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Review of Civil Engineering Applications with Distributed Optical Fiber Sensors

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Abstract

It's widely recognized that during its lifetime, civil engineering structures are subjected to adverse changes that affect their condition and structural safety. In this way, the application of Structural Health Monitoring (SHM) systems to these civil engineering structures has been a developing studied and practiced topic, that has allowed for a better understanding of structures' conditions and increasingly lead to a more cost-effective management of those infrastructures. In this field, the use of fiber optic sensors has been studied, discussed and practiced with encouraging results. The possibility of understanding and monitor the distributed behavior of extensive stretches of critical structures it's an enormous advantage that distributed fiber optic sensing provides to SHM systems. In the past decade, several R&D works have been performed with the goal of improving the knowledge and developing new techniques associated with the application of DOFS in order to widen the range of applications of these sensors and also to obtain more correct and reliable data. This paper presents, after a brief introduction to DOFS, the latest developments related with the improvement of these products as long as a review of their diverse applications on structural health monitoring with special focus on engineering structures.

1 INTRODUCTION

The control and monitoring of the aging process of civil engineering structures is of great importance for their quality and safety. There are a great number of external events that can induce damage to a structure. This damage can be defined as changes that when introduced into a system will have an adverse effect in its current or future performance [1]. In order to better control and assess this process, the practice of structural health monitoring (SHM) is used. This is defined as the act of employing a damage identification strategy for engineering and aerospace infrastructures. Nonetheless, in spite of its great potential, SHM has not been applied in large scale and in a systematic manner to civil infrastructures. One of the most significant reasons for this is the deficit of reliable and affordable generic monitoring solutions [2].

As a way of improving the inspection accuracy and effectiveness, optical fiber sensors (OFS) are one of the fastest growing and most promising researched areas, due to their features of durability, stability, small size and insensitivity to external electromagnetic perturbations, which makes them ideal for the long-term health assessment of built environment [3]. Furthermore, different kinds of sensors embedded or attached to the structure, can be used in SHM systems but only those based on fiber technology provide the ability to accomplish integrated, quasi-distributed, and truly distributed measurements on or even inside the structure, along extensive lengths [4].

Additionally, for a large scale structure, there can be a large number of point sensors needed to generate complete strain information. Although discrete short gauge sensors are able to deliver useful and interesting structural data related with the local behavior, it might neglect essential information at locations where degradation is occurring but that wasn't instrumented. In this way, distributed optical fiber sensors (DOFS) provide an important advantage over point sensors since they allow global strain measurements. The thousands of sensing points that the DOFS provide enables the mapping of strain distributions in two or even three dimensions of the instrumented structure. Consequently, real measurements can be used to reveal the global behavior of a structure rather than having to extrapolate from a few point measurements.

In the present paper, after a brief explanation of the background of DOFS, a broad and wide range of civil engineering applications are presented (bridges, dams, geotechnical structures, pipelines and historical buildings) as some other innovative implementations.

2 DISTRIBUTED FIBER OPTIC SENSORS

2.1 Basics of Fiber Optic Sensors

In basic terms, an optical fiber is a cylindrical symmetric structure that is composed by a central "core" with a uniform refractive index and with a diameter between 4-600 µm [5]. This core is then enclosed by a "cladding" with a relative lower refractive index trapping the light waves being carried in the core by the reflection at the interface between core and cladding, Figure 1. In order to grant environmental and mechanical protection to the fiber, this cladding can be covered with an external plastic coating.

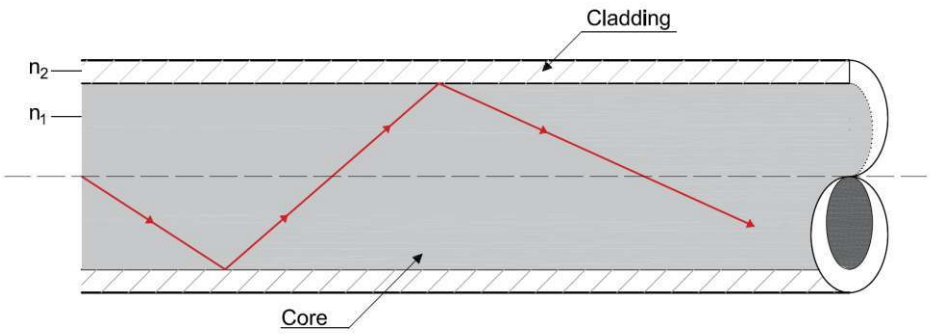

Figure 1: Light guiding and reflection in an optical fiber

There are different ways to classify optical fiber sensors (OFS) depending of which property is being considered, i.e., modulation and demodulation process, application, measurement points, etc. [6]. Nevertheless, in the scope of this article, it's reasonable to categorize DOFS into three different classes, i.e. interferometric sensors, grating based sensors and distributed sensors [7].

