# WEBINAR 4: Silos, tanks, pipelines, towers masts and chimneys – Ancillary elements in industrial facilities

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# SCOPE OF APPLICATION

- Seismic design of **ancillary elements** (non-structural components) attached to structures in industrial facilities
- Not Covered:
  - Components employing isolators, viscous or friction dampers,
  - Components that may respond by sliding or rocking
  - Interaction with other independently attached components
  - Impact with the structure or other components
  - Functioning and process interdependencies
- Covered
  - Non-interacting **single-support** yielding/elastic components
  - **Multi-support** components governed by differential support motion

# WHY OH WHY?

- EN1998-1-2 **already includes** provisions for non-structural components
- Are we replicating them?
- EN1998-4 is meant for **industrial** facilities
- Different safety standards, different requirements, different modes of application
- Ancillary elements may be upgraded, **replaced**, or modified through the structures lifetime
- Need **flexibility** in designing their supports, without necessarily reanalyzing the full structure
- Need **simplicity** in application to accommodate many **safety-critical** components
- **Uncertain structural characteristics** are they key issue

# BASIS OF DESIGN

- Design must account for
  - ancillary elements
  - connections to the supporting structure
  - interactions with the supporting structure

- Impact among components or components & structure shall be eliminated by providing adequate **clearance**
- All partial **safety factors** per EN1998-1-2
- Ensure **compatibility**!

# MODELLING

- Model = supporting **structure(s)** + component
  - Single/multi-support components that interact **statically or dynamically** with the supporting structure(s)
  - Multi-support components sensitive to **both** differential support deformation and vibration
- Model = supporting structural **member(s)** + component
  - Single/multi-support components that interact **statically or dynamically** with the supporting member(s)
- Model = component **only**
  - Single-support components without interactions, subject to **floor acceleration spectra** (= business as usual ☺)
  - Multi-support component with negligible vibrations, subject to **differential support deformations** (= business as usual ☺)

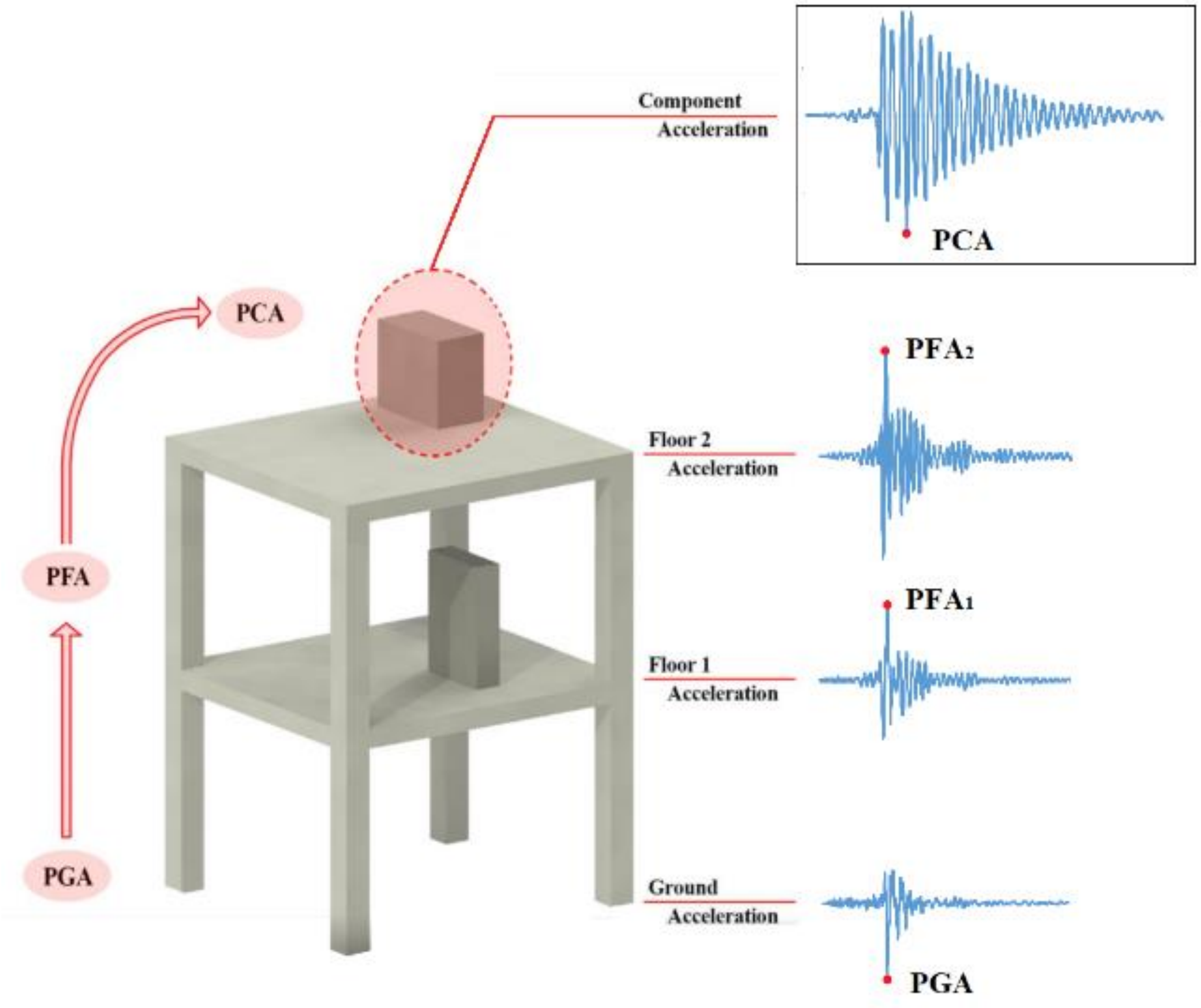
# ANALYSIS

- Model = supporting **structure(s)** + component
  - Modal response spectrum (MRSA) or response history analysis (RHA)
- Model = supporting structural **member(s)** + component
  - MRSA or RHA
  - Equivalent static analysis (ESA) given component support spectra
- Model = component **only**
  - MRSA (multi-mode)
  - ESA (single-mode) given component support spectra => Typical case!

