EU-Russia Regulatory Dialogue: Construction Sector Subgroup

Seminar 'Bridge Design with Eurocodes'

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TC250 Structural Eurocodes

Seismic design of bridges with Eurocode 8

Eduardo Carvalho
GAPRES SA, Chairman CEN/TC250/SC8

















Eurocode 8 - Design of structures for earthquake resistance

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

EN1998-2: **Bridges**

EN1998-2 to be applied in combination with EN1998-1, EN 1998-5 and the other Eurocodes

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1998-2 : 2005

August 2005

UDC

Descriptors:

English version

Eurocode 8 : Design of structures for earthquake resistance

Part 2: Bridges

Calcul des structures pour leur résistance aux séismes	Auslegung von Bauwerken gegen Erdbeben
Partie 2 : Ponts	Teil 2 : Brücken

Stage 64

CEN

European Committee for Standardisation
Comité Européen de Normalisation
Europäisches Komitee für Normung

Central Secretariat: rue de Stassart 36, B-1050 Brussels

 Ref. No. EN 1998-2 : 2005 (E)

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EN1998-2: **Bridges**

	NDPs
• Introduction	(1)
• Basic requirements and compliance criteria	(8)
• Seismic action	(4)
• Analysis	(2)
• Strength verification	(4)
• Detailing	(5)
• Bridges with seismic isolation	(4)
8 Annexes	(2)

EN1998-2: Bridges

ANNEXES

- **A** (Informative): Probabilities related to the reference seismic action. Guidance for the selection of the design **seismic action during the construction phase**
- **B** (Informative): Relationship between **displacement ductility and curvature ductility factors** of plastic hinges in concrete piers
- **C** (Informative): Estimation of the **effective stiffness** of reinforced concrete ductile members
- **D** (Informative): **Spatial variability** of earthquake ground motion: Model and methods of analysis
- **E** (Informative): Probable material properties and **plastic hinge deformation capacities** for nonlinear analysis
- **F** (Informative): **Added mass** of entrained water for immersed piers
- **G** (**Normative**): Calculation of **capacity design** effects
- **H** (Informative): Static non-linear analysis (**Pushover**)
- **J** (**Normative**): Variation of **design properties of seismic isolator units**
- **JJ** (Informative): **λ-factors** for common isolator types
- **K** (Informative): **Tests for validation** of design properties of sesimic isolator units

Objectives of EN 1998

In the event of earthquakes:

Human lives are protected

Damage is limited

Structures important for civil protection remain operational

Special structures – Nuclear Power Plants, Offshore structures, Large Dams **– outside the scope of EN 1998**

Fundamental requirements

No-collapse requirement:

Withstand the design seismic action **without** local or global **collapse**

Retain structural integrity and **residual load bearing** capacity after the event (even with considerable damage)

Flexural yielding of piers allowed. Bridge deck expected to avoid damage

For ordinary structures this requirement should be met for a **reference seismic action** with 10 % probability of exceedance in 50 years (recommended value) i.e. with **475 years Return Period**

