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Sensing systems to measure convergence in steel-lined micro-tunnels

Instrumentation et mesures de convergences de micro-tunnels chemisés

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ABSTRACT: For the purposes of site reconnaissance and health monitoring and, more specifically, in relation to underground structures, Egis collaborates with Andra on scientific experiments conducted at great depth. Sensing systems have been envisaged to monitor horizontal steel-lined micro-tunnels. One particular aspect that needs to be measured is the convergence of the liner. This article presents benchmark tests carried out by Egis on different sensor technologies.

ABSTRACT: Dans le cadre de reconnaissances et auscultations de sites et plus spécifiquement d'ouvrages souterrains Egis collabore avec l'Andra sur des expérimentations scientifiques à grande profondeur. Des instrumentations ont été envisagées pour suivre des micro-tunnels horizontaux équipés d'un chemisage en acier. Un des besoins de mesure est le suivi de la convergence de ce chemisage. Le présent article expose le benchmark mené par Egis sur différentes technologies de capteurs.

Keywords: Sensing systems, underground structures, convergence, fibre optics

1 INTRODUCTION

Andra, the French radioactive waste management agency, has built an underground research laboratory in Bure in the north-east of France (Meuse/Haute-Marne), to carry out scientific and technological experiments.

The multidisciplinary (geological, hydro-geological, geochemical and geomechanical) programme conducted in the underground laboratory at a depth of 490 metres includes a certain number of experiments to assess the constructibility, safety and reversibility of radioactive waste repositories in Callovo-Oxfordian argilites (Cigéo project for geological repositories).

Sensing has been envisaged for the monitoring of high-level (HL) radioactive waste repository tunnels which comprise horizontal micro-tunnels equipped with steel liners whose aim is principally to ensure the storage and retrieval of waste disposal packages during Cigeo's reversible one-hundred-year operating period. The convergence of the liners under mechanical loading of a rock mass, therefore needs to be monitored throughout this period.

Egis has proposed and implemented various technologies (both in-situ and on a laboratory test bench) either by the direct measurement of variations in diameter or by the indirect measurement of strain or variations in perimeter. In particular, optical fibres were placed around a circumference to determine the convergence. New measuring node technologies proposed by Morphosense were also used.

This article describes the benchmark tests conducted by Egis on the various sensors and technologies and its interpretation of the first direct and indirect convergence measurements.

The sensing, observation and health monitoring of these structures are important tools for the repository operating process. They help to obtain the information needed for the operation of long-term repositories and their potential reversibility.

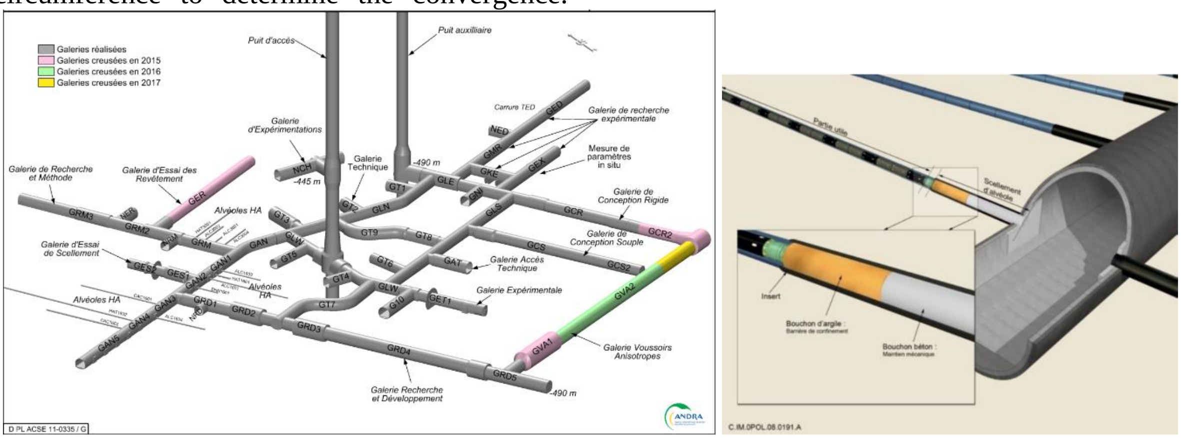


Figure 1. Layout of Andra underground laboratory galleries and diagram of an HL waste repository tunnel (2009 concept).