**Our focus!**

# FROM PGA TO PCA

- Ground motion is **modulated** by structure
  - PGA becomes PFA
- Floor motion is **modulated** by element
  - PFA becomes PCA
- **Resonance** is the enemy
  - Sensitive problem
  - Must know **periods** of structure & element, **damping** ratios, **inelasticity** developed
  - Resonance only happens under **perfect** tuning & elasticity



# THREE METHODS FOR DESIGN

- Method 1: EN 1998-1-2:2022
  - Non-dissipative (except component behavior factor)
  - Complex & accurate
  - Must know periods, mode shapes, damping ratios, behavior factor(s)
- Method 2: EN 1998-4:2022
  - Non-dissipative
  - Simplified & conservative
  - Imperfect knowledge is assumed -> Resonance assumed
- Method 3: EN 1998-4:2022
  - Dissipative
  - Requires “fuse” with certified overstrength and ductility
  - Imperfect knowledge is ok

1

2

3

# METHOD 1: NO CAKE

- Rinse & repeat for each **mode** of the structure
- Must know **periods** and **mode shapes**
- **Damping** determines amplification
- Component & structure behavior factors are important

$$F_{ap} = \frac{\gamma_{ap} \cdot m_{ap} \cdot S_{ap,j}}{q_{ap}'}$$

$$S_{ap,ij} = \frac{\Gamma_i \cdot \varphi_{ij}}{\left| \left(\frac{T_{ap}}{T_{p,i}}\right)^2 - 1 \right|} \sqrt{\left(\frac{S_{ep,i}}{q_D'}\right)^2 + \left[\left(\frac{T_{ap}}{T_{p,i}}\right)^2 \cdot S_{eap}\right]^2} \leq AMP_i \cdot \left|PFA_{ij}\right|$$

$$AMP_i = \begin{cases} 2.5 \cdot \sqrt{\frac{10}{(5+\xi_{ap})}}, & \frac{T_{p,i}}{T_C} = 0 \\ \text{linear between } AMP_i\left(\frac{T_{p,i}}{T_C} = 0\right) \text{ and } AMP_i\left(\frac{T_{p,i}}{T_C} = 0.2\right), & 0 \leq \frac{T_{p,i}}{T_C} \leq 0.2 \\ \frac{10}{\sqrt{\xi_{ap}}}, & \frac{T_{p,i}}{T_C} \geq 0.2 \end{cases}$$

# METHOD 2: SIMPLE BUT CONSERVATIVE

- Only **one mode** considered
- Amplification taken at resonance
  - Component damping @ 2%
- Simplified linear mode shape assumed if unknown
- No reduction for structural inelasticity unless **verified by pushover**
  - Conservative!
  - No need to know much about the structure, but you **pay** for it

$$F_{\mathrm{ap}} = \frac{\gamma_{\mathrm{ap}} \cdot m_{\mathrm{ap}} \cdot S_{\mathrm{ap}}}{q_{\mathrm{ap}}'}$$

$$S_{\mathrm{ap}} = AMP \cdot PFA$$

$$PFA = \Gamma_1 \cdot \varphi_{1,\mathrm{ap}} \cdot \frac{S_{\mathrm{e}}(T_{\mathrm{p},1}, \xi_{\mathrm{p},1})}{q_{\mathrm{D}}'} \geq \frac{S_{\alpha}}{F_{\mathrm{A}}}$$

$$\varphi_{1,\mathrm{ap}} = \left(\frac{z}{H}\right), \text{ if mode unknown}$$

$$q_{\mathrm{D}}' = 1, \text{ if structural inelasticity unverified}$$

# METHOD 3: FUSE FOR THE WIN

- Only **one mode** considered
- Amplification taken at resonance
  - Component damping @ 2%
- Fuse of **certified** ductility & strength diminishes resonance effects
- **Disengage** from structural & component characteristics
  - Highly **reliable**
  - Low design accelerations (component remains **functional**)
  - Low **anchorage** forces transmitted to structure
  - Higher reliability enforced at ductility: Certify for $\boldsymbol{\mu_D \cdot \gamma_{ap}}$, use $\boldsymbol{\mu_D}$