Fundamental requirements

Minimisation of Damage

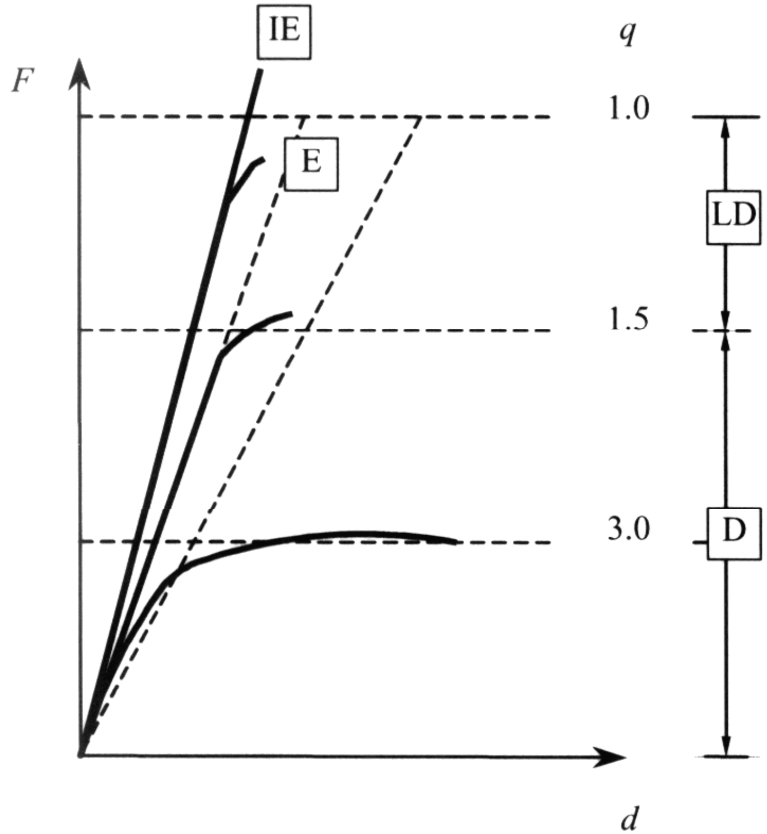
Withstand a more frequent seismic action without damage (remaining operational without interruption)

Minor damage only in secondary components (and/or in parts specifically intended to dissipate energy)

For ordinary structures this requirement should be met for a seismic action with "***high probability of occurrence***".
No recommended value is given (10 % probability of exceedance in 10 years i.e. with 95 years Return Period could be used)

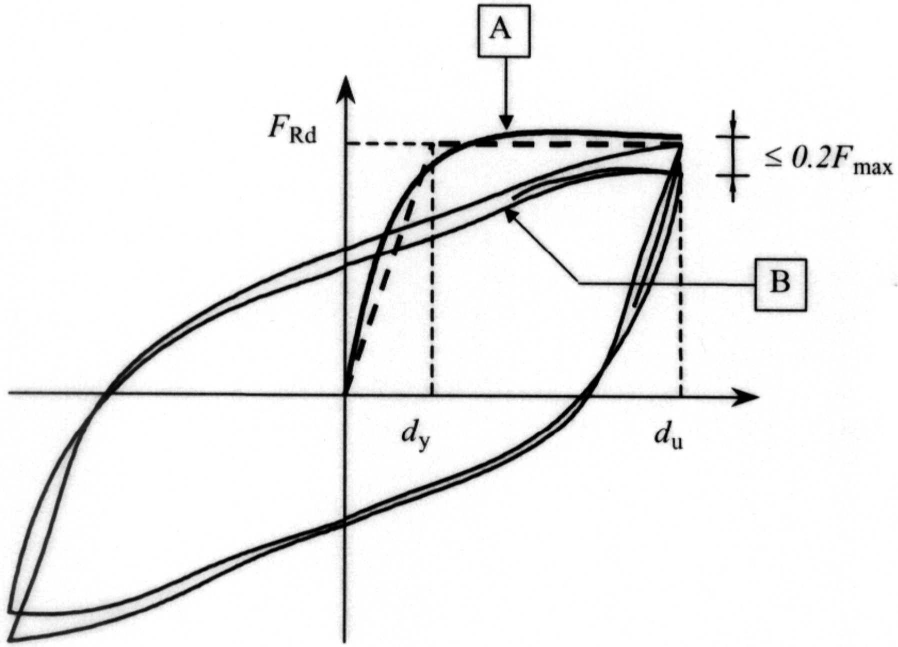
Intended seismic behaviour

- Ductile (D)
- Limited ductile/essentially elastic (LD)



Ductile behaviour

- Provide for the formation of an intended configuration of flexural plastic hinges
- The bridge deck shall remain within the elastic range
- Global F-D relation with a significant force plateau at yield. Ensure hysteretic energy dissipation over at least 5 inelastic deformation cycles



