Overview of seismic design philosophies

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Presentation outline

- Historical Background of Seismic Design Philosophy
- Capacity Design Philosophy
  - Illustrative analogy
  - Choice of plastic hinge mechanism
  - Major steps in capacity design
- Performance Based Design Philosophy
  - Current seismic design and PBSD
  - Pushover Analysis
  - Hazard and Performance levels
- Displacement Based Design Philosophy
  - Problems with force based design
  - Displacement based design procedures

Historical back ground of seismic design philosophy

- 1755 Lisbon devastating earthquake resulted in prescriptive rules for building certain kinds of buildings common in the area
- Events in Messina, Italy (1911), and Kanto Japan (1923) led to guidelines for engineers to design buildings for horizontal forces of about 10% of the weight of the building.
- 1906 San Francisco, interestingly, produced little or no code development in the USA.
- 1925 Santa Barbara convinces critical mass in California on the need for seismic requirements
- 1927 First seismic regulations as voluntary appendix in UBC 1927
- 1933 Long Beach results in CA legislature passing the Field Act (for schools) and the Riley Act (for all buildings).
- Code under constant evolution since 1927, with changes often instigated by earthquakes in CA.

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San Francisco EQ, 1906

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Santa Barbara EQ, 1925

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Historical back ground of seismic design philosophy

Target of the first seismic design codes

- Prevent collapse
- Prevent heavy materials falling to street
- Size or rareness of earthquake not specified—and probably not understood. References are to "earthquake loading"
- <u>Introduction to 1927 UBC Lateral Bracing Appendix</u>

  "The design of buildings for earthquake shocks is a moot question but the following provisions will provide adequate additional strength when applied in the design of buildings or structures."

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Historical back ground of seismic design philosophy

- Before 1960s there is no specified procedure for seismic design but they adopted design for lateral forces corresponding to about 10% of the building weight.
- ***Strength design philosophy:*** it was introduced during 1960s, and become dominant. It allows the building to act elastically during earthquake.
- ***Capacity design philosophy:*** It was introduced after an advanced understanding on responses of structure to seismic load. It allows the design of the structure in strength hierarchy of the members with respect to plastic hinge formation.
- ***Performance based design philosophy:*** The members are designed in accordance with their performance during seismic action.
- ***Displacement based design philosophy:*** structures should be designed to achieve a specified performance level, defined by drift limits, under a specified level of seismic intensity

Capacity Design Philosophy

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Capacity Design Philosophy

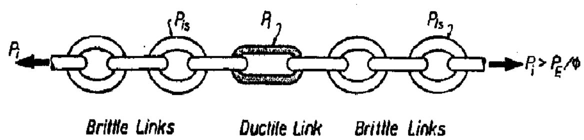
- It is a design method in which elements of the structural system are chosen, suitably designed and detailed for energy dissipation under severe deformations while all other structural elements are provided with sufficient over strength so that the chosen means of energy dissipation can be maintained.
- The critical regions of these members, often termed as ***plastic hinges***, are detailed for inelastic flexural action, and shear failure is inhibited by a suitable strength differential.
- All other structural elements are then protected against actions that could cause failure, by providing them with strength greater than that of the potential plastic hinge regions.

Capacity Design Philosophy

- The process requires the margin of strength necessary for non-yielding elements to ensure that their behavior remains elastic.
- Such forces are associated with the development of the ***over-strength*** of potential plastic hinges.
- The strategy leads to the establishment of a suitable strength or capacity hierarchy between components of the total system.

Illustrative Analogy

- To highlight the concept of capacity design philosophy, consider the chain shown below



- Using the fact that the strength of a chain is the strength of its weakest link, a very ductile link may be used to achieve adequate ductility for the entire chain

Illustrative Analogy (Cont'd)

- If the brittle links are designed to have the same nominal strength as the ductile link , the randomness of strength variation between all links, including the ductile link, would imply a high probability that failure would occur in a brittle link and the chain would have no ductility.
- Failure of the brittle links is prevented by increasing their strength in excess of the maximum feasible strength of the weak link.

