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# Lifespan Evaluation of a Nuclear Vessel in Terms of Prestress Loss

## Prévision sur 40 ans des pertes de précontrainte d'une enceinte nucléaire

## Abschätzung der Lebensdauer von Spannbeton in Nuklearreaktoren

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**SUMMARY**

The mechanical strength and tightness of the reactor buildings of French nuclear power plants are provided by biaxial prestressing of the concrete. To evaluate the "life" of the containment, in the sense of loss of prestress, the authors propose a physical-chemical model of the delayed behaviour of concrete, which is applied to the Paluel power station in Normandy. The modelling of the structure and the comparison of the simulations with in situ measurements are described over a period of 10 years.

**RÉSUMÉ**

La tenue mécanique et l'étanchéité du bâtiment réacteur de centrales nucléaires françaises sont assurées par une précontrainte biaxiale du béton. Afin d'évaluer la "durée de vie" de l'enceinte au sens de la perte de précontrainte, les auteurs proposent une modélisation physico-chimique du comportement différé du béton qui est appliqué à la centrale de Paluel en Normandie. L'article présente la modélisation de la structure et la comparaison des simulations avec les mesures in situ sur une période de 10 ans.

**ZUSAMMENFASSUNG**

Die Festigkeit und Dichtigkeit der Nuklearreaktoren in französischen Atomkraftwerken werden durch zweiachsige Vorspannung des Betons gewährleistet. Um die Lebensdauer, im Sinne von Vorspannverlusten, dieser Behälter abzuschätzen, stellen die Autoren ein auf physisch-chemischen Grundlagen basierendes Modell zur Bestimmung des zeitabhängigen Verhaltens von Beton vor, welches zur Berechnung des Paluel Kernkraftwerks in Normandie verwendet wurde. Die Modellierung des Bauwerks wird gezeigt und die numerischen Ergebnisse mit in situ Messungen über eine Periode von 10 Jahren verglichen.

## 1. THE INDUSTRIAL PROBLEM

The reactor building of a 1300 MWe nuclear power plant consists of 2 concentric containments (Fig. 1). The inner containment, biaxially prestressed, from 90 to 120 cm thick, is designed to withstand an internal pressure of 0.5 MPa, which leads to a mean initial prestress of 8.5 MPa along zz and 12.0 MPa along θθ. The outer one, designed to withstand external aggressions, is made of reinforced concrete. The construction of the containments lasts 5 years; the prestressing begins at the end of the 2$^{nd}$ year and takes 1 year, in a complex site staging. The reactor is commissioned approximately 7 years after the start of work. In the operating stage, the inner containment is subjected externally to "atmospheric conditions" (15°C, 60% HR) and internally to a temperature and a relative humidity of 30°C and 45 %.

In an accident condition, the tightness of the structure depends mainly on the residual prestress of the concrete. But the devices for surveillance of delayed strains (wire strain gauges, Invar wires, etc.) reveal kinetics of strain that regulation models [3, 5], fail to incorporate in a satisfactory manner. To improve the "management" of the set of power stations, through a better evaluation of their life, EDF undertook in 1992 a vast programme of study [6] with a view to predicting the true creep behaviour of the containments. This study includes many shrinkage and creep tests on concretes reconstituted in the laboratory, together with numerical modelling with a view to prediction of the *in situ* strains in 40 years.

