Long-term measurement of strain in concrete: durability and accuracy of embedded vibrating wire strain gauges

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ABSTRACT: Monitoring strain in the concrete of civil engineering structures such as prestressed 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. These sensors were also used in EDF's first generation power plants (gas-cooled reactors) as early as 1956. Nowadays this technology is recognized as the reference for strain measurement. For this reason EDF uses thousands of these sensors for dam and prestressed nuclear confinement surveillance.

In this study, considerable work was carried out to define the accuracy of vibrating wire strain measurements. Our article focuses on the long-term behaviour of sensors which are embedded in concrete and remain inaccessible after construction. Any long-term drift in strain measurements would be detrimental to the monitoring of a structure. One of the possible mechanisms affecting this drift may be the sliding of the wire in its bindings. Six concrete cylinders (1 meter high, 0.16 meters in diameter, and 250 kN of vertical force) were fitted with embedded vibrating wire sensors and were monitored for 8 years. We compared the embedded measurements with the measurement of surface displacements. Both measurements varied consistently over the long term. Additionally, comparisons were also made for specific tests in which the vertical force suddenly decreased. All these tests demonstrated that vibrating wire strain technology is very accurate and that there is no drift with time. Therefore, our results support the use of this technology for civil engineering structures.

1 INTRODUCTION: OBJECTIVES OF CONTAINMENT MONITORING

The containments of Pressurised Water Reactors (PWR) of the fleet currently operated by EDF are built of prestressed, reinforced concrete. Prestressing is used to balance the forces that containments would be subjected to in the event of an accident or external hazard.

Before the commissioning of the plant, an acceptance test is required to confirm the good mechanical behaviour of the containment when submitted to a pressure equivalent to the design basis accident pressure (see the construction regulations, such as ETC-C Part 3 in France, or ASME code section III in the USA). This acceptance test, also called a resistance test, requires the measurement of structural mechanical response using a wide range of instruments (displacement, strain and temperature sensors). Some of these sensors are embedded into concrete, such as Vibrating Wire Strain Gauges (VWSG) and temperature probes.

In addition to this design requirement, prestressing forces have to be monitored regularly to ensure that the containment meets the safety requirements throughout its operating life. Delayed phenomena, such as concrete creep or relaxation of cables may reduce the efficiency of the prestressing system significantly.

In France, the choice has been made to coat the prestressing 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 prestressing 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 behaviour of a containment throughout its life. In practice, long-term monitoring is carried out mainly by the sensors used for the acceptance test.

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). VWSG are still functional in dams and they are vital for the assessment of pathologies such as alkali-aggregate reactions. Due to their ruggedness and performance, these sensors have also been used for other civil structures. During the construction of EDF's fleet in the 1960s, it was decided to fit concrete containment structures with VWSGs to monitor concrete strain during operation. Today these sensors are used by EDF to monitor any changes in concrete prestressing 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 behaviour based on design assumptions.

Usually, management of industrial sensors includes periodic checking and calibration. Of course, embedded sensors cannot be checked, maintained or replaced once the concrete has been poured. Although surface sensors can be installed to replace the originally embedded sensors (Simon 2011), EDF chose to use readings from VWSGs as long as possible. A metrological assessment of the possible drift of VWSG measurement was thus necessary to convince engineers that the data trends were representative of the actual behaviour of the containment and not due to sensor drift.

2 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 alters the natural frequency of vibration of the wire and this change in frequency may be correlated with the change in strain causing it. The following equation (1) links strain (dL/L in µm/m) and the frequency of mechanical vibration.

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

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

By measuring the vibration frequency, the strain in the concrete can be assessed. Figure 1 shows a VWSG.

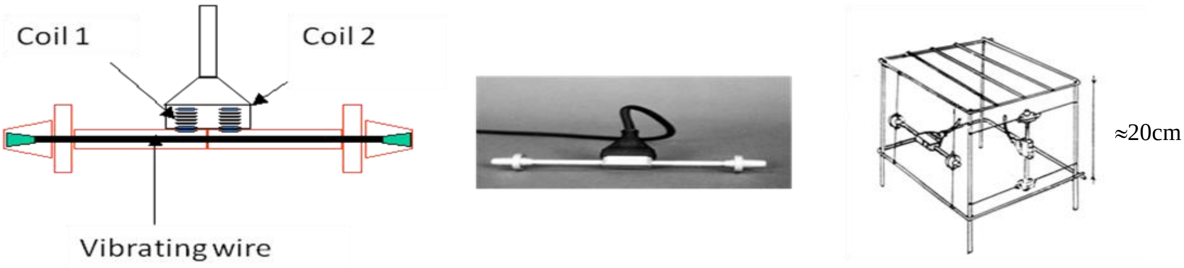

Figure 1: VWSG for the measurement of strain inside concrete.

