Seismic fragility of nuclear installations

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Organisation

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Safety Regulation
1983 - 2008

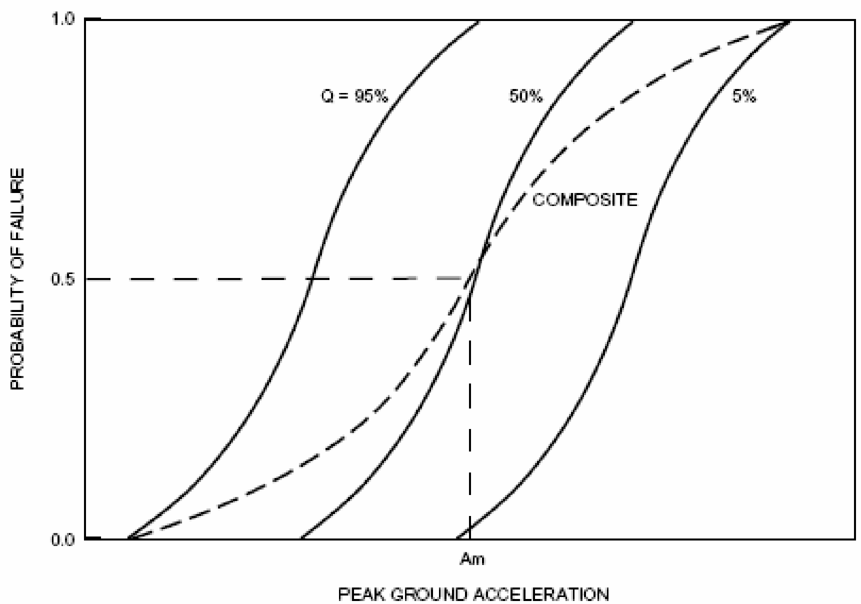
Seismic fragility of nuclear installations

- Introduction
- Seismic fragility of NPP
- Seismic fragility of components/elements by analysis
- Seismic fragility components/elements by test
- Seismic fragility components/elements by EBM
- Concluding remarks

Introduction

- Seismic fragility is the conditional probability of failure for a given value of seismic input parameter e.g.. peak ground acceleration (PGA).
- Many sources of variability in the estimation of this ground acceleration capacity
  - Epistemic randomness
  - Aleatory uncertainties

$$P_f = \Phi\left(\frac{\ln\left(\frac{a}{A_m}\right) + \beta_U \Phi^{-1}(Q)}{\beta_R}\right)$$



Introduction

- Demand: PGA '*a*'
- Capacity: ground acceleration capacity, A:

$$\mathbf{A = A_m . \varepsilon_R . \varepsilon_U}$$

- Three parameters
  - –Median ground acceleration capacity, A_m, and
  - –Two random variables ε_R and ε_U .

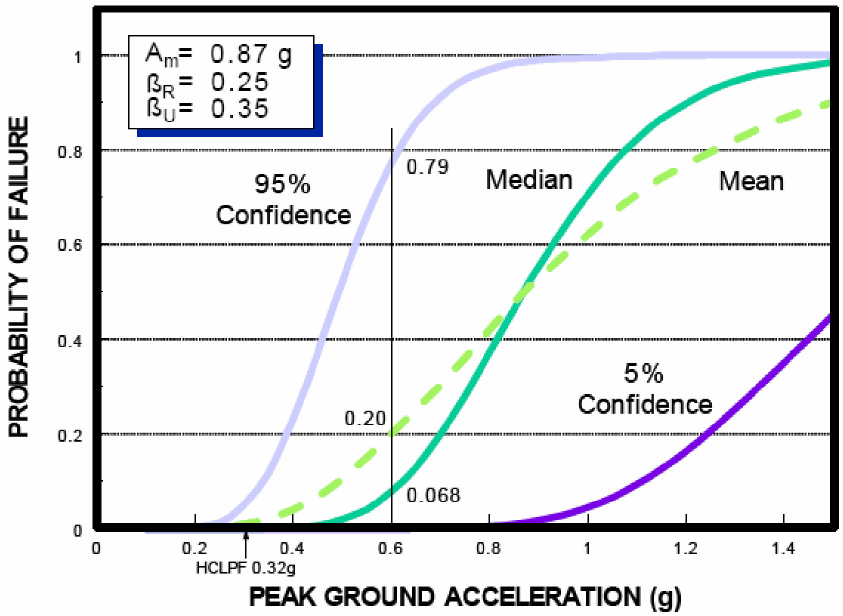
ε_R and ε_U are log-normally distributed random variables, with a unit median and logarithmic standard deviation $\boldsymbol{\beta_R}$ (epistemic or inherent randomness about the median), $\boldsymbol{\beta_U}$ (aleatory uncertainty in estimating the A_m)

Introduction

- Further, $A_m = A_{RBGM} * F'$, $F' = F_1' * F_2' * F_3'$
  - F_1: factor representing ratio of capacity and demand
  - F_2: factor representing conservatism in assessing capacity
  - F3: factor representing conservatism in assessing demand (structural response factor)
- Major part of fragility analysis involves with determination of
  - Median values of $\mathbf{F_1}$, $\mathbf{F_2}$ and $\mathbf{F_3}$, and
  - Corresponding $\beta_{u(.)}$ and $\beta_{R(.)}$

Introduction

- High confidence low probability failure (HCLPF) capacity of an NPP or its components is the PGA corresponding to 5% P_f with 95% confidence level. It could be derived from the seismic fragility descriptions or deterministically.