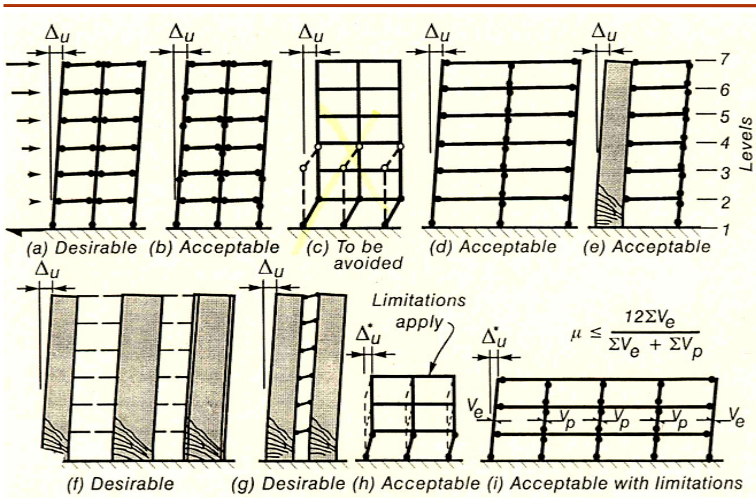
$$P_{brittle} = \Phi_0 \times P_{ductile}$$

Where Φ_0 is the over-strength factor > 1

Choice of Plastic Mechanism

- Plastic mechanisms in reinforced concrete structures must rely on flexure as the source of energy dissipation.
- The choice of designer involves thus the selection of plastic hinges in beams, columns or walls so as to form a complete mechanism to be developed in the given structural system.
- An important aim in this selection is that for a given global or system displacement **ductility demand, μ_Δ,** the associated curvature ductility at plastic hinges remain within proven limits.
- Also, the same **ultimate displacement**, Δ_u, has been assumed for all the example system shown and discussed below.

Choice of Plastic Mechanism



Major Steps in the Capacity Design

1) A kinematically admissible plastic mechanism is chosen.
2) The mechanism chosen should be such that the necessary overall displacement ductility can be developed with the smallest inelastic rotation demands in the plastic hinges.
3) Once a suitable plastic mechanism is selected, the regions for energy dissipation (i.e. plastic hinges) are designed with a relatively high degree of precision.

Major Steps in the Capacity Design

4) Parts of a structure intended to remain elastic in all events are designed so that under maximum feasible actions corresponding to over strength in the plastic hinges, no inelastic deformations should occur in those regions.
5) A clear distinction is made with respect to the nature and quality of detailing for potentially plastic regions and those which are to remain elastic in all events.

Summary - Capacity Design

- It is emphasized that capacity design is not analysis technique but a powerful design tool.
- It enables the designer to ***tell the structure what to do*** and to desensitize it to the characteristics of the earthquake, which are after all, unknown.
- It is rational, deterministic, and relatively a simple approach.
- Capacity design philosophy addresses the problem directly, and obliges the engineer to design the structure in such a way that yielding hinges can only from in pre-determined positions.

Performance Comparison - Capacity Design

Conventionally Designed Structures	Capacity Designed Structures
• Plastic hinges could develop anywhere • The plastic mechanism is arbitrary and not identified • The local ductility of the plastified region varies significantly and the global ductility of the structures is in general is small and not known • The performance under seismic excitation is not really known	• Plastic deformations are only possible within clearly identified regions • The plastic mechanism is known and is predetermined • The local ductility within the plastic hinges is adapted to the global ductility which in turn is chosen in accordance with the design class • The behavior under seismic excitation is well known
Limited safety against collapse	High safety against collapse

Performance Based Design

Introduction

- Current Codes are developed with the only intent of achieving specific performance, that is, avoidance of collapse and protection of life safety
- Experience in earthquakes at the end of the 20th century (e.g. the 1994 Northridge and 1995 Kobe Earthquakes) has forced recognition that damage, sometimes severe, can occur in buildings designed in accordance with the code.
- This led to an awareness that the level of structural and nonstructural damage that could occur in code-compliant buildings may not be consistent with public notions of acceptable performance.
- This concern led to the birth of ***Performance-based seismic engineering***, or ***Performance-Based Seismic Design***

Introduction

- Performance-based Seismic Design (PBSD) implies design, evaluation, and construction of engineered facilities whose performance under common and extreme loads responds to the diverse needs and objectives of owners-users and society.
- It is based on the premise that performance can be predicted and evaluated with quantifiable confidence in order to make, together with the client, intelligent and informed trade-offs based on life-cycle considerations rather than construction costs alone.

