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Aseizmičko projektovanje prema zadatim ponašanjima:

Šta je to?
Kako se primenjuje u praksi?
I zašto?

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Performance-based seismic design: What is it? How to do it? And why?

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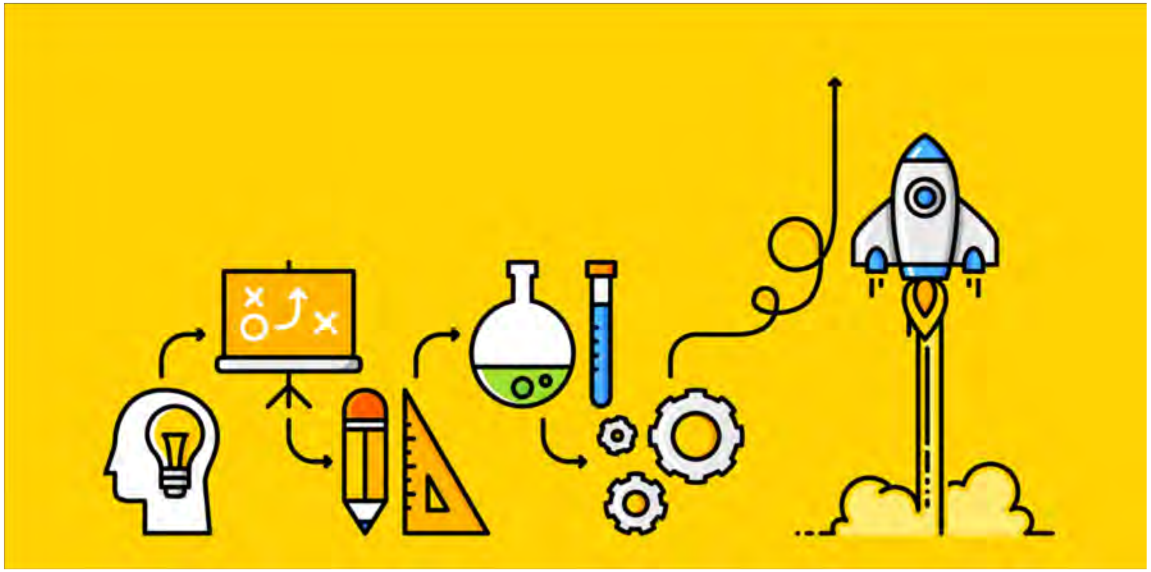
Design (as a verb)

- To design is to intentionally create a plan (or specification) for the construction of an object or system or for the implementation of an activity or process

(Wikipedia, 2019)



https://theblog.adobe.com/how-the-design-process-has-evolved/

Design
in the Presence of (Natural) Hazards

- Hazard is a source of danger:
  - A situation which poses a level of threat to life, health, property or the environment

    (Wikipedia, 2019)

- Consequences of natural hazards are of primary design concern:
  - The designed object, process or system must be able to sustain its intended function in the presence of hazard or recover it shortly thereafter

www.weirdhut.com

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Risk-Informed Design

$$\text{Risk} = \int_{\text{lifetime}} P_{robability}(\text{hazard event}) \times I_{mpact}(\text{event occurrence})dt$$

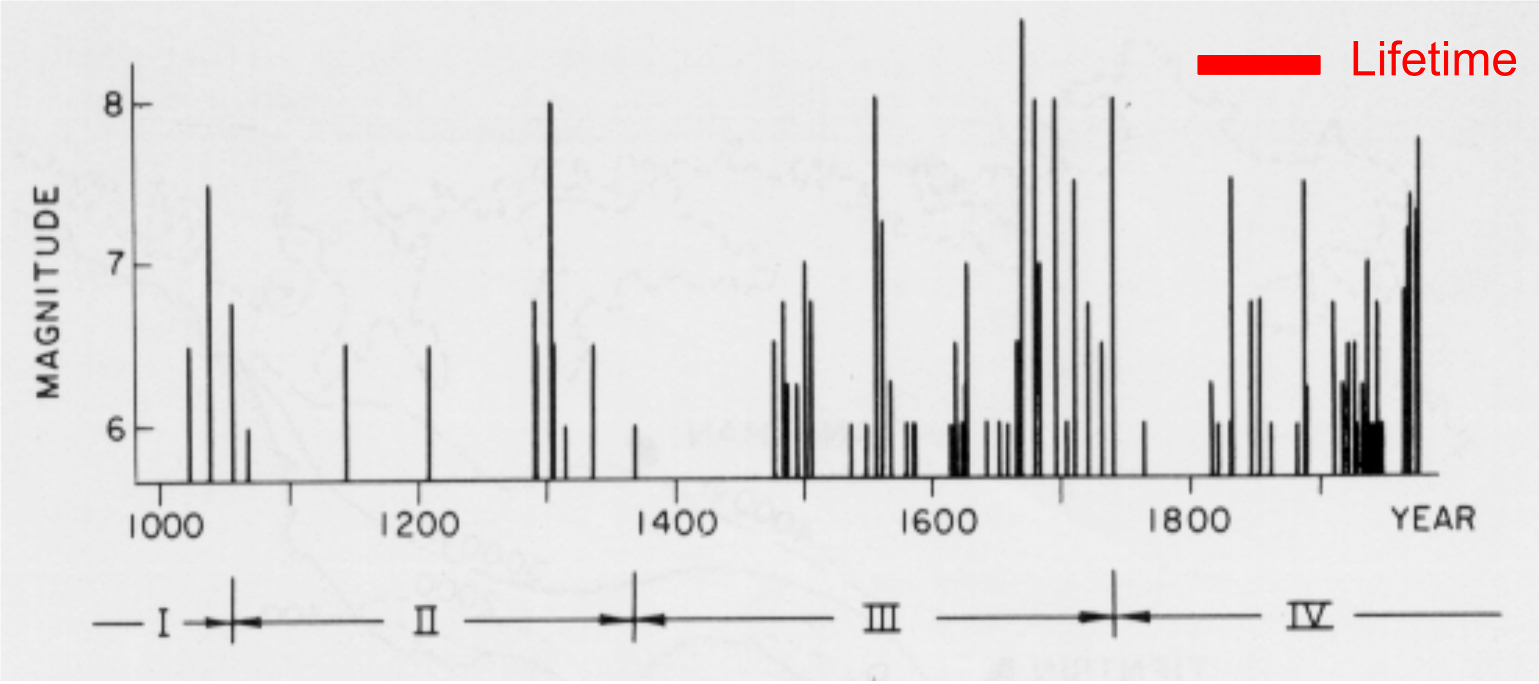
$$= \int_{\text{lifetime}} \left(\text{Hazard} \times \text{Performance}\right) dt$$

- Risk-informed design is critically concerned with the performance of objects, processes and systems during their useful life

Beichuan, China, 2008

Risk-Informed Seismic Design

How many earthquakes occur in a lifetime of a structure?



Large (M>6) earthquakes in North China tectonic province

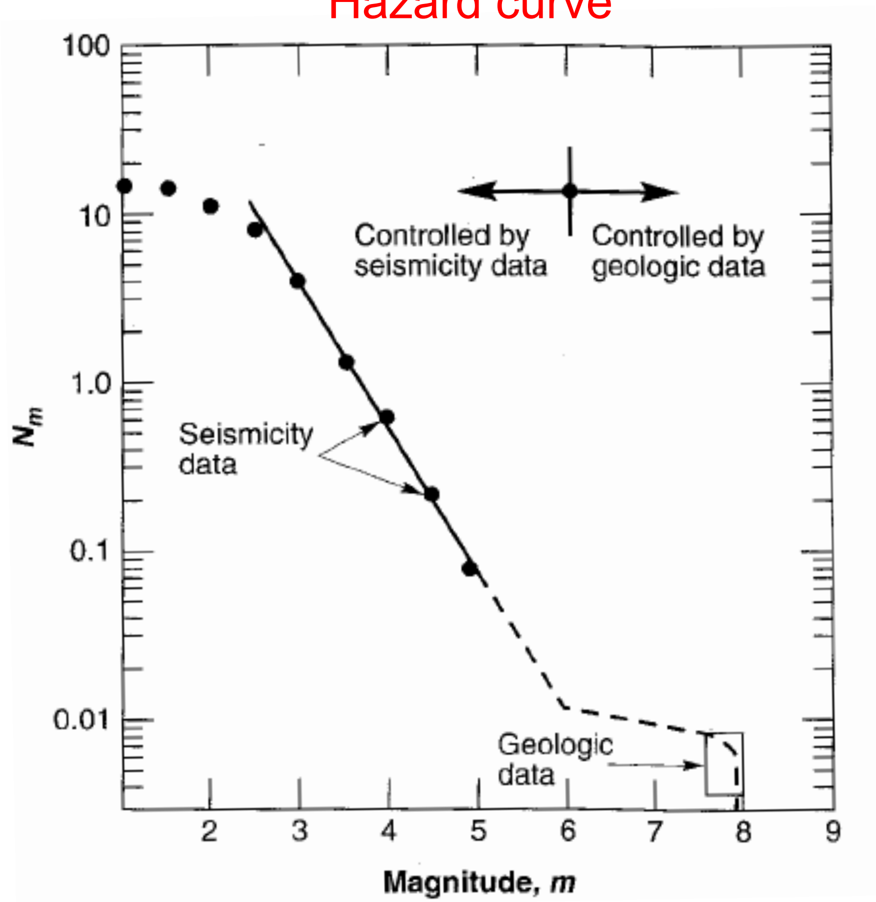
Report on the Great Tangshan Earthquake of 1976

Risk-Informed Seismic Design: Defining the Seismic Hazard

A seismically active location or a region experiences:

- Many small earthquakes
- A few large earthquakes
- Very few very large earthquakes that are at the physical limits of the earthquake sources and the soils seismic waves propagate through

Hazard curve



Kramer, 1996

Risk-Informed Seismic Design: Defining the Seismic Hazard

- Mean annual rate of exceedance of an earthquake magnitude m over time T_R

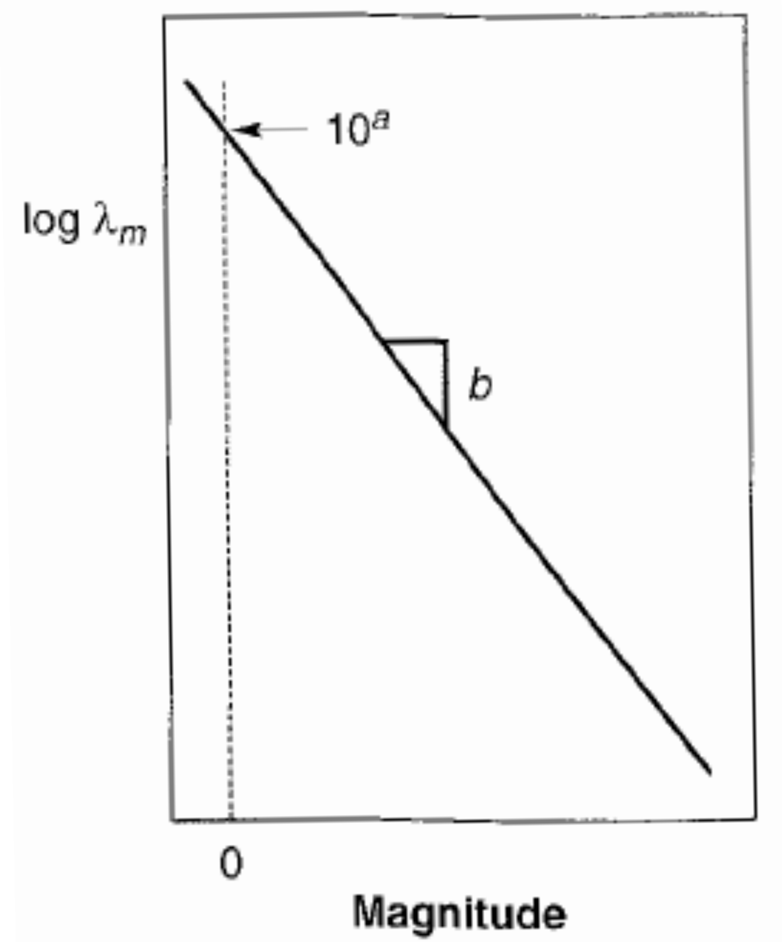
$$\lambda_m = \frac{N_{eq}(M > m | t < T_R)}{T_R}$$

- Return period $$T_R = \frac{1}{\lambda_m}$$

- Gutenberg and Richter (1944) earthquake recurrence law:

- $$\log \lambda_m = a - bm$$

Hazard curve



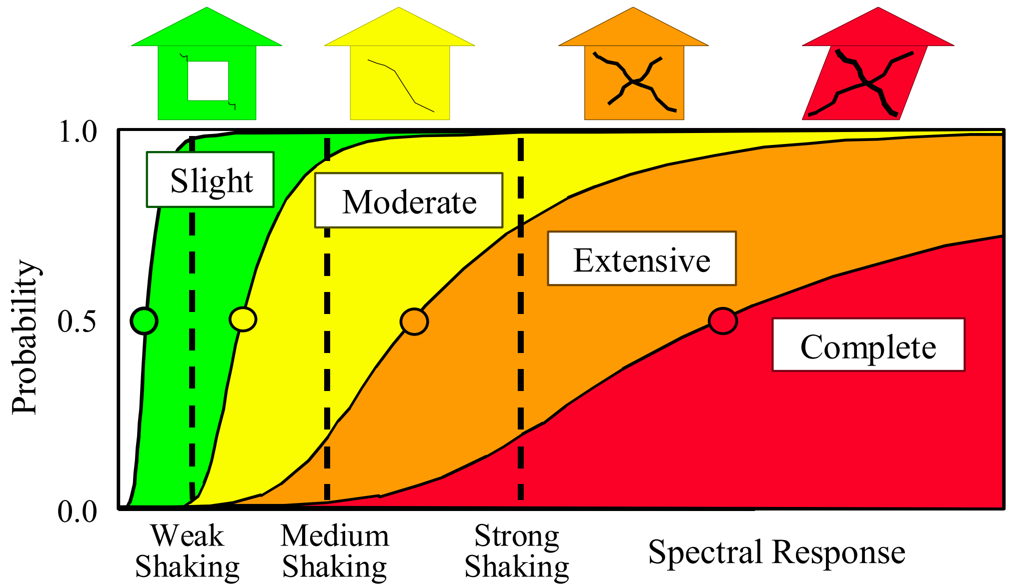
Kramer, 1996

Risk-Informed Seismic Design: Defining the Earthquake Consequences

Mahin, CEE 227 Lectures, circa 2007

Risk-Informed Seismic Design: Defining the Earthquake Consequences

- Consequences occur only if an earthquake occurs first!
  - Vulnerability functions are probabilities of exceedance of a given damage state, conditioned on the occurrence of an earthquake of a certain intensity



