

STATISTICALLY-BASED SURVEY PLANS TO ESTIMATE THE CONCRETE STRENGTH IN EXISTING RC BUILDINGS

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ABSTRACT

In the proposed study, a framework for the definition of a safety factor leading to a reliable estimate of the mean concrete strength in existing reinforced concrete (RC) buildings is presented. The main objective is to provide a methodology capable of establishing a reliable correlation between a given level of knowledge that is required (which implies that a number of destructive tests have to be carried out) and the confidence in the corresponding mean estimate of the strength that is obtained. The development of this approach requires dividing the building into areas with a potentially homogeneous concrete strength (e.g. each building storey). Furthermore, the methodology also uses the notion of “discrete structure” where the concrete strength of each structural element of a given homogeneous building section is assumed to be defined by a single strength value, which can be different than those of the remaining structural elements. The reliable value of the mean concrete strength is established by a boundary value defined according to an admissible variation with respect to the true mean value and includes the effect of uncertainty due to sampling. This admissible variation is defined by a procedure that uses both destructive and non-destructive test results. The referred boundary value allows the definition of a safety factor which represents the maximum admissible ratio between the true mean value and the corresponding reliable estimate. The presented study also proposes an alternative approach regarding the definition of the Eurocode 8-Part 3 “knowledge levels” based on the relation between the number of structural members that were tested and the total number of structural members. An adaptive confidence factor for the mean value of the material strength is then provided for each knowledge level as well as an approximation for the admissible global variability of the concrete strength in each homogeneous area of the discrete building. The proposed framework can be seen to be a more consistent statistically-based alternative to the confidence factor values proposed by Eurocode 8-Part 3.

INTRODUCTION

Assessing the seismic performance of existing structures constitutes a matter of high priority in earthquake prone areas. As recognized by earthquake engineering experts and public authorities, it is important to evaluate the safety of buildings and infrastructures. Therefore, specific code-based methods must be developed to address these issues and an adequate calibration of these methods must be carried out to analyse their practical use. Several standards (e.g. CEN, 2005; NZSEE, 2006; ASCE, 2003; ASCE, 2007; NTC, 2008; ATC, 2009) have been recently developed to address the specifics of the seismic safety assessment of existing structures.

One particularly important issue that affects the evaluation of the seismic performance of existing buildings is related to the definition of their material properties, since the construction quality

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levels and the original design standards may be very different from those currently in use. Characterizing these material properties may be achieved in different ways which may imply different levels of knowledge, depending on the level of detail provided by the survey plan and on the availability and reliability of information about the design. Therefore, the reliability of the structural properties considered in the seismic assessment will depend on the correlation between the confidence and the amount of knowledge gathered about the structure. Still, to account for the existing uncertainty, the structural properties need to be defined with values on the “safe side”.

In the case of reinforced concrete (RC) buildings, code-based methods require that a given number of tests must be carried out in the structure to determine the structural properties, namely for the concrete compressive strength. According to actual standards, characterizing the concrete strength in existing buildings can be achieved by performing destructive tests on a number of material samples extracted from the structural members. Due to the destructive nature of this approach and the significant costs that are involved (both direct and indirect), standards also suggest the complementary use of non-destructive tests, such as the rebound hammer test, in order to improve the knowledge and confidence provided by the destructive tests. Nevertheless, the sole use of non-destructive methods is not allowed by code-based approaches due to the difficulty in obtaining reliable results with non-destructive methods. The results of these methods can only be used after defining a reliable correlation between destructive and non-destructive test results.

The current European standard for the seismic safety assessment of existing buildings is the Eurocode 8-Part 3 (EC8-3) (CEN, 2005). This standard defines the minimum number of material samples that must be tested according to a general rule, i.e. by defining for each floor and each type of member the number of tests that guarantees a certain level of knowledge. EC8-3 establishes three knowledge levels (KLs): KL1, KL2 and KL3, which are termed Limited, Comprehensive and Full, respectively. For each one of these KLs, EC8-3 assigns a confidence factor (CF) that will act as a safety factor to be applied to the mean value of the material properties in order to account for the uncertainty induced by the material sampling plan. The values of the CFs proposed by EC8-3 are 1.35, 1.20 and 1.00 for KL1, KL2 and KL3, respectively. The connection between the KL and the CF value has been previously criticized (e.g. see (Elefante, 2010), (Franchin et al., 2010)) due to the lack of objectivity behind the CF values. In addition, the role of the factored concrete mean strength value and its possible connection with a lower reliable value, often called the characteristic strength, is not clear, thus introducing an additional level of uncertainty in the analysis.

The Italian code (NTC, 2008) follows a similar strategy to that of EC8-3 by also proposing three KLs and the same values for the corresponding CFs. Still, this standard introduces a guidance related to what can be regarded as an area with a potentially homogeneous concrete strength. This standard refers that the minimum number of material tests must be performed over surface areas which are lower than 320 m².

The definition of the concrete strength according to ASCE 41-06 (ASCE, 2007) states that if the analyst has information about the concrete design strength but no additional construction information is provided, a minimum of 3 material samples must be taken from each floor, 306 m³ of concrete or 929 m² of surface area. In case original design data is not available, the minimum number of material samples increases to 6. As in the Italian standard, ASCE 41-06 also introduces a guidance for what can be regarded as an area with a potentially homogeneous concrete strength. In addition, this standard also specifies that if the coefficient of variation (CoV) of the results is lower than 14%, the mean value of the samples may be considered to be a reliable value for the concrete strength, while for larger levels of variability the “mean minus one standard deviation” must be assumed as a reliable strength value. The reason for the 14% limit on the CoV value can be traced back to the studies of Bartlett and MacGregor (Bartlett and MacGregor, 1999) where it was found that a CoV of 13.5% represents the natural variability of concrete.

