Characterization of an instrumented GeoStrap® with plastic optical fiber bragg gratings

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ABSTRACT: Polymer Optical Fibres (POF) sensors have attracted significant interest in the field of earthwork structure monitoring mainly due to their high elongation capability in contrast to traditional glass optical fibres (GOF). Recent development in the POF field have shown that it is now possible to inscribe fibre Bragg gratings (FBGs) in low loss perfluorinated POF (POFBG). The perfluorinated fibres, such as CYTOP, have losses in the near infrared, at 1550nm that are approximately 0.2dB/m. CYTOP is extremely transparent as it exhibits low scattering loss due to its highly amorphous nature and low optical absorption because of the perfluorinated backbone that shift the optical losses to the infrared, at 7.7–10µm. However, it is precisely this improved loss performance that hinders the laser inscription of basic optical components such as FBGs in CYTOP; in contrast PMMA has an absorption feature that peaks at close to 325nm, which enables laser-induced material modifications using a HeCd laser. The excellent transparency of CYTOP makes it suitable for use with femtosecond laser direct write methods. We inscribe a complex FBG sensor array in CYTOP fibre and show that this robust and smart sensing strand is compatible with coating methods that are used in the geosynthetic industry. This new development extends the possibility of instrumentation from distributed strain measurements alone to potential local load, strain, temperature or pressure measurements. In this paper, the authors will present the manufacturing process of an instrumented GeoStrap® and the associated characterization using standard geosynthetic testing such as tensile test and pull-out test. The results obtained will be discussed and the prospects presented.

Keywords: POF, FBG, Geosynthetic, Optical sensor, Tensile, Pull-out

1 INTRODUCTION

For several years now, Terre Armée has a growing interest in developing a reliable optical fiber sensors embedded in a geosynthetic strip (Freitag et al. 2010) for structure monitoring or data collection for design optimisation. Embedding optical fibres into geosynthetics allows to add functionalities such as temperature, pressure, vibration and more interestingly, strain measurements.

The embedding technique developed by Terre Armée presents the advantage of placing the optical fibre at the heart of the geosynthetic as compared to other methods where an optical cable is generally knitted onto the geotextile (Nancey and al. 2007, Schneider-Gloetzl et al. 2010). Additionally, several optical fibres can be embedded in a single strip in a single manufacturing step.

The main difficulty with this embedding method is to find an optical fibre compliant enough to follow the deformation induced by the manufacturing process of viscoelastic materials (i.e shrinkage) as used in geosynthetic strips. Indeed, geosynthetic strips are manufactured by crosshead extrusion coating of a polyolefin sheath over bundles of high tenacity PET or PVA yarns.

To solve this deformation issue, the choice of polymer optical fibre (POF) has proven more successful compared to glass optical fibre (GOF) which exhibits a stiffer and more brittle behavior and generally requires specific cabling protection (Krebber 2013).

Perfluorinated POF based on CYTOP material was identified as a great candidate for this application as it presents the advantages to have excellent optical properties as well as good thermal properties.

A first series of trials carried out by Terre Armée showed that a CYTOP POF could successfully be embedded in a strip without signal alteration after extrusion over at least 100 m as shown Figure 1.

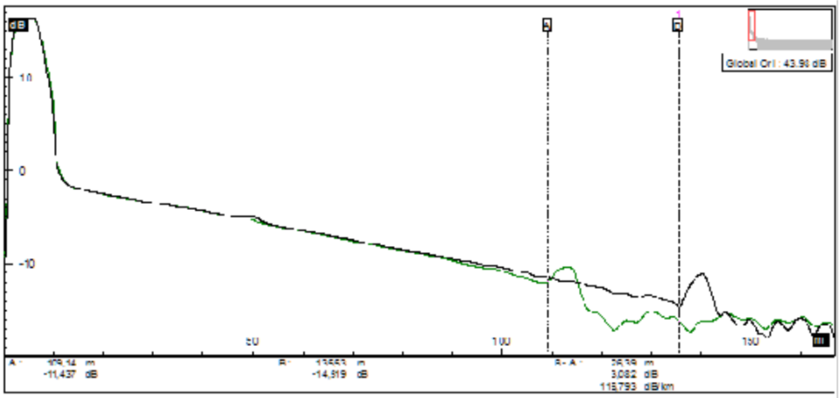

Figure 1. Comparison of the OTDR trace of the bare CYTOP POF (black trace) and the same fiber embedded in the strip (green trace).