HAZUS AEBM User Manual
https://www.fema.gov/media-library/assets/documents/24609

Risk-Informed Seismic Design: Defining the Earthquake Consequences

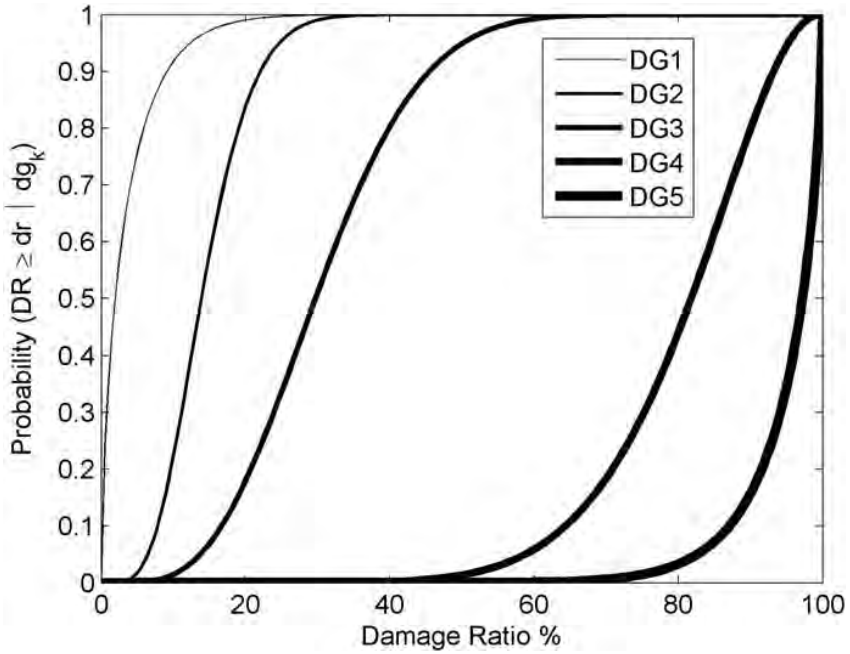
Ultimately consequences of earthquakes are expressed using common additive quantities:

- Human casualties:
  - Injuries (of various degree)
  - Deaths
- Monetized losses:
  - Direct:
    - Repairs and retrofits
  - Indirect
    - Loss of use, function, business

Olive View hospital, 1971 San Fernando earthquake

Risk-Informed Seismic Design: Defining the Earthquake Consequences

- Losses are a consequence of earthquake-induced damage:
  - Loss functions are probabilities of exceedance of a given loss amount, conditioned on the occurrence of certain damage
- Direct and indirect losses are monetized using construction management and actuarial principles



Risk-Informed Seismic Design: Quantifying the Earthquake Consequences

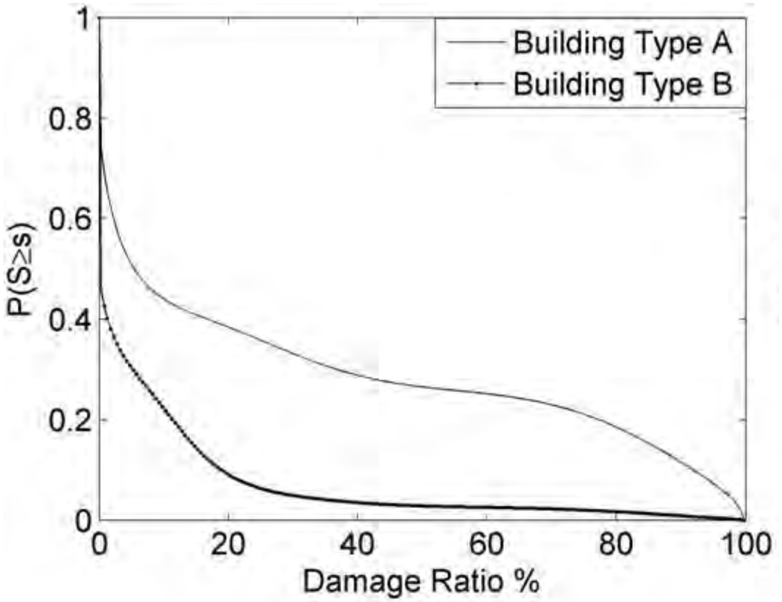
- Losses are incurred in one earthquake event over all damage states

$$P(S \leq s|im) =$$

$$\sum_{DS_k} \underbrace{G_2(S \leq s|ds_k)}_{\text{Loss function}} \underbrace{|dG_1(DS_k|im)|}_{\text{Vulnerability function}}$$

Loss function

Vulnerability function

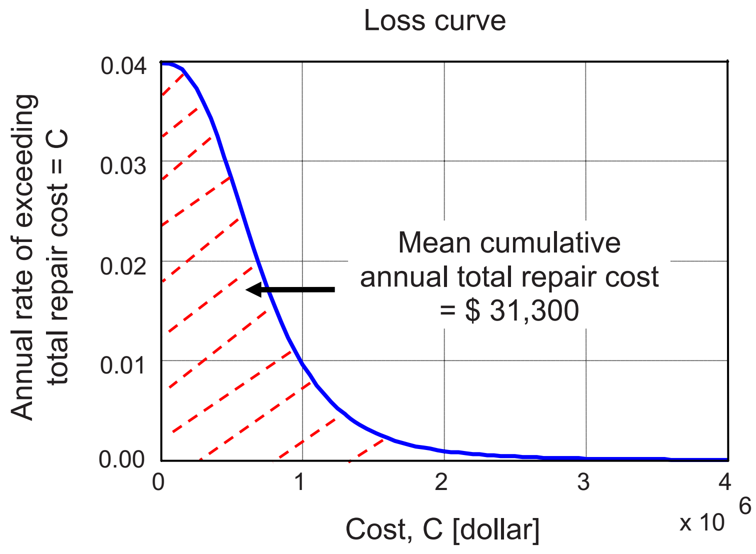


Risk-Informed Seismic Design: Quantifying the Earthquake Consequences

- Losses accumulate over the life time of a structure

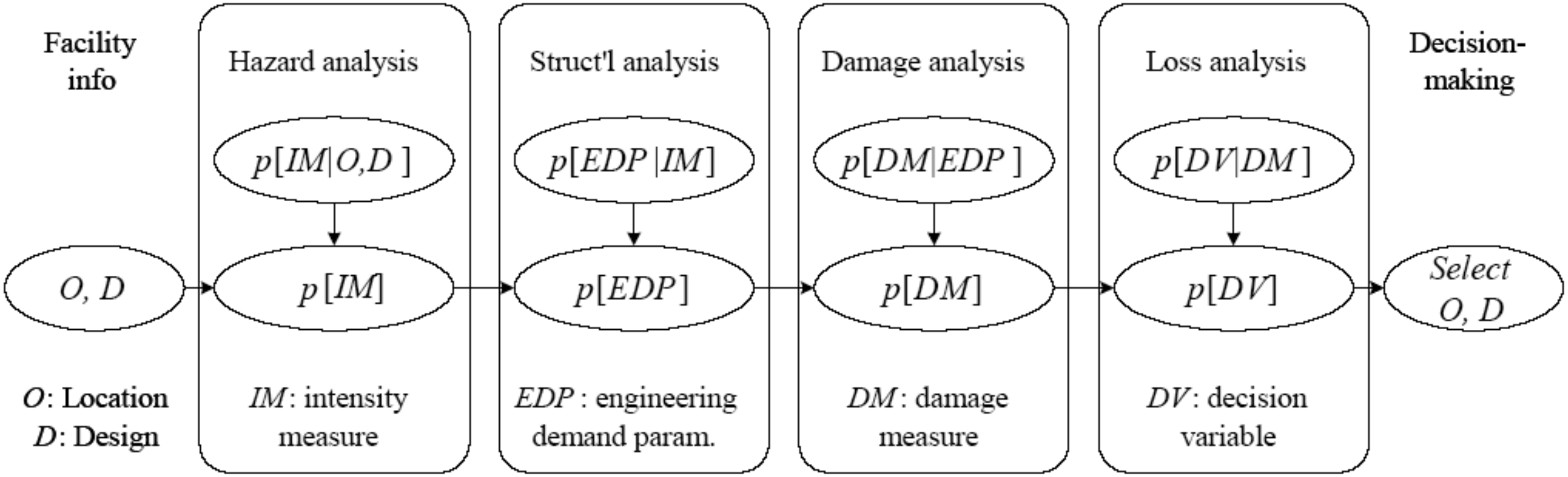
$$P(S > s) = \frac{\sum_{i=\min(im)}^{\max(im)} \left(1 - P(LOSS \leq loss \mid im)\right) * \lambda_i}{\sum_{i=\min(im)}^{\max(im)} \lambda_i}$$

- Loss curve represents the mean annual rate of exceedance of a loss threshold for a given design in a given seismic hazard environment



Risk-Informed Seismic Design: Quantifying the Earthquake Consequences

- PEER Center approach:
  - Decomposition and re-composition of the total probability integral



https://peer.berkeley.edu/research/pbee-methodology

Risk-Informed Seismic Design: Quantifying the Earthquake Consequences

$$v(DV) = \iiint G[DV|DM]\,|dG[DM|EDP]|\,|dG[EDP|IM]|\,|d\lambda[IM]|$$

Impact — **Performance (Loss) Models and Simulation** — **Hazard**

IM – Intensity Measure

EDP – Engineering Demand Parameter

DM – Damage Measure

DV – Decision Variable

ν(DV) – Probabilistic Description of Decision Variable

(e.g., Mean Annual Probability $ Loss > 50% Replacement Cost)

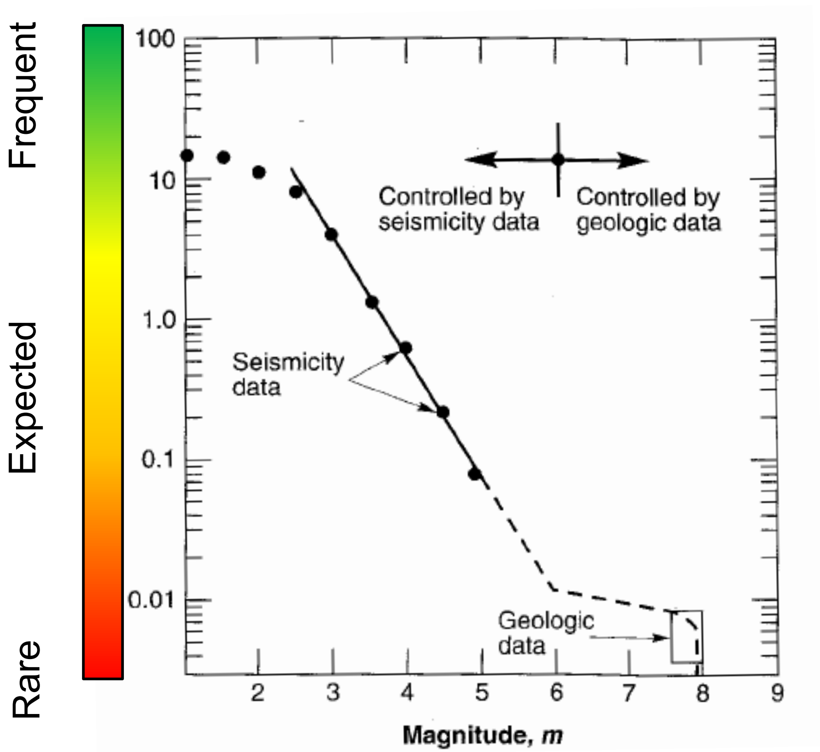
https://peer.berkeley.edu/research/pbee-methodology

Risk-Informed Seismic Design:
Defining Seismic Performance Objective(s)

Performance Objective		Acceptance criteria	
Seismic Hazard Exposure	Performance Goal	Deterministic Evaluation	Probabilistic Evaluation
How often should this performance goal be challenged during the life of a structure	What is the desired performance of a structure: Safety, utility, damage, repair cost and time, etc.	Based on quantifiable local and global engineering response parameters	Z% confidence that there is an X% probability of exceedance in Y years.

Risk-Informed Seismic Design:
Defining Seismic Performance Objective(s)

