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# Risk due to creep of prestressed concrete at moderate temperature

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**Abstract.** This study is a part of a French national project dealing with the mechanical behaviour of the containment vessel of French Nuclear Power Plants in case of a severe accident. The accident conditions are characterized by the increases of internal pressure, +0.5 MPa, and of temperature, up to 180°C, during two weeks. Heating can induce a strong increase of creep deformations kinetics leading to prestressing losses of concrete. Associated to internal pressure, tensile stress could occur in some areas of the structure and the potential cracking could affect the containment capacity of the vessel. One of the objectives of the project was thus to provide original creep data to develop accurate models, taking into account the coupled effects of temperature, desiccation and damage, and able to predict the behaviour of prestressed concrete structures in such in-situ conditions. A wide experimental program consisted of numerous creep tests under various thermo-hydro-mechanical conditions in the values range of the accident. The presented results concern uniaxial compressive and flexural creep tests respectively performed on concrete cylinders and prestressed concrete beams, at 20°C and 40°C without desiccation.

## 1 Introduction

Controlling and guaranteeing the tightness of containment vessel of Nuclear Power Plants (NPP) is a worldwide challenge. The recent French national research project “Macena” has been led to study the mechanical behaviour of the prestressed concrete vessel, corresponding to the last barrier in French NPP, in case of a severe accident. These conditions correspond to a rise of internal pressure and temperature respectively up to 0.5 MPa and 180°C during two weeks. Previous studies based on compressive creep tests have shown an increase of creep strains and of their evolutions kinetics with heating, which can be amplified by the coupled effects of desiccation or damage thermal [1]. Moreover, if heating is applied on a concrete previously loaded, this increase is stronger than if it occurs before. This phenomena is called Transient Thermal Deformation (TTD) or Transient Thermal Creep [2]. Its origins are controversy, some researchers advancing the assumption

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of a thermal damage [3], or a transient change of C-S-H viscoelastic behaviour due to thermal dilation of the inter-sheet water [4]. This phenomena is all the more necessary to evaluate that the conditions in case of a severe accident of a NPP would be such that it would occur. Moreover, temperature affects prestressing wires relaxation [5]. Thus, experiments have to be carried out at the prestressed concrete elements scale to identify thermal coupled effects for the two materials.

A part of the experimental results provided by the project Macena is presented. It concerns compressive creep tests carried out on concrete cylinders in autogenous conditions at 20°C and 40°C, with two levels of loading, moderate and high, and the flexural creep tests performed on 0.9 meter length prestressed concrete beams submitted to the same conditions. In both tests, temperature rise was applied after loading to be representative of real accident conditions which would thus induce TTD. The results analysis allowed to assess the TTD at moderate temperature coupled with high loading. A comparison of strains evolutions measured on compressive creep tests at concrete material scale and at the structural element scale, prestressed beam, before and during flexural creep is led.

## 2. Material and methods

### 2.1 Materials

Table 1 presents the rather classical concrete mix with a $W_{eff}/C$ ratio of 0.52.

**Table 1.** Concrete mix.

| Constituents | Mass (kg) for 1 $m^3$ of concrete |
|---|---|
| Sand 0/4 | 830 |
| Rolled aggregate 4/11 | 445 |
| Rolled aggregate 8/16 | 550 |
| Cement CEM I 52.5 N CE CP2 | 320 |
| Superplasticizer Techno 80 Sika plast (% of cement mass) | 2.4 (0.75%) |
| Effective water $W_{eff}$ | 167 |

At 28 days, the mechanical properties were the following (means values obtained from three tests for each property): a compressive strength $f_{cm}$ of 46.1MPa ± 1.2MPa, a Young's modulus $E_{cm}$ of 35.1GPa ± 0.2GPa and a tensile strength $f_{ctm}$ of 3.9 MPa ± 0.2MPa. For prestressed beams, a single post-tensioned cable was used. Its mechanical properties were the following: a characteristic tensile strength $f_{pk}$ of 1860MPa, a characteristic 0.1 % proof-stress of prestressing steel $f_{p0.1k}$ of 1650MPa and a Young's modulus $E_p$ of 195GPa. Its diameter and its cross-section were respectively 15.7mm and 150mm$^2$.

