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Noémie Delaplanque, Sylvain Chataigner, Laurent Gaillet, Marc Quiertant, Karim Benzarti, et al.. Durability in Alkaline Environment of a Fiber Optic Sensor Bonded at the Surface of Reinforcing Bars for Distributed Strain Measurements in Concrete Structures. European Workshop on Structural Health Monitoring (EWSHM 2022), Jul 2022, Palerme, Italy. pp.506-515, 10.1007/978-3-031-07258-1_52 . hal-03819126

HAL Id: hal-03819126

<https://hal.science/hal-03819126>

Submitted on 18 Oct 2022

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Durability in alkaline environment of a fiber optic sensor bonded at the surface of reinforcing bars for distributed strain measurements in concrete structures

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Abstract. Distributed Optical Fiber Sensors (DOFS) are gaining interest for structural health monitoring applications. Recently, they have been successfully used to monitor the strain profiles at the interface between concrete and steel or composite rebars during pullout tests. In the framework of durability studies on Glass Fiber-Reinforced Polymer reinforcing bars (rebars), this method offers interesting perspectives for monitoring the evolution of the concrete/rebar bond behavior under accelerated ageing conditions. However, the durability of the bonded DOFS instrumentation itself should be investigated in a preliminary stage, to assess possible alteration of its performance over aging, which would raise questions about the validity of strain measurements in the long term.

This article presents the first results of an experimental program aiming to address this specific issue. In this work, steel rebars were equipped with bonded optical fibers. Half-length of the instrumented rebars was subjected to hydro-thermal ageing by immersion in an alkaline solution, while the remaining length was exposed to standard laboratory conditions. After exposure, the rebars were tested in tension and the DOFS strain profiles were simultaneously measured. These strain profiles were then compared to reference measurements performed before ageing, providing insights on the influence of the ageing conditions on the response of the DOFS.

Keywords: Distributed optical fiber sensor, strain measurements, FRP rebars, concrete, bond behavior, alkaline environment, durability.

1 Introduction

Distributed Optical Fiber Sensor (DOFS) embedded in a host material or bonded at the surface of a host structure are suitable for monitoring strain distributions. Paired to an optoelectronic interrogator based on Rayleigh scattering, this sensing technology enables obtaining distributed strain profiles with high spatial resolution. It is a very promising method for monitoring strain transfer processes at the interface between concrete and (steel or composite) reinforcing bars (rebars). So far, several authors have already investigated the mechanical behavior of reinforced concrete (RC) structures using optical fibers (OF) bonded at the surface of steel rebars [1-3]. This technique was also successfully applied to analyze strain distribution in Fiber-Reinforced Polymer (FRP) rebars embedded in concrete and subjected to pull-out tests [4-5]. Besides, this instrumentation opens interesting perspective for assessing the long-term durability of the bond between Glass FRP (GFRP) rebars and concrete, since GFRPs are prone to chemical degradations in alkaline environments. However, the durability of the DOFS instrumentation itself should be investigated in a preliminary stage, in order to evaluate the reliability of strain measurements in the long term.

If the durability of DOFS bonded at the surface of concrete or embedded within concrete has been investigated in a recent work [6], to the author's knowledge, the ageing behavior of DOFS bonded to the rebars of RC structures is still an open issue. In the present study, an experimental program was proposed to investigate such behavior. Steel rebars were equipped with bonded DOFS, and then immersed in an alkaline solution at various temperatures. Tensile tests were performed on these instrumented rebars both in the unaged reference state and after exposure (specimens were loaded in the elastic domain of the steel material, and DOFS strain profiles were collected at selected load level). As it is expected that the mechanical behavior of steel doesn't change over ageing, any evolution of the strain profiles of exposed specimens would be discussed in terms of alteration/degradation of the DOFS instrumentation itself. This paper details the experimental program, reports the first results of this research and draws some preliminary conclusions.

