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A GENERAL MODEL OF RESISTANCE PARTIAL FACTORS FOR SEISMIC ASSESSMENT AND RETROFIT

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ABSTRACT

This paper presents a general model for computing partial factors on the resistance or capacity-side, to be used in codified limit-state design, accounting for epistemic uncertainty in the resistance model, aleatoric uncertainty on variables input to the model, statistical uncertainty on these variables stemming from limited available data, and target safety. The choice of resistance-side factors cannot be made independently of the demand-side ones, if a target safety is aimed at. The issue is only briefly discussed herein and derivations are carried out independently for the sake of illustration. The partial factor values can be obtained to replicate pre-existing (implicit, uncontrolled) safety from a former code, or to obtain a new consistent safety level, as desired. The format has been proposed in the framework of the ongoing Eurocodes' revision work and the discussion makes reference to Part 3 of Eurocode 8, which deals with seismic assessment and retrofit of existing structures.

Keywords: Eurocodes; epistemic uncertainty; target safety; global verification;

1. INTRODUCTION

The partial factors format, with small variations and through different paths, has become the consolidated basis of all major structural codes and guideline documents worldwide. Instances of the format differ, for instance, in whether the factors apply to individual input material properties, or globally at the resistance level, as for instance in the load and resistance factor design (LRFD). Calibration of the factors dates back several decades and has been performed with reference to simple structural systems and under load conditions different from the seismic one. A first attempt to provide a rational basis for recalibration with reference to the seismic case is due to Cornell and co-workers (Cornell et al, 2002), who, during the SAC project, revisited the LRFD, renaming it demand and capacity factor design (DCFD), and showed how to account for all relevant uncertainties on both load and resistance side, quantified, in their language, through demand and capacity[3] dispersions denoted with β's.

The current version of EN1998-3 (CEN, 2005), i.e. Part 3 of "Eurocode 8", dealing with seismic assessment and retrofit of existing buildings (Part 3 from now on), is "in its simplicity and frugality, a wise document" (Fardis, 2017). Nonetheless, in contrast to traditional code drafting practice, Part 3 was written to fill a gap in a very relevant field where the need for recommendations was high but the practical experience at the time still low. In this respect, it comes to no surprise that application in the following years has exposed the short-comings of what should be regarded as an experimental document. The ongoing revision work aims at improving the document while preserving the good aspects of its original version.

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[3] The Eurocodes denote with "action effect" and "resistance" the effect of applied actions, i.e. the structural response parameter of interest in the verification, and the corresponding limit, respectively. These are commonly referred to in the earthquake engineering literature with the terms "demand" and "capacity". In particular, the term Engineering Demand Parameter, or EDP, is also very used. In what follows they are all used interchangeably.

This paper focuses on the safety format, and on one particular aspect of this format, i.e. the partial factors to be used on the resistance side. A general formulation for these factors is proposed and discussed. The next section briefly recalls the main aspects of current Part 3. Section 2 presents the new format, section 3 illustrates calibration examples, while section 4 presents conclusions.

1.1 Brief summary of current Part 3

Safety is encoded into Part 3 within Section 2 (Performance requirements and Compliance criteria), Section 3 (Information for structural assessment) and Section 4 (Assessment). In particular, Section 2 sets out the so-called performance objectives, i.e. the coupling between target performance (i.e. a limit state not to be exceeded) and the associated design seismic action intensity. Section 3 deals with the fundamental phase of knowledge acquisition, which plays a central role in the assessment of existing structures, and should be closely related to the assessment outcome. It introduces the notion of Knowledge level (KL), which is a way to discretize acquired knowledge into three distinct levels, and of the associated Confidence factor (CF). Section 4 deals with the methods of modeling and analysis, used to derive the effect of the actions. Section 4 also introduces the distinction of brittle and ductile (failure) mechanism, and differentiates their verification: the former are checked in terms of force quantities, while the latter in terms of deformations.
The main aspects relevant to this paper as outlined in the indicated sections of the current Part 3 are:

1. Mean material properties are used in the model employed for analysis (simply the model from now on).
2. Action effects for the verification of ductile mechanisms are determined from the analysis (i.e. deformation from the mean model are used).
3. Action effects for the verification of brittle mechanisms are determined from the analysis, but if the latter is a linear one, the action effect (which is a force quantity, namely shear) is capped through principles of capacity design to the so-called plastic shear (with an a posteriori computation). The plastic shear is obtained starting from flexural strength computed using mean material properties amplified by the confidence factor.
4. Resistance for ductile mechanisms (i.e. flexure with or without axial force, checked in terms of flexural deformation) is computed using mean material properties divided by the confidence factor.
5. Resistance for brittle mechanisms (shear strength) is computed using mean material properties divided by both the confidence factor and the usual material partial factors from other relevant parts of the Eurocodes, like γ_c and γ_s.
6. A single value of CF is used, that depends on KL
7. KL is unique over the structure. It depends on information gathered in three categories, namely Geometry, (Construction) Details and Materials.

