SIMULATION OF SHRINKAGE AND CREEP IN THE VeRCoRs PRE-STRESSED CONCRETE CONTAINMENT MOCK-UP INCLUDING AMBIENT TEMPERATURE EVOLUTION

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ABSTRACT

The time evolution of concrete strains due to shrinkage and creep, sometimes called delayed strains, in a concrete containment mock-up has been simulated using the open-source finite element software OOFEM (Czech Technical University 2017). A material model based on Microprestress-Solidification theory (MPS) is employed, which physically captures the altering of shrinkage and creep through evolving ambient temperature and humidity conditions. Simulation results are compared to measurements conducted on the VeRCoRs concrete containment building (CCB) mock-up, which was built and has been operated by the company Électricité de France (EDF).

VeRCoRs CONCRETE CONTAINMENT BUILDING MOCK-UP

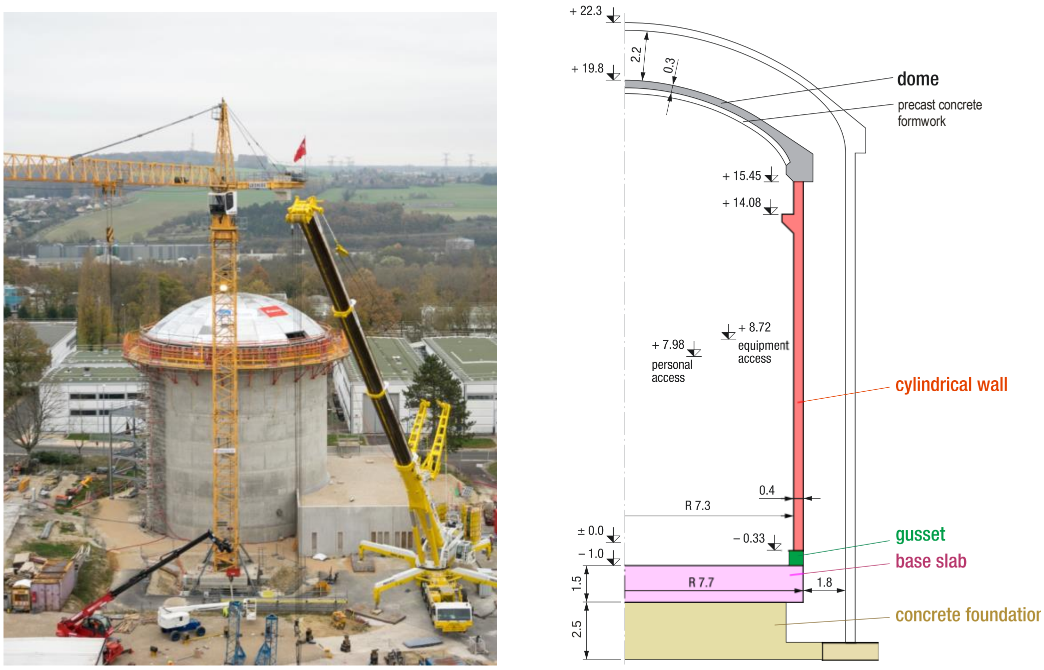
Of the total of 56 French nuclear power plants (NPP) in operation, 20 belong to the French 1300 MWe design class, which exhibits special constructional features, namely a double walled concrete containment building, whereby the inner containment is pre-stressed but possesses no metallic liner. Leak-tightness of the reactor building is supported by an active system that keeps the space between the inner and outer building under a constant depressurization. As part of the continuous effort of EDF regarding safety and life extension of its NPP fleet, an experimental mock-up of a reactor concrete containment building has been built at EDF Lab Les Renardières near Paris, France (NEA/CSNI 2019). The project was named VeRCoRs, a French acronym for **Ver**ification **R**éaliste du **Co**nfinement des **R**éacteur**s**. The objective is to investigate the structure mechanical behaviour over time and the interrelated evolution of the (air) leakage behaviour. Besides the experimental works three international numerical benchmark programs have been conducted so far to further develop the physical modelling strategies.

The VeRCoRs building is a 1/3 scale mock-up of the concrete containment building (CCB) of the 1300 MWe design class. The chosen scale of 1/3 was considered to represent an optimum between representation of the main features and acceleration of drying, and hence, ageing of the mock-up. It was estimated that the scale of 1/3 would result in an acceleration of drying by a factor of 9 in comparison with real CCBs. This has been confirmed by comparison of strain evolutions of the mock-up to the average behaviour in terms of delayed strains and leak-rate amongst the 1300 MWe NPPs of the French fleet (EDF 2022).