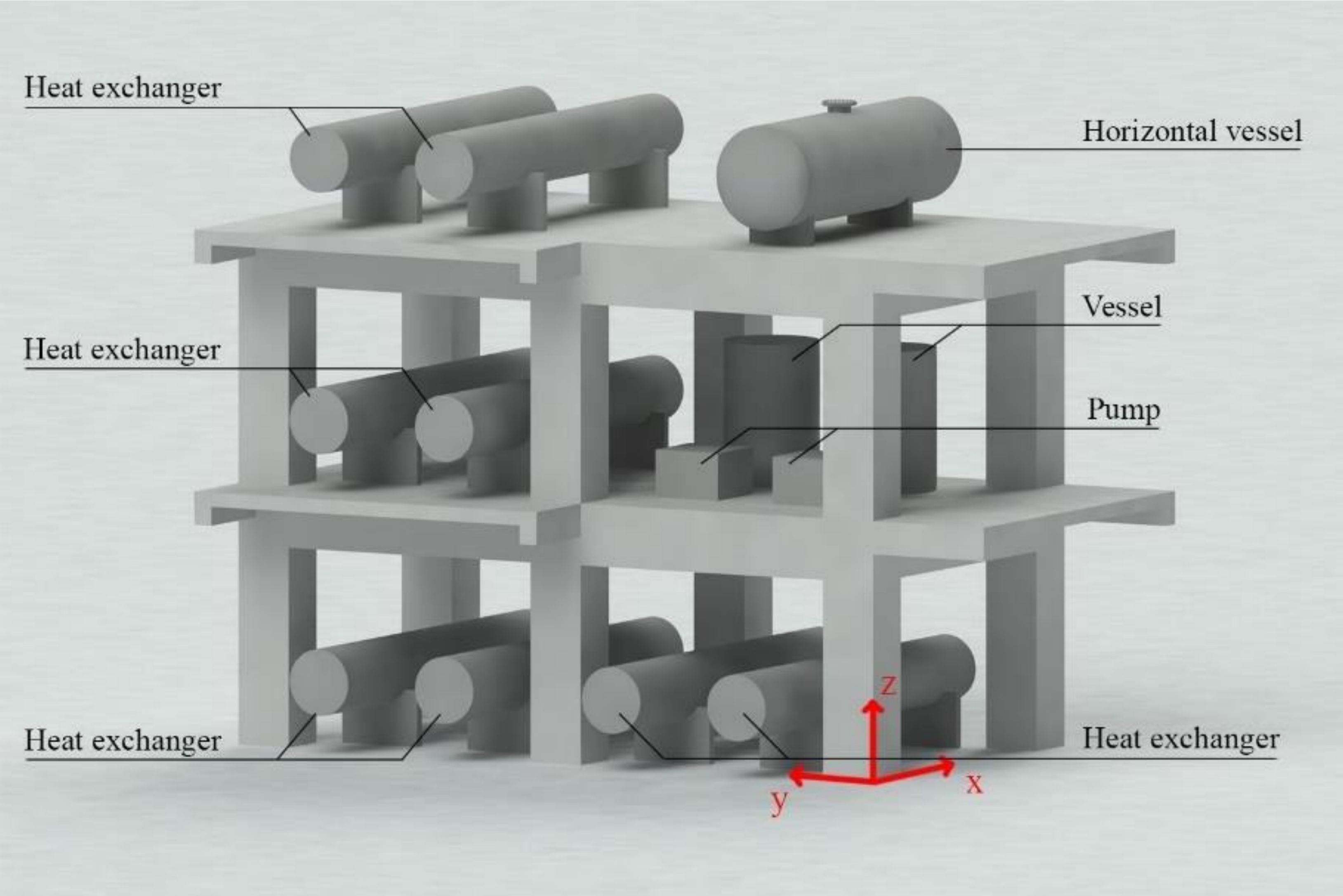
$$S_{\mathrm{ap}} = AMP \cdot PFA$$

$$AMP = max\left\{1.30;\ 0.60 + \frac{1.40}{(\mu_{\mathrm{D}} - 1.0)}\right\}$$

$$\mu_{\mathrm{D}} \geq 1.50$$

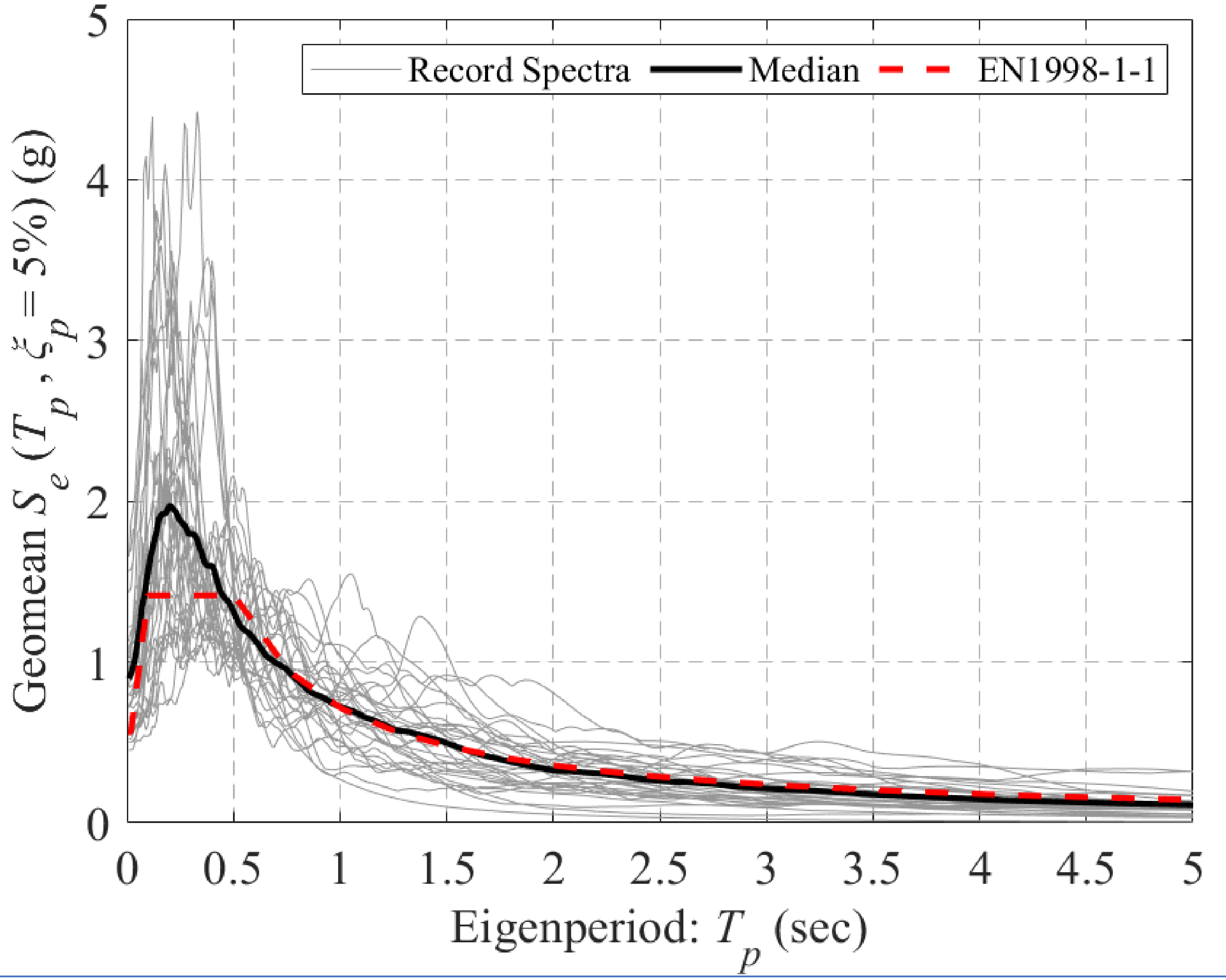
# AN EXAMPLE CASE STUDY

- Equipment-supporting RC-MRF, 8x15m plan
- Typical refinery building
- Located in Elefsina, Greece, $a_g = 0.24g$, $S_{\alpha,ref} = 0.71g$
- Consequence Class 3a
  - Perf. factor 1.75
  - $S_{\alpha,ref} = 1.24g$ for 2,500 years
- Ductility Class 2 (moderate!)
- Tp,1x ≈ Tp,1y = 0.2s
- Heavily overdesigned for fire-proofing
- Elastic response!