For the case of ACI 214.4R (ACI, 2003), the minimum number of material samples NSM_A is established by ASTM E122 (ASTM, 2000), which is defined according to an admissible difference between the sample mean and the true value of the concrete strength (e in %), the expected variability of the test results (i.e. the CoV obtained from the samples extracted from a given number of structural members, CoV_{NSM_A}) and an acceptable risk of exceeding the previously defined maximum admissible difference. When assuming a risk of 5%, the recommended sample size is given by Eq. (1).

$$NSM_A = \left(\frac{2 \cdot CoV | NSM_A}{e} \right)^2 \quad (1)$$

As can be seen from the review of existing code-based methods for assessing the concrete strength, there is no uniform approach and none of the available approaches fully controls the uncertainty in the in-situ assessment stages. It becomes clear that a unifying method should include all the aspects previously defined, i.e. an indication of the size of the sampling area, an estimate of the material variability in that area and an estimate of the statistical uncertainty associated to the level of detail of the survey plan. In the present paper, a framework is presented that accounts for all these concepts. It is based in the principle of the discrete structure (i.e. each structural member has a single concrete strength) and aims to be applied to limited areas of the structure, thus comprising a finite number of structural members, hereon designated by NSM. The framework accounts for the variability in the number of non-assessed structural members (NSM_{NA}) by defining survey plans (where NSM_A members are tested) whose statistical uncertainty is represented by the ratio between the surveyed and the real quantities. These ratios, hereon called Safety Factors, SF, rely on the finite population defined by each limited area of the structure being considered (which, as assumed by Jalayer et al. (2010), can be defined using the building's construction stages, i.e. by floor and storey) whose concrete properties are of interest. The following sections detail the main concepts and practical features of the proposed framework. Alternative proposals for the EC8-3 KLs and CFs are also presented in light of the proposed framework.

SAFETY FACTOR FOR THE MEAN CONCRETE STRENGTH BASED ON FINITE POPULATION STATISTICS

Case where the sampling mean is assumed to follow a normal distribution

The proposed approach aims to include the effect of having a finite population of members for the material property assessment, thus accounting for the effect of sampling from populations of different sizes. This was achieved by considering a confidence interval for the finite population mean, which is similar to the common confidence interval for the mean but with the addition of a finite population correction factor which reflects the size of the sample. This correction is based on the fact that when selecting a sample of size NSM_A from a finite population of size NSM , the sample mean approximately follows a normal distribution with a mean equal to the true mean μ and a standard deviation given by Eq. (2), where σ is the standard deviation of the population (see, for example, Levy and Stanley (2008) for additional details on finite population corrections for different statistics).

$$\sigma_\mu = \frac{\sigma}{\sqrt{NSM_A}} \cdot \sqrt{\frac{NSM - NSM_A}{NSM - 1}} \quad (2)$$

By considering a finite population of size NSM , an approximate 1-sided confidence interval for the mean can be defined by Eq. (3), which assumes that the sample mean obtained from a sample of size NSM_A $\bar{x} | NSM_A$ follows a normal distribution and where $z_{1-\alpha}$ is the $(1-\alpha)$ percentage point of the standard normal distribution.

$$P\left(\frac{\bar{x} | NSM_A - \mu}{\sigma_\mu} \leq z_{1-\alpha}\right) = 1 - \alpha \quad (3)$$

A safety factor SF can then be defined as the ratio between the true mean μ and the sample estimate $\bar{x} | NSM_A$ which accounts for the uncertainty of the sample estimate. Introducing SF into Eq. (3) and defining CoV_μ as σ_μ / μ one obtains

$$P(SF \leq 1 + z_{1-\alpha} \cdot CoV_\mu) = 1 - \alpha \quad (4)$$

which states that, for a known (expected) value of CoV_μ , there is a $(1-\alpha)$ probability that $SF \leq 1 + z_{1-\alpha} \cdot CoV_\mu$ if $\mu = \bar{x} | NSM_A / SF$. Therefore, the $(1-\alpha) \cdot 100\%$ upper confidence bound on the value of SF is:

$$SF = 1 + z_{1-\alpha} \cdot CoV_\mu \quad (5)$$

Considering that the true value of CoV_μ may not be known and can only be estimated, Eq. (5) can be transformed into

$$SF = 1 + z_{1-\alpha} \cdot \overline{CoV} / NSM_A \cdot \frac{1}{\sqrt{NSM_A}} \cdot \sqrt{\frac{NSM - NSM_A}{NSM - 1}} \quad (6)$$

by assuming that σ/μ can be estimated from the sample coefficient of variation for a sample of size NSM_A , $\overline{CoV} | NSM_A$.

