Decision Analysis for Seismic Retrofit of Structures

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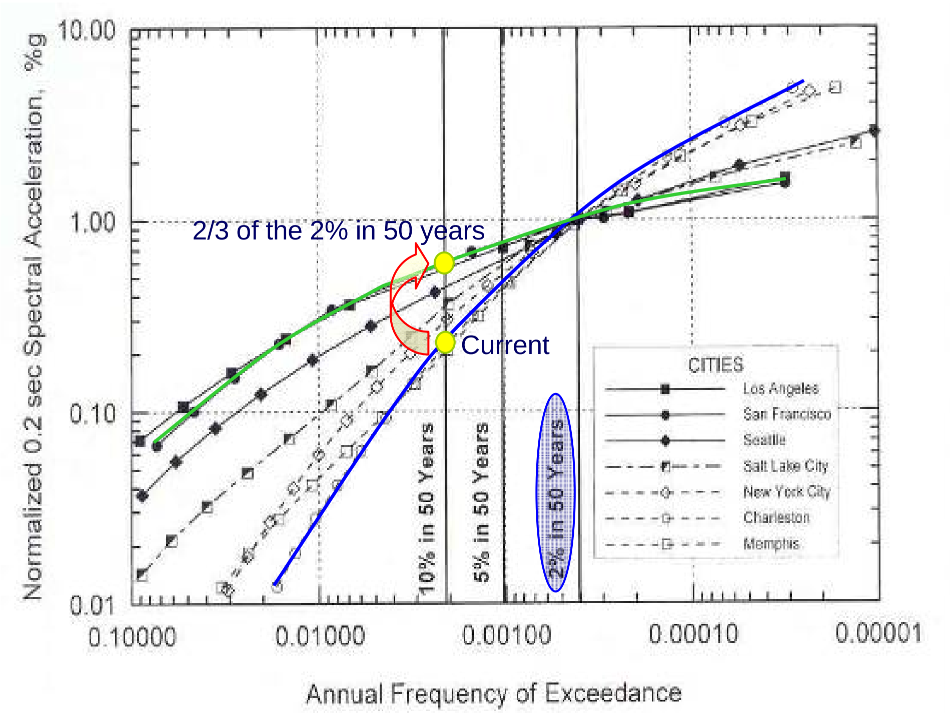
Problem statement and motivation

- The latest IBC provisions would require (if adopted) buildings in Mid-America to be designed for similar seismic events as in California
- If so, buildings in parts of Mid-America would be significantly overdesigned for less intense earthquakes



IBC 2006 requires 2/3 of the 2% in 50 year earthquake

Memphis, TN

San Francisco, CA

Normalized Hazard Curves

(Leyendecker *et al.*, 2000)

Leyendecker, E. V., Hunt, R. J., Frankel, A. D. and Rukstakes, K. S. (2000). “Development of maximum considered earthquake ground motion maps.” *Earthquake Spectra*, 16(1), 21-40.

Objectives

- Investigate how building location affects the annual probability of attaining or exceeding specified performance levels
- Develop a framework to determine the economic feasibility of seismic retrofitting
- Study the effects that achievable loss reduction, investment return period, and retrofitting cost have on the economic feasibility of seismic retrofitting
  - Compare Mid-America with California

Outline

- Annual probability of failure of an example building
- Framework to compute the Estimated Annual Loss
- Parametric study on Estimated Annual Loss (achievable loss reduction, investment return period and retrofitting cost)
- Impact of retrofit: A case study
- Conclusions

