Non-invasive tunnel convergence measurement based on distributed optical fiber strain sensing

A Piccolo¹,², Y Lecieux², S Delepine-Lesoille¹ and D Leduc²

¹ National Radioactive Waste Management Agency (Andra), F-92298, Chatenay-Malabry, France
² Université de Nantes, Laboratoire GeM UMR 6183, F-44000, Nantes, France

E-mail: arianna.piccolo@andra.fr

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Abstract

This paper demonstrates the feasibility of tunnel convergence measurement using distributed optical fiber strain sensors, exploiting Rayleigh scattering and different fiber anchoring methods on the structure’s circumference. The proposed innovative solution does not restrict the tunnel practicable section, withstands harsh environment and performs distributed measurement which can provide more information than standard methods. Here is presented an inverse analysis finite element based method to compute convergence from orthoradial strain measurement. Its performances are assessed by identifying which are the influencing parameters and how their uncertainty plays on the inverse analysis outcome. Finally its implementation as a test in a laboratory is reported, which proved the ability to determine geophysical convergence with 1 mm resolution, consistently with expected performances.

Keywords: optical fiber sensors, shape sensing, tunnel, convergence, monitoring, Rayleigh strain sensing, inverse analysis

(Some figures may appear in colour only in the online journal)

1. Introduction

When it comes to build structures like radioactive waste repository cells, structural health monitoring must be foreseen. The French deep geological repository for high-level (HL) and intermediate-level long-lived (IL-LL) radioactive waste, planned by Andra and known as the project Cigéo, requires different tasks and planning, as its monitoring to contribute to check:

(i) the long-term safety of the site and the surrounding area;
(ii) the retrievability of waste during the first decades of operation.

In order to guarantee a proper operation, convergence measurements of the repository structure should be provided, despite a harsh environment in which high temperature (up to 90 °C), hydrogen release and gamma radiations are present. The evolution of tunnel-like structure’s convergence, which is the relative displacement of two diametrically-opposed points, is a natural phenomenon. Considering that the tunnel section tends to reduce over time, it is an important parameter to monitor in order to ensure the tunnels’ expected functions/behavior. Andra is currently assessing tunnel convergence monitoring methods within its underground research laboratory (URL) [1], where sensors of different kinds are tested on HL and IL-LL waste repository cells demonstrators. These demonstrators are placed 500 m deep underground, built after circular underground excavations on a horizontal axis or slight slope dug, representing the mock-up of real radioactive waste repository cells. HLW disposal cells would contain only one disposal package per cell section, whose diameter is ~0.7 m and is at least 80 m long, with an outer metallic liner...
of 25 mm thickness. IL-LLW disposal cells would contain several disposal packages per cell section, having dimensions in the order of ∼9 m of diameter per 600 m long, with a concrete liner. Both structures are shown in figure 1, while further description is available in [2].

For each structure, standard tunnel’s convergence monitoring methods use sensors which are in many cases inside the tunnel section (e.g. invar wires [3], laser theodolites [4], angular encoders [5], LiDAR [6], displacement sensors [7]). These sensors are thus not appropriate in case of radioactive waste repository cells for which it would be required:

(i) to withstand radiation;
(ii) to allow the presence of radioactive waste and the circulation of monitoring robots.

For these reasons, another convergence measurement method should be defined, for example using a sensor to be put inside the tunnel liner or at its interface with the host-rock surrounding the structure. These requirements are also valid for railway and highway tunnel monitoring, where the traffic is regularly stopped in order to perform measuring campaigns based on standard techniques, inducing important costs. For the particular radioactive waste disposal environment,

(iii) the sensing system has to ensure convergence measurement all around the section of the structure and to use an interrogation device placed remotely to enable maintenance (distance range up to 1 km).

For HLW structures in the Cigéo concept, the surrounding clay layer applies an anisotropic external load on the steel liner. This behavior is directly related to the anisotropic extent of the excavation induced fractures network around the cell [8]. This loading anisotropy results in a radial bending of the liner causing an expected diameter reduction up to 10 mm during the operational phase (i.e. 100 years), where retrievability must be guaranteed.

Lastly,

(iv) the design should consider the required strain sensitivity to reach the millimetre sensitivity for the convergence measurement.

