Ductility demand for base isolated structures and equipment

Implication for design and beyond design conditions

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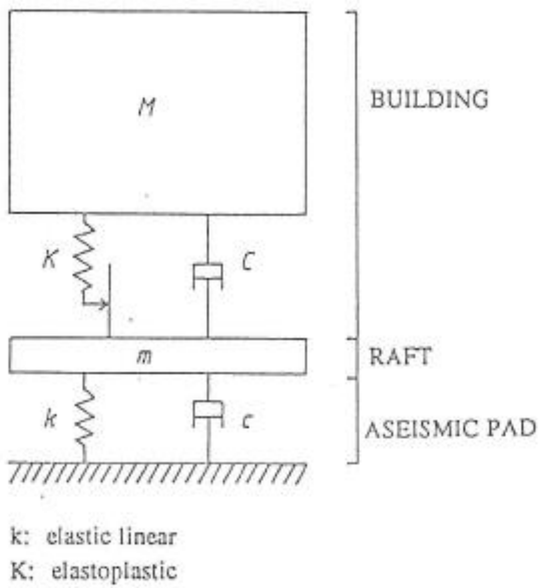
Introduction

- Present some elements on ductility demand for base isolated structures, systems and components SSCs
- *Seismic isolation decreases significantly seismic loads and floor response spectra in comparison to non isolated structures*
- Usually it is considered that with this load and acceleration decrease, the general behaviour is « elastic » or linear
- Margins evaluation and beyond design considerations change this view
- What happens for SSCs when input motion is increased?

Introduction

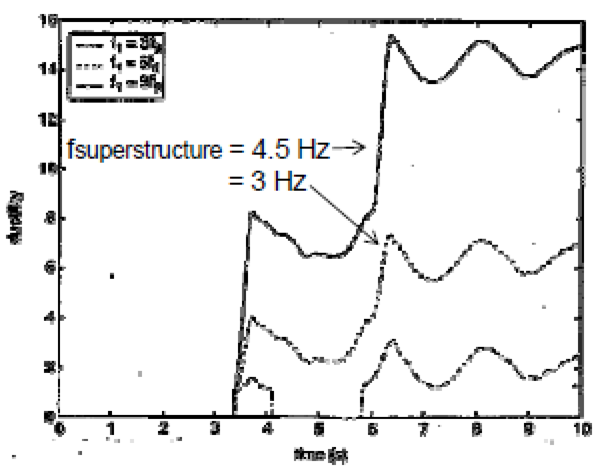


$$\mu_s = (\lambda - 1)\left(\frac{T_s}{T_r}\right)^2 + \lambda$$

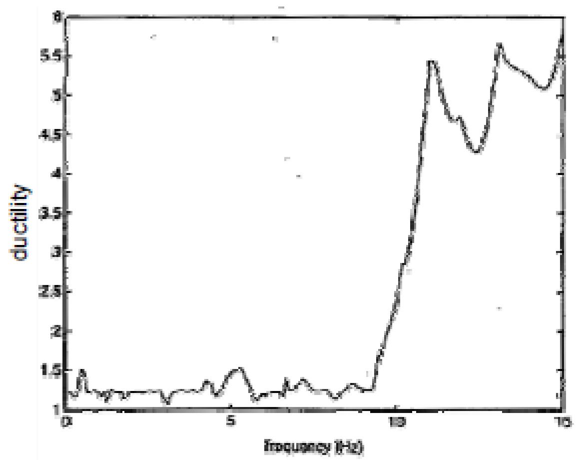
- Simple T/H analysis of a non linear base isolated structure (10th EAEE conf in Vienna 1992)
- Ductility demand is very high
- A simple formula was derived in the case of equal displacement condition (NM Newmark)
- General building codes limit the ductility of base isolated buildings to about 1.5: overstrength

Ductility demand in the superstructure

Ductility demand (El Centro , NS,1940) if the excitation level=1.2 design level
[Politopoulos and Sollogoub, 2005]



