VTT

Possible alternatives for shaker table testing in earthquake qualification of I&C cabinets

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VTT – beyond the obvious

Outline

- Problem statement
- Building plus I&C cabinet interaction
- Traditional earthquake qualification
- Method explored in this study
  - Vertical shaking direction
  - Horizontal shaking direction
  - Re-composing MDOF responses
- Suggested validation path

Problem statement

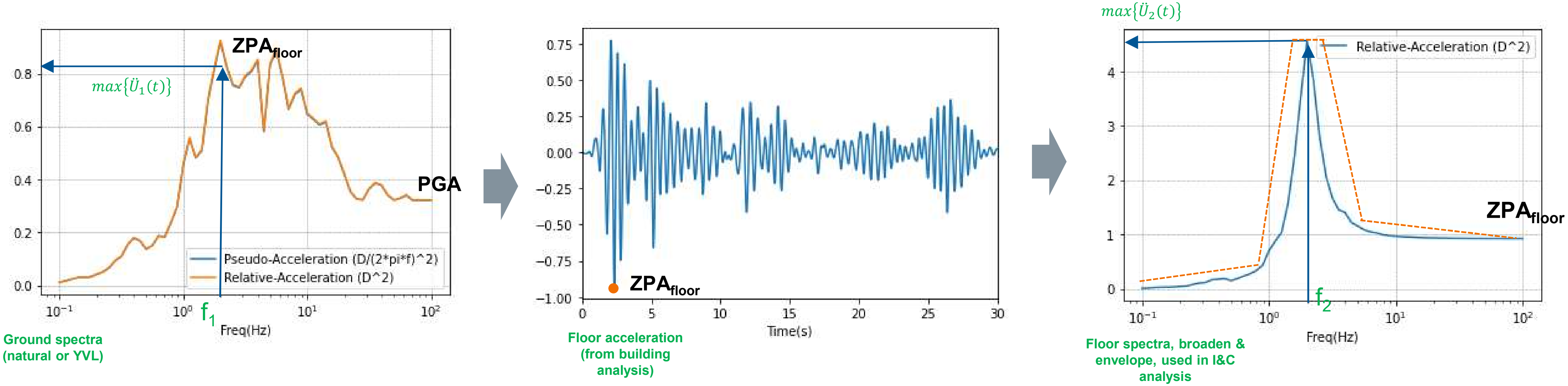
- Earthquake qualification of I&C cabinets is a very costly and has several shortcomings. It involves producing a full-scale mockup and physically testing it on a shaker-table.

    - Problem #1: The mockup is not used in the plant; it is especially difficult to reproduce the realistic fixing conditions in the lab (i.e. the boundary conditions in terms of stiffness and interactions).
    - Problem #2: Any change of an operational I&C affects the dynamics; so, ideally a re-qualification would be necessary.

- Research question: Could there be a method, relying more on analysis, which could replace all or parts of an I&C cabinet earthquake qualification process?

