BENCHMARK VERCORS 2022: MECHANICAL RESPONSE OF THE PRESTRESSED CONCRETE CONTAINMENT WALL TO AMBIENT CONDITIONS

Štěpán Krátký*, Petr Havlásek

Czech Technical University in Prague, Faculty of Civil Engineering, Department of Mechanics, Thákurova 7, 166 29 Prague 6, Czech Republic

* corresponding author: `stepan.kratky@fsv.cvut.cz`

Abstract. The VERCORS benchmark was developed to provide a solid experimental basis for numerical modeling of concrete containment buildings (CCBs) to extend their lifespan. The goal of the first phase of the third benchmark is to present a blind prediction of CCB's behavior across the whole lifespan and under periodic pressure tests. This paper summarizes the calibration of the material model based on the Microprestress-solidification (MPS) theory according to the provided laboratory experimental data. A special emphasis is given to the influence of the ambient conditions on drying creep and transient thermal creep of concrete and the calibration of the corresponding material parameters. These phenomena are studied on a representative section of the containment wall using weakly coupled thermo-hygro-mechanical analyses.

Keywords: Concrete, creep, shrinkage, drying, cyclic temperature, modeling.

1. Introduction

In the present days, the main portion of electricity in France (up to 75%) comes from nuclear power plants. Nowadays, a considerable number of atomic reactors (a little less than 20%) approach the end of their design lifespan. If this matter is not properly addressed in the near future, it might result in a vast energy shortage in France, not mentioning the increased risk of accidents.

The main factor of the limited service life is the concrete containment building (CCB). When upgrading to more powerful 1300 MW reactors, Electricité de France (EDF) decided to enhance the safety of nuclear power plants and thereby modify the old CCB design. The new design (as shown in Fig. 1) consists of two one-meter-thick prestressed concrete walls between which a constant vacuum slightly below the atmospheric pressure is maintained. Such a measure ensures that no contamination escapes from the interior.

To shut down old reactors and to build new ones proves to be enormously expensive, inconsiderate to the environment, and politically inadmissible. The other possibility is to extend the service life of existing containments by 20 years (from 40 to 60 years). That brings EDF to a complicated task to accurately predict more than half a century of CCB's lifespan. With the associated governing phenomena (creep and shrinkage of concrete and steel relaxation), such prediction becomes even more challenging.

Vercors mock-up is a diminished model of a CCB in a scale 1:3. According to the diffusion theory, the drying rate is proportional to the square of the representative depth. Therefore, at the present scale, the drying process becomes accelerated 9× which means that the extended lifetime of 60 years can be analyzed and assessed in no more than 7 years.

The Vercors mock-up (Fig. 1) was completed in 2014 and is 28 meters tall, 21 meters in diameter and with hundreds of sensors and thousands of meters of optical cables became the most studied concrete structure in the world. The wall of the inner containment is prestressed with steel tendons in both vertical and horizontal directions, which leads to the compression of 14 MPa and 8 MPa, respectively. Every 12 months, the pressure test is conducted to verify the air tightness of the containment. In the CCB, the imposed 12-hour-long overpressure can reach up to 6 bar (0.6 MPa) needs to be considered. In addition to structural loading, the walls are exposed to varying ambient conditions.