Among other criticism already brought to Part 3 and in particular to the KL/CF format, e.g. in (Franchin et al, 2010), more specific comments can be made based on the above list.
First of all, it cannot escape the attention that, for each material property (e.g. concrete strength, masonry strength, steel strength, etc), four different values are used in different parts of the procedure (items 1, 3, 4 and 5 in the list): the mean in the model, the mean divided by CF in the evaluation of deformation capacity, the mean divided by CF and the "regular" γ's for the evaluation of shear strength, the mean multiplied by CF for the evaluation of the shear demand plateau in linear analysis. This certainly is against ease of use and can lead to gross errors. It also introduces a conceptual inconsistency between the maximum shear demand computed in linear and nonlinear analyses, the former being larger than the latter, which comes from the mean model.
A second comment regards the poor link between the knowledge gathered on the structure, which determines the KL, and the assessment result. KL influences CF, but the latter acts only on the material properties. Experience has shown that often, of the three information categories, Materials is not the most important, but the mechanism encoded in current Part 3 does not reflect this accurately. Also, the use of a unique KL for the entire structure and the use of a single KL that reflects knowledge in three different categories of information (G, D and M) are too stiff to cope with the reality of assessment of existing buildings. In fact, the practice of seismic assessment in the time elapsed from the release of Part 3 has shown that:

1. In most situations knowledge cannot be increased homogenously in all three information categories.
2. In non-critical or less stressed areas the penalization corresponding to lower knowledge may well be non-influential.
3. Uncertainty exists not only on material properties, but also on geometric dimensions and construction details.

Based on the above, a new format for Part 3 was proposed whereby the single KL is replaced by distinct knowledge levels on Geometry (KLG), Details (KLD) and Materials (KLM). These are allowed to be non-uniform over the structure. In particular, a "lightweight" preliminary analysis is introduced, which is not mandatory, but if performed allows the user to focus survey and testing activities on foreseen critical areas, aiming at lower knowledge in the non-critical ones. Further, KLG, KLD and KLM are directly linked to the assessment outcome, since they determine the partial factors in the safety verifications. Finally, mean properties are used everywhere, both in the analysis model and in the resistance models for verifications, resulting in more consistent (e.g. the shear demand issue), streamlined and therefore less error-prone workflow. The next section describes and discusses the object of this paper, i.e. the way the new resistance-side partial factors are computed.

2. PROPOSED FORMAT

2.1 Nature of resistance models

Resistance or capacity models provide values of force or deformation thresholds corresponding to predefined states of damage in the structure. Sometimes these models have a firm mechanical basis, in other cases they encode past experience, or they are the result of statistical analysis of experimental results. In very general terms, capacity of a structural member (to deform, bend, absorb shear, etc) depends on the properties of the constituent materials, its geometry and the construction details. In more specific terms, however, any model must describe these aspects through a finite number of measurable variables and combine them in some mathematical form. Model building is always an exercise of parsimony where a balance between accuracy and simplicity has to be stricken. For these reasons, even the best model usually fails to capture all aspects and this leads to a discrepancy between predicted and measured capacity. As a result, while resistance is a random variable with a given (unknown) distribution, predicted resistance is a different random variable, with a different distribution. In particular, resistance may be biased with respect to actual resistance, i.e. it consistently under-predicts (or over-) the latter, or can show a larger dispersion (Figure 1a).
The way these models are formulated and presented has changed over time. Born for design purposes, where conservatism and margins of safety come at a relatively lower cost, these models in the past have been systematically produced to provide a lower bound to resistance, i.e. to be biased (Gardoni et al, 2002). Further, in most cases the models are reported without a quantification of the associated "model error", i.e. the additional variability of the predicted resistance due to the statistical lack of fit and the missing variables. This is not the case with the most recent models, which are designed to be unbiased and always reported with the associated error (see e.g. Grammatikou et al 2015, Zhu et al 2007). A recent review of these models for both RC and masonry can be found for example in (CNR, 2014).

2.2 Formulation of a general model for the resistance-side partial factor

Most models in Part 3, and especially in the revision, are recent models, with a mechanical basis and relatively strong experimental support. Models of this type usually conform to the following general formulation:

$$R = \hat{R}(\mathbf{x})\varepsilon_R \tag{1}$$

where the function $\hat{R}$, often referred to as the «formula», is conceived so as to predict the median resistance, i.e. the model is unbiased; vector $\mathbf{x}$ collects the input variables, both random and deterministic; ε_R is a unit median lognormal (LN) random variable with logarithmic standard deviation σ_{lnR} measuring the model lack of fit (uncertainty additional to that of $\mathbf{x}$). Typical values of σ_{lnR} are in the range 0,2÷0,3 for strength and in the range 0,3÷0,7 for deformation.

The total logarithmic standard deviation of R, $\sigma_{lnR,tot}$, is a function of σ_{lnR} and of the covariance matrix of $\mathbf{x}$, and is larger than σ_{lnR} (e.g. Figure 1b) The final distribution of R is a function of the distribution of the input variables $\mathbf{x}$ and of ε_R. Under the (mild) assumption of lognormality for R, a simple expression holds between $\sigma_{lnR,tot}$ and the partial resistance factor providing any given fractile R_k of the distribution of R:

$$R_k = \exp\left(\mu_{\ln R} + \kappa\sigma_{\ln R,tot}\right) = \exp\left(\mu_{\ln R}\right)\exp\left(\kappa\sigma_{\ln R,tot}\right) = \hat{R}\exp\left(\kappa\sigma_{\ln R,tot}\right) \rightarrow \gamma_{Rd} = \frac{\hat{R}}{R_k} = \exp\left(-\kappa\sigma_{\ln R,tot}\right) \qquad (2)$$

where $\kappa = \Phi^{-1}(k)$ is the number of logarithmic standard deviations from the log-mean corresponding to the k-th fractile[4]. Equation (2) shows that, given a proper resistance model, it is possible to obtain any desired fractile of the predicted resistance distribution, duly accounting for all uncertainties, in the model and in the input variables. The open problems are: 1) how to establish an appropriate target resistance fractile, i.e. the value of κ; 2) how to evaluate the total logarithmic standard deviation of R, $\sigma_{lnR,tot}$.