PBSD Documents

- Documents
  - Federal Emergency Management Agency
    - **FEMA-356** (2000) – deals with Seismic rehabilitation of existing buildings [synthesizes FEMA–273 (1996) & FEMA-274(1996)]. It is the first definitive document that laid the basis for PBD.
    - FEMA-350 (2000) – Recommended seismic design criteria for new steel moment-frame building.
  - Applied Technology Council
    - ATC-40(1996) – Seismic evaluation and retrofit of concrete buildings
  - Structural Engineers Association of California
    - SEAOC (1995) – Vision 2000 report

Current Seismic Design and PBSD

- Current seismic design practice
  - Global response modification factors (R-factors) - "core of seismic force formula" Kunnath (2005).
    - are used to approximately predict the expected inelastic demands by using elastic methods.
    - account for reductions in seismic force values due to a variety of factors including system inherent ductility, overstrength, and redundancy.

$$R = R_{\mu} R_{\Omega} R_{R}$$

  - Displacement amplification factors (C_d-factors) – used to quantify the expected inelastic displacements of the system.

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Current Seismic Design and PBSD

- Drawbacks of using R-factors
  - Are independent of the building period and ground motion characteristics.
  - Same R-factors are used for moment resisting RC, steel & braced frames.
- Both R and C_d factors are global response measures that do not provide an assessment of structural performance at the component level.
- Global response modifiers cannot alone capture:
  - Progressive distribution of nonlinearities between various structural elements
  - The resulting redistribution of seismic demands inside the structure
  - The changes that occur during the course of the seismic motion.

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Current Seismic Design and PBSD

Current Seismic design practice	PBSD
• A two-level design approach having concern for the service operational and ultimate-strength limit states for a building	• A multi-level design approach that additionally has explicit concern for the performance of a building at intermediate limit states related to such issues as occupancy and life-safety standards.
• No explicit procedures that allow an engineer to evaluate the expected performance of the final design or assess the margin of safety provided by satisfying code requirements.	• Performance objective setting, seismic demand determination & performance evaluation are explicitly addressed.
• Makes use of global response measures - R & C_d-factors.	• Provide an assessment of performance at component level
• Lateral force or base shear is the primary design parameter - "Strength based"	• Displacement Based

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Need for change in the current seismic design

- Current codes clearly serve an essential and effective role in protecting building occupants. The design basis of the code is intended to provide a basic level of safety and a relatively economical means by which to construct buildings.
- The community of design professionals needs to be able to respond to this demand with the development of design and evaluation methodologies that look at a broad range of building performance and construction techniques.
- A Performance based design option in the code will facilitate design of buildings to higher standards and will allow rapid implementation of innovative technology.

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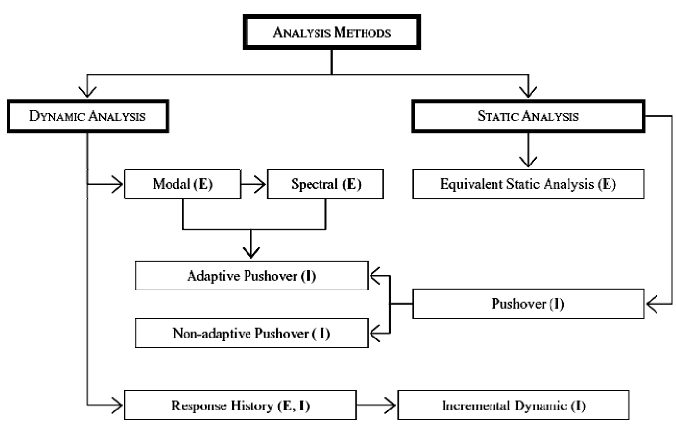
Need for change in the current seismic design

- The availability and use of PBSD will also allow building owners and a local community to determine the performance level of buildings in their own jurisdiction.
- Pushover Analysis is one of the methods used for assessing buildings' performance. It is static non linear analysis method.

Earthquake Analysis Methods



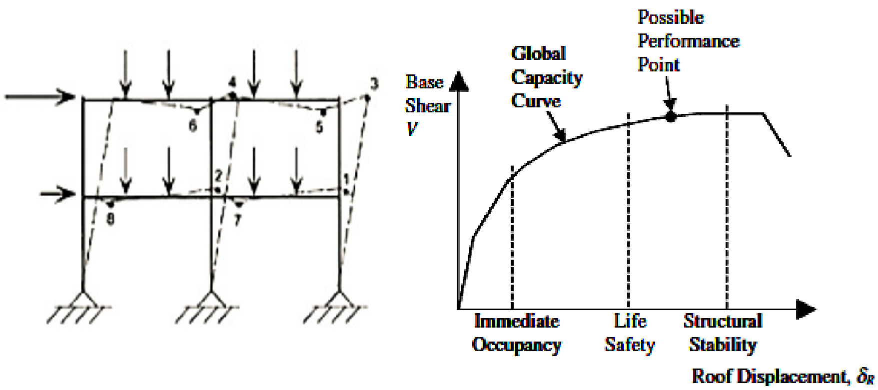
EQ Analysis Methods (Cont'd)

- FEMA 273 and ATC 40 present some simplified nonlinear analysis methods, which can be used easily and provide valuable insight in to the behavior of the structure during earthquake.
- Out of these methods the Capacity Spectrum Method (CSM) has gain popularity in the last two decades. The method is also known as Nonlinear Static Procedure (NSP) or Push-over Analysis method.

