Analytical uniform hazard floor response spectra for the design of nonstructural components

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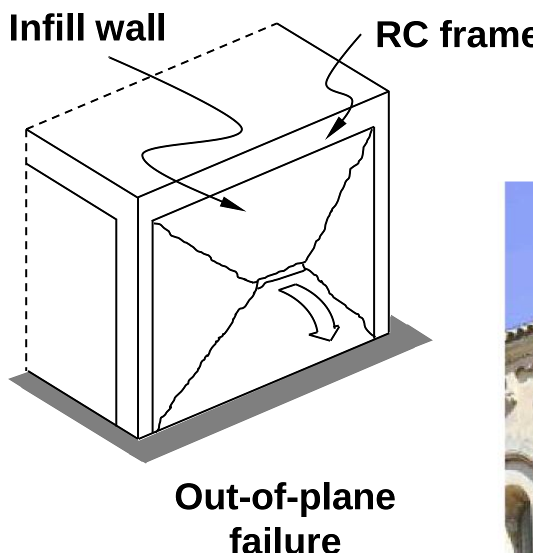
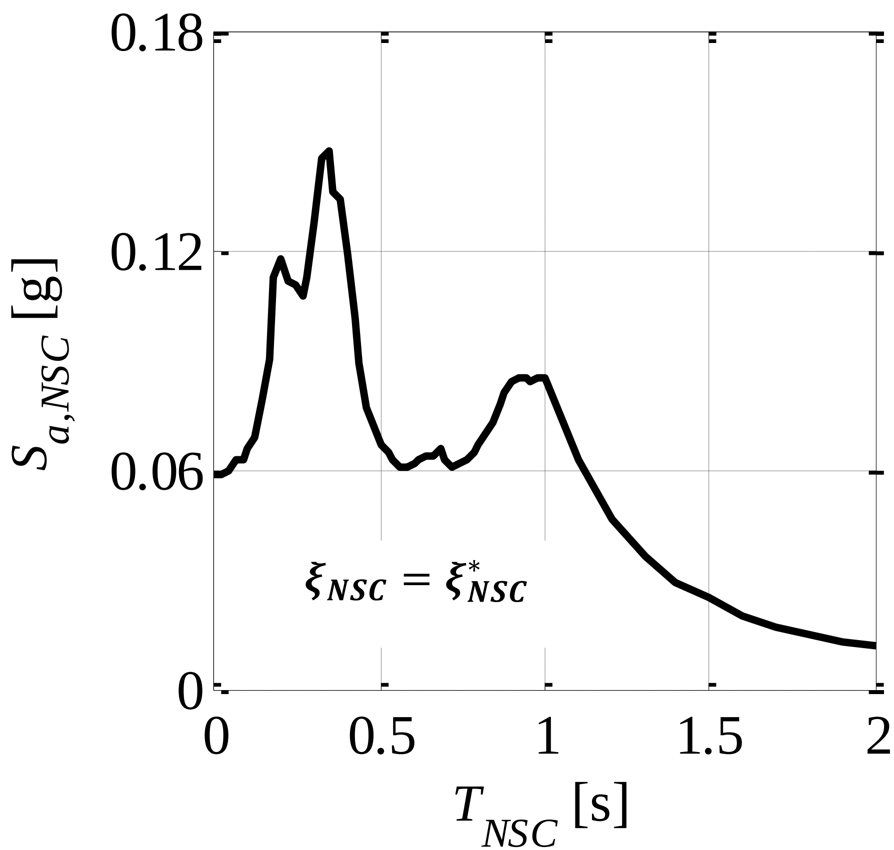
What are floor spectra used for?

- Estimating seismic demand on acceleration sensitive nonstructural components
- Estimating acceleration on structural components of unreinforced masonry buildings “local mechanisms”



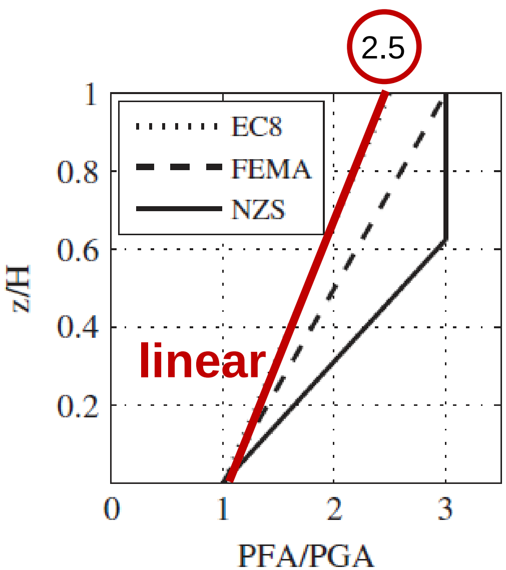
What floor spectra look like?

