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Reliable non-destructive strength assessment in existing structures: myth or reality?

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Abstract

The non-destructive assessment of concrete strength in existing structures is a complex issue which has been analyzed by a recently closed RILEM committee (TC 249-ISC) whose Guidelines and Recommendations are to be released soon. This committee has considered the state of practice, the yet existing standards and most recent innovative research results, in order to write recommendations that would improve the reliability of strength assessment with non-destructive techniques (NDT). These recommendations are based on a paradigm change: the challenge is not that of finding the true local strength, but that of estimating its value with a controlled tolerance interval and a limited risk of being wrong. Three levels of requirements are defined which correspond to different tolerance intervals on the assessed parameters and to a different amount of resources devoted to the investigation. While most of research has been devoted until now to the identification of relevant conversion models between NDT test results and strength, we have shown that the priority had to be put on other items, including the assessment of the NDT test results repeatability, the relevant definition of core locations and the checking of the final predictive error. This paper briefly describes the main innovations included in these recommendations.

Keywords: Assessment reliability; Concrete structures; Non-destructive techniques; On-site measurements; Strength assessment

1 Context, existing standards and guidelines and questions raised

Assessing the concrete strength of existing structures is required in many situations, like refurbishing, upgrading or extending the service life. The concrete strength value is also required to compute the structural capacity of a structure submitted to earthquakes. In old existing structures, when few or no documents are available, the only ways for assessing strength are to take cores or to use non-destructive techniques (NDT). The number of cores is often limited either for cost reasons or for technical reasons (including the danger to further weaken components of unknown capacity). NDT has been promoted as a mean able to provide a reliable estimate of concrete strength [1]. However, whereas many research programs have been carried out in order to develop tools and models for assessing concrete strength, one still lacks any validated methodology that guarantees the quality and efficiency of this process.

The use of NDT is based on the possibility to use a “conversion model” (commonly an empirical relationship taken from the literature or built from a calibration dataset) which enables to derive an estimated strength value from that of a NDT test result (this concept may be extended when several NDT are used in combination). In practice, various NDT are used (rebound hammer [2], ultrasonic pulse velocity measurement [3], pull-out [4], etc.) and a large variety of conversion models have been proposed.

Whereas the measurement process has been standardized for most common NDT, there is no consensus regarding the best procedure for: (a) estimating concrete strength, (b) knowing the accuracy of this assessment. Many reports and scientific papers, often based on case studies, explain how the data made available in existing structures using a variety of NDTs (e.g. see [5-8]) can be used to establish specific conversion models and derive strength estimates, but they usually fail to draw more general conclusions that could be applied as general rules of good practice. Therefore, two basic issues remain widely open: (a) the definition of the more adapted investigation program and data processing, (b) the assessment of the accuracy of the strength assessment.

Facing these open questions, structural managers and engineers remain often reluctant to use NDT in common practice and prefer to base their strength estimation on the core data. Doing so, they obviously do not consider the possible benefit of NDT: as NDT measurements do not affect

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the structure and can easily be taken at many point in a structure, a reliable way of processing such data could provide a much more informative picture of the strength pattern in the whole structure.

2 RILEM TC 249-ISC agenda

More than 25 years ago, RILEM had provided recommendations on NDT strength assessment of concrete [9], even if often cited as a reference, these recommendations suffer many drawbacks and require a profound revision. The challenge addressed by the RILEM Technical Committee In Situ Strength Assessment of Concrete (TC 249-ISC) was thus to establish a reliable methodology for carrying on NDT measurements, processing their results, and deriving strength estimation.

In this very active field for research, one can also consider some recent interesting ideas which have emerged these recent years, like:

- the analysis of various scales of heterogeneity in an existing building [10], which can take benefit of a dense mapping of the structure with NDT measurements,
- the added value than can be derived from conditional coring, which corresponds to define the location of concrete cores on the basis of prior NDT results, instead of following a preconceived sampling scheme ([11-12]),
- changing the conversion model identification techniques for better addressing the concrete variability [13].

One must also consider the yet existing EN13791 European Standard devoted to strength estimation in existing building [14]. But this standard primarily addresses the issue of concrete conformity and focuses on characteristic strength, in full agreement with Eurocodes expectations. Our purpose is different: we do not analyze safety issues, and only try to estimate true on site-strengths (i.e. local values, mean and optionally standard deviation). Another major difference is that we want to address the whole investigation process, from the definition of number and location of measurements to the delivery of strength estimates (see Fig.3 lower).