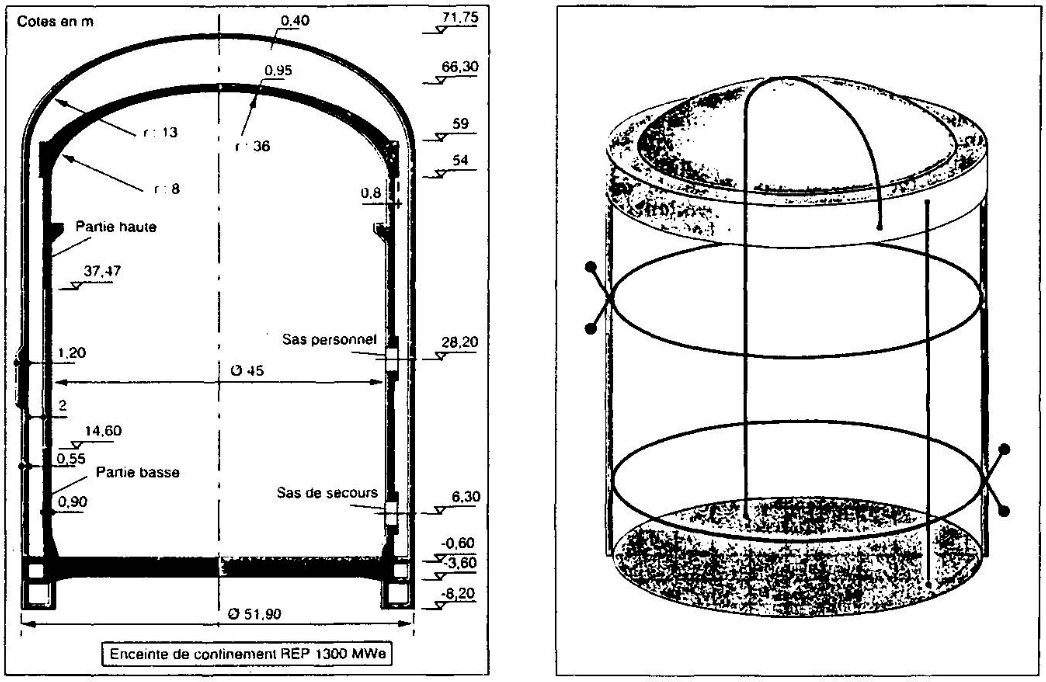


Fig. 1 Simplified diagram of containment and prestress.

## 2. MODELLING OF THE DELAYED BEHAVIOUR OF CONCRETE

An elastic calculation, by finite elements, in which the structure is subjected to an internal pressure (simulating the prestress), shows that in the running part, 15 m < z < 45 m, the shaft is deformed as an infinite cylinder, not constrained by the dome or the foundation raft. This calculation is used to validate the material approach, chosen over a relatively cumbersome numerical calculation of the whole structure.

In what follows, we shall distinguish drying creep from basic creep and drying shrinkage from endogenous shrinkage according to the commonly accepted definitions [2]. The engineering model we propose, of the equivalent continuum type, is based on a very simple principle: each physico-chemical component receives specific numerical treatment [1,2].

• As for the linear thermo-elastic strain, $\underline{\underline{\varepsilon}}_e$, we write, conventionally:

$$\underline{\underline{\varepsilon}}_e = \frac{1+\nu}{E}\underline{\underline{\sigma}} - \frac{\nu}{E}\mathrm{tr}(\underline{\underline{\sigma}})\underline{\underline{1}} + \alpha\Delta T\underline{\underline{1}} \qquad (1)$$

• The basic creep is modelled as a function of the relative humidity h (% RH) and temperature T (K). The creep function $J_{bc}$, taken from [5], is then:

$$J_{bc}(t,t_c,h,T) = \frac{1}{E_0} + h\frac{T-248}{45}\cdot\frac{28^{0,2}+0,1}{t_c^{0,2}+0,1}\Phi_{bc}(t_{eq},t_c=28,h=1,T=20°) \qquad (2)$$

$$t_{eq}(t) = \int_{s=t_0}^{t}\exp\left(-\frac{U_c}{R}\left(\frac{1}{T(s)}-\frac{1}{293}\right)\right)ds \qquad (3)$$

The viscoelastic constitutive law we use makes it possible to take the temperature and humidity history into account. If, at time $t_n$, the stress, the strain, the temperature, and the humidity, assumed constant over a time interval, are known, the strain for $t \in [t_n, t_{n+1}]$ is found by writing:

$$\varepsilon_n(t) = \varepsilon_{n-1}(t) - \sigma_{n-1}J_{bc}(t,t_n,h_{n-1},T_{n-1}) + \sigma_n J_{bc}(t,t_n,h_n,T_n) \qquad (4)$$

This formulation, which corresponds to an unloading and complete reloading, then indeed satisfies the elementary criteria of continuity.