Pushover Analysis

- **Conventional Pushover Analysis** is an incremental static non linear analysis used to determine the force-displacement relationship (response), or capacity curve, for a structure or structural element.
- In this method, forcing functions, expressed either in terms of horizontal forces or displacements, are applied to the lateral force-resisting system. Static forces or displacements are distributed along the height of the structure so as to simulate the inertia forces or their effects.

Pushover Analysis



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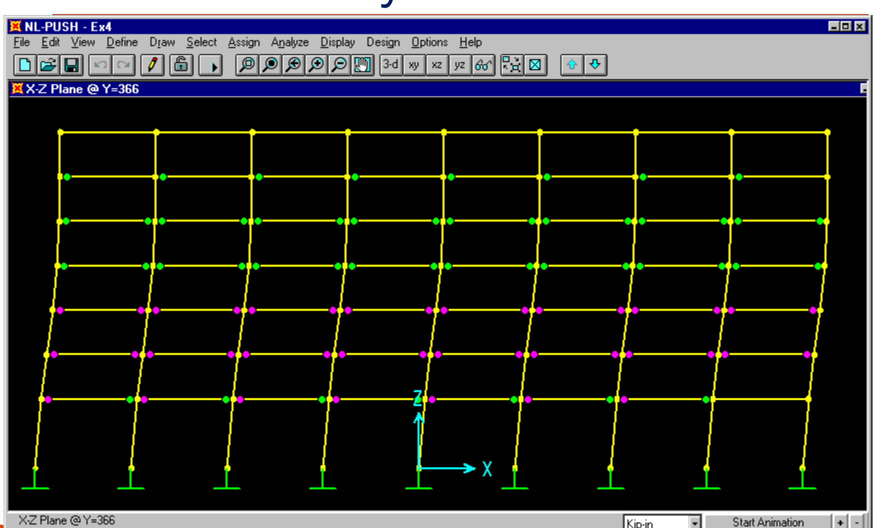
Pushover Analysis Results



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Pushover Analysis (cont'd)

- The conventional pushover analysis a very good result in assessing the performance of regular structure with uniform distribution of mass and stiffness. Other advanced methods are the adaptive, non-adaptive and modal pushover methods.
- **Adaptive Pushover** is a method by which possible changes to the distribution of inertial forces can be taken into account during static analysis.
- **Modal Pushover** is a method which considers the effect of the higher modes. The effect becomes significant for highly irregular structures

Performance based seismic design

- Performance Based Seismic Design (PBSD) is a methodology that provides a means to more reliably predict seismic risk in all buildings in terms more useful to building users and it also permits designers to:

  a) Design individual buildings that are capable of meeting the performance intended by present building codes, but with lower construction costs.

  b) Design individual buildings to achieve higher performance (and lower potential losses) than intended by present building codes.

  c) Assess the potential seismic performance of existing structures and estimate potential losses in the event of a seismic event.

Performance based seismic design

- There is increasing agreement that future seismic codes will have to be performance based, but there are widely divergent viewpoints on the meaning of performance-based design and its methods of implementation.
- The key concept in the PBSD is that of a performance objective, consisting of the specification of the design event (earthquake hazard), which the building is to be designed to resist, and a permissible level of damage (performance level) given that the design event is experienced.

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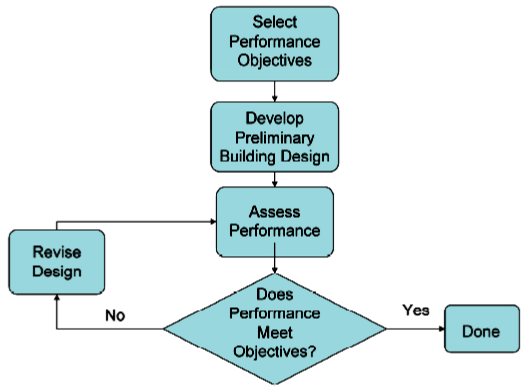
Performance based seismic design

The key steps in the performance-based design process :



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Performance objectives

- A performance objective specifies the desired seismic performance of building. Seismic performance is described by designating the maximum allowable damage state (performance level) for an identified seismic hazard (earthquake ground motion).
- A commonly used description of hazard is the probability of the seismic event in a given duration

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Performance objectives (cont'd)

Performance Objective

Hazard Level:

The level of ground motion or shaking at the site for a given earthquake.