The RILEM TC 249-ISC was established in 2012 with the objective of preparing recommendations for a relevant assessment methodology. It had to cover all steps of the analysis, from the data collection to the strength assessment and to account for:

- the need of limiting as far as possible the number of cores, in order to fit with economical and technical constraints [15],
- the uncertainty interval of estimated strength,
- the possibility of addressing additional issues, such as estimating the concrete variability which is important for safety analyses of existing structures.

Few words must be told about the possible combination of several NDT which could lead to a more reliable strength estimate. This idea was promoted by former RILEM recommendations [9] but results of experimental studies are controversial [16-17] and how combination can bring a real added-value needs to be better understood.

A last criterion has guided the TC work, that of preparing recommendations that are easy to understand and follow, in order to induce a more extensive use of NDT by engineers and structural managers.

3 Recent research progress and RILEM TC 249-ISC work

The RILEM committee was a place of exchange between experts who have a regular practice of NDT strength assessment in real cases, and academic researchers who have developed innovative ideas enabling to improve the assessment methodology. The development of Non-Destructive Techniques was kept out of the topic. Therefore, the challenge was to validate the innovative ideas that could bring some added-value in real practice. These ideas included the conditional coring, the attention paid to variability assessment or to the precision of measurement. The combination of several NDT was another issue, since many practitioners use it (following former recommendations), whereas the methodology did not seem fully validated. In fact, many questions still had to receive answers, before the TC was able to write its recommendations.

The two main ways that were followed in order to share a common view on this field were:

- benchmarks that were carried on in order to compare how different experts using the same quantity of resources (time, money) can, depending on the strategy they follow, reach different results. It was shown that the disagreement between "true" strengths and estimated strength can vary, because of: (a) some well-known driving factors defining the strategy (number of cores, repeatability of the measurements), (b) additional variables (i.e. like the fact that core locations are predefined or depend on information delivered by NDT), (c) chance (the same strategy repeated several times on the same structure will not lead to exactly the same results, for several reasons, including the measurement errors) [18],
- synthetic simulations which enabled to compare different strategies and to quantify the role of all most relevant driving factors [19],
- the shared analysis of real datasets which had been provided by experts.

The most significant result was that the TC members were quickly convinced that the non-destructive strength assessment issue deserves a paradigm change, that we will quickly explain. Fig.1 reproduces what is commonly done by practitioners, when a given conversion model, which can be either a preexisting one or a specific model adapted to the specific context, is used to transform the NDT test results into an estimated strength. The final result is the estimated strength. When the problem is more attentively analyzed, it appears that this scheme is over-simplified and that uncertainties must be considered, as described on Fig.2.

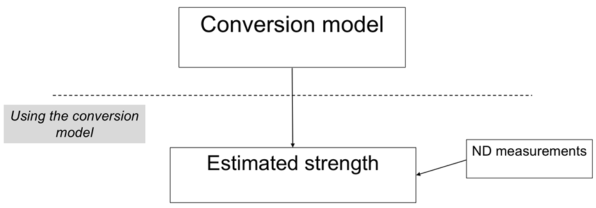

Figure 1. Usual strength estimation process.

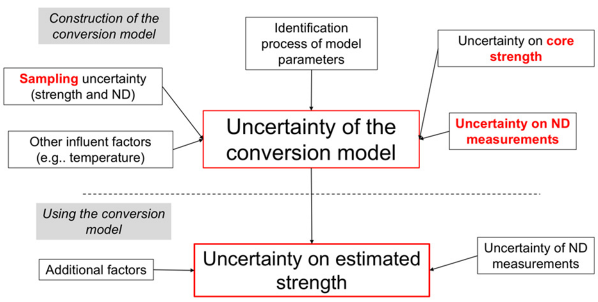

Figure 2. Uncertainties arising in the different stages of the strength estimation process.

This flowchart is divided into two stages, corresponding respectively to model identification and to model use. When some attention is paid to what happens during the full process, it is easy to understand that uncertainty (or errors) can impact the process at many stages. Significant research efforts have been recently devoted for a more systematic analysis of all the degrees of freedom of the non-destructive investigation and assessment process [18, 20-21].