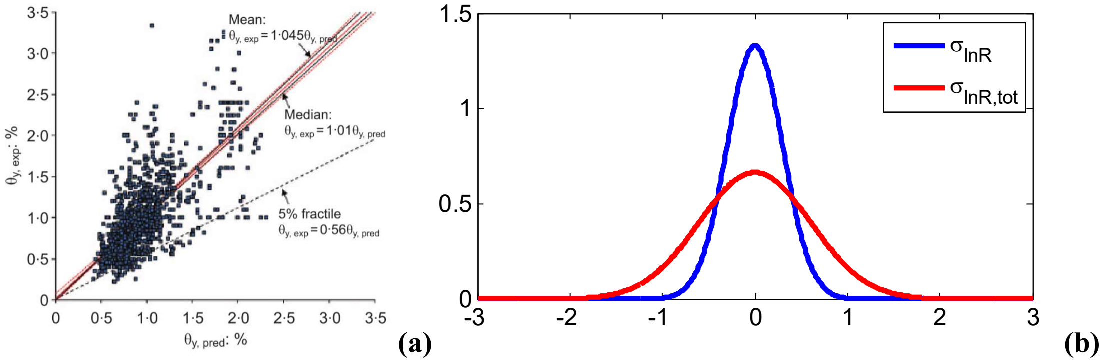


Figure 1. Capacity models: (a) experimental vs predicted values of chord rotation at yield for a RC member, according to the model in (Biskinis and Fardis, 2010); (b) increased dispersion of predicted capacity with respect to actual capacity (for an assumedly unbiased model).

2.3 Target safety at the global structural level and choice of κ at the local level

The problem of choosing an appropriate resistance fractile, and hence a value for γ_{Rd}, has no unique solution in itself because, as anticipated, in the partial factor safety format an upper fractile of demand is compared with a lower fractile of resistance, and it is their joint choice that determines what is the associated probability of exceedance of the limit state. Eurocode 8 does not declare explicitly a target collapse safety, thus targets set in Eurocode 0 (CEN, 2002), for failure probability or, equivalently, the reliability index, as a function of, among others, the consequences of failure, are implicitly the reference. There is no formal proof, however, that Eurocode 8 compliant structures respect those targets (RINTC, 2017). More generally, the appropriateness of safety targets established for non-seismic loads in the seismic case is under discussion worldwide, and annual collapse probability

[4] The symbol used to denote the partial factor on the resistance side, γ_{Rd}, is the symbol used in Eurocode 0 (CEN, 2002). As explained later in Section 2.6, though the symbol is the same the factor is different in that it divides the median resistance value, rather than the so-called characteristic one.

values regarded as appropriate for the seismic case are reported to be in the range $2\times10^{-4}\div10^{-5}$ (Dolšek et al 2017). Provided a choice is made, either by confirming the "static" or "non-seismic" target, or choosing another one, proposals for the verification (explicit check) have been advanced, remaining within the framework of the partial factor format (Dolšek et al 2017).
Herein, as anticipated, the choice on the lower fractile of resistance is made independently of that on action effects, for the sake of illustrating the formulation and targeting the same fractile of total resistance provided by the previous code for ductile failure modes (i.e. deformation thresholds). Nonetheless, one comment is in order on one crucial aspect of the problem.
Limit state exceedance is, in general but specifically for seismic conditions, a system failure event. It is especially so when the considered limit state is that of collapse. The reported target probabilities in the range $2\times10^{-4}\div10^{-5}$ refer to this system-level event (the structure failing) and could be denoted by p_C. The target failure probability at the local, component-level (the structural member failing), $p_{f,comp}$, is related to p_C, and could be lower if the system is a series arrangement of components, like e.g. piers in a simply-supported girder bridge, or higher, if the system is a parallel arrangement of components, like e.g. columns in a floor. The relation between p_C and $p_{f,comp}$ if further modified by the correlation ρ among the components' failures, which is non zero due to common cause effects (the seismic action) and to the correlation induced by construction quality, material properties, common design, etc. Solutions exist for establishing a link between p_C and $p_{f,comp}$, considering components' correlation and system arrangement, e.g. (Thoft-Christensen and Sørensen, 1982). Moreover, the component-level failure probability can be directly related to the product $\gamma_{\mathrm{Sd}}\times\gamma_{\mathrm{Rd}}$ (Pinto et al, 2004). The point made here is that, once p_C and γ_{Rd} are fixed, γ_{Sd} will follow (i.e., it can be chosen in a consistent way). Finally, it can also be observed that a direct verification of the limit state exceedance at the global level eliminates the need for the approximate passage between system and components failure events. For this reason, such a global verification format has been proposed for the revised Part 3, reflecting current consolidated practice e.g. for masonry buildings, at least in Italy.