2 IN-SITU SENSING OF A LINED MICRO-TUNNEL.

Egis has been working on geomechanical sensing in Andra's underground research laboratory since 2001. The current health monitoring project entitled "Conventional sensing of HL repository tunnel liners" aims at studying the thermo-hydro-mechanical behaviour of these structures.

In mid-2016, the liner of a 10-metre long test micro-tunnel was equipped with sensors to test the excavation method. Figure 2 shows the cross-section of the micro-tunnel, then the number of liners added, including liner n°2, indicated in red, which was equipped with sensors.

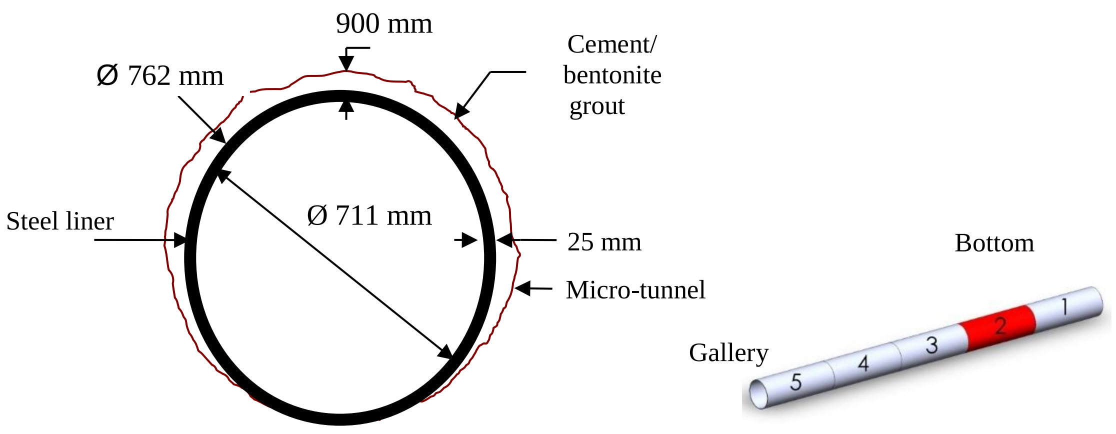


Figure 2 - Representation of a cross-section of the AHA1601 micro-tunnel and location of the liner equipped with sensors near the bottom (in red)

The following is a summary table of all the sensors tested:

Table 1. Summary Table of Sensors

Type of measurement	Type of sensor	Number of sensors
Convergence rods Displacement	Potentiometric	4
Extensometers Orthoradial strain	Wheatstone bridge resistors on inner surface of lining	8*
Extensometers Orthoradial strain	Wheatstone bridge resistors on inner surface of steel plate	4
Fibre Bragg Gratings (FBG) Orthoradial strain	HBM optical fibre gauge on inner surface of steel plate	2 x 7-point lines
Fibre Bragg Gratings (FBG) Orthoradial strain	LGS fibre optic sensor on outer surface of steel plate	2 x 7-point lines
3D angle of inclination Strain and vibration	Morphosense MEMS accelerometers	6

**option tested on other demonstrators in "HA micro-tunnel" programme but not implemented on AHA1601.*
The different types of sensors and technologies are briefly presented below.

2.1 Convergence rods

A cross-section of conversion measurements comprises four displacement sensors (horizontal, vertical and two at 45°). The displacement sensors are potentiometers with a 50-mm stroke. The layout drawing and photo below show the type of mounting inside the steel lining of the micro-tunnels.

