How to improve the quality of concrete assessment by combining several NDT measurements

Denys BREYSSE[1], Marios SOUTSOS[2], Roberto FELICETTI[3], Martin KRAUSE[4], Jean-François LATASTE[1], Andrezj MOCZKO[5]

[1] *University Bordeaux 1, Ghymac, France, d.breysse@ghymac.u-bordeaux1.fr*
[2] *University of Liverpool, UK*
[3] *Politecnico di Milano, Italy*
[4] *BAM, Berlin, Germany*
[3] *University of Wroclaw, Poland*

Abstract

RILEM TC INR-207 is devoted to the combination of non destructive techniques to improve the assessment of reinforced concrete. Several practical key applications have been selected, corresponding to the assessment of material condition, to the detection of defects or to the identification of an unknown geometry. For each application, the problem is analyzed from the point of view of added-value brought by combination. This paper explains what is the challenge when quantification is the main objective, and details what is done by TC members in a specific application, that of concrete strength assessment.

Résumé

Le TC RILEM 207-INR se consacre à la combinaison des techniques de CND pour améliorer l'évaluation du béton armé. Plusieurs applications représentatives ont été choisies, qui correspondent à l'évaluation de propriétés du matériau, à la détection de défauts ou à l'identification de grandeurs géométriques. Pour chaque application, le problème est analysé du point de vue de la valeur ajoutée apportée par la combinaison. Cet article explique quel est le défi quand on vise à quantifier les paramètres, et détaille une application particulière, celle de l'évaluation de la résistance du béton.

Keywords

Combination of techniques, guidelines, material condition, strength

1 Introduction

The condition assessment of building material is a key point when one wants to reassess existing structures whose material ageing can have resulted in some performance loss and some deterioration of the safety level. Progressive decay of performance also induces important maintenance costs, such as to prevent future deterioration and ultimate failure. Non Destructive Technique (NDT) are widely used in civil engineering for controlling new structures (quality control) as well as for assessing the level of damage of old structures and buildings whose behaviour is under question. Many companies develop NDT equipment or offer their services to building managers but even if their skill is not questioned, the lack of internationally acknowledged reference texts is a heavy handicap:

- the choice of the best-fitted technique for a specific problem is not simple,
- the relevance of the measurement process is not guaranteed by any widely accepted guidelines,
- the question of how to cope with measurement results and how to finally assess the structural properties often remains unanswered.

On another hand, many institutes and companies are involved in the improvement of techniques (developing innovative equipment or post processing of data, coupling measurements and numerical simulations, benchmarking their techniques on pilot sites...). Until now, these efforts have been mainly undertaken at a national level (with several working groups or national research projects in Germany, Britain, France, USA, Japan...) but they have not lead to general conclusions or to proposals which have been accepted by the various actors involved in the field: building managers, contractors, regulators, NDT practitioners, consulting engineers... It is considered that, due to the increasing need of validated NDT protocols (increasing need of structural assessment for ageing structures AND increasing need of quality control), it is time now to consolidate – at an international scale – the huge amount of information and knowledge that has already been produced by many experts. It is the reason why, under the auspices of RILEM, a Technical Committee has been created to address these questions.

The purposes of NDT can be classified as follows: (a) to detect a defect or a variation of properties, between two structures or inside one structure, (b) to build a hierarchy (i.e. to rank on a scale), regarding a given property, between several areas in a structure or between several structures, (c) to quantify these properties, e.g. compare them to allowable thresholds.

Detection, ranking and quantification can be regarded as three levels of requirements, the last being the strongest. Much research has been devoted to the development of techniques or of data processing for a better assessment of building materials and state of the art reports are now widely available [1-6]. Many case studies also exist where several techniques have been combined on a given structure (or on laboratory specimens), but we think that real added value will be obtained only when the question of combination has been correctly analyzed [7]. This added value can be defined in terms of: (a) accuracy of estimation of properties, (b) relevance of physical explanations and diagnosis, (c) shorter time to reach a given answer. It remains to understand why and how combination can (or not) bring the expected added-value.

2 Objectives of the TC, questions addressed and working plan

The main focus is given on the use of NDT results for structural assessment and not on the techniques themselves. The main objectives of the RILEM TC „INR" are the following ones:

- to write a state of the art report dedicated to how NDT can be handled to answer the more common generic problems that RC structures are faced with,
- to improve the calibration of techniques dealing with specific problems, through well-defined benchmarking on „model-problems" and quantifying the added value provided by the combination of methods,
- to establish recommendations for designing „international reference test sites" and qualification of techniques and/or operators for application in the building industry,

Six key questions have been identified by the expert group members which correspond to problems frequently encountered by NDT practitioners and for which combination of techniques can offer opportunities. They are related to three types of problems:

☞ identifying the material properties: (a) estimation of on-site compressive strength of concrete, (b) assessment of concrete condition and damage after accidental fire,

☞ detection of defects: (a) detecting voids in cable ducts, (b) detecting and identifying debonding problems, delaminations or interfaces, (c) monitoring or detecting failure in cable structures

☞ problems with unknown geometry: control of the thickness of a pavement and pile examination.

