Improvement of Civil Works Health Management : EDF's Global Strategy and major advances between 2008 and 2013

Pierre Stephan, Jean Salin, Erwan Galenne

IMPROVEMENT OF CIVIL WORKS HEALTH MANAGEMENT : EDF'S GLOBAL STRATEGY AND MAJOR ADVANCES BETWEEN 2008 AND 2013

Pierre Stéphan[1], Jean Salin[1], Erwan Galenne[2]

[1] *EDF R&D, 6 quai Watier, BP 49, 78401 Chatou, France*
[2] *EDF R&D, 1 avenue du Général de Gaulle, BP 408, 92141 Clamart, France*

Pierre.stephan@edf.fr, jean.salin@edf.fr, erwan.galenne@edf.fr

ABSTRACT

EDF owns different types of civil works : some are of classical design (office buildings for example) and others are of particular design (reactor containment, cooling towers, dams..). In order to improve the monitoring of each of these structures, EDF R&D takes part in many national and international projects. This article sums up the major results obtained in these projects since 2008.

KEYWORDS : *Structural Health Monitoring, Civil Works, Strategy.*

INTRODUCTION

Nowadays many civil works owners begin to realize that their structures age and come close to their theoretical initial operation lifetime (and some have already over exceeded it). Their replacement, thought at their construction, won't be easy due to its huge cost especially. Today owners prefer to extend structures lifetime in order to better prepare their inevitable replacement. However these extends of lifetime operation must be justified towards the authorities. Those are two reasons among others why Structural Health Monitoring (SHM) strongly develops for concrete structures since more than 10 years.

Researches on SHM lead to several guides [1, 2, 3, 4, 12, 16, 17, 18, 19, 24] focusing on how to manage its concrete structures. Many recommendations are written but no one gives really complete procedures and associated reliable means (for monitoring, numerical simulation, decision making) to recalculate the remaining lifetime of an aged civil work. Some questions are still not solved, about NDT (reliable inspection techniques and associated procedures are rare for concrete, unlike for metallic materials … [5]), diagnosis and decision making (help for decision making to repair or not, how to rank buildings in a maintenance program…) prognosis (degradation laws...).

Moreover, certain structures owners like EDF face other problems. Containment buildings, cooling towers, dams, water intake tunnels, dikes, auxiliary buildings (such structures also owned by other Energy producers) have all :

- Different designs : for instance, dams are large civil works submitted among all to static water pressure and hard weather conditions (temperature gradient, sunshine,…). Water intake tunnels are very long steel/concrete galleries (several kilometers) of various diameters (sometimes of several meters) submitted to water flow (so erosion), landslides, and siltation. So different designs also mean different and specific inspections difficulties to face.
- Different operation and environmental conditions : cooling towers are high, very thin (up to only 20cm thick) and always humid inside civil works. Auxiliary buildings have obviously not these operation conditions. So various operation and environmental conditions also mean different ageing conditions and various favored ageing mechanisms (leaching, corrosion…).

- Sometimes different roles to ensure : for all of its civil works, EDF has obviously to ensure their good mechanical strength. To this must be added a tightness role for the containment buildings for instance.

As it can be observed, EDF must face classic ageing phenomena (corrosion for example, ageing mechanism which could be encountered on all reinforced concrete buildings around the world), but on civil works which designs are very often unique and so very specific. Anyway, in order to ensure the good operation and mechanical strength of its structures, EDF has had to put in place a strategy to improve its skills in terms of civil works management and monitoring.

1 CIVIL WORKS LIFE CYCLE MANAGEMENT FLOWCHART PROPOSED BY EDF R&D

EDF R&D formalized its civil work lifetime management as shown in Figure 1: End User Life Cycle management flowchart. This flowchart exposes how EDF has to proceed to monitor the health of its concrete structures. It starts with the collection of all documents relative to the structures' history. Technical plans (before and, overall, after construction, if changes occurred, if possible), data about previous repairs, operation data and external events are documents which help to establish an initial mechanical state of the structure, as accurate as possible. Once done, an inspection program (which consists of in-service inspections and online monitoring) will help to estimate the current mechanical state of the structure. This will be done thanks to :

- The collection of the structure's visible damages : it means cracks, corrosion, swelling, settlement... This will form the real current state of the structure.
- The re-evaluation of the structure's materials properties : as materials age, their properties (mechanical strength, …) change. So it is necessary to find these changes in order to re-estimate the current structure's state and behavior (current residual operation lifetime) through actualized numerical calculations.

