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MECHANICAL STRAIN MEASUREMENTS BASED ON FIBER BRAGG GRATING DOWN TO CRYOGENIC TEMPERATURE – R&D STUDY AND APPLICATIONS

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Abstract

In recent years, optical fiber sensors have been increasingly used due to their outstanding performances. Their application is preferable in case of special requirements that exclude the application of conventional electrical sensors. The scientific background of optical fiber sensors is well developed. However, the characteristic of sensors employed in rather harsh environments is often different from the one determined in laboratory conditions or prior to their installation. In order to achieve long-term stable functioning and reliable measurement under severe working environments, such as those occurring at CERN (radiation, cryogenics, high magnetic and electrical field), a statistical measurement campaign was carried out following the international standard ISO 5725.

The paper describes the ongoing study to define the accuracy of optical fiber sensors based on Fiber Bragg Grating (FBG) for strain measurements, from room temperature down to 4.2 K. It also describes some of the demanding applications for which optical fiber sensors have been deployed to perform experimental strain measurements (e.g. detectors components, high-energy beam targets and dumps, superconducting magnets).

FRAMEWORK

For the High Luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN (European Organization for Nuclear Research) and for the future high-energy accelerator projects, a sustained R&D activity is required to implement advanced technologies for the development of a new generation of superconducting magnets, high-energy proton beam dumps, powerful physics detectors and cryogenic radio-frequency cavities. During the R&D phases, strain monitoring of prototype structures are paramount to validate Finite Element Analysis and understand the mechanical response of complex structures in harsh environments as cryogenic temperatures, high magnetic and electric fields, high radiation level or the vicinity of high energy proton beams. The instrumentation conventionally used to monitor the strain profile is usually based on resistive strain gauges, with compensation of temperature and magnetic field. The compensation in harsh conditions requests a large number of wires, which can be reduced by using optical fiber sensors, based on Fiber Bragg Grating (FBG). As for electrical strain gauges in the past, a test campaign is carried out to validate the optical measurement technique suitable for CERN's temperature ranges, both in terms of precision (repeatability and reproducibility) and trueness.

VALIDATION STUDY

Optical Fiber Sensors Functioning

In an optical fiber sensor based on FBG, the Bragg wavelength (λ_B) shifts with strain (ε) and temperature (T) according to Eq. (1) [1].

$$\Delta\lambda_B = \lambda_B[(1-p_e)\Delta\varepsilon + (\alpha + \xi)\Delta T] \qquad (1)$$

Where p_e is the photo-elastic coefficient of the fiber (i.e. the change of refractive index with the strain), α is the coefficient of thermal expansion of the fiber and ξ is the thermo-optic coefficient (i.e. the change of refractive index with temperature). The photo-elastic coefficient that relates to the strain is given by the manufacturer through the k factor established at room temperature and before the bonding process. The validity of this coefficient after bonding and at cryogenic temperatures is investigated in this study.

Validation Study Process

The validation of the optical fiber sensors is carried out according to ISO 5725 [2], which provides guidelines to assess measurement methods by determining values that describe the ability of the measurement to give a correct results (trueness) and to replicate a given result (precision). The data for the analysis are obtained performing thermal cycles down to 77 K and Young's Modulus measurements at room temperature, 77 K and 4.2 K, according to ASTM E111-04 [3]. This international standard describes the experimental set-up to carry out tensile tests, e.g. the preparation of the test specimens, the alignment on the testing machine and the choice of loading rate, and it explains the interpretation of data for the calculation of Young's Modulus. Several tensile specimens were instrumented with four FBGs using two different adhesives. The precision, which takes into account both the reproducibility and repeatability, is evaluated measuring the apparent strain of the specimens at room temperature and 77 K during 10 thermal cycles. The trueness tests consist of several cycles of tensile tests at different loading rates performed on a 400 kN Universal Testing Machine, at different temperatures with the use of a cryostat. The accuracy of the sensors is evaluated according to the guidelines of the international standard (Figure 1).

