Acta Polytechnica CTU Proceedings **33**:78–84, 2022
https://doi.org/10.14311/APP.2022.33.0078

PREDICTING LEAKAGE OF THE VERCORS MOCK-UP AND CONCRETE CONTAINMENT BUILDINGS - A DIGITAL TWIN APPROACH

Laurent Charpin[a,*], Jessica Haelewyn[b], Anass Cherki El Idrissi[b], Julien Niepceron[c], Benoît Masson[c], Charles Toulemonde[a], Guillaume Boulant[d], Jean-Philippe Mathieu[a], François Hamon[b], Sylvie Michel-Ponnelle[b], Jean-Marie Hénault[e], Frédéric Taillade[e], Jean-Luc Adia[a], Florian Escoffier[b]

[a] *EDF R&D MMC, Les Renardières, Avenue des Renardières, 77250 Ecuelles, France*
[b] *EDF R&D ERMES, Saclay, 7 Boulevard Gaspard Monge, 91120 Palaiseau, France*
[c] *EDF DT, 19 rue Pierre Bourdeix, 69000 Lyon, France*
[d] *EDF R&D PERICLES, Saclay, 7 Boulevard Gaspard Monge, 91120 Palaiseau, France*
[e] *EDF R&D PRISME, Chatou, 6 quai Watier, 78400 Chatou, France*
[*] corresponding author: laurent.charpin@edf.fr

Abstract.
EDF operates a nuclear power generation fleet made up of 56 reactors. This fleet contains 24 reactors designed as double-walled concrete containment building. The inner concrete containment vessel has no metallic liner and is a prestressed reinforced concrete building. The inner concrete containment vessel is designed to withstand a severe accident, in terms of mechanical and sealing behaviour. The tightness of the containment is tested every 10 years, by carrying out a pressurization test and by measuring the leak rate. The leak rate is required to be below a regulatory threshold to continue operation of the concrete containment building for the next ten years. Ageing of concrete due to drying, creep and shrinkage leads to increase prestress loss and then leak rate with time. For some containment buildings, the leak rate gets closer to the regulatory threshold with time, so important coating programs are planned to mitigate and limit the leak rate under the regulatory threshold. Therefore, it is very important for EDF to have a concrete containment building leak rate prediction tool. To address this issue, an important research program around a 1/3 scale concrete containment building mock-up called "VERCORS" have been launched at EDF. The mock-up is heavily instrumented, and its materials (concrete, prestressing cables) have been widely characterized and studied. An important numerical effort has also been made to implement structural computations of the mock-up and to capitalize these computations as well as their post-processing (so as to compare automatically with the monitoring data) in what can be called a digital twin of the mock-up. This digital twin is now used to predict the leakage of VERCORS mock-up before yearly pressure test, and also to optimize the repair programs on the real containments.

Keywords: Air leakage, concrete containment building, creep, drying, shrinkage.

1. Introduction

1.1. Industrial context

EDF is the main electricity utility in France and operates a 56 reactors fleet of Nuclear Power Plants (NPPs). PWR safety relies on three confinement barriers: fuel cladding, primary circuitry integrity, and reactor containment building. Concrete Containment Buildings (CCBs) leak-tightness is checked every 10ăyears during the Integrated Leakage Rate Test (ILRT). This test must be performed and validated in order to continue the plant operation [1].

Double-wall containment buildings leak-tightness is achieved thanks to the inner prestressed reinforced CCB (without a metallic liner) and dynamic air filtering between the two containment buildings. In case of an accident, the concrete remains in compression. The design of the containment building is calibrated to this aim. In France, the choice has been made to use grouted tendons, therefore increasing post-tension is not an option (which is singular compared to CCBs in other countries). EDF and its industrial partners has acquired a vast experience of repair solutions that are thoroughly tested and qualified in the lab and have shown good efficiency in the field. However, their operational implementation remains difficult due to accessibility and schedule considerations, and therefore needs to be optimized. To perform this optimization and ensure a high level of safety of the containments, knowledge about concrete behaviour and capability to predict concrete delayed strains as well as leak-tightness evolution are required.