• The drying shrinkage $\varepsilon_{ds}$ is taken as proportional to the weight loss $(\frac{\Delta P}{P})$ [1, 2] :

$$\varepsilon_{ds}(t) = k\left[\left(\tfrac{\Delta P}{P}\right)_t - \left(\tfrac{\Delta P}{P}\right)_0\right] \qquad (5)$$

The term $k(\frac{\Delta P}{P})_0$ results from the fact that the shrinkage induces a skin cracking of the material by blocked strain. This cracking, rarely visible to the naked eye, can be found in curves of drying shrinkage versus weight loss (Fig. 2).

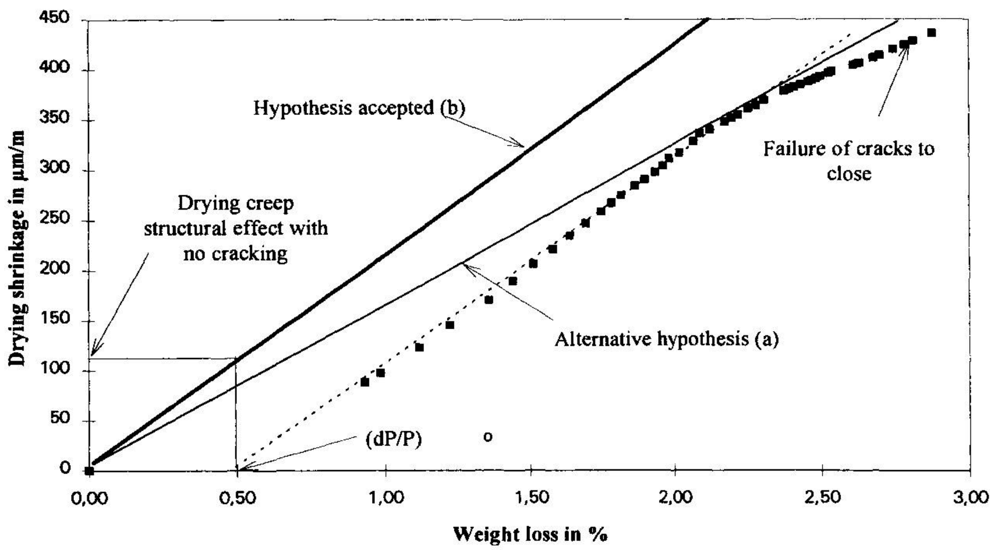


Fig. 2 Drying shrinkage versus weight loss.

Various authors [10] have observed, on very small specimens, a *quasi* linear relation between drying shrinkage and weight loss. The curve above, if the skin cracking did not appear, could be analyzed in two ways:

**a)** According to the dashed curve [4, 2].

**b)** But in our opinion [6, 7], the behaviour is represented rather by the solid curve, since the cracks can in all likelihood not close, or only very poorly.

• The drying creep $\varepsilon_{dc}$ [7, 2] results from the sum of an intrinsic creep (int) proposed by Bazant and a structural effect (str) linked to the drying shrinkage:

$$\Delta\varepsilon_{dc}^{int} = \lambda\sigma|\Delta h| \qquad \varepsilon_{dc}^{str} = kF(\sigma)\left[\left(\tfrac{\Delta P}{P}\right)_{load} - \left(\tfrac{\Delta P}{P}\right)_0\right] \tag{6}$$

where $\left(\frac{\Delta P}{P}\right)_{load} \leq \left(\frac{\Delta P}{P}\right)_0$ is the weight loss that has already occurred at the age of loading. From [9], $F(\sigma)$ is given by:

$$\sigma \leq 0 \Rightarrow F(\sigma) = 0 \qquad 0 \leq \sigma \leq 15 \Rightarrow F(\sigma) = \frac{\sigma}{15} \qquad 15 \leq \sigma \Rightarrow F(\sigma) = 1 \tag{7}$$

