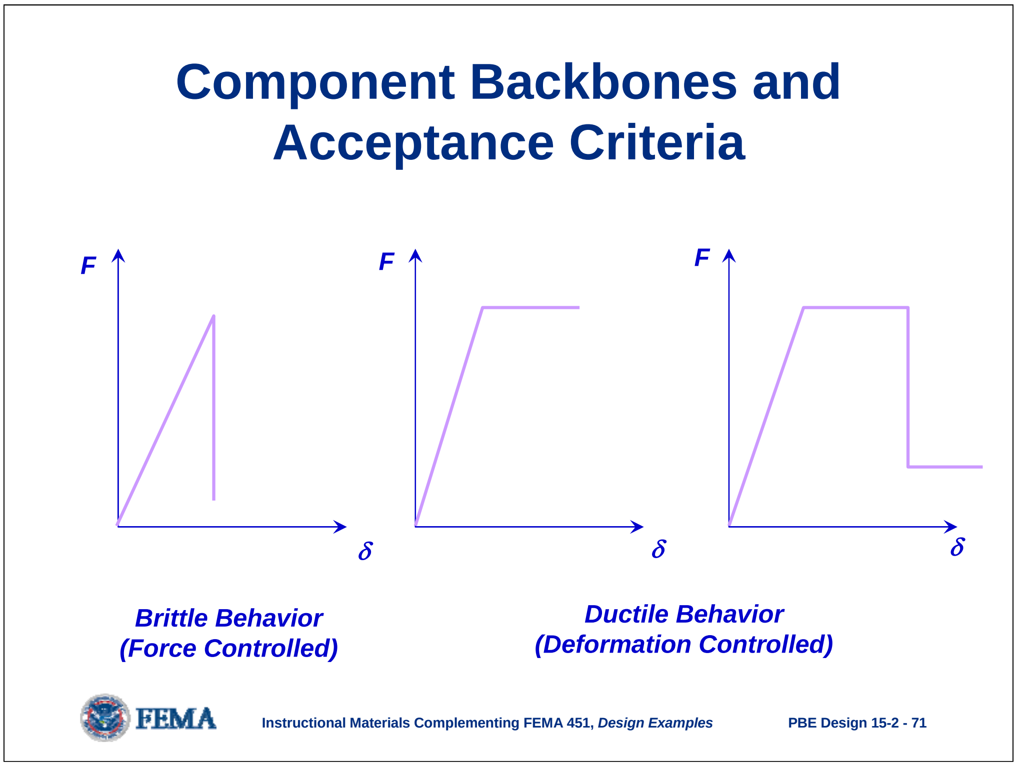
Criteria in recent performance documents, such as the SAC FEMA 350 report, are actually based on specific actions of components (flexure at member end, joint shear, etc).



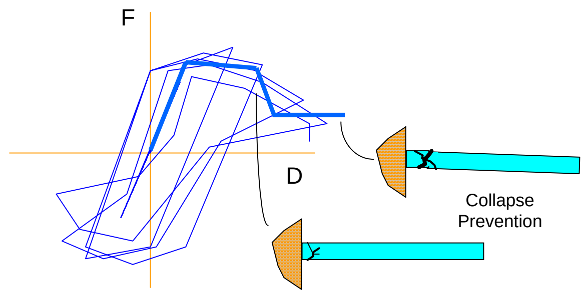
A key distinction is that components that exhibit brittle or near brittle behavior are governed by strength requirements whereas ductile behavior is checked on displacement/ductility (although force is a surrogate for displacement in some methods).

Classification as a ductile component (or action) generally requires that maximum displacement (without substantial loss of resistance) must exceed twice the effective yield displacement.

The plot at the right shows a region of strength degradation; the vertical transition is arbitrary and may need to be altered for analytical stability.

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.



For immediate occupancy this is not a significant disadvantage. For collapse prevention, this disadvantage is very important; some elements can be essentially destroyed while a structure maintains stability.

