Eurocode 8 Part 3
Assessment and retrofitting of buildings

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Introduction

- **Document of the last generation, performance- and displacement-based**
- **Flexible to accomodate the large variety of situations arising in practice**
- **Logically structured, but missing the support from extended use: improvements to be expected from future experience**
- **Normative part covering only material-independent concepts and rules: verification formulas are in not-mandatory Informative Annexes**
- **The presentation concentrates on the normative part, providing also a number of comments and tentative lines of development, based on presently accumulated experience**

Performance requirements

Hazard (return period of the design spectrum)	**Required performance**
T_R=2475 years (2% in 50 years)	**Near Collapse (NC)** (heavily damaged, very low residual strength & stiffness, large permanent drift but still standing)
T_R=475 years (10% in 50 years)	**Significant damage (SD)** (significantly damaged, some residual strength & stiffness, non-strutural comp. damaged, uneconomic to repair)
T_R=225 years (20% in 50 years)	**Limited damage (LD)** (only lightly damaged, damage to non-structural components economically repairable)
T_R values above same as for new buildings. National authorities may select lower values, and require compliance with only two limit-states	

Performance requirements: *comment*

- **EC8-3 is a displacement-based document: direct analysis/verification quantities are the displacements and corresponding distortions induced by the design seismic action, for ductile components**

- **Apart from specific (and rare) cases, use of the standard q-factor is abandoned, and the <u>appropriate seismic action is introduced in the analysis without modification.</u> Reasons:**

  – Existing buildings represent a very inhomogeneous population, in terms of age, morfology, construction type and design code, such as to rule out the possibility of accounting of their inelastic behaviour through a single parameter to be calibrated via statistical analysis

  – It is now unanimously agreed that displacements/distortions are the quantities best suited for identifying the attainment of different LS's

Compliance criteria

- **EC8 Part 3, 2.2.1(1)P: "Compliance with the requirements […] is achieved by adoption of the seismic action, method of analysis, verification and detailing procedures contained in this Part of EN1998"**

- **In the verification procedure, a distinction is made between "ductile" and "brittle" structural elements. Ductile elements are checked in terms of deformations, brittle ones in terms of forces.**

Compliance criteria: *remarks*

- **The description of the requirements for all LS's is formulated in qualitative terms and refers to more or less severe states of damage involving <u>the structural system as a whole</u>.**

- **When turning to the verification phase, however, the letter of the code appears to ask that in order for the requirements be satisfied all individual elements should satisfy the verification inequalities, which would lead to consider a building as seismically deficient even in the extreme case where a single element would be found as nonconforming.**

- **This indeterminacy is at the origin of large discrepancies in the quantitative evaluations made by different experts**

Compliance criteria: *remarks*

An alternative, perhaps more consistent approach:

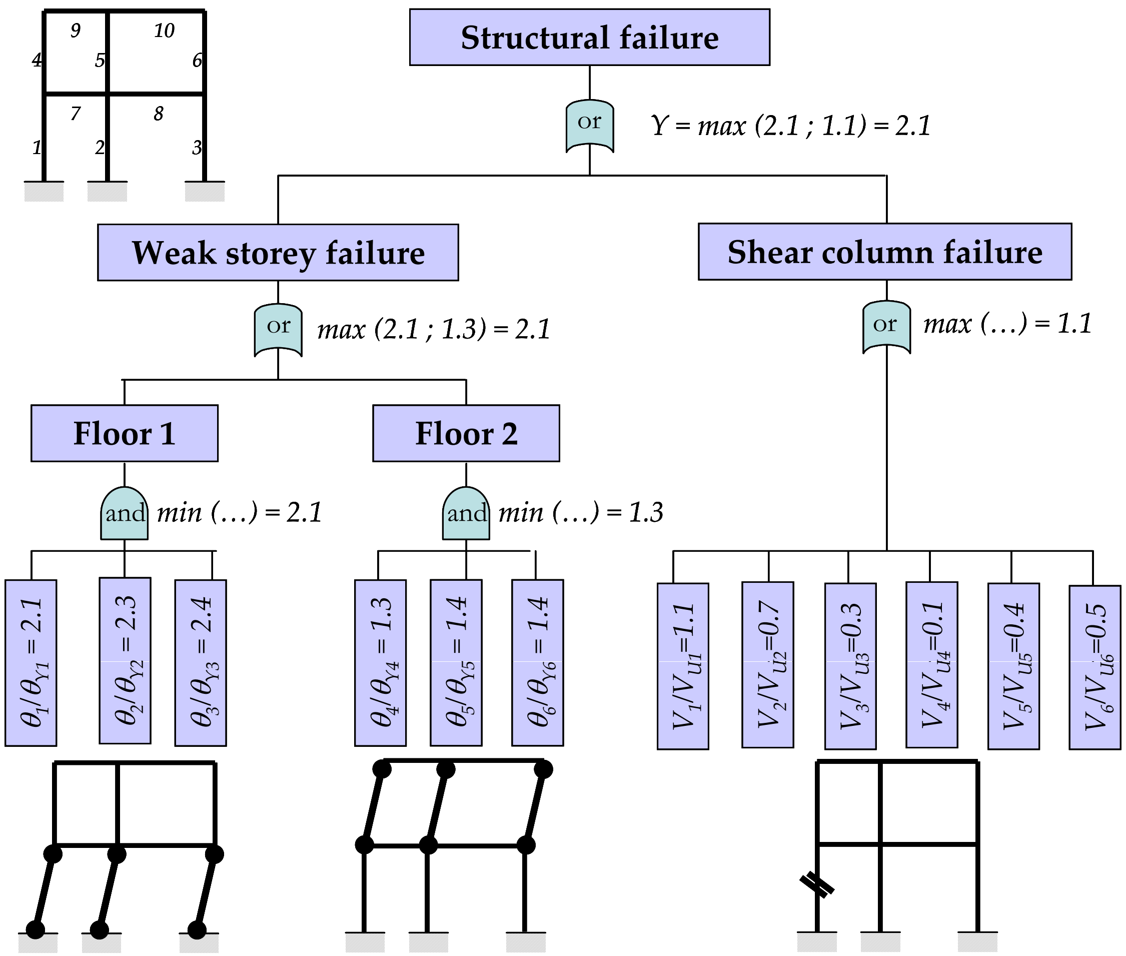
- **The analyst should identify a number of structural situations that are realistically conducive to the LS under consideration**

