Long Term Prediction of the Delayed Behavior of Concrete Structures – The Case of the VERCORS Mock-Up

Abudushalamu Aili[1] and Jean Michel Torrenti[2](✉)

[1] Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan
[2] Univ Gustave Eiffel, CEREMA, UMR MCD, 77454 Marne-la-Vallée, France
jean-michel.torrenti@univ-eiffel.fr

Abstract. The prediction of the long-term behavior of prestressed concrete structures is important in order to assess and/or extend the service life of such structures. Here, a modelling of the delayed strains (creep and shrinkage of concrete and relaxation of steel), based on the relations of the next Eurocode 2 (EC2), is used to predict the behavior of the internal vessel of the VERCORS mock-up of a French NPP. This modelling considers the influence of the temperature and of the relative humidity (varying under service conditions). The predicted delayed strains are compared with the measurements and different hypotheses are tested to improve the prediction of the delayed strains.

Keywords: Concrete · Creep · Shrinkage · Nuclear power plant

1 Introduction

The prediction of the long-term behavior of prestressed concrete structures is important in order to assess and/or extend the service life of such structures. In the case of nuclear power plants (NPPs) where the internal vessel is a biaxially prestressed structure, the prediction of the delayed deformations is also a safety concern. Indeed, in these structures, the prestressing is there to avoid tensile stresses and cracking in case of a severe accident where internal pressure and high temperature could be generated. The prediction of the evolution of delayed strains due to creep and shrinkage of concrete and of relaxation of steel is in this case very important. Here, a modelling of the delayed strains (creep and shrinkage of concrete and relaxation of steel), based on the relations of the next Eurocode 2 (EC2), is used to predict the behavior of the internal vessel of the VERCORS mock-up of a French NPP. This modelling considers the influence of the temperature and of the relative humidity (varying under service conditions). The predicted delayed strains are compared with the measurements and different hypotheses are tested to improve the prediction of the delayed strains.

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2 Modelling of Delayed Strains

As proposed in the future version of the Eurocode 2 (EC2) [1], the delayed strains of concrete are split into four components that are adjusted to experimental results available for the VERCORS containment [2]: basic shrinkage, drying shrinkage, basic creep and drying creep. The relaxation of the prestressing is also considered. An elevated temperature during service conditions (around 35 °C) is observed in NPPs. This temperature affects the delayed strains. The effect of temperature is not considered in EC2. For basic creep, a thermo-activation is considered and the magnitude of drying creep is affected by the temperature as proposed in the fib MC2010 [3]. For steel relaxation, the relation proposed by the fib MC2010 is used.

2.1 EC2 Equations for Creep and Shrinkage

The delayed strains of concrete ε^c are decomposed in the future EC2 into basic shrinkage ε^{bs}, drying shrinkage ε^{ds}, basic creep ε^{bc} and drying creep ε^{dc}:

$$\varepsilon^c = \varepsilon^{bs} + \varepsilon^{ds} + \varepsilon^{bc} + \varepsilon^{dc} \tag{1}$$

Shrinkage. Basic shrinkage ε^{bs} and drying shrinkage ε^{ds} are given as a function of mean compressive strength f_{cm} and drying time $t - t_s$ by the following equation:

$$\varepsilon^{bs} = \xi_{cbs1}\alpha_{bs}\left(\frac{0,1f_{cm}}{6+0,1f_{cm}}\right)\left(1 - e^{-0,2\xi_{cbs2}\sqrt{t}}\right) \tag{2}$$

$$\varepsilon^{ds} = \xi_{cds1}\left[(220+110\alpha_{ds1})e^{-\alpha_{ds2}f_{cm}}\right]\beta_{RH}\left[\frac{(t-t_s)}{0,035\xi_{cds2}h^2 + (t-t_s)}\right]^{0,5} \tag{3}$$

where α_{bs}, α_{ds1} and α_{ds2} are parameters that depend on the type of cement, h is the notional size, t_s is the age of the concrete at the start of drying; ξ_{cbs1}, ξ_{cds1}, ξ_{cbs2} and ξ_{cds2} are parameters to adjust the predictions to the experimental results (the default values are equal to 1). β_{RH} is a function of the relative humidity RH.