More recently, research carried out in Cyprus University of Technology demonstrated the possibility to inscribe FBGs onto perfluorinated POF based on CYTOP material (A. Lacraz et al. 2015). This work opens up the path for quasi-distributed sensing using CYTOP with the advantage of reliable and easy interrogation device.

A collaboration was then launched with Cyprus University of Technology with the objective to embed a CYTOP fibre composed of a complex array of FBGs in a geosynthetic strip and to demonstrate its sensing capacities.

In this work, we will present the manufacturing steps to obtain the instrumented strip and a series of tests carried out to characterize the strip as well as the validity of the measurements obtained with the gratings interrogation system.

2 STRIP MANUFACTURING

2.1 *Inscription of gratings*

FBG inscription in low loss fibre is difficult to perform with usual methods. Indeed, low loss polymer has by nature a low photosensitivity, even in the near-UV. Common FBG inscription techniques, using a HeCd laser, cannot be used for CYTOP.

Cyprus University of Technology develop a method for grating inscription based on Femtosecond laser which was detailed in previous work (A. Lacraz et al. 2015). The gratings are built plane-by-plane by moving the fibre under a fixed laser beam tightly focus in the core using a nanometer air-bearing precision stage. The fibre used in this work is a CYTOP POF with a core of 50µm.

2.2 *Strip extrusion*

The instrumented strip has been manufactured based on Terre Armée GeoStrap® products line. About 300m of strip equivalent to a grade 37.5kN embedded with the previously prepared fibre was produced.

The manufacturing process of the instrumented strip introduces a jacketed POF in one of the canals that compose the geostrip through the extrusion die. Nonetheless, some changes from the usual process are necessary to obtain a satisfactory result. A specific polyolefin is used in the process to lower the extrusion temperature and thus prevent any thermal damage of the POF.

In this trial, we have manufactured about 300m of instrumented strip in one shot by introducing a POF containing 25 FBGs written over its length at wavelength in the range of 1570 nm to 1520 nm.

Following manufacturing, the tensile properties of the instrumented strip have been determine using the EN 10319:2015 on the average of five tests (Table 1).

Table 1. Tensile properties of the instrumented strip

	Strength at break, σ (kN)	Elongation at break, ε (%)
Instrumented strip	38.6	11.3

3 INSTRUMENTED STRIP CHARACTERIZATION

3.1 *Determination of λ(ε) - tensile test*

The determination of the sensors strain response was carried out using a series of tensile test while interrogating and monitoring the FBG. The interrogation of the FBG was done using a spectrometer analyzer of the brand Ibsen working in the range of 1525nm to 1570nm.

The tensile tests were performed using a modified version of the EN 10319:2015 with a deformation rate of 2 %/min. Pneumatic grip was used to avoid strong bending of the fibre which may alter the optical signal. Prior testing, confirmed that the grip pressure would not disturb the interrogation of the FBG.

The test specimen was then placed between the grips separated of 200mm and the FBG was located as much as possible in the center of the gauge length. The FBG reflection spectrum was recorded simultaneously as the tensile properties. The setup of the experiment as well as the signal changes are illustrated Figure 2.

