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Strain and vibration measurements by FBG sensors for engineering applications

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Abstract: Fiber optic sensors based on the fiber Bragg grating (FBG) technology [1] is widely used to produce quasi-distributed monitoring systems to measure mechanical parameters for Structural Health Monitoring (SHM) of civil engineering structures [2]. FBG sensors are produced in the core of the optical fiber, as a short segment of fiber where a diffraction grating is produced (5–10 mm). The principle of operation of the FBGs is based on the diffraction occurring at the grating: if broadband light propagates, a quasi-monochromatic counter propagating light originates. The wavelength of the diffracted light depends on the value of the refraction index of the core along the grating which in turn is affected by both temperature and strain. Thus, by measuring the wavelength change of the counter propagating light, the change of strain and the temperature can be worked out. The PREFOS Project [3] aims to develop a novel procedure to apply the use of FBGs to monitor the prestressed strands of civil engineering prefabricated components. In this paper, we report results of an experimental campaign intended to measure the sensitivity of saddle-like sensors to induced vibration and mechanical strain. Measurements were done performing static and dynamic tests on a steel strand equipped with 3 sensors. The tests have been performed applying different tensioning to the steel strand. Static measurements were worked out applying a stepwise tensioning increase. Dynamic tests were worked out at each stepped tension level, inducing vibration by both sharp hammer impact and release of hanged weight. The paper is organized as follows, in section 1 a general description of the testbed structure used for the experiments will be provided. In section 2 the results of static analysis and dynamic tests will be presented with the dynamic behavior of the strand evaluated by performing a simple Fast Fourier Transform (FFT). Finally, the conclusions will be drawn.

Keywords: Optical sensory systems; Data processing methods

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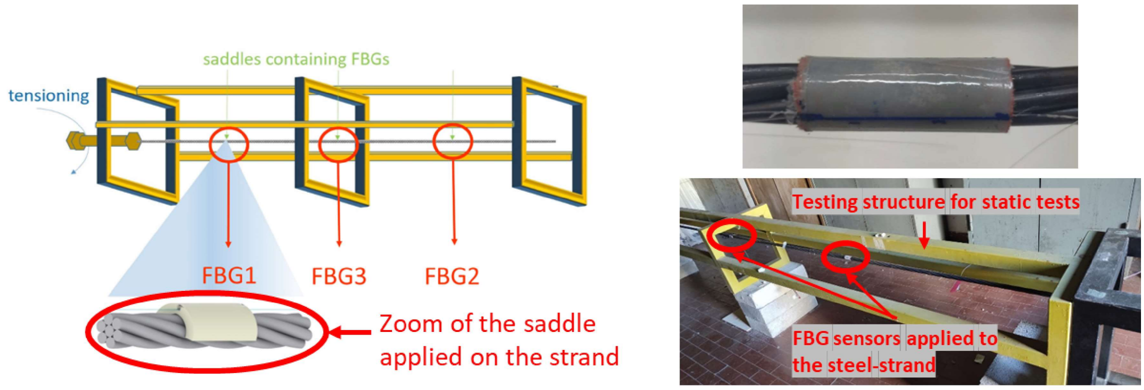
Contents

1 Introduction

An important task concurring to the final aim of the PREFOS project is to employ FBGs for SHM purposes. In fact, FBG can provide information about the strain vibration of multi-wired steel strands, which are a key structural component of prefabricated structures. The production of the proposed novel sensors has been realized by embedding FBGs in fiberglass saddle-like housings tailored to sit on the surface of the strands. Once applied to the strand, the proposed sensors can measure, by means of the embedded FBG, micro-strains on the strand. Concerning the FBGs employed, type OS1500 by Broptics with acrylate coating have been used for this application. The chosen FBGs are characterized by a strain resolution of 1,2 pm/$\mu\varepsilon$ with a length of the sensor of 5 mm, a thickness of 0,9 mm and a working wavelength range of [1500–1600] nm. The aim of the PREFOS project is to obtain a gripping procedure to be applied in industrial environment to produce prestressed prefabricated components with tensioned steel strand. For practical applications, sensors shall be prepared in some housing (to protect the FBGs) to allow safe handling and efficient structural coupling. In order to characterize the so housed sensors, a testing structure was built to tension the steel strand and to test them. The strand was instrumented with three saddles, each prepared with one FBG and tailored to fit the strand as a clip taking advantage of their elasticity. Saddles have been realized with epoxy glue with a thickness of 1,5 cm, to obtain a good embedding of the optical fiber, and a length of 3 cm to minimize the space occupied on the strand. First structural glue was rubbed on the concave surface of the saddles, then the saddled was placed on the strand and let the glue cure. It's worth to mention that the FBGs applied on the saddles have been connected in series to improve the manageability of the steel-strand.

