Monitoring of Reinforced Concrete Structures by Distributed Optical Fiber Sensors

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Abstract. Distributed Optical Fiber Sensors (DOFS) are modern-day cutting-edge monitoring tools that are quickly acquiring relevance in the Structural Health Monitoring engineering. Their most ambitious use is embedded inside plain or reinforced concrete (RC) structures with the scope of comprehending their inner-workings and long-term performance. Yet, multiple studies have shown that the bonding technique with which the DOFS are bonded to the reinforcement bars has a significant role on the quality of the extracted strain data. Whilst this influence has been studied for externally bonded DOFS, it hasn't been done for embedded ones. The present work is set on performing such study by monitoring the strain measurement quality as sampled by DOFS bonded to multiple rebars with different techniques and adhesives. These instrumented rebars are used to produce differently sized RC ties later tested in tension. The discussion of the test outputs highlights the quasi-optimal performance of a DOFS/rebar bonding technique.

Keywords: Distributed optical fiber sensors · DOFS · Distributed sensing · Reinforced concrete · Structural health monitoring

1 Introduction

Distributed optical fiber sensors (DOFS) are quickly acquiring relevance in the structural and civil engineering field [1, 2]. These modern-day cutting-edge monitoring tools are very thin glass wires able to accurately measure strains (down to 1 $\mu\varepsilon$), temperature and vibration in a completely-distributed manner (modern interrogation units can attain a spatial resolution of 0.63 mm) and with measurement frequencies of 250 Hz [3]. When deployed for the monitoring of Reinforced Concrete (RC) structures, it is possible to achieve the detection and characterization (including recognition, localization, quantification and rating) of structural damage-induced local strain changes. Additionally, DOFS have inherent advantages over common monitoring tools such as corrosion immunity, high durability, resistance to electromagnetic interference, small size, flexibility and light weight. These last features embody their large potential of these fibers as they allow for a very high degree of deployment configuration complexity, no matter if

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these imply circumferential surfaces, sharp corners, surface irregularities or, crucially, their embedment inside structural elements.

Ideally, the strains measured by a DOFS silica core should be equivalent to the actual strains present in the host structure on which the former is bonded. If this requirement was fully met, then both DOFS structural monitoring and laboratory structural investigation would simply boil down to analyzing the OBR's output data, no matter how minute the object of investigation is or how accurate the measurement requirements are. Unfortunately, this is not always the case. Indeed, the packaging and the installation of the sensors involves intermediate layers (i.e., protective coatings and adhesive layers) whose presence leads to the failure of the complete strain transfer from the host material to the sensing fiber [4]. Instead, some of the energy is converted to the shear and normal deformations of the intermediate layers thus leading to strain transfer errors. Whenever an experimental investigation requires the maximum precision possible, the shear lag induced by any host-surface/DOFS-core intermediate layers should be minimal, thus the preferable fiber is a simply cladded non-coated DOFS. In this case, though, the protective function against external damages falls entirely on the adhesive layers. Numerous experimental campaigns have been performed in the latest years [5–7] to assess which is the optimal adhesive for the deployment of thin DOFS on a RC structure's surface or inside the latter, bonded to rebar. As can be evinced, the optimal DOFS bonding techniques is still an elusive concept and, therefore, still under heavy investigation.

Note that, whilst the correct bonding of DOFS to the structure is key, its protection is also crucial, especially when embedding it inside a concrete matrix. Indeed, it was assessed [6] that the friction between DOFS and the surrounding concrete is critical for the appearance of Strain Reading Anomalies (SRAs). SRAs usually take the shape of abrupt and illogical strain profile peaks (the likes of which will be visible later on). Whilst it is possible to compensate for the latter in the data post-processing strain phase [8], it is good scientific practice to tackle the SRAs with a preventive approach. Indeed, the DOFS bonding technology could help insulate the fiber from the above mentioned disruptive friction, thus helping to gathering of data as SRA-free as possible.

The present work is intended to contribute to the advancement of this particular branch of the DOFS monitoring science. In particular, the article introduces the results of an experimental campaign featuring different DOFS deployment technologies for the monitoring of reinforcement bars (rebar) strains when embedded inside RC structures. The goal of the campaign: determining which DOFS deployment technology provides results as free as possible of inaccuracies and uncertainties.

2 The Experimental Campaign

The experimental campaign presented in the current article studies different DOFS-rebar bonding and protection techniques for the embedment of DOFS inside RC structures. Generally, when discussing the quality of a DOFS-rebar bonding technique, the verdicts should average multiple aspects. First, the cleanliness of the extracted signal (deeply related to the amount of SRAs), secondly the adhesives' resistance to the external debonding-inducing stimulus and finally the lack of any adhesive-induced alteration of the strain measurements.