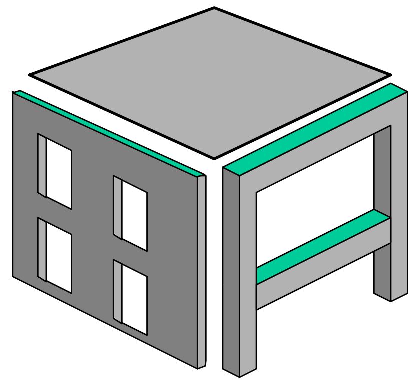
Building Configuration

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

This terminology is not general -- i.e., it is not a dictionary definition. It has been used for the past few years, since the development of FEMA 273, in earthquake engineering.

Elements

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



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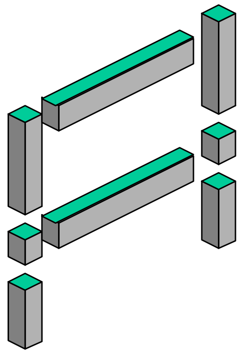
By this terminology, elements may contain many components.

Components

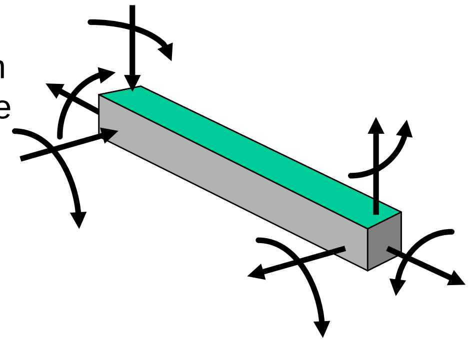


- Individual members that comprise an element:
  - Beam
  - Column
  - Joint
  - Brace
  - Pier
  - Footing
  - Damper

For shear walls, coupling beams, wall piers, etc, would be components.

Actions

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



These are the most frequently used quantities for local acceptance criteria.

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.

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This concept was developed in FEMA 273, driven by the need for realistic and economical design of strengthening of deficient existing buildings.

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.

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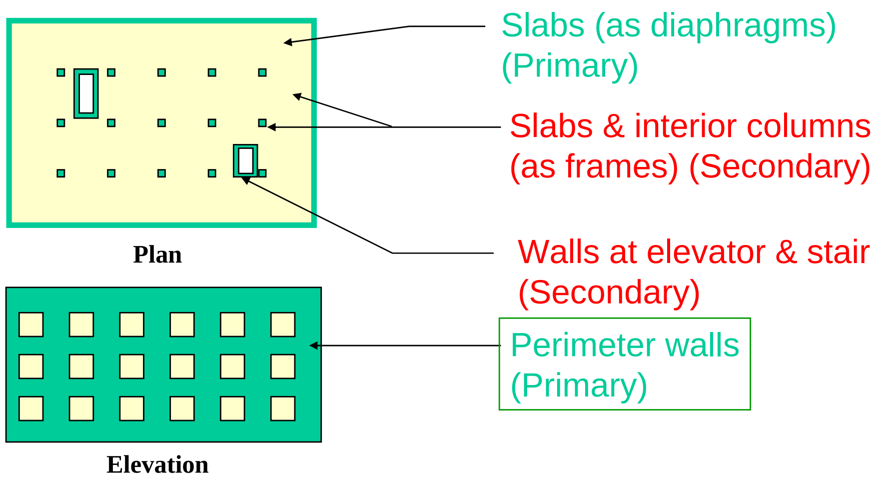
Note that secondary elements do not have to be ductile; they may be brittle. So long as their failure does not result in collapse of some portion of a building (gravity load carrying capability) and the remaining elements continue to provide adequate capacity for lateral loads, an element may be considered secondary.

Primary & Secondary



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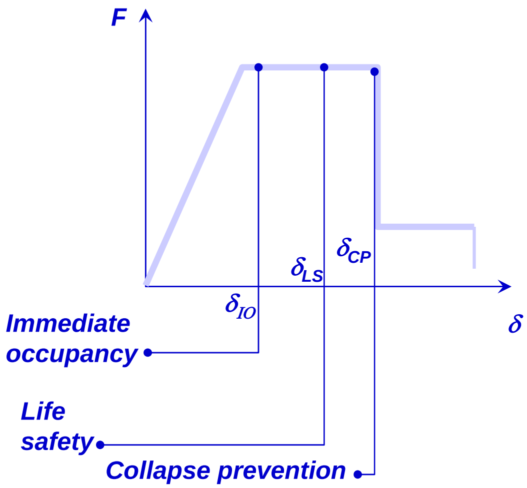
Note that the slab-column frame is primary for gravity load but not for lateral load.