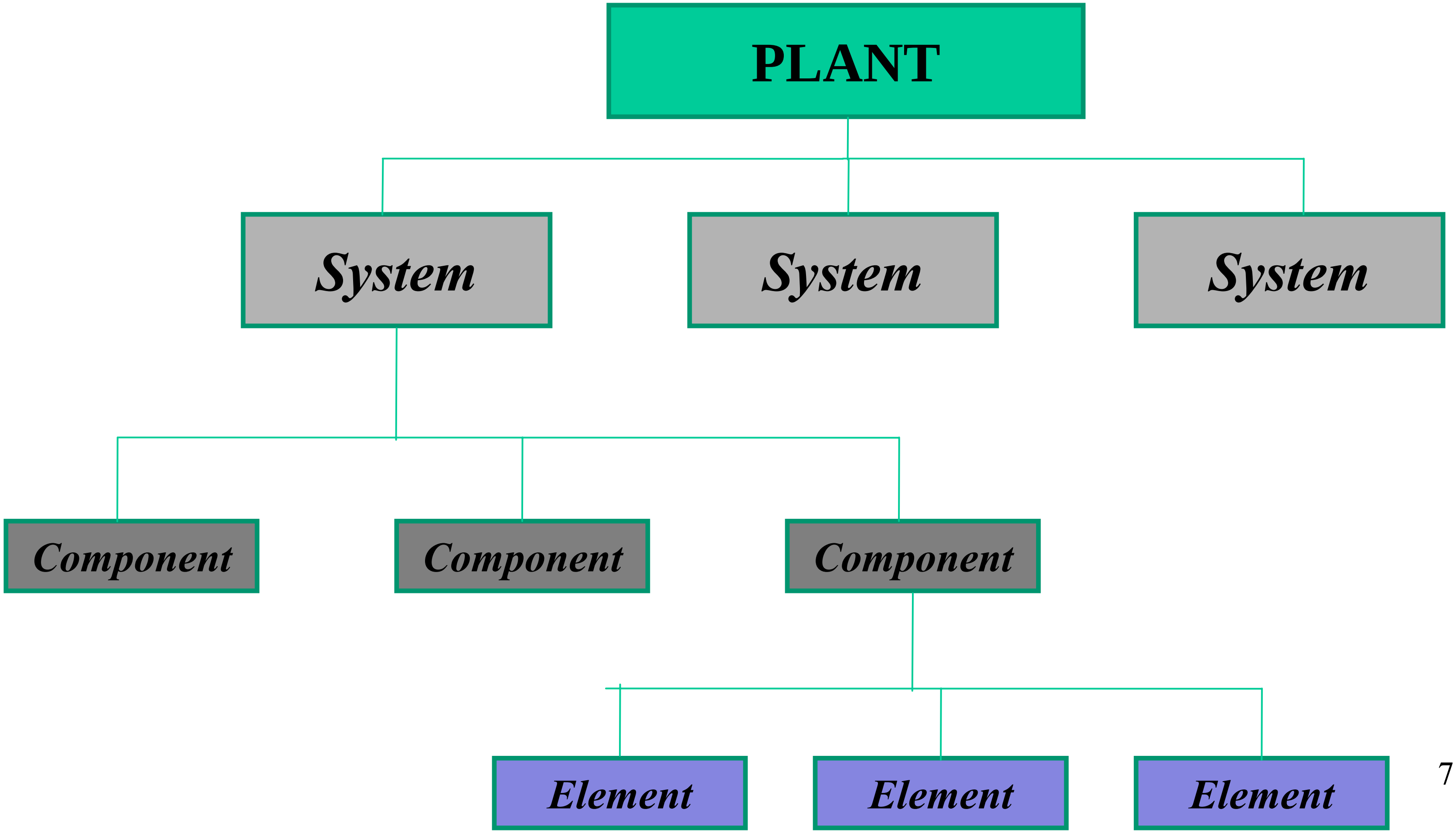


- Fragility from HCLPF value:

$$A_m = A_{HCLPF} * e^{1.645[\beta_R + \beta_u]}$$

Seismic fragility of NPP

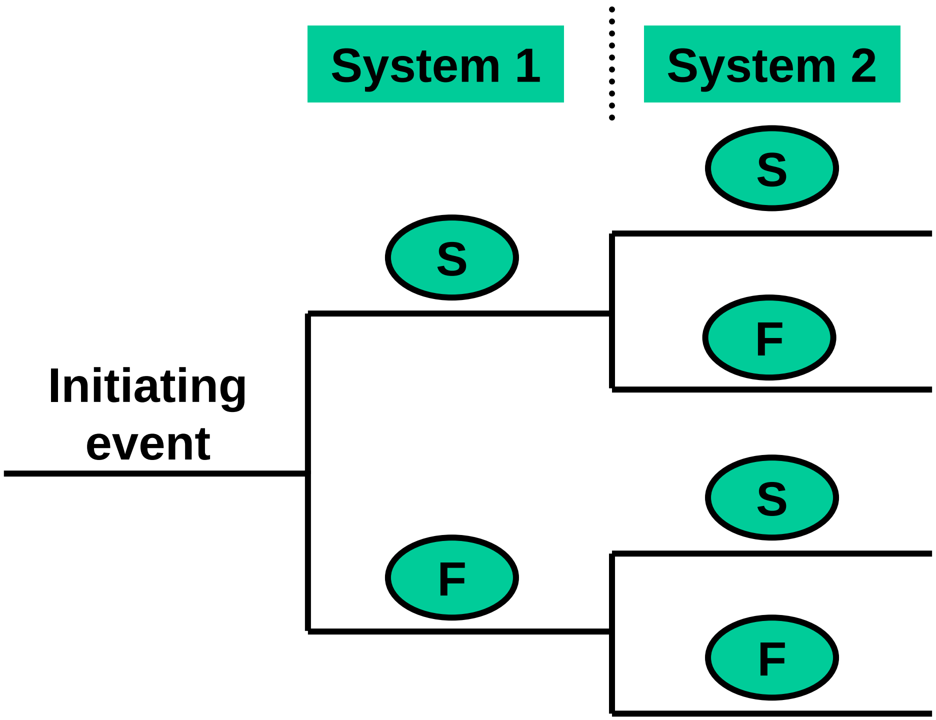
- System fragility of a plant derived from the fragility of it's constituents parts



