Probabilistic Performance-based Earthquake Engineering

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ACKNOWLEDGEMENTS:

- FIB TASK GROUP 7.7: PROBABILISTIC PERFORMANCE-BASED SEISMIC DESIGN
- DR. SELIM GÜNAY, UC-BERKELEY

Course Outline 1/2

Part I:

1. PBEE assessment methods
   - ✓ Conditional probability approaches such as SAC/FEMA & PEER formulations
   - ✓ Unconditional probabilistic approach

Questions

2. PBEE design methods
   - ✓ Optimization-based methods
   - ✓ Non optimization-based methods

Questions

3. PEER PBEE formulation demonstrated for electric substation equipment
   - ✓ Introduction
   - ✓ Hazard analysis
   - ✓ Structural analysis
   - ✓ Damage analysis
   - ✓ Loss analysis
   - ✓ Combination of analyses

Questions

Course Outline 2/2

Part II:

1. Application 1: Evaluation of the effect of unreinforced masonry infill walls on reinforced concrete frames with probabilistic PBEE

Questions

2. Application 2: PEER PBEE assessment of a shearwall building located on the University of California, Berkeley campus

Questions

3. Application 3: Evaluation of the seismic response of structural insulated panels with probabilistic PBEE

Questions

4. Future extension to multi-objective performance-based sustainable design
5. Recapitulation

Outline

1. **Application 1**: Evaluation of the effect of unreinforced masonry infill walls on reinforced concrete frames with probabilistic PBEE
2. **Application 2**: PEER PBEE assessment of a shearwall building located on the University of California, Berkeley, campus
3. **Application 3**: Evaluation of the seismic response of structural insulated panels with probabilistic PBEE

II-1 Application 1

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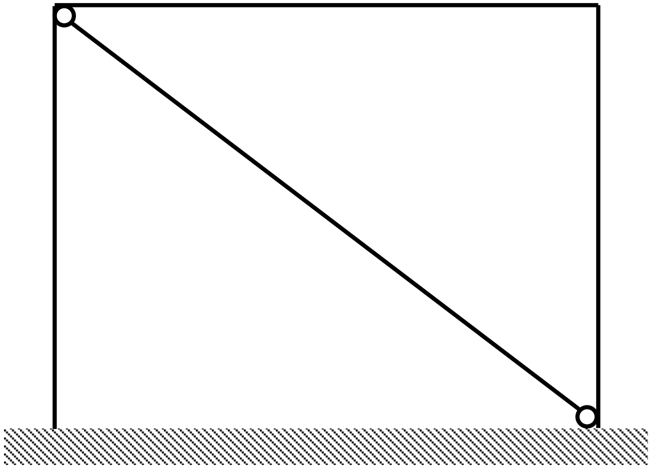
Application I

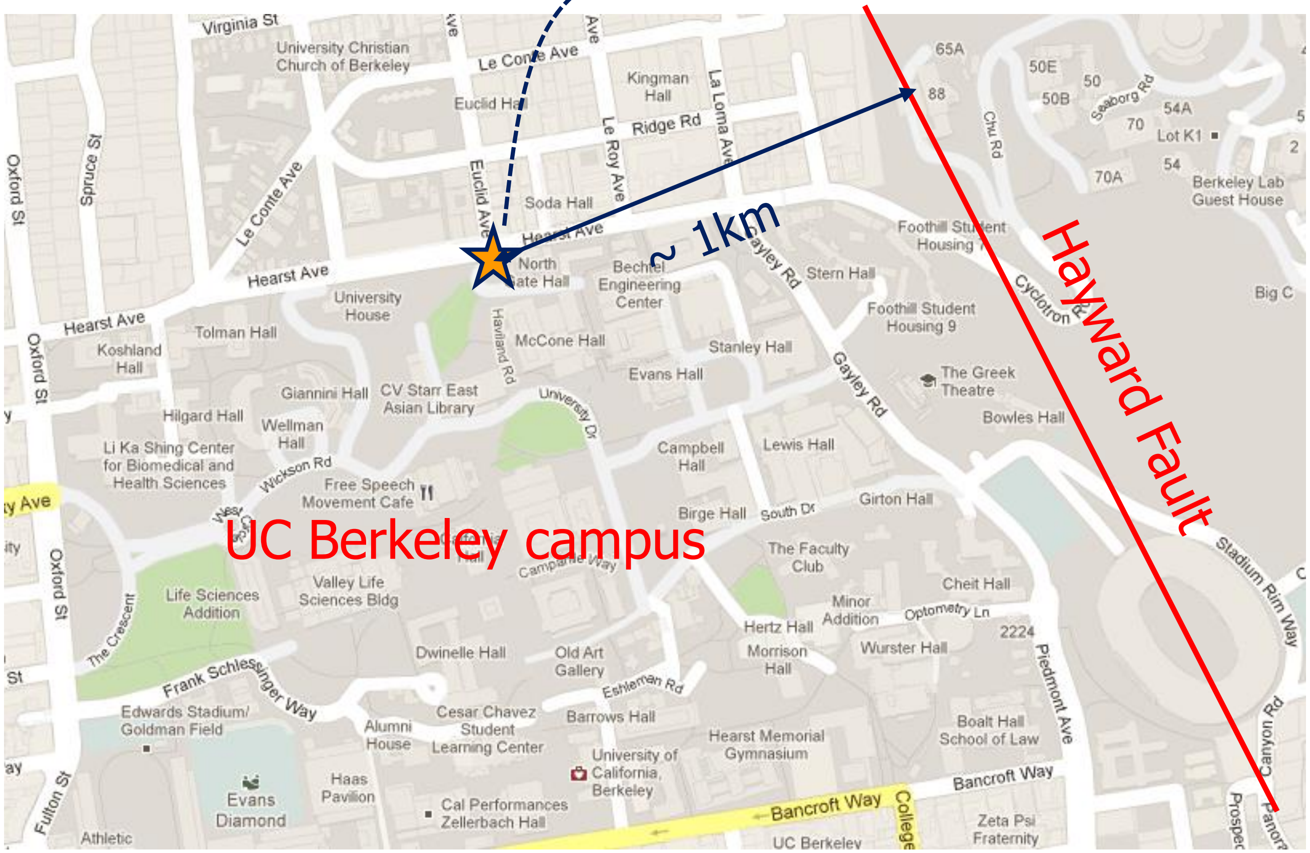
- An idealized portal frame **with and without** infill wall
- Demonstration of **hazard and structural analyses**
- The geometry of the portal frame based on dimensions of a single story RC frame with infill wall tested on UC-Berkeley shaking table [Hashemi & Mosalam, 2006].



Application I

Hazard Analysis

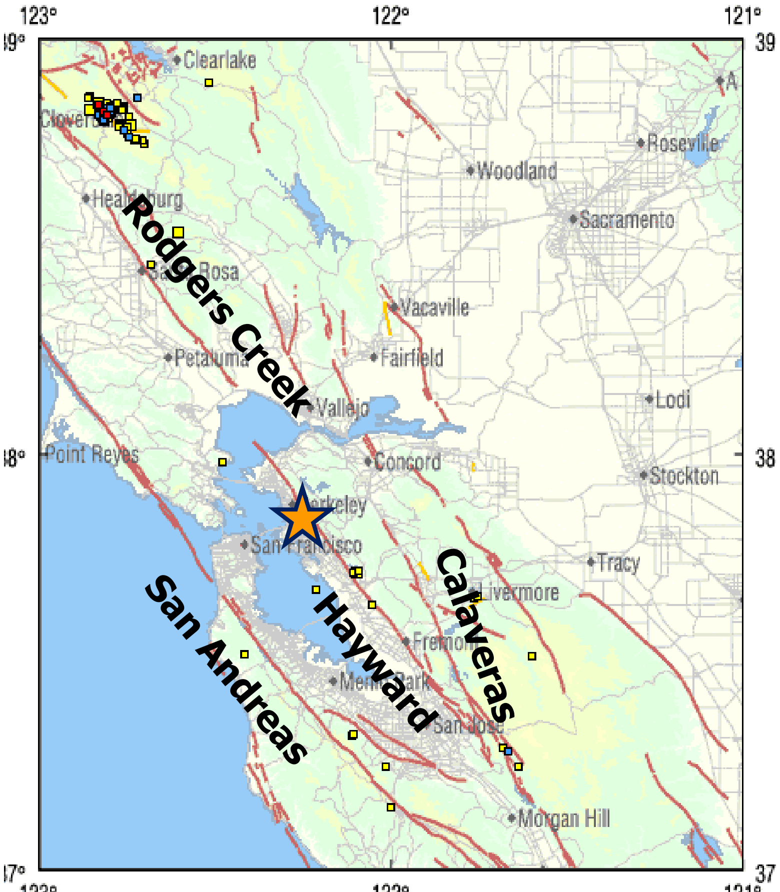
Location of the structure:
@North gate of campus
(37.877°, -122.264°)



Site class:
NEHRP D

Application I

Hazard Analysis



Source: USGS

Application I

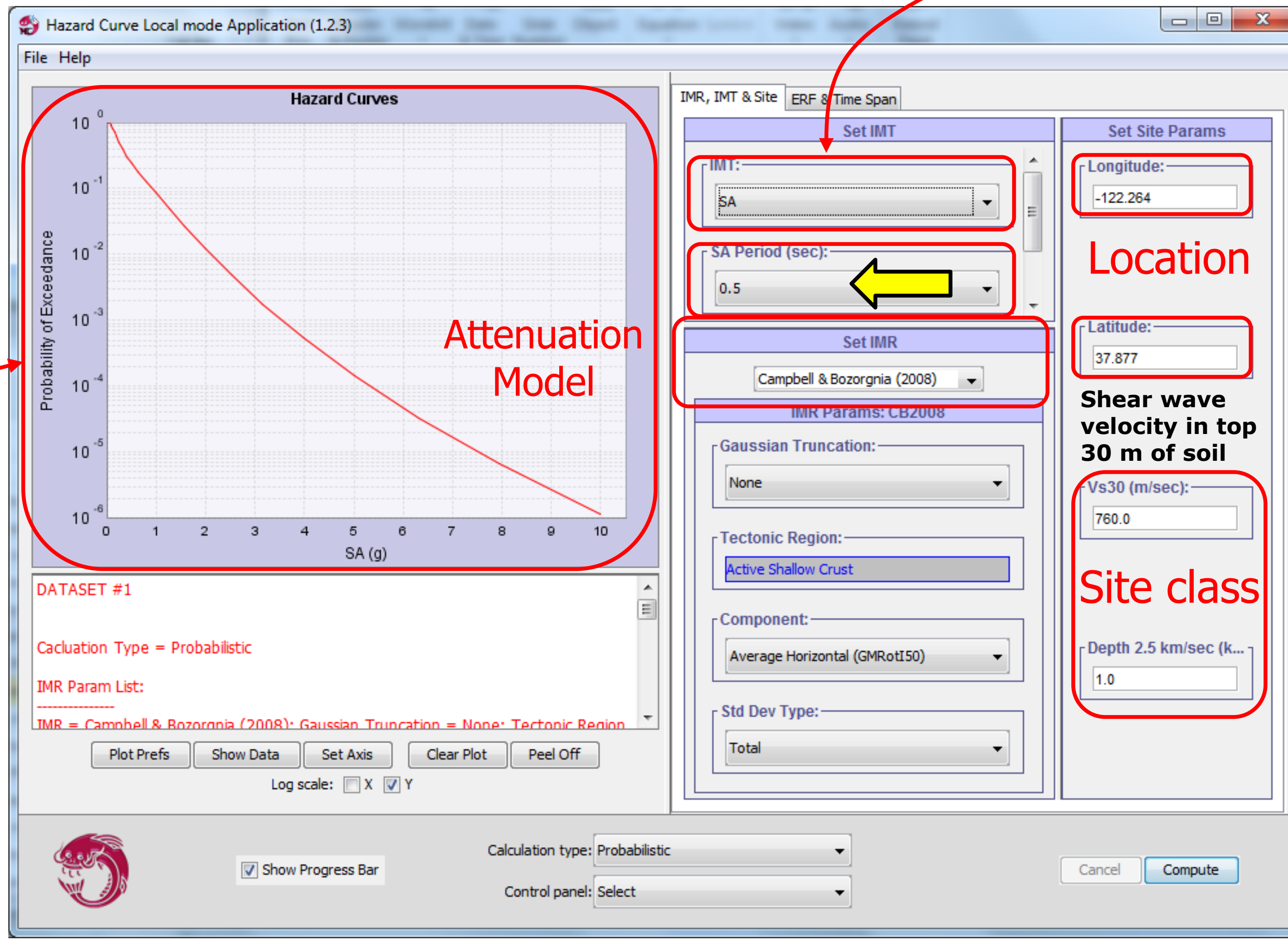
Hazard Analysis

$$P(\mathrm{IM}) = 1 - e^{-\lambda(\mathrm{IM})\,T}, T = 50 \text{ years} \Rightarrow \lambda(\mathrm{IM})$$

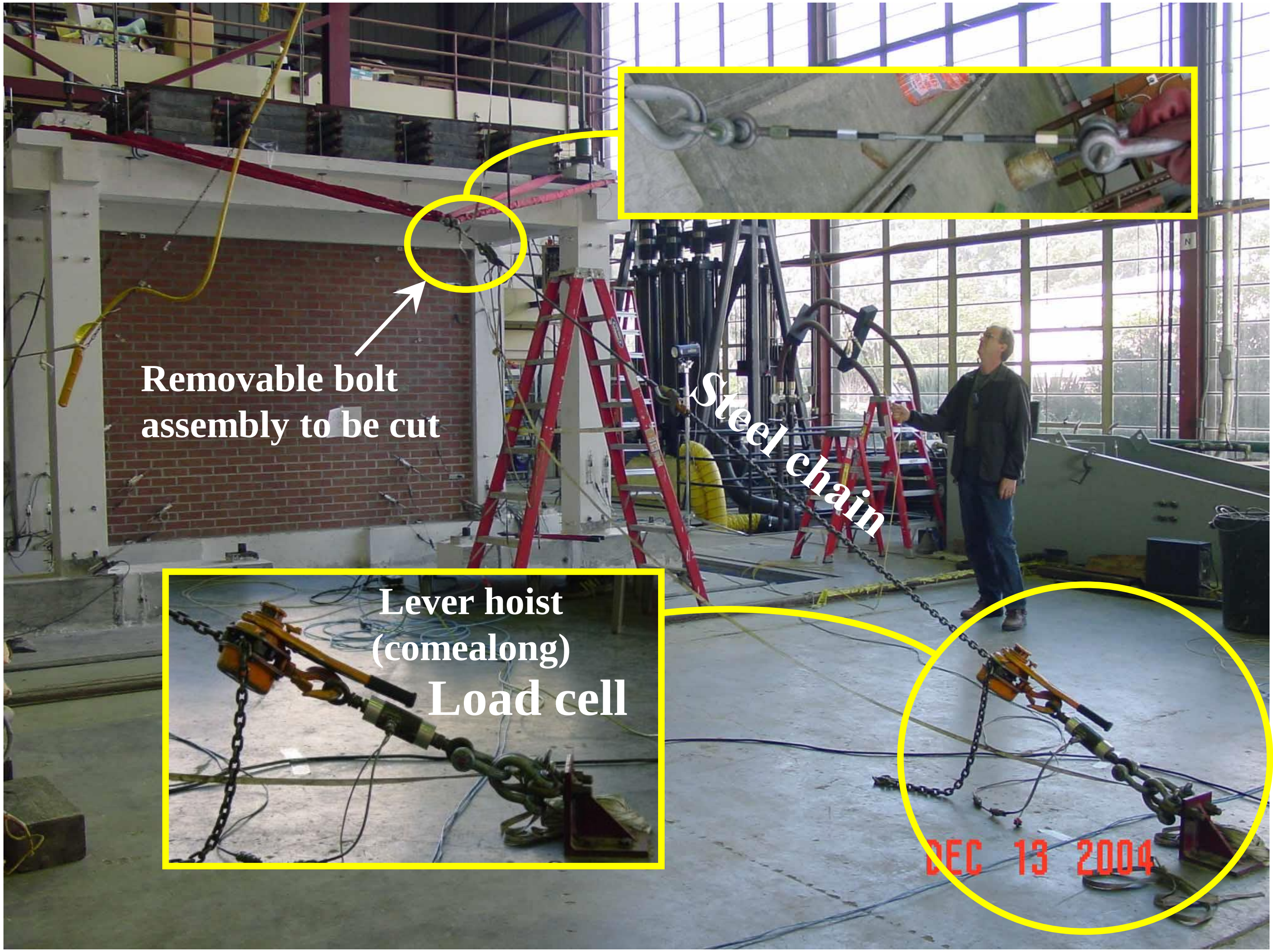
OpenSHA
http://www.opensha.org

IM type

Hazard Curve

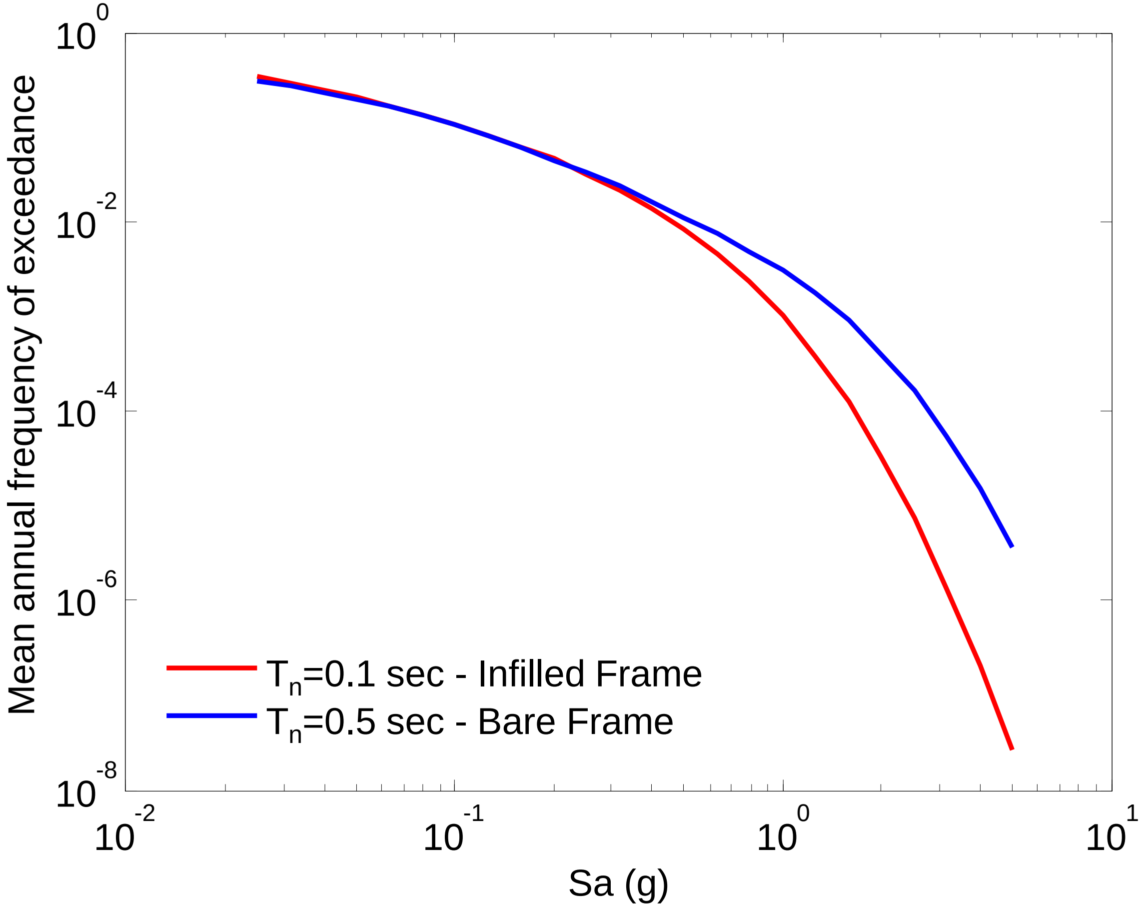


Application I



Application I

Hazard Analysis: Hazard Curve

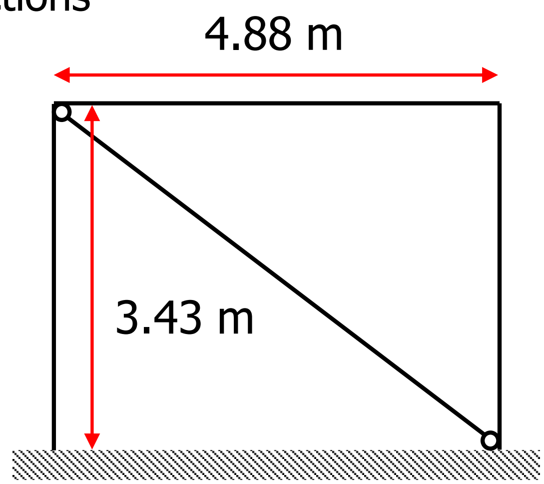


Hazard is more severe for the bare frame at this particular location

Application I

Structural Analysis

- Analytical modeling using OpenSees [2010]
- Force-based beam-column elements with fiber discretized sections
- Material for core and cover concrete: Concrete02
- Material for reinforcing bars: Steel01
- Material strengths [Hashemi & Mosalam, 2006]
  - **Concrete**: f_c' beam = 37 MPa, f_c' columns = 38 MPa
  - **Steel**: f_y = 458 MPa
- Sections:
  - **Columns**: 305×305 mm square section
  - **Beam**: 343×267 mm rectangular section
- Reinforcement:
  - **Columns**: Longitudinal: eight #6, Transverse: #3@95 mm
  - **Beam**: Longitudinal: three #6 bars (top and bottom), Transverse: #3@70 mm



