GENERAL PRINCIPLES FOR THE DESIGN OF CONCRETE BUILDINGS FOR EARTHQUAKE RESISTANCE

Phases in the design process for any concrete structure

- Conceptual design: Select type & layout of the lateral-load-resisting system and preliminary member sizes.
- Analysis: Calculate the effects of the design actions, including the seismic one, in terms of internal forces & deformations in structural members.
- Detailed design: Verify adequacy of member dimensions; dimension the reinforcement on the basis of the calculated action effects.
- End product of the design to be applied in the field: Material specifications, construction drawings that include the detailing of the reinforcement, and any other information that may be necessary or helpful for the implementation of the design.

Eurocode 8 – Design of structures for earthquake resistance

- EN1998-1: General rules, seismic actions and rules for buildings
- EN1998-2: Bridges
- EN1998-3: Assesment and retrofitting of buildings
- EN1998-4: Silos, tanks and pipelines
- EN1998-5: Foundations, retaining structures and geotechnical aspects
- EN1998-6: Towers, masts and chimneys

Objectives of the Eurocodes

The Member States of the EU and EFTA recognise that Eurocodes serve as reference documents for the following purposes :

→ as a means to prove compliance of building and civil engineering works with the essential requirements of Council Directive 89/106/EEC, particularly Essential Requirement N°1 – Mechanical resistance and stability – and Essential Requirement N°2 – Safety in case of fire;

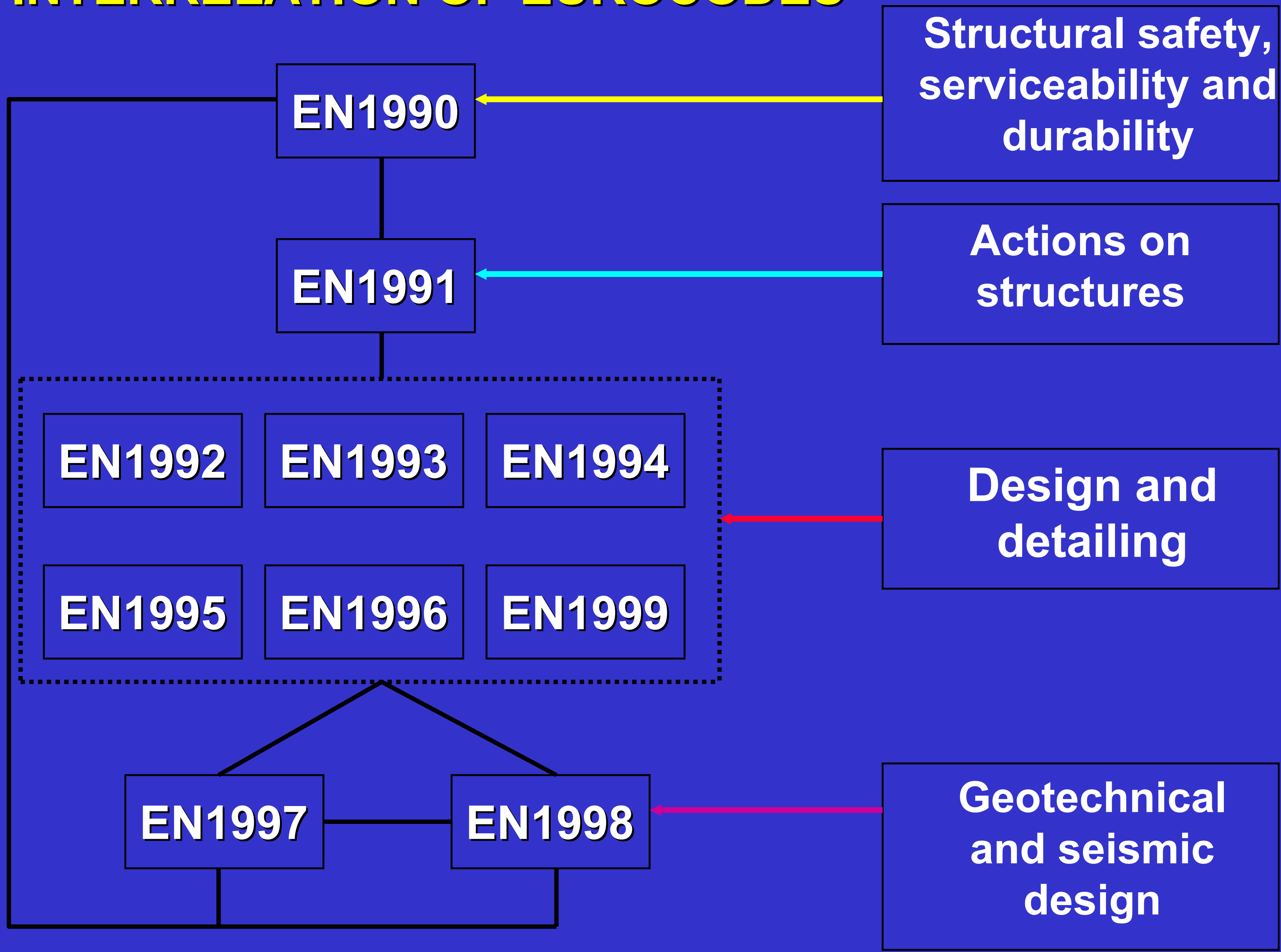
→ as a basis for specifying contracts for construction works and related engineering services;

→ as a framework for drawing up harmonised technical specifications for construction products (ENs and ETAs)

European Standards (ENs)

Design standards : The Eurocodes	
Material standards (steel, concrete, etc.) and Product standards (Structural bearings, Isolation devices, etc.)	ETAs: European Technical Approvals (FRPs, Prestressing systems, Isolation/dissipation devices, etc.)
Execution standards (e.g., standards for the execution of concrete or steel structures)	
Test standards	

INTERRELATION OF EUROCODES



IMPORTANT FEATURES OF EUROCODE-SYSTEM

- Comprehensive & integrated system covering:
  - all structural materials;
  - practically all types of construction works;
- in a consistent, harmonized & user-friendly manner

  (similar document structure, symbols, terminology, verification criteria, analysis methods, etc.),
- with hierarchy & cross-referencing among different ECs & EC-parts
- w/o overlapping & duplication.

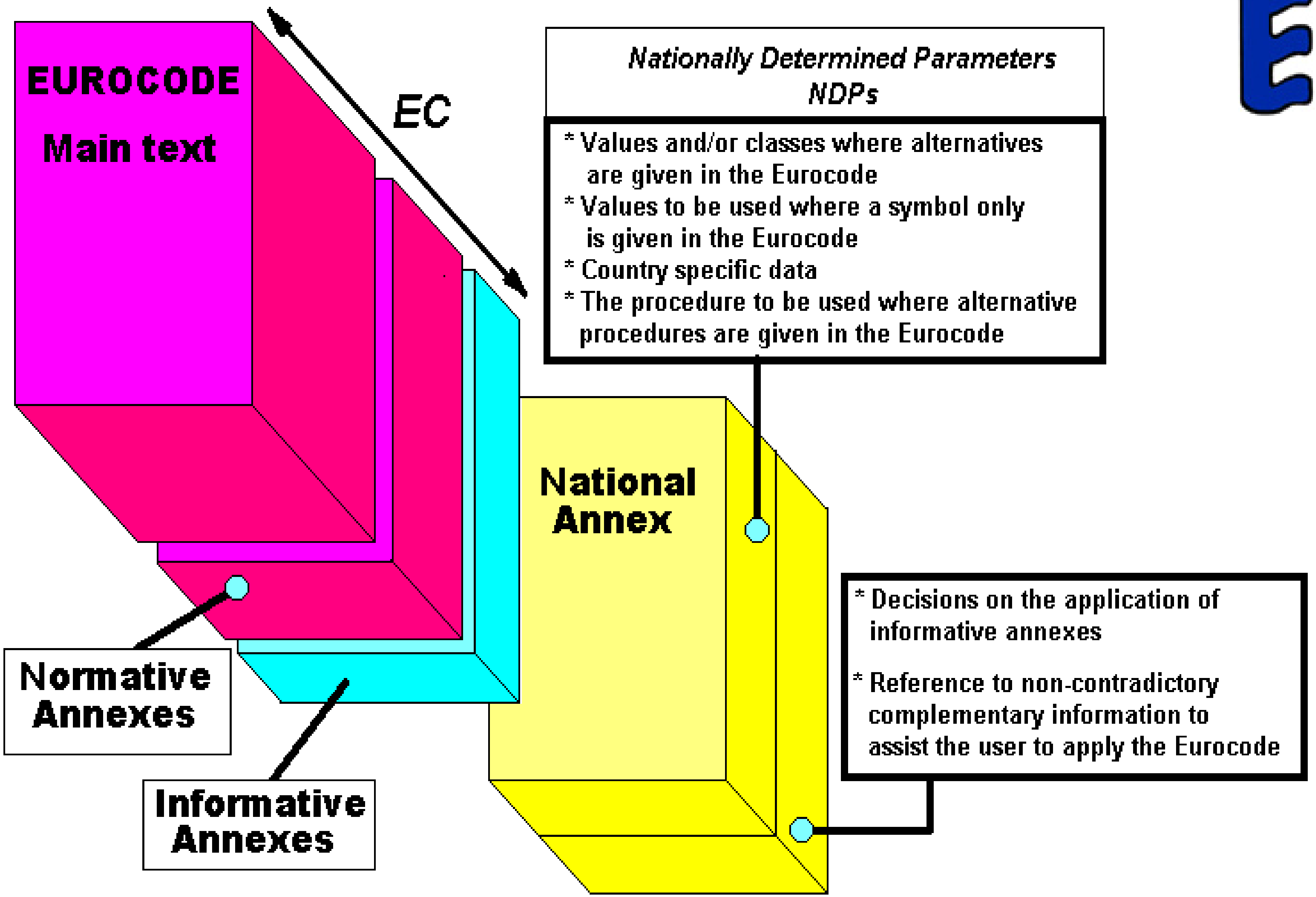
- EC-system ideal for application in a large number of countries w/ diverse traditions, materials, environmental conditions, etc., as it has built-in flexibility to accommodate such differences.