### 2.2 Thermo-mechanical conditions for creep tests

The chronology of thermo-mechanical conditions for the two types of creep tests is presented in the Fig.1. After casting, concrete cylinders and prestressed beams were kept in their moulds, covered by a plastic sheeting and stored in a curing room at 99%RH (±1%, measured by a humidity sensor) and 20°C (±1°C, measured by a temperature sensor). After one day, they were demoulded and sealed with three aluminium foils to avoid moisture exchange. They were stored at 20°C during 1 month minimum in order to stabilize hydration and be representative of the hygrometry conditions of concrete located in the mass of the real structure. At 64 days, the prestressing cable of each beam was tensioned (date $t_t$). From this date, concrete creep due to tensioning occurred in prestressed beams. At the date $t_0$, variable depending on the type of creep test (>2 months), the loading, compressive for cylinders and bending for beams, was applied. Some samples stayed in autogenous condition at 20°C, whereas others were heated at 40°C one day after loading. The heating kinetic was 0.1°C/min, as proposed by [1] to avoid thermal damage.

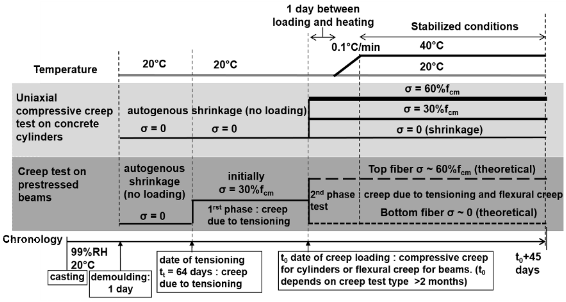

**Fig. 1.** Chronology of thermo-mechanical conditions for the two types of creep tests.

## 2.2 Description of uniaxial compressive creep tests

The uniaxial compressive tests were carried out on cylinders (11 cm in diameter, 22.4 cm in height). After curing, 6 different thermo-mechanical conditions were tested: unloaded samples at 20°C and at 40°C to follow the free strains (shrinkage and thermal dilation), moderately loaded at 30% of the compressive strength $f_{cm}$ measured at the date of the test, and highly loaded at 60%$f_{cm}$, at 20°C and 40°C for the two loading levels. 30%$f_{cm}$ is closed of 12 MPa which corresponds to those of existing prestressed concrete containment vessel. A LDVT sensor is located in each sample, in a central niche created by a removable element placed in the mould before casting [1]. It allowed to record the longitudinal strains. Gauges were also added to measure the transient strain during heating. Compressive creep devices are equipped by a hydraulic jack and a nitrogen accumulator tank to restore the pressure loss due to concrete creep [1]. The load is applied using a hydraulic pump. They were located in two different rooms: one at 20°C and a climatic chamber for test at 40°C.

## 2.3 Description of flexural creep tests

The geometry of the prestressed beams and the mechanical configuration of the 4-points flexural creep test are presented in Fig.2. The anchorage of the cable led to enlarge the cross-section at the beams ends. However, only the central part of the beams is of interest for flexural creep. The rectangular central cross-section, 80mm x 200mm, the tension force and the centred position of the cable were chosen in order to apply a uniform stress with a value of 12 MPa, neighbouring of those of the existing prestressed structure and corresponding to those of the compressive creep test at 30%$f_{cm}$. Tensioning (1$^{rst}$ phase) induced a compressive concrete creep, which, added to shrinkage and cable relaxation, reduced the initial compressive stress of 30%$f_{cm}$. During the flexural creep test (2$^{nd}$ phase), the force F was calculated to generate a compressive stress corresponding to 60%$f_{cm}$ on the top fiber, as the highest one of compressive creep test. It led to a stress null on the bottom fiber. These values were theoretical since they did not take into account the delayed materials strains (concrete and steel) occurring between the dates of tensioning $t_t$ and of flexural creep test beginning $t_0$, which both generate loss of prestressing. Two gauges were pasted on the top fiber (side of application of the force F) and two others on the bottom one of each beam to record the strains during the two phases from the demoulding.

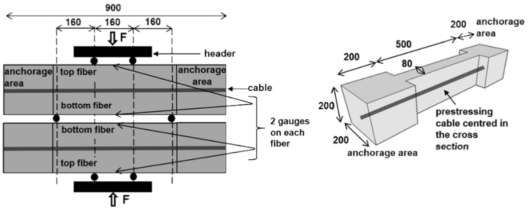

**Fig. 2.** Prestressed beams geometry with the single cable centred in the cross-section and dimensions in mm, and 4-points flexural creep loading associating two beams thanks to headers and small rollers.