Thanks to inspections' results of the structure and numerical simulations conclusions, a diagnosis can be carried out, followed by a structural prognosis : it aims at predicting the risks of collapse and so an estimation of the remaining structural lifetime.
This helps the structure's owner or operator to take a decision about the eventual repair of the structure and optimize maintenance actions. Once this decision taken, the knowledge of the structure must be updated to allow the future inspections to be the most efficient possible.
This approach has already been compared to IAEA standards and SHM described in literature [6]. It was shown that EDF R&D structure's management flowchart is totally in coherence with the best practices in the world [40] and even anticipates IAEA recommendations.
Although this flowchart shows the steps to manage the life cycle of a structure, its on-site application is not easy. As written in [5, 20, 25], ND techniques for concrete are essential for civil works inspection (only few carrots can be sampled and so the real representativeness of destructive tests is not known) but get behind on ND techniques used for metallic components. So many problems must be solved. Among all :

- The need to improve ND techniques : better understanding of them (inspected volume), increasing of their performance (depth, resolution..). Works have already been carried out on the ranking of reinforced concrete's ageing pathologies to guide studies on non destructive techniques improvements, for instance in [27],
- The need to understand the measurements carried out : different techniques allow to find the same material parameter. However, they don't often give near final results today.
- The need for procedures to apply NDT… and for staff training and qualification.
- The need to better know concrete (gradient of properties…) and its degradations mechanisms (corrosion, leaching, carbonation…).
- The need of improvement in material science : materials general knowledge and steel and concrete ageing models have to be improved

- The need of numerical simulation at structure's scale, all ageing phenomena being taken into account [26].

These problems are encountered worldwide [3]. And so, to help the achievement of its flowchart steps, EDF R&D set up the strategy explained in the following paragraph.

