Performance analysis of Distributed Optical Fiber Sensors on reinforced concrete elements under fatigue testing

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Abstract

Optical fiber sensors (OFS) have become increasingly popular on civil engineering structural health monitoring (SHM) applications in the last two decades. This is due to several advantages when compared to the more conventionally used electrical sensors. Nevertheless, while this technology has been largely studied and applied in its discrete form, the same is not true on the use of distributed optical fiber sensors (DOFS) which still is a relatively new practiced topic. There is still uncertainty regarding some aspects of the use of this technology on long-term real world applications, which would allow a more consistent and regular practice. As a result, a study of the long-term reliability performance of these sensors when instrumented to reinforced concrete structures was performed. Here, the authors performed a test where a 5 m long DOFS was bonded to a reinforced concrete beam, performing four equal segments on its bottom surface during a fatigue load test, expected to generate equal positive strain increments on each of the segments. Each segment was adhered using a different bonding agent in order to analyze the best performing one. The beam was also instrumented with conventional strain gauges for comparison purposes.

1 Introduction

All civil engineering infrastructures are subjected to the passage of time and its associated decay as well as a number of different external adverse effects, which compromises their structural integrity, and in this way the safety of its users. As of 2016, in the United States alone, 39% of the bridges in the National Bridge Inventory are older than 50 and 9,1% of the total number of bridges were considered structurally deficient. As a result, an average of 188 million trips were performed daily across these structurally deficient bridges and the most recent estimate projects the backlog of rehabilitation projects for these infrastructures at $123 billion [1].

In this way, it is of paramount importance the deployment of measures that extend and improve the lifetime period of civil engineering infrastructures, optimizing its use without hindering the safety of the users. Moreover, it is easily understandable how this enhances the competitiveness of the regions where these infrastructures are located. It is in this context that the field of Structural Health Monitoring (SHM) has been researched and developed for the past decades. However, unfortunately, SHM has not been quite practiced in a large scale and in a systematic manner in civil engineering structures, mostly due to the lack of reliable and affordable generic monitoring solutions [2].

The most common SHM implementations have been based until now on electric strain sensors, accelerometes, and inclinometers among others which present different challenges when applied in real world conditions [3]. It is in this way, that optical fiber sensors (OFS) have become one of the most popular research topics looking to its use in SHM practices. These type of sensors when compared with the conventionally used electrical sensors provide the enhanced advantages of being immune to electromagnetic interference, withstanding wide range of temperature variations, chemically inert and also being small and lightweight which facilitates its handling and transport [4]. This technology has been mostly used in the form of Fiber Bragg Gratting (FBG) sensors [5].

Nevertheless, for a wide range of applications, especially when dealing with large-scale infrastructures, the number of required point sensors for a complete strain information monitoring can become impractically high. Moreover, for the specific case of concrete structures, where it is practically impossible to know with certainty the exact location of possible crack formations, these point sensors present obvious limitations. In the more practical sense, a large number of sensors also present the difficulty of requiring an associated large number of connecting cables making all the monitoring system more complex. It is in this way that distributed optical fiber sensors (DOFS) provide a unique advantage by being capable of monitoring virtually every cross-section of the element where it is deployed with the use of up to one single sensor and one connecting cable.

2 Distributed Optical Fiber Sensors

The use of DOFS in civil engineering infrastructures SHM is still a relatively recent practice. These sensors share the same advantages of the other OFS but as mentioned before present the unique advantage of enabling the monitoring over greater extents of the infrastructure and with a small distance between the measuring points.

These sensors can be bonded or embeded to the structure to be monitored and when temperature or strain variations exist, these alterations are going to be transmitted from the material to the sensor, which will generate a variation of the scattered signal being reflected within the fiber cable. This is the phenomenon behind this distributed optical fiber sensing as defined by the interaction between the emitted light and the physical optical medium. There are three different scattering processes that occur, which are the Raman, Brillouin and Rayleigh scattering [6].

The Brillouin scattering based sensors have been the most studied and practiced within the DOFS systems in civil engineering applications. This is because this scattering technique allows for a large-range capability, which can get up to several kilometers. Nevertheless, it inherently provides a relatively low spatial resolution of 1 m which difficults its use for crack and general damage detections among different applications.

