Second generation Eurocode 8 Part 3: the European document on seismic assessment and retrofit of existing structures

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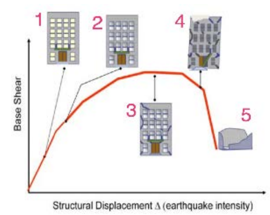
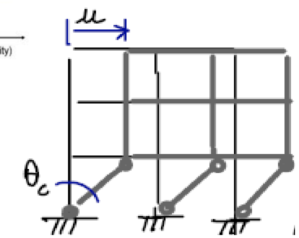
Summary

- 1st generation Eurocode 8 Part 3 (2005)

Seismic risk (consequences of damage) mostly associated with exisiting structures (e.g., Italy, 85% of $E[L]$)

- Specificity of assessmet wrt design
  - Single knowledge level (KL)
  - Confidence factor
- Forces are not good predictors of performance
  - Displacement-based
- Assessment deals with non-conforming structures
  - Nonlinear analsysis and ad hoc deformation criteria





- 2nd generation Eurocode 8 (2020)

Quantitative procedures!
Qualitative assessment based on past performance not really useful for seismic

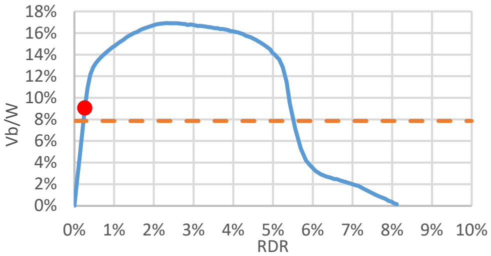
- Displacement-based approach for both assessment and design
- Multiple Knowledge Levels
- Knowledge-dependent partial factors on resistance(*)
- A probabilistic method of assessment also introduced

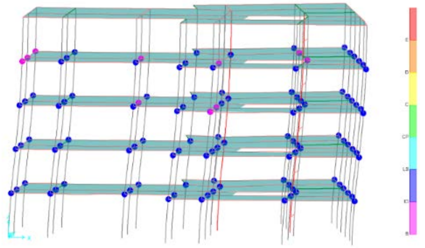
(*) Demand = Acvtion effect & Capacity = Resistance in the Eurocodes system

Eurocode 8 Part 3 2005 (1st generation)

- Primary role of knowledge acquisition (existing ≠ new)
  - Information classified into:
    - Geometry
    - (Construction) Details
    - Materials
  - Quantified by Knowledge level (KL)
    - Values: Limited, Normal, Full
    - Controlled by the least amount of information in G, D and M & unique over the structure
  - KL → Confidence factor (CF) which divides material strength: 1,35/1,20/1,00
    - CF coexists with γ_m (e.g., γ_c, γ_s) used in traditional verification format

- Inelastic and possibly defective response is the rule.
  - Rules for nonlinear static analysis
  - Novel models for:
    - inelastic deformation capacity (chord rotation)
    - shear strength of members and joints in the inelastic range
    - strength & deformation capacity of retrofitted members





Eurocode 8 Part 3 2005 (1st generation)

- Experimental nature of the document is apparent
  - Most material (models for θ_y and θ_u, or V_R) is in informative annexes
  - KL depends on G, D, M information but it only affects M (through CF)
  - CF values are judgemental
  - Not really streamlined… Four different set of material properties used:
    - Mean (E_{cm}, f_{cm}, f_{ym}) in the model, which provides action effects on ductile modes of failure (θ)
    - Mean divided by CF (f_{cm}/CF, f_{ym}/CF) for evaluating the resistance of ductile failure modes (θ_y, θ_u)
    - Mean divided by CF and γ_m ($\frac{f_{cm}}{CF\gamma_c}$,$\frac{f_{ym}}{CF\gamma_s}$) for the resistance of brittle modes (V_{Rd})
    - Mean times CF, for the demand on brittel modes (V_{Ed}) if analysis model is linear

- Nonetheless, more than 15 years of practical application
  - Increased confidence(*) in nonlinear analysis methods & displacement-based verifications and associated deformation models
  - Have shown that information should be sought where it is more relevant
  - Thousands of buildings have been assessed and retrofitted

(*) Obviously the situation in the Engineering practice is spatially non homogeneous, as it is not the seismic hazard in Europe

Eurocode 8 Part 3 2020 (2nd generation)