- Withdrawal of all conflicting national standards: **2010**

FLEXIBILITY WITHIN EUROCODE FRAMEWORK

- Eurocodes (ECs) or National Annexes cannot allow design with rules other than those in the ECs.
- National choice can be exercised through the National Annex, only where the Eurocode itself explicitly allows:
  1. Choosing a value for a parameter, for which a symbol or range of values is given in the Eurocode;
  2. Choosing among alternative classes or models detailed in the Eurocode;
  3. Adopting an Informative Annex or referring to alternative national document.
- Items of national choice in 1-2: Nationally Determined Parameters NDPs
- National choice through NDPs:
  - Wherever agreement on single choice cannot be reached;
  - On issues controlling safety, durability & economy (national competence) & where geographic or climatic differences exist (eg. Seismic Hazard)
- For cases 1 & 2, the Eurocode itself recommends (in a Note) a choice. The European Commission will urge countries to adopt recommendation(s), to minimize diversity within the EU.
- If a National Annex does not exercise national choice for a NDP, designer will make the choice, depending on conditions of the project.

IMPLEMENTATION OF EUROCODES



European Commission, Guidance Paper L: "Application and use of Eurocodes" CONSTRUCT 01/483 Rev.1, Brusells, 2001

- The determination of the levels of safety of buildings & civil engineering works & parts there-of, including aspects of durability & economy, is within the competence of Member States.
- Possible difference in geographical or climatic conditions (e.g. wind or snow), or in ways of life, as well as different levels of protection that may prevail at national, regional or local leve will be taken into account by providing choices in the EN Eurocodes for identified values, classes, or alternative methods, to be determined at the national level (named Nationally Determined Parameters, NDPs). Thus allowing the Member States to choose the level of safety, including aspects of durability & economy, applicable to works in their territory.
- When Member States lay down their NDPs, they should:
  - choose from the classes included in the EN Eurocodes, or
  - use the recommended value, or choose a value within the recommended range of values, for a symbol where the EN Eurocodes make a recommendation, or
  - when alternative methods are given, use the recommended method, where the EN Eurocodes make a recommendation,
  - take into account the need for coherence of the NDPs laid down for the different EN Eurocodes and the various Parts thereof.
- Member States are encouraged to co-operate to minimize the number of cases where recommendations for a value or method are not adopted for their nationally determined parameters.
- The NDPs laid down in a Member State should be made clearly known to the users of the EN Eurocodes and other parties concerned, including manufacturers.
- When EN Eurocodes are used for the design of construction works, or parts thereof, the NDPs of the Member State on whose territory the works are located shall be applied.
- Any reference to a EN Eurocode design should include the information on which set of NDPs was used, whether or not the NDPs .. used correspond to the recommendations given in the EN Eurocodes.

European Commission, Guidance Paper L: "Application and use of Eurocodes" CONSTRUCT 01/483 Rev.1, Brusells, 2001

- National Provisions should avoid replacing any EN Eurocodes provisions, e.g. Application Rules, by national rules (codes, standards, regulatory provisions, etc.).
- When, however, National Provisions do provide that the designer may – even after the end or the coexistence period – deviate from or not apply the EN Eurocodes or certain provisions thereof (e.g. Application Rules), then the design will not be called "a design according to EN Eurocodes".
- When Eurocodes Parts are published as European standards, they will become part of the application of the Public Procurement Directive (PPD).
- In all cases, technical specifications shall be formulated in public tender enquiries and public contracts by referring to EN Eurocodes, in combination with the NDPs applicable to the works concerned.
- However, the reference to EN Eurocodes is not necessarily the only possible reference allowed in a Public contract. The PPD foresees the possibility for the procuring entity to accept other proposals, if their equivalence to the EN Eurocodes can be demonstrated by the contractor.
- Consequently, the design of works proposed in response to a Public tender can be prepared according to:
  - EN Eurocodes (including NDPs) which give a presumption of conformity with all legal European requirements concerning mechanical resistance and stability, fire resistance and durability, in compliance with the technical specifications required in the contract for the works concerned;
  - Other provisions expressing the required technical specification in terms of performance. In this case, the technical specification should be detailed enough to allow tenderers to know the conditions on which the offer can be made and the owner to choose the preferred offer. This applies, in particular, to the use of national codes, as long as Member States maintain their use in parallel with EN Eurocodes (e.g. a Design Code provided by National Provisions), if also specified to be acceptable as an alternative to an EN Eurocode Part by the Public tender

European Commission: "Commission Recommendation on the implementation and use of Eurocodes for construction works & structural construction products". Document No. C(2003)4639, Brussels (2003)

- Member States should adopt the Eurocodes as a suitable tool for designing construction works, checking the mechanical resistance of components or checking the stability of structures.
- The Eurocodes are to be used by contracting authorities in technical specifications relating to the coordination of procedures for the award of public service contracts ... Technical specifications are to be defined by the contracting authorities by reference to national standards implementing European standards.
- Member States should take all necessary measures to ensure that structural construction products calculated in accordance with the Eurocodes may be used, and should therefore refer to the Eurocodes in their national regulations on design.

……….

- Member States should inform the Commission of all national measures in accordance with the Recommendation.

European Commission: "Commission Recommendation on the implementation and use of Eurocodes for construction works & structural construction products". Document No. C(2003)4639, Brussels (2003)

……..

- For each Nationally Determined Parameter (NDP), the Eurocodes give a recommended value. However, Member States may choose a different specific value as the NDP, if they consider it necessary in order to ensure that building and civil engineering works are designed and executed in a way that does not endanger the safety of persons, domestic animals or property.
- Member States should use the recommended values provided by the Eurocodes when NDPs have been identified in the Eurocodes. They should diverge from those recommended values only where geographical, geological or climatic conditions or specific levels of protection make the necessary. Member States should notify the Commission of the NDPs in force on their territory within two years of the date on which the Eurocodes became available.
- In order to achieve a higher level of harmonization, a comparison of the various NDPs implemented by the Member States should be undertaken and, where appropriate, they should be aligned.
- Member States should, acting in coordination under the direction of the Commission, compare the NDPs implemented by each Member State and assess their impact as regards the technical differences for works or parts of works. Member States should, at the request of the Commission, change their NDPs in order to reduce divergence from the recommended values provided by the Eurocodes.

……..

- Member States should inform the Commission of all national measures in accordance with the Recommendation.

EUROCODE PACKAGES & EC8:

- Self-sufficient packages of ENs for design of each type of construction works (building, bridge, etc.) with a specific construction material.
- EC0 (Basis of design), EC1 (Actions), EC7 (Geotechnical) & EC8: Not basis of any EC-package; in all packages as service items.
- EC8 parts to be included in EC-packages:
    - EN1998-1, -5 & -3: in packages for concrete, steel, composite, etc., buildings
    - EN1998-1, -5 & -2: in packages for concrete, steel etc. bridges
    - EN1998-1, -5 & -4: in packages for concrete liquid retaining structures & for steel silos, tanks, pipelines
    - EN1998-1, -5 & -6: in package for steel towers & masts.

EN 1998-1:2004
General rules, seismic actions, rules for buildings

1. General
2. Performance Requirements and Compliance Criteria
3. Ground Conditions and Seismic Action
4. Design of Buildings
5. Specific Rules for Concrete Buildings
6. Specific Rules for Steel Buildings
7. Specific Rules for Steel-Concrete Composite Buildings
8. Specific Rules for Timber Buildings
9. Specific Rules for Masonry Buildings
10. Base Isolation

Annex A (Informative): Elastic Displacement Response Spectrum

Annex B (Informative): Determination of the Target Displacement for Nonlinear Static (Pushover) Analysis

Annex C (Normative): Design of the Slab of Steel-Concrete Composite Beams at Beam-Column Joints in Moment Resisting Frames

Seismic performance requirements for concrete buildings

Performance-based Seismic Engineering

- Design for different "Performance Levels" at different Seismic Hazard levels
- "Basic Objective" (ordinary buildings):

Performance Level	Hazard Level	
Operational	Frequent EQ	(25-72 yrs)
Immediate occupancy	Occasional EQ	(72-225 yrs)
Life safety	Rare EQ	(475 yrs)
Near collapse	Very rare EQ	(800-2500 yrs)

- Safety-critical facilities: "Enhanced Objective“

➢ Pros: Better property protection; flexibility in conceptual design.

➢ Cons: Lots of work in design.

Performance Levels

- "Operational":

  Facility can be used according to original intention; any repairs will not disrupt occupancy or use. Practically no structural or nonstructural damage. Lifelines undamaged, or back-up systems operational.

- "Immediate occupancy":

  Facility can return to full use, as soon as utility systems are back in operation & cleanup is complete. Structure is very lightly damaged, possibly beyond yielding, w/ some residual cracks; no permanent drifts or other permanent structural deformations: pre-earthquake strength & stiffness fully retained. Non-structural components may have minor damage (e.g. distributed cracking in infill walls) to be easily & economically repaired later.

- "Life-safety":

  Life-threatening injury to occupants avoided by prevention of collapse of parts of the structure & retention of structural integrity and residual load capacity after the earthquake. Structure significantly damaged, w/ moderate permanent drifts, but retains full its vertical load-bearing capacity and sufficient residual lateral strength & stiffness to protect life during strong aftershocks. Non-structural components are damaged, but prevented from collapsing or falling. From the economic point of view, repairability is questionable and demolition may be preferable.

- "Near collapse":

  Structure heavily damaged, at the verge of local or even total collapse. Structure may have large permanent drifts and retain little residual strength or stiffness against lateral loads, but its vertical elements can still carry the gravity loads. Most non-structural elements (e.g. infill walls) collapse. Substantial but not full life safety, as falling hazards may cause life-threatening injury. The building is unsafe, as it may not survive a strong aftershock. Repair may not be technically feasible and is not economically justified.

Seismic performance requirements for concrete buildings -

The current code situation: Emphasis on life safety

IN EUROPE, SINCE 1960s (also in seismic codes)

- Instead of “Performance Level”:
- “Limit State” (LS) = state of unfitness to (intended) purpose:
  - ULS (Ultimate LS): safety of people and/or structure;
  - SLS (Serviceability LS): operation, damage to property.
- LS concept:
  - According to EN 1990 (Eurocode: Basis of structural design): LS-design is the basis for all Eurocodes (including EC8).