Performance Level :

A limiting damage state or condition described by the physical damage within the building, the threat to life safety of the building's occupants due to the damage, and the post-earthquake serviceability of the building.

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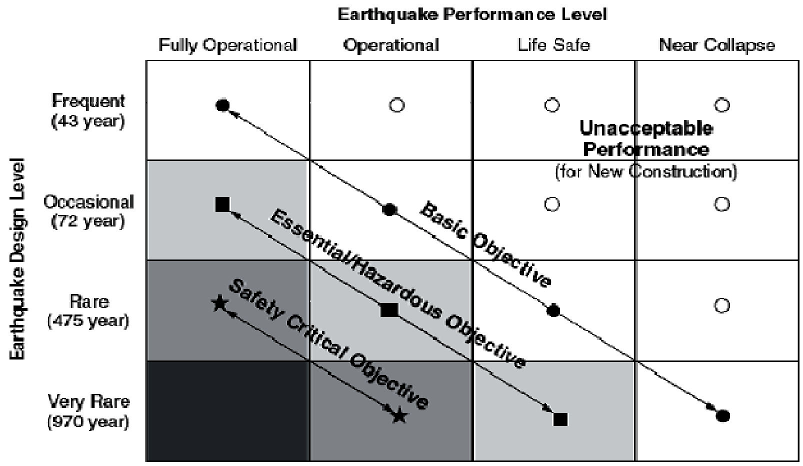
Performance objectives (cont'd)



VISION 2000

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Hazard Level

- The description of the hazard is meant to represent the seismic risk having the knowledge of the potential earthquake sources at the site. This is typically accomplished through a probabilistic seismic hazard assessment that results in a hazard curve describing mean annual frequency of exceeding a certain spectral acceleration magnitude. (According to Vision 2000)

EQ Hazard classification	Recurrence Interval	Probability of Occurance
Frequent	43 years	50% in 30 years
Occasional (BSEQ)	72 years	50% in 50 years
Rare (BDEQ)	475 years	10% in 50 years
Very rare (MCEQ)	970 years	10% in 100 years

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FEMA & ATC HAZARD LEVELS

- FEMA-356 hazard levels

Earthquake Probability of Exceedence	Mean Return Period (years)
50% in 50 years	72
20% in 50 years	255
BSE-1 10% in 50 years	475
BSE-2 2% in 50 years	2,475

- ATC-40 hazard levels

Earthquake Probability of Exceedence	Mean Return Period (years)
SE-50% in 50 years	72
DE-10% in 50 years	475
ME-5% in 50 years	2,475

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Performance Levels

- Building performance is expressed in terms of Building Performance Levels. These Building Performance Levels are discrete damage states selected from the infinite spectrum of possible damage states that buildings could experience as a result of earthquake response.

Building Performance Level

=

Structural Performance level

+

Nonstructural performance level

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Performance Levels

- FEMA-356 & ATC-40 performance level classifications
  1) Structural performance levels
  - **Immediate occupancy (IO)** level requires the building to be safe for unlimited egress, ingress, and occupancy.
  - Damage control is described as a performance range from IO to life safety level rather than a specific performance level.
  - **Life safety (LS)** level of performance suggests structural damage without partial or total collapse of structural members, which might pose a risk to life.
  - Limited safety, like damage control, is another performance range that lies between LS and the structural stability limit.
  - **Structural stability** level can be viewed as an alternative definition of **collapse prevention (CP)** wherein the structure is still capable of maintaining gravity loads though structural damage is severe and the risk of falling hazards is high.

Performance Levels

- FEMA-356 & ATC-40 performance level classifications
  2) Non-Structural performance levels
  - **Operational performance level** requires the post earthquake damage state of all nonstructural elements to remain functional and in operation.
  - **IO performance level** allows for minor disruption due to shifting and damage of components, but all nonstructural components are generally in place and functional.
  - **LS performance level** allows for damage to components but does not include failure of items heavy enough to pose a risk of severe injuries or secondary hazards from damage to high-pressure toxic and fire-suppressing piping.
  - Reduced hazard is a post earthquake damage state that considers risk to groups of people from falling heavy objects such as cladding and heavy ceilings.
  - Finally, it is also possible to include what is called a "**not considered**" performance level. This performance level is provided to cover those nonstructural elements that have not been evaluated as having an impact on the overall structural response.