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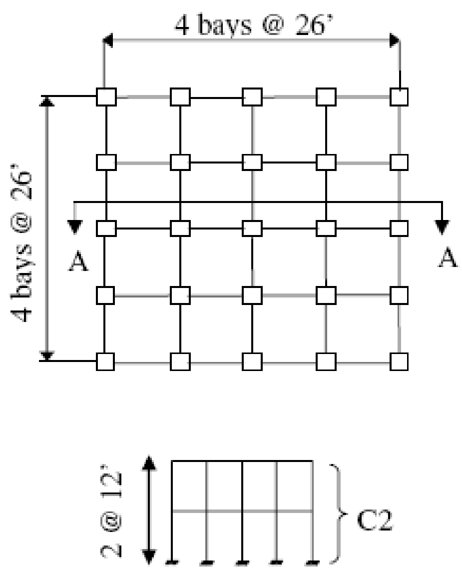
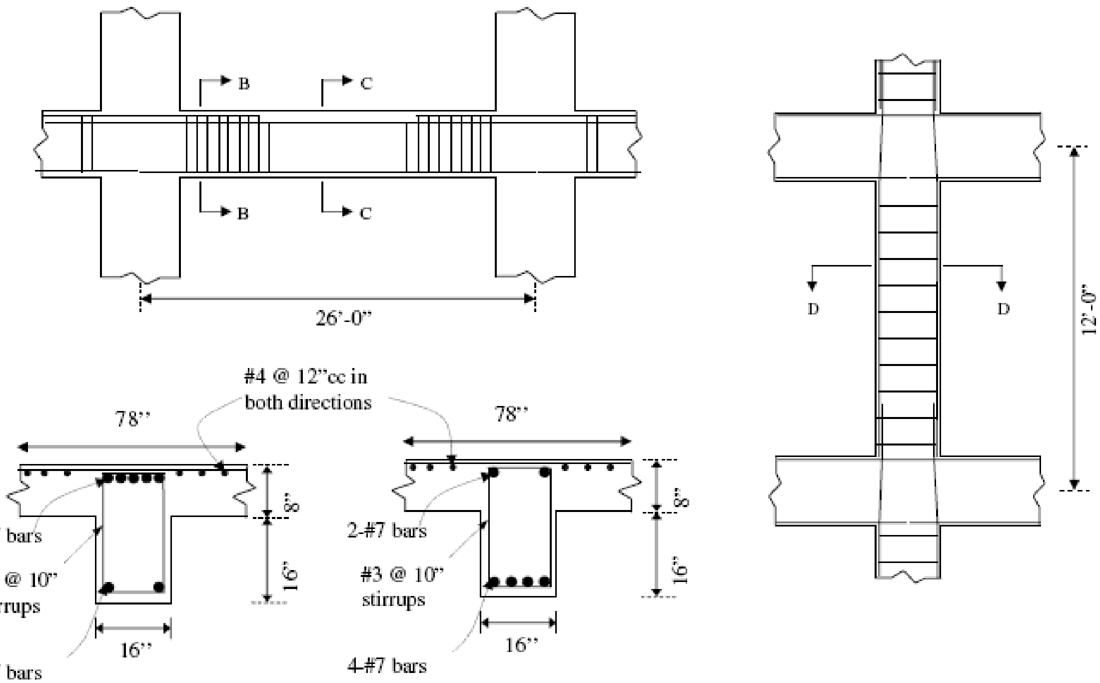
Consider a typical gravity-load designed building prone to “soft-story” failure mechanism



Plan and elevation views of the example 2-story RC building (Ramamoorthy *et al.*, 2006)



Design details (Ramamoorthy *et al.*, 2006)