The flexibility and compression resistance of optical sensing cables, along with their small dimensions and silica intrinsic characteristics, are particularly suitable for new techniques [9] as they are widely used in standard civil engineering structural health monitoring [10–13], and also in tunnels [14–16]. New methods that rely on data processing over optical fiber sensors as fiber Bragg gratings (FBGs) have been recently developed [17], however they do not comply with specifications. Indeed, distributed measurements should be preferred for large structures to reduce blind zones, influence of localization accuracy and cost. For instance, for the structure in [17] 872 FBGs have been necessary in order to monitor a tunnel of 2.6 km.

The goal of this paper is to propose a new technique for convergence measurement which relies on distributed optical fiber strain sensing cables in combination with an inverse analysis finite element method, ensuring a convergence resolution of 1 mm. In this paper the proposed method is illustrated in section 2, following a description of the employed materials to analyze its performances in a laboratory. In section 3, results of the test are showed as well as the method’s calculated sensitivity and limits on different loading cases, providing an experimental validation of the theoretical method. In section 4 possible bias and improvements are discussed, taking to conclusions in section 5.

2. Materials and methods

2.1. Laboratory mock-up

The tested structure has been built in order to be as much as possible representative of the real HLW repository cell, especially regarding its behavior under loading effort. In the real case, a total of 10 mm of convergence is expected during the operational phase, which are due to 500 m of rock pressure above the cell. The rock is the Callovo-Oxfordian claystone, which exhibits a time-dependant behavior due to the creep of the rock matrix. This phenomenon is responsible for long term deformation of the drifts or disposal cells. The deformation rate however decreases with time and becomes lower than 10⁻¹⁰ s⁻¹ after one year [18]. In order to obtain the representative displacement in laboratory conditions the thickness of the structure was reduced with respect to the real disposal cell liner (25 mm). The result is the design of a steel
ring of nominal dimensions 762 mm of external diameter, 10 mm thickness and 200 mm depth. As a consequence, for identical convergence, strain levels are expected to be smaller in the laboratory test compared to real conditions (values are around 30% of those obtained by numerical simulation of the real conditions). This makes the feasibility demonstration more difficult than in reality as the strain sensing accuracy needs to be higher. After the construction of the structure, a mean thickness value of 9.88 mm is measured (with a variance of about 0.1 mm), leading to take 9.9 mm as the reference value to be used in the numerical model. The characteristics of the steel are reported in Table 1. The simulation considers the convergence evolution up to the representative maximum value of 10 mm. In practice, the ring is anchored to a reaction frame (green wheel in figures 2 and 3), with screws whose rotation applies a vertical charge on the metallic surface. The convergence levels were monitored with help of a ruler.

2.2. Sensors

The optical strain sensing cable BRUsens V9 (supplied by former Brugg Kabel AG, now Solifos AG) was chosen for its high resistance to tensile loading, conveyed by the inner metallic reinforced fiber, and its high curvature radius tolerance. From datasheet, it is able to withstand the 1% of elongation (10 000 με) and its diameter is 3.2 mm. It is fixed in two ways on the structure: in total, the sensing cable performs two turns around the external circumference. One turn is glued all along its length (Araldite 2021-1 glue). The other is fixed with a spot welding technique, where soldered supports are distanced from each other of about 4 cm. The two anchoring methods are shown in figure 4. The anchoring methodology is very important, as strain measurements strictly depend on implementation and strain transfer function. Gluing the cable allows it to be sensitive all along its length and to possibly be influenced in the same way by compression and tension. For this particular application it is however necessary to analyze if the glue could resist over the operation time (tens of years at least) and to note that its implementation time is long (it takes hours to let the glue dry properly). Soldering instead resists in time and is faster to deploy. However the cable is only fixed punctually. As a result, longitudinal compression may induce different strain than tension, since the cable may slip between anchors. A single mode fiber with high curvature radius tolerance is required; this type of optical fiber (G657 standard) is implemented inside the selected sensing cable.

Measurements via optical fiber sensing will be compared with four displacement sensors which are positioned as in figure 3, from diameter D1 to D4. They are internally fixed to the structure’s four quadrants and used as reference sensors for convergence, as their functioning is similar to micro-tunnel’s standard convergence monitoring sensors. The radial displacement is imposed at one extremity of D1, in order to measure exactly the desired convergence. These sensors are position transducers, pivot head mounting potentiometric up to 300 mm, of the Ingress Protection classification IP67 (IEC standard 60529) suitable for harsh environmental conditions, with a resolution better than 0.01 mm.

Finally, force sensors are mounted on each movable runner, which applies the load to the structure. They are fixed between the metal plate of each runner and the screw which controls the load. Four of these sensors are employed, being of FTCN series (sensors of traction/compression) from the company Mesurex with a maximum measurable load of 10
kN and a resolution of 0.1%. In this way it is also possible to perform a comparison between the force that is applied on the structure and the one that is found by the inverse analysis model, being the main parameter of the simulation.