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 centre of the wire. Since the wire is made of ferromagnetic steel, it is sensitive to the magnetic field and starts vibrating at its natural frequency. The vibration of the wire induces a magnetic field which is detected by the coils, the frequency of which can be measured remotely. This ingenious system measures the electrical frequency of the returned signal which is the same as the mechanical vibration frequency of the wire. This physical principle is very old, since 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.

The measuring range of the sensor is about 3000 µm/m with a classical electronic frequency meter. By using modern signal processing techniques (such as Fourier transforms and use of a high pass band filter) it is possible to increase the measuring range and to recover certain VWSGs which had been declared unserviceable (see Simon et al (2011 & 2010)).

3 THE EXTENSOMETRIC COEFFICIENT PROBLEM

The extensometric coefficient K must be determined carefully because it converts the vibration frequency (measured with sufficient precision) into the strain. It is not possible to calibrate the sensor in the laboratory by connecting it to a metrological standard. In deed the sensor is designed for use in concrete and it cannot be used in air because it buckles or the welds fail as a result of of the stresses being applied.

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

$$K = \frac{4.L_c^2 \rho_c}{E_c} \tag{2}$$

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 (202.10^3 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. In reality, the electrical detection method also affects the wire’s vibration frequency. 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} µm/m/Hz^2. EDF operates thousands of vibrating wire strain sensors that monitor creep in nuclear containments. For this reason it is important to ensure

- the accuracy of the sensor (to compare it with creep tests carried out in laboratories and on models)
- the sensor's long-term resistance to drift, a point that is rarely examined over long periods by the sensor manufacturers.

4 TESTING THE ACCURACY AND DRIFT OF VWSGS

4.1 Previous tests

In 1985 an experimental study was carried out at the Central Laboratory for Bridges and Roadways *(Laboratoire Central des Ponts et Chaussées (LCPC))* on concrete cylinders 16 cm in diameter and 1 m in height (see Godart (1985)). These cylinders were fitted with three vibrating wire sensors and a means for measuring surface strain (over a length of 50 cm). Using the manufacturer's extensometric coefficient strains were overestimated by an average of 6%. The average overestimation was carried out on specimens with pure shrinkage, instantaneous loads and creep (3 months). Other comparative studies on concrete specimens are shown in the references in Godart (1985): these older studies (1976 & 1981) all overestimate the strain using vibrating wires incorporating the manufacturer's coefficient.

These tests extended over no longer than 6 months. As the useful life of nuclear confinements and dams is much longer than this it is necessary to test the sensors over longer periods: this is the subject of the next section.

4.2 Description of tests (long-term + quick short-term tests)

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 surface of the specimens. Tests were performed at CEIDRE’s laboratory in Aix-en-Provence.

The sensors attached to the surface being controlled metrologically, the drift in time of the VWSGs corresponds theoretically to the value of the difference between the measurements made at the surface 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 takes place during the test and the uncertainty of length measurement guaranteed by the calibration does not exceed 1µm.

Each test contains a new (A) and an aged sensor (B). The accelerated heat ageing process has been in place since 1997. This process consists of a series of rapid thermal cycling over a period of 96 hours from +60 °C to -20 °C.

Despite the care taken in setting up and carrying out the tests, comparing the measurements taken at the surface and the core of the concrete theoretically involves evaluating the differential mechanical behaviour of these two parts of the specimen. In the present study, this source of uncertainty was neglected and it was assumed that the strain on the surface and in the core of the cylinder were identical.

Two types of specimens were made: shrinkage specimens (no vertical force) and creep test specimens (with a vertical force of 250 kN to simulate the level of prestressing). The specificity of these tests lies in their duration: 8 years of comparison are available for the shrinkage specimens (still currently being tracked) and 6 years for the creep test specimens (which have been stopped, the sensors having reached the end of their range).

