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Division I

CONCRETE DISTRIBUTED STRAIN MEASUREMENTS FEEDBACK ON CIVIL STRUCTURES BASED ON VERCORS MOCKUP – POTENTIAL APPLICATION FOR NEW NPP's

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ABSTRACT

Monitoring strain in the concrete of civil engineering structures such as pre stressed nuclear containments is of primary importance for safety and economic purposes. Strains in concrete is commonly measured by sensors using vibrating wire technology (Vibrating Wire Strain Gages VWSG). The first such sensors were used for monitoring dams in the 1930s. Nowadays this technology is recognized as a reference for strain measurement. For this reason EDF uses thousands of these sensors for pre stressed nuclear containment surveillance.

The evolution of surveillance needs of civil structures, including the pre stressed containments but not only, leads to the development of measurement technologies which can be complementary to the ones used historically in the pre stressed containments.

Among these alternative or complementary technologies, we can mention the distributed strain measurement sensors, which allows the acquisition of local concrete strain profiles on large areas of the structure and, after integration, the estimation of the global displacements of the structure. Those developments should be used for buildings in operation, in case of malfunctioning of embedded sensors for example, and for future buildings to complete, if necessary, the "historical" surveillance devices.

In the objective of qualifying the distributed strain sensors technology, Vercors mock-up is a very important tool, with an intermediate scale between the laboratory scale and the real building scale. VeRCoRs is a 1/3 scale pre stressed concrete containment mock-up. It is composed of a large number of monitoring devices, in purpose to test and qualify distributed measurement systems in the concrete during "operation" (pre stressing surveillance) and during the pressure tests (instantaneous strain/displacement under pressure).

INTRODUCTION: DESCRIPTION OF THE MONITORING SYSTEMS INSTALLED ON VERCORS MOCK UP AND OBJECTIVE

For the comparison purpose and qualification matter, hundreds of local concrete strain and temperature sensors are embedded into the concrete of the inner containment and used as references.

In addition to these traditional sensors, we installed distributed temperature and strain sensors: fiber optic and coaxial sensors. Concerning the distributed fiber optic systems;

- An optical fiber cable was embedded during the construction of the mock-up. It was embedded at 3 thicknesses and in several levels, for a total length of about 2km. This cable contains 4 optical fibers (2 multi-mode and 2 single-mode fibers),

- The same type of optical fiber cable was glued at the surface of the inner building, vertically and horizontally,
- Theses cables can be interrogated by Raman, Brillouin and Rayleigh devices,

To complete the system, a new approach of the distributed strain measurement is evaluated based on coaxial electrical cable. This cable is glued of the external concrete face of the mock-up (circumferential and vertical directions).