2 Materials and experimental methods

2.1 Materials

The tests were conducted on two steel rebars of diameter 10 and 12mm, respectively. Each rebar was equipped with an OF sensor. Based on previous works of Quiertant et al. [3] and Chapeleau and Bassil [7], a single-mode commercially available OF with a polyimide primary coating was used. For the installation of this OF, a U-groove with a depth of 1 mm, and a length of 220 mm for the first rebar and 300 mm for the second, was previously drilled along each rebar. Then, the OF was placed inside the U-groove and sealed with a two-component epoxy adhesive. The X60 epoxy was used for bonding the OF to the 12mm diameter steel rebar, while the X120 epoxy adhesive

was used for the other rebar. Both adhesives are bi-component epoxy systems commercialized by HBM Company (Darmstadt, Germany).

In the proposed configuration, the adhesive layer acts as a coating that protects the OF from the surrounding environment, especially against chemical attacks (alkali attack in a concrete environment for instance) or against mechanical damage. However, any ageing induced evolution of this adhesive material may affect the bond characteristics of the OF/epoxy interface and/or the steel/epoxy interface, and alter the properties of the bulk epoxy material as well. Each of these phenomena, and of course the damage of the OF itself, would have detrimental effects on the strain response of the DOFS instrumentation. The durability test proposed in the following intends to verify whether the sensor remains reliable after ageing, or whether one/several of the previous degradation mechanisms may affect the accuracy of strain measurements.



Fig. 1. Picture of the steel rebar of \varnothing 12 mm, showing the OF sealed in the engraved groove

2.2 Mechanical tests and DOFS measurements

To verify if the DOFS instrumentation is resistant to alkaline environments at temperatures up to 60 °C (these ageing conditions are commonly used for durability studies on FRP rebars [6, 8]), half-length of each instrumented sample was submitted to these harsh conditions. Before being partially immersed in the ageing solution, each specimen was first submitted to an initial tensile test using an Instron universal testing machine of capacity 250 kN. This preliminary test enables to record reference strain profiles at different load levels. The different loading steps correspond to stress levels of 50, 100 and 150 MPa in steel rebars, and represent theoretical strains of 0.25 ‰, 0.5 ‰ and 0.75 ‰ (assuming a Young's modulus of 200 GPa of steel rebars) (see Table 1). Each load level was hold for 30 seconds before moving to the next plateau (see Fig. 2). The strain profiles were measured at a frequency of 23.8Hz during the entire test using a high spatial resolution optical interrogator (ODISI-B, Luna Technologies). These measurements were performed before and after ageing and compared in an attempt to detect possible changes in the response of the DOFS instrumentation. As it can be assumed that the mechanical properties of the steel rebar are not affected by the adopted ageing condition, any alteration of the strain profiles would be directly

4

attributed to an ageing-induced deterioration of the DOFS instrumentation (i.e. the adhesive interfaces, the bulk adhesive or the optical fiber itself). A load-unload path was conducted to verify the reversibility of the measured strain profiles.

Table 1. Load levels applied during the direct tensile tests. Steps 1 to 3 correspond to increasing load increments while steps 4 and 5 are decreasing increments.

Loading step	Applied tensile force (kN)		Corresponding stress (MPa)
	Steel rebar of diameter 12 mm	Steel rebar of diameter 10 mm	
1 (and 5)	5.65	3.93	50
2 (and 4)	11.31	7.85	100
3	16.96	11.78	150

