Fragility Curves:

$$P[\text{Loss}] = \sum_{s}\sum_{LS}\sum_{d} P[\text{Loss} \mid D=d] \cdot P[D=d \mid LS] \cdot P[LS \mid IM=s] \cdot P[IM=s]$$

Loss: خسارت مستقیم/غیرمستقیم ناشی از زلزله

D: خرابی (سطح خرابی)

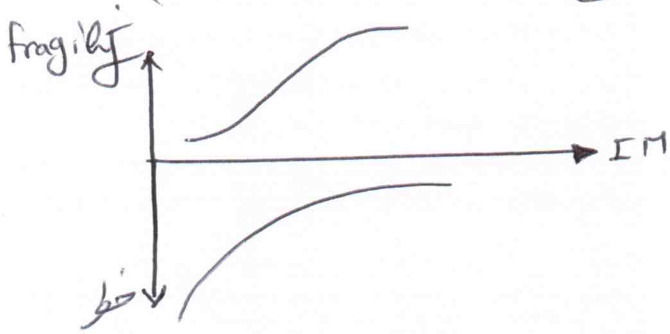
LS: سطح حدی

IM: شدت

$P[LS \mid IM=s]$ = Probability of reaching or exceeding a specified performance LS Conditioned on the $IM=s$

= Seismic Vulnerability / Fragility

چون منحنی شکنندگی برحسب IM بیان می‌گردد، مستقل از سطح خطر لرزه‌ای است (دوره بازگشت)



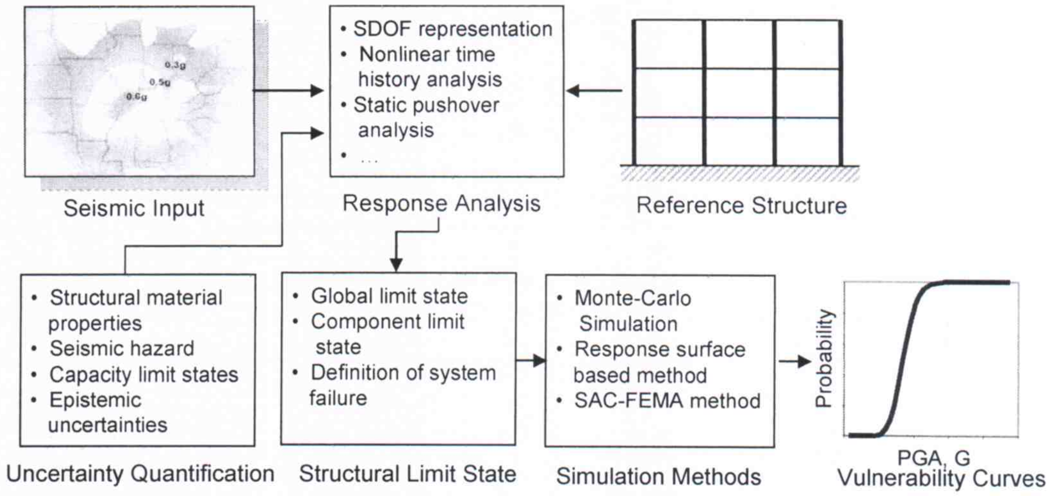


Figure 1. Components of seismic vulnerability simulation

Table 1. Categorization of fragility curves

Category	Characteristics	
براساس زلزله‌های گذشته از نظر آماری قابل اطمینان هستند مربوط به یک زلزله خاص هستند Empirical fragility curve	Feature	Based on postearthquake survey Most realistic
	Limitation	Highly specific to a particular seismo-tectonic, geotechnical and built-environment The observational data used tend to be scarce and highly clustered in the low-damage, low-ground-motion severity range Include errors in building damage classification Damage due to multiple earthquakes may be aggregated
	Sample Ref.	Orsini 1999; Spence et al. 1992 ; Ymazaki and Murao 1995; Miyakoshi et al. 1997
Judgmental fragility curve	Feature	Based on expert opinion The curves can be easily made to include all the factors
	Limitation	The reliability of the curves depends on the individual experience of the experts consulted A consideration of local structural types, typical configurations, detailing and materials inherent in the expert vulnerability predictions
	Sample Ref.	ATC-13, 1985
متکی به مدل، روش تحلیل و میزان حساسیت Analytical fragility curve	Feature	Based on damage distributions simulated from the analyses Reduced bias and increased reliability of the vulnerability estimate for different structures
	Limitation	Substantial computational effort involved and limitations in modeling capabilities The choices of the analysis method, idealization, seismic hazard, and damage models influence the derived curves and have been seen to cause significant discrepancies in seismic risk assessments
	Sample Ref.	Chryssanthopoulos et al. 2000; Mosalam et al. 1997; Reinhorn et al. 2001; Kwon and Elnashai 2010
Hybrid fragility curve	Feature	Compensate for the scarcity of observational data, subjectivity of judgmental data, and modeling deficiencies of analytical procedures Modification of analytical or judgment-based relationships with observational data and experimental results
	Limitation	The consideration of multiple data sources is necessary for the correct determination of fragility curve reliability
	Sample Ref.	Kappos et al. 1995