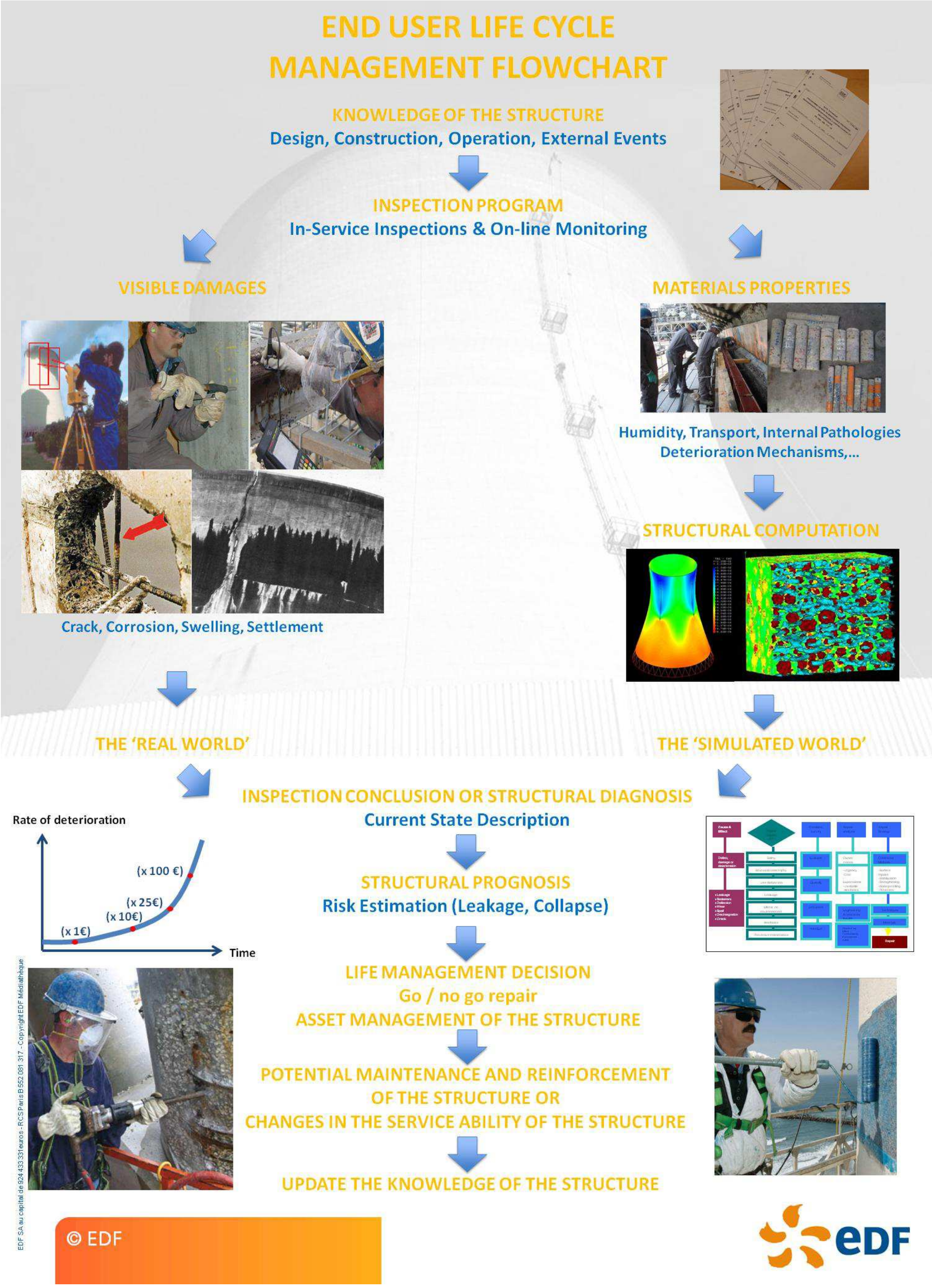

Figure 1: End User Life Cycle management flowchart

2 EDF R&D'S GLOBAL APPROACH

The EDF's double problematic (common ageing mechanisms but specific building designs and operation conditions) has imposed to EDF a particular approach in order to be as efficient as possible in the continuous improvement of the monitoring of its civil works.

Erreur ! Source du renvoi introuvable. illustrates that strategy : EDF has entrusted the care of its different families of civil works to different EDF's Engineering entities. For instance, EDF CNEPE and SEPTEN of cooling towers, CIPN of auxiliary buildings, EDF CIH of dams and hydraulic structures.

Studies about these buildings can be coarsely subdivided into 4 topics: materials, structure, non destructive examination, risks analysis. For each of these topics are associated different EDF technical entities (R&D / CEIDRE / DTG) for studies about materials (mechanical characterization or simulation), structure, NDE, and risks analysis studies.

Nowadays it is rare to find companies developing inspection techniques from laboratories to on-site use. So, in order to continually improve its knowledge about the monitoring and inspection of its structures, EDF R&D decided to take part in :

- French national projects : EDF R&D works with academic and industrial partners on common issues (material, models, damages, Non Destructive techniques, Risk Based Analysis) for all types of civil works. Concerning the monitoring of structures, it started with ANR SENSO in 2006, followed by RGC&U ACDC, to work on the re-evaluation of the materials mechanical properties (tests on specimens). In the same time, EDF took part in ANR APPLET (2007-2010) which took care of civil work diagnosis from on-site measurements and predictive models. ANR EVADEOS continues working on APPLET, SENSO and ACDC's topics but adds parts on risks analysis, lifetime prognosis and decision making (about repair or not of concrete structures [21, 22]). A detailed abstract of the content, conclusions and contributions of all of these projects will be given later in this article. The future national project GEDI will allow the concatenation of all the contributions of these previous national projects and deliver a global strategy for structural health monitoring. As it can be observed in Figure 1: End User Life Cycle management flowchart, all these projects can be integrated to the Civil work management flowchart that EDF R&D proposes.
- International projects regrouping other power plants owners. These projects aim to work on common issues encountered in their specific structures : in the nuclear domain for example, EDF R&D worked in an European Project named ACCEPPT on issues specific to Reactors Containments (localization of damages leading to potential leaks, numerical simulation of RC…). EDF works with the Cooling Tower Institute (CTI) to share research results about cooling towers. EDF also collaborates with EPRI about other research topics specific to electricity producers.

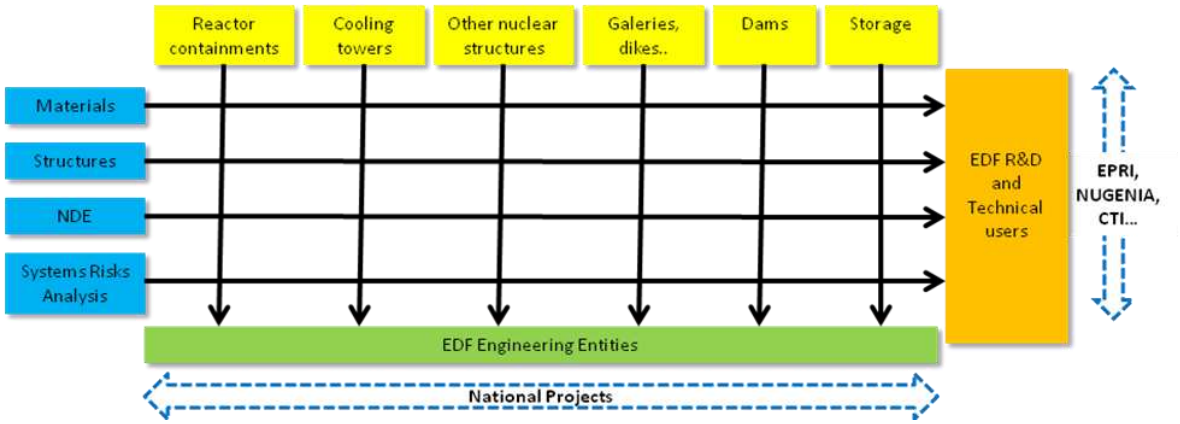

Figure 2: Double approach strategy set up by EDF for civil works ageing management

3 MAIN RESULTS OBTAINED BETWEEN 2008 AND 2014

3.1 Establishment of a civil work life cycle management flowchart applicable by owners

As it was shown in the previous paragraph, EDF R&D participates to several national and international projects in order to continuously improve its knowledge on the monitoring of structures.