This paper is organized as follows. The first section summarizes the standard laboratory experiments which supplement the mock-up with suitable data for calibration of the constitutive models which are briefly outlined afterwards. Next, with the identified material parameters, the representative periodic section of the inner containment wall is analyzed. This reduced model was created to cut the computational time of the full model and at the same time to easily verify the functionality of the most important features. A special attention is given to the sensitivity of the model to the variable ambient conditions and the associated material parameters. The response is evaluated in terms of the stresses and strains in the hoop (tangential) and vertical directions, and the evolution of the prestress. This article incorporates and extends the findings obtained within the final thesis of the first author [2].
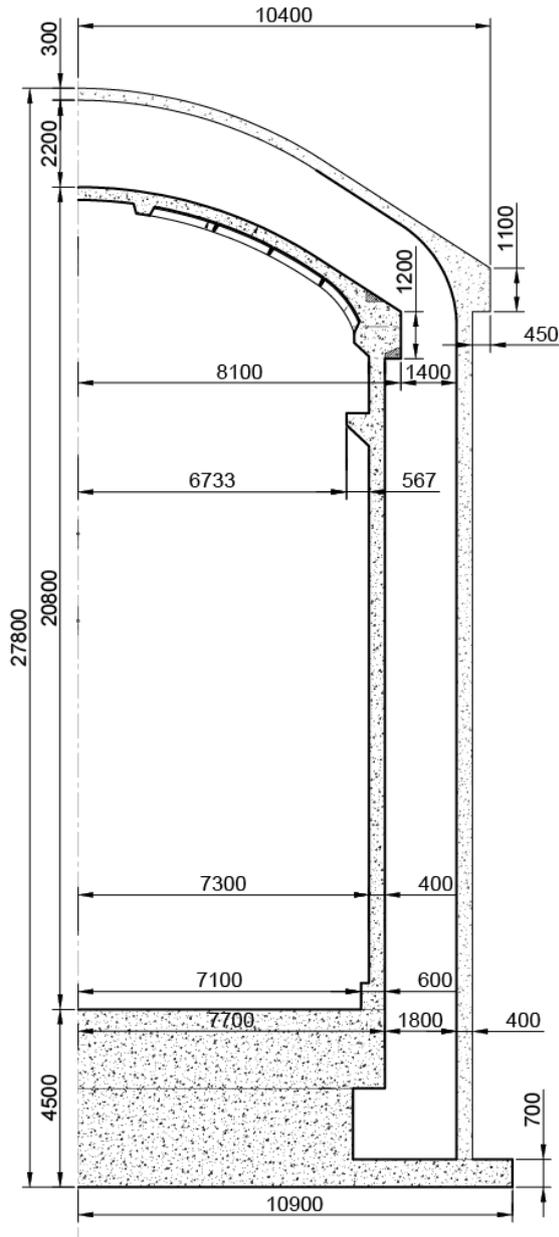
Figure 1. Section of the CCB VERCORS mock-up [1], dimensions in [mm].

2. Materials and methods

2.1. Laboratory experiments

The composition of the concrete used in the mock-up and laboratory experiments is summarized in Table 1 and is identical to the concrete of Nogent sur Seine nuclear power plant. The high value of water-to-

Ingredients	Qtty [kg/m^3]
Cement CEM I 52.5N	320
Water	167.9
Aggregates (fine 830, coarse 1005)	1835
Superplasticizer	2.6

Table 1. Concrete composition [3].

cement ratio, $w/c = 0.525$, predestines this concrete

to a larger magnitude of drying shrinkage and creep. Apart from the conventional short-term measurements at the age of 28 days ($f_{cm} = 48.7$ MPa, $E = 34.3$ GPa, $f_t = 4.4$ MPa), the laboratory data set comprised the following experiments:

- Basic creep and autogenous shrinkage
- Total creep and drying shrinkage at $h_{env} = 0.5$
- Moisture loss
- Porosity and aging sorption isotherm

Every experiment was conducted under both room (20°C) and elevated temperature (40°C).

2.2. Material models

2.2.1. Heat and moisture transport
In the present study, the heat and moisture transport are for simplicity treated as independent processes without cross-coupling. Heat conduction is idealized by using a linear transport model characterized by its heat conductivity and capacity.

Concrete drying is described by a widely accepted model proposed by Bažant and Najjar [4]. Under the assumption of linear desorption isotherm, the governing equation for the diffusion of water vapor reads

$$\frac{\partial h}{\partial t} = \nabla \cdot (C(h)\nabla h) \tag{1}$$

where ∇h is the gradient of relative humidity and $C(h)$ is the humidity-dependent diffusivity. For cementitious materials, this dependence is highly nonlinear and can be approximated as

$$C(h) = C_1 \left(\alpha_0 + \frac{1 - \alpha_0}{1 + \left(\frac{1-h}{1-h_c}\right)^n} \right) \tag{2}$$

where C_1 is the maximum diffusivity at $h = 1$, α_0 determines the ratio between minimum diffusivity at $h = 0$ and C_1, and parameters h_c and n describe the relative humidity threshold and the steepness of the transition. The ambient relative humidity is prescribed using a mixed boundary condition which relates the humidity flux J_h with the humidity difference at the boundary via surface factor f.