## 3 Experimental results

### 3.1 Shrinkage and compressive creep of concrete cylinders

The evolutions of shrinkage measured on concrete cylinders during the 20°C autogenous curing period, and after at 20°C or 40°C (in parallel of creep tests) are presented in Fig.3a. The evolutions of total strains (elastic, shrinkage, creep) from the date of loading $t_0$, for the two loading levels 30% and 60%$f_{cm}$, for the two temperatures are on Fig.3b.

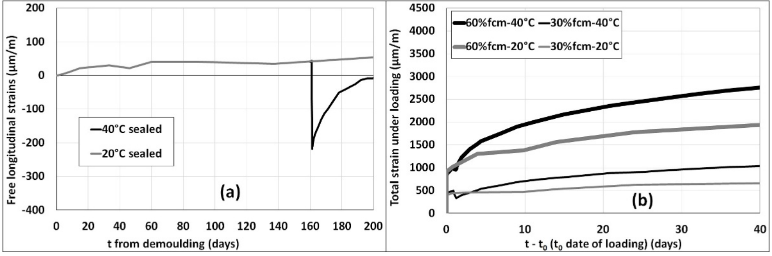

**Fig. 3.** Evolution of autogenous shrinkage at 20°C and at 40°C after 160 days (a) - Evolution of total strains under sustained loading for the various thermo-mechanical conditions (b).

The 20°C autogenous shrinkage is low (Fig.3a) in accordance with this concrete strength class. The samples heated at 40°C (at 160 days) dilate and the coefficient of thermal expansion can be estimated to 12.5µm/m/°C, slightly superior to the Eurocode 2 value [6]. When temperature is stabilized at 40°C, autogenous shrinkage seems to be thermally activated. The loss of mass, 0.58% measured at the end of test (45 days at 40°C), reveals a part of parasite desiccation shrinkage. When loading is applied (Fig.3b), elastic strains occur and are linear with the loading level, 30% or 60%$f_{cm}$. Then, delayed strains develop at 20°C, and, after one day, some samples are heated during 200min until 40°C. Dilation appears but creep strains become quickly predominant. This increase of strains evolutions kinetics corresponds to TTD. The evolutions at 30% and 60%$f_{cm}$ show that creep is non linear with stress level, as expected [3]. But this effect does not seem amplified by heating.

### 3.3 Flexural creep test

The evolutions of strains of the top and bottom fibers of the beams are presented on Fig.4 from the date of tensioning (a) and from the date of flexural loading (b).

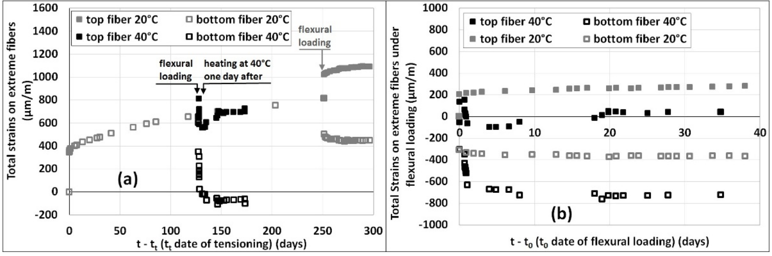

**Fig. 4.** Evolution of strains on bottom and top fibers of prestressed beams from tensioning date $t_t$ (a) and during flexural creep at 20°C and at 40°C from flexural date $t_0$ (b).

On Fig.4a, a same value of elastic strains appears on the two fibers when tensioning, since the cable is centred. Over this date, autogenous shrinkage and creep strains due to prestressing develop. Flexural loading was applied at various dates due to the availability of the climatic chamber, 120 days for 40°C series and 250 days for 20°C. The Fig.4b focuses of the strains from the date of flexural loading to make the comparison easier. Compressive and tensile strains appear respectively on top and bottom fibers, with the same amplitude for the two series, still at 20°C. At 20°C, the delayed compressive strain of the top fiber is rather low whereas the bottom one reveals a slight tensile creep. When heating at 40°C after one day of loading, dilation occurs with a same value on the two fibers. The temperature stabilization induces an increase of strains evolutions kinetics of the top fiber compared to 20°C ones. Although the thermo-mechanical conditions would generate TTD, its effect seems low. The bottom fiber delayed strain evolution is negligible.

### 3.4 Comparison of delayed strain between the two types of creep tests

The Fig.5 presents the delayed strains comparisons between the two types of creep tests.

