Performance of Distributed Optical Fiber Sensors bonded to reinforcement bars in bending

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ABSTRACT

Distributed Optical Fiber Sensors (DOFS) are optimal tools for mapping temperature, strain and vibration inside a structural element in two or even three dimensions. Thanks to their multiple sensing points, wide location range monitoring and customizable spatial resolution, the DOFS allow to paint a clear picture of the global behavior of a structure rather than reporting the tensile state of a limited number of points. This makes it ideal for the detection of deformations and cracking in reinforced concrete (RC) structures, crucial as a mean to ensure the safety of the infrastructure by identifying early signs of excessive damage and giving feedback on the structure’s ability to continue serving its intended purpose. Yet, one of the main points holding back such technique are unexplained rise of anomalies in its readings beyond a certain point of any experimental test. Indeed, during multiple DOFS-monitored structural tests (Rayleigh scattering based), researchers have come across strain reading anomalies in the form of excessively large strain peaks with no physical meaning and veracity. The present paper outlines the results obtained by an experimental test developed in the UPC’s Structure Technology Laboratory with the goal of inducing such anomalies under different conditions in order to isolate and identify the cause of their origin. The test consists in gradually bending seven steel reinforcement bars with a DOFS bonded to their bottom tensile surface. The DOFS performance is then studied for different bonding conditions (different adhesives and their layering for every bar), for constant versus varying rebar sections (some incisions were performed in the rebars) and for different loading speeds (slow, fast and impact). In this paper important conclusions are developed which shed light on such phenomena and lay the grounds for an entirely anomaly-free DOFS-monitored test on RC ties planned as follow-up test.

1. Introduction

Structural Health Monitoring (SHM) is a key process in the infrastructure lifecycle management. In order to prevent the adverse social, economic, ecological, and aesthetic impacts that may occur in case of structural deficiency, it is important to have access to tools that allow real-time diagnosis of the state of health, efficiency and eventual damage of the structures. In the modern age the most commonly used tools are electrical strain sensors, accelerometers, inclinometers, GPS based sensors, acoustic emission,

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wave propagation, etc. Along with these ones, Fiber Bragg Grating (FBG) sensors\cite{3} have also become an increasingly popular surveilling tool but, while they don’t suffer the shortcomings of the previously listed methods (insufficient reading sensitivity, fragility, sensibility to environmental disturbances\cite{2}, etc.), their punctual nature still prevents a precise damage location\cite{4}. Distributed Optic Fiber Sensors (DOFS), instead, surpass such limitation thanks to their intrinsic “distributed” nature allowing the mapping of temperature, strain and vibration distributions in two or even three dimensions therefore drawing a clear picture of the global behavior of a structure rather than reporting the tensile state of a limited number of points\cite{8}. In addition, thanks to features as high accuracy, long-term stability, durability, and insensitivity to electromagnetic influences it is a practical and resistant monitoring tool.

The main principle on which DOFS in grounded on is the light scattering that occurs whenever the photons of the emitted light interact with the physical medium where it is projected (the fiber itself) and with its local material characteristic features like density, temperature and strain\cite{5}. According to the variation of the characteristics of light scatter, the Optical Backscatter Reflectometer (OBR), to which the fibers are connected, is able to measure the variation in strain and/or temperature along the entire length of the fiber. Three different types of scattering processes may occur in a DOF sensor, Raman, Brillouin and Rayleigh scatterings. All hold particular optical features that make one more suitable than others accordingly to the research objectives. The one considered in the current paper is the Rayleigh scattering which, despite its 70m sensing range limit, can provide a high spatial resolution (up to 1 mm), which is ideal for strain and damage monitoring of a RC member’s surface\cite{6,7} or of the embedded reinforcement\cite{9-11}.