NPP building & IC cabinet

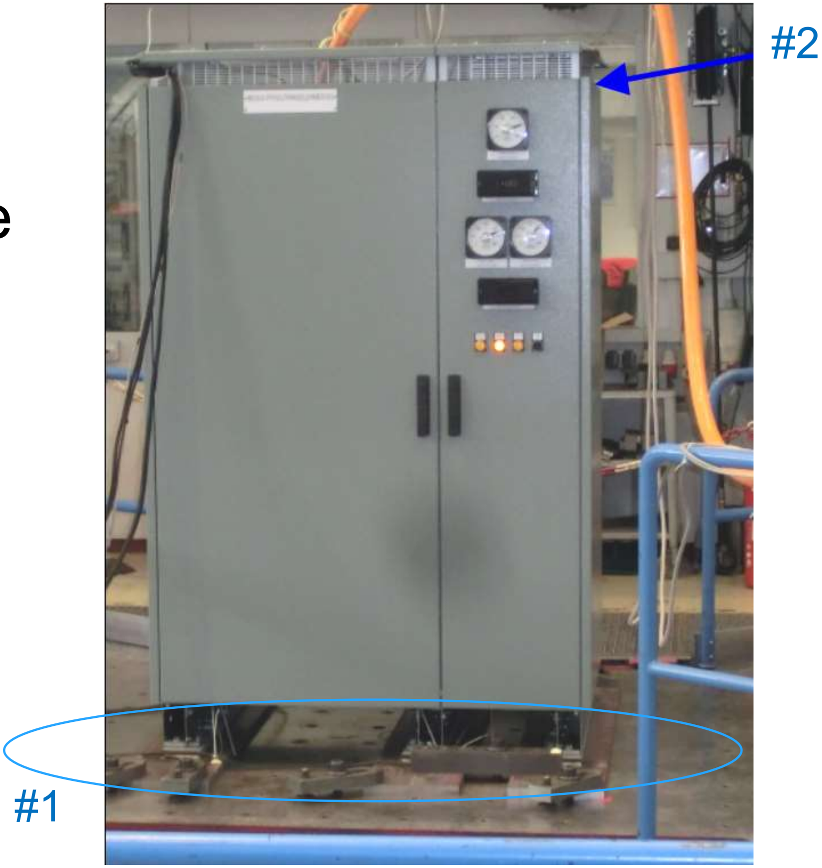
- Analysis goes two steps:



- Input to building analysis is a free-field spectra (ground response spectra); a pSA.
- The floor acceleration (ZPA) is obtained from a building model (*in figure only one mode for building is used f_1*).
- The floor spectra (enveloped and broadened) is input for the I&C analysis (*in figure only one mode for I&C is used f_2*)

Traditional qualification process

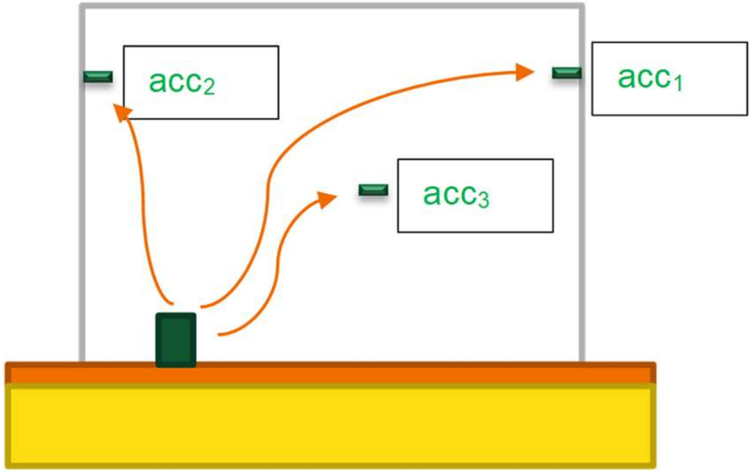
- I&C cabinet fixed on a shaking table (#1) in a way equivalent to fixing on the building floor.
- Testing with sine-sweep at the base, for mode identification, damping etc.
- Floor response-spectra compatible accelerograms used to qualify the equipment
  - (i) mechanical performance (e.g. degradations etc.) stresses measured
  - (ii) monitor responses of individual equipment (e.g. displacements (#2), accelerations etc.) and
  - (iii) monitoring system functionality.

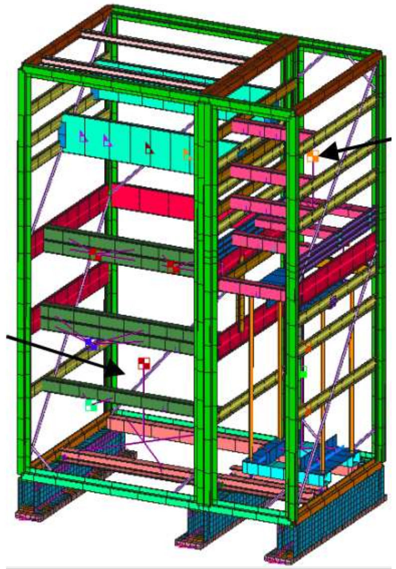


Ries *et al*, 2017

Research question (*expanded*)