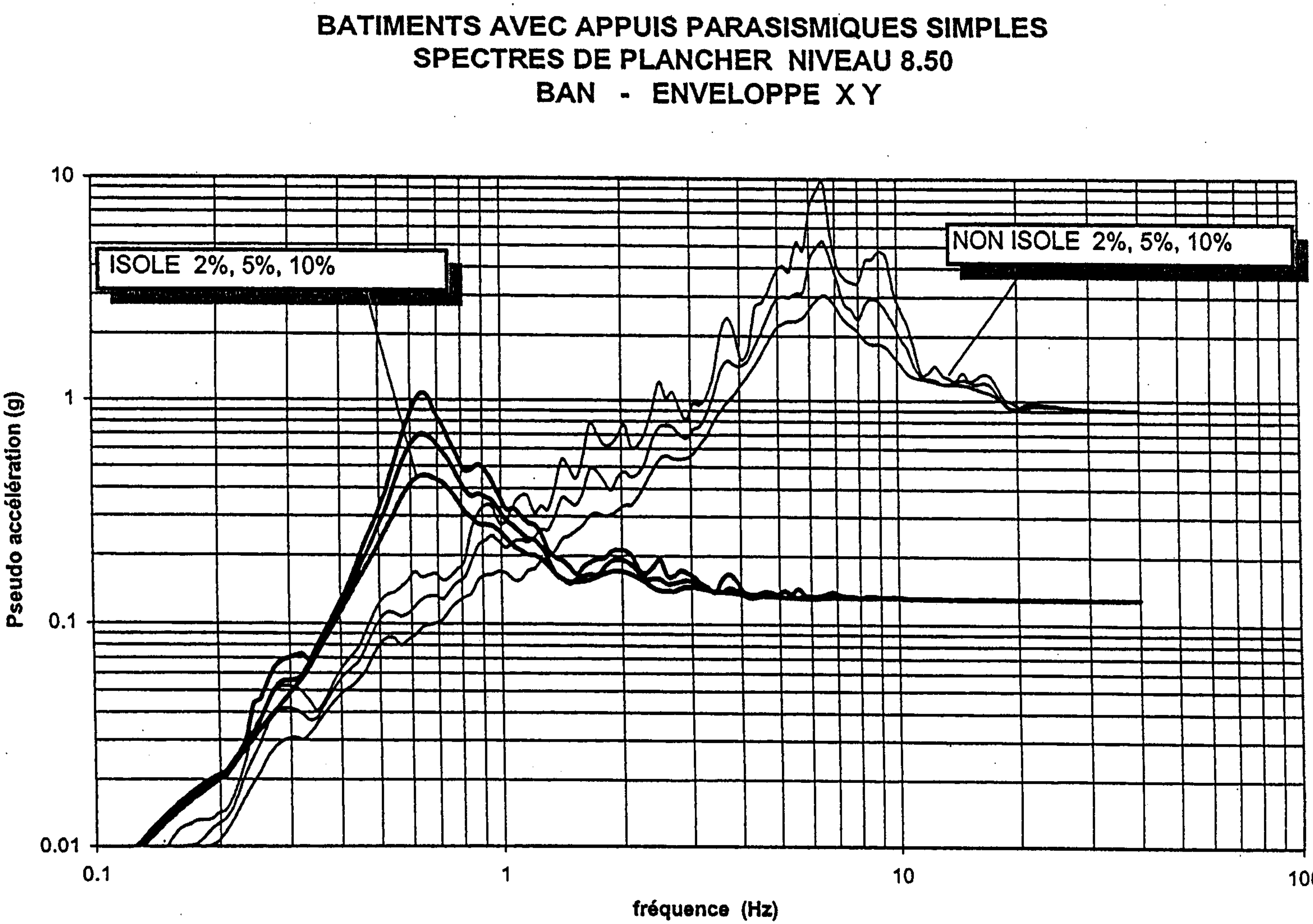
Base isolated structure



Conventional structure

Floor response spectra

- Comparison of the behaviour of isolated and non isolated SSCs using Floor Response Spectra
- This allows to examine the comparative behaviour of both Structures and components
- Example of typical floor Response Spectra


BATIMENTS AVEC APPUIS PARASISMIQUES SIMPLES
SPECTRES DE PLANCHER NIVEAU 8.50
BAN - ENVELOPPE X Y
ISOLE 2%, 5%, 10%
NON ISOLE 2%, 5%, 10%
Pseudo accélération (g)
10
1
0.1
0.01
0.1
1
10
100
fréquence (Hz)

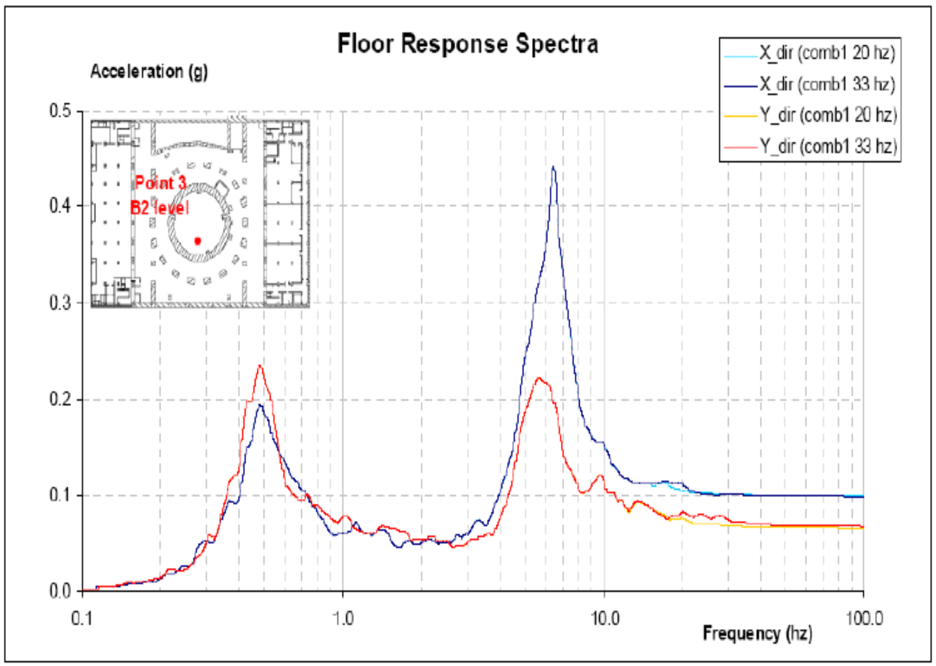
Characteristics of floor response spectra

- Conventional building
  - Peak at the building frequency, typically 4-10Hz
  - High ZPA (frequency close to the peak of ground response spectrum)
  - Amplified peak value
- Base Isolated
  - Peak at the equivalent frequency of the building on Isolation system, typically less than 1Hz
  - ZPA is « low »
  - Peak may be important, but at low frequency
  - In the medium frequency range, spectrum is almost flat, close to ZPA (in some cases the spectrum is not flat…)

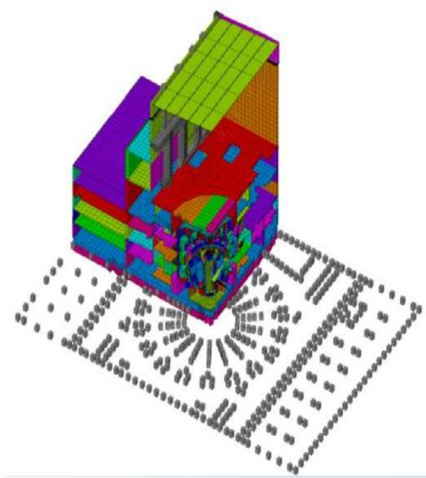
Characteristics of the floor signal Implications for ductility demand