Transverse reinforcement used to determine core concrete strength

Application I

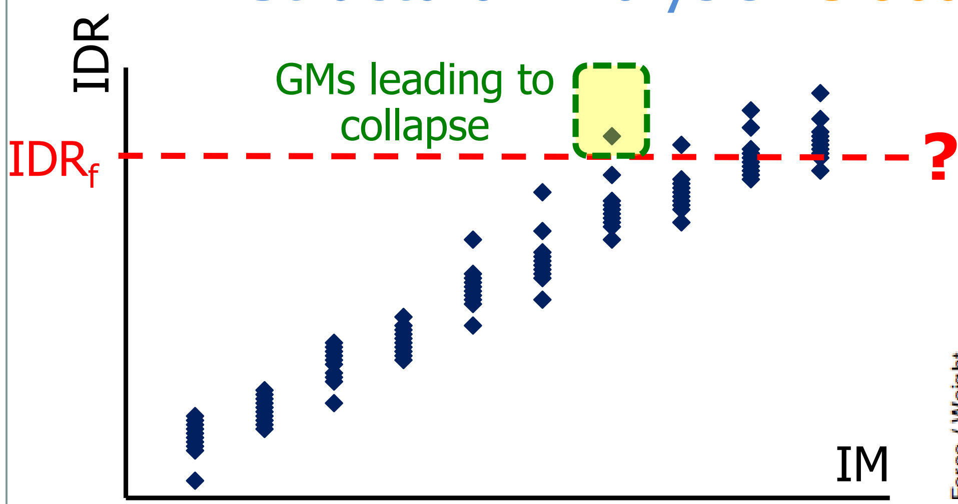
Structural Analysis

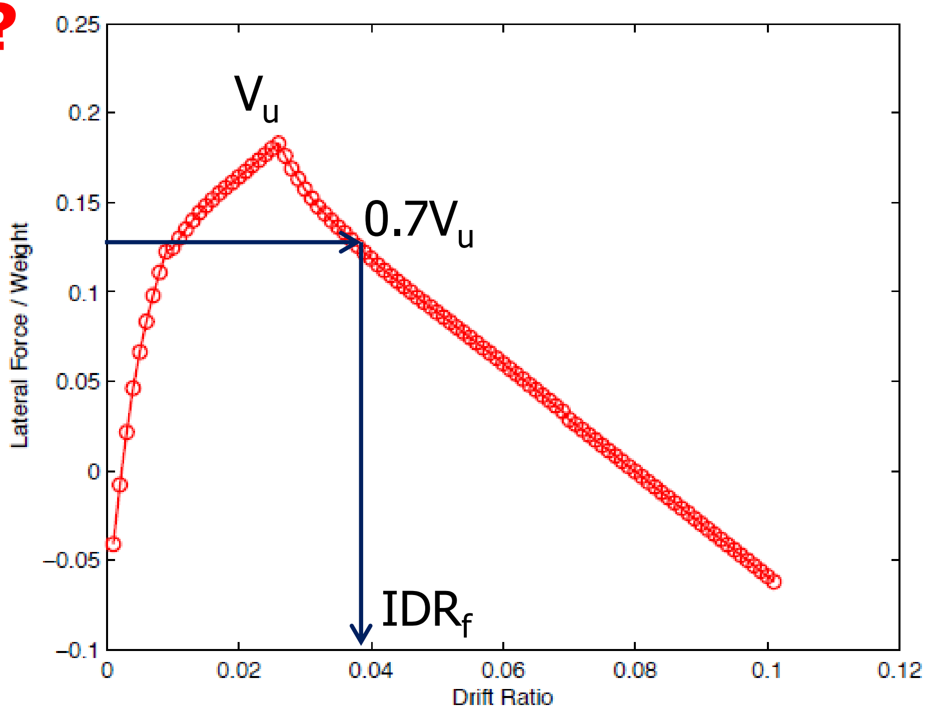
- Twenty ground motions [Lee & Mosalam, 2006] used in nonlinear time history analyses (explanation later in Application II)
- Ground motions scaled for each of the considered $S_a(T_1)$ value

  Note: Use of unscaled ground motions should be the preferred method in a real-life application
- For demonstration purposes, only uncertainty in ground motion is considered; material uncertainty is not taken into consideration
- Total number of analyses conducted for an intensity level is twenty
- Peak interstory drift ratio (IDR) & peak roof acceleration (RA) are considered as the EDPs

Application I

Structural Analysis: Global collapse determination



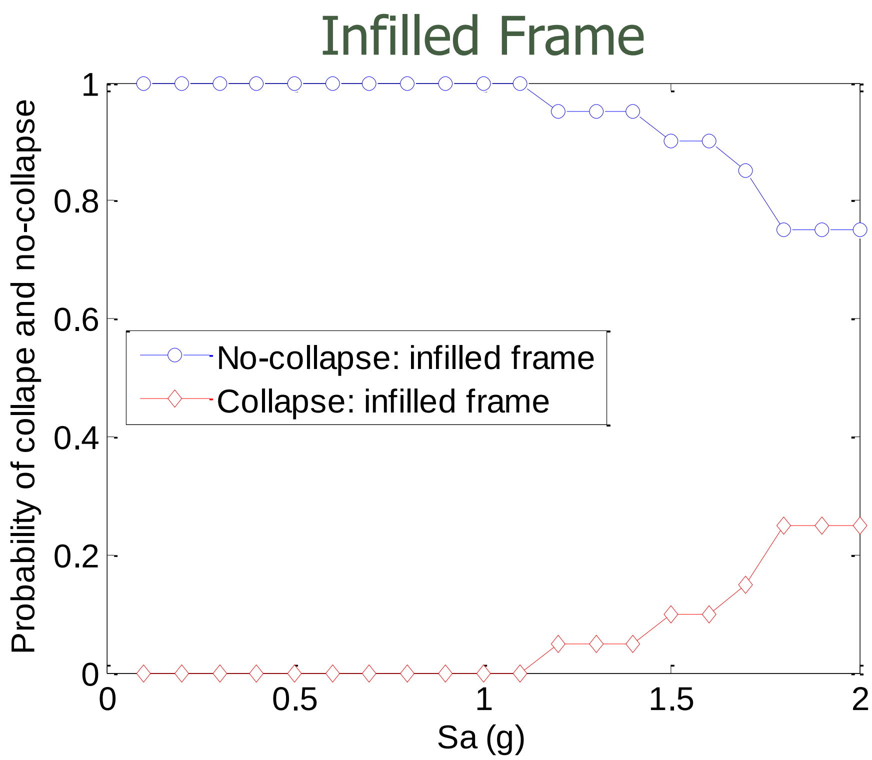


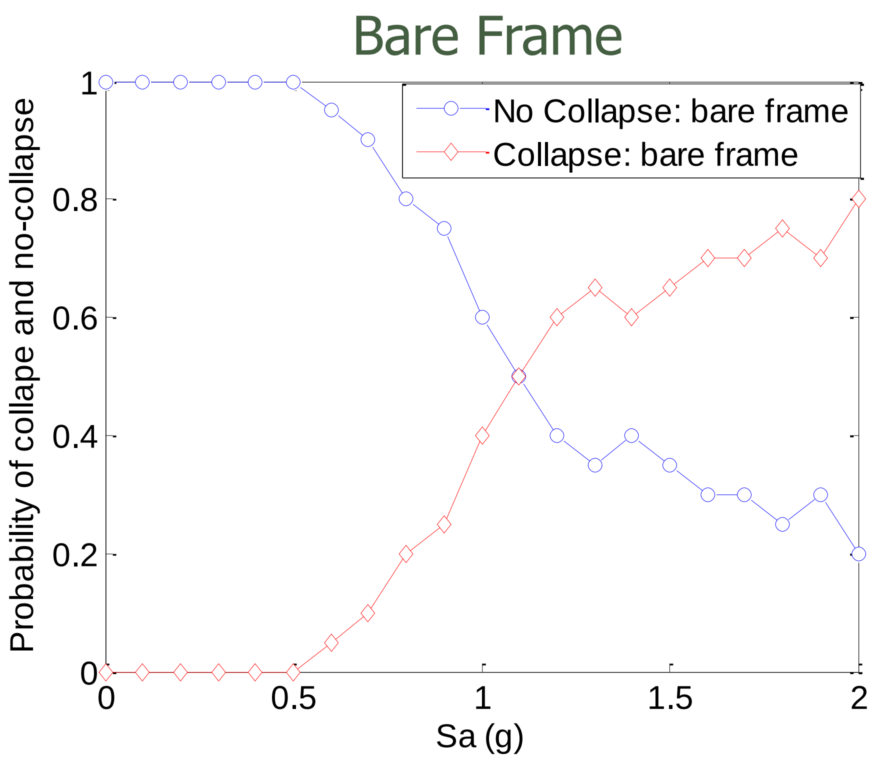
p(C|IM) =

\# of GMs leading to collapse/total # of GMs

Application I

Structural Analysis: Global collapse determination





Collapse probability is much less for the infilled frame case for all intensity levels: specific for this frame

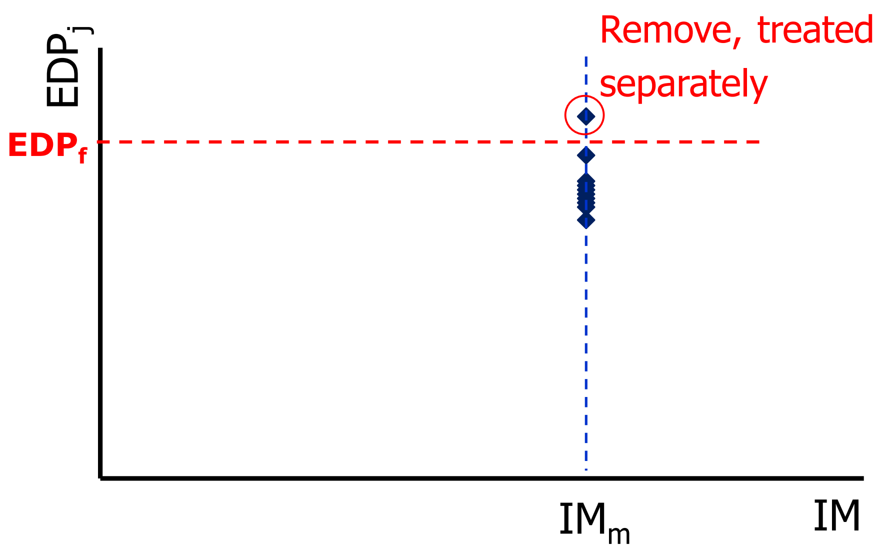
In a multistory, three-dimensional (3D) frame:

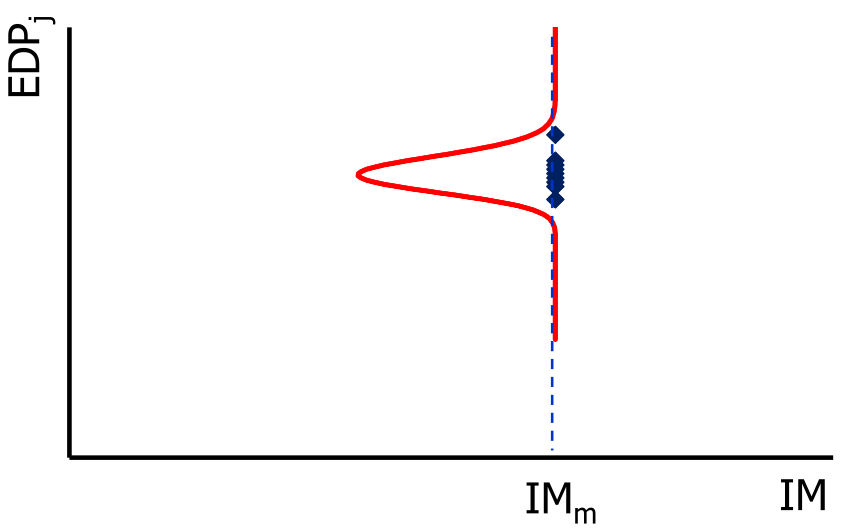
- Sudden failure of infill walls can lead to weak stories, which is usually followed by a global collapse
- Shear failure can be critical for columns because of lateral component of force transferred by infill wall

Structural Analysis

Outcome of Structural Analysis:

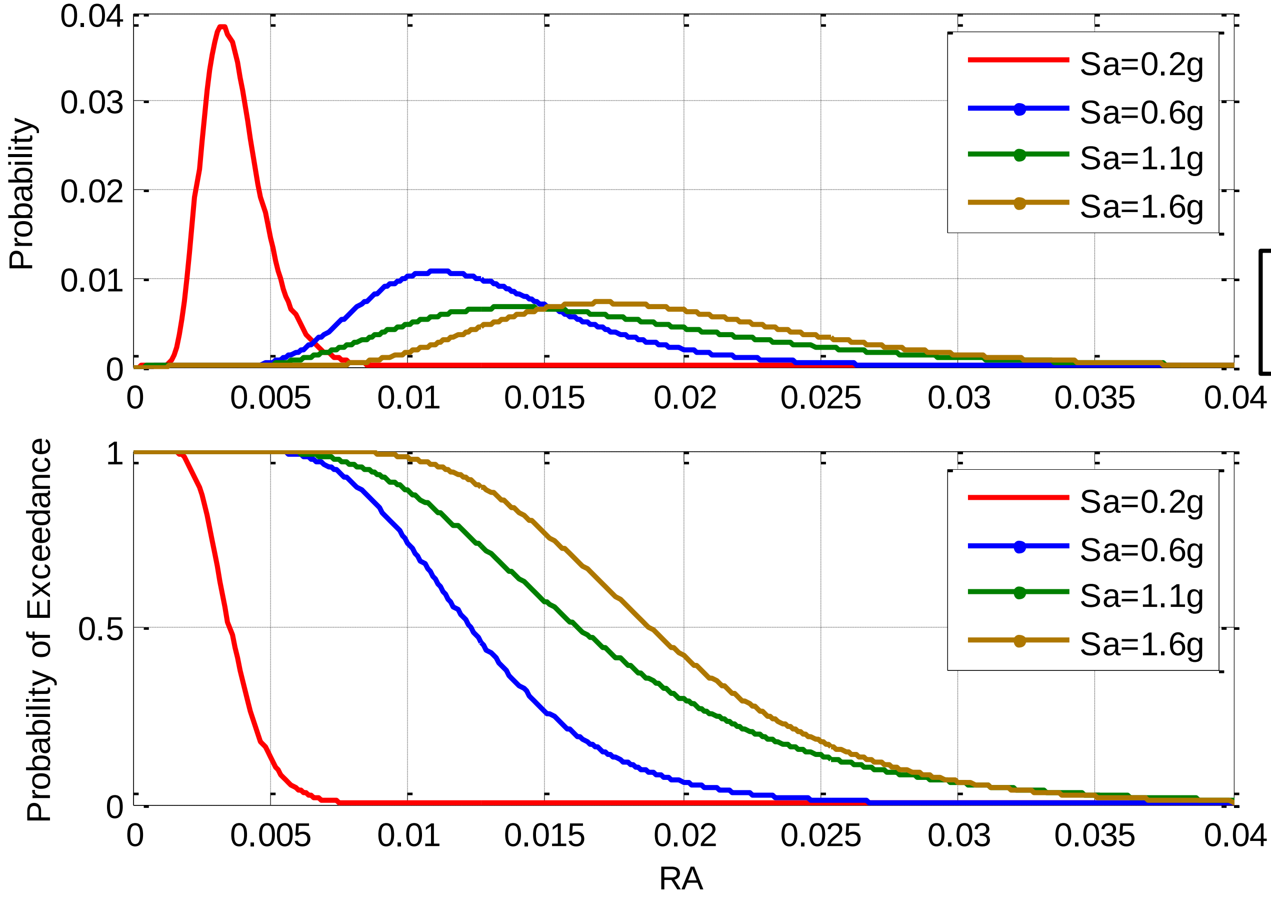
Probability of each value (index i) of each EDP (index j) for each hazard level (index m): $p(EDP_j^i|Im_m)$





Application I

Outcome of Structural Analysis: Probability and POE for IDR and RA "Only RA is shown here"



Lognormal distribution

Application I

Combination of Hazard and Structural Analyses

Total probability theorem:

Given n mutually exclusive events* $A_1,\ldots, A_n$ whose probabilities sum to 1.0, then the probability of an arbitrary event B:

$$p(B) = p(B|A_1)\,p(A_1) + p(B|A_2)\,p(A_2) + \ldots + p(B|A_n)\,p(A_n)$$

$$p(B) = \sum_i p(B|A_i)\; p(A_i)$$

Conditional probability of B given the presence of A_i

Probability of A_i

*Occurrence of any one of them automatically implies the non-occurrence of the remaining n−1 events

Application I

Combination of Hazard and Structural Analyses

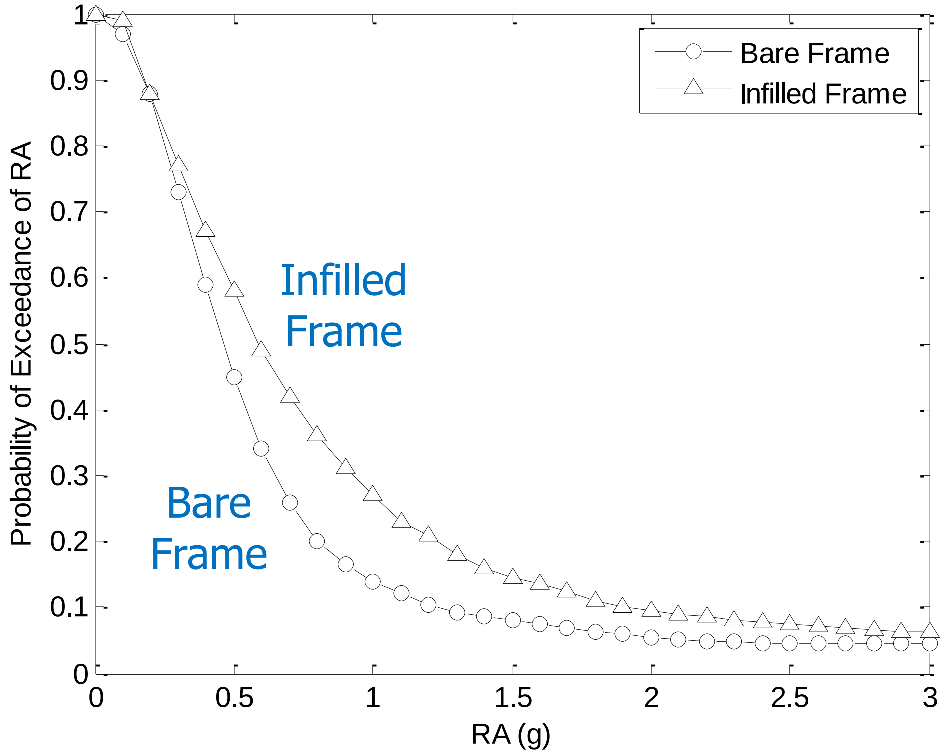
$$P(EDP^i) = \sum_m P(EDP^i | IM_m)\, p(IM_m)$$

$$P(RA^i) = \sum_m P(RA^i | Sa_m)\, p(Sa_m) \qquad P(IDR^i) = \sum_m P(IDR^i | Sa_m)\, p(Sa_m)$$

m: index for IM   i: index for EDP

Application I

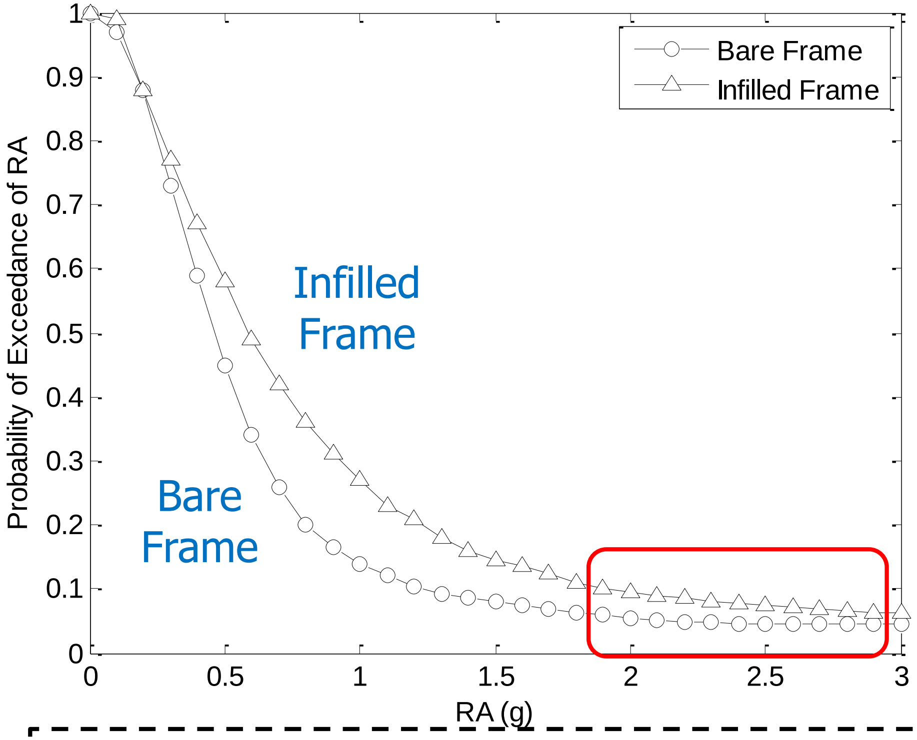
Combination of Hazard and Structural Analyses

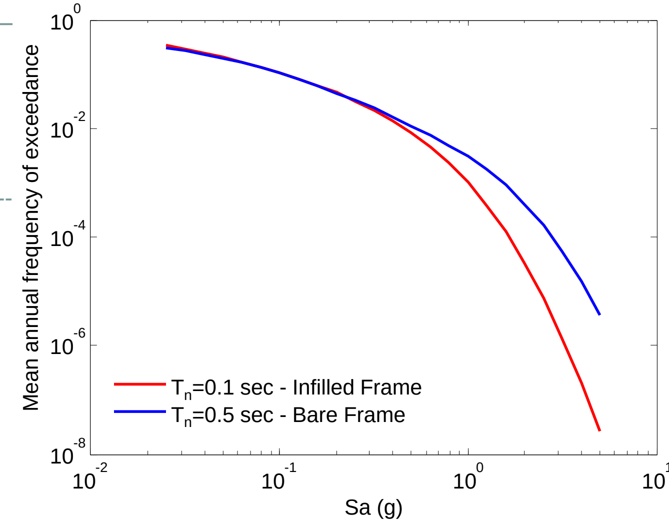


- POE of RA is larger for the infilled frame due to:
  - Initial periods for small RA values (acceleration response for 0.1 sec-infilled frame is greater than that for 0.5 sec-bare frame)
  - Lateral force capacity [next slide] (larger for the infilled frame compared to the bare frame) for large Sa

Application I

Combination of Hazard & Structural Analyses





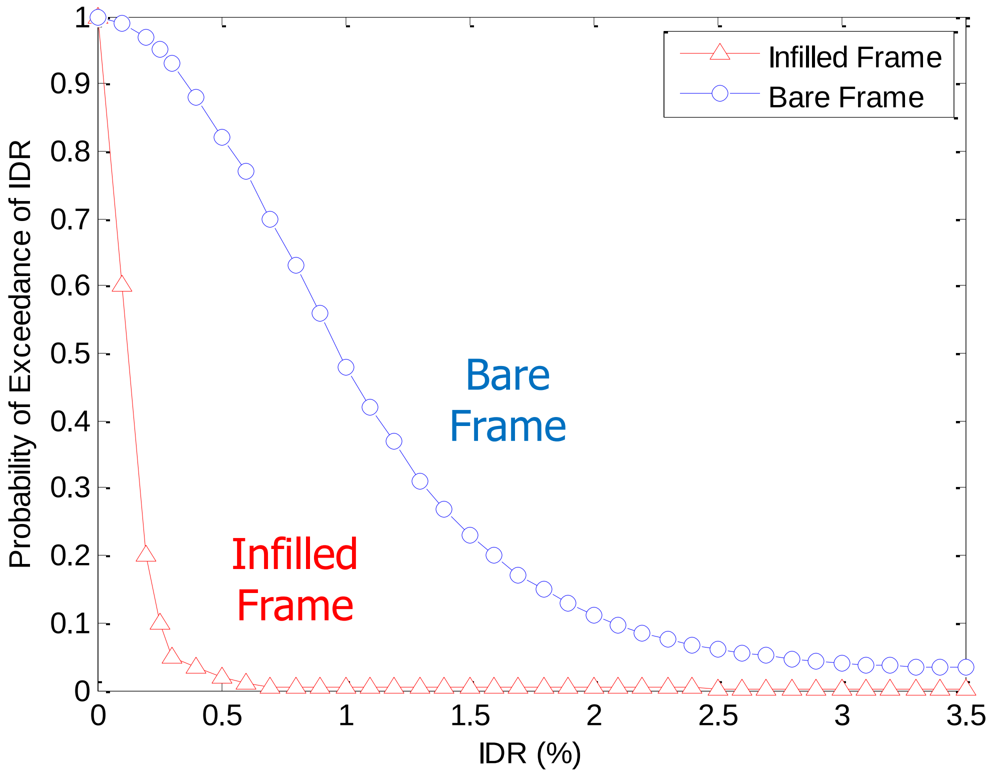
Remark:

- For each of the intensities in this region, RA is dominated by the lateral force capacity
- However, POE of RA of the two frames gets closer to each other as RA increases
- This is because probability of Sa, $p(Sa_m)$, which is a weighing factor, is smaller for the infilled frame for a large value of Sa [Hazard curve]

- Benefit of combining different analyses stages:
  - Results of structural analysis alone would indicate larger POE of the RA response for the infilled frame than that for the bare frame for larger intensities
  - However, combination of the two analyses indicates that the POEs of the RA response of the bare and infilled frames are comparable for large intensities
  - First comment is true if a large intensity earthquake is likely to occur, e.g. Hayward fault, Bay Area

Application I

Combination of Hazard and Structural Analyses



- POE of IDR of the bare frame is much larger than that of the infilled frame
- Significant contribution of the infill wall in reducing frame deformation response
- Specific to the portal frame analyzed in this application and the adopted modeling assumptions → Should not be generalized

Questions?

