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Short Communication

Mechanical characterization of bone cement using fiber Bragg grating sensors

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ABSTRACT

The aim of this work was the study and understanding of the behavior and linearity of an optical fiber Bragg grating (FBG) sensor embedded in bone cement. Test its ability to monitor strains inside bone cement during different mechanical tests, at real-time. Bone cement is a biomaterials based on polymethacrylate used as fixation method in artificial joints. Work as a bonding, load transfer and optimal stress/strain distribution inside the complex human body environment. Bone cement is the weakest element in a joint implant, being considered the main reason of prosthesis loosening.

Inside the bone cement, its temperature, longitudinal strain and load were measured using fiber Bragg gratings. All the measurements report a linear response showing a good adaptation and optimization of the load transfer between the biomaterial and the embedded optical sensor.

1. Introduction

Bone cements based on polymethacrylate (PMMA) are one of the essential elements for a cemented joint arthroplasty. These acrylic resins have been used for over 50 years for fixation of orthopaedic implants. PMMA bone cement is a cold curing powder/liquid system. The solid component consists of PMMA and/or methacrylate copolymers and can also contain radiopacifier and optionally an antibiotic. In the liquid phase, methyl methacrylate (MMA) is the main ingredient. In a cemented hip arthroplasty, bone cement is requested to sustain the forces transmitted through the hip joint (three times the body weight when walking and up to eight times body weight when stumbling) [1–3]. The long term dynamic loading promotes first the debonding from the prostheses and later, the cracking of cement mantle, endorsing the progressive implant loosening [4].

Cement strains and stresses are estimated by indirect non-invasive measurements but imprecise methods as well most of biomechanics reports for the characterized stress/strain in a surface implant. Local measurements would enable the quantification of these strains and perhaps help on the development of better materials and medical diagnostic tools.

The aim of this study is to test the ability of fiber Bragg grating (FBG) sensors to monitor strains inside bone cement. Relationships between different load test conditions and the output signal were established. Fiber Bragg grating (FBG) sensors are sensible to longitudinal and transversal strain. When embedded in bone cement they can be used to locally analyze the health structure in real-time. FBG has proven to be one of the most promising candidates for the smart structures [5–7]. Some tests had been performed with these sensors to monitor the internal health structure of composite laminates [7]. These sensors present advantages compared to other sensors, such as low power consumption, immunity to electromagnetic fields, small dimension, reduce weight and biocompatibility because of their silica composition. However these optical sensors are also sensible to temperature variation [8].

Bone cement was tested at different temperatures and load conditions according with those expected inside the human body. Like every polymers, it will expand by increasing the environmental temperature. Different specimens of PMMA bone cement were produced to study the mechanical behavior in different short-term quasi-static tests (compression, tensile and temperature) and predict its durability in function. Different test procedures allowed the measuring of tensile and compression strains on PMMA bone cement using FBG sensors. Numerical simulations (FEM) were made considering the different test conditions and the mechanical properties present in the literature.

On this study the embedded FBG was subjected to temperature variations, compression through thickness, shear and tensile loads in independent tests some of the physical parameter that bone cement is simultaneous submit in a artificial joint. FEM models enables to establish the relations between the sensors reflected light and strain and this way calibrate the system. Later it is intended to study the cement mantle with embedded sensor subjected to compression and radial expansion simultaneously, in a more complex model of the bone prostheses construct composed by a stem cone inside a tube (see Fig. 1). The final model will be