In the construction of the mock-up, everything that could be scaled, like steel rebars, prestressing cables, wall thickness, height, was scaled. The concrete formulae to build VeRCoRs was kept as much similar as the concrete formulae of the respective French plants (Charpin et al. 2021). It has a strength class of 34/37 MPa. Aggregates are from the same region, although the maximum size of the gravel is limited to 16 mm in the mock-up compared to 25 mm in the plant.

Construction works of the VeRCoRs CCB mock-up started in 2014 and were completed at the end of 2015. Figure 1 (a) shows a picture of the mock-up during construction. To allow for a development of drying similar to operating NPPs, a heating system has been installed to impose a temperature of 35°C and 50% relative humidity inside the containment and a temperature of 20°C and 60% relative humidity between the two containment walls. The mock-up is operated by EDF. Figure 1

(b) displays a cross-sectional view of the double-walled building, comprised of a reinforced concrete outer shell and a pre-stressed reinforced concrete inner shell.



(a) (b)

Figure 1. (a) Picture of the VeRCoRs mock-up during construction (EDF 2022),
(b) cross-sectional view of the VeRCoRs mock-up.

SIMULATION OF SHRINKAGE AND CREEP STRAIN EVOLUTION

Innumerable methods to compute shrinkage and creep strains have been developed over the past decades of research in the field. An overview over all methods cannot be given at this point, instead only a selection of methods popular in application is described in short to indicate their respective features and limitations.

Baweja and Bazant (Baweja & Bažant 1995) proposed a physically based method to compute shrinkage and creep strains. The method is called B3. The parameters in the prediction formulas for concrete strain are derived from the compressive strength f_c, the water-to-cement ratio w/c, the aggregate-to-cement ratio a/c, and the cement content (mass per volume) as input.

In 1991 a design code developed by CEB (**C**omité **E**uropéen du **B**éton, Euro-International Committee for Concrete) was first approved and published under the name of *CEB-FIP Model Code 1990: Design Code* (CEB 1993) and republished in 1993. CEB and FIP (International Federation for Pre-stressing) merged into fib (**f**édération **i**nternationale du **b**éton, International Federation for Structural Concrete) in 1998. An updated version of the code appeared in 1999 in fib Bulletins No. 1–3 and was co-opted in 2002 for *Eurocode 2* (DIN EN 1992-1-1). A new update is referred to as the *fib Model Code 2010* (FIB 2012) and its final version was published in 2012. The CEB and fib codes consider the total strain in concrete as the sum of the initial strain (in the sense of the instantaneous elastic strain), creep strain, shrinkage strain, and thermal strain. To achieve a wide applicability of the predictive formulas only the mean compressive strength f_{cm} of concrete was chosen as input parameter, even if this constraint might reduce accuracy in some cases (FIB 2013). The accuracy of the strain prediction can be improved through fitting of additional parameters in case laboratory experiments on shrinkage and creep are available (Barre et al. 2016).

Smilauer et al. (Šmilauer et al. 2023) investigated the performance of various models for shrinkage and creep on the basis of a revamped and appended Northwestern University database of laboratory creep and shrinkage data with 4663 data sets. In comparing their computations, they found, that the Eurocode 2 model shows the best prediction for the autogenous, drying, and total shrinkage, whereas the B3 and B4 models exhibit the best performance for the basic and total creep.

Systematic limitations of the described models concern on the one hand the input of temperature and humidity in the calculation formulas. Constant temperature and constant relative humidity are assumed over the period of observation. Multiple attempts were made to overcome this. Aili and Torrenti (Aili & Torrenti 2020) extended the fib Model Code 2010 computation methodology to include varying temperature and relative humidity. Temperature was employed as continuous function, steps in humidity were included through strain continuity requirements at the step change. Computations were compared to strain measurements performed in the VeRCoRs containment mock-up. Suza (Suza 2020) investigated multiple formulations of continuity requirements for varying temperature and humidity. Computations were compared to strain measurements in concrete beams of varying sizes, which were exposed to ambient conditions in Austria.