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Outline

1. **Application 1**: Evaluation of the effect of unreinforced masonry infill walls on reinforced concrete frames with probabilistic PBEE

2. **Application 2**: PEER PBEE assessment of a shearwall building located on the University of California, Berkeley, campus

3. **Application 3**: Evaluation of the seismic response of structural insulated panels with probabilistic PBEE

II-2 Application 2

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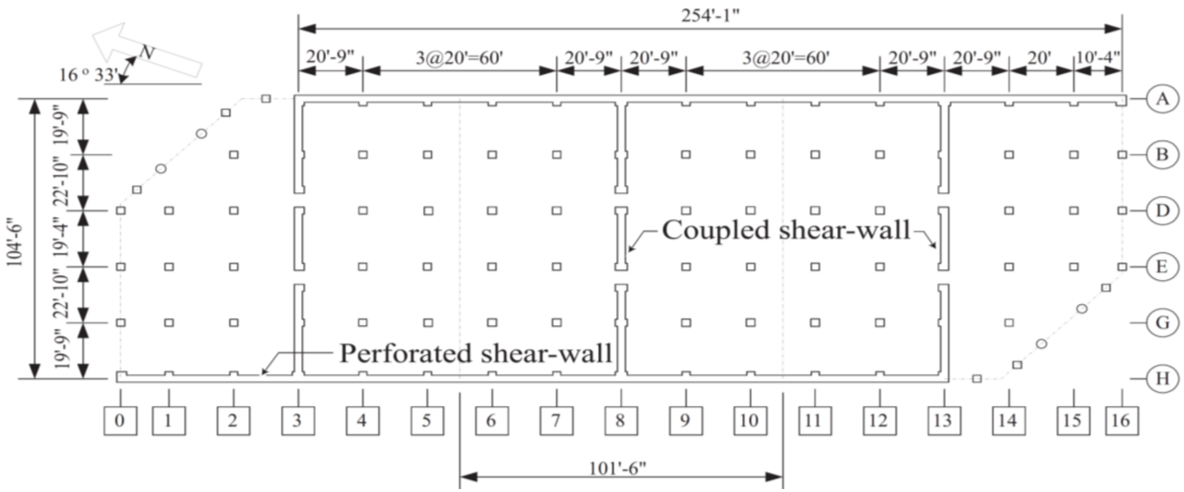
Application II

- University of California Science (UCS) building in UC-Berkeley campus
- Modern reinforced concrete shear-wall building
- High technology research laboratories for organismal biology, animal facilities, offices and related support spaces
- An example for which non-structural components contribute to the PBEE methodology due to valuable building contents, i.e. the laboratory equipment and research activities

Application II

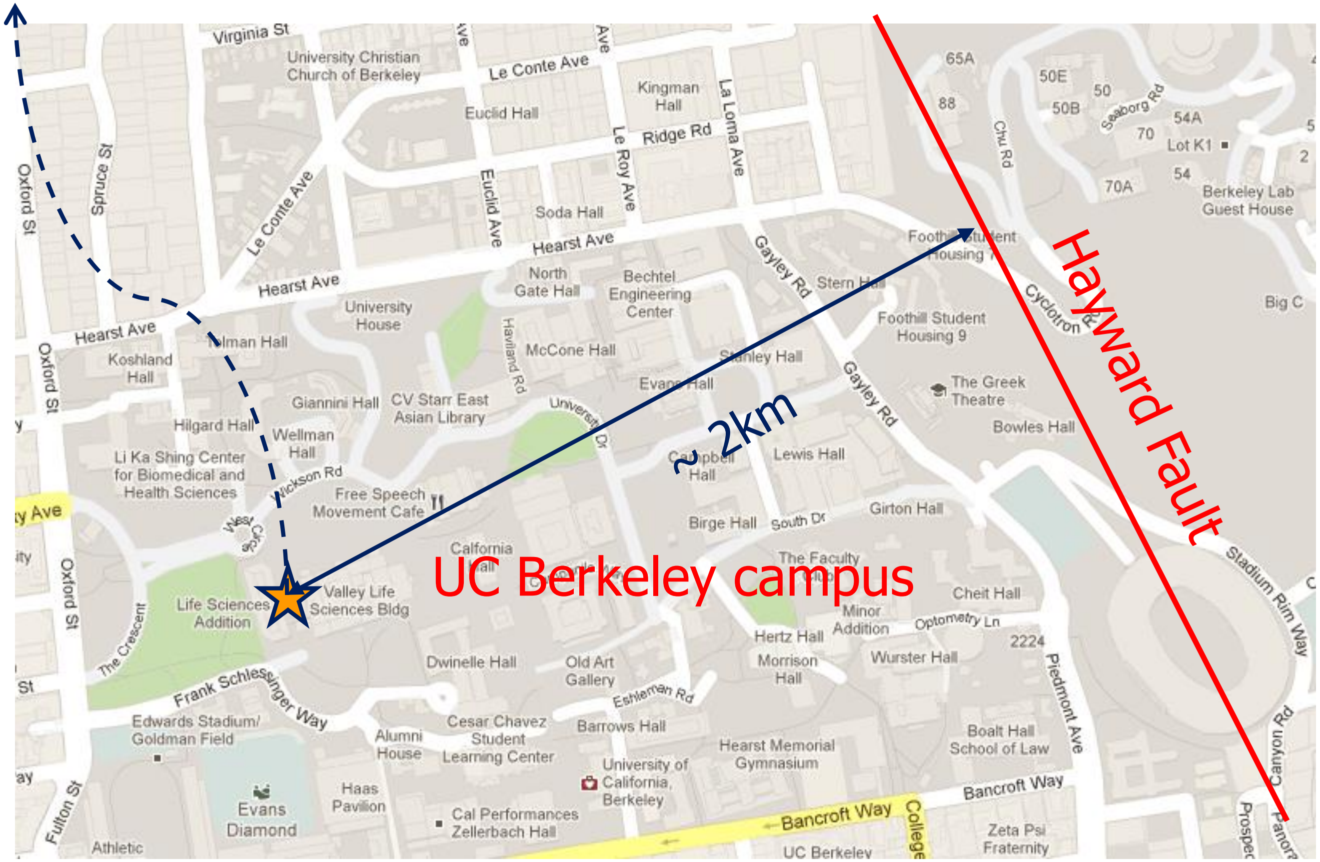


- Six stories and a basement
- Almost rectangular in plan with overall dimensions of ~93 m x 32 m
- **Gravity load resistance**: RC space frame
- **Lateral load resistance**: Coupled and perforated shearwalls
- Floors consist of waffle slab systems composed of a 114 mm thick RC slab supported on 508 mm deep joists in each direction
- Foundation consists of a 965 mm thick mat

Application II

Hazard Analysis

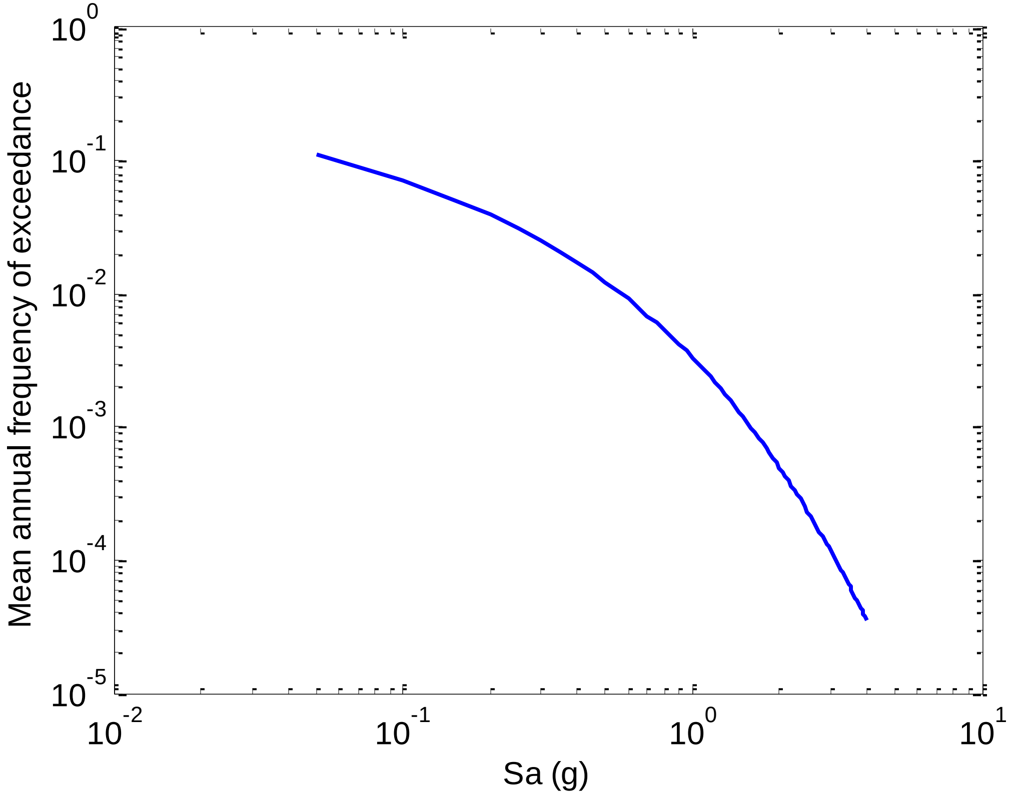
Location of the structure:
close to west gate of campus



Site class:
NEHRP C

Application II

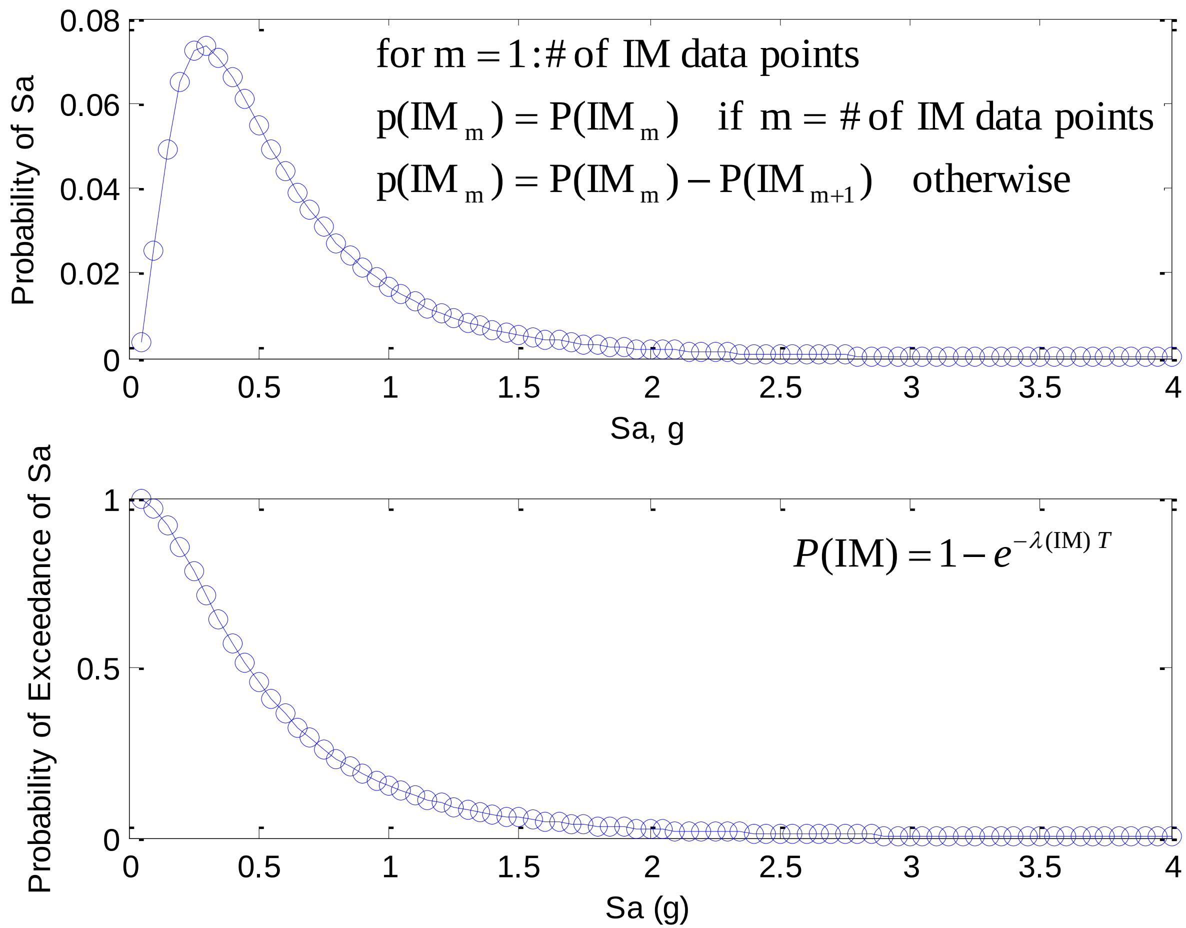
Hazard Analysis: Hazard Curve



- Lognormal distribution of S_a with the mean of 0.633g and standard deviation of 0.526g
- Matches with MAF of exceedance of S_a at periods of 0.2, 0.3 and 0.5 seconds reported by Frankel and Leyendecker [2001]

Application II

Hazard Analysis: Probability and Probability of Exceedance



Application II

Structural Analysis

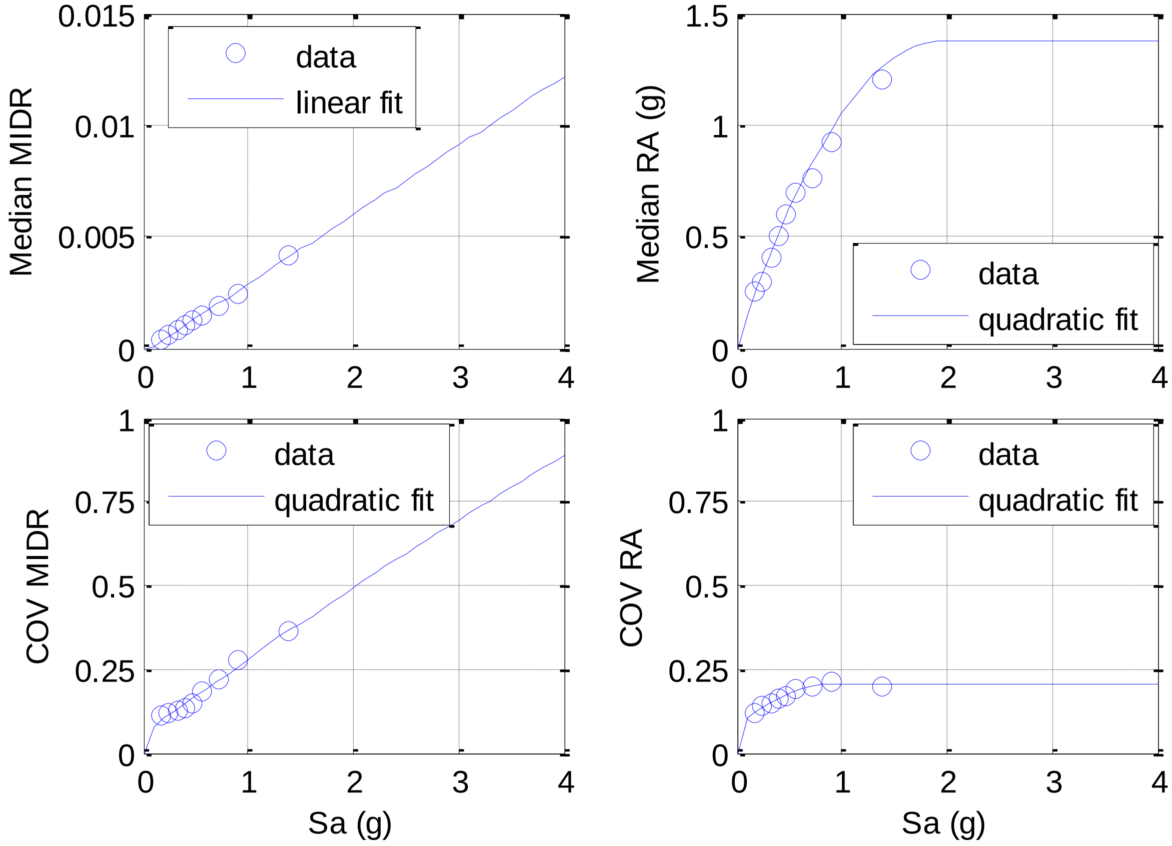
- Two damageable groups
  - Structural components: EDP = Maximum peak interstory drift ratio along height (MIDR)
  - Non-structural components: EDP = peak roof acceleration (RA)
- Twenty ground motions
  - Same site class as the building site and
  - Distance to a strike-slip fault similar to the distance of the UCS building to Hayward fault
- Nonlinear time history analyses conducted for 9 scales for each ground motion

POE(%)	90	80	70	60	50	40	30	20	10
Sa (g)	0.18	0.25	0.32	0.39	0.47	0.57	0.71	0.90	1.39
Level #	1	2	3	4	5	6	7	8	9

Application II

Structural Analysis

- For other scales, median and COV are extrapolated by curve fitting

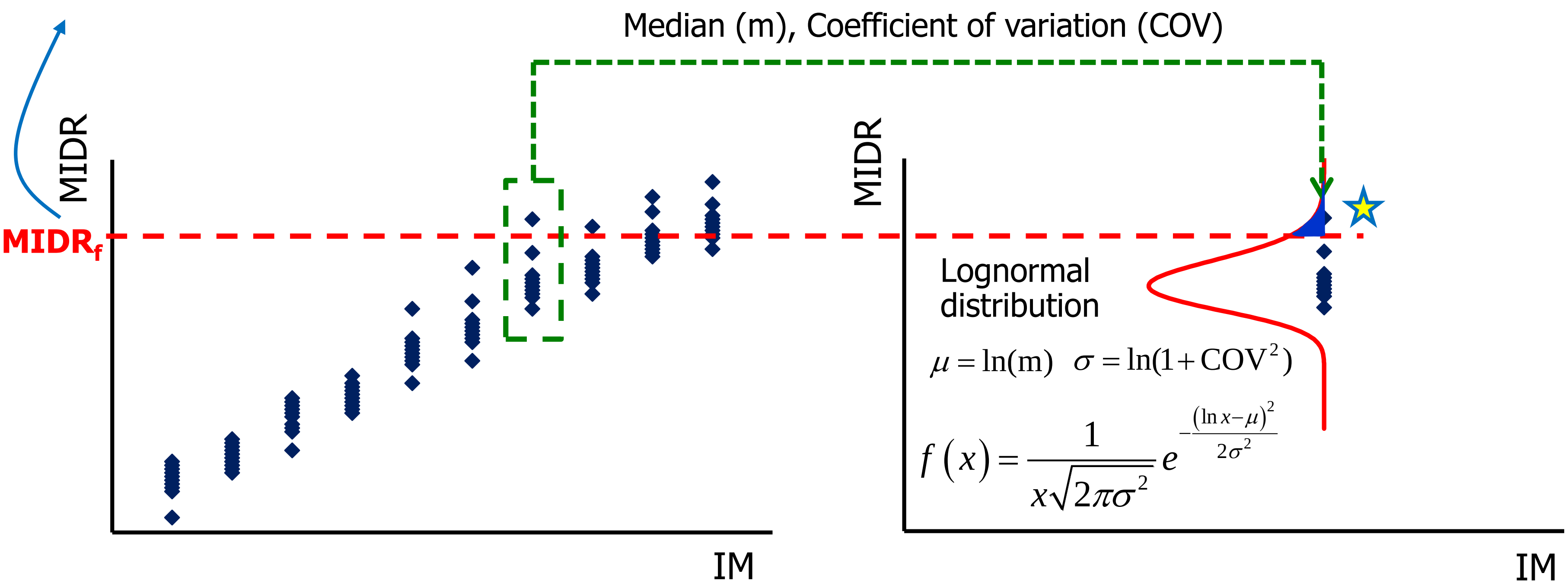


Similar concept in optimization based design example using [Aslani & Miranda, 2005]

Application II

Structural Analysis: Global collapse determination

Tests of shearwall specimens: median capacity (Hwang & Jaw, 1990)

