Long term monitoring of large nuclear waste concrete structures : cumulative thermal gradient effects and crack control

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Abstract

Large massive concrete structures built in continental environments are exposed to severe thermal gradients. Such gradients may produce irreversible and evolutive cracks through concrete elements. In such conditions, seasonal variations will affect crack width, depth and pattern such that visual inspections will differ from winter to summer periods. We propose in this paper a long-term non-destructive monitoring method to assess such thermal effects. The method called "ConcreteLife" is based on strain deconvolution through embedded vibrating wire strain gage measurements within both concrete structure and free concrete samples. Mechanical strains, free shrinkages and local thermal strains are deduced from the coupled strain-temperature measurements such that cracking events and evolution are monitored over seasonal variations.

Such a method has been used to monitor nuclear waste facilities during the last 15 years. We present in this paper long-term experimental data and ConcreteLife analysis on a Basic Nuclear Installation (INB) for solid low- and intermediate-level short-lives radioactive waste. Our analysis quantified thermal gradient biaxial stresses through the monitored large reinforced concrete structure (24m long, 21m large and 8m high). In situ monitoring over a long period (15 years) allowed us to verify that measured microcracks met the required specification in terms of width and evolution.

As the knowledge base for modern concretes is relatively short (i.e about 100 versus the required 300 or more years for nuclear waste facilities), such an approach will help to ensure that these structures will continue to meet their design requirements throughout their operational life.

Résumé

Les structures massives en béton subissent des gradients thermiques importants dans des environnements climatiques sévères de type continental. Ces gradients peuvent conduire à la fissuration du béton si l'autocontrainte engendrée excède la résistance à la traction du béton. Une détection de l'ouverture, la fermeture, la profondeur et le faciès de fissuration sera donc fortement affectée par les conditions climatiques lors de l'inspection. Une méthode de mesure des autocontraintes thermiques et des ouvertures de fissures est proposée dans cet article. Cette méthode appelée « ConcreteLife » est basée sur la déconvolution des déformations totales mesurées par capteurs extensomètriques à corde vibrante noyés dans la structure et dans des échantillons libres en béton. Les déformations purement mécaniques (déformation continue ou microfissuration) sont déduites des déformations mesurées de retrait et de dilatation thermique libres. La méthode Concretelife a été appliquée au monitoring d'ouvrages de stockage de déchets radioactifs à faible et moyenne activité et vie courte en partenariat avec l'Agence Nationale pour la Gestion des Déchets Radiactifs (ANDRA). Cette analyse menée sur quinze années de mesure a permis de quantifier les effets progressifs des gradients thermiques sur les ouvrages monoblocs de grande dimension (24m de longueur, 21m de largeur et 8m de hauteur). Le contrôle continu des ouvertures de fissures permet de vérifier la conformité de l'ouvrage vis-à-vis du cahier des charges du Maître d'ouvrage. Cette

approche permet un suivi à long terme de ces ouvrages dont la période de surveillance est estimée à trois cents ans.

Keywords

Long term monitoring, reinforced concrete structure, thermal gradients, vibrating wire strain gage, microcracks

1 Introduction

Control of cracking is an important issue for concrete reservoir and for durable reinforced concrete structures. Crack width, depth and spacing are usually specified and predicted through serviceability limit states (for instance Eurocode 2 [1,2]). On the other hand, concrete internal strains and surface cracks may be measured in order to monitor the structure within its service life. However, correlations between experimental data and structural design analysis are often difficult because measured strains and crack width are strongly correlated to complex environmental and material-based factors (temperature, water content, microcracking, creep, shrinkage…). We propose in this paper an analytical decorrelation tool coupled to a specific instrumentation method. Such an approach aims to determine experimentally the structural mechanical strains and the crack pattern evolution during the service life of concrete structures.

2 Strain deconvolution method

Measured total internal concrete strains regroups different contributions, that can be partially estimated by measuring the free concrete strains through concrete samples stored in the same environmental conditions (Fig.1 and Eq.1).

$$\varepsilon_{total} = \varepsilon_{free} + \varepsilon_{mechanical} + \varepsilon_{cracking} \quad (1)$$

with $\varepsilon_{free} = \varepsilon_{thermal} + \varepsilon_{shrinkage}$; $\varepsilon_{mechanical} = \varepsilon_{elastic} + \varepsilon_{creep}$; $\varepsilon_{cracking} = \varepsilon_{microcracking} + w/l_0$

(w is the crack width, l0 is the extensometer length)

