Proposal of a Standard Method to Define a Best Practice for Bonding {FBG} Sensors for Aerospace Use

(Article begins on next page)

Proposal of a Standard Method to Define a Best Practice for Bonding FBG Sensors for Aerospace Use

Alessandro Aimasso
Department of Mechanical and Aerospace Engineering
Politecnico di Torino
Turin, Italy
alessandro.aimasso@polito.it

Carlo Giovanni Ferro
Department of Mechanical and Aerospace Engineering
Politecnico di Torino
Turin, Italy
carlo.ferro@polito.it

Abstract— **Fiber Bragg Grating (FBG) sensors are fast becoming a key instrument for the development of the aerospace sector due to their exceptional physical-mechanical characteristics. In order to introduce these innovations on airplanes it is necessary to investigate the effect of their assembly process. Few studies have investigated the bonding strategy in any systematic way and no detailed investigation was addressed to the aerospace use. In the present work a new tool is presented; it allows to control the deposition of the resin on tensile specimens in width and thickness. This resin will bond FBG sensor with the specimen and the outcome will be compared with a traditional strain gauge placed in the opposite face. The specific objective of this study is to prepare the standards to define subsequently the best strategy to minimize the disturbance caused.**

Keywords— Fiber Bragg Grating; Aerospace; Bonding

I. INTRODUCTION

The optical fiber is a glass and polymeric material which is able to transmit an optical signal through itself [1]. Thanks to this distinguishable property, in the last decades engineering applications based on this technology have rapidly increased their importance, also including really different sectors. Optical fiber started to be employed at first for data transmission and, more in general, for communication scopes. However, more recently it has founded several applications in a large number of different fields, such as the medicine, the lighting, the civil infrastructures, etc. [2]–[4]

A typical optical fiber has got a cylindric structure and it is composed by different layers, from the inside to the outside named core, cladding and coating. The external coating is generally made by a polymeric material and its aim is only to improve the overall fiber's bending resistance, due to the extreme fragility of the other layers. Core and cladding, instead, are the two glassy inner layers that allows the fiber to correctly work. More in details, thanks to an appropriate choose of their refractive indices, if the light is entered in the fiber with the correct orientation, it will undergo a total reflection phenomenon. In this way, the light remains confined in the core and so propagating the information.

The gamma of optical fiber applications has been increased not only thanks to its capacity of data transmission, but also thanks the possibility of embedding optical sensors directly inside the fiber itself [5]–[7]. As a result, the prospect of measuring multiple physical parameters, combined with the benefits of the fiber's features, led to a new standard for sensor activity. Indeed, in modern engineering projects, sensors are required to guarantee high performances even while working in hostile environments. Optical fiber-based sensors can meet these requirements, thus resulting strategic for aerospace applications. The advantages are strictly correlated to the physical features of the optical fiber itself, such as light weight, lack of sparks, immunity to electromagnetic interferences, chemical passivity and high sensitivity. All of the abovementioned aspects contribute to make optical sensing systems possible alternative to electrical sensors or a fundamental control system for integrating data already detected.

Among the several types of optical sensors, FBGs are those more promising. Indeed, if compared to the other ones, they have some additional advantages. In particular, they are independent from the light intensity and they do not require other optical devices to correctly work, while guaranteeing high sensitivity. Another key aspect is the possibility of multiplexing: a quasi-distributed sensor (i.e., with multi-point detection) can be realised by inscribing several FBGs along the same fiber. Each sensor will therefore respond with a specific output, allowing to measure several parameters at different positions along the length of the optical fiber.

A. FBG working principle

FBG sensors are obtained directly inside an optical fiber thanks to a specific laser technique, depending on the final application [8]. In any case, at the base of their creation there is a periodic remodulation of the core's refractive index. Once the process is ended, a particular structure – called Bragg grating – is created. This structure acts like a filter against the light crossing the fiber, allowing the passage of all the frequency while reflecting a specific one. This reflected frequency is called "Bragg Frequency" and it represents the optical output of the sensor. It is quantified in terms of wavelength (Bragg wavelength) by the formula:

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

Where λ_B is the reflected wavelength, n_{eff} is the core's reflective index in the trait containing the grating and Λ the grating pitch. It is precisely the λ_B dependence on the grating pitch which makes the Bragg grating acting as a sensor. Indeed, having a direct measure about the grating deformation allows to correlate this strain with the physical parameter that

