ANALYSIS OF CONCRETE BUILDINGS FOR SEISMIC DESIGN

CONCRETE & MASONRY BUILDINGS

- Use yield-point stiffness in the analysis (EC8-Part 1: 50% of uncracked section EI):
  - Reduction in design seismic forces vis-a-vis use of full section EI
  - Increase of displacements for drift-control & P-Δ effects (governs sizes of frame members).

ANALYSIS METHODS

(& CORRESPONDING MEMBER VERIFICATION CRITERIA)

- Reference method:

  Linear modal response spectrum procedure, with elastic spectrum reduced by (behaviour-factor) q:
  - Applicable in all cases, except in base-isolated structures w/ (strongly) nonlinear isolation devices.
- If building heightwise regular & higher-modes unimportant ($T<4T_c$, $T<2s$):

  (Linear) Lateral force procedure, emulating response-spectrum method:
  - T from mechanics (Rayleigh); forces reduced by 15% if >2 storeys & $T<2T_c$
- Nonlinear analysis, static (pushover) or dynamic (t-history), for:
  - Evaluation of system overstrength factor, a_u/a_1, in redundant systems;
  - Performance evaluation of existing or retrofitted buildings;
  - Design with direct check of deformations of ductile members, w/o q-factor.
- Member verification at the ULS (for “Life-Safety” EQ):
  - In terms of forces (resistances), except:
  - If nonlinear analysis: ductile failure modes checked in terms of deformations

EC8-Part 1: REGULARITY OF BUILDINGS IN ELEVATION
(FOR APPLICABILITY OF LATERAL FORCE PROCEDURE)

- Qualitative criteria, can be checked w/o calculations:
- Structural systems (walls, frames, bracing systems): *continuous to the top (of corresponding part)*.
- Storey *K* & *m*: *constant or gradually decreasing to the top*.
- Individual floor setbacks on each side: < *10% of underlying storey.*
- Unsymmetric setbacks: < *30% of base in total.*
- Single setback at lower 15% of building: < *50% of base.*
- In frames (incl. infilled): *smooth distribution of storey overstrength.*

- (Heightwise irregular buildings: q-factor reduced by 20%)

EC8-Part 1: REGULARITY OF BUILDINGS IN PLAN
(FOR ANALYSIS OF TWO SEPARATE PLANAR/2D MODELS)

Criteria can be checked before any analysis:

- *K* & *m* ~ symmetric w.r.to two orthogonal axes.
- Rigid floors.
- Plan configuration compact, w/ aspect ratio ≤ 4;
  any recess from convex polygonal envelope: < 5% of floor area.
- In both horizontal directions:
  - r *(torsional radius of struct. system)* $\geq l_s$ *(radius of gyration of floor plan)*:
    Translational fundamental T(s) > torsional.
  - e_o *(eccentricity between floor C.S. & C.M.)* $\leq 0.3\,r$:
    Conservative bound to satisfactory performance (element ductility demands ~ same as in torsionally balanced structure).

Alternative for buildings $\leq$ 10m tall:

- In both horizontal directions: $r^2 \geq l_s^2 + e_o^2$

LINEAR ANALYSIS FOR DESIGN SEISMIC ACTION –
ULS MEMBER VERIFICATION - COMPLIANCE CRITERIA FOR LIFE SAFETY

- Reference approach:

Force-based design with linear analysis:

- Linear modal response spectrum analysis, with design response spectrum (elastic spectrum reduced by behaviour-factor q):
  - Applies always (except in seismic isolation with very nonlinear devices)
- If:
  - the building is regular in elevation &
  - higher modes are unimportant

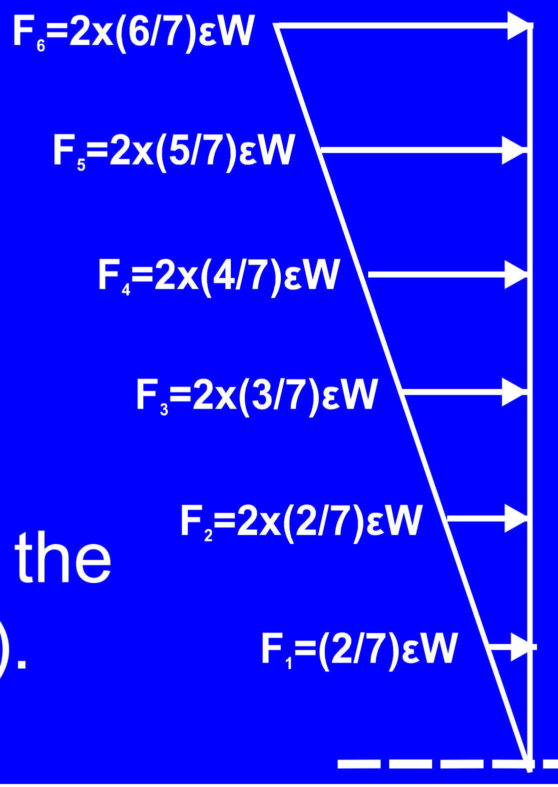
    (fundamental T <4T_c & <2sec, T_C: T at end of constant spectral acceleration plateau):