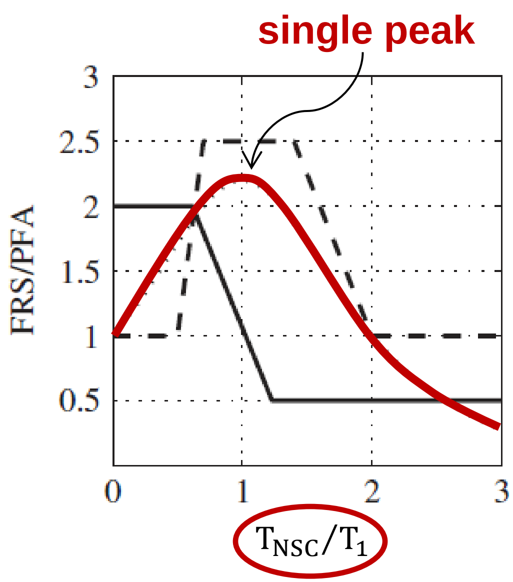
- Multi-peaked, with amplification around structural periods

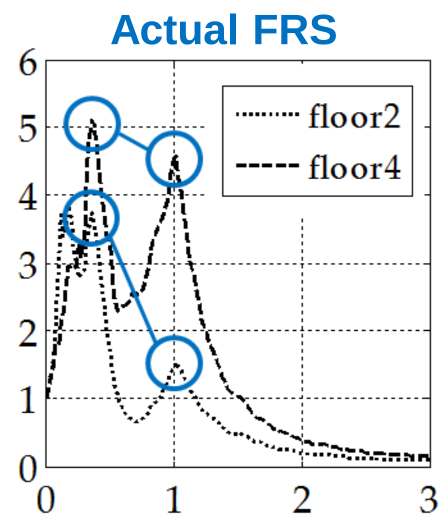


How do codes describe them?

- e.g. EC8 assumes
  - for **PFA/PGA**
    - a **linear** distribution in elevation
    - a **maximum** value of **2.5** at the roof
  - for **FRS/PFA**
    - variation with $\mathbf{T_{NSC}/T_1}$ only (a single peak at $T_{NSC}/T_1 = 1$)
    - **slight variation** with the **floor level** (max amplify. 2.5)
    - no dependence on **component damping**
  - no dependence on ground motion spectral shape (just PGA)
  - no dependence on non-linearity of response







A better way to compute them?

- Methods in the literature can be lumped into:
  - Random-vibration-based
    - Provide closed-form expressions, but only for white noise input
  - Empirically derived closed-form equations
    - Account for nonlinearity
    - Based on «envelopes» or «means» of a response-history analyses
    - Often disregard spectral shape of the input, like code equations (i.e. try to improve only on FRS/PFA)
  - Direct spectra-to-spectra methods
    - Account for spectral shape of the input ground motion
    - Deterministic floor spectra shape
    - Disregard record-to-record variability
  - Response-history analysis
    - Complete, accurate, as long as done correctly (record selection, etc)
    - Applies to linear and non linear structures
    - Too demanding for practical application by professional engineers

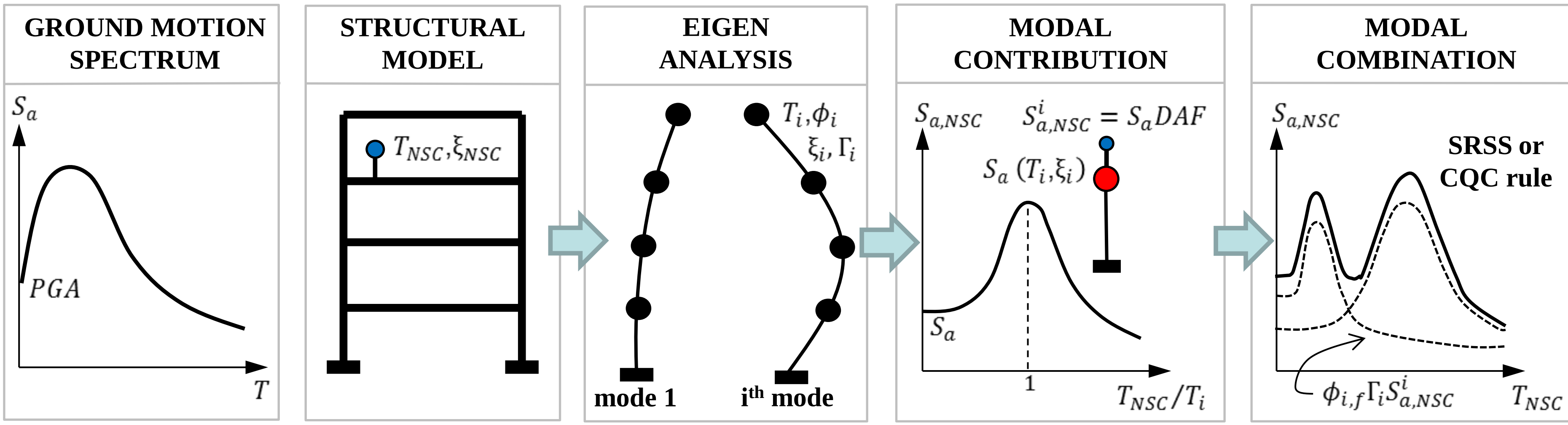
  - All methods disregard epistemic uncertainty on structure

What would be desirable?

