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LONG-TERM MEASUREMENT OF CONCRETE STRAINS IN PRE STRESSED CONTAINMENTS: MEASUREMENT UNCERTAINTY OF THE EMBEDDED VIBRATING WIRE STRAIN GAUGES (VWSG) BASED ON A 15-YEAR LABORATORY TESTING CAMPAIGN

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ABSTRACT

Monitoring strain in the concrete of civil engineering structures such as pre stressed nuclear containments, cooling towers, dams or bridges is of primary importance for safety and economic purposes. Strain in concrete is commonly measured by sensors using vibrating wire technology. The first such sensors were used for monitoring dams in the 1930s. Nowadays this technology is recognized as the reference for strain measurement. For this reason EDF uses thousands of these sensors for pre stressed nuclear containement surveillance.

In this study, considerable work was carried out to define the uncertainty measurement of C110 Telemac vibrating wire strain measurements used in French NPP's. The article focuses on the long-term behaviour of sensors which are embedded in the concrete and remain inaccessible after construction.

INTRODUCTION: OBJECTIVES OF CONTAINMENT MONITORING

The containments of Pressurised Water Reactors (PWR) of the fleet currently operated by EDF are built of pre stressed, reinforced concrete. Pre stressing is used to balance the forces that containments would be subjected to in the event of an accident (LOCA).

In France, the choice has been made to coat the pre stressing tendons with cement grout. This option offers advantages by preventing the strands from corroding. Furthermore, in the event of a strand failing, the bonds between the tendon and the grout enable some of the post-tensioning forces to continue to be transmitted to the structure. On the other hand, this option prohibits all future inspection or maintenance operations, which would have been possible for pre stressing injected with grease. This decision therefore led to the setting up of a monitoring system consisting of periodic tests (every ten years) at design basis accident pressure and monitoring the behavior of a containment throughout its life.

During the construction of EDF's PWR fleet in the 1970s, it was decided to fit concrete containment structures with VWSGs to monitor concrete strain during pressure testing and operation. The use of VWSG to measure strain into concrete has been widespread in dams' construction since the middle of the previous century, as shown in Coyne (1938) or Bellier (1956). Today these sensors are used by EDF to monitor any changes in concrete pre stressing during operation and to check the mechanical response of the containment during periodic pressure tests. Compliance with design requirements is assessed by comparing the measurement and the theoretical containment behavior based on design assumptions.

As the VWSGs are used for monitoring the pre stressing losses, the delayed and instantaneous concrete strains, the quantification of measurement uncertainties is necessary. A metrological assessment was necessary also to convince engineers that the data trends were representative of the actual behavior of the containment and not due to sensor drift.

PRINCIPLE OF STRAIN MEASUREMENT BY VIBRATING WIRE

Strain in concrete is commonly measured by sensors using vibrating wire technology. This sensor is made up of a steel wire sensing element enclosed in a protective body. The sensor is embedded in the concrete during construction. Variation of the distance between the two ends of the sensor modifies the natural frequency of vibration of the wire and this change in frequency is correlated with the change in strain causing it. The following equation (1) links concrete strain ($\frac{dL}{L}$in µm/m) and the frequency of mechanical vibration.

$$\varepsilon = \frac{dL}{L} = K * ({f_1}^2 - {f_0}^2) \qquad (1)$$

K is the extensometric coefficient (µm/m/Hz^2) and f_1, f_0 are the vibration frequencies (Hz) in states 1 and 0.

Two electromagnets adjacent to the wire are used to set the wire in vibration. Thus, the wire is set into transverse motion by exciting it with a short current pulse passed through the two electromagnetic coils positioned near the center of the wire. By measuring the vibration frequency, the strain in the concrete can be assessed. Figure 2 shows a VWSG.