Another systematic limitation of the models described so far is, that all assume a cross-sectional approach i.e., the variation of internal stresses and humidity across the cross-section is neglected. In contrast there is the material approach, where at every material point the local stress, temperature and humidity is taken into account. The B3 model can be generalized on that regard. A further development is the Microprestress-Solidification theory, where a material model has been derived (Bažant & Jirásek 2018). The implementation of the Microprestress-Solidification (MPS) material model in the finite element program OOFEM (Czech Technical University 2017) was described by Havlasek (Havl´asek 2014).

The rheological representation of the MPS material model consists of a chain of four serially coupled components. The specialized case of a solidifying Kelvin chain represents short-term creep. This model takes into account both humidity and temperature effects on creep. The Kelvin chain is serially coupled with a non-aging elastic spring that reflects instantaneous deformation. Long-term creep is captured by an aging dashpot with viscosity dependent on the microprestress, the evolution of which is affected by changes of humidity. The last unit describes volumetric deformations i.e., shrinkage and thermal strains, where drying creep is incorporated exclusively by the mentioned material approach.

Important to notice is, that to compute the structural response one needs the temperature and humidity at every material point. So, three coupled simulations must be performed, a heat conduction simulation for the temperature field driven by the ambient temperature, a moisture transport simulation for the humidity field driven by the ambient relative humidity, and a structure mechanical simulation, which computes the elastic, shrinkage, creep, and thermal expansion strains according to local conditions. The program OOFEM is employed in the computations presented in the following.

CALIBRATING THE MATERIAL MODEL

To calibrate the Microprestress-Solidification material model simulations of the laboratory experiments on concrete specimens for shrinkage and creep were fitted to respective strain measurements. The concrete specimens in the experiments were cast from the VeRCoRs concrete mix and had a cylindrical shape with a length of 1.0 m and a diameter of 0.16 m. The mix has a cement content of 320 kg/m^3, a water-to-cement ration of w/c = 0.525, an aggregate-to-cement ratio of a/c = 5.7 and produces a cylinder compressive strength of about 41 MPa.

Four different experiments were performed, which are directed to give a measure of basic shrinkage, drying shrinkage, basic creep, and drying creep strain. Following this definition, the measured strain, when drying is prohibited, is considered to be the basic compound of shrinkage, respectively creep. This is achieved through wrapping and sealing the specimens with aluminium foil, such that the water loss to the atmosphere is prevented. In the experiments considering drying, the specimens are exposed to the laboratory atmosphere of 50% relative humidity. In the two shrinkage experiments the elongation of the sealed and unsealed specimen is measured. In the two creep experiments a compressive stress of 12 MPa is applied 90 days after casting, and the elongation of the sealed and unsealed specimen is measured. During the whole course of the experiments, the ambient temperature was 20°C and the ambient relative humidity 50 %.

The cylindrical concrete specimens are modelled with a 2D axisymmetric approach. Quadrilateral elements are used to mesh the structure. In this specific scenario, where the specimens are held at 20°C all the time, the heat conduction simulation can be skipped, because no conduction occurs over the course of the experiment. A mesh for the moisture transport and the structure mechanics was generated, whereby the outline of the mesh was identical. This is a prerequisite for OOFEM to map the humidity results of the moisture transport simulation onto the mesh of the structure mechanical simulation. The two meshes can be dissimilar in respect to the shape of their respective elements. A uniform element size of 5 mm was employed in the structure mechanical mesh. In the moisture transport mesh, the elements were refined towards the surface of the modelled cylinder. At the surface an element thickness of 1 mm was achieved. The moisture transport was based on the nonlinear moisture transport theory proposed by Bazant and Najjar (Bažant & Najjar 1972).