- **Such situations depend on the building topology and involve in general both single components and specific groups of components**

The ensemble of critical situations is conveniently arranged in the classical form of a fault tree. In the fault tree representation the state of the system is described as a serial arrangement of sub-systems, some of which are made of a number of components working in parallel

Compliance criteria: *remarks*

- **Example of a fault tree representation for the NC-LS of a simple frame**



Compliance criteria: *remarks*

With reference to a fault tree representation as in the example, the *state* of the system is determined by the value of a scalar quantity defined as:

$$Y=\max_{i=1,N_S}\min_{j=1,N_i}R_{ij}$$

where:

– R_{ij} = ratio between demand and capacity at the *j*-th component of the *i*-th subsystem

– N_S = total number of sub-systems

– N_i = number of components in subsystem *i*

***Y=1* implies attainment of the LS under consisderation**

Information for structural assessment: knowledge levels 1/2

- **Amount and quality of the information usable for the assessment is discretized in EC8-3 into three "levels", called "Knowledge Levels" (KL), ordered by increasing completeness.**

- **The information refers to three aspects: Geometry, Details and Materials.**
  - The term Geometry includes structural geometry and member sizes, Details refer to the amount and layout of reinforcement (for RC structures), Materials to the mechanical properties of the constituent materials.

KL	Geometry	Details	Materials
1	From original outline construction drawings with sample visual survey or from **full** survey	Simulated design in accordance with relevant practice and from **limited** in-situ inspection	Default values in accordance with standards of the time of construction and from **limited** in-situ testing
2		From incomplete original detailed construction drawings with limited in-situ inspection or from **extended** in-situ inspection	From original design specifications with limited in-situ testing or from **extended** in-situ testing
3		From original detailed construction drawings with limited in-situ inspection or from **comprehensive** in-situ in-spection	From original test reports with limited in-situ testing or from **comprehensive** in-situ testing

Information for structural assessment: knowledge levels 2/2

- The quantitative definition of the terms: visual, limited, extended, extensive and full, as applicable to the knowledge of Geometry, Details and Material is given in the Code (as a recommended minimum, if not otherwise specified in National Annexes).

- In particular, for what concerns the levels of inspection and testing, the recommended requirements are reported in the table below.

	Inspection (of details)	Testing (of materials)
	For each type of primary element (beam, column, wall)	
Level of inspection and testing	Percentage of elements that are checked for details	Material samples per floor
Limited	20	1
Extended	50	2
Comprehensive	80	3

Information for structural assessment: confidence factor

- **Allowing a structural assessment to be carried out for different levels of knowledge requires that a proper account is taken of the corresponding different amounts of uncertainties, these latter clearly applying to all of the three quantities: Geometry, Details and Materials.**

- **The choice made by EC8-3 is to condense all types of uncertainties into a single factor, to be applied only to the mechanical properties of the materials. This factor, called Confidence Factor (CF), has a double use.**

  - It is used in the calculation of the capacities, where the mean values of the material properties, as obtained from available information and from in-situ tests, are divided by the value of the CF appro-priate for the KL.