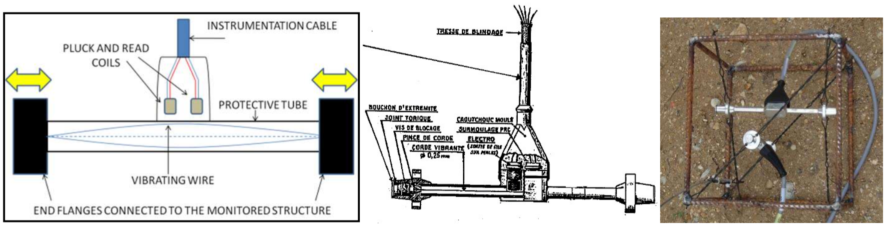

Figure 2. Description of the VWSG embedded into the concrete in pre stressed containments

A detailed description of the sensor functioning is presented in *(Simon, A., and A. Courtois, 2015)*. The first types were used on dams in about 1930. It was also used on EDF's first generation power plants (gas-cooled reactors) as early as 1956. The current PWRs of the EDF fleet are equipped with large numbers of these VWSGs (around 200 for the 1st CP0 units, generally from around 50 to 100 on CPY 900 MW and 1300-1450 MW units and from 250 to 450 on the most recent EPR's units).

The measuring range of the sensor is about 3000 µm/m with a classical electronic frequency meter.

THE EXTENSOMETRIC COEFFICIENT

Discussion on the extensometric coefficient K

The extensometric coefficient K must be determined carefully because it converts the vibration frequency (measured with sufficient precision) into the required concrete strain. As the sensor is designed for a use in the concrete, the tests performed in air in a laboratory (without the concrete middle) may not be associated to the highest level of representativeness. Consequently, calibration tests without concrete have to be considered with caution.

Nevertheless, in the standard industrial process, the sensors may be calibrated without systematic concrete samples. The experimental process for such tests requires strong metrological analysis and development.

The simplified theory of vibrating wires is used to link the strain coefficient K to the mechanical characteristics of the wire, using equation (2):

$$K = \frac{4{L_c}^2\rho_c}{E_c} \qquad (2)$$

Where L_c is the length of the wire (0.11 m), ρ_c the wire's density (7 850 $kg.m^{-3}$) and E_c its Young's modulus (202 103 Mpa). Equation (2) is much simplified because it does not take into account the elongation of the wire, the transmission of strain in the concrete to the wire through the thickness of the flanges, and the wire's bindings. Furthermore, it is the pseudo-natural frequency that is measured as the vibration of the wire is affected by damping. This pseudo-frequency also depends on the level of the excitation voltage and the time interval used to measure the frequency.

From equation (2) the extensometric coefficient, supplied by the sensor's manufacturer, is 1.88 x 10^{-3} $\mu m/m/Hz^2$ for C110 Telemac sensors.

Short term mechanical tests on VWSG – tests in "air"

EDF performed a lot of tests in air to verify the representativeness of the supplier coefficient as presented in the figure below.

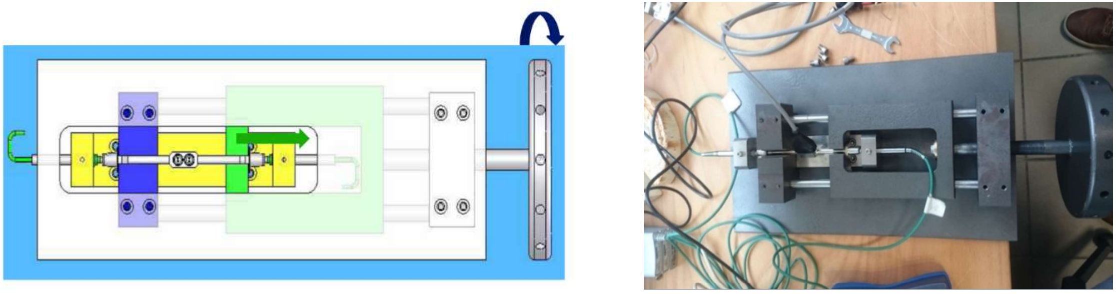

Figure 3. Description of the VWSG calibration tests in air with an experimental device using 2 LVDT sensors for the reference displacement measurements

The test in air consists in making mechanical tensile tests on the VWSG which is maintained in an experimental device allowing uniaxial 1D displacement. The displacement is measured at both side of the VWSG sensor thanks to 2 calibrated LVDT sensors. At each step of the mechanical elongation, displacements are measured by the LVDT (reference) and the wire frequency is measured on the VWSG.