2.4 Total logarithmic standard deviation of the predicted resistance $\sigma_{lnR,tot}$

A good approximate solution in closed form can be found for the problem of computing the value of $\sigma_{lnR,tot}$, for each resistance model, if the relation between resistance, input variables and error term is linearized in the log-space around the median resistance. Based on Equation (2), one can write the first order expansion of the natural logarithm of R as:

$$\ln R = \ln \hat{R}(\mathbf{x}) + \tilde{\varepsilon}_R \cong \ln \hat{R}(\hat{\mathbf{x}}) + \sum_i \left.\frac{\partial \ln \hat{R}(\mathbf{x})}{\partial \ln x_i}\right|_{\hat{\mathbf{x}}} \left(\ln x_i - \mu_{\ln x_i}\right) + \tilde{\varepsilon}_R \tag{3}$$

where $\tilde{\varepsilon}_R = \ln \varepsilon_R \sim N\left(0, \sigma_{\ln R}\right)$. By further manipulation one gets:

$$\begin{aligned} \ln R &\cong \ln \hat{R}(\hat{\mathbf{x}}) + \sum_i \frac{1}{\hat{R}(\hat{\mathbf{x}})} \left.\frac{\partial \hat{R}(\mathbf{x})}{\partial \ln x_i}\right|_{\hat{\mathbf{x}}} \left(\ln x_i - \mu_{\ln x_i}\right) + \tilde{\varepsilon}_R = \\ &= \underbrace{\ln \hat{R}(\hat{\mathbf{x}})}_{\substack{\text{median } R \text{ evaluted} \\ \text{in the median of } \mathbf{x}}} + \underbrace{\sum_i \underbrace{\frac{\hat{x}_i}{\hat{R}(\hat{\mathbf{x}})}}_{\substack{\text{correction} \\ \text{for the logarithm}}} \underbrace{\left.\frac{\partial \hat{R}(\mathbf{x})}{\partial x_i}\right|_{\hat{\mathbf{x}}}}_{\substack{\text{sensitivity of} \\ \text{median R to xi}}} \underbrace{\tilde{\varepsilon}_i}_{\substack{\text{deviation} \\ \text{of xi from} \\ \text{its median}}}}_{\substack{\text{(linear) effect of deviations} \\ \text{of } \mathbf{x} \text{ from its median}}} + \underbrace{\tilde{\varepsilon}_R}_{\substack{\text{deviation from} \\ \text{the median R} \\ \text{evaluated in} \\ \text{median } \mathbf{x}}} = \ln \hat{R}(\hat{\mathbf{x}}) + \sum_i c_i \tilde{\varepsilon}_i + \tilde{\varepsilon}_R \end{aligned} \tag{4}$$

which states that the natural logarithm of the resistance is a linear function of the zero-mean variables $\tilde{\varepsilon}_R$ and $\tilde{\varepsilon}_i$. The coefficients c_i can be interpreted (and computed) as the ratio of the tangent to the function $R(\mathbf{x})$, $\partial \hat{R}(\mathbf{x}) / \partial x_i$, to the secant, $\hat{R}(\mathbf{x}) / \hat{x}_i$, in the median resistance. Provided the linear relation in Equation (4), the mean and standard deviation of the logarithm of R (i.e. the log-mean of R

and its total log-standard deviation $\sigma_{lnR,tot}$) can be computed as:

$$\mu_{\ln R} = E[\ln R] = \ln \hat{R}(\hat{\mathbf{x}}) \tag{5}$$

$$\sigma_{\ln R,tot} = \sqrt{\sigma^2_{\ln R} + \sum_i c_i^2 \sigma^2_{\ln Xi}} \tag{6}$$

where σ_{lnXi} is the log-standard deviation of the i-th input variable.

2.5 Link between γ_{Rd}, the knowledge level and the sample size of each measured property

Equation (6) provides the means to link the resistance fractile used in a verification, through the partial factor in (2), with the actual knowledge of the input variables and the uncertainty introduced by the model error. Equation (6) can be rewritten as:

$$\sigma_{\ln R,tot,KL} = \sqrt{\sigma^2_{\ln R} + \sum_i c_i^2 \left(CF_i \hat{s}_{\ln Xi}\right)^2} \tag{7}$$

where the actual log-standard deviation of the i-th input variable, σ_{lnXi}, is replaced by its median estimate based on a limited sample size, $\hat{s}_{\ln Xi}$, amplified by a confidence factor CF_i. While the name and symbol is the same as in current Part 3, the CF is here redefined as the ratio between a desired fractile of the empirical distribution of s_{lnXi} and its median. In principle, in each single assessment case, a value for s_{lnXi}, to be used in (7) in place of $CF_i \hat{s}_{\ln Xi}$, could be estimated based on a sample of property values $\{x_{i1}, x_{i2}, \ldots, x_{in}\}$. The problem is that, consistently with the need for conservatism in verification with the partial factor format, only cases where the sample $\{x_{i1}, x_{i2}, \ldots, x_{in}\}$ leads to an estimate $s_{\ln Xi} > \hat{s}_{\ln Xi}$ are of interest, but, by definition, there is a 50% probability of underestimation of the actual log-standard deviation σ_{lnXi} of X_i (to which the median $\hat{s}_{\ln Xi}$ converges with increasing sample size, being $\hat{s}_{\ln Xi}$ an unbiased estimator). That is to say, when performing material tests or geometric surveys, it may and indeed it happens that, with limited sample sizes, samples show less variability than the real one, resulting in unconservative values for γ_{Rd}. Test values are thus better used to establish median values for the properties, while predefined $CF_i \hat{s}_{\ln Xi}$ value for each property are tied to sample size. The resulting actual value of CF is a function of KL (i.e. sample size) and of the desired fractile of s_{lnXi} (the latter being one choice in the calibration procedure).

Numerical simulation has been used to establish the empirical distribution of s_{lnXi}, as a function of the sample size, for a generic geometric variable, construction detail or material property to be investigated. Let the spatial distribution of this property over a structure of size n (i.e. the $n\times1$ vector of measurable property values, e.g. one value per member) be an instance of a random variable with mean μ and standard deviation σ. The actual mean and standard deviation of the property in the structure will be m_n and s_n. A generic testing and inspection campaign will survey/measure a sub-vector of size $m<n$, resulting in estimates m_m and s_m of the parameters. Focusing on standard deviations, s_n is the actual one for the structure investigated (σ_{lnXi}), and s_m is one value from the distribution of s_{lnXi} over all possible testing campaigns of size m.