– The SAC–FEMA Method

- Both demand and capacity depend on random variable
- The problem is "a time-variant reliability" problem.
- The SAC-FEMA method (Cornell et al. 2002) transforms time-variant problem into time-invariant problem by considering only maximum response.

$$H(S_a) = P(S_a \geq s_a, 1\ \text{year}) = K_0\, s_a^{-K}$$

$$H_D(d) = \int P[D \geq d \mid S_a = x]\, |dH(x)| = H(S_a^{d}) \exp\left[\frac{1}{2}\frac{K^2}{b^2}\beta^2_{D|S_a}\right]$$

$$\hat{D} = a\, S_a^{b}$$

$$P_{PL} = \int P[C \leq d]\, |dH_D(d)| = H(S_a^{\hat{c}}) \exp\left[\frac{1}{2}\frac{K^2}{b^2}\left(\beta^2_{D|S_a} + \beta^2_{C}\right)\right]$$

The order of magnitude of P_{PL} is dictated by the hazard and not by the demand or capacity. (Pinto et al. 2004)

این روش زمانی کارا است که

الف) پاسخ سازه را بتوان صرفاً با $Sa(T_1)$ بیان نمود

ب) خرابی در سازه را بتوان صرفاً با پارامتر MDIR نشان داد.

- Monte-Carlo Simulation Method

- is a useful method for complex systems with several random variables, x, and several failur modes.
- It is difficult to derive a limit-state function, $g(x)$

- MCS steps:
  - generate n sets of random variables x_i, $i = 1, 2, \ldots, m$ according to joint probability density, $f_x(x)$
  - each set of random variables is used to run simulation
  - The probability of failure $= \frac{n_f}{n}$

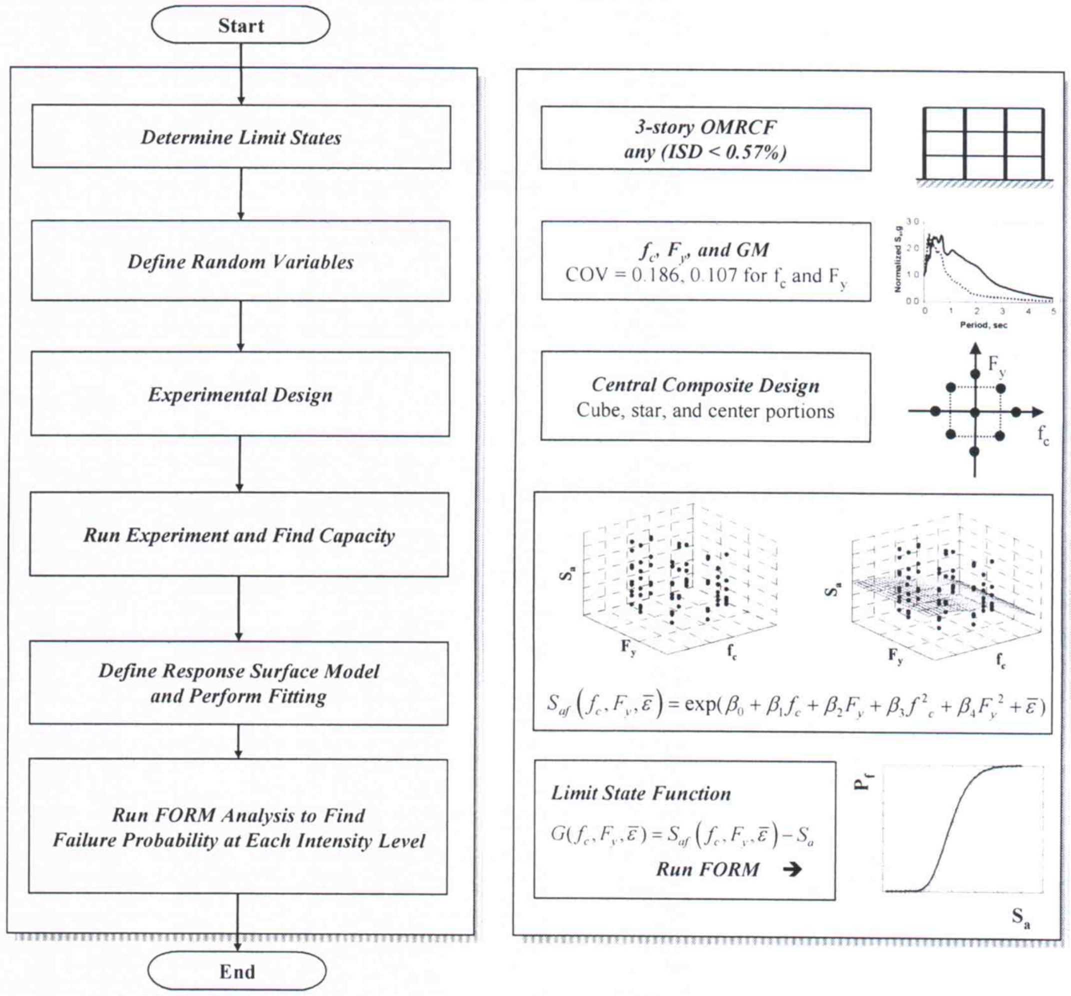
    n_f = number of simulation with $g(x) < 0$

