# ADEQUACY OF THE EC8-PART 3 PROPOSED CONFIDENCE FACTORS FOR THE ASSESSMENT OF EXISTING RC STRUCTURES

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**ABSTRACT :**

The present study addresses the evaluation of the recommended values of the Confidence Factors (CFs) proposed in the general document of Eurocode 8, Part 3. The study assesses the reliability of the proposed CFs using a probabilistic framework for their evaluation. Though the general concept behind the consideration of CFs is independent of the type of structural material, the evaluation is presented for the case of reinforced concrete structures, more specifically for the concrete compressive strength. The number of material tests is considered to be the key factor used to set the probabilistic framework of the study, which is based on the concept of confidence intervals and considers different underlying statistical distributions for the material properties of interests.

**KEYWORDS:** Confidence Factor, Eurocode 8 Part 3, existing structures, RC structures

## 1. INTRODUCTION

Much of the emphasis of earthquake engineering research and code-writing efforts has been, and still is, dedicated to new constructions. Nonetheless, assessment of the seismic safety and performance of the built environment in earthquake prone areas is a matter of high priority, as agreed by earthquake engineering experts, public authorities and the general public. In recognition of the importance of the potential seismic risk arising from existing substandard constructions, both research of methods to assess such risk and of standards and guidelines addressing the problem of structural assessment and upgrading are emerging [1-6].
There are numerous differences between the design of a new structure according to structural design codes and the analysis of the same structure after many years in service. Focusing on the assessment of the material properties of existing structures, these can be obtained with varying degrees of accuracy based on in-situ measurements. In order to account for the uncertainty of those measurements, different degrees of knowledge which reflect the type and quality of the gathered data are established by the codes [4-6]. To reflect the referred levels of knowledge in a quantitative manner and to account for them in the assessment, penalty factors can be associated to those levels which will either reduce the “capacity” or increase the “demand”.
The present study addresses the evaluation of the referred penalty factors following the definition proposed in Part 3 of Eurocode 8 (EC8-3) [5]. In this context, the referred factors will be termed Confidence Factors (CF) as proposed by EC8-3. Although the values of the CFs to be used in a given country can be found in its National Annex, recommended values of the CFs are proposed within the EC8-3 main document. The present study assesses the reliability of those recommended values by defining a probabilistic framework for the evaluation of the CFs. Though the general concept behind the consideration of CFs is independent of the type of structural material, their evaluation is presented herein for the case of reinforced concrete (RC) structures.
It should be noted that the proposed study does not address the adequacy of the CF values proposed by EC8-3 in dealing with the full range of uncertainties arising in the assessment of existing structures. More specifically, the study only focuses on the adequacy of the CF values with respect to the assessment of material properties, therefore not covering uncertainty aspects related to the geometry and structural detailing of the construction.

## 2. GENERAL FRAMEWORK FOR DEFINITION OF THE CFS

### *2.1 Overview of the EC8-3 seismic safety assessment procedures*

In terms of seismic safety and for a chosen performance requirement, EC8-3 allows the state of a structure to be quantitatively evaluated by means of linear or nonlinear types of analyses, depending on the characteristics of the structure and the choice of the engineer. Safety verifications are defined at the structural mechanism level and depend on the nature of the mechanisms. If they are ductile, one has to check that the deformation demand is not larger than an admissible deformation capacity defined according to the considered performance level. If they are of the brittle type, one has to check that their capacity in terms of strength is not exceeded by the corresponding demand.

In EC8-3, the previously referred knowledge level (KL) is defined by the combination of the knowledge available or achieved in the following items: geometry, details and materials. With reference to RC structures, geometry refers to the geometrical identification of the structural resisting system, details to the amount and detailing of the reinforcement, and materials to the mechanical properties of the steel and concrete. Knowledge on geometry is provided either by the original construction drawings and/or by survey. Details and materials are known through inspection and testing, respectively. EC8-3 defines three levels of knowledge, denoted by KL1, KL2 and KL3 in increasing order of comprehensiveness, and also defines a CF associated with each level. The recommended values of these factors are 1.35, 1.20 and 1.0, for KL1, KL2 and KL3, respectively.