For this reason, the following wavelength has been employed $\lambda_{\text{ref,FBG1}} = 1545$ nm, $\lambda_{\text{ref,FBG2}} = 1549$ nm and $\lambda_{\text{ref,FBG3}} = 1557$ nm. In the testing structure, one end of the strand is locked while at the opposite end a mechanical system consisting of a nut and a screw allows the strand to be tensioned. In particular, a step-by-step tensioning is applied, each step corresponding to a full turn of the screw. In figure 1(a) the scheme of the metallic structure that houses the strand is shown while in figure 1(b) a zoomed image of the saddle applied to the steel-strand (upper figure) and a photo of the structure used for static tests are shown (lower figure).



(a) **(b)**

Figure 1. Principle scheme of the testbed structure used for the mechanical tests (a), a zoomed image of the saddle applied on the strand (upper) and a photograph of realization the scheme for the static tests developed in ENEA research center in Frascati (lower) (b).

2 Mechanical tests

The execution of tests is fundamental to characterize the performance of the sensors equipped by FBG and prepared in the saddle-like housing, which are expected to experimentally agree with the well-known reference mechanical behaviour of the simple system under test, indeed we are interested in the characterization of FBGs for civil applications, in particular their capability to measure micro-strains on strands. So as "static tests" we refer to the analysis of the wavelength parameter as a consequence of the strand stress. We realize scales of tensions by applying different screwing levels by using a mechanical structure (figure 1(a)), here the cable has a fixed terminal and a on the other end, a system that allows you to stretch the strand by turning a screw. For "dynamic tests" we mean the study of the frequency peak variations under different tensioning levels. In section 2.1 the static analysis will be presented, and the results obtained in terms of wavelength variations will be evaluated while in section 2.2 two type of dynamic tests (hammer hit and hanging weight) will be shown and the frequency behaviour will be examined by means of a spectral analysis with FFT.

2.1 Static analysis

Static tests have been performed by applying different tensioning levels to the steel strand. This is obtained by simply screwing and unscrewing the nut applied to one of the ends of the strand. In figure 2 the wavelength variation of the FBG1 with respect to different tensioning levels is shown (since for FBG2 and FBG3 the behavior is similar, only FBG1 will be shown). Note that a "+1 screwing" consists in a complete turn of the nut which allows an increase of the tension applied on the strand and so on for the other labels. According to the results of figure 2 it turns out that an increase of the tensioning on the cable translates in an increase of the wavelength while on the contrary, a decrease of the stress on the strand implies a decreasing trend of the wavelength.

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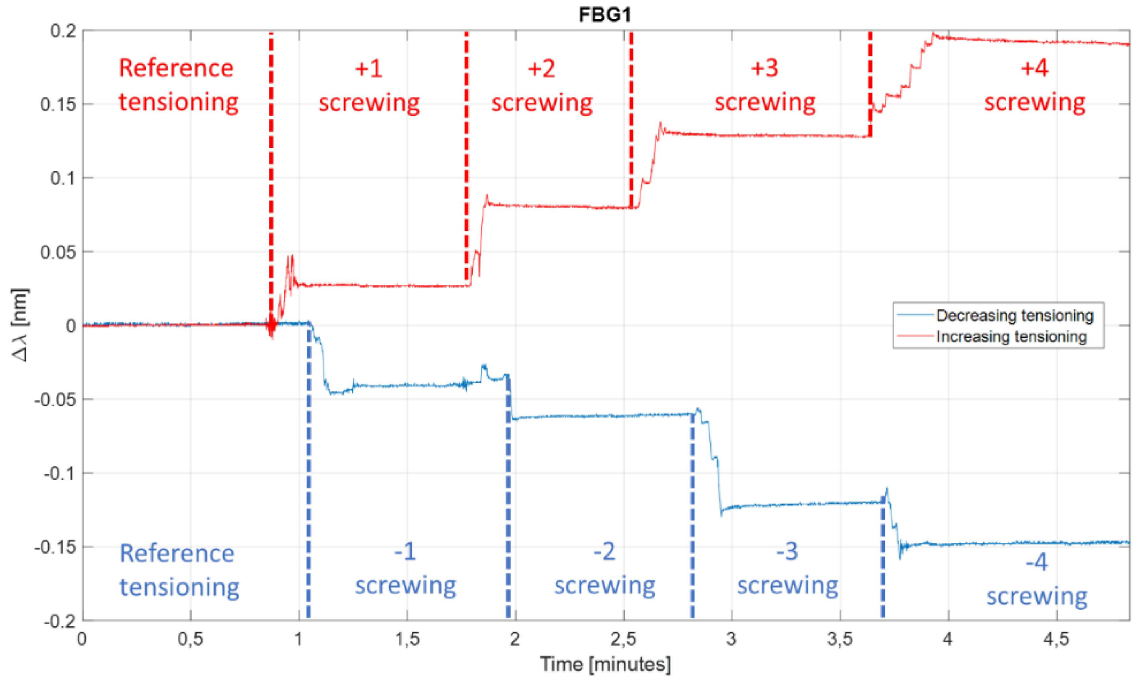