2.2 Scattering in Optical Fibers

With DOFS technology applications, the fibers are bonded to the surface or embedded inside the monitored material [4]. In this way, when strain and temperature changes are transferred to the optical fiber, the scattered signal within the fiber is modulated by these physical parameters. By measuring the variation of this modulated signal, distributed fiber sensing is achieved.

Scattering is at the origin of truly distributed fiber optic sensors (DOFS) and it can be defined, in a simple way, as the interaction between the light and an optical medium. Three different scattering processes may occur in a DOFS, namely: Raman, Brillouin and Rayleigh scattering [8].

Raman scattering is greatly dependent of the temperature of the fiber which has been explored in order to instrument very successful techniques with various applications in different areas but also distributed temperature sensors used for example in the detection of water leakage in dikes.

In a similar way, Brillouin scattering is intrinsically dependent on the fiber density, which in its turn is related with temperature and strain being in this way exploited in Brillouin based DOFS.

On the other hand, Rayleigh scattering, as a quasi-elastic or linear phenomenon, is by itself independent of almost any external physical field. In fact, in Rayleigh based DOFSs the scattering is used to measure propagation effects, which can include attenuation and gain, phase interference and polarization variation. It should be noted that Raman and Brillouin scattering are also influenced by these propagation effects but since they present a direct relation to the measured parameters, these effects are generally ignored. For a more detailed look at the DOFS' background theory the reading of the following reference is advised [9].

The DOFS that have been mostly applied in civil engineering SHM applications are based on the following techniques: Brillouin optical time domain reflectometer (BOTDR), Brillouin optical time domain analysis (BOTDA) and Rayleigh based optical frequency domain reflectometry (OFDR) that is better known by the optical backscattered reflectometer (OBR) designation.

BOTDR based sensors have been the most studied and applied measuring systems in civil structures SHM due to their extended measurement range potential that makes them very useful for the application on large structures, such as dams, pipelines, tunnels and long span bridges. Notwithstanding, some applications require a better spatial resolution than the one provided by these sensors. The BOTDA sensing technique, through the application of advanced and complex algorithms, can address this point but in the process increases the price of this technology. OBR technique (Rayleigh OFDR) offers a more cost-effective way of achieving high spatial resolution limiting, nonetheless, the sensing range to 70 meters.

A brief review of the mentioned distributed sensing techniques is presented in Table 1.

Sensing technology	**Sensing range**	**Spatial resolution**	**Main measureands**
Raman	1 km	1 cm	Temperature
	37 km	17 m	
BOTDR	20-50 km	≈ 1 m	Temperature and strain
BOTDA	150-200 km	2 cm (2 km extension)	Temperature and strain
		2 m (150 km extension)	
Rayleigh OFDR/OBR	50-70 m	≈ 1 mm	Temperature and strain

Table 1: Performance review of distributed sensing techniques

3 CIVIL ENGINEERING SHM APPLICATIONS WITH DOFS

This is still a recent and in development technology as it can be observed by the low number of DOFS applications in SHM practice. Nevertheless, some different DOFSs applications were attempted in the last two decades for different civil engineering structures such as bridges, dams, pipelines, slopes and historical buildings that are presented below.

3.1 Bridges

The instrumentation on bridges has unsurprisingly been one of the most appealing areas for the application of DOFS and one of its first successful and most complete applications was conducted on the Götaälv Bridge in Gothenburg, Sweden. This 1000 m long bridge composed by a concrete slab poured on nine steel girders that are supported on more than 50 columns presented several cracks in the girders which prompted the responsible traffic authorities to order a continuous monitoring of the structure [10]. A DiTeSt system based on BOTDA technique was successfully implemented and tested on this bridge in 2007-2009 followed by 1 year trial period and intended to work properly for 15 years.

Another Brillouin based DOFS system was implemented in the monitoring of a slab-on-girder bridge and verified by a high-precision total station system. The system was able to measure the overall response of the girder as reported by Matta et al 2008 [11].

An interesting and complete work was conducted by Glisic et al 2011 on the pedestrian Streicker Bridge at the Princeton University campus where two different optical fiber techniques were applied for almost 4 years [12]. In this process, discrete long-gauge fiber bragg grating (FBG) sensors were used for the global structural monitoring while a BOTDA system was employed for integrity monitoring. Since these sensors were embedded in the concrete during construction, they were able to capture and measure important observations regarding the early age behavior of the concrete and initial cracking.