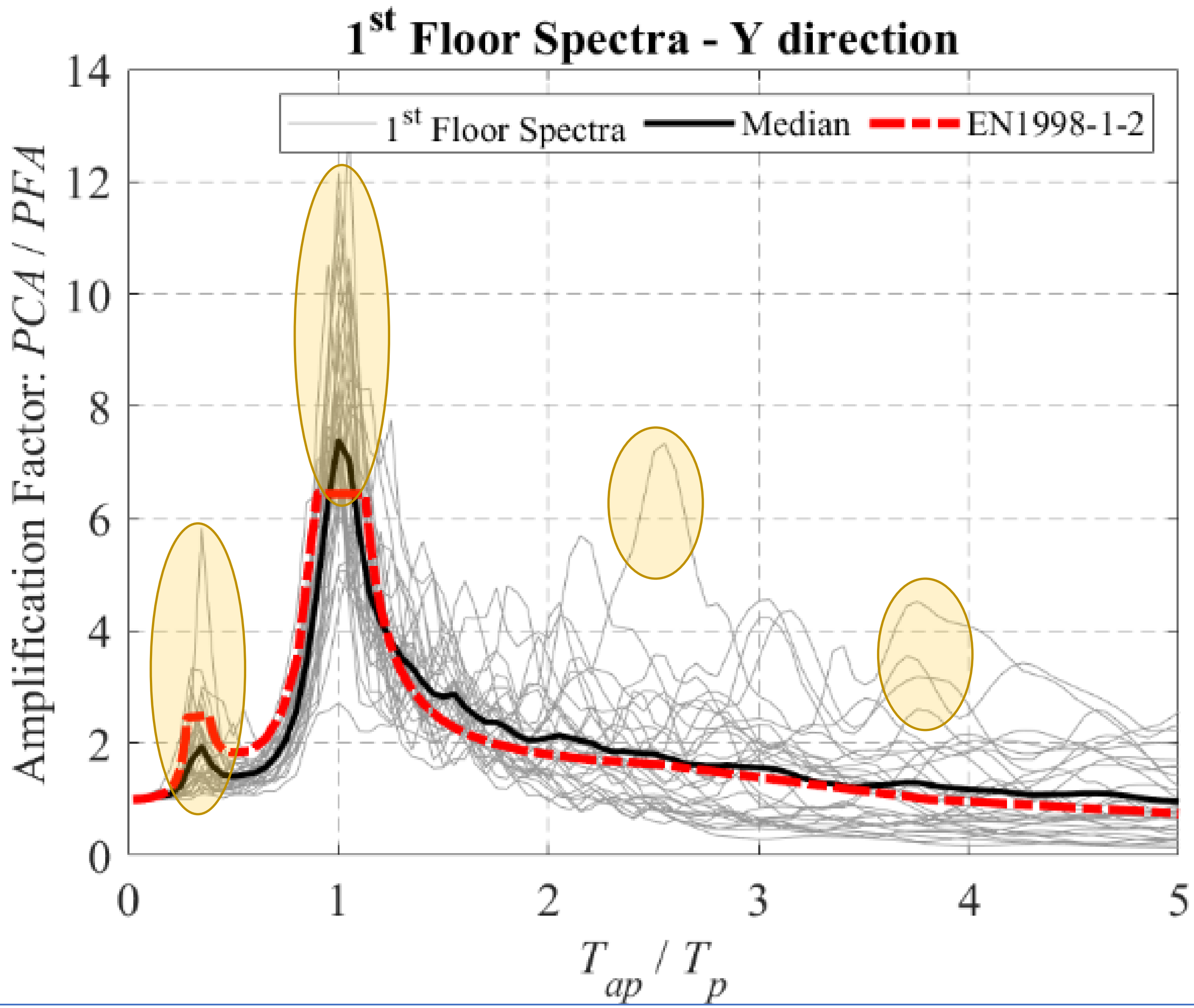
# AN EXAMPLE CASE STUDY

- Important components
  - $\gamma_{\text{ap}}$ = 1.5
  - Any additional overstrength in anchorage (i.e 4 vs 3 bolts) disregarded
- Use RHA for accurate assessment of demands
- 30 “ordinary” records
- Selected to be compatible with 2%/50yr hazard via Conditional Spectrum
- Conditioned to match $AvgS_{\text{a}}(0.1\text{–}1\text{sec})$