2. Experimental application of the Distributed Optical Fiber Sensors

2.1 Test motivation

Being such strain monitoring technique still relatively new, DOFS have been deployed only in a limited number of experimental campaigns\cite{9-12}. Most of these promote the use of such fibers thank to their efficiency and accuracy but at the same time report a phenomenon that, in a way, hold backs the DOFS technique from becoming a truly universal and trust-worthy strain reading method. This phenomenon is Strain Reading Anomalies (SRAs) in the form of localized and excessively large strain peaks which seemingly have little to no physical meaning or explanation. For example, in the same identical monitored spot the DOFS may report large tensile strains (peak in the tensile area) followed by equally large compressive strains (peak in the compressive area) just an instance after. Similarly, such opposite strain peaks can be read along the fiber a few millimeters away from each other in areas of the specimen which are uniformly in tension. This situation occurs also in the experimental test described in this paper as shown in (Fig. 3) and (Fig. 6). The singularity here described has little to no physical meaning, suggesting that it might simply be an erroneous DOFS strain reading. A comparison between the DOFS-measured strain profile with theoretical models and simultaneous strain gauges monitoring confirms such idea suggesting that these are, in fact, SRAs. These should obviously be avoided as they prevent the possibility of getting reliable measurements in the single location of the anomalies (both time-wise and geometrical-wise anomalies) and extensively increase the level of unreliability of the surrounding measurements. The present paper discusses the results of an experimental investigation campaign designed to shed light on such phenomenon and extrapolate some directives on how to run an anomaly-free DOFS-monitored experimental campaign. This will finally allow researchers to fully embrace the DOFS monitoring technique without concerns of measurement unreliability.

2.2 Test specimen and experimental setup

The authors have conceived an experimental test aimed at pin-pointing the motive behind the rise of SRAs. The test, carried out in UPC-BarcelonaTech’s laboratory, intends on inducing these in a controlled environment under different conditions in order to isolate and identify the cause of their origin. In (Fig. 1a) the specimen is represented with its dimensions. It consists of seven parallel Ø20 S500 steel
reinforcement bars with their extremities welded to two C shaped steel beams (herein the assumption of a fixed beam behavior). Six of the rebars were instrumented with a single 5 meters long DOFS while one was instrumented with strain gauges for comparison purposes. All were bonded to the lower face of the bars. The research used an Optical Distributed Sensor Interrogator (ODiSI-A) manufactured by LUNA which analyzed the Rayleigh backscatter from a standard single-mode DOFS set to measure strains and temperature. (Fig. 1b) shows the specimen positioned under the INSTRON hydraulic actuator.

**Figure 1.** (a) Specimen detailing (b) Test setup with the specimen positioned below the INSTRON hydraulic actuator

The test surveys the DOFS performance for different bonding conditions, re-bar sections and loading speed. Indeed, two kinds of adhesives are used in order to bond the DOFS to the bars. Cyanoacrylate for Bar 2 and Bar 5; silicone for Bar 3 and Bar 6; cyanoacrylate with an extra silicone layer on top for Bar 1 and Bar 4. Furthermore, Bars 4, 5, 6 are incised along their upper face in order to locally reduce their sectional area. The dimension of such incisions can be read in (Fig. 1a). As seen there, some incisions are very sharply-edged (BK1) meanwhile others appear smoother (BK2 and BK3). The bars are loaded simultaneously in their mid-span with different speeds and with two impact loads.

As mentioned above the test was designed to study multiple scenarios that cause the strain reading failure which will henceforth be called Disruption Mechanisms (DM). Below are listed seven of these, each followed by the experiment’s attempt at simulating them.

(DM-SB1) The first disruption mechanism studies the possible existence of an Anomalistic Strain Threshold (AST) beyond which any extra strains may be too high for the tensile and shear strength of the fiber’s constituting material resulting in the rise of SRAs in the produced readings. The veracity/influence of such disruption mechanism will be examined by applying an increasingly larger bending load on the rebars while constantly monitoring the strains on the lookout for the appearance of SRAs.

(DM-SB2) A second possible reason for the triggering of SRAs is the sudden exponential rise of stresses in the steel rebar (and consequently in the bonded fiber) that occurs in a section of a RC member that cracks. Here, the steel suddenly passes from simply contributing to resisting the local tensile stress concurrently with the concrete to bearing it alone (having the concrete cracked) resulting in a peaking of stresses concentrated in a single section of the rebar (and henceforth also in the DOFS) which could be even 20 times bigger than its previous value. In order to simulate such, during the test two impact loads are applied on the bars. If the fiber is able to deliver reliable readings after suffering these impacts,
then it can be assumed that DM-SB2 doesn’t affect the DOFS’s performance. It should be noted that, as mentioned earlier, the sudden increase in stresses in the rebar when a bending RC member cracks can be very large and such magnitude could not be simulated in the present test as it would have led to an excessive bending of the bars and of the DOFS. Because of such, the impact loads were limited to 0.1kN and 1.0kN causing in each bar an increase of respectively 1.6MPa and 16.0MPa.

