Modelling and Analysis

(Chapter 4 of EC8-1)

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Accelerograms
Hysteretic behaviour

STEEL

REINFORCED CONCRETE

MASONRY

PRESTRESSED CONCRETE
“Philosophy” of seismic design

PERFORMANCE STATE

operational  safe  near collapse

frequent
R=95 years
41% in 50 years

design
R=475 years
10% in 50 years

max.considered

EARTHQUAKE

PERFORMANCE STATE

operational  safe  near collapse

frequent
R=95 years
41% in 50 years

design
R=475 years
10% in 50 years

max.considered
Performance states

Base Shear Demand

Very rare events (2%/50yrs)
Rare events (10%/50yrs)
Occasional events (20%/50yrs)
Frequent events (50%/50yrs)

Lateral Deformation

PEER
Everything should be made as simple as possible, but not simpler

Albert Einstein
Scope

- EC8-1, Chapter 4, Overview and comments
  - 4.2 Characteristics of earthquake resistant buildings
  - 4.3 Structural analysis
  - 4.4 Safety verifications

- Test building
  - Modelling
  - Analysis

- Code designed versus old buildings
Basic principles of conceptual design

- Structural simplicity
- Uniformity, symmetry and redundancy
- Bi-directional resistance and stiffness
- Torsional resistance and stiffness
- Diaphragmatic behaviour at storey level
- Adequate foundation
L’Aquila 2009
L’Aquila 2009
Kobe 1995                   Izmit 1999
Kobe 1995
Chile 2010
Kobe 2010
L’Aquila 2009
Montenegro 1979
Kobe 1995
Montenegro 1979
Primary seismic members

- Members considered as part of the structural system that resists the seismic action, modelled in the analysis for the seismic design situation and fully designed and detailed for earthquake resistance in accordance with the rules of EN 1998
Members which are not considered as part of the seismic action resisting system and whose strength and stiffness against seismic actions is neglected
## Structural (ir)regularity

**Table 4.1: Consequences of structural regularity on seismic analysis and design**

<table>
<thead>
<tr>
<th>Regularity</th>
<th>Allowed Simplification</th>
<th>Linear-elastic Analysis</th>
<th>Behaviour factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan</td>
<td>Elevation</td>
<td>Model</td>
<td>(for linear analysis)</td>
</tr>
<tr>
<td>Yes</td>
<td>Yes</td>
<td>Planar</td>
<td>Lateral force(^a)</td>
</tr>
<tr>
<td>Yes</td>
<td>No</td>
<td>Planar</td>
<td>Modal</td>
</tr>
<tr>
<td>No</td>
<td>Yes</td>
<td>Spatial(^b)</td>
<td>Lateral force(^a)</td>
</tr>
<tr>
<td>No</td>
<td>No</td>
<td>Spatial</td>
<td>Modal</td>
</tr>
</tbody>
</table>

\(^a\) If the condition of 4.3.3.2.1(2)a is also met.

\(^b\) Under the specific conditions given in 4.3.3.1(8) a separate planar model may be used in each horizontal direction, in accordance with 4.3.3.1(8).
Regularity

- Regularity in plan
  - Symmetry
  - Compact plan configuration
  - Adequate in-plan stiffness of the floors
  - Small in-plan slenderness
  - Adequate torsional stiffness

- Regularity in elevation
  - No interruption of lateral load resisting systems in elevation
  - No abrupt changes of stiffness, mass and overstrength
  - Limitations of setbacks
Torsional flexibility

\[ T_\phi \geq T_x \quad \text{and/or} \quad T_\phi \geq T_y \]
\[ r_x \geq l_s \quad \text{and/or} \quad r_y \geq l_s \]
## Importance classes

### Table 4.3 Importance classes for buildings

<table>
<thead>
<tr>
<th>Importance class</th>
<th>Buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>I $\gamma_i = 0.8$</td>
<td>Buildings of minor importance for public safety, e.g. agricultural buildings, etc.</td>
</tr>
<tr>
<td>II $\gamma_i = 1.0$</td>
<td>Ordinary buildings, not belonging in the other categories.</td>
</tr>
<tr>
<td>III $\gamma_i = 1.2$</td>
<td>Buildings whose seismic resistance is of importance in view of the consequences associated with a collapse, e.g. schools, assembly halls, cultural institutions etc.</td>
</tr>
<tr>
<td>IV $\gamma_i = 1.4$</td>
<td>Buildings whose integrity during earthquakes is of vital importance for civil protection, e.g. hospitals, fire stations, power plants, etc.</td>
</tr>
</tbody>
</table>
## Importance factor