- CEN/TC250 M515 (Revision of the entire Eurocodes system)
  - Extension of scope
    - EN1998-3:2005 only dealt with buildings in RC and, marginally, steel
    - prEN1998-3:2020 includes buldings and bridges + RC, steel, masonry, timber
  - Technical updating
    - Displacement-based assessment now default, scope for force-based reduced
    - Displacement-based design introduced for new structures in Part 1-1
    - (Updated) deformation and strength models moved from annexes in Part 3 → main body of Part 1-1 (i.e., used for new & existing structures)
    - Only one set of properties used, the mean ones
      - In the (nonlinear analysis) model to determine action effects
      - In the resistance formulas (θ_y, θ_u, V_{Rd}, etc)
      - To evalutate demand on brittle failure modes (V_{Ed}, curbed to plastic shear) with linear analysis model

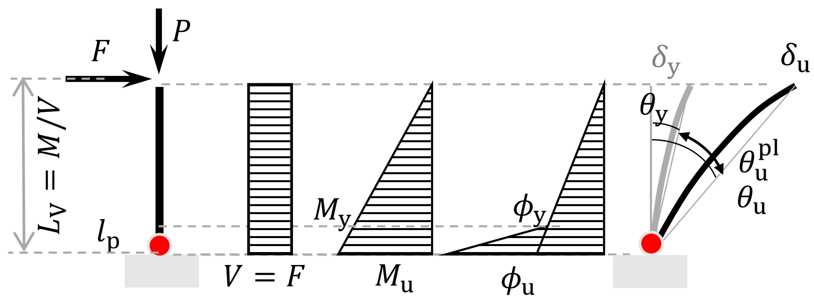
Eurocode 8 Part 3 2020 (2^{nd} generation)

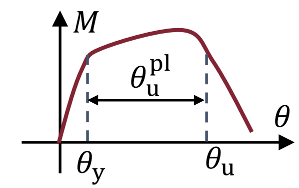
- Technical updating (cont'd)
  - More refined treatment of acquired knowledge
    - Three distinct KLs introduced for G, D and M: KLG, KLD and KLM
    - Each KL need not be uniform over the structure if newly introduced preliminary analysis is carried out(*)
  - Safety
    - On the demand side
      - Near Collape (NC) verification replaces Significant Damage (= Life safety) as default
    - On the capacity side a unified(**) partial factors' format to account for
      - Model (epistemic) uncertainty in the resistance formulas
      - Uncertainty (aleatoric and epistemic) in the input variables, classified in the Material properties, Geometric parameters, Construction details categories (***)
  - Reliability differentiation
    - Consequence class (CC), like US risk category, determine return period of seismic action for NC verification
    - Resistance of secondary & non-critical members taken equal to its median (i.e., $\gamma_{\mathrm{Rd}} = 1$)

(*) More focussed field investigations, save money and time (**) Consistency across different materials and verifications
(***) Stronger link between information and verifications

Resistance models: inelastic rotation capacity

- Resistance formulas
  - Models are a variable blend of mechanical and empirical





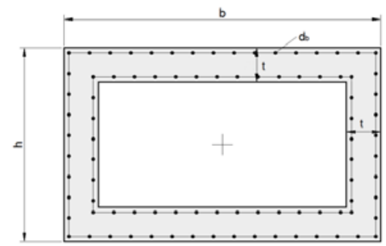
flexure slip shear

$$\theta_y = \phi_y \frac{L_V + a_V z}{3} + \frac{\phi_y d_{bL} f_y}{8\sqrt{f_c}} + 0{,}00\mathbf{11}\left(1 + \frac{h}{\mathbf{3,0}L_V}\right)$$

$$\theta_u = \theta_y + \boxed{\theta_u^{pl}}$$

$$\theta_u^{pl} = (\phi_u - \phi_y) L_{pl}\left(1 - \frac{2L_{pl}}{L_V}\right) + \Delta\theta_{u,slip}$$

RC beam/column with hollow-core section

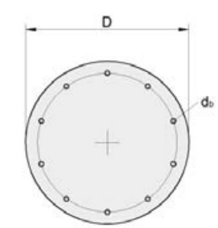


$$\theta_y = \phi_y \frac{L_V + a_V z}{3} + \frac{\phi_y d_{bL} f_y}{8\sqrt{f_c}} + 0{,}00\mathbf{25}\left(1 - \min\left(1; \frac{L_V}{\mathbf{8}D}\right)\right)$$

$$\theta_u = \theta_y + \boxed{\theta_u^{pl}}$$

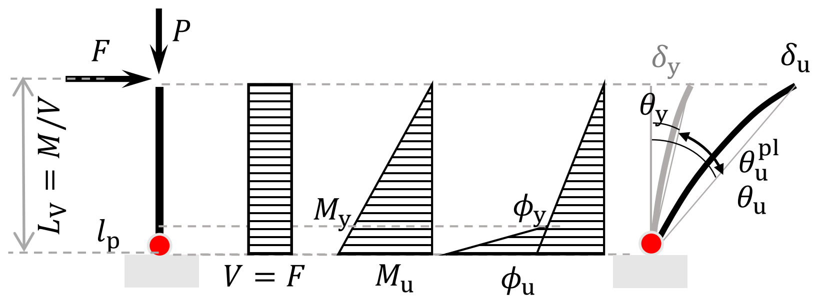
$$\theta_u^{pl} = (\phi_u - \phi_y) L_{pl}\left(1 - \frac{2L_{pl}}{L_V}\right) + \Delta\theta_{u,slip}$$