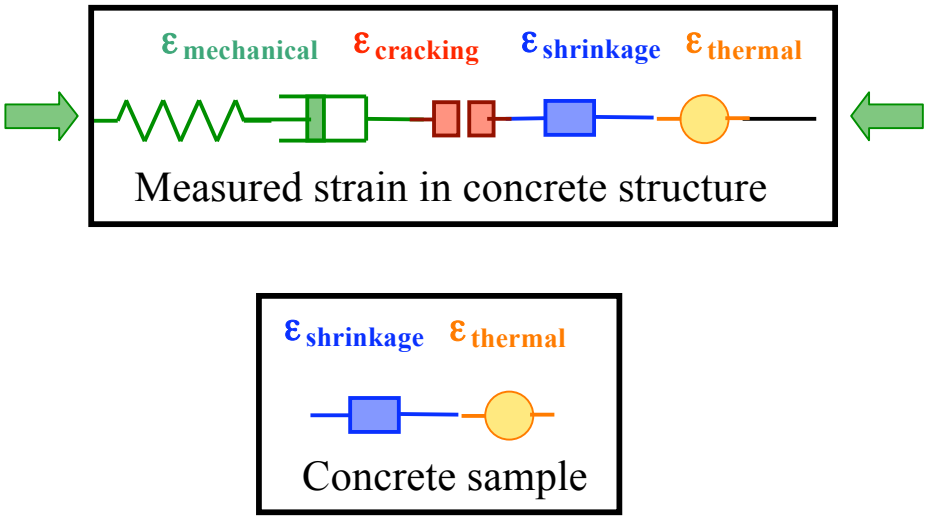

Figure 1. *Schematic of different measured strains in concrete structure and free sample ("ConcreteLife Analysis")*

3 Dedicated instrumentation method

The type, the number and the spatial distribution of strain sensors have to be optimized in order to maximize the "data interpretability" through our decorrelation tool.

3.1 Choice of high resolution long term extensometric sensors

Long term extensometric measurements in concrete structures has usually been performed through embedded vibrating wire strain gages. The use of double solenoid extensometers benefits a 60 year plus return of experience on large concrete structures (particularly on french dams [3]). In addition, such mechanical sensors provide resonant frequency data that are independent from the type of measurement device or data acquisition chain (cable length). The measurement of the solenoid resistance can also give the local change of temperature in the sensor. The sensor resolution is about one microstrain whereas the sensor accuracy is ± 10 microstrains ([4]). The same analysis could be performed through fiber optic sensors.

3.2 Sensor spatial distribution

The instrumentation of different plane sections is used to assess the mechanical behavior of a structure. The distributions of normal and transverse strains are measured through embedded extensometric sensors (Fig. 2&4). For complex structures, Finite Element Method simulations may help to identify the more sensitive sections. As explained in the previous paragraph, free samples have to be instrumented with the same types of sensor and concrete. In the case of a massive concrete section, the microstructure of the concrete will depend on its curing temperature ([5]). The use of in-situ mechanically isolated sample or external sample stored in a quasi-adiabatic box will provide a representative concrete sample (Fig 3.).

Figure 2. *Pictures of instrumented sections with vibrating wire strain gages in reinforced concrete wall (left) and slab (right)*

4 Application to a large reinforced concrete structure

We present in this paper long-term experimental data and the "ConcreteLife" analysis on a Basic Nuclear Installation (INB) for solid low- and intermediate-level short-lives radioactive waste. The instrumented structure is composed of a large massive concrete box made of Reinforced Concrete walls and slab (24m long 21m large and 8m high, fig.4). It was constructed in 1994 and filled with concrete and waste containers in 1996. The in-situ concrete free sample "ConcreteWitness" is located in the slab close to the point B4. In such a massive structure, the mechanical loadings came mainly from the early age period (1994), the

"container filling period" (1996) and the thermal gradients during seasonal thermal variations on the closed system (1996-2008).

Figure 3. *Instrumented free 16x32cm concrete samples : thermally isolated concrete sample ("ConcreteHeat") and in-situ mechanically isolated sample ("ConcreteWitness")*

4.1 Effect of seasonal thermal variations

We focus on the cumulative effects of thermal gradients in the slab. During this period, the concrete external surface of the structure was protected from drying and carbonation. As shown in fig.4, the temperature variations between the center and the side of the slab are almost in opposed phase (5 month thermal characteristic time for the slab). In the figure 5, the sensors in the transverse direction show similar measured total strains validating the Navier-Bernoulli's hypothesis ("plane-section B remains plane"), whereas the normal direction sensors show total strain gradients. The thermal decorrelation of the free sample total strain allows us to determine the in-situ coefficient of thermal dilation of concrete : α=12,1 ppm/°C. By using the Concretelife decorrelation tool, we can assess the mechanical strain evolution due to the thermal eigenstresses that develop within the slab (fig.6). We can observe that the strain evolutions are alternative, small and stabilized over ten years.