The tests allow to verify the consistency of Equation (1), in particular the linearity between the measured strain ε and the difference of the square frequencies between 2 states ${f_1}^2 - {f_0}^2$. A linear regression between both states allows to measure the extensometric coefficient K.

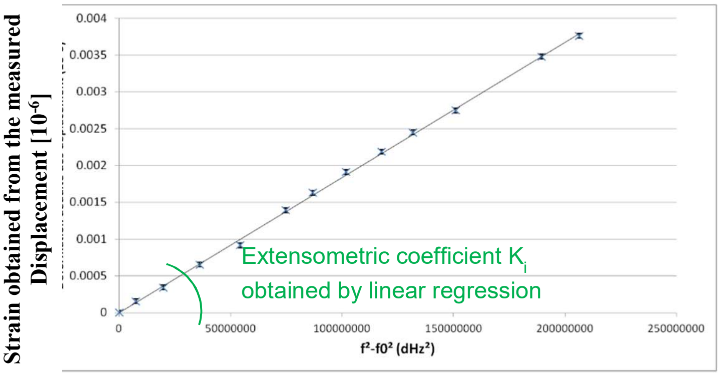

Figure 4. Results of the tensile test performed on a VWSG C110 – strain versus ${f_1}^2 - {f_0}^2$

The tests allow to verify the consistency of the extensometric coefficient. The mean value obtained is equal to 1,82.10^{-5} µm/m/dHz^2 (+/- 0.04 µm/m/dHz^2 being the standard deviation // or +/- 2.2% of the mean value of coefficient K, in relative). It was also possible to verify the conservatism of the extensometric coefficient used by EDF in its engineering analyzes of pre stressing losses, which is equal to 1.93.10^{-5} µm/m/dHz^2. More concretely, the EDF coefficient corresponds more or less to the experimental mean value +2σ (95% confidence) to +3σ (99% confidence).

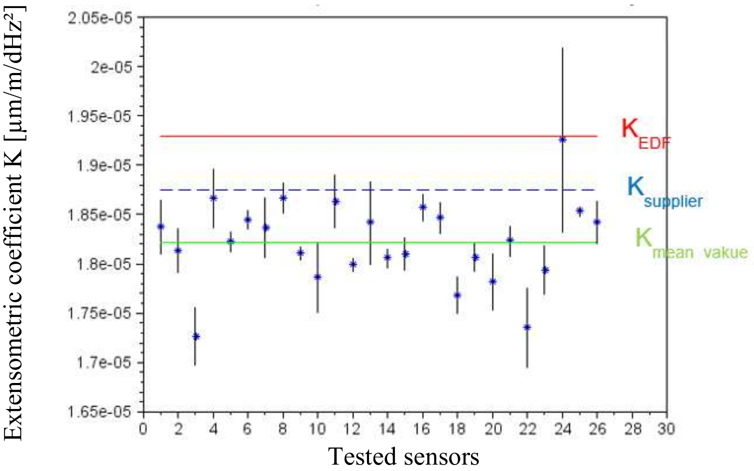

Figure 5. Results of the tensile test performed on 26 VWSG C110 – extensometric coefficients obtained by linear regression of strain versus $f_1{}^2 - f_0{}^2$

These tests are very interesting to verify the calibration data provided by the supplier but they do not take into account the potential long term effects which could affect the sensor's functioning, such as delayed drift due to ageing of the sensor or due to chemical aggression from the concrete. For this reason, it was important to complete the experimental program by performing "integral" tests with VWSG embedded into the concrete. The tests presented in the following paragraph are called "integral" because they include all the potential measurement uncertainties we can have on a real building, including the ones related to the concrete effect on the sensors during a long time period.