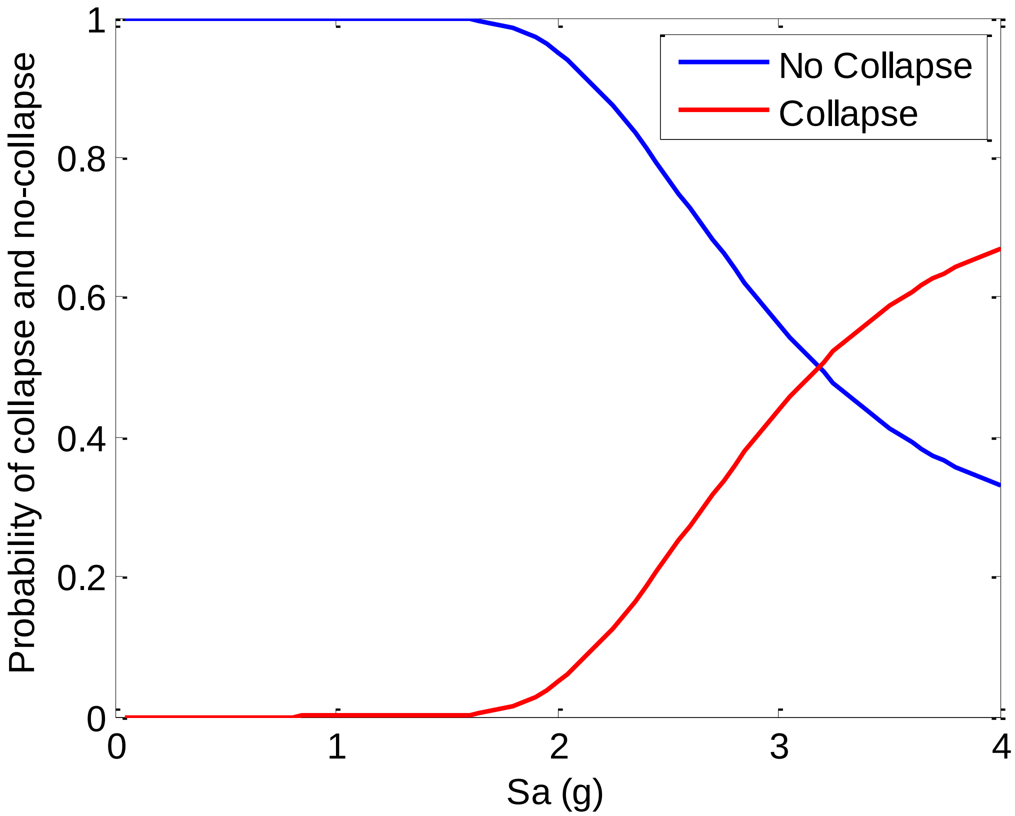


a) p(C|IM) = # of GMs leading to collapse/total # of GMs

b) p(C|IM) = shaded area ☆

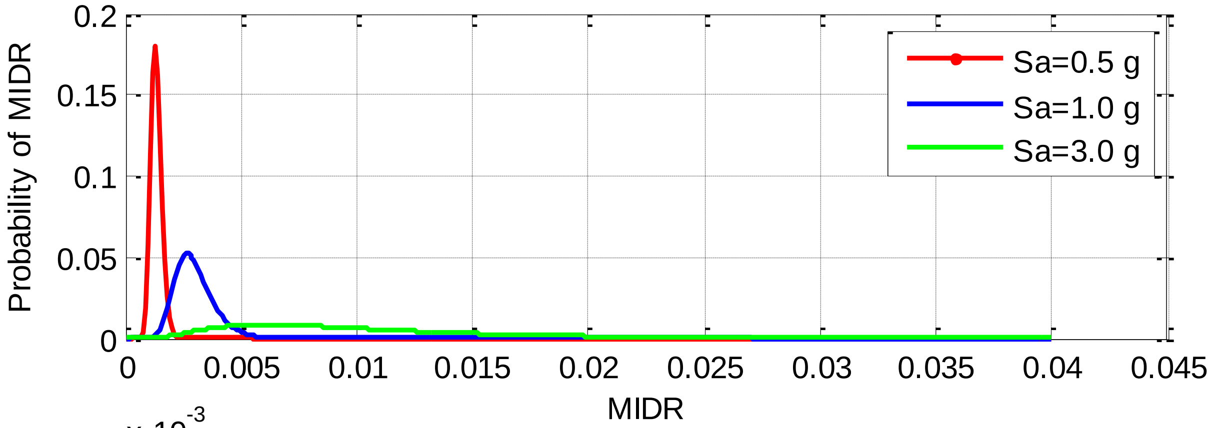
Application II

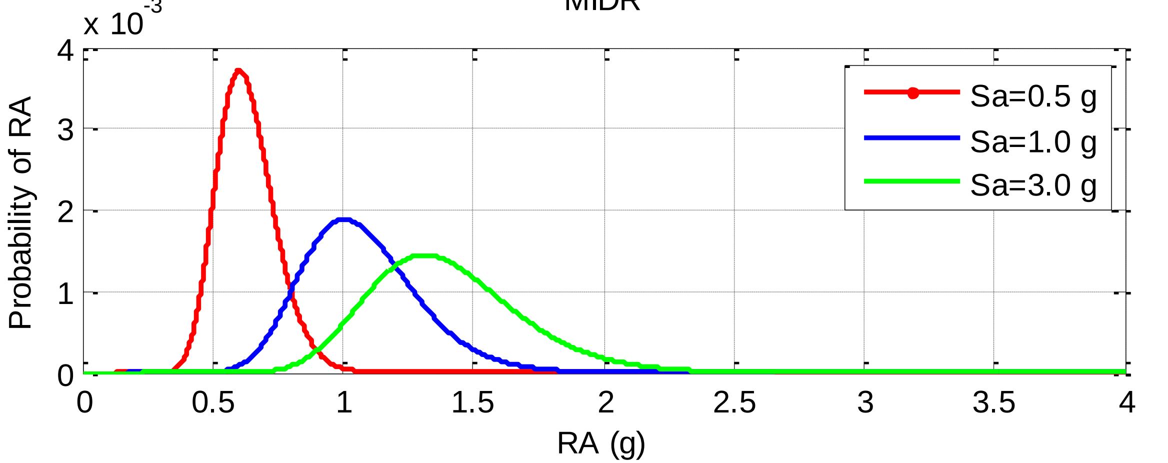
Structural Analysis: Global collapse determination



Application II

Outcome of Structural Analysis: Probability of MIDR and RA





Application II

Damage Analysis

- Damage levels considered for structural components:
  - Slight
  - Moderate
  - Severe

- Damage levels of non-structural components: Two levels based on the maximum sliding displacement experienced by the scientific equipment relative to its bench-top surface [Chaudhuri and Hutchinson, 2005]
  - Sliding displacement of 5 cm
  - Sliding displacement of 10 cm

Application II

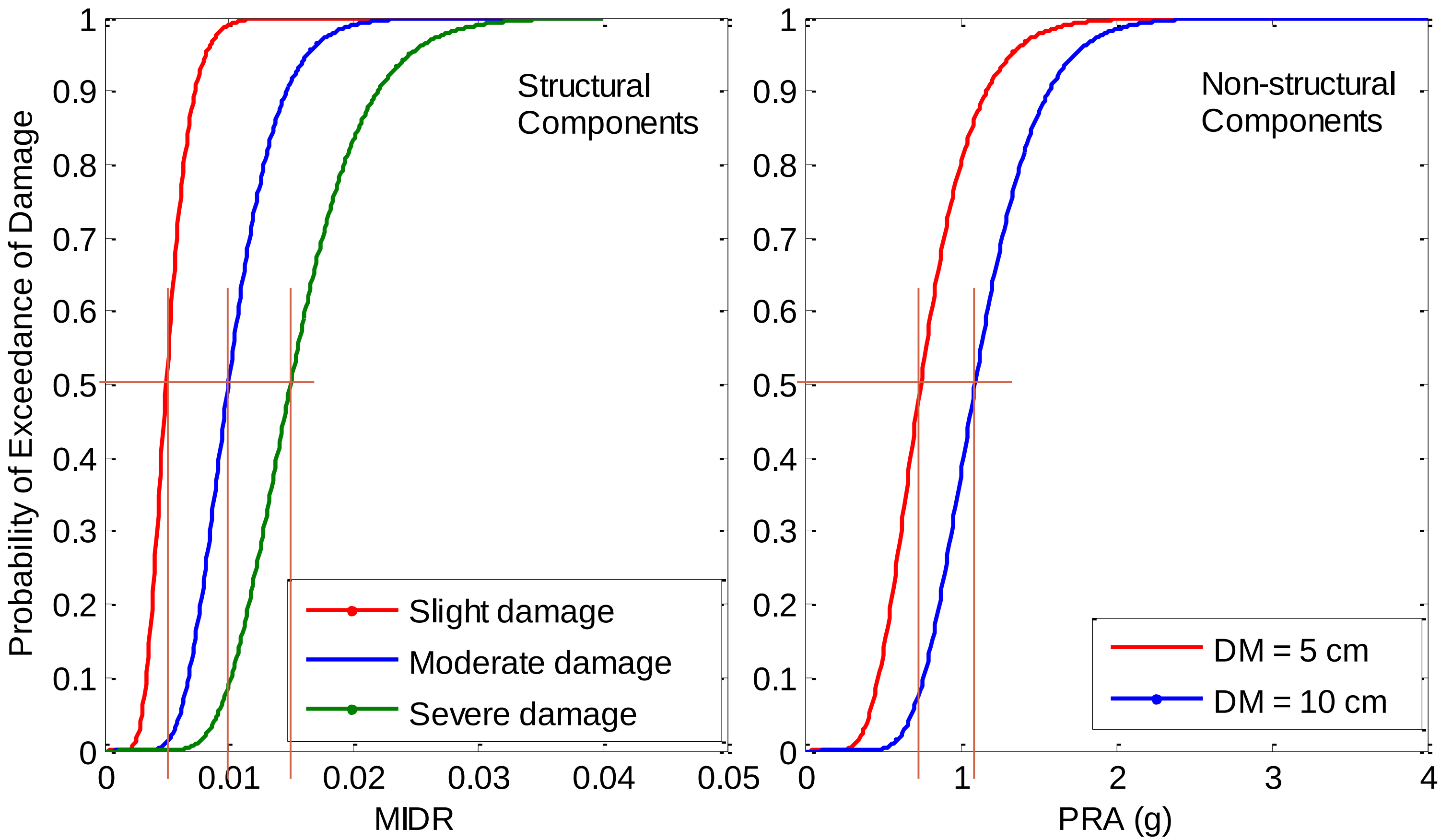
Damage Analysis

- Probability of a damage level given a value of the EDP, $p(DM_k|EDP_j^i)$, is assumed to be lognormal with defined median & logarithmic standard deviation values:
  - Structural components: shearwall tests reported in Hwang and Jaw [1990]
  - Nonstructural components: shake table tests of Chaudhuri and Hutchison [2005]

Component	Damage level	EDP	Median	Coefficient of variation
Structural	Slight	MIDR	0.005	0.30
	Moderate	MIDR	0.010	0.30
	Severe	MIDR	0.015	0.30
Non-structural	DM = 5 cm	PRA (g)	0.75	0.35
	DM = 10 cm	PRA (g)	1.10	0.28

Application II

Damage Analysis: Fragility Curves



Application II

Loss Analysis

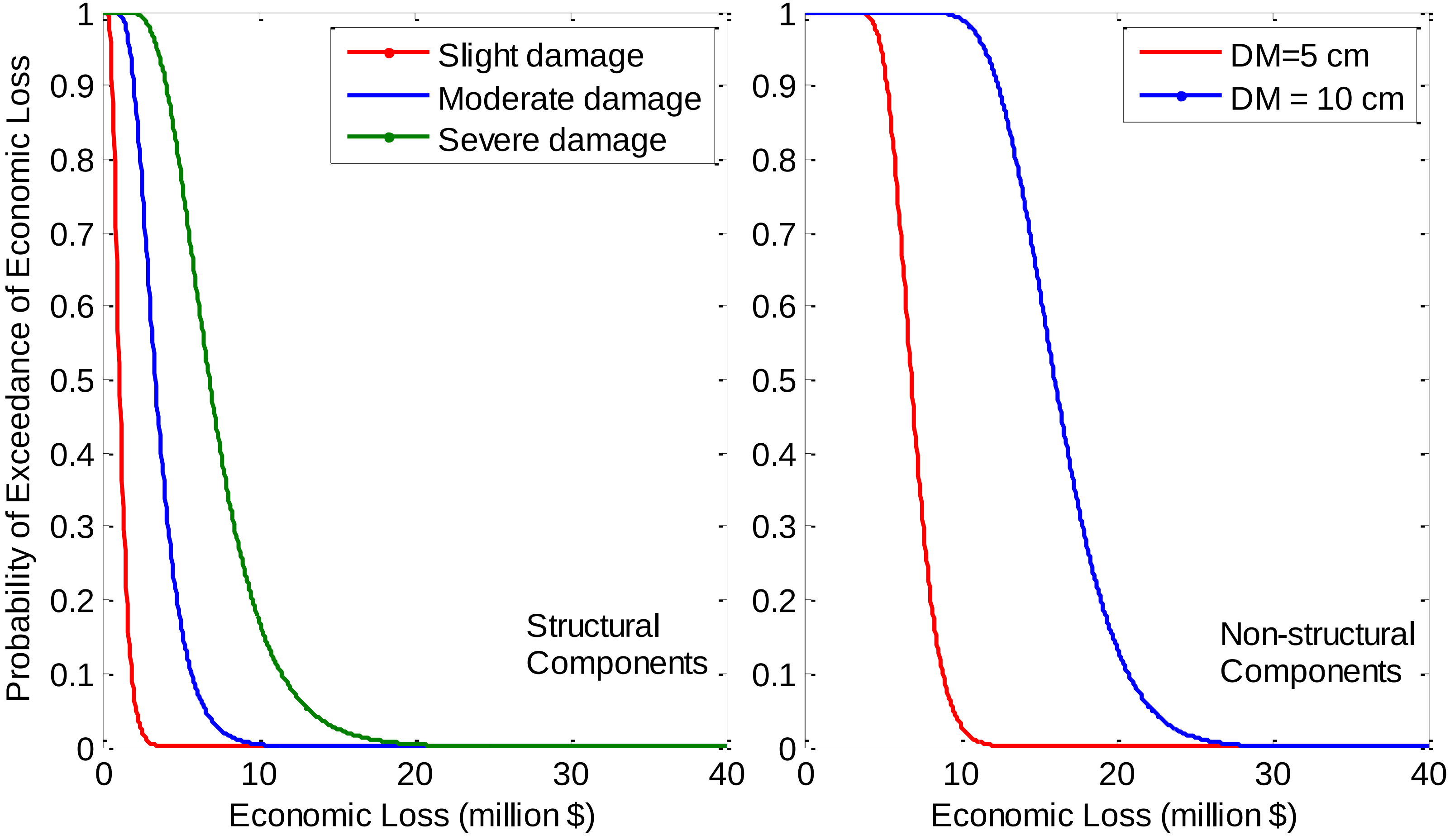
- Decision variable (DV): **monetary loss**
- The total value of the scientific equipment [SE] ≈ **$23 million** [Comerio, 2005]
- **Loss functions**: lognormal with median and coefficient of variation (COV):

Component	Damage level	Median Loss ($million) [Percent of total value of SE]	Coefficient of variation
Structural	Slight	1.15 [5%]	0.4
	Moderate	3.45 [15%]	0.4
	Severe	6.90 [30%]	0.4
Non-structural	DM = 5 cm	6.90 [30%]	0.2
	DM = 10 cm	16.10 [70%]	0.2

Larger variation due to lack of information

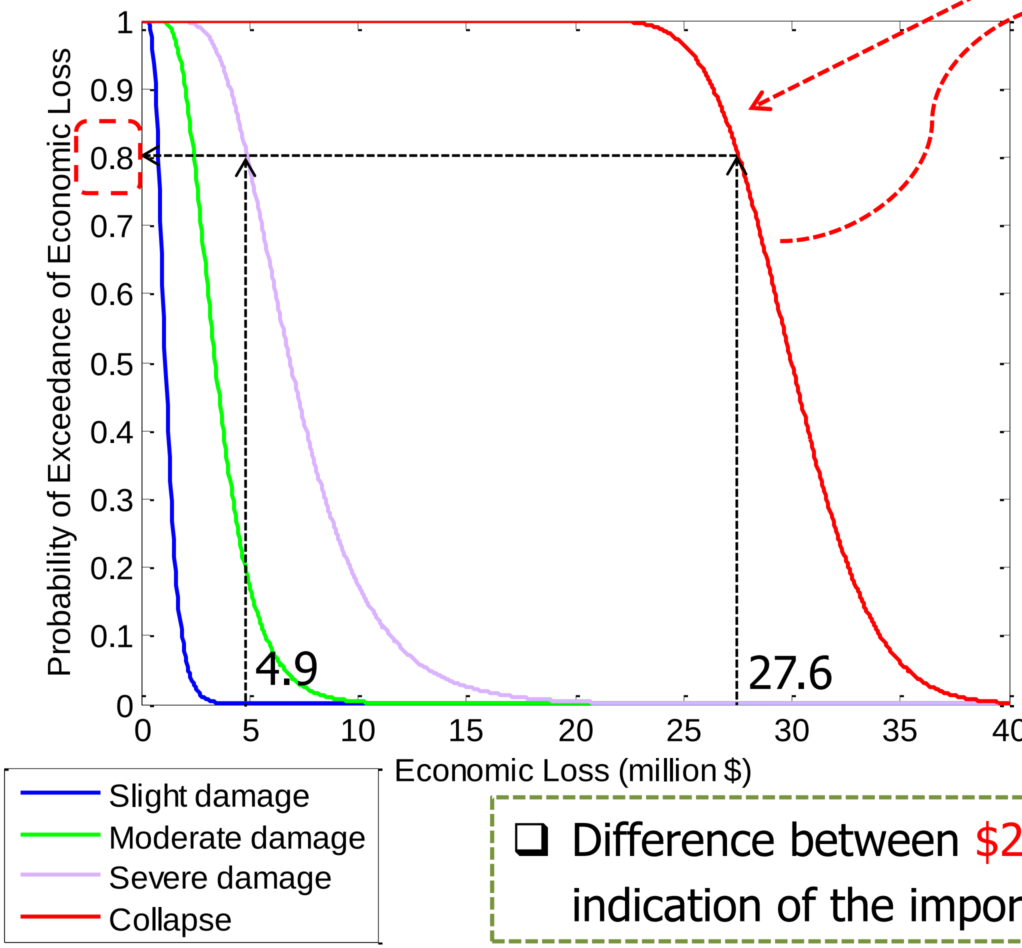
Application II

Loss Analysis: Loss Functions



Application II

Loss Analysis: Loss Function for Collapse



- ❑ Median of $30 million (total value of structural & nonstructural components)
- ❑ COV :0.2

- ❑ In case that collapse occurs, the probability of monetary loss being greater than $27.6 million is 0.8

- ❑ In case that structural components are severely damaged, the probability of monetary loss being greater than $4.9 million is 0.8

- ❑ Difference between $27.6 million and $4.9 million is a clear indication of the importance of nonstructural components

Application III

Combination of Analyses

Hazard Analysis

End product: $P(DV^n) = \sum_m P(DV^n | IM_m)\, p(IM_m)$

POE of the n^th value of the DV of the facility

Structural Analysis: Probability of no-collapse & of collapse

$$P(DV^n | IM_m) = P(DV^n | NC, IM_m)\, p(NC | IM_m) + P(DV^n | C)\, p(C | IM_m)$$

Loss Analysis: Loss function for collapse

$$P(DV^n | NC, IM_m) = \sum_j P(DV_j^n | NC, IM_m)$$

Structural Analysis

$$P(DV_j^n | NC, IM_m) = \sum_i P(DV_j^n | EDP_j^i)\, p(EDP_j^i | IM_m)$$

$$P(DV_j^n | EDP_j^i) = \sum_k P(DV_j^n | DM_k)\, p(DM_k | EDP_j^i)$$

Loss Analysis

Damage Analysis

- **m: index for IM**
- **j: index for damageable groups (DG)**
- **i: index for EDP**
- **k: index for DM**

Application II

Combination of Analyses

Single Damageable Group and no global collapse:

POE of the n^{th} value of the DV

$$P(DV^n) = \sum_m \sum_i \sum_k P(DV^n | DM_k)\, p(DM_k | EDP^i)\, p(EDP^i | IM_m)\, p(IM_m)$$

Loss **Damage** **Structural** **Hazard**

Multiple Damageable Groups and no global collapse:

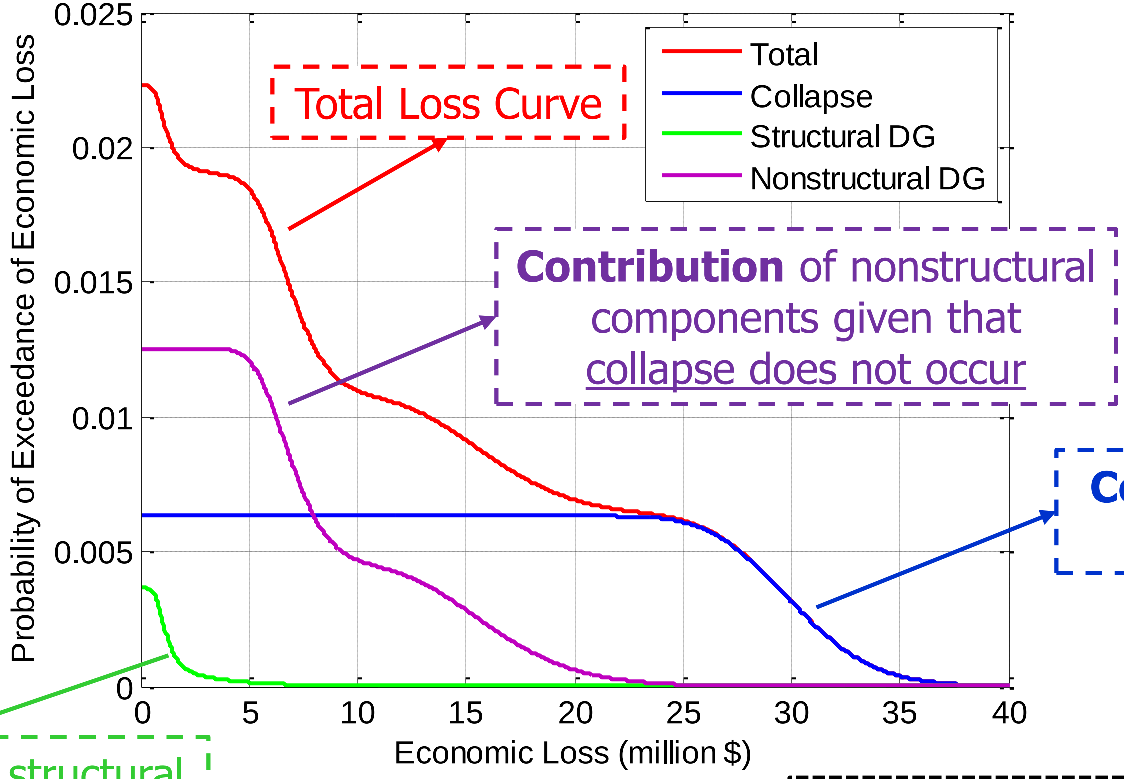
$$P(DV^n) = \sum_m \sum_j \sum_i \sum_k P(DV_j^n | DM_k)\, p(DM_k | EDP_j^i)\, p(EDP_j^i | IM_m)\, p(IM_m)$$

Multiple Damageable Groups (DGs) and global collapse:

$$P(DV^n) = \sum_m \left(\sum_j \sum_i \sum_k P(DV_j^n | DM_k)\, p(DM_k | EDP_j^i)\, p(EDP_j^i | IM_m)\, p(NC | IM_m) + P(DV^n | C)\, p(C | IM_m) \right) p(IM_m)$$

Application II

Combination of Analyses: Loss Curve

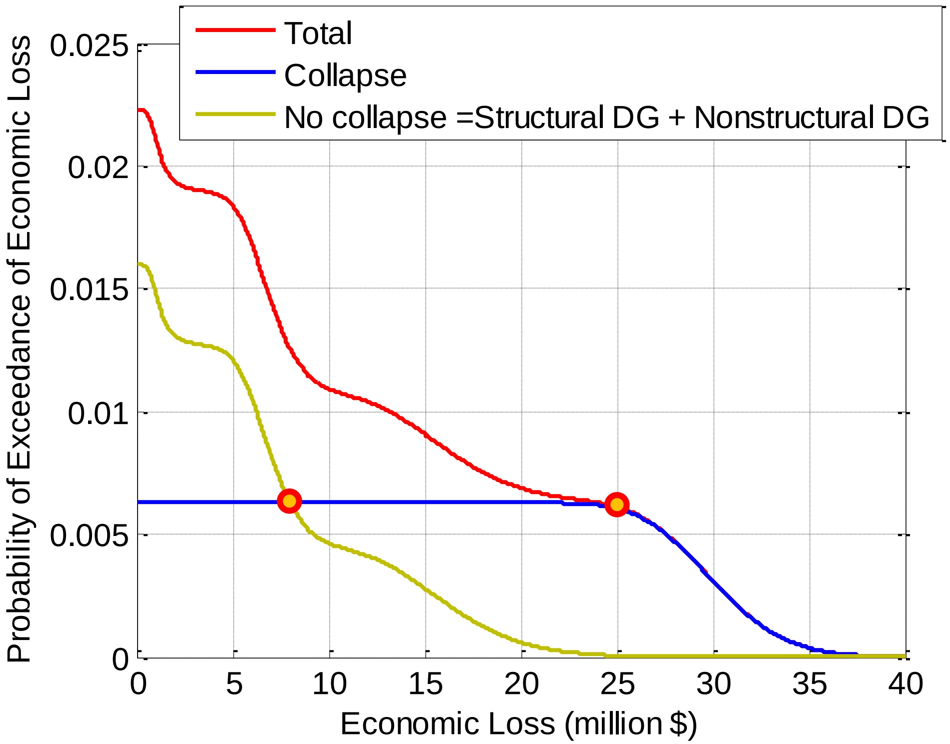


Contribution of structural components given that <u>collapse does not occur</u>

Nonstructural components significantly contribute to loss

Application II

Combination of Analyses: Loss Curve



- "No collapse" case is more dominant on the total loss curve for monetary losses **less than $8 million**
- All the loss is attributed to the "collapse" case for monetary losses **greater than $25 million**
- "No collapse" plot can be interpreted as the loss curve for a hypothetical case where collapse is prevented for all intensity levels
- The significant reduction of economic loss as a result of the elimination of collapse shows the effect of the collapse prevention <u>mandated by the seismic codes</u> from an economical perspective

Questions?