This represents typical low-rise construction in Mid-America

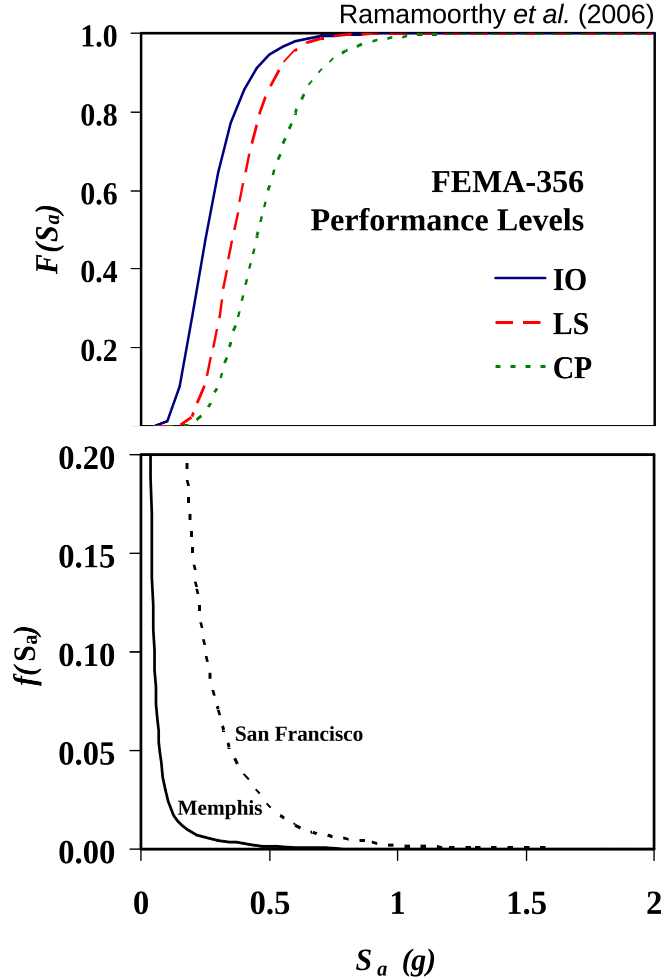
Ramamoorthy, K. S., Gardoni, P., and Bracci, M. J., (2006). “Probabilistic demand models and fragility curves for reinforced concrete frames,” *ASCE Journal of Structural Engineering*, **132** (10), 1-10.

The seismic hazard can be used to compute the annual probability of attaining or exceeding a performance level

Identical example buildings are studied in Memphis, TN and San Francisco, CA

Building location is therefore the primary factor affecting retrofit feasibility

Ramamoorthy *et al.* (2006)



- Annual probability of attaining or exceeding a performance level

$$P_f = \int_{S_a} F(S_a) f(S_a) dS_a$$

- Corresponding generalized reliability index

$$\beta = \Phi^{-1}(1 - P_f)$$

Where

S_a = Spectral acceleration

$F(S_a)$ = Fragility

$f(S_a)$ = Annual probability density of S_a at building site

Should stakeholders retrofit their buildings?

		Memphis	San Francisco
Annual Probability P_f	IO	0.00590	0.06438
	LS	0.00469	0.04693
	CP	0.00375	0.03514
Annual Reliability Index β	IO	2.52	1.52
	LS	2.60	1.68
	CP	2.67	1.81

The annual probabilities are ~10 bigger in SF than in Memphis

Reliability in Memphis within commonly acceptable range

Stakeholders also need to consider the improvements in the reliability provided by a retrofitting strategy and its expected economic benefit

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The Estimated Annual Loss can be used to determine the economic benefit of a retrofitting strategy

Estimated Annual Loss, EAL

$$EAL = V \int_{S_a=0}^{\infty} y(S_a)\, v(S_a)\, dS_a$$

Economic Benefit, B

$$B = \left(EAL - EAL_r\right)\left(\frac{1-e^{-\rho T}}{\rho}\right)$$

Indicates EAL after retrofit

V = the value of the facility and any additional value associated with it

$y(S_a)$ = total damage factor (mean repair cost of a facility as a fraction of V)