Seismic Hazard

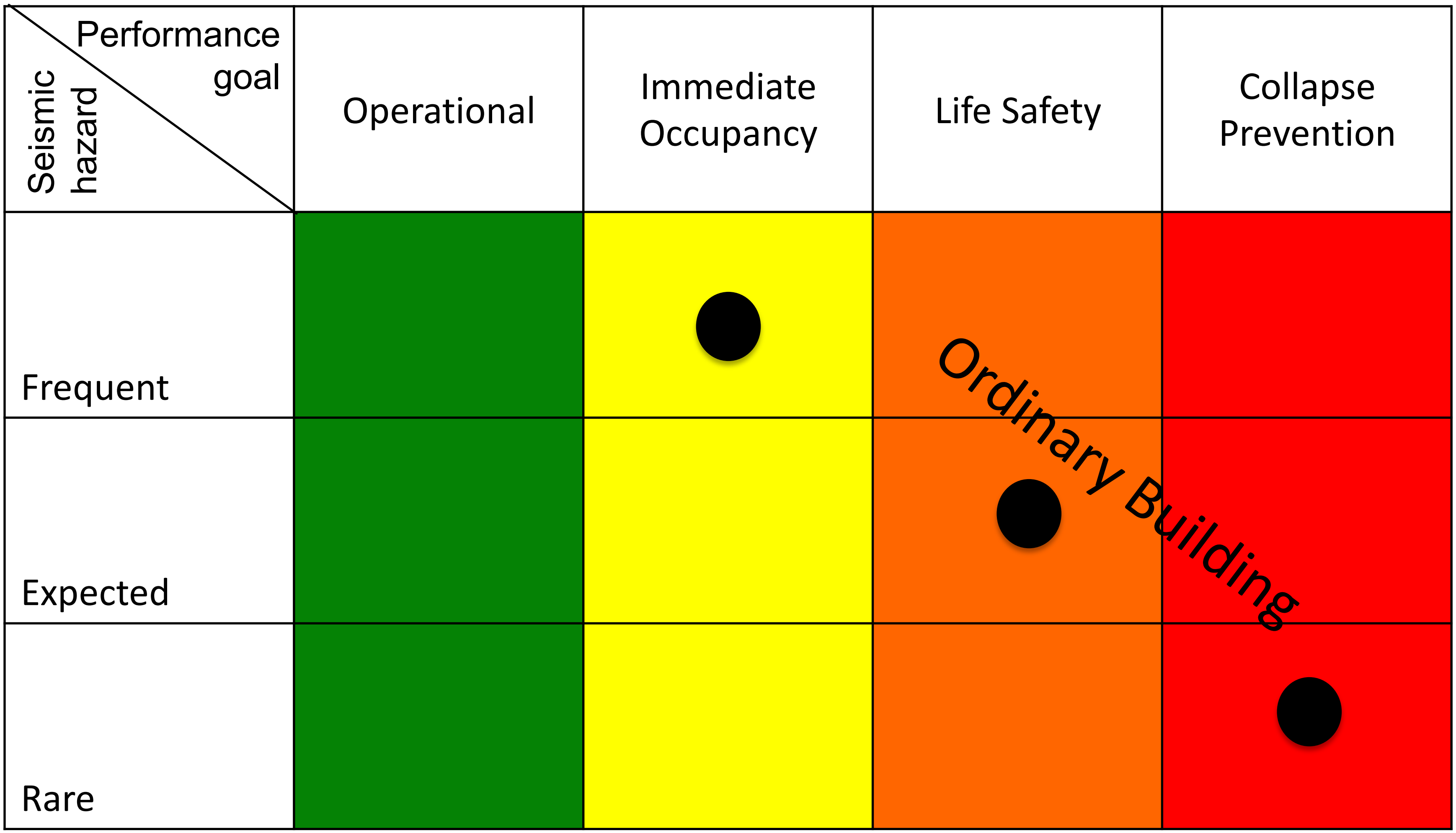


Seismic Risk

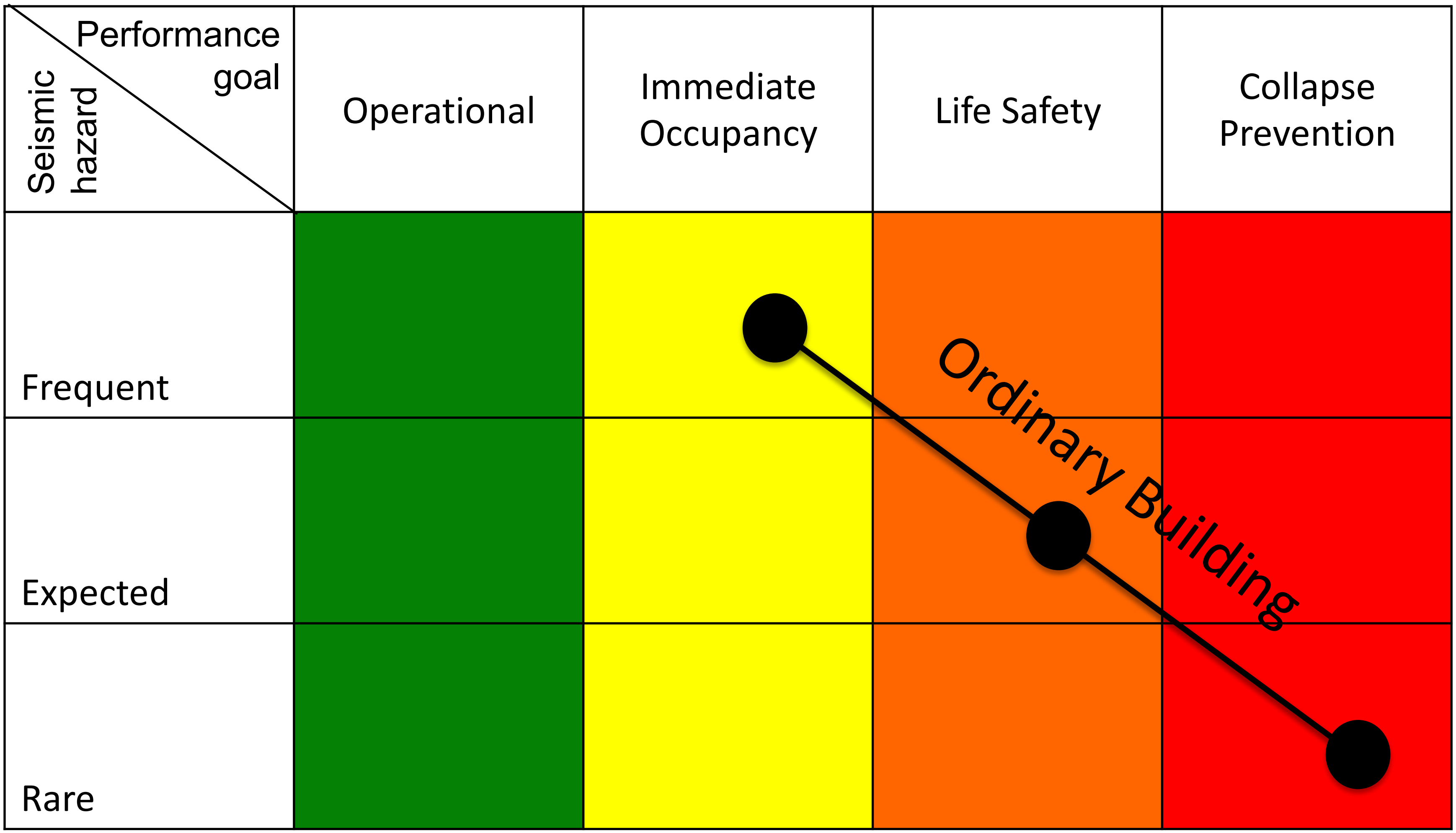
Defining Seismic Performance Objectives

Seismic hazard \ Performance goal	Operational	Immediate Occupancy	Life Safety	Collapse Prevention
Frequent				
Expected			Ordinary Building	
Rare				