2.3. Strain measurement

The cable is interrogated with a commercial device, Neubresco NBX-7020F\footnote{Neubrex Co., Ltd} exploiting Rayleigh scattering\footnote{TW-COTDR} with tunable wavelength coherent optical time domain reflectometry (TW-COTDR). It provides a strain sensitivity of $1 \mu m m^{-1}$ on a single-end measurement configuration. This technique provides a measurement of the frequency shift $\Delta \nu$ between the actual and the reference state of the fiber\footnote{Rayleigh fiber temperature strain calibration coefficients} that is related to temperature and strain influence as

$$\Delta \nu = C_T \Delta T + C_e \Delta \varepsilon,$$

where $C_T$ and $C_e$ are the Rayleigh fiber temperature strain calibration coefficients\footnote{Rayleigh fiber temperature strain calibration coefficients}. These values depend on the fiber properties. In this case, the coefficients are $C_T = -1.5 \frac{GHz}{\degree C}$ and $C_e \approx -0.173 \frac{GHz}{\degree C}$. As the temperature during the experimental test was stable, the strain is found to be $\Delta \varepsilon = \Delta \nu / C_e$. The instrument ensures a longitudinal spatial resolution of 2 cm. The distance range is 50 m, while the sampling interval is 1 cm. The frequency range is [194; 194.25] GHz with a 500 MHz step. These parameters have been chosen in order to have a trade-off between measurement accuracy and acquisition duration. With these values, measurement took a couple of minutes for each step.

2.4. Loading cases

In order to analyze the feasibility to monitor convergence for Andra’s specific application using strain measurements, two different charging cases are considered.

The first case is representative of the charge evolution on a real HLW repository cell. Main loading comes from the rock above the cell, thus the charge on the laboratory mock-up is applied to a chosen position while the diametrically opposite point is fixed and cannot move. In this way a vertical charge, as well as the reaction of the ground, are simulated. The cell is however surrounded by rock, so two other fixations are positioned at the other quadrants in order to simulate the rock constraints. They are fixed 2 mm away from the structure, in order to simulate the real placement of the structure inside the rock. This case is illustrated in figure 5(a). From now on it will be addressed as ‘four points’ case.

In the same figure, (b), the other analyzed case is represented. It corresponds to a simplified version of the first case. It has only two diametrically opposite fixations simulating a vertical convergence. This case is named ‘two points’. It was conceived to demonstrate the feasibility of the inverse FE method. For this reason this simplified model will be analyzed before the complete one.

Measured strain will be illustrated as a function of the angular position around the structure. In figure 5 the angular repartition is shown for the two cases, which will be the
reference for the result plotting, while on (c) the displacement sensors positions are shown.

2.5. Structural geometry identification based on strain measurements

Optical fibers, once applied around a circular structure, allow to measure the circumferential strain all along their length. The desired quantity is the variation of the structure’s diameter, thus it is necessary to perform an inverse analysis [23] to retrieve the deformed geometry starting from the observable measurements.

This involves a search for a set of loading parameters $F^i$ which minimizes an objective function $\Phi$:

$$\Phi(F^i) = \frac{1}{2} || \epsilon(F^i) - \tilde{\epsilon} ||,$$  (2)

where $\tilde{\epsilon}$ is the measured orthoradial strain and $\epsilon(F^i)$ the computed orthoradial strain by means of a finite element (FE) model [24] where the $F^i$ are the applied forces at a given node $i$.

The FE method is a powerful and generic method thanks to which it is possible to describe a great variety of geometries, applying the same numerical procedure to calculate different features. In this laboratory test the direction and application points of punctual forces are known, while the magnitude is not. On field the empirical knowledge will be used to determine the direction of maximum load application from the analysis of in situ investigations [8]. It would be also possible to introduce a more complex parameter setting.

The method is hereby presented:

- For a set of forces, the displacement field is computed with the FE method, for each node of the finite element mesh. Isotropic elasticity is considered for the steel structure behavior law.
- From displacement, it is possible to calculate strain $\epsilon_{ij}$ as Cauchy or engineering strain with the following formula:

$$\epsilon_{ij} = \frac{(X_i - X_j)(u_i - u_j)}{L_{ij}^2} + \frac{(Y_i - Y_j)(v_i - v_j)}{L_{ij}^2}.$$  (3)

where $(X_i, Y_i)$ are the original coordinates of node $i$, $(u_i, v_i)$ are the displacements of node $i$ in the $x$ and $y$ directions. The same notation is selected for node $j$. $L_{ij}$ is the distance between nodes $i$ and $j$ of the structure mesh. These quantities are illustrated in figure 6(a).