Case where the sampling mean is assumed to follow a lognormal distribution

A similar strategy can be established for the case where the sampling mean is assumed to follow a lognormal distribution, a situation particularly relevant when the sample size is smaller. As reported by Romão et al. (2012), a confidence interval for the mean θ of a lognormal distribution can be obtained considering that Eq. (3) is applicable and can be rearranged to give the $(1-\alpha)$ probability that

$$\bar{x} | NSM_A - z_{1-\alpha} \cdot \sigma_\mu \leq \mu \quad (7)$$

where μ and σ are the mean and the standard deviation of the associated normal distribution. By adding $\sigma_\mu^2/2$ on both sides and taking exponentials of both sides, one obtains

$$\exp(\bar{x} | NSM_A + \sigma_\mu^2/2) \cdot \exp(-z_{1-\alpha} \cdot \sigma_\mu) \leq \exp(\mu + \sigma_\mu^2/2) \quad (8)$$

Knowing that θ is $\exp(\mu + \sigma_\mu^2/2)$ and considering $\bar{y} | NSM_A$ to be its sample estimate gives

$$\bar{y} | NSM_A \cdot \exp(-z_{1-\alpha} \cdot \sigma_\mu) \leq \theta \quad (9)$$

Considering that a safety factor SF can also be defined as the ratio between θ and the sample estimate $\bar{y} | NSM_A$, and using a reasoning similar to that of Eq. (4), a $(1-\alpha) \cdot 100\%$ upper confidence bound on the value of SF can be obtained from

$$SF = \exp\left(z_{1-\alpha} \cdot \sqrt{\ln(CoV_\mu^2 + 1)}\right) \quad (10)$$

where $\sqrt{\ln(CoV_\mu^2 + 1)}$ is σ_μ . As for the normal distribution case, the true value of CoV_μ may not be known. Hence, Eq. (10) can be transformed into Eq. (11) again by involving the finite population correction factor and assuming that $\overline{CoV} | NSM_A$ is the sample estimate of the distribution's coefficient of variation.

$$SF = \exp \left(z_{1-\alpha} \cdot \sqrt{\ln \left(\frac{\overline{CoV}}{NSM_A^2} \cdot \frac{NSM - NSM_A}{NSM_A \cdot (NSM - 1)} + 1 \right)} \right) \quad (11)$$

In both the normal and the lognormal cases, the safety factor is defined by the lower bound of the confidence interval. Therefore, for a given survey plan (defined by the value of NSM_A), the safety factor establishes that the estimate of the mean concrete strength must not differ from the true value by more than the ratio given by the safety factor. Aside from this, the safety factor also establishes a reliability level (i.e. the confidence level) associated to the estimate obtained from the survey and correlates it with a level of knowledge (i.e. the relation between NSM_A and NSM), thus accounting for the sampling uncertainty of those estimates.

A METHOD TO INCLUDE THE SAMPLING UNCERTAINTY ON THE SAFETY FACTOR FOR THE MEAN CONCRETE STRENGTH

The procedure introduced in the previous section establishes a connection between the number of structural members that are assessed during the survey of the material properties and the level of confidence that can be assumed regarding the information being gathered. Despite the simplicity of the concepts involved in the previously presented equations, some practical considerations may have a significant influence in their application. For example, the effect of the potentially larger variability of the concrete strength in old buildings can be enhanced when NSM_A is small (i.e. when extracting a small number of samples from the overall population of size NSM). To illustrate this effect, four datasets (C1-C4) of concrete core test results from 4 existing buildings constructed in the 1990s were analysed. The size of these datasets is between 19 and 27. The mean concrete strength of datasets C1 to C4 is 28, 28, 30 and 36 MPa, respectively, while the CoV of the concrete strength is 0.29, 0.35, 0.38 and 0.33, respectively. In addition, a fifth dataset (C5) was also considered based on the test results of Monteiro and Gonçalves (2009). Dataset C5 has 21 test results yielding a mean concrete strength of 20 MPa and a CoV of 0.19. Dataset C5 is representative of a building with a concrete strength having a medium dispersion, while datasets C1 to C4 represent cases with a larger variability. The 5 selected datasets are assumed to represent 5 finite and homogeneous populations. Therefore, for each dataset, the sample size corresponds to the value of NSM . Aside from concrete core test results, these 5 datasets also possess Schmidt rebound hammer test results (RN) from the structural members that concrete cores were extracted from.

A comparative study was then carried out to estimate the effect of the sampling uncertainty in the estimate of the mean concrete strength for different sample sizes. The study aims to replicate real conditions regarding the assessment of concrete strength in an existing building: an analyst must select a certain number of candidate structural elements (NSM_A) where the material strength will be assessed and no information about the remaining NSM_{NA} members ($NSM_{NA} = NSM - NSM_A$) will be available. For each dataset, the study defined all the possible combinations of samples with increasing NSM_A sizes extracted from the NSM data. For each dataset, the lowest NSM_A size was 2 and the largest was NSM . For each sample, the mean of the sampled NSM_A results was calculated, as well as the ratio $\chi_{f,c,m}$ between the sample mean and the true mean (i.e. the one obtained considering the entire NSM dataset). Hence, for each sample of size NSM_A , a dataset of $\chi_{f,c,m}$ values was created. Fig. 1 presents the analysis of the $\chi_{f,c,m}$ datasets for increasing values of the ratio between NSM_A and NSM , namely in terms of the evolution of the mean of $\chi_{f,c,m}$ and of the corresponding CoV.