(linear) Lateral force procedure emulating response-spectrum method:
  - T from mechanics (Rayleigh quotient);
  - Reduction of forces by 15% if >2 storeys & T<2T_c

– Member verification at the Ultimate Limit State (ULS) for "Life-Safety" EQ in terms of forces (resistances)

LINEAR ANALYSIS FOR DESIGN SEISMIC ACTION *Cont'd*

- Reference approach is modal response spectrum analysis, with design spectrum:
  - Number of modes taken into account:
    - All those with modal mass ≥ 5% of total mass in one of the directions of application of the seismic action;
    - Sufficient to collectively account for ≥ 90% of total mass in each direction of application of the seismic action.
  - Combination of modal responses:
    - CQC (Complete Quadratic Combination);
    - SRSS (Square-Root-of-Sum-of-Squares) if ratio of successive modal periods < 0.9 & > 1/0.9.
- Lateral force procedure:
  - Static lateral forces on storey or nodal masses proportional to the mass times its distance from the base (inverted triangular heightwise distribution).



EC8-PART 1: FOR ALL MATERIALS:

- "Secondary seismic elements":
  - Their contribution to resistance & stiffness for seismic actions neglected in design (& in linear analysis model too);
  - Required to remain elastic under deformations imposed by the design seismic action.
  - Designer is free to assign elements to the class of "secondary seismic elements", provided that:
    - Their total contribution to lateral stiffness ≤ 15% of that of "primary seismic elements";
    - Regularity classification does not change.
  - Option convenient for elements outside EC8's scope (eg, prestressed elements, flat slab frames, etc).

ANALYSIS FOR ACCIDENTAL TORSION

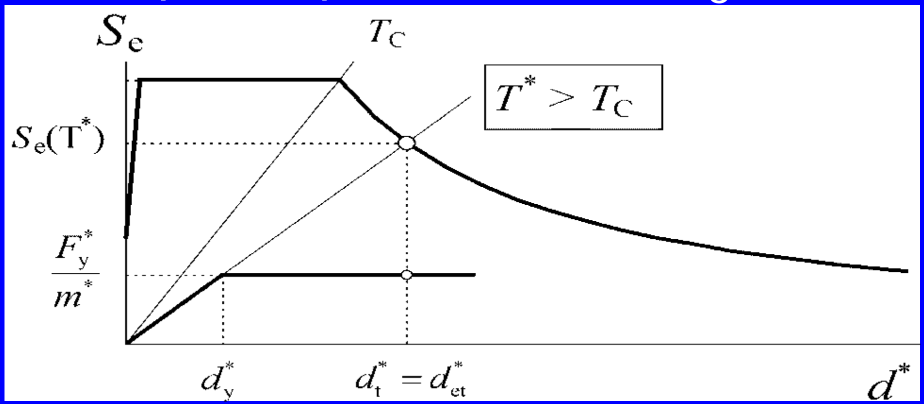
- Accidental displacement of masses in the direction normal to the horizontal seismic action component, by:
  - $e_i = \pm 0.05L_i$ ($\pm 0.1L_i$ if there are irregular-in-plan masonry infills), where L_i : plan dimension normal to the horizontal seismic action component and parallel to e_i
- Taken into account by means of:
  1. Linear static analysis under torques (w.r.to vertical axis) on storey or nodal masses equal to the storey or nodal forces of the lateral force procedure, times $e_i = 0.05L_i$ (same sign at all storeys or nodes)
  2. Superposition of the action effects due to the analysis in 1, to the seismic action effects due to the horizontal seismic action components w/o the accidental eccentricity (from lateral force or modal response spectrum procedure), with the same sign as the seismic action effect due to the horizontal seismic action component.