Performance Levels

Combinations of Structural and Non-structural Levels to form Building Performance Levels

Non-structural Performance Levels	Building Performance Levels					
	Structural Performance Levels					
	SP-1 Immediate Occupancy	**SP-2 Damage Control (Range)**	**SP-3 Life Safety**	**SP-4 Limited Safety (Range)**	**SP-5 Structural Stability**	**SP-6 Not Considered**
NP-A Operational	1-A Operational	2-A	NR	NR	NR	NR
NP-B Immediate Occupancy	1-B Immediate Occupancy	2-B	3-B	NR	NR	NR
NP-C Life Safety	1-C	2-C	3-C Life Safety	4-C	5-C	6-C
NP-D Reduced Hazards	NR	2-D	3-D	4-D	5-D	6-D
NP-E Not Considered	NR	NR	3-E	4-E	5-E Structural Stability	Not Applicable

Legend
- (white) Commonly referenced Building Performance Levels (SP-NP)
- (grey) Other possible combinations of SP-NP
- NR Not recommended combinations of SP-NP

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Structural Performance levels

- When a building is subjected to earthquake ground motion a pattern of lateral deformations that varies with time is induced into the structure.
- At any given point in time, a particular state of lateral deformation will exist in the structure, and at some time within the period in which the structure is responding to the ground motion, a maximum pattern of deformation will occur.

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Structural Performance Levels (cont'd)

- At a relatively low level of ground motion, limited induced deformation and the resulting stresses within elastic range.
- At a more severe level of ground motion, larger induced deformation and components will be strained beyond elastic range.

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Target building Performance levels

Operational
(Negligible Damage)

Immediate Occupancy (IO)
(Light Damage)

Life Safety (LS)
(Moderate Damage)

Collapse Prevention (CP)
(Severe Damage)

Collapse
(Complete Damage)

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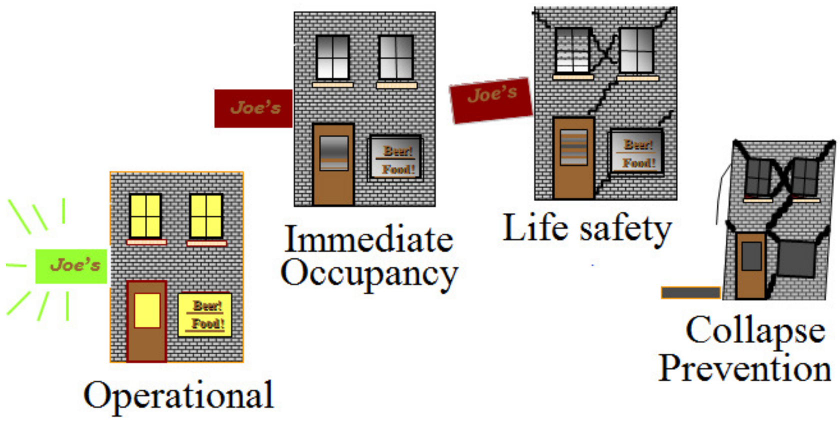
Target building performance levels



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Performance Levels (Vision 2000)

Operational	Continuous service, negligible structural and non-structural damage.
Immediate Occupancy (IO)	Most operations & functions can resume immediately, structure is safe for occupancy. Essential operations protected, non essential facilities disrupted. Repair required to restore some non essential services. Damage is light.
Life Safety (LS)	Damage is moderate, but structure remains stable. Selected building systems, feature or contents may be protected from damage. Life safety is greatly protected. Building may be evacuated following earthquake. Repair possible, but may be economically impractical.
Near collapse (CP)	Damage severe, but structural collapse prevented. Non-structural elements may fall.

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Latest developments in PBSD

- The development of methodologies on which future seismic design codes and practices can be based. Such methodologies need to incorporate new developments in demand and capacity descriptions and loss estimation strategies that are based on probabilistic concepts. The application of these methodologies should result in a performance that can be quantified and should provide consistent seismic protection for existing and new structures.