Ductile behaviour

- **Resistance verifications** (for **Reinforced Concrete** in accordance with Eurocode 2, with some additional rules for shear and for **Steel Structures** in accordance with Section 6 of EN 1998-1 for dissipative structures)
- **Capacity design:** Shear and joints
- **Overstrength factors**
- **Detailing for ductility:** Global ductility μ_d and local ductility μ_{φ} (curvature) and μ_{θ} (rotation)
- **Ductility verification:** Deemed to satisfy rules in Section 6

Limited ductility/Essentially elastic

- Deviation from ideal elastic provides some hysteretic energy dissipation.
- Corresponds to a value of the behaviour factor $q \leq 1,5$
- Values of q in the range $1 \leq q \leq 1,5$ are mainly attributed to the inherent margin between design and probable strength in the seismic design situation (*overstrength*)

Reliability differentiation

Target reliability of requirement depending on consequences of failure

- Classify the structures into **importance classes**
- Assign a **higher or lower return period** to the design seismic action

In operational terms multiply the reference seismic action by the **importance factor** γ_I

Importance classes for bridges

Class III: Bridges of critical importance for maintaining communications, especially in the immediate post-earthquake period; bridges the failure of which is associated with a large number of probable fatalities and major bridges where a design life greater than normal is required

Class II: General road and railway bridges (average importance)

Class I: Bridges meeting the following conditions simultaneously (less than average importance):

− the bridge is not critical for communications, and

− the adoption of either the reference probability of exceedance, *PNCR, in 50 years for the* design seismic action, or of the standard bridge design life of 50 years is not economically justified.

Importance factors for bridges (recommended values):

$$\gamma_I = 1{,}3;\ 1{,}0 \text{ and } 0{,}85$$

Importance factor and return period

At most sites the annual rate of exceedance, $H(a_{gR})$, of the reference peak ground acceleration a_{gR} may be taken to vary with a_{gR} as: $\mathbf{H(a_{gR}) \sim k_0\, a_{gR}^{-k}}$ with the value of the exponent k depending on seismicity, but being generally of the order of 3.

If the seismic action is defined in terms of the reference peak ground acceleration a_{gR}, the value of the importance factor γ_I to achieve the same probability of exceedance in T_L years as in the T_{LR} years for which the reference seismic action is defined, may be computed as: $\gamma_I \sim (T_{LR}/T_L)^{-1/k}$

Hence, the implicit return periods for the 3 Importance Classes are:

Class III: 1.044 years (~ 5% in 50 years)

Class II: 475 years (10% in 50 years)

Class I: 292 years (~15% in 50 years)

Ground conditions

Five ground types:

A - Rock

B - Very dense sand or gravel or very stiff clay

C - Dense sand or gravel or stiff clay

D - Loose to medium cohesionless soil or soft to firm cohesive soil

E - Surface alluvium layer C or D, 5 to 20 m thick, over a much stiffer material

2 special ground types S_1 and S_2 requiring special studies

Ground conditions defined by **shear wave velocities** in the **top 30 m** and also by indicative values for N_{SPT} and c_u

Ground conditions

Table 3.1: Ground types

Ground type	Description of stratigraphic profile	Parameters		
		$v_{s,30}$ (m/s)	N_{SPT} (blows/30cm)	c_u (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.	> 800	_	_
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, characterised by a gradual increase of mechanical properties with depth.	360 – 800	> 50	> 250

Ground conditions

Table 3.1: Ground types

Ground type	Description of stratigraphic profile	Parameters		
		$v_{s,30}$ (m/s)	N_{SPT} (blows/30cm)	c_u (kPa)
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of metres.	180 – 360	15 - 50	70 - 250
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil.	< 180	< 15	< 70

Ground conditions

Table 3.1: Ground types

Ground type	Description of stratigraphic profile	Parameters		
		$v_{s,30}$ (m/s)	N_{SPT} (blows/30cm)	c_u (kPa)
E	A soil profile consisting of a surface alluvium layer with v_s values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with $v_s > 800$ m/s.			
S_1	Deposits consisting, or containing a layer at least 10 m thick, of soft clays/silts with a high plasticity index (PI > 40) and high water content	< 100 (indicative)	_	10 - 20
S_2	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in types A – E or S_1			