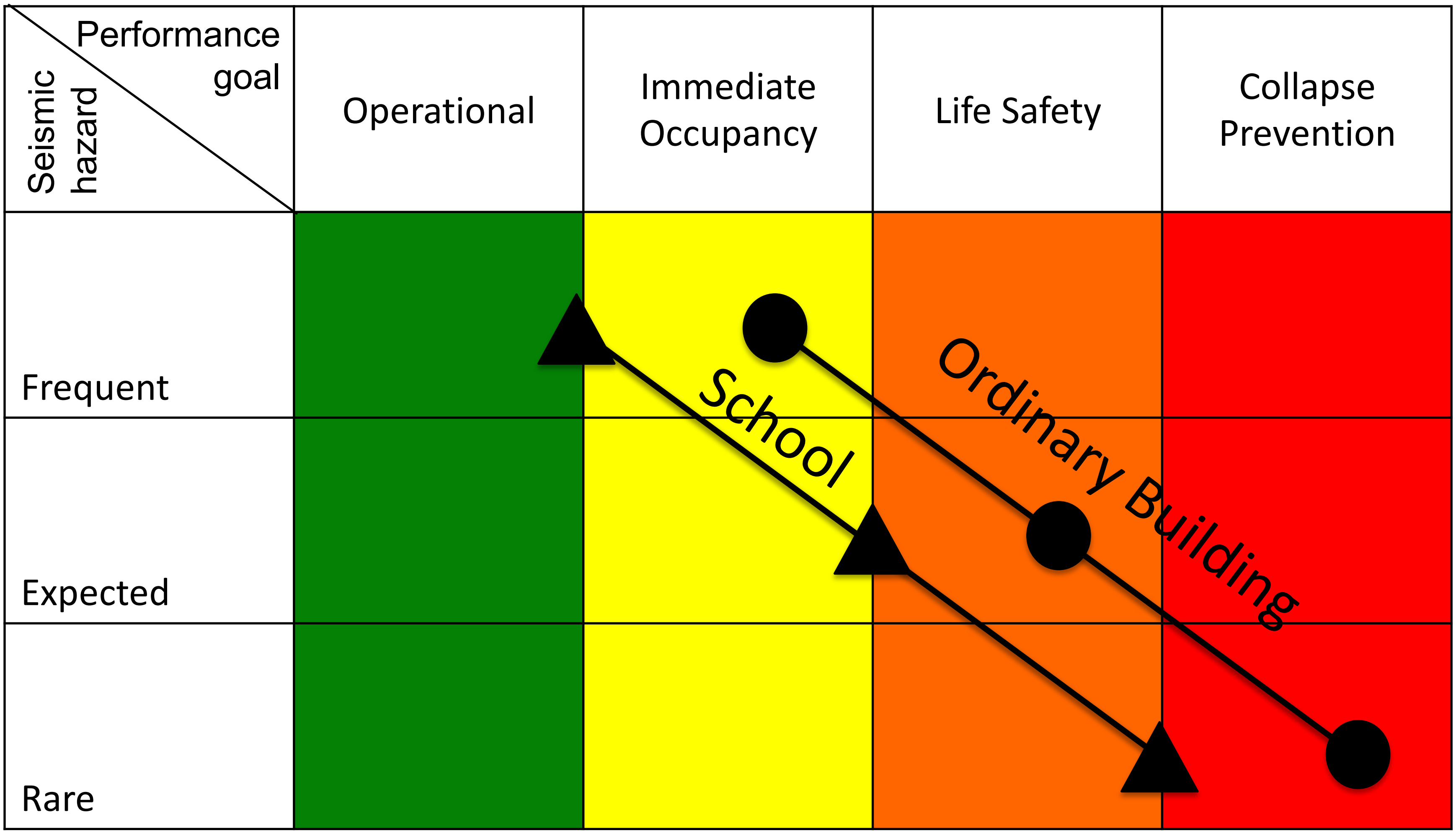
Defining Seismic Performance Objectives



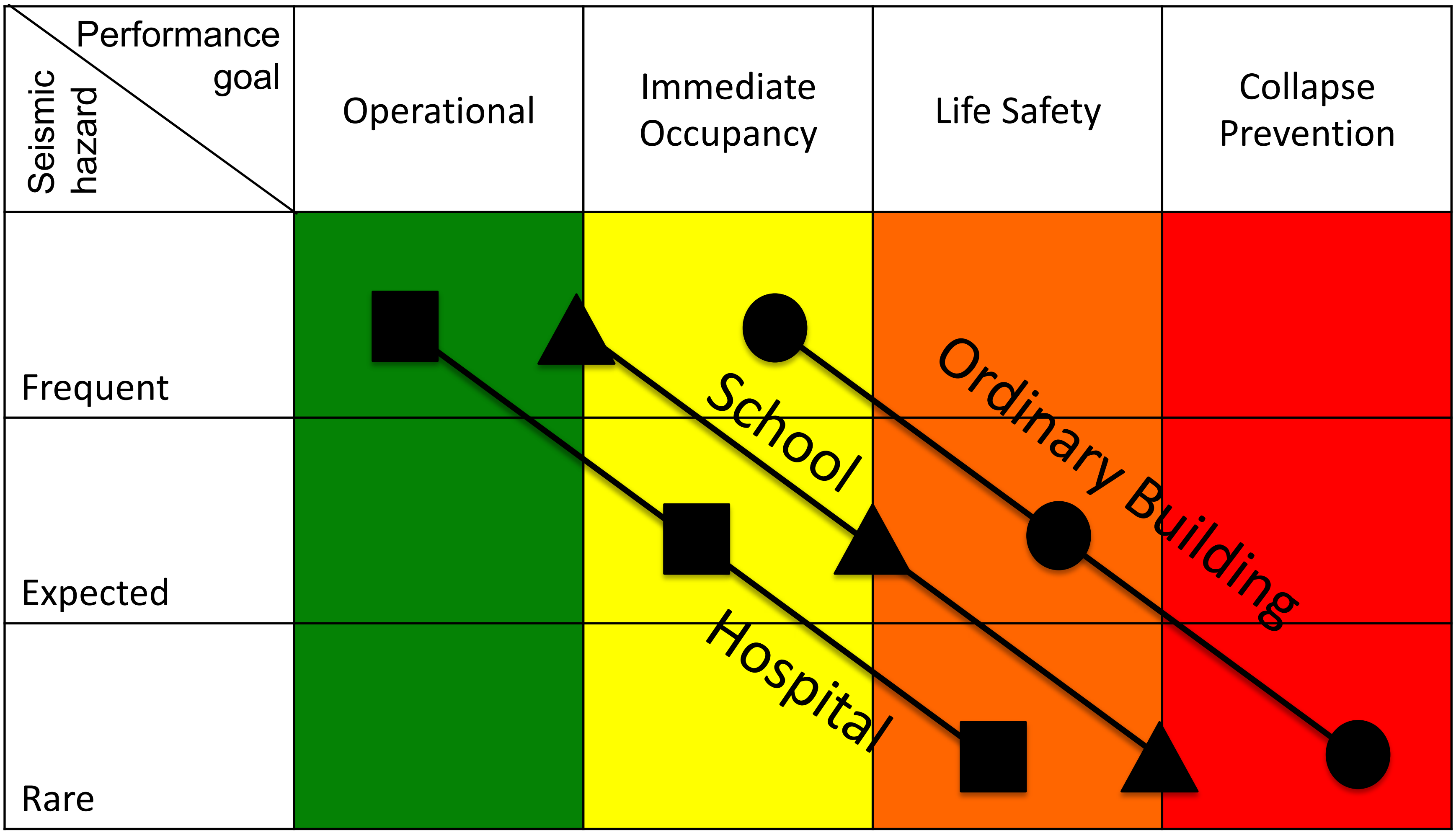
Defining Seismic Performance Objectives



Defining Seismic Performance Objectives

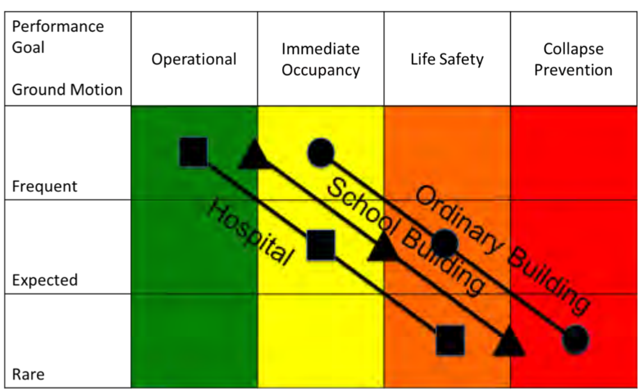


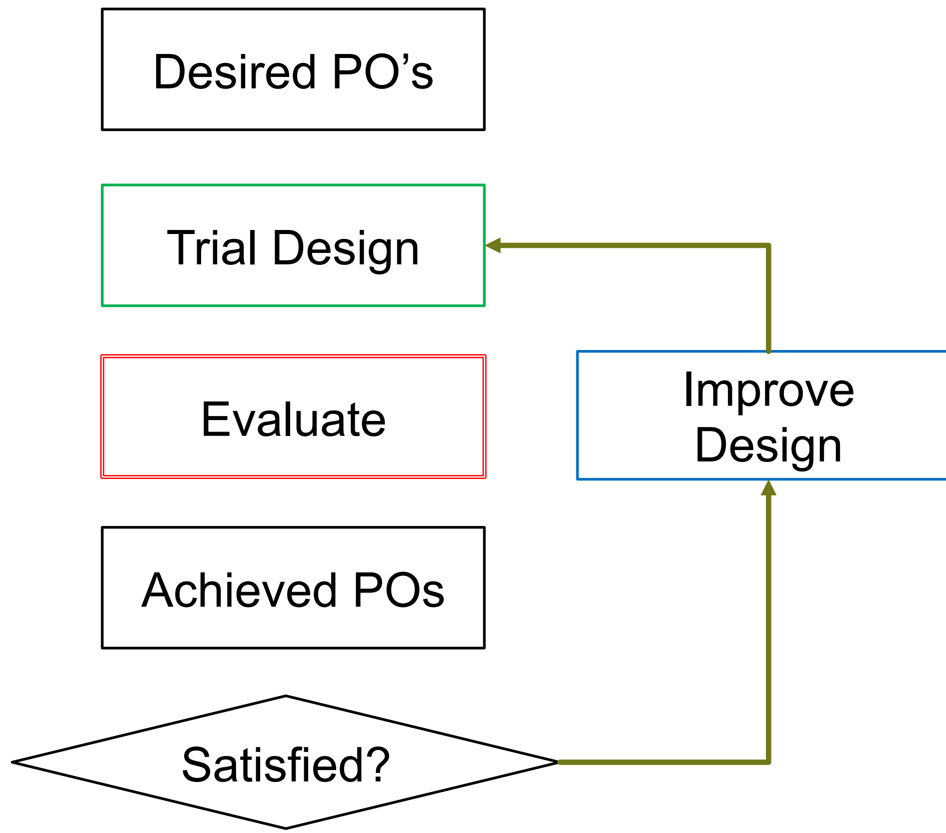
Defining Seismic Performance Objectives



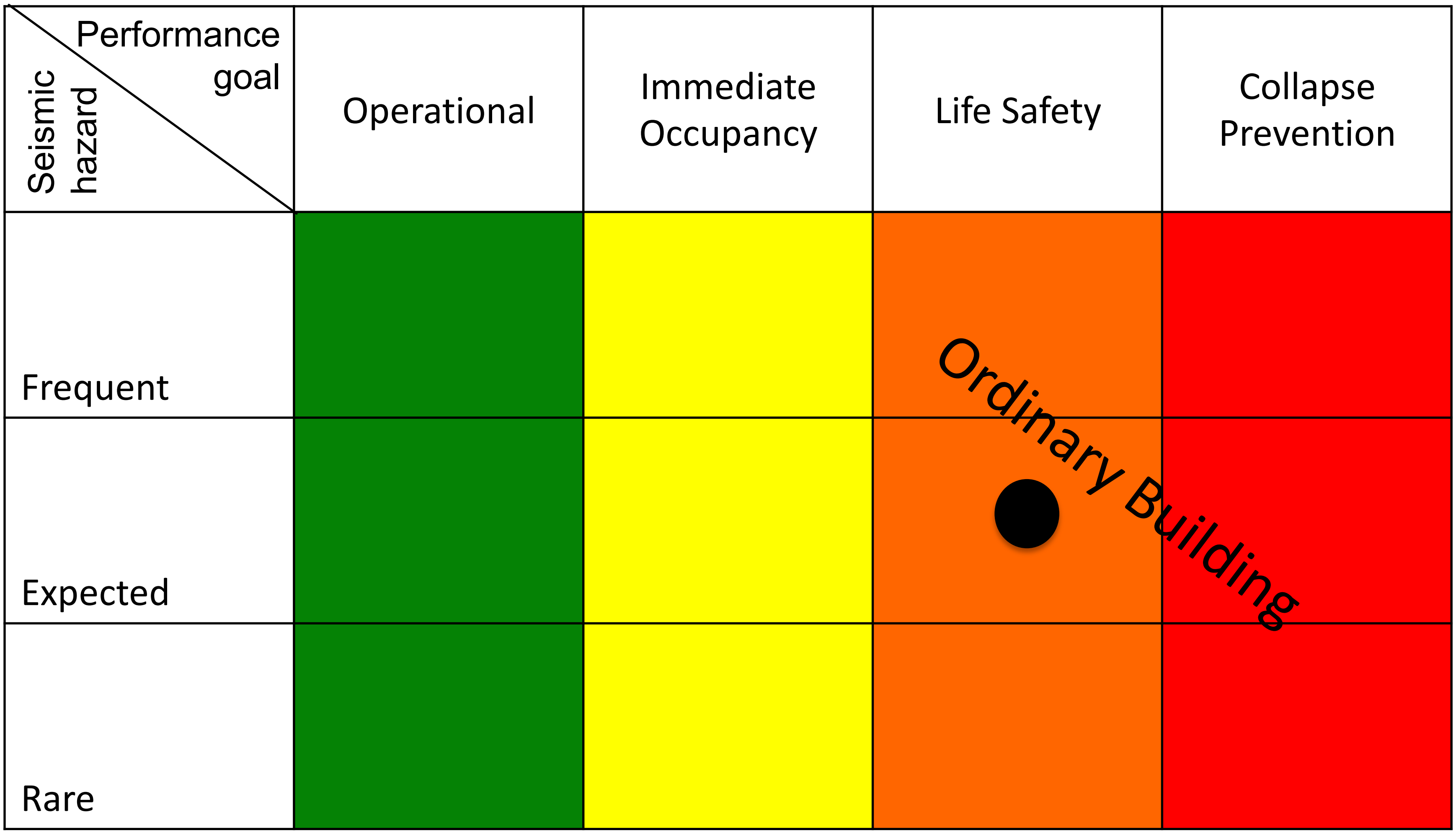
Performance-Based Risk-Informed Seismic Design

- Directly address the needs of the owner(s) of of the user(s) of the structure, process or system in the life time of their risk exposure environment(s)





Practical Performance-Based Seismic Design

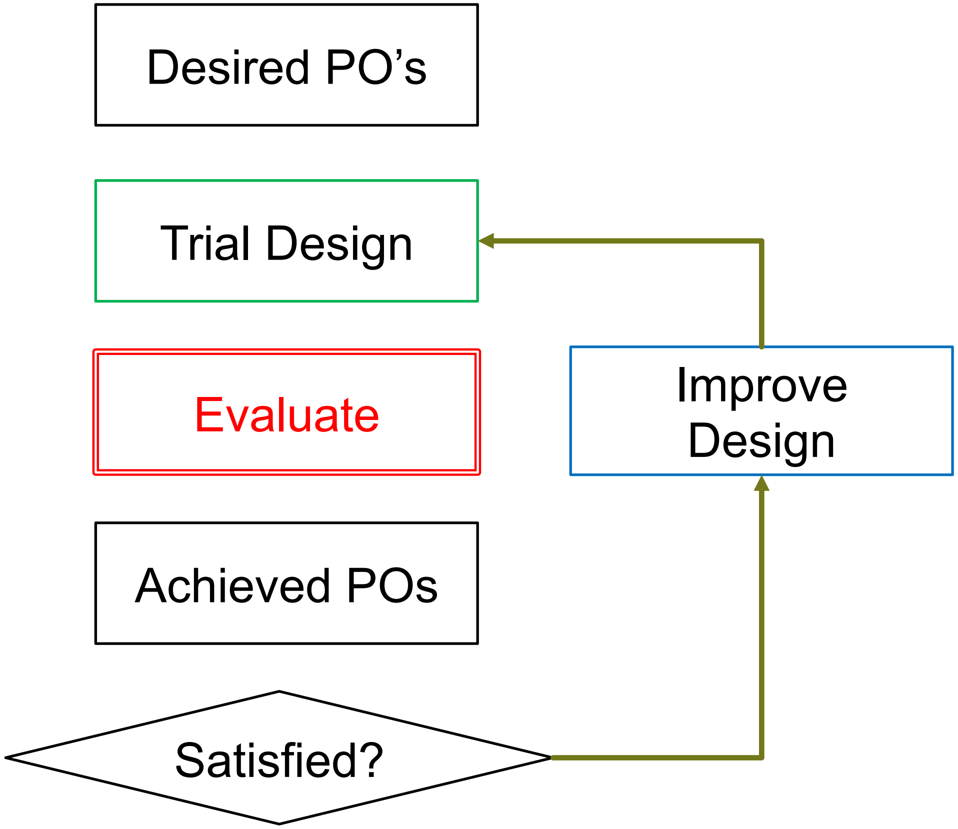


Practical Performance-Based Seismic Design: Life-Safety

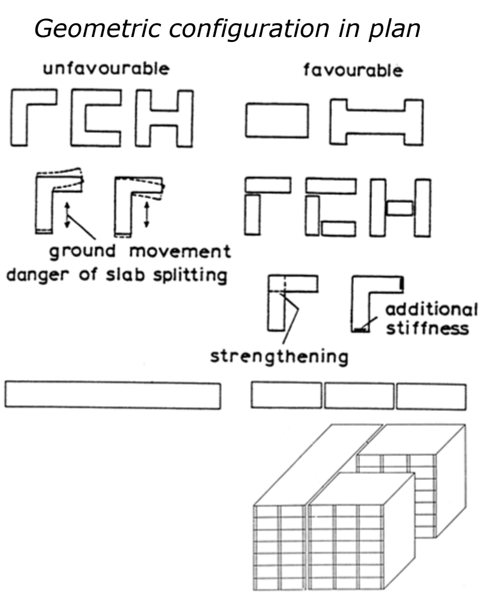
Performance Objective		Acceptance criteria	
Seismic Hazard Exposure	Performance Goal	Deterministic Evaluation	Probabilistic Evaluation
Once in a life time 10% probability of exceedance in a 50 year period	Life safety: Significant, possibly irreparable structural and nonstructural damage, some injuries, no loss of life	Structure and element drift, deformation ductility and strength limits	90% confidence that there is an 10% probability of exceedance in 50 years.

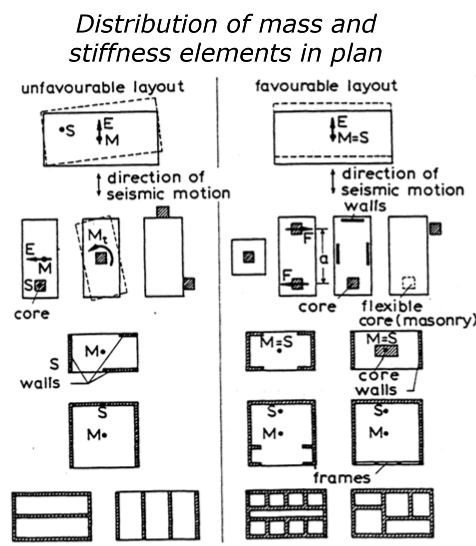
Practical Performance-Based Seismic Design: Life-Safety

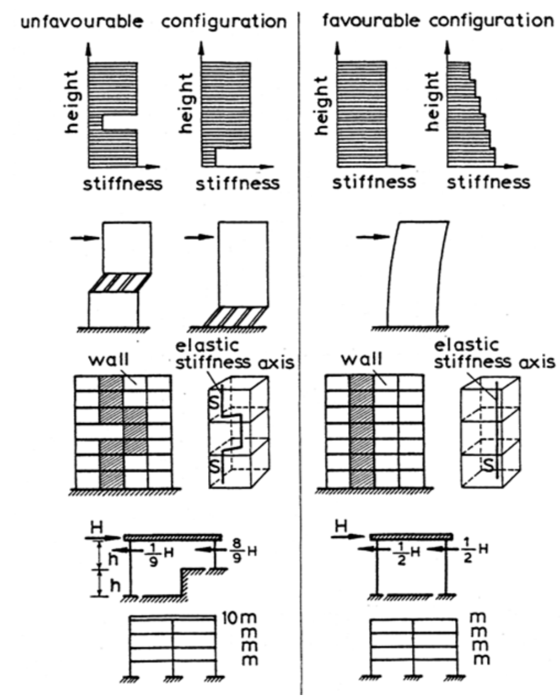
- How to do this?
  - Focus on seismic performance evaluation of a given design
- Three approaches:
  - Indicator-based evaluation
    - Use a number of building characteristics to verify performance
  - Quasi-dynamic evaluation
    - Use a "simple" method to verify performance
  - Dynamic evaluation
    - Use a "no-compromise" method to verify performance



Life-Safety PO Evaluation: Indicator-Based Approach







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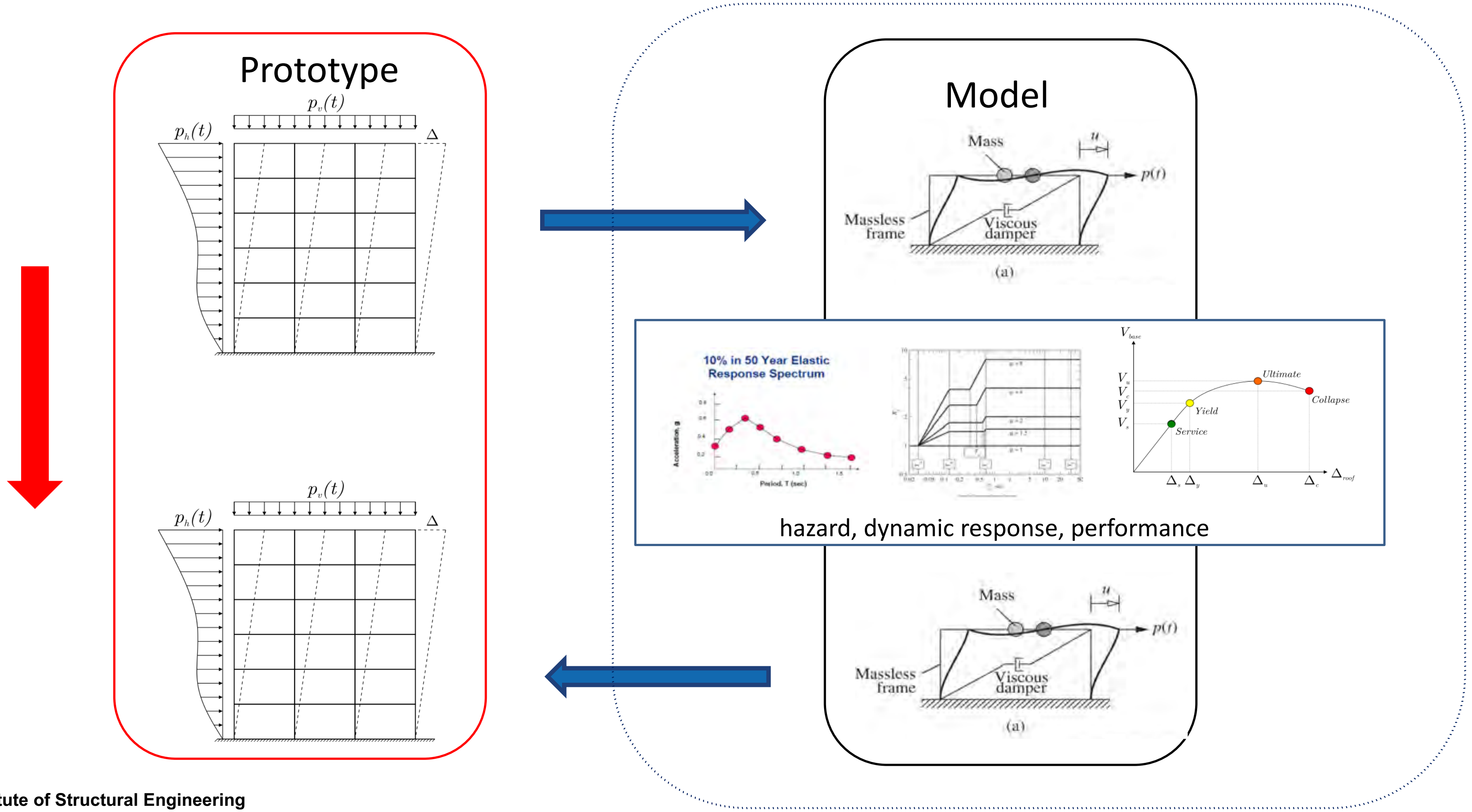
After EuroCode 8