In the first main stage (that of the conversion model identification) have been highlighted the respective influences of:

- statistical (sampling) uncertainty, due to the limited size of the dataset on which the model is calibrated, i.e. typically the number of cores,
- measurement uncertainty, on strength measurements as well as on NDT measurements, which mostly depends on the technique itself, but also on the device, on the expertise of who takes the measurement and on the environmental context. This also includes all biases that can appear during the drilling and core preparation.
- factors related to the identification process itself (from data to model parameters), like for instance the choice of the mathematical shape of the model, or the method that is used to select the location of cores. This set contains a large number of degrees of freedom and offers a large potential for improvement,
- additional uncontrolled factors, not considered in the analysis and that can have some influence on strength, on NDT test result, or on their relationship (i.e. temperature or carbonation).

The consequence is that the resulting conversion model is influenced by a random error component, and that another model (i.e. another set of parameters) would have been identified if the same process had been repeated [20]. TC members reached the conviction that the two most influencing factors governing the accuracy of the conversion model are the number of cores (sampling set size) and the quality / repeatability of NDT measurements. The former factor was already well-known, but the latter was not and deserves to be fully considered.

When the second global stage of the flowchart is considered, one has now an “uncertain” conversion model to which new data are applied (new NDT test results), with possibly different or additional uncontrolled influencing factors. It must be clear that the final output, i.e. the estimated strength is the result of a random process, and must be considered as such. Therefore, attention must be paid to its statistical distribution.

4 A new paradigm for on-site NDT strength estimation

These statements have lead us to revise the framework which has been followed for many decades by practitioner. The classical paradigm was deterministic, and the challenge was to find the “true value” of concrete strength. The revised paradigm must consider uncertainties and risk and thus can be written as Eq.1.

$$p\,(f_{c,\,true} - \Delta f_{c,\,true}) < f_{c,\,est} < p\,(f_{c,\,true} + \Delta f_{c,\,true}) = 1- \alpha \quad (1)$$

where $f_{c,\,true}$ is the true value (unknown) of concrete strength, $f_{c,\,est}$ is the estimated concrete strength, $\Delta f_{c,\,true}$ is the half of tolerance interval on the true strength and (1- α) is the confidence level of the estimation (or α is the risk of a wrong assessment, i.e. outside the prescribed tolerance interval). According to the revised paradigm the challenge is no more to identify the true strength but to estimate it with some tolerance interval, and at a given (accepted) risk. One can note that Eq. 1 can be modified if the tolerance interval is defined in relative terms (i.e. percentages) instead of absolute ones.

In order to write its recommendations, the TC had therefore to better understand and quantify the respective role of all uncertainties described on Fig.2. The number of cores is the first (and best known) factor, and its role has been identified in all standards, which usually prescribe a “minimum number of cores” [14, 22]. Within the new paradigm, it is considered that the larger this number, the more accurate will be the estimation (i.e. the smaller the tolerance interval for given risk level). However, because of the combined effects of all uncertainties on the final estimation, there is no simple mathematical expression of the relationship between the number of cores and the final accuracy. They were addressed into details in specific studies which considered both real data and synthetic data [19, 23].

5 The revised paradigm urges to consider two new items: EQL and TRP

Two new concepts have been defined and will have to be considered in the TC recommendations, namely the Estimation Quality Level (EQL) and the Test Result Precision (TRP). To keep the analogy with shooting, the EQL corresponds to the size of the target for a given distance and the TRP refers to the quality of the shooter/rifle combination.

How these two concepts are considered is now briefly described.

The EQL corresponds to the degree of requirement of the strength estimation challenge that can be adapted to fit a variety of situations, from those when few resources are available (limited budget, few data…) to those when one has more resources, thus a larger sample size. The ambition of the challenge has to be adapted to the available means. The strength assessment process can be carried in all cases, but without forgetting that the final accuracy obviously depends on the resources devoted to the task.