A common working plan has been defined, constraining each problem to be tackled following the same logic. Thus the work is divided in three parts: (a) identifiying the ability of individual techniques for assessment regarding this problem, based on the yet existing state-of-the-art, (b) considering possible added value provided by combination of techniques and providing examples, (c) identifying existing "test-sites", what they can bring and what kind of questions remain open. All members also contribute to a common task which consists in defining more general and more formal recommendations about the combination of techniques. A last contribution is the description of techniques which can be used for such or such problem. This description remains basic to avoid any duplication with yet existing publications.

3 Combining Non Destructive Techniques

3.1 Current practice

When wanting to address material condition, the expert can try to get only a qualitative view, for instance by identifying spatial variations in the measured parameters. He can be more ambitious, and try to quantify these variations, for instance because he needs some input values for structural computations before repair or for reliability assessment. If expertise is required in the first case, it is not sufficient in the second one that also requires a validated methodology such as to ensure the quality of estimates. Many case studies exist where several techniques have been combined on a given structure (or on laboratory specimens), but the real added value obtained after combination has scarcely been analyzed [8]. The combination of techniques can follow various objectives, like for instance confirming with a second technique what has been observed with a first one, zoning the area where a more sophisticated investigation will be performed in the following, decreasing the number of borings by identifying the areas where borings will be more informant. The ways of performing combination of techniques have been recently classified into four types [7]:

- Type [A]: comparison of results obtained via two or more techniques, so as to confirm measurements and recorded variations,
- Type [B]: comparison of results obtained via two or more techniques, so as to improve the interpretation of results,
- Type [C]: use of a "quick" technique to have a first rough mapping, followed by a second "slow" technique in the areas selected in the first step,
- Type [D]: use of a second technique to identify a parameter so as to correct its effect on the first measurement. This helps to eliminate a bias factor in the first measurement and to improve accuracy and quality of interpretation.

Most publications and practical applications correspond to the first three types, the second technique being more or less used such as to confirm/reinforce information or presumptions given by the first technique. The last type is by far the more ambitious. It deals more with quantification (whatever is the parameter to be quantified: physical, mechanical, geometrical...). One of the most usual application of type [D] coupling is SonReb methodology, that will be discussed below.

3.2 What can be added-value ?

We will call here "added-value" the fact that a parameter will be estimated with higher accuracy by using several techniques instead of only one (other "added-values" can be an improvement in interpretation of measurement, by eliminating some possible explanations, or obtaining quicker results... but they will not be considered here). When one try to combine techniques, the question is "how to merge" information provided by each technique? Thus, soon arise the three questions of influent parameters, scale and quality of information, that we will detail now. The generic problem comes from the use of ONE NDT, which is sensitive to TWO or several parameters. In this situation, a second technique, also sensitive to these two parameters (or only to the second one) can enable to capture and eliminate the effect of the second one. The second parameter can be either the property which is looked for (material property, geometrical dimension...) or an environmental one (e.g. air temperature and humidity whose changes with time and environmental conditions will affect all electrochemical measurements) whose knowledge will help analysis. Figure 1 illustrates how the relations between physical (e.g. porosity) and mechanical (e.g. strength) parameters and NDT properties can be complex, and also depend of external parameters (here linked to environmental context), which is currently not well mastered and sometimes not even considered !

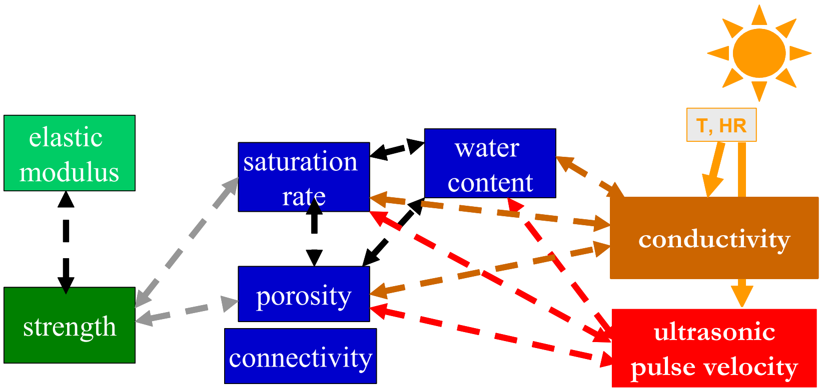

Figure1. *Generic diagram of relations between engineering properties, physical parameters, NDT measurements and sources of noise.*

