Non Destructive Testing of concrete: transfer from laboratory to on-site measurement

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ABSTRACT

The evaluation of mechanical and chemical properties of concrete by non-destructive evaluation requires the adaptation of the techniques and of theirs exploitations. Under the ACDC national project, we developed, a methodology for the characterization of structures in which the reality of the material and the environmental conditions are taken into account. Correlations laws from the laboratory between non-destructive measurements and characteristics of the concrete are readjusted by several procedures. We invert the non-destructive evaluation and exploit the complementarity of the four techniques implemented (ultrasonic , electromagnetic, resistive and capacitive) through a process of data fusion. We develop the steps of the pre auscultation and the auscultation and define an estimator with a quality intrinsic of data fusion. Inversion procedures were defined and tested on two industrial structures. They rely on the consistency of non destructive measures or on data obtained from destructive testing. We present methods and results, the selection criteria and the approach adopted for operation. Ours propositions are written in a recomandations book to guide the auscultation.

KEYWORDS : Diagnosis, Non Destructive Evaluation, Readjustment, Confidence, Concrete, Data Fusion

INTRODUCTION

The evaluation and the monitoring of the concrete characteristics and pathologies are the key points to anticipate the residual life of civil engineering structures. Non Destructive Evaluations (NDE) are apparently an acceptable economic solution. They provide on-site measurements by following procedures that allow setting up sustainability indicators of concrete by data inversion. The Non Destructives Techniques (NDT) and their exploitations are initially studied in the laboratory. They lead to correlation laws between the measures called "observables" and the characteristics of the concrete called "indicators".

The Senso project [1] has developed these laws in a multilinear format for a broad class of concrete and characterisation. The combination of techniques and therefore of observables sensitive to different material parameters can be traced back to the chosen indicators. The parameters to evaluate are: porosity, saturation, compressive strength and modulus of elasticity. For example, ultrasound velocity evolves greatly with the strength of concrete and the porosity. The electromagnetic waves velocity depends on the moisture content. Their combination allows us to extract indicators from the couple of indicators [2].

The generalization of these laws for an application to the data measured on site is not possible due to many factors generating biasses. Especially the nature of aggregates and cement, the environmental conditions at the time of measurement, the different stresses (mechanical, chemical, temperature) and the exposure to wind and rain influence the result of the measurement. Concrete becomes a material that evolves spatially and temporally. The transfer of the correlation developed in laboratory requires an adaptation and calibration phase in order to take into account the potential biases identified above. This is the aim of the French project "Analysis and Capitalisation for the Diagnosis of Constructions" which is summarised in this article. It was funded by the "Designing and Building for Sustainable Development" program of the RGCU and MEDDE.

The general objective of this project is to develop the methodologies and tools necessary for this transfer from the laboratory to the on-site measurement. It was realised in 36 months through the close collaboration of five research institutions LMA-LCND, LMDC, IFSTTAR, I2M, EC Lille and two infrastructure managers' partners, EDF and SETRA.

We developed our work in defining the successive points of the methodology (protocols, fusion, measurement and readjustment), application on site and selection of procedures. We applied the approach to the case of two structures made available by the SETRA and EDF.

1 METHODOLOGY

1.1 Tools

In this work, we implement the data fusion [3] in order to exploit complementary information data, but that can be conflicting. We work with the theory of the possibilities to combine the observables relying on experimental correlations between each observable and the researched indicators. We integrate a mathematical operator of fuzzy logic [4]. This takes into account the state of potential conflict issued from the observables. The correlation are given in the form of multilinear regressions

$$O_k = a_k + \sum_{j=1}^{p} b_k^j \cdot I_j \; . \tag{1}$$

where $(O_k)_{1\le k\le m}$ is the measure of the observable k and $(I_j)_{1\le j\le p}$ correspond to the values of the j indicators associated to the O_k value. The b_k^j are the dependence coefficients of the observable k to the j indicators. a_k is the constant.

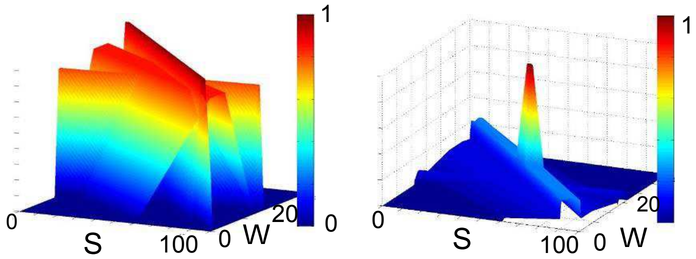

Figure 1: Weighted possibilities distributions for U.S. velocity, capacity, and radar amplitude in the space of indicators: saturation S (%) and porosity W (%).