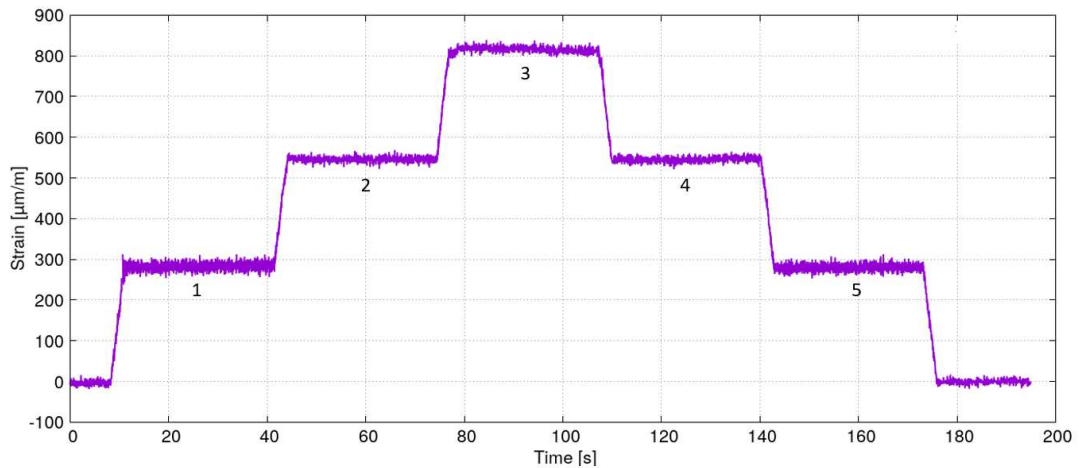


Fig. 2. Applied strain history recorded by the DOFS during the tensile test on steel rebars

2.3. Ageing of the specimens

The exposure condition consisted in immersing the DOFS the instrumentation into an alkaline solution at a given temperature (either 20 °C or 60 °C). In this line, each rebar (equipped with the bonded DOFS) was conditioned in an ageing cell, as shown in Fig. 3. A specific cap made it possible to install the cell without damaging the optical fiber. The two parts clamping mechanism was designed to fit the rebar and the OF, hence limiting the risk of damage during installation (See Fig. 4). A polyurethane sealant was used to seal the ageing cell (see Fig. 5).

The cell was filled with an alkaline solution composed of sodium hydroxide (NaOH) and potassium hydroxide (KOH), at concentrations of 0.1 mol/L (4 g/L) and 0.5 mol/L (28.05 g/L), respectively. This solution is commonly used in durability and corrosion studies [6, 8], as it is suitable for simulating the pore solution of concrete at early age.

5

Only the half bonded length of the OF is immersed in the alkaline solution, as shown in Fig. 3. When performing tensile tests afterwards on the exposed rebars, this configuration allows comparing the strain responses of the immersed and non-immersed sections of the OF, and hence to evidence possible alteration of the OF instrumentation induced by the alkaline environment (that may be related either to a degradation of the adhesive bond, an evolution of the bulk properties of the adhesive, or the alkali attack of the OF itself). It is to note that the overall setup was stored in the laboratory environment for the ageing condition at 20 °C, while it was placed in an oven for the condition at 60 °C.