From EN1990 (Eurocode – Basis of structural design):

- **Seismic design situation:** $$\sum_{j\geq 1} G_{k,j} "+" P "+" A_{Ed} "+" \sum_{i\geq 1} \psi_{2,i} Q_{k,i}$$

$\sum_{j\geq 1} G_{k,j}$ **: Permanent actions (characteristic or nominal values)**

P **: Prestressing**

$\psi_{2,i} Q_{k,i}$ **: Variable actions (quasi-permanent values)**

$A_{Ed} = \gamma_I A_{Ek}$ **: Design Seismic action**

A_{Ek} **: Characteristic Seismic action,** γ_I **: Importance factor of structure**

From EN1990 & EN1998-1 (Eurocode 8 – General):

A_{Ek}: «Reference Seismic action»:

Reference Probability of Exceedance, P_R, in design life T_L of structure
(or Reference Return Period, T_R)

IMPORTANCE CLASSES - IMPORTANCE FACTORS

Importance class	Building	Recommended γ_I value (NDP)
I	Minor importance for public safety	0.8
II	Ordinary	1.0 (by definition)
III	Large consequences of collapse (schools, assembly halls, cultural institutions etc.)	1.2
IV	Of vital importance for civil protection (hospitals, fire stations, power plants, etc.)	1.4

EN1990 - Eurocode: Basis of structural design:

Design working life: the assumed period for which a structure is to be used for its intended purpose with anticipated maintenance but without major repair being necessary.

For :

- Definition of design actions (e.g. wind, earthquake)
- Determination of material property deterioration (f.i. fatigue, creep)
- Life cycle costing
- Development of maintenance strategies

In EN1998-1 – Eurocode 8 – General:

- Presumed design working life T_L : 50 years
- Different values can be considered through Importance factor of the structure (reliability differentiation).

In EN1990 - Eurocode: Basis of structural design:

- **Ultimate limit states concern:**
  - the safety of people
  - the safety of the structure
- **Serviceability limit states concern:**
  - the functioning of the structure
  - the comfort of people
  - the appearance of the structure

Limit State / Design Situation	U.L.S.		S.L.S.
		• loss of equilibrium of the structure or any part of it, considered as a rigid body; • failure by excessive deformation, transformation of the structure or any part of it into a mechanism, rupture, loss of stability of the structure or any part of it, including supports and foundations; • failure caused by fatigue or other time-dependent effects.	
Persistent	✓		✓
Transient	✓		✓
Accidental	✓		
Seismic	✓		✓

EN 1998-1: Adaptation of L.S. Design of new buildings, to Performance-based concept:

- Verify explicitly No-life-threatening-collapse requirement ("Life Safety" performance level) for "rare" Earthquake (reference seismic action for structures of ordinary importance: NDP – recommended: 475 years).
- Limit damage through damage limitation check for "frequent" Earthquake (EQ for structures of ordinary importance: NDP – recommended: 95 yrs).
- Prevent collapse under any conceivable Earthquake through "Capacity Design”

EN 1998-3: Assessment and retrofitting of buildings: EXPLICIT PERFORMANCE-BASED APPROACH:

Assessment & Retrofitting for different Limit States under different Seismic Hazard levels

- Limit States (Performance Levels)
  - Damage Limitation (: Immediate Occupancy)
  - Significant Damage (: Life Safety)
  - Near Collapse.
- Flexibility for countries, owners, designers:
  - How many & which Limit States will be met and for what Hazard Level:
    - to be decided by country, or
    - (if country doesn't decide in National Annex) by owner/designer
  - Hazard Levels: NDPs - No recommendation given

    Noted that Basic Objective for ordinary new buildings is:
    - Damage Limitation: Occasional EQ (225yrs)
    - Significant Damage: Rare EQ (475yrs)
    - Near Collapse: Very rare EQ (2475yrs)
- Safety-critical facilities: Enhanced Objective, via multiplication of seismic action by importance factor γ_I

EN 1998-1: SEISMIC ACTION FOR DAMAGE LIMITATION CHECKS

- Seismic action for “damage limitation”: NDP.

  Recommended for ordinary structures: 10%/10yrs (95yr EQ); ~50% of “design seismic action” (475 yr seismic action).
- In buildings: Interstorey drift ratio calculated for “damage limitation” action via “equal displacement rule” (elastic response):
  - <0.005 for brittle nonstructural elements attached to structure;
  - <0.0075 for ductile nonstructural elements attached to structure;
  - < 0.01 for nonstructural elements not interfering w/ structural response.
- Although the recommended ~50% of 475 yr (design) seismic action is a low estimate of the 95 yr seismic action, in concrete, steel or composite frame buildings damage limitation checks control member sizes.

Conclusion: In Eurocode 8:

The Design Seismic action is defined as the one for which the No-(life-threatening-)collapse requirement is verified

The Reference Return Period of the Reference Seismic action is a NDP, with recommended value of 475 years (corrresponding Reference Probability of Exceedance in the structure's design life of 50 years: 10%)

The Reference Seismic action is described (through the national zonation maps) in terms of a single parameter: the Reference Peak Ground Acceleration on Rock, $a_{gR.}$

The design ground acceleration on rock, a_g, is the reference PGA times the importance factor: $a_g = \gamma_I a_{gR}$

In addition to the Reference Peak Ground Acceleration on Rock, the Reference Seismic action is defined in terms of the Elastic Response Spectrum for 5% damping.

Force-based design for energy-dissipation & ductility, to meet no-(life-threatening-)collapse requirement under Design Seismic action:

- Structure allowed to develop significant inelastic deformations under design seismic action, provided that integrity of members & of the whole is not endangered.
- Basis of force-based design for ductility:
  – inelastic response spectrum of SDoF system having elastic-perfectly plastic F-δ curve in monotonic loading.
- For given period, T, of elastic SDoF system, inelastic spectrum relates:
  – ratio $q = F_{el}/F_y$ of peak force, F_{el}, that would develop if the SDoF system was linear-elastic, to its yield force, F_y, ("behaviour factor")

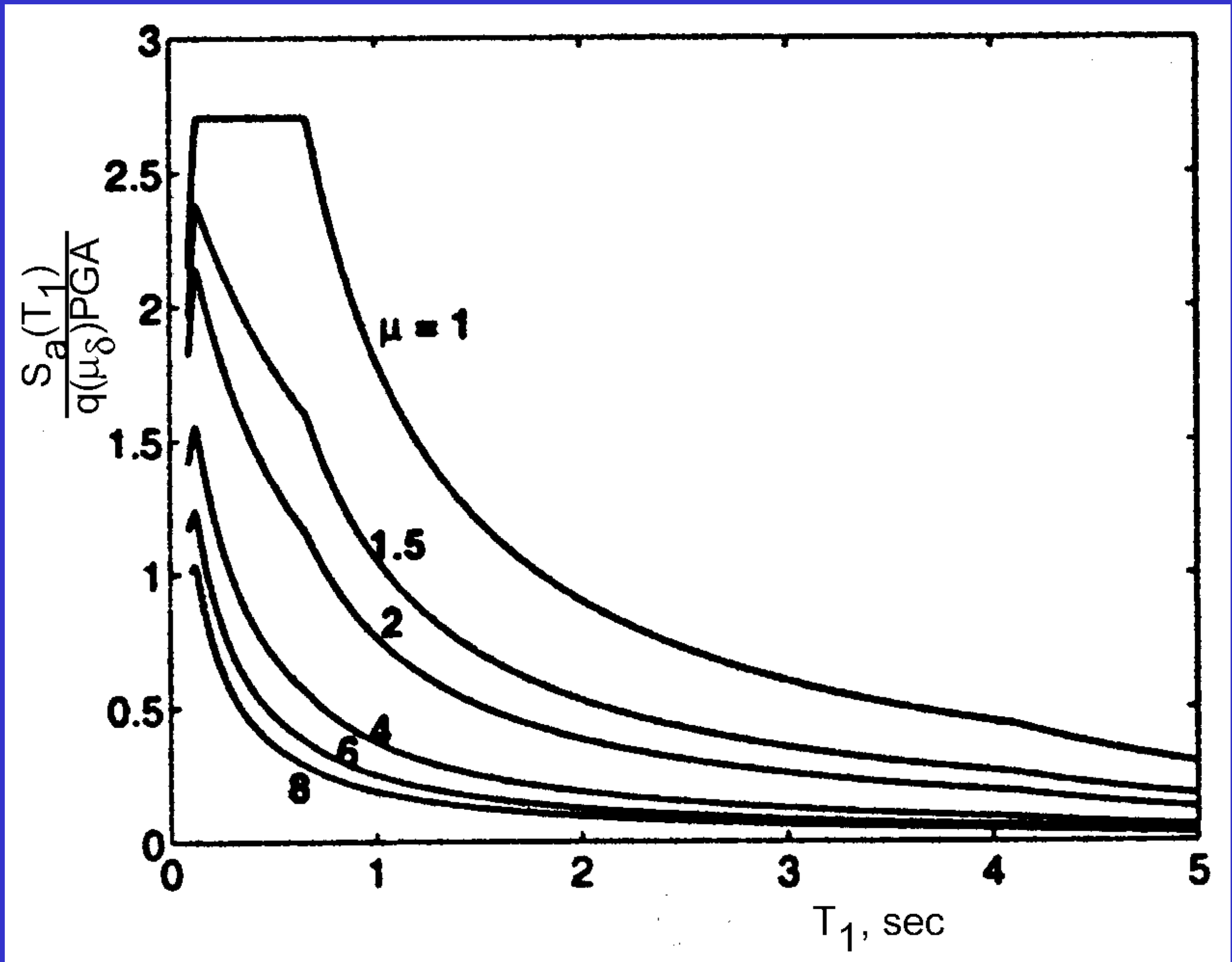
  to

  – maximum displacement demand of the inelastic SDOF system, δ_{max}, expressed as ratio to the yield displacement, δ_y : displacement ductility factor, $\mu_\delta = \delta_{max}/\delta_y$

Inelastic spectra (Vidic et al) adopted in Eurocode 8

$\mu_\delta = q$ if $T \geq T_C$

$\mu_\delta = 1 + (q-1)\frac{T_C}{T}$ if $T < T_C$



Inelastic spectra for T_C=0.6s normalised to peak ground acceleration, PGA

Implementation of Eurocode 8 seismic design philosophy

1. Damage limitation (storey drift ratio < 0.5-1%) under the damage limitation earthquake (~50% of “design seismic action”), using 50% of uncracked gross section stiffness.
2. Member verification for the Ultimate Limit State (ULS) in bending under the “design seismic action”, with elastic spectrum reduced by the behaviour factor q.
3. In frames or frame-equivalent dual systems: Fulfilment of strong column/weak beam capacity design rule, with overstrength factor of 1.3 on beam strengths.
4. Capacity design of members and joints in shear.
5. Detailing of plastic hinge regions, on the basis of the value of the curvature ductility factor that corresponds to the q-factor value.