  - It is also used as a multiplier of the mechanical properties of the ductile components when the strength of these latter is used to determine the actions affecting brittle components or mechanisms.

  - The suggested values of the CF are 1.35, 1.20 and 1.0 for KL1, KL2 and KL3, respectively.

Information for structural assessment: *remarks*

- **The reliability format adopted by EC8-3 has the advantage of simplicity, but is subject to a number of practical and also theoretical limitations that might possibly be removed in future editions**

- **The following main aspects are illustrated next:**

  – Extension of material tests
  – Availability of documentation
  – Nature of the uncertainties to be dealt with
  – Use of a single factor (CF)

Information for structural assessment: *remarks*

- **On the extension of material tests**

  – The present close relation between the number of in-situ material tests and the Knowledge Level conveys naturally the idea that the more this number is increased the higher is the KL achieved. Actually, however, the increase of the number of tests has the only effect of reducing the standard error in the estimate of the mean (assuming that the materials tested belong to a single population, which in many cases is questionable)

Information for structural assessment: *remarks*

- **On the availability of documentation, both original and through surveys**
  - In the majority of cases, seismic assessments are being carried out not because of planned renovation or extension works, or because of a visibly precarious structural state of a building. They are mostly required by Public Authorities who want to be aware of the state of risk of their building stock consisting, for example, of schools, hospitals, administration offices, state banks, etc.
  - Availability of original drawings is quite rare, at least in some countries, for pre-WWII RC buildings, and continues until well into the late Sixties of the last century.
  - Complete or partial lack of the original drawings, i.e. of the structural geometry and of the details, could in theory be remedied by a more or less extensive survey and in-situ inspections.
  - All mentioned public buildings, however, are in continuous use, which makes it completely impractical to collect the needed information by exposing sufficient portions of the concrete structure, examining reinforcement layout and taking steel and concrete samples.

Information for structural assessment: *remarks*

- **On the nature of uncertainties**

  – In all those cases where assessment is conducted with the structure still in use, the major sources of uncertainty inevitably refer to geometry and details, more than to materials.

  – The former are not only more relevant than the latter, they are different in nature. They are in principle removable, if surveys and investigations were possible to the point of allowing the setting up of a fully realistic structural model, but this is seldom if ever the case. It is equally quite rare in many countries to be able to start the assessment process on the basis of a complete and credible design documentation.

Information for structural assessment: *remarks*

- **On the limits of the CF approach**

  – In the first place, it is clear that the Confidence Factor covers only one part of the over-all uncertainty, i.e., that related to the material properties, whose role is in the majority of cases secondary.

  – The uncertainty on geometry and details cannot be covered with factors, since a certain element is there or it is not, with a particular arrangement of the reinforcement or with another, and so on, and one is not in the position of ascertaining the real situation.

Methods of analysis: linear

q-factor approach

- **The method is applicable to reinforced concrete (q=1.5) and steel structures (q=2) without restrictions**
- **Higher values of q are admitted if they can be analytically justified (a rare situation in practice)**
- **With such small values of q the method is generally quite conservative (it may indicate the need for unnecessary interventions), hence it should find application for buildings having a visible overcapacity relative to local seismic hazard)**
- ***<u>No mention is made of this method for masonry structures</u>***

Methods of analysis: linear

Linear analysis with unreduced elastic seismic action (1/2)

- **Lateral force and modal response spectrum**

- **Usable subject to a substantial uniformity, over all ductile primary elements, of the ratio between elastically calculated demand and corresponding capacity, i.e.**

  $\max(D_i/C_i)/\min(D_i/C_i)\cdot 2.5$ (suggested, but not >3)

- **Limited practical experience indicates that when the above condition is satisfied the results from elastic multi-modal analysis compare well with those from non linear**

- **The above condition represents a physical quantitative definition of *regularity* of a structure from a seismic point of view, more accurate than the semi-quantitative and rather arbitrary definitions given in EC8 Part 1**

Methods of analysis: linear

Linear analysis with unreduced elastic seismic action (2/2)

- **The lateral force method is less accurate and not computationally advantageous: it might well be dropped**
- **Modal response spectrum is accurate when the conditions for applicability are satisfied but the percentage of buildings complying with them is anticipated being not very large**
- **Application of linear methods to <u>masonry structures</u> is problematic due:**
  - The condition related to D/C ratios is not of clear application, especially in case of a FE modelling of the structure
  - There are additional strict conditions to be fulfilled: vertical continuity of all walls, rigid floors, maximum stiffness ratio between walls at each floor less than 2.5, floors at both sides of a wall are at the same height