The VERCORS programme is the current main effort at EDF to bridge the gap between material scale knowledge of concrete behaviour and leak-tightness prediction.

1.2. VERCORS mock-up, a unique experiment

A 1/3 scale mock-up of a double-wall CCB has been built by EDF in the south of Paris (EDF Lab Les Renardières). It is called VERCORS (Vérification Réaliste du Confinement des Réacteurs / realistic assessment of reactors containment, Figure 1). For more details on the project and the first international simulation benchmark (organized in 2015 on VERCORS early-age behaviour), the reader can refer to [2]. The second VERCORS benchmark about long-term mechanical behaviour and leak-tightness has been reported in [3]. A third benchmark has started in January 2021.

In addition to cost, the huge advantage of the scale reduction is the acceleration of drying: since the mock-up is 1/3 compared to real containment buildings, it is expected to dry 9 times faster. In addition, the 1/3 scale makes it possible to reduce all featured of the mock-up (tendons, rebars, etc.), therefore representativity to real containment buildings is very satisfactory. Aggregate size and sensors have not been reduced by the same ratio for practical reasons.

VERCORS was built starting in 2013 in less than 1 year. Prestressing started after completing concrete casting, at least 28 days after casting of the dome. The first IRLT has been performed in the end of year 2015. In March 2016 the air conditioning system, ensuring representative temperature and humidity conditions both in the inner containment and between the two containments, has been started. Then, IRLTs have been performed every year (except during the covid lock-out period), to represent the tests performed every 10 years on real CCBs.

Instrumentation has been the focus of large efforts, with both the classical instrumentation found on CCBs but in much larger numbers (more than 300 vibrating wire strain sensors, 200 PT100 temperature sensors, pendula and invar wires) and also innovative sensors (2 km of optic fibers, 20 TDR moisture sensors, 80 strain gages on rebars).

VERCORS concrete has been thoroughly characterized in EDF and national and European partner labs to achieve a consistent knowledge of elastic properties, strength, drying properties, delayed strains at different ages and different temperatures. More information can be found in [4].

1.3. Leak-tightness model strategy

The strategy to use VERCORS to be able to predict the CCB behaviour during IRLTs and to optimize coating programs relies on the construction of a CCB digital twin. It is based on physical ideas described in [5]. The present paper is the focus of the two first steps, as described on Figure 2:

- Validation of the physical models (for drying, shrinkage and creep at moderate temperature) using laboratory data obtained in EDF laboratories and in MACENA PIA project and a comparison of the staggered Thermo-Hygro-Mechanical analysis to VERCORS results.
- Calibration of a global analytical leakage model on existing VERCORS ILRT results, which is then used to predict the leakage during next IRLTs.

1.4. Objective of the present paper

In this paper, the procedure presented in Figure 2 to the VERCORS mock-up is followed. The main assumptions of the structural computation will be presented as well as the results obtained. Then, the global leakage model and its results will be presented.

2. VERCORS structural computation

The objective of this T-H-M computation is twofold: validating the models involved by comparison to the monitoring data on the VERCORS mock-up, and providing inputs to the leak-tightness model.

2.1. Model assumptions

Most assumptions of the VERCORS modelling have been presented elsewhere [2], so only the main features as well as references will be provided in the present paper. All computations are performed with code_aster (`www.code-aster.org`) in the framework of the VERCORS digital twin developed at EDF.

2.1.1. Constitutive modelling

The thermal model is a linear conductivity model. The thermal model parameters (heat capacity, conduction coefficient) have been measured on VERCORS concrete.