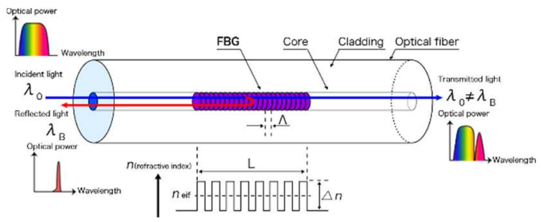


Fig. 1. FBG working principle

induces it. The most common situation is represented by the influence of temperature and mechanical strain on the reflected wavelength.

Thus, the general rule governing an FBG sensor is:

$$\Delta\lambda = K_T \Delta T + K_\varepsilon \Delta\varepsilon \quad (2)$$

II. FBG IN AEROSPACE APPLICATIONS

FBG sensors can guarantee high performance even in hostile environments, in presence of strong electromagnetic interference and high thermal variations. These characteristics, together with the advantages of optical fibers already described in the introduction, make FBGs extremely interesting for the aerospace sector [9]. In particular, the physical parameters most easily measured are temperature and strain. Although not the only possible ones, these are two parameters of great importance for monitoring components and/or systems during their overall lifecycle.

In recent years, several examples of laboratory studies and test campaigns aimed at verifying the potential advantages of integrating optical sensors into aerospace systems, covering both space and aeronautic fields.

A first and significant application is structural monitoring. Thanks to the micrometer fiber's diameter, it results suitable for integration into "smart" components, directly by insertion into the material during the manufacturing process [10][11]. This technique can be adopted, even if with a different methodology, for both metallic and composite pieces. Optical fiber can either provide surface information through direct adhesion to the structure, by operating like an "optical strain gauge" [12], [13].

A further interesting aspect is the possibility of placing FBGs for monitoring remote locations or explosive environments (such as tanks), in terms of temperature and structural integrity. The electrical passivity of the fiber and its inability to create sparks make it particularly suitable for this type of application, in which traditional sensors cannot be used. Moreover, in an optical data acquisition system the electronic components – required to convert the FBG data into physical information – can be located away from areas of high temperature or otherwise particularly hazardous.

Finally, a significative field of interest for FBGs is thermal sensing. At first, the small fiber cross-section leads to minimizing the disturbance introduced by the sensor itself with a significant advantage over a traditional sensor [14]. This could be particularly challenging for thermal test in space applications, in which very thin layers shall be tested. More in general, lots of aerospace system need to have temperature information also in remote location, in which FBGs could represent the best solution. Moreover, they appear to be suitable both for cryogenic and high temperature applications. For what concerning cryogenic applications, the interest is mainly correlated for space application and some studies have been conducted to analyse the FBGs sensitivity for this particular thermal range [15]. Instead, more information is already available for high temperatures: in this case, the focus is related to the thermal monitoring of aircraft propulsion system [16]. Nowadays, for this application, mainly thermocouples with high thermal resistance are used. However, they are subjected to degradation due to high-temperature oxidation, erosion and intrusion of contaminants into the probes and wiring. Furthermore, thermocouples are easily affected by background radiation, electromagnetic interference and/or other environmental factors, leading to inaccuracies of up to 50°C. Optical sensors provide great potential for the development of new high-temperature resistant measuring systems, because silica fibers, manufactured and coated using appropriate methods, can now withstand thermal cycling at temperatures close to 1000°C with a life time far superior to traditional sensors.

The brief overview just described about possible FBGs aerospace applications explains solutions that seem to be extremely strategic. However, they are, for the most part, studies and test campaigns conducted in laboratories and still not carried out in real systems. Only during Proba 2 mission a first in flight test was carried out for testing optical sensors in space [17]. Furthermore, nowadays it is not available a standard procedure for FBG and optical fibers integration in aerospace systems and/or components. But the high sensibility of the FBG and the need of standardize the sensors calibration process, impose to develop a simple but reliable way to bound the fiber on the components that shall be monitored

A. The bonding method

The fiber bonding process is a key aspect for optical sensors applications. Indeed, the FBG's cross sensitivity to several physical parameters at the same time, imposes to define a standard process in order to avoid possible errors during the measures. To demonstrate this, a simple test campaign was conducted by the research team [18]. In this experiment, two FBGs were mounted on two equal carbon samples. The first sensor was glued three months before the test campaign, while the second one the day before. For this reason, at the beginning the fiber remained attached for the first days to a micro mover, in order to allows the glue to completely solidify, and then it was detached from it, when the data collection was still operating. Each bonding was realized without a specific support to define the quantity of glue employed, but only developing a specific test bench in order to maintain fixed the fiber during the process.