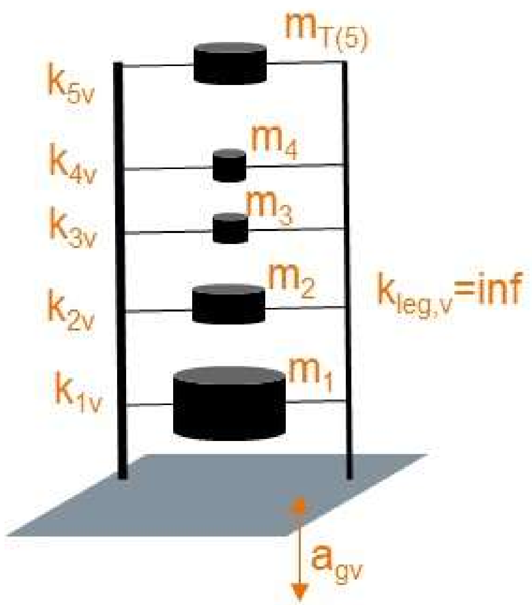
- Could qualification in-situ be carried out, without moving the I&C from its location?
- Shakers/hammers could be used for loading; modal properties could be used to calibrate FEM, but we don't want to accept qualification by FEM.
- Re-composing the dynamic response of MDOFs to base shaking, without shaking the base...

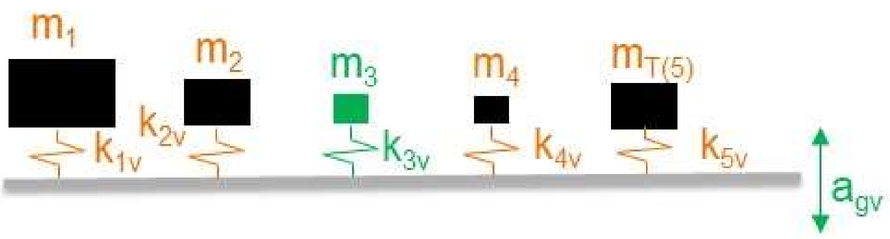




Ries *et al*, 2017

I&C cabinet in vertical direction





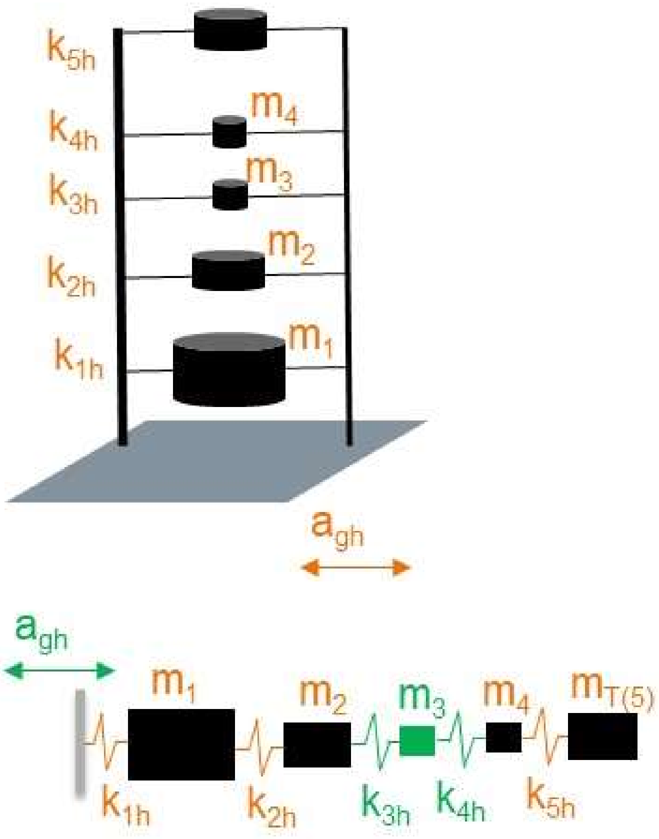
- Vertically for m_3 equations are decoupled:

$$m_3 \cdot \ddot{U}_{g3v}(t) + k_{3v} \cdot U_{g3v}(t) = -m_3 \cdot a_{gv}(t)$$

- Green are known:
  - m_3 from documentation of the I&C, and
  - k_{3v} can be calculated from the frequency f_{3v}, identified from an accelerometer measurement on #3.