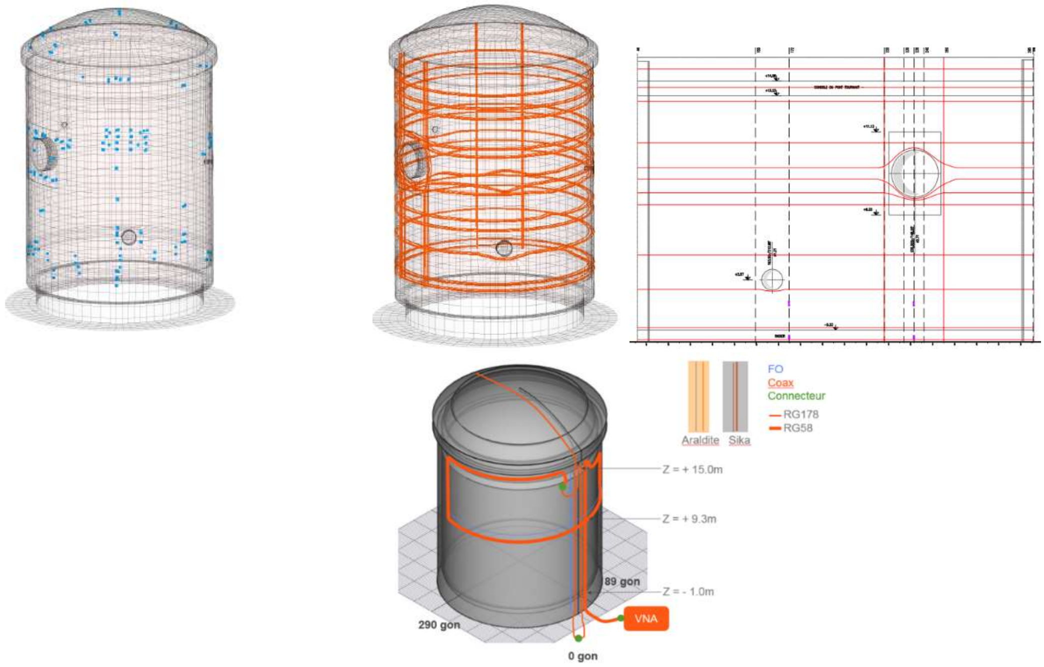

Figure 1. Local and distributed concrete strain measurement on Vercors Mockup – embedded devices at the top (VWSG at the left and Optical Fiber on the right) and glued on the external face devices at the bottom (Optical Fiber and Coaxial Cable)

The objective of this paper is to make a quantitative comparison of the measurements obtained by the distributed strain devices, calculating geometric average strain on all or part of the structure and integrated strains to obtain the overall displacements. These values can be compared respectively to the measurements of local concrete strains (VWSG) and integral displacements (pendulums/invar wires). The purposes are therefore to evaluate the ability of these devices to measure local/global strains and displacements and to ensure the consistency with the "historically qualified" devices used in containments and with the surveillance requirements of such civil structures.

PRINCIPLE OF DISTRIBUTED STRAIN MEASUREMENT

Optical fiber

The fiber optic sensors rely on the electromagnetic wave reflections. It consists of launching a light impulsion into the fiber optic. As the light interacts with the fiber optic, a small part is backscattered to the sensor, with a frequency shifted depending on the strain and temperature conditions.

Three main effects are used by interrogators: Rayleigh and Brillouin measurements are sensitive to temperature and strain. Raman measurements are sensitive to temperature. These devices provides temperature or strain profiles along the fiber with a distance range, a spatial resolution and an uncertainty depending on the interrogator. Typically, Brillouin devices have a distance range of several kms, a spatial resolution of 50cm and an strain uncertainty of around +/-20µm/m, whereas Rayleigh devices have a distance range of 70m, a spatial resolution of 1cm and an strain uncertainty of around +/-1µm/m,

For both Brillouin and Rayleigh interrogators, the raw measurement is a spectral shift, $\Delta\nu$, linked to strain, ε, and temperature variation, ΔT, between two fiber states, described by:

$$\Delta(x) = C_\varepsilon \varepsilon(x) + C_T \Delta T(x) \qquad (1)$$

$C\varepsilon$ and C_T are calibration coefficients ($C\varepsilon$ in MHz/µε and C_T in MHz/°C).

Coaxial Cable

In addition to the Optical Fiber developments, EDF proposed a distributed strain measurement solution based on the interrogation of a coaxial electrical cable. This method has been patented by EDF in 2016 (Patent No. FR3059780, 2016). The measurement principle is based on the measurement of the electrical impedance of an electrical line as a function of frequency; this is called frequency domain reflectometry (FDR) measurement. The electrical line is connected to a Vector Network Analyser (VNA). After calibration, the VNA measures the reflection coefficient in impedance (S_11) as a function of the frequency (f). Each section of the coaxial electrical cable is characterized by an electrical impedance (Z_C (x)). The characteristic impedance Z_C (x) of the coaxial cable and the propagation speed v_c (x) of an electrical signal depend on the geometry of the cable section and the electrical permittivity (ε_r) of the dielectric material. Under the effect of a stress (temperature, mechanical strain), the characteristic impedance is modified. The characteristic impedance variation ΔZ between two states of stress is expressed by:

$$\Delta Z(x) = C_\varepsilon \varepsilon(x) + C_T \Delta T(x) \qquad (2)$$

with $C\varepsilon$ (Ω/µm/m) and C_T (Ω/°C) proportionality coefficients respectively in strain and temperature depending on the electrical line.