Seismic zonation

Competence of National Authorities

Described by a_{gR} (reference peak ground acceleration on type A ground)

Corresponds to the **reference return period** T_{NCR}

Modified by the Importance Factor γ_I to become the **design ground acceleration** (on type A ground) $a_g = a_{gR} \cdot \gamma_I$

Objective for the future updating of EN1998-1:
European zonation map with **spectral values** for **different hazard levels** (e.g. 100, 500 and 2.500 years)

Basic representation of the seismic action

Elastic response spectrum

Common shape for the ULS and DLS verifications

2 orthogonal **independent** horizontal **components**

Vertical spectrum shape **different** from the horizontal spectrum (common for all ground types)

Possible use of **more than one spectral shape** (to model different seismo-genetic mechanisms)

Account of **topographical effects** (EN 1998-5) and **spatial variation** of motion (EN1998-2) required in some special cases

Definition of the horizontal elastic response spectrum

(four branches)

$0 \le T \le T_B \quad S_e(T) = a_g \cdot S \cdot (1 + T/T_B \cdot (\eta \cdot 2{,}5 - 1))$

$T_B \le T \le T_C \quad S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5$

$T_C \le T \le T_D \quad S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5\,(T_C / T)$

$T_D \le T \le 4\,\mathrm{s} \quad S_e(T) = a_g \cdot S \cdot \eta \cdot 2{,}5\,(T_C \cdot T_D / T^2)$

$S_e(T)$	**elastic** response spectrum
a_g	**design ground acceleration** on type A ground
T_B T_C T_D	**corner periods** in the spectrum (NDPs)
S	**soil** factor (NDP)
η	**damping** correction factor (η = 1 for 5% damping)

Additional **information** for $T > 4$ s in Informative Annex in EN 1998-1

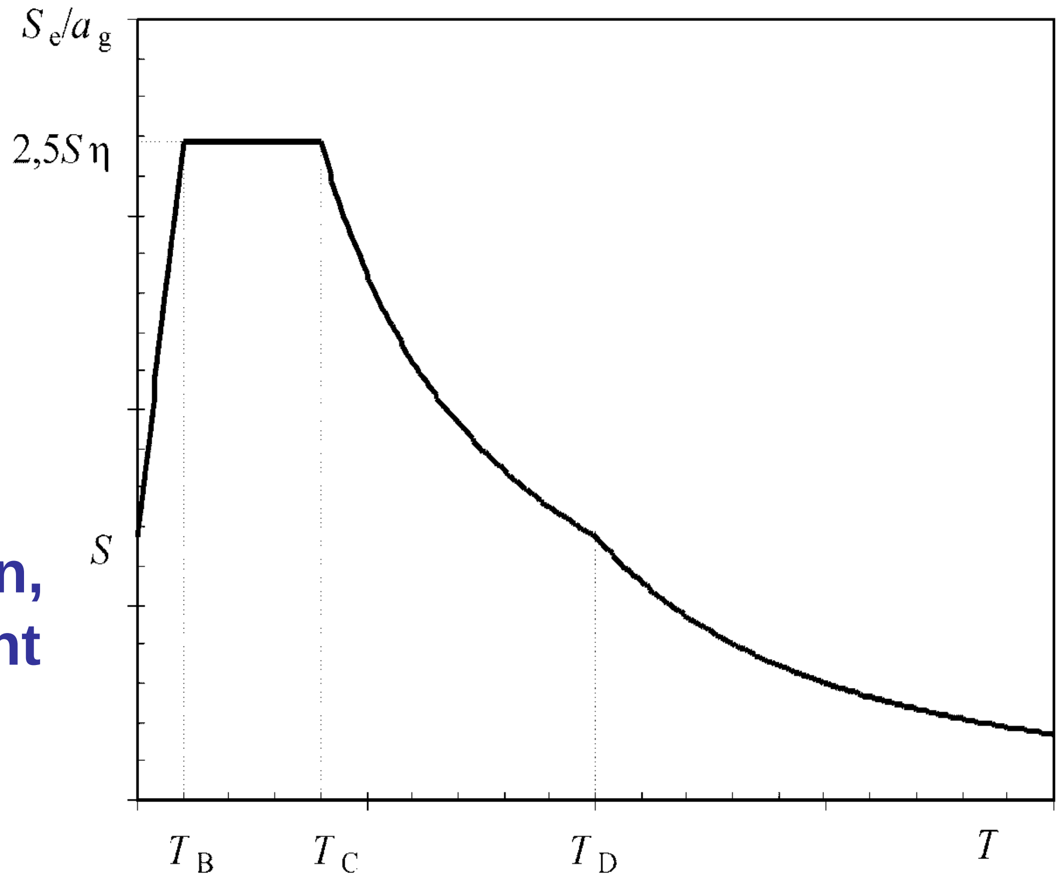
Normalised elastic response spectrum (standard shape)