From the safety assessment stage point of view, depending on the selected method of analysis and on the type of mechanism to be checked, the demand may be increased by the CF while the capacity may be reduced by the same CF. The latter case is the focus of the presented study for which EC8-3 defines two different situations. With respect to the safety assessment of a certain ductile mechanism, its capacity is obtained from a given expression [5] considering mean material strength values divided by the CF. In the case of a brittle mechanism of a primary element, EC8-3 sets a larger safety margin as the capacity is obtained from a given expression [5] considering mean material strength values divided by the CF and by the partial safety factor of the corresponding material. Of the two situations, the former is addressed herein as it is seen to be more critical.

### *2.2 Quantification of the CFs and minimum number of material tests*

EC8-3 defines a simple approach for the characterization of the CF, for the purpose of characterization of the materials. When there is no prior knowledge about the materials under assessment, the CF values depend mainly on the number of tests that are performed to assess the material properties of interest, hereon simply referred as strength values. In the absence of prior knowledge and having chosen a given KL, EC8-3 defines the minimum number of tests by multiplying the constants 1, 2 and 3, associated to limited, extended and comprehensive levels of testing, by the number of floors and by the number of primary element types. For example, considering the simple case of a one-storey RC frame structure with only beams and columns as primary elements and considering that KL1 is the selected KL, the minimum number of tests is 2 (one in a beam and one in a column). Although not clearly stated in EC8-3, if two different concrete grades are used in this structure, for example one for beams and one for columns, the minimum number of tests can be interpreted as being 1 for each concrete grade. Following the same reasoning, if the selected KL is KL3, the previously obtained minimum number of tests are now 6, for the case of one concrete grade, and 3 for each concrete grade, for the case of two concrete grades. Although for taller structures the minimum number of tests will be proportionally larger, the fact remains that for shorter structures, and considering the amount of uncertainty that it carries, EC8-3 allows the determination of mean strength estimates based on a single test result, irrespective of the type of material.

## 3. PROBABILISTIC DEFINITION OF THE CFS

### *3.1 Basic hypotheses and definitions of the study*

In the context of EC8-3, an estimate $\overline{X}$ of the mean value $\mu$ must be divided by a CF that is larger if one has less knowledge about the materials. Consequently, a critical safety situation can be established for the case when $\overline{X}$ overestimates $\mu$. Therefore, the present study addresses the probabilistic quantification of the CFs that adjust the mean estimate of a material strength, reflecting the KL that is attained in the assessment, in order to provide a design value of the strength that is on the safe side.

Within the scope of the study, it is also assumed that the CFs proposed by EC8-3 guarantee a certain level of reliability of the material strength value (after its adjustment by the CF) that is associated to the minimum number of tests. Although the referred level of reliability is not easy to quantify, it is also addressed herein by associating certain confidence levels to the quantification of the CFs, by defining the probabilistic quantification of the CFs based on the concept of confidence interval (an interval of real numbers expected to contain the true value of a population parameter, with a specified confidence).

For the case of safety assessment of RC structures, both steel yield strength and concrete compressive strength values are of interest. Since the framework for the CF definition proposed by EC8-3 is material independent, it is considered that performing the study for the material strength that exhibits larger variability represents the critical situation. Since it is generally accepted that the inherent variability of the steel yield strength is lower than that of the concrete compressive strength, some of the basic hypotheses of the study are set for the case of concrete compressive strength assessment. Nonetheless, part of the study is presented in a material independent form and can, therefore, be applied to any material and property.

When concrete compressive strength test results are referred in this study, they are assumed to result from any type of test (e.g. core compression tests, rebound hammer tests, ultrasonic pulse velocity tests, pull-out tests, among others). It is also assumed that compression test results have been converted to the corresponding in-place concrete strength. In terms of number of tests, and based on the previously exposed, the critical situation occurs for a one-storey structure with beams and columns of different concrete grades as primary elements. To assess the strength of each concrete grade, the minimum number of tests can be interpreted as being 1, 2 and 3 for each concrete grade for levels KL1, KL2 and KL3, respectively.

