Digital twining to assess the performance of aging nuclear concrete containment buildings

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Abstract

Predicting the performance of nuclear concrete containment buildings in the context of extending the operational lifetime of the French nuclear power plants fleet is a major challenge for safety assessment. Indeed, the safety margins should remain satisfactory considering the aging phenomena and the appropriate regulations. To ensure an accurate risk assessment, IRSN has developed an operational approach based on three pillars in the following order: (a) the experimental analysis of complex Thermo-Hydro-Mechanical phenomena; (b) the continuous development of physically representative nonlinear laws; (c) the digital-twin-based modelling of nuclear Structures, Systems and Components. These pillars are essential to meet the needs of IRSN to assess safety within the aforementioned context. The recent advances made for each are continuously shared with scientific and technical international community. A relevant example is the ongoing editing of a guidance report on the modeling best-practices of CCBs directed by IRSN in the framework of the European H2020/ACES project with the participation of many national and international Laboratories, Operators, TSOs and Regulators. This paper gives a synthesis of the actions and the advancements IRSN has made in the recent years regarding this topic.

1. Introduction

France has a large fleet of nuclear Pressurized Water Reactors (PWR) under operations that were constructed between the early 70's and the late 90's with an initial design lifetime of 40 years. For some PWRs, this due date will be reached soon which instigated the question of a lifetime extension beyond 40 years to meet the increasing demand of electricity. This topic is of high importance for PWRs operators, for governmental strategies drafters and for public safety actors. Indeed, such extension is conditioned by satisfactory safety margins considering the aging phenomena of civil works and the appropriate Regulations.

In this paper, we focus only on the performance of Concrete Containment Buildings (CCB) which are a non-replaceable component and are the last barrier preventing the release of radioactive elements in the case of an unfortunate nuclear accident scenario. For double walled CCBs, which have no metallic liners, the tightness of the structure is naturally jeopardized over time because of several ageing phenomena. They include all chemical, thermal, hydric and mechanical state evolutions over time of the reinforced and prestressed concrete. On one hand, to monitor such performance, Integrated Leakage Rate Tests (ILRT) are performed every 10 years with a visual inspection of the damage state and a global measurement of the air leakage rate at the structural scale. It consists of monitoring the mechanical and leakage behavior of the CCB whilst increasing the inner relative pressure up to 4.2 bars. It is during those ILRTs that operators apply some coatings and injections or any other solution to enforce the tightness of the CCB. On the other hand, to anticipate such maintenance operations in a proactive way, operators should be able to predict the evolution of ageing phenomena (drying, creep, shrinkage, relaxation) and to correctly assess the damage state (prestressing losses, cracks) and the leak-tightness state of the structure during future pressure tests or severe accident scenarios. The final goal shared by operators and TSOs is to assess accurate margins based on the present state of the structure and forecast such margins to verify their sufficiency beyond 40 years.

To reach such goal, IRSN as a French TSO has contributed actively over the last years, and is still doing so, to the understanding of the physical framework of Chemo-Thermo-Hydro-Mechanical behavior of concrete at the material and structural scales. The COBRA project carried out exclusively by IRSN is a major example dealing with the realistic investigation of the tightness of 1300 MWe PWRs [1].

Once the physical framework understood (to the best extent possible), IRSN develops and implements physical models using open-source FE codes such as Cast3m [2]. These models are validated at the material and structural scales by achieving comparative analyses between blind numerical results and experimental measurements at the points of interest (temperatures, relative humidity, strains, crack openings, permeability, etc.). The gaps between numerical and experimental results are assessed and are used to quantify the confidence level in the model's predictive capacities.

A good illustration of such validation process is the contribution of IRSN to the VeRCoRs benchmark III under the umbrella of OECD-NEA [3].