Two remarks can be made:

- when two parameters to which a given technique is sensitive are varied simultaneously, one cannot identify the reason for the observed variation without additional information. Such is usually the case when a variation in water content (due to varying environmental conditions) is superimposed on a variation in the concrete microstructure (porosity of the paste for instance). In this case, it is not possible to establish a direct link between the observed variation of the measured property (wave velocity, electrical resistance ...) and the physical cause. This is, of course, a crucial point for diagnosis since a variation of the microstructure can reveal some defect or damage when the variation in water content (which can also depend on the microstructure, since the water content in a highly porous saturated concrete will be larger than in a dense saturated concrete) also depends on the environmental context (temperature, exposure to the sun, dominant wind...),
- the combination of two non-destructive techniques can provide additional information only if the sensitivity to the two parameters is different for the two techniques.

The black and gray arrows denote some correlation between properties and the red arrows denote some sensitivity of a technique to parameters. At the center, one finds material properties X (in blue boxes), which are representative of the material: porosity and connectivity on one hand, water content and saturation rate on the other hand. The former can be considered as constant with time (at least at short term, since they can vary due to chemical processes), while the latter can vary due to environmental changes, since timber, concrete or stone are hygroscopic materials. On the left part of the diagram, one has the engineering properties Y which are related the material properties (gray double arrows), even if the relations are very complex. Finally, on the right part, one has physical properties T measured through NDT (here electrical conductivity and UPV), which depend on material properties (red double arrows) but also on some bias factors, for instance temperature at the time of the measurement (orange arrows). Environmental factors EF have also to be taken into consideration, they influence the T factors, probably because they interfere on X properties.

The assumption on which NDT is based is that a correlation exists between Y and T, for instance between a length and the time of arrival of a signal. However, this correlation is not perfect, since, in fact, these two properties are usually macroscopic properties which result from some combination of physical material properties at the micro-scale (porosity, water content, crack-shapes, connectivity, strength of bonds in the composite…). Let us denote with X these basic physical properties. This graph shows that:

- the assessment of Y parameters does not reduce to a direct and simple Y = g(T) relation,
- any existing correlation between two techniques (here radar and resistance) will also follow a very complex way, which must be understood before being used.

Identifying the Y values from T measurements requires one to have a model (either theoretical or empirical), like T = f(Y, EF), whose inversion will lead to Y values. Thus, the quality of the final Y assessment depends on:

- the quality and relevancy of the basic model f, which comes from theory, literature or preliminary tests, for instance during a calibration stage,
- the quality of measurements T, since measurement errors will propagate during inversion,
- the good degree of complimentarity between techniques: as soon as one has two unknowns, one needs at least two measurements, T1 and T2, whose dependency to unknowns has to be different, such as to ensure a good inversion.

Finally, one has also to consider scales. Concrete is a very complex material, heterogeneous at all scales, notwithstanding with additional heterogeneities like more damaged areas, carbonation layer, fire front... All NDT techniques provide a physical measurement which must be linked to the investigated volume, and this volume depends on the technique and on the device (for instance offset between transducers). Thus, the way heterogeneities are "averaged" varies from case to case.

4 Combination of techniques for concrete strength assessment

4.1 Available NDT for strength assessment

Determination of in-situ concrete strength is traditionally performed for two reasons either for evaluating of an existing structure, or for monitoring strength development during new construction. In the second case, the use of in-situ tests not only increases safety but can result in substantial savings in construction costs by permitting accelerated construction schedules. The principal application of in-place tests is to estimate the compressive strength of the concrete. Most design codes, e.g. ACI 318, BS8110 and Eurocode 2, are based on the compressive strength of either standard cylinders or standard cubes. Although in-place tests can be used, the significant characteristic of most of these tests is that they do not directly measure the compressive strength of the concrete in the structure. Instead, they measure some other property that can be correlated to compressive strength. Then (a) a valid relationship between the results of in-place tests and the compressive strength of cylinders or cubes must be established, and (b) there must be an agreed statistical procedure to convert the estimated in-place cylinder or cube strength to characteristic strength. At present, there are no standard practices for developing the required relationship. In addition to the above, there are no generally accepted guidelines for interpretation of in-place test results. Sound and proven to work statistical procedures should be used to interpret in-place tests. It is not sufficient to simply average the values of the in-place test results and then compute the equivalent compressive strength by means of the previously established relationship. It is necessary to account for the uncertainties that exist.