Figure 2. Wavelength variations on FBG1. The rad trace indicates an increase of the tensioning on the steel strand while the blue trace refers to a decrease on the stress level of the cable.

2.2 Dynamic analysis

The aim of dynamic tests is to prove the good capability of the saddle-like prepared sensors to monitor the operational frequencies of the strand, assessing its use for the common SHM procedures based on dynamic monitoring [4]. The analysis was performed by striking the strand by giving a hammer blow to the strand and then by hanging a weight (3,75 kg) at the center which was then instantaneously released from the strand to obtain an elastic oscillation. For hammer blow measurements, the tests have been performed with three different decreasing tensioning since a further slackening of the tension applied would cause an excessive noise on experimental data acquired while the hanging weight measurements have been realized by increasing the strain on the multi-wire cable. In both tests FFTs were evaluated highlighting a strict dependence correlation between the frequency values of the FFT peaks and the tensioning levels. That was clearly expected by basic theory of vibrating string but was here tested to validate the capability of the saddle sensor to be used for frequency based SHM techniques. In figure 3(a)–(b) the time traces of the wavelength variations of FBG1 installed on the steel strand for both experiments are reported, while in figure 3(c)–(d) the FFTs of the time signals of the dynamic tests conducted are shown. In figure 4 an interpolation with the least-square method has been used in order to correlate the frequencies of the first peak with the tension applied to the strand. As for static measurements, also for dynamic ones only FBG1 will be shown since FBG2 and FBG3 exhibit a similar behavior.

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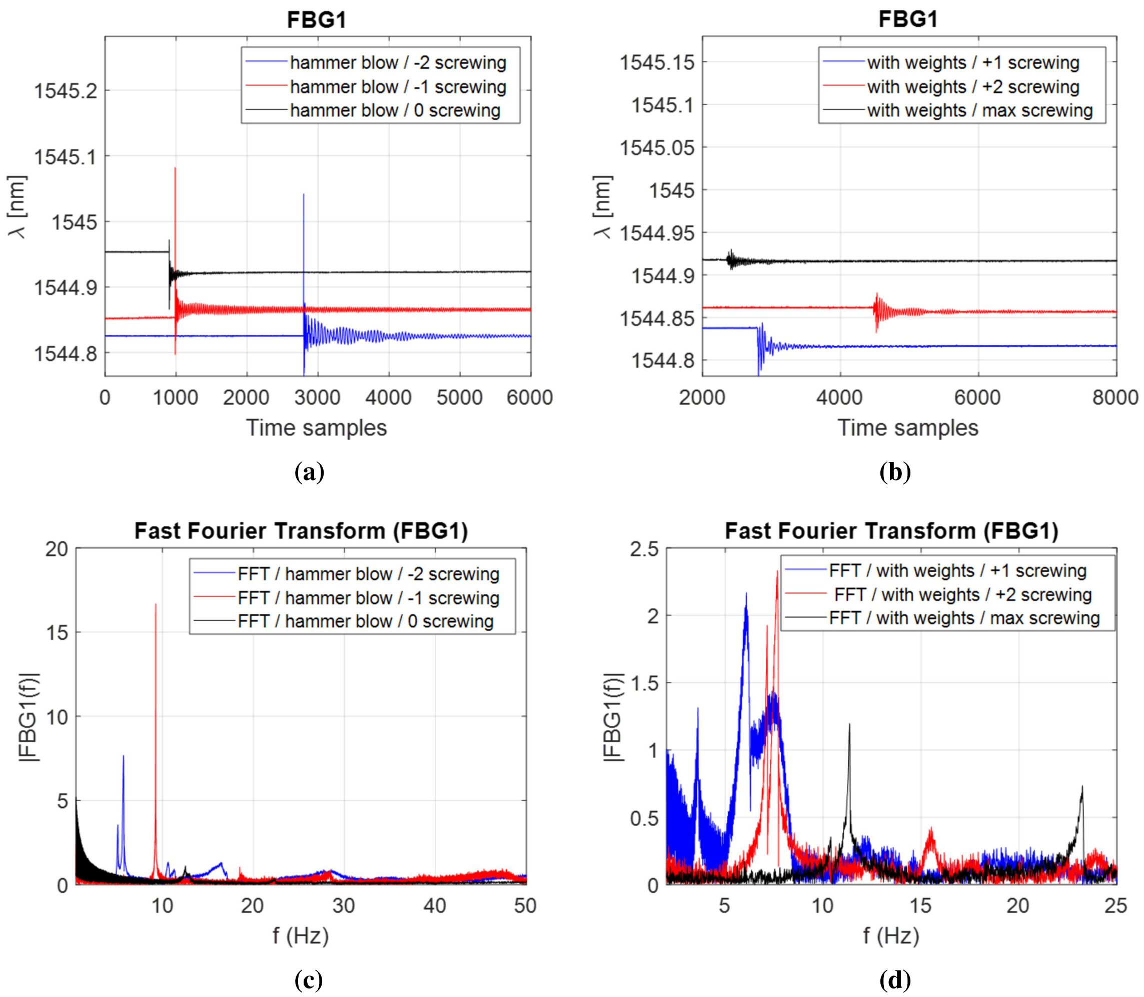