The drying model is that developed in Granger's works from Mensi's earlier developments [6]. It is a non-linear diffusion model using water concentration as an unknown (hence, boundary conditions needs to be expressed in water concentration which requires the knowledge of the desorption isotherm, since the ambient moisture is known from air relative humidity). The drying model and calibration issues are presented in detail in [6], and the parameters used in this study are available in [7].

The mechanical model is based on Benboudjema and Sellier's works as well as internal EDF works [8–10]. It is an additive model taking into account elasticity, drying shrinkage, basic creep and drying creep. The calibration of the model is described in [7] as well.

This calibration phase involving a large number of drying, shrinkage and creep experiments at 20 °C and

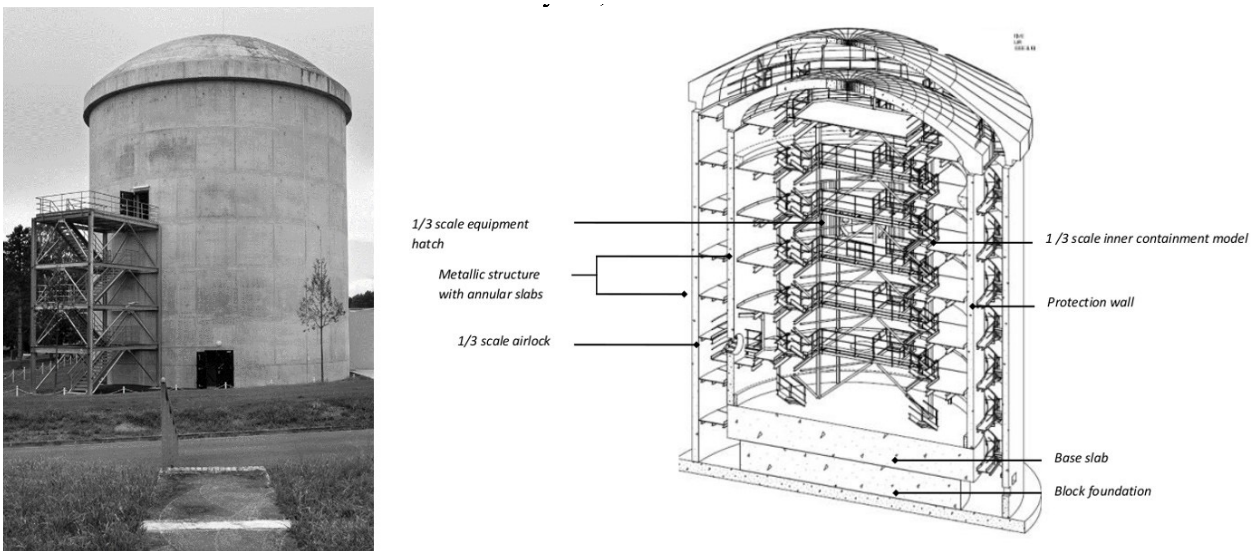

Figure 1. Outer containment wall of the VERCORS mock-up and sectional schematic view