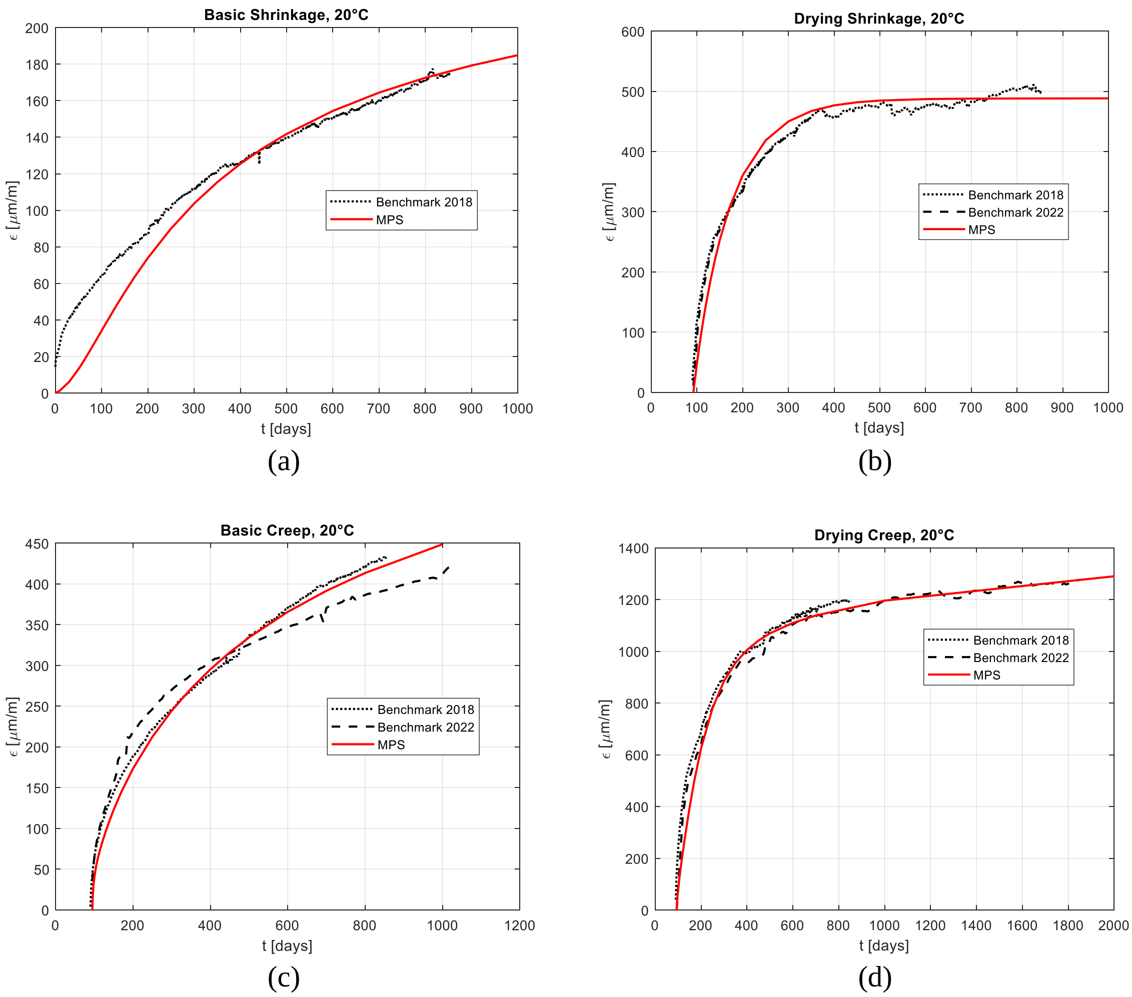


Figure 2. Strain evolution over time for laboratory experiments and simulation for:
(a) basic shrinkage,
(b) drying shrinkage,
(c) basic creep,
(d) drying creep.

Figure 2 shows the measured strain evolutions over time for the four shrinkage and creep experiments performed in the framework of the VeRCoRs Benchmark 2018 and 2022 together with simulations using the MPS material model. Within the 2022 benchmark, the provided measured basic shrinkage data was faulty. Therefore, the data from the 2018 benchmark is used instead. For the other three experiments, namely drying shrinkage and basic and drying creep, measurement data from both the 2018 and 2022 benchmark are used. In comparing the simulated strain evolutions to the measured ones, one can conclude, that creep can be fitted best with high accuracy; the drying shrinkage evolution is fitted also quite well. Only for the evolution of basic shrinkage, which takes high values considering the water-to-cement ratio, simulation and measurement deviate for the first year. This is regarded acceptable, because beyond one year the curves fit very well.

VeRCoRs SIMULATION MODELS AND RESULTS

Following the 2022 benchmark a segment of the CCB within the cylindrical wall, which was called PACAR region by EDF, is thoroughly investigated. It is situated at a height of +7.0 to +9.0 m at an angle of 350 to 380 gradians i.e., away from the penetrations where the tendons run in a regular pattern. A segment of the cylindrical wall with a thickness of 0.4 m, a circumferential extend of 2.5 gradians (about 0.3 m) and a vertical extend of 0.264 m has been modelled. The dimensions reflect the spacing of meridional and circumferential tendons. Away from penetrations, the 122 circumferential tendons have an equidistant spacing, but are set with an alternating radius of r = 7.537 m and r = 7.63 m. To capture the recurring pattern one of each are included in the model. Figure 3 shows the structure mechanical mesh.