Two important assumptions are additionally considered for the case of concrete compressive strength. It is assumed that concrete compressive strength can either follow a normal, lognormal or Weibull distribution [7, 10-13]. Secondly, it is also assumed that strength variability, characterized herein by its coefficient of variation (CoV), is within the range of 6% to 20% [9, 10, 12, 14-16]. Although larger CoV values can be found in the literature [10, 14], a maximum of 20% is considered to be a significantly high CoV for normal strength concrete, either site-mixed or ready-mixed.

### *3.2 Definition of the CFs for the case of a normal distributed strength*

For the case of a normal distributed strength, the CFs are characterized based on the definition of the confidence interval for the mean of the normal distribution with known variance.

Considering that $X_1, X_2, \ldots X_n$ is a random sample drawn from a normal distribution with unknown mean $\mu$ and known standard deviation $\sigma$, the sample mean $\overline{X}$ is known to be normally distributed with mean $\mu$ and standard deviation $\sigma/\sqrt{n}$. By standardizing $\overline{X}$ one obtains variable $Z$:

$$Z = \left(\overline{X} - \mu\right) \Big/ \left(\sigma/\sqrt{n}\right) \tag{1}$$

which follows a standard normal distribution and leads to

$$P\left(-z_{1-\alpha/2} \leq \left(\overline{X} - \mu\right) \Big/ \left(\sigma/\sqrt{n}\right) \leq z_{1-\alpha/2}\right) = 1-\alpha \tag{2}$$

where $z_{1-\alpha/2}$ is the $(1-\alpha/2)$ percentage point of the standard normal distribution. The one-sided lower bound expression equivalent to Eq. (2) is

$$P\left(\left(\overline{X} - \mu\right) \Big/ \left(\sigma/\sqrt{n}\right) \leq z_{1-\alpha}\right) = 1-\alpha \tag{3}$$

where $z_{1-\alpha}$ is the $(1-\alpha)$ percentage point of the standard normal distribution. Based on the previously established critical safety situation, the definition of an adequate CF value must verify the following inequality:

$$\overline{X}/CF \le \mu \;\Leftrightarrow\; CF \ge \overline{X}/\mu \tag{4}$$

yielding the minimum CF value that verifies it as $CF = \overline{X}/\mu$. Combining this result with Eq. (3) yields

$$P\left(CF \le 1 + z_{1-\alpha} \cdot CoV/\sqrt{n}\right) = 1 - \alpha \tag{5}$$

where the CoV is $\sigma/\mu$ and states that, for a known (expected) value of the CoV, there is a $(1-\alpha)$ probability that the CF has to be lower or equal than $1 + z_{1-\alpha} \cdot CoV/\sqrt{n}$ in order to correct the estimate $\overline{X}$ in a safety perspective. Therefore, the $(1-\alpha)\cdot 100\%$ upper confidence bound on the value of CF is:

$$CF \le 1 + z_{1-\alpha} \cdot CoV/\sqrt{n} \tag{6}$$

To set the CF values, one is interested in the limiting values given by Eq. (6), hereon termed $CF_{LIM}$, for increasing values of the number of tests $n$, for a prescribed $(1-\alpha)$ confidence level and a given CoV. In the situation of assessing the adequacy of the CFs recommended by EC8-3, the definition of a single CF value for each KL must involve the most unfavourable conditions, namely in terms of number of tests and CoV. Although, on the basis of the previously exposed, critical situations can be identified for these two parameters, there is little guidance for the case of the $(1-\alpha)$ confidence level that should be chosen. Even though there is no apparent justification, a minimum confidence level of 75% is commonly considered in the assessment of existing structures context. Other suggestions propose to select the confidence level according to the importance of the structure [17, 18] defining levels of 75%, 85%-90% and 95% for ordinary, important and very important structures, respectively. For the study presented herein, the confidence levels must be defined as a function of the KLs set by EC8-3, thus reflecting also the minimum number of required material tests. Assuming a minimum confidence level of 75% and considering that a confidence level of 95% is sufficiently large for practical purposes, confidence levels of 95%, 85% and 75% are proposed for levels KL1, KL2 and KL3, respectively. These values are set based on the fact that as the KL increases, the degree of uncertainty about the materials decreases, thus the amplitude of the confidence interval, defined by the confidence level and reflecting the uncertainty, can be smaller. To observe the evolution of the $CF_{LIM}$ values for levels KL1, KL2 and KL3, Fig. 1(a), (b) and (c) present the upper limits given by Eq. (6) for increasing values of $n$ (from 1 to 30), the previously defined range of the CoVs (6% to 20% in 2% steps) and the corresponding confidence levels (75%, 85% and 95%). For the larger CoV and for the minimum number of tests of the corresponding KL, the computed $CF_{LIM}$ is also represented in each graph ("underlined" value). As expected, the computed CFs indicate that, irrespective of the selected confidence level, $CF_{LIM}$ asymptotically tends to 1.0 as $n$ tends to infinity. Moreover, the analysis of the "underlined" values shows that, for the previously set of hypotheses, the CF values proposed by EC8-3 for KL1 and KL2 seem adequate, while for KL3 there is a significant difference between the proposed value and the obtained $CF_{LIM}$. Given the difference between the obtained $CF_{LIM}$ value for KL2 (i.e. 1.15) and the EC8-3 proposed value (i.e. 1.20), an attempt was carried out to increase the confidence level up to 90%. Fig. 1(d) shows that, for the aforementioned conditions and for a confidence level of 90%, the obtained $CF_{LIM}$ value still agrees with the EC8-3 proposal. On the basis of this result, a confidence level of 90% is considered hereon for KL2.

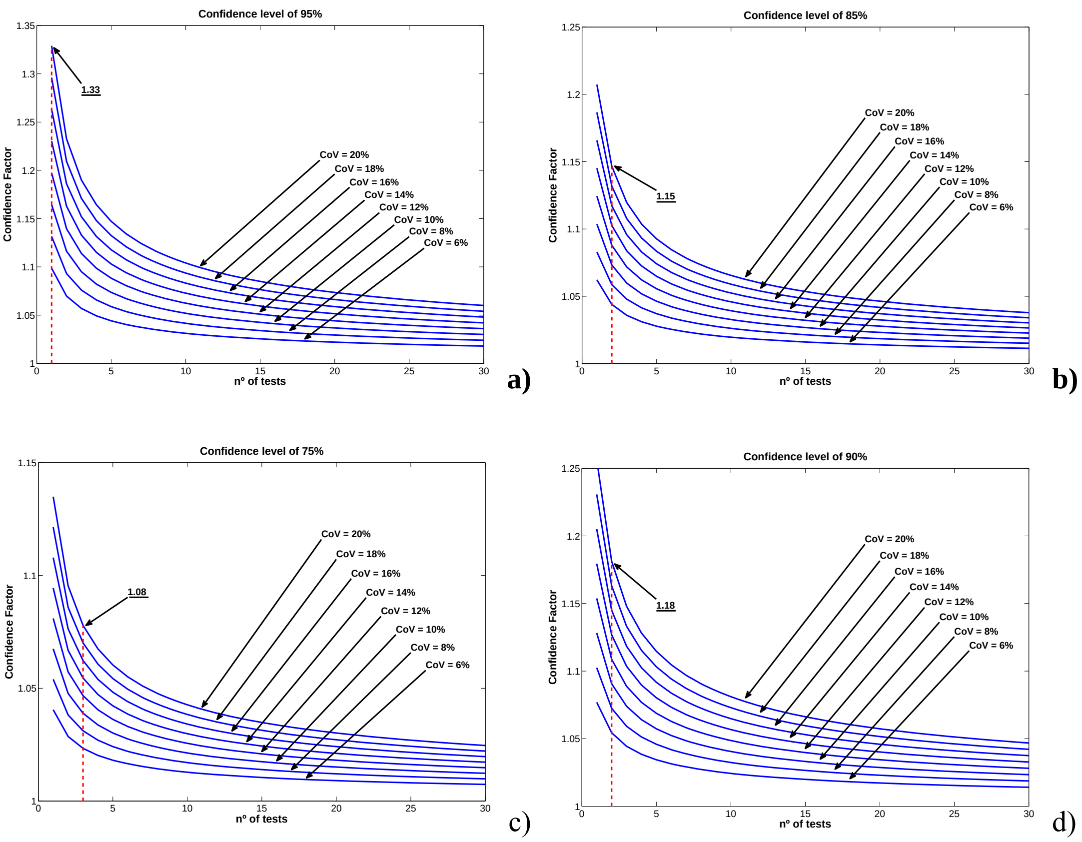


Figure 1. Values of $CF_{LIM}$ considering a normal distributed strength, for increasing values of $n$, the selected range of CoVs and $(1\text{-}\alpha)$ confidence levels of (a) 95%, (b) 85%, (c) 75%, (d) 90%.

