## Layered sensing cables vs. monolithic DFOS strain sensors

## Why it is better to use DFOS sensors for strain measurements?

In scientific articles and marketing publications as well as on the websites of manufacturers of fibre optic measurement solutions, the names “*sensing cables*” and “*fibre optic sensors*” are very often used interchangeably. This is because these terms are incorrectly taken to be synonyms describing one and the same technical solution. The careless, interchangeable use of these terms can be misleading for those who are trying to select measurement equipment for their own applications or want to start using DFOS techniques. Poorly selected measuring tools can destroy many months of effort which went into preparing an experiment or into conducting measurements on a construction site. This article aims to highlight the differences between sensing cables and fibre optic sensors. These are two completely different technical solutions designed to perform different functions.

1. Sensing cables
   1. Introduction

The first applications in which optical fibres were used to monitor the technical condition of structures were related to spacecraft and aircraft components. In space technology and aviation, early detection of any damage that affects the integrity of structural components is essential, both to ensure safety and to perform rapid repairs in order to maintain the required operational status. An example of such application was **U.S. patent 5,015,842 submitted in 1990 by E. A. Fradenburgh and R. Zincone of United Technologies Corporation**, which aimed to solve the problem of covering the maximum area with the minimum number of optical fibres so as to enable damage sites in spacecraft structures made of composite to be precisely detected. In the patent, damage to the composite structure caused a fibre to break. The drawback of this solution, as well as of similar ones, was the manner of detecting the damage, which required a fibre embedded in the composite to be broken. A solution which would enable the detection of areas subject to large strains without the risk of damaging optical fibres was required.

### D:\dane_lukasz\shmsystem\wniosek_epsilon_temp\artykuł\zdj_1.png

Fig. 1. Different types of sensing cables

* 1. Protective metal coatings for optical fibres

The solution to the problem of optical fibres breaking inside composite structures was presented in the article “The Importance of Coating to Structurally Embedded Optical Fiber Sensors” **[*Dasgupta, A., Sirkis, J. S., and Liu, C., “The Importance of Coating to Structurally Embedded Optical Fiber Sensors,” Proceedings of ISA International Conference, New Orleans, pp. 1673–1693, 1990*].** The solution to the problem presented in the article consisted in placing optical fibres – before embedding them in the composite structure – inside elastic-plastic metal coatings, which were able to permanently deform in response to a given destructive load applied to the composite. The task of elastic-plastic protective metal coatings is to distribute locally occurring significant stress along the optical fibre, which prevents its destruction. This article was of fundamental importance, setting out research directions for fibre optic sensors in which the optical fibre used for measurements is placed inside a protective metal coating.

The design of detection protective coatings was presented in the **“Metal Coated Fiber Optic Damage Detection Sensors With System” patent filed by James S. Sirkis from the University of Maryland in 1993 (U.S. patent 5,245,180).**



Fig. 2. U.S. 5,245,180, Fig. 1 – Optical fibre inside the protective coating embedded in the composite matrix

The task of the detection protective coating is to protect the optical fibre against damage and to “store” information about the occurrence and location of stresses dangerous to the composite structure. After this information has been “stored”, measurements can be taken after the spacecraft or aircraft has returned to earth without the need for reflectometers being placed on board and measurements being taken with a frequency on an order of at least a few Hz. The plastically deformed detection coating keeps optical fibre strains despite the fact that external forces have ceased, which makes it possible to determine that an event occurred during flight which was dangerous for the composite structure. Appropriate selection of mechanical parameters of the detection coating (its material, e.g. aluminium, gold, silver, copper, and its thickness) results in a mechanical sensor memory being created, which is activated after a stress level which is destructive for the composite has been exceeded. It should be noted here that the parameters of the elastic-plastic detection coating must be designed individually for each monitored structure depending on the value of the strain and the resulting stress which is considered dangerous (destructive) for a given material or part of the structure.

### 

Fig. 3. U.S. 5,245,180, Fig. 5 – Relationship between detection coating dimensions and the value of the force which destroys the composite for different coating materials. Pmax – force which destroys the composite; Ppt – tensile force acting on the optical fibre; a, b – protective coating dimensions

**An optical fibre in a protective metal coating is used in many sensing cable designs**. The main reason cited by manufacturers for placing optical fibres inside a protective metal coating is to isolate the fibre from the external environment, e.g. hydrogen and other chemicals, and to increase the sensor’s resistance to mechanical loads and local damage. However, it should be remembered that the protective metal coating becomes plastic under the influence of external forces already at strain values which are relatively small in comparison to the optical fibre’s measuring capabilities. **Plastic strain of the metal coating causes the strain of the optical fibre to be maintained even after the external force has ceased, which results in the fibre inside such coating having a mechanical memory of events.** Where the strains do not cause the coating to fully clamp the optical fibre, then there is a change in the manner in which the fibre interacts with the protective metal coating, which has a very significant effect on the measurement of the strain of the structural element analysed using the sensing cable. Additional tangential stresses emerge between sensor layers, which interfere with the measurement, often making its interpretation impossible.