In practice, this means that the practitioner (structural manager, NDT specialist) is free of choosing the tolerance interval on the expected outputs and, as a consequence, to adapt his resources. This choice must be made at the very beginning of the process, before taking the first measurements, and impacts all following steps. The revised paradigm amounts to defining:

(a) a target, that was the local strength in Equation 1, but the same expression remains valid for other parameters, as the mean strength or the standard deviation of strengths,
(b) a tolerance interval, which can be absolute or relative,
(c) an accepted risk level. As the strength estimation is a random process, this risk level quantifies the probability that one estimation among a series of repeated estimations falls within the tolerance interval.

The RILEM TC has defined three different EQLs that correspond to progressively more ambitious requirements for the assessment, as described in Table 1 (this table has been simplified for the sake of clarity and is an abstract of that which is included in the recommendations). Three targets are considered, which are respectively the mean strength, the strength standard deviation (concrete variability) and the mean error on the local strength value RMSE. At the first level EQL1, estimating the mean strength is the unique challenge, with a tolerance interval of +/- 15% around its true value. At the two other levels, the three targets are considered, with more ambitious objectives for EQL3 than for EQL2.

The Test Result Precision (TRP) is the second major issue, since the measurement uncertainties are a major governing factor regarding the accuracy of the final estimated strength. Following the same analogy, it corresponds to the scatter (in trajectories and velocities) of the bullets when they get out of the rifle. In practice, this parameter is easy to quantify, by simply repeating NDT measurements at a same test location or at a close distance. Recommendations prescribe how many test results are required in order to assess TRP, which can be expressed either by the standard deviation of test results or by their coefficient of variation (COV_{rep}). Table 2 (which is an abstract of what is defined in the recommendations) illustrates how the TRP level is derived from the measured COV_{rep}, both for rebound test results and ultrasonic pulse velocity test results.

Table 1. relation between estimation quality levels (EQL) and the target tolerance intervals on strength assessment (simplified version).

Estimated property	EQL1	EQL2	EQL3
Mean	±15%	±15%	±10%
Standard deviation	not addressed	4 MPa	2 MPa
RMSE	not addressed	6 MPa	4.5 MPa

The threshold values given in the Table result from an analysis of the sensitivity of each non-destructive technique to strength variations, and from a review of what level of repeatability can be obtained in practice. For instance, it can be pointed out that commonly available UPV test results (with direct measurements) will fall in the TRP2 class, or even in TRP1 class in some cases, while typical RH test results will mostly fall in TRP2 or TRP3 classes. The TRP1 class is very difficult to obtain with rebound measurements on a real structure, which affects the precision of the conversion model and, as a consequence, that of the concrete strength estimation.

6 The recommended assessment process – short presentation

Our purpose is not to detail in this short letter the full recommended assessment process, that is published separately [24]. We can have however a quick view of the flowchart of Fig.3, which summarizes the key-steps of this process.

As we explained previously, the two main innovations are the prior choice of the target EQL and the measurement of the TRP, which is recommended in all cases, and mandatory for EQL2 and EQL3. The interest of conditional coring has been confirmed, especially when one has few cores and a good repeatability of NDT test results. Therefore, this conditional coring is recommended, and does not induce any additional cost.

Table 2. Definition of the TRP classes (COV_{rep} = coefficient of variation for repeatability of test result).

	TRP1 high precision	TRP2 medium precision	TRP3 poor precision
rebound (RH)	$COV_{rep} \leq 3\%$	$3\% < COV_{rep} \leq 7\%$	$COV_{rep} > 7\%$
ultrasonic pulse velocity (UPV)	$COV_{rep} \leq 1\%$	$1\% < COV_{rep} \leq 3\%$	$COV_{rep} > 3\%$

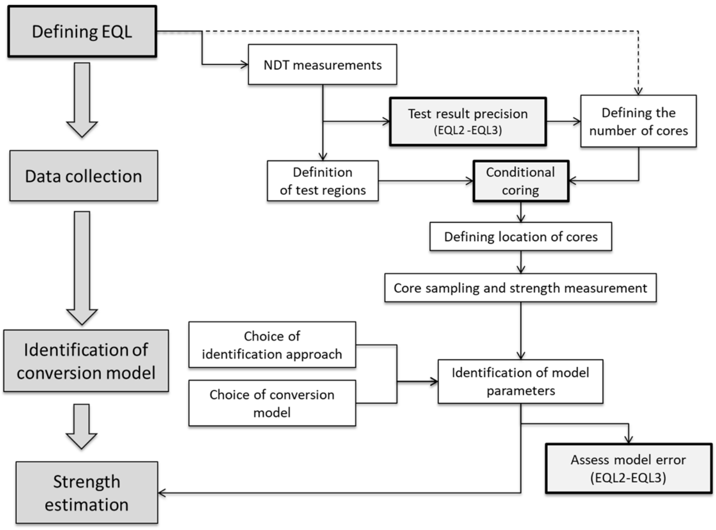

Figure 3. Detailed steps of the recommended concrete strength assessment process.