Creep. The basic creep function reads:

$$\varphi_{bc}(t, t_0) = \xi_{bc1}\frac{1}{C}ln\left(1 + \frac{(t-t_0)}{\tau\xi_{bc2}}\right) \tag{4}$$

where τ is a characteristic time depending on the age at loading of the concrete; ξ_{bc1} and ξ_{bc2} are parameters that may be adjusted to the experimental results. C is the creep modulus and is a function of f_{cm}.

The drying creep function is:

$$\varphi_{dc}(t, t_0) = \xi_{dc1}\beta_{dc}(f_{cm}, RH, t_0)\beta_{dc,t-t0} \tag{5}$$

with

$$\beta_{dc,t-t0} = \left[\frac{t-t_0}{\xi_{dc2}\beta_h + t - t_0}\right]^{\gamma(t_0)} \tag{6}$$

Again, ξ_{dc1} and ξ_{dc2} are parameters that may be adjusted according to the experimental results (the default values are equal to 1).

2.2 Influence of Temperature on Creep and Shrinkage

Shrinkage. Shrinkage is certainly affected by temperature. MC2010 proposes relations to consider the effect of temperature on shrinkage. But these relations are given for a constant temperature which is far from the real temperature history in the VERCORS mock-up (see Fig. 5). It is of course possible to evaluate an equivalent time considering the thermo-activation of hydration for the basic shrinkage and of drying for drying shrinkage. But, here, for a sake of simplicity, we neglect the effect of temperature on shrinkage.

Creep. For drying creep, the relations proposed by MC2010 are used (for the amplitude and the kinetics) (see [3] and [4]). For basic creep, we consider 3 cases:

- No thermo-activation of basic creep
- The creep modulus C (see Eq. 4) is affected by thermo-activation (as proposed in [5, 6 and 7]
- The characteristic time τ (see Eq. 4) is affected by thermo-activation as proposed by Frech-Baronet on the basis on micro-indentation creep tests [8]

2.3 Comparison with Laboratory Tests

Creep and shrinkage tests were performed on the concrete of the VERCORS mock-up [9]. Using the possibility to adjust the relations of EC2 to these tests, Figs. 1 and 2 show that it is possible to obtain a very good agreement with the experiments. Table 1 gives the fitted values of the parameters used in Eqs. 2 to 6.

Table 1. Fitting parameters of MC2010 shrinkage and creep models

Basic shrinkage		Drying shrinkage		Basic creep		Drying creep	
ξ_{cbs1}	ξ_{cbs2}	ξ_{cds1}	ξ_{cds2}	ξ_{bc1}	ξ_{bc2}	ξ_{cds1}	ξ_{cds2}
1.5	0.3	1.0	1.4	2.0	1.4	1.2	0.4