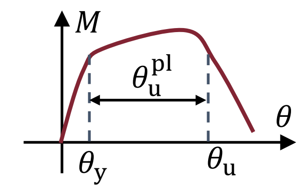
RC beam/column with circular section



Resistance models: inelastic rotation capacity

- Resistance formulas
  - Models are a variable blend of mechanical and empirical





flexure / slip / shear

$$\theta_y = \phi_y \frac{L_V + a_V z}{3} + \frac{\phi_y d_{bL} f_y}{8\sqrt{f_c}} + 0{,}00\mathbf{19}\left(1 + \frac{h}{\mathbf{1,6}L_V}\right)$$

$$\theta_u = \theta_y + \boxed{\theta_u^{pl}}$$

$$\theta_u^{pl} = \kappa_{conform}\boxed{\kappa_{axial}}\kappa_{reinf}\boxed{\kappa_{concrete}}\boxed{\kappa_{shearspan}}\kappa_{confinement}\boxed{\theta_{u0}^{pl}}$$

$$\kappa_{axial} = 0{,}2^{\nu}$$

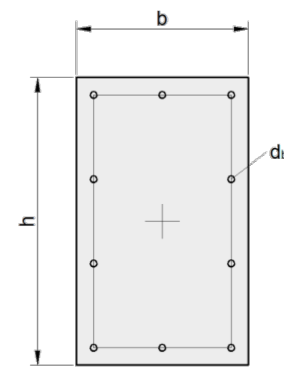
$$\kappa_{shearspan} = \left(\frac{1}{2{,}5}\min\left(9; \frac{L_V}{h}\right)\right)^{0{,}35}$$

$$\kappa_{concrete} = \left(\min\left(2; \frac{f_c(MPa)}{25}\right)\right)^{0{,}1}$$

0,039 rad

$(f_c = 25\text{MPa}, \nu = 0, \frac{L_V}{h} = 2{,}5)$

RC beam/column
with rectangular section



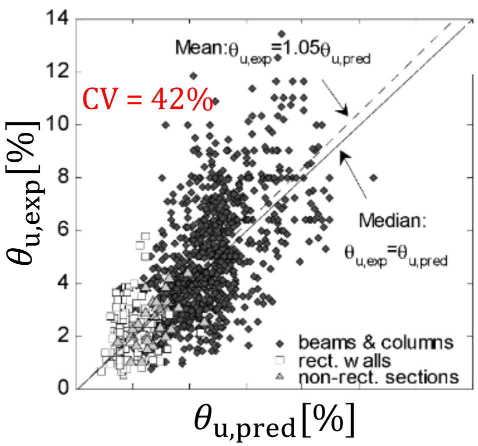
Resistance models: inelastic rotation capacity

- Resistance formulas
  - Variable blend of mechanical and empirical
  - Unbiased, CV of exp/pred ratio (model uncertainty) is available
    - "Design" models usually conservative, CV not documented

Reinforced concrete

$$\theta_{\mathrm{y}} = \phi_{\mathrm{y}} \frac{L_{\mathrm{V}} + a_{\mathrm{V}} z}{3} + \frac{\phi_{\mathrm{y}} d_{\mathrm{bL}} f_{\mathrm{y}}}{8\sqrt{f_{\mathrm{c}}}} + 0{,}0019\left(1 + \frac{h}{\mathbf{1,6} L_{\mathrm{V}}}\right)$$

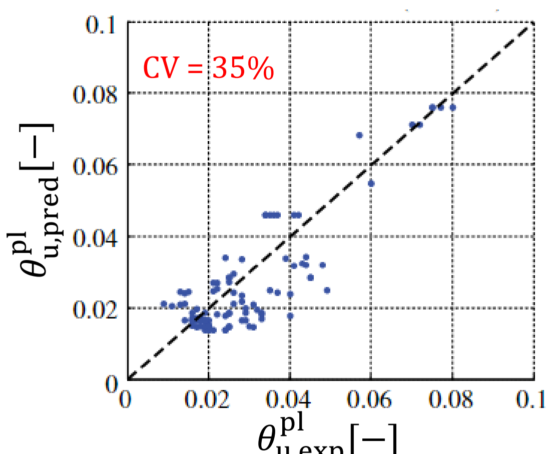
$$\theta_{\mathrm{u}} = \theta_{\mathrm{y}} + \theta_{\mathrm{u}}^{\mathrm{pl}}$$