For EDF it started with the ANR SENSO [7, 23] project in 2006. SENSO aims at finding reliable indicators for determining the damage level of a structure. This would help for their initial dimensioning or for their re-calculation after inspections (so for diagnosis and prognosis).

SENSO consists in a large experimental campaign (in labs) mixing destructive and non destructive tests on several different concrete specimens. For instance, concrete parameters as porosity (e/c from 13 to 18%), type of aggregates and saturation (from 30 to 100%) varied in the concrete specimens. Some concrete carrots from an industrial site were also sampled. Many ND techniques were assessed to determine concrete characteristics (porosity, Young's modulus, water content) : resistivity, surface waves (US), compression wave, radar (GPR), Rebound Hammer and capacitive techniques. For assessing and adjusting non destructive tests results, destructive tests were carried out (porosity, Young's modulus, Compression strength, carbonation depth, Chlorides content). All results were gathered in a large database. As different tests can provide the same material parameter, they were then used in a data fusion software (developed during the project) to find the most reliable values of these parameters.

In addition to the synergy between researchers from different profession (NDT, modeling, structures owners, data treatment,..), the main important results were the following :

- From an experimental point of view, it was shown that :
    - Reinforcement of concrete has a great influence on the measurement : a minimal distance from rebar to NDT has to be respected to find reliable values.
    - Concrete surface roughness influences the measurement : the best results (signal/noise ratio) were obtained from concrete poured in wooden formwork, and not in plastic formwork as it could have been thought,
    - Aggregates types play an important role in the Young's modulus of concrete. Water content greatly influences concrete resistivity,
    - Storage conditions of concrete specimens may have an influence on measurements.
    - Non Destructive techniques need to be improved and their characteristics (Elementary inspected volume for instance) better known.
    - Procedures for in-situ Non destructive Evaluation have to be written down,
    - Correlation between NDE outputs and materials characteristics must be generalized.

- From a numerical point of view :
  - The data fusion software was tested from results obtained in lab's experiments and from on-site experiments. The data fusion procedure was assessed only for results obtained in labs.

As it can be observed, many questions stay unsolved at the end of SENSO : data fusion was not operational and NDT needs improvements, especially in the significance of the measurement domain. The elementary inspected volume for each ND technique had to be precised for a better comparison between experimental results.

That is why a new project called C2D2 ACDC [8, 36, 37, 38] started in 2010. It finalized the transfer of ND techniques use from laboratories to on-site. It allowed to obtain 4 reliable indicators in a homogeneous concrete : saturation, Young's modulus, compression strength and porosity. In fact :

- A complete methodology was proposed for the inspection of industrial civil works. It consists of an inspection in 2 steps :
  - A pre-inspection to determine probably damaged zones on the structure. Four ND techniques are advised for this job : Impact Echo, resistive and capacitive methods and sclerometer. The procedure to use these techniques, their efficiency (in m^2/h), cost, sources of error and data processing time are also given.
  - An inspection of the previously localized zones by destructive and non destructive techniques. Rebound Hammer, US, GPR and sclerometer can be used to obtain saturation state, Young's modulus, compression strength and porosity. The different steps to carry out this inspection are detailed : the localization of steel rebars, the planning of inspections and the procedures to follow for each inspection mean. In fact it is advised to use several inspection means (but not too much) of different physical principles (electromagnetic, US, …) for a reliable determination of a material parameter. Destructive methods must then be used to adjust the results (saturation, Young's modulus, compression strength and porosity) obtained by NDT. The corresponding specimens are carrots extracted from positions where extreme values of material parameters have been localized during ND Examination.
- The data fusion software has been improved since SENSO and assessed for in-situ measurements. New correlation laws have been implemented and an adjustment between destructive tests in labs and NDE in situ is available.

All these new main results have been gathered in recommendations for civil work owners.