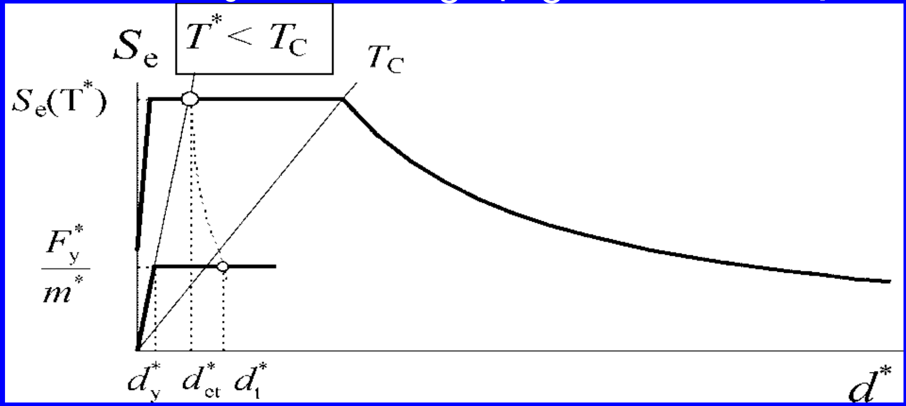
2^{nd}-ORDER (P-Δ) EFFECTS IN ANALYSIS

- 2^{nd}-order effects taken into account at the storey level (index: i) through their ratio to the 1^{st}-order effects of the seismic action (in terms of storey moments): $\theta_i = N_{tot,i}\Delta\delta_i / V_i H_i$
  - $N_{tot,i}$ = total vertical load at and above storey i in seismic design situation;
  - $\Delta\delta_i$ = interstorey drift at storey i in seismic design situation, equal to that calculated from the linear analysis for the design spectrum, times the behaviour factor q ("equal displacement rule");
  - V_i = storey shear in storey i due to the design seismic action;
  - H_i = height of storey i.
- If $\theta_i \leq 0.1$ at all storeys, 2^{nd}-order effects may be neglected (this is normally the case, as indirect consequence of interstorey drift limitation under the damage-limitation seismic action);
- If $\theta_i > 0.1$ at any storey, 2^{nd}-order effects are taken into account by dividing all 1^{st}-order effects from the linear analysis by $(1-\theta_i)$;
- $\theta_i > 0.2$ at any storey (never the case, thanks to interstorey drift limit for damage-limitation seismic action): do geometrically nonlinear analysis
- Buildings designed for the seismic action are stiff enough for the 2^{nd}-order effects under gravity loads alone to be negligible.

NONLINEAR ANALYSIS FOR DESIGN SEISMIC ACTION – ULS MEMBER VERIFICATION - COMPLIANCE CRITERIA FOR LIFE SAFETY

- Allowed: Displacement-based design, w/o q-factor:
  - Nonlinear analysis, static (pushover) or dynamic (t-history)
    - Fairly detailed rules for calculation of deformation demands.
    - For pushover analysis (N2 method):
      - Target displacement from 5%-damped elastic spectrum (Vidic et al, '94):
        - equal displacement if $T>T_C$ $\mu=1+(q-1)T_c/T$, if $T<T_C$ (T_C: transition period)





  - Member verification at the ULS (for "Life-Safety" EQ) in terms of:
    - deformations in ductile members/mechanisms (no deformation limits given);
    - forces (resistances) for brittle members/mechanisms
  - Deformation capacities can be taken from National Annex or Annex A of EC8-Part 3 (Assessment & retrofit)

COMBINATION OF ACTION EFFECTS OF INDIVIDUAL SEISMIC ACTION COMPONENTS

- For linear analysis, or nonlinear static (Pushover) analysis:
  - Rigorous approach : SRSS-combination of seismic action effects EX, EY, EZ of individual components X, Y, Z: $E=\pm\sqrt{(EX^2+EY^2+EZ^2)}$
    - Very convenient for modal response spectrum analysis (single analysis for all components X, Y, Z, combination of X, Y, Z is done simultaneously with that of modal contributions).
  - Approximation:

    $$E=\pm\max(|EX|+0.3|EY|+0.3|EZ|;\ |EY|+0.3|EX|+0.3|EZ|;\ |EZ|+0.3|EX|+0.3|EY|).$$
  - In nonlinear static (Pushover) analysis, component Z is always neglected and internal forces from above combinations cannot exceed member force resistances
- For time-history nonlinear analysis:
  - Seismic action components X, Y, Z are applied simultaneously.