On the other hand, optical frequency domain reflectometry (OFDR) systems, which use Rayleigh scattering, provide a spatial resolution as high as one millimeter being in this way suitable for damage detection and location. This technology is however currently limited to a length of 70 m although this is expected to be greatly enhanced in the near future.

In this study, the authors use the ODiSI A model from LUNA technologies, Figure 1, which is an optical backscattered reflectometry (OBR) system based on the aforementioned Rayleigh OFDR. This technology is presented in greater detail in the following publications [6], [7].

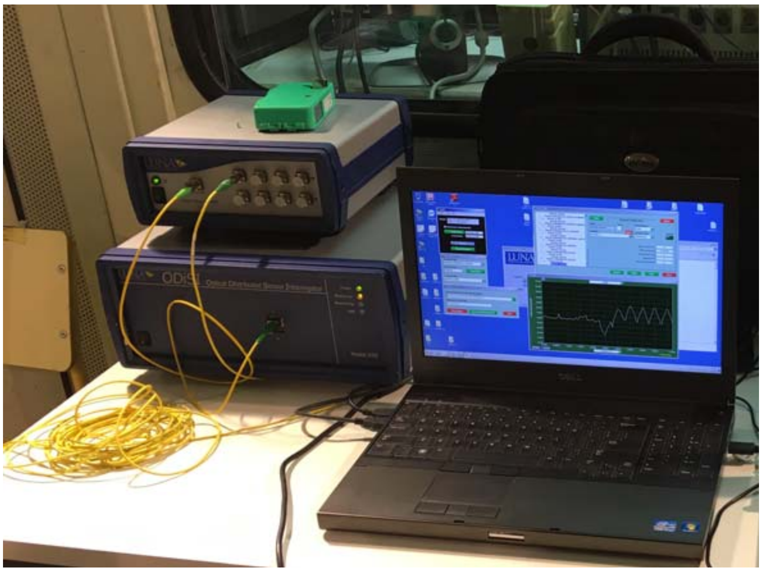

Figure 1. DOFS system used in this experimental campaign

3 Fatigue testing motivation

Despite successful and encouraging applications where distributed optical fiber sensing technology was used [8]–[10], due to its relatively novelty there are still several uncertainties regarding its use on civil engineering infrastructures. One of these uncertainties, for example, is related with the performance of these sensors when monitoring real world applications for long term monitoring periods regarding the stability and reliability of the measurements.

Very few publications can be found regarding the fatigue performance of Rayleigh based OFDR DOFS. An engineering note from the manufacterers of the system used in this same experiment, *Luna Innovations Incorporated*, [11] describes an experiment where polyimide coated distributed DOFS were instrumented to fiberglass coupons and subjected to a +/-2000 με and +/-4000 με cyclic load. Here it was demonstrated the superior performance of the distributed optical fiber sensors when compared with resistive gauges since the applied DOFS survived the fatigue tests and demonstrated consistency in their strain measurements through the end of the test. On the other hand, the resistive gauges showed cumulative zero-shift in microstrain from an early period of the fatigue test, which just increased in magnitude throughout the test cycle.

More recently, Wong et al, 2016 described the study of the use of also a similar Rayleigh based OFDR distributed sensors to monitor the fatigue in a flush step lap joint composite structure used in aerospace engineering [12]. Here it was reported that it was possible to monitor the fatigue damage propagation until failure using the mentioned DOFS system. The distributed sensor was also able to follow the crack propagation generated along the adhesion of the stepped lap joint due to the fatigue loading.

Along these lines, the authors decided to assess the performance of these DOFS for a large number of cycle loads but within conditions similar to what is normally observed in bridge structures. This is inserted in the scope of the authors' current research, which is related to the use of this type of distributed sensing on the SHM of bridges and other large-scale concrete structures . In this way, an experimental campaign was devised in where reinforced concrete specimens were instrumented with DOFS and loaded with a high number of cycles. The test setup is described in the next section.

4 Experimental test setup

In order to assess the performance of the DOFS for the monitoring of reinforced concrete elements subjected to a high number of load cycles, a reinforced concrete beam was used. This beam was characterized by having 600 mm length and a square cross-section of 150 mm width by 150 mm height. The element also had two longitudinal ϕ12 rebars and four ϕ6 stirrups of S500 grade steel. A scheme of the tested beam is pictured in Figure 2.