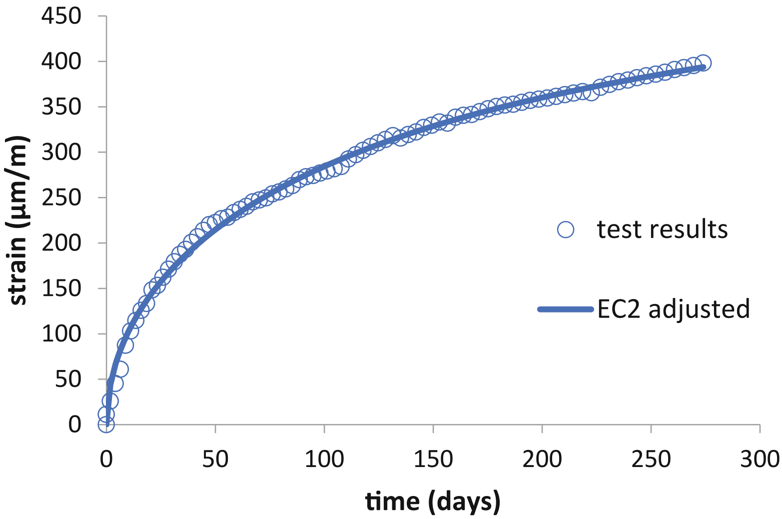

Fig. 1. Comparison between experimental results and modeling of drying shrinkage

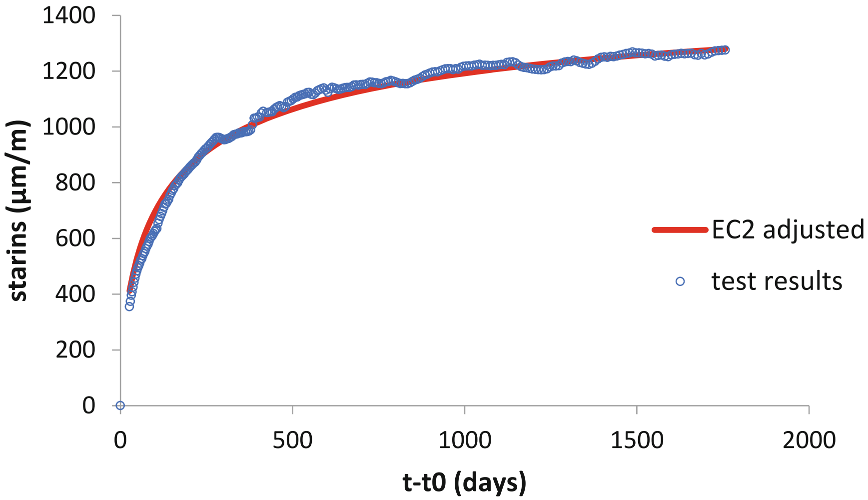

Fig. 2. Comparison between experimental results and modeling of total creep (basic + drying)

2.4 Relaxation

The relaxation kinetics of prestressing in prestressing tendons is expressed by the time evolution of relaxation loss $\rho(t) = (\sigma_0 - \sigma(t))/\sigma_0$, where σ_0 and $\sigma(t)$ are the stress at the time of prestressing and at time t, respectively. If the relaxation loss after 100 h and after 1000 h is denoted as ρ_{100} and ρ_{1000} respectively, the time evolution of relaxation loss is given by:

$$\rho(t) = \rho_{1000}\left(\frac{t}{1000}\right)^{k} \tag{7}$$

where $k = \log(\rho_{1000}/\rho_{100})$. Supposing that elastic modulus of prestressing tendons is constant, the stress evolution under a constant strain ε_0 reads as:

$$\sigma(t) = E_s\varepsilon_0(1 - \rho(t)) \tag{8}$$

The Eq. 7 is applicable to predict the relaxation under the same constant temperature. For temperature other than 20 °C, the relaxation loss is obtained by multiplying the stress loss at 20 °C by the following temperature-dependent parameter:

$$\alpha_T(T) = \frac{T}{20\,^\circ\mathrm{C}} \tag{9}$$

Figure 3 shows the comparison of this model with experiments on the prestressing tendons used for the VERCORS mock-up [10]. For the cases with varying temperature, the Eq. 9 will be used in the application of the superposition principle.

