NJESR/ July-2023/Volume-5/Issue-7 E-ISSN-2582-5836

DOI-10.53571/NJESR.2023.5.7.18-32

An Examination Of Distributed Optical Fiber Sensors For Use In Civil Engineering

Sushama.K.K
Lecturer
Department Civil Engineering
Government Polytechnic College
Maharajas Technological Institute
Thrissur

(Received:5June2023/Revised:29June2023/Accepted:1July2023/Published:8July2023)

Abstract

The application of structural health monitoring (SHM) systems to civil engineering structures is a growing field of study and practice that has led to a better understanding of the conditions of those structures and increasingly to management of those infrastructures that is more cost-effective. In this field, the utilization of fiber optic sensors has been contemplated, talked about and rehearsed with empowering results. SHM systems greatly benefit from the ability to comprehend and monitor the distributed behavior of extensive stretches of critical structures through the use of distributed fiber optic sensing. A number of research and development (R&D) studies have been carried out over the course of the last ten years with the intention of expanding the range of applications for distributed optical fiber sensors (DOFS) and obtaining data that is both more accurate and more reliable. After providing a brief overview of the theoretical foundations of DOFS, this article presents the most recent advancements in the development of these products through a comprehensive review of their numerous applications in civil engineering structures and a wide range of laboratory experiments.

Keywords: Optical Fibers, Monitoring Of Structural Health; Sensing Of Distributed Fibers, Civil engineering

Introduction

Motivation For SHM

Some of the most important pillars of society are thought to be the highway and railway transportation systems. In this complicated framework, scaffolds and viaducts expect a significant job on account of their unmistakable capability of joining these organizations as their essential hubs. They are subjected to ever-increasing traffic volumes as well as heavier rail and truck loads, which have a negative impact on these structures' long-term performance. Over 11%

of the 607,380 bridges in the United States are deemed structurally deficient, and the cost of fixing these bridges is estimated to be $76 billion [1]. A nation's competitiveness in the global economy and its resilience to adverse conditions can both be significantly enhanced by maintaining its civil infrastructure. As a result, in order to reduce these costs, a structure, especially in the modern era, needs to be able to reliably produce information about any changes in its structural health condition and communicate it to the responsible operators and decision makers promptly, either automatically or on demand. A modern structure must be equipped with a system that includes a "nervous subsystem," a "brain," and "voice lines" and is able to sense structural conditions in order to accomplish these objectives [2].

For the safety and quality of civil engineering structures, it is critical to control and monitor their aging process. Additionally, a variety of external factors have the potential to harm a structure. Changes that, when incorporated into a system, will have a negative impact on its current or future performance are referred to as damage [3]. Structural health monitoring (SHM) is the process of employing a damage identification strategy for engineering and aerospace infrastructures. The system's objective when dealing with long-term SHM is to provide up-to-date information regarding the structure's capacity to continue serving its intended purpose and function despite the effects of the aforementioned aging process and the accumulation of damage caused by the operational environment. In addition, SHM systems can quickly assess and screen the condition of a structure in the event of an extreme or accidental event like earthquakes, an increase in water levels, or unanticipated loads. The early discovery of primary breakdowns permits the increment of the help life-season of the design while diminishes the support costs.

The process of identifying damage has probably existed qualitatively since man began using tools [3]. Despite this, SHM has recently been a rapidly developing area in aerospace and engineering, particularly civil engineering. Over the past two decades, the engineering and academic communities have shown a lot of interest in the innovation of SHM technologies and the creation of large-scale SHM systems [4]. Nonetheless, regardless of its extraordinary potential, SHM has not been applied in huge scope and in an efficient way to common foundations. The absence of generic monitoring solutions that are both dependable and affordable is one significant factor in this [2].

Optical Fiber Technology In SHM Of Built Environment

Currently, engineers trained in visual inspection assess buildings, bridges, dams, tunnels, and other crucial civil engineering infrastructures. This assessment can sometimes be inaccurate due to differences in their backgrounds for safety condition assessment. To further develop the investigation exactness and effectiveness, optical fiber sensors (OFS) are quite possibly of the quickest developing and most encouraging explored region, because of their highlights of strength, steadiness, little size and harshness toward outside electromagnetic annoyances, which makes them ideal for the drawn out wellbeing evaluation of assembled climate [3].

In addition, electric strain sensors, accelerometers, inclinometers, GNSS-based sensors, acoustic emission, wave propagation, and so on are the foundations of the SHM strategies that are utilized the most frequently. However, when implemented in real-world applications, each of them poses real obstacles [4]. SHM systems can utilize a variety of embedded or attached sensors, but only those based on fiber technology are capable of carrying out integrated, quasi-distributed, and truly distributed measurements along extensive lengths on or even inside the structure [2].

