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
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

\[
F_{ap} = \frac{\gamma_{ap} \cdot m_{ap} \cdot S_{ap,j}}{q_{ap}}
\]

\[
S_{ap,ij} = \frac{T_i \cdot q_{ij}}{2} \left[ \left( \frac{S_{ep,i}}{q_D} \right)^2 + \left( \frac{T_{ap}}{T_{p,i}} \right)^2 \right]^{1/2} \leq AMP_i \cdot |PFA_{ij}|
\]

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

\[
F_{ap} = \frac{\gamma_{ap} \cdot m_{ap} \cdot S_{ap}}{q_{ap}'}
\]

\[
S_{ap} = AMP \cdot PFA
\]

\[
PFA = \Gamma_1 \cdot \varphi_{1,ap} \cdot \frac{S_e(T_{p,1}, \xi_{p,1})}{q_D'} \geq \frac{S_\alpha}{F_A}
\]

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

\[
q_D' = 1, \text{ if structural inelasticity unverified}
\]
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 $\mu_D \cdot \gamma_{ap}$, use $\mu_D$

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

$$AMP = \max \left( 1.30, 0.60 + \frac{1.40}{(\mu_D - 1.0)} \right)$$

$$\mu_D \geq 1.50$$
AN EXAMPLE CASE STUDY

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

• Important components
  – $\gamma_{ap} = 1.5$
  – 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 $\text{Avg} S_a(0.1-1\text{sec})$
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):
  - $\mu_D = 1.5 \implies AMP = 3.4$
  - $\mu_D = 2.0 \implies AMP = 2.0$
  - $\mu_D = 3.0 \implies AMP = 1.3$

If you need lower AMP, use base isolation!
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 3: FRAGILITIES

$P[D > C | PGA]$ vs. PGA (g)

- $T_{ap}/T_{p,1} = 0.25$
- $T_{ap}/T_{p,1} = 0.50$
- $T_{ap}/T_{p,1} = 0.75$
- $T_{ap}/T_{p,1} = 1.00$
- $T_{ap}/T_{p,1} = 1.25$
- $T_{ap}/T_{p,1} = 1.50$
- $T_{ap}/T_{p,1} = 1.75$
- $T_{ap}/T_{p,1} = 2.00$
- $T_{ap}/T_{p,1} = 2.25$
- $T_{ap}/T_{p,1} = 2.50$
METHOD 1: FRAGILITIES

• $2^* \text{ and } 3^* = \text{approx. mode shape}$

• 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!