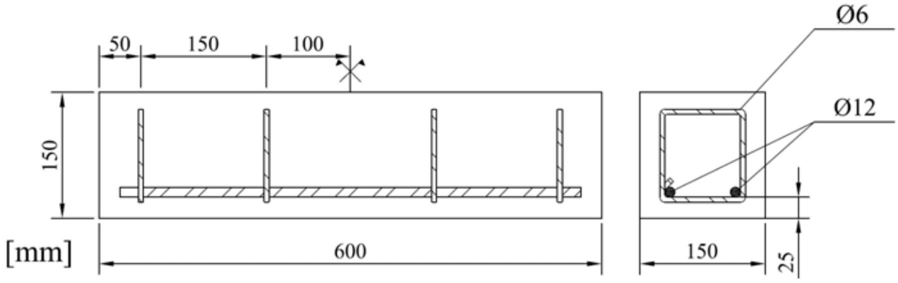

Figure 2. Beam definition scheme (Dimensions in mm)

In the specimen, a 5.2 m long polyimide DOFS was externally bonded with a pattern consisting on three horizontal segments in the lateral face of the beam and four equal horizontal segments in the bottom surface as shown in Figure 3. Notwithstanding, in this paper, only the results from the segments adhered to the bottom surface are considered.

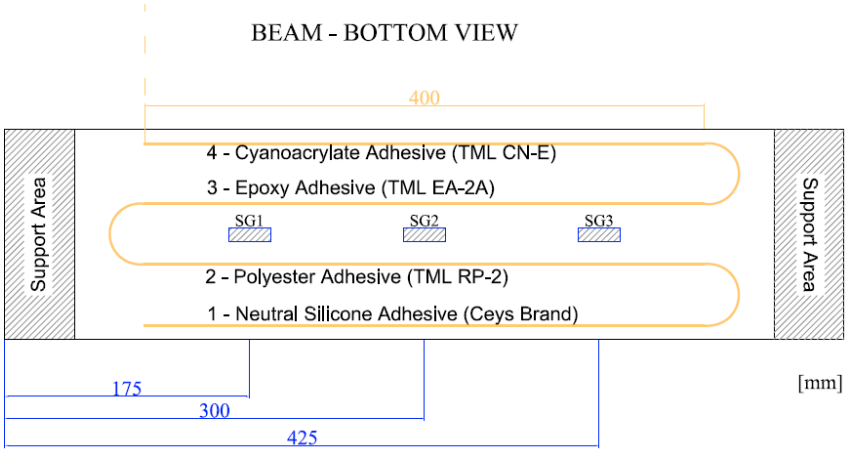

Figure 3. Instrumented sensors at the tested concrete beam

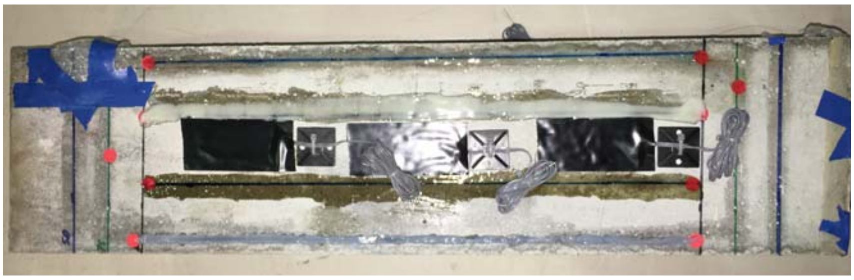

Figure 4. Photograph of the bottom surface of one the tested specimens

As an additional point of interest in the study, different types of adhesives were used to bond the DOFS to the concrete in order to analyze its fatigue performance and choose the optimal one for future applications. In this way, a cyanoacrylate, epoxy, polyester and neutral cure silicone adhesives were used as depicted in Figure 3 and 4.

Furthermore, for comparison purposes, three 30 mm length electrical strain gauges from Tokyo Sokki Kenkyujo Co., Ltd were adhered to the bottom surface of the concrete beam. The specimen was loaded in a three-point bend test and in this way, the measurements obtained by each segment of the DOFS could be directly compared between them and the three strain gauges, Figure 5.