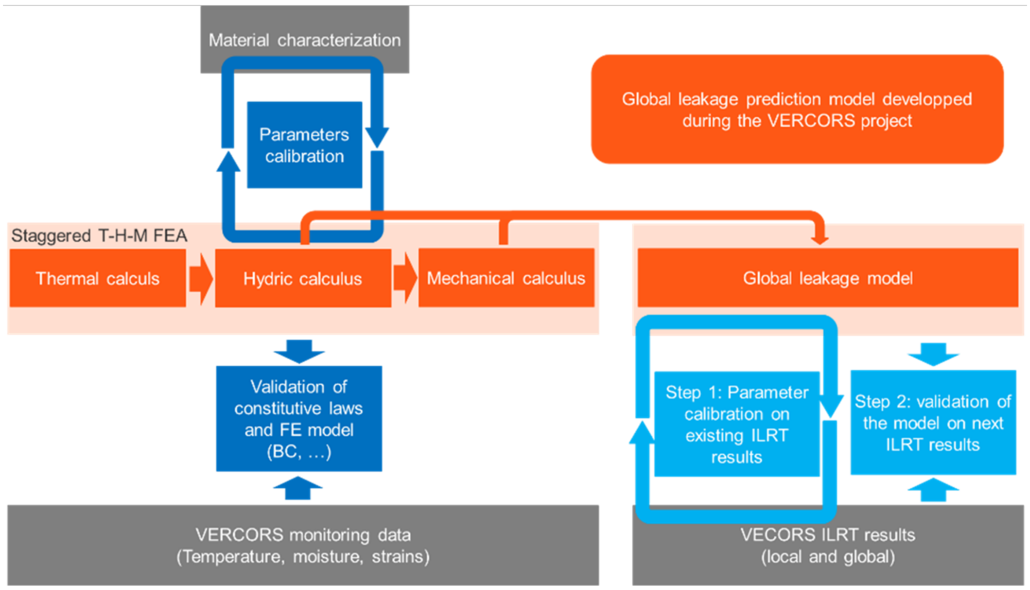

Figure 2. Model validation strategy proposed in the present paper, corresponding to points 1 and 2 of the above strategy.

40 °C yields a set of parameters which is used in the present study.

Concerning the properties of prestress cables, they were communicated by Fressinet who did the post-tensioning. The relaxation of prestressing cables is not accounted for. Passive reinforcements are not taken into account in the model.

The mechanical model is based on Benboudjema and Sellier's works as well as internal EDF works [6, 7, 11]. It is an additive model taking into account elasticity, drying shrinkage, basic creep and drying creep. The calibration of the model is described in [5] as well.

This calibration phase involving a large number of drying, shrinkage and creep experiments at 20 °C and 40 °C yields a set of parameters which is used in the present study.

Concerning the properties of prestress cables, they were communicated by Fressinet who did the post-tensioning. The relaxation of prestressing cables is not accounted for. Passive reinforcements are not taken into account in the model.

2.1.2. FE model

The numerical model of the VERCORS mock-up is focused on the inner pre-stressed concrete containment building. The mesh used for thermal and hydric computations is composed of 331962 nodes and 304928 hexahedral linear elements, while the mesh used for the mechanics computation is composed of 211776 nodes and 40656 hexahedral quadratic elements (Figure 3).

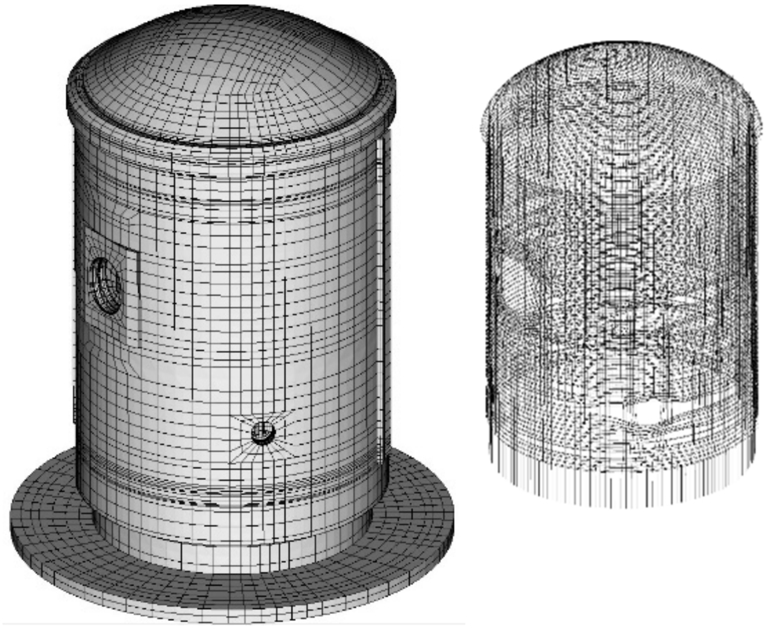

Figure 3. VERCORS mesh. The pre-stress cables are individually modelled using bar elements. Deviations around the access hatch and other passages through the walls are represented. The metal elements closing the through-wall passages (pipes, hatches) are also modelled in 3D. The mesh is refined at the surface of concrete to correctly capture the drying gradients. In the cylindrical part, the wall thickness is discretized using 12 elements which size vary between 2 cm and 6 cm.