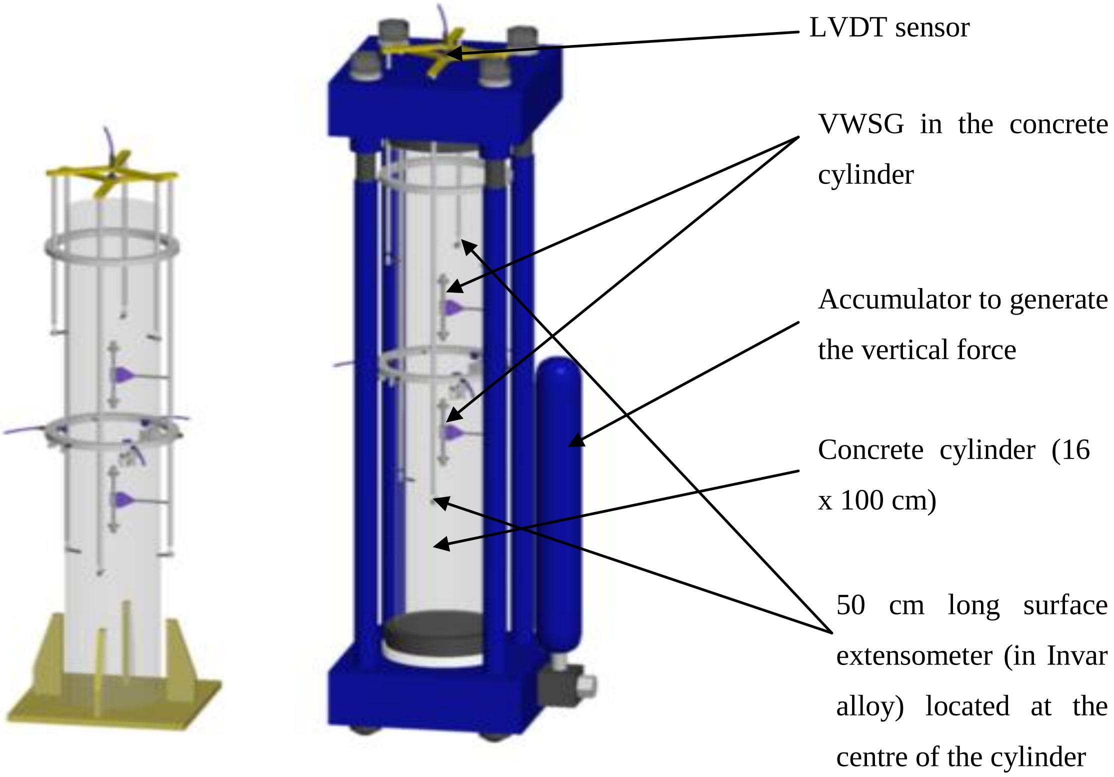

Figure 1: Concrete cylinder for measuring shrinkage (left) and creep (right), with the accumulator to generate the vertical force).

4.3 Results

Figure 2 shows the change over several years of strains measured for a shrinkage specimen and a creep test specimen. It is thus possible to compare the strains measured on the surface by the LVDT system and strains measured by the vibrating wire in the concrete core. All VWSGs showed the same behaviour: a tendency to overestimate the strain compared with surface measurements. 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} $\mu m.m^{-1}Hz^{-2}$, the value used historically by EDF and slightly higher than the value recommended by the manufacturer of the sensor.

It is possible to recalculate an optimized coefficient which would enable surface strains and those measured by VWSG to be combined. This optimized coefficient is, on average,

$1.81 \pm 0.1 \times 10^{-3}$ µm.m^{-1}Hz^{-2}, slightly below the manufacturer's extensometric coefficient. It therefore follows from these tests that VWSGs overestimate the strain in the concrete.

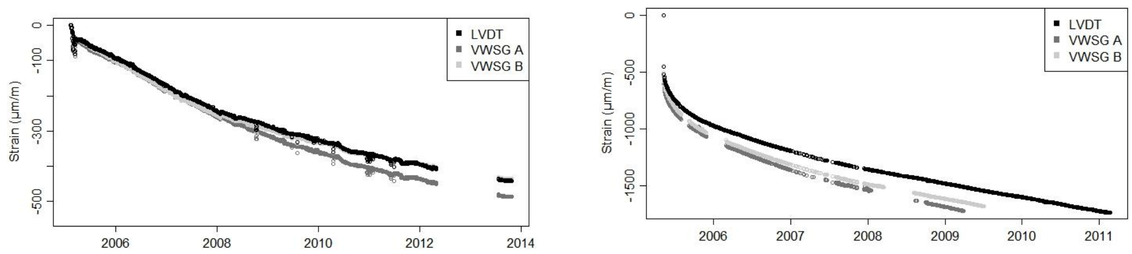

Figure 2: Strain (in µm/m) versus time for shrinkage 3 (left) and creep 2 (right) tests.