The selection of a select few points that are intended to illustrate the structural behavior is typically the foundation of standard monitoring practice [4]. The number of point sensors required to generate comprehensive strain data can rapidly increase for a large structure. In areas where degradation occurs but is not instrumented, discrete short-gauge sensors may omit important information, despite providing interesting and useful structure-related data. Long-gauge sensors can be used to cover larger extensions of structures, allowing for the detection and characterization of phenomena with global effects on the structure. In any case, the solid location and portrayal that happens a long way from instrumented regions keeps on being trying since it relies upon significant level calculations whose presentation might diminish because of outer obstructions that can veil the genuine harm, for example, temperature varieties, load changes, exceptions and missing information in observing outcomes [5]. For global strain measurements, distributed optical fiber sensors (DOFS) are preferable to point sensors.

The a huge number of detecting focuses that the DOFS gives empowers planning of strain circulations in two or even three aspects. In this way, genuine estimations can be utilized to uncover the worldwide way of behaving of a design as opposed to extrapolation from a couple of point estimations.

Through light scattering, it is anticipated that a truly distributed optical sensor can measure temperature, strain, and vibration data at any point along an entire fiber. The extraordinary test has been to foster these sensors such that they can accomplish suitable awareness and spatial goal [3]. Fortunately, significant progress has been made in this direction over the past few decades.

There have been a number of FOS-related general state-of-the-art papers published [6] as well as numerous reviews of these sensors' applications to civil engineering structures [3]. An exhaustive DOFS cutting edge paper was introduced in [1] where the hypothetical foundation of the most utilized DOFS strategies was broadly explained and where some thoughtful designing applications, particularly centered around spans, were introduced. Geotechnical structures, pipelines, dams, bridges, and laboratory experiments are just a few of the innovative civil engineering applications that are discussed in this paper. Others include laboratory experiments and an ever-increasing number of other applications. Moreover, lastly, a survey of the powerful capacities of conveyed detecting and the most viable difficulties related with the execution of these sensors are introduced.

Fiber Optic Sensors

The primary reference of fiber optic sensors connects with the adaptable endoscopes created in the principal half of the 20th 100 years. With it came an upset in the medication field that proceeds to the current day [3]. The modern era of optical fiber sensors, on the other hand, began in earnest in 1977 for long-distance telecommunications and has grown at an exponential rate over the past four decades. Taking advantage of advancements in optoelectronic concepts, sensing applications are a minor offshoot of this technology. By 1982, attractive, acoustic, pressure, temperature, speed increase, gyro, removal, liquid level, force, photograph acoustic, flow, and strain sensors were among the fiber optic sensors previously created and being explored [4] This cutting edge time of fiber optic sensors was potential because of the advancement of very low-misfortune optical strands in the last part of the 1970s [3].

By providing communications links with greater performance, greater dependability, and ever-increasing bandwidth costs, the fiber optic communications industry has literally revolutionized the telecommunications industry. The ability of fiber optic sensors to replace more conventional electric sensors has improved as component prices have decreased and quality has improved [5].

The use of fiber optic sensors comes with a number of inherent advantages. Among these, it is possible to highlight their immunity to corrosion, light weight, small size, high sensitivity, high temperature performance, resistance to electromagnetic interference, and large bandwidth.

Beginning presentation of this innovation into the business sectors that were straightforwardly contending with customary sensor innovation over the most recent twenty years of the previous century was somewhat sluggish. The high cost of suitable components was largely to blame for this. However, as can be seen in Figure 1, the situation has changed since then, and the forecasts for the future are extremely optimistic.

The cost of both previously available and recently introduced components continues to decrease with each successful fiber optic product that is developed. Applications for fiber optic sensors are anticipated to expand rapidly by 2020 in a number of areas. This technology's ever-increasing capabilities and lower costs make it very appealing to end users [2-3] for applications in aerospace, industrial, medical instrumentation, and structural health monitoring and damage assessment systems in civil structures.

Fiber optic sensor based checking strategies are exceptionally welcome for non-horrendous appraisal of a wide range of designing designs chiefly due to the accompanying reasons: They are able to form sensor chains using a single fiber, can withstand chemically aggressive environments, can be integrated into extremely restricted areas of structural components, and cannot be destroyed by lightning [2-6].

Basics Of Fiber Optic Sensors

An optical fiber is simply a symmetrical cylindrical structure with a uniform refractive index [7] and a central "core" with a diameter of 4 to 600 m. The light waves that are being carried in the core by reflection at the interface between the core and cladding in Figure 2 are then encircled by a "cladding" with a relative lower refractive index. This cladding can be covered with an external plastic coating to provide the fiber with mechanical and environmental protection. Because it is a physical medium, the optical fiber is constantly affected by things outside of it. Along these lines, it encounters mathematical and optical changes because of those equivalent irritations. To ensure dependable signal transmission and reception, it is preferable to minimize these effects in communication applications. Be that as it may, in fiber optic detecting, the reaction to these outside actuated impacts is deliberately upgraded [7]. Inside or outside of the optical fiber (in another medium), this alteration of some of the guided light's properties can occur. As a result, two distinct types of sensors can be distinguished: both external and internal [6].