The analysis of the results presented in Fig. 1 shows that, for all samples sizes and for all datasets (irrespective of their inherent variability), the mean of $\chi_{f,c,m}$ converges to the true mean value, as seen by the horizontal lines of Fig. 1a). On the other hand, as shown in Fig. 1b), the CoV of $\chi_{f,c,m}$ exhibits a larger variability which is, in part, influenced by the inherent variability of the datasets. Although the variability of $\chi_{f,c,m}$ can be seen to be related to the global variability of the dataset, the CoV values shown in Fig. 1b) are, nonetheless, lower than the CoV of the original datasets. As expected, the variability of $\chi_{f,c,m}$ decreases as the sample size increases. The rate of this reduction of the variability

can be seen to be similar to the evolution of the finite population correction factor that reduces the weight of the sampling variability as the value of the relative sample size NSM_A/NSM increases. For the dataset with the larger CoV, assessing 10% of NSM leads to a CoV of $\chi_{f_{c,m}}$ around 0.20-0.25, while for dataset C5 this CoV decreases to 0.13.

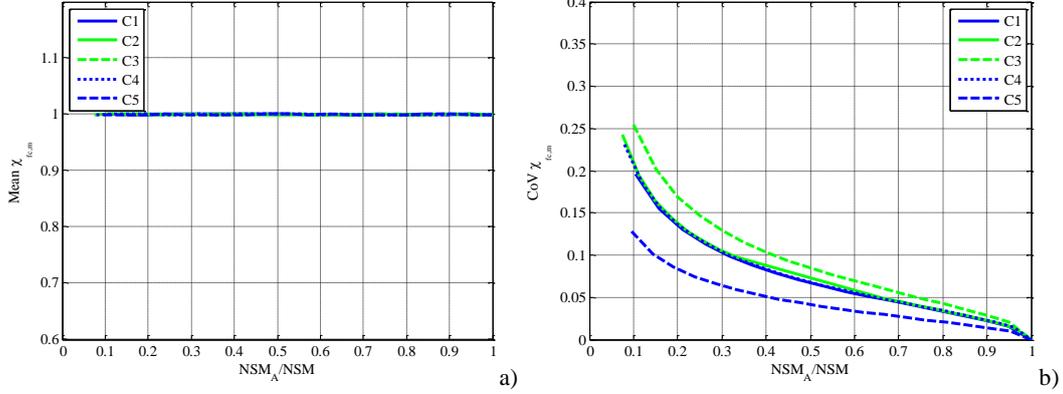


Figure 1. Assessing the sampling uncertainty regarding the mean core strength estimate for increasing values of NSM_A/NSM : a) mean values of $\chi_{f_{c,m}}$ and (b) evolution of the corresponding CoV, $CoV \chi_{f_{c,m}}$.

In light of the results presented in Fig. 1b, it is possible to analyse how the sampling uncertainty about the mean is correlated with the global population variability. It may seem to be incoherent to correlate the variability in the central value for a given knowledge level (i.e. a sample size NSM_A) with the unknown global variability (since only a sample of size NSM_A is analysed). Nevertheless, a reliable estimate of the global variability is able to be obtained from non-destructive test results, as will be presented later in the paper. To explore the potential correlation between the uncertainty in the central value and the global variability of the population, two types of data were used during this analysis. Four datasets were collected from the study by Chen et al. (2013) to establish a training set and determine the correlation. Then, datasets C1 to C5 were used as a testing group to evaluate the performance of the correlation that was established. Following the rationale used for the analysis of the mean sampling uncertainty, all the combinations of all possible sample sizes were defined for each of the training datasets and, for each sample size NSM_A , the CoV of $\chi_{f_{c,m}}$, $CoV \chi_{f_{c,m}} | NSM_A$, was computed. The value of $CoV \chi_{f_{c,m}} | NSM_A$ obtained for each sample size and training dataset was then normalized by the global CoV of the corresponding dataset to establish the normalized parameter β_{CoV} :

$$\beta_{CoV} = \frac{CoV \chi_{f_{c,m}} | NSM_A}{CoV_{fc} | NSM} \quad (12)$$

Based on the multiple values obtained for β_{CoV} , a regression model was constructed correlating β_{CoV} with the relative sample size NSM_A/NSM , hereon represented by factor ζ . Figure 2a presents the evolution of the values obtained for β_{CoV} and the corresponding fitted curve. Several regression models were tested but the one represented by Eq. (13) is the one which minimizes the fitting error. The range of applicability of Eq. (13) is between 0.05 and 0.95. For values higher than 0.95, β_{CoV} was assumed to be equal to one.

$$\beta_{CoV} = \frac{-0.140 \cdot \zeta + 0.208}{\zeta + 0.222} \quad (13)$$

Figure 2b presents the values obtained for β_{CoV} using the testing data (datasets C1-C5) along with the corresponding estimates obtained from Eq. (13). It can be seen that, for these datasets, Eq. (13) defines a conservative estimate of the true value of β_{CoV} for most cases. Hence, it can be assumed that Eq. (13) provides a reasonable measure of the sampling uncertainty affecting the estimate of the mean.

Furthermore, since the mean of $\chi_{f_{c,m}}$ was seen to be equal to 1.0 for all sample sizes, the variability of $\chi_{f_{c,m}}$ corresponds to the variability of the mean estimate of the concrete strength conditioned on the sample size being considered, i.e. $\text{CoV}\chi_{f_{c,m}}|\zeta = \text{CoV}_{f_{c,m}}|\zeta$. The sampling uncertainty associated to the estimate of the mean conditioned to the sample size and to the global variability of the population given by Eq. (13) indicates that:

$$\text{CoV}_{f_{c,m}}|\zeta = \beta_{\text{CoV}}(\zeta) \times \text{CoV}_{f_c}|\text{NSM} = \overline{\text{CoV}} / \text{NSM}_A \cdot \frac{1}{\sqrt{\text{NSM}_A}} \cdot \sqrt{\frac{\text{NSM} - \text{NSM}_A}{\text{NSM} - 1}} \quad (14)$$