- by increasing the number of simulation, the CMS results converge to the closed form simulation.

- To reduce the variance of estimated probability, different sampling techniques may be applied, e.g. Importance or Latin Hypercube sampling.

Response Surface Approach:

Limit state function = $g(x) = C(x) - D(x)$



(a) Flow Chart (b) Application to 3-story OMRCF

Figure 2. Flowchart of RSM for seismic vulnerability analysis

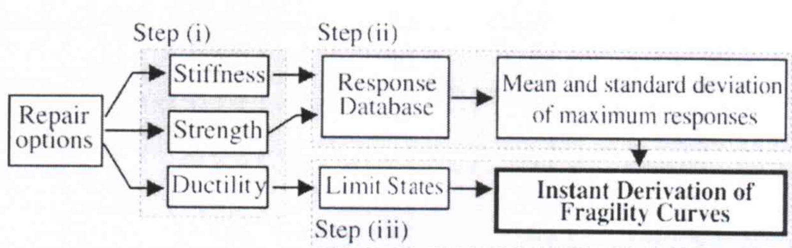


Figure 3. Overall procedure of the parameterized fragility curves

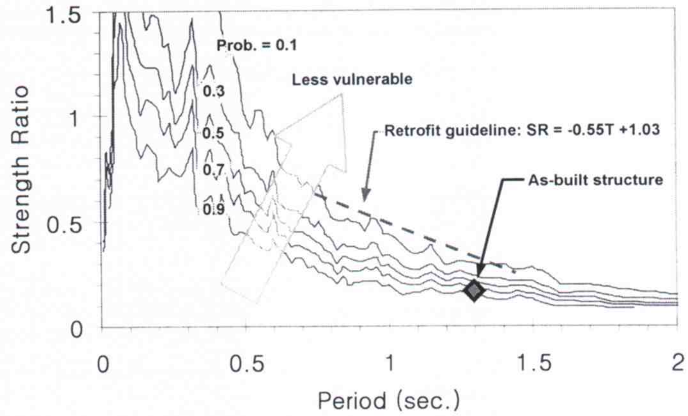
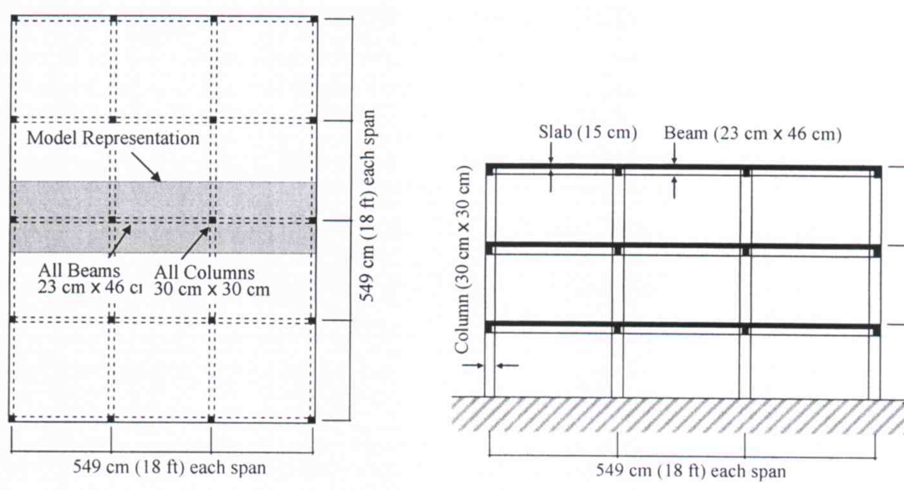