<table>
<thead>
<tr>
<th>Importance factor</th>
<th>Return period T (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>230</td>
</tr>
<tr>
<td>1.0</td>
<td>475</td>
</tr>
<tr>
<td>1.2</td>
<td>780</td>
</tr>
<tr>
<td>1.3</td>
<td>1000</td>
</tr>
<tr>
<td>1.4</td>
<td>1250</td>
</tr>
</tbody>
</table>

*(based on data for Slovenia)*
Combination of loads (EC0)

\[
\sum_{j \geq 1} G_{k,j} \hspace{1em} ^{+} \hspace{1em} P \hspace{1em} ^{+} \hspace{1em} A_{E,d} \hspace{1em} ^{+} \hspace{1em} \sum_{i \geq 1} \Psi_{2,i} Q_{k,i}
\]

- Permanent loads “G”
- Prestressing loads “P”
- Seismic loads “A”
- Variable – live loads “Q” (factor \( \Psi_2 \) in EC1)
Determination of masses

\[ \sum G_{kj} + \sum \psi_{Ei} \cdot Q_{ki} \]

\[ \psi_{Ei} = \varphi \cdot \psi_{2i} \]

Table 4.2: Values of \( \varphi \) for calculating \( \psi_{Ei} \)

<table>
<thead>
<tr>
<th>Type of variable action</th>
<th>Storey</th>
<th>( \varphi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Categories A-C*</td>
<td>Roof</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Storeys with correlated occupancies</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Independently occupied storeys</td>
<td>0.5</td>
</tr>
<tr>
<td>Categories D-F* and Archives</td>
<td></td>
<td>1.0</td>
</tr>
</tbody>
</table>

* Categories as defined in EN 1991-1-1:2002.
Pseudo 3D model
Cracked sections

- In **concrete** buildings, in **composite steel-concrete** buildings and in **masonry** buildings the stiffness of the load bearing elements should take into account the **effect of cracking** (Secant stiffness to the initiation of yielding of the reinforcement).

- The elastic flexural and shear stiffness properties of concrete and masonry elements may be taken to be equal to **one-half** of the corresponding **stiffness** of the uncracked elements.
Cracked sections

\[ T_{cr} = T \sqrt{2} \]
Accidental eccentricity

\[ e_{ai} = \pm 0.05 \, L_i \]

\( L_i \) is the floor-dimension perpendicular to the direction of the seismic action
# Methods of analysis

<table>
<thead>
<tr>
<th></th>
<th>STATIC (^{a})</th>
<th>DYNAMIC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LINEAR</strong> (^{b})</td>
<td>Lateral force method</td>
<td>Modal response spectrum analysis</td>
</tr>
<tr>
<td><strong>NONLINEAR</strong></td>
<td>Nonlinear static (pushover) analysis</td>
<td>Nonlinear response-history analysis</td>
</tr>
</tbody>
</table>

![Graph](image)

- \(^{a}\) combined with response spectrum
- \(^{b}\) combined with behaviour factor
Behaviour factor

- Factor used for design purposes to reduce the forces obtained from a linear analysis, in order to account for the non-linear response of a structure, associated with the material, the structural system and the design procedures
Behaviour factor - background

\[ R_\mu = \frac{F_e}{F_y} = \frac{D}{D_y} = \mu \]

\[ R_s = \frac{F_y}{F_d} \]

\[ R = \frac{F_e}{F_d} = R_\mu \cdot R_s \]

Eurocode 8

\[ R \equiv q, \quad R_s > \frac{\alpha_u}{\alpha_1} \]
Ductility classes

\[ F = \begin{cases} F_e & \text{for } F_{y1} \\ F_{y2} & \text{for } F_{y2} \\ DCM & \text{for } D \\ DCH & \text{for } D \\ D_y1 & \text{for } D_y1 \\ D_y2 & \text{for } D_y2 \\ D & \text{for } D \end{cases} \]
# Behaviour factor