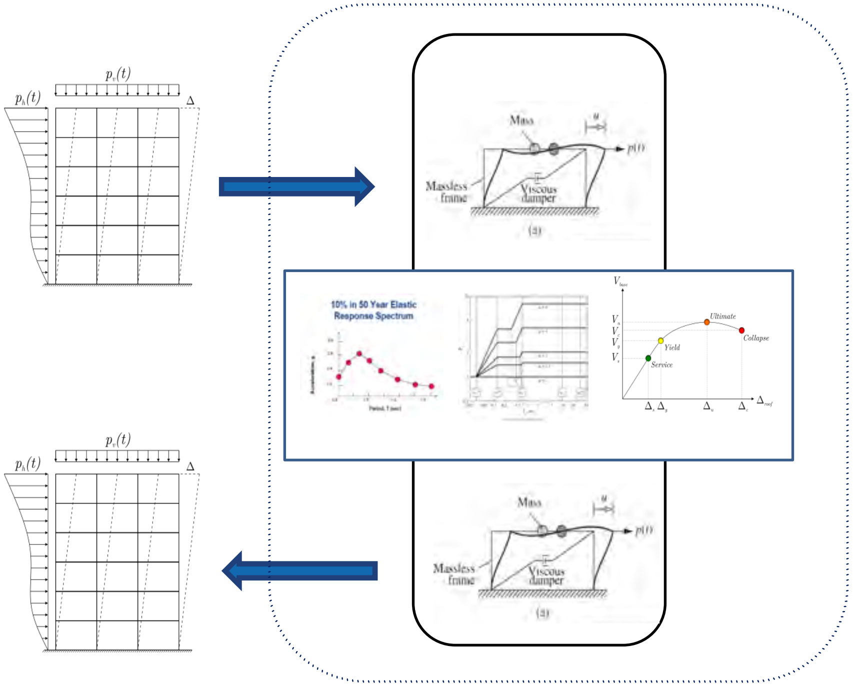
http://teicm.panagop.com/files/seismicdesignerasmus/Lecture05.pdf

Life-Safety PO Evaluation: Dynamic and Quasi-Dynamic Approach



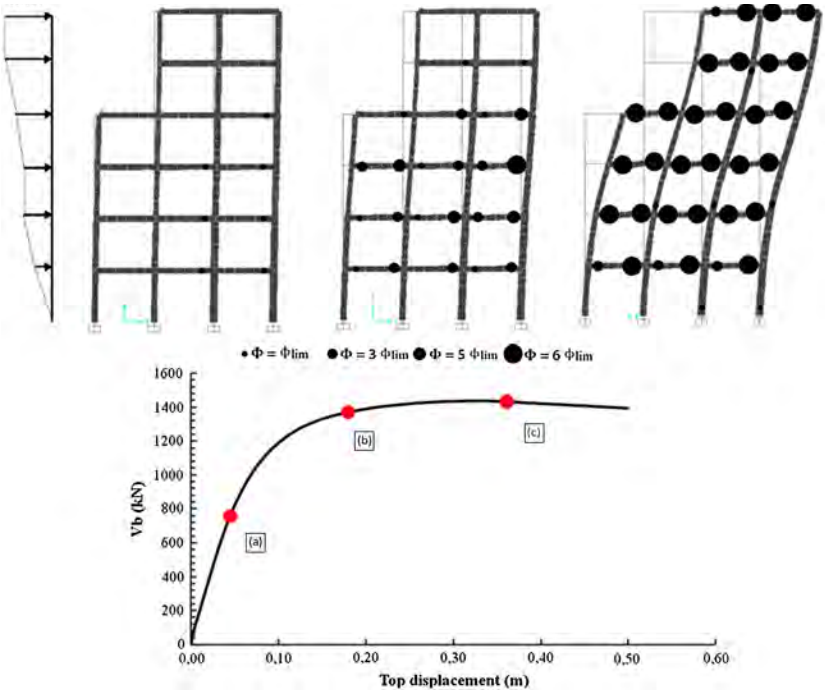
Life-Safety PO Evaluation: Quasi-Dynamic Approach

- Develop a model of the structure
- Define a “simple” system that conserves the most important dynamic characteristics of the structure
- Examine the seismic response of the “simple” system for a given seismic hazard:
  - Find the deformation and force demands
- Convert the outcomes to the model of the structure



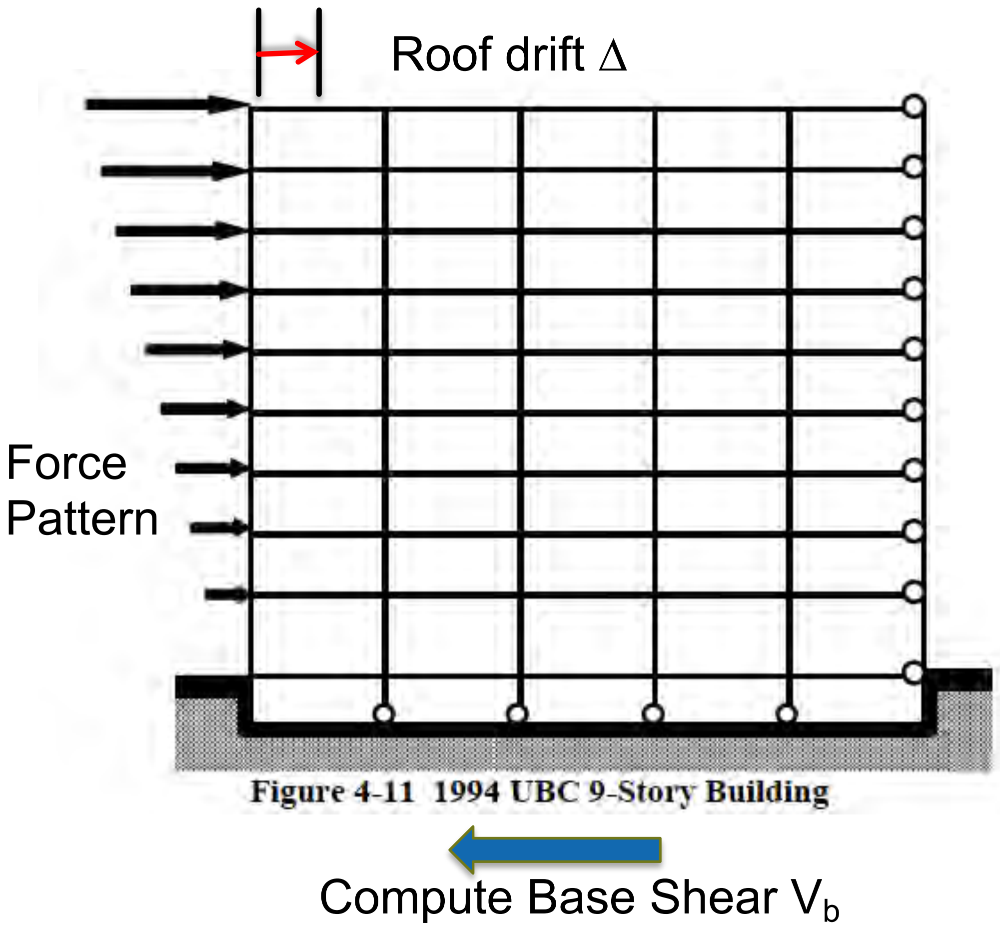
Life-Safety PO Evaluation: Nonlinear Static Pushover Analysis

- Belongs to the family of seismic response spectrum methods
- Two uses:
  - In evaluation, used to determine the force and deformation capacities of the structures
  - In design, used to determine the force and deformation demands on the structures for a given design seismic hazard



Cimellaro et. al, 2014

Life-Safety PO Evaluation: Nonlinear Static Pushover Analysis



- Apply a lateral force pattern representative of the first-(fundamental)-mode response
- Push the structure sideways until the model of the structure collapses
- Plot the relation between the structure base shear and roof drift:
  - This is the nonlinear static pushover curve

Life-Safety PO Evaluation: Nonlinear Static Pushover Analysis

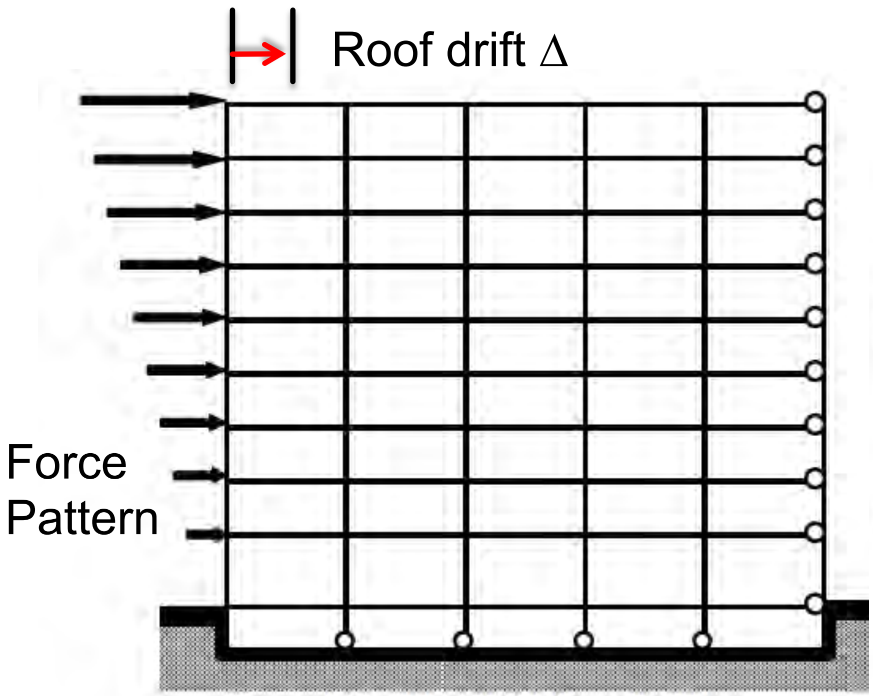
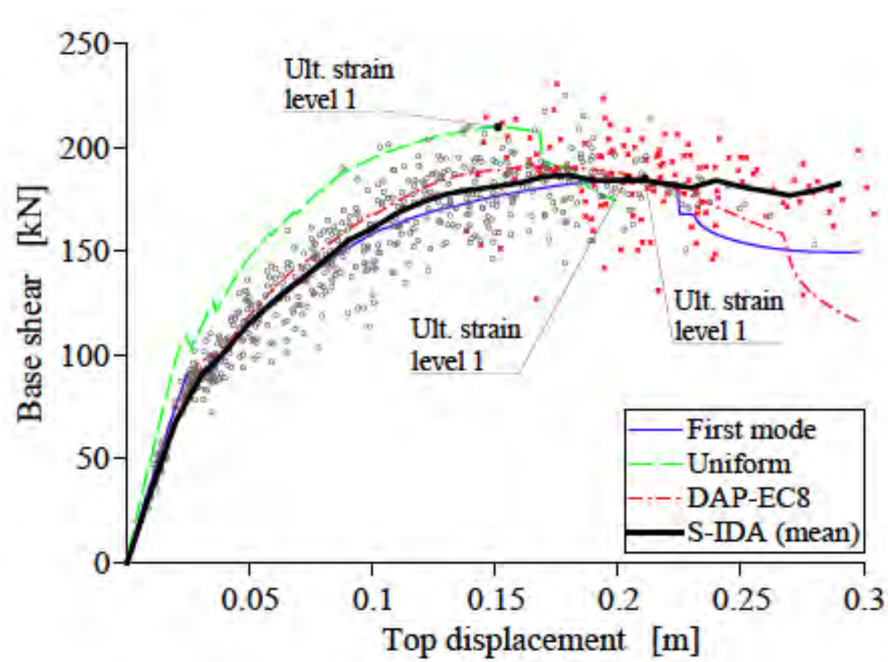