In turn, each of these fiber categories has a number of subclasses, and in some cases, sub-subclasses with a lot of fiber sensors. Depending on the property that is being considered, such as the modulation and demodulation process, application, measurement points, etc., there are various ways to classify optical fiber sensors (OFS). 8]. However, they can be divided into three distinct classes based on the purpose of this paper: distributed sensors, interferometric sensors, and sensors based on gratings [3] The first two have been extensively studied and utilized in monitoring applications for civil engineering [3]. As a result, the focus of this paper is on the latter.

Distributed Fiber Optic Sensors

Distributed Optical Fiber Sensors (DOFS) have the same advantages as other OFS. However, they enable truly distributed monitoring of variations of one-dimensional structural physical fields all along the optical fiber. Moreover, an extra advantage in regards to disseminated detecting is that it just requires a solitary association link to impart the obtained information to the perusing unit in inverse of the enormous number of in any case required associating links while utilizing discrete sensors. DOFS is more cost-effective because of this feature, and it also opens up a wide range of important applications, like the continuous (in space and time) monitoring of large civil engineering structures.

It should be noted that quasi-distributed FBG sensors can also be used to achieve distributed sensing in a sense. Likewise, this has been the most famous optic fiber procedure for spatial ceaseless estimations, since 2/3 of the SHM projects which incorporates fiber sensors, have selected semi disseminated FBG [2]. Be that as it may, in this method, rather than permitting a consistent checking along the fiber way, a limited number of areas are estimated. The best and utilized sort of semi conveyed sensors depend on Fiber Bragg gratings by multiplexing a significant number of these sensors in the frequency space [7]. As a result, in order to function as a kind of distributed sensor, FBG sensing relies on wavelength division multiplexing (WDM). The maximum number of gratings that can be multiplexed with this approach is typically less than one hundred. However, the number of these sensors that can be integrated is increased by applying time division multiplexing (TDM) to each wavelength channel and assigning a single central wavelength to each grating.

With DOFS innovation, the filaments are attached to the surface or inserted inside the material [2]. At the point when strain and temperature changes are moved to the optical fiber, the dissipated sign inside the fiber is balanced by these actual boundaries. By estimating the variety of this regulated sign, circulated fiber detecting is accomplished.

Civil Engineering SHM Applications With DOFS

The extraordinary greater part of photonic detecting innovation applied in the structural designing region is comprised by discrete sensors like FBG. Over the course of the past few decades, numerous publications have conducted extensive research on this topic. Since this cutting-edge paper is so extensive, it only covers applications of fiber optics technology for truly distributed sensing.

These days, DOFS sensors are an appealing innovation that offers unrivaled execution and benefits when contrasted and more regular sensors applied in SHM practice. They are ideal for applications where reliability in challenging environments is essential, despite their apparent high cost. Moreover, they offer lower establishment and upkeep costs.

However, as evidenced by the small number of DOFS applications in SHM projects, this technology is still in its infancy. Regardless, some unique DOFSs applications were made over the most recent twenty years in various structural designing designs, for example, spans, dams, passages, pipelines and slants that are introduced beneath. Likewise, a lot of work has been finished, and examined beneath, determined to work on these sensors' capacities by executing different research facility tests.

Research Facility Tests

To guarantee the appropriate activity of DOFS, one of the main viewpoints to consider is the right exchange of the measurands from the observed construction to the sensor. Zeng and co., for instance, utilized a Brillouin scatter-based DOFS to measure the strain on a 1.65 m reinforced concrete beam and examine two distinct installation strategies: fiber bonded to steel reinforcing bars and fiber embedded in GFRP (glass fiber reinforced polymer) rods [5]. The optical fiber strand was found to be effectively protected and strain data were measured using both methods. In contrast, Hoult et al. utilized nylon-coated sensing cables and polyimide for a series of axial tension tests on steel plates [3]. Generally speaking, the polyimide-covered fiber introduced a higher precision and a superior relationship with the outcomes got with electrical strain checks. However, at crack locations, its measurements appeared to be incorrect. However, due to the slippage that occurs between the inner core and the nylon coating, although the nylon-coated fiber can be utilized for crack detection and general deterioration, it does not offer the same level of accuracy as the polyimide cable.

Furthermore, the collection of accurate strain measurements may occasionally be hindered by the DOFS protection. Quiertant et al. were able to effectively measure the strain on a RC structure after cracking by overcoming or at least reducing these issues. tested the use of an OBR interrogation unit and fiber optic sensors in rebars through a series of experiments with the intention of taking strain measurements in ultra-high performance fiber reinforced concrete structures, as shown in Figure [4].

The chosen method for installing the optical fiber—an FO bonded on the rebar surface or mounted into a groove—as well as the geometry of the groove and the type of used optical fiber—subject primarily to its coating material—a polyimide fiber with a diameter of 250 m or an acrylate coated fiber with a diameter of 190 m—were the tested parameters in these experiments. The best results were then obtained with a fiber optic sensor with a polyimide coating embedded in a rebar-cut groove.