Table 5.1: Basic value of the behaviour factor, $q_0$, for systems regular in elevation

<table>
<thead>
<tr>
<th>STRUCTURAL TYPE</th>
<th>DCM</th>
<th>DCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame system, dual system, coupled wall system</td>
<td>$3.0 \alpha_0 / \alpha_1$</td>
<td>$4.5 \alpha_0 / \alpha_1$</td>
</tr>
<tr>
<td>Uncoupled wall system</td>
<td>$3.0$</td>
<td>$4.0 \alpha_0 / \alpha_1$</td>
</tr>
<tr>
<td>Torsionally flexible system</td>
<td>$2.0$</td>
<td>$3.0$</td>
</tr>
<tr>
<td>Inverted pendulum system</td>
<td>$1.5$</td>
<td>$2.0$</td>
</tr>
</tbody>
</table>

(3) For buildings which are not regular in elevation, the value of $q_0$ should be reduced by 20% (see 4.2.3.1(7) and Table 4.1).
Overstrength factor = \( \alpha_u / \alpha_1 \)
Montenegro 1979
Kobe 1995
Overstrength factor

- **Wall- or wall-equivalent dual systems**
  - wall systems with only two uncoupled walls per horizontal direction: $\alpha_u / \alpha_1 = 1,0$
  - other uncoupled wall systems: $\alpha_u / \alpha_1 = 1,1$
  - wall-equivalent dual, or coupled wall systems: $\alpha_u / \alpha_1 = 1,2$

- Irregular in plan: reduced values
- Pushover analysis: increased values
Lateral force method

- Regular structures with small influence of higher modes
  - $T_1 \leq 4 \, T_C$  or  $T_1 \leq 2.0 \, s$

$$F_b = S_d(T_1) \cdot m \cdot \lambda$$
Lateral force method

- Approximate formulas for the period $T_1$

- Distribution of horizontal forces

$$F_i = F_b \cdot \frac{s_i \cdot m_i}{\sum s_j \cdot m_j} \quad \text{or} \quad F_i = F_b \cdot \frac{z_i \cdot m_i}{\sum z_j \cdot m_j}$$

- Accidental eccentricity

$$\delta = 1 + 1,2 \left( \frac{x}{L_e} \right)$$
Approximate formulas for $T_1$

Rayleigh

$$T_1 = 2\pi \sqrt{\frac{\sum_{j} u_j^2 m_j}{\sum_{j} u_j p_j}}$$

Empirical formula

$$T_1 = C_t H^{3/4}$$
Modal response spectrum analysis

Displacements:

\[ U_{i,\text{max}} = \Phi_i \Gamma_i S_{Di} = \Phi_i \Gamma_i \frac{T_i^2}{4\pi^2} S_{Ai} \]

Forces:

\[ F_i = M \Phi_i \Gamma_i S_{ai} \]

\[ \Gamma_i = \frac{L_i}{M_i} \]

\[ L_i = \Phi_i^T M s \]

\[ M_i = \Phi_i^T M \Phi_i \]
The response of all modes of vibration contributing significantly to the global response shall be taken into account

- the sum of the effective modal masses amounts to at least 90% of the total mass of the structure
- all modes with effective modal masses greater than 5% of the total mass are taken into account
Effective masses

\[ m_i^* = \frac{L_i^2}{M_i} \]

\[ L_i = \Phi_i^T M s \quad M_i = \Phi_i^T M \Phi_i \]

\[ \sum_{i=1}^{n} m_i^* = \sum_{j=1}^{m} m_j = M \]
Combination of modal responses

\[ E_E = \sqrt{\sum E_{Ei}^2} \quad \text{(SRSS)} \]

if \( T_j \leq 0.9 T_i \)

Otherwise more accurate procedure, such as \( \text{CQC} \)
Accidental eccentricity

Accidental torsional effects

\[ M_{X,i} = F_{X,i} \cdot 0.05L_{Y,i}, \quad M_{Y,i} = F_{Y,i} \cdot 0.05L_{X,i} \]
Pushover analysis

- N2 method (basic)
  - Target displacement: Annex B (informative)

- Extended N2
  - Higher mode effects in plan and elevation
  - Complies with the EC8-3 requirement “4.4.4.5 Procedure for estimation of torsional and higher mode effects”
Combination of effects of components