Figure 4-11 1994 UBC 9-Story Building

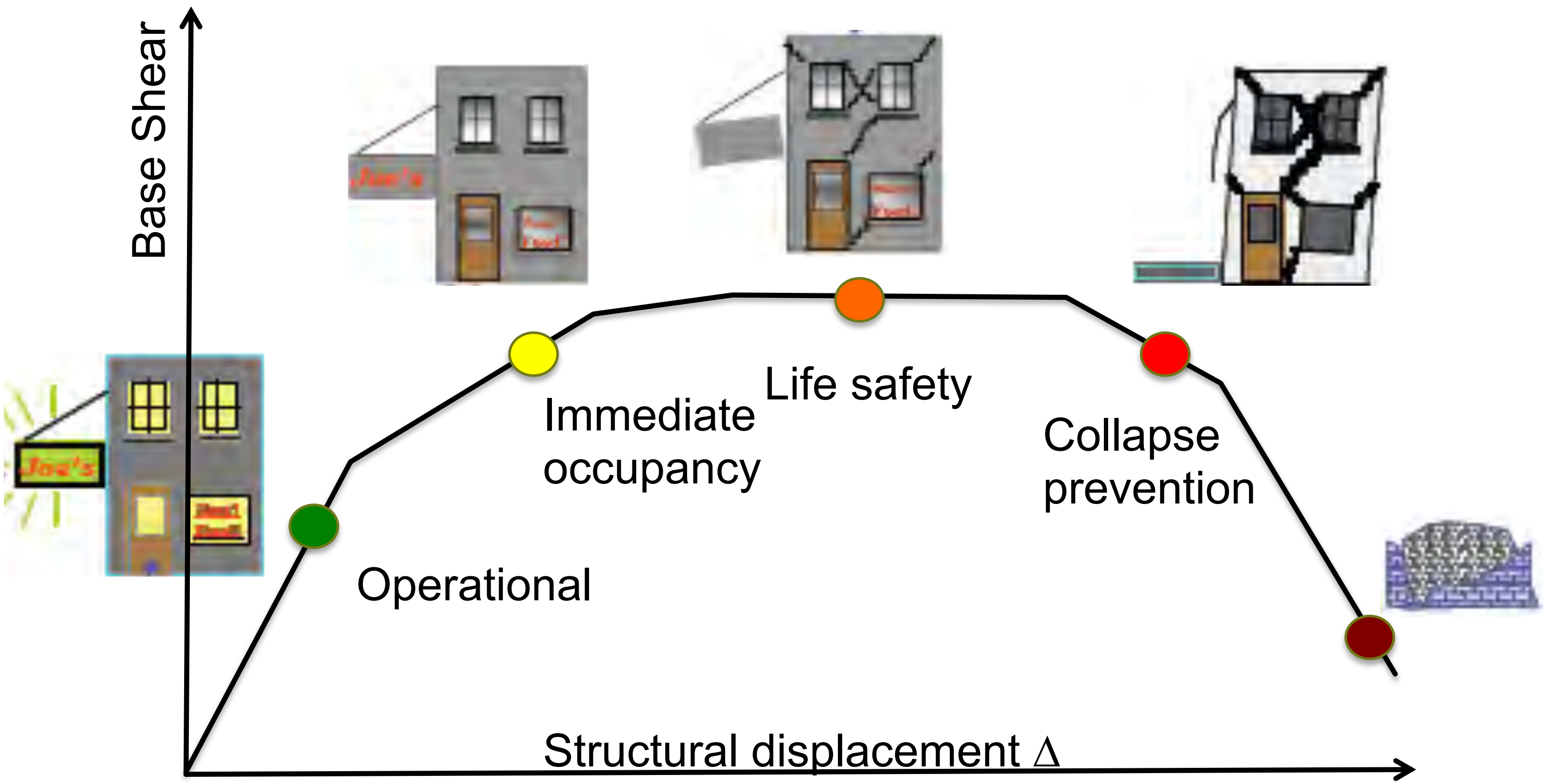
Compute Base Shear V_b



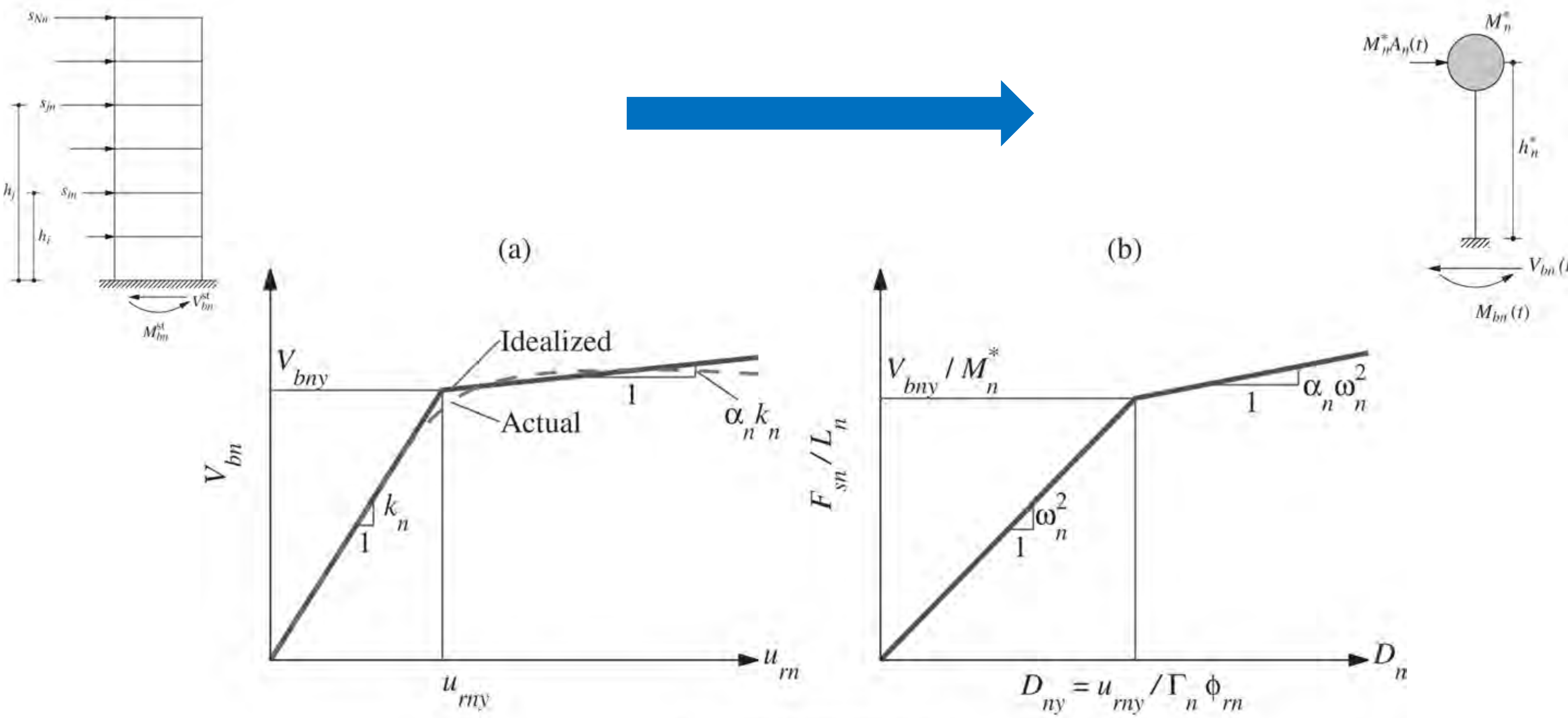
Diotallevi, et al. U. di Bolognia

Life-Safety PO Evaluation: Nonlinear Static Pushover Curve

- This is the capacity of the structure



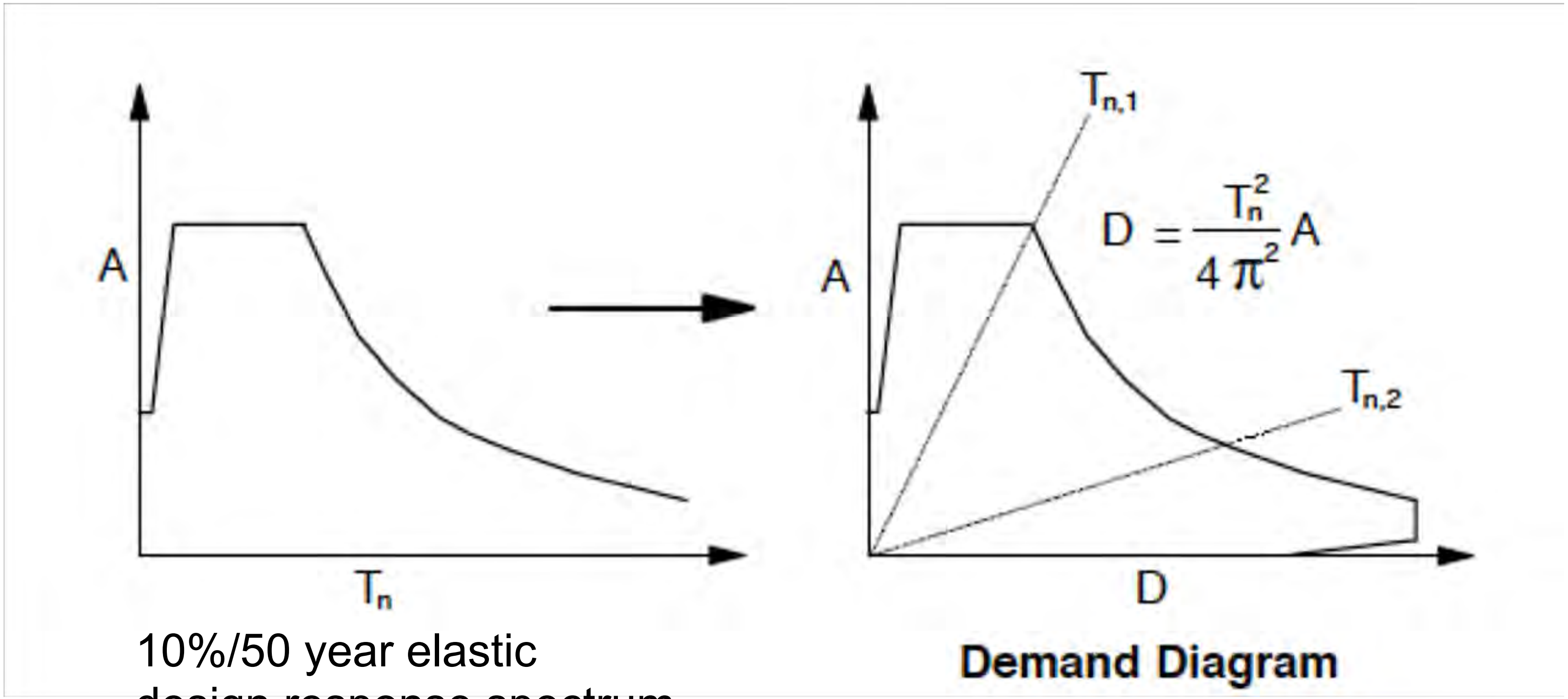
Life-Safety PO Evaluation: Capacity Spectrum Method