Crack detection in RC structures is one of the most sought-after applications for DOFS, as previously stated. However, Brillouin-based DOFS has a number of drawbacks, one of which is that it does not detect or measure very significant strain changes that occur over lengths shorter than one-half of the spatial resolution, making it difficult to use this technology for crack detection. Deif and co. investigated the possibility of increasing the spatial and strain resolutions of distributed BOTDA sensors to solve this problem [5]. On a RC beam that was subjected to a four-point bending configuration, the strain distributions on the top and bottom surfaces were extracted using a multiple-peak fitting technique. The read-out resolution of the measurements was increased from 15 cm (of the sensor) to 5 cm thanks to the multi-peak fitting technique. As shown in Figure 5, the system was able to record damage accumulation, but it was unable to precisely locate crack formation.

Glisic and Inaudi likewise assessed the exhibition of the utilization of a high level calculation that was created to keep away from this limit through a few research facility tests where the dispersed temperature and strain checking framework depended on the progressions in Brillouin recurrence [1-4]. A specific setup was built for these tests, and it was used to tension 10 cm of optical fiber using various previously defined values. These recreated break openings were accurately and effectively distinguished and restricted.

In addition, the decision was made by these authors to develop a sensor delamination mechanism at the crack's location in order to guarantee that the system would continue to function even under extremely high strain levels. This was done in light of the fact that this developed algorithm was only suitable if local stress was redistributed over a minimum length of 10 cm. They paid particular attention to the adhesive they chose because of this.

The DOFS was glued to metallic supports that were given a relative translation movement with the intention of simulating a 0.5 mm crack opening. This delamination mechanism and the chosen adhesive were then tested in the laboratory using a specific setup. The test results demonstrated the mechanism of delamination, as well as the appropriate adhesive selection and installation methods. This demonstrated the system's ability to locate and identify cracks with openings smaller than 0.5 millimeters. After that, this system was put through its paces on a pipeline [8] and put into use for the monitoring of a bridge [4], and the crack detection method that was put into use performed well.

Zhang and co. explored the improvement of a wellbeing checking framework (HMS, Figure 6), that joined BOTDR and multiplexed FBG methods determined to execute it on restored substantial brace spans [8]. For this, a progression of static and dynamic stacking tests to an essentially upheld built up substantial T-shaft reinforced by remotely post-tensioned ligaments were executed.

Challenges When Using Distributed Optical Fibers

The limited spatial resolution and monitored length range of DOFS systems are just two of many obstacles that must be overcome when using them, as is the case with any monitoring sensing system. In any case, presumably the major functional worry with fiber sensors in SHM of structural designing designs is to guarantee that the actual sensor isn't harmed during the establishment or estimation process. Due to the extreme fragility of bare fibers, this is difficult to accomplish.

As found in the various applications displayed in this article, a correlation of unmistakable coatings and securities for the optical fiber when applied to different designs is of outrageous significance. The use of a coating that is relatively thick reduces the likelihood of fiber rupturing and makes the sensor installation process simpler; However, it is not guaranteed that all stress and strain will be transferred to the sensor from the monitored structure. The quality of the measured strains, on the other hand, improves in applications where the coating is very thin or even absent. However, when the sensor is applied to the structure (either embedded or glued to the surface of the structure), it requires a lot of care and effort to avoid damaging the sensor, which also means that long-term applications on exposed structures are limited. Any DOFS-based monitoring system should carefully consider this compromise, which is unique to each implementation.

The possibility of introducing bending stresses in the fiber during the field installation process—which could be very detrimental due to the particularly weak scattering signals—is another concern associated with the application of DOFS. If sufficient care is not taken, this could happen.

Also, in substantial designs, for reinforced applications, the harshness of the substantial surface and the heterogeneity because of the presence of totals of a few sizes prompts a significantly more noteworthy test. In order to achieve a strong bond between the sensor and the instrumented structure, a pre-treatment to smooth the surface (brushing) and cleaning of the grease and other undesirable particles in the areas where DOFS are intended to be bonded are essential. Low peaks and discontinuities also show up when analyzing the measured data because of the same surface irregularities and concrete spalling and flaking. Because of this, special care should be taken during this step as well to avoid making incorrect assumptions.

Last but not least, when employing DOFS systems in a damage/deterioration SHM system, it is essential to include some redundancy in the sensor network to guarantee relevant results even in the event of a sensor failure.

Conclusions

Journal articles and project reports from recent decades have demonstrated that SHM practice is now a mature and well-established field. In addition, OFS has received an exponential increase in interest within this field, leading to the presentation of a number of studies and applications in recent years. In any case, instances of the disseminated capability of this innovation are still in a generally early practice stage. Consequently, the subject of distributed fiber optic sensing in SHM practice, particularly its applications in civil engineering structures, was extensively discussed and reviewed in this paper.