The measurements lasted one week, during which the sensors were exposed to the same environmental conditions in the laboratory. The results are clearly observable in fig. 2. The trend of FBG 1 (ch1) showed optical variations only due to temperature changes. The newer sample, instead, showed a mean descending trend during the first two days phases, followed by a sudden exponential decrease induced by the remotion of the tensioner. Finally, in the last days the trends are comparable, but without coinciding, as desirable.

Two aspects must be highlighted from this simple test. At first, the gluing phase induces a transitory phase in data given by FBG, in which the sensor could not work and during which data are not reliable. Then, at the end of the transitory phase for the FBG 2, the two sensors, even if exposed to the same conditions, give different values.

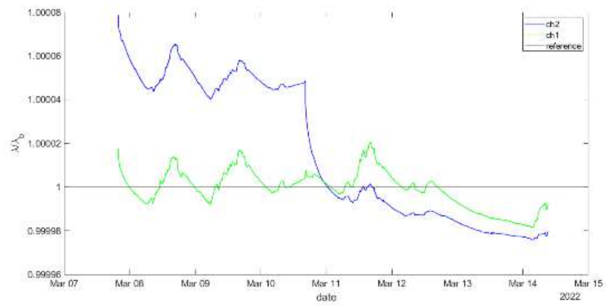


Fig. 1 Comparison between two FBG glued without a specific standard procedure

This implies a post- integration calibration process for each sensor: for industrial aerospace applications it is not acceptable. For this reason, in this work a proposal of a standard method is presented in the following paragraphs.

III. PROPOSED METHODOLOGY

As stated into paragraph 2.1 the effect of bonding technique and curing seems to affect quantitatively the outcome of the FBG sensors. In Literature, some relevant studies have cast some light on the problem itself [19], [20].

The issue of bonding technique on FBG has received considerable critical attention and a standardization is crucial to achieve repeatability and stability of the measurements obtained. In order to face this problem in this short communication a two-step practice is proposed to address a standardization in all the phases of FBG sensitization for structural measurements. In the first step, different dimension of bonding will be tested in order to assess if and how the bonding layer affects the measurements achieved by FBG. In the second step, having selected a bonding standard different curing technique will be imposed in order to evaluate the best the effect of glue curing in FBG sensorization. The desired outcomes are twofold: on one side its intention of the writers to propose a standard and secondly a calibration curve that permit to compute the real displacement taking into account the bonding technique without re performing any subsequent calibration.

The specimen selected is suitable for tension testing for wrought and cast aluminum and has been designed according to ASTM B557-15 [21]. A series of different specimens will be laser-cut from the same plate of aluminum 2026 T6 to ensure the repeatability of the curve and so to evaluate the influence of different bonding

A. Special Tool Design

In order to apply the correct bonding strategy to the specimen a special tool has been designed. An artistic view is reported in Fig. 3

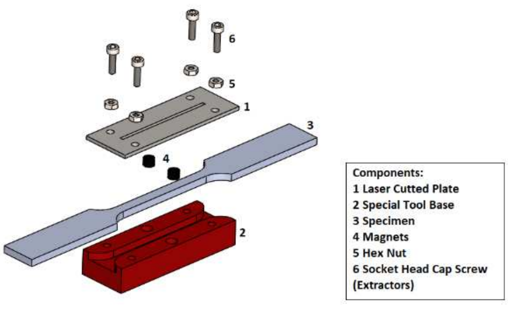


Fig. 2 Artistic View for the Deposition Standard Tool

The special tool is composed by five elements. The calibrated plate (number 1 in Fig. 3) is made of Stainless steel and has a laser-cut square cavity in the middle and a calibrated thickness. The thickness of the plate and the width of the cavity controls both thickness and width of the resin deposited on the specimen (number 3 in the picture). The calibrated plate is attached to the base (number 2 in red) by two magnets (number 4 in Fig. 3) and centered with the four screws (number 6 in Fig. 3). Four hexagonal nuts (number 5 in Fig. 3) are welded on top of the calibrated plate to act as mechanical retainer and permit to the four screws to be extractor after the application of the resin. On the centre bottom layer of the calibrated plate a vertical track is machined with a thickness of 0.3mm to permit the passage of the optical fibre and the evacuation of the air during the gluing phase.