Seismic fragility of NPP

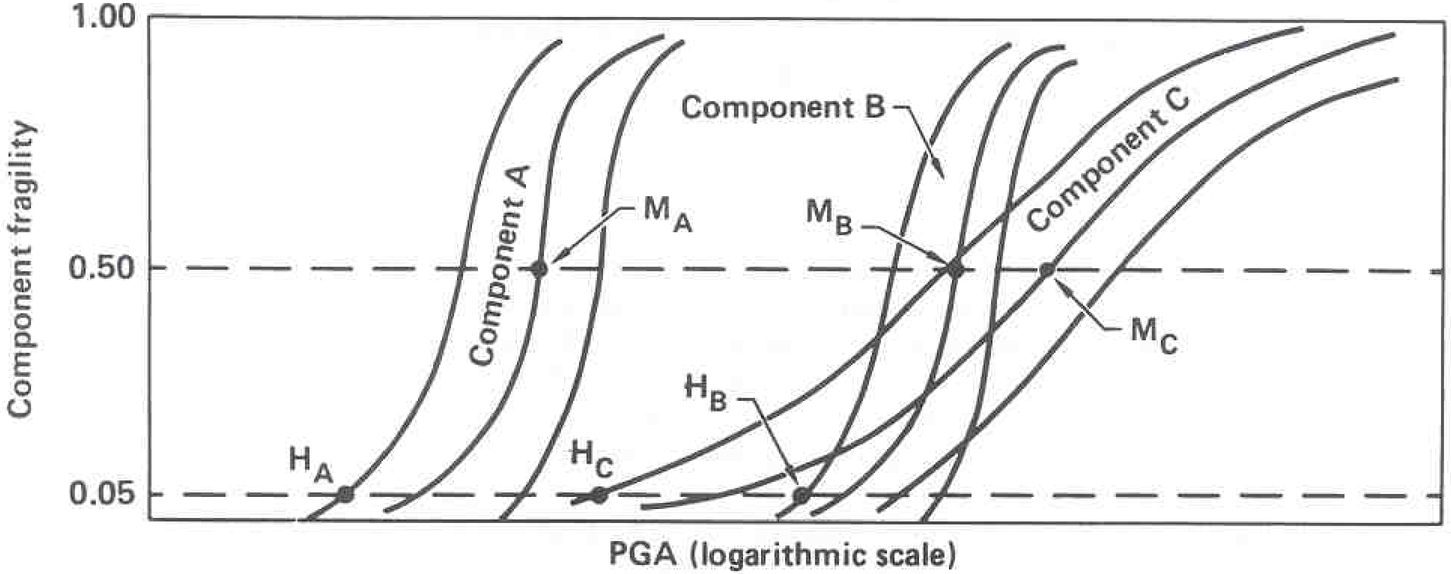
Plant fragility

- **Plant** fragility is determined form either HCLPF value or fragility of **systems** following failure path or success path deriving from the plant event tree.



Seismic fragility of NPP

Plant fragility



Situation – 1: Core melt occurs when any one of the three systems fail

Overall median capacity = median capacity of A, the weakest link.

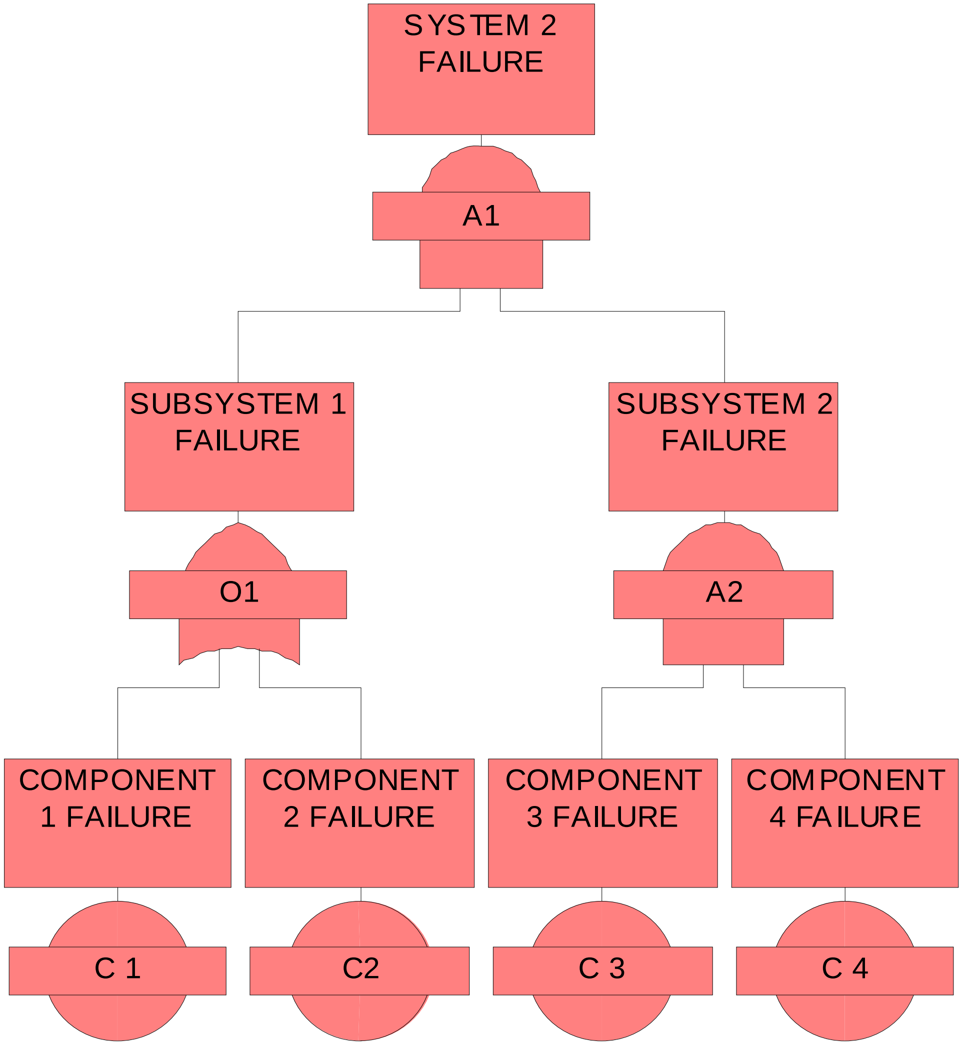
Situation – 2: Core melt occurs only when all the three systems fail

Overall median capacity = median capacity of C, system of highest capacity.