The sensors directly measure the variation in the diameter of the liner under the effect of mechanical loading. The main disadvantage of this type of measuring technique is its size which is not compatible with the presence of waste disposal packages. Non-intrusive (indirect) convergence measuring methods therefore appeared to be necessary and have been tested.

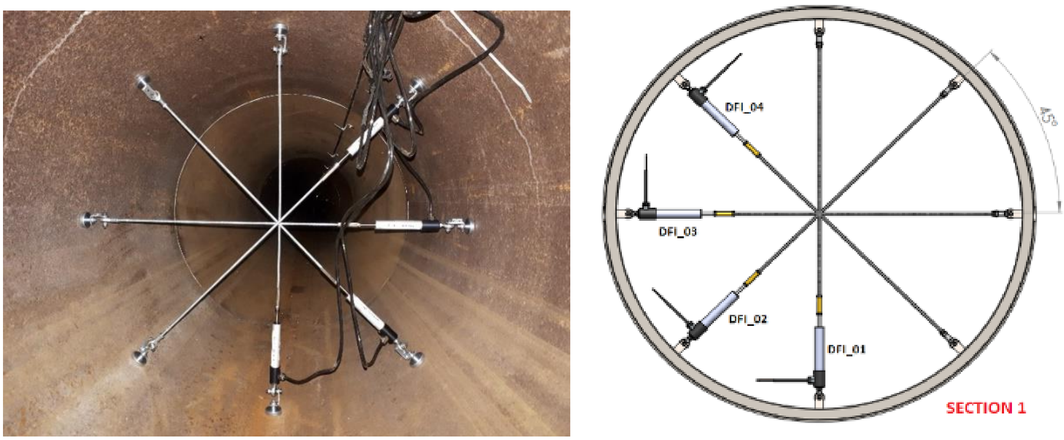


Figure 3 - Position of numbered sensors inside a sensor-equipped section of the micro-tunnel and corresponding photo.

2.2 Strain gauges on liner

Local strain measurements were taken with the usual resistance gauges glued directly to the inner surface of the liners.

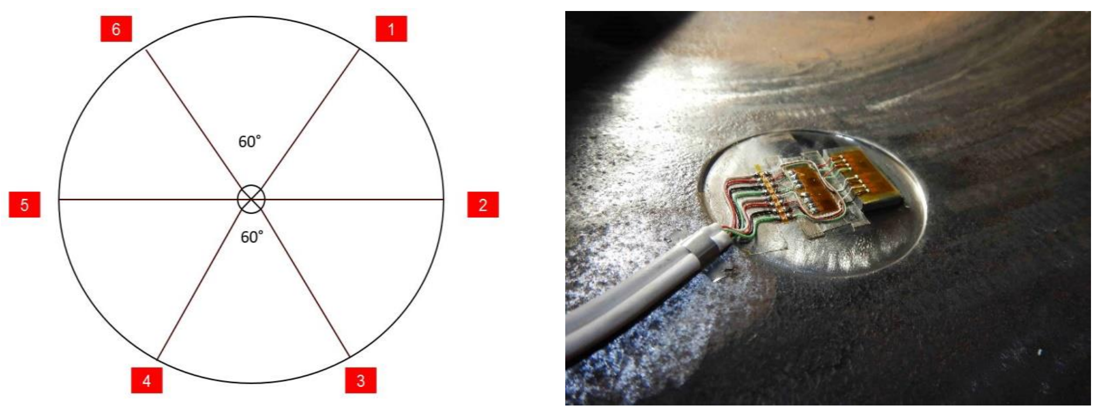


Figure 4 - Position of local strain measurements and photo of mounting

Measurement of the orthoradial strain (expressed in microstrain units: με) remains an indirect convergence measurement. The sensor units were not placed directly on the liner of the AHA 1061 tunnel, but on a pre-equipped steel plate.