Control of inelastic seismic response through capacity design

- Not all locations or parts in a structure are capable of ductile behaviour & energy dissipation.
- “Capacity design” provides the necessary hierarchy of strengths between adjacent structural members or regions & between different mechanisms of load transfer within the same member, to ensure that inelastic deformations will take place only in those members, regions and mechanisms capable of ductile behaviour & energy dissipation; the rest stay in the elastic range.
- The regions of members entrusted for hysteretic energy dissipation are called in Eurocode 8 “dissipative zones”; they are designed and detailed to provide the required ductility & energy-dissipation capacity.
- Before their design & detailing for the required ductility & energy-dissipation capacity, “dissipative zones” are dimensioned to provide a design value of ULS force resistance, R_d, at least equal to the design value of the action effect due to the seismic design situation, E_d, from the analysis:

$$E_d \leq R_d$$

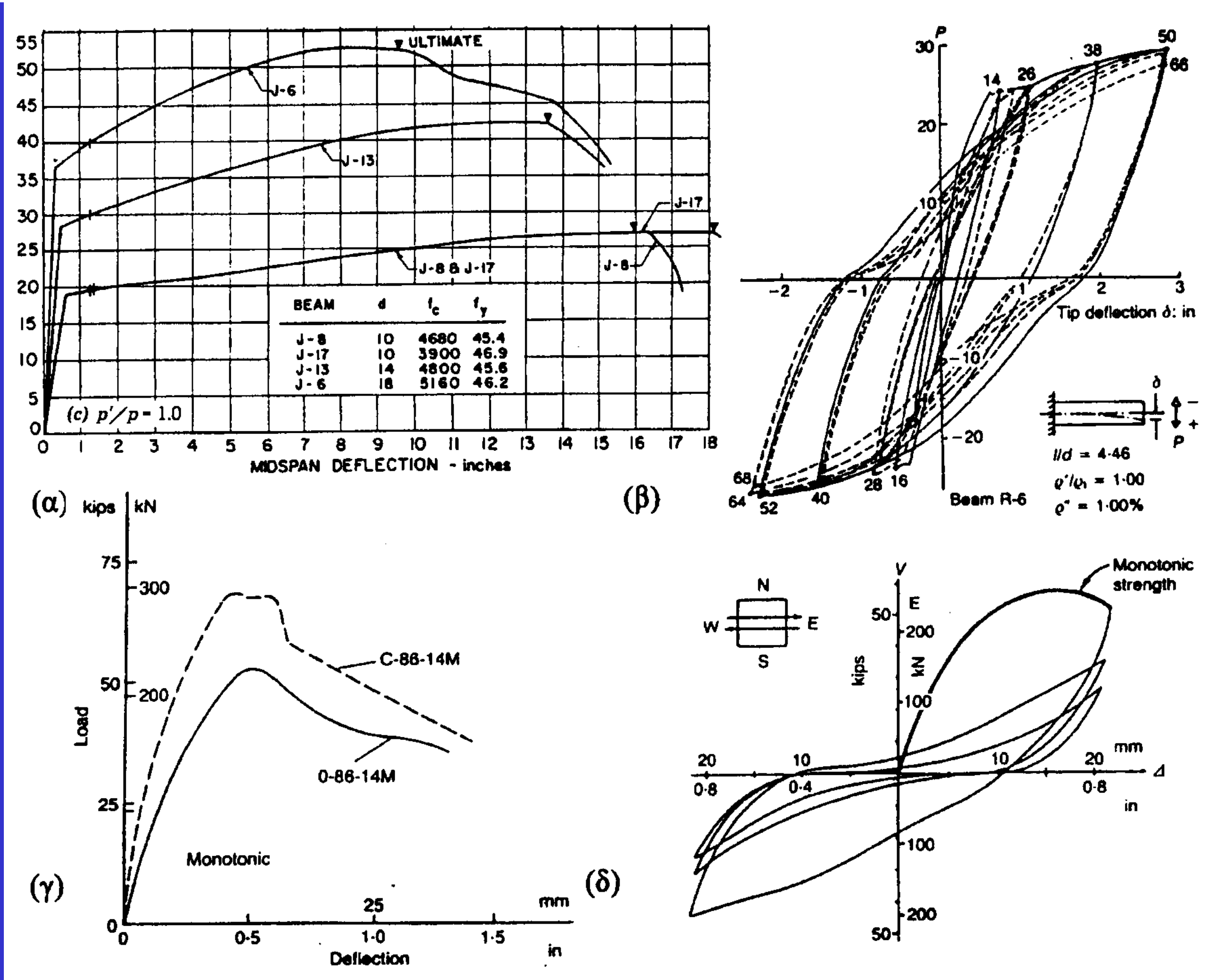
- Normally linear analysis is used for the design seismic action (by dividing the elastic response spectrum by the behaviour factor, q)

NDP-partial factors for materials, in design value of ULS force resistance, R_d:

- Recommended in Eurocode 8:
  - Same values as for persistent & transient design situations.
  - In concrete buildings:
    - γ_c=1.5,
    - γ_s=1.15.

Criteria for the selection of elements where inelastic deformations are allowed to take place, instead of being capacity-designed to stay in the elastic range:

- "Ductility": the inherent capacity of the element to develop large inelastic deformations & dissipate energy under cyclic loading, without substantial loss of its force-resistance.
- The importance of the element for the stability of other elements & the integrity of the whole (greater importance of vertical elements compared to the horizontal ones; importance increases from the top of the building to its foundation).
- The accessibility of the element and the difficulty to inspect & repair any damage.



Ductile behaviour: (a) monotonic loading; (b) cyclic loading;
Brittle behaviour: (c) monotonic loading; (d) cyclic loading.

Control of inelastic seismic response: Soft-storey collapse mechanism, to be avoided through proper structural configuration:

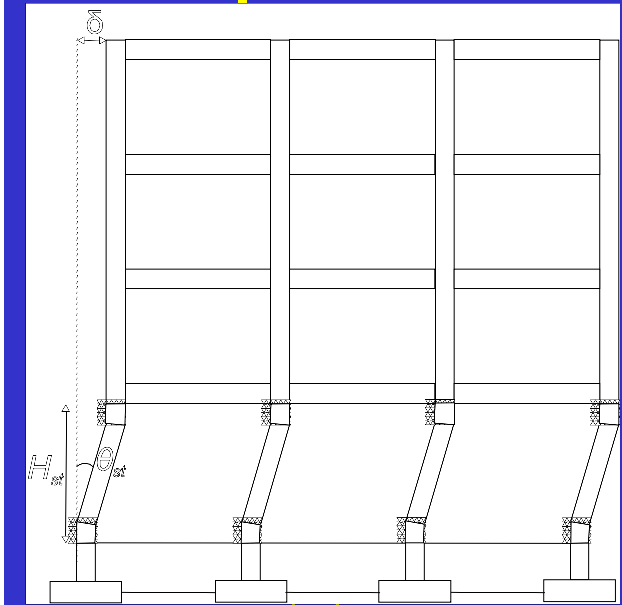
– Strong-column/weak beam frames, with beam-sway mechanisms, involving:

plastic hinging at all beam ends, and
either plastic hinging at column bottoms, or
rotations at the foundation.

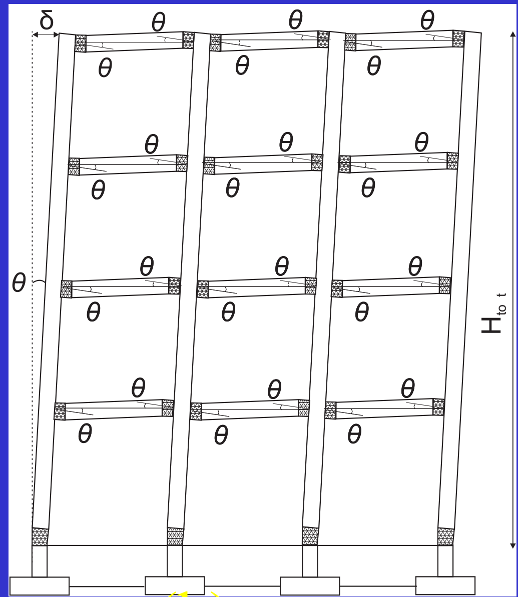
– Wall-equivalent dual frames, with beam-sway mechanism, involving:

plastic hinging at all beam ends, and
either plastic hinging at wall & column bottoms, or
rotations at the foundation.