Figure 4. Fragility contours and a retrofit guideline

- Example:



(a) Plan view (b) Elevation

Figure 5. Configuration of reference RC frame

- A typical ordinary moment resisting concrete frame structure
- The model is verified based on the data from the test on the State University of New York shaking table.
- The results are structure-specific
- The building is designed for only gravity loads (no seismic detailings)

Three Limit States:

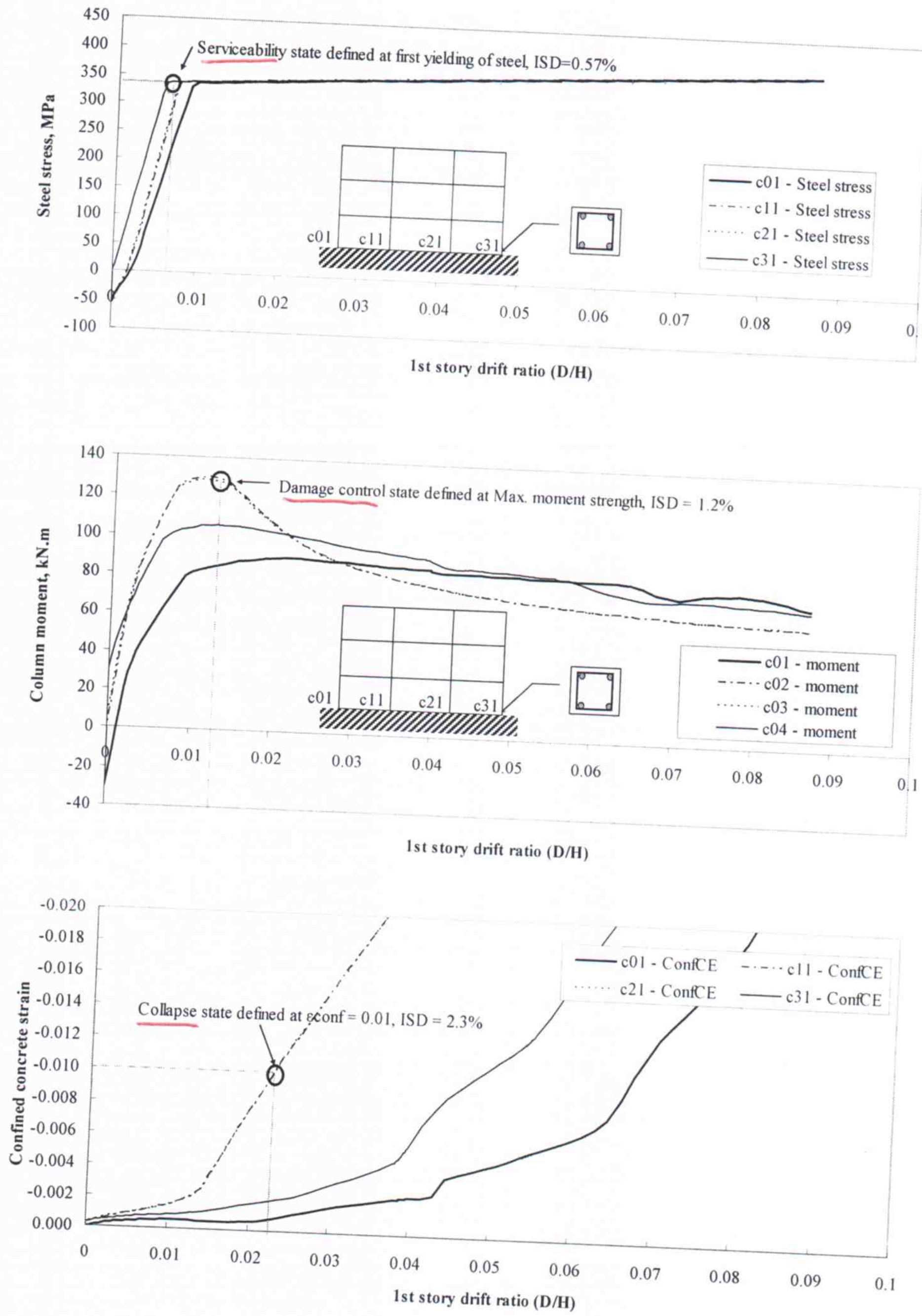


Figure 6. Definition of limit states

- Design code: ACI 318-89 ($f_y = 276$ MPa & $f'_c = 24$ MPa)
- Only interstory drift is used as a global measure of damage and the local damage of individual element (beam, column, ...) is not taken into account.
- The limit states are applied to the 2nd & 3rd stories.