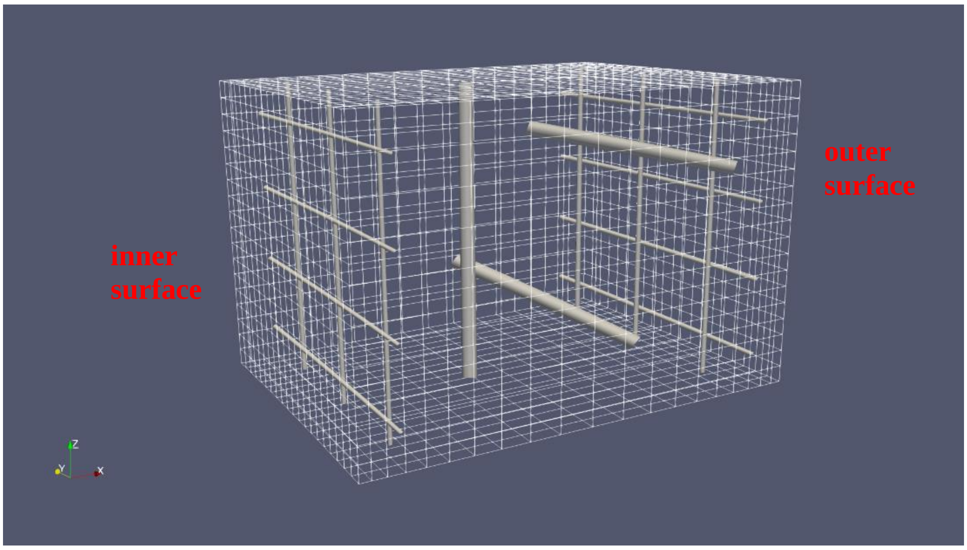
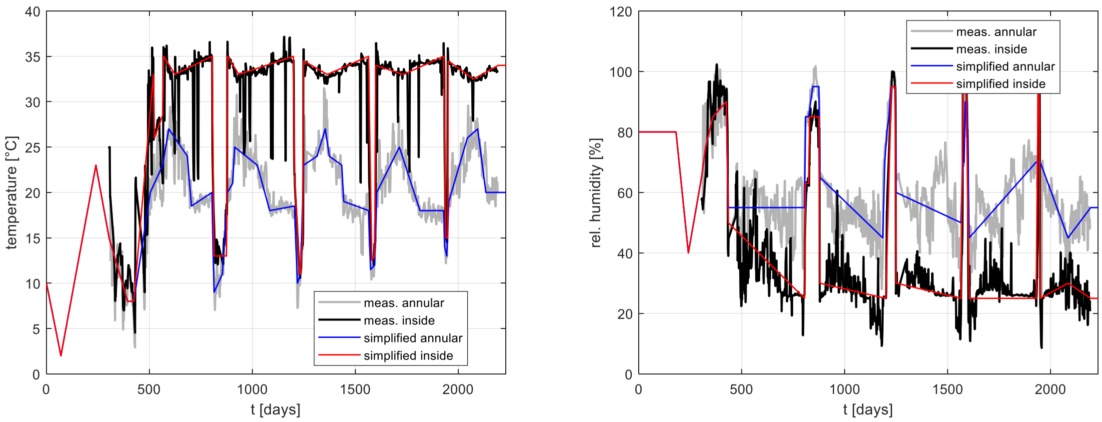


Figure 3. Wireframe representation of the structure mechanical mesh for the PACAR region containing bending reinforcement near inner and outer surface, one meridional and two circumferential tendons.

The concrete structure is modelled by solid elements, the steel reinforcement, and the tendons by beam elements. The element edge length increases from 1 cm at the inner and outer surface to 3 cm towards the centre. The MPS material model is assigned to the concrete structure, a linear elastic material model is used for the reinforcement, and a material model for relaxation of prestressing steel as proposed by the fib Model Code 2010 (FIB 2012) respectively Bazant and Yu (Bažant & Yu 2013) for the tendons. In the meshes for heat conduction and moisture transfer, elements are further refined towards the surface with an element edge length of 2 mm at the inner and outer surface. Linear heat conduction and nonlinear moisture transfer as proposed by Bazant and Najjar (Bažant & Najjar 1972) was employed.