S_a = spectral acceleration

$v(S_a)$ = average annual frequency of experiencing ground motion intensity S_a

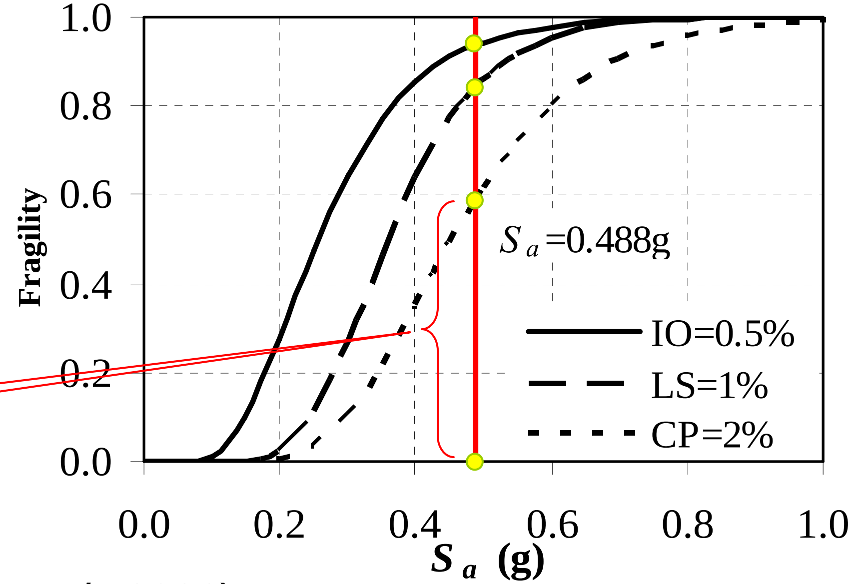
ρ = discount rate

T = investment return period

The total damage factor, $y(S_a)$, represents the mean repair cost of a facility as a fraction of V

Data for Example Building

Performance Level	Damage State	Probability, $P_{k\|IM}$ ($S_a = 0.488$g)
	Insignificant (I)	0.063
PL1: IO →	Moderate (M)	0.094
PL2: LS →	Heavy (H)	0.256
PL3: CP →	Complete (C)	0.587



$$y(S_a) = \sum_{k=1}^{4} \left(\mu_{L_k} \times P_{k|S_a} \right)$$

(Bai *et al.*, 2006)

Mean of the Damage Factor (structural damage as a percentage of V) associated to each damage state, *k*

Probability of being in each damage state for given Sa

EAL in Memphis = **0.4% of V** vs. EAL in San Francisco = **4.0% of V**

Bai, J.-W., Hueste, M. B. D., and Gardoni, P., (2006). "A Probabilistic Framework for the Assessment of Structural Losses due to Seismic Events," *ASCE Natural Hazards Review* (submitted)

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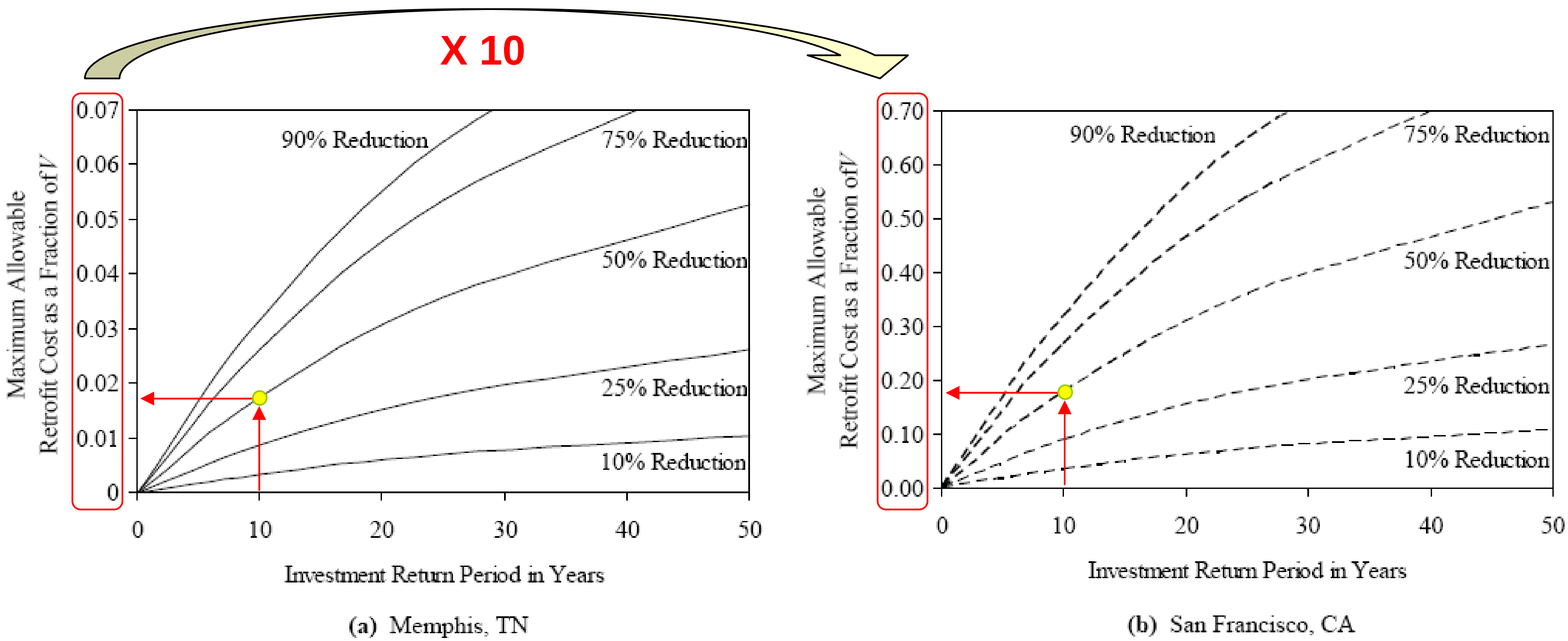
Retrofit feasibility is studied considering investment return period, reduction in *EAL*, and retrofit cost