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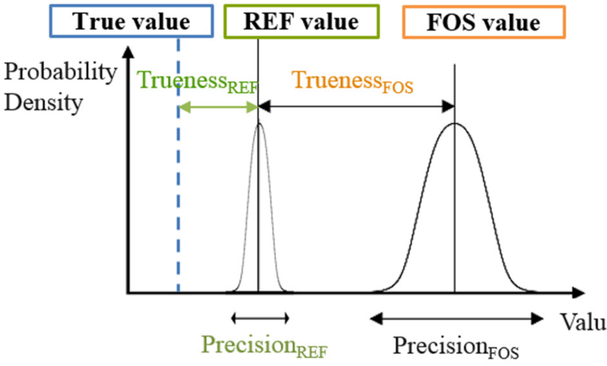

Figure 1: Precision and trueness of the measurements done with optical fiber sensors (FOS) and of the reference measurement (REF).

The reference value for trueness evaluation is represented by the Young's Modulus measured with resistive strain gauges, which is in turn characterized by its own accuracy (also evaluated in reference to the Young's Modulus literature value) [4-6]. The precision assumes the data distributed according to a normal law and a confidence interval of 95%: $Precision_{FOS} = 2.28\sigma$, where σ is the square root of the arithmetic mean of the square of the standard deviations of the measurements done at 77 K over 16 FBGs. The trueness is the deviation of the measurement average of Young's Modulus from the average Young's Modulus measured with electrical strain gages on the same specimens.

Validation Study Results

The study started 4 years ago and the repeatability, reproducibility and trueness have been evaluated and compared every year. Table 1 summarises, as an example, the results obtained in 2017 for specimens instrumented using Araldite® glue. The precision calculation is based on reproducibility and repeatability at 77 K, even at lower temperatures (4.2 K), because of the negligible thermal contraction of steel below 77 K.

Table 1: Results of Precision, Trueness and Accuracy for Tests Done on Specimens Instrumented with Araldite® Glue in 2017

Araldite® 2017	
Apparent Strain at 77 K Mean Value [μm/m]	-3909
Repeatability at 77 K [%]	0.2
Reproducibility at 77 K [%]	0.9
Precision at 4.2 K [%]	0.9
Trueness at 4.2 K [%]	5.2
Accuracy at 4.2 K [%]	5.3

APPLICATIONS

Lightweight Structures

CERN's specialized devices such as particle detectors are built to have high rigidity and low weight, which comes at a cost of their high fragility. Shocks and vibration issues are a key element for their successful transport, handling operations around the CERN infrastructure and for their operation underground. A proposal is to embed optical fiber sensors directly inside their elementary components (multi-layer carbon fiber composite structures) to measure strains during all the aforementioned activities. Thanks to the dynamic response of the optical fiber itself and the use of fast speed optical interrogators, vibration measurements can also be performed simultaneously. A test campaign was launched at CERN to validate this approach and handle integration complications. Figure 2 plots the force versus strain measured with optical fiber sensors embedded in the middle of two 6-layer uniaxial carbon fiber specimens during several cycles of tensile loading/unloading. The stiffness was evaluated to be 357 ± 15 GPa against the supplier specification of 338 GPa. The result shows also good linearity and repeatability. Additional tests are ongoing to measure oriented carbon fiber structures.

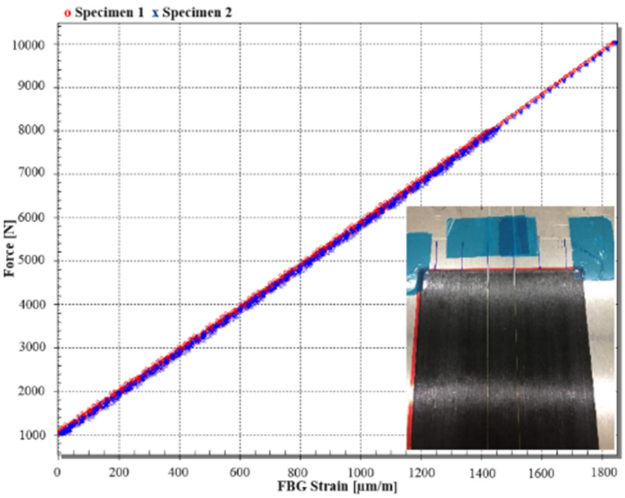

Figure 2: Force versus strain measured with an embedded optical fiber sensor in unidirectional Prepreg laminates (inset) during tensile tests.

Superconducting Magnets

For the High Luminosity upgrade of the Large Hadron Collider, several superconducting magnets are currently under development. Strain monitoring during assembly, cool down and powering tests is crucial to check the integrity of the structure itself and to validate the Finite Element Analysis in view of the series production.