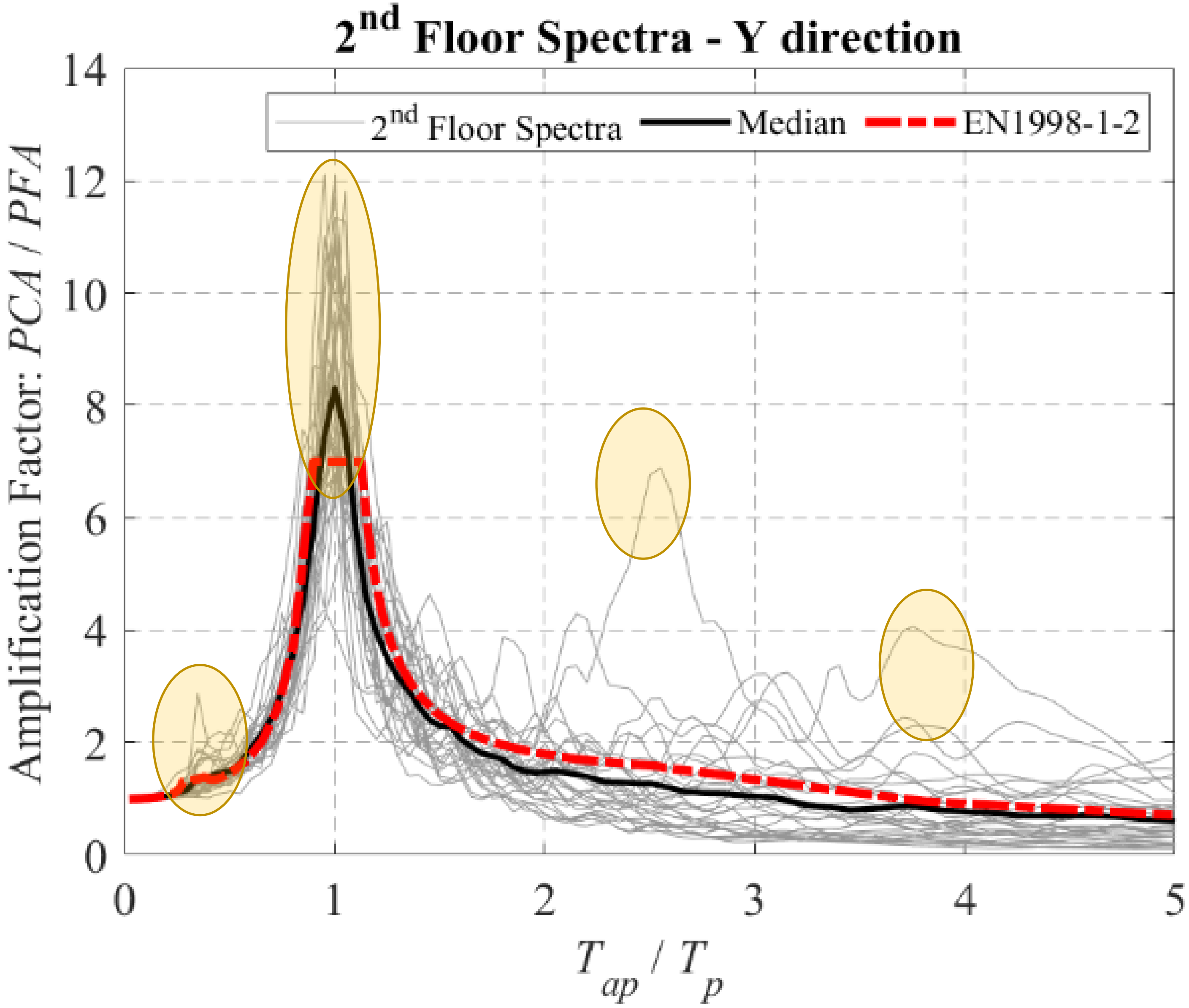
# METHOD 1: FLOOR SPECTRA 1

- Excellent accuracy
  - Max AMP = **7.07**
  - Some records go higher
  - Still ok
- **Higher modes** also captured
- Localized **peaks** at higher normalized periods can happen
- Impossible to predict without RHA
- Code is not **magic**!
- Still, pretty **rare** events



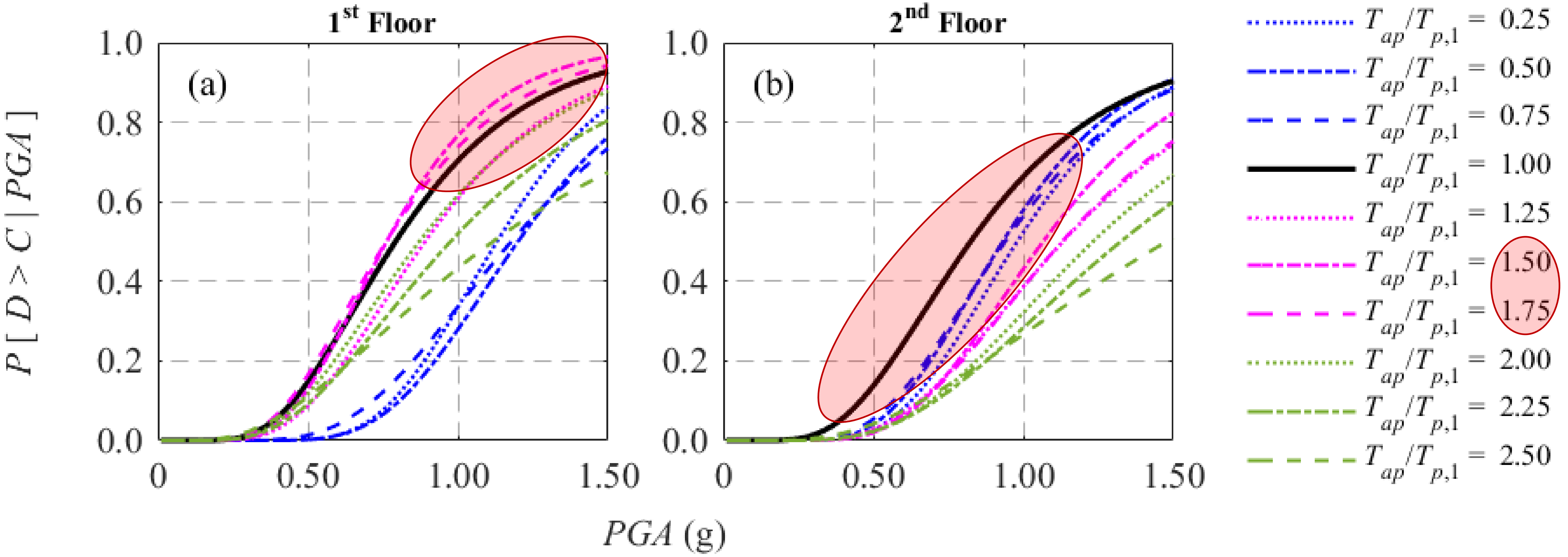
# METHOD 1: FLOOR SPECTRA 2

- Excellent accuracy
  - Max AMP = **7.07**
  - Some records go higher
  - Still ok
- **Higher modes** also captured
- Localized **peaks** at higher normalized periods can happen
- Impossible to predict without RHA
- Code is not **magic**!
- Still, pretty **rare** events