(DM-SB3) Whenever a RC member suffers damage, according to the stress-transfer approach\cite{13}, its cracked sections present a peaking of stresses in the rebar while the tensile state of the sections distant from the cracks remain mostly unaltered. This is due to stresses being transferred from concrete to steel the closer the case-study section is to the cracked section. The speed of such transfers is a function of the transmission length \( l_t \) which can be short, leading to a quick transfer, or long, leading to a slower transfer. An excessively speedy transfer of forces could result in the malfunction of the DOFS and therefore in the rise of SRAs. In order to simulate different transmission lengths, three of the seven rebars presented incisions with steep or inclined/smooth edges. The reduced area of the rebars leads to increased carried stresses in the incised sections, similarly to what happens in RC member sections that have cracked compared to those that haven’t. A steep edge of the incision (Block 1) can be compared to a short transmission length \( l_t \) while a sloping one (Block 2, 3) can be compared to a long \( l_t \). The strains in these three rebars are closely monitored in order to verify whether a drastic section variation gradient (Block 1) could cause SRAs and if so whether they cause it earlier than softer-edged incisions or not.

(DM-AD1) Taking in consideration a cracking RC member with inside DOFS-instrumented rebars, if the adhesive positioned on top of the fiber isn’t protective enough (not thick enough or composed of excessively deformable material), then the cracking concrete friction against the fiber may cause alterations in it leading to SRAs. In the present test, DM-AD1 wasn’t checked, being it deprived of concrete.

(DM-AD2) The fragility, deformability and segmented behavior of the adhesives could lead, when under stress, to their delamination and cracking altering the performance of the embedded fiber. During the loading phase the adhesives are monitored in order to spot any eventual deterioration.

(DM-AD3) An incorrect DOFS confinement design may lead to altered strain readings so, similarly to before, the adhesives are monitored during the test in order to spot any delamination.

(DM-AD4) It is possible that the viscosity of the adhesive (significant when using silicone) influences the fiber’s performance allowing an amount of slip between the fiber and the adhesive. In order to check the veracity of the present disruption mechanism and assuming a higher viscosity of silicone compared to cyanoacrylate the DOFS strain lectures are scrutinized in attempt to see if one of the two adhesives causes premature SRAs.

### 2.3 Test procedure and outputs

The experimental test was designed as following (Fig. 2). The specimen was first loaded at a loading speed of 0.35 kN/min. At 880 seconds the first of the two impact loads is applied (0.1 kN) followed by a second one (1.0 kN) at 1835 seconds. Both impact loads are followed by a 60 seconds hold during which the OBR has enough time to make several measurements to verify the consequential strain reading ability of the fiber as from (DM-SB2). The second loading sequence started after the second impact and its speed (1.12 kN/min) is kept constant until the specimen’s plasticity was reached.
The different outputs of the DOFS measurements are herein presented. The global strain diagram, as reported from the DOFS, describes the tensile state of the fiber’s supporting structure (or lack thereof as later shown) over its whole 5.21 m length. (Fig. 3) is a two dimensional representation of such diagram at three specific instances and increasing load levels. (Fig. 4) instead, expands on the previous graph by adding an extra dimension, time. It is therefore possible to visualize in one graph the strain evolution in time of all six bars, including the appearance of SRAs. In both graphs, the strain profiles of the six DOFS-instrumented bars are represented by the six peaks while the sections of the fiber reporting deformation equals to 0 με are those that aren’t bonded to any surface and act as simple connections between the glued sections. (Fig. 5) sets itself the goal of comparing the strain profile of the rebars at a global load of 30.0 kN in an attempt to verify their similarity considering their identical geometrical, material and loading conditions. In addition, the readings of the strain gauges are also superimposed. Finally, (Fig. 6) represents the strains measured in the mid-spans of the six bars from the start of the test (point O) until its end including the instances at which the impact loads were applied (I₁ and I₂).
Figure 4. Three dimensional representation of the DOFS-measured strains over time along the fiber