Latest developments in PBSD

- The development of more reliable analytical procedures that permit performance evaluation of a wide variety of soil-foundation-structure systems and their components, of nonstructural systems and of building contents, at all levels of performance, ranging from cosmetic structural or nonstructural damage to structural deterioration leading to collapse, with due consideration given to the uncertainties inherent in the assessment of seismic demands and capacities.

Summary PBSD

- Performance-Based Seismic design (PBSD) is a building design that is based on a set of dedicated performance requirements and that can be evaluated on the basis of solution independent performance indicators.
- The performance-based design approach is a means to enhance the professionalism and the client orientation of the building design sector. It is aimed at satisfying the real client needs and leaves the design process open for creative and innovative solutions.
- The performance-based approach makes 'integral design', with parallel, interrelated contributions from all design disciplines imperative.

Displacement Based Design

Introductions – Displacement Based Design

- The design method attempts to design a structure which would achieve a given performance limit state under a given seismic intensity, essentially resulting in uniform-risk structures, which is philosophically compatible with the uniform-risk seismic spectra incorporated in most design codes.
- This design method appears to be more intellectually satisfying than the alternatives, it is best equipped to address the ***deficiencies of conventional force-based design***, simple to apply and better suited to incorporation in design codes. (Calvi and Priestley, 2007)

Problems with Force Based Design

1. **Interdependency of strength and stiffness:**
   The stiffness (hence natural periods, elastic strengths, and strength distribution through the structure) can not be accurately determined until the structure is fully designed;
2. **Inadequate representation of variation of hysteretic characteristics** of different structural systems**;**
3. **Simplistic and inappropriate definition of behavior factors** for whole categories of structures, and a lack of appreciation that ductility capacity can vary widely within a structural class.

Problems with Force Based Design

4. **Inadequate representation of the influence of foundation flexibility on seismic response;**
5. **Inadequate representation of structural performance of systems** where inelastic action develops in different members at different levels of structural response.
6. **Inadequate representation of structures with load paths** (e.g. a bridge with an elastic load path involving superstructure action spanning between abutments, and an inelastic load path involving ductile action of the piers).

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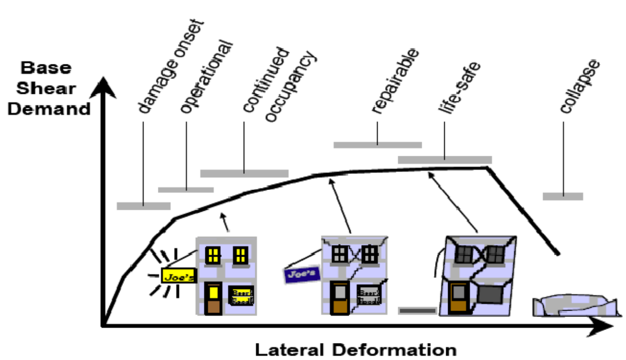
Displacement based design

- In the last 15 years it is recognized that damage in earthquakes is primarily related to the deformations that structures sustain not the forces.



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Displacement based design

- The fundamental philosophy behind the Direct Displacement Based Design (DDBD) is that structures should be designed to achieve a specified performance level, defined by drift limits, under a specified level of seismic intensity.
- The design concept is thus very simple. Such complexity that exists relates to the determination of the "substitute structure" characteristics, of the design displacement and the development of design displacement spectra.

Displacement based design fundamentals

In DDBD mainly the structure is characterized by

- The ***design drift*** which is the starting point, where drift is defined as the inter-story displacement divided by the story height ($\theta_d = \Delta_i / hi$)
- ***Secant stiffness***, K_e, at maximum displacement response Δ_d
- A level of ***equivalent viscous damping*** appropriate to the hysteretic energy absorbed during inelastic response
- The ***design forces*** necessary to achieve the design drift limit which is directly found

Displacement based design fundamentals

- The design method is illustrated in the Figure (shown in the next slide) which considers a SDOF representation of a frame building, though the basic fundamentals apply to all structural types. The bi-linear envelope of the lateral force displacement response of the SDOF representation is shown. An initial elastic stiffness K_i is followed by a post yield stiffness of rK_i.
- While force-based seismic design characterizes a structure in terms of elastic, pre-yield, properties (initial stiffness K_i, Elastic damping), DDBD characterizes the structure by secant stiffness K_e at maximum displacement Δd, and a level of equivalent viscous damping ζ, representative of the combined elastic damping and the hysteretic energy absorbed.