- This numerical strain has to be compared with the experimental one, to retrieve the loading force(s) and the corresponding deformed geometry. To do so, it is necessary to calculate the difference (error) between the two orthoradial strains and choose the force(s) $F^i$ which minimizes its root mean square (rms). The detailed formulas will be given later on, once symmetry properties of the proposed loading cases are taken into account to simplify calculation.

- Once the appropriate charge is found, the corresponding displacement can be selected from previous calculation. Then the deformed geometry and finally convergence can be calculated, for each node, as

$$x_i = X_i + u_i; \ y_i = Y_i + v_i (\forall \ i, \ i \ mesh \ node)$$

$$d_i = \sqrt{(x_i + 180° - x_i)^2 + (y_i + 180° - y_i)^2}$$

$$\Delta d_i = d_i - D,$$  (6)

where $(X_i, Y_i)$ are the original coordinates of node $i$ and $D$ is the original diameter of the structure, which is constant for circular sections. The new diameters are simply calculated as distances between opposite points. The difference between the diameters of the deformed and original geometry gives the diametrical convergence $\Delta d$ (as in figure 6(b)).

The finite element model used in this study consists of 2880 quadrangle elements—4 elements in the thickness and 1 element every 0.5°—with bilinear interpolation functions and 4 Gauss integration points. Mesh, loads and boundary conditions are shown in figure 7. The number of finite elements was defined after a preliminary study, which was performed on a thick tube subjected to internal pressure. This tube has identical internal and external diameters as the mock-up.

3. Results and discussions

3.1. Two points load application case

In the two points case, a force and the corresponding opposite reaction are vertically applied to the ring, which remains elastic. As it is possible to apply the hypothesis of small strain and small displacement, the structure is modeled according to the principle of superposition of the effects for which if $F^u \rightarrow (u^a, \ v^a)$ then $\alpha F^u \rightarrow (\alpha u^a, \ \alpha v^a)$ where the exponent $\alpha$ means “unitary”.

It is then possible to charge the ring with a unitary force and find the applied force as

$$F_{CY} = \frac{1}{N} \sum_{i=1}^{N} (\alpha \epsilon_{ij}^u - \hat{\epsilon}_{ij})^2$$

$$F = \alpha F^u, \ \hat{\epsilon} = \alpha \epsilon^u \ \text{and} \ \alpha = \arg\min(\Phi),$$  (7)

where $N$ is the number of elements of the mesh, $\alpha$ represents the magnitude of the charge, $\epsilon^u$ is the theoretical orthoradial strain resulting from the unitary force and $\hat{\epsilon}$ is the experimental one. In this case $\alpha$ is swept with unitary precision.
The opposite point is kept fixed by imposing no displacement for it while building the finite element model.

3.2. Four points load application case

This case can be seen as the previous one plus adding two other forces which represent the reactions at the two lateral runners. As the reaction should be the same, being positioned symmetrically with respect to the charge, only one amplitude for these two forces is searched for optimisation. They are represented as the two orange forces in figure 5(a). If, as before, the loading of unitary forces is considered, the model should be optimised to find two amplitudes $\alpha$ and $\beta$. In fact, if for $F_1$, $||F_1,x|| = 0$, $||F_1,y|| = 1 \rightarrow u_1, \varepsilon_1$ and if for $F_2$, $||F_2,x|| = \pm 1$, $||F_2,y|| = 0 \rightarrow u_2, \varepsilon_2$, then $\alpha F_1 + \beta F_2 \rightarrow \alpha u_1 + \beta u_2 \rightarrow \varepsilon_{TOT}$.

In order then to find $\alpha$ and $\beta$, arbitrary values of $\alpha$ and $\beta$ are coupled to calculate the displacement. $\varepsilon_{TOT}$ is then computed and $F$ is retrieved proceeding as before, so

$$\Phi = \frac{1}{N} \sum_{i=1}^{N} (\varepsilon_{TOT,i} - \bar{\varepsilon})^2$$  \hspace{1cm} (8)

$$(\alpha, \beta) = \text{argmin}(\Phi) \rightarrow F = \alpha F_1 + \beta F_2.$$

3.2.1. Sensitivity analysis. In order to understand the robustness of the adopted model to calculate convergence, a sensitivity analysis is performed. The focus is on how much the measurement noise and the number of measurement points affect results. Noise values are chosen to be representative of experimental data.