Figure 5. Comparison between the different DOFS-measured strain profile segments bonded to each rebar and by the strain gauges for a global load value of 30.0 kN

Figure 6. (a) The DOFS-measured strains of the mid-span of every bar along time (b) DOFS-measured strains of the mid-span of every bar along time after erasing the SRAs
The following observation are essential to the understanding of the above represented DOFS outputs:

- In (Fig. 3) and (Fig. 4) on both sides of each tensile peak the compressive state of the bars is accurately measured by the DOFS even if just partly since the fiber was not glued until the bars’ supports. This, despite effectively preventing the researchers from learning what exactly is the strain profile in those areas, isn’t a great loss due to the fact that, thanks to the linearity of the first part of the compressive profile of the bars, it is easy to extend and extrapolate the strain state of the remaining portion.

- (Fig. 3) clearly shows some SRAs in the mid-span of Bar 2 and Bar 3 that in the strain profile extrapolated at an applied global load of 43,82Kn. As visible the strain readings are impossible in those segments. In (Fig. 4), instead, the SRAs are visible as the vertical spikes coming out of the modelled data surface.

- In (Fig. 3) the last three strain peaks correspond to the readings of Bars 4, 5, 6. A loss of linearity in these segments is evident and correspond to the rebars’ sections that have been incised making their geometrical localization very easy. Before and after the incision’s variation in the profile, the linearity is re-acquired. This demonstrates the DOFS’s ability to read strains free of SRAs despite the presence of incisions with and without steep edges therefore discarding (DM-SB3) as a possible disruption mechanism.

- In (Fig. 5) the similarity among the strain profiles of the six bars is evident along with their correspondence with the strain gauges’ measurements. The only aspects that differentiate the graphs are the local increase in strain in correspondence to the incisions and a malfunction of Strain gauge 2 probably due to a damage suffered during the gluing process. This embodies one more advantage of the DOFS; differently than the strain gauges, the latter doesn’t require fixing at every sensing point, making so that the correct positioning of the fiber is enough to ensure its reading capacity and reliability at each point. The comparison among each bar’s strain profile along with their coherence with the strain gauges’ measurements is a testament to the performance and the reliability of the DOFS as a strain sensing technique.

- In (Fig. 6) the strain profiles correspond well with the applied load. Yet a slight difference between the six bar’s strain evolution graph is evident. The reason behind it is the lack of perfect planarity of the top surface of the specimen. Obviously some rebars are slightly higher than others therefore being loaded first and to a higher extent.

- The strain profiles report correctly and precisely the strain variation due to the varying loading speed and are clear even beyond the yielding of the steel rebars (around 2500με for S500 steel marked as point A). It should be noted that here, also in agreement with (Fig. 2), the strain profiles don’t report a change of linearity beyond the steel yielding strain, due to the fact that the bars aren’t loaded uniformly and therefore yield at successive instances. As a matter of fact, the load-displacement curve doesn’t deviate from its linear trend until the extremities of all the bars haven’t yielded. Only once the last of the six bars acquires plastic hinges (both sides of Bar 4 yield at around 3800 seconds), the load/displacement and load/strain diagrams begin to clearly deviate from linearity. This point will henceforth be called Plasticity point (represented point B).

- All the segments of the DOFS have successfully recorded both impact loads demonstrating the fiber’s ability to correctly withstand and record a sudden stress increase of 1.6MPa and 16.0MPa therefore discarding (DM-SB3) as a possible disruption mechanism.

- Reliable measurements were taken both with cyanocrylate and silicone until high strain levels, removing DM-AD4 from the possible causes of the rise of SRAs. Meanwhile for DM-AD2 and DM-AD3 no apparent debonding was noticed while only a small crack in cyanocrylate was spotted. Yet, no anomalous correlation can be found in the cracked section suggesting that only the most superficial layer of the adhesive has cracked, leaving intact the one below in direct contact with the DOFS. As a consequence of such, assuming a correct positioning of the adhesive these two disruption mechanisms can be discarded from the possible causes of rise of SRAs. On the disruption mechanism DM-AD1, instead, the absence of concrete in the test prevented from checking the role that the friction of cracking concrete has in the rise of SRAs.
3. Discussion of the experimental results and studying of the anomalistic phenomena