In 2010, Villalba et al implemented a the OBR system in a newly built highway viaduct in Barcelona, therefore marking the first time that a distributed sensing method with millimetric spatial resolution was used for the load test of a real, newly built concrete bridge [13].

Regier & Hoult 2014 also deployed with some level of success OBR based DOFS on the monitoring of a reinforced concrete bridge, The Black River Bridge in Ontario, Canada [14]. The obtained results were validated by other instrumentation such as strain gauges. Additionally, the DOFS acquired data was used to calculate deflections that had a good agreement with measurements collected by displacement transducers sensors.

Finally and more recently, Rodríguez et al 2016 instrumented one span of a bridge in Barcelona, Spain also with the OBR system during a rehabilitation of the bridge that consisted on the widening of its deck as seen in Figure 2 [15]. In this study, it was necessary to take into account the temperature influence since the monitoring was conducted through several months, spanning from summer to winter. This system enabled the control of the strain variation on the deck through its different stages of the widening process.

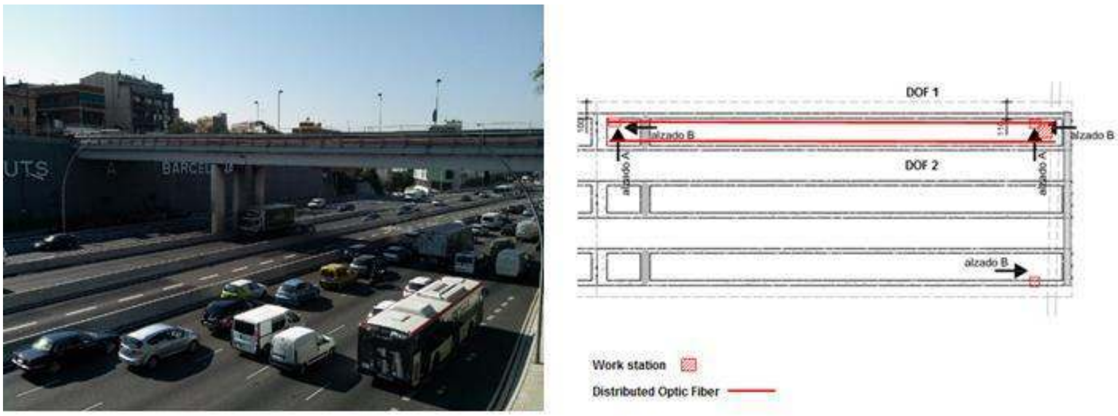

Figure 2: Sarajevo Bridge at Barcelona (left) and general scheme of DOFS monitoring scheme (right) [15]

3.2 Dams

As it happens with bridges, also dams are an appellative subject for DOFS instrumentation due to their grand dimensions. One of the first implementations of Brillouin based DOFS on the monitoring of a dam is reported by Thévenaz et al on the Luzzone dam in the Swiss Alps [16]. Here it was possible to map the temperature distribution of the structure observing how much time it took to cool the central area of the structure that got up to temperatures of 50 ºC that would be otherwise unnoticed. An application of the BOTDA based system, DiTeSt, was reported by Inaudi & Glisic for Plavinu dam in Latvia [17]

Raman based DOFS are more sensitive to temperature variation than its Brillouin counterpart. Different applications of these sensors on dams have been reported: Birecik gravity dam in Turkey 1997; Shimenzhi arch bridge in Xinjiang, China 2000; Wala dam and Mujib dam in Jordan (2001) [18]. The application of these sensors to the detection of leakage in canals and dikes is also reported in [19] In all of these applications, the acquisition of detailed temperature distributions was possible due to DOFS.

3.3 Geotechnical structures

Another field that has seen a great interest in the application of DOFS is the monitoring of geotechnical structures such as slopes. Traditionally, the applied instrumentation is based on discrete sensors what makes it difficult to obtain a global behavior of the slope. Furthermore, these sensors tend to be incompatible with the deformation of the rock-soil mass turning its application into a pointless effort.

Shi et al successfully tested the instrumentation of a BOTDR based DOFS for slopes. This technique was also studied and deployed on Nanjing Gulou tunnel [20] and Xuanwuhu lake tunnel [21] in China and Royal Mail tunnel at London, U.K [22].

Wu et al also installed BOTDR based sensors for the monitoring of the deformation of soil layers and pore water pressure in a 200 m borehole over almost two years in Suzhou, China also deploying FBG sensors. From the results it was possible to observe the unparalleled potential of the application of DOFS for soil subsidence monitoring as it was possible to obtain the strains developed at any depth of the soil layers.