<u>The above remarks point towards a generalised recourse to non linear methods</u>

Methods of analysis: non-linear static 1/3

- **The reference version of the pushover method in EC8-3 is the same as in Part 1**
- **This versione provides satisfactory results when:**
  - The structure is essentially symmetric and torsionally rigid
  - The effects of the higher modes are negligible
- **The case of unsymmetrical (but still single-mode dominated) buildings is treated in EC8 Part 1 by means of an hybrid procedure whereby:**
  - The loading pattern is still planar (*uniform* or *modal*)
  - The displacements of the stiff/strong sides of the building obtained from the pushover analysis are amplified by a factor based on the results of spatial modal analysis
- **In EC8 Part 3 a note is added in 4.4.5 saying that when T_1¸ $4T_C$ or T_1>2s the effects of higher modes should be taken into account (not a 'P', hence not obligatory)**

Methods of analysis: non-linear static 2/3

- **Multi-modal pushover: a convenient proposal (Chopra and Goel, 2002)**
  - Use several (spatial) lateral load patterns, corresponding to all *significant* modes: $\mathbf{F_i} = \mathbf{M\Phi_i}$
  - Perform a pushover analysis and evaluate the desired response quantities R, for each modal pattern and for each of the two horizontal components of the seismic action E_X and E_Y and for the two signs ($R_{E_X} \neq -R_{E_{-X}}$)
  - Combine the results from the above analyses according to the SRSS rule

$$R = R_G + \sqrt{\sum_i (R_{i,E_X}-R_G)^2 + (R_{i,E_Y}-R_G)^2}$$

Methods of analysis: non-linear static 3/3

- **Problem with modal combination of member forces (absolute value)**
  - Unrealistically high normal forces and bending moments
  - Shear forces not in equilibrium with bending moments
- **Shear verification of columns: influence of the value of N both in the demand V(N) and in the capacity $V_R(N)$**
  - Approximate solution: evaluate the D/C ratio mode by mode $V_i(N_i)/V_R(N_i)$ (same sign of N_i on both D and C) and then check:

    $[\sum_\iota (V_i(N_i) / V_R(N_i))^2]^{½} \leq 1$

    (damage variable analogy)

Members verifications: demand quantities

- **Ductile members (beam-columns & walls in flexure):**
  the demand quantity is the chord-rotation at the ends, as obtained from the analysis, either linear or non-linear

- **Brittle mechanisms (shear):**
  the demand quantity is the force acting on the mechanism

  – Linear analysis: the ductile transmitting mechanisms can be:
    - below yielding: the force is given by the analysis
    - yielded: the force is obtained from equilibrium conditions, with the capacity of the ductile elements evaluated using mean values of the mech. prop.'s multiplied by the CF

  – Non-linear analysis: forces as obtained from the analysis

Members verifications: capacities

- **Ductile members (beam-columns & walls in flexure)**
  - expressions of the ultimate chord-rotations are given for the three performance levels, the values of the mech. properties are the mean values divided by the CF.

- **Brittle mechanisms (shear)**
  - expressions for the ultimate strength are given for the NC-LS, the values to be used for the mechanical properties are the mean values, divided by both the usual partial °-factors and the CF

Member verifications: synopsis

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Linear Model (LM)</td><td colspan="2">Non-linear Model</td></tr>
<tr><td>Demand</td><td>Capacity</td><td>Demand</td><td>Capacity</td></tr>
<tr><td rowspan="7">Type of elment or mechanism (e/m)</td><td rowspan="4">Ductile</td><td colspan="2">Acceptability of Linear Model
(for checking of $\rho_i = D_i/C_i$ values)</td><td rowspan="7">From analysis.
Use mean values of properties in model.</td><td rowspan="4">In terms of deformation.
Use mean values of properties divided by CF.</td></tr>
<tr><td>From analysis.
Use mean values of properties in model.</td><td>In terms of strength.
Use mean values of properties</td></tr>
<tr><td colspan="2">Verifications (if LM accepted)</td></tr>
<tr><td>From analysis.</td><td>In terms of deformation.
Use mean values of properties divided by CF.</td></tr>
<tr><td rowspan="3">Brittle</td><td colspan="2">Verifications (if LM accepted)</td><td rowspan="3">In terms of strength.
Use mean values of properties divided by CF and by partial factor.</td></tr>
<tr><td>If $\rho_i \leq 1$: from analysis.</td><td rowspan="2">In terms of strength.
Use mean values of properties divided by CF and by partial factor.</td></tr>
<tr><td>If $\rho_i > 1$: from equilibrium with strength of ductile e/m.
Use mean values of properties multiplied by CF.</td></tr>
</table>