It is also easy to understand that, for a given EQL, the required number of cores will strongly depend on the TRP (this justifies the need of assessing TRP and, if possible, to increase the quality of measurements, as it will allow to reduce the number of cores). Fig.4 illustrates this relation.

These curves correspond to a specific concrete and cannot be taken at face value for any situation. They just explain how more accurate test results enable to reduce the number of cores, while keeping the same tolerance interval on the target (here mean strength). For instance, with TRP1 measurements (identified from Table 2), 3 cores correspond to 10% risk-level, while respectively 5 and 8 cores are required for TRP2 and TRP3 for the same risk and same tolerance interval (these numbers would respectively become 4, 7 and 10 for a 5% risk level).

Recommendations contain a series of tables which deliver the recommended minimal number of cores, both for rebound and ultrasonic pulse velocity measurements, for all EQL, all TRP and a wide range of concrete properties.

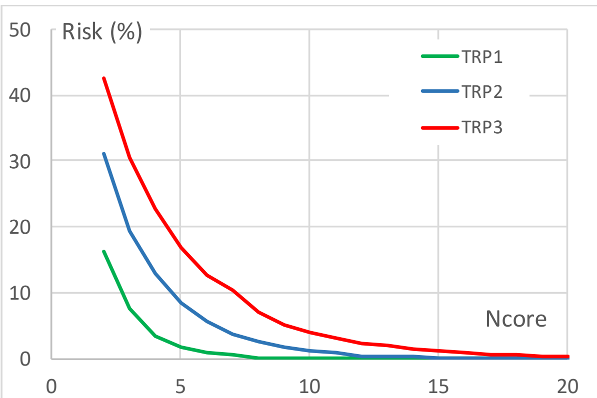

Figure 4. Indicative relation between the risk value, TRP and number of cores (warning: these curves correspond to a specific concrete and cannot be taken at face value).

We will just comment a last point, that of assessing the model predictive error. This task is highly recommended in all cases and mandatory at EQL3. Several methods enable to assess this error without any additional measurement, and are described in the recommendations. The investigator can thence provide his assessment result with an additional guarantee.

7 Conclusion and additional research needs

New RILEM recommendations establish a revised framework whose ambition is to improve the field practice of non-destructive strength estimation of concrete in existing structures. They are the result of a six-year collaborative work between leading experts in that field and include several recent research results. These recommendations have been written considering the practical context of structural investigation, the limited amount of resources that are usually devoted to this task, and in order to provide a reliable procedure easy to understand and to implement. The focus is given to the local strength estimation, to the concrete variability estimation (which was not detailed in this letter) and to the mean predictive error. The recommendations and guidelines will be published soon by RILEM and we are firmly convinced that these two documents will contribute to a more efficient and less controversial use of non-destructive techniques for on-site estimation of concrete strength.

TC members have also identified some important issues that would deserve further studies. While we have focused on the material scale (i.e. identification of material properties), these new issues are mostly related to the structural scale. Concrete strength assessment is often the first required step of a larger process, that of structural safety assessment. When a structure safety is to be assessed, the material characteristics of its components need to be known but all components have not the same weight on the structural safety, because of their structural role (e.g. local/global stability) or their location in the structure. Optimizing the investigation program thus would require to consider both the reliability of strength estimation in the components (topic of the present recommendations) and the sensitivity of the structural response to these parameters. This could lead to define an uneven distribution of cores in the structure.

Another issue is that of "test regions" that we have defined as a part of the structure (or set of components) in which concrete has the same statistical properties. One specific conversion model can be identified for each test region, which can imply two or three models in single structure, and increase the required number of cores. The option of merging all components in a single population would reduce the number of cores, but could be dangerous if the conversion models are really different. It would be useful to consider this question and to make recommendations for the investigation program at the structural scale.

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