- Conventional building
  - Frequency content in the medium range
- Base Isolated
  - Low frequency signal, almost sinusoïdal
- Ductility demand
  - Conventional building
    - There is a possible ductility demand up to a frequency of 15-20Hz
  - Base isolated building
    - The ductility demand is possible only up to few Hz
    - ***Almost all SSCs cannot take profit of ductility***
    - ***Seismic Loading is to be considered essentially as « Primary', force driven loading***

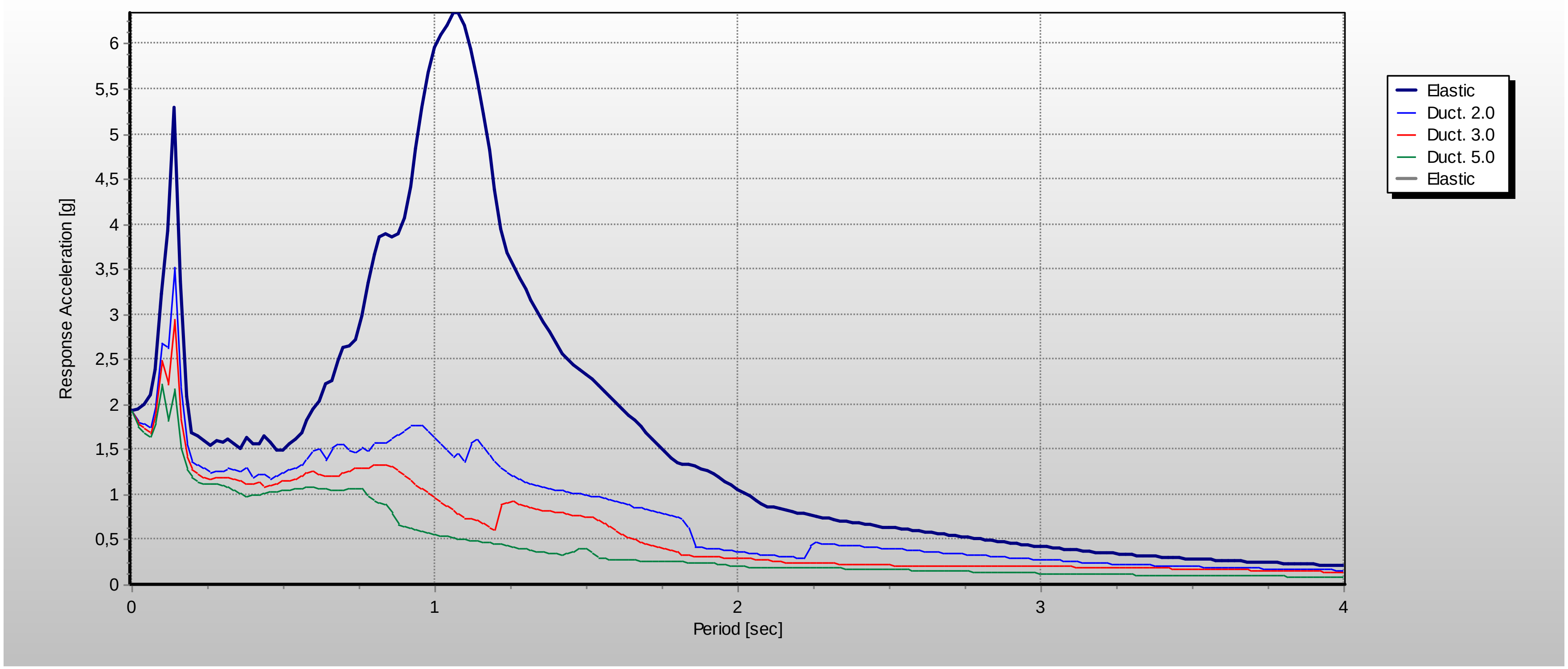
Floor Response Spectrum
« 2nd peak » Amplification



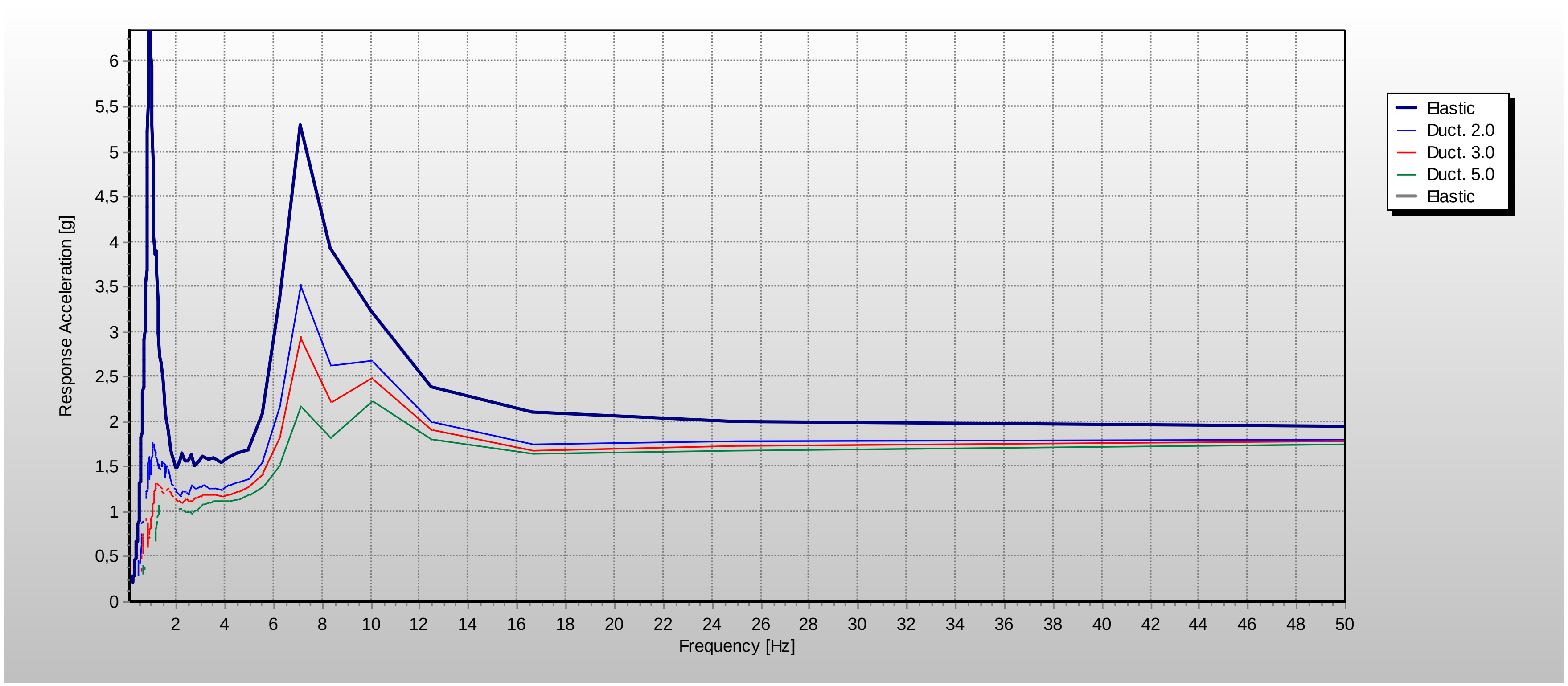
Example: ITER (fusion experimental reactor) [Combesure et al, 2010]