More recently, using BOTDA sensing technology, Zhu et al built a medium sized model of soil nailed slope in laboratory that was then subjected to a surcharge loading test, Figure 3. It was possible to obtain horizontal strain distributions within the slope mass that can be used to define the location of the potential slip surface in the slope [23].

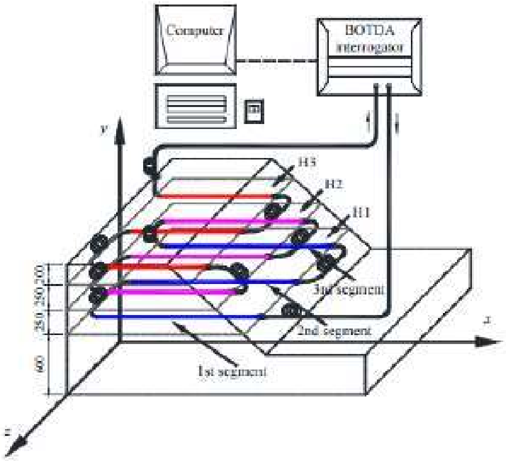

Figure 3: Layout of the BOTDA sensing fiber in the model slope (unit: mm) [23]

Klar et al evaluated the possibility of deploying both BOTDA and Rayleigh scattering based DOFS for tunneling induced ground displacements [24]. For this, the authors concluded that, due to the sensors low rigidity, they deformed in accordance with the mentioned ground displacements. With this study it was also concluded that DOFS technology provided interpretation of results that were only matched by multiple sub-millimeter displacement measurements.

3.4. Pipelines

Another field that has seen a significant increase of the interest in the application of the distributed sensing technology is the Oil and Gas industry. The most universally used techniques are based on Brillouin (distributed) and FBG (quasi-distributed) technologies.

An interesting large scale experiment performed on a pipeline is described by Glisic & Oberste-ufer in 2011 [25]. Here, a relative translation with an angle of approximately 50 ° was induced by hydraulic jacks between two parts of a 13 m long concrete pipe with an exterior diameter of 30.48 cm and successfully measured with a distributed fiber sensor based on Stimulated Brillouin scattering as shown in Figure 4.

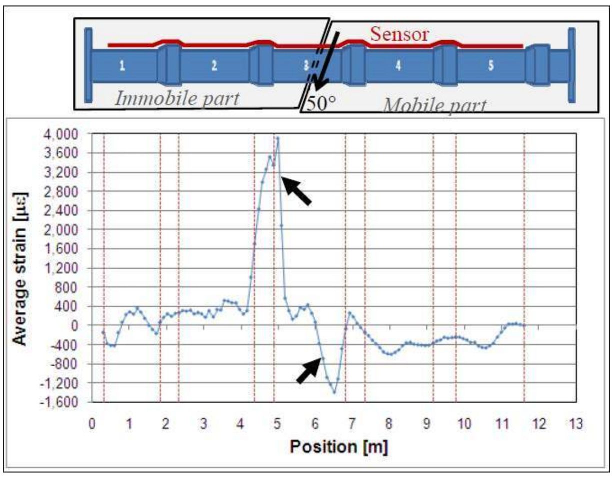

Figure 4: Sensor measurement with detected damage [25]

More fruitful applications of Brillouin based DOFS to pipeline monitoring are described by Inaudi & Glisic [17] for a 35 years old gas pipeline near Rimini, Italy and by Lim et al for the deformation monitoring of a non-circular PVC pipe due to the dead weight of its carrying water [26].

3.5 Historical Buildings

The field of historical buildings is also starting to be a great focus of DOFS monitoring given its immense importance in the cultural heritage of any society. The particular case of discrete FOS monitoring has been extensively studied and practiced in this area. However, the same hasn't been true for the case of DOFS.

One of the few published examples is described by Bastianini et al in [27] regarding the application of Brillouin as a cheaper and effective complement monitoring of Palazzo Elmi-Pandolfi in Foligno (Italy) that was subjected to retrofitting techniques. With this experiment the efficiency of strain monitoring through Brillouin based DOFS was confirmed even for reasonably weak strain levels [27].

Another interesting example is described in [15] with the application of the OBR for the monitoring of a slab during the replacement of two columns of *Sant Pau Hospital* (an UNESCO World Heritage Site) in Barcelona, Figure 5. Here, the implemented DOFS allowed to effectively measure the slab stress redistribution induced by the column replacement procedure and in this way assess its structural stability and safety.

