Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division I

DELAYED STRAINS OF CONTAINMENT BUILDINGS IN OPERATIONAL AND ACCIDENTAL CONDITIONS: PROGRESS RESEARCH IN ACES PROJECT

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ABSTRACT

ACES (towards improved Assessment of safety performance for long-term operation of nuclear Civil Engineering Structures) is an EURATOM funded research project with a main objective to advance the assessment of safety performance of civil engineering structures by solving scientific and technological problems that currently hinder the safe and long-term operation of Nuclear Power Plants (NPP) reliant on safety-critical concrete infrastructure. The ACES Work Package WP4 focus on research related to creep and shrinkage, that aims to improve the modelling capability for drying and delayed strains of Concrete Containment Buildings (CCBs) in operational and accidental condition. In this paper, the main progress made during the first year of the project is presented.

INTRODUCTION

In nuclear power plants, containment vessels are irreplaceable components which in most concepts represent the last safety barrier between the environment and the radioactive elements. Some containment buildings are made of concrete with a single or double wall, and with or without a metallic liner for leaktightness function. For concrete containment building, these are made of reinforced and pre-stressed concrete. The containments are made of reinforced concrete with biaxial prestressing designed to withstand a severe accident load after a long lifetime. The severe accident corresponds to a situation where the containment is subjected to steam at temperature up to 170°C under pressure at 5.2 bars. Whereas, during the operational phase of the building, the containment vessel is subjected to an environment with moderate temperature (about 40°C) and low humidity (35%RH for vessels without metallic liner) inside the reactor. Outside the reactor ambient condition are applied. Long term Operation management is evaluated periodically (every ten years in France), by Integrate Leak Rate pressure test (ILRT), to continue to operate the reactor. In France, this operating licence for the next ten years is given if the leakage rate measured during the ILRT is below a strict regulatory threshold imposed by the nuclear safety authority.

Concrete delayed strains due to prestress loading and environment condition could induce prestress loss (and increasing of leak rate for concrete containment building without metallic liner) or reduce the structural ability to withstand in case of severe accident. Faced with this phenomenon of ageing, several solutions are used depending on the operators. For example, in France, in the 1300-14500 MWe NPP, a filtration system exists in the space between the two concrete containment building and polymer coatings are used to limit leakage. Work Package 4 in ACES H2020 project will enhance the understanding of the behaviour of containments in operational and accidental conditions, focusing on 3 different aspects:

- In operational condition, how can we predict the mechanical ageing of prestress concrete containments and its consequences from material data and structural information (geometry, monitoring data, etc)?
- In accidental situation, what is the impact of high temperature on concrete strains?
- How can we manage the fact that concrete depends on the materials used and therefore from one structure to another, its behaviour is very different because the materials (aggregates) that make it up come from local quarries?

In this paper, the progress made during the first year of the ACES project on these three issues is presented. In the following, the structure of WP4 is presented and then the highlights of the first year of the project are described.

OBJECTIVE

The aim of actions related to creep and shrinkage is to improve the modelling capability for drying and delayed strains of containment buildings.

The first objective is to use the VERCORS mock-up at EDF in France to compare/validate different modelling approaches around the world for thermo-hydro-mechanical and leakage aging of reinforced and prestressed concrete structures subjected to drying and moderate temperature effects (20-40°C) [1, 2, 3]. The third Benchmark VERCORS organized in this WP corresponds to this objective.

The second objective proposes to analyse method, which allow replacing the non-existent tests for the concrete of real CCB. In fact, a second Benchmark of the different approaches making it possible to predict the mechanical behaviour of concrete at 20°C from the knowledge of its mixture formulation is proposed. Therefore, propositions will be performed to improve the Code Model 2010 related to the temperature and biaxial behaviour of concrete.