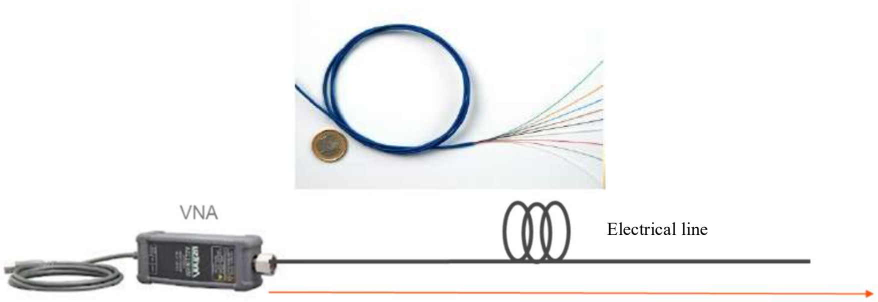

Figure 2. AFL 4804 (top) and Coaxial Cable (bottom) installed on VeRCoRS mock up

MEASUREMENT OF THE INSTANTANEOUS STRAINS DURING THE PRESSURE TEST

Strains in tangential direction of the optical fibers embedded into the concrete and glued on the external concrete surface

In this paragraph the instantaneous strains measured during the VeRCoRS pressure test are compared between the Optical Fibers embedded into the concrete, the ones glued on the external concrete face and the embedded VWSG.

Optical fibers in the cable embedded in concrete are interrogated with a Brillouin unit and optical fibers in the cable surface mounted are interrogated with a Rayleigh unit.

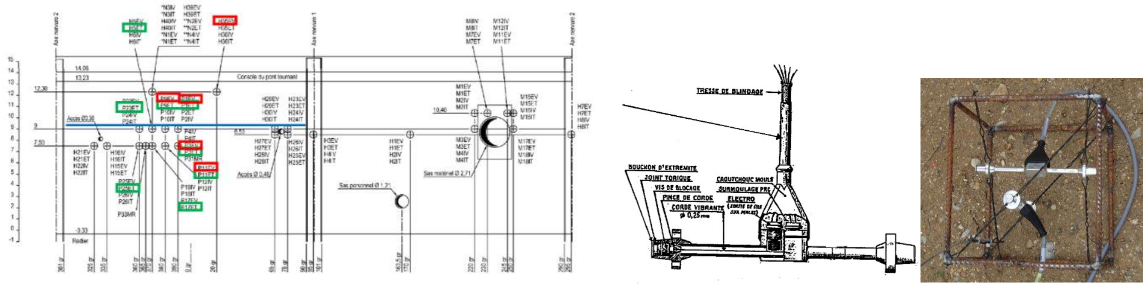

Figure 3. Location of the considered VWSG (left) and figures of the used VWSG (right)

Thermal correction is is based on a deterministic correction using material thermal properties. The thermically corrected Optical Fiber data are calculated by the following formulae and compared to the corrected data provided by VWSG:

$$\varepsilon_{\_OF\_corr} = \varepsilon_{\_OF\_raw} - C_T/C\varepsilon_{\_OF} * \Delta T_{(external\ face)} - \alpha_{\_c} * \Delta T_{average(external/internal\ face)} \qquad (3)$$

with $\varepsilon_{\_OF\_raw}$ and $\varepsilon_{\_OF\_corr}$ respectively the raw and corrected measured strains with Optical Fibers. We consider the calibration coefficients of:

- a Brillouin measurement for a standard single-mode optical fiber having only a primary coating (excluding cable), C_T = 1.0 MHz/°C and $C\varepsilon$ = 0.05 MHz/µm/m. This gives a $C_T/C\varepsilon$ Optical Fiber ratio interrogated with Brillouin of 20 µm/m/°C,
- a Rayleigh measurement for a standard single-mode optical fiber with only a primary coating (excluding cable), C_T = -1.25 MHz/°C and $C\varepsilon$ = -0.15 MHz/µm/m. This gives a $C_T/C\varepsilon$ Optical Fiber ratio interrogated with Rayleigh of around 8.3 µm/m/°C,
- This $C_T/C\varepsilon$ coefficient corresponds to the thermal behaviour of the fiber alone and it is associated to the temperature variation at the location of the external optical fiber $\Delta T_{(external\ face)}$.

We consider also concrete thermal expansion with a coefficient $\alpha_{\_c}$ of 10 µm/m/°C. It is associated to the temperature variation of the whole concrete section, as the average between internal/external face temperature variation $\Delta T_{average(external/internal\ face)}$.