Figure 2a shows results of one simulation. Each curve corresponds to one instance of the structure, with two sizes n considered (100 and 40), subject to a 1000 instances of testing campaigns, with two different sizes m considered (10% and 30% of positions surveyed). The plotted quantity is the ratio of s_m to s_n, and the plots show the estimator is unbiased. What is of interest is the spread of the values, which coincides with that of s_m and is obviously larger for smaller values of m/n.

By repeating the simulation for increasing values of the structure size n (between 10 and 100, representative, e.g. of a small one by one bay, two floor building and of a larger 3 by 4 bays, 3 floors building, respectively), one can plot values of the ratio m/n, or percentage of members to be investigated to obtain a target ratio CF of s_m/s_n, ranging for instance between 2,0 and 1,33. The result is shown in Figure 2(b). These curves can be fitted with an analytical expression to finally yield an equation that, as a function of the desired CF, larger for lower confidence or KL, provide the number of tests/measurement as a function of structure size:

$$p = p_1 n^c \leq 100 \tag{8}$$

The three pairs of values for the constant term p_1 and the (negative) slope c in Figure 1b can be attributed to a minimum, average and high knowledge level (this is actually the denomination of KLs in the current draft of the revised Part 3). Such a rational link between the number of measurements, the structure size, the resulting uncertainty of estimation and, ultimately, through Equations (7) and (2), the resistance value to be used in verifications, is missing in the current version of Part 3 (CEN, 2005). In particular, a similar relationship, with tests increasing less than linearly in number with the structure size, should be applied also to destructive testing methods.
Finally, results refer to a simulation with $\mu = 1{,}0$ and $\sigma = 0{,}10$, but a parametric study shows that they are not sensitive to the underlying distribution, confirming that such simulation can be used to establish a link between a fractile of $s_m = s_{lnXi}$ independently of the nature of the variable.

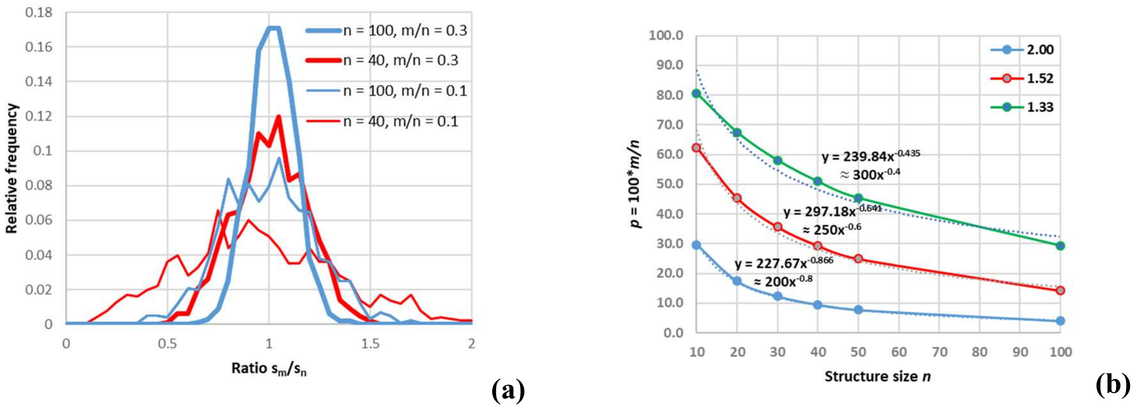


Figure 2. (a) Empirical distribution of the ratio of the standard deviation s_m of a sample of size m to the standard deviation s_n evaluated with $m<n$ values measured from the sample; (b) Percentage of measures (ratio m/n) as a function of structure size (number of values m) for a set of CF values. The actual values used in the code are in a more intuitive progression (second approximate expression in b).

2.6 Summary and discussion of partial factor model and difference with current practice

The previous sections have introduced an analytical expression, equation (2), that, under the mild assumption of lognormality for the predicted resistance, provides the value of the partial factor γ_{Rd} that gives any given fractile dividing the predicted median. The expression for γ_{Rd} requires knowledge of the total variability of the predicted resistance, which is a function of the variability of the input variables to the resistance model and of the model error term. An analytical expression for this total variability, equation (6), is determined based on linearization in log-space around the median. Equation (6) is then modified into equation (7), which allows for imperfect knowledge of the input variables. The achieved level of knowledge is linked to the number of measures on one side, and to the estimated s_{lnXi} on the other.
Based on the above one possibility is to provide equations (2) and (7) and let the code user evaluate the partial factor for each verification. This option, though more transparent, is certainly against ease of use. The alternative is to provide directly values of γ_{Rd}, tabulated for combinations of KLG, KLD and KLM, and for each and every capacity formula in the code. The only difficulty in the associated calibration work, described in the next section, is to cover a sufficiently wide range of input parameter combinations for each formula, so as to provide γ_{Rd} values that are applicable in all cases of practical interest.
The above framework is formally compatible with the Eurocodes, since in Eurocode 0 (CEN, 2002),

the following expression for the design value of resistance R_d is introduced (equation 6.6 in the code):