TESTING THE ACCURACY AND DRIFT OF VWSGS

Objectives of the tests in concrete samples

The additional objectives of the tests in concrete samples are the following:

- Quantify the accuracy/measurement uncertainty of the sensor in its concrete environment
- Verify the sensor's long-term resistance to drift, a point that is rarely examined over long periods by sensor manufacturers nor operators

The tests performed the 1970's and the 1990's on the VWSG were presented in (Simon, A., and A. Courtois, 2015). These tests extended over no longer than 6 months. As the operation life of nuclear containments is much longer than this, it was necessary for EDF to test the sensors over longer periods.

Description of tests in concrete samples (long-term tests)

In 2005, EDF made six concrete cylinders (1 meter high, 0.16 meters in diameter, and 250 kN of vertical force) which were fitted with embedded vibrating wire sensors and were monitored to measure shrinkage and creep. The concrete samples were made with a concrete mix representative of the one used for concreting the pre stressed containment of a French unit (non-drying conditions of the samples). The laboratory conditions are 20°C +/-1°C for temperature and 50% +/- 0.5% for Relative Humidity.

Two types of 3 specimens each were made: shrinkage specimens (no vertical force) and creep test specimens (with a vertical force of 250 kN to simulate the level of pre stressing of around 12 MPa). The specificity of these tests lies in their duration: 15 years of comparison are available for the shrinkage specimens and from 3 to 6 years for the creep test specimens (which have been stopped when the sensors reached the end of their range).

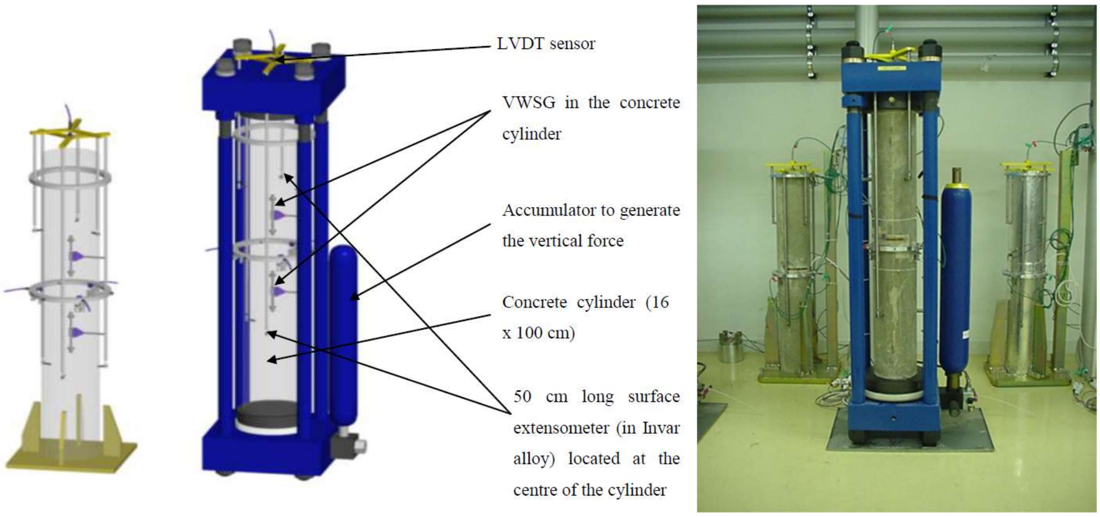

Figure 6. *Concrete cylinder for measuring shrinkage (left) and creep (right), with the accumulator to generate the vertical force.*

The principle is to compare the strain measurements made by the vibrating wire strain gauges embedded in the 16 x 100 cm of concrete specimens to measurements made by Linear Variable Differential Transformers (LVDT) displacement transducers attached to the external surface of the specimens. Tests were performed at EDF Direction Industrielle laboratory in Aix-en-Provence.