In comparison with conventional instrumentation based on resistive strain gauges, which requires a large number of wires to compensate temperature and magnetic field effects, optical fiber sensors offer many advantages, such as:

- Radiation hardness of the fiber;
- Immunity against magnetic and electric field;
- Reduced mass and cabling (several measuring points on the same fiber, small curvature radius, etc…);
- Possibility to connect to the optical fiber's network to place read-out systems in a safe and accessible place.

Nevertheless, thermal compensation needs to be done also with optical fiber sensors to obtain the absolute strain values over the entire lifetime of the magnet structure.

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Coupling to the validation study presented in this paper, a first prototype magnet was equipped with both technologies: resistive and optical strain gauges. A comparison of the results obtained shows good agreement between the two measuring techniques.

Collimation System

The LHC performance depends on the functionality of the beam collimation system, essential for safe beam cleaning and machine protection. Interactions between particle beams and absorber materials were produced at CERN's High Radiation to Materials facility within the HRMT-23 experiment [7]. The aim of this experiment was to investigate the behaviour of three collimator jaws made of novel composite absorbers (copper diamond, molybdenum carbide graphite, and carbon fiber carbon), subjected to the beam impact. Part of the instrumentation was installed directly on the specimens as shown in Fig. 3. Resistive strain gauges measured the strain produced in the jaws by shockwave propagation at a sampling frequency of 4 MHz and optical fiber sensors at a sampling frequency of 1 kHz to measure bending natural frequencies and plastic deformation of the jaw after the beam impact.

Figure 3: Collimator jaw equipped with resistive strain gauges and distributed optical fiber sensors over its length.

Validation of the bending strain was done in laboratory conditions performing a three point bending test. Strain measurements along the jaw axis (Fig. 4) demonstrates the performance of the measurements in terms of resolution, which was determined to be in the order of 10^{-6} strain for 0.1 mm jaw deflection.

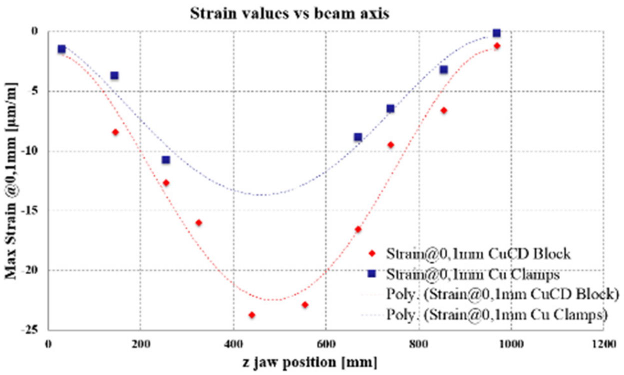

Figure 4: Strain measured with optical fiber sensors over the jaw length during 3-point bending test (0.1 mm jaw deflection).

Beam Dump Facility

A new facility to test targets and dumps against high-energy particle beams is under construction at CERN. Its main characteristic is that the specimens are cooled by a 4 m/s water flow in a pressurised tank at 22 bar. In this demanding situation, measuring the strain induced by the beam impact with optical fiber sensors would overcome difficulties typical of electrical strain gauges, such as the large number and size of radiation hard cables and the waterproofness. The sensors are implemented in the CERN optical network with standardised protocol. Nevertheless, optical fiber sensor manufacturers do not provide specifications for several requirements such as resistance against water flow and pressure. For this reason, they have been tested in a purpose made test-rig. The first campaign shows the sensors' capability to resists mechanically against these two harsh environmental conditions. Regarding the radiation hardness, the sensors are coated with polyimide [8].

CONCLUSION & NEXT STEPS

The paper describes the validation campaign currently ongoing to characterize strain measurements based on optical fiber sensors. The precision of the bonding procedure is crucial for CERN applications and is established according to ISO 5725. The trueness is evaluated by performing tensile tests down to 4.2 K: the results will enable the evaluation of the accuracy of the measurements in cryogenic conditions and the variability of the k factor with the temperature changes. Following this qualification, several applications were equipped with this promising technology to evaluate the response of the fiber in real conditions. The next steps within the R&D activities will be improved services as connectors, feedthroughs, plugs and splices.

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