Control variables

- S, T_B, T_C, T_D (NDPs)
- η ($\geq$ 0,55) damping correction for $\xi \neq 5$ %

Fixed variables

- Constant acceleration, velocity & displacement spectral branches
- acceleration spectral amplification: 2,5



Different spectral shape for **vertical spectrum** (spectral amplification: **3,0**)

Correction for damping

$$\eta = \sqrt{10/(5+\xi)} \geq 0{,}55$$

To be applied only to elastic spectra

Elastic response spectrum

Two types of (recommended) spectral shapes

Depending on the characteristics of the most significant earthquake contributing to the local hazard:

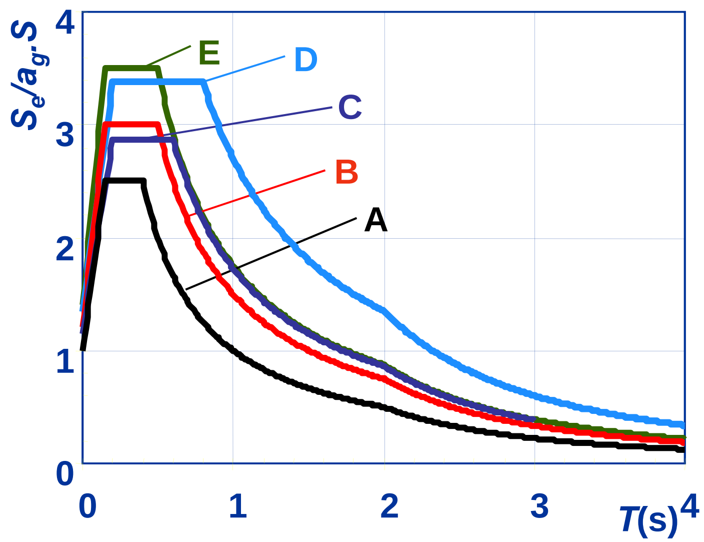
- **Type 1 - High and moderate seismicity regions ($M_s > 5,5$)**
- **Type 2 - Low seismicity regions ($M_s \leq 5,5$); near field earthquakes**

Optional account of **deep geology effects** (NDP) for the definition of the seismic action

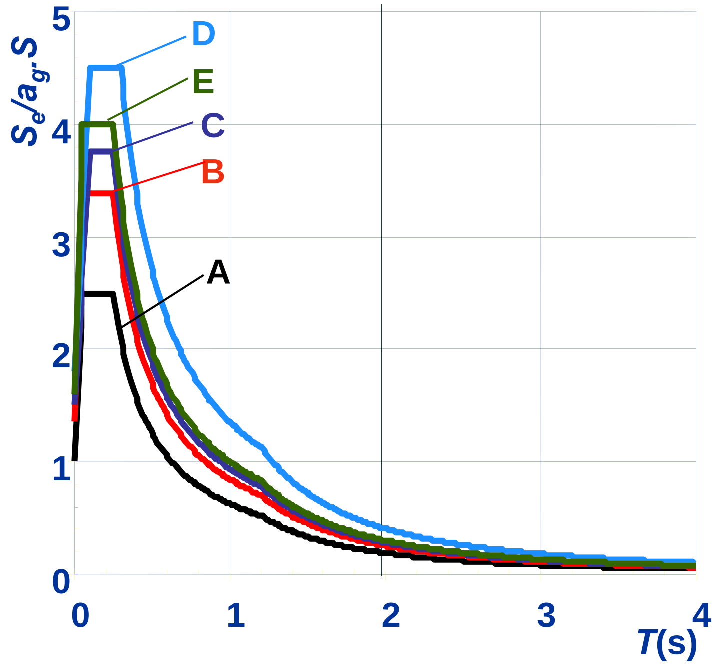
Recommended parameters for the definition of the response spectra for various ground types