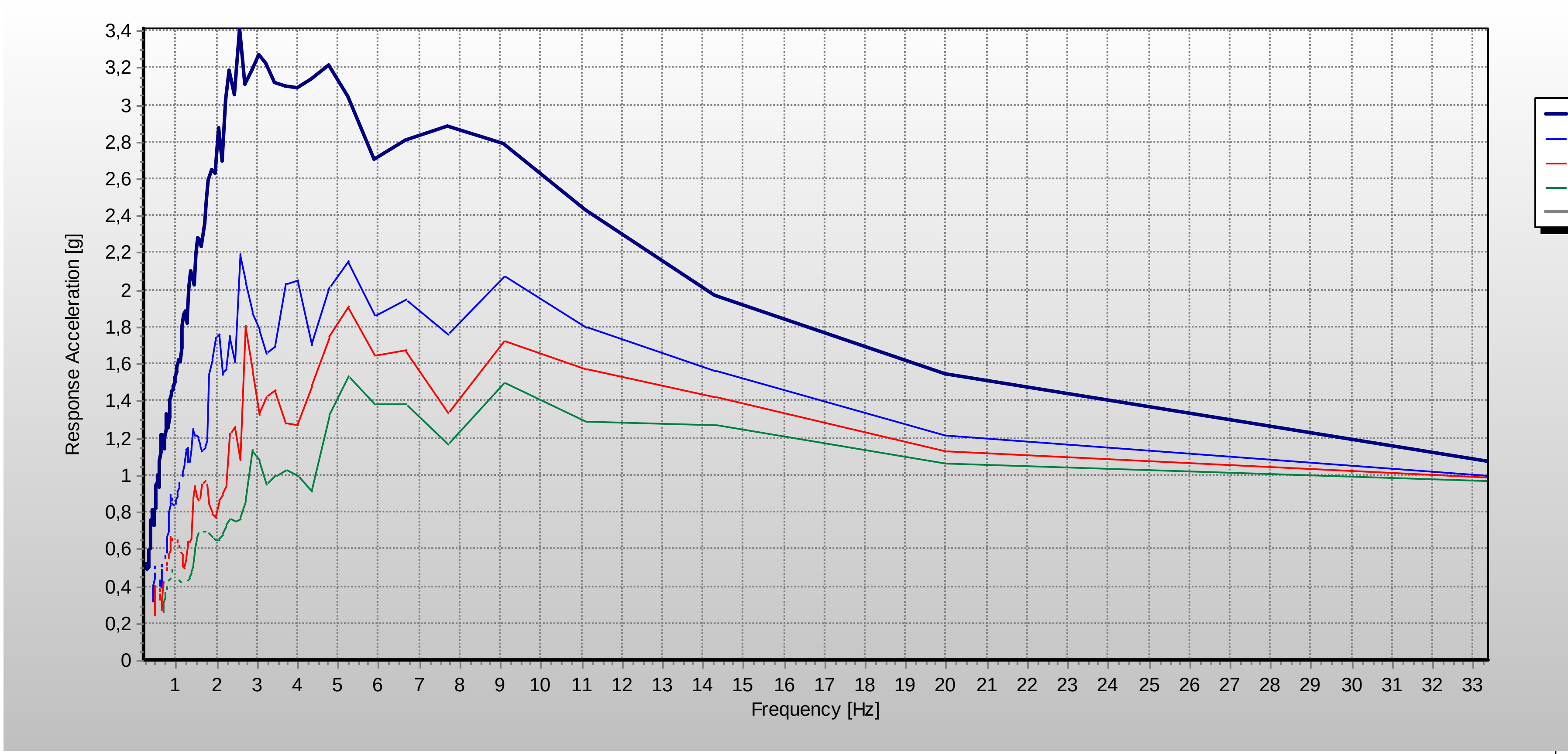
Base Isolated Structure inelatic FRS Period