Finally, all this knowledge and all those modelling tools once verified and validated [4] are used to forecast the behavior of real and full scale CCBs using digital twinning techniques with a constant updating of the model's inputs and results based on the observed evolution of concrete behavior on site. This allows IRSN, as a TSO, to update continuously the safety margins assessment under serviceability and accident conditions given the best available knowledge of the structural behavior so far. One of the latest applications deals with the assessment of the functional and seismic fragility curves of CCBs under severe accident within level 2 PSA studies.

2. Experimental investigation of Thermo-Hydro-Mechanical behavior of concrete: COBRA program

The modeling of leakage through the inner wall of 1300 MWe nuclear reactors CCBs in case of severe accident is a challenging task. In these conditions, the relative pressure and the temperature rise to 4.2 bars and around 150 C along with the dispersion of steam and aerosols in the vessel. These conditions differ from those considered during ILRTs which justifies the question of transposability of containment performance during ILRTs compared to sever accidents. In this context, the COBRA project has been designed by IRSN to study and predict the leakage and the aerosol retention through a Representative Structural Volume (RSV) of the 1300 MWe inner wall under various THM covering ILRTs and severe accident conditions. This project includes both an experimental and a simulation part. Two reinforced concrete mock-ups have been built. One was poured in a single cast whereas the other was made in two casts to study the influence of concrete construction joints on the mechanical and leakage behavior. Their geometry is inspired from dogbone samples in which the zone of interest (marked in red in **Figure 1**-left) is made of "B11" concrete (the same concrete is used in some French CCBs).

The first phase consists of creating cracks in this zone. The flanges are pushed apart by six 1500 kN actuators that induce a uniform tensile stress state. It is possible to monitor the crack opening values by adjusting the actuators load. In a second phase, an injection vessel is mounted on one side of the zone of interest (upstream side) while a gathering vessel in mounted on the other side (downstream side). Thanks to the measurement capabilities of IRSN including flowmeter, helium tacking, aerosol generators and spectrometers, the leakage ratio and the aerosols retention are assessed for increasing damage states (maximum historical imposed displacement), crack openings, relative pressures, in the absence and in the presence of steam. These experiments will provide first results and evidence regarding the representativeness of ILRT results compared to the severe accident outcomes.