Figure 5: Sant Pau Hospital, Barcelona (left) and DOFS installed on the masonry vaults (right) [15]

3.6 Other

Beyond the already discussed applications for DOFS, these sensors can still find its purpose in other fields due to its vast and remarkable versatility.

One example of this is the application of an OBR sensor system for the monitoring of a concrete cooling tower in Spain, Figure 6, by Casas et al [28]. After the appearance of two main vertical cracks on this structure this DOFS system was instrumented to monitor the structural behavior before and after crack repair extending the lifetime of this structure by presenting the origin of these cracks and the appropriate repair methods.

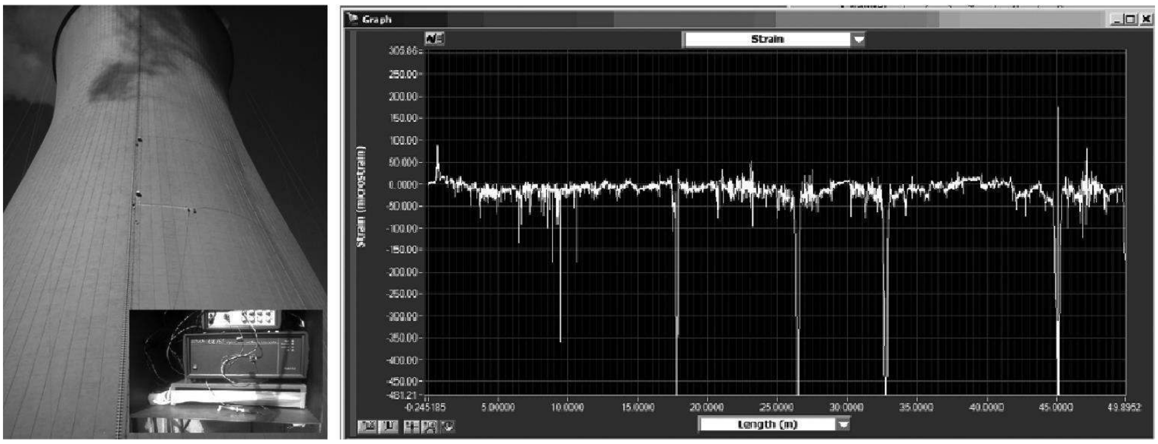

Figure 6: Instrumented concrete cooling tower (left); Strain-fiber length on the outside surface tower (right) [28]

Another interesting use of DOFS is described by Lan et al in [29] for the monitoring of loss of prestress in concrete beams. For this they proposed a novel smart strand that combined BOTDA and FBG sensors on a single optical fiber embedding it into a 5 mm diameter fiber-reinforced polymer (FRP) rebar. Different prestressed RC beams were tested with this strand which results were compared with more conventional sensors. The viability of this system was confirmed by showing not only the spatial distribution of prestress loss but also its time history for both construction and in-service phase.

4 CONCLUSIONS

In the past decades, Structural Health Monitoring has been showed to become a matured subject through the great number of studies and reports made on this topic. Within this area, the application of optical fiber sensors to SHM practice has seen an exponentially increase of interest as it is perceived by the large number studies and applications presented in the past few years. On the other hand, the topic of distributed optical fiber sensors is still at a relatively early practice stage with limited examples of real world applications described in technical literature. Notwithstanding, there are already some examples of DOFS practice in civil engineering applications and, as a result, in the present paper, a review of these works was presented.

Firstly, and in a very brief way the concept of SHM and the most important and used DOFS associated techniques were presented. Later, a general and illustrative review of the state-of-the-art applications of different DOFS in bridges, dams, geotechnical structures, pipelines, historical buildings among others were showed.

As perceived from the examples showcased in this article, this is still a developing technology that needs more experimental validation and testing. Each application is unique and, in this way, the choice of the most appropriate deployable DOFS technique is consequence of the inherent monitoring parameters such as the size of the instrumented structure, desired resolution, acquisition speed and so forth. As an example, while Brillouin based techniques can easily be deployed in structures with several kilometers and therefore acquire global information of the structure, their resolution is not ideal for local damage identification. On the other hand, a cost-effective technique based on Rayleigh OFDR sensing has been developed and can be used in order to achieve high spatial resolution in the order of mm that however has a sensing range limitation of 70 m. Nevertheless, due to its great and unique advantages in the detection, location and quantification of cracking in concrete structures [30] and to the large versatility of applications that it can cover, this system is assumed as one of the most promising sensor technologies for civil engineering SHM.

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