These possibility distributions (figure 1a) are combined as shown in figure 1b. The estimation of the saturation S and of the porosity W is made on the basis of the fusion of the velocity of the ultrasonic waves transmitted V, the capacity C and the amplitude of the radar signal A.

The first solution is that the correlations are deduced from the Senso project [2]. The second way is to generate new correlations with measures made on site or/and in the laboratory with cores extracted especially from the structure [5].

1.2 Protocols

A first level of protocols details the evaluation of each observable [6]. These protocols detail the technique, the measurement, the number and the use made of the results.

A second level of the protocol defines the general auscultation of the structure. Each work is a special case. The specifications statement of the project by the owner led to a proposal of process proposed by the civil engineering expert to define the number of measures, their distribution on the structure, the planning. It adds the cores number and additional information obtained by NDT. This protocol follows four general steps:

Step 1: Measure. They consist in measuring observables based on techniques selected by the expert. They are selected from the 22 observables in the following list (table 1)

Technique	N°	Code	Observable
Ultrasounds	1	US-moy	Mean Surface Wave Group velocity (m/s)
Ultrasounds	2	US-ap	Surface Wave apparent velocity (m/s)
Ultrasounds	3	US-1cm	Surface Wave velocity 1 cm (m/s)
Ultrasounds	4	US-3cm	Surface Wave velocity 3 cm (m/s)
Ultrasounds	5	UP-250	Transmitted Pressure Wave velocity (m/s), 250 kHz
Ultrasounds	6	US-at	Mean Surface wave attenuation (dB/m)
Impact Echo	7	IE-Edyn	Impact Echo, Young dynamic modulus (Gpa)
Impact Echo	8	IE-VP	Impact Echo, Pressure Wave velocity (m/s)
Capacity	9	Ca-gel	Large electrode capacity, Permittivity
Capacity	10	Ca-mel	mean electrode capacity = Permittivity
Resistivity	11	Re-5cm	Quadrupole resistivity 5 cm
Resistivity	12	Re-10cm	Quadrupole resistivity 10 cm
Resistivity	13	Re-We5	Wenner resistivity 5cm
Radar	14	Ra-ampl	Peak to peak amplitude
Radar	15	Ra-VTo	Radar velocity direct wave (cm/s)
Radar	16	Ra-VNa	Radar velocity direct wave (cm/s)
Radar	17	Ra-te15	Arrival time, offset 14,7 cm
Ultrasounds	18	US 3cm L	Surface Wave, velocity 3 cm (m/s)
Test Hammer	19	RH	Rebound Hammer (number of rebounds)
Ultrasounds	20	US Pundit	Wave velocity (m/s)
Ultrasounds	21	US 3,5cm L	Surface Wave, velocity 3,5 cm (m/s)
Ultrasounds	22	UPEVs	Ultrasounds Pulse Echo, Shear wave velocity (m/s)

Table 1: Definition of the 22 observables measured in the project ACDC

These observables are chosen by configurations of 3, 4 or 5 selected with the analysis of their sensitivity to NDT measurement errors [7].

Each observable is measured according to a protocol written in the recommendations book included in the project report [6].

The experts define an experimental plan to optimize the implementation of auscultation areas and to planning the tests. The plan, the list of observables and the physical conditions to access the measure areas constitute the starting point for the organization of the site. It must respect the phases for pre-visits and reinforcement plan determination, the temporal delay of interventions of all analyser's teams and the protocols for determining each observable.
Two possible steps are proposed to the owner according to its specifications:

A pre-auscultation performed by techniques with a high performance and with a wide gird of measurements. A first qualitative exploitation of the results can be used to define zoning. It allows selecting the most apparently contrasting areas in terms of indicators.
A second step is then defined. A set of new and more accurate non-destructive measurements is proposed. The cores will be made for the destructive evaluation indicators in the areas identified previously. It is possible to optimise the number of cores and of NDE points [8]. It is based on a geostatistical analysis of the data through the establishment of variograms determining the correlation lengths for each observable.

Step 2 : NDE interpretation
The results are presented as a cartography which qualitative values. The observables are evaluated by the variances of the repeatability (V1), the variances of reproducibility (V2) [9] and by the variances associated with the variability of the measures on all of the structure. It is deduced their ability to extract a significant information from the measurement noise [2].