Seismic fragility of NPP

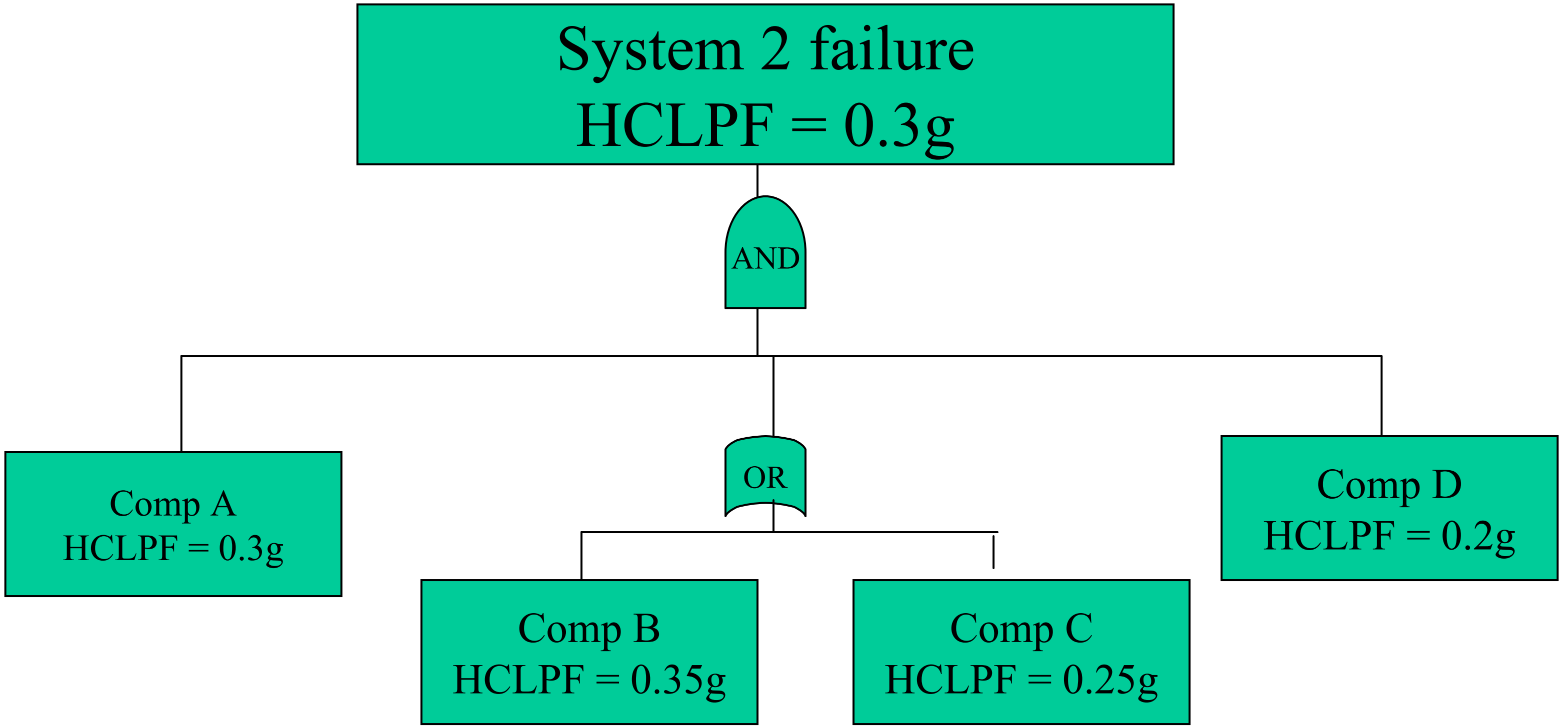
System fragility

- **System** fragility is determined form either HCLPF value or fragility of **components** following fault tree diagram of the system



Seismic fragility of NPP

System fragility



The HCLPF of system is given by Boolean expression

SF = A*(B+C)*D

= Max (A, min(B, C), D) = Max (0.3g, min(0.35g, 0.25g), 0.2g)

= Max(0.3g, 0.25g, 0.2g) = 0.3g

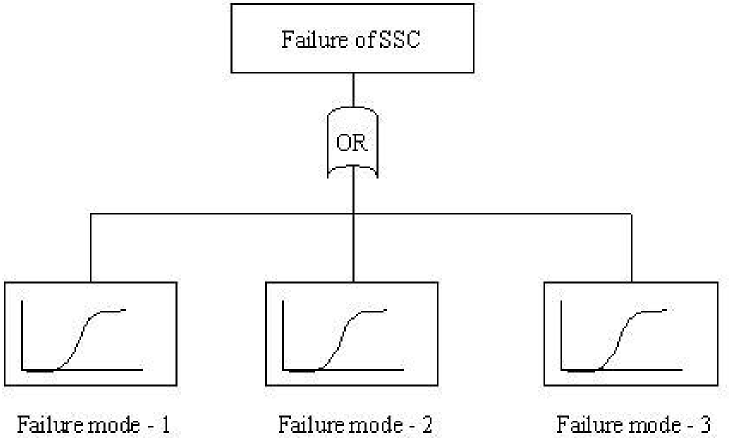
Seismic fragility of NPP
Component fragility

- **Component** fragility is determined directly, or form either HCLPF value or fragility of **elements.**
- Two approaches exist when determined from element fragilities
  - Minimum of element HCLPF or fragility
  - Weakest link method
- Methods of determining fragility parameters
  - Direct method: **analysis and testing**
  - Indirect method: **experience based method (EBM) adopting plant walk down.**

Seismic fragility of NPP

Component fragility: weakest link model

- A component is considered to be failed if any element fails.
- For real component, this is conservative.



- An element of a component will not fail if it survives against all failure modes

$$P_s = \prod_{i=1}^{n} \left(1 - P_{fi}\right), i = 1, n$$

- **Probability of failure, P_F**

$$P_F = 1 - P_s = 1 - \prod_{i=1}^{n} \left(1 - P_{fi}\right)$$

P_{fi} is the probability of failure of the component against i^{th} failure mode and n is the total number of failure modes

Seismic fragility of NPP

Approaches for **determining** component fragility

NO.	CATEGORY	METHOD OF QUALIFICATION
1.	Reactor core assembly	Analysis
2.	Reactor coolant system vessels (RPV, Pressurizer etc)	Analysis
3.	Reactor coolant pump	
4.	Primary coolant piping	
5.	Large diameter piping	
6.	Intermediate piping	
7.	Large vertical storage vessels with formed heads	
8.	Large vertical storage tank – flat bottom	
9.	Large horizontal vessels and heat exchangers	
10.	Small-medium vessels and heat exchangers	
11.	Buried pipe	
12.	Large vertical centrifugal pumps with motor drive	
13.	Large vertical pumps	
14.	Motor driven compressors	
15.	LMOV'S (Large motor operated valves)	
16.	Large relief and check valves	
17.	Small valves	Analysis/EBM
18.	Hydraulic and air operated valves	Analysis/EBM
19.	Emergency AC power (Diesel generators)	Testing/EBM
20.	Emergency DC power (Batteries on racks)	EBM
21.	Switchgear	Testing/EBM
22.	Dry transformers	Testing/EBM
23.	Control panels and racks (Floor mounted)	Testing/EBM
24.	Instrumentation panels	Testing/EBM
25.	Auxiliary relay cabinets	Testing/EBM
26.	Local instruments	Testing/EBM
27.	Motor control centers	Testing/EBM
28.	Invertors	Testing/EBM
29.	Cable trays	Analysis
30.	Breaker panels	Testing/EBM
31.	Air handling units	Testing/EBM
32.	Ductwork	Analysis
33.	Control rods and drives	Analysis/testing
34.	Ceramic insulators	Testing/EBM
35.	Dampers, diffusers, extractors	Testing/EBM
36.	Battery chargers	Testing/EBM
37.	Civil engineering structures	Analysis

Seismic fragility of NPP

Element fragility

- **Element** fragility is determined for each failure modes
- Methods of determining fragility parameters
  - Direct method: **analysis and testing**
  - Indirect method: **experience based method based on plant walk down.**