Steel

$$\theta_{\mathrm{y}} = \frac{L(1-n)}{6(\nu_{\mathrm{b}})EI_{\mathrm{x}}} M_{\mathrm{y}} = \frac{L_{\mathrm{V}}}{3}\frac{M_{\mathrm{y}}}{EI_{\mathrm{x}}}\frac{(1-n)}{\nu_{\mathrm{b}}}$$

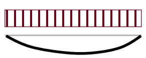
$$\theta_{\mathrm{u}}^{\mathrm{pl}} = 7.37\left(\frac{h}{t_w}\right)^{-0.95}\left(\frac{L_b}{i_y}\right)^{-0.5}(1-\nu_G)^{2.4}$$



(*) Examples from Grammatikou et al 2018 and Lignos and Krawinkler 2011

Resistance models: shear strength in RC

- Resistance formulas
  - Variable blend of mechanical and empirical
  - Unbiased, CV of exp/pred ratio (model uncertainty) is available



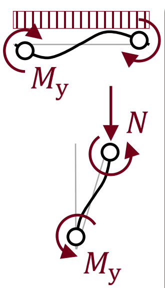
EN1992

$$V_{\mathrm{Rc}} + V_{\mathrm{Rs}} \leq V_{\mathrm{Rmax}}$$

prEN1992:2020

$$V_{\mathrm{Rc}}(\epsilon_x) + V_{\mathrm{Rs}} \leq V_{\mathrm{Rmax}}(\epsilon_x)$$

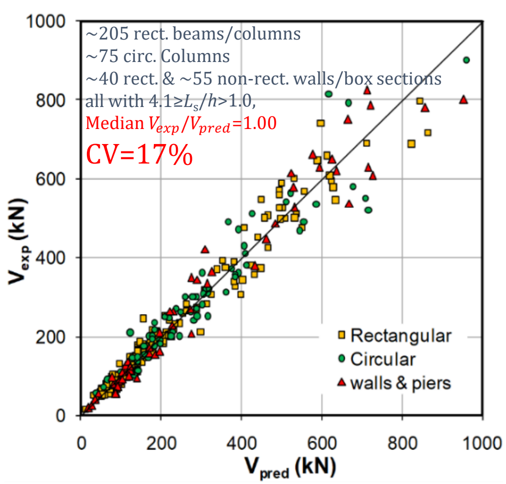
$$\epsilon_x = \frac{1}{2\,\mathrm{A_{s1}}\,E_{\mathrm{s}}}\left(\frac{M}{z} - \frac{N}{2} + \frac{V}{2}\cot(\theta)\right)$$



EN1998-3:2005

$$(V_{\mathrm{Rc}}^{*} + V_{\mathrm{Rs}})k(\mu) \leq V_{\mathrm{Rmax}}^{*}$$

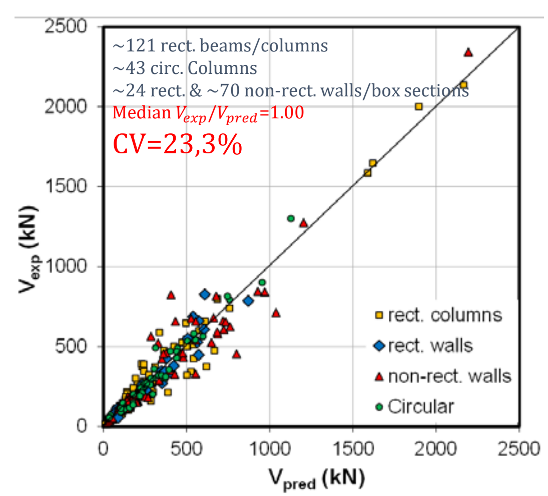
$$(V_{\mathrm{Rc}}^{*} + V_{\mathrm{Rs}})k(\mu) + V_{\mathrm{RN}} \leq V_{\mathrm{Rmax}}^{*}$$



prEN1998-1-1:2020

$$V_{\mathrm{Rc}}(\epsilon_x) + V_{\mathrm{Rs}} + V_{RN} \leq V_{\mathrm{Rmax}}(\epsilon_x)$$