In order to comprehensively study the phenomenon of anomalies rising in the DOFS strain readings it is essential to analytically define what is an SRA. The authors suggest here a novel way of identifying them. Given that, by definition of SRA, they correspond to geometrical discontinuities of the Strains/Time or Strains/DOFS coordinate diagrams, it is sufficient to set a specific value of strain increment that, when compared to the difference of strain values between two consecutive measurements, if surpassed it indicates the presence of an anomaly. In the present research such value was set to be 200με. The scale of the SRAs and of such strain limit can be seen in (Fig. 7).

Figure 7. DOFS-measured strains of fiber coordinate 3.02m along time

With this in mind it is possible to study the SRA mechanism as it appeared in the current test’s output data. According to (Fig. 6a), the strain profiles of the six rebars are clear and SRA-free until the Plasticity point (Point B). Beyond this point the profiles are completely dominated by SRAs making it impossible to yield any reliable strain values. If the SRAs would be removed from (Fig. 6a), the remaining strain profiles would look like (Fig. 6b). It is noticeable in the later graph that the different bars’ profiles start curving at point B which is in agreement with (Fig. 2). Coincidentally, the SRAs seem to spring up at this instance too suggesting that a loss of linearity in the specimen’s load-displacement curve, could indeed be what triggers the SRAs. On the other hand, the hypothesis of the SRAs being born after the surpassing of a specific threshold AST, as suggested by (DM-SB1), shouldn’t be ruled out yet, as, in the current experiment, the SRAs seem to be activated in proximity of a strain value of 4000με. This value, as further discussed later, could very well be the AST.

However, the anomalistic analysis should not only be run in the mid-span of the rebars, but on its entire length. Indeed, SRAs can very well rise far from the bar’s mid-span and could do that even before SRAs appear in there. (Fig. 8) is a 2-dimensional graph representing the DOFS-measured strains in the six bars versus the test time where the SRAs can be identified as black bars. (Fig. 9) zooms in (Fig. 8) to focus strictly on Bar 5 and show the existence of two kinds of SRAs. The first kind, defined as Harmless Anomalies (HL-SRA) are those anomalies that do not prevent successful strain readings later on in the test (as in (Fig. 7)). These anomalies prevent the lecture of strains in a punctual way along time and represent more of a nuisance to the researcher than a deal-breaking issue. Harmful Anomalies (HF-SRA), on the other hand, are the first of a number of anomalies occurring in the same fiber section (fiber coordinate) after which for all the remaining duration of the test it is impossible to extract any further reliable strain readings. Finally, (Fig. 10) plots, for every section of the rebars, the strain values at which the first HL-SRA and HF-SRA spring up therefore giving a graphical representation of the SRAs relation with the strains.
Figure 8. Two dimensional representation of DOFS-measured strains along time over the whole span of the fiber bonded to the rebars and of the SRAs

Figure 9. Two dimensional representation of DOFS-measured strains along time over the span of the fiber bonded to the Bar 5 and example of distinction between harmless and harmful SRAs
Figure 10. Plotting of DOFS-measured strain values at which the first HL-SRA and HF-SRA are recorded in each DOFS coordinate with anomalies

Some interesting observations can be developed based on the graphical data of (Fig. 8-10):

- Except in a few DOFS sections, the SRAs start beyond the specimen’s plasticity point reached around 3800 seconds (around 4000με).
- SRAs are often concentrated in specific areas where all neighboring sections give evidence of anomalistic behavior. Such areas can be defined as Anomalistic areas.
- Averagely SRAs seem to spring up from the mid-span of the rebars first which, not coincidentally, are the most stressed points of the seven rebars. The anomalies later spread outwards towards the neighboring section, as evident in Bars 2, 3, 6, forming an anomalistic area (Fig. 8).
- In Bars 4, 5, 6, the SRAs also rise in the incised sections concurrently or soon after having appeared in the mid-span (particularly evident in Bar 5). This further confirms the hypothesis of SRAs springing up from highly stressed rebar sections.
- HF-SRAs are usually proceeded by HL-SRAs.
- Despite in some rebars HL-SRAs seem to start slightly before the specimen’s plasticity point (Bar 3 starts having HL-SRAs as soon as 3000 seconds at section 2.97m) in most occur only later. Meanwhile all HF-SRAs happen strictly after such point.
- In some cases (such as DOFS coordinate 3.02m in (Fig. 7)), a DOFS section containing anomalies can be characterized strictly by HL-SRAs guaranteeing intervals of strain readability all test long.