In parallel, in 2007, the ANR APPLET project [9] started and aimed at working on concrete structure lifetime by an approach based on prediction, performance and probabilities. More precisely, it consisted, on one hand, in a large experimental work (in laboratories and on site) on degradation phenomena of reinforced concrete. It means especially corrosion (general knowledge, influence of cracking, interface concrete/steel rebar strength, corrosion rate), accelerated carbonation (carbonation depth), and leaching (depth). It aimed also at assessing different measurement procedures for corrosion rate (potential method, polarization resistance based method), concrete resistivity and porosity. All the experimental results were also collected in a database available for every project members.

This leads to many important results :

- On measurement methods, it was shown that concrete resistivity is a relevant parameter for quantifying concrete variability. However, there is no norm about how to measure this parameter. Moreover, resistivity is highly influenced by concrete water content i.e the quantity of water used to humidify the concrete surface is of great importance. Then it is concluded that a potential measurement allows giving a probability of corrosion but can't quantify it. Potential measurements are also influenced by humidity and temperature. Finally polarization resistance based method by commercial devices (Gecor, Galvapulse) to assess corrosion rate raises many questions on their main hypothesis, the polarized surface.

- On the knowledge about corrosion of reinforced concrete : it was shown that corrosion products in a reinforced concrete structure lead to traction forces in concrete and so cracks initiations. Cracks on concrete surface also facilitate corrosion initiation. It is noted that corrosion also reduces the adhesion strength between steel rebar and concrete. Finally, it seems that corrosion rate is not the same all around a corroded rebar in a concrete media.
- On inspection procedures : Different procedures for accelerated carbonation and porosity measurement have been compared and improved. On site tests' experience feedback shows the need for rebar dimension and localization before starting any concrete characteristic measurement.

On the other hand, APPLET project provided many results on and for numerical models. First, thanks to experimental results, statistical distribution laws for every measured parameters (compression strength, permeability, resistivity, traction resistance, Poisson modulus…) were determined. That allows the consideration of the variability of structures' local characteristics, uncertainties linked to ongoing phenomena and measurement errors. Then probabilistic dimensioning models were proposed for chlorides penetration (Deby [34]) and carbonation (Hyvert et al. [35]). Models for concrete cracking due to corrosion were also developed and predictive models of reinforced concrete degradation were improved.
Although all these numerous significant advances, many questions remained unsolved :

- On measurement methods :
    - Concrete resistivity : no norm existed for its measurement. Moreover, this parameter is strongly linked to concrete water content so procedures should take into account the surface humidification.
    - Corrosion rate : Gecor and Galvapulse assume a certain surface polarized on rebar. However, the calculation of this surface asks questions. Moreover, the corrosion rate calculation needs the knowledge of concrete resistivity and rebars localization.
- On structure's diagnosis :
    - Electrochemical measurements do not allow distinguishing corrosion initiation and propagation,
    - The concrete structure lifetime assessment has not been studied (strength of a corroded concrete structure ?).
- On numerical models :
    - Probabilistic dimensioning models and concrete degradation models are too complex (too many parameters to take into account for instance) to be used in engineering structures or by structures owners.

To sum up, SENSO, ACDC and APPLET projects permit to reach several objectives :

- The understanding the significance of the measurements carried out by different ND techniques (US [30], EM [39], Fiber optics [15, 19]..) : the elementary inspected volume of each NDT and the influence of several parameters (distance from steel rebars..) have been determined.
- The realization of a reliable measurement on-site, on a homogeneous concrete : it includes a methodology and a data fusion procedure,
- The better understanding of concrete degradations, more particularly corrosion (carbonation or chlorides based) and estimating of their influence on concrete strength at lab's scale by modeling them.

However, for a structure owner, these results are not enough to know when he will have to plan maintenance on its structures. In fact, no model is proposed to give the structure mechanical strength at the time of the inspection.
That is why the ANR EVADEOS [10] project was launched in 2011 (and is still ongoing). Its aim is to propose a methodology for concrete civil work management (SHM). It will include the structure's assessment and diagnosis phases, and a decisions making tool (Is maintenance necessary

today for my structure ?). This project focuses only on corrosion. In order to reach these new goals, ANR EVADEOS proposes :

- An experimental part, in labs and in two industrial sites :
  - To improve a technique for determining corrosion rate of steel rebars (following concrete carbonation) : the resistance polarization method has been improved [28]. A new probe has been developed, reducing the polarized zone to a point on a steel rebar (and not a surface, which causes discussions in APPLET for Gecor and Galvapulse). A methodology for applying it on site has been proposed and validated.
  - To study the influence of material properties gradient, here porosity. In ACDC, concrete was always homogeneous.
  - To study the spatial, temporal and climatic variabilities, and so improve the data fusion software developed in SENSO and ACDC.
- A numerical part :
  - To synthesize and benchmark models for initiation and/or propagation of corrosion : a distinction between engineering models and complex models is done. The best models will be used for the diagnosis and prognosis of concrete structure's health.
  - To develop a decisions making tool for structures owners.