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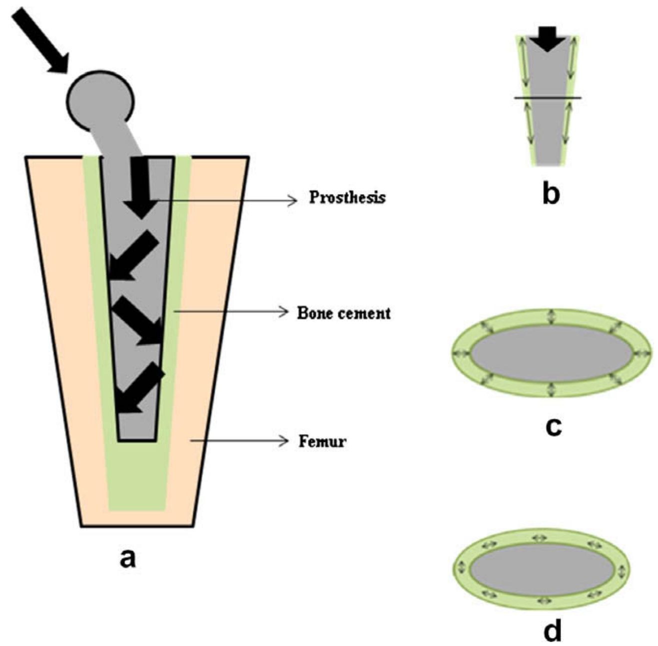

Fig. 1. (a) Bone prostheses construction and the different force that is subject and distribution, (b) load applied stem engage (subside), (c) cross-section of stem enlarges leading bone cement to radial compression, and (d) bone cement submitted to hoop tension.

Table 1
ISO 5833 compression test and DIN 53455 tensile tests of Palacos-R40 after mixing [1]

Palacos-R		2 h	2 days	28 days
Compression test	Stress at failure (MPa)	73	86	108
	Strain at failure (%)	6.8	7.1	7.8
	Modulus of elasticity (MPa)	1920	2170	2500
Tensile test	Stress at failure (MPa)	52	53	52
	Strain at failure (%)	2.9	2.7	2.6
	Modulus of elasticity (MPa)	2720	3050	3020

more realistic, since it will composed of a composite femur with a real stem implanted and loaded dynamically according to human physiologic locomotion.

With this work, we were able to establish the feasibility of embedding FBG devices on this biocompatible material and guaranteeing functionality of the sensor.

1.1. Fiber Bragg grating sensor physical phenomena

FBG are formed when a permanent periodic variation of the index of refraction of the core is created along a section of an optic fiber, by exposing the optic fiber to an interference pattern of intense ultra-violet light. The photosensitivity of silica glass permits the index of refraction in the core to be increased by the intense laser radiation. If the optical fiber with a FBG is illuminated by a broadband light source, the grating diffractive properties promote that only a very narrow wavelength band is reflected back (Fig. 1).

The centre wavelength, λ_B, of this band can be expressed by the well known Bragg condition

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

where n_{eff} is the average effective index of the core and Λ_B is the grating period.

FBG sensors are wavelength-modulated sensors. Gratings are simple, intrinsic sensing elements, and give an absolute measurement of the physical perturbation it senses. Their basic principle of operation is to monitor the wavelength shift associated with the Bragg resonance condition. The wavelength shift is independent of the light source intensity. When the fiber is stretched or compressed along its axis, the period of the grating and n_{eff} change. The same is observed when the temperature fluctuates.

2. Experimental results

PALACOS® R-40 was the bone cement used in this work. According to clinical registers presents high longevity in total hip and keen replacements. Its mechanical proprieties are well established in the literature (see Table 1).

Bone cement samples had been prepared mixing manually the powder (PMMA) and the liquid (MMA) components at room temperature (23 °C).

One sample per test was prepare, all them containing a FBG sensor with the dimensions, $120 \times 50 \times 2$ mm^3 for the tensile and temperature and $75 \times 50 \times 3$ mm^3 for compression tests, (see Fig. 3).

The sizing of the samples is based on the different mechanical tests specifications and set-up's specifying that the thickness cannot be superior then 3 mm. Bone cement components when mixed generate an exothermic and high thicknesses on the cement mantle can take to the bone cells necrosis [1].