For accidental phases and particular operational situations involving exposition of concrete to temperatures higher than 70°C, the material modelling is less mature. Hence, the WP4 is focused on improving the understanding and modelling of the material behaviour. An ambitious experimental program has already started on VERCORS concrete at high temperatures. This experimental program will be completed, and material modelling will be performed and shared between the project partners.

DESCRIPTION OF THE WORKS

The work carried out in WP4 of the European Aces project involves an effort of 145 person-months (PM), among 7 partners: EDF, CTU, CEA, IRSN, SCK-CEN, ENERGORISK, and ORNL. The Work Package 4 of ACES project is structured in 3 tasks.

Task 4.1 VERCORS benchmark 3, benchmarking structural computation codes for the prediction of the strains during the service life of a containment building (EDF) (M1-M42)

VERCORS is a 1/3 double-wall containment mock-up operated at EDF since 2015. The aim of this mock-up is to study extensively the evolution of strains, prestress and leak-tightness of the inner prestressed concrete containment (without a metallic liner), in order to validate models which will be subsequently used for the prediction of the same quantities for EDF containments.

Two VERCORS benchmarks have already been organized (the second with OECD support). An important European and international participation induced very interesting knowledge exchange between the teams. During this third benchmark, the focus is placed on collaborative definition of the benchmark conditions (data accessible to participants, the output that will be requested from the participants) and the collaborative writing of a guidance document for structural computations of containment buildings. The participation is opened to teams outside the ACES project, to maximise participation. The work is divided into 6 subtasks:

- Subtask T4.1.1 Discussions about the topics to be addressed (EDF, all partners) (M1-3)
- Subtask T4.1.2 Gathering of data, public announcement of the benchmark (EDF) (M4-6)
- Subtask T4.1.3 Performing the simulations (all benchmark participants) (M7-18)
- Subtask T4.1.4 Comparison of the results and writing of a preliminary report (EDF) (M19-24)
- Subtask T4.1.5 Restitution workshop, final report, journal paper (EDF) (M25-30)
- Subtask T4.1.6 Guidance report on the best practices for ageing calculations of concrete containment buildings (IRSN, EDF, VTT, all ACES partners) (M31-42)*(Deliverable D4.1)*

Task 4.2 Effects of temperature on drying and delayed strains of concrete (EDF) (M1-48)
Concrete of confinement structures can be exposed to high temperatures (up to 170°C) in case of an accident or in specific operational phases involving the release of steam in concrete buildings. Temperature has a huge influence on the moisture state of concrete. However, the behaviour of concrete under high temperature, high humidity and pressure is not well known. The moisture evolution of concrete and the related delayed strains (creep, shrinkage), cannot be predicted using the currently available models.

In order to improve the understanding and the modelling of these phenomena, the first aim of this sub-WP is to build-up on the already available database on VERCORS concrete (coming from EDF studies and the MACENA French national program, containing drying, creep and shrinkage tests at 20°C, 40°C, 70°C and creep and shrinkage tests at 100°C and 180°C) in order to obtain a large and comprehensive database about the effect of temperature on concrete conditions and its moisture state and delayed strains. The news tests will complement the database by performing drying and mechanical tests under pressure and performing tests in temperature after a long period under loading at ambient temperature, which is more realistic for accidental conditions. This database will be used to extend to these conditions and validate already existing and validated (for moderate temperature) empirical models. Two main improvements will be performed related to drying in high temperature and non-isothermal conditions, and the occurrence of transient thermal strains. The work will be divided in 8 subtasks:

- Subtask 4.2.1a Experimental investigation of the behaviour of VERCORS concrete at temperatures 20-100°C (EDF) (M1-30) *(Deliverable D4.2)*
- Subtask 4.2.1b Experimental investigation of the behaviour of VERCORS concrete in LOCA conditions (pressure 4 bars, temperature up to 150°C, high relative humidity around 80%) (CEA) (M1-30) *(Deliverable D4.3)*
- Subtask 4.2.2a Destructive characterization post TH damaging (mechanical aspects: Young's modulus, compressive and tensile strength, fracture energy, nano-indentation) on VERCORS concrete samples (CEA) (M25-39) *(Deliverable D4.4)*
- Subtask 4.2.2b Destructive characterization post TH perturbation (microstructural aspects: SEM/EDX, MIP, TGA, XRD, N2-adsorption) (SCK-CEN) (M16-30)
- Subtask 4.2.3 Constitutive modelling of the behaviour of VERCORS concrete at elevated temperatures, building-up on the existing EDF model and MPS model (EDF, CTU) (M1-30)
- Subtask 4.2.4 Assessment and improvement of Fib code model 2010 formulas for high temperature and biaxial loading conditions (IRSN) (M37-48) *(Deliverable D4.5).*

Task 4.3 Prediction of creep and shrinkage from the mix at ambient temperature (CTU) (M1-36)
The previous VERCORS benchmarks and many other studies have shown that current phenomenological models for containment structures are capable of predicting the strain evolution of these structures when calibrated against experimental laboratory data on the concrete of the containment. However, for most structures, appropriate experimental characterization is not available. The aim of this sub-WP is to benchmark numerical models that can predict the creep and shrinkage behaviour directly from the mix. An interesting challenge is that very different kinds of models that are not often compared will be benchmarked against the same database. A second very challenging aspect would be the validation of the models for

concretes containing blended cements (including additions now commonly used for nuclear buildings such as fly ash or grounded blast furnace slag). The benchmark will be restricted to ACES partners, each bringing a specific tool. The work will be divided in 7 subtasks:

- Subtask 4.3.1 Discussion about the validation data for the benchmark (CTU) (M1-6)
- Subtask 4.3.2 Gathering of the database from Northwestern University/RILEM databases, and results available in the ACES partners laboratories (CTU) (M7-12)
- Subtask 4.3.3 Simulation of the validation data with Vi(CA)2T (Young's modulus, basic creep) (EDF) (M13-24)
- Subtask 4.3.4 Simulation of the validation data with B4 and FIB Code Model (all properties at a structural element level) (CTU) (M13-24)
- Subtask 4.3.5 Simulation of the validation data with MOSAIC (Young's modulus, creep), requires a concrete sample (ORNL) (M13-24)
- Subtask 4.3.6 Simulation of the validation data with SCK-CEN micromechanics code (shrinkage, sorption isotherm) (SCK-CEN) (M13-24)
- Subtask 4.3.7 Comparison of the results, proposition of a methodology, writing of a paper (CTU) (M25-36) *(Deliverable D4.6)*

DELIVERABLE OF THE WP4

The expected deliverables of WP4 of the ACES project are given below:

- **D4.1** Guidance report on best practices for CCB ageing calculations. This report will continue the analysis based on report of Task 4.1.4, by stating which method yield the most accurate results and are also highly computationally efficient, thus proposing a methodology for structural calculations of containment buildings. (M42) (IRSN)
- **D4.2** PhD thesis on the characterization and phenomenological modelling of delayed strains in LOCA conditions (M30) (EDF)
- **D4.3** Results of testing under pressure in LOCA conditions on VERCORS concrete (M30) (CEA)
- **D4.4** Results of destructive mechanical characterization and microstructural evolution of samples after exposure to LOCA ambient conditions (M39) (CEA)
- **D4.5** Propositions of evolutions of the FIB code model to properly take into account moderate temperature and biaxial effects on creep and shrinkage (M48) (IRSN)
- **D4.6** Prediction from the mix benchmark results (preferably directly in the format of a journal article) (M36) (CTU)