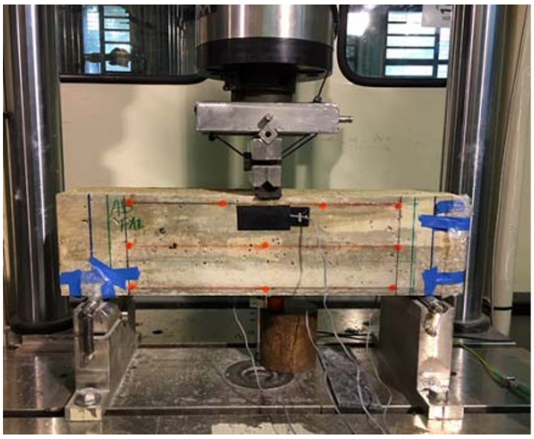

Figure 5. Load arrangement on tested reinforced concrete beam

Moreover, at the time of the production of the concrete for the tested beam specimen, additional cylindrical samples were produced. Afterwards, these samples were tested close to the date of the test on the beam. Subsequently, the mean compressive strength (f_{cm}), the mean tensile strength (f_{ctm}) and the mean Young modulus of the concrete (E_c) were obtained as shown in Table 1. With this, the expected maximum tensile strain (ε_{ct}) was also obtained.

Table 1.Concrete material properties

Properties	f_{cm} [MPa]	f_{ctm} [MPa]	E_c [MPa]	ε_{ct} [με]
Concrete	48.027	3.944	37886.64	104.1

As mentioned before, the idea was to introduce in the specimen a stress range that would replicate the stress range due to vehicular loads in a standard and common reinforced concrete bridge as presented in Figure 6.

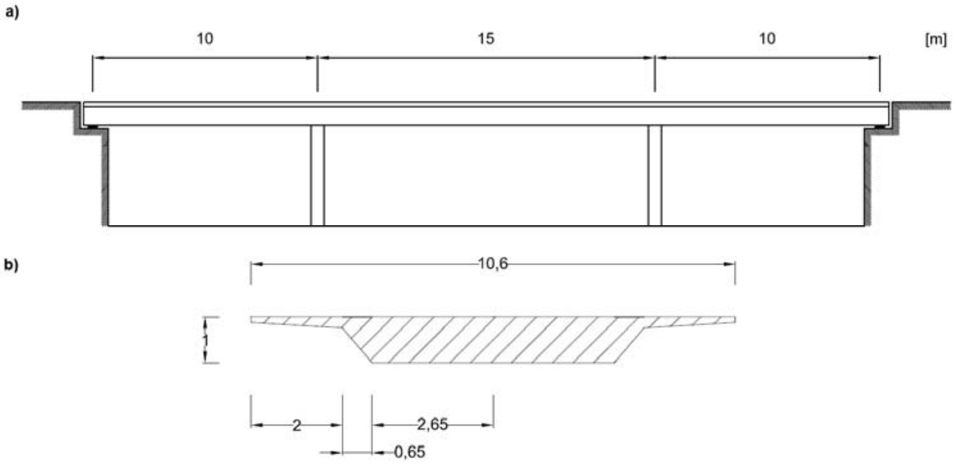

Figure 6. Scheme of bridge for stress amplitude calculation - a) elevation; b) cross-section (Dimensions in m)

Therefore, the two load stages considered for the input of the load cycles were as follows: the lower stress level corresponding to the sole actuation of the self-weight and the higher stress level to the combination of self-weight plus additional traffic. This additional traffic is represented as a four-axle truck with a force of 120 kN by axle and multiplied by a dynamic factor of 1.3, as described in Fatigue Load Model 3 of EN 1991-2 [13].

Table 2. Load scenarios considered on the load cycles input

	Load combination	Maximum bending moment [kN.m]	σ [MPa]	Equivalent load to apply to beam specimen [kN]	Expected strain [με]
Load Cycle Level [inf]	self-weight	3712.9	2.612	11.75	68.9
Load Cycle Level [sup]	self-weight + additional traffic	4336.3	3.050	13.73	80.5

The stress increments were applied with a frequency of 4 cycles per second up to a 2 million cycles. The applied load level was not expected to generate strain higher than the beams's concrete ε_{ct} and thus not expected to induce cracking as seen on Table 2.