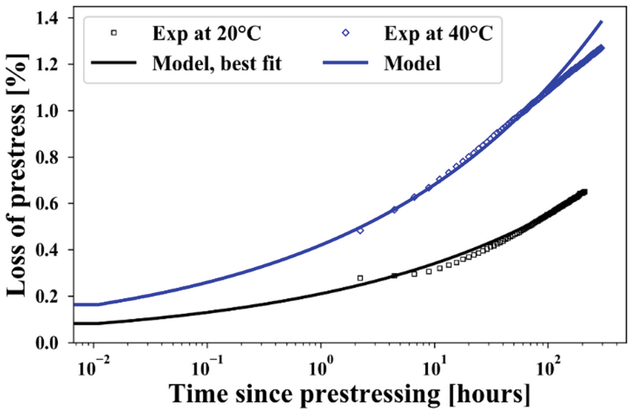

Fig. 3. Comparison between experimental results and modeling of the relaxation of the tendons at 20 °C and 40 °C; $\rho_{100} = 0.551$ and $\rho_{1000} = 0.893$

3 Modelling of the Containment

3.1 General Considerations

Considering the history of temperature and relative humidity (see 3.2), and the biaxial stress state, we compute the total delayed strain of concrete in horizontal (or tangential) and vertical directions using the superposition principle and the relations for creep, shrinkage and relaxation that were presented before. Due to the biaxial stress state, Poisson's effects are to be considered. The Poisson's ratio for basic creep ν_b is considered to be equal to 0.2 [11, 12] and we assume that the Poisson's ratio for drying creep is also 0.2, though other values such as 0 was also considered elsewhere [13]. The method is fully described in [4]. Note that, except for the fitting of laboratory tests, the prediction of the delayed behavior of the mock-up is done without adjustment on the in-situ measurements.

3.2 In-Situ Measurements

The VeRCoRs Mock-up

To better predict the delayed behavior of the containment of NPPs, the company operating the French nuclear power plants (EDF) has built a mock-up, named VERCORS, of a double containment building, at the 1/3 scale [9]. The ratio 1/3 has been chosen in order to accelerate the drying phenomenon.

Boundary Conditions

Since our modeling concerns only a material point, the relative humidity was approximated from the recorded value of relative humidity in the inner containment and in the annular space. Considering that the fluctuation of relative humidity inside concrete would be much less than that of the air, we took a simplified relative humidity history as shown in Fig. 4.

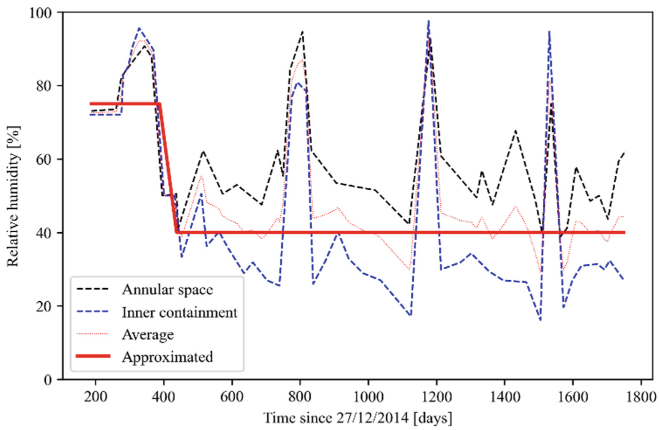

Fig. 4. Measured relative humidity in the annular space and inner space, simplified relative humidity for the modeling

Based on the measurement of the temperature at the annular space and inner space, we took the simplified temperature history shown in Fig. 5 for the modeling unit. The rationale behind this simplification is partly lie in the fact that temperature variation inside the thick concrete shall be slower comparing to that in the air, given the low heat coefficient of concrete. Note that the mean temperature is below 30 °C which is lower than in a real containment (where it is closer to 40 °C [14]).