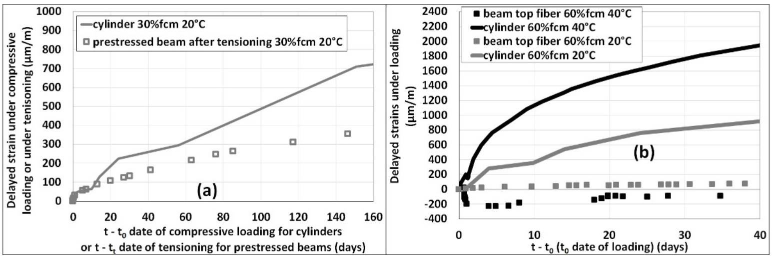

**Fig. 5.** Delayed strains comparisons: 30%$f_{cm}$ compressive creep vs beam submitted to tensioning at 20°C (a). 60%$f_{cm}$ compressive creep vs beam top fiber during flexural loading at 20°C and 40°C (b).

The Fig.5a shows that the delayed strains of cylinder and of extreme fibers of beams are similar during 10 days. But, over, the evolutions separate and the difference increases due to the loss of prestressing induced by concrete shrinkage, creep and steel relaxation. On Fig.5b, the amplitudes and kinetics of delayed strains evolutions measured on cylinders at 60%$f_{cm}$ for the two temperatures are significantly stronger than those recorded on the beam top fiber from the date of flexural loading. This result can be explained by the fact that the previous tensioning period has decreased the stress in the beam. Thus, the stress on compressive fiber, certainly inferior to 60%$f_{cm}$ and associated to the non linear effect of loading, could partially explained the discrepancy. Another explanation could be the consolidation of concrete induced by tensioning which would consummate its creep potential [7,8] attenuating the delayed strain evolution during flexural creep, even at 40°C.

## 4 Conclusions

This study is a part of the program of the French national research project on the behaviour of the containment vessels of Nuclear Power Plants in case of a severe accident. The results concern compressive creep test of concrete cylinders and flexural creep test of prestressed beams at 20°C and 40°C. Compressive creep test has revealed the occurrence of Thermal Transient Deformation (TTD) when heating is applied on previously loaded concrete. This phenomena is characterized by an increase of delayed strains evolutions kinetics. The strains evolutions under two loading levels showed the non linearity of creep with stress, but this effect seemed not to be amplified by heating. In case of beams, the TTD seemed weaker. The comparison of results of the two types of creep test showed that delayed strains of 30%$f_{cm}$ compressive creep tests became quickly greater to those measured on beams only submitted to the same initial stress due to tensioning ($1^{rst}$ phase), because of the loss of prestressing due to shrinkage and creep, and steel relaxation. During the beam flexural creep test ($2^{nd}$ phase), the delayed strain of the most compressive beam fiber developed a much lower TTD than those of 60%$f_{cm}$ compressive creep test. This result can be both attributed to a real stress inferior to 60%$f_{cm}$ in case of beams due to the loss of prestressing from tensioning date, and also to the concrete consolidation during this phase which would have consummated its creep potential, attenuating the later delayed strains.

## References

1. W. Ladaoui, T. Vidal, A. Sellier, X. Bourbon, Analysis of interactions between damage and basic creep of HPC and HPFRC heated between 20 and 80°C, Materials and Structures 46 (2013) 13-23
2. H.M. Fahmi, M. Polivka, B. Bresler, Effects of sustained and cyclic elevated temperature on creep of concrete, Cement and Concrete Research 2 (1972) 591-606.
3. J.M. Torrenti, Basic creep of concrete-coupling between high stresses and elevated temperatures, European Journal of Environmental and Civil Engineering, published online (2017). https://doi.org/10.1080/19648189.2017.1280417
4. H. Cagnon, T. Vidal, A. Sellier, X. Bourbon, G. Camps, Transient Thermal Deformation of High Performance Concrete in the range 20°C - 40°C, Mag. Concr. Res. (accepted).
5. P. Chhun, A. Sellier, L. Lacarriere, S. Chataigner, L. Gaillet, Incremental modeling of relaxation of prestressing wires under variable loading and temperature. Constr. Build. Mater. 163, 337–342 (2018)
6. EN 1992-1-1 (2004) (English): Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings
7. P. Acker, J.M. Torrenti, F. Ulm, Comportement du béton au jeune âge - Traité mécanique et ingénierie des matériaux, Hermès-Lavoisier, Paris, 2004
8. A. Sellier, S. Multon, L. Buffo-Lacarriere, T. Vidal, X. Bourbon, G. Camps, Concrete creep modelling for structural applications: non-linearity, multi-axiality, hydration, temperature and drying effects, Cement and Concrete Research 79 (2016) 301-315.