The FBG sensor is a glass fiber with a diameter of 125 μm, the sensibility zone corresponds to length of the grating, 10 mm. The

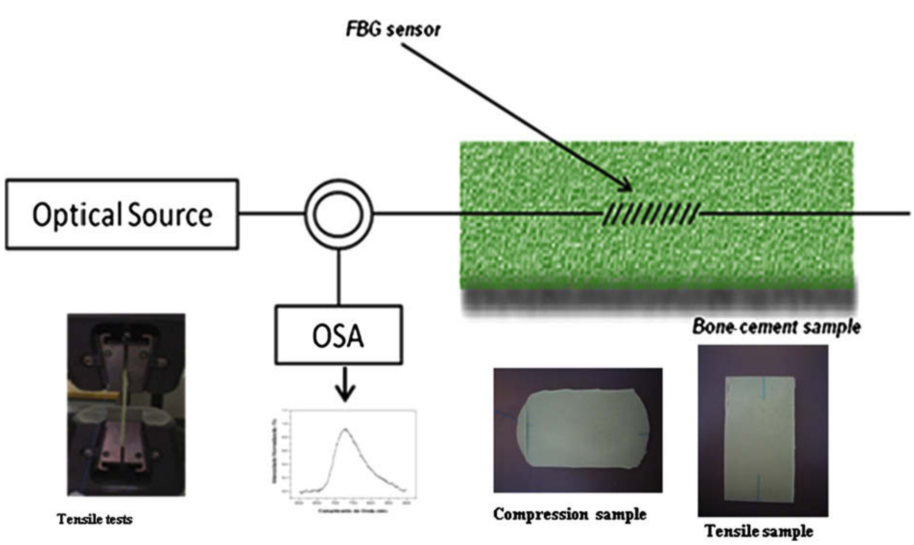

Fig. 2. Scheme of signal acquisition and the bone cement samples.

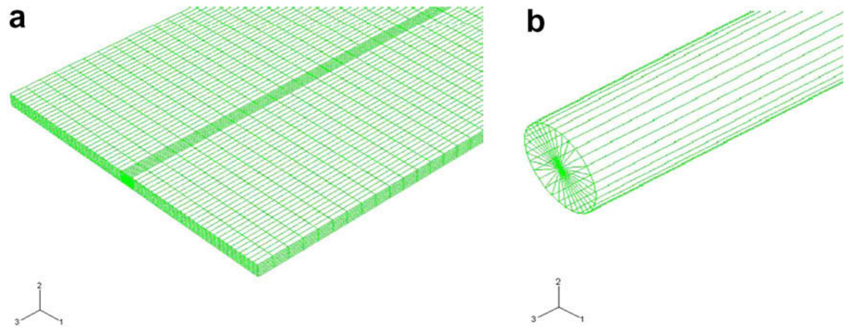

Fig. 3. Parametric FEM mesh: (a) global mesh of compression sample with 57600 elements and 67195 nodes, and (b) detail of FBG sensor with 1200 elements.

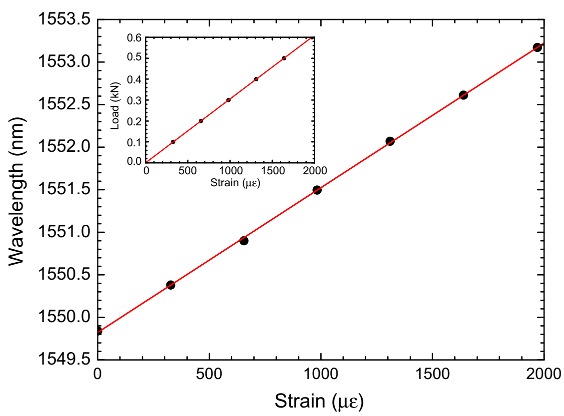

Fig. 4. Strain variation $\Delta\varepsilon$ in the longitudinal direction of the FBG and central wavelength proportional to the applied load.