	Seismic action Type 1				Seismic action Type 2			
Ground Type	S	T_B (s)	T_C (s)	T_D (s)	S	T_B (s)	T_C (s)	T_D (s)
A	**1,0**	**0,15**	**0,4**	**2,0**	**1,0**	**0,05**	**0,25**	**1,2**
B	**1,2**	**0,15**	**0,5**	**2,0**	**1,35**	**0,05**	**0,25**	**1,2**
C	**1,15**	**0,2**	**0,6**	**2,0**	**1,5**	**0,1**	**0,25**	**1,2**
D	**1,35**	**0,2**	**0,8**	**2,0**	**1,8**	**0,1**	**0,3**	**1,2**
E	**1,4**	**0,15**	**0,5**	**2,0**	**1,6**	**0,05**	**0,25**	**1,2**

Recommended elastic response spectra



Type 1 - $M_S > 5{,}5$



Type 2 - $M_S \leq 5{,}5$

Design spectrum for elastic response analysis

(derived from the elastic spectrum)

$0 \leq T \leq T_B \qquad S_d(T) = a_g \cdot S \cdot (2/3 + T/T_B \cdot (2{,}5/q - 2/3))$

$T_B \leq T \leq T_C \qquad S_d(T) = a_g \cdot S \cdot 2{,}5/q$

$T_C \leq T \leq T_D \qquad S_d(T) = a_g \cdot S \cdot 2{,}5/q \cdot (T_C/T)$
$\geq \beta \cdot a_g$

$T_D \leq T \leq 4\text{ s} \qquad S_d(T) = a_g \cdot S \cdot 2{,}5/q \cdot (T_C \cdot T_D/T^2)$
$\geq \beta \cdot a_g$

$S_d(T)$ **design** spectrum

q **behaviour factor**

β **lower bound** factor (NDP recommended value: **0,2**)

Specific rules for **vertical action**:

$a_{vg} = 0{,}9 \cdot a_g$ or $a_{vg} = 0{,}45 \cdot a_g$; $S = 1{,}0$; $q \leq 1{,}5$

Alternative representations of the seismic action

Time history representation (essentially for NL analysis purposes)

Three simultaneously acting accelerograms

- **Artificial accelerograms**
  Match the elastic response spectrum for 5% damping
  Duration compatible with Magnitude ($T_s \geq$ 10 s)
  Minimum number of accelerograms: 3

- **Recorded or simulated accelerograms**
  Scaled to $a_g \cdot S$
  Match the elastic response spectrum for 5% damping

Spatial variability of the seismic action

Spatial variability shall be considered if one of the following holds:

- More than one ground type occurs in the supports of the bridge
- The length of continuous deck exceeds $L_{lim} = L_g/1,5$
  L_g - Distance beyond which motion is uncorrelated

Ground Type	A	B	C	D	E
L_g (m)	600	500	400	300	500

Recommended values

Simplified model for accounting for the spatial variability and additional information in Annex D

Modelling - Mass

- **Mass** of Permanent loads and Quasi-permanent values of the Variable loads (ψ_2 Q_k)
  (For traffic loads: ψ_2 **= 0,2 in road bridges**; ψ_2 **= 0,3 in railway bridges**)

- Mass of **entrained water** added to the mass of immersed piers
  (Procedure for calculation in **Informative Annex F**)