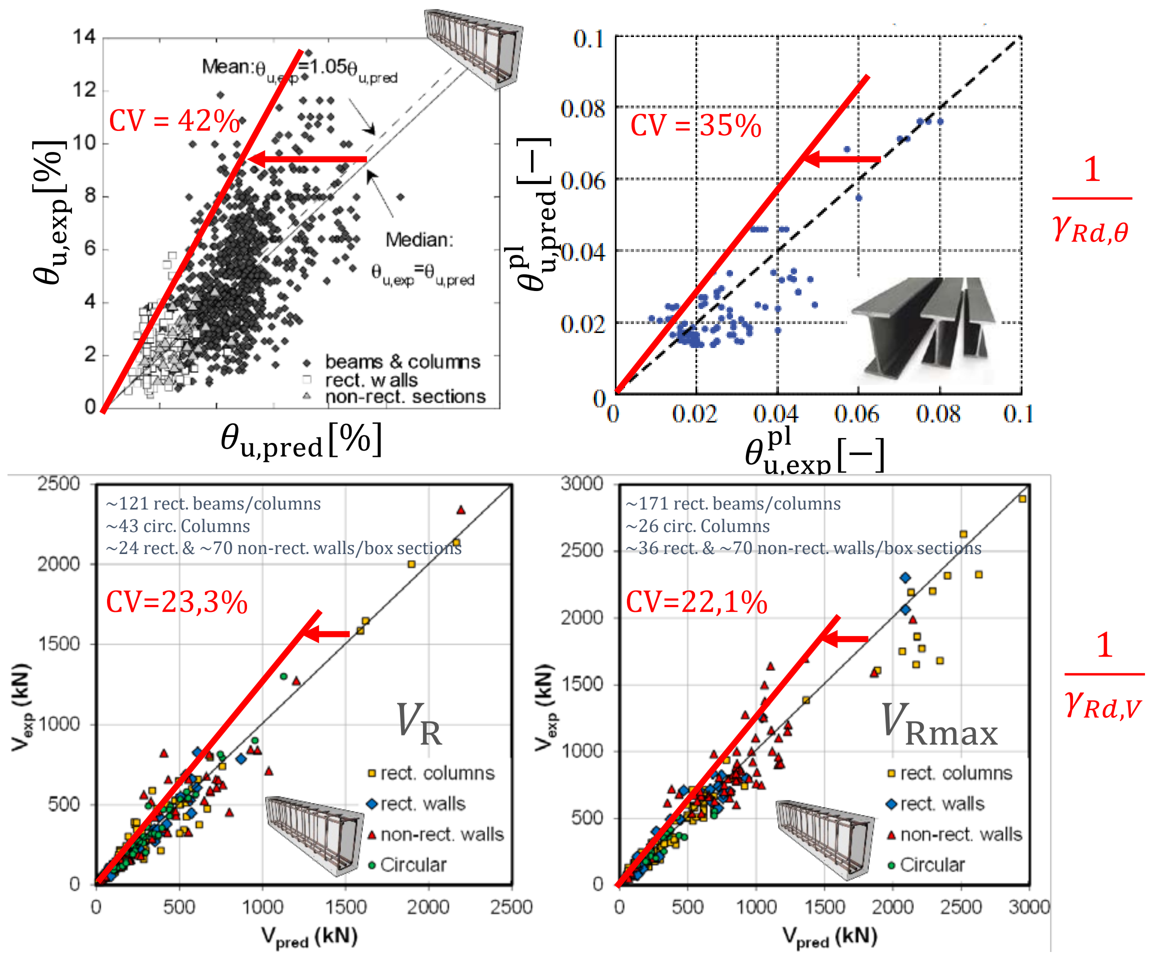
$$\epsilon_x = \frac{1}{2\,\mathrm{A_{s1}}\,E_{\mathrm{s}}}\left(\mu\frac{M}{z} - \frac{N}{2} + \frac{V}{2}\cot(\theta)\right)$$



(*) Examples from Biskinis et al 2004 and Biskinis and Fardis 2018

Partial factors on resistance

- Evaluation of median of resistance with best estimate properties
- Lower fractile for verification through a single member-level partial factor