2.1.3. Boundary conditions and loadings

The thermal and hydric boundary conditions are very important since drying, creep and shrinkage are highly influenced by temperature and humidity. The ambient temperatures and humidity are the results of:

- The external weather (especially in the early months of the experiment during which the external containment was not completed).
- The behaviour of the air-conditioning system which is designed to impose temperature and humidity similar to field conditions (both inside the containment and in the space between internal and external containment), but needs to be stopped for about 3-4 weeks for ILRTs.
- The supply of humidity due to the flooding of the basement raft during ILRTs (which is related to the procedure also used on real CCBs to measure the leakage through the containment wall only), which brings moisture close to 100 % RH during about 2 weeks.

In this work, the boundary conditions used are a schematic representation of the available measurements. For the temperature, the temperature sensors installed on the wall surface are used (due to significant boundary layer effects, the wall temperature is quite different to ambient temperature, which has also been modelled directly in other works, but is not presented here). For moisture, the RH measurements performed on both sides of the containment walls are used.

The mechanical boundary conditions are as follows: displacements at the bottom surface of the basement raft are assumed to be zero. The post-tension of the cables is performed in 8 phases instead of the 35 real phases. It was shown to be equivalent in terms of post-tensioning global and local mechanical behaviour.

Finally, and most importantly, the computation starts at the beginning of drying of concrete (shortly before the beginning of prestress). Hence, early-age effects are not represented. Then, the mechanical fields must be understood as relative to the mechanical state at the end of the early-age period.

2.1.4. VERCORS digital twin

The data associated to VERCORS (monitoring, materials), the parameters identification procedures, the structural computation of VERCORS and related post-processing functions have been capitalized in what can be described as the digital-twin factory of VERCORS.) The aim of such a tool is to improve quality and traceability of the studies, and also to save time when changes are performed to a part of the study. The different tools needed for building such a digital twin are described in a more detailed manner in [4].

2.2. Results of the staggered T-H-M analysis modelling

In this section, some comparison to monitoring results are presented, and some conclusions are drawn on the validation of the models.

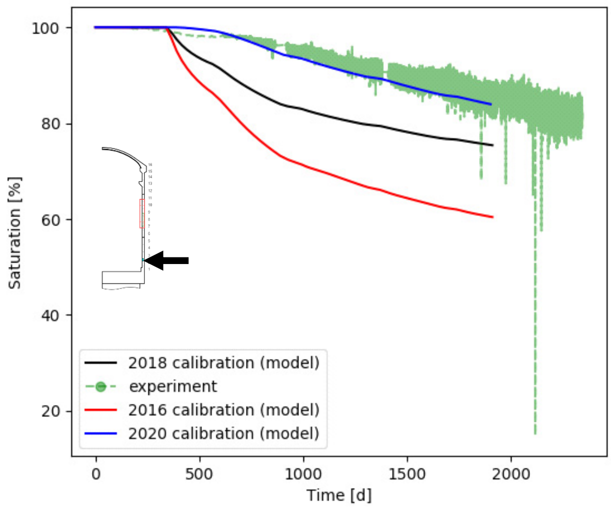

Figure 4. Simulated and measured moisture (bottom of the wall, see arrow)