Performance Evaluation Primary Components



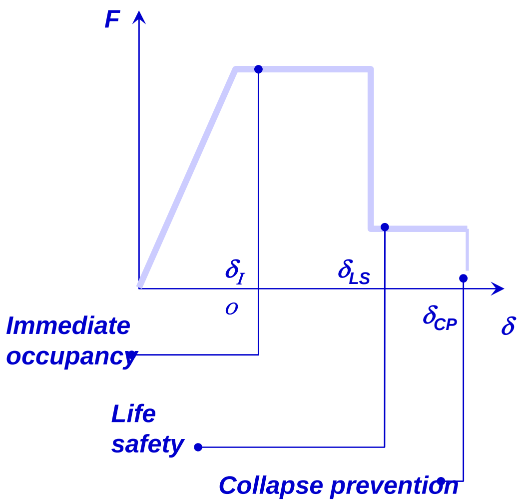
δ_{IO} - based on appearance of damage

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

δ_{LS} - 75 % δ_{CP}

The force versus displacement relation shown is very generalized. The maximum displacement for collapse prevention is usually defined as that displacement where resistance (*F*) falls below some fraction (say 75%) of the maximum resistance..

Performance Evaluation
Secondary Components



δ_{IO} - based on appearance of damage

δ_{CP} - based on complete failure of element

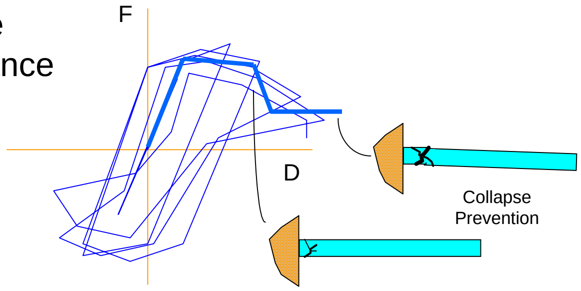
δ_{LS} - 75% δ_{CP}

Note that collapse prevention is essentially the loss of all capacity for secondary components, which is a much larger displacement than allowed for primary components.

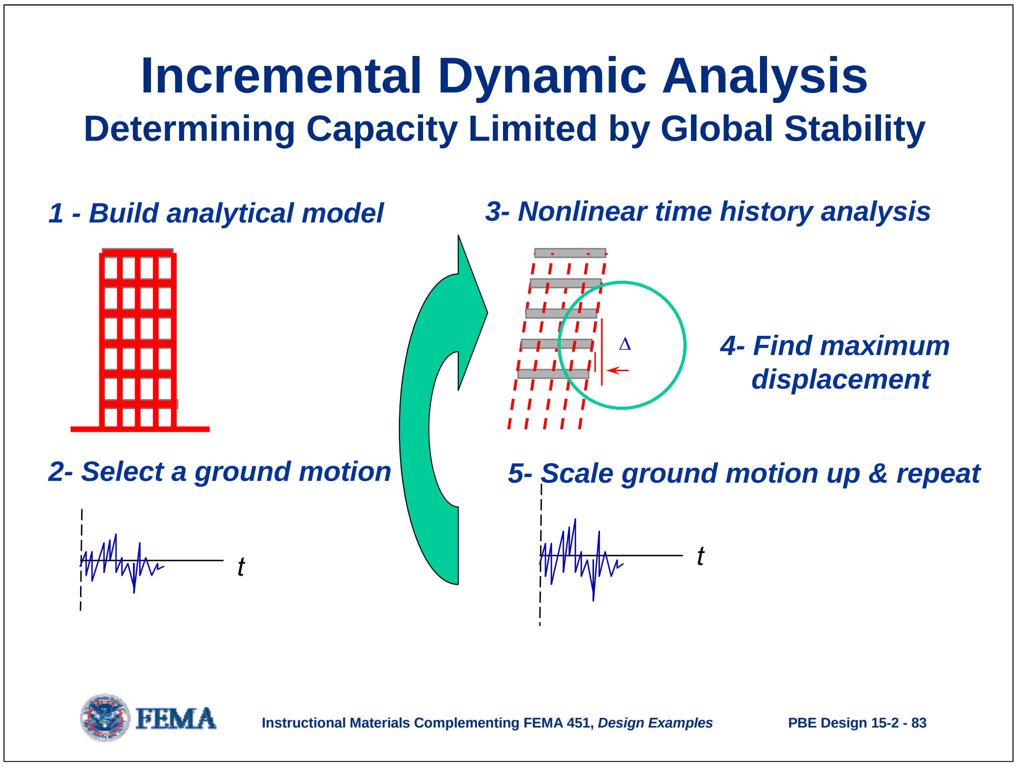
Also note that immediate occupancy is unchanged from primary components. For this performance level, the perception of damage is important.