SRSS

\[ E_{Edx} + 0,30E_{Edy} \]

\[ 0,30E_{Edx} + E_{Edy} \]
If $a_{vg}$ is greater than 0,25 g (2,5 m/s²) the vertical component of the seismic action should be taken into account

- for horizontal or nearly horizontal structural members spanning 20 m or more
- for horizontal or nearly horizontal cantilever components longer than 5 m
- for horizontal or nearly horizontal pre-stressed components
- for beams supporting columns
- in base-isolated structures
**Displacement calculation**

$$d_s = q_d d_e$$

- $d_s$ displacement induced by the design seismic action
- $q_d$ behaviour factor for displacements ($q_d = q$, unless otherwise specified)
- $d_e$ displacement determined by a linear analysis based on the design response spectrum

**Upper limit**: value from the elastic displacement spectrum

Torsional effect are taken into account
Actual displacements

\[ q = \frac{F_e}{F_d} \]

\[ D = q \ D_d \]
Non-structural element

- Architectural, mechanical or electrical element, system and component which, whether due to lack of strength or to the way it is connected to the structure, is not considered in the seismic design as load carrying element
Non-structural elements

- For non-structural elements of great importance or of a particularly dangerous nature
  - Floor-response spectra

- For other non-structural elements
  - Simplified procedure
Non-structural elements

Simplified analysis

\[ F_a = \left( S_a \cdot W_a \cdot \gamma_a \right) / q_a \]

\[ S_a = \alpha \cdot S \cdot \left[ 3 \left( 1 + z/H \right) / \left( 1 + \left( 1 - T_a/T_1 \right)^2 \right) - 0.5 \right] \]

- \( W_a \) weight of the element
- \( \gamma_a \) importance factor for the element
- \( q_a \) behaviour factor for the element
Floor acceleration spectrum (simplified)

Normalized floor acceleration spectrum

\[ \frac{S_a}{a_gS} \]

\( \left\{ \begin{array}{l} \frac{z}{H} = 1.0 \\ \frac{z}{H} = 0.5 \\ \frac{z}{H} = 0 \end{array} \right. \)

\( H \) total height, \( T_a \) period of the element, \( T_1 \) period of the structure

\( q_a = 1, \gamma_a = 1, \)
Additiona l measures for masonry infilled frames

- Provisions apply to frame or frame equivalent dual concrete systems of DCH and to steel or steel-concrete composite moment resisting frames of DCH with interacting non-engineered masonry infills
  - Recommendation: adopt also for DCM or DCL concrete, steel or composite structures with masonry infills

- Irregularities in elevation

- Irregularities in plan

- Damage limitation of infills
Friuli 1976
Safety verifications (1) - Ultimate limit state

Resistance condition

\[ E_d \leq R_d \]

\( E_d \) demand, \( R_d \) capacity

\( P-\Delta \) effects need not be taken into account if

\[ \theta = \frac{P_{\text{tot}} \cdot d_r}{V_{\text{tot}} \cdot h} \leq 0.10 \]
Safety verifications (2)

- Global and local ductility condition
  - Specific material related requirements shall be satisfied, including, when indicated, capacity design provisions
  - Prevention of storey mechanisms

\[ \sum M_{Rc} \geq 1.3 \sum M_{Rb} \]
Capacity design

YES !

NO !
Capacity design
Kobe 1995
Kobe 1995
Kobe 1995
Safety verifications (3)

- Equilibrium condition
- Resistance of horizontal diaphragms
- Resistance of foundations
- Seismic joint condition
Damage limitation state

Limitation of interstorey drift

• non-structural elements of brittle materials
  \[ d_r \nu \leq 0.005 \text{ h}, \quad d_r \leq 0.01 \text{h} \]

• ductile non-structural elements
  \[ d_r \nu \leq 0.0075 \text{ h} \]

• non-structural elements do not to interfere with structural deformations, or without non-structural elements
  \[ d_r \nu \leq 0.010 \text{ h} \quad d_r \leq 0.02 \text{h} \]

\[ \nu = 0.4 \text{ (importance classes III and IV)} \]
\[ \nu = 0.5 \text{ (importance classes I in II)} \]
Return period *versus* (importance) factor