- Nowadays in most cases design of the structure involves modal analysis and a uniform hazard response spectrum
- Design of non-structural components should be carried out with the same accuracy/effort, within the same analysis framework
- If the NSC is such as to modify the response of the structure (heavy), then it should be modelled
- For all other acceleration sensitive NSCs, a uniform hazard floor response spectrum should be derived, within or beside the main structural analysis, to be used for the design of the component (its connection, usually)

Spectra-to-spectra: a good compromise?

- They miss something, but they:
  - Account for all modes (dynamic properties of the structure)
  - Account for site spectral shape
  - integrate very well within the usual structural design workflow (where multi-modal response spectrum analysis is the norm)



- How can they be improved upon?
  - Replacing the deterministic model for the dynamic amplification function (DAF), e.g. Calvi & Sullivan 2014:

$$S_{a,NSC} = S_a DAF \qquad DAF = 1/\sqrt{(1 - T_{NSC}/T_i)^2 + \xi_{NSC}}$$

  - Introducing epistemic uncertainty & nonlinearity

Spectra-to-spectra: the proposal

- A UHFRS can be easily obtained from demand hazard curves in terms of floor spectral acceleration (EDP)

$$\lambda_{S^i_{a,NSC}}(x) = \int_0^\infty G_{S^i_{a,NSC}}(x|y)|d\lambda_{IM}(y)| \rightarrow S_{a,NSC} = \sqrt{\sum_i \sum_j \rho_{ij}\left(\phi_{i,f}\Gamma_i\, S^i_{a,NSC}\right)\left(\phi_{j,f}\Gamma_j\, S^j_{a,NSC}\right)}$$

- This can be done in closed form, for instance with the solution provided by our gracious Host, provided an IM-EDP relationship is available

("Divamva", 2013)

$$S^i_{a,NSC}(\lambda^*) = exp\left[a + \frac{1}{2k_2}\left(-k_1 + \sqrt{\frac{k_1^2}{q} - \frac{4k_2}{q}\, ln\frac{\lambda^*}{k_0\sqrt{q}}}\right)\right] \qquad q = \frac{1}{1+2k_2\sigma^2}$$

- It turns out that such a relationship can be derived «once and for all» for a NSC standing on a SDOF (modal contribution) and applied at different geographical locations with good approximation

$$ln s_{NSC} = a + \mathrm{b} ln s + \sigma\varepsilon \rightarrow ln s_{NSC} = a + ln s + \sigma\varepsilon \rightarrow ln(s_{NSC}/s) = a + \sigma\varepsilon$$