The test specimens were produced by instrumenting several rebars with DOFS and later embedding them inside concrete prisms thus obtaining DOFS-instrumented RC tensile members (RC ties). The geometrical features of the RC ties were designed with two goals in mind, namely studying the performance of DOFS bonding techniques whenever the concrete remains whole and when it cracks. In order to produce these opposite scenarios, some RC ties were characterized by longitudinal lengths inferior and superior, respectively, to the theoretical mean crack spacing (referred to as s_{rm} in the fib Model Code 2010). An illustration of the resulting members can be visualized in Fig. 1a.

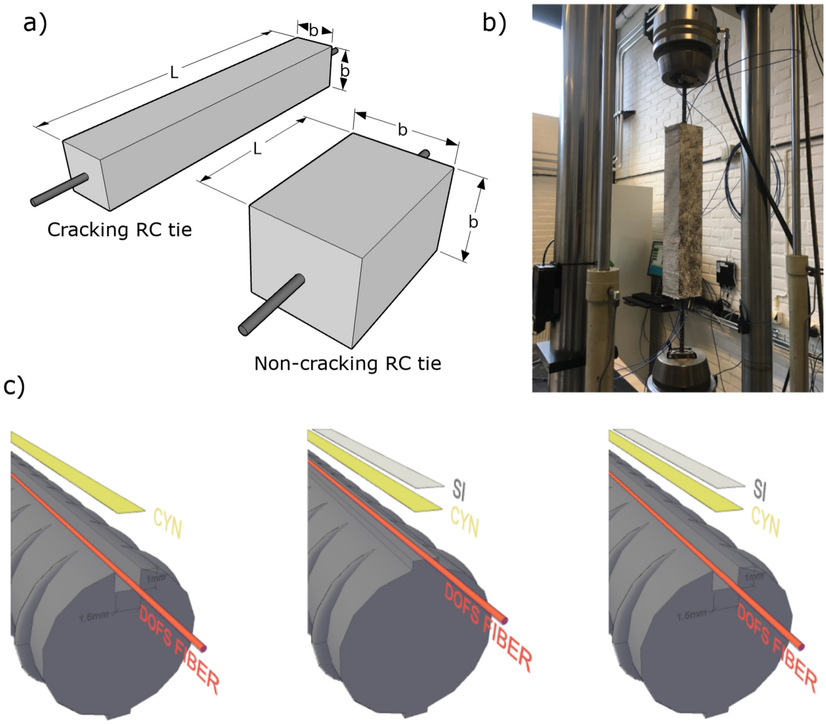

Fig. 1. Test setup: (a) illustration of the geometry of the tested RC ties (b) the specimens during the tensile tests (c) the employed DOFS-rebar bonding technologies.

The geometrical features of the complete set of tested RC ties can be visualized in Table 1. The specimens were subjected to tensile load by means of a Universal Testing Machine (see Fig. 1b).

The loading program was a simple displacement-controlled monotonic tensile load increased at a speed of 1.5 mm/min until the rebar yielding.

The rebars were instrumented with DOFS by means of different techniques as illustrated in Fig. 1c. The first saw DOFS being positioned inside a longitudinally incised groove before being bonded with cyanoacrylate (CYN). The second saw DOFS being

Table 1. Geometrical features of the tested RC ties

Specimen code	Cross sectional dimensions b [mm]	Longitudinal length L [mm]	Embedded rebar diameter [mm]
15D20_24	150 × 150	240	20
15D20_27	150 × 150	270	20
8D16	80 × 80	600	16
10D16	100 × 100	600	16

glued directly to the surface of the rebar with CYN but the addition of a silicone (SI)-based protective layer. The last saw DOFS being positioned inside a groove, bonded with CYN and further covered with SI. The rebars of most RC ties were monitored on both sides by means of a single DOFS twisted backwards in order to investigate multiple bonding techniques inside a single member.

3 The Experimental Test Results

The present section is intended to display only the main results of the experimental campaign rather than all of its results. For an integral view of such results, please refer to Bado et al. [7].

The first key result was provided by member 15D20_27 whose DOFS was deployed with a combination of groove + CYN. The test was intended to substantiate whether the mere presence of the groove could guarantee sufficient protection to the DOFS without requiring an extra protective layer. Figure 2 displays the extracted strain profiles. As expected, in those sections embedded inside concrete, the friction of the latter on the unprotected DOFS led to the appearance of multiple SRAs in the profile, drastically disrupting its interpretation. This result suggests the inadequacy of the groove + CYN bonding technique. It should be mentioned, though, that a possible influencing parameter could be the actual depth of the groove (quite shallow in the present test).