Fig. 5. Sample with a void.

grating was located in each sample in the middle of the thickness (see Fig. 3). Considering that bone cement mechanical properties take time to stabilize, all samples have been tested two days after processing (see Table 1).

Compression and tensile tests had been performed using an INSTRON®, model 428, universal test machine, with displacement control. In the tensile tests the load was applied in increments of 0.1 kN at 0.5 mm/min until the sample fracture (see Fig. 2). Compression through thickness was applied at 0.5 mm/min by steps of 1 kN. The optical reflected spectrum was recorded at the end of each step using an Optical Spectrum Analyzer (ANDO) (see Fig. 2).

2.1. Finite numerical method (FNM)

A numerical finite element model was used to estimate the transversal/longitudinal stresses induced at the optical fiber/host material interface by the optical fiber presence. It can be noticed that this stress concentration is local. The area of influence can be easily determined (see Fig. 4). Both compression and tensile samples were modeled through Finite Element Analysis (FEA) using the solver Abaqus 6.6-1 in static conditions. The mesh was created using the pre-processor FEMAP V9.2. The model was composed by quadratic solid elements (wedge and cubic elements) with three degrees of freedom for each node. The tensile and compression models were composed by 107512 and 67195 nodes, respectively. Numerical results for the tensile tests report that strain variation during the tests, ε_{33} (grating length) is 3.04×10^{-4} kN/με(see Fig. 3 – axle 33 and Fig. 4). In the compression test models the strain variation ε_{22} (FBG radial direction see Fig. 3 – axle 22 and Fig. 6) is -2.749 (nm/mm)/kN.

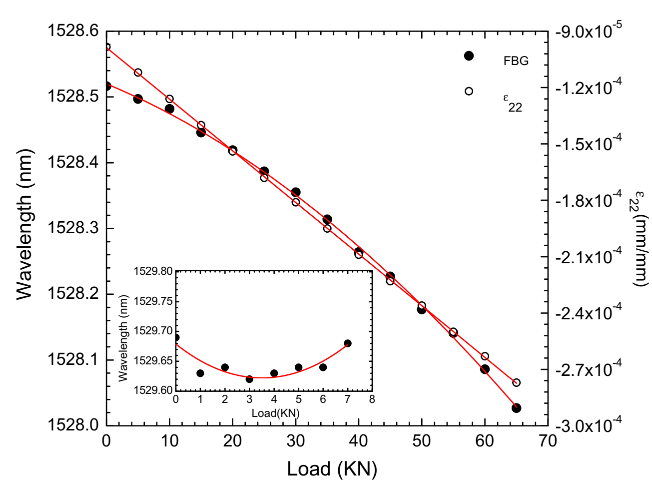

Fig. 6. Strain variation $\Delta\varepsilon$ in the transversal direction of the FBG and the central wavelength proportional to the applied load after the 35 KN load. In the inside graphic we can observe the non linearity behavior that is obtained before the 35 KN load.

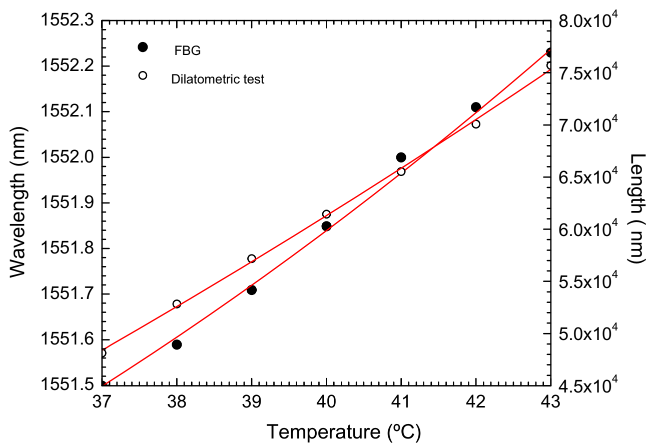

Fig. 7. Temperature measurements by FBG and dilatomeric tests (37 °C; 43 °C).