A theoretical perfect frequency shift trace was obtained by simulating the charge onto a point of the structure using the finite element method, where the mesh is made of 720 measurement points all around the circumference. The applied charge is of 4500 N, which represents a little more than 10 mm of convergence. Convergence calculation is performed applying the inverse analysis method starting from this trace and the ones obtained adding different levels of noise $B$ (from 0.1% to 10% of the maximum frequency shift value obtained by simulation). More precisely, noise is added to each measurement point value. Its amplitude is a random number, chosen from the uniformly distributed interval $[-B; B]$. The error between the convergences obtained with and without noise is then calculated. The simulation is performed 1000 times (for each noise level) in order to compute the mean value $\mu$ and standard deviation $\sigma$ distributions of the error. This procedure is repeated assuming a different number of measurement points $N$, by first interpolating the perfect trace and then adding noise accordingly to the chosen level.

Some results are shown in the following. The distribution of errors in case of 10% noise level is shown in figure 8, for different $N$. In each case their distribution follows a normal distribution.

Standard deviations decrease with the number of measurement points, as in figure 9. Their distribution over...
different noise levels is similar between different $N$. The same evolution is followed by the maximum error.

A focus on the 10% noise level is reported in figure 10, where the evolution of the standard deviation for different $N$ is represented. It is then compared with a theoretical distribution where $\sigma_N = \sigma_0 \sqrt{N}$, which represents the relationship between each couple $(N; \sigma)$ and the others. The two curves are almost superimposed. From these figures it could be noticed that the retrieved convergence error is very small even for the highest evaluated noise, in the order of 1%–3% for the worst cases ($N = 50$ or 100 for example), as the imposed convergence is a little more than 10 mm. The method is thus very accurate and tends to smooth the noise effect, which is a useful feature when in situ measurement is to be done.

The study shows that a high number of measurement points makes the geometry identification procedure more robust. This result emphasizes the interest of distributed strain measurement technology, rather than a local one (as FBGs), capable of performing a more precise measurement locally.

### 3.2.2. Experimental validation

#### 3.2.2.1. Two points load application case

In this case the fixed point is charged at one point, thanks to the runner and the corresponding screw, while the diametrically opposite point is immobilized thanks to a blocked runner (figure 5(b)). Different convergence levels are imposed, measured with a ruler: from 2 to 10 mm, with a 2 mm step. One measurement was also performed at 9 mm, in order to evaluate the resolution (the target resolution is 1 mm).

Resulting strain measurements are then given as input of the model, obtaining the corresponding forces which minimize the error between experimental and simulated strain. A comparison example is shown in figure 11, for 10 mm of imposed displacement. As illustrated, the maximum strains are about 400 με in traction and 800 με in compression. These are only the 30% of the values that will be encountered in the real application, taking to a maximum of 2700 με in compression. These values are therefore within the standard working range of the employed cable.

The inverse analysis—finite element method applied to both the glued and the soldered cables give very similar results and the two curves, representing the experimental and the simulated strain, are in great accordance.

Moreover, convergence measurement based on the FE model allows filtering out peak values which result after cross-correlation of Rayleigh scattering traces, when large evolutions have occurred. These spikes are due to the random nature of Rayleigh spectral response and they can occur in every cross-correlation based technique when strain levels reach several tens of microstrains [25]. In other studies (as [17]) convergence is directly computed from strain measurements, thus each measurement error reflects on results. In the proposed methodology, displacement and convergence are obtained via the FE model, with strain measurements as input.

Once the optimum force is determined, it is possible to finally obtain convergence. In parallel, convergence was calculated starting from the force sensors measurement. The same model was applied, but measured force was used as direct input to the FE model, instead of going through the inverse analysis process. In this way it is possible to compare the computed forces with the actual load and the corresponding convergence results. The comparison between the calculated versus measured forces is illustrated in figure 12.

Figure 12 shows that the glued and soldered cables give almost the same results for each load level. The force obtained from distributed strain measurements is 10% higher than the value measured by the force sensor and the theoretical targeted value (dotted line). The same difference reflects on calculated convergence values, which are shown in figure 13. The comparison between measured convergence (by displacement sensor) and the one calculated with the model is reported. The figure also shows the convergence calculated with the force sensors’ measurement.