In the figure below we note:

- a geometric variability of the distributed strain measurement which is very close between the glued Optical Fiber and the embedded Optical Fiber with a scattering (standard deviation) of the distributed strain measurement of the order of +/- 10 µm/m in the area without geometric singularities;
- the capacity of the distributed strain device to measure with a good level of confidence the strains in singular areas, for example around the equipment hatch,
- a very good correlation of tangential strains in the cylinder, between embedded Optical Fiber interrogated with Brillouin, glued Optical Fiber interrogated with Rayleigh and embedded VWSG,

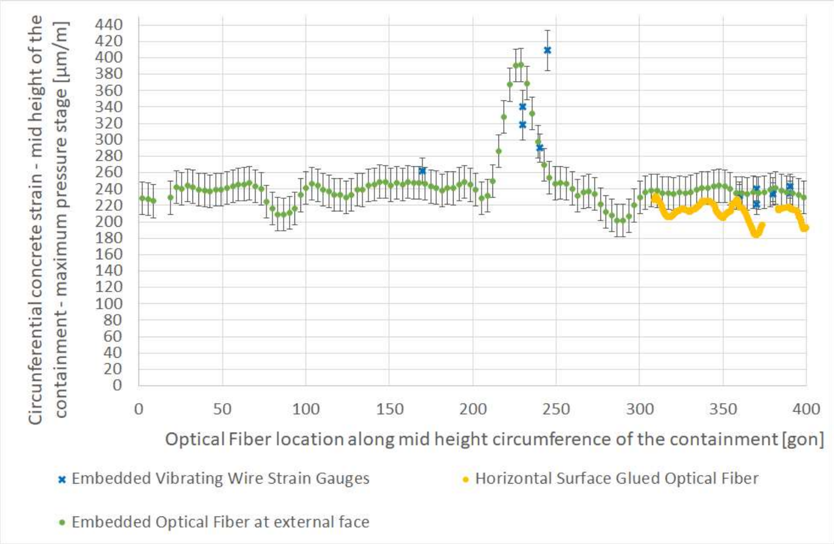

Figure 4. Circumferential concrete strain measured with VWSG, Glued and Embedded Optical Fiber [µm/m]- mid height of the containment - maximum pressure stage during VD5 pressure test

Considering the Optical Fibers measurements versus pressure, we note that the amplitudes at maximum pressure, the linearity and reversibility of the behavior are satisfactory, and relatively comparable to the VWSG measurements:

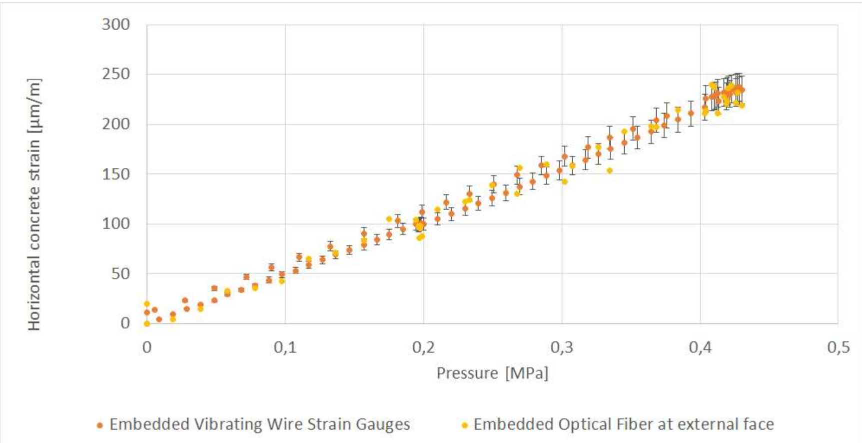

Figure 5. Concrete strain measured with VWSG and Embedded Optical Fiber [µm/m] versus pressure - mid height of the containment - VD5 pressure test

For the comparison to the global measurements corresponding to the radial displacements provided by the pendulums, the strains are integrated over the entire horizontal measurement length of the Optical Fiber L. Consequently, the variation of radial displacement ΔR induced by the tangential strains of the Optical Fiber ε_i at each measuring step x_i is calculated by $\int_0^L \varepsilon_i \,.\, dx_i$.