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



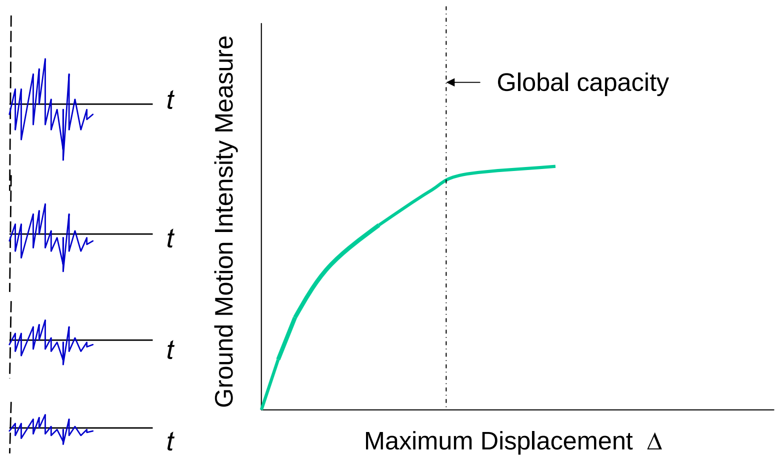
The introduction of the primary/secondary distinction removes the primary disadvantage of local criteria.



This dynamic analysis requires reliable component action resistance/displacement relations. When it has that, and other reasonably accurate modeling criteria are satisfied, this becomes a tool for checking global stability. It is a relatively new concept, and to date has shown some surprising results

Incremental Dynamic Analysis

Determining Capacity Limited by Global Stability



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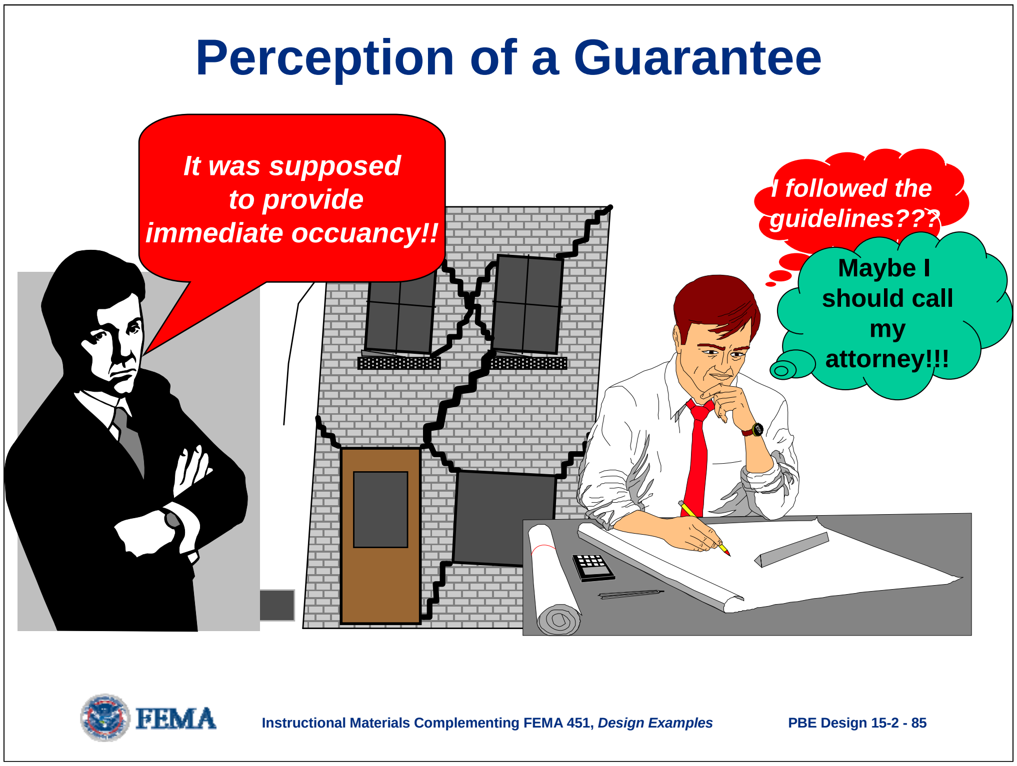
In this example, the same ground motion is repeatedly applied, simply scaling the amplitude up in each successive step. Here the response is relatively uniform, and the global capacity is relatively obvious. This nice result is not always obtained.