The LVDT sensors attached to the surface are controlled metrologically. The drift in time of the VWSGs corresponds theoretically to the value of the difference between the measurements made at the surface (reference) and those made by the embedded sensors. The LVDT sensors on the surface were calibrated at the beginning and end of the experiment. No dismantling took place during the test. The external displacement measurement uncertainty of the whole system (including uncertainty on the LVDT sensor obtained by calibration, on the geometry of the invar system installed on the sample, on the temperature effects) is estimated to be +/- 3µm (95% confidence).

In the objective of studying the potential scattering of the measured extensometric coefficients, each sample contains a non-aged sensor (A) and an aged sensor (B). As a reminder, the accelerated heat ageing process has been in place in the 80’s, it consists of a series of rapid thermal cycling over a period of 96 hours from +60 °C to -20 °C.

Creep and shrinkage test Results

Figure 7 and 8 show the evolution over several years of the measured concrete strains for the 3 shrinkage test specimens and the 3 creep test specimens. It is possible to compare the strains measured on the external surface by the LVDT system (reference) and the strains measured by the embedded vibrating wire in the concrete core. All VWSGs showed the same behavior: a tendency to overestimate the strain compared with surface measurements. Creep/shrinkage trends are very well measured by the experimental devices and the measurement scattering is residual.

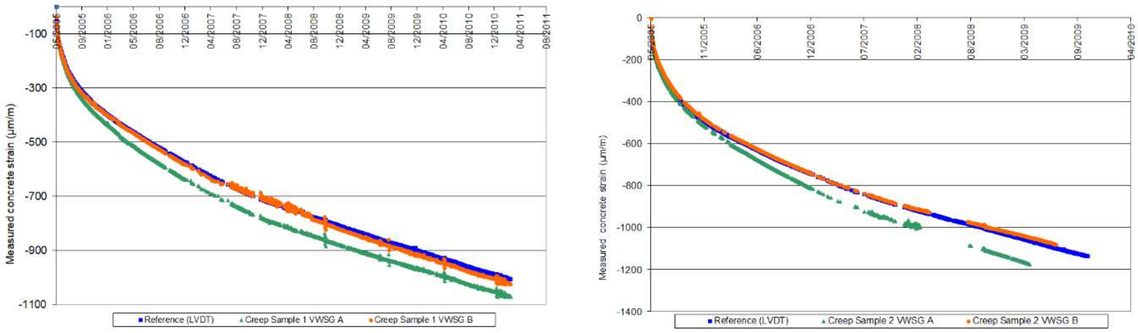

Figure 7: *Strain (in µm/m) versus time for creep samples tests (LVDT in blue, VWSG A and B in green and orange)*

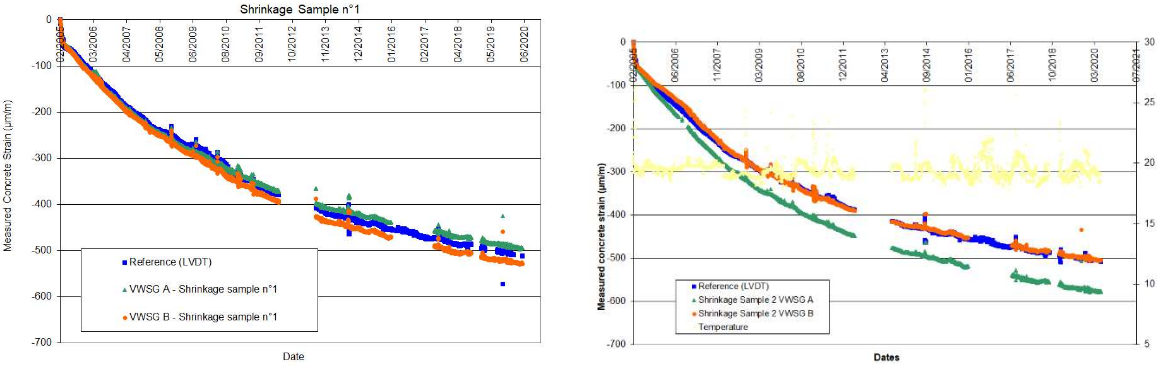

Figure 8: *Strain (in µm/m) versus time for shrinkage samples tests (LVDT in blue, VWSG A and B in green and orange, temperature of the laboratory in yellow)*

All the results (6 concrete cylinders, 12 sensors in total) are shown in Table 1. The strains were calculated using an extensometric coefficient of 1.93 x 10^{-3} µm.$m^{-1}Hz^{-2}$, the value used historically by EDF and slightly higher than the value recommended by the manufacturer of the sensor (conservative approach).