mean **stdv**

$$a, \sigma = f(r = T_{NSC}/T_i\,, \xi_{NSC})$$

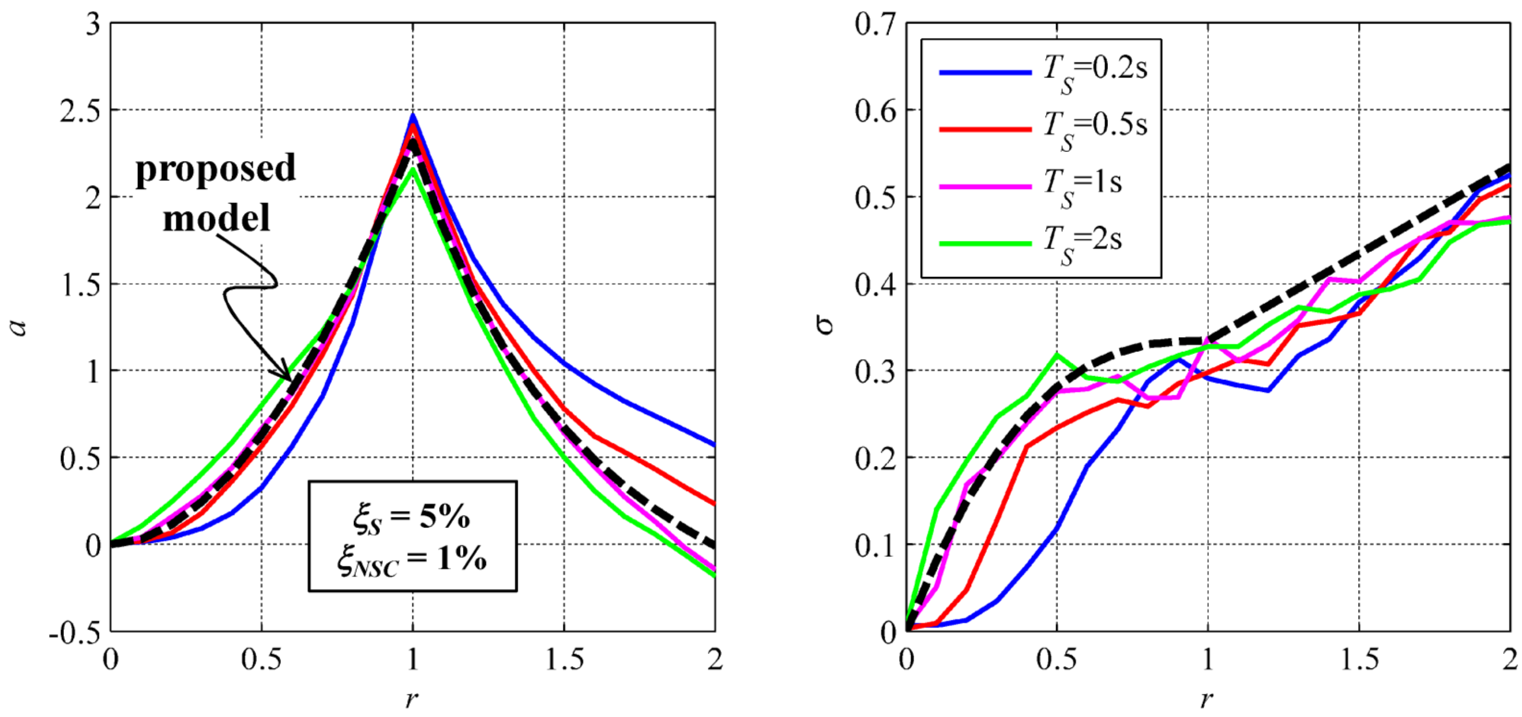
The IM-EDP relation

- A cloud analysis was carried out on 20x20x2x10=8000 cases:
  - $T_S = 0.1s{:}\,0.1s{:}\,2s$
  - $T_{NSC} = 0{:}\,0.1T_S{:}\,2T_S$
  - $\xi_S = 2\%, 5\%$
  - Ten values of $\xi_{NSC} = 1\%$ to 15%

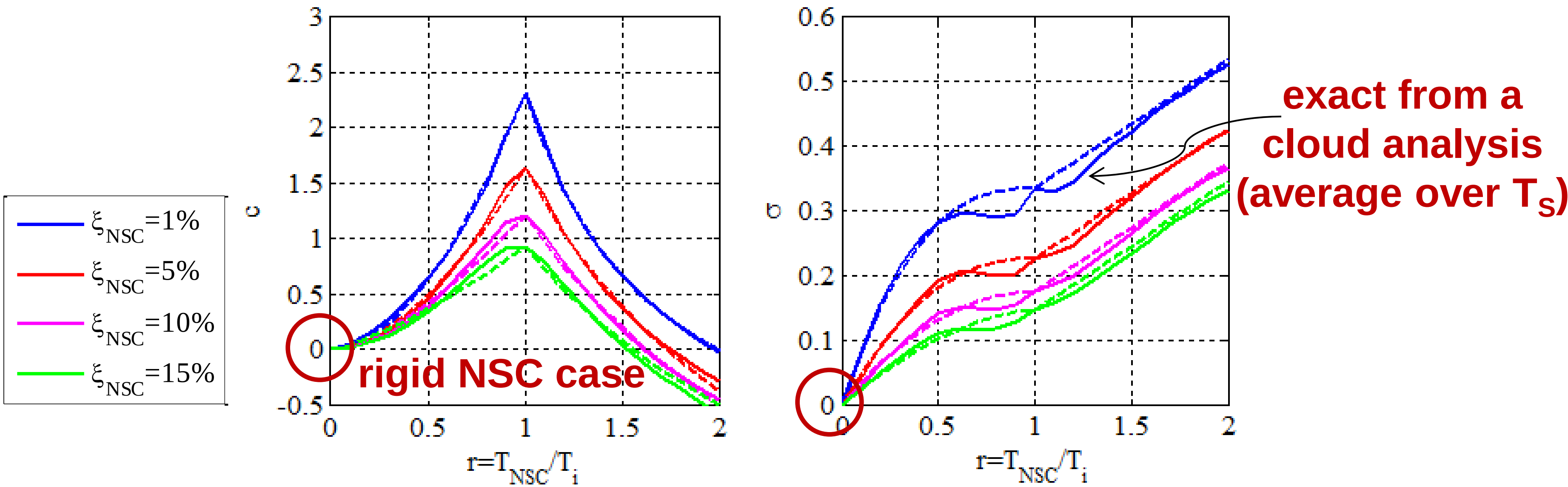
- Ground motions:
  - Campbell and Bozorgnia, without Mw<5, and records with recognizable velocity pulses: 715 records (Set 1)
  - Set 2: California-only, 408 records
  - Set 3: non-California records, 307 records
  - Set 4: Set 2 with Vs30 < 360m/s, 230 records
  - Set 5: Set 2 with Vs30 > 360m/s, 178 records

The IM-EDP relation

- Use of $r = TNSC/T_S$ in place of T_S and T_{NSC}



The IM-EDP relation



$$a(r) = a^t\, r^{n_1} \quad r \le 1$$
$$a(r) = a^t + n_2(r^{n_3} - 1) \quad r > 1$$

$$\sigma(r) = \sigma^t\, [1 - (1 - r)^{n_4}] \quad r \le 1$$
$$\sigma(r) = \sigma^t + n_5(r - 1) \quad r > 1$$