Table 2
Optical sensor behavior for the different assay

Sensitivity calculated	Experimental	Error (square error, N)
Tensile tests	1.7 pm/με	R = 0,99988,7
Compressive tests	$-(5{,}4739E^{-2}x - 4{,}01)x$ pm/kN	R = 0,992,14
Temperature	138.75 pm/°C	R = 0,99644,12

2.2. Thermal tests

The thermal test intended is to study the capability of the FBG sensors to monitor the bone cement expansion under temperature variation. The Sample was heated up to were heated up to 43 °C and then cooled by steps of 1 °C down to 37 °C, in a climatic chamber, the optical reflected spectrum was record in each step. The central wavelength of the thermal variation in the FBG sensor is approximately 10 pm/°C and the thermal expansion of silica fiber glass is around 5 (μm/m)/°C. Bone cement thermal expansion was characterized by a dilatometric test, getting a thermal expansion coefficient of 38,5 (μm/m)/°C in the temperature range [25 °C; 40 °C], with a square error of 0.994.

The experimental results for the FBG sensor embedded in the bone cement host show a thermal variation of 138.75 pm/°C (see Fig. 7).

2.3. Tensile tests

In the experimental results the embedded FBG sensor demonstrated a linear response and a strain coefficient sensitivity of 1.7 pm/με (see Fig. 4). However, in the Fig. 5 is possible to see that voids occur after cure, due to residual monomer evaporation, acting as stress concentrators and taking gradually to decreasing the properties of the bone cement and consequently crack [4].

2.4. Compression tests

The experimental results for the compression test report two different behavior of the central wavelength, before and after the 35 kN load (see Fig. 6). The stabilization occurs after the 35 kN load where the FBG embedded sensitive coefficient is describe by a second degree polynomial (see Table 2 and Fig. 7). Result similar with the ones report in the articles [7]. The justification for this behavior can be due to the internal adaptation of the FBG sensor in the host material, with possible closure of voids in the bone cement.

3. Results and discussion

The sensing capability of a material layer, using embedded sensors, requires acknowledgement of the host material and the sensor material properties, the interface resistance that depends on embedment conditions, and the external solicitations. Numerical simulations together with experimental data can be used to establish an *in situ* calibration.

In this work, three solicitations presented on the complex environment that bone cement is subjected in a cemented implant (temperature variation, compression and tensile stress) were assessed. The understanding of correlations between solicitations and changes in the reflected FBG spectrums will allow, in the future advances, to analyze more complex environments and build the so expected smart bone implants.

The parameters measured with this sensor for strain variation $\Delta\varepsilon$ in longitudinal direction of FBG was 1.7 pm/με. In fact this results show a high linearity as was expected. Nevertheless, the bone cement sample reflects its weakness to tensile in part by the presence of voids, one of the many causes of implant loosening.

The radial solicitation of the FBG sensor for the applied load in this application had a sensitive coefficient of $-(5{,}4739E^{-2}x - 4{,}01)x$ pm/kN. The compression result report a quadratic relation with the applied load, several reasons can be explicit in these results, like the adjustment of both materials to each other, voids presence or heaven the fact that the radial solicitation is not the most sensible in the FBG sensors.

Relatively to the temperature, the FBG sensor reports a thermal expansion of 138.75 pm/°C, this value associates three different phenomena: thermal expansion of bone cement and the glass from the fiber, one value is approximately 13% of the other, and the temperature variation ΔT.

This study allows establish a calibration scheme that later, in *in vitro* tests, allow to split a global result in elementary ones, according to the relative position of the sensor in the prosthesis (see Fig. 1). This study shows that optical fiber sensors are an interesting alternative measuring technique for an *in situ* characterization of these types of biomaterials.

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