- No need to know the rest of the system to calculate e.g. $\ddot{U}_{g3v}(t)$, only the #3 shelve frequency.

I&C cabinet in horizontal direction



- Horizontally e.g. for m_3 equations are coupled:

$$m_3 \cdot \ddot{U}_{g3h}(t) - k_{3h} \cdot U_{gh2}(t) + (k_{3h} + k_{4h}) \cdot U_{g3h}(t) - k_{4h} \cdot U_{g4h}(t) = -m_3 \cdot a_{gh}(t)$$

- Greens can be known; but modal identification of the whole MDOF system needed for $k_{1h}, k_{2h}, \ldots k_{5h}$.

- The calculation for U_{g3v} and $\ddot{U}_{g3v}(t)$ involves knowing the motions of other points, i.e. #2 and #4.

Re-composing of MDOF responses

- MDOF response quantity can be calculated from SDOF responses; result is correct if all modal contributions are included. E.g. in cabinet 5th DOF model:

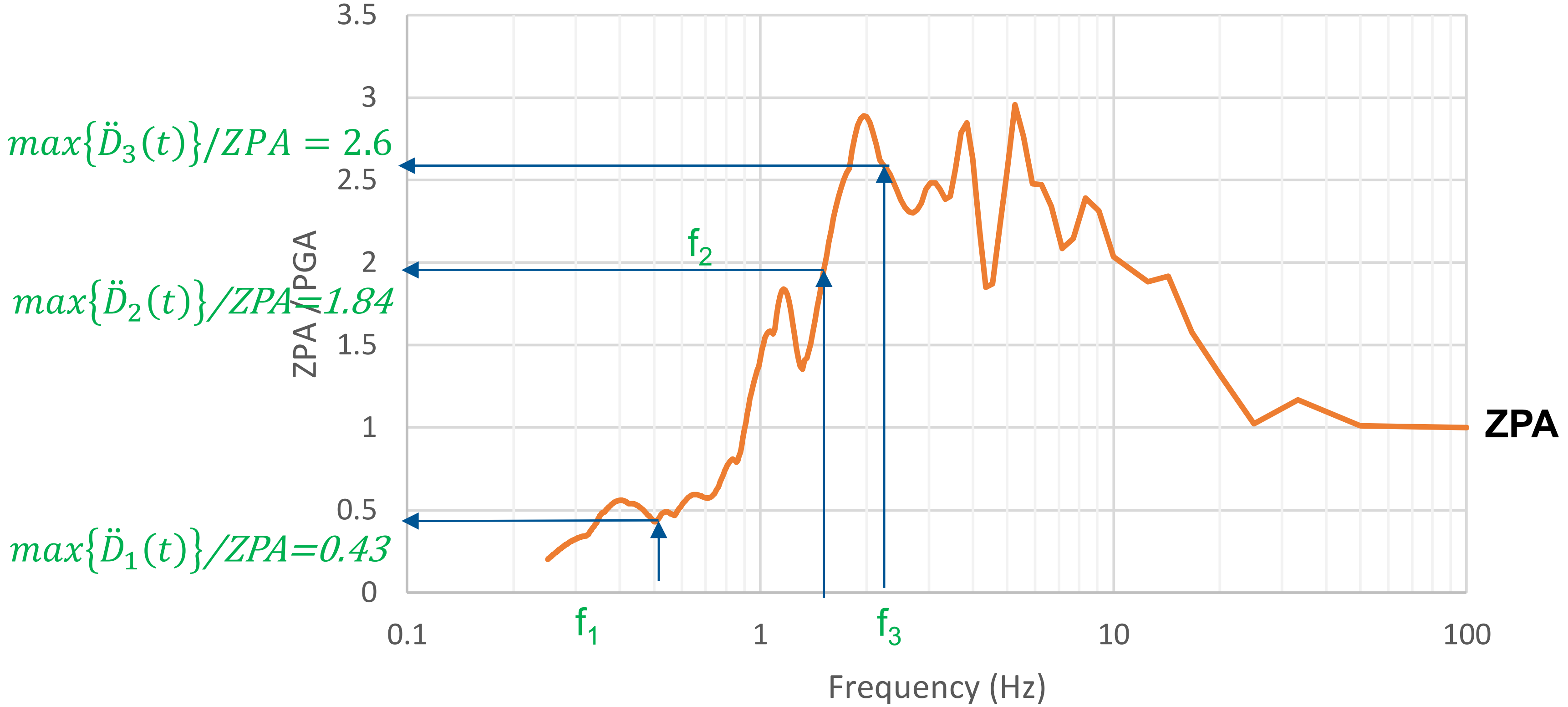
$$U_5(t) = \sum_{n=1}^{N} \Gamma_n \cdot \Phi_{5n} \cdot D_n(t)$$