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II-3 Application 3
[Outline of Procedure]

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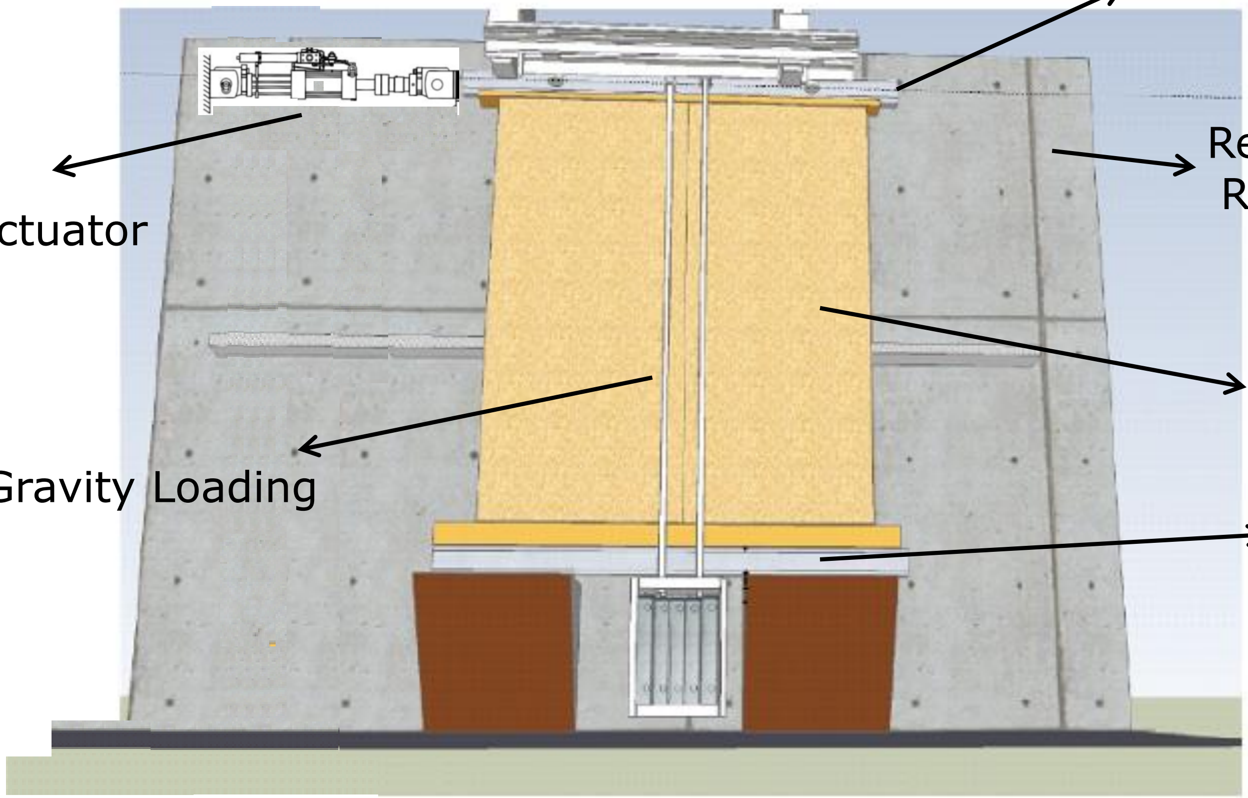
Application III

Recall HS

Application III

- Structural Insulated Panels (SIPs) are composite panels for energy efficient construction
- Composed of an energy-efficient core placed in between facing materials
- Their application in seismic regions is limited by unacceptable performance as demonstrated by cyclic testing
- Limited number of tests with realistic dynamic loading
- Hybrid simulation is ideal to test SIPs with a variety of structural configurations and ground motion excitations

Application III



Application III

Application III

Test Matrix

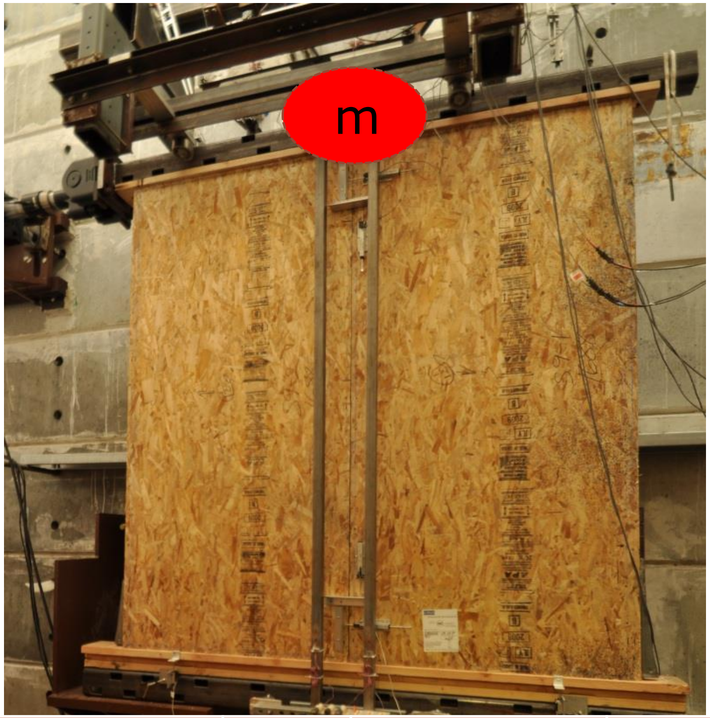
Specimen	Protocol	Gravity	Nail spacing [in]	Remarks
S1	CUREE	No	6	Conventional wood panel
S2	CUREE	No	6	-
S3	CUREE	Yes	6	-
S4	HS	Yes	6	Near-fault pulse-type GM
S5	HS	Yes	3	Near-fault pulse-type GM
S6	CUREE	Yes	3	-
S7	HS	Yes	3	Long duration, harmonic GM
S8	HS	Yes	3	Near-fault GM; 3 stories computational substructure

1. Compare the responses of conventional wood panel vs SIPs
2. Investigate the effects of:

- A parameter related to the design and construction of panels: **Nail spacing**
- Parameters related to loading:
  - ✓ Presence of gravity loading
  - ✓ Lateral loading: *CUREE protocol vs HS*
  - ✓ Type of ground motion (Pulse type vs Long duration, harmonic)
- Parameter related to HS: *Presence of an analytical substructure*

Application III

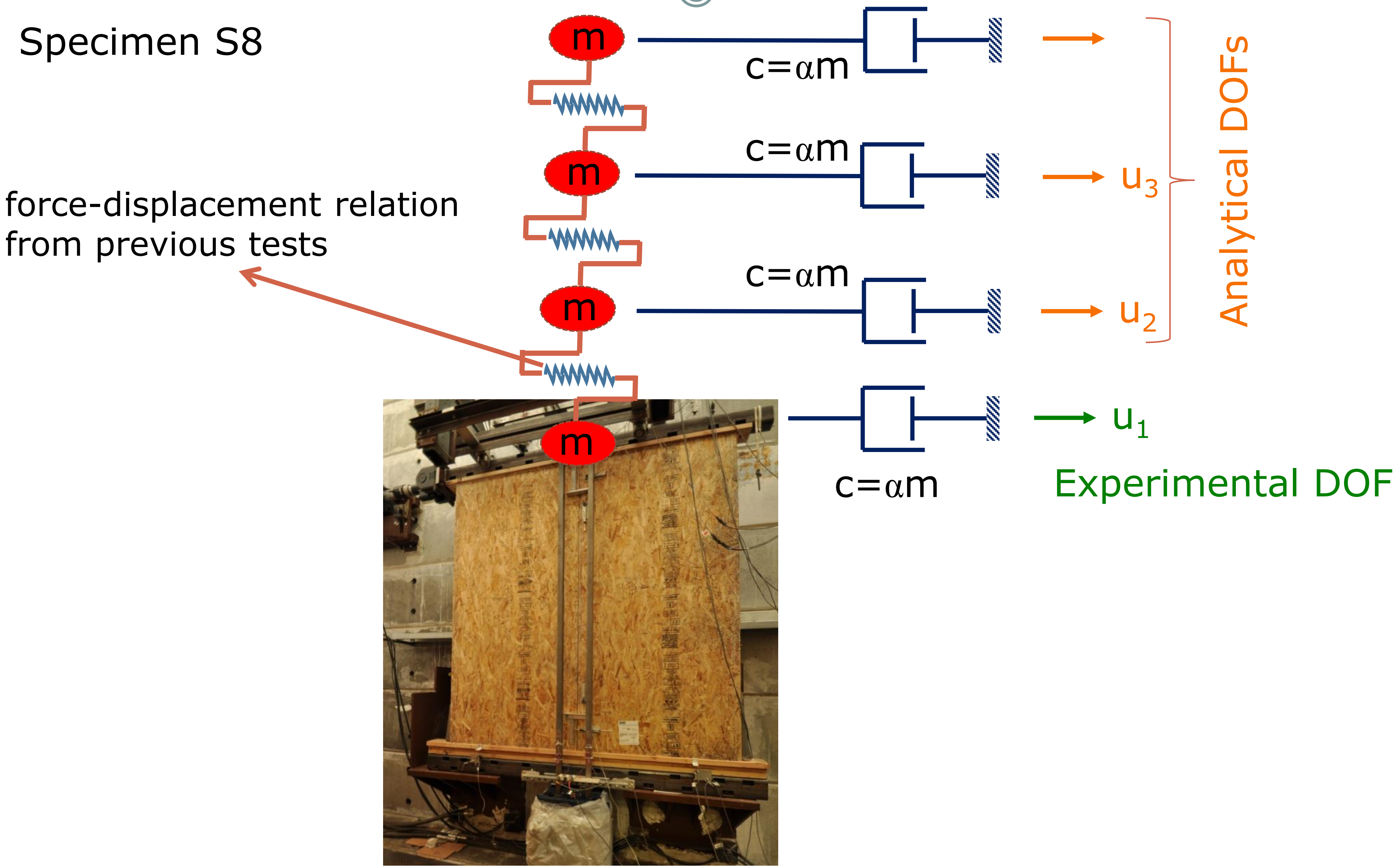
Specimens S4, S5, S7



Specimen	m (kip-sec²/in)	ξ	k (kip/in)	c (kip-sec/in)	T (sec)
S4	0.0325	0.05	18	0.0076	0.27
S5	0.0325	0.05	32	0.0102	0.20
S7	0.0325	0.05	32	0.0102	0.20

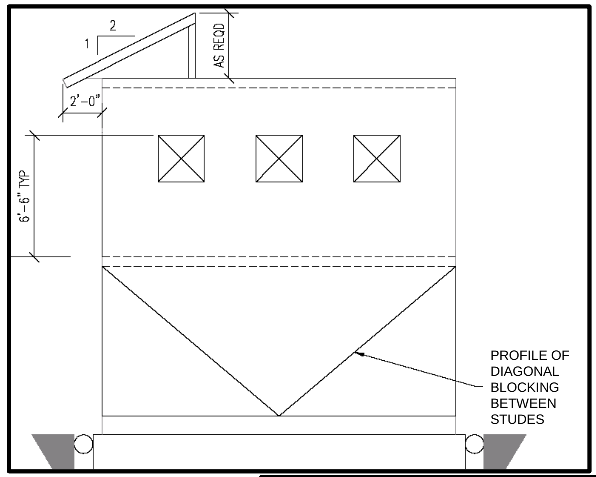
Hybrid Simulation

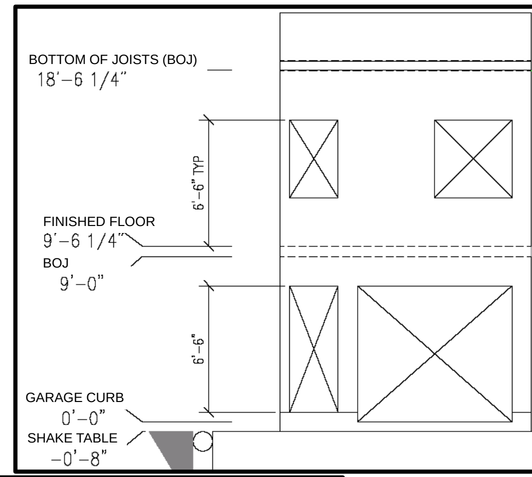
Specimen S8



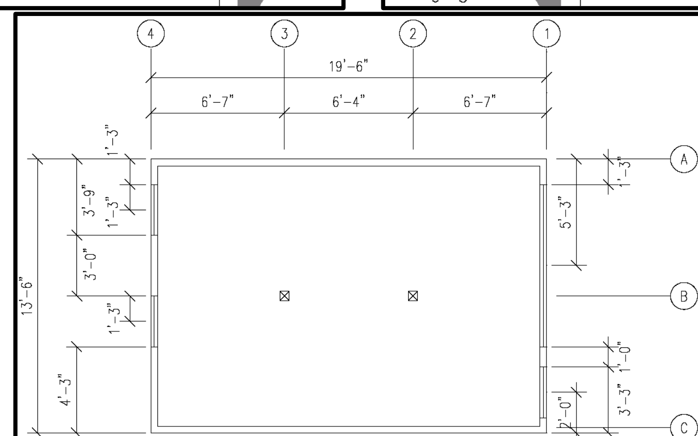
Application III

Objective: Make use of the tests for the performance evaluation of a 3D structure using PEER PBEE methodology





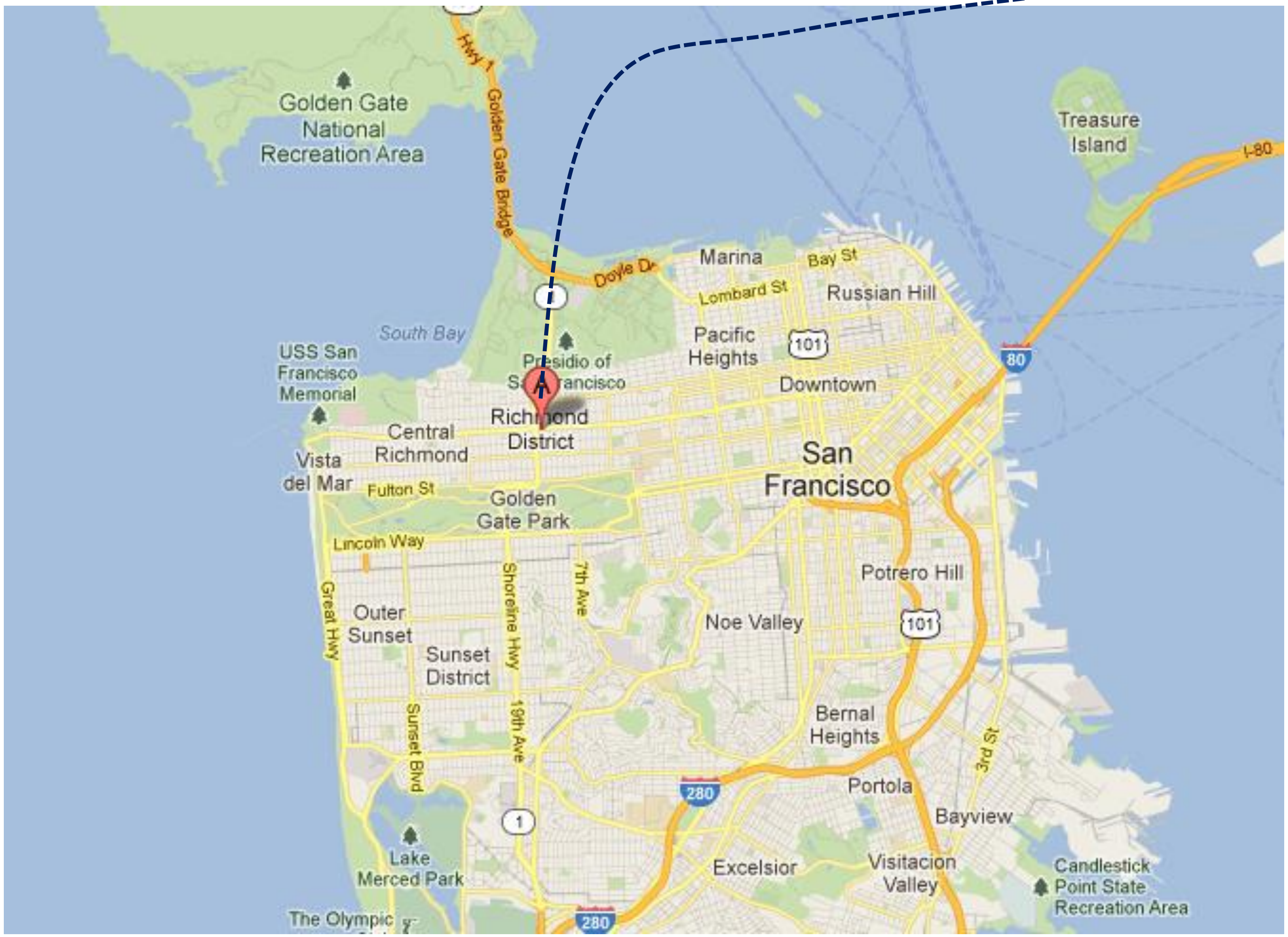
1940's San Francisco house-over-garage tested at UC-Berkeley [Mosalam et al., 2009]



Application III

Hazard Analysis

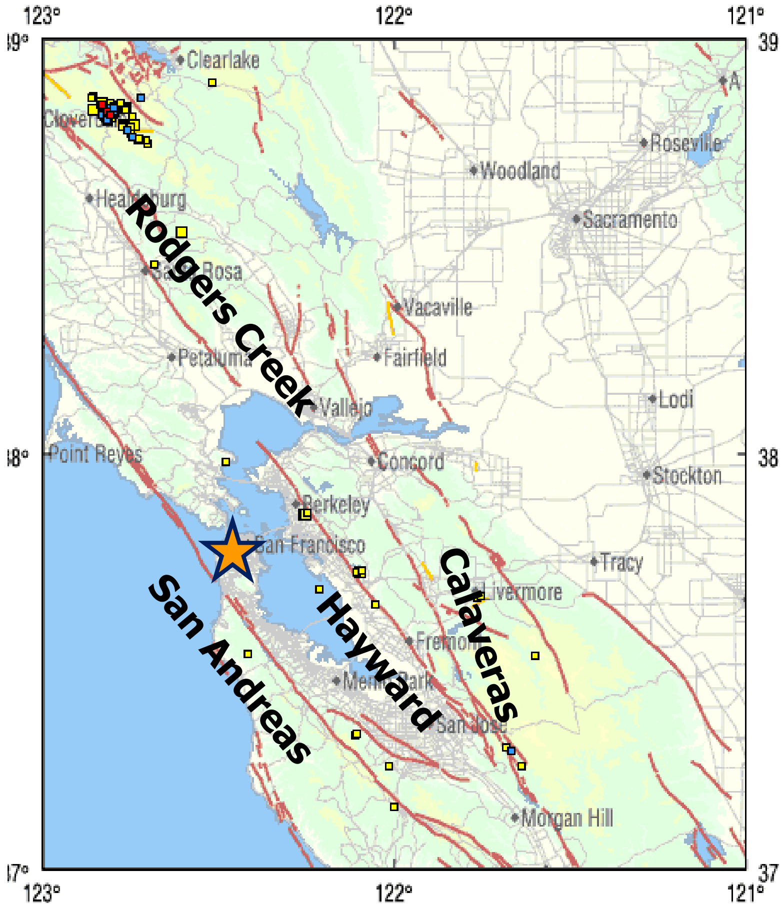
Location of a house over garage in San Francisco