- The mode accounts for geometric nonlinearity and material inelasticity.

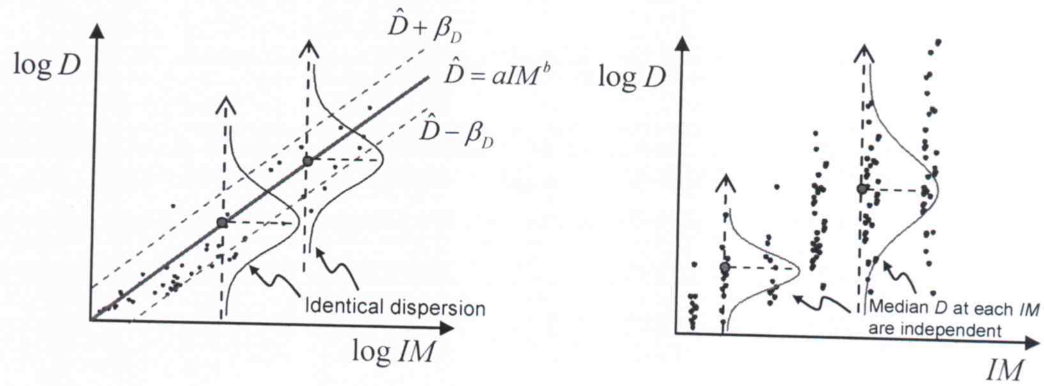


Figure ~~**Error! No text of specified style in document.**~~7. MCS method adopted for fragility curve derivation
(a) Intensity measure-demand relationship in SAC-FEMA method (b) The MCS based approximation

- It is assumed that uncertainties in structural response are due to uncertainties in material strength and seismic hazard.
- For each ground motion set → 10 randomly generated steel, 10 " " Concrete } → 100 model at each PGA level
→ The distribution parameters of ISD_{max} at each PGA are calculated assuming log-normal distribution

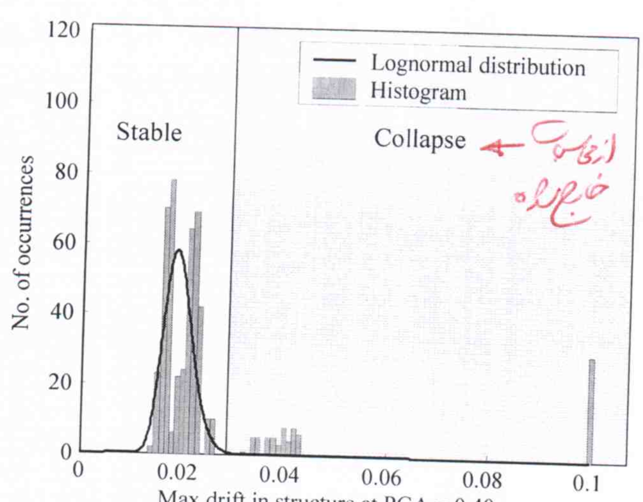


Figure ~~**Error! No text of specified style in document.**~~8. Lognormal distribution of seismic demand before collapse
(Ground motion – Set AV-2, PGA = 0.40g)