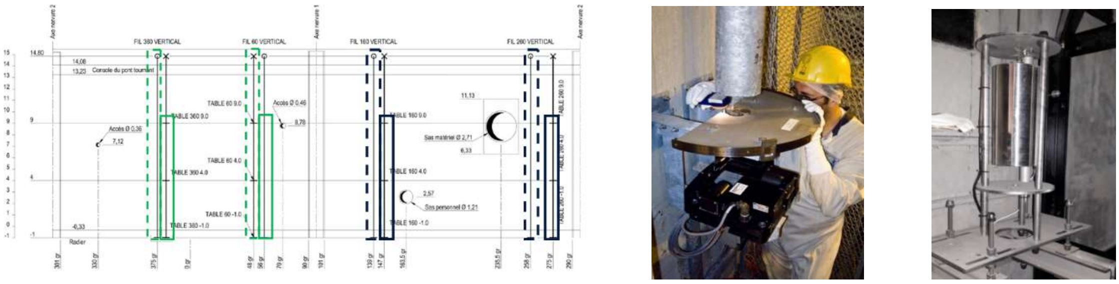

Figure 6. Location of the considered pendulums/invar wires (left) and figures of the used devices (right)

The displacement amplitudes between the pendulums and the optical fiber are comparable, with a gap covered by the uncertainties of both measuring devices:

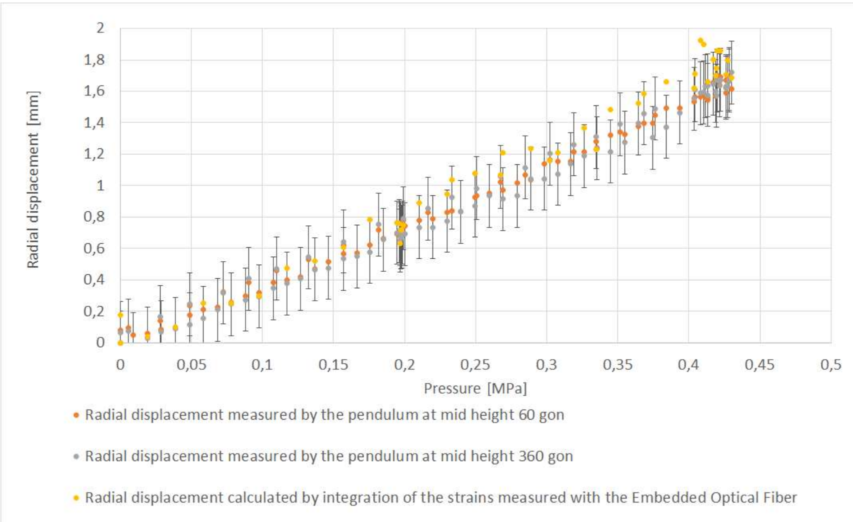

Figure 7. Concrete strain measured with Embedded Optical Fiber integrated over the length [mm] versus pressure – comparison to mid height pendulums - VD5 pressure test

Strains in vertical direction of the optical fiber and coaxial cable glued on the external concrete face
Optical fibers in the cable surface mounted are interrogated with a Rayleigh unit.
The same methodology is applied for the comparison of strains in the vertical direction. We note:

- a good correlation on vertical strains, between Optical Fiber and Coaxial Cable glued on the external concrete face and the measurements of embedded VWSG,
- that the distributed strain devices allow to measure correctly the maximum strains in the current area and those with strong variation, near the singular zones like the gusset at the bottom of the containment,
- the average differences between the technologies are of the order of 10 to 20 µm/m. The measurements are therefore comparable