$$R_d = \frac{1}{\gamma_{Rd}} R\left\{X_{d,i}; a_d\right\} = \frac{1}{\gamma_{Rd}} R\left\{\eta_i \frac{X_{k,i}}{\gamma_{m,i}}; a_d\right\} \qquad i \geq 1 \tag{9}$$

where the γ_{Rd} is a “a partial factor covering uncertainty in the resistance model, plus geometric deviations if these are not modelled explicitly”, and $X_{d,i}$ is the design values of the i-th material property, obtained dividing the characteristic value X_k by the corresponding material partial factor γ_m (the other quantities appearing in (9) are the design value of geometrical data a_d and a conversion factor η_i accounting for things such as moisture effects, volume and scale effects, etc). The above format is almost never used and usually it is replaced by:

$$R_d = R\left\{\eta_i \frac{X_{k,i}}{\gamma_{M,i}}; a_d\right\} \qquad i \geq 1 \tag{10}$$

where $\gamma_{M,i}=\gamma_{m,i}\times\gamma_{Rd}$. Either (9) or (10) do not provide a consistent fractile of resistance across different models. Actually, the fractile of resistance obtained is unknown and can only be determined a posteriori. The new format, embraces and actually widens the definition of γ_{Rd}, to include in it not only “uncertainty in the resistance model, plus geometric deviations” but also uncertainty in the material properties and construction details.

$$R_d = R\left\{X_{50\%,i}; a_{50\%}\right\} / \gamma_{Rd} \qquad i \geq 1 \tag{11}$$

The choice of computing the design value as a chosen, controlled fractile of resistance, starting from the median, is convenient because recent models are formulated to provide the median, and because usually resistance values correspond to force or deformation ordinates of the constitutive relation of members. With the proposed format resistance is computed only once (the median) for both response analysis (values that go into the model) and verifications (values that are divided by γ_{Rd}).

2.7 Mean or median

One last important aspect needs to be commented before illustrating an example of calibration. In the previous text the central value of resistance, as well as of input variables to resistance models, has been described through the median. While median and mean coincide for symmetric distributions, and in particular for the Gaussian one, they don’t for non-symmetric ones. The «mean» is ubiquitously used in the code because the expected value (mean) of a function (the response) of Gaussian variables (the material properties, the system, etc) is the function computed in the mean of these variables, and properties have traditionally been modeled as Gaussian. Material properties, geometric dimensions, etc, but also spectral accelerations and other intensity measures, or vertical loads, are indeed positive definite, non-symmetric quantities and the Gaussian model is conceptually flawed. Most, if not all, these properties can be modelled as lognormal (i.e. they pass the hypothesis rejection test). Interestingly enough, the expected value of a function of lognormal variables is well approximated by the function computed in the median of the variables. That is to say, it would be time to move from the mean to the median also in the code, e.g. prescribing that analysis be performed with the median, rather than the mean model, and so on. In any case, for practical purposes, since the two asymptotically coincide for small values of the dispersion:

$$\mu_X = \exp\left(\mu_{\ln X} + 0.5\sigma^2_{\ln X}\right) = x_{50\%} \exp\left(0.5\sigma^2_{\ln X}\right) \rightarrow \lim_{\sigma_{\ln X}\rightarrow 0} \mu_X = x_{50\%} \tag{12}$$

for many variables mean and median can be almost used interchangeably.

3. CALIBRATION EXAMPLE

This section illustrates the calibration of the γ_{Rd} factor for the case of shear resistance of RC members. Shear resistance is given by the model:

$$\hat{V}_R(\mathbf{x}) = \frac{h-x}{2L_V}\min\left(N;0{,}55A_c f_c\right) + \left[1-0{,}55\min\left(5;\mu_\Delta^{pl}\right)\right]\times$$
$$\times\left[0{,}16\max\left(0{,}5;100\rho_{tot}\right)\left(1-0{,}16\min\left(5;\frac{L_V}{h}\right)\right)\sqrt{f_c}A_c + V_w\right] = V_N + c\left(\mu_\Delta^{pl}\right)\left(V_c+V_w\right) \tag{13}$$

characterized by a model error term with σ_{lnR} = 0,25. The input variables collected on vector **x** are the steel and concrete strength, f_y and f_c, the section height and web width h and b_w, the shear span L_V, the shear reinforcement ratio ρ_w (not shown but entering into the steel contribution V_w), the normalized axial force ν. All input variables are modelled as lognormal, with medians varying across a space of 3888 combinations and constant dispersions. In particular, in order to provide tabulated values of γ_{Rd} dependent only on the (KLG, KLD, KLM) combination, but not on the particular member considered (i.e. the value of **x**), the following values (i.e. their resulting 3888 combinations) have been considered to span a reasonable range of application for existing RC buildings:

1. Steel yield strength f_y: 250 MPa, 350 MPa and 450 MPa. Dispersion σ_{lnXi} = 0,10. Affected by KLM
2. Concrete strength f_y: 15 MPa, 30 MPa and 45 MPa. Dispersion σ_{lnXi} = 0,15. KLM.
3. Section height h: 0,3 m, 0,5 m, 0,7 m and 1,0 m. Dispersion σ_{lnXi} = 0,05. KLG.
4. Web width b_w: 0,3 m, 0,4 m and 0,5 m. Dispersion σ_{lnXi} = 0,05. KLG.
5. Shear span L_V: 1,2 m, 1,5 m and 1,8 m. Dispersion σ_{lnXi} = 0,20. KLG.
6. Shear reinforcement ratio ρ_w: 0,001, 0,002 and 0,003. Dispersion σ_{lnXi} = 0,20. KLD.
7. Axial force ratio ν: 0,05, 0,20, 0,40 and 0,50. Dispersion σ_{lnXi} = 0,10. KLG.