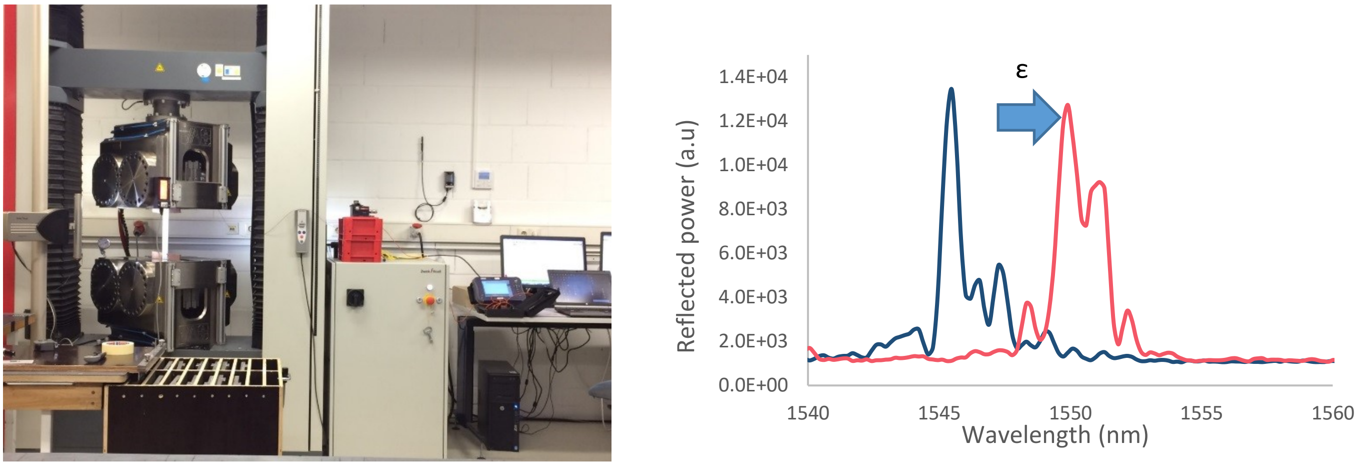

Figure 2. Setup of the tensile testing and FBGs response evolution with strain

From the spectrometer, we followed the evolution of the resonant shift of the grating (Figure 2) corresponding to the variation of the axial strain during the tensile tests. Using a center of gravity algorithm, the position of the resonance was plotted as function of the time and a quasi-linear relationship between the wavelength shift and the elongation was drawn as shown Figure 3. The strain coefficient of the FBG was evaluated at 1.52 pm/με which is comparable to other plastic or silica fibre gratings (Yuan et al. 2010, Luo et al. 2010).

It is important to note that for each test the FBG signal was lost at an average value of 1.3% (±1%). This shows that the strain range of FBG sensors written in CYTOP fibre with the method detailed above is quite small. As a matter of comparison, it was demonstrated that FBGs written in PMMA POF exhibit strain range up to 3.6 %.

This limited strain range is quite disappointing as CYTOP material was expected to present higher strain behavior. However, there is room for strain range improvement using annealing techniques enabling enhancement of the strain range capacity of the sensor (Yuan et al. 2010).

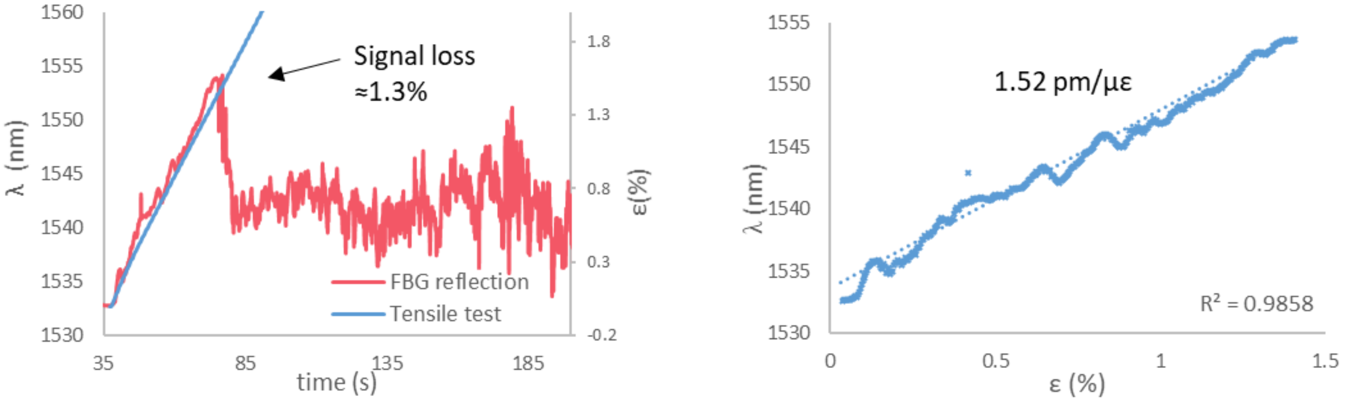

Figure 3. Analysis of the FBGs interrogation response during tensile test and determination of the strain coefficient.