Capacity models for RC members: flexure

- **Mechanically-based models capable of accounting for all internal deterioration mechanisms that develop in inadequately detailed RC members are not available**
- **Resort has been made to a large database collecting tests made in the past in order to derive empirical expressions.**

$$\theta_{um} = 0.01(0.3)^{\nu}\left[\frac{\max(0.01;\omega')}{\max(0.01;\omega)} f_c\right]^{0.225}\left(\frac{L_s}{h}\right)^{0.35} 25^{\alpha\rho_{sx}\frac{f_{yw}}{f_c}} 1.25^{100\rho_d}$$

where ν = normalised axial force

ω, ω' = mech. reinforc. ratio of compression and tension reinf.

L_s = shear span

h = net height of the section

α = confinement effectiveness factor

ρ_{sx}, ρ_{dx} = transverse and diagonal reinforcement ratio

Capacity models for RC members: shear

- **The well-known three-terms additive format for the shear strength has been retained. The expressions for the three contributions have been derived using the same database as for the flexural capacity, augmented by test results of specimen failing in shear after initial flexural yielding:**

$$V_R = 0.85\left[\frac{h-x}{2L}\min\left(N;0.55A_c f_c\right)+\left(1-0.55\min\left(5;\mu_\Delta^{pl}\right)\right)\times\right.$$

$$\left.\times 0.16\max\left(0.5;100\rho_{tot}\right)\left(1-0.16\min\left(5;\frac{L_s}{h}\right)\right)\sqrt{f_c}+V_w\right]$$

where x = neutral axis depth

N = compressive axial force ($=0$ if tensile)

A_c = cross-section area

μ_Δ^{pl} = plastic part of ductility demand

ρ_{tot} = total longitudinal reinf. ratio

V_w = contribution of transverse steel

$$\frac{V_{R,predicted}}{V_{R,experimental}} = 1$$

$$CoV = 15\%$$

Members verifications under bidirectional loading

- **Bidirectional loading is the standard situation due to the simultaneous application of the orthogonal components of the seismic action**

- **No guidance in EC8 Part 3 (lack of adequate knowledge of the behaviour at ultimate)**

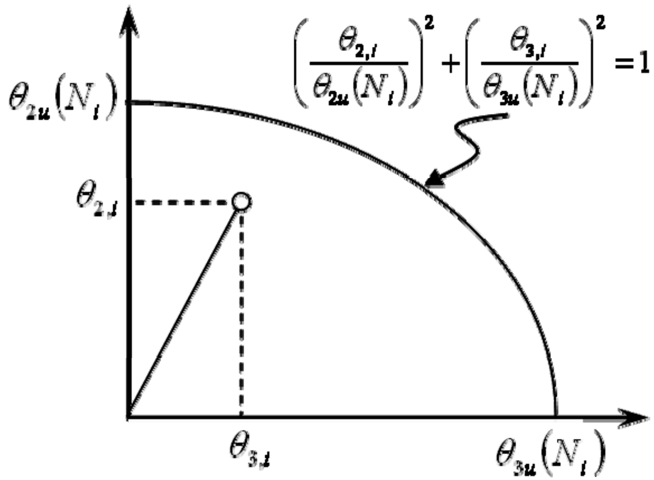
- **Limited experimental evidence (Fardis, 2006) supports the assumption of an *elliptical interaction domain* for biaxial deformation at ultimate**

- **Proposal:**

  – For each mode evaluate the *bidirectional demand/capacity ratio*

  $$\mathrm{BDCR}_i = [(\theta_{2i}/\theta_{2u,i})^2 + (\theta_{3i}/\theta_{3u,i})^{2}]$$

  – Check that $\sum_i (\mathrm{BDCR}_i)^2 \cdot 1$



Capacity models for strengthened members (Informative Annex)

The section covers traditional strengthening techniques, such as concrete and steel jacketing, as well as the use of FRP plating and wrapping, for which results from recent research are incorporated.