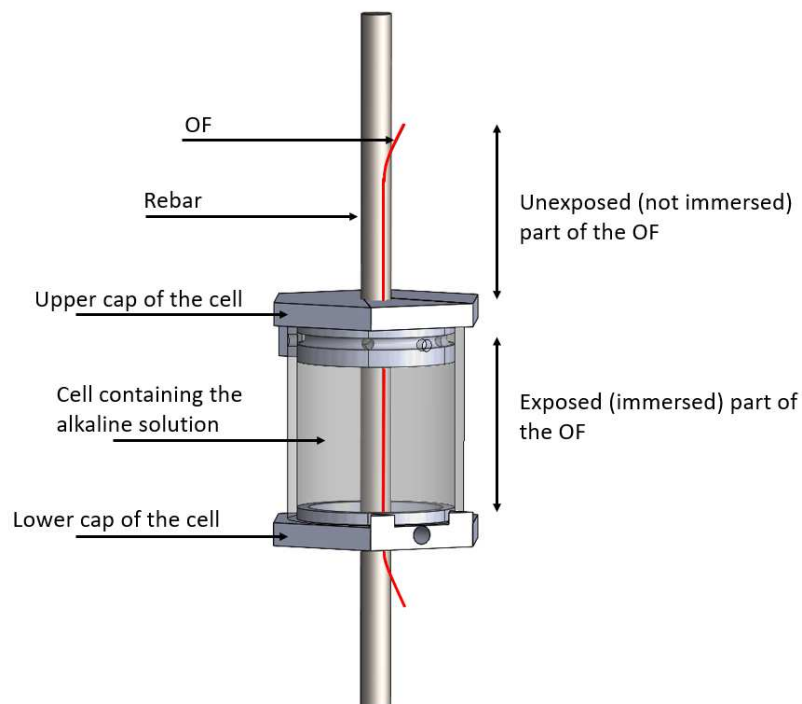


Fig. 3. Experimental set-up used for conditioning the instrumented steel rebars

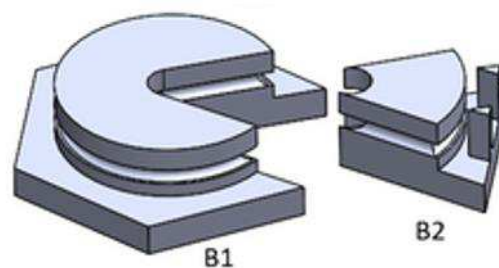


Fig. 4. Two parts clamping mechanism of the lower cap of the aging cell

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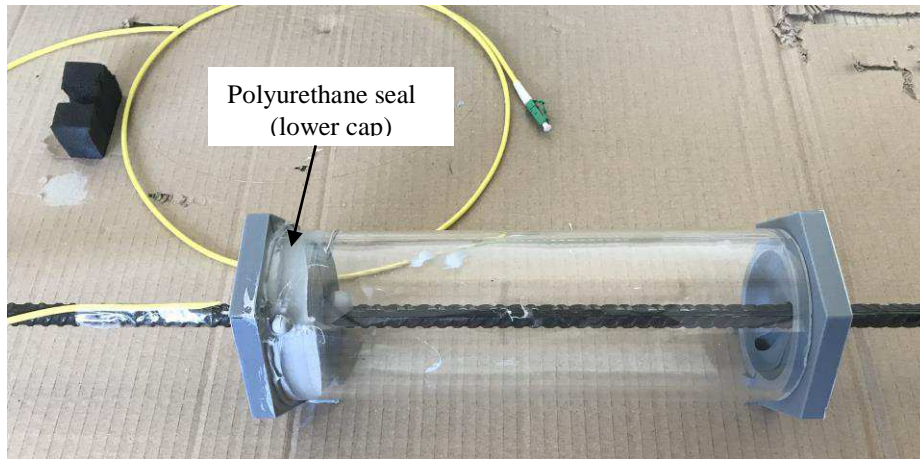


Fig. 5. Steel rebar of diameter 10 mm installed in the aging cell

3 Results

Figure 6 shows the strain profiles recorded at different load levels during the tensile test on the unaged instrumented steel rebar of diameter 12 mm. The x axis corresponds to the relative position along the rebar, and the bonded section of the optical fiber is located at abscissas between 0.175 and 0.37 m. Strain profiles collected at stress levels of 50 MPa, 100 MPa and 150 MPa are displayed together in the graph. They provide average strain values of about 300 $\mu\text{m/m}$, 500 $\mu\text{m/m}$ and 800 $\mu\text{m/m}$, respectively, which can be considered as reference data for the unaged DOFS instrumentation. Furthermore, it is interesting to note that profiles collected at increasing increments (levels 1 to 3) are consistent with those obtained at decreasing increments (levels 3 to 5), showing the repeatability of strain measurements.

Figure 7 gathers the strain profiles collected during tensile tests at a stress level of 150 MPa, both for the unaged rebar (reference state) and for the same rebar after one-month exposure in the aging cell at 20 °C. An additional measurement was carried out on the aged rebar after changing its direction upside down in the grips of the tensile machine, in order to verify the symmetry of the test setup (the corresponding profile is denoted “measurement after ageing 2” in the graph).

Figures 6 and 7 represent acquisitions made on the same frame. However, the two graphs display different ranges of relative positions because the acquisitions in the reference and aged states were made at different times and requested disconnecting/reconnecting the acquisition line to the ODISI interrogator. Therefore, the length of OF connecting the rebar to the interrogator was different from one test to another.