$$\ddot{U}_5(t) = a_{gh}(t) + \sum_{n=1}^{N} \Gamma_n \cdot \Phi_{5n} \cdot \ddot{D}_n(t)$$

- Where:
  - $D_n(t)$ and $\ddot{D}_n(t)$ are the displacement and acceleration of the SDOF's. They are knowns.
  - The MDOF quantities are the participation factor of each mode Γ_n and the mode shape Φ_{5n}.

Focusing on peak quantities simplifies

- Not really interested in $\ddot{D}_n(t)$, but in max($\ddot{D}_n(t)$).
- Can be obtained from the floor-spectra, based on each frequency (f_i):



Summing modal responses approximately

- The max responses are not at the same time so:

$\max(a_5) \neq \max(a_{5,1}) + \ldots + \max(a_{5,5})$. Approximate solutions:

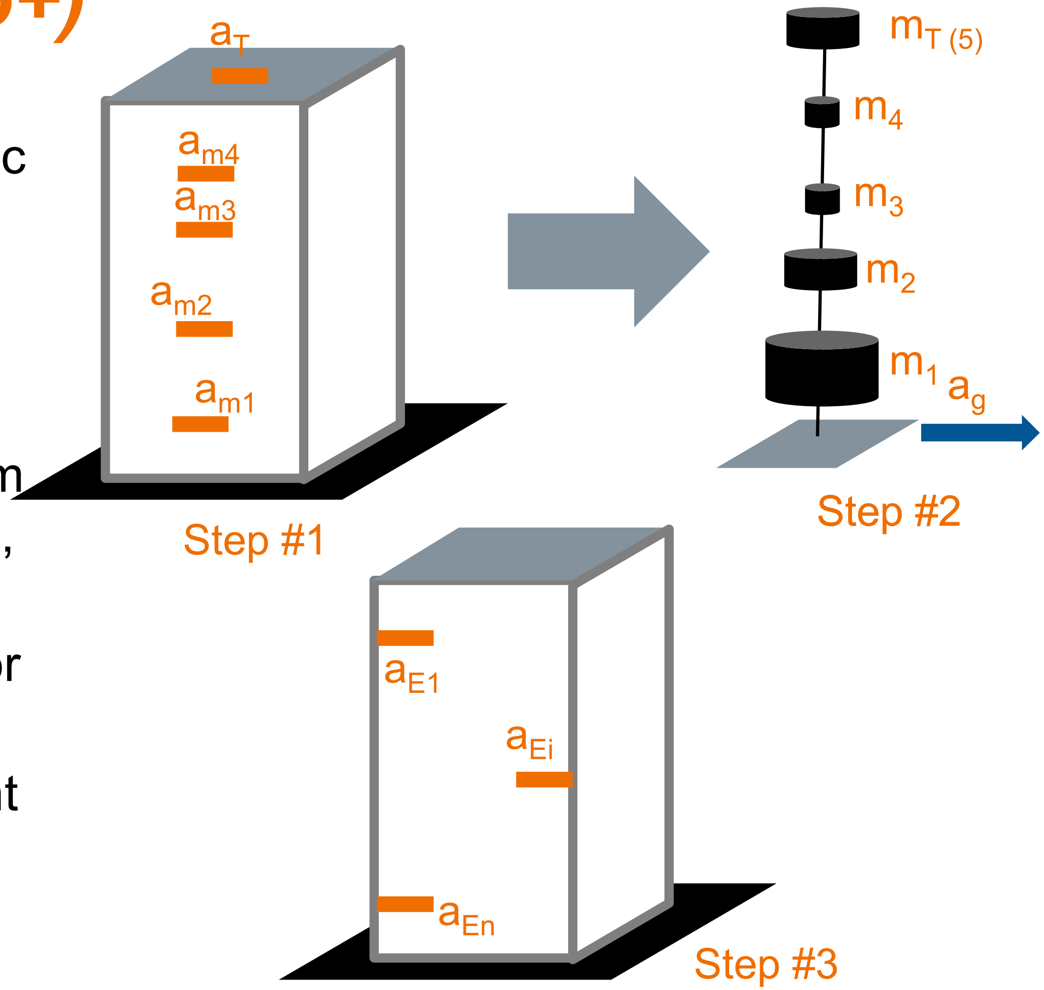
$$ABS, max(u_5) \approx \sum_{i=1}^{5} abs(u_{5,i}),\ SRSS, max(u_5) \approx \sqrt{\sum_{i=1}^{5} (u_{5,i})^2},\ CQC$$