The idea of SHM and the function of fiber optic sensors were first discussed. The most widely used distributed sensing techniques—time domain reflectometry and frequency domain reflectometry—were then described and elaborated on using background theory. Following that, a comprehensive summary of the most recent applications of various DOFS in geotechnical structures, pipelines, bridges, and dams was presented. This was complemented by the most recent research on this technology's advancements in a variety of fields and state-of-the-art laboratory experiments that led to field applications. It is worth focusing on that the applications found on this paper just cover the sensor plan and essential execution methods and execution. For additional data in regards to every one of the applications, the perusing of the separate references is encouraged. At long last, a short outline of the most significant difficulties related with the utilization of DOFS in SHM was introduced.

There is still a great deal of research and development to be done in order to fully establish this technology as a viable solution for SHM applications in civil engineering. The endeavor to improve the goal of these sensors is something that ought to be gone on in later works to make better harm observing arrangements in view of these sensors. Also, the distinguishing proof of the most suitable coatings and establishment strategies for every execution ought to be additionally explored to give overall rules to the utilization of this innovation in structural designing SHM eventually.

This article shows that DOFS-based systems can be used in a variety of applications, highlighting their impressive adaptability and the need to tailor this system to each solution. The size of the structure, the spatial resolution, the acquisition speed, and other factors all play a role in determining the best DOFS method. While techniques based on Brillouin are able to easily cover a great deal of ground and, as a result, gather global information about a structure, their resolution is not ideal for identifying damage. A few endeavors to further develop this goal have been made and are introduced in this survey. However, in order to achieve high spatial resolution using Rayleigh OFDR sensing, a more cost-effective method must be developed. This technology is still new and growing, but it is expected to play a significant role in structural health monitoring in the near future if it is properly developed and utilized.

References

[1]. Leung, C.K., Wan, K.T., Inaudi, D., Bao, X., Habel, W., Zhou, Z., Ou, J., Ghandehari, M., Wu, H.C. and Imai, M., 2015. Optical fiber sensors for civil engineering applications. Materials and Structures, 48, pp.871-906.

[2]. Barrias, A., Casas, J.R. and Villalba, S., 2016. A review of distributed optical fiber sensors for civil engineering applications. Sensors, 16(5), p.748.

[3]. Masoudi, A. and Newson, T.P., 2016. Contributed Review: Distributed optical fibre dynamic strain sensing. Review of scientific instruments, 87(1), p.011501.

[4]. Dakin, J.P., 1993. Distributed optical fiber sensors. Distributed and Multiplexed Fiber Optic Sensors II, 1797, pp.76-108.

[5]. Ding, Z., Wang, C., Liu, K., Jiang, J., Yang, D., Pan, G., Pu, Z. and Liu, T., 2018. Distributed optical fiber sensors based on optical frequency domain reflectometry: A review. Sensors, 18(4), p.1072.

[6]. Liu, X., Jin, B., Bai, Q., Wang, Y., Wang, D. and Wang, Y., 2016. Distributed fiber-optic sensors for vibration detection. Sensors, 16(8), p.1164.

[7]. Ashry, I., Mao, Y., Wang, B., Hveding, F., Bukhamsin, A.Y., Ng, T.K. and Ooi, B.S., 2022. A review of distributed fiber–optic sensing in the oil and gas industry. Journal of Lightwave Technology, 40(5), pp.1407-1431.

[8]. Dakin, J.P., 1987. Multiplexed and distributed optical fibre sensor systems. Journal of Physics E: Scientific Instruments, 20(8), p.954.

[9]. Yan, M., Tan, X., Mahjoubi, S. and Bao, Y., 2022. Strain transfer effect on measurements with distributed fiber optic sensors. Automation in Construction, 139, p.104262.

[10]. Barrias, A., R. Casas, J. and Villalba, S., 2018. Embedded distributed optical fiber sensors in reinforced concrete structures—A case study. Sensors, 18(4), p.980.

[11]. Sun, X., Yang, Z., Hong, X., Zaslawski, S., Wang, S., Soto, M.A., Gao, X., Wu, J. and Thévenaz, L., 2020. Genetic-optimised aperiodic code for distributed optical fibre sensors. Nature communications, 11(1), p.5774.

[12]. Yan, Y., Zheng, H., Zhao, Z., Guo, C., Wu, X., Hu, J., Lau, A.P.T. and Lu, C., 2021. Distributed optical fiber sensing assisted by optical communication techniques. Journal of Lightwave Technology, 39(12), pp.3654-3670.

[13]. Kishida, K., Imai, M., Kawabata, J. and Guzik, A., 2022. Distributed Optical Fiber Sensors for Monitoring of Civil Engineering Structures. Sensors, 22(12), p.4368.

[14]. Ashry, I., Mao, Y., Wang, B., Hveding, F., Bukhamsin, A.Y., Ng, T.K. and Ooi, B.S., 2022. A review of distributed fiber–optic sensing in the oil and gas industry. Journal of Lightwave Technology, 40(5), pp.1407-1431.