As a rule of thumb, the budget for a retrofit that reduces *EAL* by any given percentage is 10 times greater in San Francisco than in Memphis

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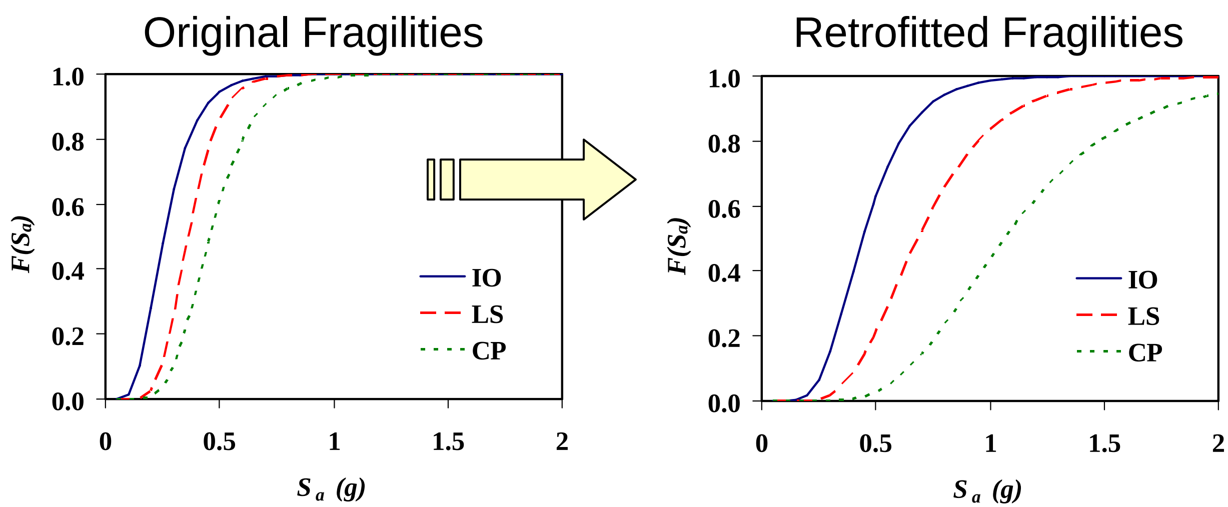
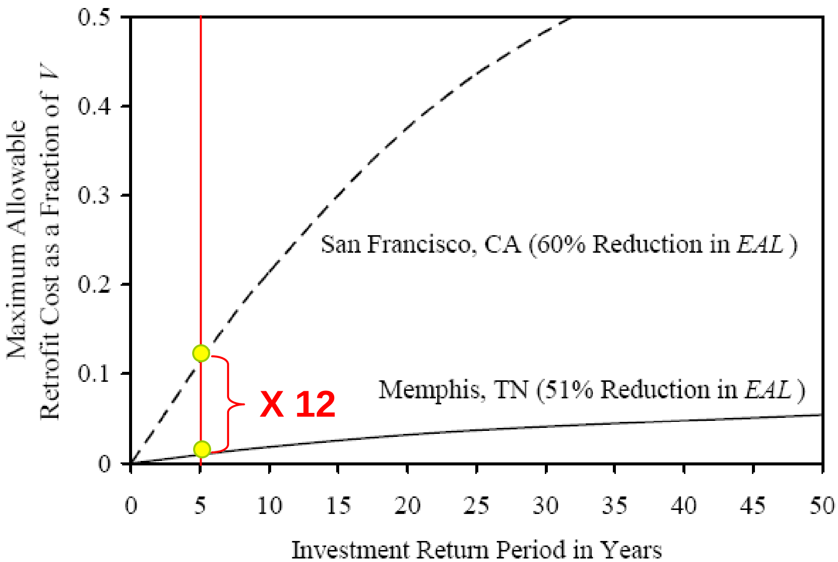
Retrofitted fragility curves are used for a case study