This relation enables Eqs (6) and (11) to now be written as Eqs. (15) and (16), respectively:

$$SF = 1 + z_{1-\alpha} \cdot \beta_{\text{CoV}}(\zeta) \times \text{CoV}_{f_c}|\text{NSM} \quad (15)$$

$$SF = \exp\left(z_{1-\alpha} \cdot \sqrt{\ln\left(\left(\beta_{\text{CoV}}(\zeta) \times \text{CoV}_{f_c}|\text{NSM}\right)^2 + 1\right)}\right) \quad (16)$$

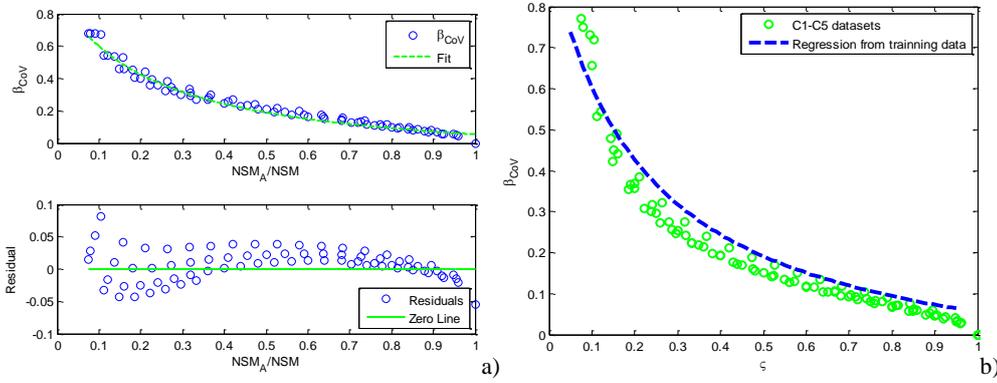


Figure 2. Empirical correlation between β_{CoV} and ζ : a) derivation using training datasets and b) comparison between the correlation defined and the testing datasets.

Since $\text{CoV}_{f_c} / \text{NSM}$ is unknown, an approximation based on auxiliary data needs to be defined to obtain SF. A reasonable estimate of $\text{CoV}_{f_c} / \text{NSM}$ can be established based on results obtained from the Schmidt rebound hammer test. This type of non-destructive test presents several practical advantages, namely the fact that it causes very little damage to the structure and that it can easily be performed over a large number of structural members. Still, a correlation is required in order to transform the variability of the rebound test results $\text{CoV}_{\text{RN}}|\text{NSM}$ into the variability of the concrete strength values. Pairs of concrete core strength and rebound test values RN obtained from in situ and laboratory tests reported in literature studies (Szilágyi, 2013; Fabbrocino et al., 2005; Brognolli, 2007) were selected to establish the referred correlation. The validity of this correlation was then tested against the concrete core strength values and rebound test results RN pairs of datasets C1 to C5. According to Fig. 3a, the data from datasets C1-C5 is within the 75% prediction bounds of the fitted correlation model, a situation which is found to be satisfactory and demonstrates the validity of the proposed correlation.

Since the proposed correlation was defined using the true value of $\text{CoV}_{\text{RN}}|\text{NSM}$ of a given dataset, and since this true value can only be defined when all the structural members are tested, an estimate of the minimum number of structural members that must be tested in order to obtain a reliable enough estimate of $\text{CoV}_{\text{RN}}|\text{NSM}$ was determined. A simulation study was carried out to determine the effect of the sampling uncertainty in the estimate of $\text{CoV}_{\text{RN}}|\text{NSM}$ using datasets C1 to C5. For each dataset, all the possible combinations of samples with increasing NSM_A sizes extracted from the NSM data were defined. For each sample of size NSM_A , the CoV of the RN values, $\text{CoV}_{\text{RN}}|\text{NSM}_A$, was calculated and divided by $\text{CoV}_{\text{RN}}|\text{NSM}$ obtained for the full sample. By analysing the evolution of the mean of these

ratios, it was seen that a relation NSM_A/NSM in the range of 50-60% was enough to have a value of $CoV_{RN}|NSM_A$ with a 5% margin of error with respect to the true value.

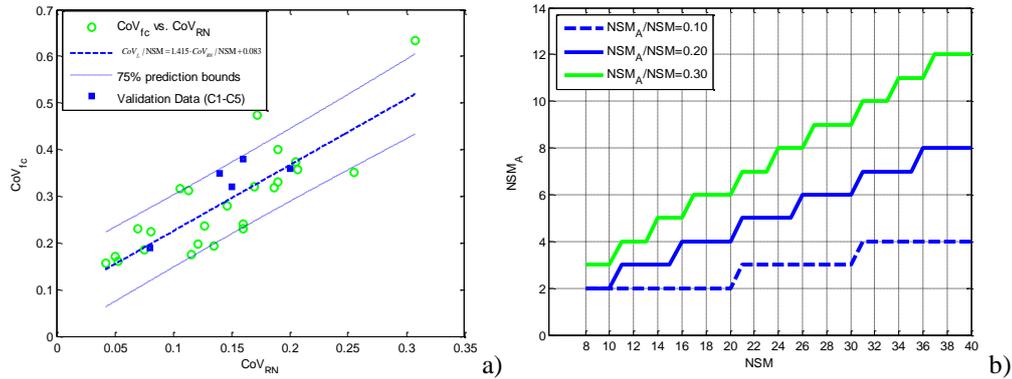


Figure 3. Correlation between CoV_{fc}/NSM and $CoV_{RN}|NSM$ along with the 75% prediction bounds and the results of datasets C1-C5 (a); Variation of the absolute number of tests for the assumed KLs (b).