[15]. Zhu, Z.C., Chu, C.W., Bian, H.T. and Jiang, J.C., 2022. An integration method using distributed optical fiber sensor and Auto-Encoder based deep learning for detecting sulfurized

rust self-heating of crude oil tanks. Journal of Loss Prevention in the Process Industries, 74, p.104623.

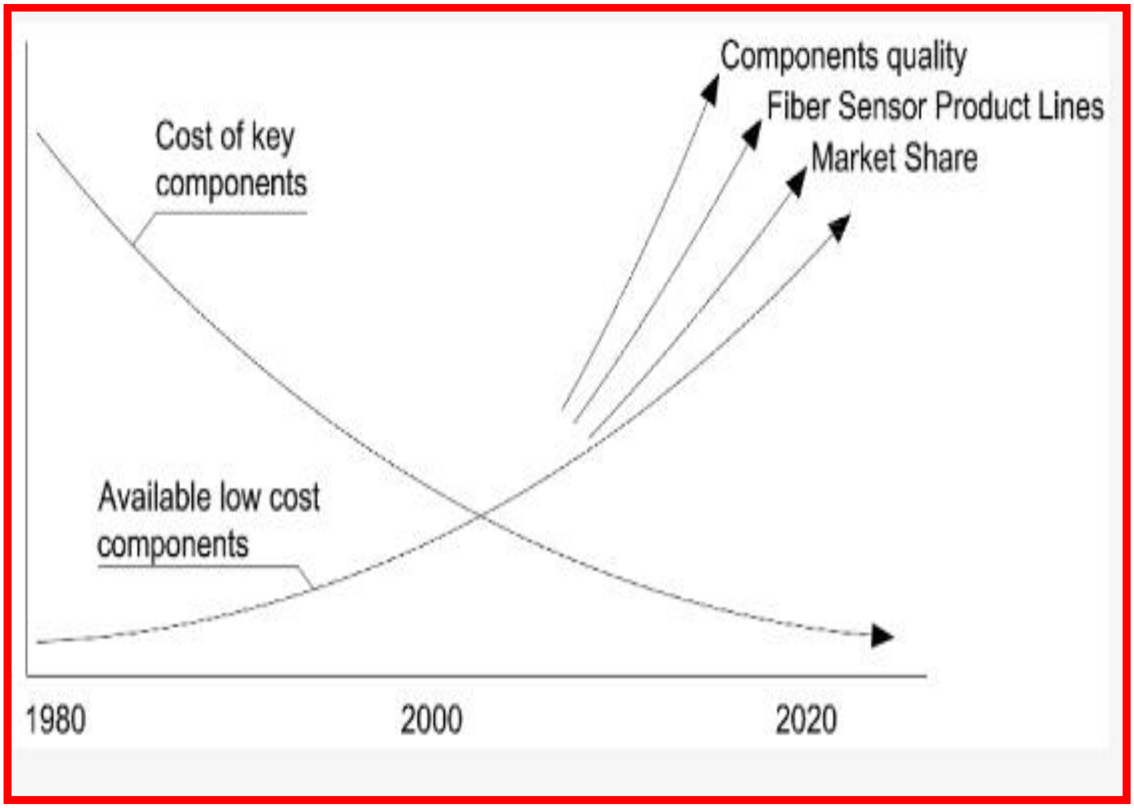

Figure 1. Trends for fiber optic sensors (adapted from [2]).

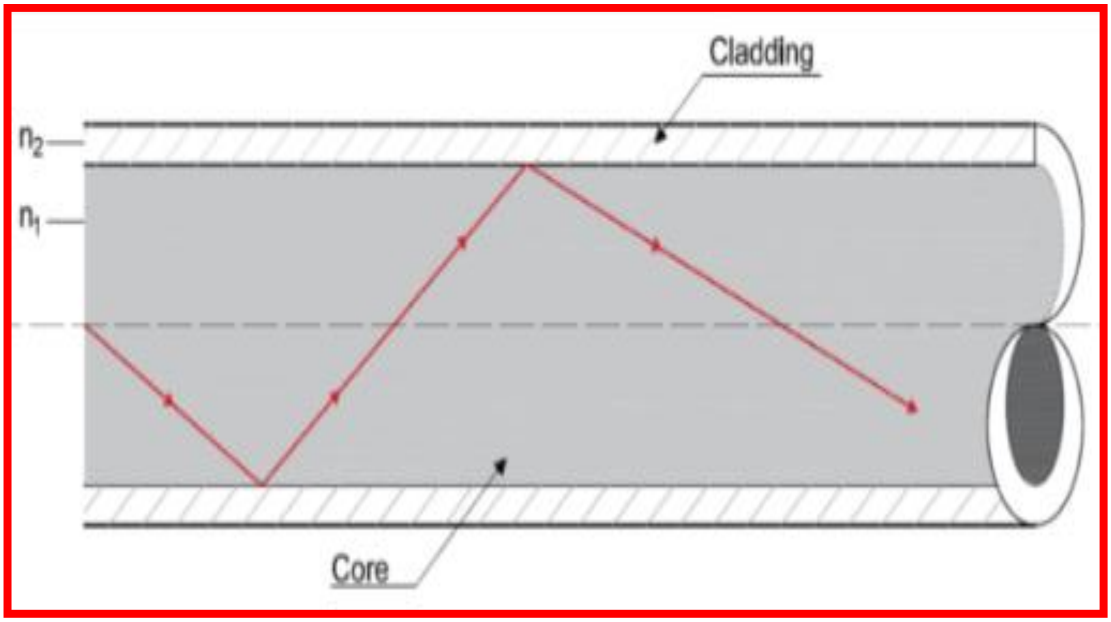

Figure 2. Light guiding and reflection in an optical fiber.