Valid for Slovenia
Test example

RC building
6 stories + 2 basements
Description of building
Description of building

TYPICAL PLAN

Diagram of a typical plan of a building showing the layout of rooms and corridors.
Description of building

BASEMENT

[Diagram showing building layout with dimensions and labels]
ELASTIC RESPONSE SPECTRUM

- \( a_g = \gamma_I \cdot a_{gR} = 0.25g \)
  - importance class II (\( \gamma_I = 1.0 \))
- Soil B, Type 1
  - \( S = 1.2 \)
  - \( T_B = 0.15 \text{s}, T_C = 0.5 \text{s}, T_D = 2.0 \text{s} \)
- Damping 5%
Vertical actions

- **Permanent loads “G”**
  - self weight of the structure + 2 kN/m²

- **Variable – live loads “Q”**
  - office building (category B) ⇒ 2 kN/m²

- Vertical loads (G, Q) were distributed to the elements
Seismic masses (1)

- Masses from permanent loads “G” ⇒ factor 1.0
- Masses from live loads “Q” ⇒ factor $\Psi_{Ei}$

$$\Psi_{Ei} = \varphi \cdot \Psi_{2i}$$

- factor $\varphi = 1.0$ (roof storey), $\varphi = 0.5$ (other)
- factor $\Psi_{2i} = 0.3$ (category B)
- 15% (30%) mass from Q is taken into account
## Seismic masses (2)

*Only masses above level 0 are taken into account*

<table>
<thead>
<tr>
<th>Level</th>
<th>Storey mass ( m ) (ton)</th>
<th>Moment of inertia MMI (ton( \cdot )m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROOF</td>
<td>372</td>
<td>33951</td>
</tr>
<tr>
<td>5</td>
<td>396</td>
<td>36128</td>
</tr>
<tr>
<td>4</td>
<td>396</td>
<td>36128</td>
</tr>
<tr>
<td>3</td>
<td>396</td>
<td>36128</td>
</tr>
<tr>
<td>2</td>
<td>396</td>
<td>36128</td>
</tr>
<tr>
<td>1</td>
<td>408</td>
<td>37244</td>
</tr>
<tr>
<td>( \Sigma = )</td>
<td>( 2362 ) ton</td>
<td></td>
</tr>
</tbody>
</table>

\[
MI = m \cdot I_s^2 = m \cdot \frac{l^2 + b^2}{12}
\]
Structural model – general (1)

- 3D (spatial) model
- All element are modelled as line elements
  - peripheral walls are modelled with line elements and a rigid beam at the top of the each element
- Effective widths of beams (EC2)
- Rigid offsets are not taken into account
  - Infinitely stiff elements are used only in relation to walls W1 and W2
- Rigid diaphragms at each floor
  - slabs are not modelled
Structural model – general (2)

- Masses and mass moments of inertia are lumped at centres of masses
  - Only masses above the top of the peripheral walls are taken into account
- Cracked elements are considered
  - 0.5*As, 0.5*I, 0.1*It
- All elements are fully fixed in foundation
- Infills are not considered
Structural model – general (3)
Structural model – effective width EC2

Level -1 and 0

Level 1, 2, 3, 4, 5, Roof

BINT1
BINT2

BEXT1
BINT1
BINT2
BEXT2

BINT1

\[ l_o = 0.7 \times 7 = 4.9 \, \text{m} \]

\[ l_o = 0.7 \times 6 = 4.2 \, \text{m} \]

BINT2

BEXT1

\[ l_o = 0.7 \times (7-2) = 3.5 \, \text{m} \]

BEXT2

\[ l_o = 0.7 \times 6 = 4.2 \, \text{m} \]
Structural model – peripheral walls

Assumed effective width

Direction Y
WB2* (21/0.3 m)