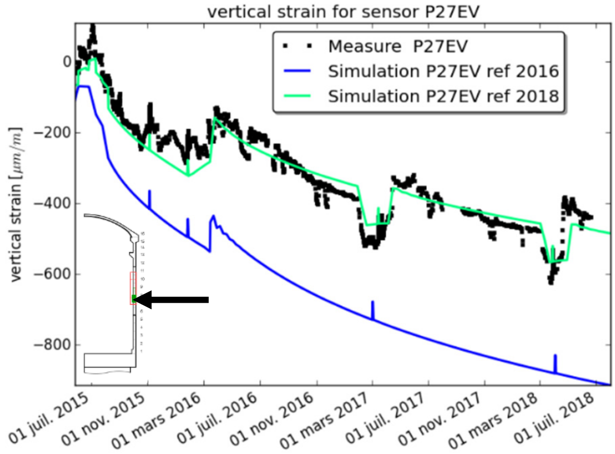

Figure 5. Simulated and measured strain (middle part of the wall, see arrow)

2.2.1. Hydric behaviour

First, the results of the hydric computation are compared to moisture sensor results available on the VERCORS mock-up. These results have been obtained using TDR sensors [6, 12, 13]. The comparison is shown for one of the sensors on Figure 4. The set of parameters studied here is the set called "2018" on Figure 4. It has been calibrated on drying experiments performed on well-hydrated samples at RH close to 50 %, see [7]. The simulation assumes an initial saturation ratio of 1 which is consistent with the fact that the VERCORS concrete has been artificially kept wet during construction. The "2016" set of parameter performs poorly and is considered as non-representative of the field concrete since it was calibrated on a drying test performed at 24h (non-mature concrete). The 2018 model does not perfectly match the experiment: a fast drying is predicted before the heating system is turned on (600 days or March 2016), whereas for the TDR post-processing, it has been assumed that the saturation is still equal to 1 when heating is turned on.

2.2.2. VERCORS digital twin

This inability to reproduce the moisture field with the "2018" identification lead to different investigations:

- As explained in [6], the calibration of Granger model on mass-loss data is an ill-posed problem. The set of parameters might be inadequate for this reason. The calibration is now being improved by using other sources of data: mass-loss at different RHs, moisture profile measurements in large samples in VERCORS mock-up.
- The model itself might be inadequate for the extrapolation from small laboratory samples to large samples. Therefore, a new model is currently tested on VERCORS mock-up based onăRichard-Fick's law [14].
- The calibration procedure for the TDR sensor, linking permittivity to saturation, is also a complicated process [13], a precise temperature dependence correction is required.

As a comparison, another set of parameters called "2020" has also been used. The identification of the thermal activation coefficients of the model has been refined, which enables predicting more accurately the slow drying before heating is turned on.

2.2.3. Mechanical behaviour

The strain computed in the mechanical computation are then compared with measured strains. It is chosen here to use the vibrating wire sensors as a reference as they are available on CCBs.

As an example, the comparison is performed on one sensor (at mid-height) on Figure 5. The total strain is represented (the strain is corrected from effects of temperature on the sensor, but not from thermal dilation effects of the structure).

The comparison of simulation and measurements for the "2018" set of parameters is quite satisfactory. Many conclusions car be drawn:

- The low strain occurring before the start of the AC/heating system in March 2016 is well reproduced.
- The acceleration of the strain kinetics after March 2016 is also well reproduced, showing that the thermal activation is well represented (at least globally) in the model.
- The swelling related to water uptake during the pressure tests (due to lower temperature and higher moisture) is underestimated.