The next step is to choose values for the confidence factors and a target resistance fractile. Even though this example shows calibration only for the shear resistance, this operation has been performed also with reference to other resistances, like chord rotation thresholds. In order to arrive at consistent safety across multiple verifications, the choice was made to target for all resistances the 16% fractile, corresponding to a value of κ = -1, which was found to be the fractile of total resistance provided by the procedure in the previous code, for the deformation threshold θ_u. Similarly, the same CF values for the same KL were also adopted across all resistance models, and, since as shown in Section 2.5, the link between CF and the sample size does not depend on the nature of the investigated quantity, the same CF were adopted for G, D and M variables. In particular, the values chosen are 2,0, 1,5 and 1,3, for knowledge level (on G, D or M) equal to 1, 2 and 3, respectively (see Figure 2b).

A number of resistance values are then computed for each of the 3888 cases. The first ones are the resistances according to the current code (CEN, 2005), denoted with R_{KLi} to underline the use of a single knowledge level and computed for each of the three levels, and employing the partial factors on the material properties γ_c and γ_s, as well as the additional factors CF and γ_{el}. The second is the median resistance $\hat{R}$. The third is the resistance computed according to the new proposal, using for each of the 3888 cases the associated γ_{Rd}, computed in the particular value of **x** according to Equations (2) and (7), and denoted R_{ijk}, where the subscripts range from 1 to 3 and indicate the KLG, KLD and KLM, respectively. Finally, the fourth is the resistance computed according to the new proposal, dividing the median one by γ_{Rd}, but using for the latter the average value (for each KLG, KLD and KLM combination) over the 3888 cases. This last value is denoted by $\tilde{R}_{ijk}$.

Comparison between current code values and the new proposal can be carried out only on the "diagonal cases", i.e. those cases where knowledge in the three categories has reached the same level (KLG=KLD=KLM). Figure 3 shows scatter plots of R_{iii} versus R_{KLi}, on the left, and $\tilde{R}_{iii}$ versus R_{KLi}, on the right. The plots show how, for this resistance model, the proposed format and associated choices (values of CF and κ) lead to a higher resistance than the current code. The plots also show that the approximation of using a mean value for γ_{Rd} over a large number of different members leads basically to the same results. Indeed, the γ_{Rd} values over the 3888 cases show very limited variability, with coefficient of variation that ranges, depending on the *ijk* combination, between 2% and 6%, with an average of 4%.

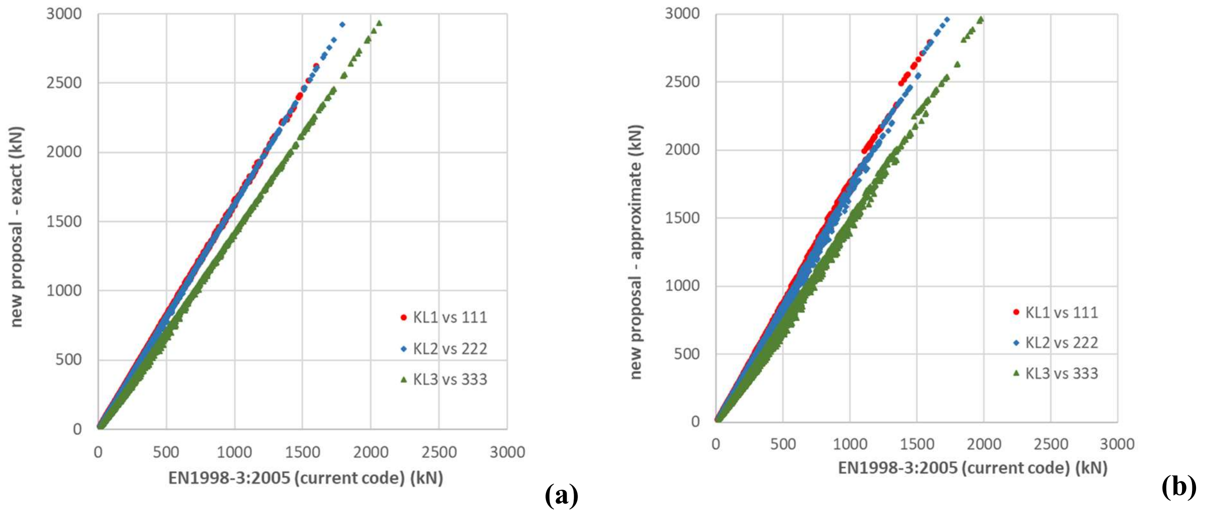


Figure 3. Shear resistance of RC members, diagonal cases, i=j=k: (a) New capacity with "exact" case-dependent γ_{Rd}, R_{ijk}, vs former capacity R_{KLi}; (b) New approximate capacity (average γ_{Rd}) vs former capacity.

The (average) γ_{Rd} values for the 3×3×3=27 combinations of KL's are reported in Table 1, where the values corresponding to diagonal cases are underlined. These can be compared with the average values of the ratio of the design resistance according to the current Part 3, to the median resistance, as done in Table 2.

