Analysis of RC buildings under earthquakes with arbitrary orientations.

Results and Challenges

PhD student: Despoina Skoulidou, FEUP
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The angle of seismic incidence in the seismic safety assessment procedure of individual buildings

- Eurocode 8 Part 3 (deterministically-oriented approach)

4-stage procedure:
1) Limit State/s
2) Level of knowledge
3) Structural analysis
4) Safety verifications

- PBEE framework (Probabilistic approach)

\[ \lambda(L) = \int \int \int G(L \mid DM) \cdot dG(DM \mid EDP) \cdot dG(EDP \mid IM) \cdot dP(IM) \]

Decision!
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Problems integrating the critical angle

- Practical
  - ✔ EDP
  - ✔ Frequency content
  - ✔ Seismic intensity
  - ✔ Behaviour factor
  - ...

Inexistent techniques to predict the critical angle.

- Conceptual
  - Overall performance of a realistic 3D structure and compliance (or not) with a Limit State.
  - Unique demand parameter able to characterize the global response of the structure:

Proposed framework to define a global demand parameter

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Analytical procedure proposed for LFA.
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Critical angle of incidence in LFA

\[
K_{X,Y,Z} = \begin{bmatrix}
K_{XX} & K_{XY} & K_{XZ} \\
K_{YX} & K_{YY} & K_{YZ} \\
K_{ZX} & K_{ZY} & K_{ZZ}
\end{bmatrix}
\]

\[
K_{I,II,III} = \begin{bmatrix}
K_I & 0 & 0 \\
0 & K_{II} & 0 \\
0 & 0 & K_{III}
\end{bmatrix}
\]

\[
T_1, T_2
\]
Critical angle of incidence in LFA

\[ \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} \]

\[ \begin{bmatrix} k_1 & 0 & 0 \\ 0 & k_2 & 0 \\ 0 & 0 & k_3 \end{bmatrix} \]

\[ A_{I,'1'} \]

\[ A_{II,'1'} \]

\[ \theta_{III,I'} \]

\[ f(K_{I,II,III}, \text{geometry}, \alpha) \]
Critical angle of incidence in LFA

\[
\mathbf{K}_{\text{II}} = \begin{bmatrix}
K_{XX} & K_{XY} & K_{XZ} \\
K_{YX} & K_{YY} & K_{YZ} \\
K_{ZX} & K_{ZY} & K_{ZZ}
\end{bmatrix}
\]

\[
\mathbf{K}_{\text{III}} = \begin{bmatrix}
K_1 & 0 & 0 \\
0 & K_2 & 0 \\
0 & 0 & K_3
\end{bmatrix}
\]

\[
T_{\text{unc}}(\alpha) = \frac{T_1 \cdot T_2}{\sqrt{\cos^2(\alpha) \cdot T_2^2 + \sin^2(\alpha) \cdot T_1^2}}
\]

\[
\begin{bmatrix}
u_{I,1}'^A \\
u_{II,1}'^A \\
\theta_{III,1}'
\end{bmatrix} = f(K_{I,II,III}, \text{geometry}, \alpha)
\]
Critical angle of incidence in LFA

\[
\begin{bmatrix}
K_{xx} & K_{xy} & K_{xz} \\
K_{yx} & K_{yy} & K_{yz} \\
K_{zx} & K_{zy} & K_{zz}
\end{bmatrix}
= \begin{bmatrix}
K_{I} & 0 & 0 \\
0 & K_{II} & 0 \\
0 & 0 & K_{III}
\end{bmatrix}
\]

\[T_{\text{unc}}(\alpha) = \frac{T_I \cdot T_H}{\sqrt{\cos(\alpha)^2 \cdot T_{II}^2 + \sin(\alpha)^2 \cdot T_I^2}}\]

\[F(\alpha) = \begin{cases}
    m \cdot 2.5 \cdot a_g \cdot S \cdot \eta \cdot \frac{T_C}{T(\alpha)}, & \text{for } 0 \leq \alpha \leq \alpha_{TC} \\
    m \cdot 2.5 \cdot a_g \cdot S \cdot \eta, & \text{for } \pi - \alpha_{TC} \leq \alpha \leq \pi + \alpha_{TC}
\end{cases}\]
Critical angle of incidence in LFA