The best practice is followed, an earthquake occurs, and the client/owner is unhappy about the performance.

Engineers have long talked about “earthquake *resistant* construction”, and the public has usually heard “earthquake *proof* construction.” This goes back to the communication problem discussed earlier. Performance based earthquake engineering encourages more effective communication. This by no means solves all the problems associated with perception of a guarantee, but it can help

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.

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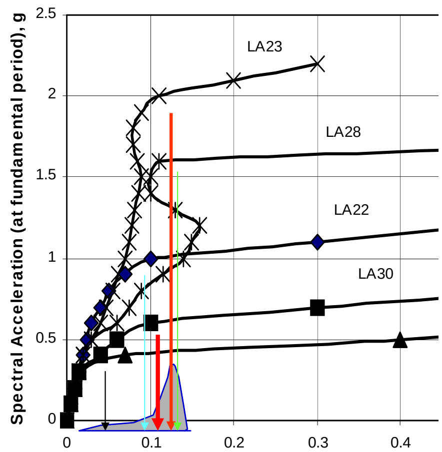
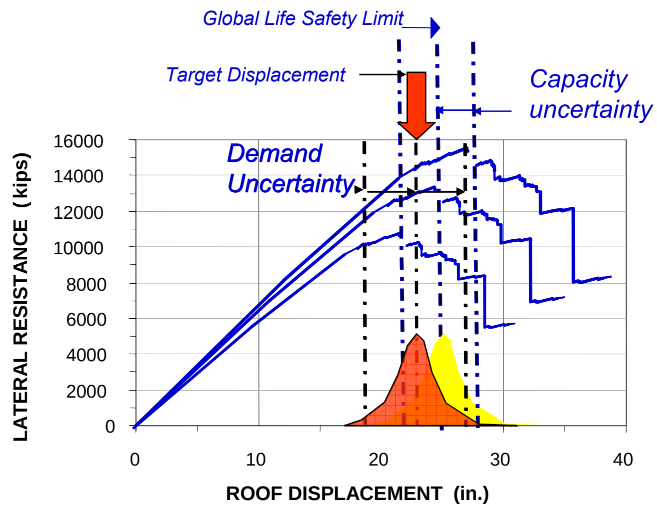
The amount of uncertainty about earthquake ground motion, dynamic response, and especially inelastic response is very large compared to most of the structural engineering design problems.

Ground Motion and Capacity are Uncertain and Variable



This shows the results of incremental dynamic analyses on one system subjected to several different ground motions. Clearly there will not be one unique displacement; there is scatter in the results