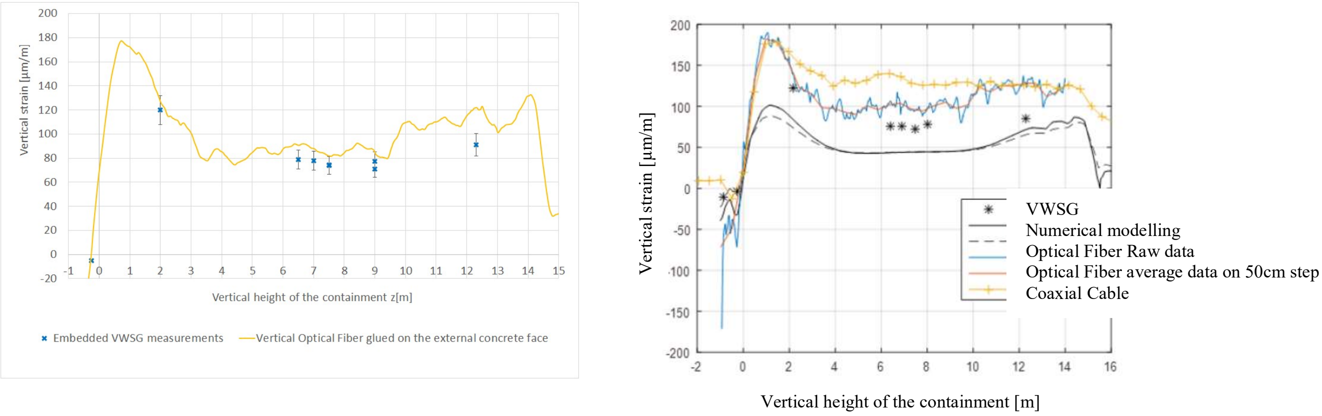

Figure 8. Vertical concrete strain measured with VWSG and glued optical fiber during VD5 pressure test (left) - Vertical concrete strain measured with VWSG, glued optical fiber and coaxial cable during VD3 pressure test (right)

AGEING OF THE CONTAINMENT - MEASUREMENT OF CREEP/SHRINKAGE WITH THE DISTRIBUTED STRAIN DEVICES

In addition to the instantaneous strains measured during the pressure tests, distributed strain measurement systems must be assessed for the measurement of delayed phenomena due to creep and shrinkage, related to concrete ageing.

Even if we note some strain variations due to thermal effects which are still imperfectly corrected, the figure below shows that the measurements in the fiber optic cable embedded in concrete are in agreement with the ones obtained with the Vibrating Wire Strain Gauges during the periods of time between the pressure tests since the beginning of operation of the mock-up, where the concrete is ageing affected by creep and shrinkage:

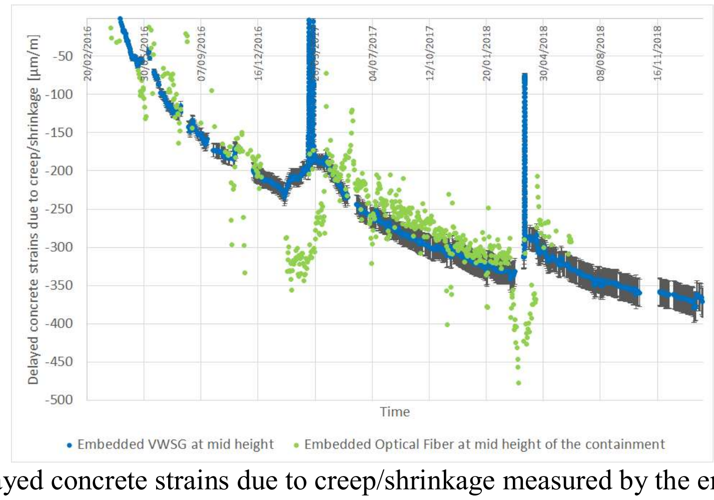

Figure 9. Delayed concrete strains due to creep/shrinkage measured by the embedded optical fiber compared to Vibrating Wire Strain Gauges

CONCLUSION

In the case of distributed fiber optic system with a cable embedded in concrete or surface mounted, we note:

- a very good agreement of results with VWSG, the differences corresponding to measurement uncertainties of each devices,
- a moderated spatial variability of the distributed strain measurement in the order of +/- 10 µm/m ,
- that the linearity of the containment behavior is reproduced satisfactorily by embedded and surface mounted fiber optic cable,
- that the reversibility of the containment behavior is reproduced satisfactorily, with a hysteresis of the tangential strain of the order of 20µm/m for the optical fiber (10µm/m for the VWSG), which represents less than 10% of the total amplitude,
- that the distributed strain measurement systems are able to measure in a representative way the variations of strains in current and singular areas,
- that the Brillouin interrogator is able to detect a mechanical behavior evolution in the order of 20µm/m,
- that the displacement measurements, assessed by strain integration are in good agreement with the ones measured by pendulums and invar wires.

Concerning the distributed coaxial system with a surface mounted cable, we note that:
- the strain measurements are in agreement with VWSG and distributed fiber optic systems in the current zone,
- the calibration coefficients, which depend on the cable and the installation method, is an R&D issue.

This R&D study on Vercors mockup will be completed by a laboratory testing program, in order to qualify the technologies for future NPP's applications.

These distributed monitoring systems are complementary of traditional local strain sensors like VWSG and global displacement sensors like pendulums and invar wires.

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