Seismic fragility of NPP

Element fragility

- **Element** fragility is determined for each failure modes
- If failure modes are independent

$$P_F = 1 - \prod_{i=1}^{n} \left(1 - P_{Fi}\right)$$

- If failure modes are dependent ***(A component will fail at i^{th} mode if it survives all the previous modes)***

$$P_F = 1 - \left(1 - P_{F1}\right) \prod_{i=2}^{n} \left[1 - \left\{ \prod_{j=1}^{i-1} \left(1 - P_{Fj}\right) \right\} P_{Fi} \right]$$

Seismic fragility of component/element by analysis

$$F_1 = F_S = \frac{S - R_N}{R_T - R_N}$$

S = Seismic capacity; R_T = Total demand; R_N = Concurrent non-seismic demand

$$F_2 = F_\mu$$

$$F_3 = F_R$$

Seismic fragility of component/element by analysis

$$F_\mu = \left(\sqrt{2\mu - 1}\right) \in$$

Amplified region of response spectrum (2 to 8 Hz)

$$F_\mu = \mu^{0.13} \in$$

Rigid equipment

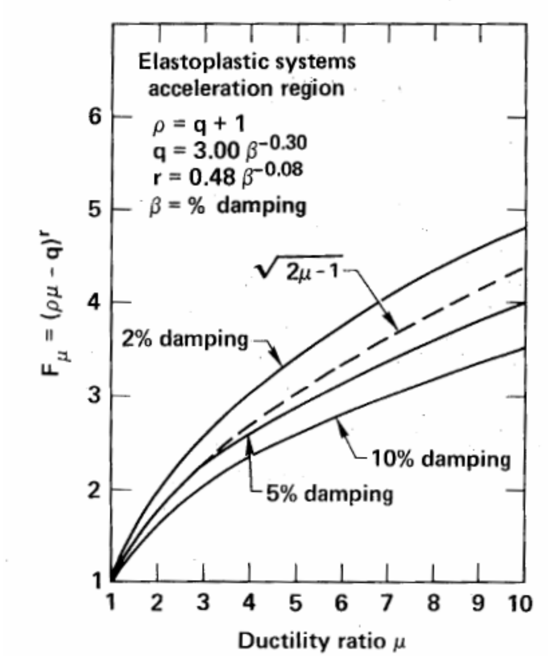
$$F_\mu = (\rho\mu - q)^r$$

Where

$\rho = q + 1;\ q = 3.00\ \delta^{-0.30}$

$r = 0.48\ \delta^{-0.08}$

and δ is the % of damping



Seismic fragility of component/element by analysis

$$\overline{F}_R = \overline{F}_{RS} = \overline{F}_{SA} * \overline{F}_{SS} * \overline{F}_{\delta} * \overline{F}_M * \overline{F}_{MC} * \overline{F}_{EC} * \overline{F}_{SD}$$

Civil

F_{SA}: **Factor for ground motion and associated response spectra for a given PGA.**

F_{SS}: **Soil structure interaction factor.**

F_{δ}: **Factor energy dissipation i.e. damping.**

F_M: **Structural modeling factor.**

F_{MC}: **Factor for combination of modes and earthquake analysis results.**

F_{EC}: **Factor for combination of earthquake components**

F_{SD}: **Factor to reflect the reduction of seismic input with depth**

Seismic fragility of component/element by analysis

$$\overline{F}_R = \overline{F}_{RE} * \overline{F}_{RS}$$

Mechanical

$$\overline{F}_{RE} = \overline{F}_{QM} * \overline{F}_{SA} * \overline{F}_{M} * \overline{F}_{\delta} * \overline{F}_{MC} * \overline{F}_{EC}$$

$$\overline{F}_{RS} = \overline{F}_{SA} * \overline{F}_{\delta} * \overline{F}_{M} * \overline{F}_{SS}$$

F_{SA} : *Factor associated with the floor spectra used for analysis*

F_{QM} : *Factor used with qualification method*

Seismic fragility of component/element by analysis

- Values of median response factors and logarithmic standard deviations are taken from literature.

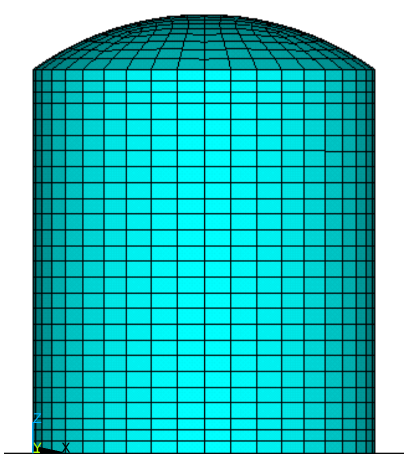
$$\overline{F}_{(R)} = \prod \overline{F}_{(.)}$$

$$\beta_{\#(R)} = \left[\sum \beta_{\#(.)}{}^2 \right]^{1/2}$$

- Values of
  - median response factors F_1, and F_2 are generally calculated or may be taken from literature; $F_{(.)}$ from literature for calculating F_3, and
  - Logarithmic standard deviations $\beta_{\#(.)}$ are taken from literature; # = R or U

Seismic fragility of component/element by analysis

Loc. No	Description	*Induced moment (kN.m)*	*Mom. capacity (kN.m)*	$F_S = F_1$
1	*Raft wall junction*	8.71×10^6	16.90×10^6	1.94
2	*Top of thickened portion*	7.81×10^6	16.10×10^6	2.06
3	*Containment wall EL 100m*	6.13×10^6	12.29×10^6	2.01