Drawing of the special tool proposed are reported in Appendix A.

The proposed special tool has been constructed with 3d printing FDM Technology (FUNMAT HT) using PLA in order to verify the proposed drawing and the assembly technique

B. Special Tool Operation

The operation to standardize the deposition of the FBG on the specimens are the reported subsequently:

- The specimen is placed in the machined cavity of the special tool base; the fibre is on the specimen and retained at the end with scotch adhesive;
- The selected calibrated plate is sprayed with non-adhesive composite (silicon-based spray oil) and then placed on top of the base; caution must be placed in verifying that the optical fibre pass through the centre bore in the bottom face of the plate;
- Magnets retain in contact the calibrated plate with the base while screws permit the centring of the plate on the specimen;
- Bonding resin can be applied with a calibrated dispenser in the square bore (a syringe could be used for this purpose);
- After the solidification phase, the special tool can be removed. In order to ease the removal of the calibrated plate from the specimen the four screws can be screwed inside in order to extract the late in a smooth and plane manner.

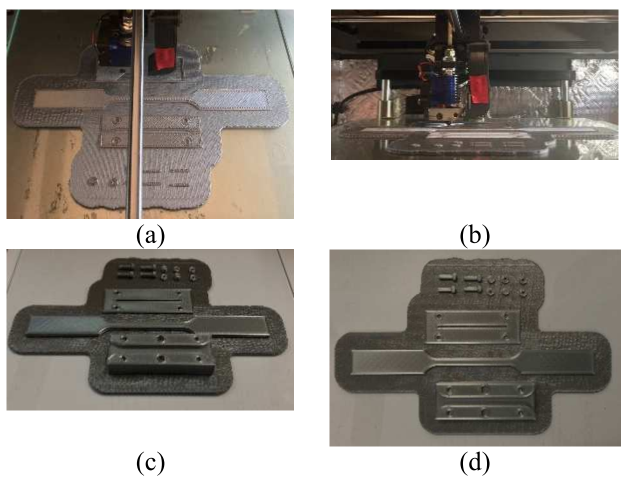


Fig. 3 Manufacturing of the mock-up of the special tool: a) and b) manufacturing phase, c) and d) job finished with all parts

In this manner is assured that the same amount of resin is placed on each FBG specimen, assuring repeatability and stability of the method. Several bonding strategies could be evaluated only by changing the top calibrated plate. In this manner will be possible to compute correction table that apply the shift error induced by different type of bonding technique without re perform any further calibrations.