The importance of a stiff & strong vertical spine in buildings



(a)



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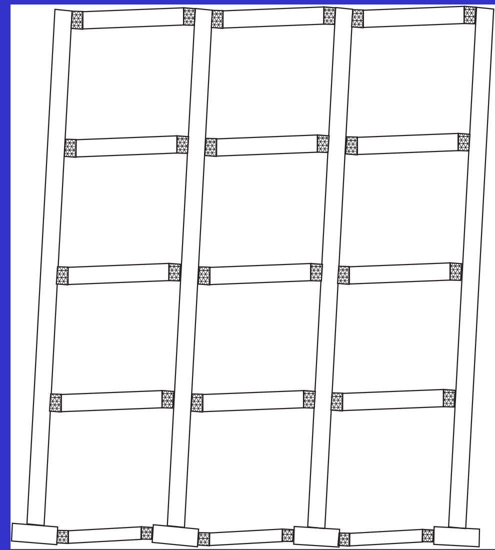
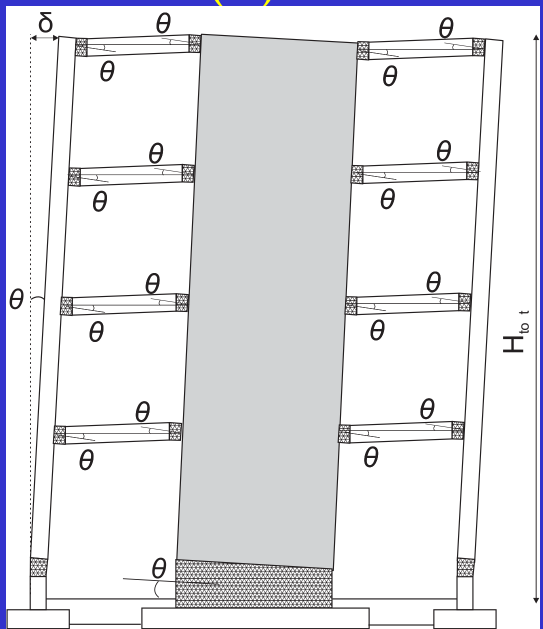
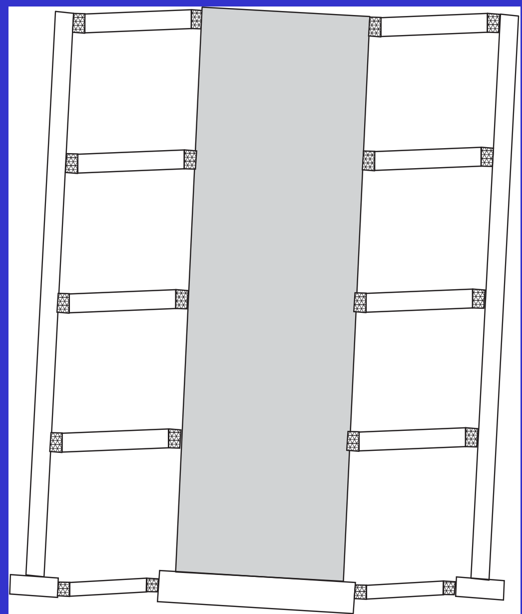


(c)



(d)



(e)

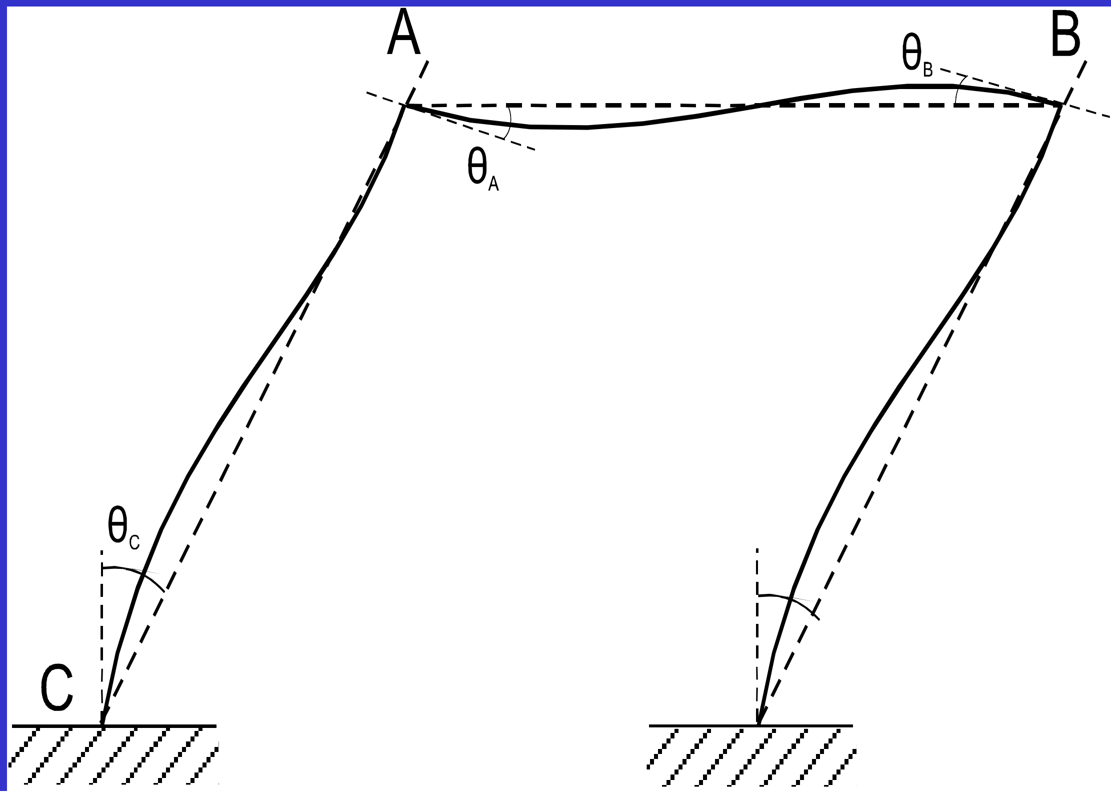
(a) soft-storey mechanism in weak column/strong beam frame

(b), (c): beam-sway mechanisms in strong column/weak beam frame

(d), (e): beam-sway mechanisms in wall system

Maximum chord rotation demands in plastic mechanisms

- In beam-sway mechanisms of strong column/weak beam frames or wall systems:
  - at beam ends or at the base of vertical elements: $\theta = \delta / H_{tot}$
- In soft-storey mechanisms of weak column/strong beam frames:
  - at the base of vertical elements: $\theta = \delta / h_i$ (H_{tot}/h_i times greater)



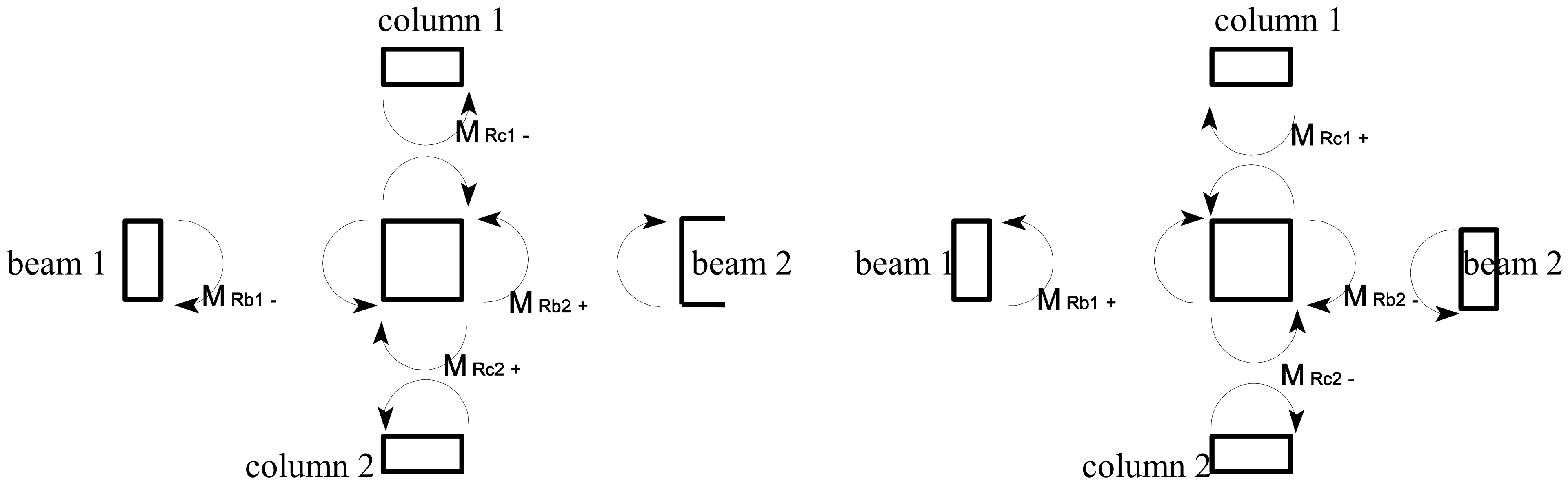
Definition of chord rotation at member ends

Fulfilment of strong column/weak beam capacity design rule, with overstrength factor γ_{Rd} on beam strengths:

$$\sum M_{Rc} \geq \gamma_{Rd} \sum M_{Rb}$$

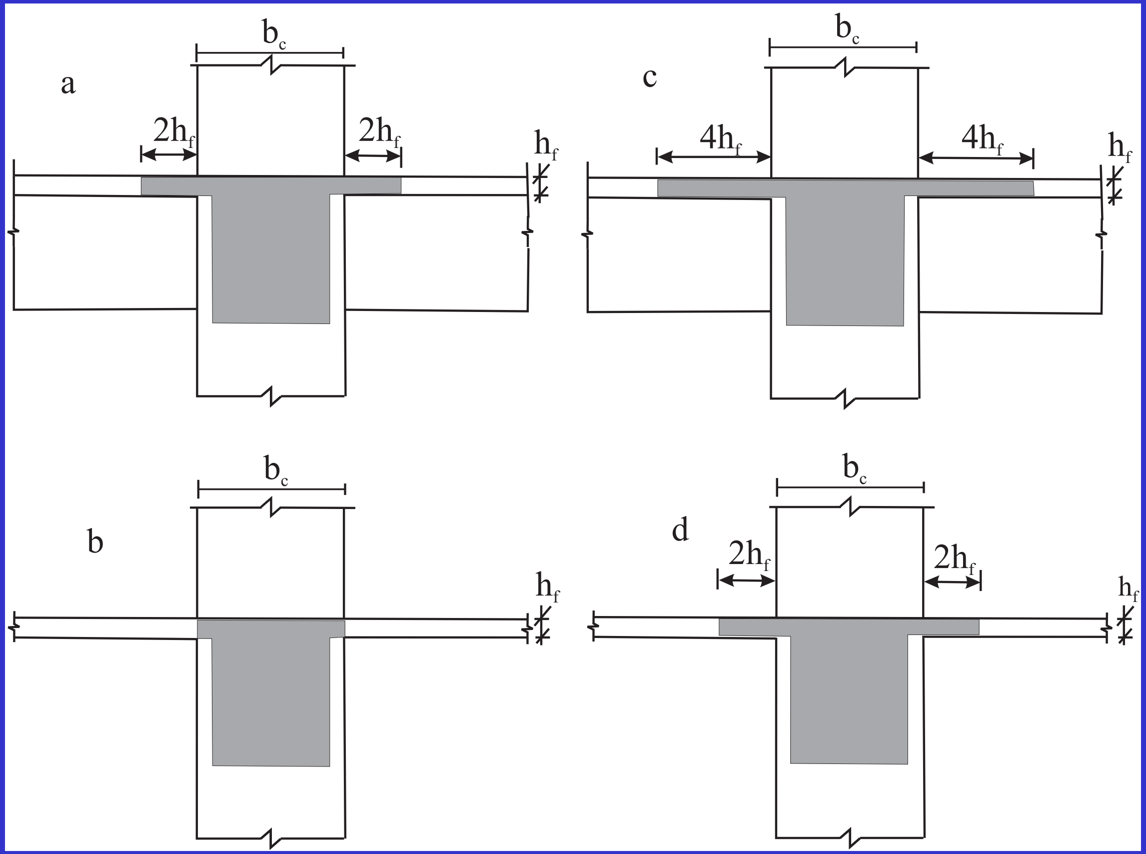
- Eurocode 8: γ_{Rd} = 1.3; strong column/weak beam capacity design required only in frames or frame-equivalent dual systems (frames resist >50% of seismic base shear) with more than two storeys (except at top storey joints).
- US codes: γ_{Rd} = 1.2; strong column/weak beam capacity design required for all columns that are taken into account for earthquake resistance ("primary")