Base Isolated Structure inelatic FRS Frequency

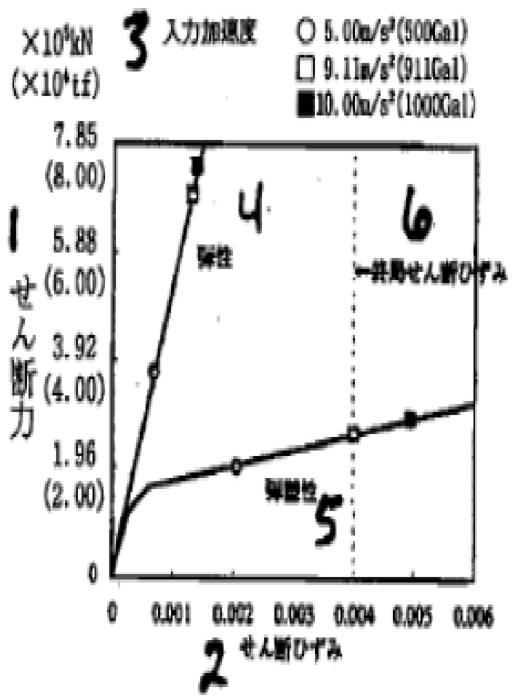


Inelastic Spectra – RG1.60 spectrum Frequency



Ductility Demand ½

From JEAG 4614-2000: Technical Guidelines for seismic isolated structural design of NPP –in Japanese



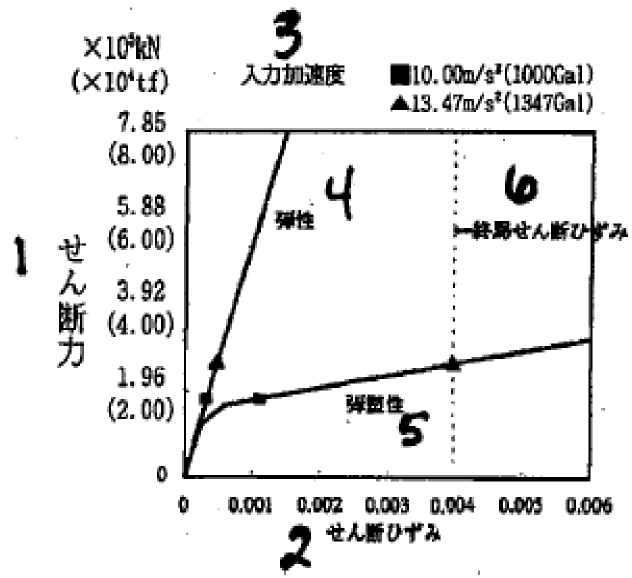
Non isolated building

(b): Seismically Non-Isolated Building Model

[(1): Shear Force; (2): Shear Strain; (3): Degree of Input Acceleration; (4): Elasticity (5):

Ductility Demand 1/2

Figure 7.2.1-3: Comparisons of the Respective Elastic Responses and Elastoplastic Responses of the Seismically Isolated and Seismically Non-Isolated Buildings



Isolated building

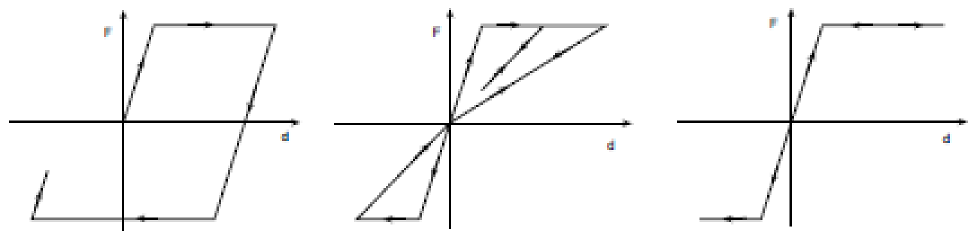
(a): Seismically Isolated Building Model

[(**1**): Shear Force; (**2**): Shear Strain; (**3**): Degree of Input Acceleration; (**4**): Elasticity; (**5**): Elastoplasticity; (**6**): Eventual Shear Strain]

Influence of superstructure's and bearings constitutive laws

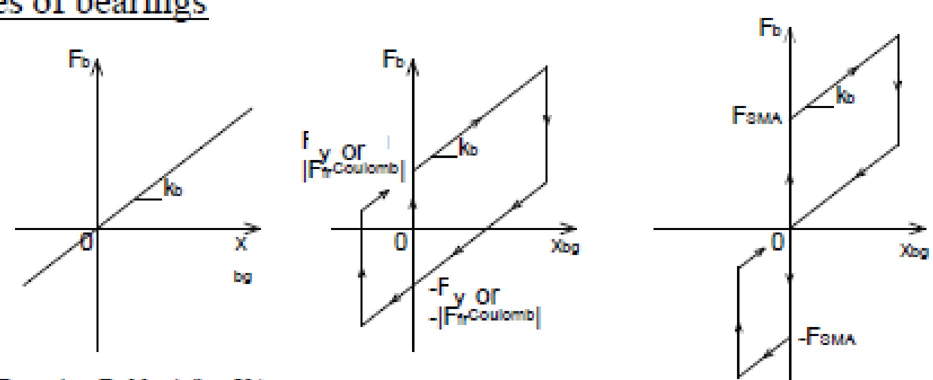
[Politopoulos and Pham, 2009]

Superstructure's constitutive laws



(a) elastoplastic (b) origin oriented (c) nonlinear elastic

Types of bearings



LDRB (Low Damping Rubber) ξ = 5%
LDRB (Low Damping Rubber) ξ = 25 %

LRB (Lead Rubber)
FPS (Friction Pendalum) Coulomb

SMA (Shape Memory Alloys)

+ velocity dependent FPS, Active Control (AC), Semi-active Control (SAC)

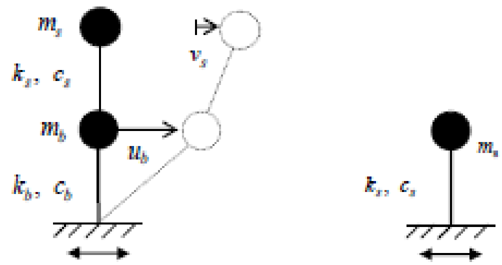
Probabilistic Considerations

- Monte Carlo analyses in order to assess the effect of variabilities on the results:
  - Conventional Structure
  - In-Structure equipment
  - Structure, designed elastically

- *The SSC are designed to the mean response spectrum*

Structure behaviour

What happens if the excitation is slightly different from that considered for the design?