The total delayed strain $\varepsilon_{tot}$ is then found by adding together the different contributions:

$$\varepsilon_{tot}(t) = \varepsilon_e(t) + \varepsilon_{ds}(t) + \varepsilon_{bc}(t) + \varepsilon_{dc}^{int}(t) + \varepsilon_{dc}^{str}(t) + \varepsilon_{tc}(t) \tag{8}$$

where $\varepsilon_{tc}$ is a transcient thermal creep. It should be noted that only the basic creep must follow the constitutive law established in (4). As for the sequencing of the calculations, a thermal calculation is performed first of all. It is followed by a calculation of hygral diffusion (transient, nonlinear) in which the coefficient of hygral diffusion is a function of the water content $C(\underline{x},t)$ and of the temperature $T(\underline{x},t)$ given by the previous calculation:

$$\frac{dC}{dt} = \mathrm{div}(D(C,T)\underline{\mathrm{grad}}(C)) \tag{9}$$

Finally, a 3rd calculation, viscoelastic, uses the foregoing results and calculates, at each time step, the total delayed strain at each point of integration of the mesh. Note that the fact of linking the three calculations in this order presupposes some conventional decouplings between the various delayed strains (9). The main physical parameters of the model are then determined from the results of the experimental programme, mechanical tests, a weight loss test, and a complete test of delayed behaviour (endogenous shrinkage, total shrinkage, basic creep, and creep at 50 % RH).

- The free water content is given by $C_0 = w_0 - 0{,}9 \cdot 0{,}22c_0$ where $c_0$ is the weight of cement and $w_0$ the quantity of water. C(h) is evaluated by recent desorption results.
- $J_{bc}(t, 28, h = 1, 20°)$ is fitted to the basic creep test.
- $D(C,T) = A \cdot 10^{-13} \exp(0{,}05C)\frac{T}{293}\exp(-\frac{U_T}{R}(\frac{1}{T} - \frac{1}{293}))$ is fitted to the weight loss test.
- k and $(\Delta P/P)_0$ are fitted to fig. 2.
- $\lambda$ is fitted to give the total strain.
- $\alpha$ = 10.10-6 °C$^{-1}$ and $U_T$ and $U_c$ are values taken from the literature.

The results of the various simulations are given in fig. 3, which shows in particular the shares of the various delayed strains calculated on a laboratory sample of 16 cm diameter..

## 3. SIMULATION OF STRAINS ON CONTAINMENT

When the various parameters of the model have been determined, it is possible to predict the results on a structure (fig. 4) from the staging of prestressing and the boundary conditions (in temperature and humidity) and compare the simulations performed with measurements made *in situ* over a period of 10 years (fig. 5).

The study of the containment is limited to study of an annulus 6 m high and 90 cm wide calculated in axisymmetry. To model the initial prestress, the test body is subjected to a

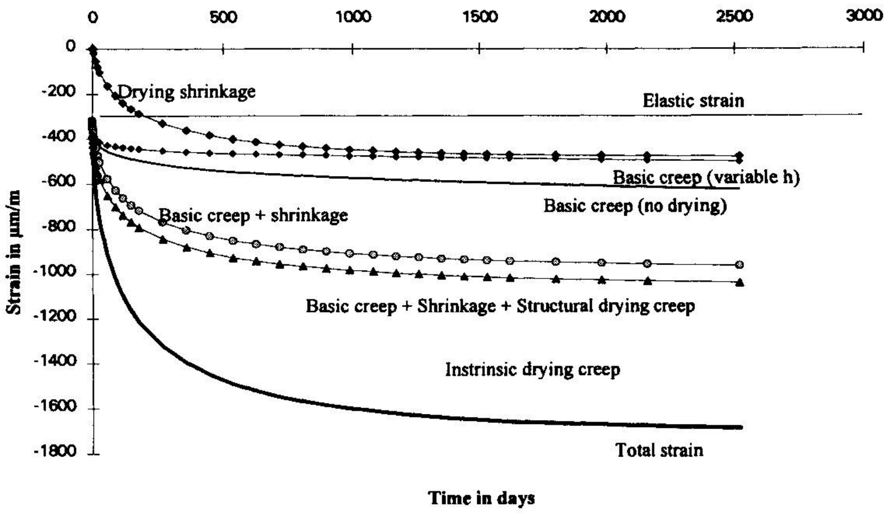


Fig. 3 Breakdown of delayed strains of Paluel on specimen ∅ 16 cm.