In summary, the present research has allowed us to observe the following. The SRAs seem to proliferate at a much later instance than the application of the two impact loads (in both full and incised bars) in the most stressed sections (mid-span or/and incisions). As a consequence, both DM-SB2 (for small impact loads) and DM-SB3 can be discarded as potential triggers of the SRAs. Harmless anomalies (HL-SRAs) rise earlier than Harmful ones (HF-SRAs) but, being the proliferation of the latter more troublesome in experimental tests, they are the focus for the determination of an anomalistic strain threshold AST of 4000με (DM-SB1). According to (Fig. 10) 83% of HF-SRAs are triggered at a strain...
level beyond 4000με. The other 17% of HF-SRAs are curiously all triggered on the edges of anomalous areas. This could be plausible considering the presence of the following phenomenon. Assuming the anomalous behavior of a DOFS section affects all neighboring sections triggering premature SRAs, then it would be sufficient that one singular section (the mid-span of the rebar for example) reaches the AST, therefore suffering of the first SRA, to start a chain reaction leading to the creation of the anomalous area. The specimen reached this strain level simultaneously (around 3800 seconds) to the change in deformative behavior and deviation from its previously linear load-displacement graph. The coincidence of these two phenomena prevents the pin-pointing of which of the two is the trigger of the SRAs. Further experimental investigation is therefore required.

3. Conclusions

The experimental test demonstrated once again the large potential of DOFS for strain measurements on/inside civil engineering structures. As expected the measured strains were congruent both with the structure’s expected theoretical response and with the strains measured in parallel by the strain gauges. The fiber’s performance was tested under many load setups such as different speeds and impact loads and has kept providing reliable results until very late in the test (more than double of the yielding stress) and in a completely distributed manner. The Strain Reading Anomalies, above defined as SRAs, is a phenomenon that, when appearing, prevents the correct reading of strain provided by the DOFS. Two kinds of SRAs have been identified, Harmless SRAs (HL-SRAs) and Harmful SRAs (HM-SRAs) of which only the latter represents a serious threat for the research. The latter, by definition, is an anomaly that, when appearing in the readings of a DOFS’s section, represents the end of the strain reading capacity if that section until the test’s end. Differently, if a HL-SRAs is present in the measured strain profile, it is possible that in the future measurements the anomalous section gets back to providing good measurements. In order to comprehend the SRA phenomenon, seven possible causes for its rise, named Disruption Mechanisms (DM), were checked. The test showed that, despite some HL-SRAs appeared earlier, most of the SRAs and all the HF-SRAs occur beyond a specific moment which sees simultaneously the reaching of the strain value of roughly 4000με (possible AST) in all the bars and the yielding of the fixed ends of the bars which caused a variation in the specimen’s load-deformation behavior. One or both these elements seem to have triggered the rise of SRAs. Additionally, the SRAs develop in groups of neighboring fiber sections defined as Anomalistic areas which correspond to portions of the rebar that are heavily stressed (such as the mid-span and the incised sections). Finally, of the seven possible DMs, the only ones that weren’t excluded by the present test are the following:

- (DM-SB1) The existence of a Strain Anomaly Threshold (AST) beyond which the constitutive material of the fiber can’t bear any more stresses without showing anomalies in the readings was only partially confirmed. On the other hand, when the fibers are already under stress they may suffer a sensibility to variations in the mechanical behavior of its support.
- (DM-SB2) The present test was designed in such a way that only minor impact loads could be applied. Therefore, in order to correctly simulate the peaking of stresses that rebars experience whenever a crack opens in a specific section, further experimentation is required with higher impact loads or actual cracking concrete.
- (DM-AD1) The absence of concrete in the test prevented the checking of the role that the friction of cracking concrete has in the rise of SRAs.

An experimental campaign will follow up on the present one by studying the influence of the remaining disruption mechanisms on RC tie members.

References