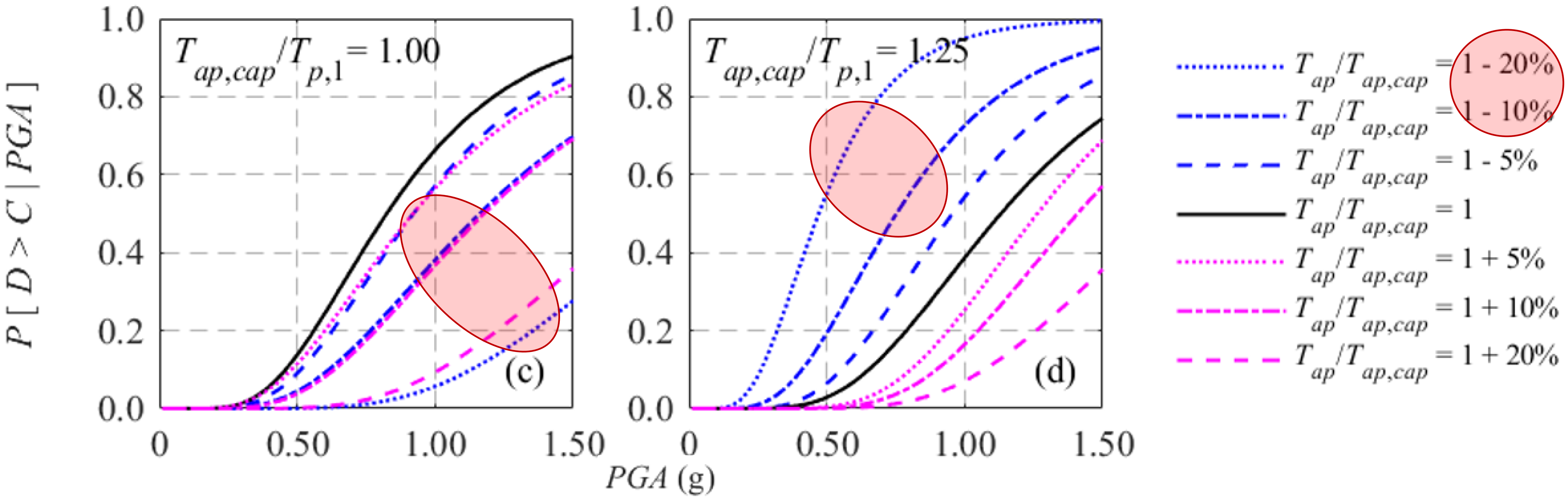
# METHOD 1: FRAGILITIES

- If you know everything, Method 1 is excellent (minus some **exceptions**)



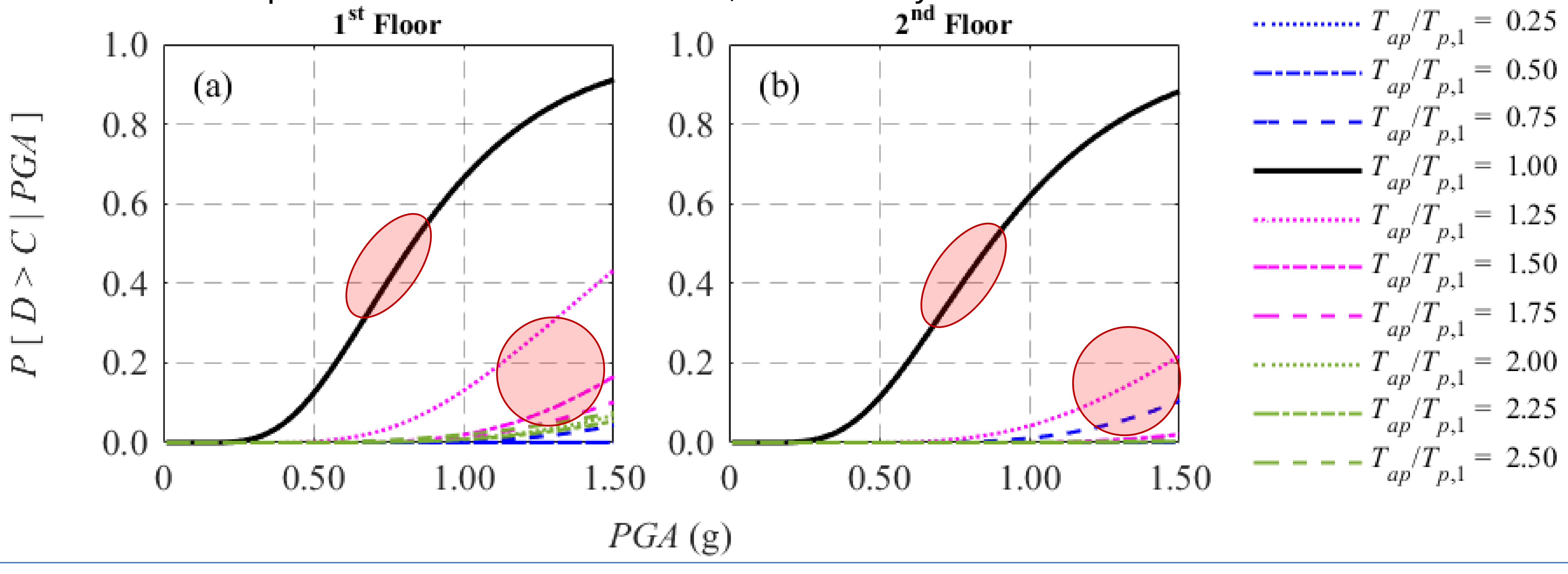
# METHOD 1: FRAGILITIES

- If you thought you were **at resonance** and you are not, then you are ok! **(conservative)**
- If you thought **you were away** but true period is close to resonance, you are **in trouble**
- So, how sure are you of the **actual** structure & component periods**?**



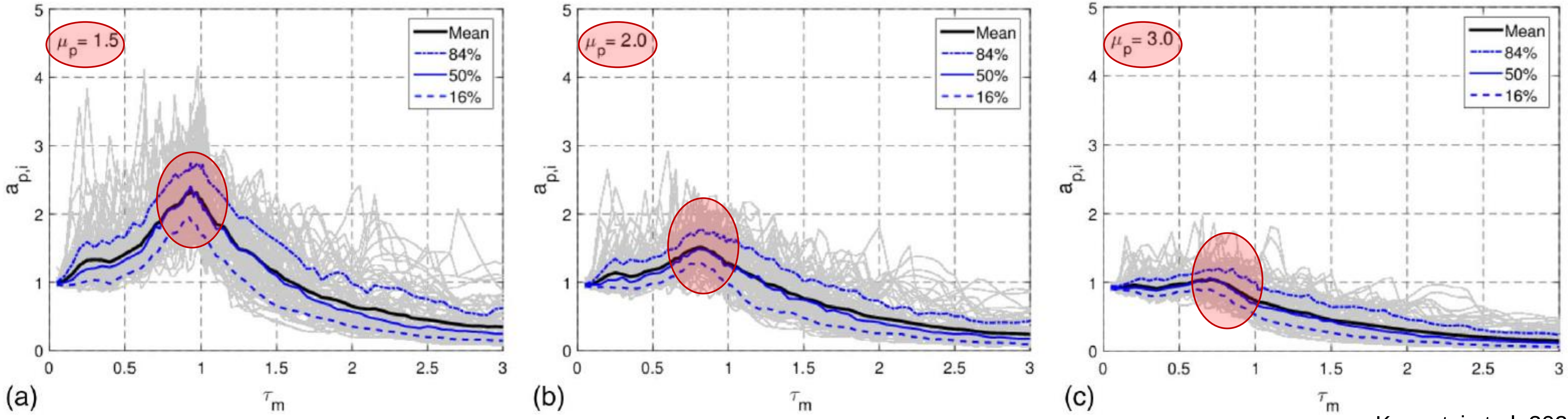
# METHOD 2: FRAGILITIES

- Once you assume resonance everywhere, everything is super-conservative
- Cost = 1-2 bolts more, for most components
- When component is indeed in resonance, same safety as Method 1