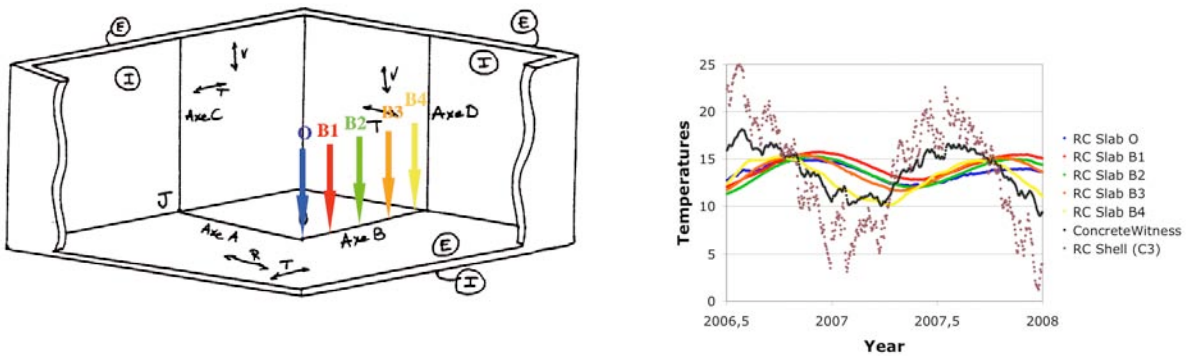

Figure 4. *Instrumented sections and typical seasonal thermal variations within the slab*

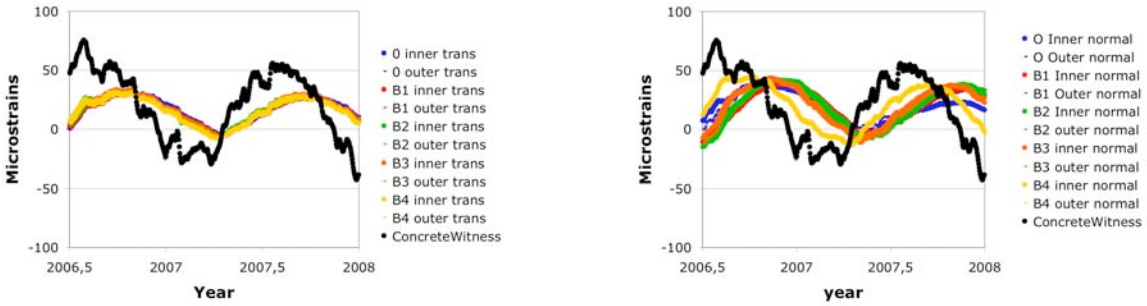

Figure 5. *Transverse (left) and Normal (right) total strains in the instrumented slab section in comparison with free sample total strains*

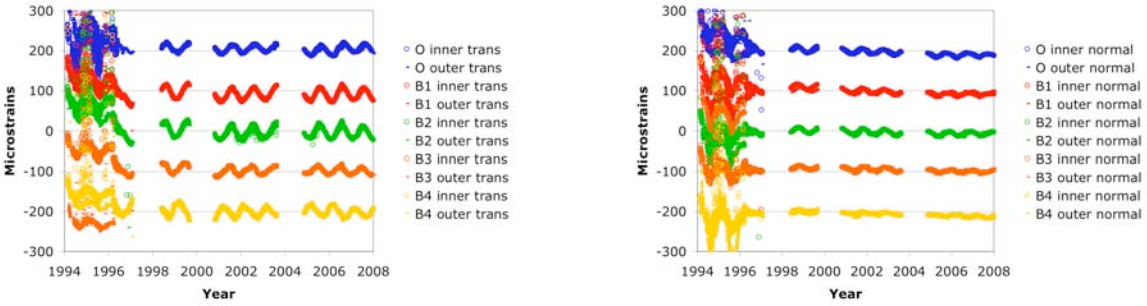

Figure 6. *Mechanical strain evolution for transverse (left) and normal (right) sensors*

The biaxial eigenstress variations may be estimated through apparent elastic derivation, taking into account the observed reversible relaxation behavior ($E_{apparent}$= 20 GPa, ν=0.2) :

$$\Delta\sigma_{Normal} = \frac{E}{1-\nu^2}\left(\Delta\varepsilon_{elastic}^{Normal} + \nu\cdot\Delta\varepsilon_{elastic}^{Transverse}\right) \qquad \Delta\sigma_{Transverse} = \frac{E}{1-\nu^2}\left(\Delta\varepsilon_{elastic}^{Transverse} + \nu\cdot\Delta\varepsilon_{elastic}^{Normal}\right) \qquad (2)$$

Figure 7 confirms that eigenstresses develop more in the transverse direction. No cracking occurs during this period.