2.3 Strain measurements on a steel plate.

All the additional sensor units including metal strain gauges and various fibre optic sensors (2 fibres on the inner surface and 2 fibres on the outer surface using Fibre Bragg Grating technology) were placed on a steel plate with an outside diameter of 711 mm and a thickness of 2 mm screwed to the inside of the liner.

The diagram below shows the position of the different sensors on the circular plate:

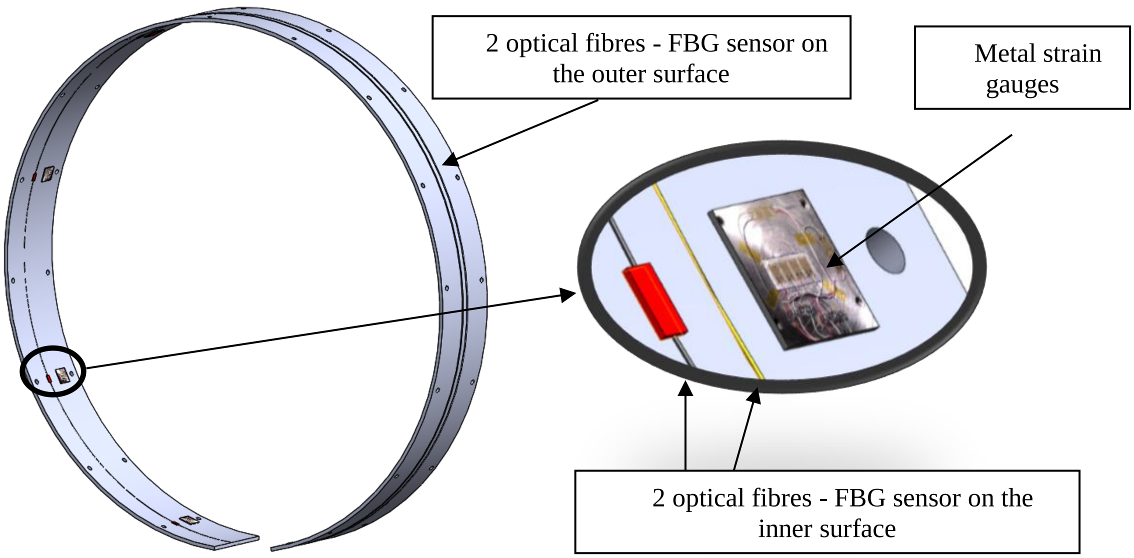


Figure 5 - Steel plate pre-equipped with optical fibres and strain gauges

Two circular engravings 4 mm wide and 0.5 mm deep were machined on the outer surface to take 2 optical fibres equipped with Fibre Bragg Grating sensors at different wavelengths (so that they can each be associated with a single optical fibre in order to reduce the size and benefit from the advantages of multiplexed sensors). Fibre Bragg Grating sensors are also present on the inner surface of the steel plate, near the strain gauges.

2.4 Measurement of geometric variations using accelerometric sensors

Morphosense inertial sensors (simultaneous measurement of strain in 3D and vibration in 3 directions) were installed on the same steel plate as the strain gauges and optical fibres. The Morphosense sensors were positioned in the same locations as the resistive strain gauges and the optical fibres (Figure 6).