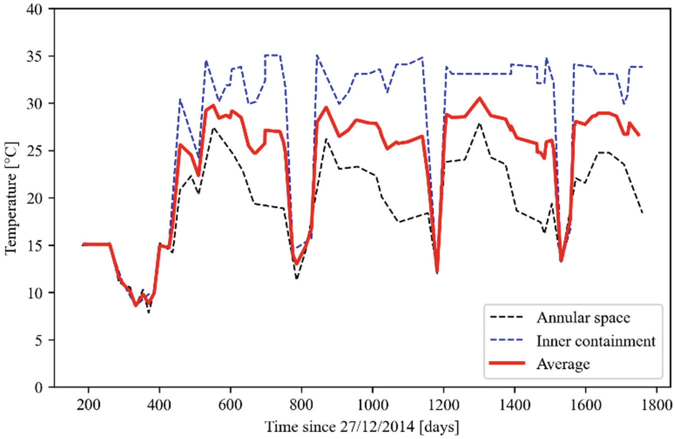

Fig. 5. Temperature history applied in the simulation

Sensors
The VERCORS mock-up is equipped with a comprehensive monitoring system, including a large number of strain sensors (vibrating wires). In our case, we compare our modelling with the measurements of several sensors situated at mid-height and in an area far from singularities. The measurements in the vertical direction (V) and the horizontal direction (T) are considered. Two measures of the prestressing tendons are also available and are compared with the predicted evolution.

3.3 Comparison Between Modelling and In-Situ Measurements

Figures 6 and 7 show the comparison between modelling and experimental measurements of the strains and Fig. 8 the comparison of the loss of vertical prestressing. Compared to the variability of the measurements, it could be seen that the modelling gives acceptable predictions of the deformations.

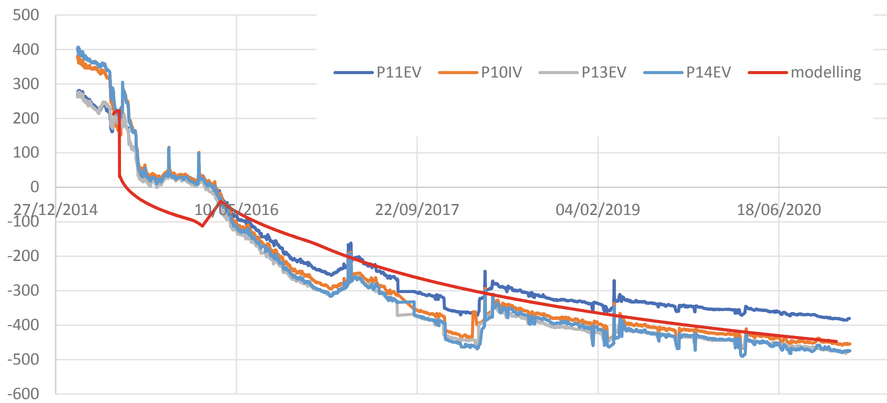

Fig. 6. Modeled vertical strain compared with the measurement of vibrating wires

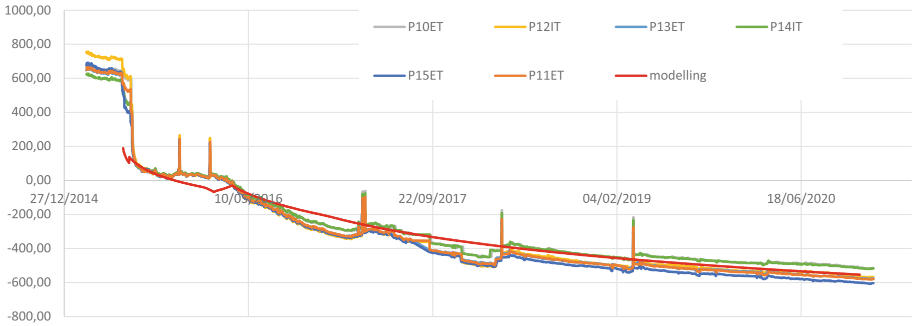

Fig. 7. Modeled tangential strain compared with the measurement of vibrating wires