Beam & column flexural capacities at a joint in Capacity Design rule



But:

Width of slab effective as tension flange of beams at the support to a column:

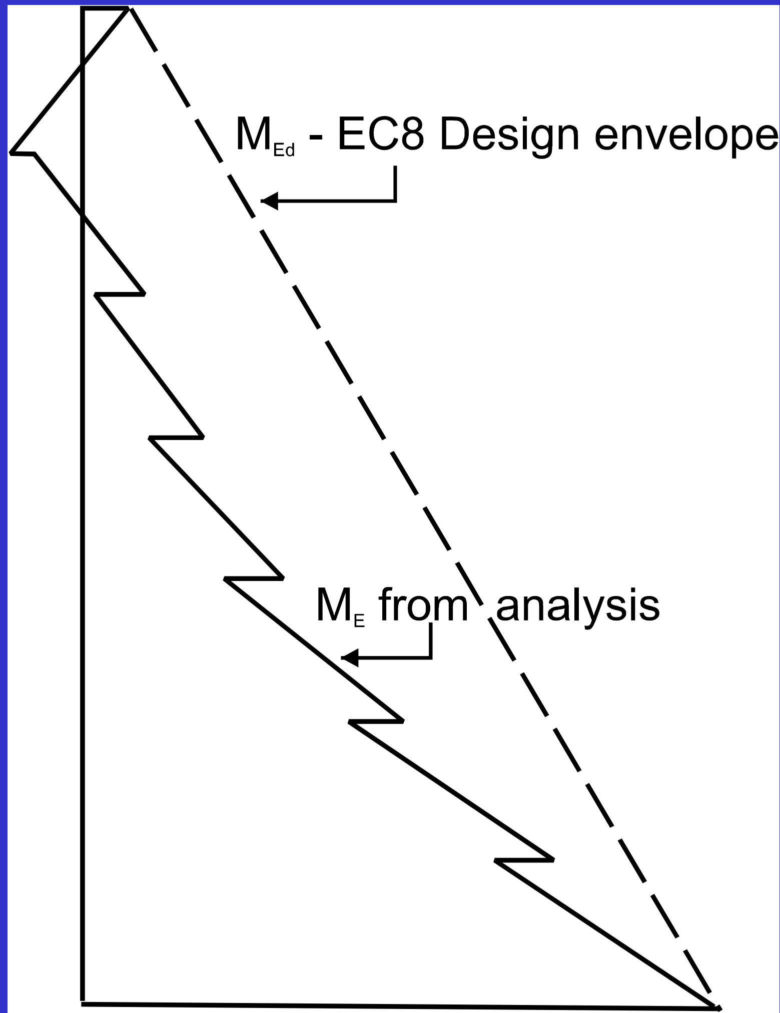


Eurocode 8 (a, b: at exterior column; c, d: at interior column): too small – unsafe for capacity design;

US codes (25% of beam span on each side of web): realistic.

Strong column/weak beam capacity design not required in wall or wall-equivalent dual systems (walls resist >50% of seismic base shear)

But:
design of ductile walls in flexure, to ensure that plastic hinge develops only at the base:



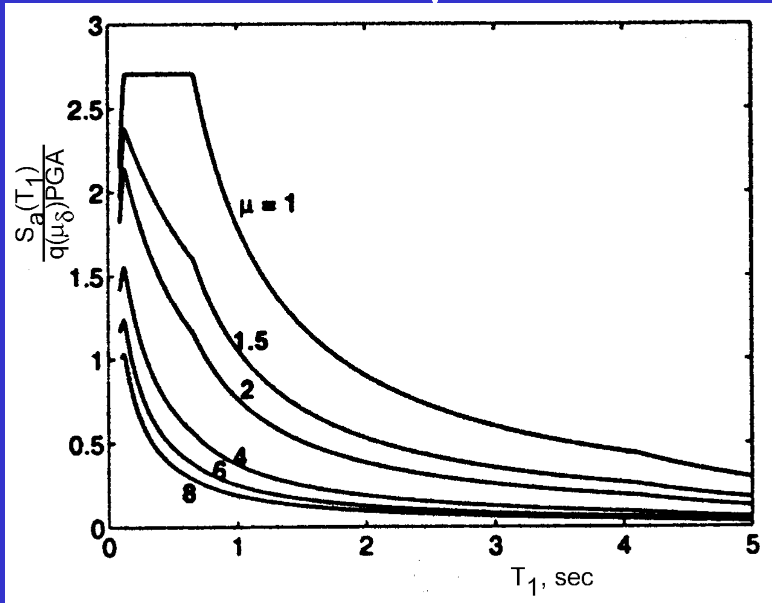
Typical moment diagram in a concrete wall from the analysis & linear envelope for its (over-)design in flexure according Eurocode 8

Trading-off strength & ductility in earthquake-resistant design (ductility as an alternative to strength)

- For given period, T, of elastic SDoF system, the inelastic spectrum relates:
  - The ratio $q = F_{el}/F_y$ of the peak force, F_{el}, that would develop if the SDoF system were linear-elastic, to its yield force, F_y, ("behaviour factor"), to
  - The maximum displacement demand on the inelastic SDoF system, δ_{max}, expressed as ratio to the yield displacement, δ_y : displacement ductility factor, $\mu_\delta = \delta_{max}/\delta_y$

$$\mu_\delta = 1 + (q-1)\frac{T_C}{T} \quad \text{if } T < T_C$$

$$\mu_\delta = q \quad \text{if } T \geq T_C$$



- $\mu_\delta \uparrow \;\rightarrow\; q \uparrow$

The pros of ductility (high μ_δ, high q)

- Resistance to seismic action is greater than the "design seismic action" (thanks to capacity design & detailing for ductility).
- Easier verification of the foundation.
- Better protection of equipment or nonstructural parts that are sensitive to accelerations (due to the reduction of floor response accelerations).

- **But:** Little benefit in cost (savings in longitudinal steel & in beams are offset by increases in transverse reinforcement & in vertical members).

The pros of strength (low μ_δ, low q) :

- Construction is easier and simpler.
- Certain buildings have anyway significant resistance to earthquake forces, w/o having been designed for them:
  - For low-to-moderate seismicity,
  - low-to-medium-rise buildings, controlled by gravity-load,
  - tall & flexible buildings dominated by wind, etc.

  Can benefit from margin of lateral strength, to avoid complex/ expensive detailing for ductility.
- If the structural layout is complex/irregular: it's better to design for nearly elastic response under design seismic action.
- Less structural damage, not only during frequent or moderate earthquakes, but also due to the design seismic action.

- **But:** non-structural damage to parts sensitive to deformations ~same (response displacements ~same).

EUROCODE 8 DESIGN CONCEPTS FOR SAFETY UNDER DESIGN SEISMIC ACTION

1. Design for energy dissipation & ductility: **q >1.5**
   - Global ductility:
     - Structure is forced to remain straight in elevation through strong shear walls or columns ($\Sigma M_{Rc}>1.3\Sigma M_{Rb}$ in frames):
   - Local ductility:
     - Plastic hinges are detailed for a ductility capacity derived from q-factor;
     - Brittle failures are prevented by overdesign/capacity design
   - Capacity design of foundations & foundation elements:
     - On the basis of overstrength of ductile elements of superstructure.

     (Or: Foundation elements - incl. piles - designed & detailed for ductility)
2. Design w/o energy dissipation & ductility: **q ≤ 1.5** for overstrength; design only according to Eurocode 2 (Ductility Class “Low”– DCL). Allowed only:
   - for Low Seismicity (NDP; recommended: PGA on rock ≤0.08g)
   - for superstructure of base-isolated buildings.

EUROCODE 8 Ductility Classes for Dissipative Structures:

- Two Ductility Classes (DC):
  - DC H (High).
  - DC M (Medium).
- Differences in:
  - q-values (usually $q > 4$ for DCH, $1.5 < q < 4$ for DCM)
  - Local ductility requirements

    (ductility of materials, member detailing, capacity design against brittle failure modes)

Seismic Design Philosophy for RC buildings according to Eurocode 8

- **Ductility Classes (DC)**
  - Design based on **energy dissipation** and **ductility**:
    - **DC (M) Medium** q = 3 x system overstrength factor (≈1.3).
    - **DC (H) High** q = 4-4.5 x system overstrength factor (≈1.3).