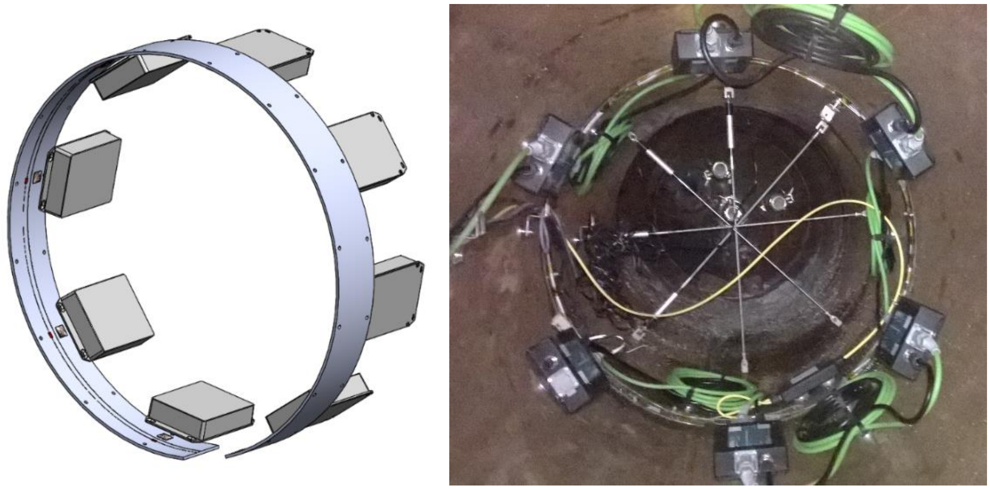


Figure 6 - Steel plate pre-equipped with Morphosense sensors and photo taken in micro-tunnel.

2.5 Data logging

The FBG measurements were carried out using an LGS interrogator unit while a Campbell data logger was used for the analog sensors. The measurements were taken over a period of 16 months.

3 EQUIPPING OF AN EGIS TEST BENCH WITH SENSORS IN THE LABORATORY

In addition, Egis designed a test bench in its test laboratory to meet Andra's specifications with the purpose of applying conventional loads to a steel component representing part of and HL tunnel liner. The aim was to test methods for indirectly measuring the convergence of a tubular structure based on orthoradial strain measurements.

The dimensioning of the mock-up (a liner section) and the loading methods were designed to respect the constraints and requirements inherent to the tests:

- A representative mock-up of an HL liner component with an outside diameter of 762 mm.
- A maximum ovalisation (convergence) of 10 mm on the diameter.
- Tests conducted in the linear elastic stage of the mock-up.

Digital simulations (Plaxis and SolidWorks) were carried out to determine the dimensions of the test bench. Two loading cases (2-point and 3-point loading) were used for the digital simulations and resulted in the following dimensions for the liner sections:

- Outside diameter: 762 mm
- Width: 200 mm
- Thickness: 10 mm.

Figure 7 shows the principle of the test benches with up to 4 support systems to apply the 2-point and 3-point loading methods (i.e. 4 x 15° apart). The sensing system tested on the steel test specimen comprises the following:

- 10 temperature self-compensating strain gauges (8 on the outer surface and 2 on the inner surface).
- 8 FBG (Fibre Bragg Gratings) optical sensors on the outer surface (paired with the strain gauges).
- 4 convergence rods on the inner surface
- 2 optical fibre measurement cables distributed over the outer surface (1 glued

and 1 held in place by welded metal foil) using Brillouin & Rayleigh measuring technology.