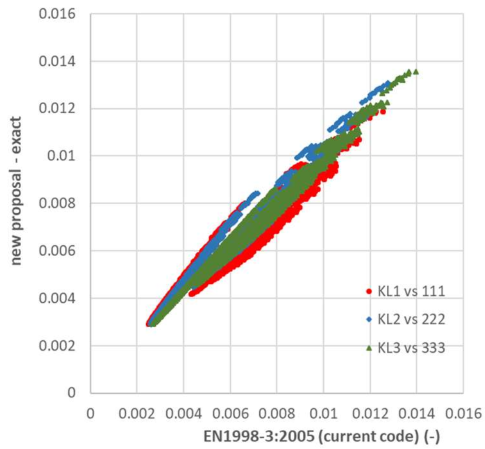
Table 1. Shear resistance of RC members, values of γ_{Rd} for the 27 combinations of KLG, KLD and KLM.

KLG		**1**			**2**			**3**		
KLD		**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
KLM	**1**	<u>1,64</u>	1,62	1,61	1,56	1,53	1,53	1,53	1,51	1,50
	2	1,61	1,59	1,58	1,52	<u>1,50</u>	1,49	1,49	1,47	1,46
	3	1,60	1,58	1,57	1,51	1,49	1,48	1,48	1,46	<u>1,45</u>

Table 2. Shear resistance of RC members, values of γ_{Rd} for the 27 combinations of KLG, KLD and KLM.

Mean of:	**i=j=k=1**	**i=j=k=2**	**i=j=k=3**
$\boldsymbol{\gamma_{Rd} = R_{iii}/\hat{R}}$	1,64	1,50	1,45
$\boldsymbol{\gamma_{eq,KL} = R_{KLi}/\hat{R}}$	2,63	2,36	1,99

As expected the equivalent values are larger than the proposed ones, consistently with the scatter plots in Figure 3 showing a systematically lower capacity predicted by the current code. The comparison allows to appreciate the combined effect of the CF, γ_c, γ_s and γ_{el}, which amounts to reductions of resistance to about 50% (1/1.99) to 38% (1/2.63) of the median value. The latter values seem low and this observation is in line with the widespread feeling the current code procedure results in too penalizing values for the shear resistance. This is confirmed by the observation of Figure 4, analogous to Figure 3, but referring to another resistance model, i.e. the ultimate deformation capacity expressed in terms of chord rotation θ_u. These plots, whose derivation is not shown here, have been determined by assigning a model error term with σ_{lnR} = 0,35 (Biskinis and Fardis, 2010), using a total number of input parameters combinations equal to 52488, and keeping, as already said, the same values of CF and κ employed for the shear resistance. As it can be seen from these plots, in this case the dots distribute around to one to one line (again with quite limited dispersion). This means that the new proposal and the current code yield the same level of protection, i.e. they produce estimates of resistance that correspond to the same fractile from the predicted resistance distribution. Indeed, the average values of γ_{Rd} and of $\gamma_{eq,KL}$ compare very well in this case (from 1,5 to 1,7).



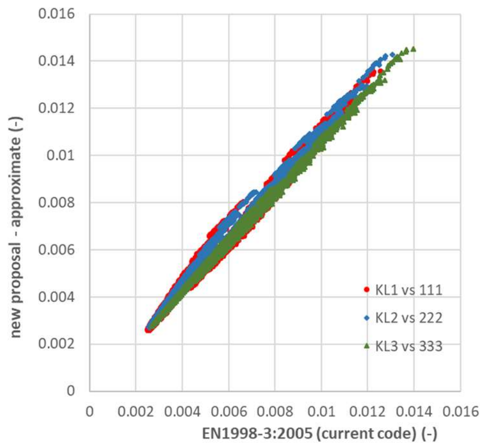


Figure 4. Ultimate chord rotation of RC members, diagonal cases, i=j=k: (a) New capacity with "exact" case-dependent γ_{Rd}, R_{ijk}, vs former capacity R_{KLi}; (b) New approximate capacity (average γ_{Rd}) vs former capacity.

These results illustrate how the current code procedure results in uncontrolled and non-uniform fractiles of the corresponding resistance distributions for each resistance model. The new format achieves on the other hand this homogeneity, and, if the current level of protection against the ductile flexural failure (fractile of θ_u) is considered acceptable, it results in less onerous estimates of shear resistance with respect to the current code, the latter often regarded as being overly conservative.

4. CONCLUSIONS

This paper discusses some aspects of the safety verifications in the current Part 3 of Eurocode 8, devoted to seismic assessment and retrofit of existing structures, and makes a proposal for modification. The core of the proposal is a new general model for the evaluation of a single resistance partial factor capable of accounting for the specific resistance model error, as well as for the uncertainty, inherent and associated to statistical estimation with limited sample size, of all the input variables to the model, describing geometry, construction details and material properties. One major aspect of the proposed formulation is that the knowledge level achieved in any single variable is explicitly linked with the number of measurements of the variable, as a proportion of the maximum number of measurements for the variable (number of locations, or structure size), i.e. to the effort of the testing/inspection campaign.

The problem of linking the margin taken on the resistance side at the local, member-level, with the margin taken on the action effect side, with the aim of ensuring explicit target global (structure-level) safety levels is also mentioned.

The calibration example shows that it is possible to simplify the format and provide easy-to-use tabulated values for the resistance partial factor for each formula in the code. Comparison with current code resistance values also provide some insights on the current code, which is shown to yield to non-uniform level of protection over the different resistance models.

The formulation has a rational basis, it is easy to use and does not imply an increase in the required safety, and hence cost. With appropriate choices for the uncertainty associated with each input

variable, it is difficult to see why it should be limited only to evaluate resistance within the context of seismic assessment of existing structures and not be extended to other loads or to design of new members.
Problems not covered in this paper include the evaluation of resistance partial factors for models that do not conform to Equation (1), or for use in a global (structure-level) verification format.

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