3.2 *Strain measurements during pull-out test*

To further characterize the instrumented strip, Pull-out test was performed while interrogating FBGs sensors.

Pull-out tests are generally used to determine the apparent friction of a geotextile with a granular soil under controlled confinement (f*). Here the aim was to observe the local changes of the strain/tension at periodic location in the strips (FBGs position) under control confinement.

The test was carried out following the test procedure described by ASTM D6706 in sand with a confinement of 30 kPa and a pull-out strain rate of 1mm/min.

A piece of strip, with two FBGs P1 and P2 written at different wavelength and positioned at 105cm and 75cm respectively in the pull-out box (Figure 4), was tested and evaluated using the same technique presented above. The test presented here was only carried out up to 4kN at the face with a test duration of approximately 13 minutes.

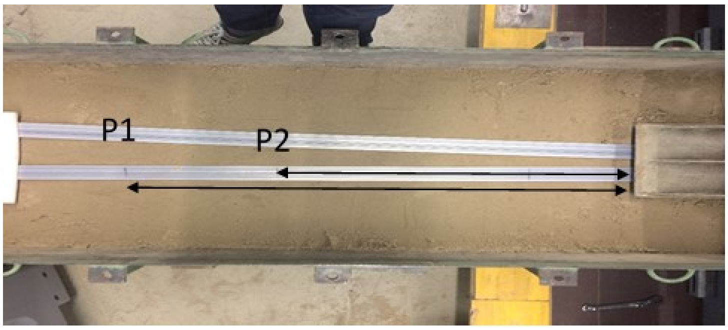

Figure 4. Pull-out test set up

The signal analysis was perform using the same algorithm applied previously for both sensors (P1 and P2). The strain coefficient determined by the tensile test was used to obtain the strain at P1 and P2. Figure 5 illustrates the strain measured by each sensor as a function of time. As expected, the closest sensors from the face P2 start deformation first and the ultimate strain measurement is lower at P1 for a given time.

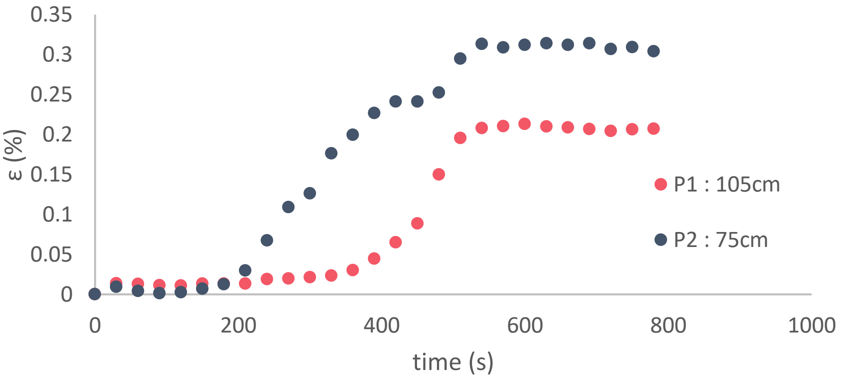

Figure 5. Strain measurements obtain by FBGs interrogation during Pull-out test

The validity of the measurements is quite difficult to evaluate since the authors did not introduce a sensor or a gauge length that could be used to build a comparative study.
In order to estimate their validity, we decided to use a theoretical approach using a pull-out simulation developed several years ago (Segrestin et al. 1996) and based on the displacement measurement at the face of the box.
This model consists in estimating the tension line in the reinforcement as a function of the confinement, the friction coefficient and the applied tension at the face as illustrated Figure 6.