Base isolated structure   conventional structure

Random variables for main structures.

Random variable	Probability distribution	Mean	COV
Peak ground acceleration	lognormal	1	0.2
Frequency of excitation	normal	2.95	0.2
Ductility capacity-1	lognormal	3 Characteristic $\mu_{capacity} = 3.6$	0.25
Yield force	normal	$F_{y\ characteristic}/0.835$	0.10
Stiffness of structure (k_1)	normal	k_1	0.10
Stiffness of bearings (k_0)	normal	$k_0 = (2\pi f_0)^2(m_1 + m_0)$	0.20

1000 artificially generated signals
Updated Latin Hypercube Monte Carlo simulations

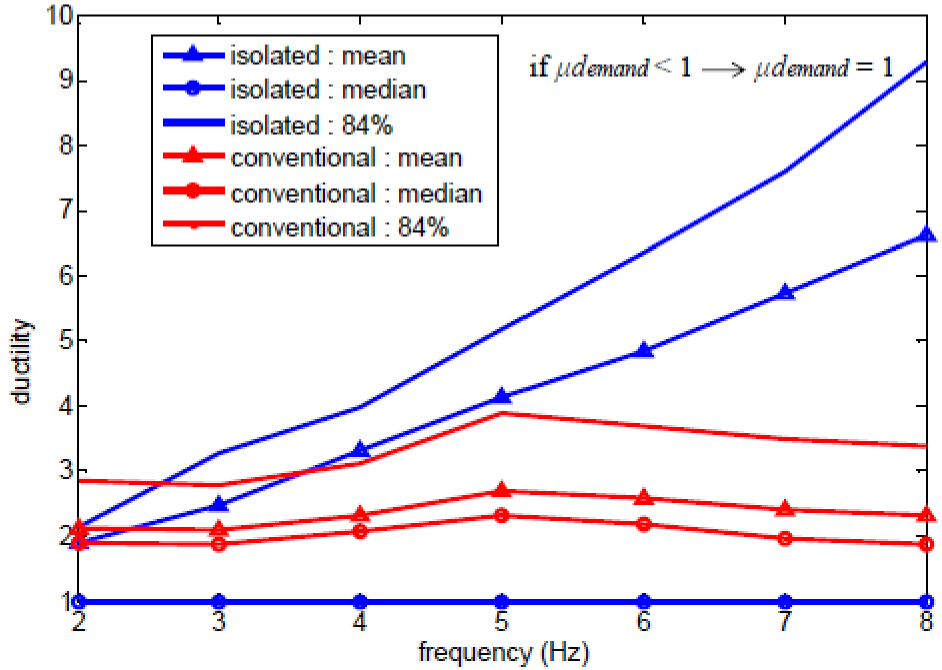
Ductility demand

elastic-perfectly plastic superstructure on « linear elastic » LDRB

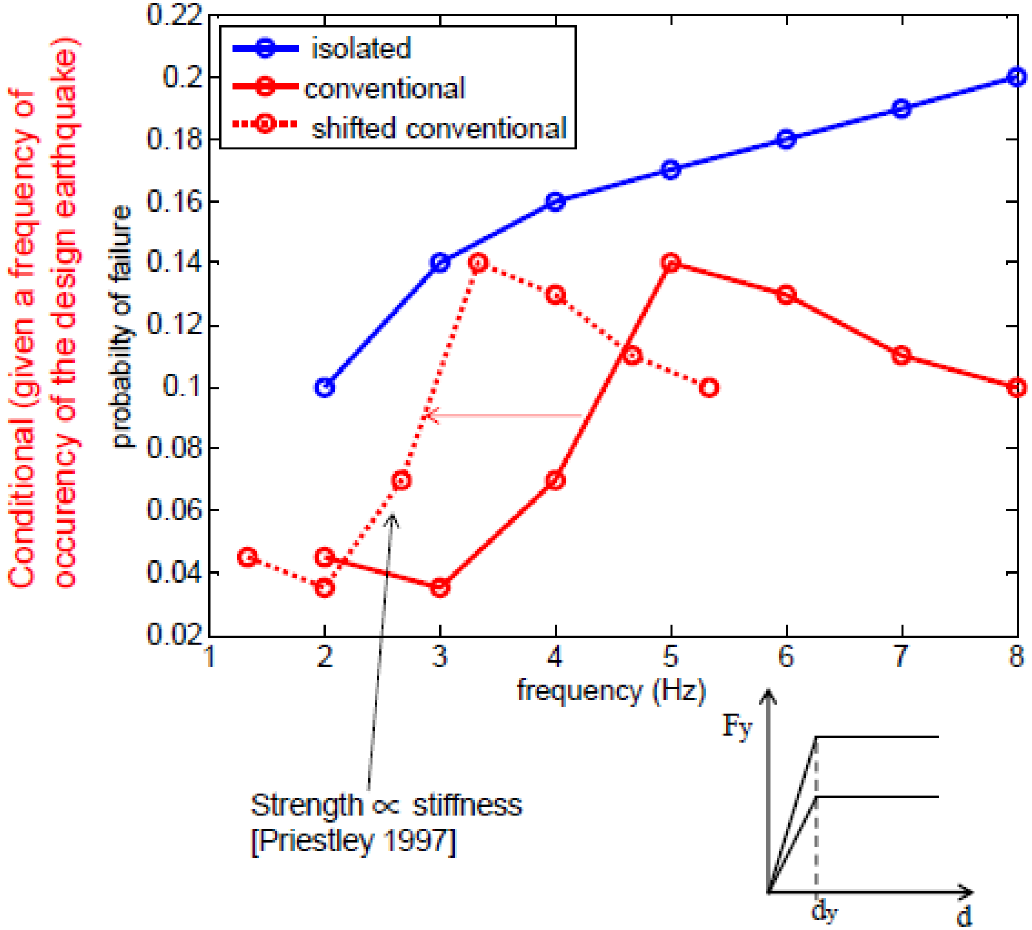
practical method : strength = mean elastic spectrum (x mass)/$\sqrt{2\mu - 1}$ (for $f < 5$ Hz)