On the contrary, the previous set of parameters "2016" performs much less well. Indeed, this set of parameters was only partly calibrated on VERCORS concrete. Hence, we see that despite an unsatisfactory representation of the moisture in the concrete wall, the mechanical prediction using the "2018" set of

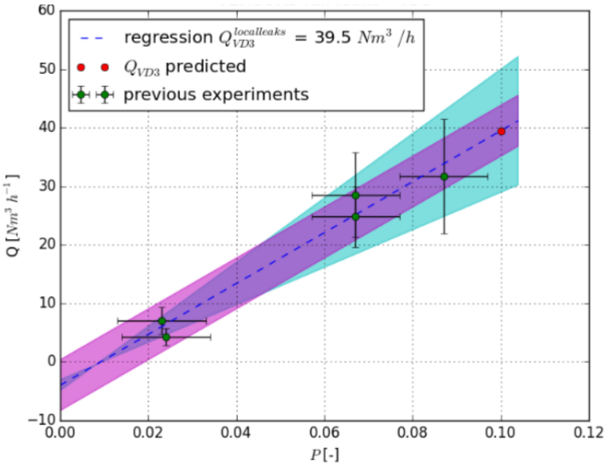

Figure 6. Local leakage prediction method.

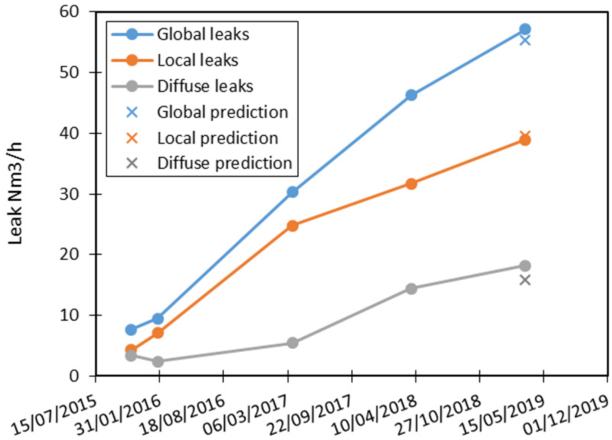

Figure 7. Leakage measurements and VD3 prediction (o = measurements, x = prediction).

parameters are consistent with measurements. This shows that the calibration procedure of mechanical behaviour can "compensate" an unsatisfactory hydric calibration to a certain extent. To improve our understanding of this phenomenon, new studies will be started to quantify the uncertainty of the moisture and strain predictions depending on the constitutive models calibration methodology.

3. VERCORS leak prediction

3.1. Model assumptions

The leakage model is based on the assumption that leaks through the wall can be classified into two categories:

- Diffuse leaks that flow mostly through the concrete porosity. Hence, these leaks are insensitive to the crack opening, but mostly related to the sound concrete permeability and its evolution, which is itself driven by concrete saturation.
- Localized leaks (which are measured during the ILRT using leak boxes which collect and measure the flux of the air flowing through localized defects). Hence, these leaks are sensitive to the mechanical state of the containment since cracks can open and close due the pressure applied during the ILRT. This effect is considered to be dependant to the evolution of the prestress.

3.1.1. Porosity leaks

The input for the computation of the diffuse leaks is a moisture profile computed with the T-H-M model. Then, a second computation is performed to reproduce the air-flux through the wall at a given saturation profile. The model used requires the knowledge of the VERCORS Van Genuchten isotherm parameters to compute the relative permeability according to Mualem's law. The model intrinsic permeability is calibrated in order to reproduce the correct porosity leak flow in "VD2" test of 2018. The model is then used to predict the porosity leakage in "VD3" test in 2019, using the same parameters but changing the saturation profile according the T-H-M computation results. The saturation profile used corresponds to the computation labelled "2016" in the previous figures, since at the time when the study was performed, it was thought to best reproduce the TDR measurements (which have since then been corrected).

3.1.2. Local leaks

The evolution of local leaks is assumed to be proportional to the prestress decrease (average on the full mock-up and the 2 in-plane directions in this approach). An affine relation is found between the prestress loss and the local leakage, which is used to extrapolate the value of the local leakage to the next VD by using the predicted prestress loss, as shown on Figure 6.

3.2. Leak-tightness prediction results

Using this methodology, a prediction for the leakage drying the "VD3" pressure test is obtained, only based on information which were already available before the pressure test. The results are shown on Figure 7 as well as the measured result.