In our case with multiple observables, a quality estimators (EQ) [7] allows quantifying the quality and reliability of the indicator evaluation. This estimator is based on the morphology of the possibilities surface produced by data fusion and more specifically on the emergence of the peak solution as shown by "hs" in figure 2.

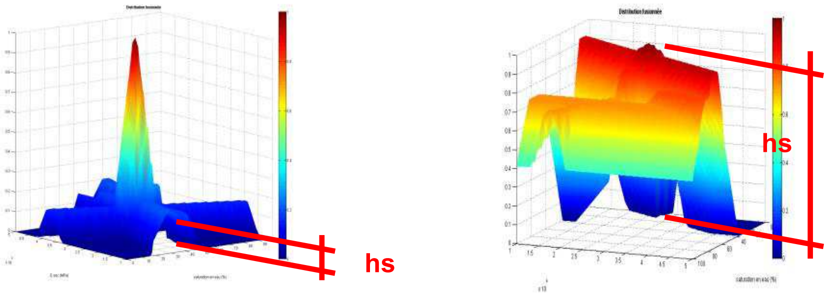

Figure 2: Fusion of the three distributions of three observables in the space with 2 indicators
a) coherent distributions b) non coherent distributions

Quality assessment is associated with the consistency of the information obtained from the observables and not of the absolute value of the indicator. The smaller the hs, the more important the estimator, the better the quality and the more reliable the information. This EQ is evaluated for each point and is averaged to give the quality of inversion on a specific structure zone with a configuration of observables.

In the case of a pre auscultation performed first, a detailed auscultation is then implemented in the process and then supplies a new database of NDE.

Step 3 : Coring
The location of coring is decided according to four criteria: mapping measures from the pre-auscultation or auscultation, accessibility areas to core, the budget allocated by the owner and the range of uncertainty given to assessment indicators. After sampling, the cores are conditioned to be conserved in the same conditions up to be tested in laboratory.

Step 4 : Indicators Quantification

At this stage, we have at our disposal estimated values of indicators with inversion procedures of combined NDE data. We use "target or references' values" to readjust the correlation. They are the results of Destructive Testing (DT). The objective of this step is to match the two sets of data (NDE inverted and DT) after ensuring the consistency of the NDE results by DT for all the evaluated points. The initial correlation laws are either replaced by new laws determined on the basis of laboratory samples made on the structure [5] or readjusted by correcting coefficients of equations (1) on the targeted values.

In this paper, we deal only with three procedures described below with three steps.

A first step matches the average value of the indicators issued from the inversion of the NDE measurements with the average obtained by destructive testing (Figure 3).

This process is called readjustment by the mean value (Senso MV). It consists in varying only the coefficient a_k of the equation 1 that has been determined in the Senso project.

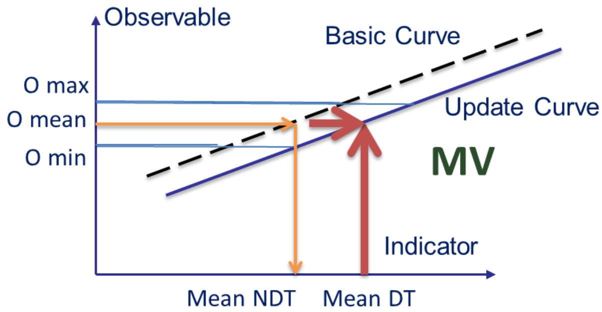

Figure 3: Principle of readjustment by the entries on the mean value MV of Destructive Testing.

A second step consists to make the best convergence of the inversion results and this simultaneously for all the points evaluated by NDT. For this, we vary the coefficients a_k and b_k^j of equation 1 from the Senso project. So, we optimize a cost function (2) to ensure the convergence of possibility distributions in the indicators plans I_1 et I_2.

$$J\left[\left(a_k, b_k^j\right)_{1\le k\le m}^{1\le j\le p}\right] = \sum_{i=1}^{q}\left(1 - EQ_i\left[\left(a_k, b_k^j\right)_{1\le k\le m}^{1\le j\le p}\right]\right)^2 \qquad (2)$$

Figure 4 a shows this operation called readjustment by coherence (Senso COH) for 4 point with NDE and 3 with DT.