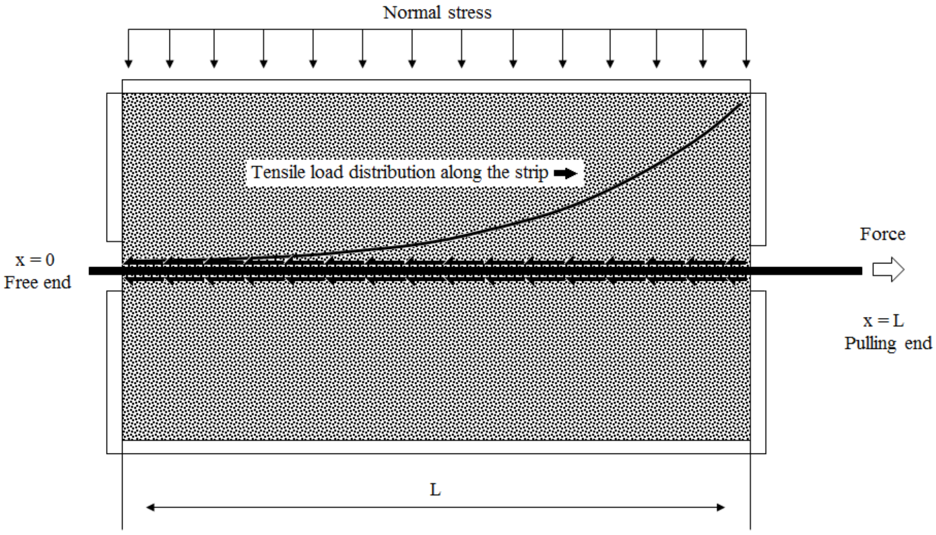

Figure 6. Tensile load distribution during a Pull-out test

Using this model, we were able to simulate the load applied at various point in the box and compare it to our measurements.

In this simulation, we used a friction coefficient (f*) of 1.5 which is generally obtained in laboratory testing for this type of strip in sand. The determination of the tension at each point was done using an elastic modulus of 300kN based on the tensile test of the strip carried out previously.

In Figure 7 we have plotted the measurements obtained for three different times (3, 7 and 13 minutes) and at the three different positions known in the set up (at the face, at 75 cm and at 105 cm) versus the results obtained from the simulation considering test condition parameters (distance, elastic modulus, pressure…).

The results show that the measurements quite agree with the theory. This confirms that the instrumented strip could be a useful tool to measure the local stress or strain in a structure, or could be used as a R&D tool to improve numerical models and optimize designs.

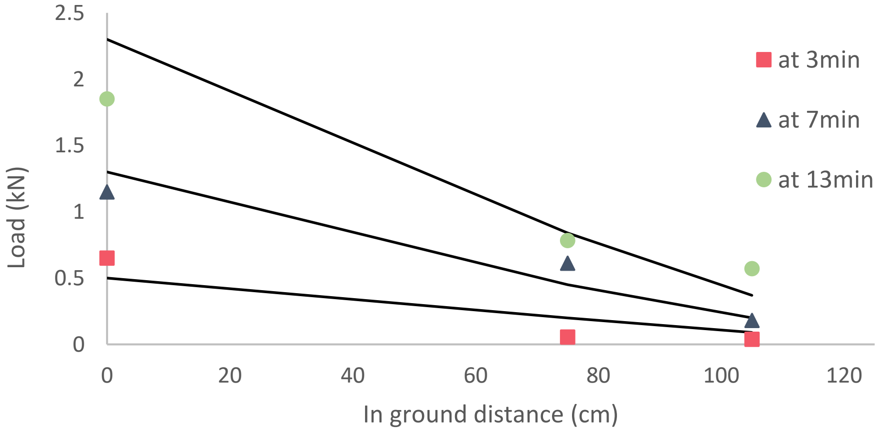

Figure 7. Comparison between calculated load from FBGs response (dots) and simulation results (lines) at different distance in the Pull-out box.

4 CONCLUSION

The aim of this work was to determine whether a geosynthetic strip embedded with a perfluorinated POF containing complex FBGs arrays could be used as a sensor for structure monitoring.

First, we have demonstrated that a POF with Bragg Gratings could be embedded in a geotextile strip during extrusion without damaging its optical properties. Then through classical geosynthetic testing we have shown the efficiency of the sensor and its capacity to measure local stress and strain with a relative precision.

Even if there is still optimization work to be done to obtain a reliable sensor with a larger range of measurement and to fully explore the sensing possibility, these first results are highly promising for future development.

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