Retrofitted column-to-beam strength ratio of 1.8 is used to deter the "soft-story" failure mechanism

(Ramamoorthy *et al.*, 2006)



Maximum allowable retrofit cost for a 5-year return period is nearly 12 times greater for the example building if in San Francisco than if in Memphis

Should stakeholders retrofit their buildings?

		Memphis		San Francisco	
		Original	Retrofit	Original	Retrofit
Annual Probability P_f	IO	0.00590	0.00390	0.06438	0.03720
	LS	0.00469	0.00239	0.04693	0.01922
	CP	0.00375	0.00125	0.03514	0.00773
Annual Reliability Index β	IO	2.52	2.66	1.52	1.78
	LS	2.60	2.82	1.68	2.07
	CP	2.67	3.02	1.81	2.42

The reliability in Memphis of the original (unretrofitted) case-study building is still higher than that of the retrofitted building in San Francisco

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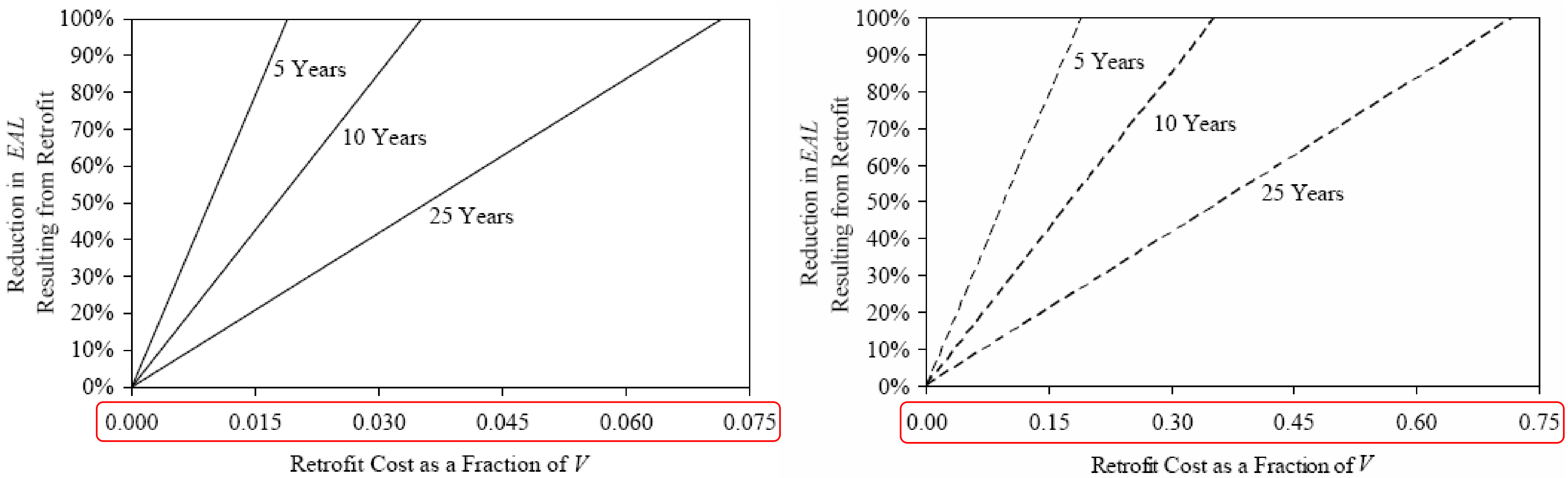
Conclusions

- The annual probability of exceeding a specified performance level for a gravity-load designed building in San Francisco is about 10 times greater than if the same building is located in Memphis
- Using 2/3 of the 2% earthquake intensity for the design basis of structures will not create uniform reliability (or probability of failure) on an annual basis throughout the US. It will only ensure that buildings throughout the US will not collapse under the 2% Maximum Credible Earthquake (MCE). However, for less intense earthquakes, buildings in parts of Mid-America will be significantly overdesigned as compared to California.
- The retrofit of gravity-load designed buildings might not be financially viable in Mid-America
- In Mid-America, the indirect value (higher importance use, expensive contents, human lives, etc.) will have to be significantly greater than the direct structural value for the retrofit to be economically feasible, which may be the case for emergency headquarters, hospitals, etc.