The leakage predictions are very close to the measurements (for local and diffuse leaks). Therefore, the global leakage model is considered very satisfactory. It is believed that despite being a quite simple model, it correctly captures the leakage behaviour of the mock-up.

4. Perspectives

In 2020 many changes will be brought to the VERCORS modelling:

- New efforts on the drying law (validation and calibration) will be made.
- Our ability to do the same predictions using a reduced set of monitoring data for calibration (as they are available on CCBs) will be tested.

- Works a localized version of the leakage model will be continued, in order to be able to predict better where on the mock-up leakage occurs, assess the effect of local prestress loss and take refurbishment into account in a more efficient manner.

  Moreover, A third benchmark has started in 2021.

References

[1] A. Simon, A. Courtois. Structural monitoring of prestressed concrete containments of nuclear power plants for ageing management, *Structural Mechanical in Reactor Technology* **21**:6-11, 2011.

[2] M. Corbin, M. Garcia. International benchmark VERCORS 2015 - overview, synthesis and lessons learned, EDF, SEPTEN, 2015.

[3] L. Charpin, J. Niepceron, M. Corbin, et al. Ageing and air leakage assessment of a nuclear reactor containment mock-up: VERCORS 2nd benchmark. *Nuclear Engineering and Design* **377**, 2021. https://doi.org/10.1016/j.nucengdes.2021.111136.

[4] J.-P. Mathieu, L. Charpin, P. Sémété, et al. Temperature and humidity-driven ageing of the VeRCoRs mock-up, Euro-C, Austria, 2018.

[5] L. Charpin, C. Toulemonde, J. L. Adia, et al. Double wall containment buildings leak-tightness prediction: strategy and application, in International RILEM Conference on Early-age and Long-term Cracking in RC Structures, 2021.

[6] L. Charpin, A. Courtois, F. Taillade, et al. Calibration of Mensi/Granger constitutive law: evidences of ill-posedness and practical application to VeRCoRs concrete, TINCE 2018, Paris-Saclay, France, 2018.

[7] L. Charpin, J. Haelewyn, J.-P. Mathieu. Identitication of drying, creep and shrinkage constitutive laws for concrete at 20C and 40C, application to VERCORS mock-up, in SMSS, Rovinj, Croatia, 2019.

[8] F. Benboudjema. Modélisation des déformations différées du béton sous sollicitations biaxiales. Application aux enceintes de confinement de bâtiments réacteurs des centrales nucléaires, Doctoral dissertation, Université de Marne la Vallée, 2002. https://doi.org/10.1051/978-2-7598-1846-4.c009.

[9] A. Sellier, L. Buffo-Lacarrière. Vers une modélisation simple et unifiée du fluage propre, du retrait et du fluage en dessiccation du béton. *European Journal of Environmental and Civil Engineering* **13**(10):1161-82, 2011. https://doi.org/10.1080/19648189.2009.9693184.

[10] A. Foucault, S. Michel-Ponnelle, E. Galenne. A new Creep model for NPP containment behaviour prediction, SSCS 2012, Aix en Provence, France, 2012.

[11] L. Granger. Comportement différé du béton dans les enceintes de centrales nucléaires : analyse et modélisation, Ecole Nationale des ponts et Chaussées, Ph.D. thesis, 1996.

[12] D. Vautrin, F. Taillade, A. Courtois, et al. Adaptation of a TDR probe design for the estimation of water content in concrete, TINCE, Paris, 2016.

[13] V. Guihard, J. Haelewyn, A. Courtois, et al. Relevance and means for measuring water content in concrete structures. An illustration with PWR concrete containment, TINCE, Paris, 2018.

[14] J. Carette, F. Soleilhet, F. Benboudjema, et al. Identifying the mechanisms of concrete drying: An experimental-numerical approach. *Construction and Building Materials* **230**, 2020. https://doi.org/10.1016/j.conbuildmat.2019.117001.