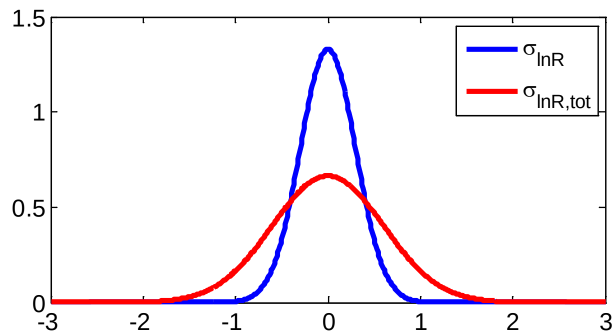


Partial factors on resistance: formulation

- Fractile k can be obtained from median, if $\sigma_{\ln\mathrm{R,tot}}$ is known

$$R_\mathrm{k} = e^{\mu_{\ln\mathrm{R}} + \kappa\sigma_{\ln\mathrm{R,tot}}} = \hat{R}e^{\kappa\sigma_{\ln\mathrm{R,tot}}} \rightarrow \gamma_\mathrm{Rd} = \frac{\hat{R}}{R_\mathrm{k}} = e^{-\kappa\sigma_{\ln\mathrm{R,tot}}}$$

- The total logarithmic standard deviation is a function of
  - Model uncertainty (CV of exp/pred) $\sigma_{\ln\mathrm{R}}$
  - Variability (aleatoric+statistical) of input variables (e.g., $f_\mathrm{c}, L_\mathrm{V}, \rho_\mathrm{w}$)



- All formulas in Eurocode 8 can be put in the form

$$R(\boldsymbol{x}) = \hat{R}(\boldsymbol{x})\epsilon_\mathrm{R} \rightarrow \ln R(\boldsymbol{x}) = \ln\hat{R}(\boldsymbol{x}) + \tilde{\epsilon}_\mathrm{R}$$

Input variables ← → Model error

Partial factors on resistance: formulation

- Linearization of $\ln\hat{R}(\boldsymbol{x})$ around $\hat{\boldsymbol{x}}$ leads to an expression for $\sigma_{\ln \mathrm{R,tot}}$

$$\ln R\,(\boldsymbol{x}) = \ln \hat{R}\,(\hat{\boldsymbol{x}}) + \sum \left.\frac{\partial \ln \hat{R}}{\partial \ln x_{\mathrm{i}}}\right|_{\hat{\boldsymbol{x}}} \left(\ln x_{\mathrm{i}} - \mu_{\ln x_{\mathrm{i}}}\right) + \tilde{\epsilon}_{\mathrm{R}} =$$

$$= \ln \hat{R}\,(\hat{\boldsymbol{x}}) + \sum \frac{\hat{x}_{\mathrm{i}}}{\hat{R}(\hat{\boldsymbol{x}})} \left.\frac{\partial \hat{R}}{\partial x_{\mathrm{i}}}\right|_{\hat{\boldsymbol{x}}} \left(\ln x_{\mathrm{i}} - \mu_{\ln x_{\mathrm{i}}}\right) + \tilde{\epsilon}_{\mathrm{R}} =$$

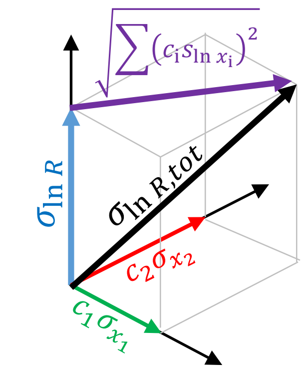
Median @ median

Correction for the log

Sensitivity to x_{i}

$$= \ln \hat{R}\,(\hat{\boldsymbol{x}}) + \sum c_{\mathrm{i}}\, \tilde{\epsilon}_{\mathrm{i}} + \tilde{\epsilon}_{\mathrm{R}}$$

Tangent/Secant



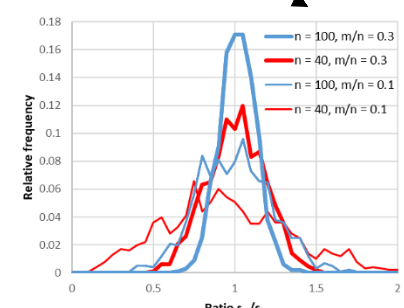
- Total logarithmic standard deviation is then

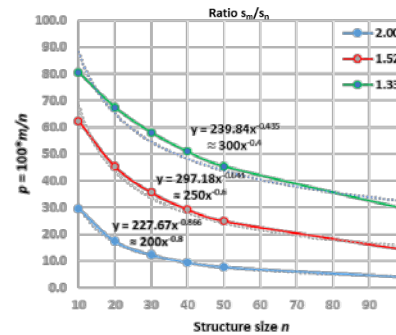
$$\sigma_{\ln \mathrm{R,tot}} = \sqrt{\sigma^2_{\ln \mathrm{R}} + \sum \left(c_{\mathrm{i}} \sigma_{\ln x_i}\right)^2}$$

- The $\sigma_{\ln x_i}$ is only imperfectly known (limited testing)

$$\sigma_{\ln \mathrm{R,tot}}(KL) = \sqrt{\sigma^2_{\ln \mathrm{R}} + \sum \left(c_{\mathrm{i}} s_{\ln x_i}\right)^2}$$