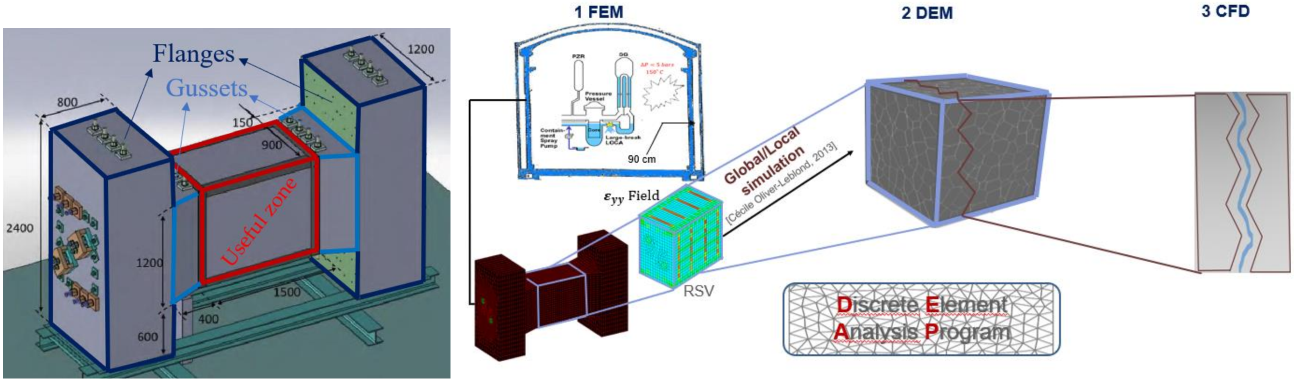


Figure 1: (left) COBRA mock-up (right) Numerical strategy for COBRA project

Based on the previous experimental results, the expected scientific advancements shall concern the experimental characterization of the concrete fracture features; including crack geometry, fluctuation of crack opening values, tortuosity and roughness [6][8][9][10] that have a non negligeable effect on the measured leakage. It will also tackle the best practice to model leakage through concrete cracks; based on the coupling of a CFD simulation with ''standard'' existing finite elements methods [12][13][14], eXtended Finite Element Methods (X-FEM) [15], with Embedded Finite Element Methods (E-FEM) [8] or with most recent approaches such as DEAP "Discrete Element Analysis Program" developed at the LMPS (Laboratoire de Mécanique de Paris-Saclay, formerly named LMT Cachan) [16][17][19] where cracks are explicitly represented. For this last option, a weak and sequential global/local coupling between a continuous damage model and the beam particle model is applied to reduce the computational time cost of the discrete simulations. Only the heavily damaged areas are re-analyzed within DEAP by extracting the displacements from the FEM simulation at the boundary of local area simulated in DEAP.

The obtained cracking pattern is then post-processed and imported in a CFD software (Ansys CFX). This numerical strategy is summarized in in Figure 1-right. This FEM/DEM/CFD simulation chain will eventually be calibrated on the experiments to develop a predictive tool for the assessment of air leakage though cracked walls. Its development is carried out as a part of a collaborative Ph.D. thesis between IRSN and LMPS.

3. Validation of numerical Thermo-Hydro-Mechanical models at the structural scale: VeRCoRs benchmark

To test the validity of its physical THM models (see Figure 3) [23] , IRSN has participated to the 3rd edition of the international VeRCoRs Benchmark organized by EDF under the umbrella of OECD-NEA [6][3]. This benchmark revolves around a 1:3 scaled CCB mock-up heavily monitored with realistic operating conditions throughout its accelerated aging process (7 years at the mock-up scale are equivalent to around 60 years at the full scale). It aims at improving and identifying the best modeling practices on the issues of early age [20] and delayed behavior of concrete [21] in addition to the forecast of air leakage [22][23] through cracks and trough porous and partially saturated media [24] (see Figure 2). As the French TSO, IRSN had an objective of confronting its methodology to reference experimental results and measure how accurate its current practice is compared to the others (laboratories, operators, design offices, etc.).

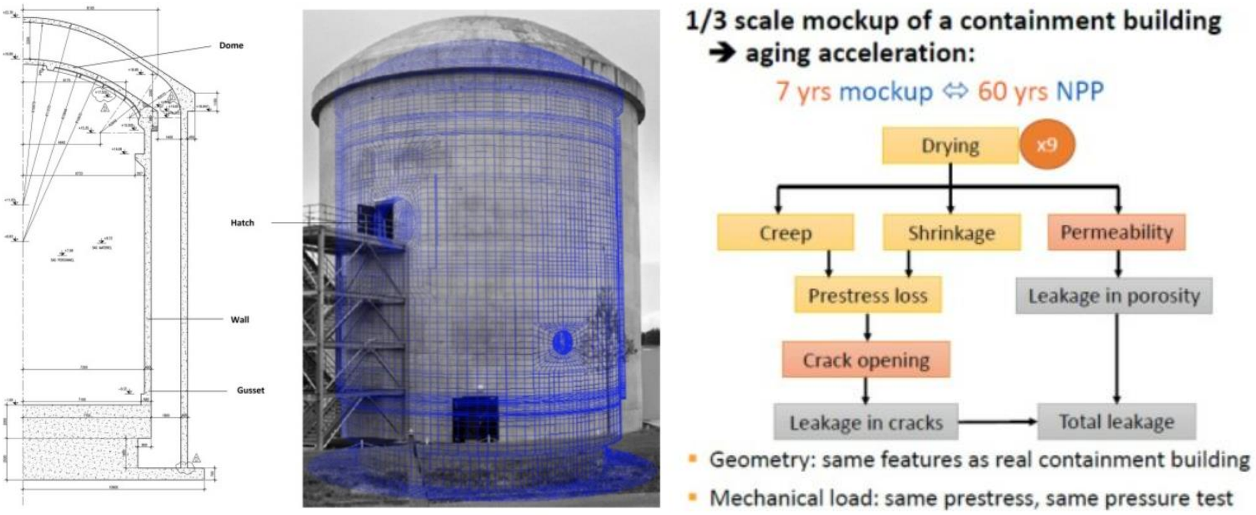


Figure 2: Aging process of the VeRCoRs mock-up (from [11])