|  |  |  |  |
| --- | --- | --- | --- |
| a) | D:\dane_lukasz\shmsystem\wniosek_epsilon_temp\artykuł\zdj_2.png | b) | D:\dane_lukasz\shmsystem\wniosek_epsilon_temp\artykuł\zdj_3.png |

Fig. 4. a) Sensing cable with an exposed piece of metal tube (straight tube)  
b) Cable with a piece of bent metal tube – where the metal coating becomes plastic, this results in permanent strains which distort our observation of phenomena

* 1. Layered construction

The manner and principle of operation of coatings in sensing cables are clarified by a patent filed by **F. Ravet of Omnisens in 2014 (U.S. patent 2014/0033825 A1)**, showing methods for detecting plastic strains in structures (“**Method and Assembly for Sensing Permanent Deformation of a Structure**”). The patent describes most of the sensing cables available on the market.

|  |  |  |  |
| --- | --- | --- | --- |
| a) |  | b) | D:\dane_lukasz\shmsystem\wniosek_epsilon_temp\artykuł\v_1.png |

Fig. 5. a) U.S. 2014/0033825 A1, Fig. 3a – optical fibre in a plastic coating or multiple plastic coatings;  
b) photo of a sample implementation

|  |  |  |  |
| --- | --- | --- | --- |
| a) |  | b) | D:\dane_lukasz\shmsystem\wniosek_epsilon_temp\artykuł\v_3.png |

Fig. 6. a) U.S. 2014/0033825 A1, Fig. 3c – optical fibre in a metal coating with additional metal reinforcing elements,   
in a plastic coating or multiple plastic coatings; photo of a sample implementation

The patent specification presents a solution for detecting permanent deformations of the monitored structure by means of layered fibre optic sensors. The sensors deform plastically when the structure is deformed. The sensors’ task is to register the event so that after the structure has returned to its original shape, it is possible to determine where the extreme strain occurred.

This goal is achieved owing to the layered structure of the sensor. When the sensor reaches the assumed strain value, there is slippage between the layers. The layers separate and move relative to one another. This behaviour of the sensor protects the optical fibre from breaking by reducing its strain while at the same time it results in the event being mechanically registered. The mechanical slippage of the layers sustains optical fibre tension after the external force has ceased, which enables the strain which occurred to be detected at any time. **In order for layered sensors to fulfil their role properly, they must be custom-designed and manufactured for the structure in case, taking into account sensor installation** **locations** so that the protective coating around the optical fibre becomes plastic at a precisely defined strain value. This means that it is impossible to make universal layered cables which would work in all applications.

Since the layered construction of sensing cables allows the layers to slip in an uncontrolled manner relative to one another, it is not possible to transfer the strain to the optical fibre in order to obtain unequivocal results over a sufficiently wide range of strain values. The following is an example of a sensing cable available on the market with a layered structure in which the layers can move relative to one another.

|  |  |  |  |
| --- | --- | --- | --- |
| a) | D:\dane_lukasz\shmsystem\wniosek_epsilon_temp\artykuł\zdj_4.png | b) | D:\dane_lukasz\shmsystem\wniosek_epsilon_temp\artykuł\zdj_5.png |

Fig. 7. a) Photo of the sensor with two plastic layers – blue on the outside, yellow on the inside; b) Photo of the removed coating (blue shifted relative to yellow) – the possibility of coatings being removed and shifted relative to one another means that the record of strains is ambiguous. After a relatively low force has been exceeded, slippage occurs between the sensor layers

The mechanical parameters of the plastic from which sensing cables are made should be noted as well. Most frequently, these are plastics such as PA and HDPE. In tensile and compression testing, these materials reach plastic deformation very quickly, which makes it impossible to conduct correct measurements. Fig. 8 shows an example of measuring changes in crack width using a layered sensor. As the crack becomes wider with the increase in the force applied to the structure, the layers slip. The strain value in the crack is decreased rather than increased – see Fig. 8. Once the strain resulting in the metal coating of the optical fibre becoming plastic has been exceeded, the ability to deform the fibre at this point will be completely blocked. Once the load has been removed, despite crack width having being reduced or even the crack having closed, this phenomenon will not be recorded by the sensing cable.