- One way is to accept that we need a simple I&C cabinet model & work out the dynamics. Not a FEM, but only a "*stick*" model.

- But can we simplify it further for I&C cabinets?!

Proposed “*Conservative response re-composition method (M#5+)*”

- No need for shake-table, but a simple dynamic model is needed.
- Step #1: Modal identification with hammer. Obtain modal frequencies (f_1, f_2, f_3,), mode shapes and damping.
- Step #2: Estimate masses (m_1, m_2, m_3…) from documentations & calculate stiffnesses (k_1, k_2, k_3…). Build a simplified dynamic model.
- Step #3: Calculate accelerations from the floor shaking (a_g), at each mass location m_i.
- Step #4: Interpolate acceleration to equipment location a_{Ei}. Match the a_{Ei} with component resiliences.



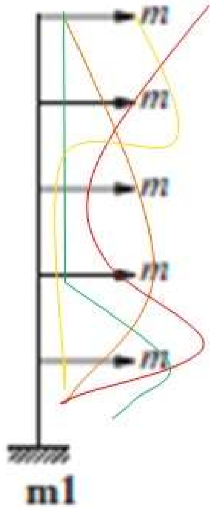
Simplifying the modal participation factor (Γ_n)

- To calculate it one needs mode shapes (Φ), known from the hammer test and the distribution of the masses $\bar{\mathrm{r}}$ which is problematic; estimates exists at best.
  - Calculate the coefficient vector ($\bar{L}$)

$$\bar{L} = \Phi^T \cdot M \cdot \bar{\mathrm{r}}$$

  - and the participation factor (Γ_i):

$$\Gamma_i = \frac{\bar{\bar{L}}_i}{\widehat{M}_{ii}}$$



- Monte Carlo simulation could be used to calculate Γ_i with reasonable “m” distributions

Summary / Suggested validation path

- Conservative response re-composition (M#5+) is a promising method to (i) estimate dynamic response of an I&C cabinet and (ii) qualify individual components to acceleration. But it cannot handle (iii) system functionality.

- A simplified dynamic model is needed. Could be programmed in PYTHON with hammer test results and masses as inputs. Output is accelerations at equipment locations.

- The path to validate the level of conservativeness, would be
  - In step (1) to make comparative studies with sophisticated FEM and
  - In step (2) with shake table tests.

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