Previous figures and table 1 show the overestimation of the concrete strains measured by the VWSG compared to the reference LVDT. For the 6 concrete samples, the mean overestimation is equal to +22 µm/m (+/- 26 µm/m // standard deviation) or +4.1% (+/- 4.9% // standard deviation).
These data are consistent with safety requirements.

Table 1: Mean values (over time) of the difference between surface extensometers and VWSGs measurements // (+) corresponds to an overestimation by the VWSG

	Mean $\Delta\varepsilon$ over time 15y for shrinkage and 3y to 6y for creep (absolute)	Mean $\frac{\Delta\varepsilon}{\varepsilon}$ over time 15y for shrinkage and 3y to 6y for creep (relative to the total strain)
Shrinkage 1 VWSG A	-4 µm/m	-0.5 %
Shrinkage 1 VWSG B	+14 µm/m	+4.7 %
Shrinkage 2 VWSG A	+49 µm/m	+14 %
Shrinkage 2 VWSG B	-3 µm/m	-2 %
Shrinkage 3 VWSG A	+27 µm/m	+8 %
Shrinkage 3 VWSG B	+1 µm/m	+0.7 %

Creep 1 VWSG A	+58 µm/m	+8.4 %
Creep 1 VWSG B	+10 µm/m	+1.3 %
Creep 2 VWSG A	+58 µm/m	+7.2 %
Creep 2 VWSG B	+57 µm/m	+6.8 %
Creep 3 VWSG A	-10 µm/m	-0.5 %
Creep 3 VWSG B	+3 µm/m	+0.5 %
Mean value +/- 1 standard deviation (over the 6 samples)	+22 µm/m +/- 26 µm/m	+4.1% +/- 4.9%

It is possible to recalculate an optimized extensometric coefficient by fitting LVDT surface strains and those measured by the embedded VWSGs. This optimized coefficient is, on average, 1.83 x 10^{-5} (+/- 0.1) µm.m^{-}1.dHz^{-2}.

VWSG measurement uncertainty

The main result of these concrete samples is the measurement of the difference Δε between the concrete strains measured by the VWSG ε_{VWSG} and the reference strains measured by the LVDT ε_{LVDT}. As we analyze creep and shrinkage concrete samples for which the total concrete strains ε are not the same, it is more relevant to consider the relative strain $\frac{\Delta\varepsilon}{\varepsilon}$ en %, so:

$$\frac{\Delta\varepsilon}{\varepsilon} = \frac{\varepsilon_{VWSG}}{\varepsilon} - \frac{\varepsilon_{LVDT}}{\varepsilon} \qquad (3)$$

According to the GUM method, we can calculate the uncertainty u(X) of a given parameter X with:

$$u\left(\frac{\varepsilon_{VWSG}}{\varepsilon}\right) = \sqrt{u^2\left(\frac{\Delta\varepsilon}{\varepsilon}\right) + u^2\left(\frac{\varepsilon_{LVDT}}{\varepsilon}\right)} \qquad (4)$$

$u\left(\frac{\Delta\varepsilon}{\varepsilon}\right)$ is the uncertainty of the difference between both measurements VWSG and reference LVDT. This uncertainty and the standard deviation σ are considered to be equal so :

$$u\left(\frac{\Delta\varepsilon}{\varepsilon}\right) = \sigma\left(\frac{\Delta\varepsilon}{\varepsilon}\right) \quad (5)$$

It is consequently necessary to calculate the “error” $\frac{\Delta\varepsilon}{\varepsilon}$ over time and its scattering (standard deviation value $\sigma\left(\frac{\Delta\varepsilon}{\varepsilon}\right)$). Figure 9 shows that the “error” $\frac{\Delta\varepsilon}{\varepsilon}$ (as a % relative to the LVDT measurement) is constant over time for years. Even if we observe some variations at the beginning of the test, when the concrete drying evolution is probably maximized, we observe that there is no drift observed in any of the 12 sensors over a period of at least 10 years and up to 15 years.