ALTERNATIVE PROPOSAL FOR THE EC8-3 CONFIDENCE FACTORS

As previously referred, EC8-3 (CEN, 2005) defines the material safety factor (the so-called Confidence Factor, CF) according to 3 different Knowledge Levels (KL) that are associated to absolute values of the number material tests that need to be carried out for each building floor and per element type. By defining absolute values for the number of tests, EC8-3 has no control over the sampling uncertainty that affects the statistical characterization of the material properties. Hence, using the hypothesis of a discrete structure with NSM members, Eqs. (15) and (16) can be used to define safety factors connecting the ratio NSM_A/NSM with a specified level of confidence in the estimate of the mean value of the concrete strength.

Alternative definition of the minimum number of tests for each Knowledge Level (KL)

A first step towards the definition of an integrated KL-CF method is to establish minimum sample sizes for the knowledge level definition and that correspond to the minimum number of destructive tests that have to be carried out. After analysing the evolution of the SFs calculated using Eqs. (15) and (16) for different CoV values and NSM_A/NSM ratios, a minimum reference ratio was established for each knowledge level KL1, KL2 and KL3. These ratios were considered to be 10% for KL1, 20% for KL2 and 30% for KL3. The 30% limit was established since it is assumed that a higher reliability level needs to be obtained while inducing a moderate level of structural damage during the survey. The 20% and 10% values reflect a reduction of 1-2 destructive tests for different NSM_A/NSM ratios from KL3 to KL2 and from KL2 to KL1. Figure 3b presents the evolution of the minimum number of destructive tests according to the reference NSM_A/NSM ratios. It can be seen that for KL1, the required number of destructive tests remains the same for variations of 10 in the value of NSM. A minimum value of 2 was always considered in order to be able to estimate a mean value. For KL2, the assumed NSM_A/NSM ratio indicates the required number of destructive tests increases each time NSM increases by 5. A similar increase is observed for KL3 each time NSM increases by 3. These trends were only analysed up to a NSM value of 40 since it was assumed that such limit value of NSM is representative of the maximum number of structural members of the same type that may exist in an homogeneous area of 320m² (the limit value suggested in the Italian Code (NTC, 2008)). When only 8 structural members or less are present, a minimum of 2 destructive tests is always necessary for KL1 and KL2, and a minimum of 3 for KL3. Considering an example structure with 20 structural members (i.e. NSM = 20), a minimum of 2 tests is required for KL1, 4 tests for KL2 and 6 tests for KL3.

Definition of Confidence Factors compatible with the proposed Knowledge Levels

Using the proposed definition for the minimum number of destructive tests required for each KL, SFs reflecting a specific level of confidence in the estimate of the mean concrete strength can now be established using Eqs. (15) and (16). Figure 4 presents the evolution of the SF values as a function of increasing values of CoV_{fc} / NSM for different α -levels of confidence and for the 3 KLs previously defined in terms of the reference NSM_A / NSM ratios. The results based on the normal distribution, Eq. (15), are presented in Fig. 4a (KL1), Fig. 4c (KL2) and Fig. 4e (KL3), while those based on the lognormal distribution, Eq. (16) are presented in Fig. 4b (KL1), Fig. 4d (KL2) and Fig. 4f (KL3).

A global analysis of the results of Fig. 4 indicates that, for each KL for all the considered confidence levels, the necessary SFs are slightly larger when using the lognormal distribution. These differences and the fact that it represents a more conservative approach, indicates this model is more adequate to define the values of SF. After setting this condition, it is necessary to decide which confidence level should be assigned to each knowledge level. Little guidance can be found with respect to the selection of an adequate confidence level to establish material strength values. Still, some rationale seems to exist regarding the bounds for possible values of the confidence level. As stated by Romão et al. (2012), a minimum confidence level of 75% is generally considered in the context of structural assessment (ACI 228.1R-03, 2003). On the other hand, it is common to find the value of 95% being suggested as a maximum value for all practical purposes. Figure 4 presents the evolution of SF for various $(1-\alpha)$ confidence levels ranging from 0.75 to 0.95, in steps of 0.05. As can be seen, for all KLs, there are significant differences between the SF values obtained for the 95% and 75% confidence levels. On the other hand the results obtained for the 85% and the 80% confidence levels are very similar. Also, the results obtained for the 85% confidence level are much closer to those obtained for the 95% confidence level than to those obtained for the 75% one. Based on the results indicating the evolution of SF, an analyst can easily select a knowledge level to determine the corresponding SF that must be used to establish a safe estimate of the mean concrete strength accounting for a desired level of confidence and for a known or admissible level of the concrete strength variability.

Comparison of the EC8-3 CF values with the proposed SF values

Since 3 KLs associated with 3 different relative sample sizes were selected in the previous analysis, it can be assumed that the length of the confidence interval associated with the corresponding SFs could also be established using a similar reasoning. Therefore, instead of selecting the same confidence level for all the KLs, one may alternatively define a higher confidence level (i.e. a larger confidence interval) for KL1 since there is less information for that KL. For the remaining KLs, lower confidence levels (i.e. with smaller confidence intervals) may, therefore, be progressively established. This fact can be analysed bearing in mind the reduction of the sampling uncertainty about the mean that is obtained when NSM_A increases. Hence, if one assumes a maximum confidence level of 95% for the case where NSM_A is lower (i.e. KL1), the minimum confidence level of 75% can be associated to the case where NSM_A is larger (KL3). An intermediate confidence level may then be established KL2. Since the reduction in the SF is approximately 50% from a confidence level of 90% to a confidence level of 75%, the value of 90% was assumed for the intermediate level of knowledge (KL2). Figure 5a presents the evolution of SF for the confidence levels selected for each KL as a function of increasing values of CoV_{fc} / NSM .