Site class: NEHRP D

Application III

Hazard Analysis

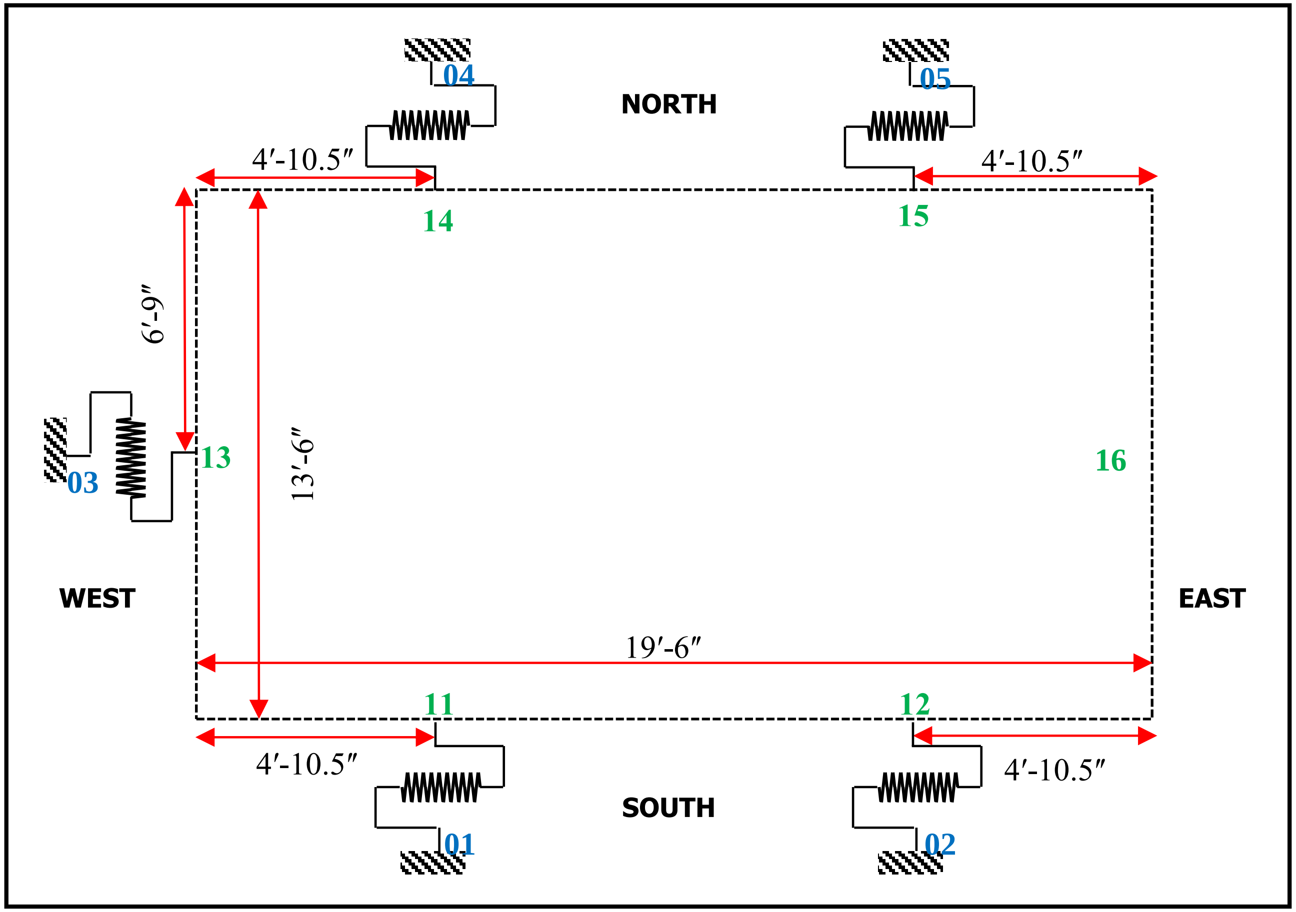


Source: USGS

Application III

Structural Analysis

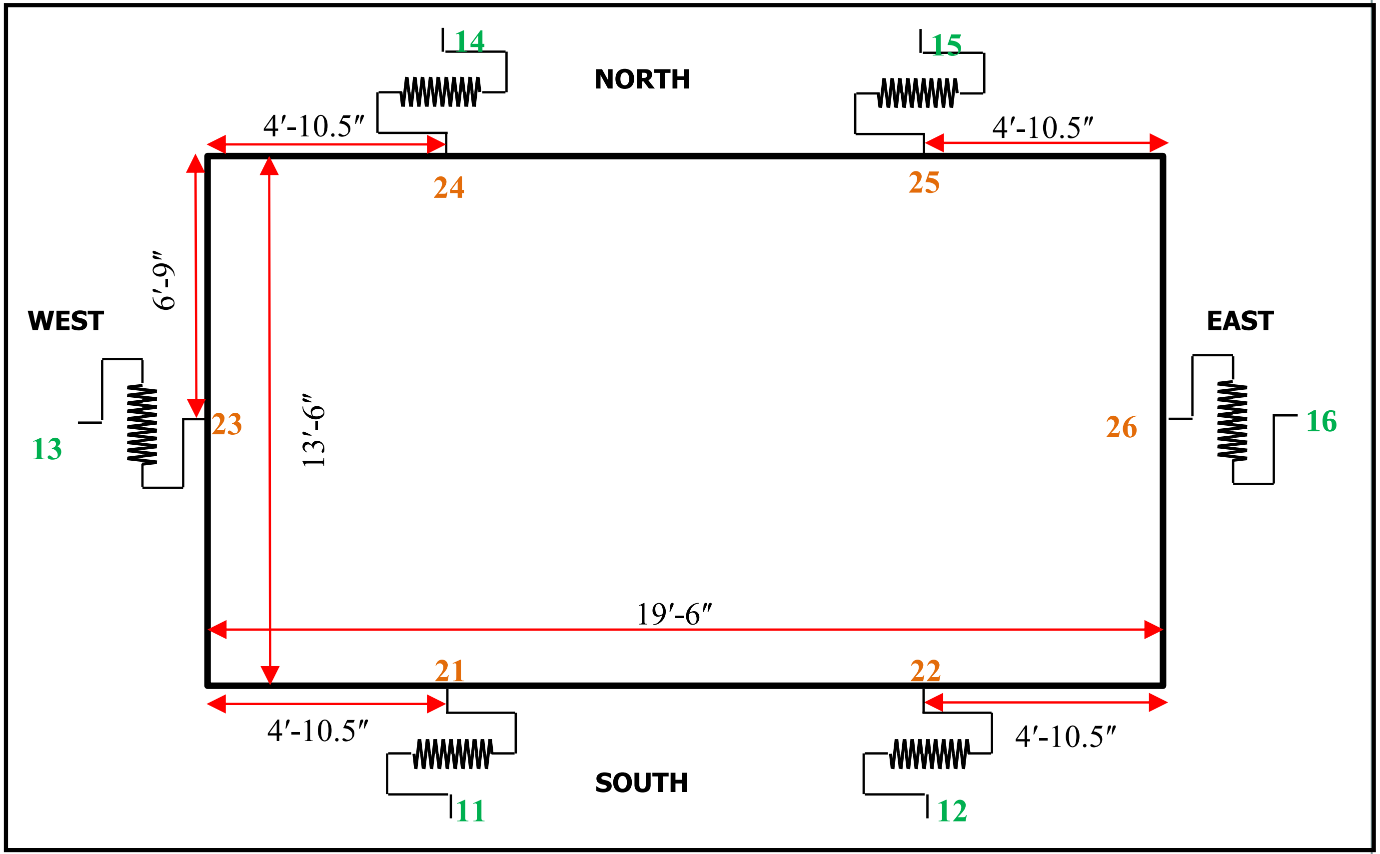
Level 1 Plan View



Application III

Structural Analysis

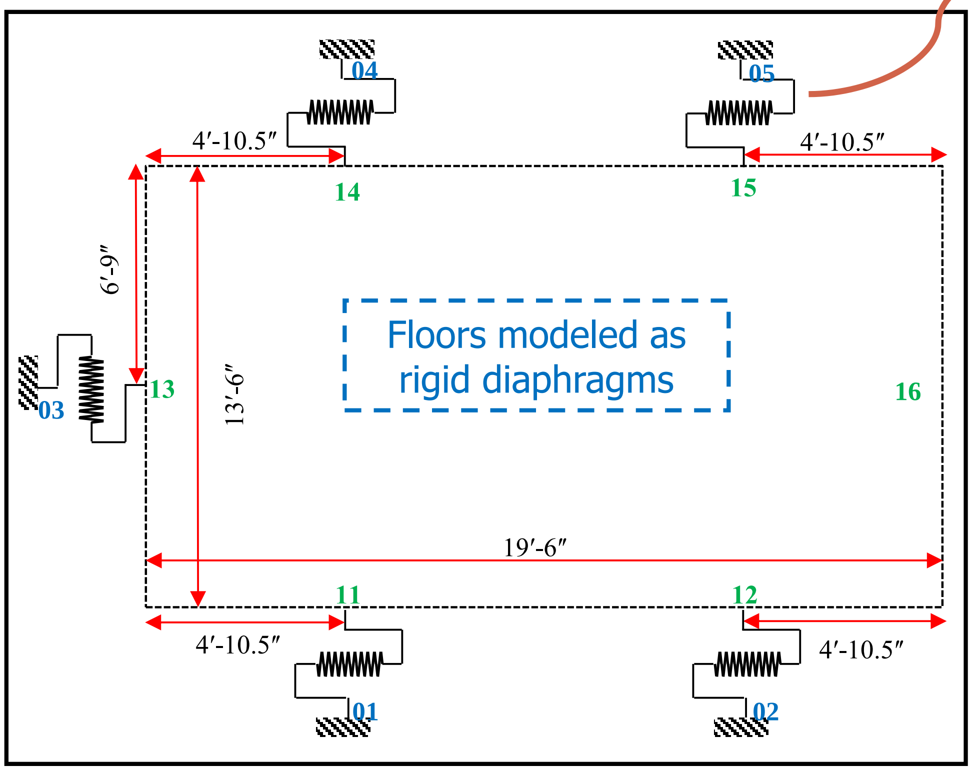
Level 2 Plan View



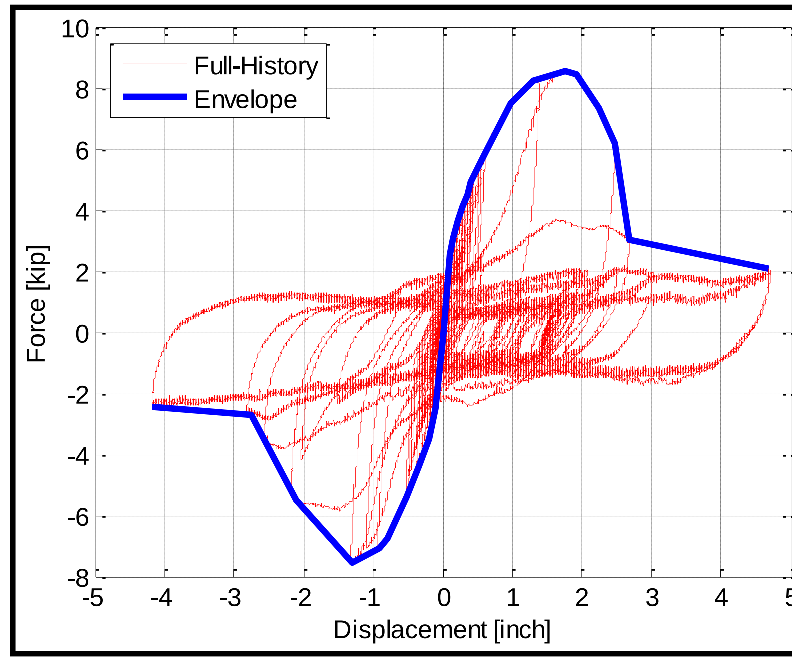
Application III

Structural Analysis

Level 1 Plan View



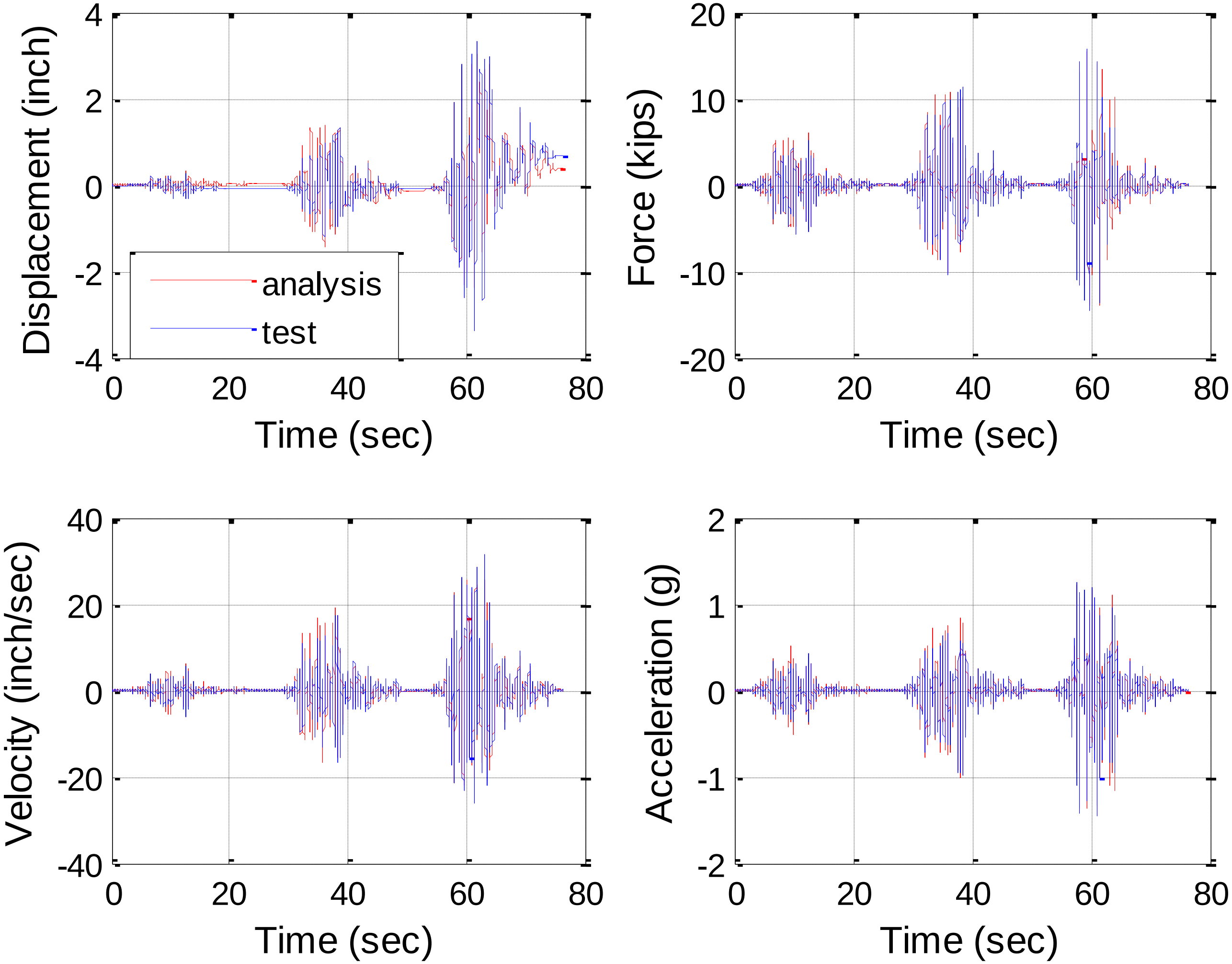
- Envelope of the force deformation relationship of the springs obtained from the tests



- Parameters used to define the hysteretic relationship are calibrated in the analysis (next slide)

Application III

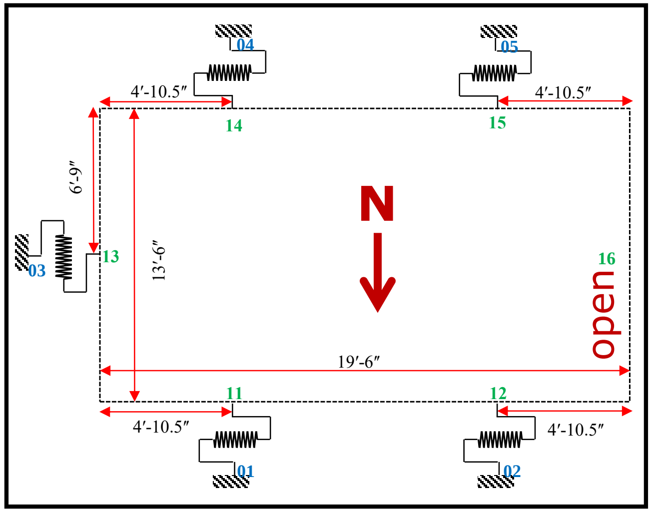
Structural Analysis



Application III

Structural Analysis

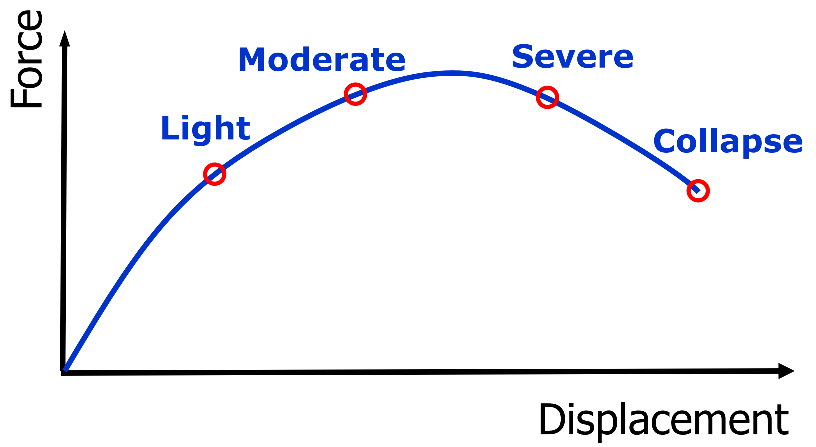
- 3182 ground motions from the used version of PEER NGA database
  http://peer.berkeley.edu/peer_ground_motion_database/
- Unscaled ground motions
- Ground motions seperated into bins based on $S_a(T_1)$
- T_1 is the period in the north south direction which is the critical mode because of torsional coupling
- Nonlinear time history analyses using the 3182 ground motions for each analytical model corresponding to a specimen
- **EDP**: Maximum Interstory Drift (MIDR)



Application III

Damage Analysis

- Conduct pushover analysis for each analytical model corresponding to a different specimen
- Determine the damage levels on each pushover curve
- Obtain MIDR values at the pushover steps corresponding to the determined damage levels for each analytical model
- Determine the median and coefficient of variation of MIDR for each damage level from the values obtained from each analytical model



Application III

Loss Analysis

- ❑ Determine the median value of loss corresponding to each damage level as a percentage of total value of the building
- ❑ Determine the corresponding coefficient of variation
- ❑ Obtain the loss curves from a probabilistic PBEE

Questions?

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http://www.ce.berkeley.edu/people/faculty/mosalam

Course Outline 2/2

Part II:

1. Application 1: Evaluation of the effect of unreinforced masonry infill walls on reinforced concrete frames with probabilistic PBEE

Questions

2. Application 2: PEER PBEE assessment of a shearwall building located on the University of California, Berkeley campus

Questions

3. Application 3: Evaluation of the seismic response of structural insulated panels with probabilistic PBEE

Questions

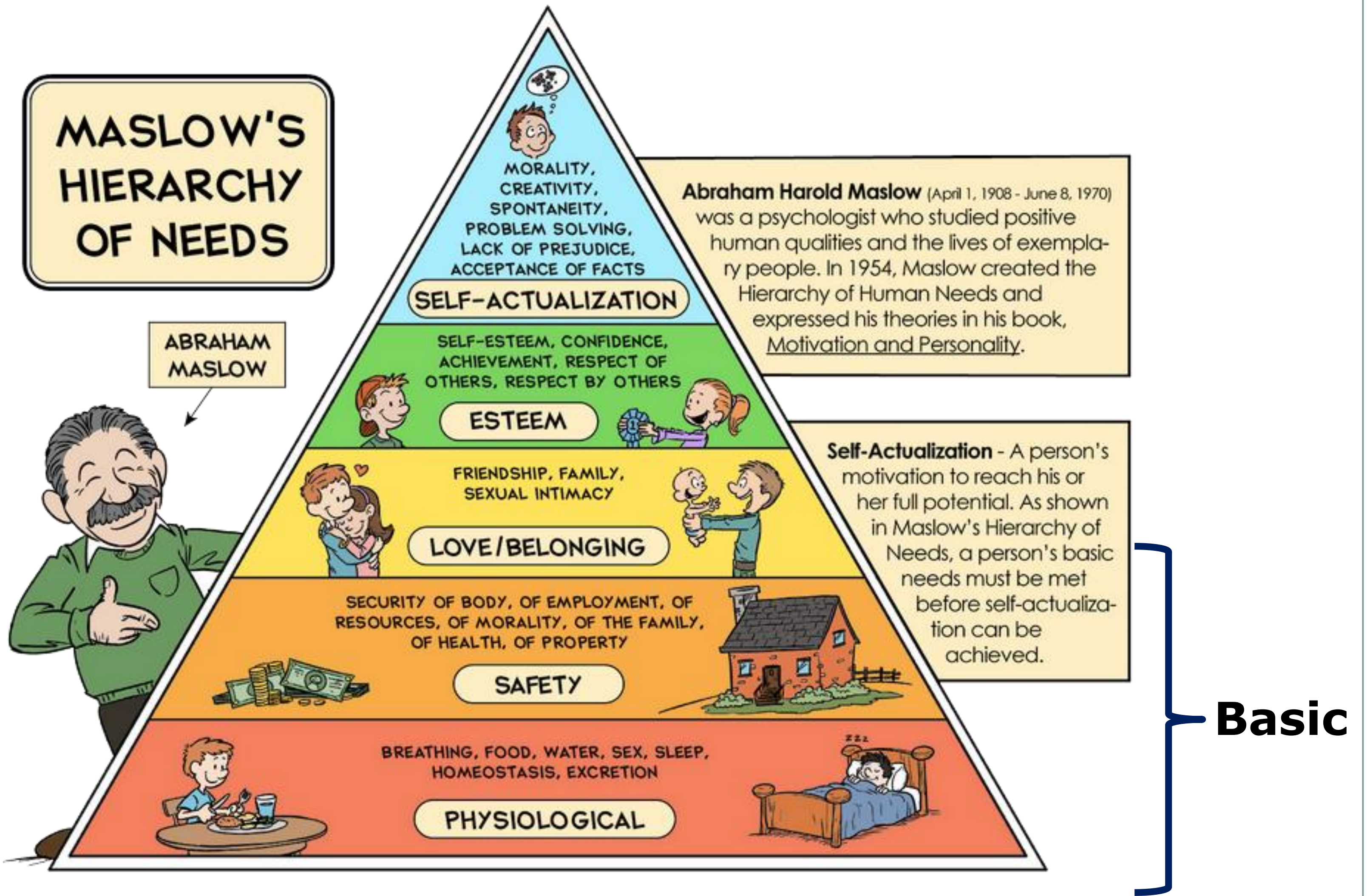
4. Future extension to multi-objective performance-based sustainable design
5. Recapitulation

II-4 Future Extension & II-5 Recapitulation

KHALID M. MOSALAM, PROFESSOR

UNIVERSITY OF CALIFORNIA, BERKELEY

Introduction



Introduction

Resiliency & Sustainability

PEER PBEE

Required to guarantee the fulfillment of the basic needs of the future generations

Establish safety and move to the upper levels

Introduction

Analogy to Hierarchy of Needs (Maslow, 1963)