It is also instructive to track the error over time. Figure 3 shows that the error (as a %age relative to the LVDT measurement) is constant over time; there is no drift observed in any of the 12 sensors over a period up to 8 years.

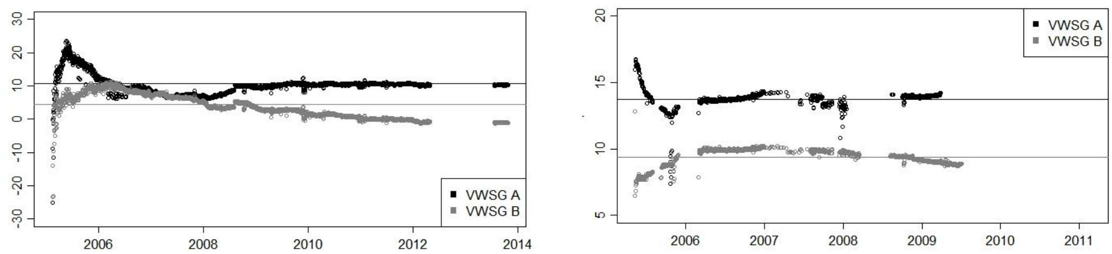

Figure 3: Overestimation (in %) by VWSG over time for shrinkage 3 (left) and creep 2 (right) tests.

In the continuing series of creep tests, three specimens constructed in 2005 were subjected to a simulated strain amplitude and kinetic test on nuclear containment. Each specimen was fitted with a new VWSG and an artificially aged VWSG. The test consisted of increasing the strain up to 150 µm/m in half a day. The press, which was used as a reference, was controlled by measuring the LVDT displacement. Figure 4 shows the results of the loading. There is good correlation between the results from the aged sensor (Creep 2B = F2V) and the reference. The new sensor (Creep 2 A = F2NV) overestimates the strains by 13% compared with the reference.

Table 1: Comparison between surface extensometers and VWSGs

	Overestimation		Optimized K (10^{-3} µm.m^{-1}Hz^{-2})
Shrinkage 1 VWSG A	-3 µm/m	-2 %	1.9546
Shrinkage 1 VWSG B	11 µm/m	4 %	1.8432
Shrinkage 2 VWSG A	42 µm/m	17 %	1.6477
Shrinkage 2 VWSG B	-5 µm/m	-2 %	1.9552
Shrinkage 3 VWSG A	26 µm/m	11 %	1.7536
Shrinkage 3 VWSG B	6 µm/m	4 %	1.8962
Creep 1 VWSG A	138 µm/m	13 %	1.7174
Creep 1 VWSG B	97 µm/m	9 %	1.7752
Creep 2 VWSG A	159 µm/m	14 %	1.6958
Creep 2 VWSG B	115 µm/m	9 %	1.7663
Creep 3 VWSG A	19 µm/m	2 %	1.9075
Creep 3 VWSG B	63 µm/m	5 %	1.8398