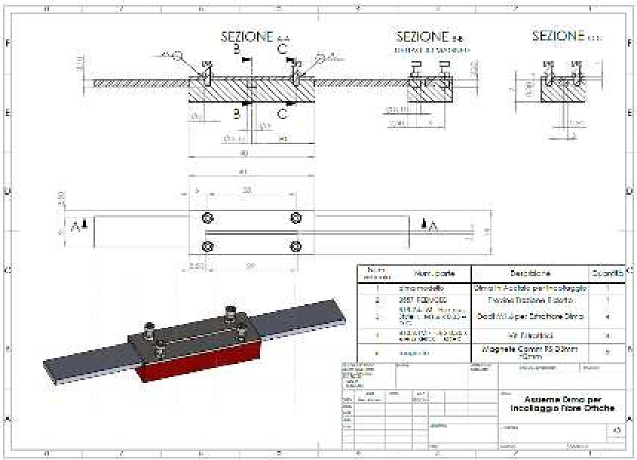
IV. Further Development

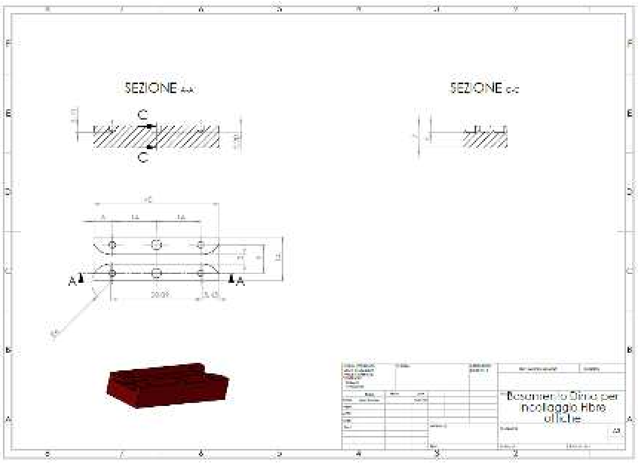
The present study lays the groundwork for the future research into the application of FBG on structural analysis. Thanks to the developed tools will be possible to evaluate quantitatively and with a great accuracy the effect of bonding on the output provided by FBG sensor. A natural progression of this work will be to execute experimentally different bonding strategy with a DOE (Design of Experiment) approach in order to focus on determining the effect and the calibration table. Continued efforts are needed to make FBG more accessible to the aerospace Industry. The Authors are willing to share the drawings, models and results as a plan for the long-term standardization of this instrument

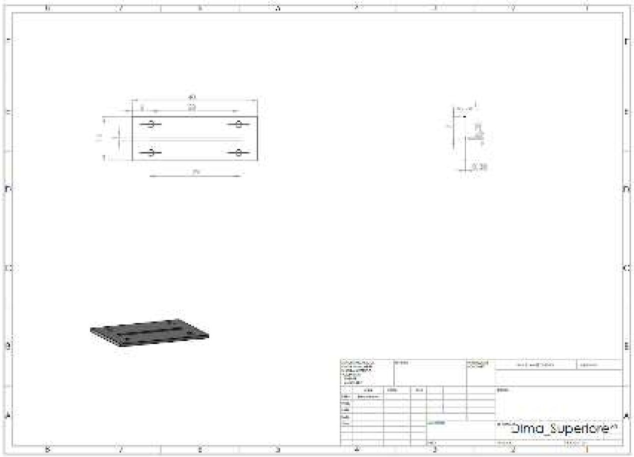
Acknowledgment

Authors would like to acknowledge the Photo NeXT Research Group for materials and support provided.

Appendix A. drawings of the special tool







References

[1] A. Behbahani, M. Pakmehr, and W. A. Stange, “Optical Communications and Sensing for Avionics,” in Springer Handbooks, Springer Science and Business Media Deutschland GmbH, 2020, pp. 1125–1150. doi: 10.1007/978-3-030-16250-4_36.

[2] U. Utzinger and R. R. Richards-Kortum, “Fiber optic probes for biomedical optical spectroscopy,” J Biomed Opt, vol. 8, no. 1, p. 121, 2003, doi: 10.1117/1.1528207.

[3] J. A. C. Heijmans, L. K. Cheng, and F. P. Wieringa, “Optical fiber sensors for medical applications - Practical engineering considerations,” IFMBE Proc, vol. 22, pp. 2330–2334, 2008, doi: 10.1007/978-3-540-89208-3_559/COVER.

[4] C. K. Y. Leung et al., “Review: optical fiber sensors for civil engineering applications”, doi: 10.1617/s11527-013-0201-7.

[5] G. Cavaccini and M. Iodice, “Alenia Shm Fiber Optic Bragg Grating (Fobg) Strain Sensors Technology: Applications And Requirements Porous silicon optical sensors View project Holographic interferometry View project,” 2006. [Online]. Available: http://www.rto.nato.int/abstracts.asp.

[6] V. R. Mamidi, S. Kamineni, L. N. S. P. Ravinuthala, V. Thumu, and V. R. Pachava, “Characterization of encapsulating materials for fiber bragg grating-based temperature sensors,” Fiber and Integrated Optics, vol. 33, no. 4, pp. 325–335, Jul. 2014, doi: 10.1080/01468030.2014.932472.

[7] S. J. Mihailov et al., “Ultrafast laser processing of optical fibers for sensing applications,” Sensors, vol. 21, no. 4. MDPI AG, pp. 1–23, Feb. 02, 2021. doi: 10.3390/s21041447.