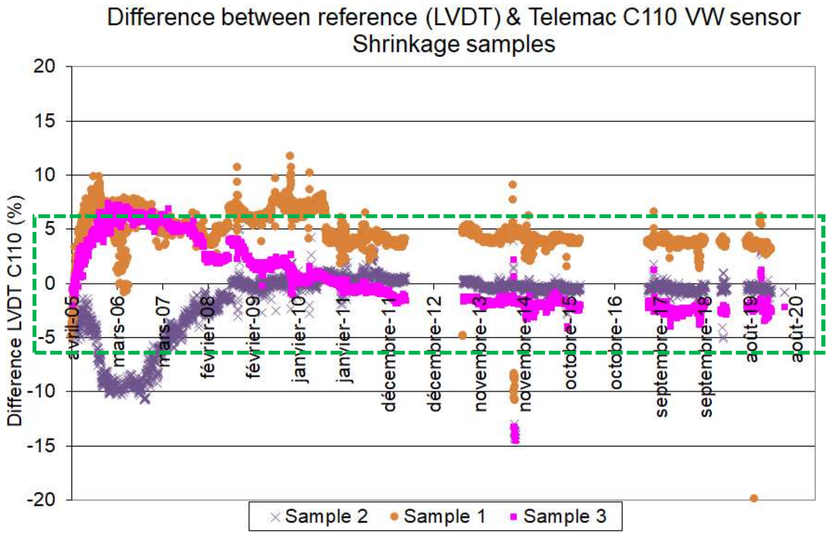

Figure 9: Overestimation (in %) by VWSG over time for shrinkage samples

The total strains measured on creep and shrinkage samples are respectively equal to 1200 µm/m and 550 µm/m. Given:

- the external displacement measurement uncertainty of the whole LVDT system estimated to be $u(d_{LVDT})$=+/- 3µm at 95% confidence ($U(d_{LVDT})=2*u(d_{LVDT})=2*u(\varepsilon_{LVDT})*L$ where L=0.5m is the distance between both upper and lower anchorage of the rebars allowing the displacement measurement so $u(\varepsilon_{LVDT})$=+/- 3µm/m),
- the uncertainty of the difference between both measurements VWSG and reference LVDT $u(\Delta\varepsilon/\varepsilon)$ calculated as the standard deviation $\sigma(\Delta\varepsilon/\varepsilon)$

We calculate the VWSG measurement uncertainty $u\left(\frac{\varepsilon_{VWSG}}{\varepsilon}\right)$ below:

Table 2: VWSG measurement uncertainty $u\left(\frac{\varepsilon_{VWSG}}{\varepsilon}\right)$ calculated from the tests

	Uncertainty $u(\Delta\varepsilon/\varepsilon)$ calculated as the standard deviation $\sigma(\Delta\varepsilon/\varepsilon)$ [%]	Uncertainty $u(\varepsilon_{LVDT}/\varepsilon)$ [%]	Obtained VWSG uncertainty $u(\varepsilon_{VWSG}/\varepsilon)$ [%]
Shrinkage sample 1	+/- 2.1	+/- 0.5	+/- 2.3
Shrinkage sample 2	+/- 3.7		+/- 3.9
Shrinkage sample 3	+/- 3.1		+/- 3.3
Creep sample 1	+/- 0.5	+/- 0.25	+/- 0.6
Creep sample 2	+/- 1.7		+/- 1.8
Creep sample 3	+/- 0.9		+/- 1
Mean value (over the 6 samples)			+/- 2.2%

The VWSG measurement uncertainty at 95% confidence (k=2) is consequently equal to $U\left(\frac{\varepsilon_{VWSG}}{\varepsilon}\right)$=+/-4.4%, in laboratory conditions.