The use of fibre optic strain sensors instead of sensing cables enables correct measurements of cracks to be conducted, i.e. with increasing crack width, local strain extremes will also become greater – see Fig. 9.

### image001

Fig. 8. A graph showing layer slippage in a sensing cable: when the force increases, slippage results in the strain graph becoming wider instead of the measured value becoming greater

### 

Fig. 9. An example of correct measurement using DFOS strain sensors – the shape of the fibre strain graph within the crack is preserved in subsequent test stages due to the sensors’ excellent adhesion to concrete

1. DFOS strain sensors

### 

Fig. 10. Example of dedicated DFOS strain sensors

The purpose of using fibre optic strain sensors for distributed measurements is to enable the observation of selected physical phenomena by means of optical changes which take place in optical fibres. The main task of the sensor used for measuring strain changes is to unambiguously transfer local changes in the length of the monitored (measured) structure or medium to the glass core of the optical fibre over the sensor’s entire measuring range. The sensor’s measuring range must enable the entire process observed to be recorded.

To meet these requirements, fibre optic sensors exhibit the following characteristics:

1. **Monolithic structure**.The optical fibre becomes an integral part of the sensor core already at the production stage. Thanks to the elimination of layers, the sensor’s construction ensures the unambiguous transfer of strains from the measured medium to the measuring optical fibre.



Fig. 11. DFOS strain sensor cross-section

1. **High measurement range**. While the DFOS technology allows optical fibre strain to be measured in the +/-4% range (total measurement range of 80,000 µε), sensing cables only enable measurement in a range of up to 1.5% (most models: 1%). DFOS strain sensors make it possible to utilize the full measurement capabilities of optical fibres. What is very important, DFOS sensors work both in tension and compression without need for pre-tensioning.
2. **Rough external surface enabling good interaction with surrounding material**. Thanks to appropriate braiding on the outer surface, DFOS strain sensors enable very good cooperation with the monitored material (e.g. soil, concrete) and the unambiguous transfer of structural strains to the sensing fibre inside the sensor core. The photos below show an attempt to pull a DFOS strain sensor out of a concrete specimen.

### 

Fig. 12. An attempt to pull a DFOS strain sensor out of a concrete sample

### 

Fig. 13. Examples of DFOS strain sensor external surfaces

1. Examples
   1. Example: pretensioning of sensing cables

In the light of the above, let us consider the frequent need to pre-tensioning of sensing cables in order to enable them to measure strains in compression zone. This process results in permanent plastic strains of individual layers or slippage between them. Instead of increasing the strain level uniformly under increasing tension load, the plastic and slippage zones occur within the sensing cable. As a result, there are damaged zones where the measuring range has been exceeded, and these alternate with the fibre relaxed. The measurements in tension test using a layered cable result in characteristic peaks (distortions) in strain values (Fig. 14) which can often be seen in published works. Such a pretensioned sensing cable is virtually useless for any precise measurements and structural safety assessment. What is more, after relieving the cable, the strains do not come back to zero, but remember some plastic events (Fig. 15), do not indicating actual deformation state of the structure.

### 

Fig. 14. **Irregular, incorrect strain measurement results obtained using a sensing cable** during axial tensile testing under laboratory conditions (according to theoretical predictions, graphs should be straight lines)

### 

Fig. 14. Comparison of strain results between the layered cable and monolithic sensor in axial tension tests (strain distributions over length and means strain during subsequent load steps)

|  |  |  |  |
| --- | --- | --- | --- |
| a) |  | b) |  |

Fig. 15. a) **Irregular, incorrect strain measurement results obtained using a sensing cable** in the pretensioning phase during its installation within pile reinforcement; b) view during installation [Kania et al. 2018 – *A Static Pile Load Test on a Bored Pile Instrumented with Distributed Fibre Optic Sensors*]

As opposed to sensing cables, monolithic DFOS strain sensors can operate within a broad range of tension and compression loads; measurements can be made in the +/- 2% or +/- 4% range (depending on the sensor type) without the need for pretensioning.

* 1. Example: crack detection

Another example is the detection and monitoring of cracks, especially within the concrete structures subjected to variable mechanical loads or variable environmental. The DFOS measurement allows for precise identification of cracks, indicate their locations any and estimation of crack width changes. This is main goal for technical assessment of concrete structures. In sensing cables experiencing the slippage of the fibre against intermediate layers, it is a high risk of not detecting the cracks, which is not acceptable from safety point of view. **It is better to have no information about the structural state, rather to have wrong information.** The example below shows the comparison of the results between layered cable and monolithic sensor embedded in the same reinforced concrete beam, connected simultaneously to the same DFOS interrogator. All the peaks detected by the sensor corresponds to cracks (which was confirmed by independent reference methods), while strain profiles in sensing cables are smooth and do not show the cracks at all.