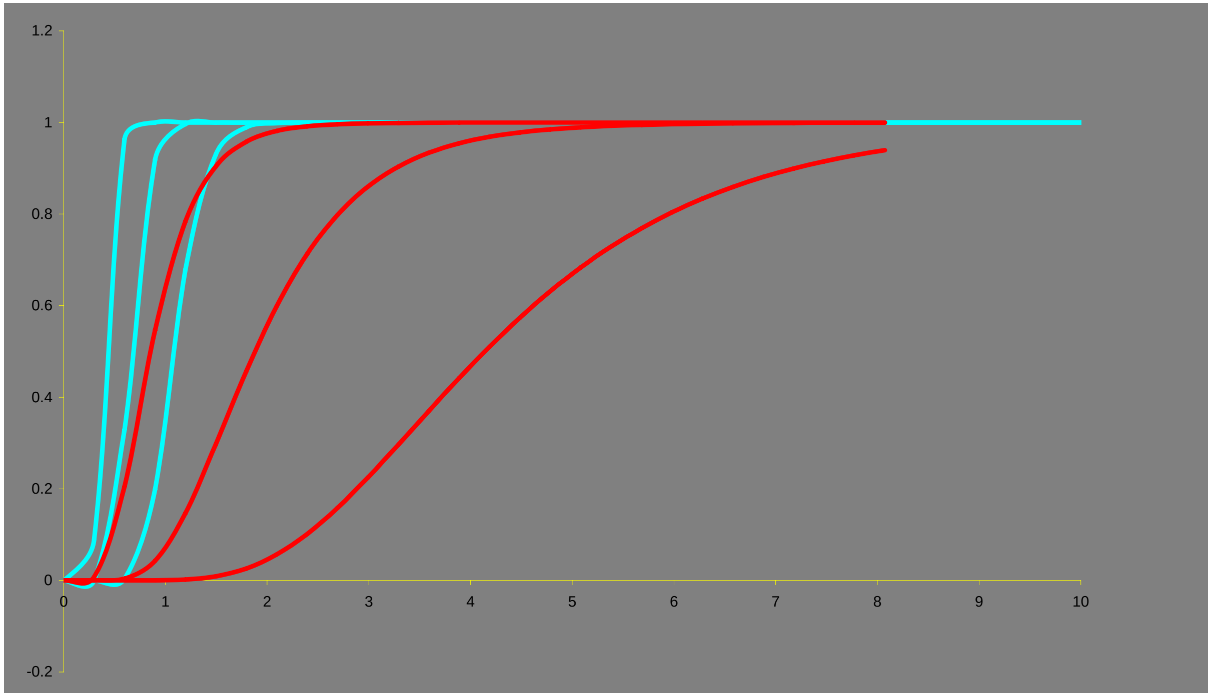


$A_{RBGM} = 0.2g$

Factors	*Median value*
F_{SA}	1.25
F_δ	1.25
F_M	1.0
F_{MC}	1.0
F_E	1.0
F_{SD}	1.0
F_{SS}	1.3
$\boldsymbol{F_3 = F_{RS}}$	***2.03***

Seismic fragility of component/element by analysis

PHEC piping				
	A_m	β_R	β_U	*HCLPF*
Piping	1.88g	0.43	0.48	0.42g
Supp	0.66g	0.22	0.30	0.26g

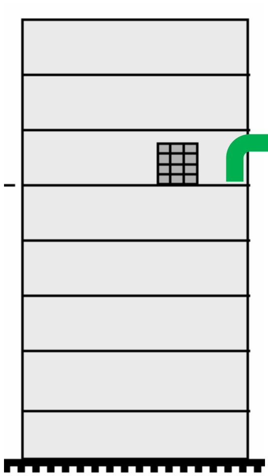


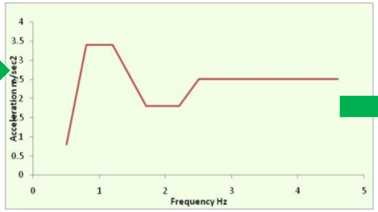
Seismic fragility of component/element by test

- Test Response Spectrum
  - Is the motion experienced by the component being tested.
  - It is measured using the instrumentation available in the shake table
  - The response spectrum corresponding to this motion is called the Test response spectrum (TRS).

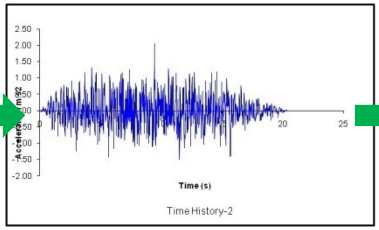
- Required Response Spectrum
  - Specifies requirements to be met.
  - RRS could be specified by the FRS at the location where the component, when a site specific test is being carried out or a general spectrum like the performance level spectrum provided in IEEE 693 for a generic test.

Seismic fragility of component/element by test

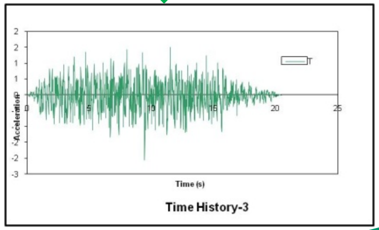




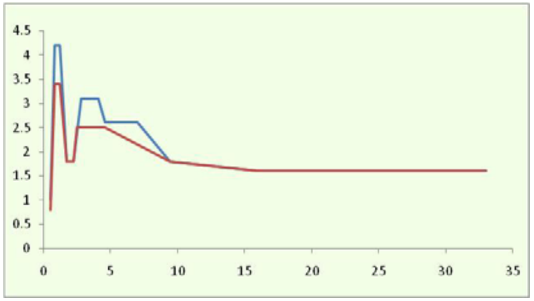
RRS



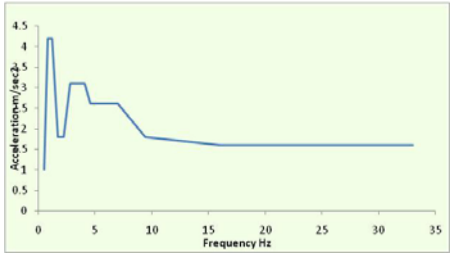
Input to actuators



Acceleration measured on the table



TRS envelops RRS



TRS

Seismic fragility of component/element by test

$$F' = F_1' * F_2' * F_3'$$

F_1 *is the factor representing ratio of capacity and demand*

$$F_1 = \alpha . \tau$$

F_2 *is the factor representing the conservatism that is judged to exist in the TRS based on the testing methods used*

F_3 represents the structure response factor

Seismic fragility of component/element by test

$$\tau = \frac{TRS}{RRS}$$

$$\alpha = \frac{C_T C_I}{C_C D_R}$$

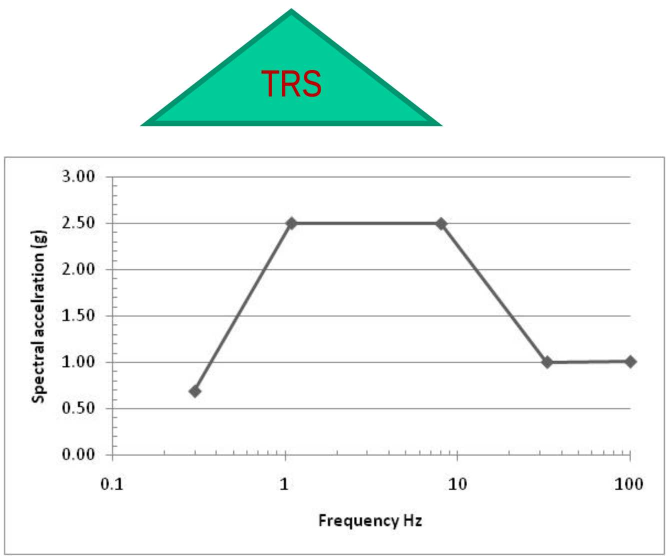
Cabinet based test

$$\alpha = \frac{C_T C_I}{C_C \dfrac{AF_C}{F_{MS}} D_R}$$

Device based test

C_C	Clipping factor for narrow banded demand
C_T	Clipping factor for narrow banded TRS
C_I	Capacity increase factor
D_R	Demand reduction factor
AF_C	Cabinet amplification factor
F_{MS}	Multi axis to Single axis conversion factor