HIGHLIGHTS OF THE FIRST YEAR OF THE PROJECT

Task 4.1 VERCORS benchmark 3

For the purposes of launching the third VERCORS Benchmark, a series of meetings to discuss the following points was initiated by EDF: themes, data given to participants, data used for comparison to the simulations, formatting of results, formatting of information about the models used by participants, exploitation of results, objectives in terms of publication of the papers writer by the participants (and consistent review process to set up), objectives in terms of publication of an overview of the benchmark paper, verification of the schedule, objectives of the guidance report and people involved, following these meetings, the scope of the Benchmark have been determined. This involves two steps:

- A first prediction of the aging behaviour and the leakage of the VERCORS mock-up based on model calibration only on laboratory data. As well as the strict minimum in terms of structural information. This stage lasts 6 months.
- A second prediction step for which the participants will be able to update their prediction based on the monitoring data made available. This stage lasts 6 months too.

The VERCORS Benchmark 3rd started on 03.15.021 following the sharing by EDF of all the data useful for the calibrations of the laws of behaviour and for the first stage. There are 64 registered for the benchmark and we expected 10 team's contribution for the end of April 2022. Figure 1, shows the expected comparison of the contributions to the VERCORS Benchmark, with the example of the comparison of two calculation methods for the prediction of the deformations of the structure.

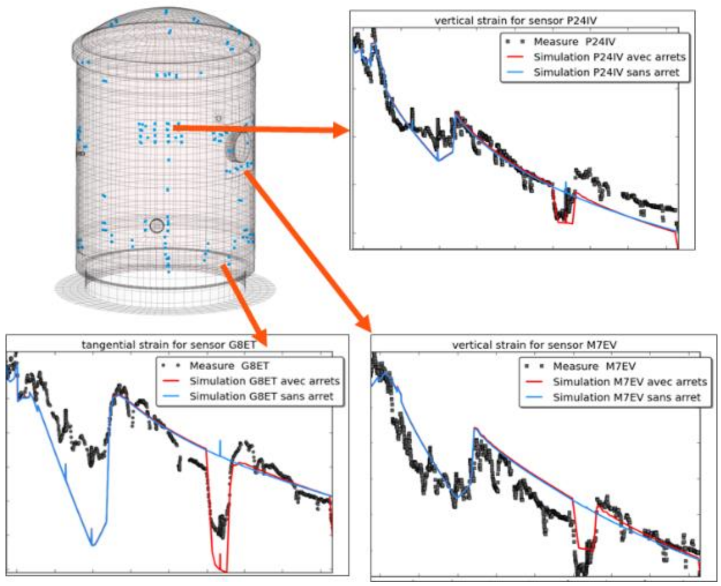

Figure 1: Prédiction des déformations de la maquette VERCORS

Task 4.2 Effects of temperature on drying and delayed strains of concrete

The first year of the project was focused on the experimental investigation subtasks and preliminary numerical work have been realized. The subtask 4.2.1a is linked to the thesis of Herman Koala between EDF, LMDC, CEA and CTU. The first year of the PhD thesis realized at LMDC, was mainly dedicated to semi-structural experiment, flexural creep on prestressed concrete beam at 70°C. The experimental campaign (see Figure 2) related to this first year was completed on November 2020 and the results are ongoing analysing.