Moreover, due to extensive duration of the test, it was decided to record the data being measured every 50 thousand cycles when possible during 5 minutes (1200 cycles). Additionaly, the DOFS were configured to record measurements every 5 seconds and with a spatial resolution of 1 cm.

5 Discussion of results

Following the conduction of the three-point load test, the measured data is processed and assessed. It is important to mention that although the data from the DOFS was measured with a sampling acquisition frequency of 0.2 Hz, the data from the strain gauges and from the load actuator was measured with a sampling acquisition frequency of 1 Hz and then decimated and synchronized in order to correspond to the DOFS data.

Furthermore, it is also important to mention that during the conduction of the test there was an electrical power shut-off that occurred at the 180664 cyles mark. After this, the test resumed from this step and continued smoothly until the end.

In this way, Figure 7 depicts the measured data by the DOFS segments adhered to the bottom surface of the concrete over the number of performed load cycles. It is possible to observe how all the adhered segments measure the strain distribution along the beam bottom length over the applied number of load cycles. In this comparison step, it is also noticeable how the silicone bonded segment presents a smoother spatial measurements when compared with the remaining used adhesives, especialy comparing with the cyanoacrylate bonded segment which presents some irregularities and even a small peak close to its midpoint.

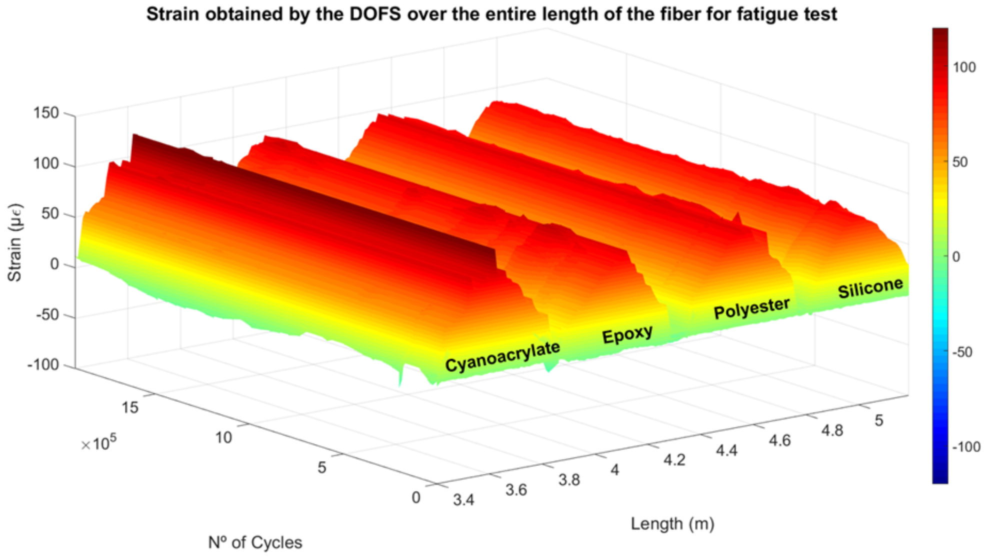

Figure 7. Strain obtained over the four segments on the bottom surface of the tested reinforced concrete beam

In Figure 8, the measured data by the DOFS bonded segments at their midpoints is compared to the data measured by the strain gauge at the same location (SG2). The first immediate remark is the difference between all the DOFS bonded segments and SG2. It is observed how all the segments except the cyanoacrylate bonded one start with a measured strain below of what was expected as described in Table 2.

Here it is also observable how after the beginning of the load process there is an increase of the DOFS measured strain until the 150x10^3 cycles mark followed by a small decrease until it relatively stabilizes around the 400x10^3 cycles. This stabilization is considerably more noticeable in the silicone and polyester bonded segments when compared with the remaining two.

Comparing with SG2 is visible that the initial measured strain is also below what was expected followed by a small increase until 72.61 με at 100x10^3 cycles when it decreases until stabilizing around 67 με at the 250x10^3 cycles mark.