Chopra, 2012

Life-Safety PO Evaluation: Elastic Seismic AD Response Spectrum

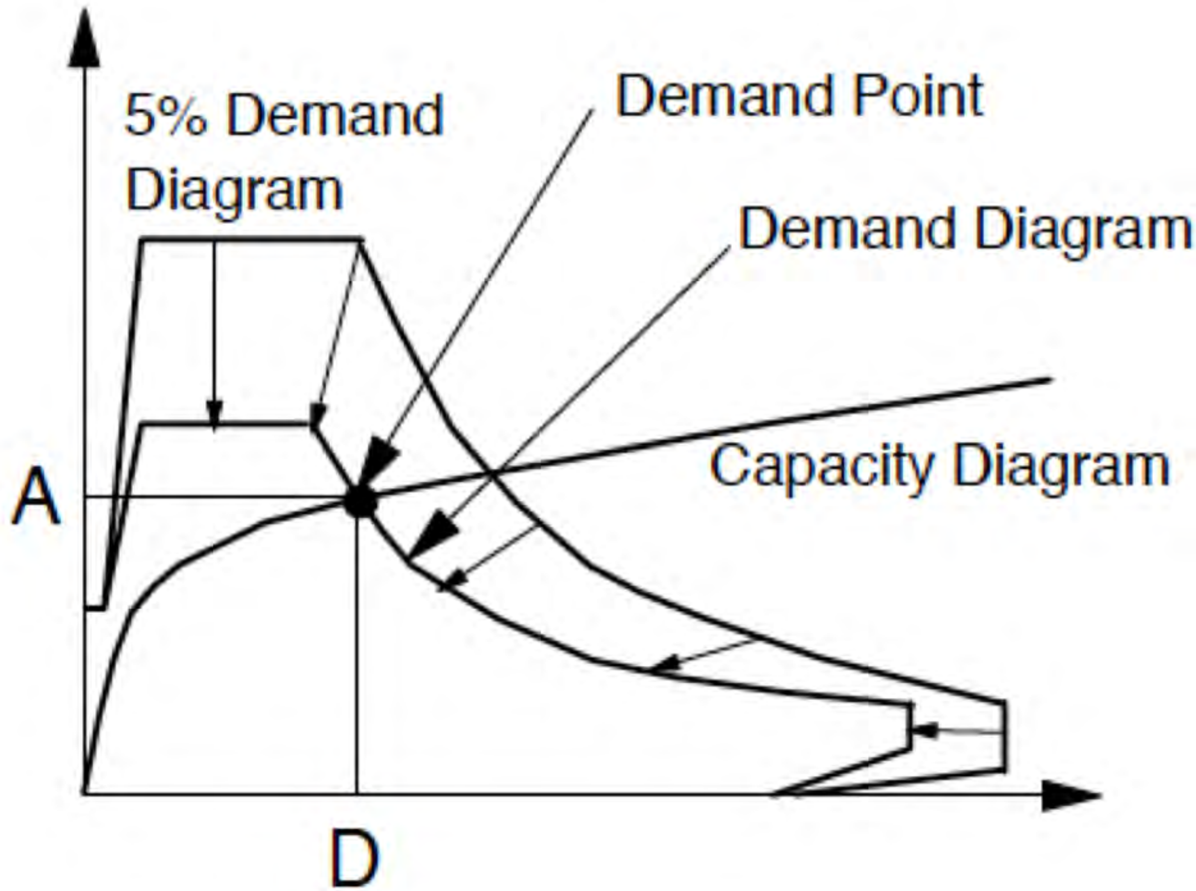
- This is the demand for the structure



10%/50 year elastic
design response spectrum

Goel and Chopra, 1999

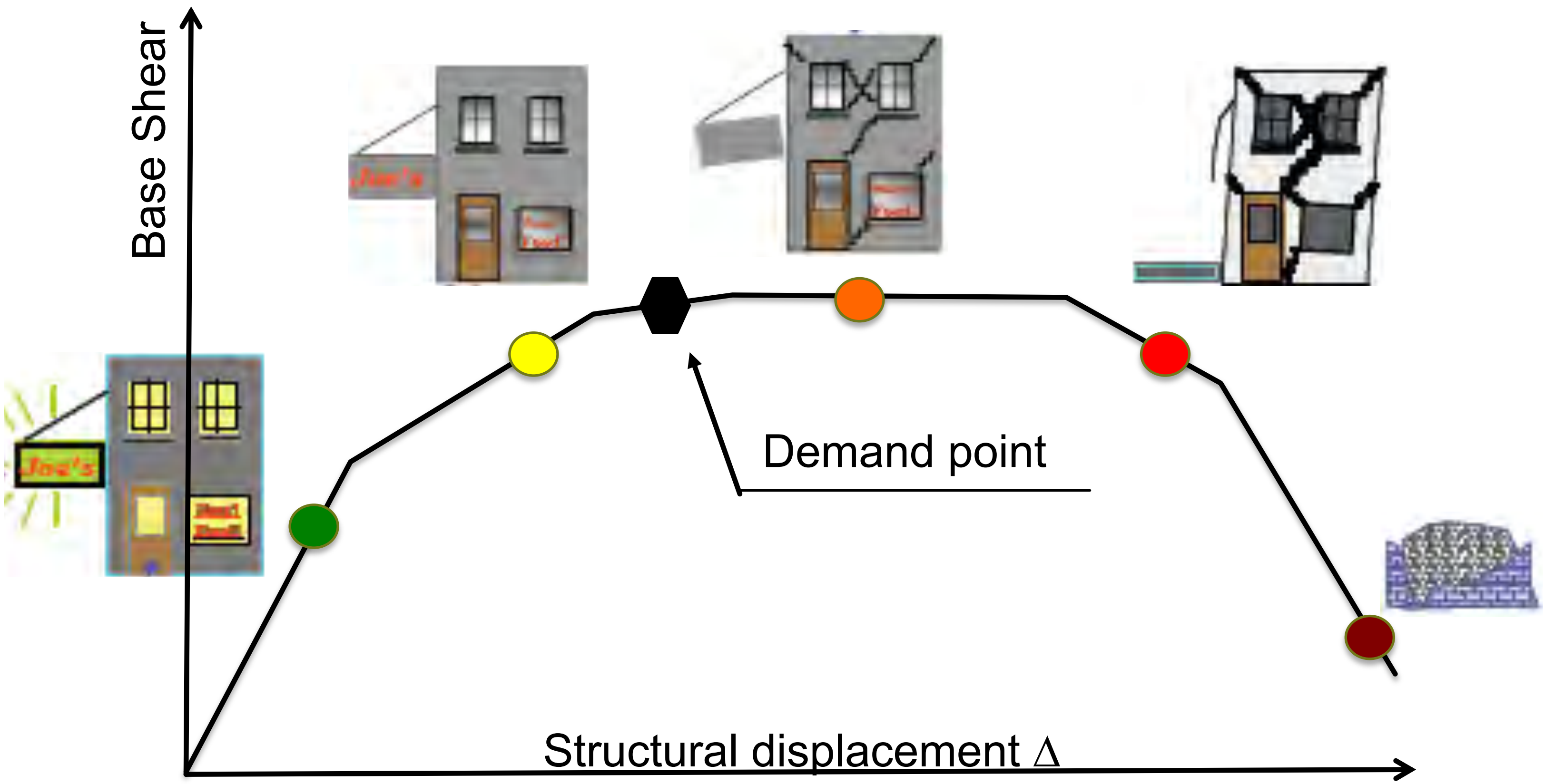
Life-Safety PO Evaluation: Capacity Spectrum Method



Goel and Chopra, 1999

Life-Safety PO Evaluation: Nonlinear Static Pushover Curve

- Locate the Demand Point on the Capacity Pushover Curve

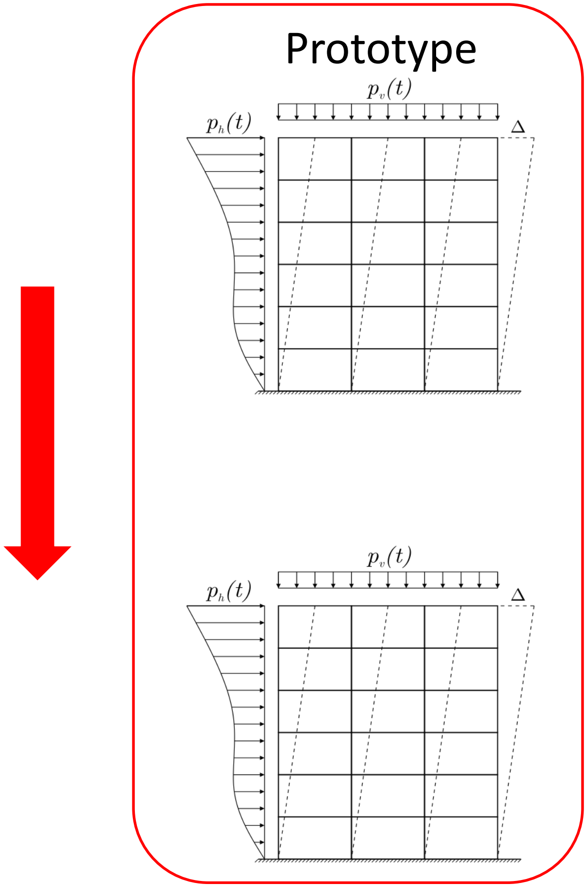


Practical Performance-Based Seismic Design: Life-Safety

Performance Objective		Acceptance criteria	
Seismic Hazard Exposure	Performance Goal	Deterministic Evaluation	Probabilistic Evaluation
Once in a life time 10% probability of exceedance in a 50 year period	Life safety: Significant, possibly irreparable structural and nonstructural damage, some injuries, no loss of life	Structure and element drift, deformation ductility and strength limits	90% confidence that there is an 10% probability of exceedance in 50 years.

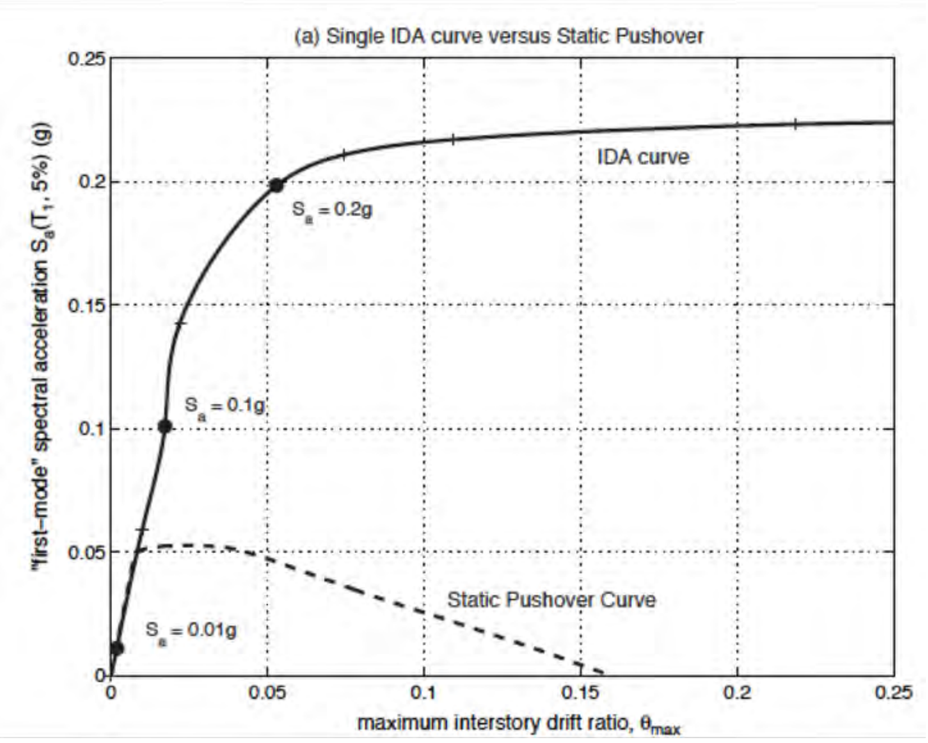
Life-Safety PO Evaluation: Dynamic Approach

- Develop a model of the structure
- Select a suite of ground motions to represent the seismic hazard exposure of the structure
- Perform a (large) number of non-linear time history analyses to compute the pertinent response quantities
- Compute the statistical distributions of these quantities



Life-Safety PO Evaluation: Incremental Dynamic Analysis

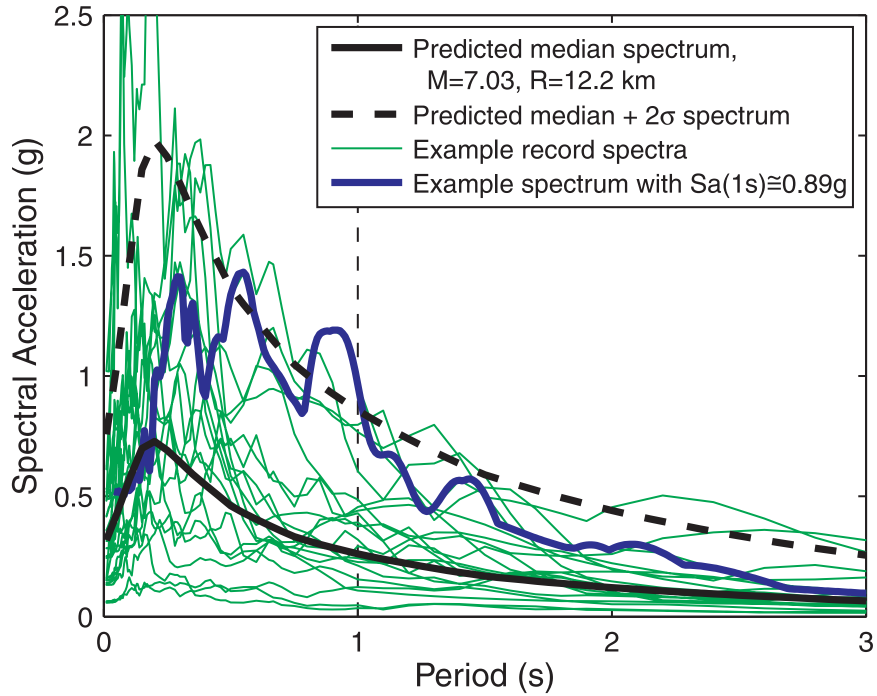
- A "combination" of static pushover analysis and dynamic time-history analysis:
  - Select a ground motion record
  - Conduct a time history analyses with incrementally upscaled ground motion record
  - Plot peak base shear and roof drift points on force-deformation (pushover) graph



Vamvatsikos & Cornel, 2002

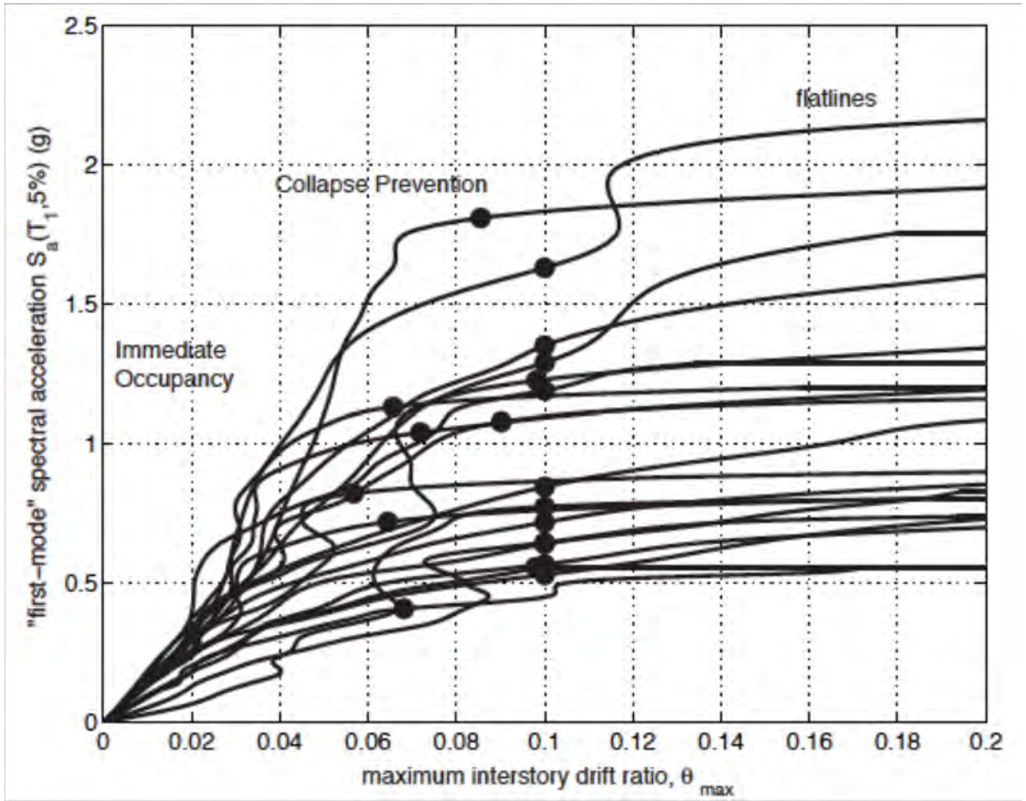
Life-Safety PO Evaluation: Incremental Dynamic Analysis

- Select ground motion time histories to represent the seismic hazard environment
- Prefer unscaled ground motions recorded in the same or in similar seismic hazard regions
- Avoid excessive scaling:
  - Up to 4 times may be OK
  - Choose strong records, too!



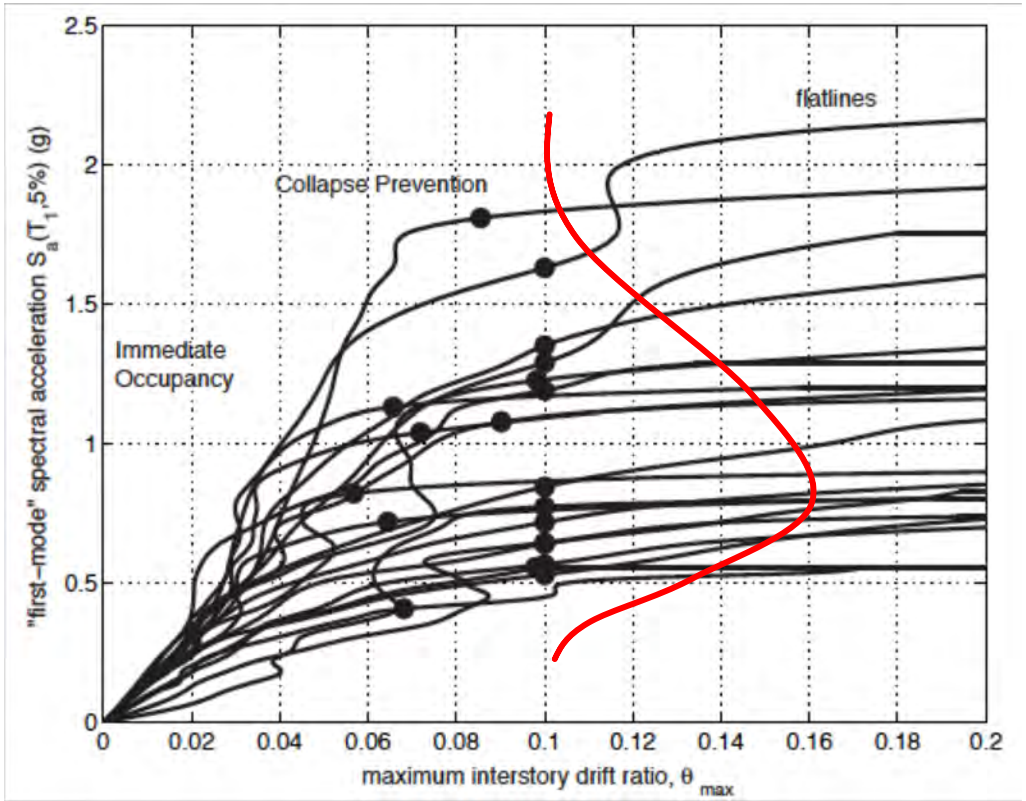
Life-Safety PO Evaluation: Incremental Dynamic Analysis