- 7 Morphosense sensors on the inner surface

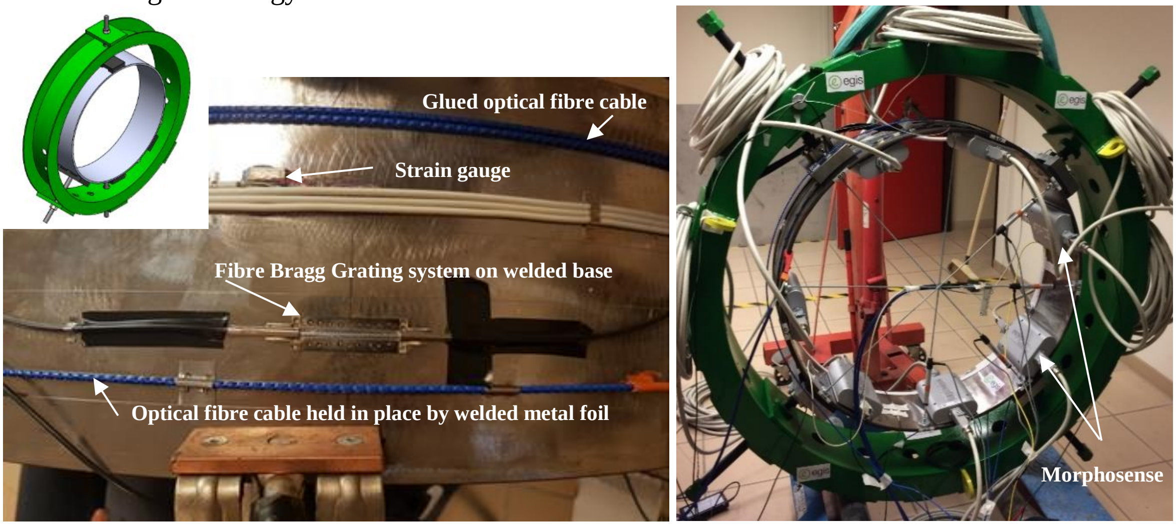
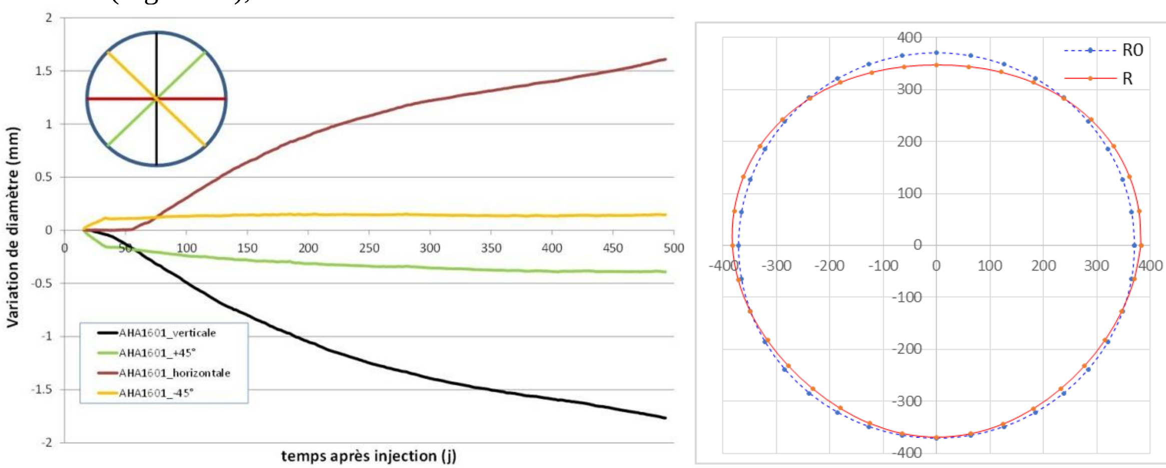


Figure 8: Photos of test bench and sensing equipment used

4 FIRST RESULTS

The maximum convergence observed for the in-situ tests at Andra after about 16 months of monitoring is in the order of 1.5 mm, non-stabilised (Figure 9a), for an inside diameter of 711 mm. Calculation algorithms were developed to interpret the indirect measurements (gauges, optical fibres and Morphosense sensors). An example of the results is given in graphic form in Figure 9b.



Figures 9a) Variations in diameter (convergence rods) in the AHA1061 and 9b) Calculation of variations in the elastic curve on the Egis bench based on the results of the Fibre Bragg Gratings sensors.

The tests conducted on the laboratory test bench enabled two loading cases to be studied (2-point and 3-point support) in increments up to a convergence greater than 10 mm.
In the 2-point tests, a comparison between the orthoradial strain measurements obtained using strain gauges and FBG gauges, and the diameter measurements obtained using convergence rods, shows the following:

- Almost perfect similarity of results for each pair of sensors, in accordance with the loading symmetry;
- Similarity of measurement uncertainty values (typically ±5 με and ±0.5mm).
- Good repeatability and reversibility of measurements.