Seismic fragility of component/element by test



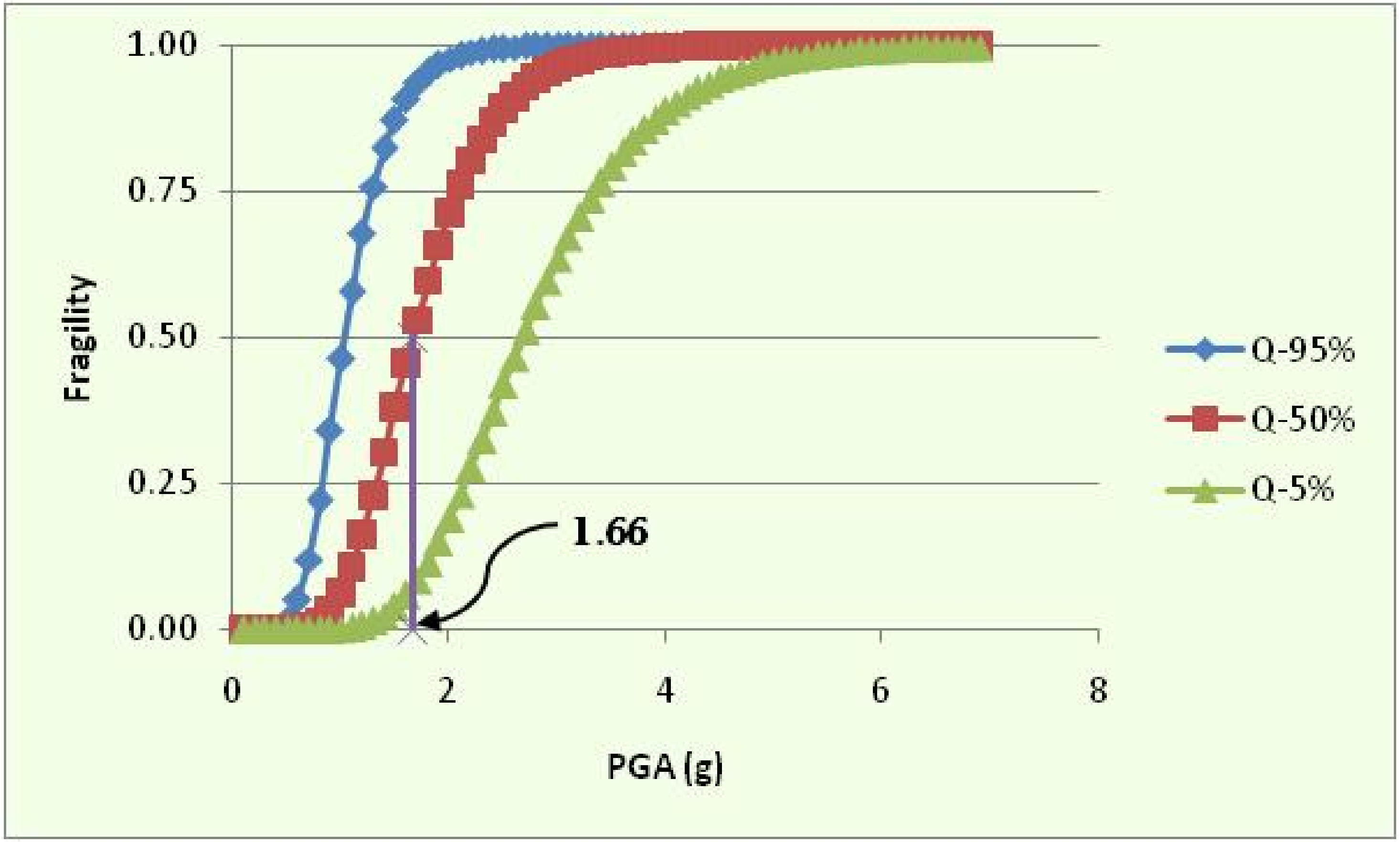
- MCC located in first floor, demand given by FRS derived from 3 time histories. PGA of site = 0.2g
- Natural frequency of MCC is approximately 10 Hz.
- Similar MCC qualified by shake table testing for IEEE 693 performance level high spectrum anchored to a PGA of 1.0g .

Seismic fragility of component/element by test

Factor	*Peak Value*
TRS	2.5g
RRS	0.705g
α	3.55
C_I	1.1
C_C	1.0
C_T	1.0
D_R	1.0
τ	1.1

Factor	*Median*	β_R	β_U
$F_1 = \alpha . \tau$	3.905	0	0
F_2	1.40	0.22	0.09
$F_3 = F_{RS}$	1.67	0.24	0.27
F	9.13	0.33	0.29
A_m	*1.66g*	*0.33*	*0.29*

Seismic fragility of component/element by test



Seismic fragility of component/element by EBM

$$F' = F_1' * F_2' * F_3'$$

F_1 *is the factor representing ratio of capacity and demand*

$$\boldsymbol{F_1 = \alpha . \tau}$$

α is generally taken as unity

F_2 *is the factor representing the ratio of the ground motion level at which the component ceases to perform its intended function to the experience data capacity spectrum (Reference spectrum or GERS)*