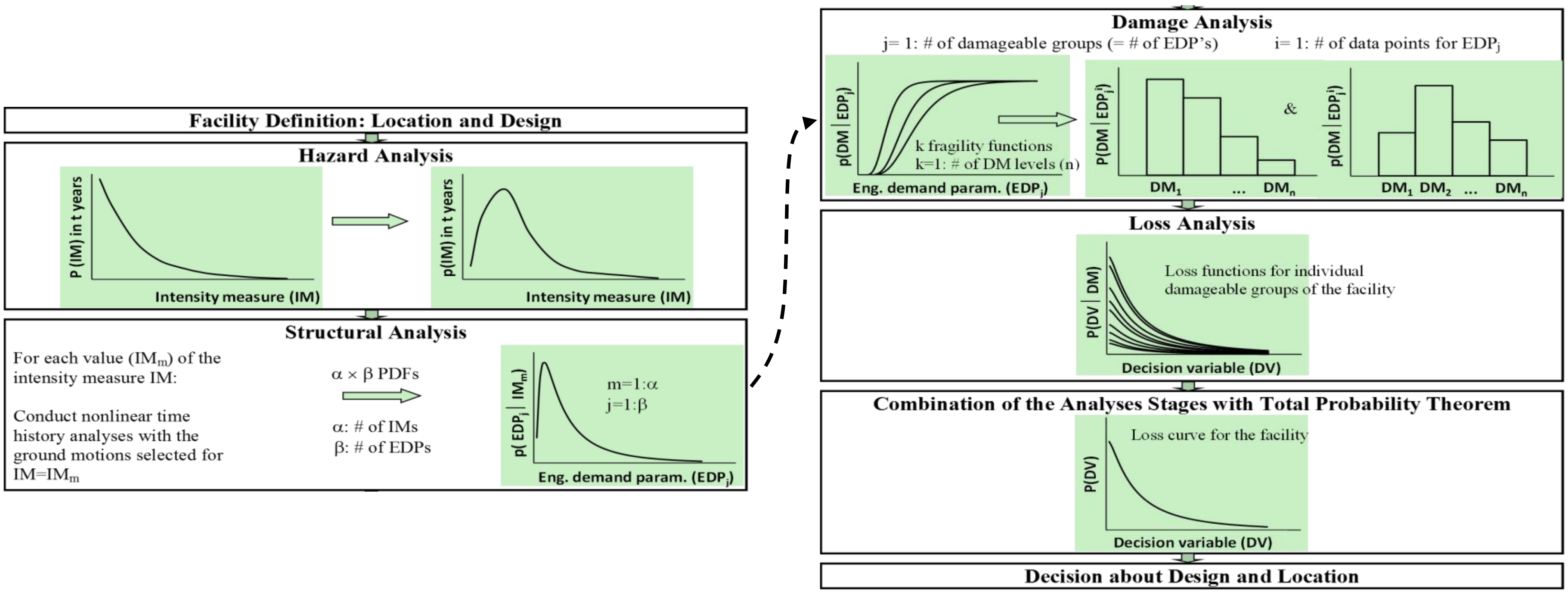
- Basic Needs: Safety Objective → PEER PBEE Probabilistic Formulation
- Upper Level Needs for sustainability: Environmental safety and human comfort objectives → Uncertain and probabilistic by nature
- Motivation for an inherent extension of PEER methodology to a generalized probabilistic multi-objective framework

Objective	Required Analysis Type						
	Hazard	Structural	Damage	Climate	Energy	Sustainability	Life Cycle Cost
Structural Safety	√	√	√				√
Environmental Responsibility				√	√	√	√
Human Comfort				√	√	√	√

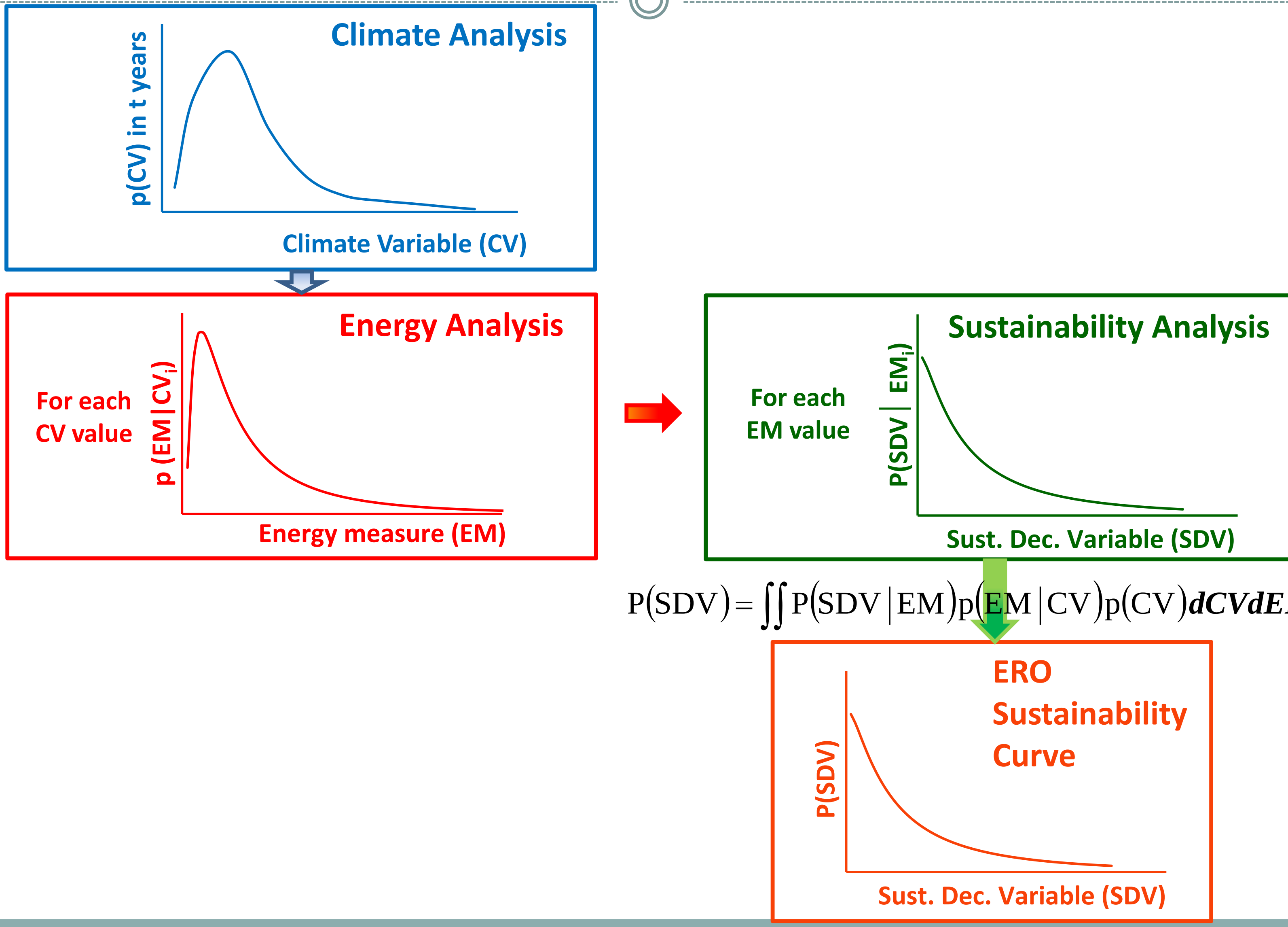
Extended Framework: Safety Objective

Structural Safety Objective:

$$P(DV)=\iiint P(DV|DM)\,p(DM|EDP)\,p(EDP|IM)\,p(IM)\,\boldsymbol{dIM\,dEDP\,dDM}$$



Extended Framework: Environmental Responsibility Objective (ERO): Sustainability



$$P(SDV) = \iint P(SDV \mid EM)\, p(EM \mid CV)\, p(CV)\, \boldsymbol{dCVdEM}$$

Extended Framework: Environmental Responsibility Objective (ERO): Sustainability

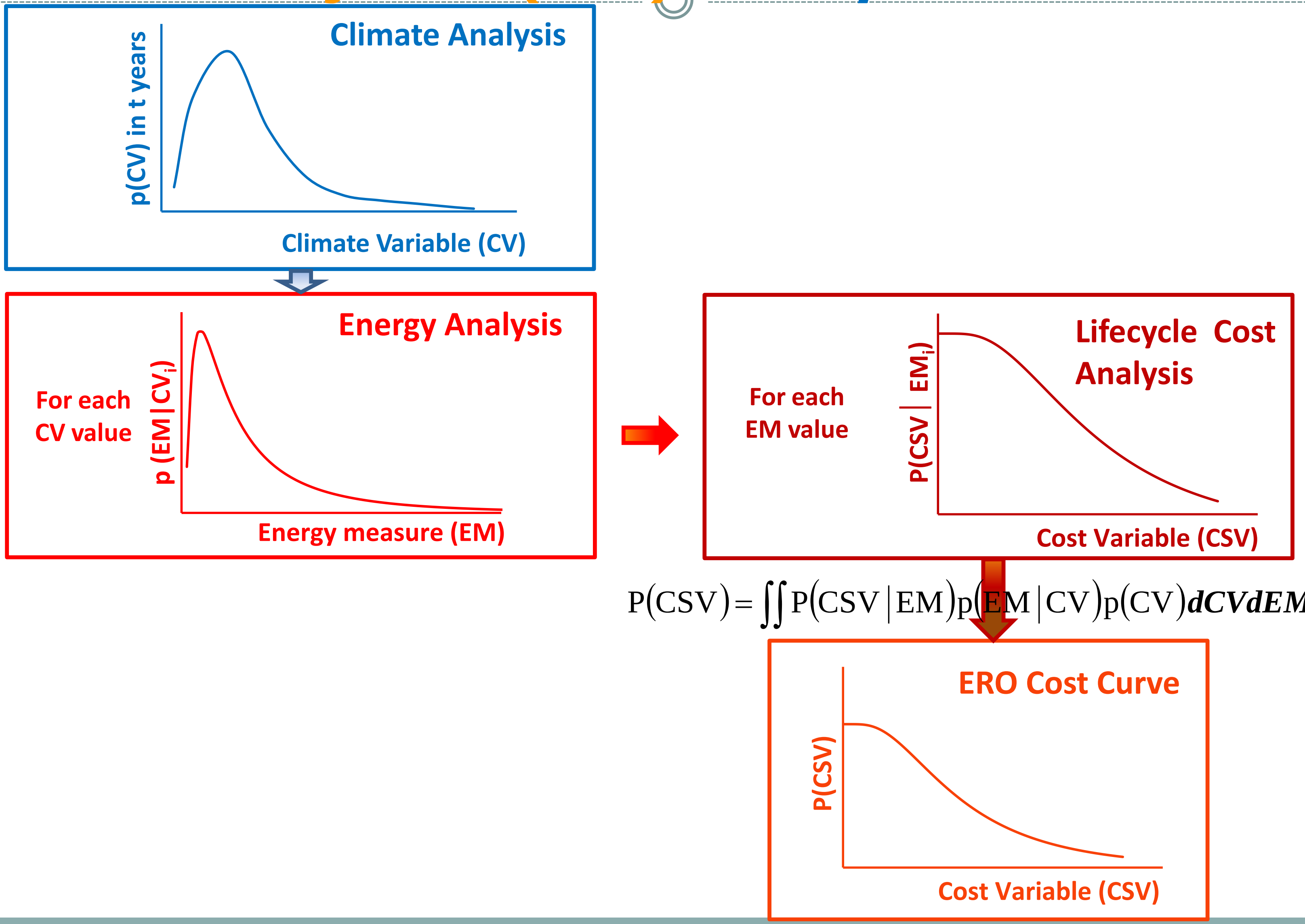
$$\mathrm{P}\left(\mathrm{SDV}\right) = \iint \underbrace{\mathrm{P}\left(\mathrm{SDV} \mid \mathrm{EM}\right)}_{\text{Sustainability Analysis}} \underbrace{\mathrm{p}\left(\mathrm{EM} \mid \mathrm{CV}\right)}_{\text{Energy Analysis}} \underbrace{\mathrm{p}\left(\mathrm{CV}\right)}_{\text{Climate Analysis}} \boldsymbol{dCVdEM}$$

SDV : Sustainability Decision Variable, e.g. Carbon or ecological footprint

EM : Energy measure, e.g. Building energy

CV : Climate Variable, e.g. Temperature change

Extended Framework: Environmental Responsibility Objective (ERO): Life Cycle Cost



$$P(CSV) = \iint P(CSV \mid EM)\, p(EM \mid CV)\, p(CV)\, \boldsymbol{dCVdEM}$$

Extended Framework: Environmental Responsibility Objective (ERO): Life Cycle Cost

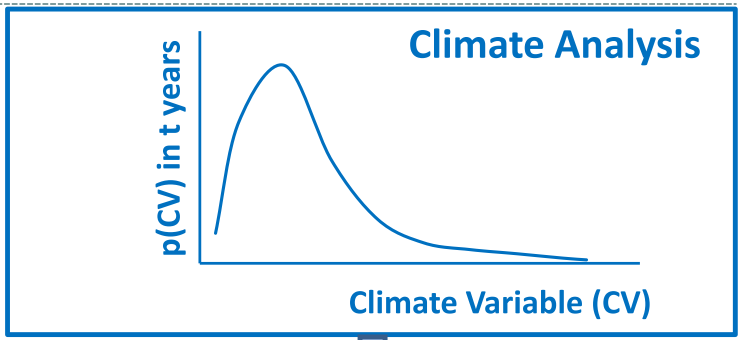
$$P(CSV) = \iint \underbrace{P(CSV|EM)}_{\text{Lifecycle Cost Analysis}} \underbrace{p(EM|CV)}_{\text{Energy Analysis}} \underbrace{p(CV)}_{\text{Climate Analysis}} \boldsymbol{dCVdEM}$$

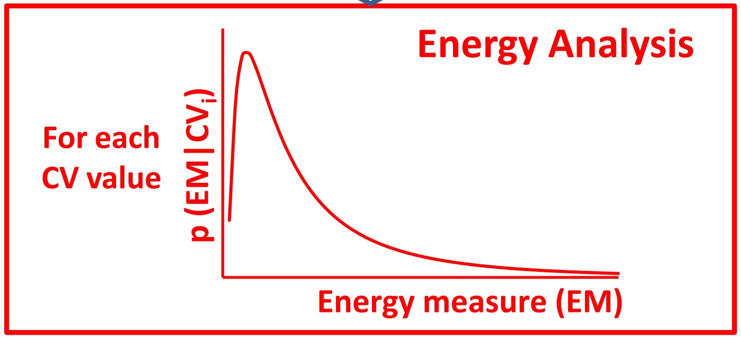
CSV: Cost/Saving Variable, e.g. Ratio initial cost/savings during lifecycle

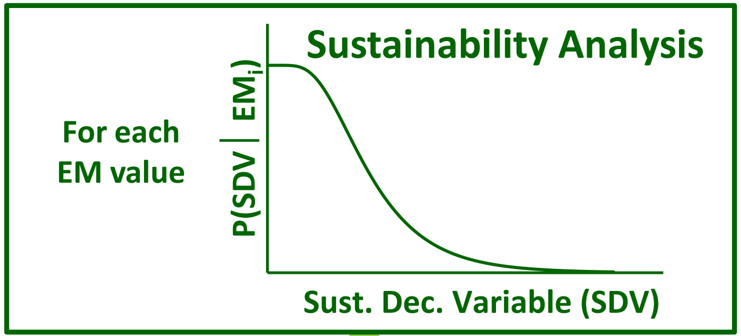
EM: Energy measure, e.g. Energy consumption

CV: Climate Variable, e.g. Temperature change

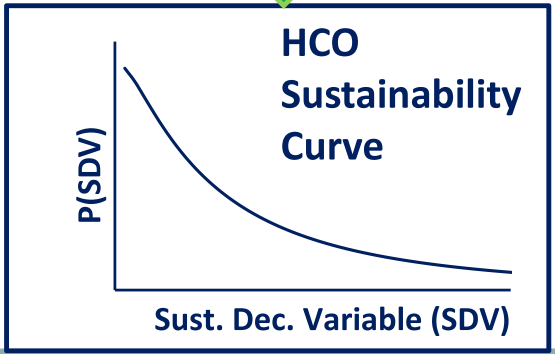
Extended Framework: Human Comfort Objective (HCO): Sustainability







$$P(SDV) = \iint P(SDV \mid EM)\, p(EM \mid CV)\, p(CV)\, \boldsymbol{dCVdEM}$$



Extended Framework: Human Comfort Objective (HCO): Sustainability

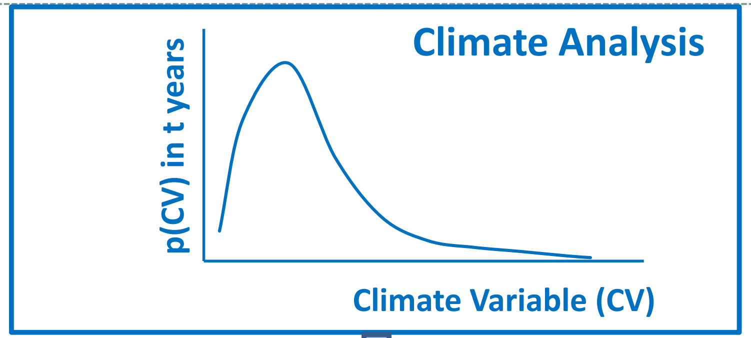
$$P(SDV)=\iint \underbrace{P(SDV\,|\,EM)}_{\text{Sustainability Analysis}}\underbrace{p(EM\,|\,CV)}_{\text{Energy Analysis}}\underbrace{p(CV)}_{\text{Climate Analysis}}\boldsymbol{dCVdEM}$$

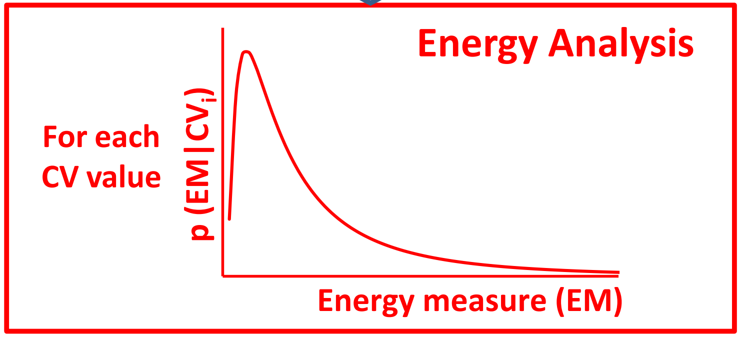
SDV : Sustainability Decision Variable, e.g. Human productivity

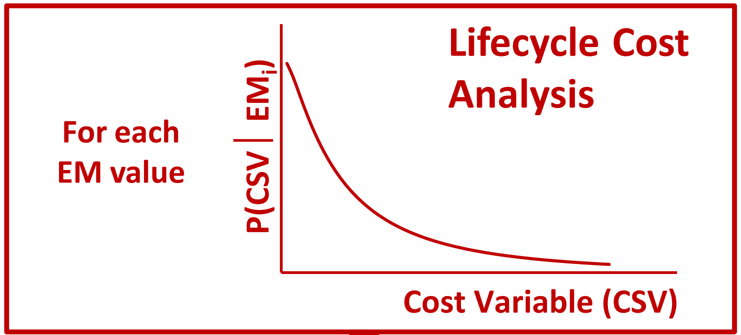
EM : Energy measure, e.g. Energy consumption

CV : Climate Variable, e.g. Temperature change

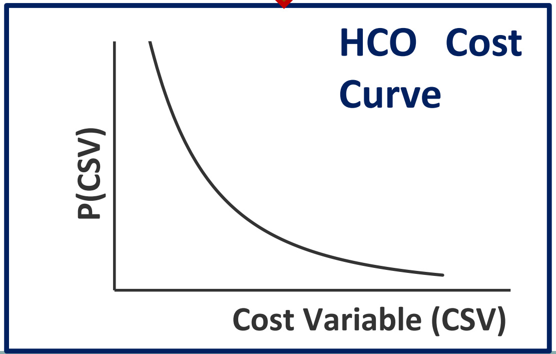
Extended Framework: Human Comfort Objective (HCO): Life Cycle Cost







$$P(CSV) = \iint P(CSV \mid EM)\, p(EM \mid CV)\, p(CV)\, \boldsymbol{dCVdEM}$$



Extended Framework: Human Comfort Objective (HCO): Life Cycle Cost

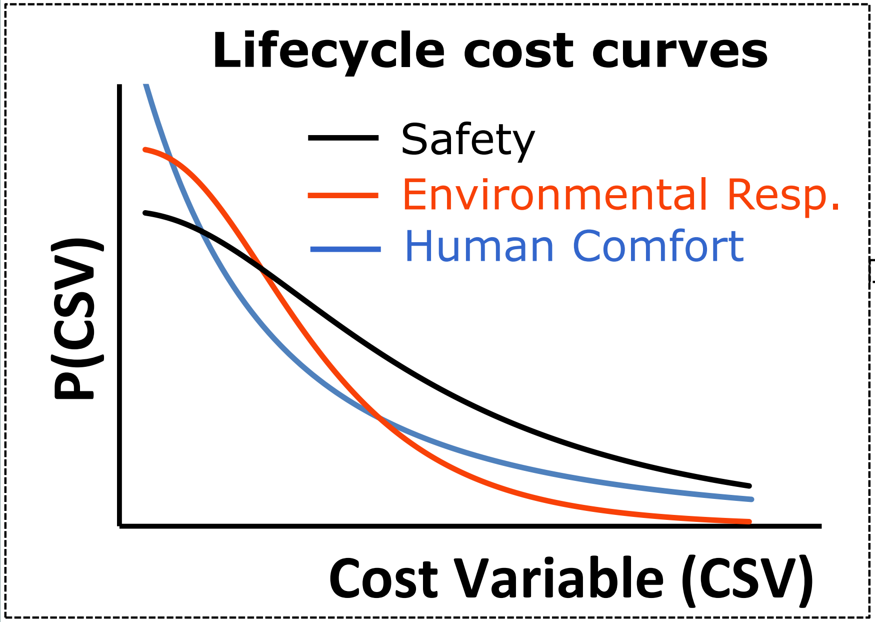
$$P(CSV) = \iint \underbrace{P(CSV \mid EM)}_{\text{Lifecycle Cost Analysis}} \underbrace{p(EM \mid CV)}_{\text{Energy Analysis}} \underbrace{p(CV)}_{\text{Climate Analysis}} \boldsymbol{dCVdEM}$$

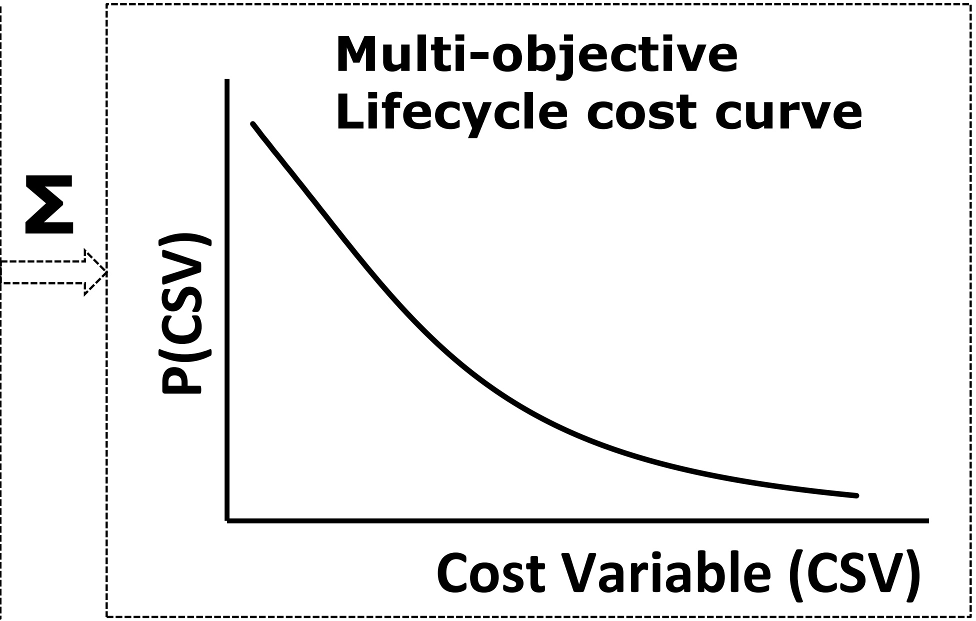
CSV : Cost/Saving Variable, e.g. Ratio initial cost/savings during lifecycle