- **Damping ratio** values for elastic analysis :
  - Welded steel: $\xi = 0{,}02$
  - Bolted steel: $\xi = 0{,}04$
  - Presstressed concrete: $\xi = 0{,}02$
  - Reinforced concrete : $\xi = 0{,}05$

Modelling - Stiffness

- For linear analysis methods adopt the **secant flexural stiffness** at yield (in Limited Ductile bridges the unreduced stiffness of gross concrete sections may be used)
- For Prestressed and Reinforced **concrete decks** the flexural stiffness of the **gross sections** should be used
- Reduced **torsional stiffness** of concrete decks:
  - Open sections: Ignore torsional stiffness
  - Presstressed box sections: 50% stiffness
  - Reinforced concrete box sections: 30% stiffness

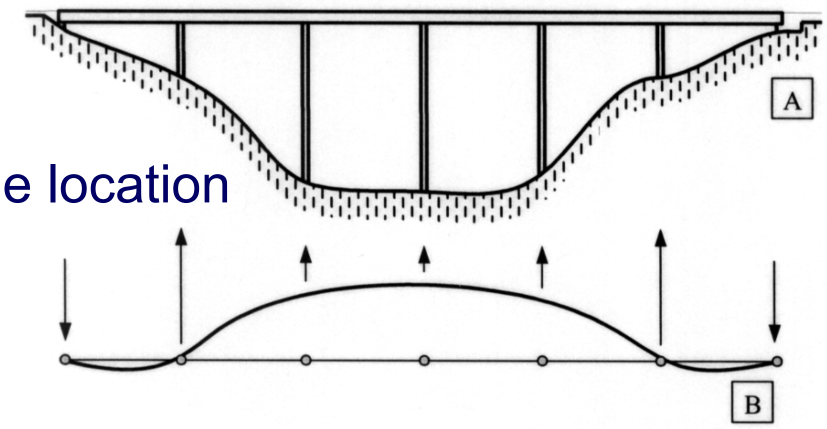
Regularity

- Local **force reduction factor** (for member i):

  $r_i = q\, M_{Ed,i} \,/\, M_{Rd,i}$

  $M_{Ed,i}$ - Maximum value of design moment at the intended plastic hinge location from the analysis

  $M_{Ed,i}$ - Design flexural resistance with actual reinforcement



- A bridge is considered **regular** if:

  $\rho = r_{max} \,/\, r_{min} \leq \rho_0$ (recommended value $\rho_0 = 2{,}0$)

- For **irregular bridges** the ***q* factor is reduced**:

  $q_r = q\, \rho_0 \,/\, \rho \geq 1{,}0$

Regularity of the bridge conditions the admissible methods of analysis

Methods of Analysis

- **Linear dynamic analysis – Response spectrum method**

  Significant modes: Sum of effective mass > 0,9 total mass

  Combination of modes:

  Square root of the sum of squares (SRSS) or

  Complete Quadratic Combination (CQC) for closely spaced modes

  Combination of components of seismic action:

  Square root of the sum of squares (SRSS) of each component

- **Fundamental mode method** (static forces)

  Field of application limited to very simple situations (Rigid deck model; Flexible deck model and Individual pier model)

- **Nonlinear dynamic time history analysis**
- **Static nonlinear analysis (pushover analysis)**

Maximum values of the behaviour factor q

Valid for normalized axial load: $\eta_k \leq 0,3$

Type of Ductile Members	Seismic Behaviour	
	Limited Ductile	Ductile
Reinforced concrete piers:		
Vertical piers in bending	1,5	$3,5\ \lambda(\alpha_s)$
Inclined struts in bending	1,2	$2,1\ \lambda(\alpha_s)$
Steel Piers:		
Vertical piers in bending	1,5	3,5
Inclined struts in bending	1,2	2,0
Piers with normal bracing	1,5	2,5
Piers with eccentric bracing	-	3,5
Abutments rigidly connected to the deck:		
In general	1,5	1,5
Locked-in structures (see. **4.1.6(9), (10)**)	1,0	1,0
Arches	1,2	2,0

* $\alpha_s = L_s/h$ is the shear span ratio of the pier, where L_s is the distance from the plastic hinge to the point of zero moment and h is the depth of the cross-section in the direction of flexure of the plastic hinge.