where the p parameters a^t, σ^t and n_i are calculated as follows

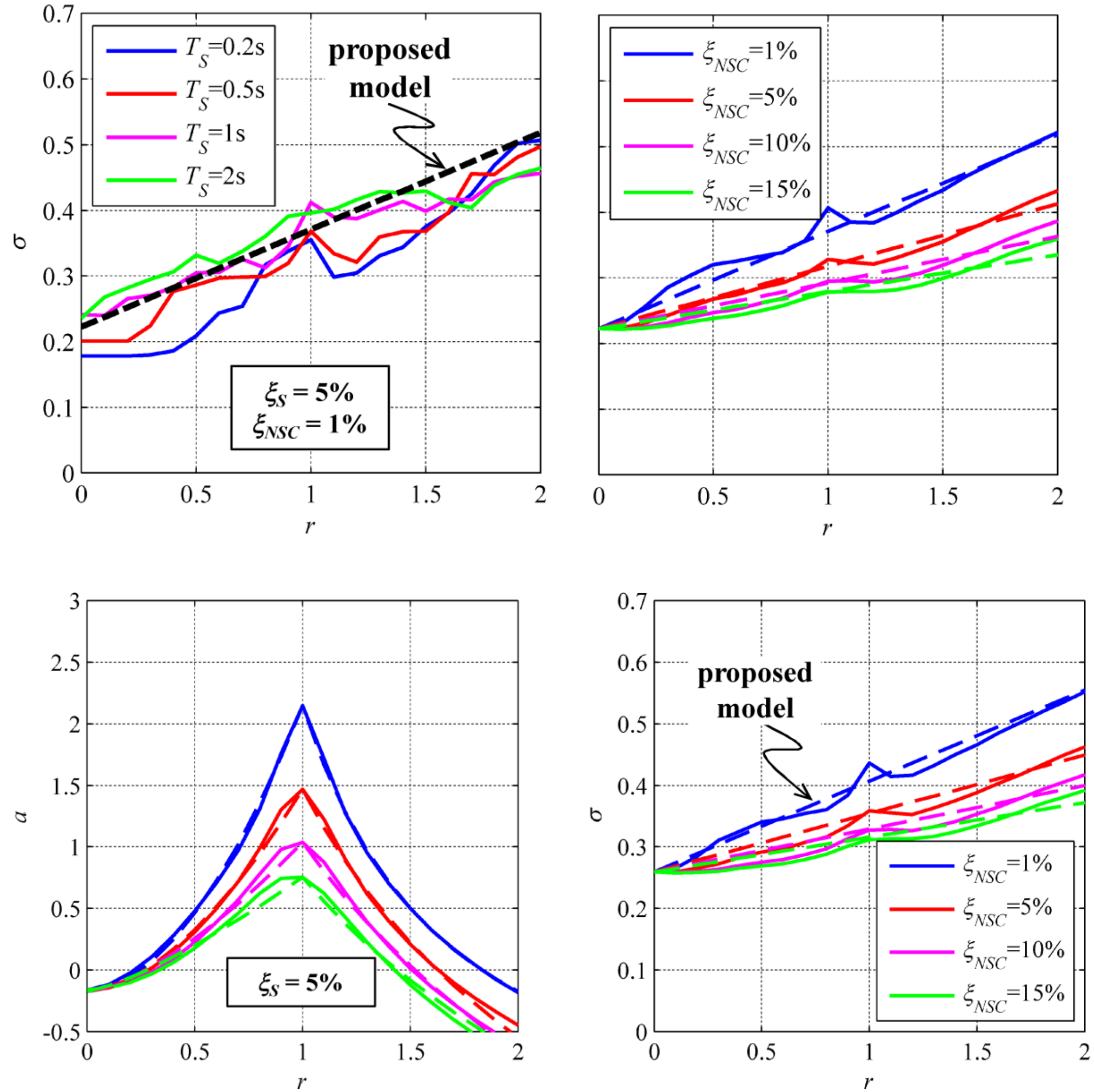
$$p = m_0 + m_1 z + m_2 z^2 + m_3 z^3$$

$$z = ln(100\xi_{NSC})$$

The IM-EDP relation

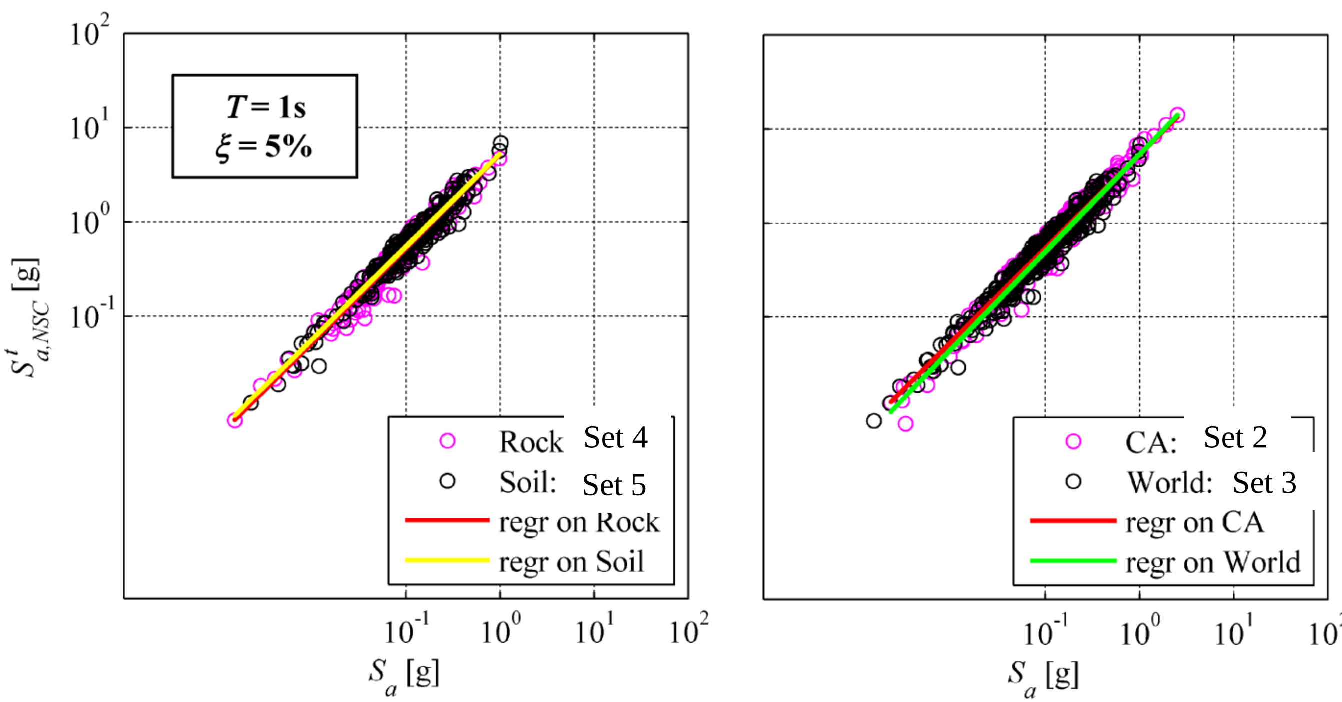
$$IM = Sa_{,gm}$$