Optical fiber cable sensing gives as output a convergence that is close to the reference sensors value, while coherently there is still a difference with respect to the force sensor results. This kind of discrepancy could be due to different causes, which will be addressed in the discussion section.
Despite this small difference, the method is able to retrieve convergence measurements and discriminate the different charge levels. The accuracy mainly depends on the implementation of the test and remains as small as 1 mm.

3.2.2.2. Four points load application case. In this case the ring is charged at the same point as before, however two runners on the orthogonal direction are kept fixed 2 mm from the ring at rest (in figure 5(a), the two orange rectangles). In this way, while the ring is being charged, it would gradually reach the physical constraints as it would be exposed on-site with the repository cell and the surrounding rock. Imposed displacement goes from 2 to 10 mm with a 2 mm step. In figure 14 the result from the application of the method to strain measurements in case of 10 mm of imposed convergence is shown. In this case a slight difference can be seen between the two different anchoring methods and this consequently affects simulation result.

In figure 15 calculated optimal forces are compared with the measured force sensor values, both in the direction of the charge D1 and in the orthogonal direction D3 where reaction forces are excited. In figure 15(a), force sensor values are the ones reported by the sensor at the charge position D1, while on (b) values are the mean of the two other sensors placed in the orthogonal direction D3. This has been done in order to perform a proper comparison: in the direction D3 in the FE model two equal forces are applied, thus only one force value is retrieved at the output. In both cases, error bars’ values are the differences between the two force sensors positioned on the same axis, D1 or D3, at opposite sides of the diameter.

The reference force is estimated with a 20% uncertainty for the position D1 and up to 200 N for D3, as represented by error bars. The glued cable shows results that are almost superimposed to the force sensor, while soldered cable error is about 20%–30% for the position D1 (where errors are almost always within the error bars) and from 40% to more in direction D3.

In figure 16 convergence comparison is represented, both all around the ring for an imposed displacement of 10 mm (a) and for all convergence levels at the charge direction (b).

Results on convergence reflect what was found regarding force: glued cable results are close to the ones obtained via direct model by force sensors values, in all four diametrical directions. Displacement sensors are not exactly aligned with imposed values of convergence, which could be due measurement uncertainty, as the ruler has a sensitivity of 0.5 mm. In this complex case, the methodology enables to provide the convergence with uncertainty of 2 mm and sensitivity of 2 mm, which is the imposed displacement step.

Finally it should be noticed that the soldered sensing cable results are less promising compared to the glued ones. This result was expected, as glue is supposed to guarantee an identical traction behavior for all contact points between the structure and the sensor.
be possible to establish an analytic model based on simplification. As the numerical model is a simple structure, it could be possible to establish an analytic model based on simplified hypothesis of beam theory. This model is not the most suitable for inverse analysis as it tends to underestimate strain. However, we chose to introduce it at this stage of the discussion in order to understand the origins of the small discrepancies between force and convergence values directly measured by reference sensors and their identification from strain measurement.

A circular ring of average radius \( r \) is considered to be subject to two sets of diametrically opposed concentrated forces (see figure 17(a)). Due to the symmetries, the study is limited to the analysis of the internal forces on the upper half ring (see figure 17(b)).

For this structure, considering the parameterization of the figure 17, the internal forces are:

\[
T_z = -\frac{1}{2} F \sin \theta \\
N_z = -\frac{1}{2} F \cos \theta \\
M_z = \frac{Fr}{2\pi} (\pi \cos \theta - 2) 
\]

where \( F \) is the applied force. The axial strain \( \varepsilon_{yy} \) yielded by the optical sensor is given by equation (12):

\[
\varepsilon_{yy} = \frac{N_z}{ES} - \frac{M_z}{EI} x \approx -\frac{M_z}{EI} x \approx \frac{3Fr}{\pi Ebe^3} (2 - \pi \cos \theta)x, 
\]

where \( S \) is the ring section, \( E \) the Young’s modulus, \( I \) the second moment, \( e \) the thickness of the structure and \( b \) its width. \( x \) is the distance between the strain sensor axis and the neutral axis of the ring, i.e. \( x = \frac{r}{2} + d \) where \( d \) is the distance of the center of the fiber from the surface of the ring. Relation 12 shows which parameters influence the final result. Both the material and the shape of the structure have an impact on the yielded strain. In figure 13(a)), the values of the selected reference sensors (displacement sensors) are not perfectly superimposed to the red dotted line which represents the imposed convergence. The same applies to the convergence calculated by the direct model with force sensors values as input, which should be perfectly in line with the imposed values. This discrepancy is due firstly to uncertainty on the sensors measurement: (i) the fiber is not located exactly on the surface of the structure, because the cable diameter is 3.2 mm, and (ii) installation can lead to angular deviations of the sensor (non-perfect circular section). Secondly, uncertainty is due to the ring structure parameters (shape, thickness and material). These uncertainties in structural parameters are the origin of the difference between the direct measurement of convergence and the one calculated using the direct finite element model combined with force measurements.