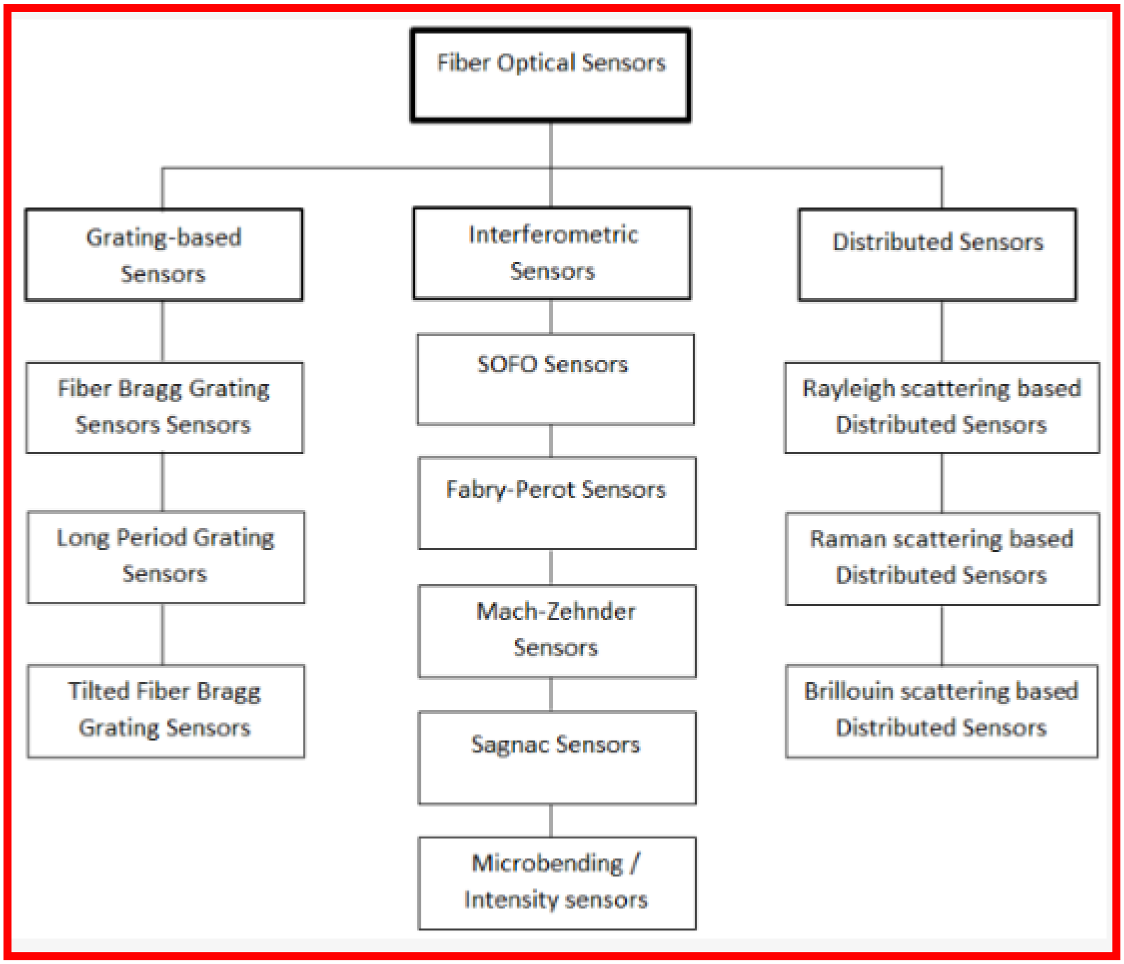

Figure 3. Overview of fiber optic sensor technologies (adapted from [3]).