2.2.2. Structural analysis
The mechanical behavior of concrete is described by a modified constitutive model based on the Microprestress-solidification (MPS) theory [5]. Under sealed conditions and constant room temperature, the behavior is defined by the basic creep compliance function of the B3 model [6] which is entirely captured by 4 parameters $q_1 - q_4$.

Yet, in concrete, changes both in relative humidity and temperature give rise not only to volume changes (shrinkage/swelling or thermal dilation), but also to further creep (Pickett effect or transitional thermal creep). This additional creep is primarily controlled by the parameter k_3 which is different from the original MPS model and which has been introduced [7] to

minimize the size effect on drying creep. Shrinkage strain and relative humidity are linearly linked via their rates,

$$\dot{\varepsilon}_{sh} = k_{sh}\dot{h} \tag{3}$$

where k_{sh} is a material parameter usually treated as a humidity- and age-independent constant.

In the analysis, the stresses in steel reinforcement are far below its yield stress, therefore it is described by an isotropic linear elastic material with Young's modulus set to 200 GPa.

The behavior of prestressing tendons is characterized by a generalized model from Eurocode 2 for Class 2 steel with reduced relaxation characteristic strength 1620 MPa and $E = 190$ GPa. The influence of elevated or variable temperature on the rate of relaxation and prestress losses due to friction or slip at the anchors are not considered.

2.3. Computational models and calibration strategy

The experimental data sets which served for the calibration of the material models for concrete (rheological and diffusion properties) were provided by EDF at the beginning of the benchmark. At room temperature the experiments were done on cylinders 160×1000 mm while at the elevated temperature the dimensions were 100×200 mm. The experimental data had to be compensated for the spurious shrinkage strains caused by unintended moisture leaking.

The basic creep parameters $q_1 - q_4$ of the B3 model were determined first. The deformation of the creep experiment which started at the age of 90 days was compensated for the autogenous shrinkage measured on the companion specimen. (Since the measurements began at the age of 90 days, the recorded value and was very small, $\approx 50 \times 10^{-6}$.) Owing to the homogeneous stress state, the calibration was done using an analytical expression for the compliance function of the B3 model. The identified values which were slightly different from the prediction given by the B3 model are summarized in Table 3.

In the remaining experiments, the stress state in the specimen is no longer uniform, which explains why a more advanced computational model was necessary to be developed. The resulting axisymmetric models with suitable boundary conditions reflect the behavior of a thin representative section from the mid-height. In this region, the stress distribution can be considered as a function of the distance from the axis of the specimen and entirely free from the boundary effects.

The numerical problem was solved using a staggered scheme. In every time step, the heat and moisture transport subproblems were solved first and subsequently were followed by the structural analysis which utilized the computed fields of temperature and relative humidity.

Calibration procedure continued with the parameter controlling the magnitude of drying shrinkage and the parameters of the Bažant-Najjar diffusion model. The

suitable values were determined by hand fitting and the response of the models was checked against the evolution of drying shrinkage and moisture loss at room temperature.

With these parameters set, the parameter k_3 was identified from the drying creep experiment, and finally, the effect of elevated temperature was tuned by adjusting parameter k_{Tc} of the modified MPS theory.

The summary of all material parameters is listed in Table 3. Visual outputs of the calibration can be found in the final thesis of the first author [2].

Parameter	Value
q_1	9.0×10^{-6} MPa^{-1}
q_2	70.0×10^{-6} MPa^{-1}
q_3	25.0×10^{-6} MPa^{-1}
q_4	6.0×10^{-6} MPa^{-1}
k_{sh}	1.0×10^{-3}
k_3	10
k_{Tm}	6.5

Table 2. Identified parameters of material model MPS.