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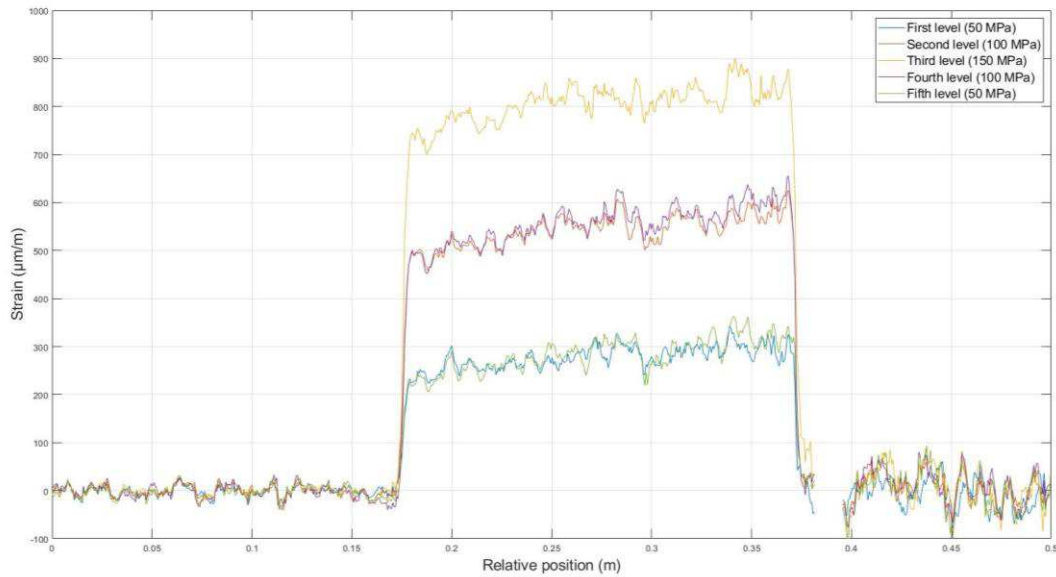


Fig. 6. Reference strain profiles recorded during the tensile test on the unaged instrumented steel rebar of diameter 12 mm, at the different load levels 1 to 5 (see Table 1 and Fig. 2)