[8] X. Zhou, Y. Dai, J. M. Karanja, F. Liu, and M. Yang, “Fabricating phase-shifted fiber Bragg grating by simple postprocessing using femtosecond laser,” Optical Engineering, vol. 56, no. 2, p. 027108, Feb. 2017, doi: 10.1117/1.OE.56.2.027108.

[9] E. J. Friebele et al., “Optical fiber sensors for spacecraft applications,” Smart Mater. Struct, vol. 8, pp. 813–838, 1999, Accessed: Feb. 01, 2023. [Online]. Available: www.iop.org

[10] R. P. Beukema, “Embedding Technologies of FBG Sensors in Composites: Technologies, Applications and Practical Use.”

[11] F. Heilmeier et al., “Evaluation of strain transition properties between cast-in fibre bragg gratings and cast aluminium during uniaxial straining,” Sensors (Switzerland), vol. 20, no. 21, pp. 1–19, Nov. 2020, doi: 10.3390/s20216276.

[12] H. Wang, S. Li, L. Liang, G. Xu, and B. Tu, “Fiber grating-based strain sensor array for health monitoring of pipelines,” SDHM Structural Durability and Health Monitoring, vol. 13, no. 4, pp. 347–359, 2019, doi: 10.32604/sdhm.2019.05139.

[13] Q. Zhang, D. Zhang, J. Li, B. Shui, and Y. Guo, “Strain measurement inside a strong pulsed magnet based on embedded fiber Bragg gratings,” in OFS2012 22nd International Conference on Optical Fiber Sensors, Oct. 2012, vol. 8421, pp. 84213P-84213P–4. doi: 10.1117/12.966334.

[14] A. Aimasso, M. D. L. D. Vedova, and P. Maggiore, “Innovative sensor networks for massive distributed thermal measurements in space applications under different environmental testing conditions,” in 2022 IEEE 9th International Workshop on Metrology for AeroSpace, MetroAeroSpace 2022 - Proceedings, 2022. doi: 10.1109/MetroAeroSpace54187.2022.9856275.

[15] E. S. de L. Filho, M. D. Baiad, M. Gagné, and R. Kashyap, “Fiber Bragg gratings for low-temperature measurement,” Opt Express, vol. 22, no. 22, p. 27681, Nov. 2014, doi: 10.1364/oe.22.027681.

[16] M. Pakmehr and A. Behbahani, “Optical Exhaust Gas Temperature (EGT) Sensor and Instrumentation for Gas Turbine Engines Advanced Pressure Sensing for Gas Turbine Engines View project Intelligent systems View project”, doi: 10.14339/STO-MP-AVT-306-18-PDF.

[17] I. McKenzie, S. Ibrahim, E. Haddad, S. Abad, A. Hurni, and L. K. Cheng, “Fiber Optic Sensing in Spacecraft Engineering: An Historical Perspective From the European Space Agency,” Frontiers in Physics, vol. 9. Frontiers Media S.A., Nov. 15, 2021. doi: 10.3389/fphy.2021.719441.

[18] A. Aimasso, M. D. L. Dalla Vedova, A. Esposito, and P. Maggiore, “Analysis of the fixing process of FBG optical sensors for thermomechanical monitoring of aerospace applications.”

[19] T. Heng, L. Dong-guang, W. Yan-ping, and W. Qing-lin, “Document code: A Article ID,” vol. 15, no. 4, 2019, doi: 10.1007/s11801-019-8183-5.

[20] Y. Shu, W. Chen, W. Zhang, X. Lei, and X. Liu, “Effects of bonding layer on the available strain measuring range of fiber Bragg gratings,” Applied Optics, Vol. 53, Issue 5, pp. 885-891, vol. 53, no. 5, pp. 885–891, Feb. 2014, doi: 10.1364/AO.53.000885.

[21] “ASTM-B557-15-Standard-Test-Methods-for-Tension-Testing-Wrought-and-Cast-Aluminum-and-Magnesium-Alloy-Products”.

[22] “FBG | Optical products (photo devices) | Sensors & Medical Products | Products & Services | TATSUTA Electric Wire & Cable Co., Ltd.” https://www.tatsuta.com/product/sensor_medical/optical/fbg/ (accessed Feb. 01, 2023).