Concerning optical fiber strain sensing cable results, it is important to notice that there is an overall error on the calculated force (and therefore on convergence) which is proportional to the imposed convergence value. Different convergence levels are properly discriminated, while there is inaccuracy on the single value. This proportionality difference is due to the choice of the strain sensitivity coefficient, which reflects a not perfect strain transfer function [26]. It also explains why soldered and glued cable results are different.

Error spikes are often present when using cross-correlation based techniques exploiting Rayleigh scattering, as the TW-COTDR. They affect measurements when strain level exceed few tens of microstrains. In section 3.1 the influence of white noise on convergence measurement was studied, however white noise might not be the best choice in order to represent the error affecting measurement. A specific study on how to filter out such spikes prior giving measurements as input to the FE model is in perspective. Brillouin scattering-based measurement techniques is another solution to limit strain measurement errors.

4. Discussion

The direct model used in the inverse analysis procedure relies on a simplification of a 3D finite element model: a 2D plane stress finite element model, which is the assumption made for this test. As the numerical model is a simple structure, it could be possible to establish an analytic model based on simplified hypothesis of beam theory. This model is not the most suitable for inverse analysis as it tends to underestimate strain. However, we chose to introduce it at this stage of the discussion in order to understand the origins of the small discrepancies between force and convergence values directly measured by reference sensors and their identification from strain measurement.

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where \( S \) is the ring section, \( E \) the Young’s modulus, \( I \) the second moment, \( e \) the thickness of the structure and \( b \) its width. \( x \) is the distance between the strain sensor axis and the neutral axis of the ring, i.e. \( x = \frac{r}{2} + d \) where \( d \) is the distance of the center of the fiber from the surface of the ring. Relation 12 shows which parameters influence the final result. Both the material and the shape of the structure have an impact on the yielded strain. In figure 13(a)), the values of the selected reference sensors (displacement sensors) are not perfectly superimposed to the red dotted line which represents the imposed convergence. The same applies to the convergence calculated by the direct model with force sensors values as input, which should be perfectly in line with the imposed values. This discrepancy is due firstly to uncertainty on the sensors measurement: (i) the fiber is not located exactly on the surface of the structure, because the cable diameter is 3.2 mm, and (ii) installation can lead to angular deviations of the sensor (non-perfect circular section). Secondly, uncertainty is due to the ring structure parameters (shape, thickness and material). These uncertainties in structural parameters are the origin of the difference between the direct measurement of convergence and the one calculated using the direct finite element model combined with force measurements.

Concerning optical fiber strain sensing cable results, it is important to notice that there is an overall error on the calculated force (and therefore on convergence) which is proportional to the imposed convergence value. Different convergence levels are properly discriminated, while there is inaccuracy on the single value. This proportionality difference is due to the choice of the strain sensitivity coefficient, which reflects a not perfect strain transfer function [26]. It also explains why soldered and glued cable results are different.

Error spikes are often present when using cross-correlation based techniques exploiting Rayleigh scattering, as the TW-COTDR. They affect measurements when strain level exceed few tens of microstrains. In section 3.1 the influence of white noise on convergence measurement was studied, however white noise might not be the best choice in order to represent the error affecting measurement. A specific study on how to filter out such spikes prior giving measurements as input to the FE model is in perspective. Brillouin scattering-based measurement techniques is another solution to limit strain measurement errors.
**Figure 14.** Experimental and optimized simulated strain comparison for the glued (a) and soldered (b) cable for the four points load case, at 10 mm of imposed displacement.

**Figure 15.** Forces comparison for the 4 P case: (a) forces at diameter D1; (b) forces at diameter D3.

**Figure 16.** Convergence comparison for the four points load case: (a) convergence all around the ring for 10 mm of imposed displacement; (b) convergence at diameter D1 for each imposed displacement value.
In figure 15(a)) the discrepancy between the load and the reaction in the direction of the charge, which is represented by the error bars amplitude, is noticeable. In an ideal situation these two forces should be equal in amplitude and opposite in sign. This may represent a behavior of the charge on the structure which is not expected, leading to inconsistent values between sensors and model output. This is one of the reasons why results are not matching perfectly and it could be due to the real shape and dimensions of the structure under test. In fact, regarding the structure, both the shape and the thickness of the ring have some discrepancies with respect to the perfect mesh built for the FE model. The ring is not perfectly circular, as the diameters measured at the positions of the four displacement sensors differ of some mm. Moreover, the thickness of the metal is not regular, both at different angular positions and at the two opposite sections of the ring (in depth). This is particularly important, as thickness is elevated by a cubic factor in equation (12).