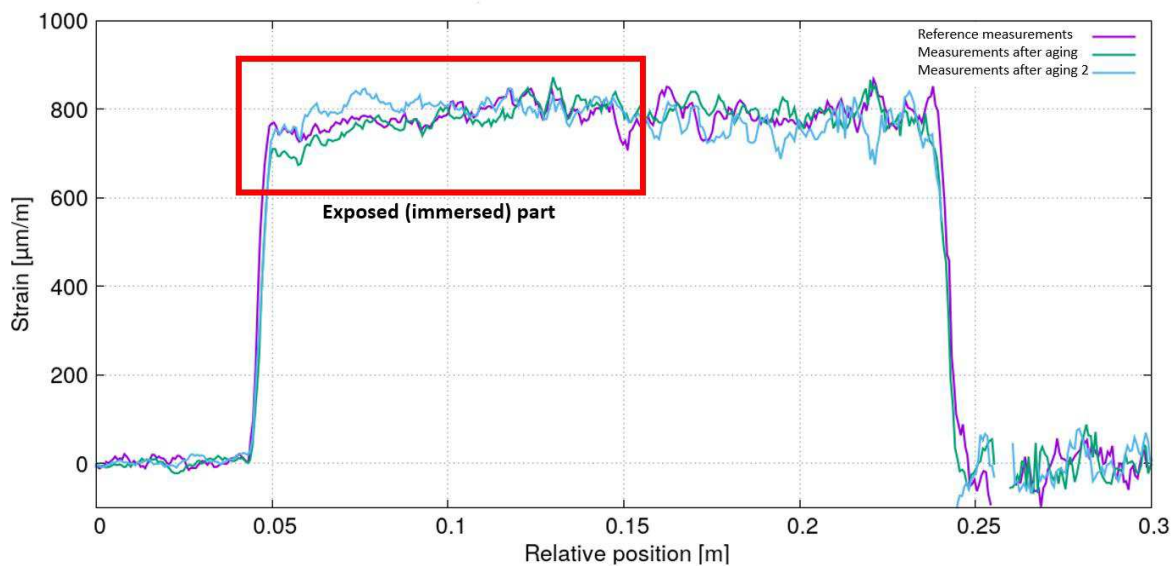


Fig. 7. Comparison of the strain profiles recorded during tensile tests on the 12 mm steel rebar at a stress level of 150 MPa, in the reference state and after one-month exposure in the ageing cell at 20 °C ("ageing 2" refers to the aged specimen that was turn upside down in the press)

From Fig. 7, it is found that i) the strain profiles of the aged rebar are superimposed to the reference profile and ii) that the average strain level is roughly constant along the immersed and non-immersed sections of the aged rebar. This result suggests that exposure for one month in the alkaline solution at 20°C did not alter the DOFS measurements, and consequently did not induce any significant degradation of the bonded DOFS instrumentation. However, it is important to note that during aging, some leakage of the alkaline solution occurred in the ageing cell and the level of the solution was lowered by one third. Therefore, it was necessary to perform an additional test to confirm the result.

To confirm the previous trend, a second steel rebar of diameter 10 mm was also equipped with the same bonded DOFS instrumentation. In this case, a more severe ageing condition was chosen, as the section of the rebar located inside the ageing cell was immersed in the alkaline solution at 60 °C. This corresponds to the most severe accelerated condition used in the framework of durability studies on FRP composite rebars (an objective is to instrument such FRP rebars with bonded DOFS in future work).

Figure 8 displays the reference strain profiles recorded during the tensile test on the unaged specimen, at the same stress levels as for the previous experiment, namely 50 MPa, 100 MPa and 150 MPa (and again for increasing / decreasing load increments as reported in Table 1). At these stress levels, the average strain values are about 200 $\mu\text{m/m}$, 400 $\mu\text{m/m}$ and 700 $\mu\text{m/m}$ respectively. One can note that the strain profiles are not flat, contrary to what was observed on the first rebar. This suggests a preexisting curvature on the present 10 mm steel rebar. This specific shape of the strain profiles will be taken into account when analyzing the experimental data after ageing.

Figure 9 gathers the strain profiles collected during tensile tests at a stress level of 150 MPa, both for the unaged 10 mm rebar (reference state) and for the same rebar after one month exposure in the aging cell at 60 °C. Here again, the graph shows that the strain profiles are similar in the reference and aged states, and that the profile of the aged rebar is not modified along the section immersed in the solution. These results confirm the previous observations made on the first rebar, and do not show any significant degradation of the DOFS instrumentation after one month exposure at 60°C in the alkaline solution. However, in future work, ageing tests should be conducted over longer periods in order to confirm the reliability of the DOFS instrumentation in the long term. In addition, a complementary durability study should be carried out specifically on the epoxy adhesive used to bond the OF.

Besides, a next experimental campaign will be carried out on FRP composite rebars. In this case, the alkaline solution is able to diffuse into the rebar (unlike for steel rebars), which may affect the properties of the FRP itself [8], but also the response of the DOFS instrumentation.