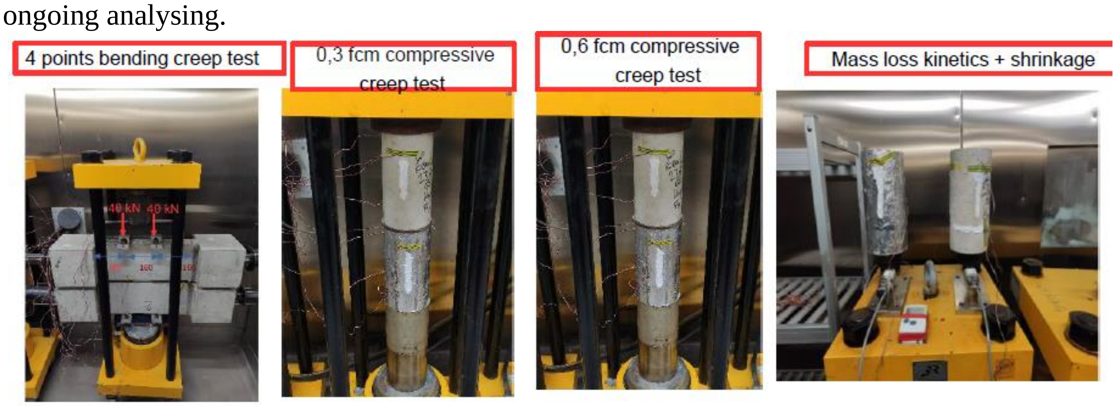

Figure 2: 4 points bending creep test on prestress beam experimental setup

The second stage of the PhD thesis concerns the material scale experiment at EDF, drying, shrinkage and creep in compression on cylinder specimens (11X22cm) at 90°C. The experimental devices for these tests in temperature up to 90°C were designed and received at EDF (Figure 3). The validation tests of the design are realized. The first results of this campaign have been obtained and are under analysing.

Figure 3: Drying, shrinkage and creep experimental devices in temperature up to 90°C

Transient creep occurs when the temperature is raised from 20°C to 70°C or 90°C for loaded samples (cylinder specimen or prestress beam under flexure) before this heating. Furthermore, its intensity depends on the water content of the concrete at the time of heating. The work is therefore directed towards the evaluation of this transient deformation at LOCA conditions and towards an improvement of the behaviour models to take it into account.

Task 4.3 Prediction of creep and shrinkage from the mix at ambient temperature

The first year focused on available data for uniaxial creep and shrinkage phenomena, gathered at room/laboratory temperatures. The largest existing database resides at North-eastern University under the supervision of Prof. Bažant, this database was revamped into MySQL version and cleared for many inconsistencies [4]. Currently, the database contains 1729 mixes, 3368 shrinkage tests and 1438 creep tests. Task participants will add even more recent data from their labs, particularly EDF and ENERGORISK.
Micromechanical models for creep / shrinkage identified further necessary actions for successful benchmark, such as available desorption isotherms or a physical sample for uCT scanning at ORNL, mostly accomplished. Concretes from blended cements were identified as important construction materials in the near future, yet the database contains scarcely such mixes. To overcome this shortcoming, data for blended cements / cements with mineral admixtures have been added to the database. Table 1 presents the statistics of the database used in the Benchmark of deferred deformation prediction from formulation information only.

	Shrinkage type					Creep type			
	Autogenous	Drying	Drying?	Total	Total?	Basic	Basic?	Total	Total?
OPC (CEM I-Type I-V) + 0	**39**	**26**	122	**204**	149	**60**	203	**69**	231
OPC + slag	0	0	0	**12**	9	4	0	0	0
OPC + FA	**17**	0	0	**11**	17	0	2	9	4
OPC + limestone	0	0	0	5	0	0	0	0	0
OPC + MK	1	1	0	0	0	3	0	3	0
OPC + SF	**13**	**13**	0	**35**	0	2	39	1	16
OPC + other filler	0	3	0	7	18	**18**	0	0	0
Not OPC + whatever	1	0	779	0	0	3	0	3	0
Total Sets	**71**	**43**	901	**274**	193	**90**	244	**85**	251
DataPoints	1110	1694	2797	5591	1313	1352	6123	743	4858

Table 1 : Statistics from the Creep & shrinkage database on the restraint

CONCLUSION

Progress on 3 main topics related to the ageing and severe accident behaviour of containments is presented in this article:

- The 3rd VERCORS Benchmark compares several approaches to modelling the ageing and leakage of double-walled containments without liners.
- Experimental data on the behaviour of concrete at high temperature provides insights into the ability to predict the behaviour of containments under severe accident loading
- The Benchmark on creep prediction based on concrete formulation knowledge alone, gives perspectives on the prediction of these properties for containments without laboratory test data

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