# METHOD 3: CONCEPT

- Four **nominal** ductility levels for fuse: $\mu_D = \{1.5; 2.0; 2.5; 3.0\}$
- Important elements, manufacturer must certify for 1.5 $\mu_D$
- Increasing nominal $\mu_D$ **is not meant** to increase safety, only $\gamma_{ap} = 1.5$ does this
- Increasing nominal $\mu_D$ decreases **forces & accelerations** (i.e., protect functionality)

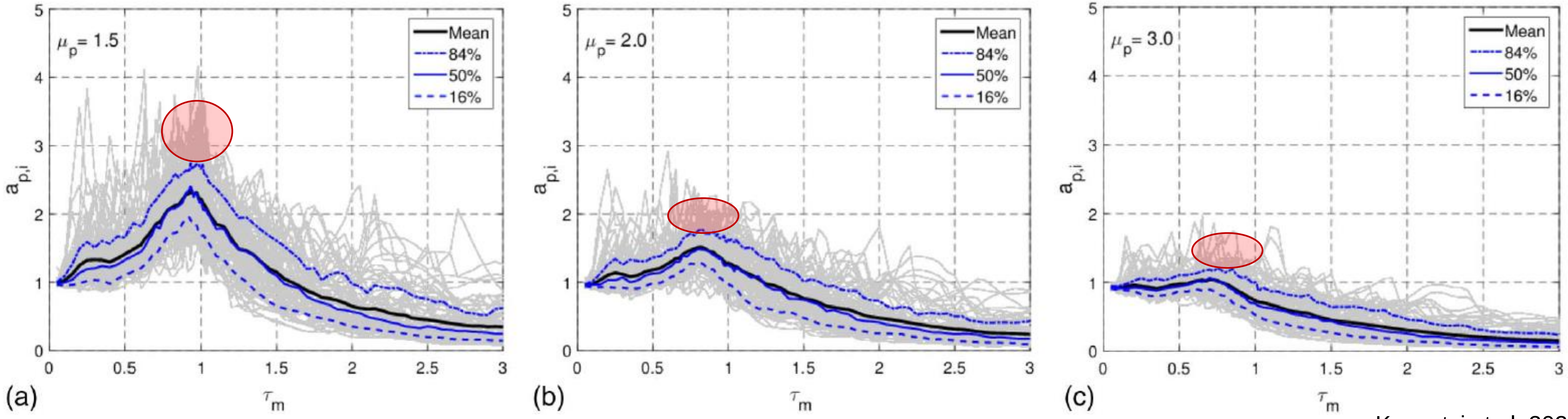



Kazantzi et al. 2020

# METHOD 3: CONCEPT

- This decrease is substantial (~90% values used):
  - $\mu_D = 1.5$ => AMP = **3.4**
  - $\mu_D = 2.0$ => AMP = **2.0**
  - $\mu_D = 3.0$ => AMP = **1.3**

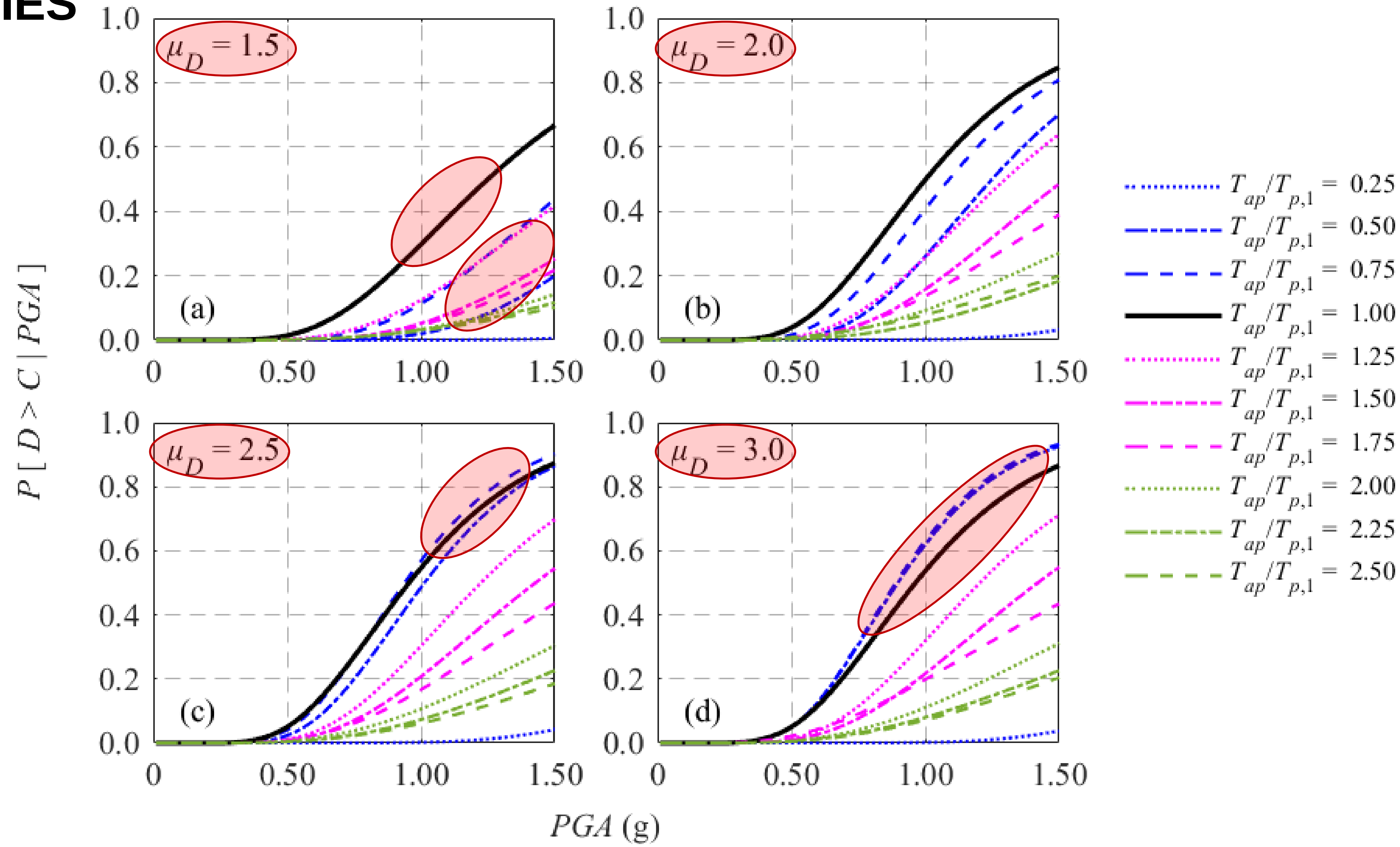
If you need lower AMP, use base isolation!