Capacity, Demand, and Performance Prediction



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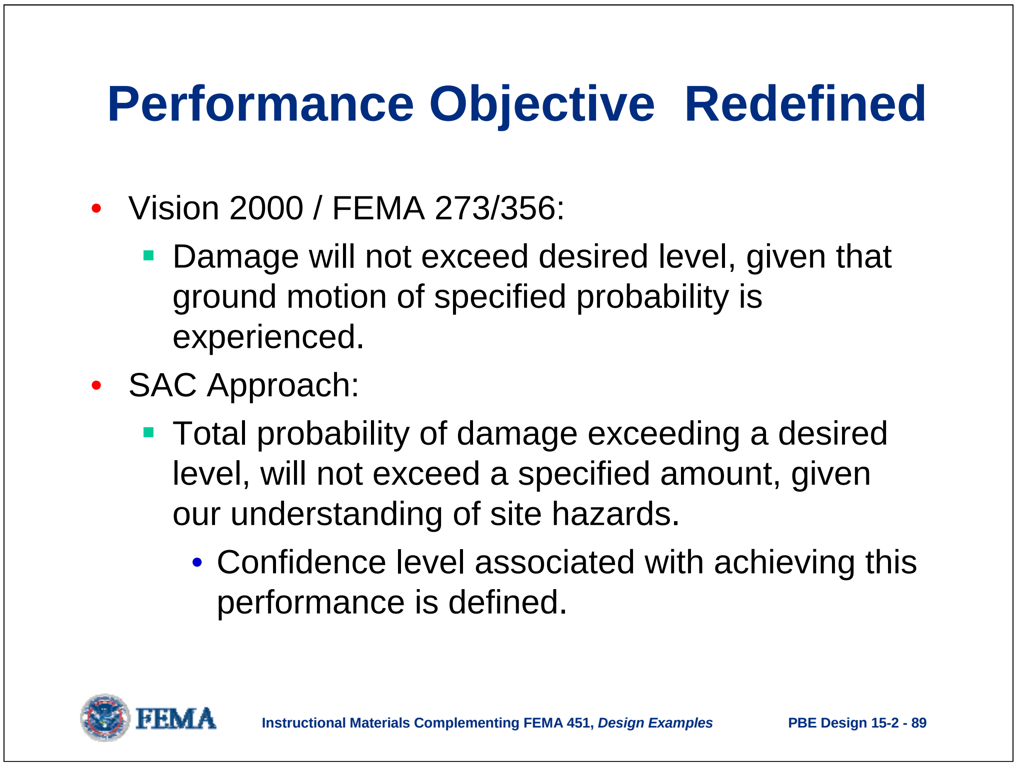
The resistance/displacement relation is not certain, the ground motion is uncertain, therefore the demand is uncertain. The capacity is uncertain. In this example the median capacity exceeds the median demand. However, capacity uncertainty in yellow and demand uncertainty in pink have substantial overlap, therefore there is uncertainty about whether the limit will be met.



The FEMA 273 approach appears relatively deterministic to the user, with the exception that capacity reduction factors can vary with the degree of knowledge about the resistance.

SAC extended the degree of consideration of variability in two significant ways: factors to account for uncertainty in demand are explicitly selected, depending on several parameters, and the confidence level of meeting a criterion is computed.

Performance Objectives Redefined

highly
I am moderately confident
not very

that there is less than x% chance in 50 years

that damage will be worse than
Immediate occupancy
Collapse prevention

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How confident is confident enough? -- Similar to how safe is safe enough? However some quantification is much better than none at all, plus it gets rid of the perception of a guarantee.

The “x% in 50 years” is the selected hazard probability level.

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

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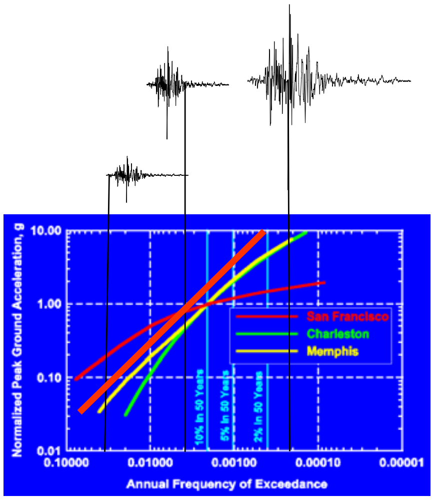
Within the integral is the probability that demand exceeds capacity given a certain ground motion, to be integrated over the probability of occurrence of the ground motion

Note that b is the slope of the demand vs ground motion relation at the level of interest