$r_{\mathrm{i}}\sigma_{\ln x_i}$





Partial factors on resistance: formulation

Table 5.1 — KLG on Geometry as a function of collected information

Original design documents (outline or detailed construction drawings)	Extent of survey*		
	L	E	C
Not available	KLG1	KLG2	KLG3
Incomplete set	KLG2	KLG3	
Complete set	KLG3		

* L: limited; E: extended; C: comprehensive (see **3.1.3**)

(2) If discrepancies between the structural drawings and the survey results are significant, a more extensive dimensional survey should be performed (e.g., from limited to extended), or a lower KLG should be adopted.

(3) For each type of element (column, wall, beam, floor diaphragm, etc.), the minimum percentage of structural elements (reinforced concrete or steel) that should be surveyed for dimensions is given by Formula (5.1), depending on the required extend of survey.

$$p = p_1 n^{-c} \leq 100 \qquad (5.1)$$

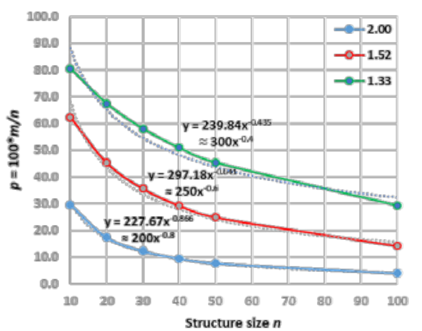
where:

n is the total number n of elements of this type in the structure, determined according to **(5)**;

p_1 and c are coefficients which should be taken from Table 5.2 for each level of survey.

Table 5.2 — Minimum requirements for different levels of survey (vertical elements*)

Level of survey	Limited (L)	Extended (E)	Comprehensive (C)
p_1	200	250	300
c	0,8	0,6	0,5



Partial factors on resistance: calibration

- $\sigma_{\ln \mathrm{R,tot}}(\boldsymbol{x}, \boldsymbol{KL}) \rightarrow \gamma_{\mathrm{Rd}}(\boldsymbol{x}, \boldsymbol{KL})$ depends on the structural member, i.e. $\boldsymbol{x}$

$$\gamma_{\mathrm{Rd}}(\boldsymbol{x}, \boldsymbol{KL}) = e^{-\kappa\sqrt{\sigma^2_{\ln \mathrm{R}} + \sum\left(c_{\mathrm{i}}(\boldsymbol{x}) s_{\ln x_i}\right)^2}}$$

$$\boldsymbol{KL} = \{KLG \quad KLD \quad KLM\}$$

- Luckily $\gamma_{\mathrm{Rd}}(\boldsymbol{x})$ is reasonably stable with $\boldsymbol{x}$

Min., Average, High

- Further, KLG, KLD, KLM each has 3 values
  - This leads to $3^3 = 27$ values of $\gamma_{\mathrm{Rd}}(\boldsymbol{x})$

- One KL, however, normally dominates each formula

Sum only over x_{i} belonging to KLj (e.g., f_{c} is KLM)

$$\text{“}\frac{\partial \sigma_{\ln \mathrm{R,tot}}}{\partial KL}\text{”} = \frac{\sqrt{\sum_{j \in KL}\left(c_{\mathrm{j}} s_{\ln x_{\mathrm{j}}}\right)^2}}{\sigma_{\ln \mathrm{R,tot}}}$$

- It is possible to evaluate on a large parameters’ space the factor for each formula and then tabulate an average value as a function of the dominant KL

Partial factors on resistance: calibration

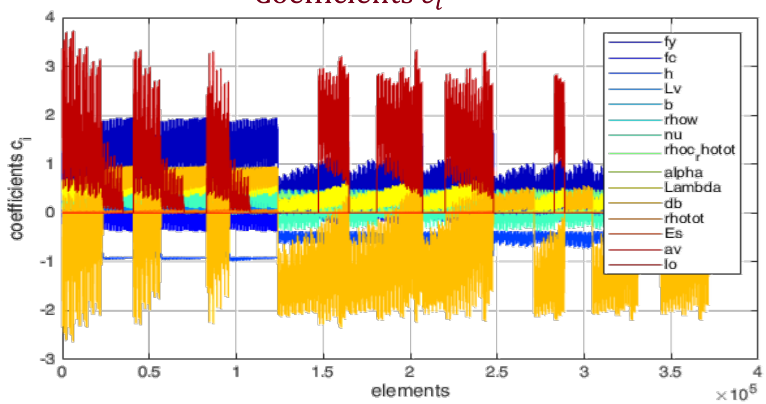
- For each formula a parameter space has been defined
- 27 values of $\gamma_{\mathrm{Rd,KL}}(\boldsymbol{x})$ have been computed, then simplified to 3 wrt to dominant KL
- For now, «calibration» = matching the resistance implied by the previous code (2005)