As ANR EVADEOS is still ongoing, all results can't be presented in this article. It is hoped that it will lead to a detailed civil work management methodology and so to tools usable by engineering companies and structures' owners.

In the near future, a national project named GEDI [11] will start to finalize the work done in SENSO, ACDC, APPLET and EVADEOS. It will indeed focus on the policy of sustainable management of concrete structures (establishment, implementation), decisions making, repair, experience feedback capitalization and staff training, at two scales : a structure alone, and a fleet of civil works (prioritization of actions on structures especially, as done for cooling towers in [14]). The expected issues are :

- A database on civil works damages,
- Guidelines and software on civil works management,
- Staff skills and Training standards.

So we can conclude that industrial procedures and methods for managing and monitoring of concrete infrastructures are nowadays on the way. National projects allow advances that a company can't do easily alone, that is to say :

- mixing people from different professions and workplaces (academics, engineering companies, structures owners and operators) to meet, exchange and work together to the same goal, a better and sustainable management of concrete infrastructures.
- Adopting a civil work management methodology approved by a large community of concrete structures owners,
- Having more easily a larger national and international credibility.

Even if many progresses have been made, the way to a sustainable management of concrete infrastructures is still long. It is indeed necessary to communicate about the recent advances and so enlarge the number of users adopting them. The national project GEDI aims to do it.

4 WORKS ON COMMON ISSUES ENCOUNTERED IN EDF'S SPECIFIC STRUCTURES

As it has been written previously (see **Erreur ! Source du renvoi introuvable.**), EDF R&D also works with other power plants owners in order to solve problems or degradations specific to this type of structures.

For instance, containment buildings are designed to :

- Resist to several aggressions, natural ones (wind, humidity, ageing..) but also terrorist ones (plane's crash for example),
- Assure a minimum leak rate in case of nuclear accident. A specific test is carried out every 10 years in order to check this leak rate.

This last characteristic is specific to nuclear power plants owners. That is why companies in this domain regroup in international projects to work on problems encountered on this type of building. For containment reactor, EDF takes part to the European project named ACCEPPT which is still ongoing. This project has been mounted thanks to NUGENIA's association [33] which is dedicated to R&D nuclear fission technologies (with a focus on Gen II and II technologies). This project gathers European nuclear power plants owners, engineering companies and universities on the improvement of the containment reactors (designed with steel liners) monitoring (NDT for liner's cracks detection, liner blistering during loss of coolant accident, containment reactor ageing models and simulation..). In this field, specific tests, bibliographic studies and numerical simulation have been carried out.
Concerning cooling towers monitoring, EDF R&D is interested in studies made by the VGB. For example, in [12], one can find instructions for the management of cooling towers (recommendations on maintenance, repairs, monitoring, dismantling and associated documentation).
As a last example, EDF collaborates with EPRI and ICOLD (specific for large dams) to share studies about all concerning electricity production.

5 CONCLUSIONS AND FUTURE WORK

This article sums up the EDF R&D strategy to improve its concrete structures health monitoring and carry out the related inspections. For problems common to every concrete structures owners, EDF R&D collaborates with academic and industrial partners in national projects. For issues specific to power plants owners, EDF R&D works with other power plants owner in international projects. Feedback experiences from these projects show that :

- Concerning ND techniques, it is necessary to work on the significance of the measurement : understanding the physics of the inspection mean is of primary importance. This point is also highlighted in [3, 13, 15].
- National and international projects allow people from different professions and workplaces to discuss and work together. It creates a synergy which leads to important and concrete results. This also permits to get funding and credibility that a company alone can't quickly obtain.

Thanks to these collaborations, main results have been reached :

- Some ND techniques have been transferred from labs to site : procedures to carry out on-site measurements have been written down. Works on this subject continue in the new national project ANR ENDE which will help other non destructive techniques to be transferred from labs to site thanks to large structures mock-ups (PACE [31] and VERCORS[32])
- A better understanding of concrete degradations and consequences,
- Large databases have been created,
- Concrete degradation modeling (corrosion especially) has been improved. It will be soon (at the end of EVADEOS) possible to recalculate the mechanical strength of a corroded structure (prognosis).

Other results are expected after EVADEOS, as a decision making and prognosis tool for instance. Then the national project GEDI will start and finalize the work done in SENSO, ACDC, APPLET and EVADEOS. Studies on the policy of sustainable management of concrete structures (establishment, implementation), decisions making, experience feedback capitalization and staff

training, at two scales (a structure alone, and a fleet of civil works (prioritization of actions on structures especially)) will begin.
A last important point is that a large communication and lobbying will then be necessary to share the results (methodologies, significance of the measurement of every non destructive techniques used) of these projects.