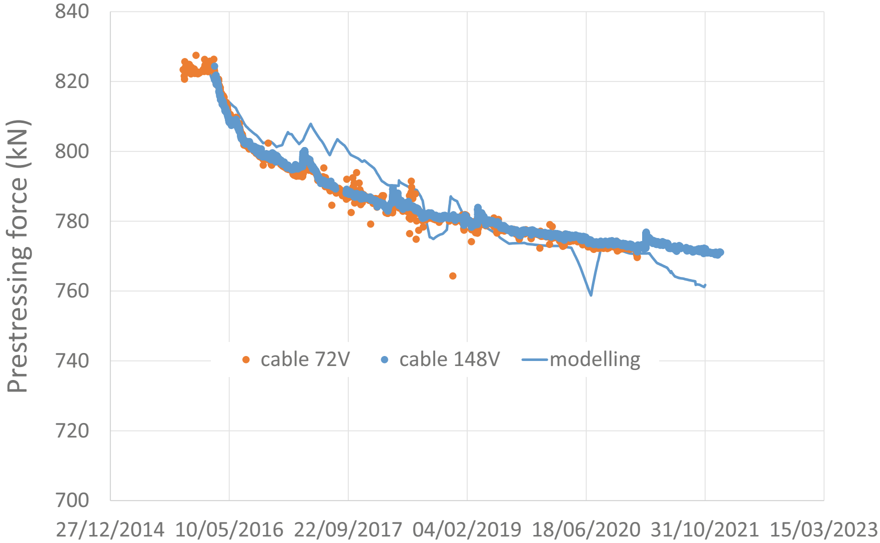

Fig. 8. Evolution of the prestressing force

3.4 Discussion of the Results

This section discusses the impact of thermo-activation on the delayed strain of the mock-up. In addition to the simulation with accounting thermo-activation on C in Eq. 4, two other simulations were performed: one without thermo-activation and the other with thermo-activation on characteristic time τ in Eq. 4. The basic creep in horizontal direction from the three simulations are displayed in Fig. 9, showing the impact of thermo-activation is rather small for the given temperature history in the case of the mock-up. Therefore, thermo-activation on basic creep can be neglected for the given temperature history in the case of the mock-up.

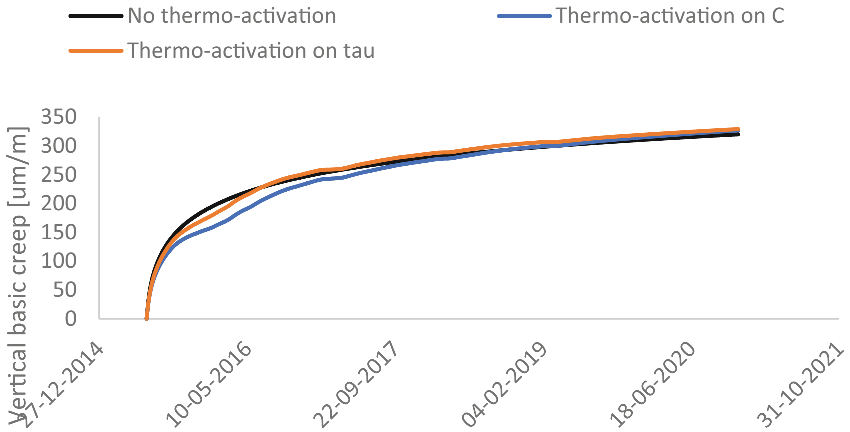

Fig. 9. Comparison of the contribution of basic creep on tangential strains with different assumptions for the thermo-activation of basic creep.

4 Conclusions

Delayed deformations of the VERCORS mock-up are estimated using shrinkage and creep relations of the future Eurocode-2 [1] and MC2010 [3]. Analytical simulation of a single material point considering the coupling between strain of concrete and stress relaxation in prestressing tendons is able to consider impact of varying relative humidity and temperature. Modeling results of the single point are comparable to the strain measurement on the mock-up hence could be used to quick-estimate the margin of safety. It is found that the thermo-activation on basic creep does not play significant role in the case of the mock-up but this result could be different for a real NPP.

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