Parameter	Value
C_1	28.2 mm^{2}day^{-1}
α_0	0.055
h_c	0.7
n	10
f	1.08 mm day^{-1}

Table 3. Identified parameters of material model Bažant–Najjar for moisture diffusion.
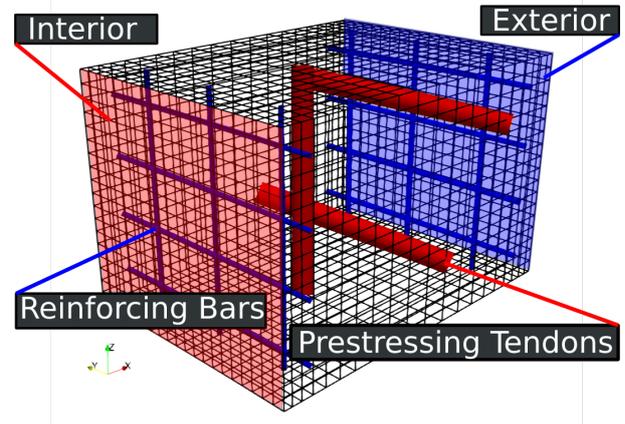
Figure 2. Computational model of the representative section for the structural sub-problem.

Despite the impressive extent of the VERCORS experimental program, the laboratory data do not provide sufficient evidence for proper calibration of the material model under general ambient conditions. The obstacle is that the investigated inner containment of the mock-up is subject to cyclic temperature and humidity which produce an additional increase in the creep rate of concrete. In the literature, this subject is covered rather insufficiently, although the

scarce existing data indicate that the creep rate is most significant during the first cycle (both thermal and humidity) and with subsequent cycling gradually decreases.

Another computational model was created to investigate the influence of the cyclic ambient conditions on the behavior of the containment wall and to estimate a suitable value of the parameter k_{Tc} which is responsible for the damping of the transitional thermal creep under temperature cycles This model is a representative section (Figure 2) of the inner containment wall. As shown in the Figure, in addition to both vertical and horizontal prestressing cables, the model comprises conventional reinforcement. The dimensions of the computational model are determined by the spacing of the cables. In the tangential (horizontal) direction of the wall, the model corresponds to an angle of $2\pi/160$ as there are 160 equally spaced vertical cables. The lateral sides are not parallel. The horizontal cables have two different radii, and for this reason the height of the model is double of the vertical spacing, 264 mm.

In the transport subproblems the spatial discretization is refined towards the inner and outer surface. Due to the zero flux in the vertical direction, only one element per height of the model is used. In the hoop direction, the discretization is uniform and is identical to the structural subproblem.

The boundary conditions of the structural analysis restrain the displacement normal to the lateral sides of the model. In the vertical direction, the periodic conditions are defined which permits not only overall elongation or shortening, but also warping of the horizontal surfaces. With these boundary conditions, the model should realistically capture the behavior at mid-height of the containment inner wall where the influence of the stiffener at the top and the massive foundation at the bottom is negligible. The self-weight is not considered since the effect would be very subtle in contrast to vertical prestressing. The reinforcement is discretized by linear truss elements which are connected to the linear hexahedral FE mesh of concrete (shown in Figure 2) by means of hanging nodes. The slip between steel and concrete can be neglected due to the rotational symmetry of the structure and the resulting uniformity of the loading.

3. Results and discussion

3.1. Overall behavior

The Figures presented in this Section document the evolution of stresses or strains computed with different combinations of ambient conditions and/or material behavior of concrete and prestressing steel. The notation in the legends is consistent and is summarized in the following list.

- J_b + relax: basic creep of concrete ($h_{env} = 0.98$), relaxation of prestressing steel, $T = 20°C$ throughout the simulation

- J_b + no relax: ditto + no steel relaxation
- h_{env1}: creep and shrinkage at constant ambient temperature $T = 20°C$ and humidity from Table 4, steel relaxation
- $h_{envi} + T_i$: creep and shrinkage at ambient conditions specified in Tables 4 and 5, steel relaxation unaffected by temperature
- + test: additional internal overpressure

Notation	Description
h_{env1}	constant after 250 days
h_{env2}	cyclic changes, piecewise constant
h_{env3}	cyclic changes, piecewise linear
$h_{env1} = 0.26$ on the inner side and 0.58 on the outer side with cyclic periods of $h_{env} = 0.98$ on both faces.	