6 REFERENCES

[1] N.R. Buenfeld, R.D. Davies, Hassan A. Karimi, CIRIA Guide*: Intelligent Monitoring of Concrete Structures* - CIRIA S. C661 (Paperback), 2008
[2]Advanced surveillance, diagnostic and prognostic techniques in monitoring structures, systems and components in nuclear power plants, *IAEA Nuclear Energy Series n° NP-T-3.14*, 2013
[3] JB Coble et al., Prognostics and Health Management in Nuclear Power Plants: A Review of Technologies and Applications*, PNNL-21515*, US DOE, July 2012
[4] Rücker W. et al., F08b : *Guideline for Structural Health Monitoring,* SAMCO Final Report 2006
[5] Salin J, COFREND's Civil Engineering sector revives?, *La lettre d'information des professionnels des contrôles non destructifs*, Septembre 2013, n°6, p. 8-9
[6] Stephan P, Salin J, Ageing management of concrete structure: Assessment of EDF methodology in comparison with SHM and AIEA guides. *Construction & Building Materials* (2012), Vol. 37, pp 924-933
[7] Rapport final du projet SENSO, septembre 2009, http://www-lmdc.insa-toulouse.fr/SENSO/EspPartSENSO/Documents-SENSO/Memoire-SENSO.pdf
[8]Rapport final du projet RGCU C2D2 ACDC, 2014, to be published
[9] Rapport final du projet APPLET, 2010, http://or.lcpc.fr/applet/__DEPOT/pgcu06_applet_rapport_final_241110_v2.pdf
[10] Projet EVADEOS, 2011, http://www-lmdc.insa-toulouse.fr/evadeos/accueilevadeos.htm
[11] GEDI, http://www.developpement-durable.gouv.fr/Projets-nationaux.html
[12] *Instruction sheet : Code of practice for lifecycle management of reinforced concrete cooling tower in power plants*, R 613e, VGB Powertech e.V, 2010, ISBN 978-3-86875-053-9
[13] H. Wiggenhauser et al., Non destructive testing of nuclear power plant concrete structures : state of art report, BAM, April 30th, 2013.
[14] Nhu-Cuong Tran et al., Cooling tower fleet ranking strategy, Proceedings of the International Association for Shell and Spatial Structures (IASS) *Symposium 2013 BEYOND THE LIMITS OF MAN",* 23-27 September, Wroclaw University of Technology, Poland, J.B. Obręebski and R. Tarczewski (eds.)
[15] J.M Hénault, Approche méthodologique pour l'évaluation des performances et de la durabilité des systèmes de mesure répartie de déformation : application à un câble à fibre optique noyé dans le béton, PhD Thesis, November 18th, 2013
[16] N. Badez, EDF Reactor Building Containment: monitoring of the pre-stressed concrete structure, *Proceedings of the OECD-NEA-CSNI : Ageing management of thick walled Concrete structures including ISI, maintenance and Repair, Instrumentation methods and safety assessement in view of LTO*, Prague, 1-3 October 2008
[17] A. Courtois, J.-M. Hénault, A. Simon, Y.-L. Beck, J. Salin, La surveillance en exploitation des enceintes de confinement et des aéroréfrigérants à tirage naturel du parc nucléaire d'EDF, *Revue Générale du Nucléaire*, n°2, p49-59, 2011/Monitoring operating containments and natural draft cooling towers of EDF's nuclear fleet, International Journal of Nuclear, No. 2, p49-59, 2011
[18] H. Stephens, Containment Inspection Program Guide Update, *ASME Section XI, Subsections IWE and IWL*, EPRI, Technical update, December 2007
[19] Nuclear Maintenance Applications Center : Guideline for cooling Tower Inspection and Maintenance, *EPRI*, Palo Alto, Ca: 2011.1021060
[20] J-L. Valfort, EDF experience with concrete ageing, IAEA - *Regional Workshop on Ageing Management Programmes Associated with Nuclear Power Plant Concrete Structures*, Husinec - Řež, Czech Republic, 19 to 21 November, 2012
[21] Beaudouin F., Meuwisse C., « Combining rank-dependent models and rule-based aggregation for experts' joint decision making », *Group Decision and Negotiation GDN 2013*, Stockholm, 17-20 June 2013