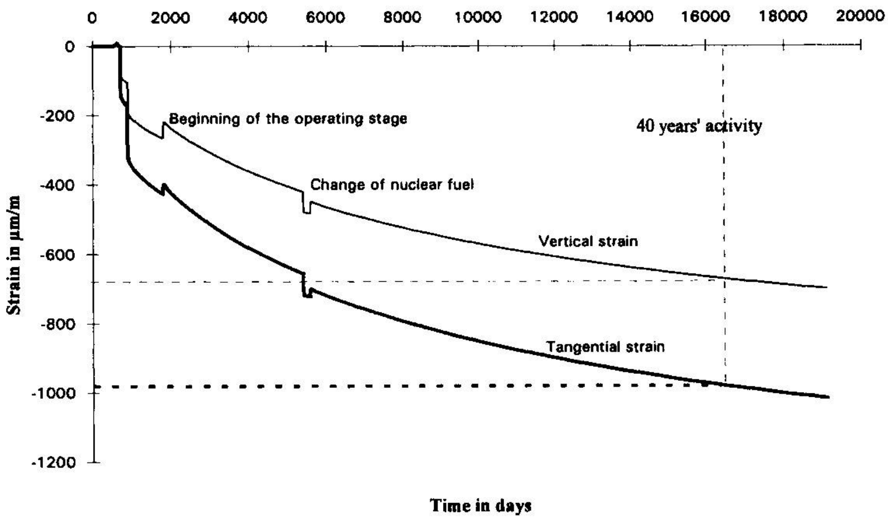


Fig. 4 Simulations of Paluel containment for a constant initial prestress.

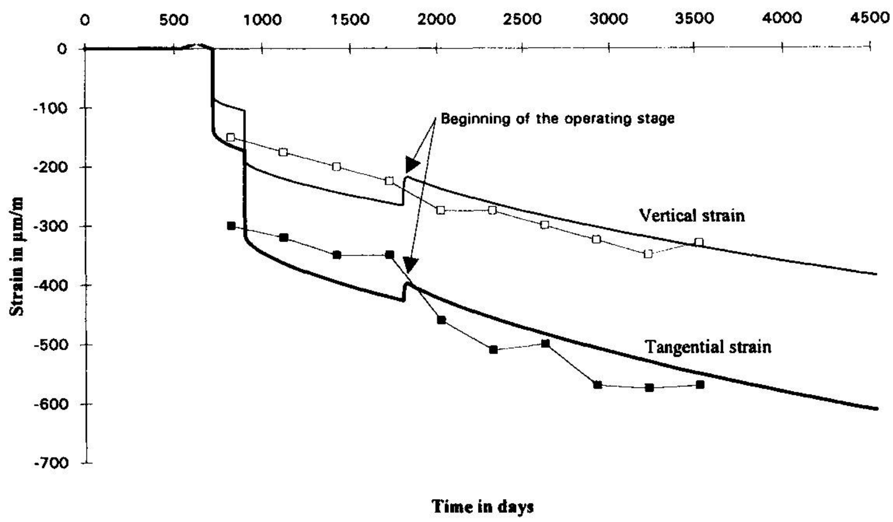


Fig. 5 Comparison between simulations and *in situ* measurements over a 10-year period.

constant pressure along $e_{zz}$ of $p_{zz}$ = 8.5 MPa and a constant pressure along $e_{rr}$ calculated as follows $p_{rr} = \frac{\sigma_{\theta\theta}}{R_{ext}} = \frac{12}{24} = 0{,}5$ MPa to model the prestress along $\theta\theta$.

## 4. CONCLUSION

In structural calculations, the behaviour of the concrete is taken into account in accordance with regulations that give an average response for the material. It should however be recalled that the delayed strains of a particular concrete (for a given range of strengths) can be rather far from the tendency indicated by the regulation. For sensitive industrial applications, it is therefore recommended that a study of the delayed behaviour of the concrete used should be undertaken when the building of the structure is started. In the case of nuclear containments, the shrinkage and creep results obtained in the laboratory are used to judge the delayed strains to come and therefore the life of the structure. However, the phenomena of delayed strains can be investigated only by relatively long tests (2 years); this time is often incompatible with construction site planning. If it is desired to guard against the hard-to-control influence of the constituents (aggregates, binder), the use of a high-performance concrete (compatible with the design criteria of the structure), one that is particularly good in terms of shrinkage and creep, [8], can help to substantially reduce the risks related to losses of prestress.

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