Direction X
WB1* (30/0.3 m)
Structural regularity

- Criteria for regularity in elevation

- Criteria for regularity in plan

1) Slenderness $\lambda = \frac{L_{\text{max}}}{L_{\text{min}}} < 4$

2) Eccentricity $< 30\%$ * torsional radius

3) Torsional radius $< \text{radius of gyration}$

**Direction X:** $e_{0X} \leq 0.30 \cdot r_X$

**Direction Y:** $e_{0Y} \leq 0.30 \cdot r_Y$

**Direction X:** $r_X > l_s$

**Direction Y:** $r_Y > l_s$
Structural regularity in plan

- **Structural eccentricity** $e_0$ and centre of stiffness
  - 3 static load cases in each storey ($F_{Xi} = 1$, $F_{Yi} = 1$, $M_i = 1$)
  - Loads are applied in centres of mass (CM)
  - Determine rotation $R_{Zi}$ due to $F_{Xi}$, $F_{Yi}$ and $M_i$
  - Determine $e_{0i}$ and centres of stiffness ($XCR_i$, $YCR_i$)

\[
\begin{align*}
  e_{0x,i} &= \frac{R_{Z,i} \left( F_{X,i} = 1 \right)}{R_{Z,i} \left( M_i = 1 \right)} \quad \Rightarrow \quad XCR_i = e_{0x,i} + XCM_i \\
  e_{0y,i} &= \frac{R_{Z,i} \left( F_{Y,i} = 1 \right)}{R_{Z,i} \left( M_i = 1 \right)} \quad \Rightarrow \quad YCR_i = e_{0y,i} + YCM_i
\end{align*}
\]
Torsional radius \((r_X, r_Y)\)

- 3 static load cases in each storey \((F_{TXi} = 1, F_{TYi} = 1, M_{Ti} = 1)\)
-Loads are applied in centres of stiffness (CR)
- Determine rotations \(R_{Zi} (M_{Ti})\), displacement \(U_{Xi} (F_{Xi})\) and \(U_{Yi} (F_{Yi})\)
- Determine torsional \((K_{M,i})\) and lateral stiffnesses \((K_{FX,i}, K_{FY,i})\)
- Determine \(r_{Xi}\) and \(r_{Yi}\)

\[
K_{M,i} = \frac{1}{R_{Z,i} (M_{Ti} = 1)}, \quad K_{FX,i} = \frac{1}{U_{X,i} (F_{TX,i} = 1)}, \quad K_{FY,i} = \frac{1}{U_{Y,i} (F_{TY,i} = 1)}
\]

\[
r_{X,i} = \sqrt{\frac{K_{M,i}}{K_{FY,i}}} \quad \text{and} \quad r_{Y,i} = \sqrt{\frac{K_{M,i}}{K_{FX,i}}}
\]
Structural regularity - criteria

- Criteria for regularity in elevation

- Criteria for regularity in plan

1) \[ \lambda = \frac{L_{\text{max}}}{L_{\text{min}}} < 4 \]

2) Direction X: \( e_{0x} \leq 0.30 \cdot r_x \)
   Direction Y: \( e_{0y} \leq 0.30 \cdot r_y \)

3) Direction X: \( r_x > l_s \)
   Direction Y: \( r_y > l_s \)

Structure is regular in plan and in elevation

Irregular in elevation if basement is also considered !?
Structural type of the building

- **UNCOPLED WALL SYSTEM**
  - The structural system is defined as a wall system, when 65% (or more) of the shear resistance is contributed by walls
  - Application of shear resistance is difficult
  - EC8 allows that shear resistance may be substituted by shear forces
  - **Base (above basement) shear force taken by walls amounts to 72% (direction X) and 92% (direction Y) of the total shear force**

Dual wall equivalent system?
Behaviour factor $q$

- Structural type: **uncoupled wall system**
- Ductility class: **DCM**
  
  $$q_0 = 3.0$$

- Structural (ir)regularity: **regular in elevation** - no reduction $q_0$
- Factor associated with prevailing failure mode: $k_w = 1$
  
  $$q = k_w \cdot q_0 = 3.0$$
### Periods, effective masses and modal shapes (1)

<table>
<thead>
<tr>
<th>Mode</th>
<th>T (sec)</th>
<th>$M_{\text{eff,UX}}$ (%)</th>
<th>$M_{\text{eff,UY}}$ (%)</th>
<th>$M_{\text{eff,MZ}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.92</td>
<td>80.2</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>0.68</td>
<td>0.0</td>
<td>76.3</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>0.51</td>
<td>0.2</td>
<td>0.0</td>
<td>75.2</td>
</tr>
<tr>
<td>4</td>
<td>0.22</td>
<td>15.0</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>5</td>
<td>0.15</td>
<td>0.0</td>
<td>18.5</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>0.12</td>
<td>0.2</td>
<td>0.0</td>
<td>17.6</td>
</tr>
</tbody>
</table>

$$\sum M_{\text{eff}} = 95.7 \quad 94.7 \quad 93.1$$

**ETABS program**

1. Mode (predominantly translational in direction X)
2. Mode (translational in direction Y)
3. Mode (predominantly torsional)
1. MODE – predominantly translational in X direction
Periods, effective masses and modal shapes (3)