TPT:

$$P(ISD > ISD_{Limit}) = P(ISD > ISD_{Limit} | E_1) \cdot P(E_1) + P(ISD > ISD_{Limit} | E_2) \times P(E_2) = P(ISD > ISD_{Limit} | E_1) P(E_1) + 1.0 \times P(E_2)$$

$P(E_1)$: احتمال پایداری سازه

$P(E_2)$: احتمال ناپایداری عدم سازه

Fragility Curve:

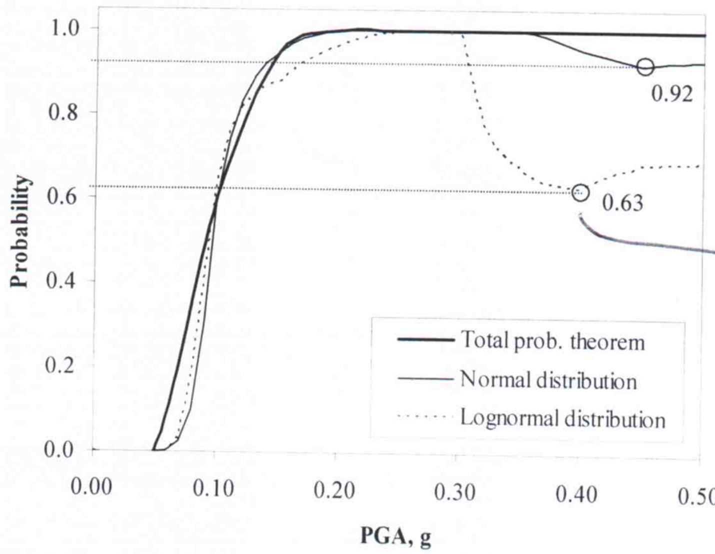
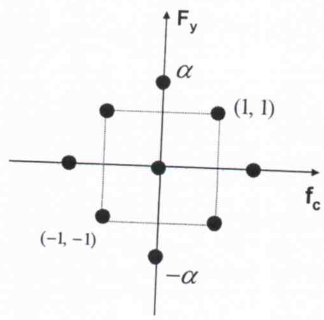
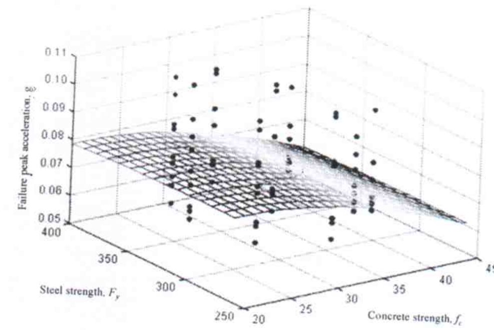


Figure 9. Fragility curves from various methods
(Ground motion – Set AV-2, Limit state = ISD 0.57%)

misleading average and coefficient of variation of unstable structures.

Response Surface Method (RSM)





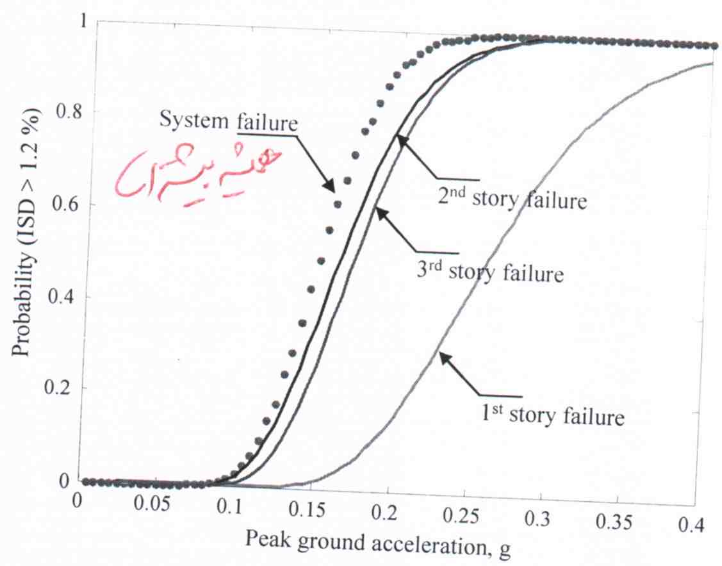


Figure 10. Comparison of failure probabilities of components and a system

$$P(\text{System failure} \mid IM=PGA) = P(ISD_1 > LS \text{ or } ISD_2 > LS \text{ or } ISD_3 > LS \mid IM=PGA)$$