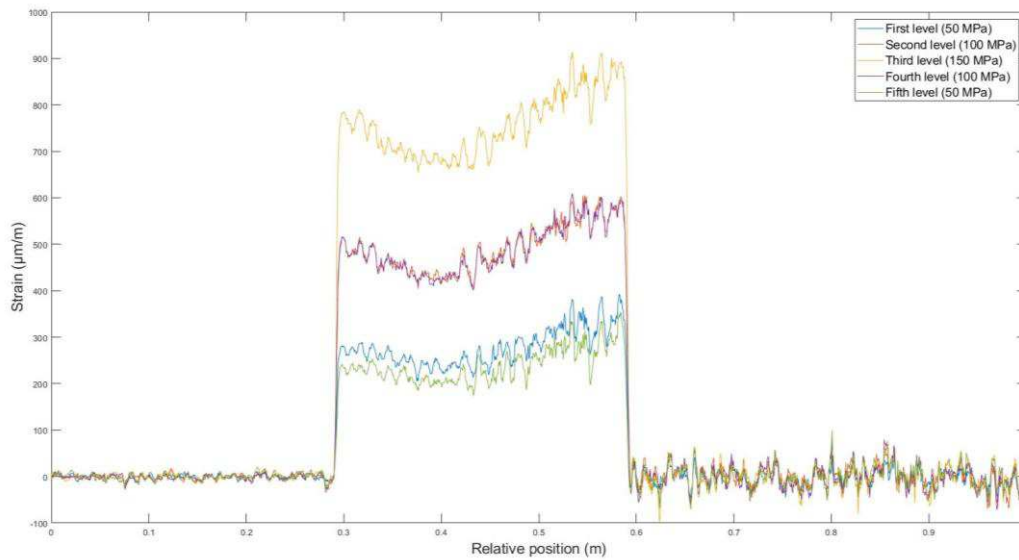


Fig. 8. Reference strain profiles recorded during the tensile test on the unaged instrumented steel rebar of diameter 10 mm, at the different load levels 1 to 5 (see Table 1)

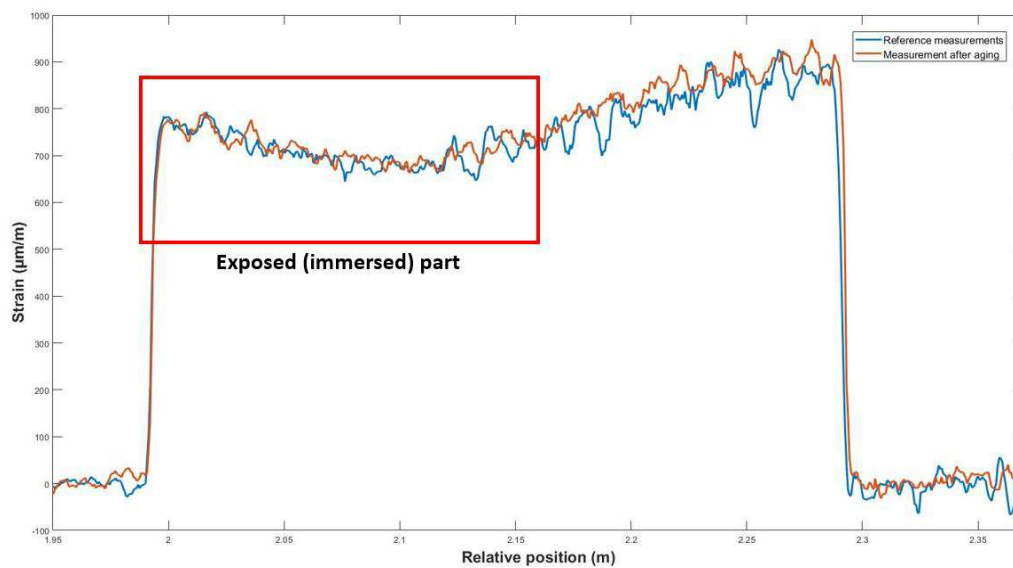


Fig. 9. Comparison of the strain profiles recorded during tensile tests on the 10 mm steel rebar at a stress level of 150 MPa, in the reference state and after one month exposure in the ageing cell at 60 °C

4 Conclusion

In this research, it was demonstrated that a DOFS instrumentation bonded at the surface of steel rebars is not affected by a one-month immersion period in an alkaline solution at temperatures up to 60 °C. This is a first important step for demonstrating the reliability and the durability of this instrumentation. However, similar experiments should be conducted over longer periods to evaluate the long-term ageing behavior. In future work, additional tests will be performed on instrumented FRP composite rebars to determine if bonded DOFS are suitable for durability studies on FRP reinforced concrete specimens in the laboratory or for the long-term monitoring of real FRP RC structures in the field.

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