Figure 4 shows the recorded temperature and relative humidity averaged inside the inner containment building and the annular space (room between inner and outer containment building) together with the simplified temperature and relative humidity evolutions employed in the simulations. The investigated segment of the cylindrical wall is situated in lift number 8 of the building structure; the date of casting of this lift on 17th November 2014 marks the time t = 0 in the simulation runs. However, the recording of ambient temperature and relative humidity started on 17th September 2015. For this interval of 304 days, no measurement of ambient conditions was available. The simplified temperature evolutions utilized in the simulations were extrapolated from the temperature measurements within the concrete structure, which accompanied the strain measurements. The humidity evolution was extrapolated according to the regional seasonal evolution.



(a) (b)

Figure 4. (a) temperature and (b) relative humidity inside the inner containment building and in the annular space over time.

The air-conditioning system was switched on 9th March 2016 (t = 478 days). The step-like changes in temperature and humidity occurring on t = 848, 1228 and 1583 days after casting refer to pressure tests performed on the concrete containment building. There is a step-like change at t = 1941 days after the start of the recording, where a pressure test was scheduled, but was skipped in the end during COVID restrictions. For a period of 1 to 2 month, the air-conditioning is switched off, the over-pressure test is performed followed by inspection of concrete cracking through spraying of soapy water on the surface. The latter raises of course the ambient relative humidity. The pressure test at design pressure refers to a requirement by French nuclear standards every 10 years of operation. The defined threshold of 1.5% of the air mass leakage per day must not be exceeded. In the scaled mock-up the interval of 10 years transforms to a shortened interval of 1/9 x10 years = 13 months.

The simplified temperature and relative humidity evolutions are fed into the heat conduction and moisture transport simulations through boundary conditions. Regarding the heat transfer, EDF gave a value of 8 W m^{-2} K^{-1} for the convective exchange coefficient. For the moisture transfer of the ambient atmosphere to the structure a surface factor of 1 mm/day as proposed by (Havl´asek 2014) for concrete mixes similar to VeRCoRs is assumed.

At first the moisture transport is investigated in the simulations. EDF performed measurements of water content with TDR sensors (**T**ime **D**omain **R**eflectometry) cast in the concrete structure. The output signal of the sensor is saturation ratio, which can be transformed into values of relative humidity by a nonlinear function, the desorption isotherm. EDF provided measurement values together with a model fit, which are displayed in Figure 5. A good fit can be achieved for a relative humidity ranging from 40 to 90%, whereas a significant difference between measurement and model fit occurs above 90% relative humidity. EDF constituted that the initial water saturation state of VeRCoRs concrete is homogeneous and is estimated to be at a saturation ratio of S_{r0} = 88.16%. This is translated to an initial relative humidity value of 98% in the performed simulations.

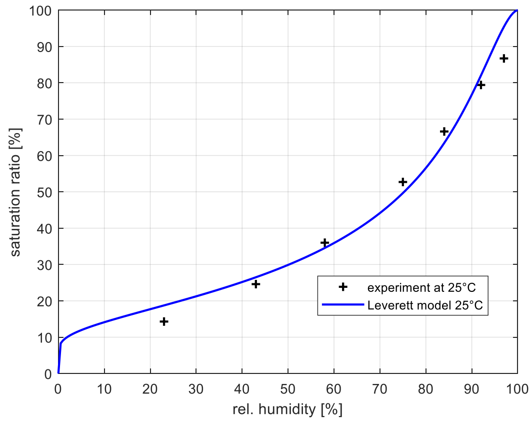
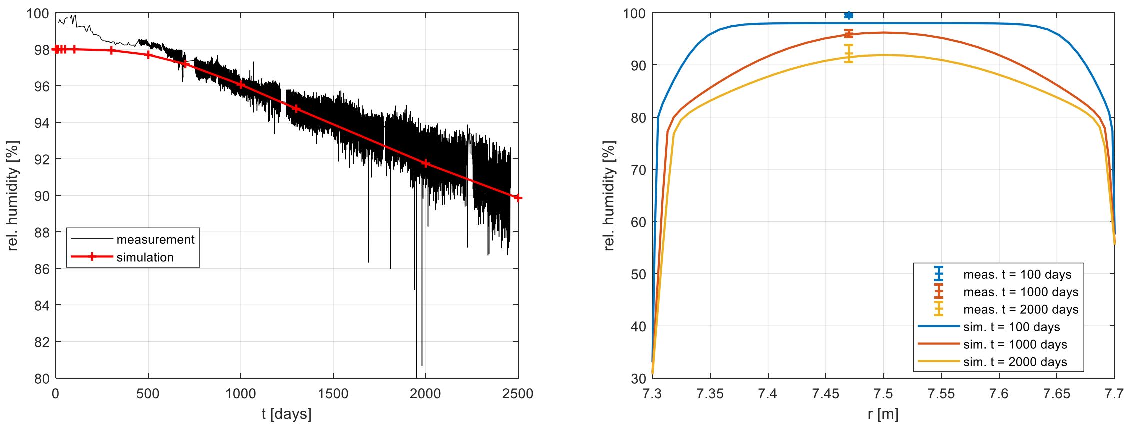