Moving on to members 15D20_24, Fig. 3 displays its DOFS extracted strain profiles. These were sampled on the opposite faces of the rebar, the first of which (henceforth referred to as Face A) used CYN and SI whilst the opposite (Face B) added a groove. Note that the grooves were not as long as the rebars themselves (see the RC tie illustration of both Figs. 2 and 3). This last feature allowed to check, on a single face, the DOFS reading performance of two separate bonding techniques i.e., with and without a groove.

In Fig. 3 it can be observed that the measuremernets performed in those rebar sections that did not include a groove were characterized by larger amount of measurement noise than the ones sampled in the presence of a groove. The noise magnitude seemingly increased with the load.

Along with higher signal noise levels, the strain profiles coming from Face A also included a larger amount of SRAs, attributable to the lack of a protective groove. Notably, during the monitoring of 15D20_24, the two face of the rebar provided differently shaped plots. In particular, Face A's profile inside the concrete, lost the central pointy tip

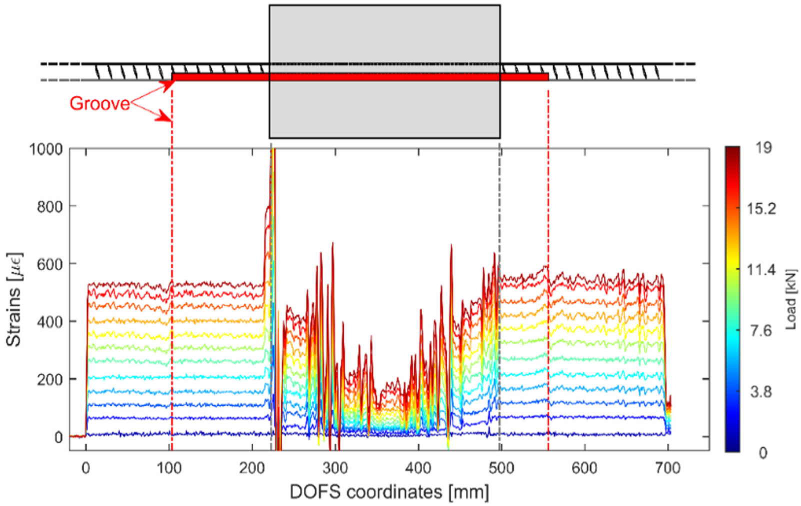

Fig. 2. DOFS strain profiles extracted from member 15D20_27 with the fiber bonded by means of groove + CYN

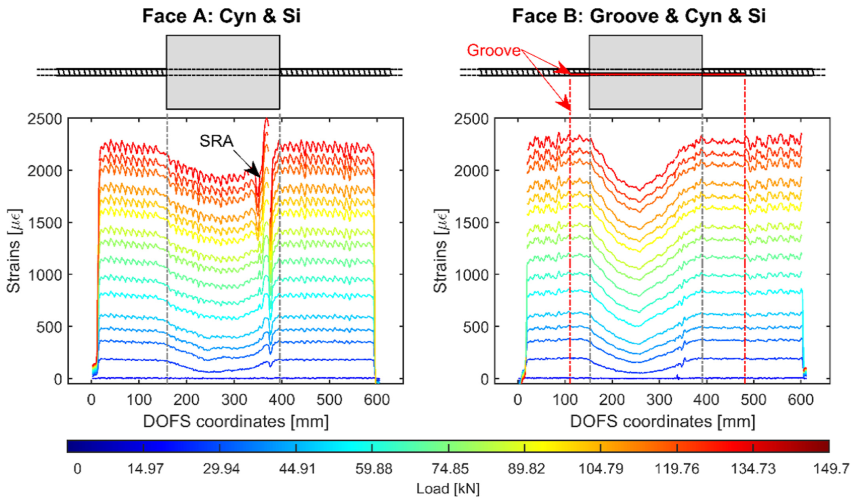

Fig. 3. DOFS strain profiles extracted from faces A and B of member 15D20_24

(expected in RC tie tests) in favor of a more curvilinear shape. Such difference can be attributed to a non-overlookable bending of the RC tie during the test, induced by a lack of straightness of the bar itself. Whilst the latter could be accounted for with a bending compenstion study, the effect of such bending on the DOFS (or on the adhesives bonding it) is unknown and deserving of further studies. A possible such effect could have been the additional stretching that the bending-induced-tension of the concrete communicated to the adhesives (especially on the very deformable silicone) and thus to the fiber. This is in line with other researchers' results [5, 6] that suggest a certain "strain relaxing" and "strain redistributing" influence of the silicone when it is used as a DOFS protecting material. Unfortunately, this phenomenon strongly influences the recommendability of the present bonding technique for this particular use.