Table 4. Definition of ambient relative humidity.

Notation	Description
T_1	constant after 90 days
T_2	cyclic changes, piecewise linear
$T = 28°C$ on the inner side and 25°C on the outer side with cyclic periods of $T = 10°C$ on both faces.	

Table 5. Definition of ambient temperature.

In the following Figures, time $t = 0$ corresponds to the concrete age of 90 days. Until $t = 45$ days when the prestressing is applied, the structural model of CCB wall is subject only to ambient conditions as specified by the keyword in the legend.

Figure 3 shows the evolution of strain in the hoop and vertical directions computed with different setup of the computational model. The results suggest that drying plays a fundamental role in the behavior of the containment wall. In the hoop direction, the strain after 2500 days of drying doubles the response of the models with basic creep only (red and purple curves), in the vertical direction the increase is even higher. Temperature cycling (blue and green curves) causes a dramatic increase in strain whose rate is almost linear during the first 4 years.

The computed evolution of the hoop stress in the middle and close to the inner surface is shown in Fig. 4. Prior to prestressing, the hoop stress close to the inner surface (Fig. 4 right) induced by the drying shrinkage reaches almost 5 MPa. Such a high tensile stress would have caused cracking which is not captured by the present material model. However, the crack depth would have been insignificant in contrast to the wall thickness and in addition to this, soon afterwards the containment wall becomes prestressed in both vertical and hoop directions which restores compression in the entire cross-section.

The hoop stress in the middle of the wall is induced primarily by prestressing and only partially by the internally restrained drying shrinkage and nonuniform thermal strains. Therefore, the decrease in stress magnitude in the middle of the wall can be attributed to the relaxation of the prestress caused by both creep
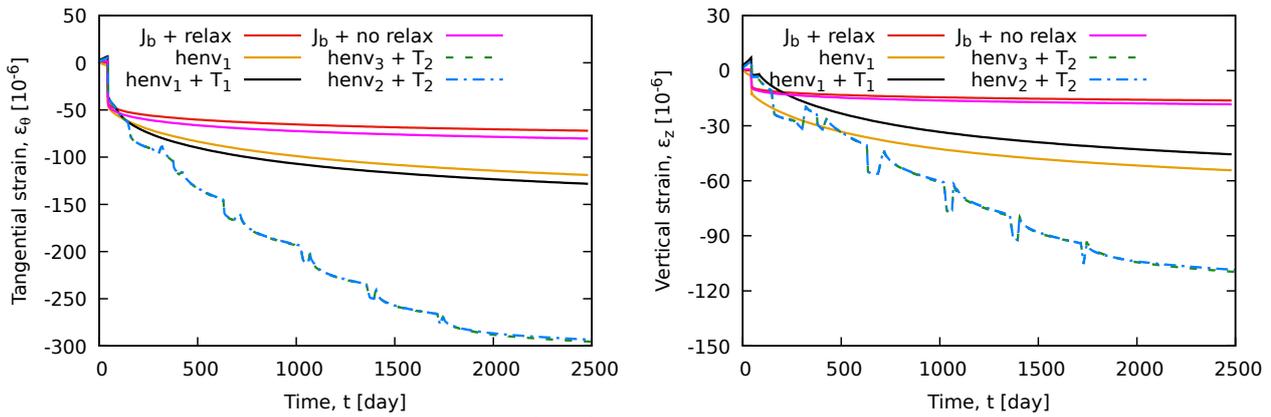
FIGURE 3. Evolution of hoop (left) and vertical (right) strain in the center of the wall computed for different histories of ambient conditions, with basic creep only and with no steel relaxation.
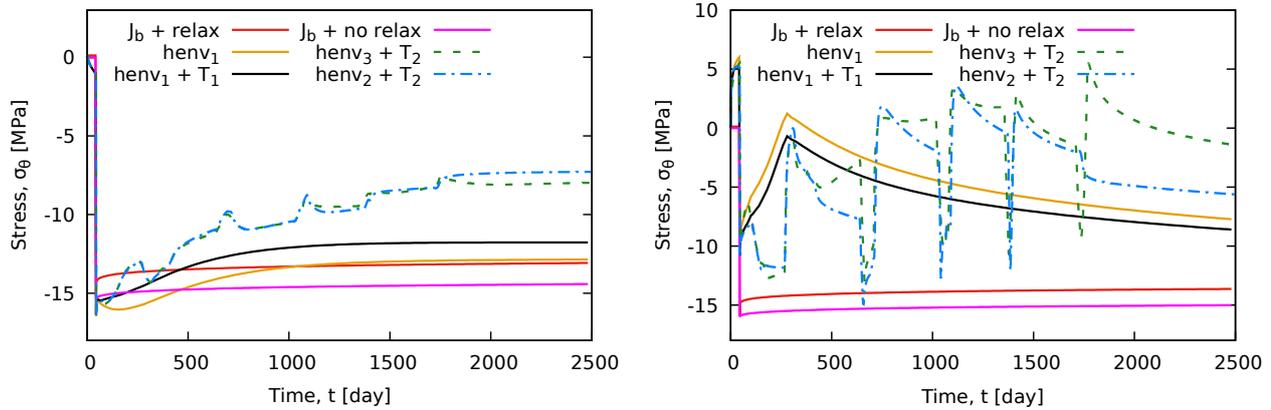
FIGURE 4. Evolution of hoop stress σ_θ in the middle (left) and close to the inner surface (right) of the CCB concrete wall.