Thank you

Appendix

Retrofit feasibility is studied considering investment return period, reduction in EAL, and retrofit cost



(a) Memphis, TN

(b) San Francisco, CA

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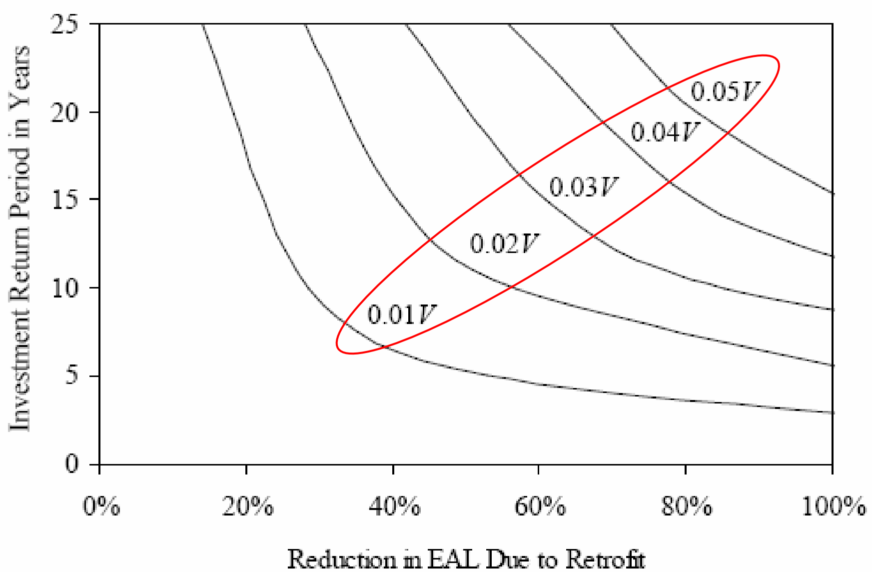

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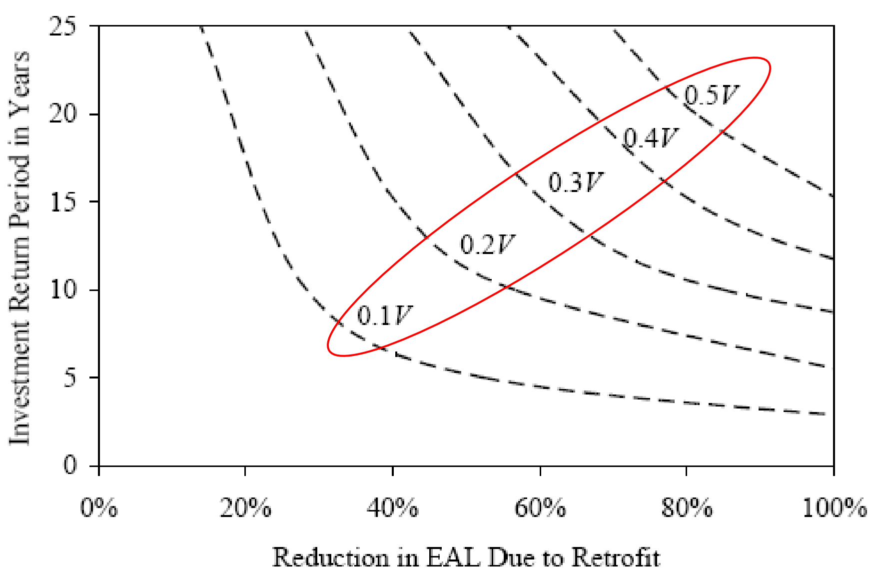

(b) San Francisco, CA