2. MODE – translational in Y direction
Periods, effective masses and modal shapes (4)

3. MODE – predominantly torsional
Modal response spectrum analysis RSA

- Modal response spectrum analysis was performed independently for the ground excitation in two horizontal direction
- Combination of different modes – CQC
- Combination of results in two directions – SRSS
- Design spectrum was used
- Accidental eccentricity was taken into account
- Seismic design situation
Accidental torsional effects

- Results of analysis without accidental torsion (SSRS of two horizontal directions) + envelope of accidental torsional effects
  \[
  \text{SRSS} \ (E_x, E_y) + \text{ENVE}(\pm M_x, \pm M_y)
  \]

- Results of analysis without accidental torsion + accidental torsional effects, for each horizontal direction. SRSS combination of two horizontal directions
  \[
  \text{SRSS} \ (E_x \pm M_x, E_y \pm M_y)
  \]
RSA – Accidental torsional effects

**Add. torsional effects**

- **SRSS** (EX,EY) + ENVE(±MX,±MY)
- **SRSS** (EX±MX, EY±MY)
- **Without**
RSA – shear forces

Direction X

- Roof: 848
- L5: 1440
- L4: 1849
- L3: 2183
- L2: 2473
- L1: 2693
- L0: 2693
- L-1: 2693
- L-2: 2693

12% of the total weight

Direction Y

- Roof: 1094
- L5: 1882
- L4: 2444
- L3: 2882
- L2: 3223
- L1: 3452
- L0: 3452
- L-1: 3452
- L-2: 3452

15% of the total weight
RSA - displacements

Direction X

Storey

L2
L3
L4
L5
Roof

Displacements (m)

L-2
L-1
L0
0.03 0.06 0.09 0.12 0.15

Direction Y

Displacements (m)

L2
L3
L4
L5
Roof

L-2
L-1
L0
0.03 0.06 0.09 0.12 0.15

CM
Average
RSA – Damage limitations

Direction X

Direction Y

\( \alpha / \gamma = 0.005 / 0.5 = 1\% \)

\( \alpha / \gamma = 0.0075 / 0.5 = 1.5\% \)

\( \alpha / \gamma = 0.01 / 0.5 = 2\% \)
RSA – second order effects

Direction X

Direction Y

Storey

Sensitivity coefficient $\theta$

$\theta = 0.1$
Force distribution

Direction X

Lateral force method
Force distribution

Direction Y

\[ 2x \]

Lateral force method
Shear forces

Direction X

Lateral force method
Shear forces

Direction Y

Lateral force method
Code designed versus old buildings

SPEAR BUILDING
Pushover curves

- **Test**
- **EC8 H**

![Graph showing pushover curves with labels for different forces and yield points, including 
\( \mu = 6.5 \) and \( \mu = 3.2 \).]
Determination of seismic capacity (NC)

- Test
- EC8 H
Probability of “failure”

\[ PGA_{475} = 0.25 \text{ g} \times 1.15 = 0.29 \text{ g} \quad \text{(seismic hazard map, soil type C)} \]

\[ PGA_c = 0.25 \text{ g} \quad \text{(test building),} \quad PGA_c = 0.77 \text{ g} \quad \text{(EC8 building)} \]

\[ P_{NC} = 0.78 \times 10^{-2} \quad \text{or 32\% in 50 years} \quad \text{(test building)} \]

\[ P_{NC} = 2.67 \times 10^{-4} \quad \text{or 1.3\% in 50 years} \quad \text{(EC8 building)} \]
Discussion of results

\[ \text{PGA}_C = 0.77 \text{ g} \]

“The code is too conservative!?”

\[ P_{NC,50} = 1.3 \% \]

“The probability is too high!?”

How high is the tolerable probability?
How safe is safe enough?