Moving on to the cracking members, Fig. 4 displays the DOFS and DIC (Digital Image Correlation) outputs of members 10D16 and 8D16 where, just like before, Faces A used CYN + SI to bond the DOFS whilst Face B added a groove to the mix.

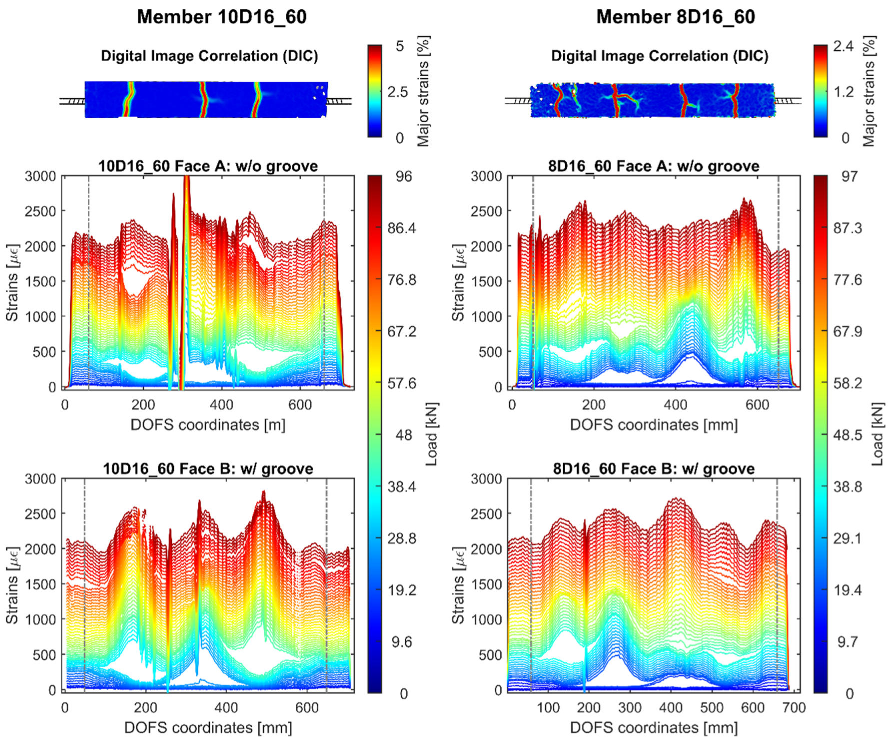

Fig. 4. 10D16 (left) and 8D16's (right) DIC and DOFS outputs; The DOFS strain profiles are reported for Face A and Face B of both members, in each of which DOFS is deployed with different bond technologies

In Fig. 4, despite a relevant amount of bending, a clear variation of the strain profiles can be noticed in correspondence to the cracks. These variations took the form of single or double pointed peaks whose axes coincide with the cracks displayed in the DIC. Indeed, as observed numerous times in literature [2], DOFS can efficiently detect and locate the formation of cracks inside RC structures. Furthermore, once again, the measurement noise produced by the combination of groove + CYN + SI is inferior to the one produced by CYN + SI. Finally, when it comes to SRAs, their presence was generally inferior whenever the DOFS bonding technology included a groove. Yet, 10D16 displayed a consistent amount of SRAs in both faces, demonstrating that even the combination of groove + CYN + SI is not completely fail-proof.

4 Conclusions

The main results extracted from the current experimental campaign were as follows:

- None of the studied bonding techniques could completely guarantee the removal of all SRAs. Yet, the combination of a longitudinally incised groove + CYN + SI was the bonding technique that led to the smallest amount of SRAs thus preserving the readability and reliability of the strain data;
- An unexpected phenomenon, possibly connected to the under-performance of the above bonding technique, caused an alteration of the DOFS strain readings whenever the fiber was in the presence of extra bending-induced tension (smoothened strain profiles as in Fig. 3, Face A);
- Despite its superior performance compared with other bonding techniques, the combination of groove + CYN + SI suffered gravely from the above issue and thus cannot be referred to as an ideal DOFS-rebar bonding technique but simply as the most performant among the studied ones;
- Further research is then required on substituting SI with an equally protective adhesive that does not suffer as much from shear deformation, thus allowing the transfer of the strains from the surface to the DOFS unaltered.

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