    (reduction by 20% for heightwise irregular; reduced system overstrength factor for planwise irregular buildings)
- The aim of design is to control **inelastic seismic response**:
  - Structural **layout** and relative **sizing** of members to ensure a beam-sway mechanism.
  - **Detailing** of plastic hinge regions (beam ends, base of columns) to sustain inelastic deformation demands.
- Plastic hinge regions detailed for **deformation demands** related to **behaviour factor q**:
  - $\mu_\delta = q$ if $T>T_c$
  - $\mu_\delta = 1+(q-1)T_c/T$ if $T\leq T_c$

Basic value, q_o, of behaviour factor for regular in elevation RC buildings in Eurocode 8

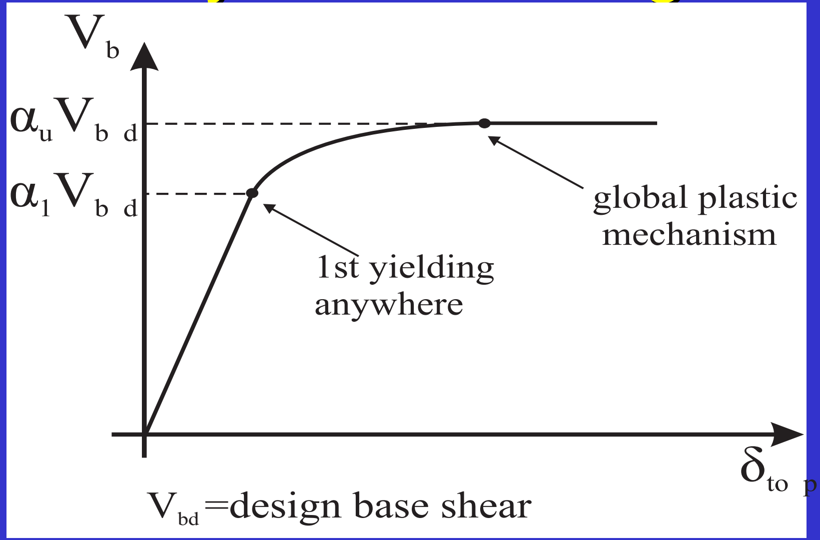
Lateral-load resisting structural system	**DC M**	**DC H**
Inverted pendulum system*	1.5	2
Torsionally flexible structural system**	2	3
Uncoupled wall system (> 65% of seismic base shear resisted by walls; more than half by uncoupled walls) not belonging in one of the categories above	3	$4\alpha_u/\alpha_1$
Any structural system other than those above	$3\alpha_u/\alpha_1$	$4.5\alpha_u/\alpha_1$

*** :** at least 50% of total mass in upper-third of the height, or with energy dissipation at base of a single element (except one-storey frames w/ all columns connected at the top via beams in both horizontal directions in plan & with max. value of normalized axial load ν_d in combination(s) of the design seismic action with the concurrent gravity loads ≤ 0.3).

**** :** at any floor: radius of gyration of floor mass > torsional radius in one or both main horizontal directions (sensitive to torsional response about vertical axis).

- Buildings irregular in elevation: behaviour factor ***$q = 0.8q_o$***;
- Wall or wall-equivalent dual systems: *q* multiplied further by $(1+a_o)/3 \leq 1$ (a_o: prevailing wall aspect ratio = $\Sigma H_i/\Sigma l_{wi}$).

α_u/α_1 in behaviour factor of buildings designed for ductility: due to system redundancy & overstrength



Normally:

α_u & α_1 from base shear - top displacement curve from pushover analysis.

- α_u: seismic action at development of global mechanism;
- α_1: seismic action at 1st flexural yielding anywhere.

- $\alpha_u/\alpha_1 \leq 1.5$;
- default values given between 1 to 1.3 for buildings regular in plan:
  - = 1.0 for <u>wall systems w/ just 2 uncoupled walls per horiz. direction;</u>
  - = 1.1 for:
    one-storey frame or frame-equivalent dual systems, and
    <u>wall systems w/ > 2 uncoupled walls per direction;</u>
  - = 1.2 for:
    one-bay multi-storey frame or frame-equivalent dual systems,
    <u>wall-equivalent dual systems & coupled wall systems;</u>
  - = 1.3 for:
    <u>multi-storey multi-bay frame or frame-equivalent dual systems.</u>
- for buildings irregular in plan:
  default value = average of default value of buildings regular in plan and 1.0

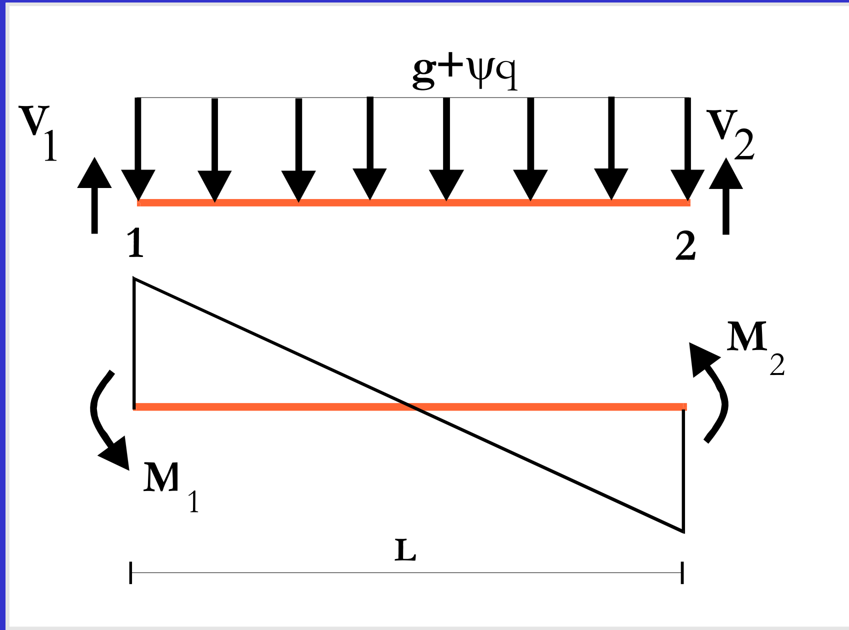
Capacity design of members, against pre-emptive shear failure

I. Beams

Equilibrium of forces and moments on a beam

$$V_1 = V_{g+\psi q,1} + \frac{M_2 + M_1}{l_{cl}}$$

$$V_2 = V_{g+\psi q,2} - \frac{M_1 + M_2}{l_{cl}}$$

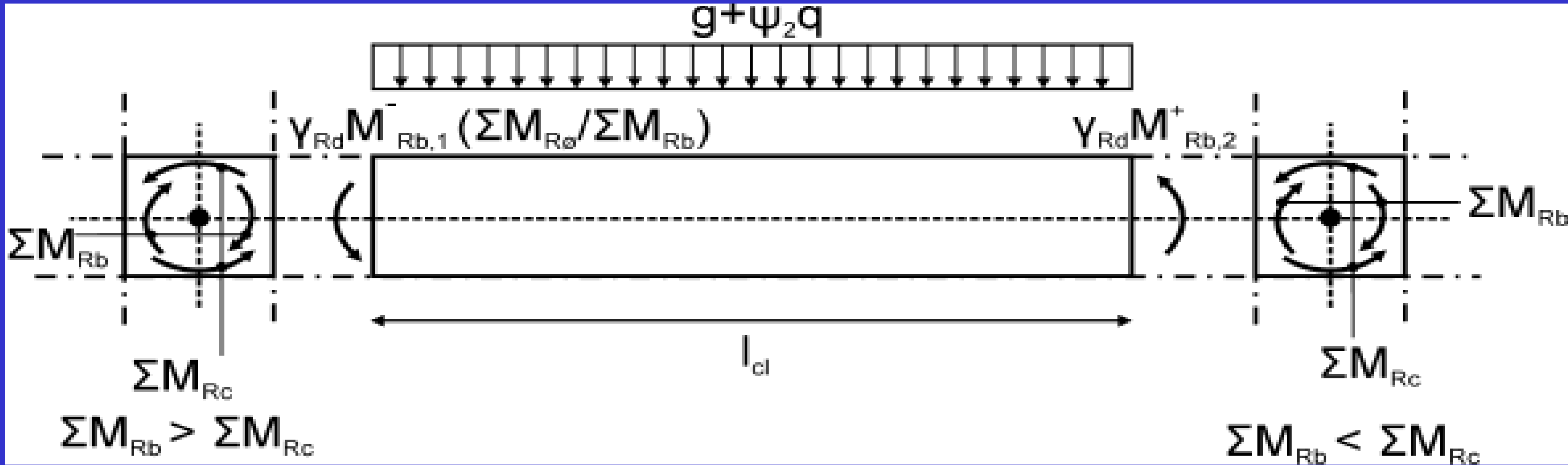


Capacity-design shear in a beam weaker than the columns:

$$V_{CD,1} = V_{g+\psi q,1} + \gamma_{Rd} \frac{M^{-}_{Rd,b1} + M^{+}_{Rd,b2}}{l_{cl}}$$

$$V_{CD,2} = V_{g+\psi q,2} + \gamma_{Rd} \frac{M^{+}_{Rd,b1} + M^{-}_{Rd,b2}}{l_{cl}}$$

Capacity-design shear in beams (weak or strong) - Eurocode 8



$$\max V_{i,d}(x) = \frac{\gamma_{Rd}\left[M_{Rd,bi}^{-}\min\left(1;\frac{\sum M_{Rd,c}}{\sum M_{Rd,b}}\right)_i + M_{Rd,bj}^{+}\min\left(1;\frac{\sum M_{Rd,c}}{\sum M_{Rd,b}}\right)_j \right]}{l_{cl}} + V_{g+\psi q,o}(x)$$

$$\min V_{i,d}(x) = -\frac{\gamma_{Rd}\left[M_{Rd,bi}^{+}\min\left(1;\frac{\sum M_{Rd,c}}{\sum M_{Rd,b}}\right)_i + M_{Rd,bj}^{-}\min\left(1;\frac{\sum M_{Rd,c}}{\sum M_{Rd,b}}\right)_j \right]}{l_{cl}} + V_{g+\psi q,o}(x)$$

Eurocode 8:

- in DC M γ_{Rd}=1.0,
- in DC H γ_{Rd}=1.2 & reversal of V accounted for, depending on: $\zeta_i = \frac{\min V_{i,d}(x_i)}{\max V_{i,d}(x_i)}$

II. Columns

Capacity-design shear in column which is weaker than the beams:

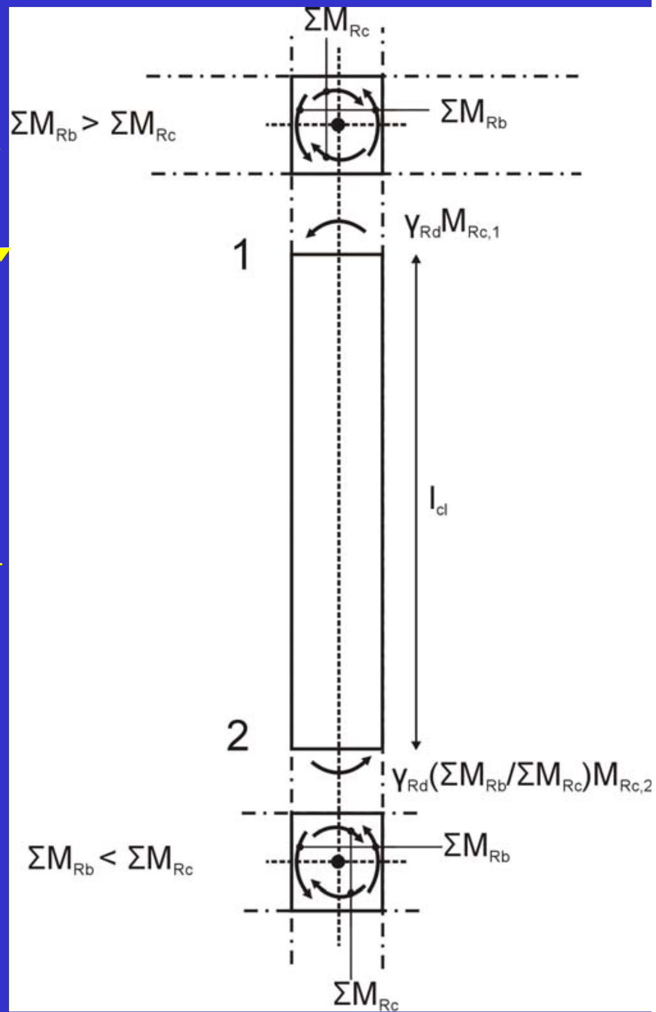
$$V_{CD}^{+}=\gamma_{Rd}\frac{M_{Rd,c1}^{+}+M_{Rd,c2}^{-}}{h_{cl}} \qquad V_{CD}^{-}=\gamma_{Rd}\frac{M_{Rd,c1}^{-}+M_{Rd,c2}^{+}}{h_{cl}}$$

Capacity-design shear in (weak or strong) columns - Eurocode 8:

$$V_{CD,c}=\gamma_{Rd}\frac{M_{Rd,c1}\min\left(1;\frac{\sum M_{Rd,b}}{\sum M_{Rd,c}}\right)_{1}+M_{Rd,c2}\min\left(1;\frac{\sum M_{Rd,b}}{\sum M_{Rd,c}}\right)_{2}}{l_{cl}}$$

Eurocode 8:

- in DC M γ_{Rd}=1.1,
- in DC H γ_{Rd}=1.3



Capacity-design shear in (weak or strong) columns – Other codes:

$$V_{CD}=\gamma_{Rd}\frac{\left[\min\left(M_{Rd,c};\frac{\min(\sum M_{Rd,c},\sum M_{Rd,b})}{\sum|M_{Ec}|}|M_{Ec}|\right)\right]_{1}+\left[\min\left(M_{Rd,c};\frac{\min(\sum M_{Rd,c},\sum M_{Rd,b})}{\sum|M_{Ec}|}|M_{Ec}|\right)\right]_{2}}{l_{cl}}$$

III. Walls

Eurocode 8:

Over-design in shear, by multiplying shear forces from the analysis for the design seismic action, V'_{Ed}, by factor ε:

DC M walls:

$$\varepsilon = \frac{V_{Ed}}{V'_{Ed}} = 1.5$$

DC H squat walls ($h_w/l_w \leq 2$):

Over-design for flexural overstrength of base w.r.to analysis

M_{Edo}: design moment at base section (from analysis),

M_{Rdo}: design flexural resistance at base section,

γ_{Rd}=1.2

$$\varepsilon = \frac{V_{Ed}}{V'_{Ed}} = \gamma_{Rd}\left(\frac{M_{Rdo}}{M_{Edo}}\right) \leq q$$

DC H slender walls ($h_w/l_w > 2$):

Over-design for flexural overstrength of base w.r.to analysis & for increased inelastic shears after plastic hinging at base.

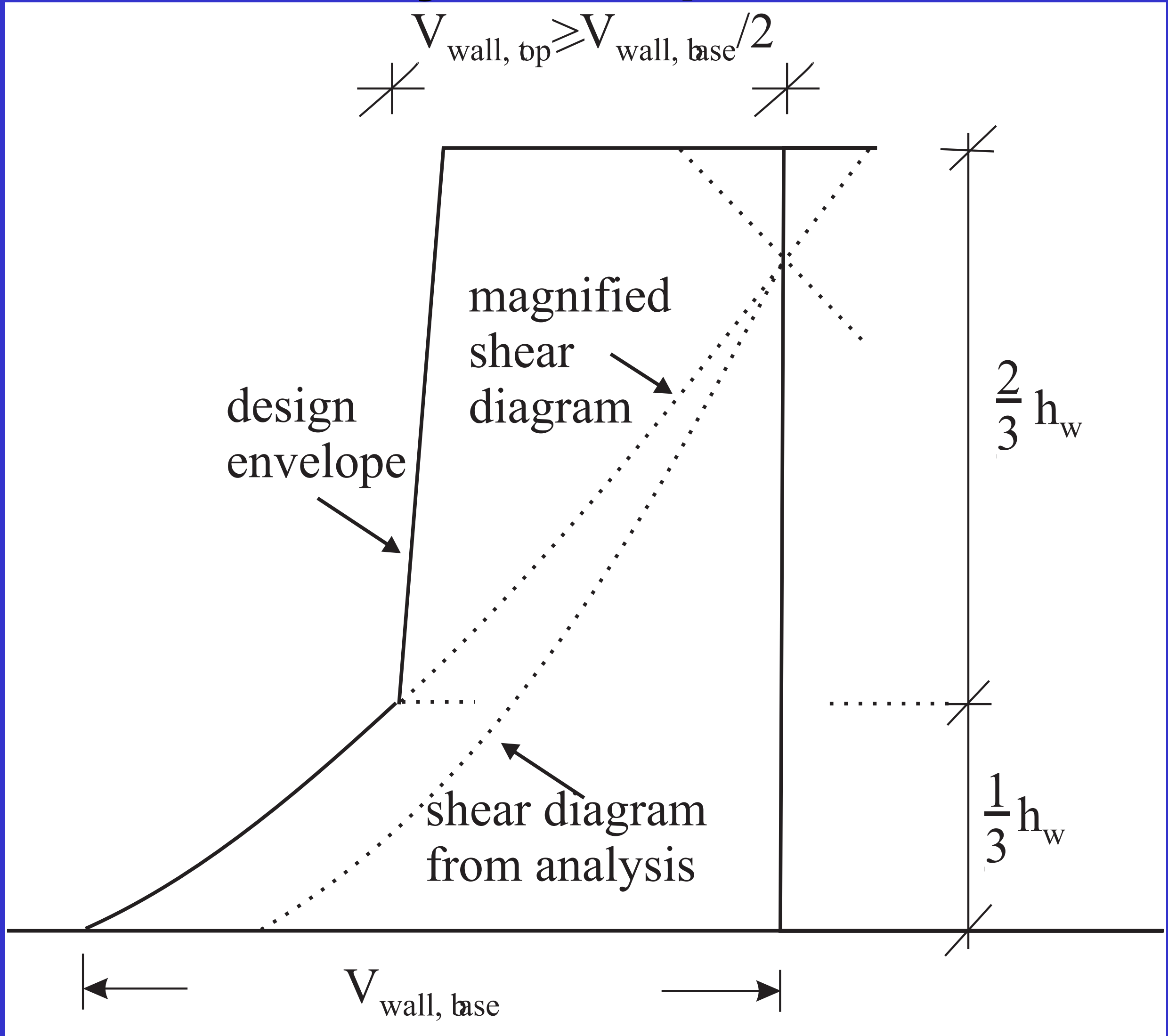
$S_e(T)$: ordinate of elastic response spectrum

T_C : upper limit T of const. spectral acc. region

T_1 : fundamental period.

$$\varepsilon = \frac{V_{Ed}}{V'_{Ed}} = \sqrt{\left(\gamma_{Rd}\frac{M_{Rdo}}{M_{Edo}}\right)^2 + 0.1\left(q\frac{S_e(T_C)}{S_e(T_1)}\right)^2} \leq q$$

Design shear forces in "ductile wall" of dual structural systems per Eurocode 8



To account for increase in upper storey shears due to higher mode inelastic response (after plastic hinging at the base)

Seismic design of the foundation

- **Objective:** The ground and the foundation system should not reach its ULS before the superstructure, i.e. remain elastic while inelasticity develops in the superstructure.
- **Means (in Eurocode 8):**
  - The ground and the foundation system are designed for their ULS under seismic action effects from the analysis derived for q=1.5, i.e. lower than the q-value used for the design of the superstructure; or
  - The ground and the foundation system are designed for their ULS under seismic action effects from the analysis multiplied by $\gamma_{Rd}(R_{di}/E_{di}) \leq q$, where R_{di}= force capacity in the dissipative zone or element controlling the seismic action effect of interest, E_{di}= seismic action effect there from the elastic analysis and γ_{Rd}=1.2
    - For individual spread footings of walls or columns, R_{di}/E_{di} is the minimum value of M_{Rd}/M_{Ed} in the two orthogonal principal directions at the lowest cross-section of the vertical element where a plastic hinge can form in the seismic design situation;
    - For common foundations of more than one elements, $\gamma_{Rd}(R_{di}/E_{di})$ =1.4;

    or
  - The ground is designed for seismic action effects as above, but the foundation system is designed and detailed for ductility like the superstructure.

Implementation of Eurocode 8 seismic design approach for ductility

- Damage limitation (storey drift ratio < 0.5-1%) under the damage limitation earthquake (~50% of "design seismic action"), using 50% of uncracked gross section stiffness.
- Member verification for the Ultimate Limit State (ULS) in bending under the "design seismic action", on the basis of analysis results for elastic spectrum reduced by the behaviour factor q.
- In frames or frame-equivalent dual systems: Fulfil strong column/weak beam capacity design rule, with overstrength factor of 1.3 on beam strengths.
- In walls: ULS dimensioning of wall in bending above the base for overstrength w.r.to analysis results for the "design seismic action".
- Capacity design of members (& joints) in shear.
- Detailing of plastic hinge regions, on the basis of curvature ductility factor derived from the q-factor.