$$IM = Sa_{,max}$$

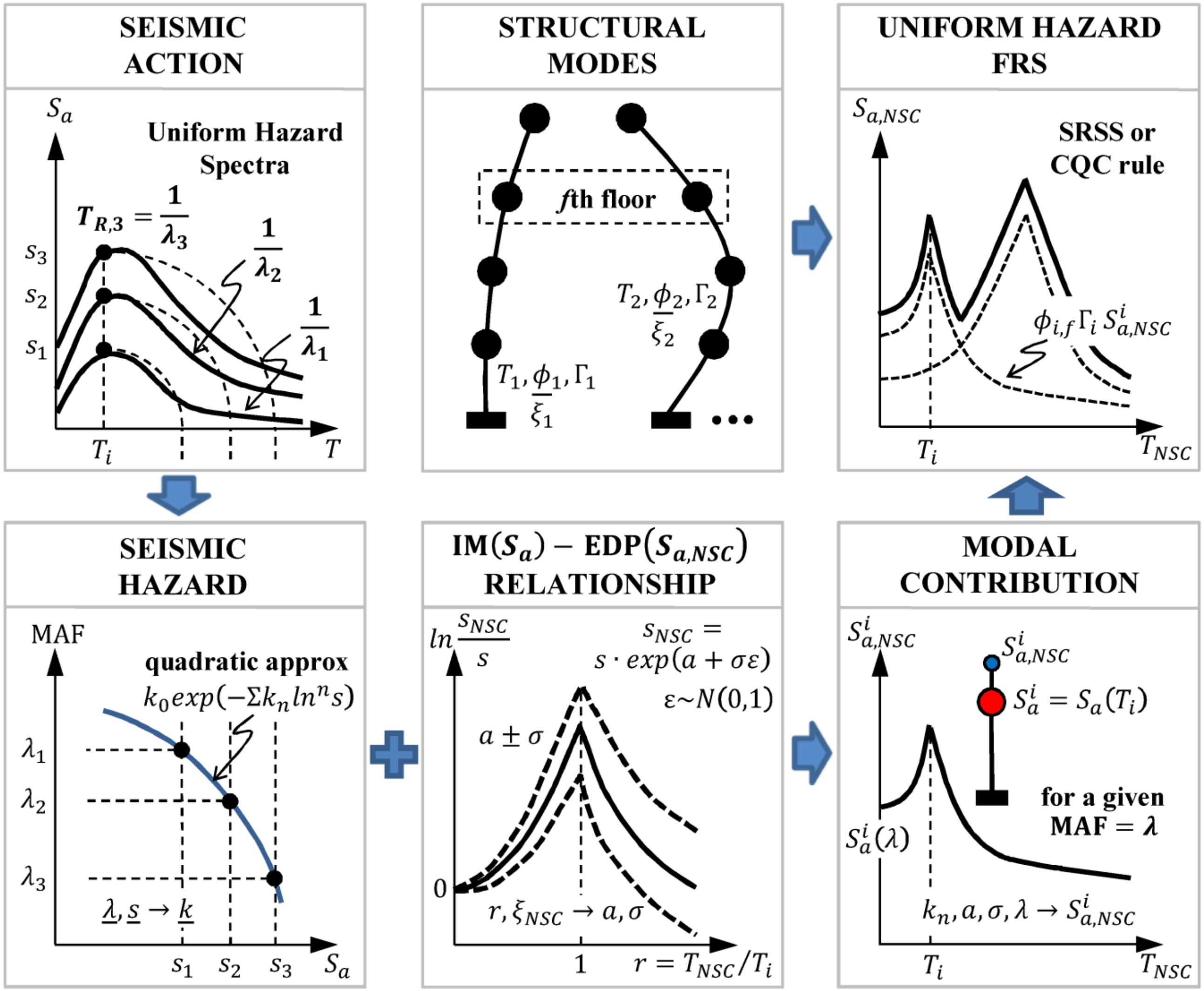


The IM-EDP relation

- Dependence on structural damping, geographical location and site soil conditions is negligible (here shown only on Sa,tuning, but true for all ordinates)