The experimental uncertainties on the fiber thickness and its actual position lead to a non-symmetrical forces repartition, and contribute to discrepancies between direct convergence measurements (retrieved by force sensors values applied to the FE model) and the ones obtained by inverse analysis.

All these analysis improved the final results with respect to using all nominal parameters values. This shows the importance of sensors calibration and of adapting the model to the structure under test. The resulting forces discrepancies are about 10% for the two points load case and about 20%–30% for the four points load case. These uncertainties are consistent with the discrepancies between the model and measurements. Moreover, the employed mock-up is less deformable than what it would be in the final application in situ, leading to the conclusion that in reality the same accuracy would be obtained with greater ease. For other applications, if load and strain become larger, the error would indeed increase since the discrepancy is proportional. For example, for the two points load case the correlation coefficient of the linear regression of force values is around 0.999 for both sensors. This difference can be corrected by fitting the sensitivity coefficient $C_s$. It was not in the purpose of this study, as it is focused on the demonstration of the feasibility of the convergence measurement method. In real application a calibration of the instrumented structure is recommended, which has been considered too expensive for a feasibility demonstration.

In the end, despite all detected uncertainties, it is important to highlight that it is possible to determine convergence values. What is more, this methodology provides the whole shape of the structure. In figure 18, the original shape and the ones retrieved by applying the proposed method to soldered cable results are superimposed. Even if this anchoring method appeared to be the less efficient, it is still able to give information of convergence all around the structure. Distributed optical fiber sensing is hence able to provide more information than local sensors like displacement sensors used here as reference.
5. Conclusion

This paper demonstrates the feasibility of using distributed optical fiber sensing cables for convergence measurements, thanks to their combination with an inverse analysis—finite element approach. The proposed method represents an innovation in the field of structural health monitoring and especially for radioactive waste repository cells. The method (i) is compatible with harsh environment [27, 28], (ii) it does not occupy the inside of the tunnels (thus it does not stop circulation nor takes the place of radioactive waste), (iii) it is suitable for big structures, as optical fiber range can easily reach thousands of meters and (iv) convergence is obtained for all points of the section of the structure. Convergence is obtained with 1 mm resolution and it is possible to distinguish in a proper way different levels of charge, not only punctually but also in a distributed manner all along the desired structure employing only one sensor. The implementation method of sensors plays also an important role in measurements, as well as environmental conditions. This study allowed also evaluating performances of two different kinds of implementation: the glued sensor appears more effective than the soldered one.

The accuracy of the output depends mainly on the numerical model of the structure and the sensor calibration, while the method itself is robust as it has been shown in the sensitivity analysis. The study demonstrates that the higher number of measurement points makes the geometry identification procedure more reliable. This result emphasizes the interest on using a distributed strain measurement technology rather than a local one (as it could be using fiber Bragg gratings), capable of performing a more precise measurement locally. The method is experimentally validated, despite uncertainties on the mechanical behavior of involved materials and on the structure (shape, thickness, etc). Moreover, this method can be used for structures of very different dimension, as distributed optical fiber sensors can reach kilometric length without losing significant resolution and accuracy.

Rayleigh scattering was here implemented for its high sensitivity [29], however Brillouin scattering [30, 31] could also be used, in order to avoid error spikes and if, for example, a wider range of deformation is expected. The proposed methodology allows filtering out most of measurement errors due to Rayleigh cross-correlation. Next step will be to add another method to filter out measurement errors. In the near future the implementation of this convergence measurement method to Cigéo repository IL-LLW cell mock-up is planned in the underground lab (100 m long structure), as well as the combined application of this method with a temperature compensation performed via Raman scattering. The performances of the optical fiber sensor cable will be also investigated, especially its resistance and reaction to the compressive forces given by the surrounding rock and the anchoring method in the target application. Future work will evaluate also the ageing of distributed strain sensing cables in the specific environment of Cigéo, like for example the impact of radiation, water tightness, and the possible crush due to clay breakout.

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ORCID iDs

A Piccolo https://orcid.org/0000-0003-2878-8058

Y Lecieux https://orcid.org/0000-0002-9441-310X

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