More detail on following slides

Hazard Level and Load Severity

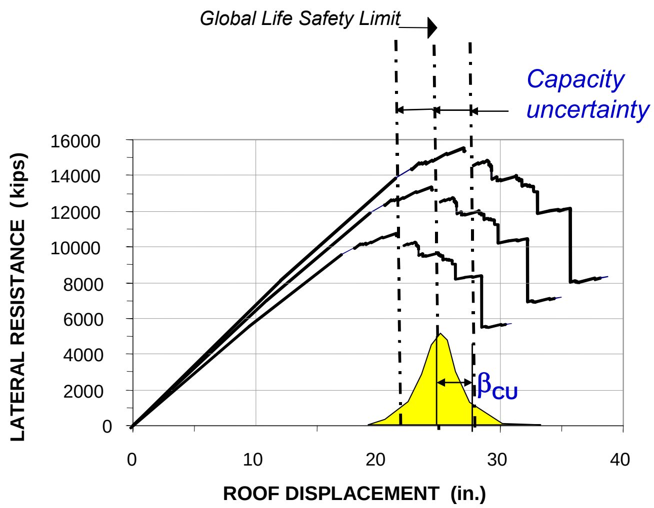


- Minor earthquakes occur frequently.
- Moderate earthquakes occur occasionally.
- Major earthquakes occur rarely.

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

This chart shows the hazard level vs frequency of occurrence normalized to a design point a 10% in 50 years. The parameter k, used in following slides, is the slope at the design point. It does not capture variations in shape of the total curve, but it does capture the variations in slope, which can be substantial

Uncertainty in Capacity b_{CU}



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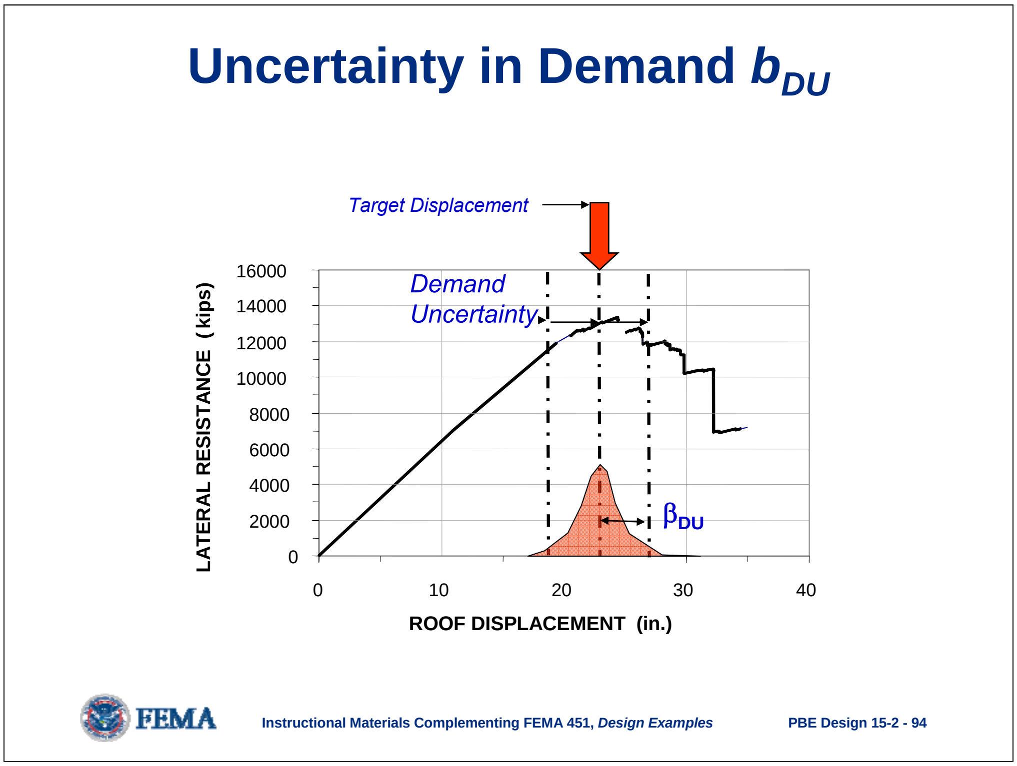
For this example the capacity limit is taken at essentially the beginning of nonlinear behavior, which happens to be the beginning of capacity degradation for this system. Beta is a measure of the scatter about the mean capacity limit



Uncertainty in demand can come from uncertainty in ground motion, uncertainty in dynamic response, and uncertainty in analytical prediction

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

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

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

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In the SAC approach two “load” factors (gammas) are used, along with one resistance factor.