Guidance in the use of externally bonded FRP is given fo the purposes of:

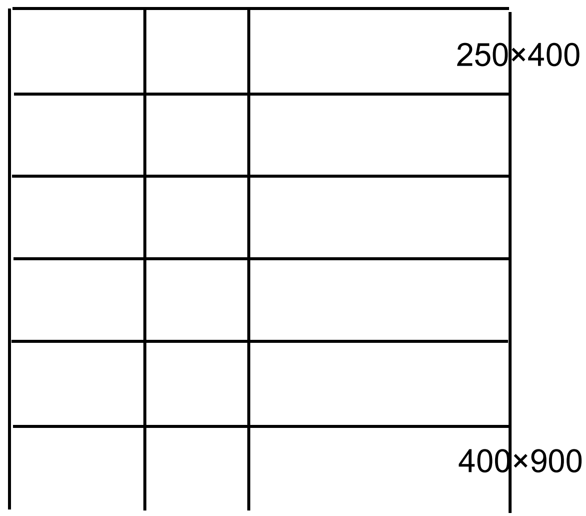
- increasing shear strength (contribution additive to existing strength)
- increasing ductility of critical regions (amount of confinement pressure to be applied, as function of the ratio between target and available curvature ductility)
- preventing lap-splice failure (amount of confinement pressure to be applied, as function of the bar diameters and of the action already provided by existing closed stirrups)

Discussion

- **Variability of results obtainable following alternative allowable code procedures**

- **Simple demonstrative example**
  - KL3→CF=1
  - ULS definition: series system, exceedance of chord-rotation or shear capacities in column elements

- **Choices**
  - Method of analysis: nonlinear static (NLS) and dynamic (NLD)
  - Model: standard fiber model (B), plastic hinge model with flexure and shear degradation (A)
  - Infills: inclusion (T), exclusion (NT)
  - Column reinforcement ratio: ρ_{min} = 8‰, ρ_{max} = 12‰
  - Shear strength capacity model: Biskinis-Fardis (BF), Kowalsky-Priestley (PK)



