NATIONAL TECHNICAL UNIVERSITY OF ATHENS
LABORATORY OF EARTHQUAKE ENGINEERING

Design of Structures for Earthquake Resistance

Basic principles

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Lecture 2

Performance levels

- Define earthquake loadings with various probabilities of occurrence
- Define various acceptable level of damage
- Combine each earthquake loading with an acceptable level of damage

Frequency of occurrence of the seismic excitation	Performance level →	Very small damage Damage limitation level	Significant damage Collapse prevention	Close to collapse
	Large Frequent earthquakes		unacceptable	unacceptable
	Small Rare earthquakes			
	Very small Very rare earthquakes			

Performance requirements of seismic codes

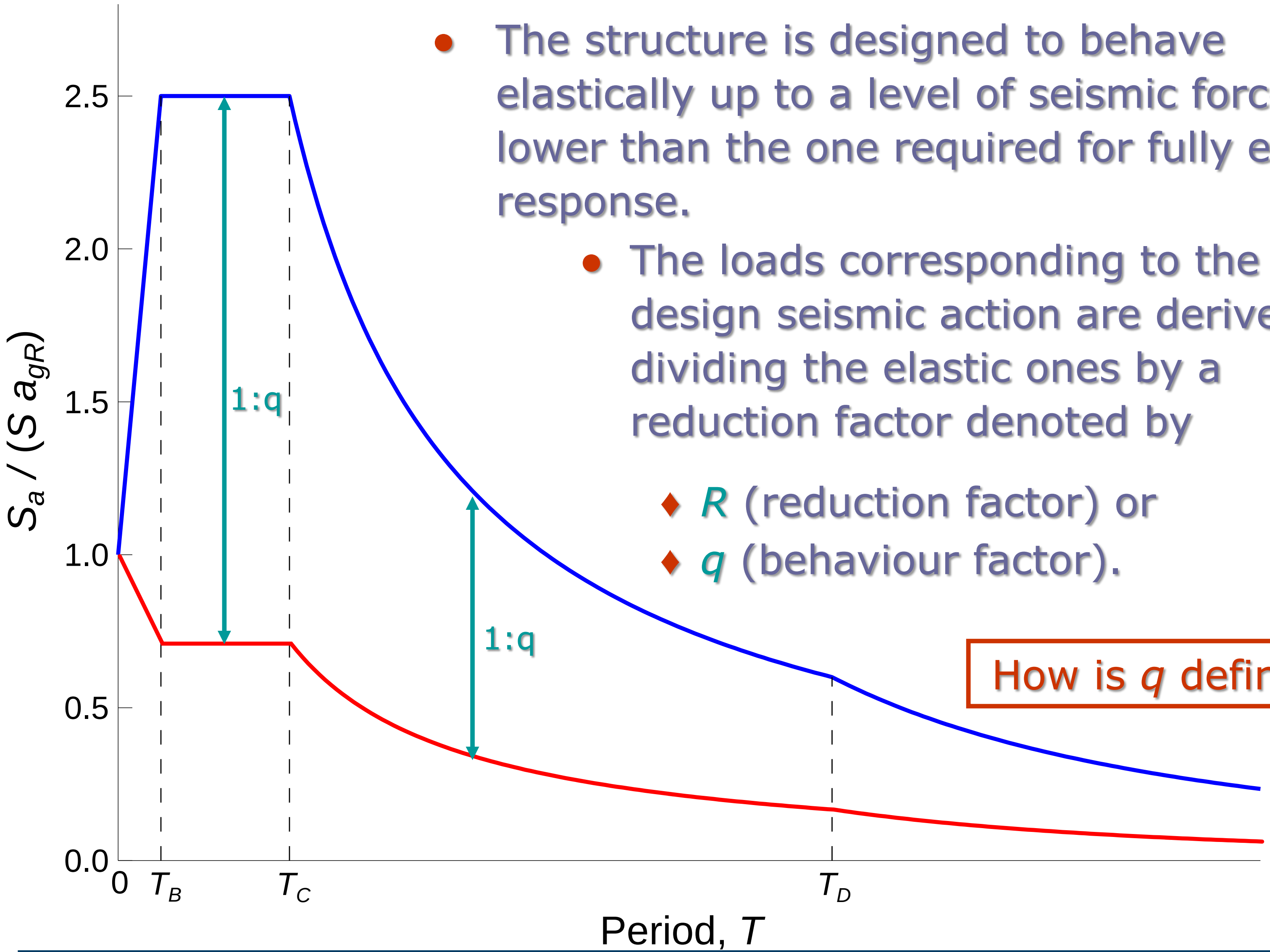
Most codes are based on two performance levels:

- Damage limitation level
  - The structure is expected to experience limited structural and non-structural damage during frequent earthquakes. In this limit state:
    - The structural members retain their strength and stiffness.
    - No permanent deformations and drifts occur.
    - No repair is needed.
  - The seismic action is usually termed as the serviceability earthquake. Reasonable probability of exceedance = 10% in 10 years (mean return period = 95 years).
  - Compliance criteria are usually expressed in terms of deformation limits.

Performance requirements of seismic codes

- Collapse prevention level
  - Ensure prevention of collapse and retention of structural integrity for an earthquake with a small possibility of occurrence during the life of the structure:
    - Significant damage might happen.
    - The structure should be able to bear the vertical loads and retain sufficient lateral strength and stiffness to protect life during aftershocks.
  - The seismic action is referred as the design earthquake. For structures of ordinary importance: 10% probability of exceedance in 50 years (mean return period of 475 years).
  - Compliance criteria are expressed in terms of forces (force-based seismic design).

Design concept



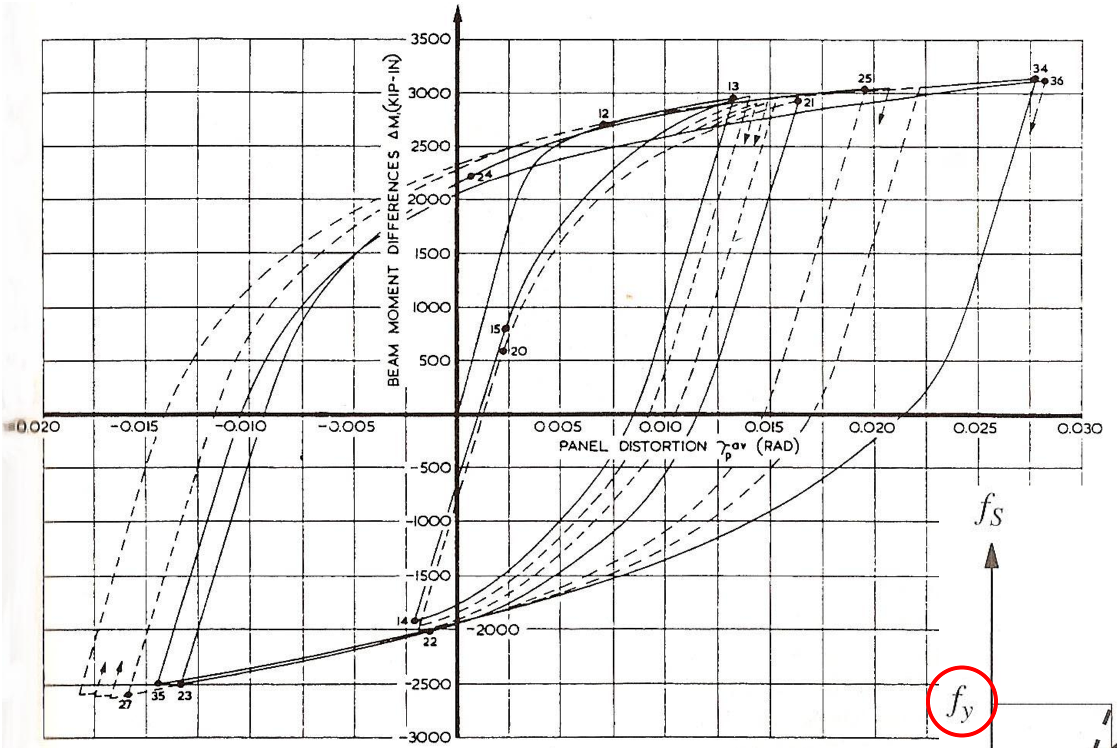
- The structure is designed to behave elastically up to a level of seismic forces lower than the one required for fully elastic response.
  - The loads corresponding to the design seismic action are derived by dividing the elastic ones by a reduction factor denoted by
    - *R* (reduction factor) or
    - *q* (behaviour factor).