conventional $\mu > 1$ isolated $\mu = 1$

characteristic $\mu capacity$ (95% probability of exceedance) = 3.6



Failure probability – Structure



SSC failure probability application

- Equipment: elastoplastic behavior
- Isolated building 0.6Hz
- Fixed based building: 8.5Hz
- Monte Carlo analysis
  - Input signal amplitude
  - Characteristics of the equipment
    - Median frequency
    - Yield stress
    - Allowable ductility

Results for SSC

Probability of failure

Equipment frequency Fréquence de l'équipement	Isolated structure Structure isolée	Fixed base structure Structure conventionnelle
0.6	0.1 %	3.6 %
1	5.9 %	1.5 %
3	12 %	0.9 %
5	17 %	1.4 %
8	17 %	0.1 %
10	17 %	2.3 %
30	17 %	16 %

If the yield stress of the eqipment in the base isolated structure is multiplied by 1.6, the failure probability is comparable to the fixed base case

$F_y / 0.835$

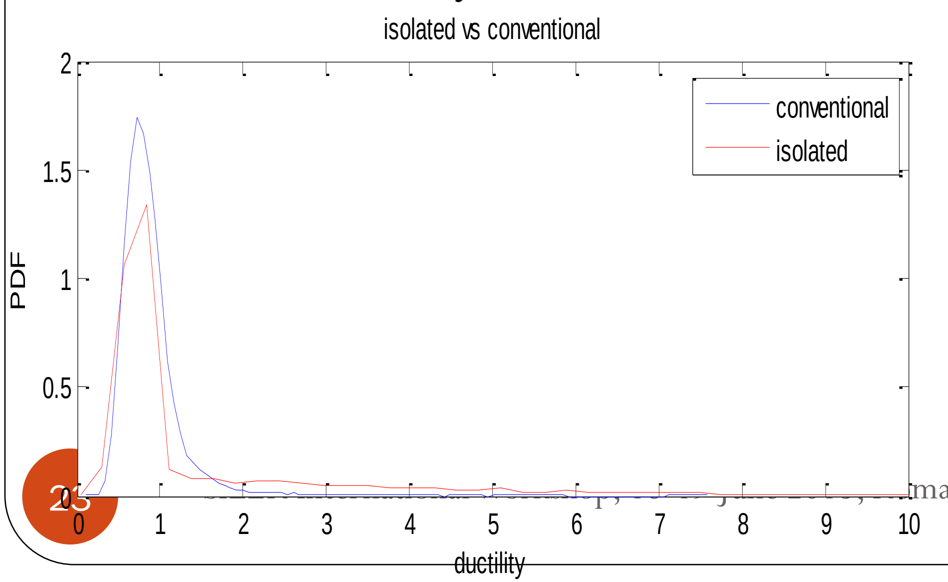
Probability of failure for a structure

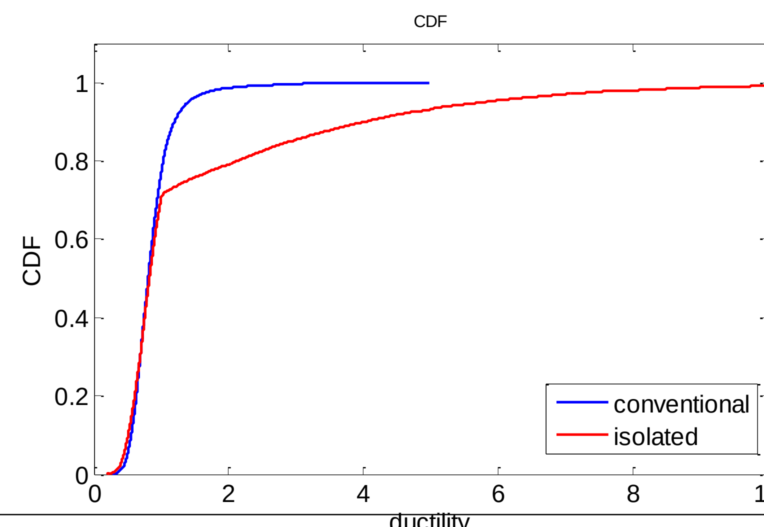
- Frequency of superstructure and conventional structure : 6 Hz
- Isolation frequency 0.5 Hz,
- Structure's damping 5%, , isolation damping 10%
- Elastic linear bearings, failure in bearings not considered
- Origin oriented non linear behaviour

Random variable	***Probability distribution***	***Mean***	***COV***
Peak ground acceleration	Lognormal		0.2
Frequency of excitation	Normal	2.95	0.2
Ductility capacity -1	Lognormal	3	0.25
Yield force	Normal	$F_y / 0.835$	0.10
Stiffness of the structure	Normal	k_s	0.10
Bearing stiffness	Normal	k_b	0.20

Results

- Failure defined as maximum given ductility
- Probability of failure of fixed base about 30 to 100 times lower than base isolated
- With a complementary margin of 1.5 – 2 for BI structure, probabilities of failure are comparable
- Ductility distribution





Japanese presentation 15WCEE (2012)

Fig. 3.4 presents the reduction of the base displacement for different isolation systems. Each data point represents median of the ratio of the maximum base displacement to the maximum base displacement for elastic superstructure response, $u_{b0}/u_{b0,el}$, observed from each earthquake. The maximum base