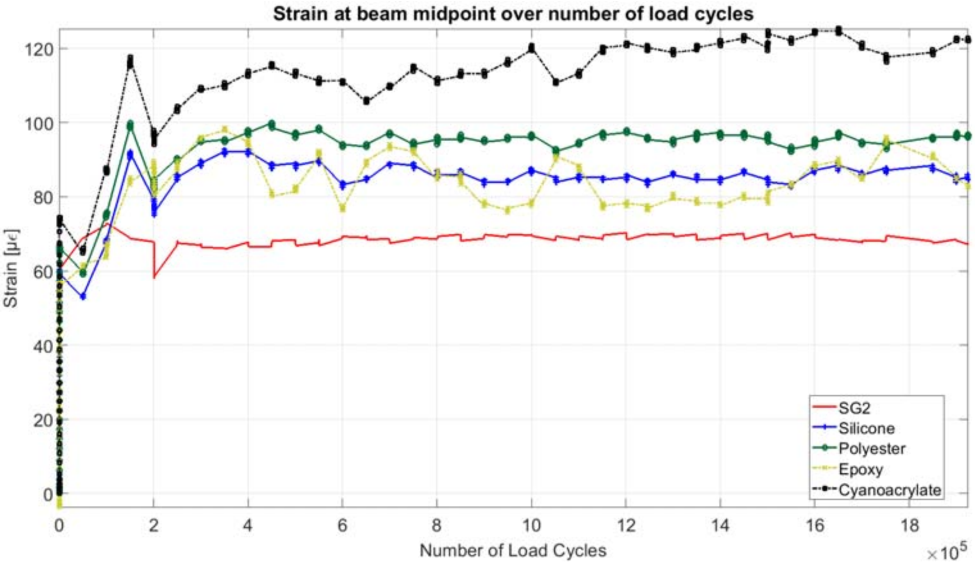

Figure 8. Comparison of measured strain at DOFS segments midpoints, strain gauge 2 and the interval of expected strain

In Figure 9, the readings of each DOFS segment at the beginning and end of the applied load cycles is represented, together with the corresponding measurements of the strain gauges. Here it is even more noticeable how although the DOFS measurements match very well the ones acquired by the strain gauges at the beginning of the load cycles, at the end of these, the two set of sensors present distinct readings. The average strain increment observed for the DOFS due to the fatigue load was of 29.6 με whereas the SG2 measured an increment of just 9.7 με.

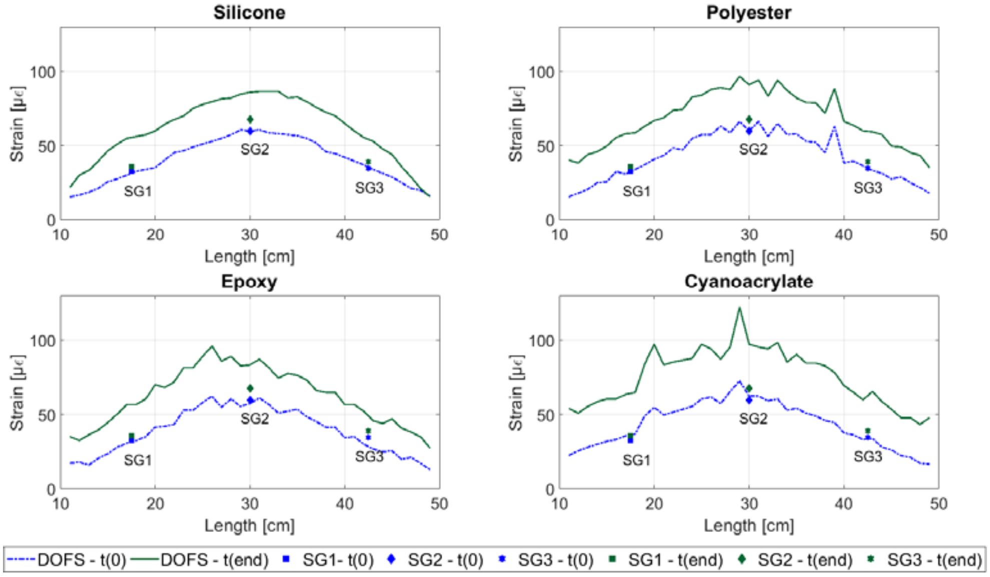

Figure 9. Measured strains by the DOFS and strain gauges at the beginning and end of the applied load cycles

It is important to mention that after the conclusion of the test and therefore for an applied load of 0 kN the DOFS measurements present residual readings that when reseted to the measurements at the end of the cycles have the same magnitude of the readings at its beginning. These results were not initially expected and further analysis is currently being performed in order to obtain more assertive conclusions about these findings.