and shrinkage of concrete. Steel relaxation leads to an initial yet considerable drop in prestressing which occurs during the first day. Afterwards, this effect becomes negligible (see comparison in Fig. 5). It is apparent that the highest decrease of prestress is associated with cyclic temperature and humidity loading (blue and green lines).

3.2. RESPONSE TO AMBIENT CONDITIONS AND PRESSURE TESTS
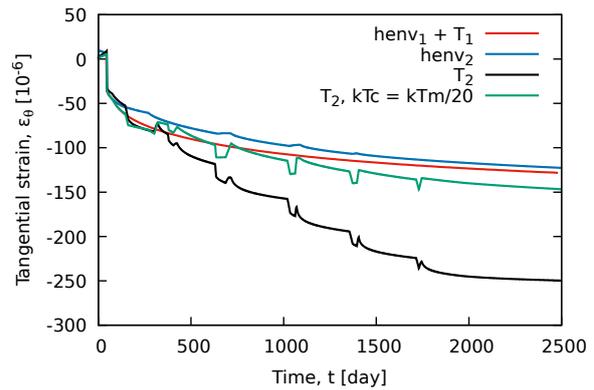
FIGURE 6. Calibration of material parameter k_{Tc} responsible for the cyclic transient thermal creep.

The analysis was performed with different histories of the ambient conditions which differed by the degree of simplification. The aim was to estimate the influence of this simplification which can significantly reduce the computational time.

The results unanimously show that the temperature defined by a cyclic history T_2 gives rise to an enormous increase in compliance which is only slightly affected

FIGURE 5. Decrease in prestress in horizontal tendons due to steel relaxation, concrete creep and shrinkage.