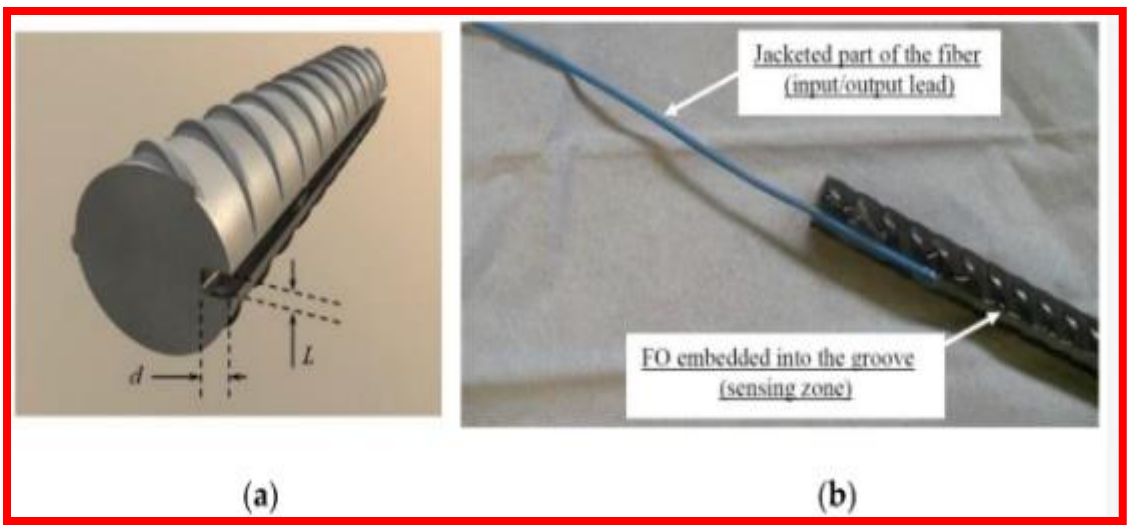

Figure 4. *Geometry of the groove in the rebar (**a**) detail view of the end of the bonded zone (**b**) [4].*

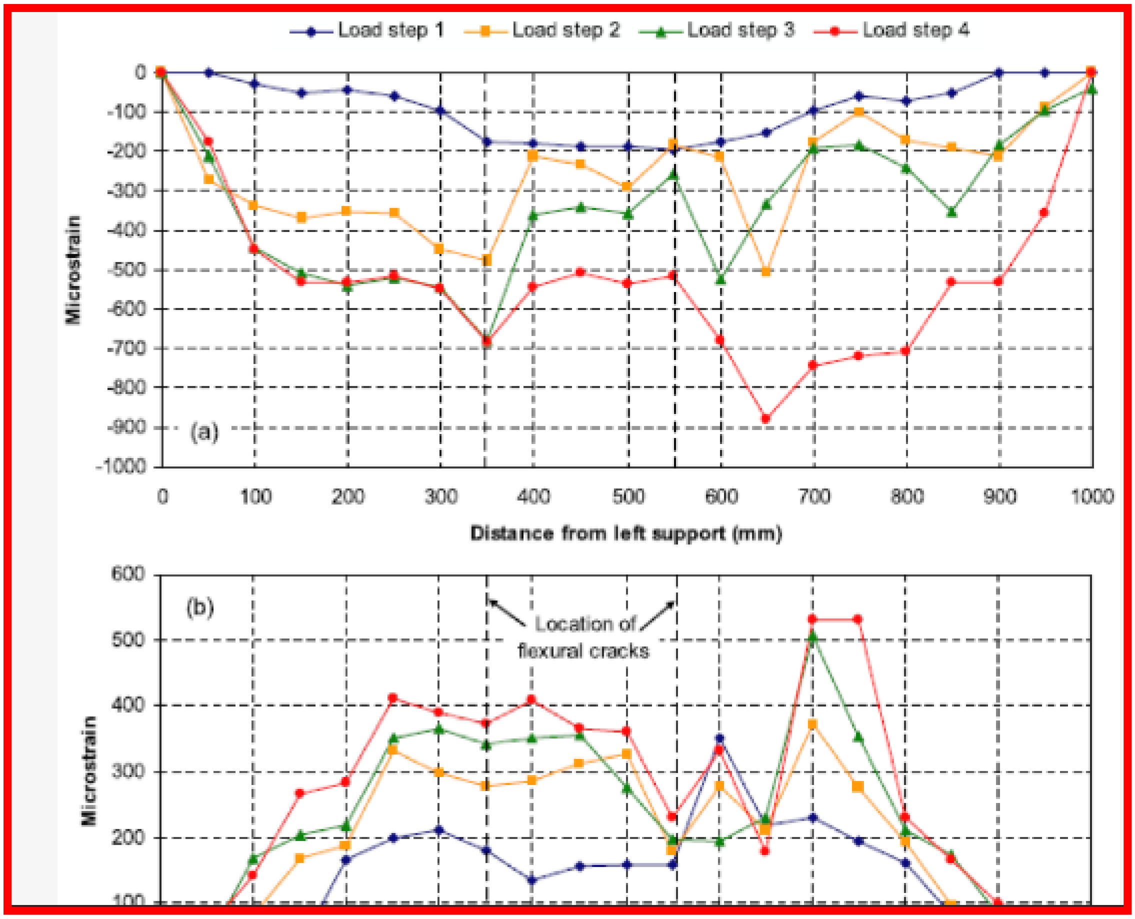

Figure 5. (a) Compressive and (b) tensile strain distributions measured by distributed Brillouin sensors [5]