[22] Beaudouin F., Meuwisse C., «Classement de tours aéroréfrigérantes en fonction du risque global de ruine Développement et mise en oeuvre d'un système d'aide à la décision", *Proceedings of the JFMS*, Aix-en-Provence - 9-10 avril 2014
[23]G. Villain, Z. M. Sbartaï, X. Dérobert, V. Garnier, J-P. Balayssac, Durability diagnosis of a concrete structure in a tidal zone by combining NDT methods: Laboratory tests and case study, *Construction and Building Materials* 37 (2012) 893–903
[24] Guidebook of non destructive testing of concrete structures, Training course series 17, *IAEA TCS 17*, 2002, ISSN 1018–5518
[25] E. Martin, NDT for Nuclear Industry : needs and trends for the future, *Proceeding of SHMNDT*, 2013, www.ndt.net
[26] E. Galenne et al., The aim of computational methods for managing concrete structures in nuclear power plants, *EURO-C Congress*, 2014
[27] J. Busby, G. Carpenter, Extended Proactive Materials Degradation Analysis, Presentation at *Regulatory Information Conference*, Rockville MD, March 13-15, 2012
[28] M-E. Mitzithra, Detection of corrosion of reinforced concrete on cooling towers of energy production sites, PhD Thesis, October 21st, 2012
[19] Y. Siali-Mamdem, Capteurs à fibres optiques répartis par effet Brillouin : séparation de la dépendance à la température et à la déformation, PhD Thesis, October 10th, 2012
[30] A. Quiviger, Ultrasons diffus pour la caractérisation d'une fissure dans le béton. : approche linéaire et non linéaire, PhD thesis, November 11th, 2012
[31] N. Herrmann, L. Gerlach, H. Müller, Y. Le Pape, C. Bento, C. Niklasch, D. Kiefer, Experimental investigation of the crack behaviour of prestressed concrete containment walls considering the prestressing loss due to aging, *Proceedings of SMiRT* 20, 2009
[32] Galenne E., Masson B. (2012). "A new mock-up for evaluation of the mechanical and leak-tightness behaviour of NPP containment building" *Proc., CCSC 2012*, Aix-en-Provence, France
[33]NUGENIA association, http://www.nugenia.org/
[34] Deby, Fabrice. Approche probabiliste de la durée des bétons en environnement marin, PhD Thesis, March 29th, 2009
[35] N. Hyvert, Application de l'approche probabiliste à la durabilité des produits préfabriqués en béton, PhD Thesis, April 10th, 2009
[36] G. Villain et al., Comparison of durability indicators obtained by non destructive testing methods to monitor the durability of concrete structures, *Proceedings of EWSHM 2014*, Nantes, July 8th -11th 2014
[37] V. Garnier et al., Non destructive testing of concrete : transfer from laboratory to on-site measurement, *Proceedings of 7th EWSHM*, Nantes, 8-11 July 2014
[38] J. Salin et al., *Recueil des recommandations*, projet ACDC-C2D2, Journée de restitution, 21 mars 2014, Toulouse, 72p.
[39] Sbartai M., Développement d'un outil d'évaluation non destructive des bétons par ondes EM – Simulations numériques et expérimentations, *Journées COFREND*, Bordeaux, 20-22 May 2014
[40] J. Aimonino, S. Jacq, Safety-classified steel cylinder reinforced concrete pipelines: mechanism of corrosion, diagnosis and maintenance strategy, *Congrès Diagnobéton*, Toulouse, 19 et 20 mars 2014

7 ABBREVIATIONS

ANR APPLET (2007-2010): Durée de vie des ouvrages : Approche predictive, Performantielle et probabiliste (Civil works lifetime : approach focused on Prediction, probabilities and performance)
ANR SENSO (2006-2009): Stratégie d'Evaluation non destructive pour la surveillance des ouvrages en béton (Strategy of non destructive examination for the monitoring of concrete civil works)
RGC&U C2D2 ACDC (2009-2013): Analyse et capitalisation pour le diagnostic des constructions (Analysis and capitalization for the diagnosis of structures)
ANR VD EVADEOS (2011-2015) : Evaluation non destructive pour la prédiction de la dégradation des structures et l'optimisation de leur suivi (Non destructive examination for structures damages prediction and their monitoring)
PN GEDI : Gestion durable des infrastructures (Sustainable management of infrastructures)

PN IREX CEOS.fr (2008-2012) : Comportement et Evaluation des Ouvrages Spéciaux : fissuration et retrait (Behaviour and Evaluation of special civil works : cracking and shrinkage)
ENDE project (2014-2018) : Evaluation Non Destructive des Enceintes de confinement des centrales nucléaires (Non destructive assessement of Nuclear powerplants Reactor containments)
PN : Projet National (National Project)
ANR : Agence nationale de la recherche (National Research Agency)
ICOLD : International Commission on Large Dams
EPRI : Electric Power Research Institute (www.epri.com)
ACCEPPT : Ageing of Concrete and Civil structure in Nuclear Power Plants (www.nugenia.org)
RC : Reactor Containment