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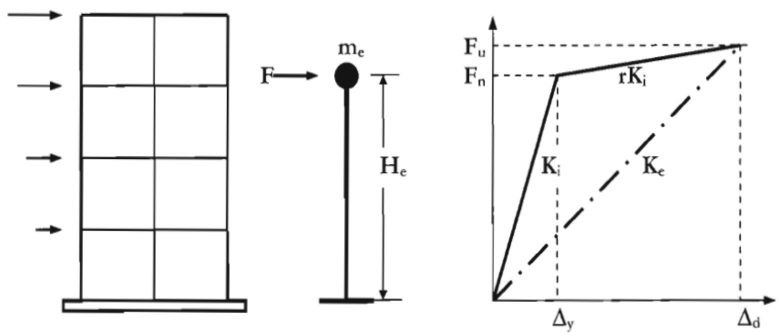
Displacement based design fundamentals



(a) SDOF Simulation (b) Effective Stiffness K_e

Fundamentals of direct displacement-based design

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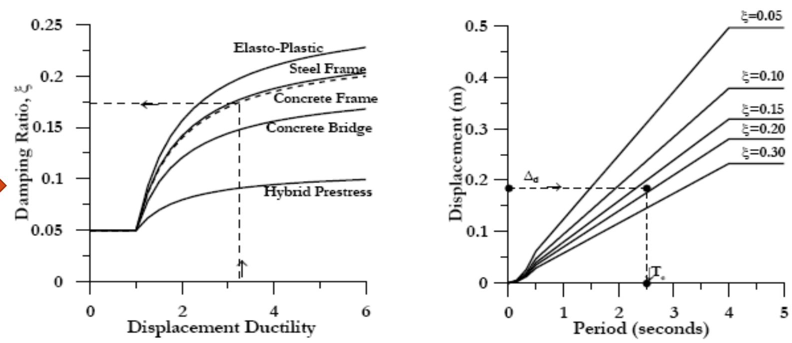
Displacement based design fundamentals



(c) Equivalent damping vs. ductility (d) Design Displacement Spectra

DDBD procedure

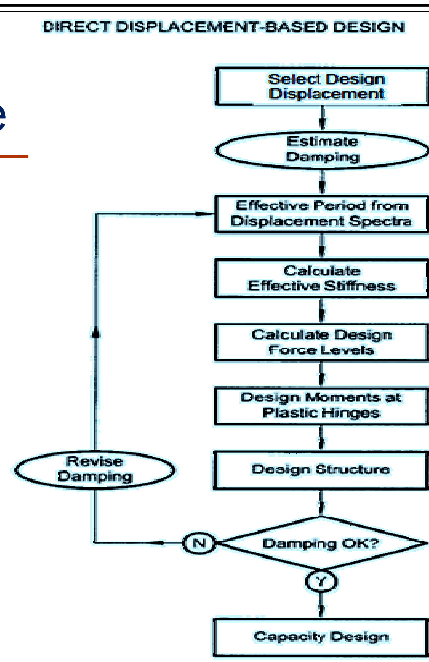
$Set\ \Delta_d \Rightarrow get\ \mu$

$use\ \mu \Rightarrow get\ \xi$

$use\ \Delta_d\ \&\ \xi \Rightarrow get\ T_e$

$use\ T_e\ \&\ m_e \Rightarrow get\ k_e$

$\therefore V_b = k_e\, \Delta_d$



Simple calculation procedure for DDBD

Characteristic displacement: $\Delta_d = \sum_{i=1}^{n}\left(m_i \Delta_i^2\right) / \sum_{i=1}^{n}\left(m_i \Delta_i\right)$

Equivalent mass: $m_e = \sum_{i=1}^{n}\left(m_i \Delta_i\right) / \Delta_d$

Effective height (buildings): $H_e = \sum_{i=1}^{n}\left(m_i \Delta_i H_i\right) / \sum_{i=1}^{n}\left(m_i \Delta_i\right)$

Design displacement ductility: $\mu = \frac{\Delta_d}{\Delta_y}$

Equivalent viscous damping: $\xi_{eq} = 0.05 + C \cdot \left(\frac{\mu - 1}{\mu \pi}\right)$

Effective stiffness: $K_e = 4\pi^2 m_e / T_e^2$

Design base shear: $F = V_B = K_e \Delta_d$

Summary Direct DBSD

- Direct displacement-based seismic design is a simple procedure for determining the required base shear strength to ensure that a structure responds at the design drift limit
- Use of direct displacement-based design will result in more consistent designs than force-based design criteria, and will generally result in reduced design forces, particularly for regions of moderate seismic intensity

That is all for Today