- Statistically analyze the IDA outcomes to determine the probability distribution of earthquake intensity for a desired performance objective, defined by roof or interstory drift



Life-Safety PO Evaluation: Incremental Dynamic Analysis

- Determine the confidence that the probability of exceedance of the performance objective is low enough over the observed life time of the structure



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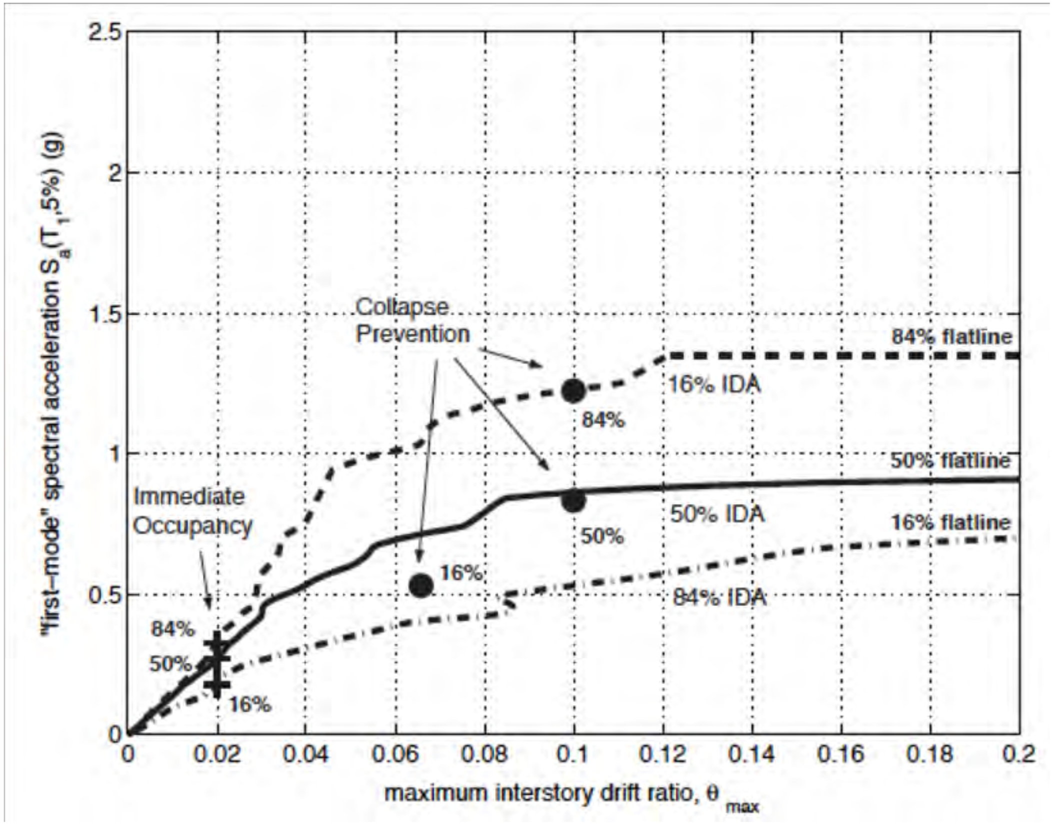

Practical Performance-Based Seismic Design: Life-Safety

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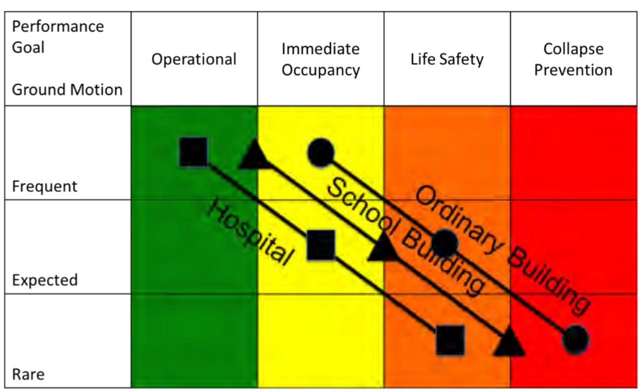
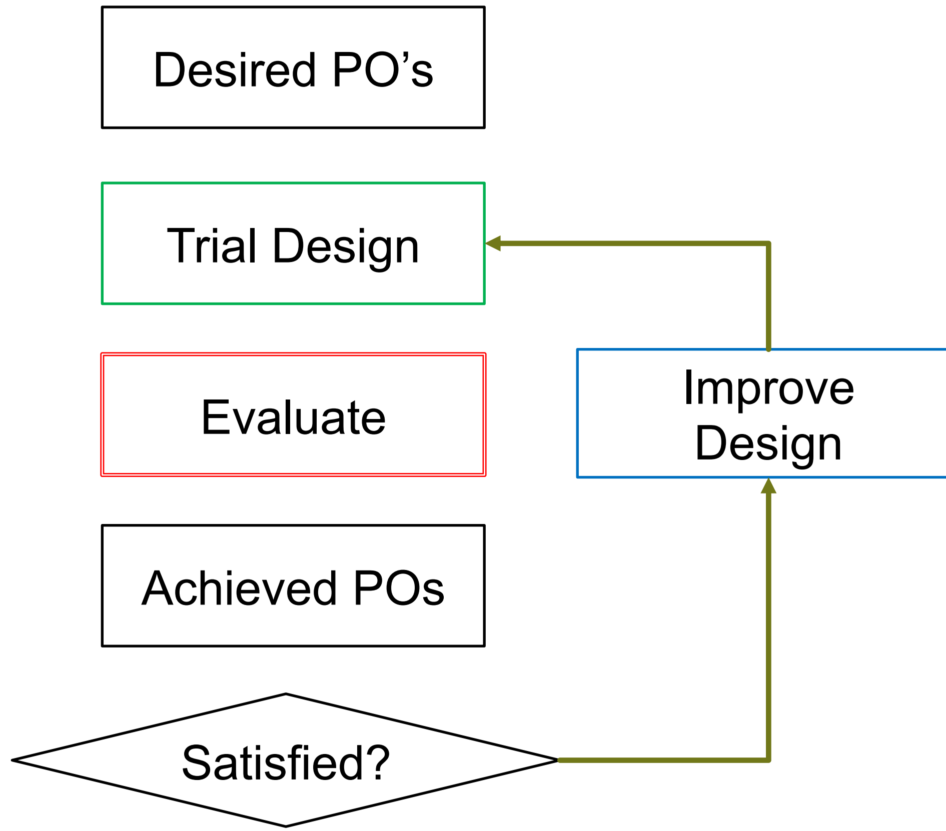
Performance-Based Risk-Informed Seismic Design

- Directly address the needs of the owner(s) of of the user(s) of the structure, process or system in the life time of their risk exposure environment(s)





Performance-Based Risk-Informed Seismic Design

Shortcomings:

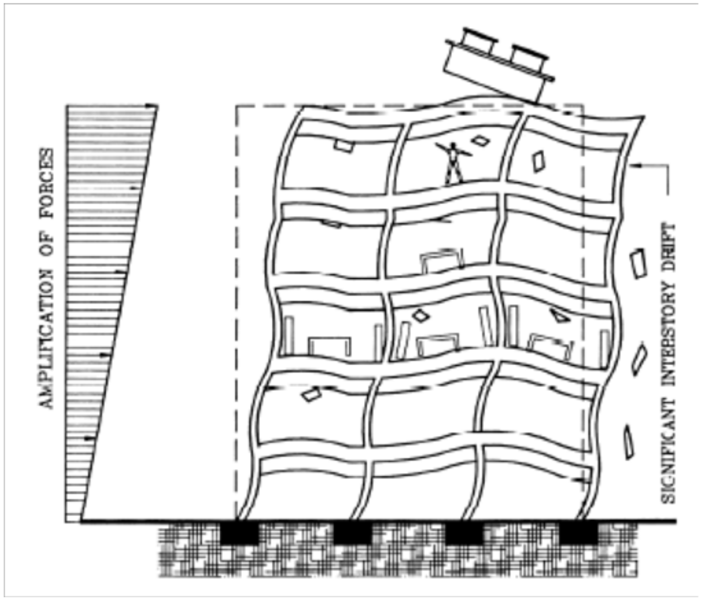
- It is quite demanding:
  - Good knowledge of the seismic hazard environment
  - Excellent non-linear modeling and analysis skills
  - Ability to transfer probabilistic conclusions into design actions
- It is time-consuming
- It is difficult to convince investors to finance this above-code minimum work

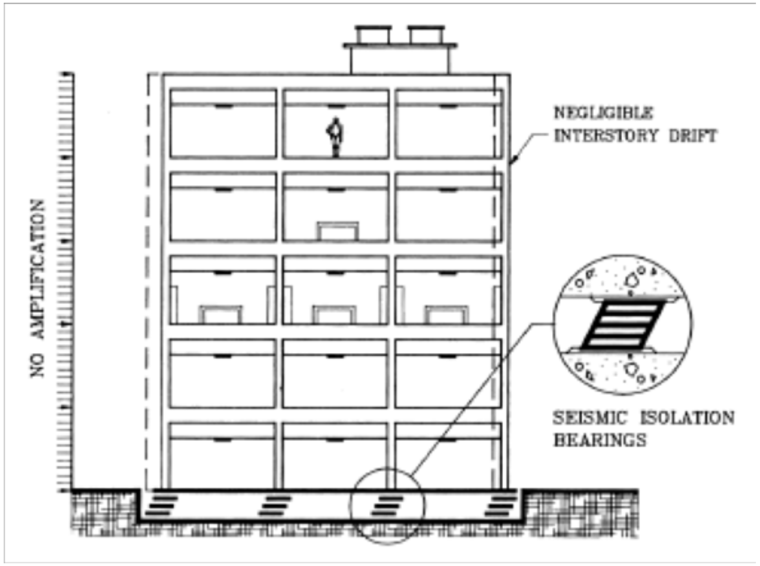
Benefits:

- It rewards an engineer with better knowledge about and confidence in the good behavior of the structure
- It allows an extension from engineering to financial decisions:
  - Makes it possible to address the true risk exposure of the owner or the user
- Explicitly differentiates between excellent and average designs

Performance-Based Risk-Informed Seismic Design

- Rewards desiring with seismic response modification techniques to enhance performance
  - Base isolation, damping, buckling-restrained bracing…





Performance-Based Design

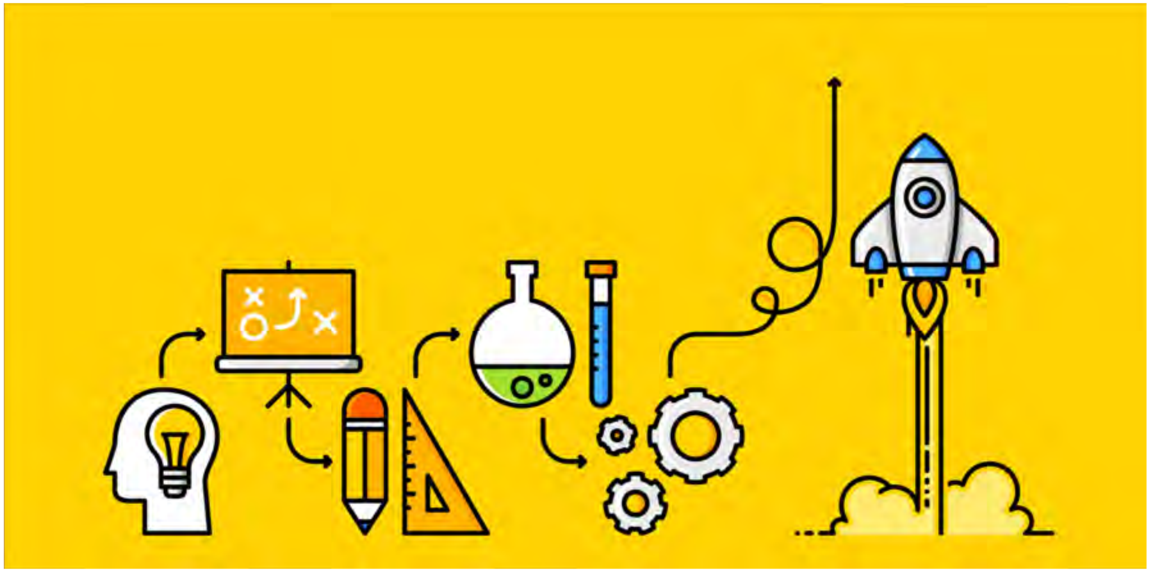
- Design to achieve specified results rather than to adhere to particular technologies or prescribed means
  (Moehle, EERI Distinguished Lecture, 2005)

- Transcends seismic design

- Applies to "engineering for extremes":
  - Fire protection engineering
  - High-wind engineering
  - High-water engineering (e.g. tsunami)

Engineering for Extremes

- To design is to intentionally create an object or system or process that can sustain and/or quickly recover from extreme events



https://theblog.adobe.com/how-the-design-process-has-evolved/

Links

- Seismic hazard:
  - http://www.efehr.org/en/home/
  - http://www.efehr.org/en/hazard-data-access/hazard-spectra/
  - http://www.share-eu.org
  - http://www.sera-eu.org/en/home/
  - https://www.globalquakemodel.org
  - http://earthquake.usgs.gov/hazards/designmaps/
- Swiss resources:
  - http://www.seismo.ethz.ch/en/knowledge/seismic-hazard-switzerland/
  - http://www.seismo.ethz.ch/en/knowledge/seismic-risk-switzerland/
  - http://www.seismo.ethz.ch/en/knowledge/seismic-risk-switzerland/seismic-risk-tool/

Links

- PEER Center tools for seismic hazard and risk analysis:
  - https://simcenter.designsafe-ci.org/research-tools/regional-workflow/
  - https://simcenter.designsafe-ci.org/research-tools/ee-uq-application/
  - https://simcenter.designsafe-ci.org/research-tools/pbe-application/
- FEMA P58 seismic performance assessment tools
  - https://www.fema.gov/media-library/assets/documents/90380
- GEM OpenQuake platform:
  - https://www.globalquakemodel.org/openquake

Links

- Useful software:
  - OpenSees: http://opensees.berkeley.edu/index.php
    - Python interpreter: https://openseespydoc.readthedocs.io/en/latest/
    - GUI in GiD: http://gidopensees.rclab.civil.auth.gr
- IDA resources:
  - http://users.ntua.gr/divamva/software.html

- Companies doing seismic risk assessment
  - https://www.avantstructural.com
  - http://www.hbrisk.com