### *3.3 Definition of the CFs for the case of a lognormal distributed strength*

For the case of a lognormal distributed strength, the CFs can be characterized using the same approach as for the case of the normal distribution. Considering that $Y_1, Y_2, \ldots Y_n$ is a random sample from a lognormal distribution with unknown mean $\theta$ and known standard deviation $\delta$, the variable $X = \ln(Y)$ follows a normal distribution with mean $\mu$ and standard deviation $\sigma$. Upon this, it follows that Eq. (3) is applicable and can be rearranged to give the $(1-\alpha)$ probability that

$$\overline{X} - z_{1-\alpha} \cdot \sigma / \sqrt{n} \leq \mu \tag{7}$$

which, by adding $\sigma^2/2$ on both sides and taking exponentials of both sides, leads to

$$\exp\left(\overline{X} + \sigma^2/2\right) \cdot \exp\left(-z_{1-\alpha} \cdot \sigma / \sqrt{n}\right) \leq \exp\left(\mu + \sigma^2/2\right) \tag{8}$$

Knowing that $\theta$ is $\exp\left(\mu + \sigma^2/2\right)$ and considering $\overline{Y}$ to be its sample estimate gives

$$\overline{Y} \cdot \exp\left(-z_{1-\alpha} \cdot \sigma / \sqrt{n}\right) \leq \theta \tag{9}$$

Considering a reasoning similar to that of Eq. (4) yields

$$\overline{Y}/CF \leq \theta \;\Leftrightarrow\; CF \geq \overline{Y}/\theta \tag{10}$$

yielding the minimum CF value that verifies it as $CF = \overline{Y}/\theta$. Combining this result with Eq. (9) leads to

$$CF \leq \left[ \exp\left( -z_{1-\alpha} \cdot \sqrt{\ln\left(CoV^2+1\right)/n} \right) \right]^{-1} \tag{11}$$

where $\sqrt{\ln\left(CoV^2+1\right)}$ is σ. Similarly to Eq. (6), Eq. (11) gives the upper confidence bound $CF_{LIM}$ for which CF has a $(1-\alpha)$ probability of being lower or equal to, in order to correct the estimate $\overline{Y}$ in a safety perspective.

As for the case of the normal distribution, evolutions of $CF_{LIM}$ can be obtained using Eq. (11) for increasing values of $n$, the previously defined range of the CoVs and the confidence levels of each KL. For conciseness sake, graphical representations of the referred evolutions are not presented herein. It is, nonetheless, noted that Eq. (11) gives larger $CF_{LIM}$ values than Eq. (6). For the larger CoV (20%) and for the minimum number of tests of each KL, the $CF_{LIM}$ values are 1.39, 1.20 and 1.08 for KL1, KL2 and KL3, respectively. When comparing these results with the CF values proposed by EC8-3, it is seen that only the value of KL2 agrees with the EC8-3 proposal. In order for the $CF_{LIM}$ of KL1 to meet the EC8-3 proposed value (i.e. 1.35), there is the need to either reduce the prescribed confidence level or to reduce the maximum admissible CoV. Therefore, one of the following two situations can be observed:

- When fixing the CoV to 20% and $n$ is 1, the $(1-\alpha)$ confidence level that yields a $CF_{LIM}$ of 1.35 is 93.5%;
- When fixing the $(1-\alpha)$ confidence level to 95% and $n$ is 1, the CoV that yields a $CF_{LIM}$ of 1.35 is 18.5%.

Considering that the observed reduction can be seen to be relatively small, one is inclined to validate the adequacy of the EC8-3 proposal for KL1. Moreover, considering that the number of tests is fixed to 1 in both cases, a number that will most surely be exceeded in real situations, if the number of tests is set to 2, the $CF_{LIM}$ value for a CoV of 20% and a confidence level of 95% is now 1.26, well below the EC8-3 proposal for this KL.