Figure 10 shows a few results of 3-point loading. Loading is applied in increments. The orthoradial strain measurements given by the FBG sensors enable the shape of the loaded test specimen to be reconstructed.

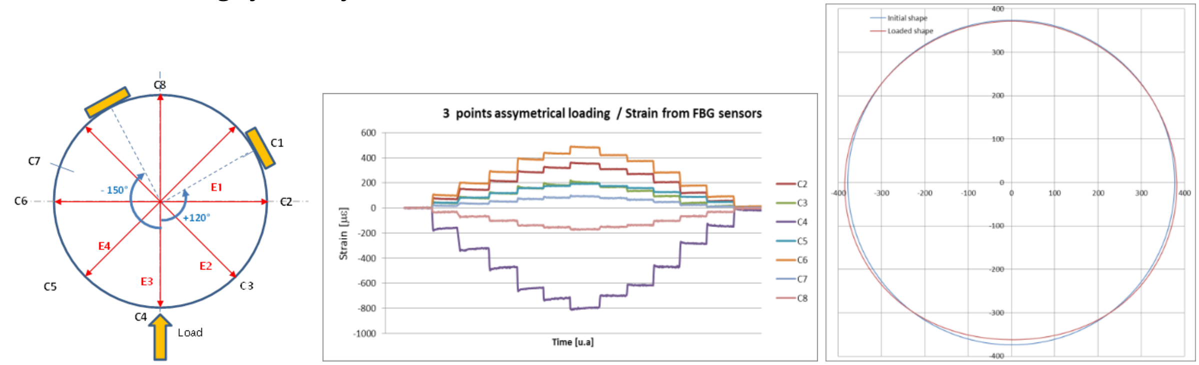


Figure 10: Case of asymmetrical 3-point loading: a) Positioning of FBG sensors and loading direction b) Response of FBG sensors and reversibility c) Elastic curve of structure under maximum loading calculated according to orthoradial strain values of FBG sensors.

The comparative results of the strain gauges, Fibre Bragg Grating sensors and Morphosense sensors (3D elastic curve) remain coherent with the measurement uncertainty (in the order of ±5 με and taking into consideration the differences in sensor positions).

These measurements also agree with the results of the digital simulations.

It should be noted that putting the bench into the vertical position with the resulting loss of symmetry leads to a more significant dispersion in the repeatabilty and reversibility of the measurements.

However, as illustrated in figure 10, the strain data from the FBG sensors enable the shape of the loaded test specimen to be reconstructed in the case of asymmetrical 3-point loading.

This particular loading case highlights the potential of the measuring technique based on a network of multiplexed optical fibre sensors in quasi-distributed mode.

5 CONCLUSIONS

A benchmark test was carried out by equipping the liners of micro-tunnels with sensors in Andra's underground laboratory in order to measure their convergence under mechanical loading.

The aim was to compare several indirect convergence measuring techniques compatible with the presence of waste disposal packages.

The tests were designed to assess the capacity of various conventional and innovative technologies to measure convergence (optical fibres and 3D accelerometric sensors).

Based on digital simulations, Egis developed a specific test bench to study the anistropic behaviour of tubular sections representing parts of liners used for HL waste repository tunnels.

Significant strain values were obtained during the mechanical tests (while remaining in the elastic region of the structure tested). The measurements obtained using the different sensors, under two or three point loading, corresponded well.

In terms of optical measurements, different types of optical fibre cables and the systems used to attach them to the test specimens were tested for future qualification purposes.

The Egis test bench study is being continued with the specific aim of optiminising convergence calculation algorithms based on indirect measurements.

6 ACKNOWLEDGEMENTS

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