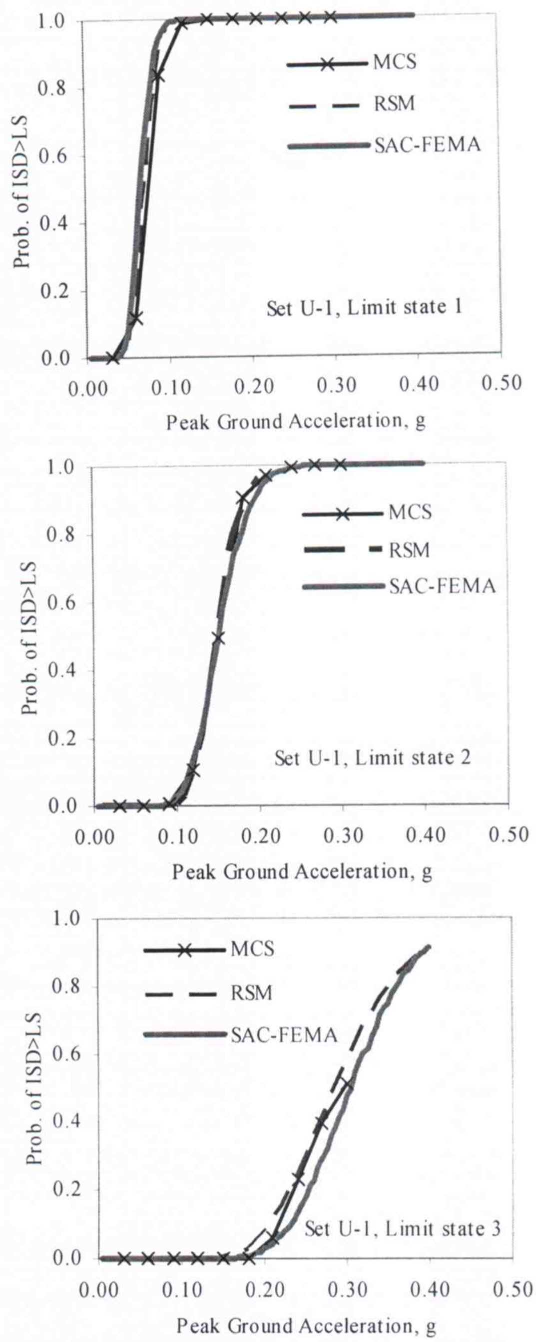


Figure ~~**Error! No text of specified style in document.**~~11. Fragility curves from MCS, RSM, and SAC-FEMA method

The MCS is the most time-consuming procedure.

- RSM needs scaling but SAC-FEMA doesn't need it.

Comparison of fragility curves from SDOF approximation with those from MDOF model

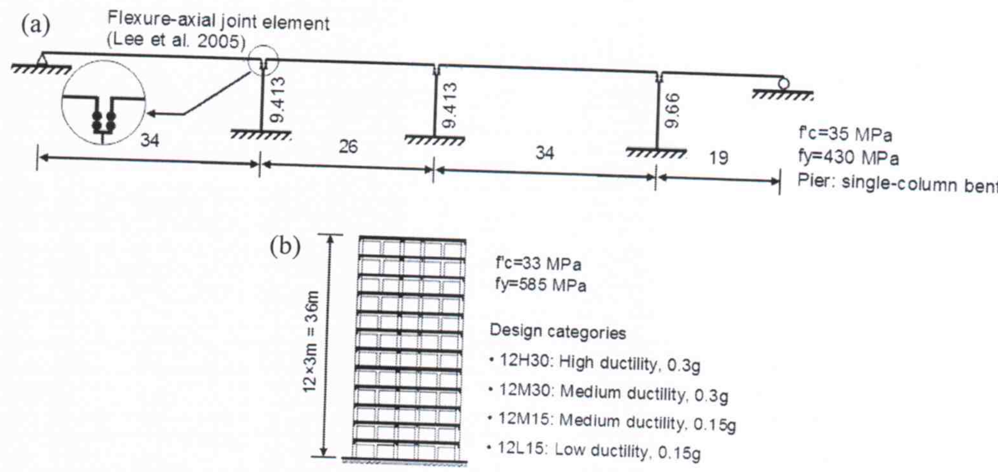


Figure 12. Reference structures for the comparison of fragility curves SDOF and MDOF: (a) Hanshin Expressway route 3 viaduct, (b) mid-rise RC frame building

LS1: light damage , LS2: collapse prevention

SDOF models can be an efficient approximation for structures with limited irregularities.