The results presented for the 3 KLs and the corresponding confidence levels can be compared with the CF values proposed by other standards. As shown before, EC8-3 (CEN, 2005) and the Italian code propose a similar approach to define the survey planning operations to assess material properties. These standards relate a certain value of NSM_A associated to a KL and correct the mean estimate of the concrete strength by CF. It must be noted that the CF value proposed by these standards for KL3 (CF = 1.0) is unrealistic unless the concrete strength is assessed in all the structural members. Given the CF values these standards propose for KL2 and KL1, 1.20 and 1.35, respectively, a reference value of 1.10 is proposed for the CF of KL3 to be used in the following analysis. To compare the performance of the proposed approach leading to SF values of each knowledge level and of the CF values proposed by EC8-3 and the Italian standard, Figure 5b replicates the results of Fig. 5a with 3 additional curves representing the CF values, termed $CF-KL1_{EC8-3}$, $CF-KL2_{EC8-3}$ and $CF-KL3_{EC8-3}$.

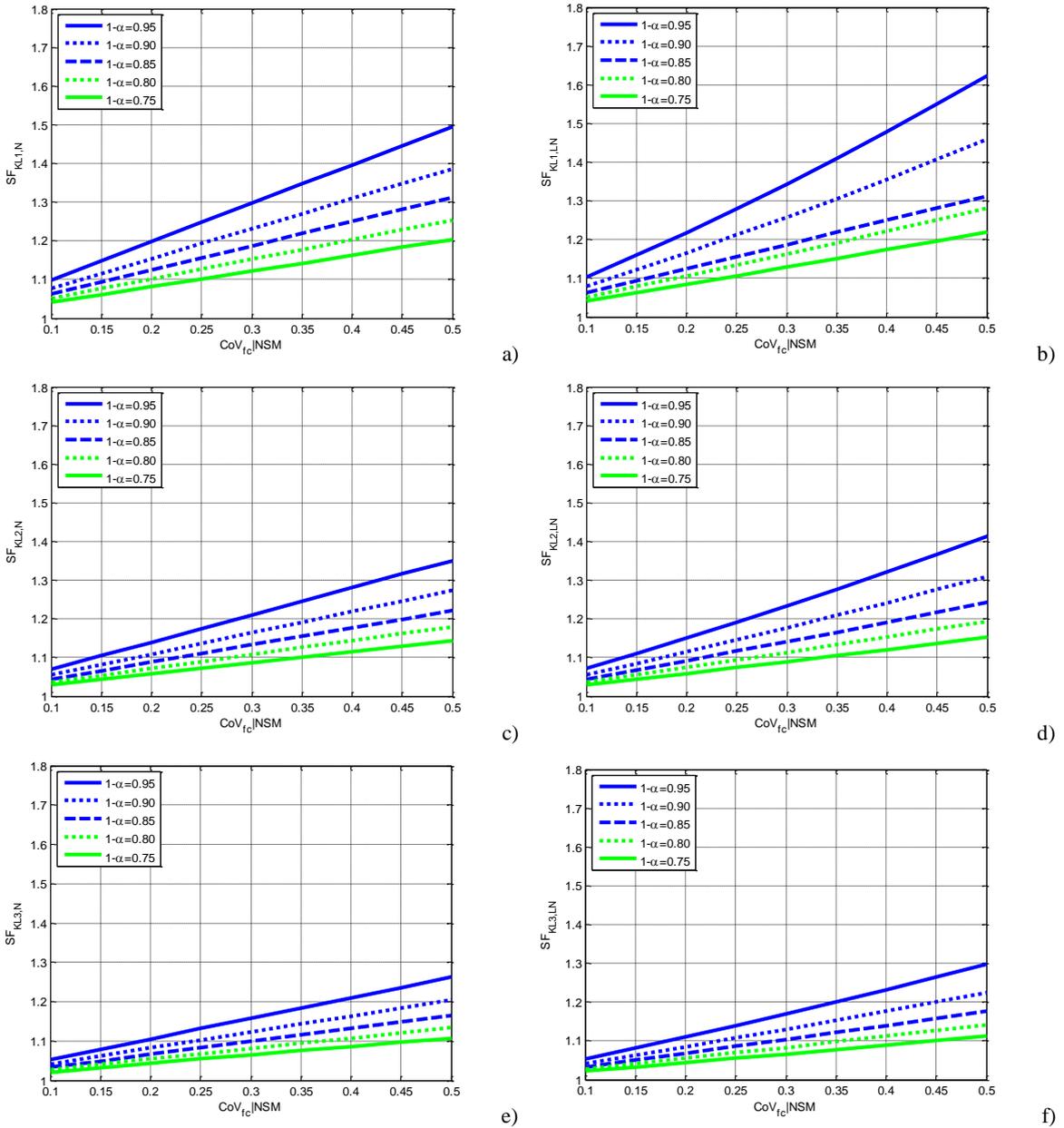


Figure 4. Evolution of SF for different KLs and confidence levels: KL1 (normal (a) and lognormal (b) distribution), KL2 (normal (c) and lognormal (d) distribution) and KL3 (normal (e) and lognormal (f) distribution)