### 

Fig. 17. Comparison between the strain results in the cracked zone of concrete beam measured by layered cable (no cracks detected) and monolithic sensor (all crack detected) – results over entire beam length of 400 cm

### 

Fig. 17. Comparison between the strain results in the cracked zone of concrete beam measured by layered cable (no cracks detected) and monolithic sensor (all crack detected) – close-up to the 40 cm section

1. Conclusion

Layered cables, especially those with steel layers inside, are sensing tools with mechanical event memory. Their primary role, resulting from their original design, is to store information about the occurrence of a condition which was unsafe in the past for the structure in question. This information is stored as a result of local events being transferred into the optical fibre through the plastic strains of layers and coatings and slippage between individual cable layers. Sensing cables cannot be universal – they must be custom-designed and manufactured for each installation so that they remember dangerous events in the application in question, accounting for the loads predicted **[“Method and assembly for sensing permanent deformation of a structure”, Omnisens website]**. Owing to their characteristic layered structure, sensing cables have very small measuring ranges. In most specifications the value of 1% is defined, but practice shows that even this value is difficult to achieve (for example during measurements of local crack-induced strain peaks).

As opposed to sensing cables, DFOS strain sensors are universal measurement tools which ensure the unambiguous transfer of structural into the optical fibre. The sensors’ task is to record the monitored phenomena faithfully. Their monolithic design prevents slippage and enables the sensor to deform in a large range, so as to take advantage of the full optical fibre operation range (up to +/-4%), which results in an 8% measurement range. It should be noted here that the high strain range of optical fibres makes it possible to freely observe concrete cracking or ground movements without the threat of damaging the sensors. In the case of steel structures, the monolithic sensors allow us to observe the yielding and detecting the plastic zones.

**Learn more about monolithic DFOS strain sensors:**

1. Ł. Bednarski, R. Sieńko, T. Howiacki, K. Zuziak, The Smart Nervous System for Cracked Concrete Structures: Theory, Design, Research, and Field Proof of Monolithic DFOS-Based Sensors, Sensors 22 (2022) 8713. <https://doi.org/10.3390/s22228713>.
2. T. Howiacki, R. Sieńko, Ł. Bednarski, K. Zuziak, Crack Shape Coefficient: Comparison between Different DFOS Tools Embedded for Crack Monitoring in Concrete, Sensors 23 (2023) 566. <https://doi.org/10.3390/s23020566>.
3. Ł. Bednarski, R. Sieńko, T. Howiacki, K. Badura, Thermal compensation of monolithic distributed fibre optic sensors: From the lab to the field, Measurement 238 (2024) 115280. <https://doi.org/10.1016/j.measurement.2024.115280>.
4. B. Piątek, T. Howiacki, M. Kulpa, T. Siwowski, R. Sieńko, Ł. Bednarski, Strain, crack, stress and shape diagnostics of new and existing post-tensioned structures through distributed fibre optic sensors, Measurement 221 (2023) 113480. <https://doi.org/10.1016/j.measurement.2023.113480>.
5. T. Howiacki, R. Sieńko, Ł. Bednarski, K. Zuziak, Structural monitoring of concrete, steel, and composite bridges in Poland with distributed fibre optic sensors, Structure and Infrastructure Engineering 20 (2023) 1213–1229. <https://doi.org/10.1080/15732479.2023.2230558>.
6. R. Sieńko, Ł. Bednarski, T. Howiacki, K. Badura, Cracks Detection During Early-Age Concrete Hydration Using Distributed Fibre Optic Sensing: From Laboratory to Field Applications, RILEM Bookseries (2023) 1069–1080. <https://doi.org/10.1007/978-3-031-33211-1_96>.
7. K. Zdanowicz, Ł. Bednarski, T. Howiacki, R. Sieńko, Verteilte Dehnungsmessungen von Spannbetonbauteilen mit faseroptischen Sensoren, Beton und Stahlbetonbau 117 (2022) 539–547. <https://doi.org/10.1002/best.202200035>.
8. P. Popielski, B. Bednarz, R. Sieńko, T. Howiacki, Ł. Bednarski, B. Zaborski, Monitoring of Large Diameter Sewage Collector Strengthened with Glass-Fiber Reinforced Plastic (GRP) Panels by Means of Distributed Fiber Optic Sensors (DFOS), Sensors 21 (2021) 6607. <https://doi.org/10.3390/s21196607>.