For $\alpha_s \geq 3$ $\quad \lambda(\alpha_s) = 1,0$

$3 > \alpha_s \geq 1,0$ $\quad \lambda(\alpha_s) = \sqrt{\frac{\alpha_s}{3}}$

Correction of values of the behaviour factor q

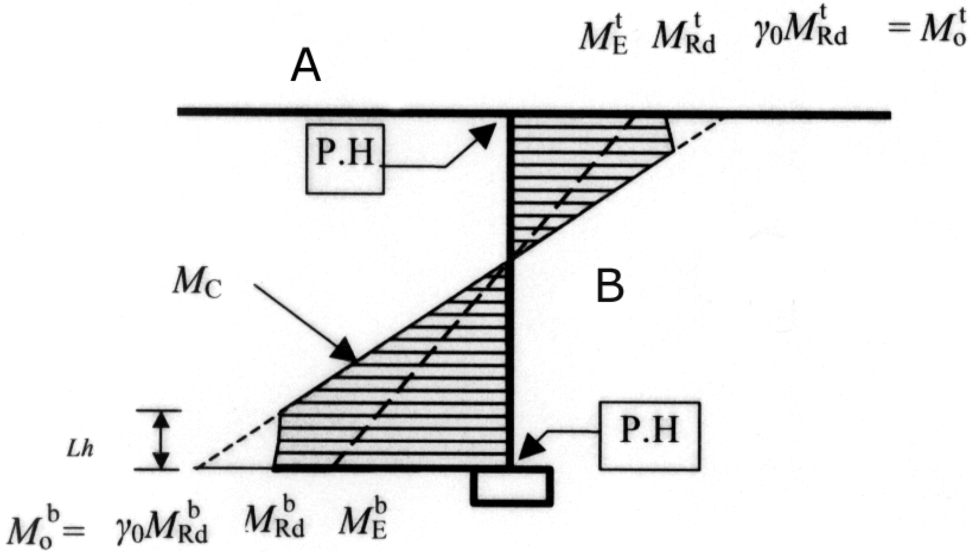
- Reduction for **normalised axial load** η_k for $0,3 < \eta_k \leq 0,6$:

  $$q_r = q - ((\eta_k - 0,3) / 0,3) \times (q - 1) \geq 1,0$$

- If locations of plastic hinges are **not accessible** for inspection and repair:

  $$q_r = 0,6 \times q \geq 1,0$$

Capacity Design



M_E - Moment (from the analysis) at the plastic hinge location
M_{Rd} - Design flexural resistance with actual reinforcement
$M_0 = \gamma_0 M_{Rd}$ - **Overstrength moment** (for the calculation of shear)

Recommended values:

For concrete members $\gamma_0 = 1,35$
For steel members $\gamma_0 = 1,25$

Detailing

- Confinement of concrete piers
- Avoidance of buckling of longitudinal reinforcement
- Foundations
- Bearings and seismic links
- Abutments and retaining walls

Seismic Displacements

Seismic displacement: $d_E = \pm \eta \mu_d d_{Ee}$

d_{Ee} displacement computed with the design spectrum (including the q factor)

η damping correction factor

μ_d displacement ductility factor

$T \geq T_o = 1{,}25 T_C$ $\mu_d = q$

$T < T_o$ $\mu_d = (q - 1)(T_0/T) + 1 \leq 5q - 4$

Clearances

Structural and non-structural detailing should **accommodate the displacements** in the seismic design situation

Seismic situation *displacement:* $d_{Ed} = d_E + d_G + \psi_2 d_T$

d_E Seismic displacement
d_G Long term displacement (prestress, creep, shrinkage)
d_T Thermal displacement
ψ_2 Quasi permanent combination factor

Thank you for your attention