Figure 5. Desorption isotherm of VeRCoRs concrete mix at a temperature of 25°C.

Only measurement results of a single TDR sensor, which was situated at a radius of r = 7.47 m near the centre of the wall, were provided by EDF. Figure 6 (a) shows the comparison of the measured and simulated humidity evolution over time. The measured relative humidity was reconstructed according to the model fit displayed in Figure 5. A good match can be achieved for times greater 300 days, when the reconstructed relative humidity drops below 98%. One can also observe that the noise of the sensor steadily increases, but the simulation fits the averaged signal quite well. From t = 0 (casting of concrete) to t = 300 days differences occur between simulation and measurement, which can be explained by the poor desorption isotherm fit at very high saturation ratio values as already described above. In Figure 6 (b) the humidity profile over the thickness of the wall is given for various points in time; the measured values are included with their respective scatter.



(a) (b)

Figure 6. (a) TDR measurement at r = 7.47 m together with simulation results of humidity, (b) simulated relative humidity profile through the thickness of the cylinder wall.

Finally, the evolution of shrinkage and creep strains are investigated in the structure mechanical simulation. Figure 7 shows the measured and simulated strain evolutions over time at various sensor locations. From the available sensor recordings, the measurements of the sensors P1, H5 and H6 are chosen. All sensors are located at a height of +8.0 m; the sensors P1 and H5 are near the outer surface at a radius of r = 7.65 m, the sensor H6 is near the inner surface at a radius of r = 7.40 m. At each sensor location there is a strain measurement in tangential/circumferential and in vertical direction. All strain measurements are temperature compensated. The pressure acting on the inner surface during the pressure tests were omitted in the simulations.