Figure 3. Time behavior of wavelength and FFTs with different tensioning (increasing and decreasing) levels of FBG1 for (a-c) hammer blow experiments and (b-d) hanging weights tests.

3 Conclusions

In this paper, the results of mechanical tests on saddle-like sensors for the PREFOS project have been shown. Concerning static tests, they have been conducted by stretching the strand and analyzing the wavelength variations of the FBGs according to the screwing applied. The results have shown that in correspondence of a slackening of the stretch the wavelengths are characterized by a decreasing behavior, while an increase of the screwing causes a raise of the wavelengths. Dynamic tests have been performed by striking the strand either by giving a sharp blow or by hanging a weight at the center to obtain an elastic oscillation. To study the dynamic behavior of the strand, a spectral analysis has been conducted. According to the results of spectral analysis, the frequency values at which are located the FFTs values scale accordingly to the tension applied.

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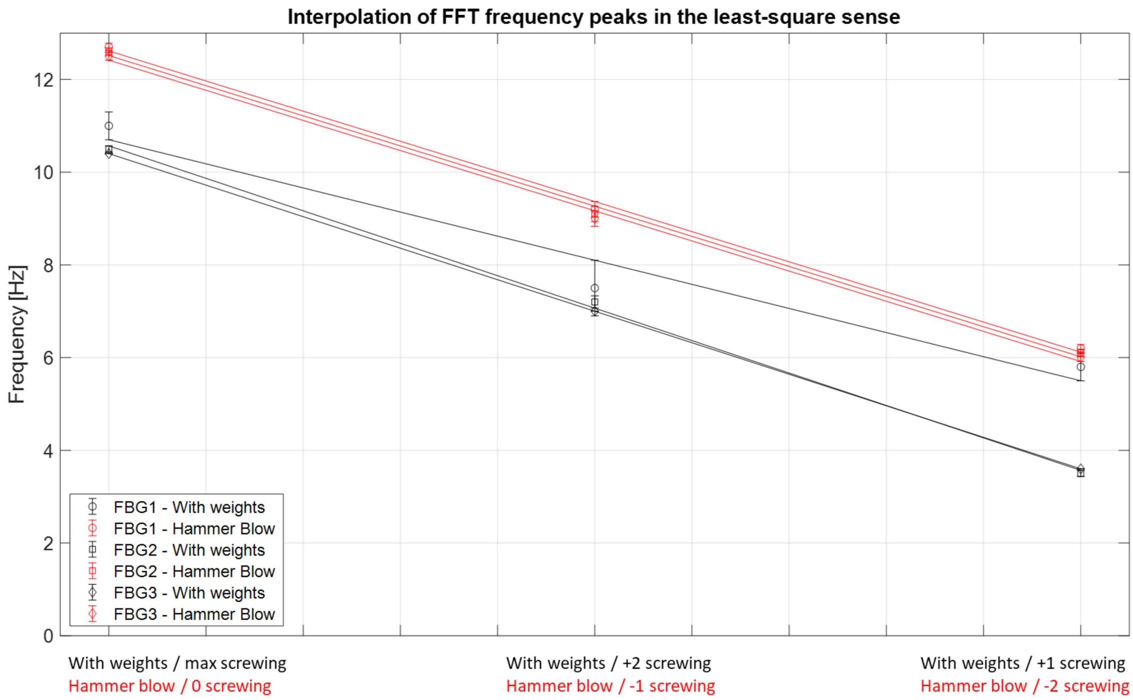

Figure 4. Interpolating curves (in the least-square sense) of FFTs frequency peaks with tensioning levels.

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