As a final conservative approach, EDF concluded that the reasonable conservative value for the concrete strains measured by the embedded VWSG is U$\left(\frac{\varepsilon_{VWSG}}{\varepsilon}\right)$=+/-5 %, that is to say +/-5% of the total strain measured during operation (long term monitoring).

Additional tests on concrete samples

Some other tests were performed to assess the potential influence of some parameters on the measurement uncertainty obtained experimentally for VWSG.

The aim is to evaluate the potential influence of the anchorage length of the LVDT system on the comparison between VWSG measurements ("core" of the concrete sample) and LVDT ("surface" measurement).

Figure 10: Tests performed with different anchorage length of the LVDT system (16mm which is the reference of the previous 6 samples, 40mm and 70mm)

The tests on additional samples showed that the anchorage depth of the LVDT measurement system would lead to a deviation of the order of +/-10 µm/m, comparing the shorter and longer anchorage depths. This value, which is comparable to the measurement uncertainty of the whole process, can be considered as residual. This parameter is consequently not influent on the previous conclusion.

The concrete samples were also used in short term duration tests, consisting of simulating the pressure tests imposed to the containment, by de compressing and re compressing the concrete sample up to around 400 µm/m. The same philosophy, comparing the reference LVDT sensor to the embedded VWSG during the equivalent pressure tests, allowed to check the consistency and robustness of the conclusion, either for long term and short term loadings.

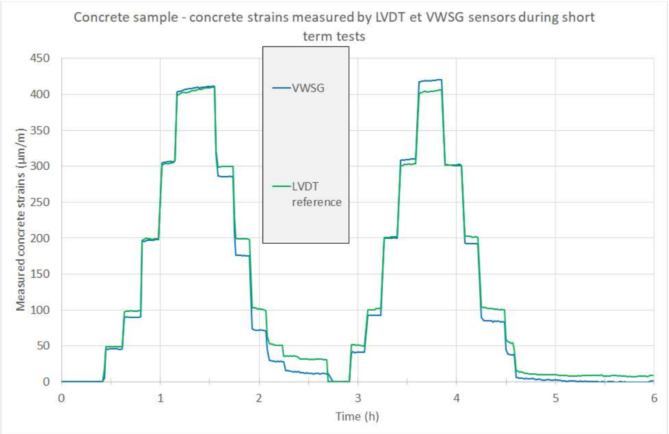

Figure 11: Tests performed with different anchorage length of the LVDT system (16mm which is the reference of the previous 6 samples, 40mm and 70mm)

CONCLUSION

The results of this exhaustive 15 years testing program, including calibration of sensors with “in air” mechanical tests, creep/shrinkage tests on concrete samples, confirm the VWSGs' absence of drift over time and robustness of the strain measurement. This is the main result of these tests, which strengthens the view for using these sensors for operational monitoring of pre stressed containments. The extensometric coefficient K used by EDF is likely to overestimate the actual strains (+4 %) with a scatter of the order of +/-5%.

As a final conservative approach, EDF concluded that the conservative value (95% confidence) for the concrete strains measured by the embedded VWSG is $U\left(\frac{\varepsilon_{VWSG}}{\varepsilon}\right)$=+/-5 %, that is to say +/-5% of the total strain measured during operation (long term monitoring). For a delayed concrete strain due to creep/shrinkage of the order of -1000 µm/m, the overall uncertainty measurement is +/- 50 µm/m.

Additional tests allowed to check the consistency and robustness of the conclusion, either for long term and short term loadings.

The article presents the methodology for determining the overall uncertainty measurement of VWSG and the quantitative value obtained. The obtained value is consistent with the measurement requirements of the Civil studies (for verification of pre stressing losses purpose at end of operation).

The VWSG therefore remain the instrumentation of reference for measuring strains in the containments of EDF's fleet.

EDF is currently reproducing a comparable but time optimized experimental program, for assessing the measurement uncertainties of Roctest VWSG used in EPR HPC.

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