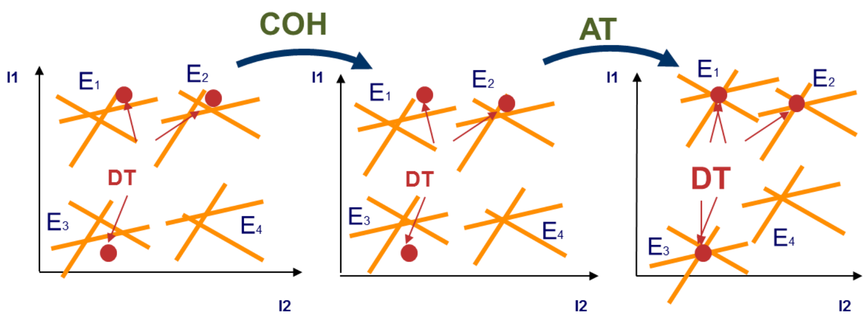

Figure 4: Readjustment by the output: 1st NDE interpretation COH, 2nd indicators evaluation AT

The third step consists after the MV or/and COH steps to adjust the coefficients of the correlation in order to match the two sets of data (NDE inverted and DT) only for the points that carried out the two types of evaluation. This operation shown in Figure 4 b is called affine transformation (AT).

In our applications, we implement the three procedures:
Senso VM   Senso VM+AT   Senso COH+AT.

2 ON SITE APPLICATION

We only present the on-site application developed in the north of the France. The structure is a motorway bridge located in Marly (figure 5a). The selected indicators are those studied in SENSO and we are estimating only two of them at the same time using the data fusion process. In In order to obtain the largest contrast for these indicators, two pillars of the bridge are selected because of their exposure to different weather conditions (wind, sun and rain).

We have organized the work in two steps. The first corresponds to the prior auscultation on the basis of a measurement pattern applied to a large surface (figure 5b) using high efficiency NDT (radar, ultrasound, impact echo, capacity). From the results of rapid techniques, we have selected 6 measurement zones leading to the definition of 6 evaluations. The second step corresponds with all the techniques to a methodical auscultation of the 6 zones selected during prior auscultation and displaying significant observable gaps. We have made NDT measurements on 50 points and 20 cores that are sampled on these zones so as to determine the reference values of the indicators. 7 cores are selected to be the references values of the indicators and to carry out the readjustment.

Figure 5 : On site test and example of identification of the measurement zones
a) Structure   b) Prior auscultation pattern   c) Auscultation zones

We have developed the following procedure:

- Visual identification of the most different pillars, definition of surfaces to be auscultated 2*2m²
- Generation of the prior auscultation pattern with 16 points (figure 5 b)
- Auscultation by rapid techniques (Impact Echo, Radar, Peak to peak amplitude radar, Ultrasound transmission, Resistivity, Capacity)
- Fusion and comparative cartography
- Identification of the 6 measurement zones. Parallel auscultation of all the teams
- Generation of the auscultation pattern with 50 points (figure 5c))
- Coring on the zones identified during prior auscultation
- Implementation and comparison of the two readjustment procedure

The tests have been realized over a week's time in the presence of all the partners according to the pre-established protocols.

3 RESULTS

Our goal is to evaluate the ability of the different procedures to estimate indicators. We have selected a configuration of 4 observables (UP-250, Ca-gel IE-Edyn, Ra-ANS).

We define evaluation criteria:

Criterion 1: The capacity of an inversion method to retrieve the values of the indicators obtained by destructive testing. For the bridge of Marly, we got 7 points leading to DT. Figure 6 shows that all three procedures are able of finding the 7 reference values of the indicators.

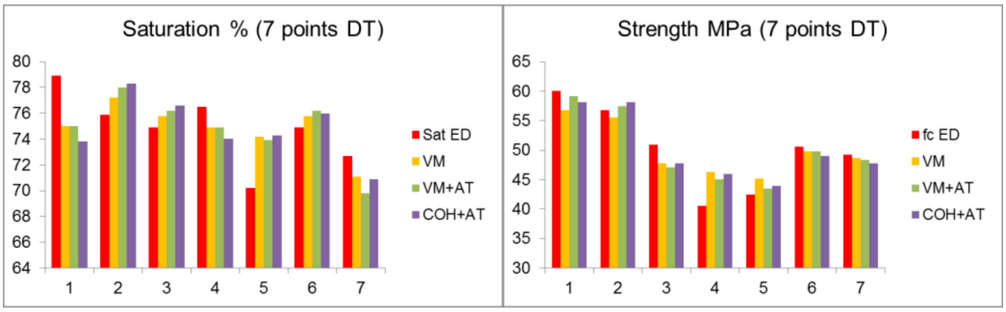

Figure 6 : Comparison of indicators evaluations by inversion and by DT for the 7 points
a) saturation b) strength

The differences between the results of the procedures are not important. Resistance is particularly well predicted and we are able to give the indicator for each point. Saturation is less because of its low amplitude variation between the maximum and minimum values of DT which is close to measurement uncertainties of DT (figure 6a and 6b).