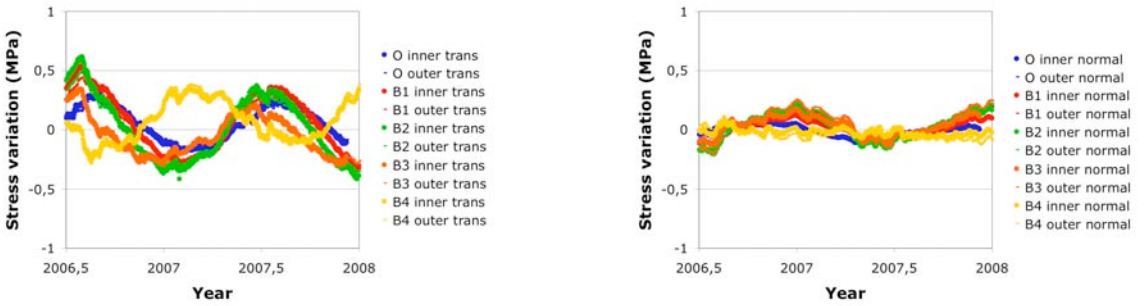

Figure 7. *Eigenstress variations for transverse (left) and normal (right) direction*

4.2 Crack control during the filling period (1996)

Continuous recording (3h interval) allowed us to detect a local cracking event during the filling period in the Reinforced Concrete slab (fig. 8). By monitoring the instantaneous released mechanical strains and by using the Navier-Bernoulli hypothesis on the reinforced concrete section, we can compute the maximum crack opening width w_{max}*=20 micrometers* and the crack depth *h=0.17m* for a total slab depth of *0.4m*. The detected microcrack meets the design requirement and appears to be passive during the period 1996 - 2008 (fig. 6). Such a microcrack could not be monitored through visual inspection.

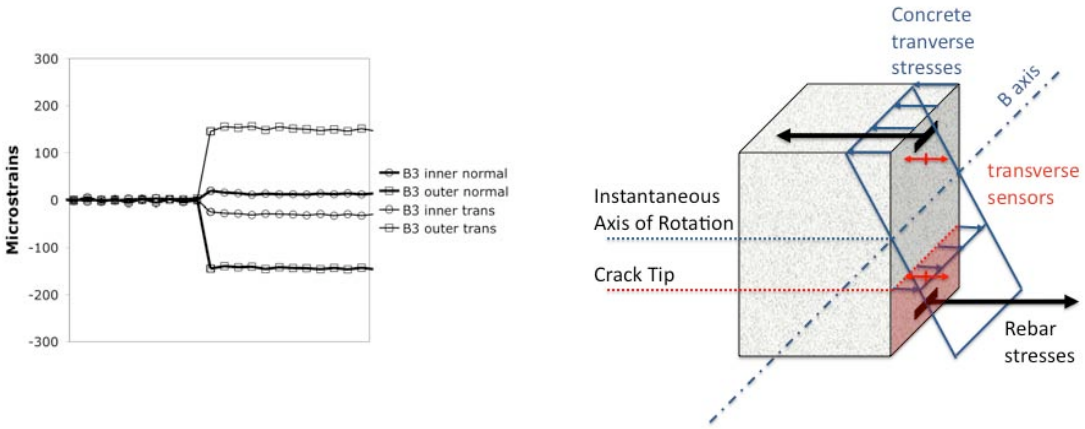

Figure 8. *Local mechanical strains during microcracking - Corresponding section B3 in slab*

5 Conclusions

A decorrelation tool coupled to a dedicated instrumentation approach allowed us to monitor the mechanical behavior of a large reinforced concrete structure over a long period (15 years). Concrete mechanical strains and crack geometry can be assessed and compared to structural design computations. As the knowledge base for modern concretes is relatively short compared to the required surveillance period for nuclear waste facilities, such an approach will help to ensure that these structures will continue to meet their design requirements throughout their operational life.

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