Beams: 250×700 at all floors

Concrete f_c = 20 MPa

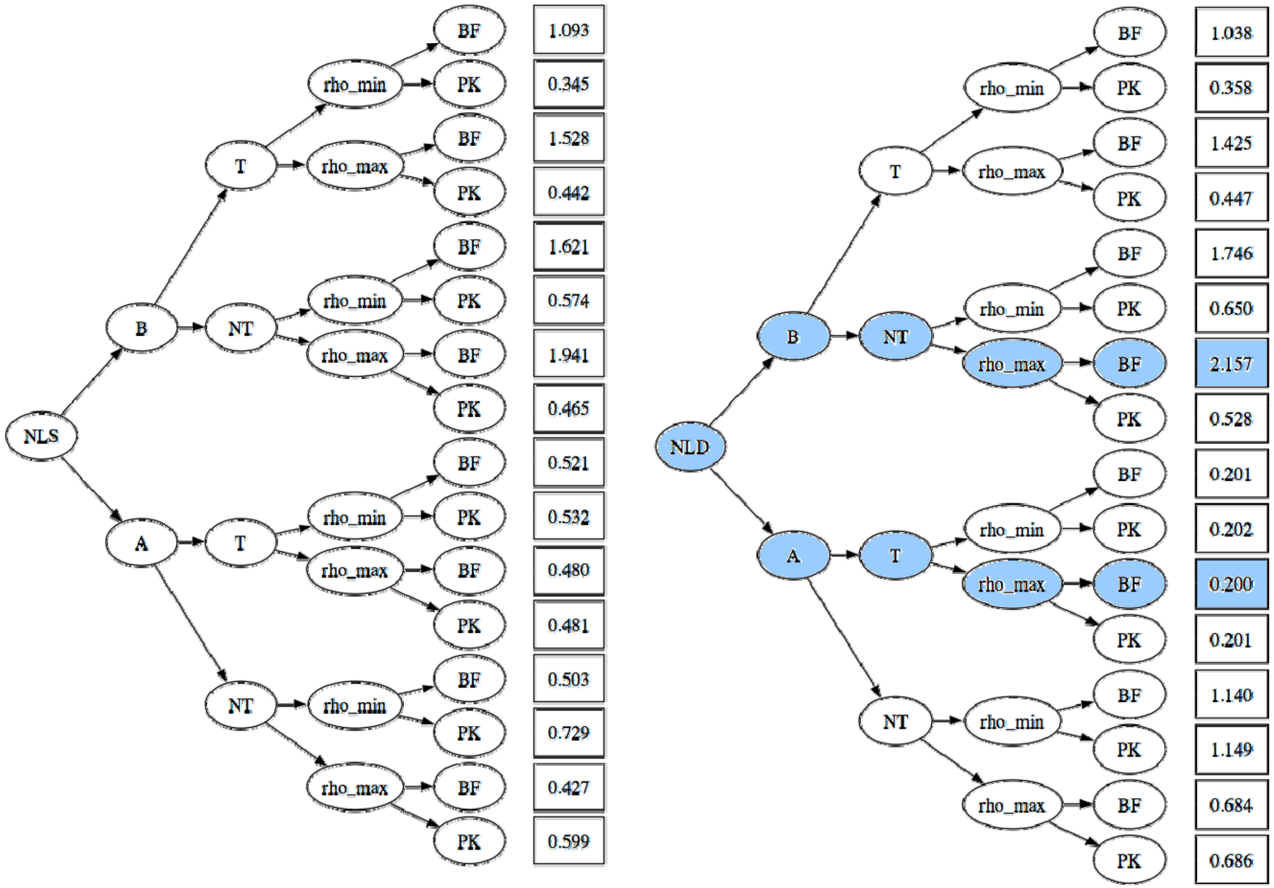
Steel f_y = 275 MPa

Infills f_m = 4.4 MPa

Discussion

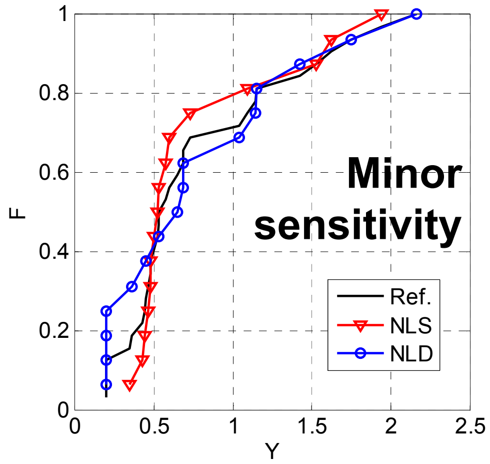
Variability of the results for the 2^5=32 combinations of the choices

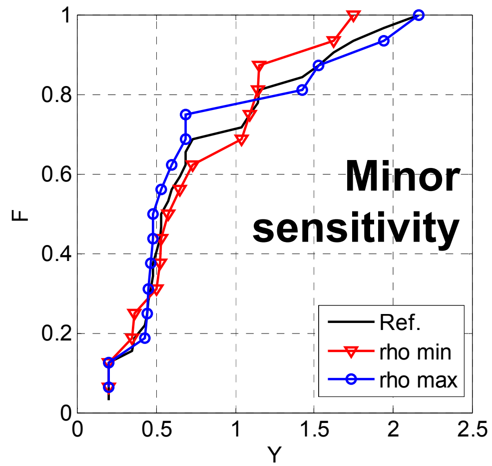
(values in boxes represent the global D/C ratio at ultimate, obtained by adopting the choices indicated along the branches)

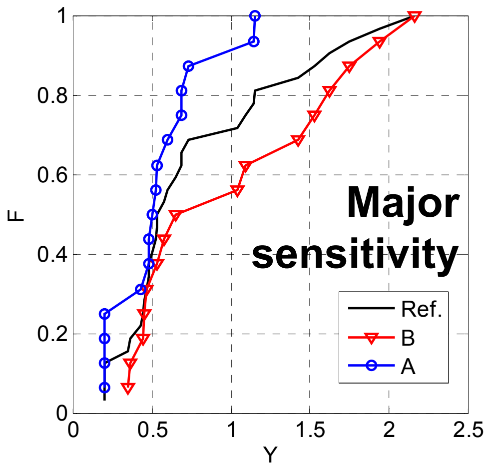


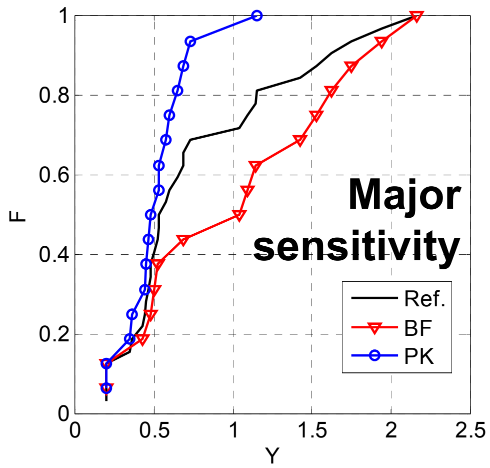
Discussion

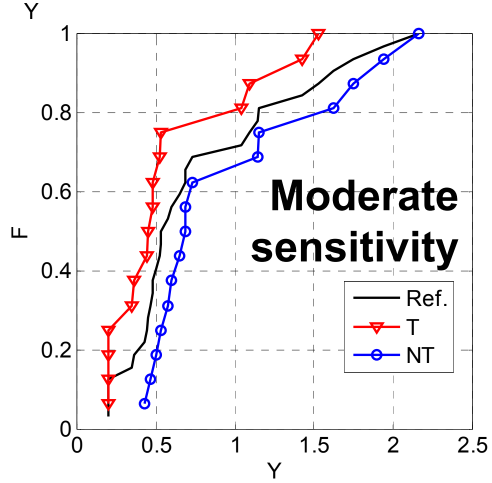
All five figures show the complete CDF of the 32 values (black). Further, each figure includes two CDFs made of 16 values, corresponding to the two alternatives for each choice