### *3.4 Definition of the CFs for the case of a Weibull distributed strength*

The two-parameter Weibull distribution, with $\gamma$ and $\beta$ as the shape and scale parameters, respectively, was chosen to characterize the CFs in the case of a Weibull distributed strength [12]. Unlike for the case of the normal and the lognormal distributions, mathematically tractable confidence intervals for the mean μ of the Weibull distribution are not available. A simulation approach was, therefore, selected to assess the $CF_{LIM}$ values for the Weibull distribution case. The simulation method started with the selection of a concrete class characterized by having a compressive strength with chosen $\mu$ and CoV, the former being selected from the range of 12 MPa to 50 MPa, in 1 MPa steps, and the latter being selected from the previously set range, considering 2% steps. Knowing $\mu$ and CoV, parameters $\gamma$ and $\beta$ can be determined based on the following:

$$\mu = \beta \cdot \Gamma\left(1+1/\gamma\right) \tag{12}$$

$$CoV = \left[ \Gamma\left(1+\frac{2}{\gamma}\right) - \Gamma^2\left(1+\frac{1}{\gamma}\right) \right]^{1/2} \Big/ \Gamma\left(1+\frac{1}{\gamma}\right) \tag{13}$$

where $\Gamma(.)$ is the Gamma function. Based on Eq. (13), parameter $\gamma$ can be determined for the known CoV using a standard Newton-Raphson method after which parameter $\beta$ can be obtained using Eq. (12). Then, 50000 samples of a chosen size $n$ were randomly drawn from the referred Weibull distribution. Next, the mean value of each sample $i$ was computed and divided by $\mu$ to yield $CF_i$, the CF value of sample $i$. After computing $CF_i$ values for all samples, considering all possible values of $\mu$ from the previously set range and for a given CoV, an empirical CDF was defined, for which $CF_{LIM}$ corresponds to the $(1-\alpha)$ percentile. The simulation process is then repeated for different values of size $n$, from 1 to 30, and for the previously set range of CoV values.

To observe the evolution of the $CF_{LIM}$ values for levels KL1, KL2 and KL3, Fig. 2 (a), (b) and (c) present the results obtained from the referred simulation study for increasing values of $n$ (from 1 to 30), the previously defined range of the CoVs (6% to 20% in 2% steps) and the corresponding confidence levels (75%, 90% and 95%). As for the case of the normal distributed strength, for the larger CoV and for the minimum number of tests of the corresponding KL, the computed $CF_{LIM}$ is also represented in each graph ("underlined" value). The analysis of the "underlined" values shows that, for the previously set of hypotheses, the CF values proposed by EC8-3 for KL1 and KL2 appear to be adequate while the proposed value for KL3 is significantly different from the obtained $CF_{LIM}$, as reported for the case of normal and lognormal distributed strengths.