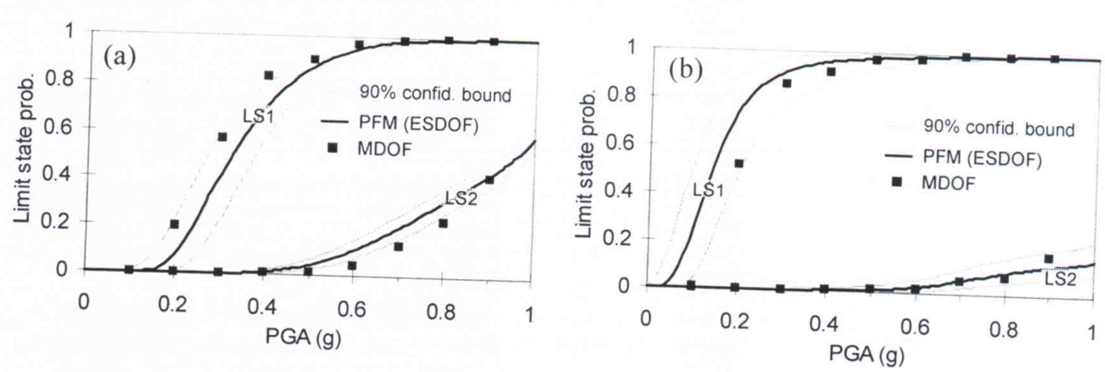
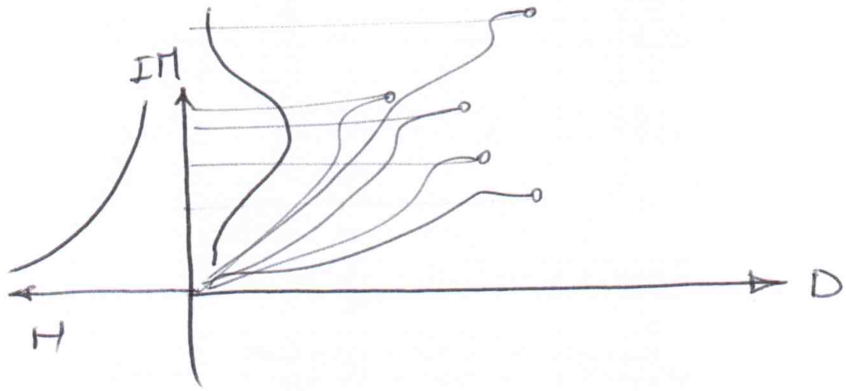
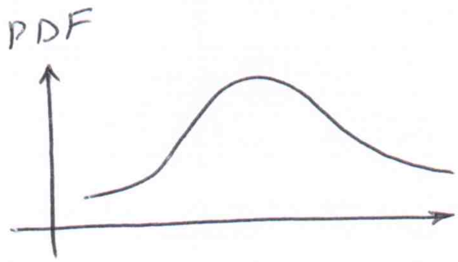


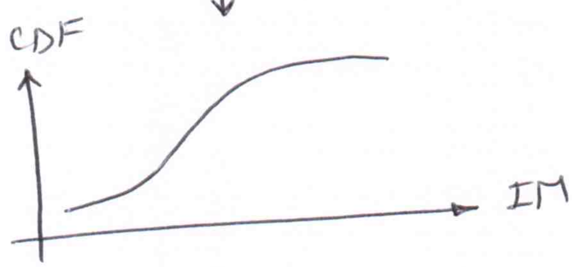
Figure **Error! No text of specified style in document.**13. Comparison of fragility curves: (a) bridge example, (b) building example

IM approach





↓



← Fragility Curve

MAF = mean annual frequency = $\int$ Fragility $|dH|$

$\approx$ Fragility $\times$ Hazard

در هر سطح از Hazard زلزله‌ها فرق می‌کند چون مربوط به سطح خطر استفاده شده است!