Kazantzi et al. 2020

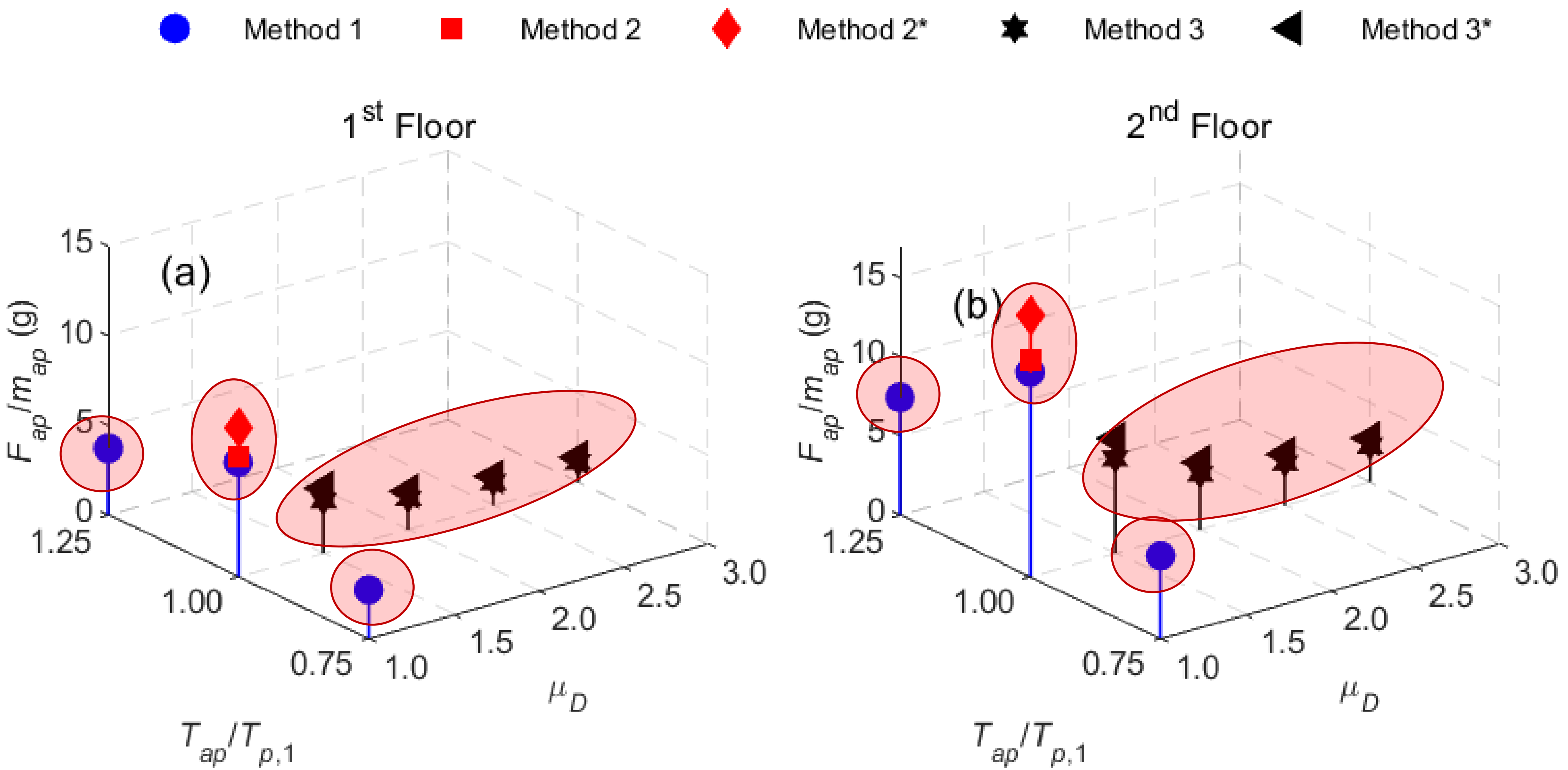
# METHOD 3: FRAGILITIES

- In resonance => a bit safer than Method 1
- Out of resonance => conservative
- $\mu_D = 1.5$ more conservative
- Higher ductilities provide similar levels of safety
- Minor exceedances for $\mu_D = \{2.5; 3.0\}$
- Remember, you know only component mass
- ….but you certified the fuse!



# METHOD 1: FRAGILITIES

- 2* and 3* = approx. mode shape
- If out of tune, Method 1 is best, Method 2 is too conservative
- If in tune, all methods work
- If you have no idea, Method 3 always delivers
- …but who makes the fuse?



# CONCLUSION

- All three methods are **viable**

- Make sure you **respect** their assumptions:
  - Do not assume you know the **period** because your model provides it!
  - Do not assume any piece of steel can become a **fuse**
  - In ductile design, **overstrength** can be the enemy

- Have fun and stay safe with EN1998-4:2022!