EM : Energy measure, e.g. Energy consumption

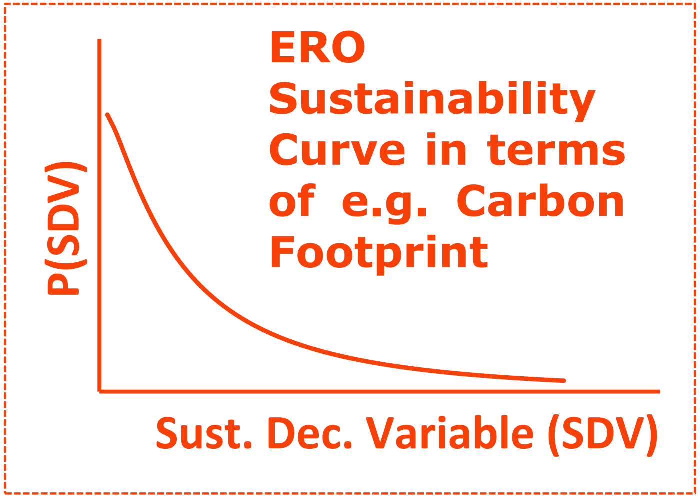
CV : Climate Variable, e.g. Temperature change

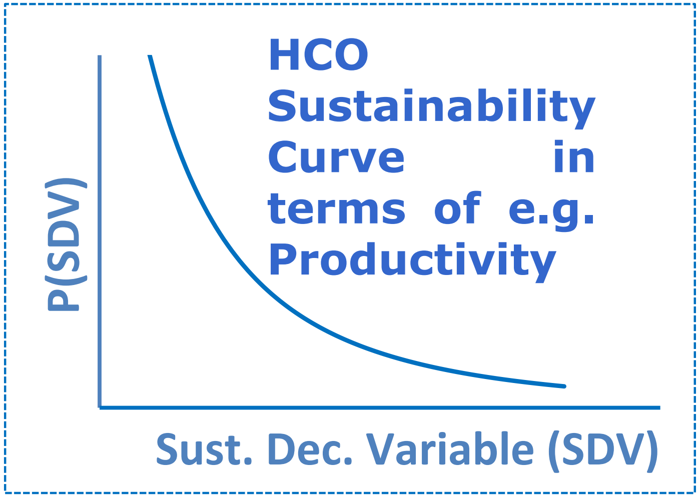
Extended Framework: Multi-objective Life Cycle Cost

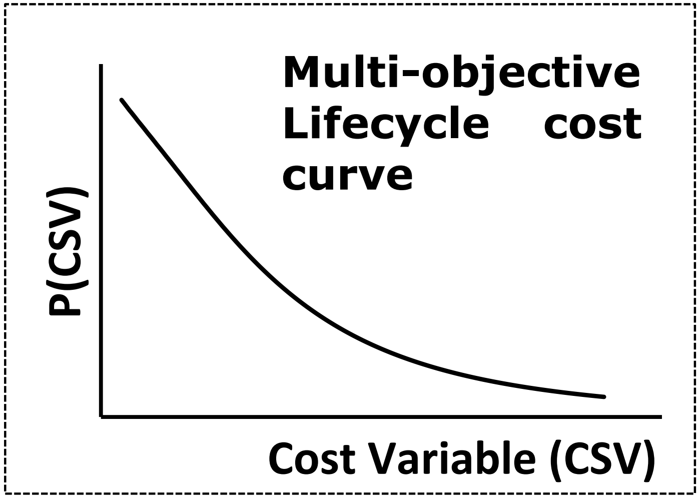




Extended Framework: Decision Tools







Framework for Performance-based Engineering (PBE) Approach to the Holistic Best Design Decision

Multi-Criteria Decision-Making:

Compared to other daily products,

- The life cycle of a building/structure is long;
- The number of stakeholders/users is large;
- The requirements and circumstances related to the building/structure are unpredictable.

→ **MAUT/MAVT (Multi-Attribute Utility/Value Theory)**

Steps:

- Tree Construction
- Value Function
- Weight Assignment
- Selection Amongst Alternatives

Extended Framework: Systematic Decision

❑ MIVES: Decision-Making Process

- **Tree Construction**

San José and Garrucho (2010); Pons (2011)

✓ Objectives
✓ Relevance
✓ Difference-making for each one of the alternatives
✓ Minimal number of items

Integrated Value Model for Sustainable Assessment (Modelo Integrado de. Valor para una Evaluación Sostenible – MIVES)

Iyengar (2012)

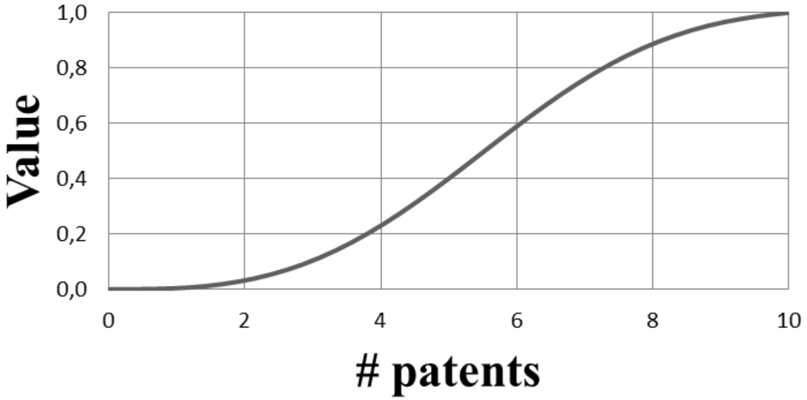
✓ Cut: Use 3 levels of unfolded branches, and every branch to have 5 sub-branches or less in the successive unfolding steps;
✓ Concretize: Use indicators that experts and stakeholders can understand;
✓ Categorize: Use more categories and fewer choices; and
✓ Gradually increase the complexity.

Extended Framework: Systematic Decision

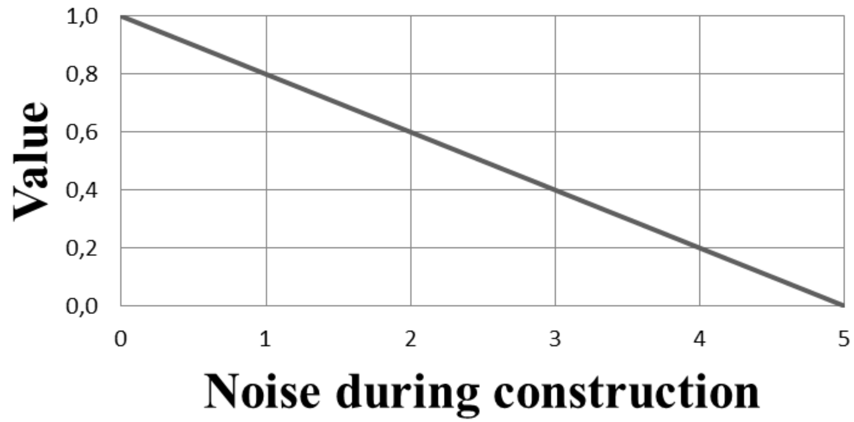
❑ MIVES: Decision-making Process

- **Value Functions**
  - ✓ Non-negative increasing/decreasing functions, $0 \leq V^i\left(X_k^i\right) \leq 1$
  - ✓ Linear, concave, convex, S-shaped, etc.
  - ✓ Presence of value functions allows for consideration of a broad range of indicators and allows the use of indicators with different units.

Examples



Number of new patents used in building design



Annoyance to neighbours (noise) during construction

Extended Framework: Systematic Decision

MIVES: Decision-making Process

- **Weight Assignment**

Requirement	W_{req} %	Criteria	W_{crit} %	*i*	Indicator	W_{ind} %	Unit
Functional	10.0	Quality perception	30.0	1	User	75.0	0-5
				2	Visitor	25.0	0-5
		Adaptability to changes	70.0	3	Modularity	100.0	%
Economic	50.0	Construction cost	50.0	4	Direct cost	80.0	$
				5	Deviation	20.0	%
		Life cost	50.0	6	Utilization	40.0	$
				7	Maintenance	30.0	$
				8	**Losses**	**30.0**	**$**
Social	20.0	Integration of science	10.0	9	New patents	100.0	#
		⋮	⋮	⋮	⋮	⋮	⋮
Environmental	20.0	Construction	20.0	15	Water consumption	10.0	m^3
				16	CO_2 emission	40.0	Kg
				17	Energy consumption	10.0	MJ
				18	Raw materials	20.0	Kg
				19	Solid waste	20.0	Kg
		Utilization	40.0	20	Noise, dust, smell	10.0	0-5
				21	Energy consumption	45.0	MJ/year
				22	CO_2 emission	45.0	kg/year
		⋮	⋮	⋮	⋮	⋮	⋮

Extended Framework: Systematic Decision

❑ MIVES: Decision-making Process

- **Selection Amongst Alternatives**

Integration of values of every indicator of any alternative *k*

$$V_k = \sum_{i=1}^{N_{ind}} W^i_{req} \cdot W^i_{crit} \cdot W^i_{ind} \cdot V^i\left(X^i_k\right)$$

Weights — Value function

✓ The value of each alternative is determined → The alternative that has the highest value, i.e. closest to 1.0, becomes the most suitable alternative, i.e. the "best" solution.

Extended Framework: Systematic Decision

PBE approach: PBE-MIVES

- **Multiple Indicators in a Direct Probabilistic Manner**

Assume **3** indicators DV_{CO2}, DV_E and DV_{ST} are considered and corresponding PDFs are:

$$f_{CO2}\left(DV_{CO2}=a\right)=A,\quad f_E\left(DV_E=b\right)=B,\quad f_{ST}\left(DV_{ST}=c\right)=C$$

For weights w_{CO2}, w_E and w_{ST}, the overall value for the indicators is:

$$V\left(a,b,c\right)=V_{CO2}\left(a\right)+V_E\left(b\right)+V_{ST}\left(c\right)=w_{CO2}u_{CO2}\left(a\right)+w_E u_E\left(b\right)+w_{ST}u_{ST}\left(c\right)$$

If DV_{CO2}, DV_E and DV_{ST} (with value functions u_{CO2}, u_E, and u_{ST}) are **mutually independent**, the joint PDF is:

$$\begin{aligned} f(a,b,c) &= f_{CO2,E,ST}(DV_{CO2}=a, DV_E=b, DV_{ST}=c) \\ &= f_{CO2}(DV_{CO2}=a)\, f_E(DV_E=b)\, f_{ST}(DV_{ST}=c) = ABC \end{aligned}$$

else,

$$\begin{aligned} f\left(a,b,c\right) &= f_{CO2,E,ST}\left(DV_{CO2}=a, DV_E=b, DV_{ST}=c\right) \\ &= f_{CO2}\left(DV_{CO2}=a\right) f_{E|CO2}\left(DV_E=b \middle| DV_{CO2}=a\right) f_{ST|CO2,E}\left(DV_{ST}=c \middle| DV_{CO2}=a, DV_E=b\right) \end{aligned}$$

Therefore, **the conditional probability distribution** should be defined.

$$P\left(DV^n=a\right)=p\left(DV>DV^n=a\right)=\int_a^\infty f_{DV}\left(DV\right)d\left(DV\right)$$

where $P(DV^n)$ is the POE of n^{th} value of DV, and $p(DV > DV^n = a)$ is the probability of DV exceeding a, n^{th} value of DV.

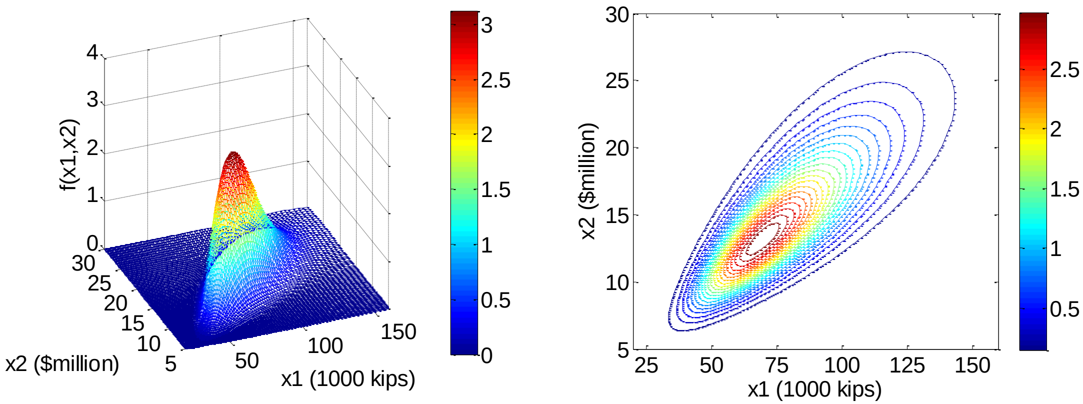
Extended Framework: Systematic Decision

❑ PBE approach: PBE-MIVES

▪ Application to the UCS Building

- ✓ Two alternatives with different fuel consumption (in Btu) ratios

  Electricity : Natural gas = 5 : 2 (Plan 1), Electricity only (Plan 2)
- ✓ Bivariate lognormal distribution assumed for energy expenditure and CO_2 emission for **50** years (building life span).
- ✓ Each mean value estimated based on data for **office buildings** in the West-Pacific region (by DOE, EIA, & EPA).
- ✓ Standard deviation assumed as 30% of the corresponding mean value.
- ✓ Coefficient of correlation was assumed as 0.8.



PDF of energy expenditure (x_1) and CO_2 emission (x_2) for Plan 1

Extended Framework: Systematic Decision

PBE approach: PBE-MIVES

Application to the UCS Building

Requirement	W_r [%]	Criteria	*i*	Indicator	W_i [%]	Unit
Environmental	25.0	Utilization	1	CO_2 emissions	100.0	1000 kips
Economic	75.0	Life cost	2	Energy expenditures	60.0	$million
			3	Losses	40.0	$million

Linearly decreasing value functions

$$u(x) = 1.0 \quad if\ x \le x_a$$
$$= 1.0 - (x - x_a)/(x_b - x_a) \quad if\ x_a < x \le x_b$$
$$= 0.0 \quad if\ x > x_b$$

→ The following was computed to compare Plans 1 and 2:

$$V_{prob} = \int_\Omega V f d\Omega$$

Expected value of an alternative → rank different alternatives

If no loss, i.e. $x_3 = 0$

Case 1: $0 \le x_1 \le 80$, $0 \le x_2 \le 15$

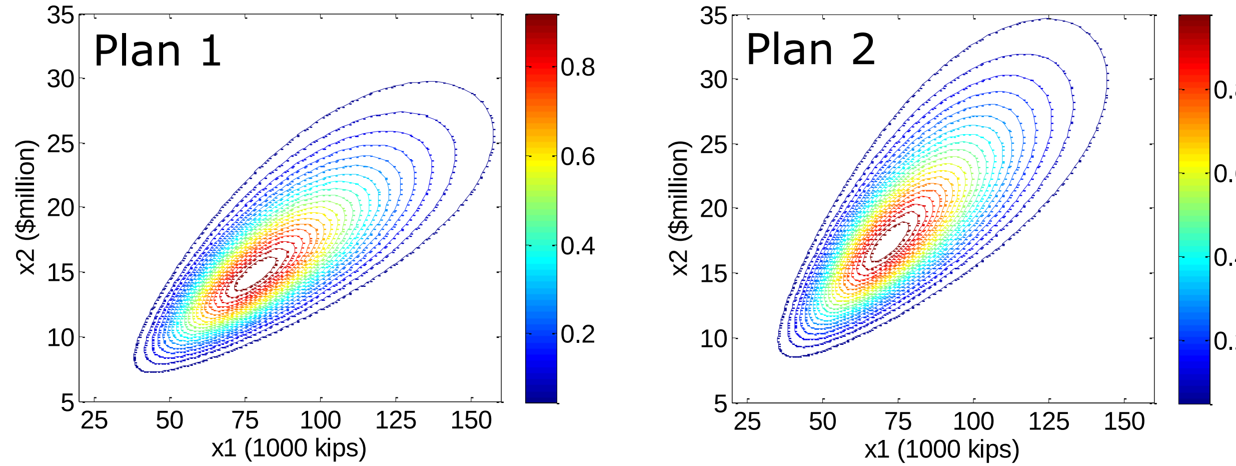
✓ Plan 1: $V_{prob} = 309.52$

Plan 2: $V_{prob} = 223.56$

Case 2: $0 \le x_1 \le 80$, $0 \le x_2 \le 20$

Plan 1: $V_{prob} = 393.95$

✓ Plan 2: $V_{prob} = 449.61$



Contours of Vf of energy expenditures (x_1) and CO_2 emissions (x_2) for Plans 1 and 2 of the UCS example building [Monetary loss due to structural damages $x_3 = 0$]

Extended Framework: Systematic Decision

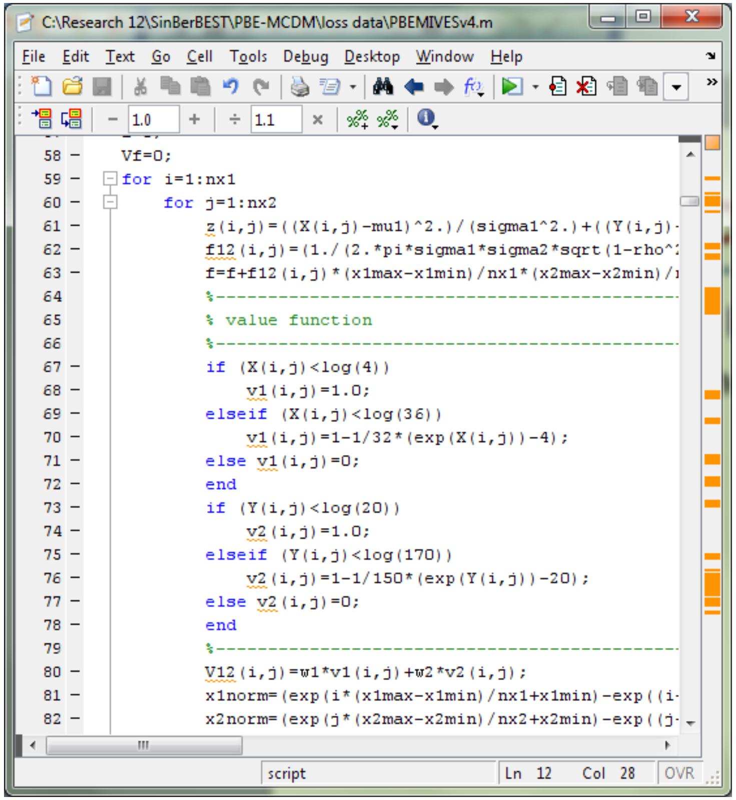
❑ PBE approach: PBE-MIVES

- ✓ The probabilistic nature of the indicators can be considered in MCDA either indirectly by the calculation of the value of each indicator in a probabilistic manner or directly by formulating the value determination equation in a probabilistic framework.

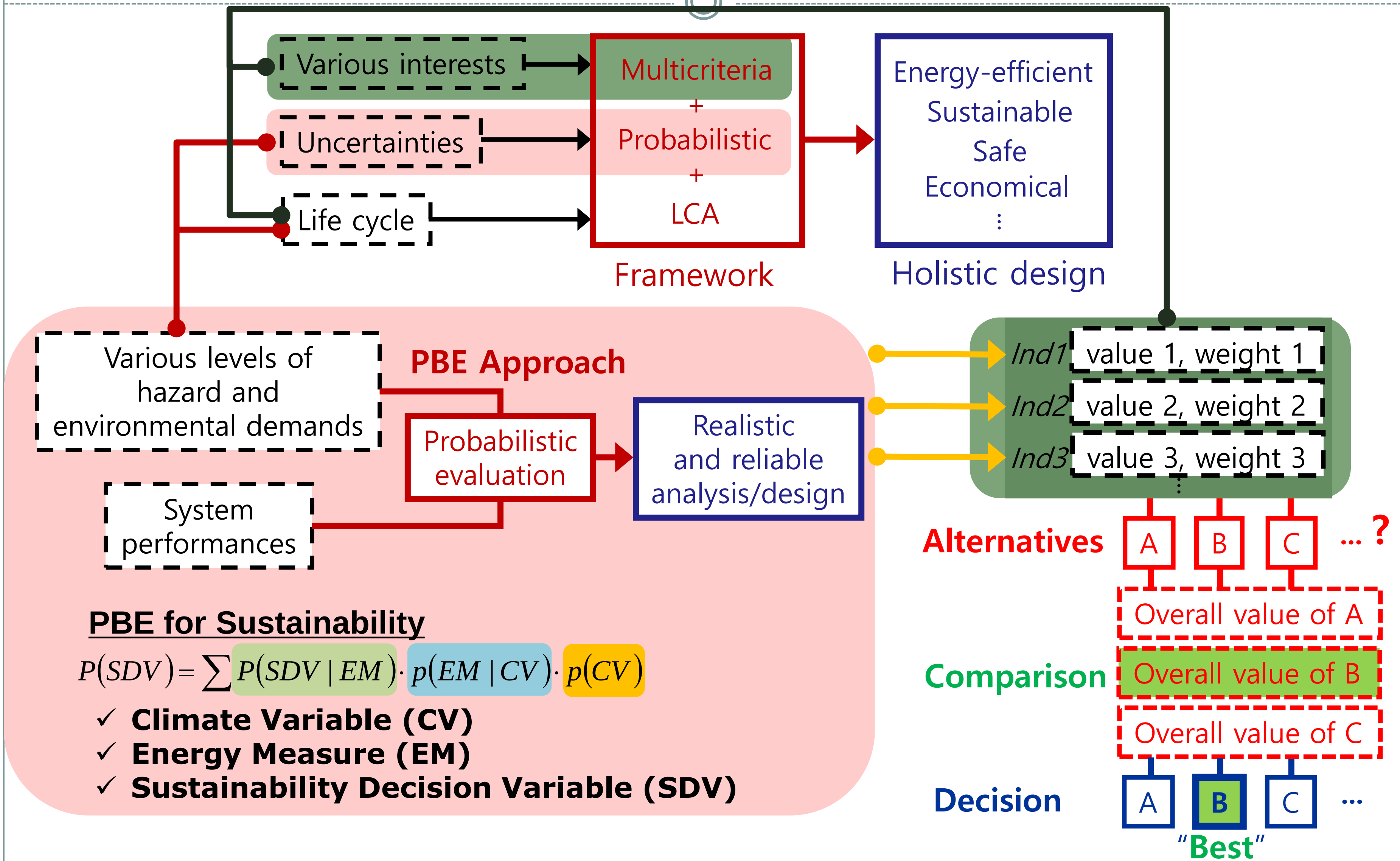
- ✓ The correlation between the different indicators is taken into account in the direct formulation and it is the preferred method when there is significant interdependency between indicators.

- ✓ As shown in the comparison of V_{prob} in the UCS example building, considered range of indicators can change the value of the alternatives and affect the final decision. Therefore, attention should be paid to the selection of the proper range of indicators.

Matlab code for PBE-MIVES



RECAP: Framework for PBE for "Best" Decision of Energy-efficient & Sustainable Building Design



PBE for Sustainability

$$P(SDV) = \sum P(SDV \mid EM) \cdot p(EM \mid CV) \cdot p(CV)$$

- ✓ **Climate Variable (CV)**
- ✓ **Energy Measure (EM)**
- ✓ **Sustainability Decision Variable (SDV)**

Questions?

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