Combination of the two orthogonal components using a directional combination rule, e.g. a percentage $\lambda$ combination rule:

$$u^A(\alpha) = \sqrt{\left( F(\alpha) \cdot u^A_{I,1}(\alpha) + \lambda \cdot F(\alpha + \frac{\pi}{2}) \cdot u^A_{I,1}(\alpha + \frac{\pi}{2}) \right)^2 + \left( F(\alpha) \cdot u^A_{II,1}(\alpha) + \lambda \cdot F(\alpha + \frac{\pi}{2}) \cdot u^A_{II,1}(\alpha + \frac{\pi}{2}) \right)^2}$$

or the SRSS:

$$u^A(\alpha) = \sqrt{\left[ F(\alpha) \cdot u^A_{I,1}(\alpha) \right]^2 + \left[ F(\alpha + \frac{\pi}{2}) \cdot u^A_{I,1}(\alpha + \frac{\pi}{2}) \right]^2 + \left[ F(\alpha) \cdot u^A_{II,1}(\alpha) \right]^2 + \left[ F(\alpha + \frac{\pi}{2}) \cdot u^A_{II,1}(\alpha + \frac{\pi}{2}) \right]^2}$$
Critical angle of incidence in LFA

Combination of the two orthogonal components using a directional combination rule, e.g. a percentage $\lambda$ combination rule:

$$u^A(\alpha) = \sqrt{\left( F(\alpha) \cdot u_{I,1}^A(\alpha) \pm \lambda \cdot F(\alpha+\frac{\pi}{2}) \cdot u_{I,1}^A(\alpha+\frac{\pi}{2}) \right)^2 + \left( F(\alpha) \cdot u_{II,1}^A(\alpha) \pm \lambda \cdot F(\alpha+\frac{\pi}{2}) \cdot u_{II,1}^A(\alpha+\frac{\pi}{2}) \right)^2}$$

or the SRSS:

$$u^A(\alpha) = \sqrt{\left( F(\alpha) \cdot u_{I,1}^A(\alpha) \right)^2 + \left( F(\alpha+\frac{\pi}{2}) \cdot u_{I,1}^A(\alpha+\frac{\pi}{2}) \right)^2 + \left( F(\alpha) \cdot u_{II,1}^A(\alpha) \right)^2 + \left( F(\alpha+\frac{\pi}{2}) \cdot u_{II,1}^A(\alpha+\frac{\pi}{2}) \right)^2}$$

Maximize to get the critical angle:

$$\frac{du^A(\alpha)}{d\alpha} = 0 \quad \Rightarrow \quad \alpha_{crit}$$
Problems integrating the critical angle

- **Practical**
  - ✓ EDP
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Inexistent techniques to predict the critical angle.

Analytical procedure proposed for LFA.

Unique demand parameter able to characterize the global response of the structure:

Proposed framework to define a global demand parameter.
Global structural 3D response: Preliminary results

- Definition of one demand parameter able to describe the average global response: **Initial approach**
  
  ✓ Proposed parameter: drift of the Centre of Mass, $dr_{CM}$
  ✓ Global response: Average drift of all columns, $dr_{ave}$
  ✓ Hypothesis: Both response parameters attain their maximum value for the same angle of seismic incidence, $\theta_{dr_{CM}=\max} = \theta_{dr_{ave}=\max}$
Global structural 3D response: Preliminary results

- Structures analyzed (plasticity lumped at member ends)

<table>
<thead>
<tr>
<th>Structure No</th>
<th>Height (m)</th>
<th>Columns (cm)</th>
<th>Beams (cm)</th>
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</thead>
<tbody>
<tr>
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<td>25×50</td>
</tr>
<tr>
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<td>25×50</td>
</tr>
<tr>
<td>3</td>
<td>4.0</td>
<td>25×50</td>
<td>25×40</td>
</tr>
<tr>
<td>4</td>
<td>4.0</td>
<td>25×25, 25×40</td>
<td>25×50</td>
</tr>
<tr>
<td>5</td>
<td>4.0</td>
<td>40×40</td>
<td>25×60</td>
</tr>
</tbody>
</table>
Global structural 3D response: Preliminary results
Global structural 3D response: revised approach

- Definition of one demand parameter able to describe the average global response: **revised approach being proposed**.

  ✓ Proposed parameter: **the interstorey drift** remains the main suspect for the global demand parameter.

  ✓ Global demand: in terms of **structural losses**.

  ✓ Hypothesis: Definition of a point where the **structural loss**, quantified based on its **drift**, is correlated to the total **structural loss**.

**How:**

- Determination of structural loss of a storey using an element-based approach based on **chord rotation – loss functions** (Haselton et al., 2008).

- Structural loss of a storey using **empirical EDP – loss functions** (Ramirez & Miranda, 2009).
Seismic safety assessment of 3D structures integrating the critical angle

- **Practical**
  - Procedures to determine the **critical angle** of incidence of a **response parameter**.  
  - e.g. methodology proposed for LFA.

- **Conceptual**
  - Definition of a **response parameter** able to describe **global structural performance**.  
  - e.g. interstorey drift expressing total structural loss.

Maximizing the **global response parameter** with respect to the **angle of incidence** in order to obtain the **total critical structural response**.