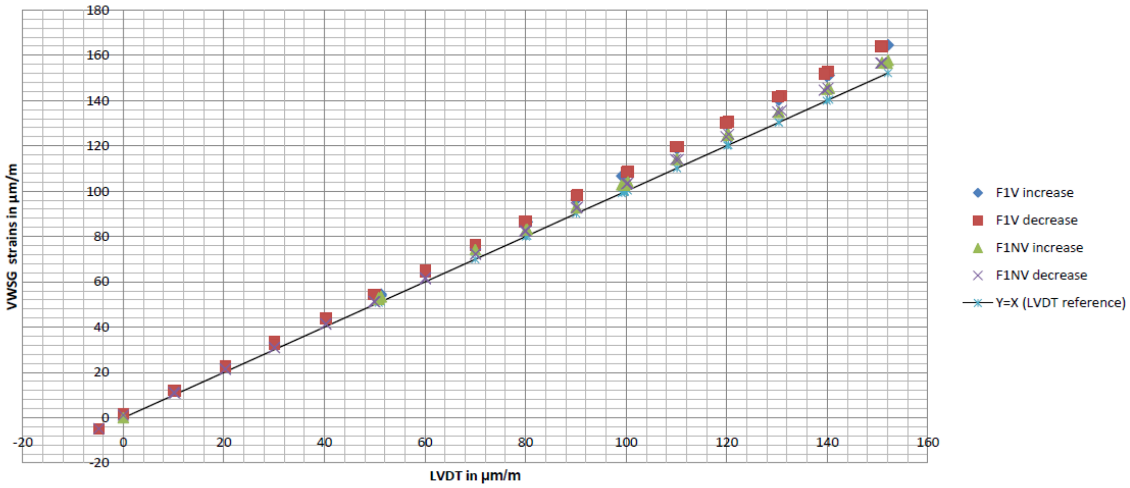

Figure 4: Strain (in µm/m) measured by VWSG versus strain (in µm/m) measured by LVDT. Comparison of the response of a new extensometer (Creep 2 A = F2NV) and an aged extensometer (Creep 2B = F2V) relative to the LVDT reference

The same trend is observed in other specimens, with overestimations of the strain ranging from 11% to 19%. It is a reassuring conclusion that all the VWSGs slightly overestimate the strains compared with the LVDT reference. These data are consistent with safety requirements.

4.4 Interpretation

These results are very reassuring for the long term behaviour of the sensor: there is a slight tendency to overestimate strains (of the order of 7% for sensors A and B combined). This overestimation of strain is on the side of structural safety. Another important result of these tests is the absence of sensor drift over time because the %age error remains constant over time across the 12 sensors. This accuracy error can be corrected by optimizing the extensometric coefficient; thus, the accuracy error is not at all detrimental in detecting a change in the behaviour of a structure which could, for example, be shown by a change in slope.

Note also that there is some variability in the extensometric coefficient (of the order of 5%).

The LVDT measurement on the surface is reliable and can be calibrated: the uncertainty of measurement which has been checked before and after tests does not exceed 4 µm/m. The difference in accuracy between VWSGs and LVDT may be explained by the different sensor's location. In deed these results are based on the fact that the strain at the core of the concrete is the same as that measured by the inserts on the surface (which penetrate 16 mm into surface of the concrete cylinder). This hypothesis may be wrong as shown by Boucher 2015: strains in the centre of concrete are slightly higher than strains at the surface. For a small cylinder (16 cm of diameter) this effect must be negligible but we should carry out more tests with longer inserts in order to prove it properly.

5 CONCLUSIONS AND PROSPECTS

The results of these tests are quite reassuring and confirm the VWSGs' absence of drift over time. This is the main result of these tests, which strengthens the view for using these sensors for operational monitoring. Concerning accuracy, the extensometric coefficient used by EDF is likely to overestimate the actual strains (7%) with a scatter of the order of 5% on the extensometric coefficient on these tests.

The local nature of the measurement is sometimes difficult to interpret (versus displacement between two points of the structure) as there is important measurement variability from one point to another in similar areas. This variability in the local measurement is offset by the fact that vibrating wire technology has excellent resolution and does not drift over time. The VWSG therefore remains the instrumentation of reference for measuring strains in the containments of EDF's fleet.

6 REFERENCES

ASME code 2010, section III, division 2. Code for concrete containments. New York, USA : American Society of Mechanical Engineers.

Bellier J. 1956. Applications de l'extensométrie acoustique aux travaux publics. Annales ITBTP, Essais et Mesures 36 (in French)

Boucher M. 2015, Massive Structure Monitoring: Relevance of Surface Strain Measurement, *Concreep-10, Mechanics and Physics of Creep, Shrinkage and Durability of Concrete and Concrete Structures*, September 21-23, 2015, Vienna, Austria

Coyne, A. 1938 Quelques résultats d'auscultation sonore sur les ouvrages en béton, béton armé ou metal. Annales de l'ITBTP, juillet-août 1938 (in French)

ETC-C 2012, EPR Technical Code for Civil Works. Paris, France : AFCEN.

Godart, B., 1985, Etude expérimentale du comportement de cordes vibrantes noyées dans des éprouvettes en béton sollicitées en fluage, Laboratoire Central des Ponts et Chaussées, Paris, France (in French)

Simon, A., and L. Rongieras, 2010, Reinstatement of Vibrating Wire Piezometers in Zoned Earth-Fill Dams, *8th ICOLD European Club Symposium*, 22-23 September 2010, Innsbruck, Austria

Simon, A., and A. Courtois, 2011, Structural Monitoring of Prestressed Concrete Containments of Nuclear Power Plants for Ageing Management, *Structural Mechanics in Reactor Technology*, 6-11 November 2011, New Delhi, India.