All factors depend on the ratio of two slopes: k being the slope of the hazard curve, b being the slope of the demand vs ground motion level relation; both evaluated at the design point (tangent, not secant)

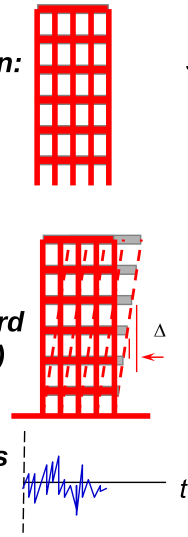
Gamma depends on the variability inherent in the prediction of demand (incorporates scatter in response of real structures to real ground motion)

Gamma-sub-a depends on the bias and variability introduced by structural analysis, and varies with the method

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.*

$$\gamma \gamma_a D$$

In FEMA 350 gamma factors vary with the performance level, the type of moment frame connection, and the height of the building, and gamma-sub-a factors vary with these three factors plus the type of analysis procedure used

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

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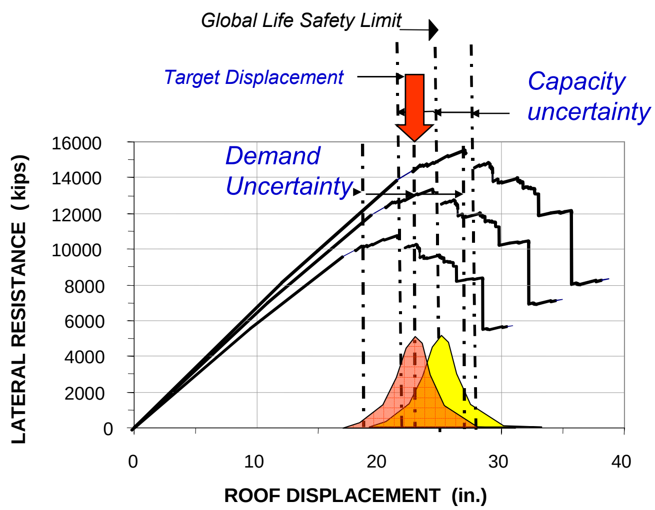
Capacities (C) and resistance factors phi are specified for various types of connection details.

The lambda values shown are approximate for an uncertainty level in demand and capacity on the order of 30 to 40%

Low Confidence $\lambda > 1$



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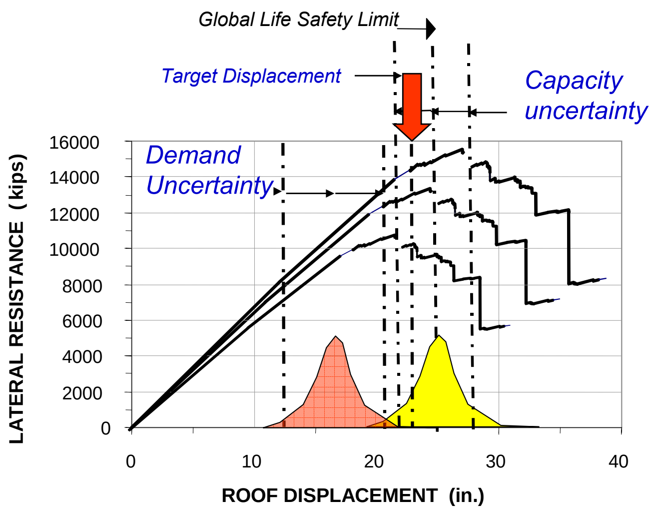
Note significant overlap of demand and capacity

High Confidence λ < 1



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Very little overlap of demand and capacity. If the uncertainties were very small, then the ratio of demand to capacity would only need to be slightly less than 1.0 for high confidence. We have large amount of uncertainty, therefore the ratio must be less than 1.0 for reasonable high confidence.

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.

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At this time, the approach for steel moment frames is relatively complex. The profession certainly does not understand it well. Thus, further development is appropriate, is underway, and changes should be expected.

The amount of work to develop the quantitative values for other systems will be expensive and time consuming.