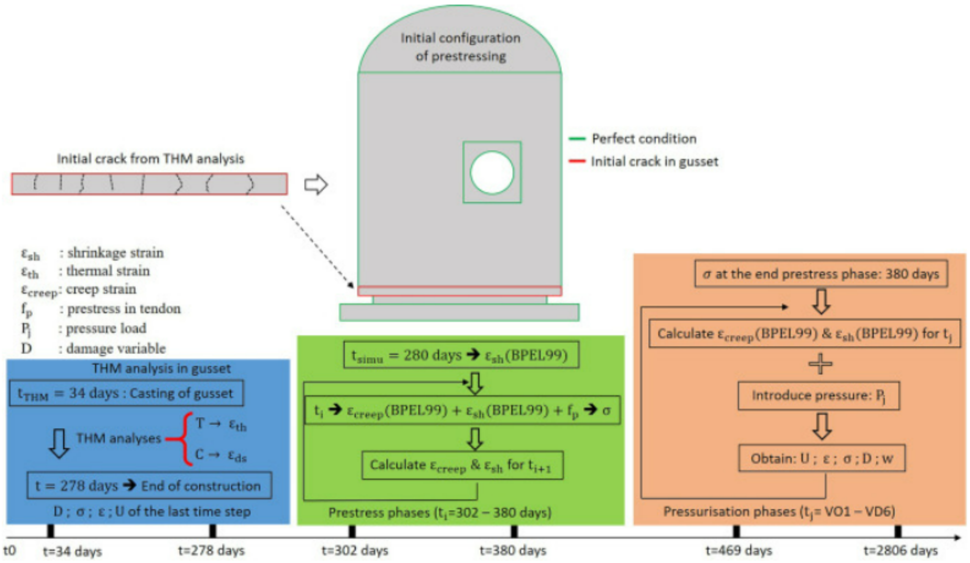


Figure 3: Overview of the THM modelling strategy (from [23])

IRSN has successfully implemented operational and efficient physical models and numerical tools allowing an accurate blind prediction of concrete behavior from the specimen up to the structural scales in ILRTs conditions. In case of the VeRCoRs mock-up predictive modelling, IRSN succeeded to predict in a satisfactory way: (a) cracking patterns at early age; (b) the evolution of prestressing losses in the structure due to the delayed behavior of concrete; (c) the evolution of the crack opening over time; (d) the evolution of the air leakage through the whole mock-up under 4.2 bars relative pressurization tests (see Figure 4).

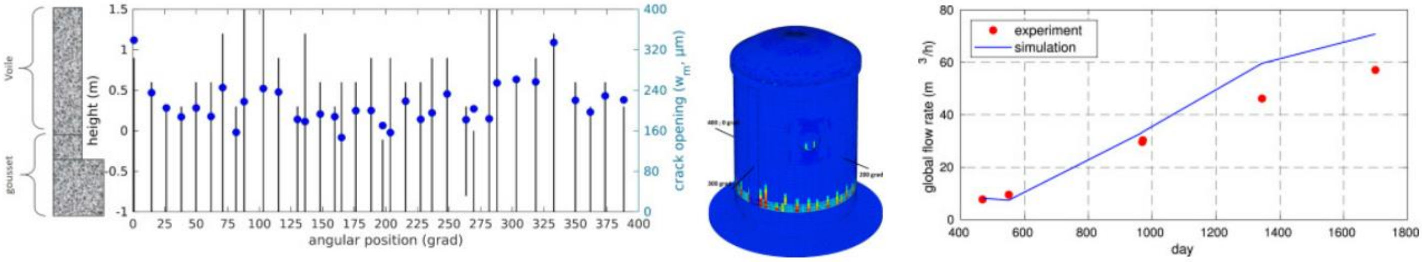


Figure 4: Illustration of the accurate prediction of the cracking pattern and of the evolution of air leakage rates over time (from [23])