Many techniques can be used for in-place tests, some of them have been standardized: rebound Hammer (ASTM C 805), Penetration Resistance (ASTM C 803/C 803M), Pullout test (ASTM C 900), Pull-off test, Break-off number (ASTM C 1150), Ultrasonic pulse velocity (ASTM C 597), Resistivity Methods, Shear-Wave Method. Table 1 summarizes their merits.

Table 1: *Principal Strength Tests - relative merits.*

Test method	Cost	Speed of test	Damage	Representativeness	Reliability of absolute strength correlations
Core	high	slow	moderate	moderate	good
Pull-out	moderate	Fast	Moderate/minor	Near surface only	Moderate/good
Penetration resistance	Moderate	Fast	Minor	Near surface only	Moderate
Pull-off	moderate	Moderate/fast	Minor	Near surface only	Moderate/good
Internal fracture	Low	Fast	minor	Near surface only	Moderate/poor
Ultrasonic pulse velocity	low	fast	minor	good	poor
Surface hardness	Very low	Fast	Very minor	Surface only	poor

4.2 Added-value of combination

The use of several NDT offers several intersting ways:

- possibility of identifying multi-variable correlation,
- possibility of building strength relationships with higher correlation coefficients than when the methods are used individually,
- possibility of uncoupling effects of bias factors, like moisture content and aggregate type, which affect differently strength estimates with each test.

The SonReb methodology is the better known methodology for using such a combination [9] even if it suffers many drawbacks, the main being that there is no theoretical relation between velocity of waves and strength, and that modelling of relations between material strength and NDT results (UPV and surface hardness) remains mostly empirical [10-11]. The generic relations write $f_c = k\, N^a\, V^b$ where f_c, N and V are respectively the rebound number and the UPV, and where k, a and b are empirical constants. A recent publication [12] has analyzed the effects of model uncertainties on the the quality of assessment, while some of the authors have recently analyzed the effects of the quality of the measurements on the assessment [10]. They developed a series of numerical simulations of the SonReb measurements, considering a varying quality/variability of the N and V measurements. Figure 2 plots how the coefficient of correlation r (y-axis) between true strength and estimated strength decreases if the variability of rebound number measurement cov (N) increases. Three situations have been considered, corresponding to: (a) strength estimation with V measurement only, (b) strength estimation with N measurement only, (c) strength estimation with both measurements. The curves on Figure 2 correspond to these three situations, with the unique bold curve for (a), the three dotted lines for (b) and the three curves for (c). The three lines and three curves correspond to a varying quality of sonic measurement

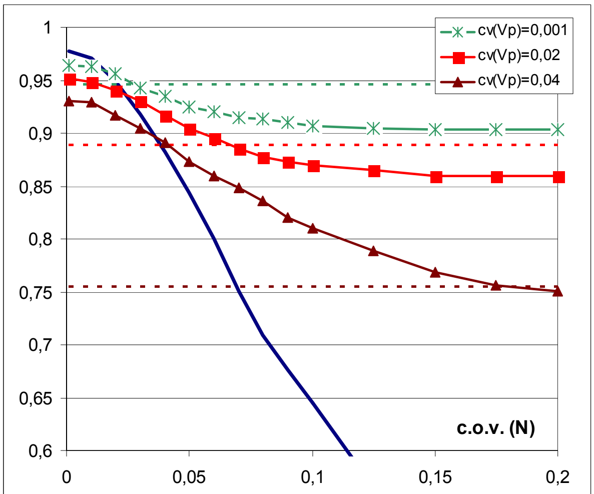

Figure2. *Variation of correlation between estimated strength and true strength (y-axis) for a varying quality of rebound number measurement N, for three situations.*

The combination of techniques appear to have an added-value only in a given domain, when the curves of situation (c) are above both the unique bold curve (N only) and the corresponding horizontal line (V only). For instance, if cov(V) = 0.02, the combination is interesting for 0.02 < cov (N) < 0.07. For smaller values of cov (N), il is preferable to use rebound only for estimation, while for larger values, the best is to use sonic measurements only. The conclusion is that the combination of techniques can (hopefully !) be efficient in a certain domain, but if one of the two techniques is too noisy, it is preferable to use only one good technique than to combine them!

5 Conclusions

RILEM TC INR-207 is devoted to the combination of non destructive techniques to improve the assessment of reinforced concrete. Six practical key applications have been selected, corresponding to the assessment of material condition, to the detection of defects or to the identification of an unknown geometry. We have explained what is called "added-value" of combination and shown how this question is addressed for each application studied in the TC, focussing on the challenge of quantification of parameters. The problem of material strength assessment has been detailed, and the complexity of combination has been discussed. The TC task is still in progress, devoted on one hand to generic considerations, which will be valid for any problem of combination, and on the other hand to discuss the six practical applications on the basis of real on-site examples, for which the added-value of combination can be demonstrated.

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