by the chosen history of relative humidity. Having identified the source of this unrealistic response, a parameter k_{Tc} was introduced and based on previous experience set to $k_{Tm}/20$. With this approach, the response of the computational model can be damped in further temperature cycles provided that the temperature does not exceed its maximum previously attained value. The responses obtained with the original and modified formulation are shown in black and green color in Fig. 6.
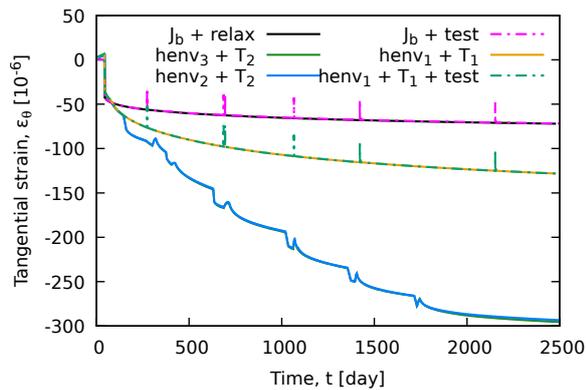
Figure 7. Evolution of hoop strain in the center of the wall - pressure tests.
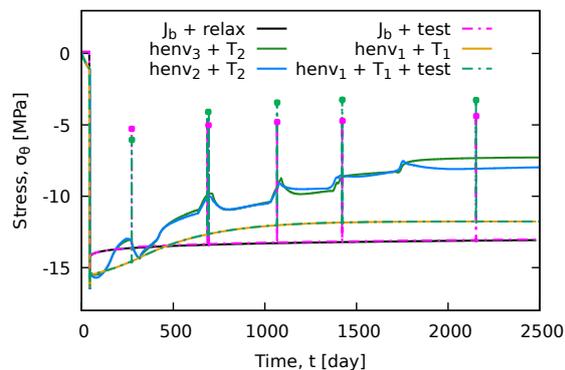
Figure 8. Evolution of hoop stress in the center of the wall - pressure tests.

Response to regular pressure tests is presented in Figure 7 and 8. With the simplified model, the overpressure affects only the hoop stress which rises by ≈ 8.5 MPa, see Figure 8. In contrast to the sustained loading by prestressing and drying, the pressure tests provide an interesting insight into the evolution of the incremental stiffness which increases with concrete aging and decreases with temperature cycles.

4. Conclusions

This paper briefly outlined a procedure used for the calibration of constitutive models for the rheological properties and moisture diffusion of VERCORS concrete. With the basic material parameters set, attention was paid to the behavior of the inner containment

wall subject to ambient conditions and regular pressure tests. The conclusions can be summarized as follows.

- A computationally efficient model was developed to study the influence of cyclic temperature and relative humidity on concrete creep. Such an extensive study could not have been executed and analyzed using a full computational model of the containment.

- The original version of the MPS model is not suitable for simulating concrete subject to cyclic temperature. Based on the data from the literature, the computed unrealistically high compliance was reduced by incorporating the parameter k_{Tc} set to $0.05\, k_{Tm}$.

- The values of the most important material parameters were determined based on the provided experimental data. A simplified history of the ambient conditions suitable for the blind prediction of the containment was selected. The developed simplified model of the containment wall will serve for checking the plausibility of the structural response of the full computational model.

References

[1] Direction Production Ingeniere, EDF. Project maquette vercors, plan general, 2012.

[2] Štěpán Krátký. *Benchmark VERCORS 2022 - blind prediction of mechanical response of reinforced concrete containment, Bc. Thesis (in Czech)*. Czech Technical University in Prague, 2021.

[3] Direction Production Ingeniere, EDF. Specification of VERCORS benchmark 3, 2021.

[4] Z. P. Bažant, L. J. Najjar. Nonlinear water diffusion in nonsaturated concrete. *Materials and Structures* **5**:3–20, 1972. https://doi.org/10.1007/BF02479073.

[5] Z. P. Bažant, A. P. Hauggaard, S. Baweja, F. J. Ulm. Microprestress solidification theory for concrete creep. I: Aging and drying effects. *Journal of Engineering Mechanics* **123**:1188–1194, 1997.

[6] Z. Bažant, S. Baweja. Creep and shrinkage prediction model for analysis and design of concrete structures: Model B3. *Adam Neville Symposium: Creep and Shrinkage - Structural Design Effects* 2000.

[7] Z. Bažant, P. Havlásek, M. Jirásek. Microprestress-solidification theory: Modeling of size effect on drying creep. In N. Bicanic, H. Mang, G. Meschke, R. de Borst (eds.), *Computational Modelling of Concrete Structures*, pp. 749–758. CRC Press/Balkema, EH Leiden, The Netherlands, 2014.