How is *q* defined?

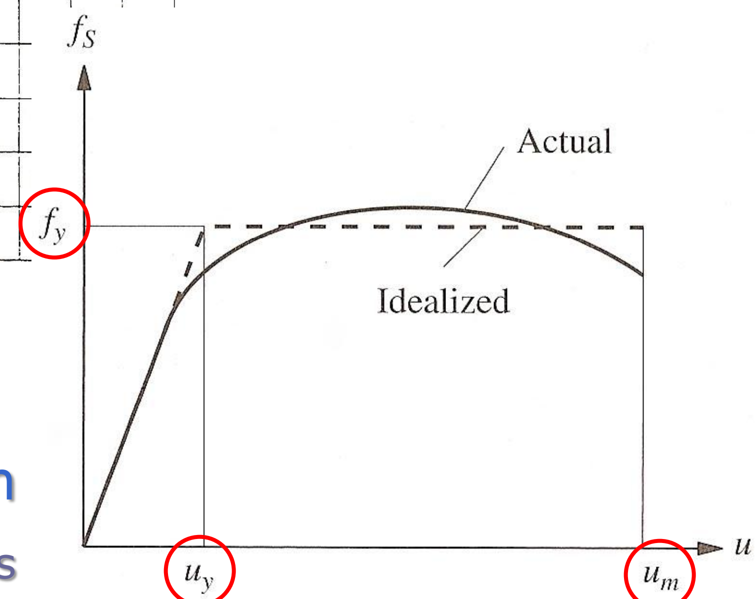
Ductility capacity

- The collapse mechanism of the structural members is related to their deformation and not to the forces induced to them during the seismic action.
- In order to comply with the non-collapse criterion, an overall ductile behaviour should be ensured.
- In other words: the structure should have an adequate capacity to deform beyond its elastic limit without substantial reduction in the overall resistance against horizontal and vertical loads.
- This is achieved through proper dimensioning and detailing of the structural elements.
- In addition, capacity design concepts are applied, in order to ensure that ductile modes of failure (e.g. flexure) should precede brittle modes of failure (e.g. shear) with sufficient reliability.

Nonlinear response



Force-deformation relation



Elastoplastic idealization

Same area under the two curves

Basic definitions

- Yield strength behaviour factor:

$$q_y = \frac{f_e}{f_y}$$

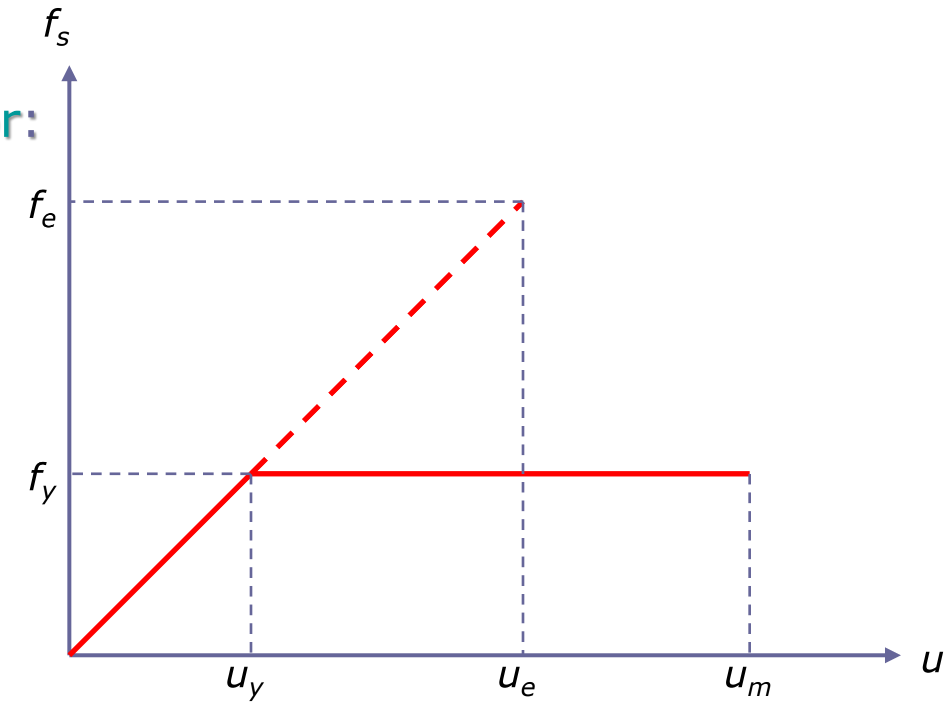
- Ductility factor:

$$\mu = \frac{u_m}{u_y}$$

- It can easily be proved:

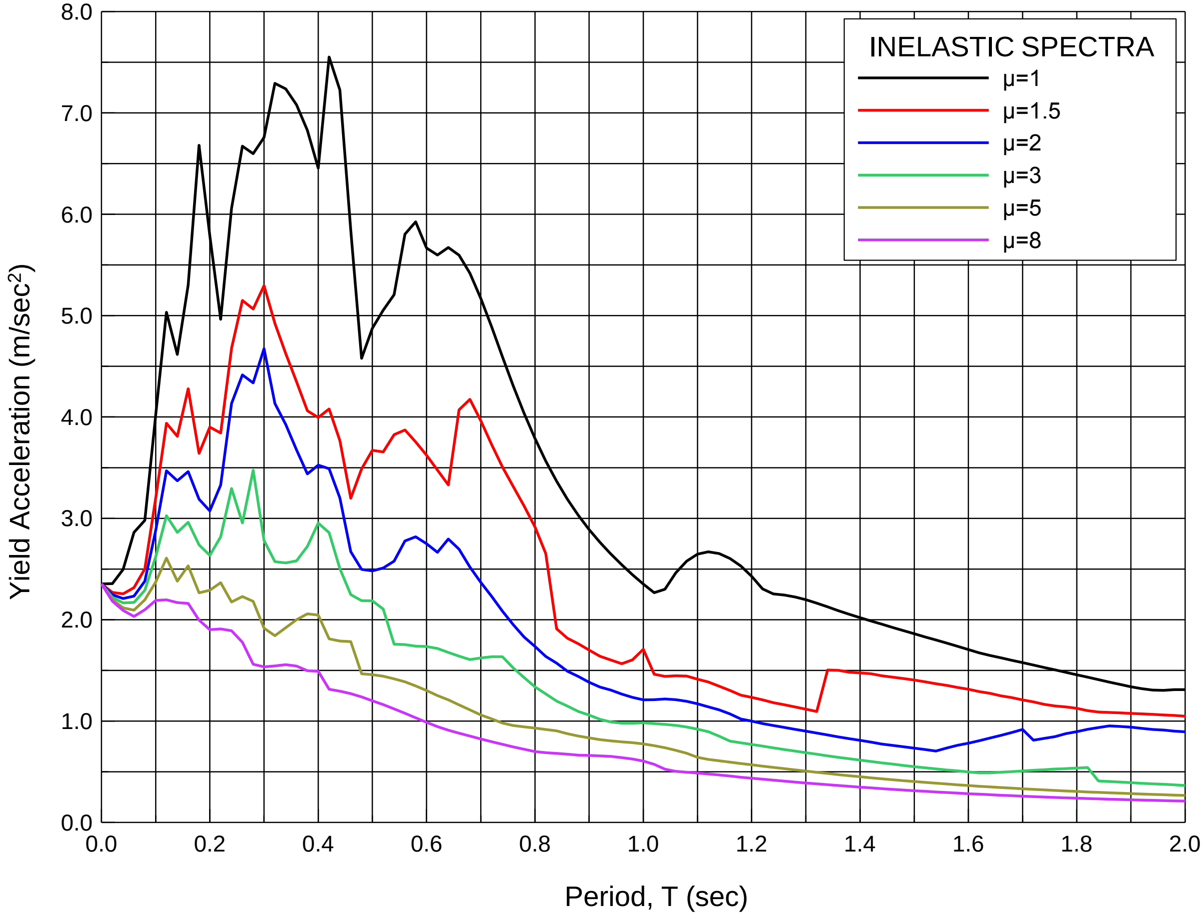
$$\frac{u_m}{u_e} = \frac{\mu}{q_y}$$

- As larger is μ as larger is the plastic deformation $\Rightarrow$ more damage.
- For μ close to 1, the response is close to the elastic.



Inelastic response spectra

Inelastic spectra for constant ductility



Ductility factor

- The damage that will be induced to the structure is directly related to the ductility factor, μ.
- For the non-collapse performance criterion, certain values can be assigned to the allowable maximum value of μ, depending on:
  - The material (ductile or brittle).
  - The structural system (the more isostatic is the structure the less is the allowable value of μ).
  - The structural irregularities in plan or in elevation and the torsional sensitivity (reduce the allowable value of μ).
  - The connections and the bracing types (steel structures).

Relations q_y - μ

- For $T>T_C$ the equal displacement assumption is made:

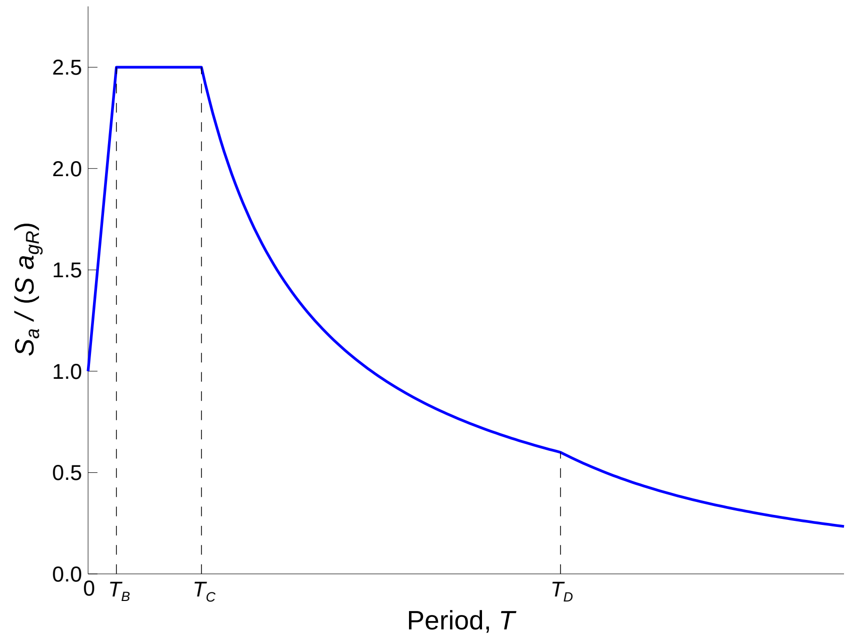
$$q_y = \mu$$

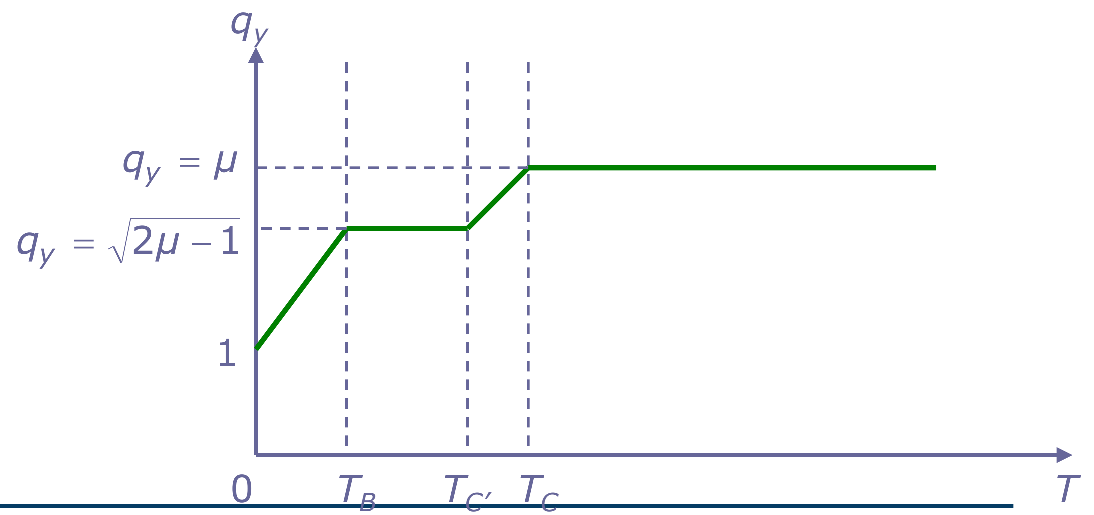
- For $T_B<T<T_{C'}$ the equal energy assumption is made:

$$q_y = \sqrt{2\mu - 1}$$

- For T close to zero (very stiff structures) the response is elastic:

$$q_y = 1$$





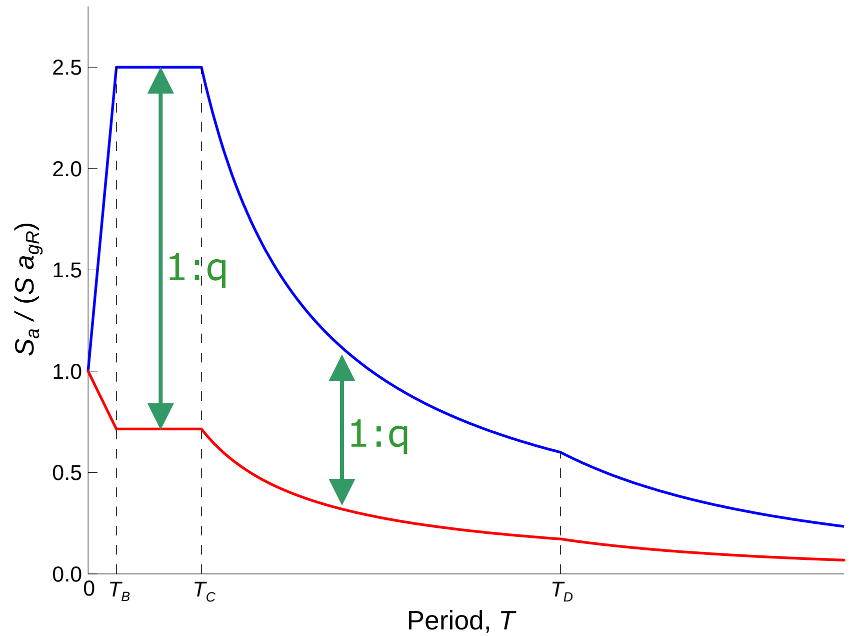
Design value of q

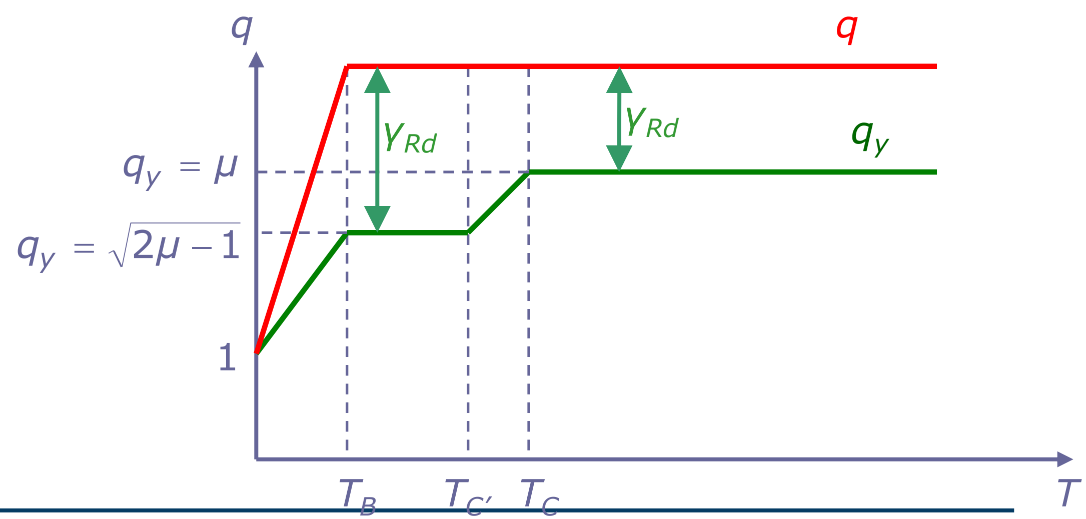
Design value of the behaviour factor:

$$q = \gamma_{Rd} \cdot q_y$$

(γ_{Rd}= overstrength)

- Usually, rigid structures possess larger overstrength than flexible ones $\Rightarrow$ we usually assume constant value of q for $T>T_B$.





Ductility classes (EC8)

- Ductility Class High (DCH)
  - Strict detailing criteria should be fulfilled.
  - Provides higher safety margins against local or global collapse under seismic actions stronger than the design earthquake.
- Ductility Class Medium (DCM)
  - Compared to DCH, certain detailing rules are relaxed.
  - The design leads to slightly easier to construct structures.
  - Provides good performance during moderate earthquakes.
- Ductility Class Low (DCL)
  - For low seismicity areas.
  - The structure is designed according to EC2 without special seismic considerations.
  - Large values of q are allowed.

Proper detailing

Aims to:

- provide the structure with an adequate capacity to deform beyond its elastic limit without substantial reduction of the overall resistance against horizontal and vertical loads.

Example for concrete structures:

Special rules are applied for the confinement reinforcement (stirrups) at column-to-beam joints and at critical regions of columns and beams.

Capacity design

Aims to:

- ensure that ductile modes of failure (e.g. flexure) should precede brittle modes of failure (e.g. shear) with sufficient reliability
- prevent the formation of a soft-story mechanism
- ensure that certain parts of the structure will remain elastic if it is so desired (e.g. foundation, bridge deck, etc.)

Example for concrete structures:

At column-to-beam joints, the sum of the design values of the moments of resistance of the columns should be larger than 1.3×the sum of the design values of the moments of resistance of the beams:

$$\sum M_{Rc} \geq 1.3 \cdot \sum M_{Rb}$$

Design procedure

- Define the seismic loads for:
  - The appropriate seismicity, the soil conditions at the site and the importance of the structure.
  - The appropriate value of the behaviour factor, *q*
    - Material
    - Structural system
    - Irregularites
    - Ductility class
- Perform a structural analysis of the structure for the seismic and non-seismic loads, assuming elastic response.
- Combine the individual load cases according to the code provisions to get the envelop of the member loads.

Design procedure (cont'd)

- Perform the dimensioning of the beams in flexure.
- Check the beams in shear using the capacity design approach (based on the flexural strength of the beams).
- Perform the dimensioning of the columns in flexure using the capacity design approach (based on the flexural strength of the beams framing with the columns at the joints).
- Check columns in shear using the capacity design approach (based on the flexural strength of the columns).
- Perform a detailed dimensioning of the joints in order to assure their integrity during the design earthquake.
- Perform the dimensioning of the foundation using the capacity design approach (based on the flexural strength of the columns).
- Design displacements: $d = q \cdot d_E$, d_E = from seismic analysis.