Assumed $\sigma_{\ln x_i}$

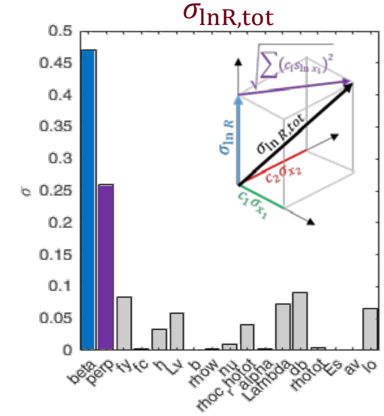
		type	$\sigma_{\ln x_i}$ (existing)
f_y	steel yielding stress	KLM	0.10
f_c	concrete resistance	KLM	0.15
d_b	long.rebar diameter	KLD	0.20
ν	normalized axial load	KLG	0.10
ρ_{tot}	total long.geom.ratio	KLD	0.20
ρ_w	trasversal geom.ratio	KLD	0.20
E_s	steel elastic module	KLM	0.00
a_v	boolean variable	KLG	0.00
Λ	overlapping ratio	KLD	0.20
l_o	long.reinf. sovrapp. length	KLD	0.10
μ	ductility parameter	KLG	0.20

Table 1: Variability in the *shared* parameters.

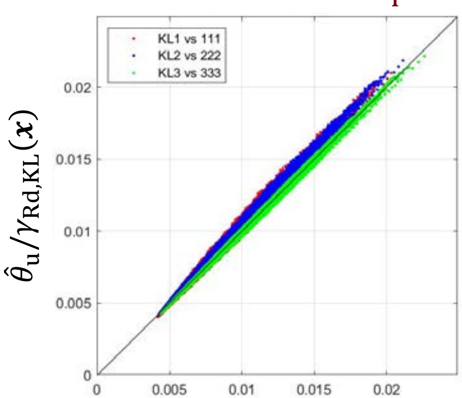
Coefficients c_i



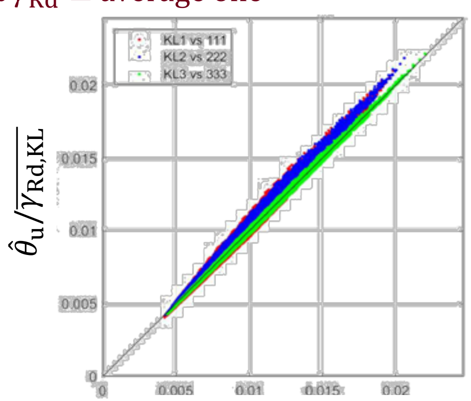
$\sigma_{\mathrm{lnR,tot}}$



Member-dependent γ_{Rd} ≅ average one



θ_u in EN1998-3:2005



θ_u in EN1998-3:2005

$3^3 = 27\ \gamma_{\mathrm{Rd}}$ values and dominant KL (Details in this case)

KLG:	1	1	1	2	2	2	3	3	3
KLD:	1	2	3	1	2	3	1	2	3
KLM:1	1.66	1.61	1.60	1.65	1.60	1.58	1.64	1.59	1.58
KLM:2	1.66	1.61	1.60	1.65	1.60	1.58	1.64	1.59	1.58
KLM:3	1.66	1.61	1.59	1.64	1.60	1.58	1.64	1.59	1.57

(b) γ_{Ra,θ_u} (G/D/M sens. = 0.058 0.190 0.008)

Simplified table with 3 γ_{Rd} values (dominant KL only)

KLD	1	2	3
γ_{Rd}	1,67	1,62	1,57

(*) Example: rectangular RC member with short lap-splice and ribbed bars

Conclusions

- Seismic assessment and retrofit design in Eurocode 8 is
  - Quantitative
  - Displacement-based
  - Employs nonlinear analysis and inelastic deformation criteria

- Safety on the resistance side is ensured by using γ_{Rd}, member-level partial factors on resistance that
  - Divide the median resistance evaluated with best-estimate properties
    - The same properties that enter into the (nonlinear) model
  - Are consistently derived across all materials and failure modes
  - Account for model uncertainty and uncertainty on input variables
  - Are tabulated vs the dominant KL
    - Each formula is most sensitive to one between Geometry, Details and Materials
  - Can be changed at national level with a single formula (*)

(*) not shown! Note that this reduces the number of NDPs to just one