F_3 represents the structure response factor

Seismic fragility of component/element by EBM

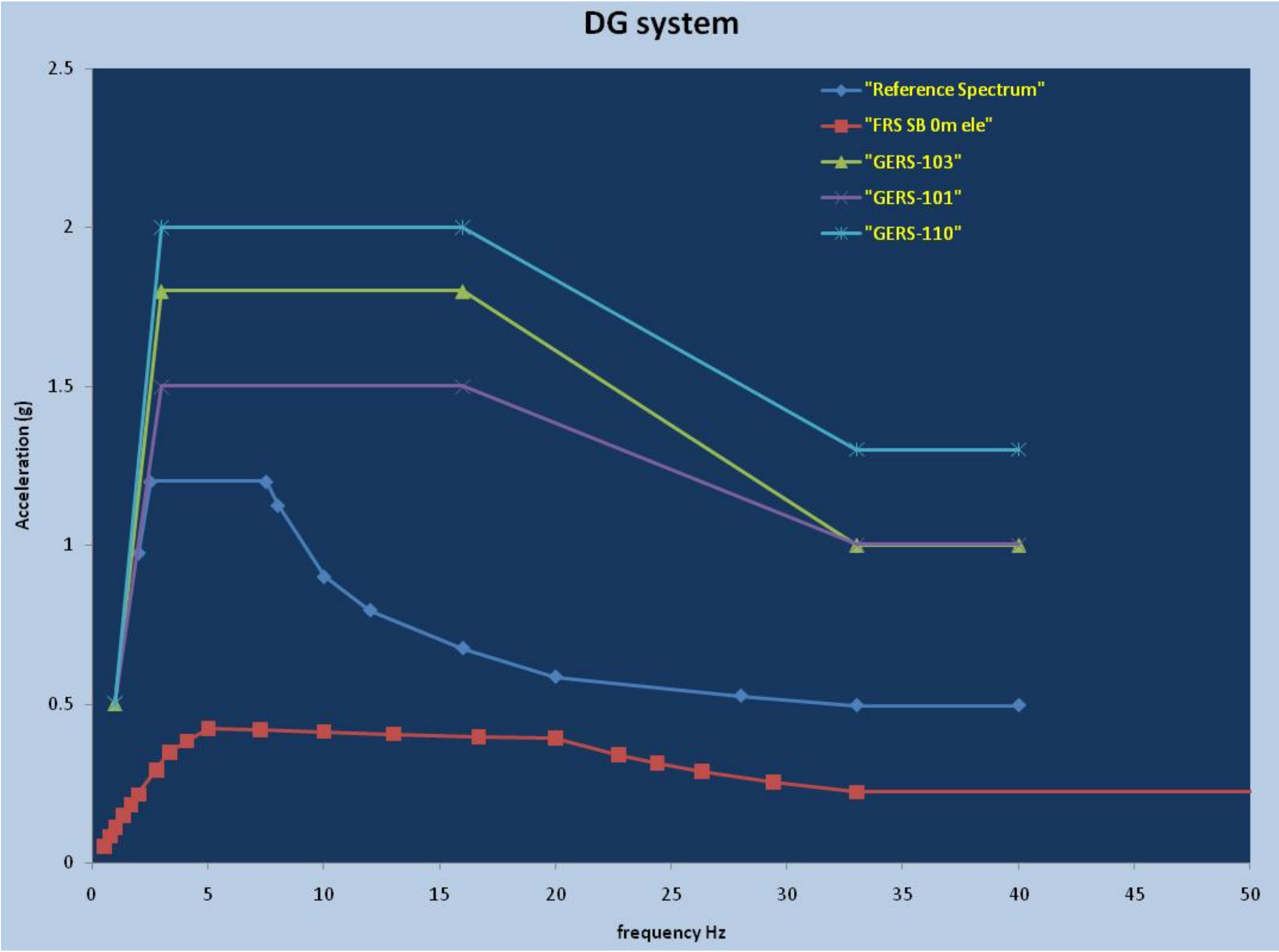
$$\tau = \frac{SCS}{SDS}$$

- SCS: Seismic capacity spectrum,
  - Reference spectrum or GERS
- SDS: Seismic demand spectrum
  - Floor response spectrum

Spectrum used to define capacity	F_2	β_C
Reference spectrum	2.35	0.30-0.60
GERS (Non-relay)	1.49	0.25
GERS (relay)	1.07	0.20

Seismic fragility of component/element by EBM

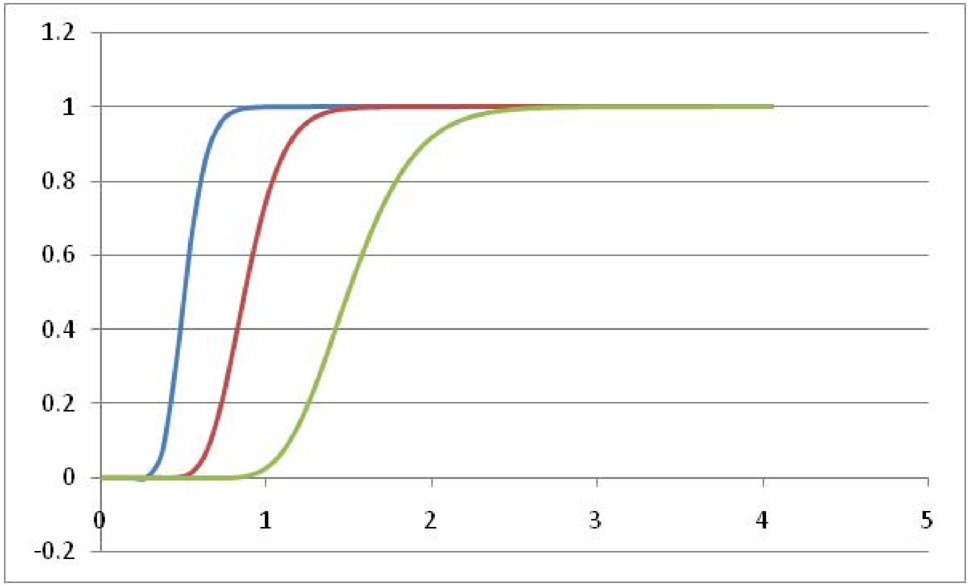
Equip class & description	Demand	Capacity
E8 – I &C panels	FRS – SB 0m el.	RS
E3 – LVSG	FRS – SB 0m el.	GERS 103
E2 – MCC	FRS – SB, TB 0m el	GERS 101
E7 – Battery chargers	FRS – SB 0m el	GERS 110
M13 – Diesel transfer pump	FRS – SB 0m el	RS
M17 – Diesel generator	FRS – SB 0m el	RS



Seismic fragility of component/element by EBM

Component	**SCS**	**SDS**	$\mathbf{F_1}$	$\mathbf{F_2}$	F_3	F	$\boldsymbol{\beta_R}$	$\boldsymbol{\beta_{\underline{U}}}$
Diesel Generator	0.5g	0.21g	2.38	2.35	1.28	7.16	0.41	0.46

Am	1.5g
βr	0.41
βu	0.46



Concluding remarks.

- Seismic fragility analysis is an efficient method for ensuring over all seismic safety of an nuclear power plant
- It is a hybrid method with well mix of theory of reliability and experienced gain from the performance of components during actual earthquake.
- The methodology is applicable to any complex engineering industires.

Thank you