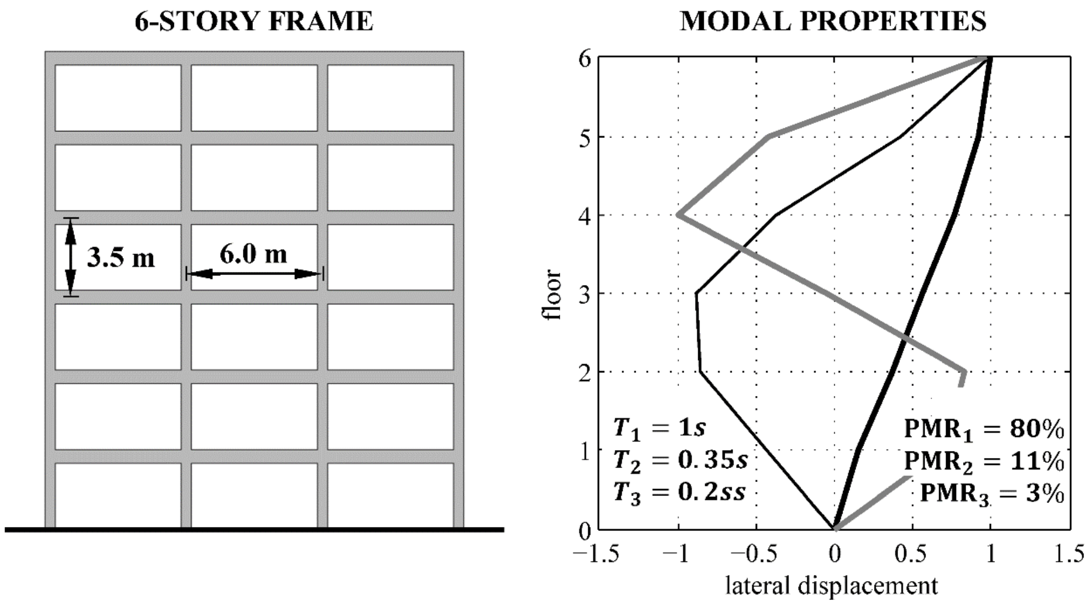


Uniform hazard floor response spectra



MDOF validation

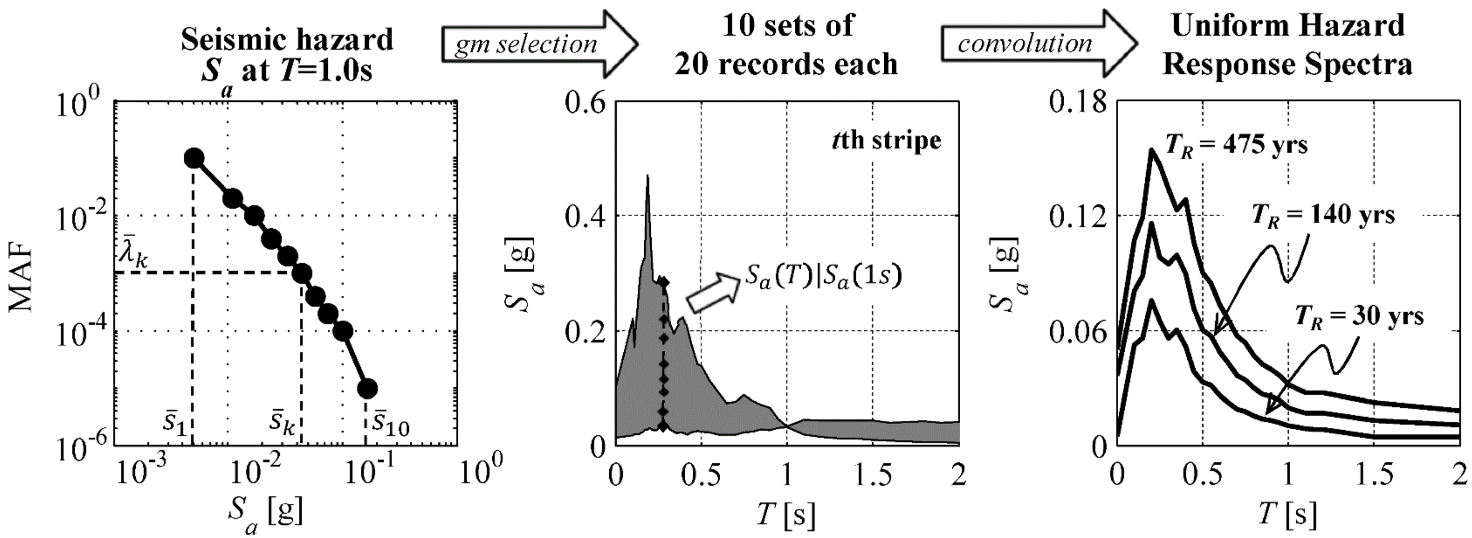
- 6 storey RC frame in Milan, Italy



MDOF validation

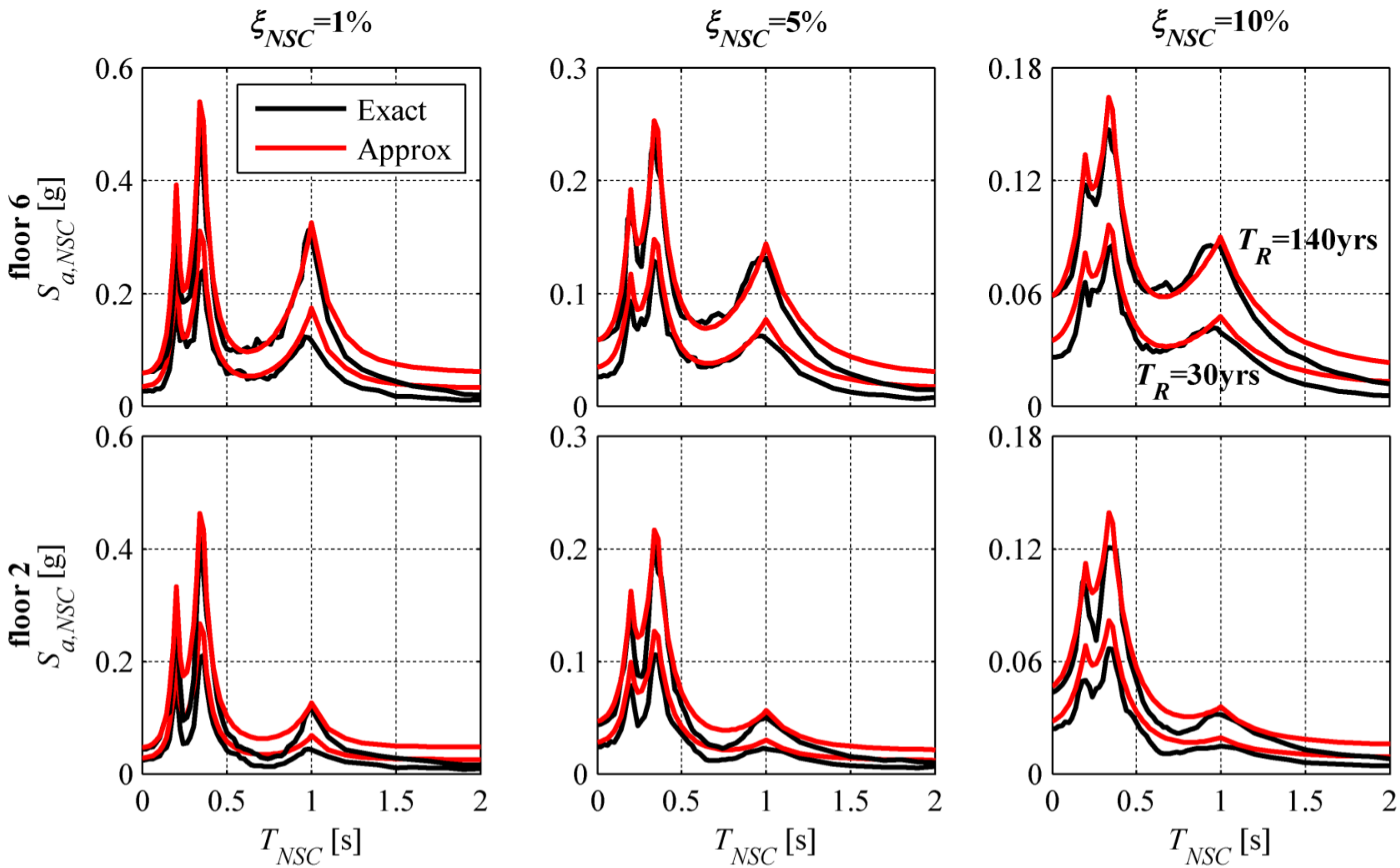
- Hazard for $S_{a\ \max}(TS = 1s)$ + CS-selected records from RINTC project

$$\lambda_{S_a^*}(s^*) = \int G_{S_a^*|S_a}(s^*|s)|d\lambda_{Sa}(s)| \cong \sum_{t=1}^{N_S} \hat{G}_{S_a^*|S_a}(s^*|s_t)|\Delta\lambda_{Sa}(s_t)|$$



$$\lambda_{S_{a,NSC}}(s_{NSC}) = \int G_{S_{a,NSC}|S_a}(s_{NSC}|s)|d\lambda_{Sa}(s)| \cong \sum_{t=1}^{N_S} \hat{G}_{S_{a,NSC}|S_a}(s_{NSC}|s_t)|\Delta\lambda_{Sa}(s_t)|$$

MDOF validation



Epistemic uncertainty