6 Conclusions

In this document, the performance of DOFS when instrumented on reinforced concrete structures under fatigue testing was performed. A 5.2 m polyimide DOFS was instrumented on a reinforced concrete beam, which was submitted to 2 million load, cycles under a three-point load configuration. The applied load amplitude was representative of what would be expected on a common concrete bridge. As an additional point of interest, four different types of bonding adhesives were used for the implementation of the DOFS to the beam.

It was observed, how the used adhesives influenced the DOFS readings as each bonded segment presented different levels of magnitude for the strain readings during the entire loading process. Furthermore, apart from the differences in values it was seen how the silicone and polyester bonded segments presented a more defined stabilization of its measurements compared with their cyanoacrylate and epoxy counterparts. This stabilization is more in accordance to what was verified by the strain gauge measurements although the order of the measured values of this sensor were distinct of all DOFS segments readings.

These are the initial findings of the performance of the DOFS technology under a high number of load cycles and further analysis is necessary for a more resolute outcome.

Acknowledgements

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References

[1] A. (American S. of C. Engineers), “2017 Infrastructure Report Card ASCE,” 2017.

[2] B. Glisic, D. Hubbell, D. H. Sigurdardottir, and Y. Yao, “Damage detection and characterization using long-gauge and distributed fiber optic sensors,” *Opt. Eng.*, vol. 52, p. 87101, 2013.

[3] J. N. Kudva, C. Marantidis, J. D. Gentry, and E. Blazic, “Smart structures concepts for aircraft structural health monitoring,” in *1993 North American Conference on Smart Structures and Materials*, 1993, pp. 964–971.

[4] J. R. Casas and P. J. S. Cruz, “Fiber Optic Sensors for Bridge Monitoring,” *J. Bridg. Eng.*, vol. 8, no. 6, pp. 362–373, 2003.

[5] P. Ferdinand, “The Evolution of Optical Fiber Sensors Technologies During the 35 Last Years and Their Applications in Structure Health Monitoring,” *EWSHM-7th Eur. Work. Struct. Heal. Monit.*, 2014.

[6] A. Barrias, J. Casas, and S. Villalba, “A Review of Distributed Optical Fiber Sensors for Civil Engineering Applications,” *Sensors*, vol. 16, no. 5, p. 748, May 2016.

[7] G. Rodriguez, J. R. . Casas, and S. Villalba, “SHM by DOFS in civil engineering: a review,” *Struct. Monit. Maint.*, vol. 2, no. 4, pp. 357–382, Dec. 2015.

[8] S. Villalba and J. R. Casas, “Application of optical fiber distributed sensing to health monitoring of concrete structures,” *Mech. Syst. Signal Process.*, vol. 39, no. 1, pp. 441–451, 2012.

[9] G. Rodríguez, J. R. Casas, and S. Villaba, “Cracking assessment in concrete structures by distributed optical fiber,” *Smart Mater. Struct.*, vol. 24, no. 3, p. 35005, 2015.

[10] A. Barrias, G. Rodriguez, J. R. Casas, and S. Villalba, “Application of distributed optical fiber sensors for the health monitoring of two real structures in Barcelona,” *Struct. Infrastruct. Eng.*, 2018.

[11] N. A. A. Rahim *et al.*, “Superior fatigue characteristics of fiber optic strain sensors,” *LunaInc Eng. Note Roanoke, VA, USA*, 2013.

[12] L. Wong, N. Chowdhury, J. Wang, W. K. Chiu, and J. Kodikara, “Fatigue damage monitoring of a composite step lap joint using distributed optical fibre sensors,” *Materials (Basel).*, vol. 9, no. 5, p. 374, 2016.

[13] CEN (European Committee For Standardization), “EN 1991-2.” 2002.