4. Digital-twin-based assessment of the performance of French nuclear concrete containment buildings under operations

Digital twin modeling in the present paper refers to the process in which IRSN combines simulation techniques and data gathered from sensors, historical records for CCBs and so on allowing us for exploring a virtual twin of a physical and real CCB within normal or accidental conditions (see Figure 5). Several aspects are encompassed within this framework: (a) analysis of data provided by operators; (b) understanding of the physical behavior based on the numerical models through sensitivity analysis and parametric studies; (c) quantification of uncertainties of material properties, of sensors of boundary conditions and so on; (d) model updating to reduce the prediction uncertainties over time (see Figure 6) and account for the most recent structural state of the structure prior to any predictive analysis.

It is important to note that once the digital twin of a CCB is established, predictive simulations of all sorts could be achieved. Most of them are blind in the sense that the simulated operational duration is beyond the present age of the structure and the accidental conditions have not occurred luckily so far. The goal is to allow the anticipation/prediction of the structure's behavior if such conditions are met in the future given the best available knowledge at the present time.

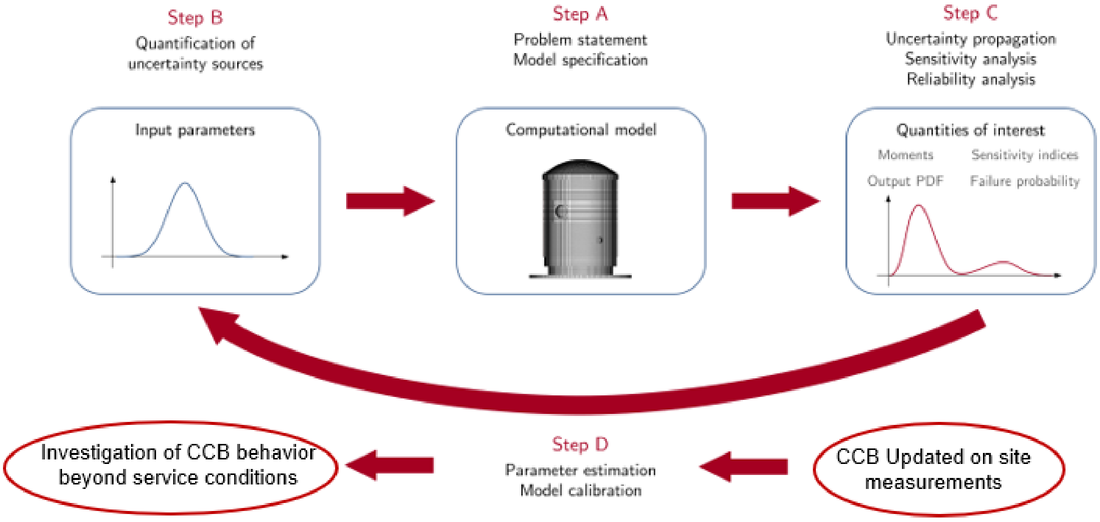
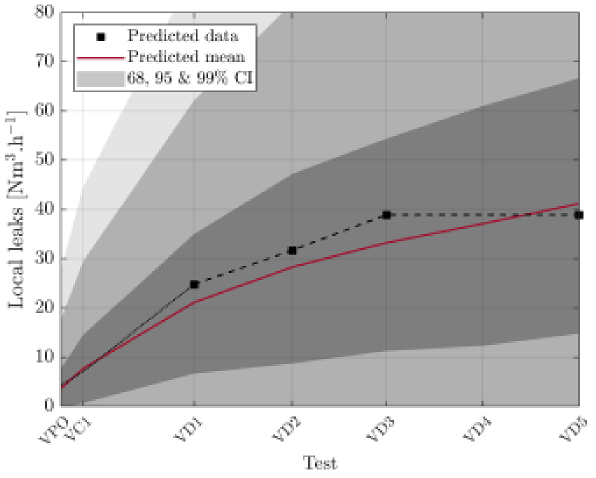