Discussion

- **In the example the major influence on the variability of the results is due to fundamental uncertainties that are epistemic in nature, i.e. they cannot be reduced by additional tests and inspections**

- **In many cases, further, there are limits to the type and number of inspections that can be performed, hence a measure of epistemic uncertainty is de facto in varying degrees always present**

- **Epistemic uncertainty cannot be covered by factors, except for material properties whose relevance is generally minor**

Discussion

- **A classical statistical tool for dealing with problems of this kind is te “logic tree”, whereby, on the basis of the overall knowledge available, the analyst sets up a number of alternative models, and associates to each choice entering a model a weight representative of his subjective belief on the validity of the choice itself**

- **Each model provides an outcome of the assessment, characterised by a probability which is the product of the probabilities assigned to the branches of the tree**

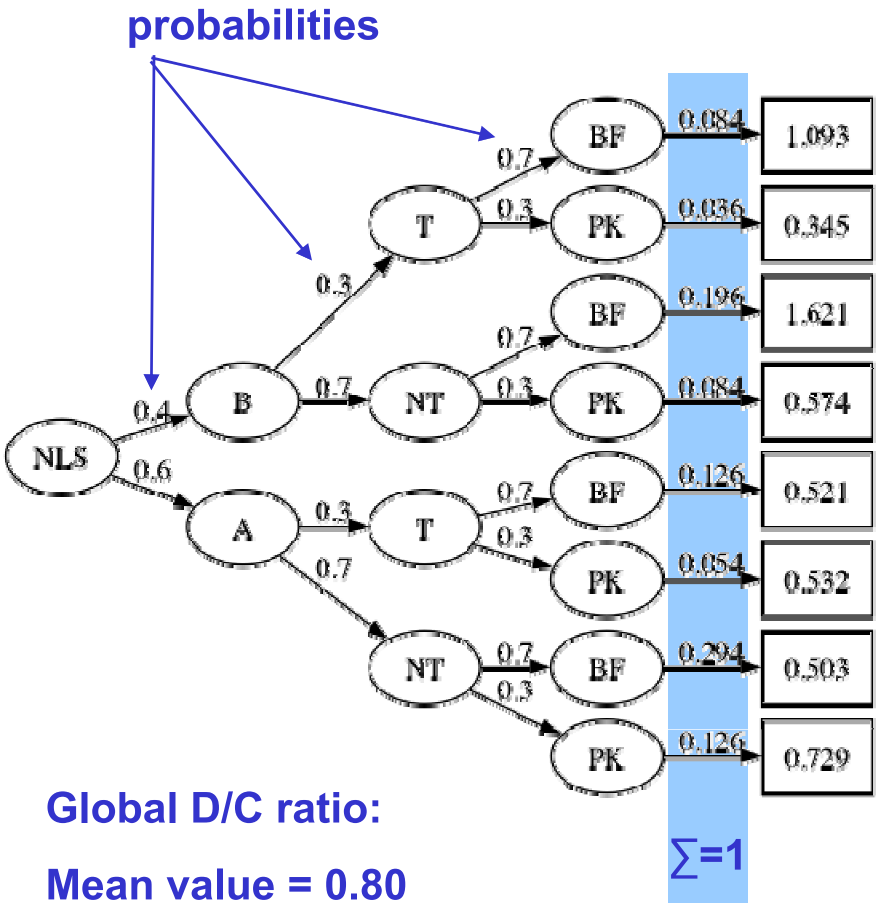
- **The ensemble of the outcomes provides thus an approximate discrete distribution of the system’s D/C ratio, from which statistics such as mean, dispersion and confidence interval can be obtained**

Discussion

- **The application of the logic tree is illustrated with reference to the previous example frame.**

- **The uncertainties considered in the construction of the tree are those that have shown to have more significance, i.e. modelling strategy, shear strength model and consideration of infills' contribution to response.**

- **The subjective probabilities weighting the choices are:**
  - – Modelling: 0.6 for the advanced modelling, 0.4 for the basic one;
  - – Shear-strength model: 0.7 for EC8-3 model, 0.3 for the alternative one;
  - – Infills: 0.3 if present, 0.7 if absent.



Global D/C ratio:

Mean value = 0.80

Standard dev. = 0.44