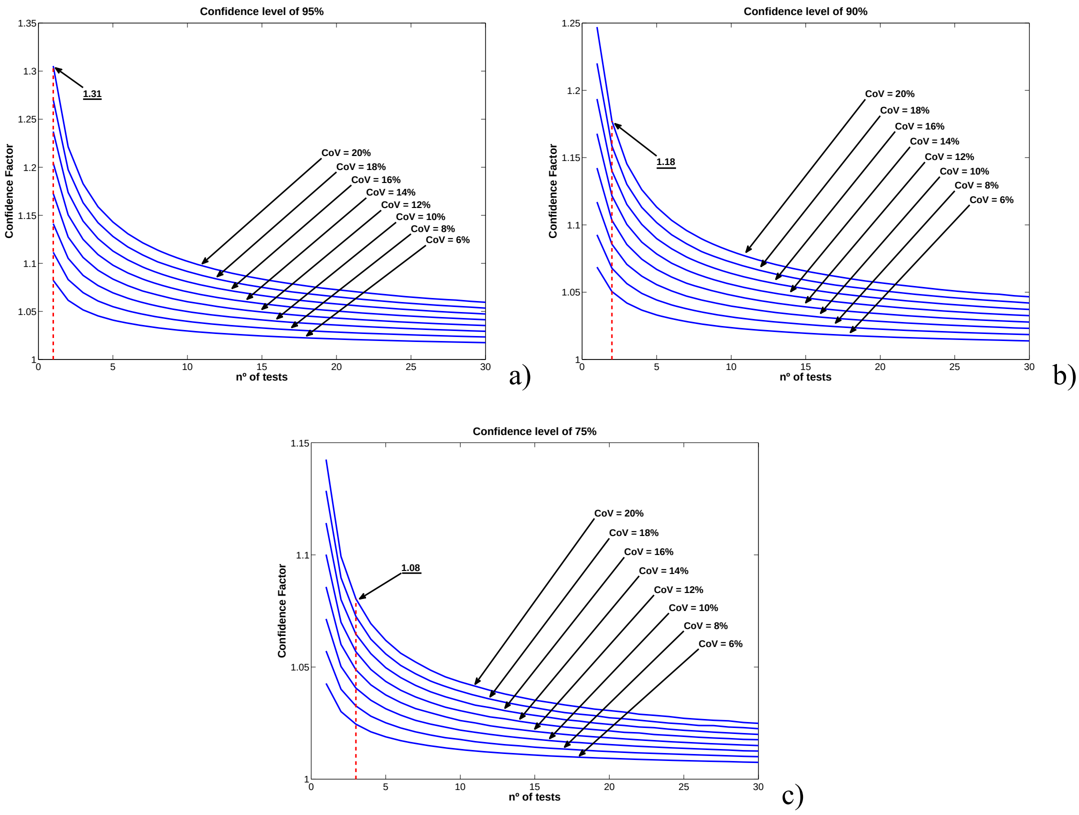


Figure 2. Values of $CF_{LIM}$ considering a Weibull distributed strength, for increasing values of $n$, the selected range of CoVs and $(1-\alpha)$ confidence levels of (a) 95%, (b) 90% and (c) 75%.

## 4. CONCLUSIONS

The present study addresses the evaluation of the recommended values of the CFs proposed in the main document of EC8-3. In the context of the assessment of the material properties, the CF adjusts the mean estimate of a material property in order to reflect the KL that is attained in the assessment, in order to provide a design value of the property that is on the safe side.

In this study, the reliability of the EC8-3 proposed values is assessed using a probabilistic framework, in which the number of material tests is the key aspect for the quantification of the CFs, assuming the inexistence of prior knowledge. Although the general concept behind the CFs is independent of the type of structural material, the evaluation is presented for the case of RC structures, more specifically for the concrete compressive strength.

Different underlying statistical distributions are assumed for the concrete compressive strength (normal, lognormal and Weibull distributions), different confidence levels are associated to the quantification of the CF of each KL (95%, 90% and 75% for KL1, KL2 and KL3, respectively) and a critical safety situation is established for the case when the estimate of the mean strength overestimates the real mean value. Furthermore, and although the quantification of the CFs is presented for different situations in terms of number of tests and dispersion of the strength, the EC8-3 proposed values are compared with results of the study obtained for the limit cases of a number of tests equal to 1, 2 and 3, for KL1, KL2 and KL3, respectively, and for a CoV of 20%.

The analysis of the obtained results allows concluding that, for the previously set of hypotheses, the CF values proposed by EC8-3 for KL1 and KL2 seem to be adequate, even though the conditions of the study were slightly revised for the case of the lognormal distribution. In the case of KL3, the results obtained do not agree

with the EC8-3 proposed value (i.e. 1.0). Irrespective of the selected distribution type, the value obtained is 1.08. Moreover, even for larger values of the number of tests (i.e. 30), the obtained CF value is still larger than 1.0. When this KL is considered, the CF value proposed by EC8-3 for KL3, which can be seen to be significantly lower than the study results, leads, therefore, to a lower structural safety level.
In summary, considering the previously set of conditions of the analyses, the EC8-3 proposed values for the CFs of KL1 and KL2 are in agreement with the results obtained by the proposed study. With respect to the proposed CF value for KL3, the study suggests that a larger value (e.g. 1.10) should be used instead.

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