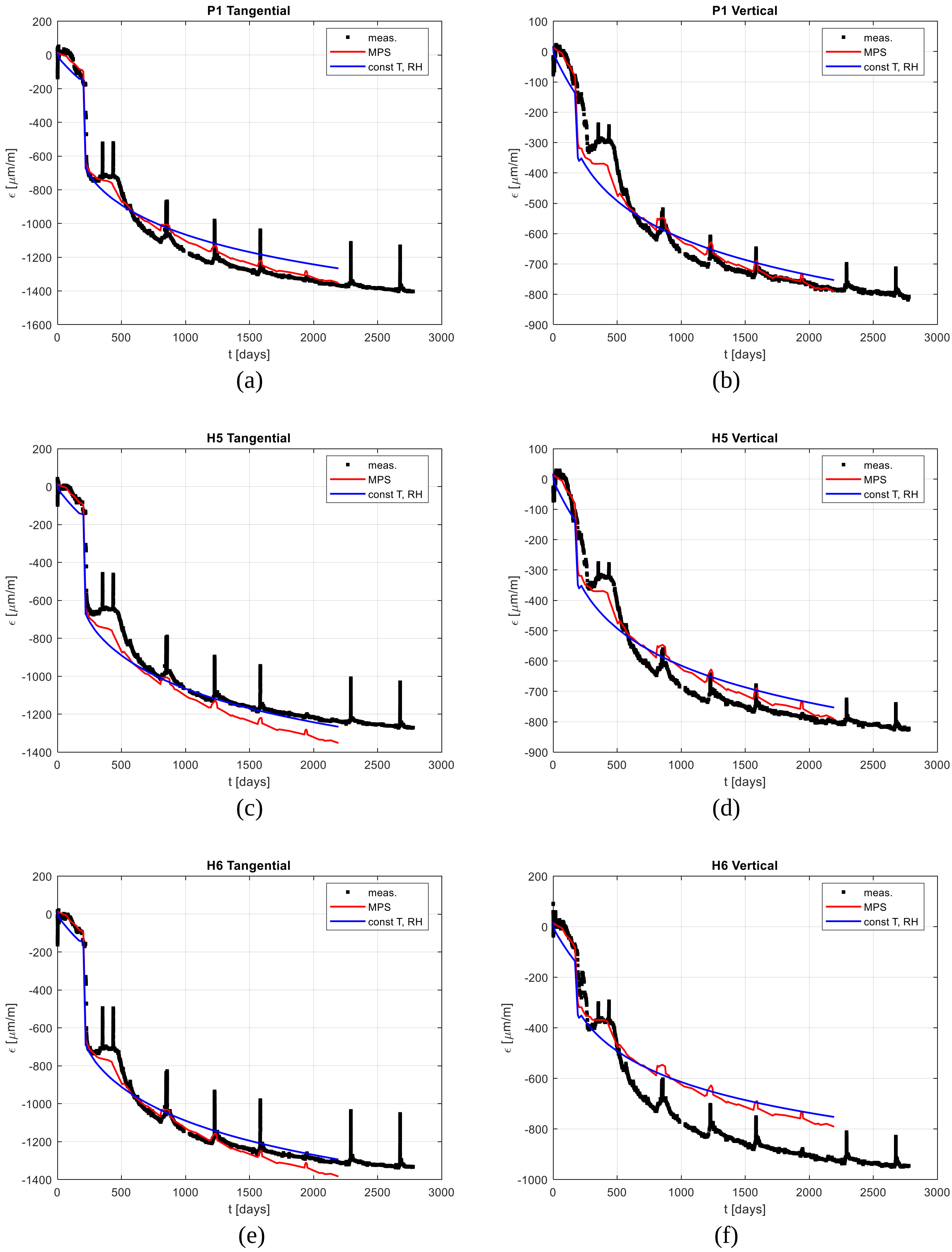


Figure 7. Measured and simulated strain evolutions starting from the casting of concrete;
MPS indicates the consideration of evolving temperature and relative humidity;
const T, RH indicates constant values for temperature and relative humidity
(T_i = 35°C, RH_i = 30%, T_a = 20°C, RH_a = 55%)

Two sets of simulations were performed. In the first one denoted by *MPS* in the graphs, the temperature and relative humidity evolutions as depicted in Figure 4 are employed as boundary conditions of the heat conduction and moisture transport simulations. In the second set of simulation denoted by *const T, RH* constant temperature and constant relative humidity are used as boundary condition. The chosen temperature and relative humidity values are the averages during the time periods, where the air-conditioning was working, which simulated conditions of a nuclear power plant in operation.

Analysing the simulated strain results, one finds a different behaviour for tangential strain evolutions compared to strain evolutions in vertical direction. The tangential tensioning is dominated by the nearest tendon and the single steep decrease in strain at t = 220 days (25th June 2015) is very well reproduced in the simulation. Concerning the vertical direction, the single tensioning at t = 192 days (28th May 2015) by the nearest vertical tendon in the simulation does not reproduce the complex multi-step strain decrease found in the measurement. The greatest deviations between simulation and measurement are found for sensor H6 i.e., near the inner surface, as depicted in Figure 7 (f).

Considering the actual varying evolution of temperature and relative humidity compared to the application of constant values in the simulations produces only deviations of about 90 µm/m for tangential strains and 40 µm/m for vertical strains after 2200 days. This period of about 6 years would correspond to 9 x 6 years = 54 years for a full-sized nuclear power plant applying the scaling factor of 9 for shrinkage and creep.

CONCLUSION AND OUTLOOK

With the Microprestress-Solidification (MPS) material model, which is implemented in the open-source finite element simulation software OOFEM, shrinkage and creep strains can be simulated locally according to the local time-varying temperature and relative humidity distribution within the concrete structure. Paramount to accurate shrinkage and creep strain predictions is a calibration of the employed material model based on shrinkage and creep experiments conducted with the concrete mix under investigation. Consideration of varying temperature and relative humidity over the simulation period had only a minor effect in the simulations. GRS plans to further investigate this finding with a detailed model of the whole VeRCoRs concrete containment building mock-up. The pressure boundary conditions during the pressure test will be included in the simulation model; with the extended MPS material model including damage the impact of repeated loading will be investigated.

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