Criterion 2: The quality of the inversion results that is measured by the mean DT from the 50 inverted points. The results of the three procedures are identical.

Criterion 3: The indicator values after inversion of the 50 points and their distribution within ± 1.5 standard deviation as shown in Figure 7a (saturation) and 7b (strength). The three procedures give very similar results.

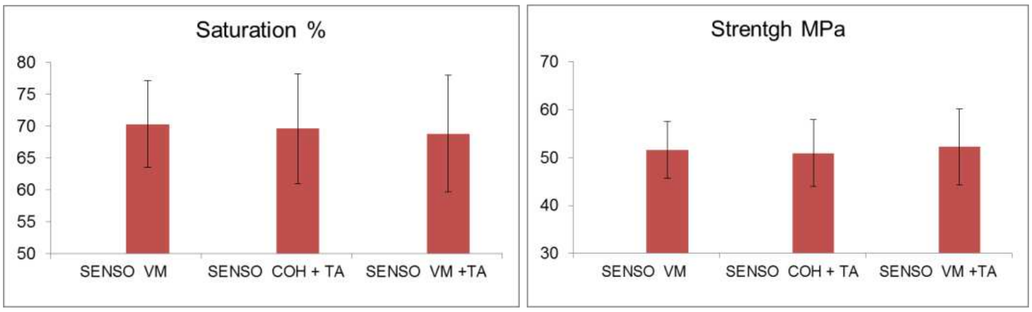

Figure 7 : Comparison of indicators evaluations from NDE and their variations amplitude (± 1.5 σ) for the 50 points. a) Saturation b) Strength

Criterion 4: The distribution of EQ following three classes of quality: EQ> 0.5; 0.5> EQ> 0.2 and 0.2 > EQ. In the latter area are the cases whose assessment by inversion is characterized by a poor quality. They are outliers because the NDE are probably false. They have to be deleted from this data of the outputs or reconsider them in a new experimental plan.

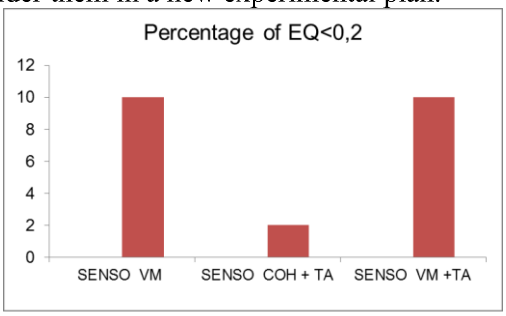

Fig 7: Percentage of EQ <0,2 for the three tested procedures.

This criterion is quite discriminating for the procedures. The percentage of outliers is actually lower in the case of the Senso COH + AT procedure. This is in agreement with the principle of the calculation that optimizes the coherence.

4 CONCLUSIONS

The ACDC project was finished in March 2014. We managed to propose a procedure to readjust correlation laws that characterize the evolution of the observables as a function of the indicators. Corrections are made in order to refocus the variations of the indicators obtained by inversion on the mean values of the indicators measured by DT. A second way is to optimize simultaneously the consistency of the results of all the points with the inverted NDE. Based on the principle of the data fusion and the possibilities theory we have developed a quality estimator issued from the fusion. We have presented in this paper the three procedures that we selected to evaluate the indicators. The most relevant criterion to evaluate these procedures is the percentage of points with a low EQ. The most relevant procedure consists in readjustment of the correlation of Senso with their consistency and after to apply an affine transformation. However, it is expensive in computation time.

The general approach that we defined in the recommendations produced during the project is to make a readjustment with the Senso correlations by the MV + AT. It is inexpensive. If the result shows a significant percentage of bad QE, in the second step the procedure (Senso COH + AT) should be applied to optimize the consistency.

These procedures are applied with success to evaluate the indicators strength, saturation and porosity. The first development of this approach is to adapt it to the case of other indicators such as carbonation. The second is the study of uncertainties linked to the errors included in the process attached to NDE, correlation laws and output. The latter are supposed references values but have large uncertainties of evaluation by Destructive Testing.

ACKNOWLEDGES

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