Figure 5: Overview of the IRSN digital-twin based modelling strategy of CCBs (adapted from [5])

One should also note that the number of involved inputs is very important, and the computational time is relatively high (especially for nonlinear calculations). Therefore, IRSN usually couples the twin model with a metamodel based on a limited number of calculations to obtain an explicit approximation of the model's response over the domain of interest by selecting adapted fitting mathematical functions.



(a) Prior (b) Posterior - after VD1 test

Figure 6: Illustration of the uncertainties reduction thanks to model updating based on in situ measurements of air leakage rates of the VeRCoRs mock-up (from [5])

In that sense, IRSN has recently conducted a level 2 PSA of the functional performance of nuclear CCB during accidental conditions [25]. These calculations accounted for ageing phenomena under service conditions (mostly early age behavior of concrete, creeps and shrinkages and thermal strains) before considering the occurrence of an accident (numerically) leading to an increase of temperature and pressure inside the containment building. Such an increase induces more damage in the wall's thickness and eventually reduces the containment capacity of the nuclear building. As an output of such calculations, IRSN has successfully assessed the fragility surface of CCBs giving a conditional probability of exceeding a given leakage rate threshold given thermomechanical loading indicators (see Figure 7).

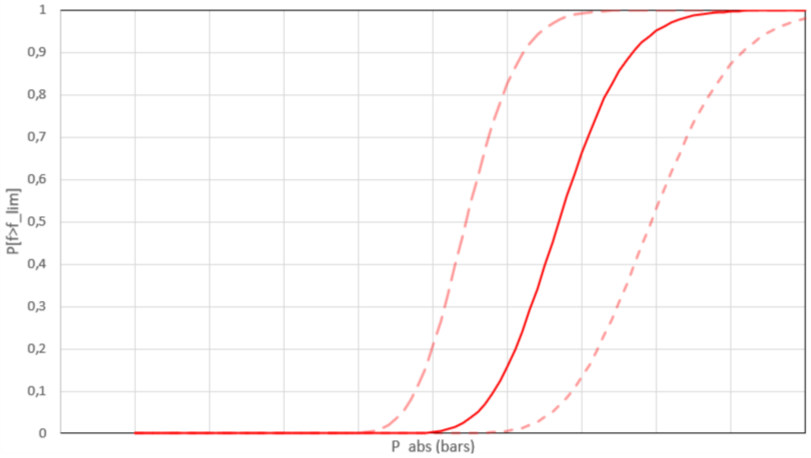


Figure 7: Example of fragility curves for a fixed accidental temperature and increasing inner pressure and its associated confidence intervals at 5 and 95% (from [25])

5. Conclusions

In this paper, IRSN shares its essential pillars to meet its needs as a French TSO providing competent, reliable, and impartial technical expertise to the French nuclear regulatory body. Those three pillars revolve around the experimental investigation of complex and coupled physical phenomena, the numerical model validation at material and structural scales and finally the digital twining of CCBs to perform up to date investigations. For each pillar, IRSN is strongly engaged in making the state of science and technology move forward by conducting applied research and development (R&D) activities, thus providing both the knowledge and the analytic tools needed to ensure a high level of safety in the nuclear field. The recent advances made for each are continuously shared with scientific and technical international community. A relevant example is the ongoing editing of a "Guidance report on the modeling of CCBs" directed by IRSN in the framework of the European H2020/ACES project with the participation of many national and international Laboratories, Operators, TSOs and Regulators (U.S. Nuclear Regulatory Commission, U.S. Sandia National Laboratories, GRS from Germany, EDF from France, VTT Technical Research Centre of Finland and others).

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