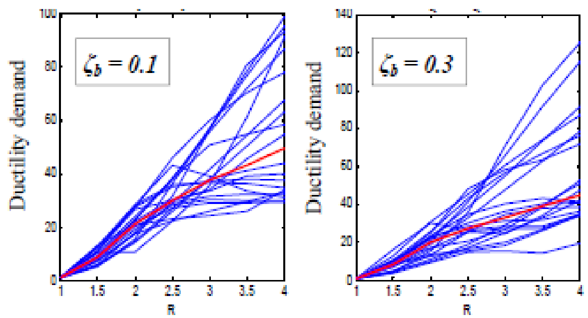


Figure 3.2. Ductility demand and median response from 20 ground motions

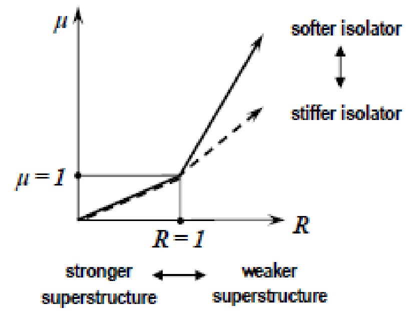


Figure 3.3. Effect of superstructural strength on ductility demand without considering pounding

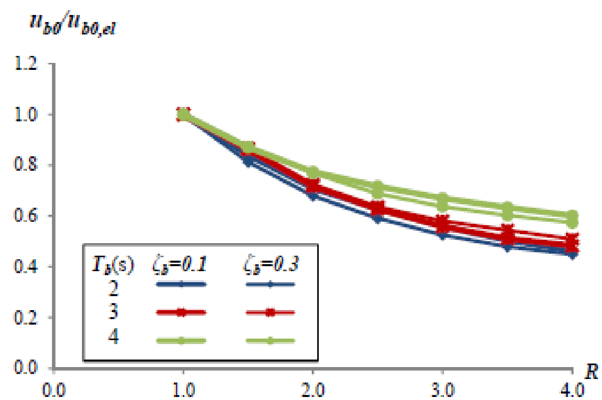
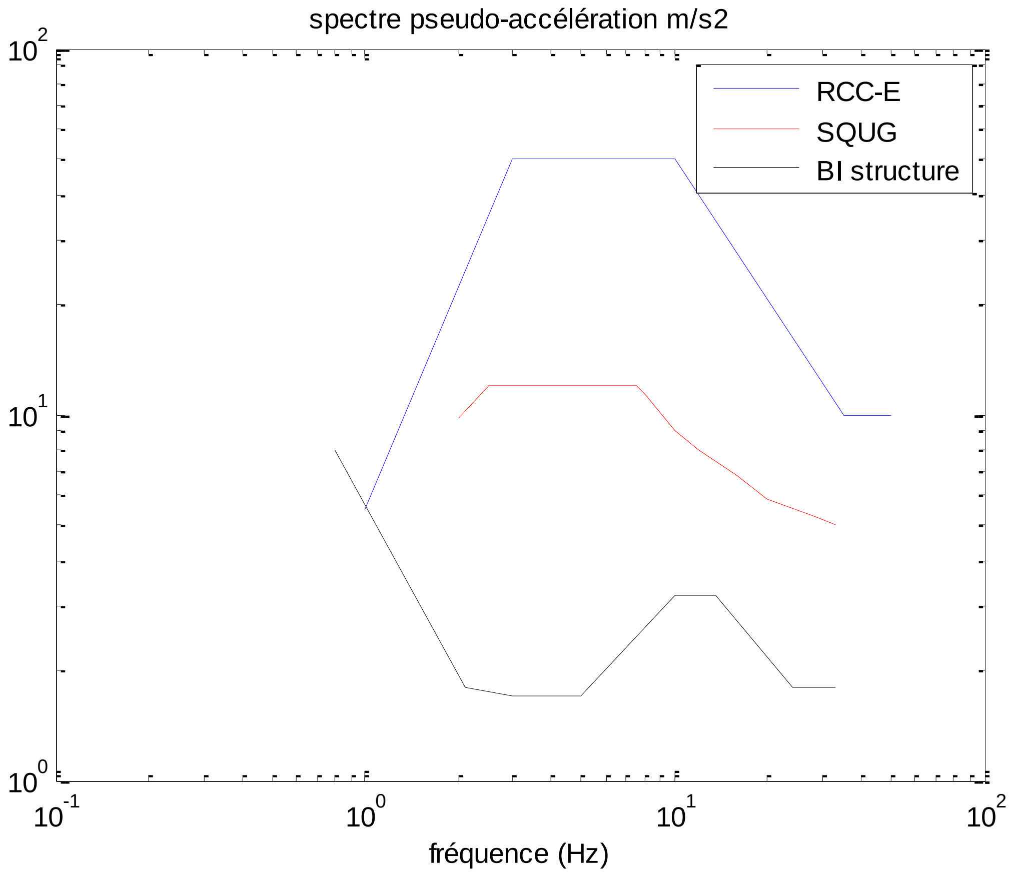


Figure 3.4. Reduction of $u_{b0}/u_{b0,el}$ ratio observed from the median responses

Margins and Beyond design Considerations

- Margins evaluation and Post-Fukushima exercices, such as by SMA approach, need to be adapted, for instance in the reduction factors
- Behaviour of some components is not linear even for moderate forces (shear walls)
- Good understanding of ultimate behaviour is necessary: Superstructure/isolation system/Pedestals/lower raft
- Design of the moat gap
- Equipment behaviour:

Equipment behaviour



Conclusions

- Ductility demand for isolated SSC may be important
- Many nuclear (and other) structures and equipment had significant margins, but some (totally or partially) may be designed by seismic loading cases (such as anchorages): This must be checked, and supplementary margins (1.5 - 2) should be applied for loads and FRS
- These elements must be considered in base-isolated nuclear installation design
- Fragility evaluation
  - Non linear 3D analyses