By comparing the CF values and the evolution of the proposed SFs, it can be seen that for both approaches to be compatible, the admissible variability of the concrete strength (i.e. CoV_{fc} / NSM) must be limited. By analysing the range of CoV_{fc} / NSM for which CF-KL1_{EC8-3} and CF-KL2_{EC8-3} cross their corresponding SF curve (CF-KL3_{EC8-3} was left out since 1.10 is not the true value proposed by the standards), it can be seen that CoV_{fc} / NSM should be limited to a value around 0.30. For KL1, a CoV_{fc} / NSM of 0.30 leads to an SF value of 1.34 while, for KL2, an SF value of 1.18 is obtained. For KL3, the SF value corresponding to a CoV_{fc} / NSM of 0.30 is 1.07. Therefore, based on this analysis, the CF values proposed by EC8-3 and the Italian standard for KL1 and KL2 can only be found to be acceptable as long as CoV_{fc} / NSM is lower than 0.30. For the case of KL1, the proposed approach based on the definition of SF leads to a more statistically sound proposal since the CF value of 1.0 proposed by the EC8-3 and the Italian standard is unrealistic. Furthermore, since the CF values will yield concrete strength estimates that might be too conservative when CoV_{fc} / NSM is significantly

lower than the proposed limit of 0.30, an approach defining a safety factor that varies according to the level of strength variability found during the assessment is seen to be more flexible and useful.

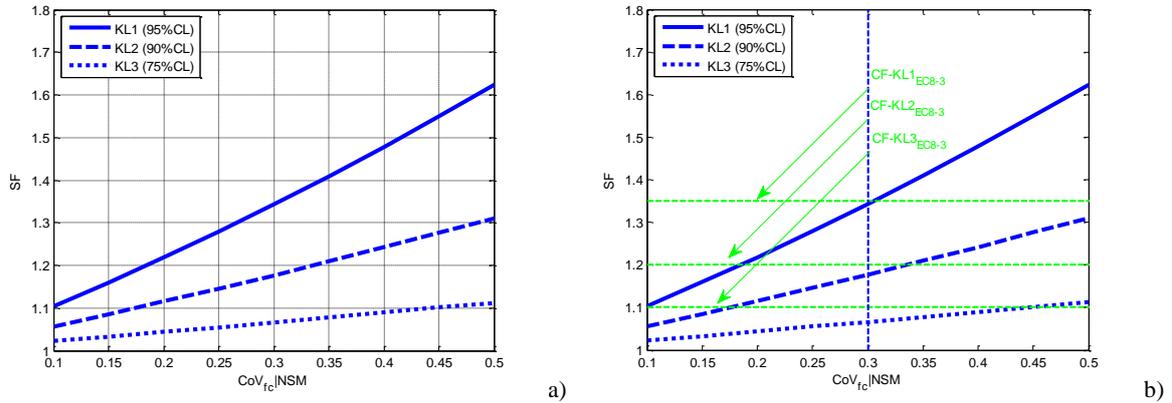


Figure 5. Evolution of SF for the selected confidence levels of each KL (a) and comparison of the SF values with the CFs proposed by the EC8-3 and the Italian standard. (b).

CONCLUSIONS

The proposed paper presents a framework for the quantification of a reliable mean estimate for the concrete strength in existing buildings by controlling the sampling uncertainty associated to the survey procedures. The proposed framework uses finite population statistics and a discrete idealization of the structure of the building. Based on empirical relations representing the reduction of the sampling uncertainty about the mean as a function of the relative number of structural members that are assessed, safety factors were proposed for the sample mean of the concrete strength conditioned on a given relative sample size (i.e. the number of structural members that are assessed with respect to the total number of structural members). Safety factor expressions were established for the case where the mean of the concrete strength is assumed to follow a normal distribution and for the case where it is assumed to follow a lognormal distribution.

The proposed safety factors depend on the previously referred relative sample size and on the global variability of the concrete strength. An empirical method was also proposed to estimate the global variability of the concrete strength using results of the Schmidt rebound hammer test. After defining the analytical formulation of the proposed safety factor, evolution curves were defined for different confidence levels after associating minimum values for the necessary relative sample size associated with each knowledge level. These relative sample sizes were 10% for KL1, 20% for KL2 and 30% for KL3, with respect to the total number of structural members of a storey or floor under characterization. For these KLs, safety factor curves were defined for confidence levels ranging from 0.95 to 0.75. From the analysis of these curves, a specific confidence level was assigned to each knowledge level. For KL1, a 95% confidence level was considered while for KL3, a 75% confidence level was assumed as the minimum value. For KL2, an intermediate level of 90% was considered since it yielded results halfway between those obtained from the curves having confidence levels of 75% and 95%. This approach where a single confidence level was assigned to each knowledge level was then compared with the CF values proposed by EC8-3 and the Italian standard. From this comparison, the CF values proposed by the standards for KL1 and KL2 were seen to yield adequate (and conservative) results that are in agreement with those that can be obtained using the proposed safety factor approach, as long as the global variability of the concrete strength, CoV_{fc} / NSM , is lower than 0.30.

Finally, it is noted that since part of the proposed approach is based on empirical relations, such as those defined by Eq. (13) and in Fig 3a, future studies may improve these relations by using additional data for the development of the proposed correlations.

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