Simplified sensor design for temperature-strain discrimination using Fiber Bragg Gratings embedded in laminated composites

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ABSTRACT

Several easy-to-manufacture designs based on a pair of Fiber Bragg Gratings structure embedded in Carbon Fiber Reinforced Plastic (CFRP) have been explored. These smart composites can be used for strain and temperature discrimination. A Finite Elements Analysis and Matlab software were used to study the mechanical responses and its optical behaviors. The results exhibited different sensitivity and using a matrix method it is possible to compensate the thermal drift in a real application keeping a simple manufacture process.

Keywords: Fiber Bragg Grating, Smart materials, Carbon Fiber Reinforced Plastic, Finite Element Analysis

1. INTRODUCTION

Optical fiber sensors have been proved as a very reliable technology to measure many different parameters of advanced structures. Particularly, Fiber Bragg Gratings (FBGs) have been widely employed to obtain strain and temperature measurements in different scenarios [1]. Due to the cross sensitivity to temperature, strain sensitivity can also introduce certain errors when just this parameter has to be considered. In the literature, several works for simultaneous measurement of strain and temperature were explored such as: different types of FBGs [2], superstructure gratings [3], reversed index gratings [4] or even FBG printed in special optical fibers like Bowtie [5] or microstructured [6].

Since the emergence of the composite materials, FBGs have been proved as a highly compatible technology applicable to measure the mechanical response of a hosting structure [7]. Several attempts stand out in this field to monitor the manufacturing process and even to obtain usable data while the structure is under operation. However, when working with FBGs, the temperature compensation step is always required to achieve high precision and resolution. There are several works that obtain the strain and the temperature parameters using highly compatible technologies such as embedding a pair of FBGs in composites with different number of layers [8] or varying the kind of composite material [9]. These solutions create different responses when strain and/or temperature are applied. However, the proposed solutions rely on different thickness or materials during the manufacture of the sensor head which can be a problem during the sensor installation (i.e. embodiment or reinforcement).

In this work, some designs are proposed to obtain different strain responses within a carbon fiber composite plate with the same thickness. These plates are instrumented with pairs of FBGs that respond differently to strain and keep the same thermal sensitivity in the same host material and thickness. The different strain slope between the FBGs allows discriminating both contributions of each perturbation. Three alternative designs have been simulated both mechanically and optically taking into account their complexity to be manufactured.

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2. PROPOSED DESIGNS

The goal of the designed plates is to obtain a different sensitivity between two section areas where the FBGs are located to allow discrimination between the strain measurements. Since the host material is the same for both FBGs (i.e. Carbon Fiber Reinforced Plastic, CFRP) their thermal sensitivities are similar but their responses to strain are given by the plate shape.

To keep the quality of the sensing head, the strain profile to which the FBG is subjected in the plate area should be uniform and the FBG spectral response is maintained constant. However, this requirement is difficult to achieve in the designs where different strain sensitivities are also required so, a strain profile can be just considered uniform within a deformation range. All the proposed designs are based on a 4-layer plate of unidirectional carbon fiber reinforced plastic. The designs have been simulated using the Abaqus Finite Element Analysis software (Dassault Systèmes Inc.) and are described in the next section.

2.1 Holed plate

The first geometry is a rectangular plate with two small holes drilled close to the right FBG to increase the strain response in this section area. The two holes are symmetrically located with respect to the FBG guarantying a higher deformation within the area. To a given distance between the holes (D), there is an ideal diameter that creates a practically flat deformation in the central area. A simulated plate of 150 mm by 30 mm with two holes of d=5 mm diameter distanced D=11 mm is showed in the figure 1.

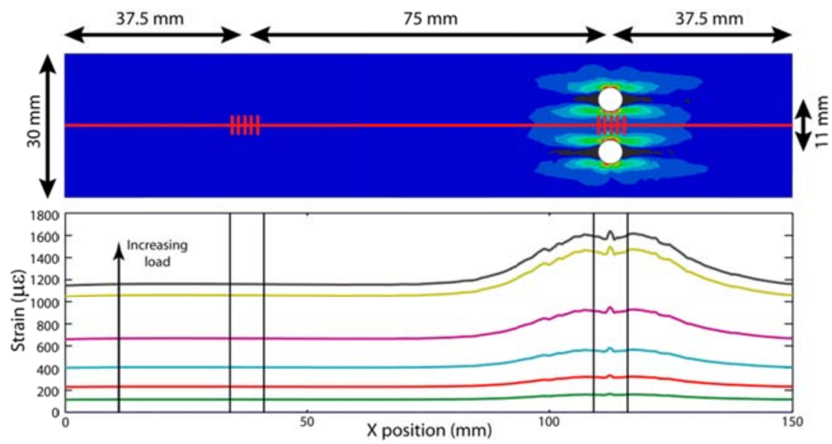

Figure 1.Strain distribution over the plate surface and plate dimensions (up). Strain profile along the axial direction for different applied loads (down). The holes close to the FBG increase the strain sensitivity.

It is a simple design, starting from a rectangular shaped plate, two small holes are just required to achieve different strain sensitivities. However, the position of the holes is a critical point because some misalignments during the drilling process will generate a non-uniform strain distribution within the FBG length, limiting the maximum allowable deformation.

2.2 Triangular plate

The plate is manufactured with a triangular shape, decreasing the plate width as the length increases. This reduction creates different strain sensitivities for each plate section area, being the highest at the narrower section. The sensitivity variation relays in the stress redistribution from a narrower to a wider section but this process is driven by the material response and limits the width gradient. For a given material and plate length, there is a maximum useful width difference. The simulated plate length is also 150 mm and its width has been decreased from 30 mm to 10 mm as shown in Fig. 2.

This design overcomes the aligning problems during the drilling stage of the holed plate, however the manufacturing process of the starting plate (triangular shaped) is more complex. Another possible drawback is the increasing strain sensitivity within the entire plate length, that will never allow an uniform FBG strain profile, however the achieved flatness is enough for most of real applications.

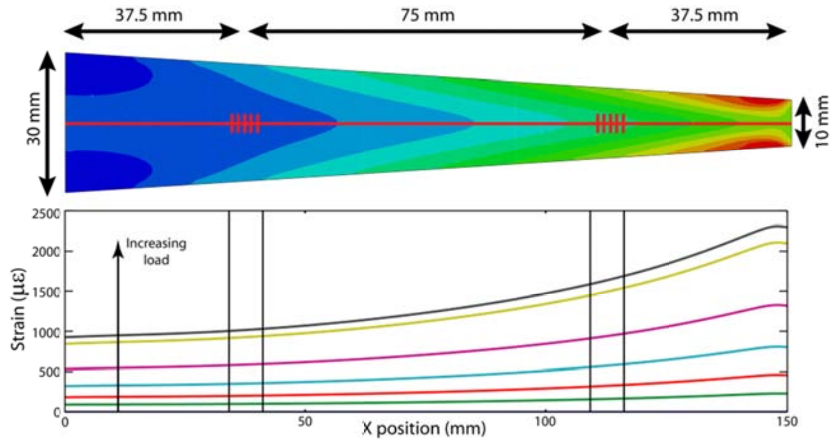

Figure 2.Strain distribution over the plate surface and plate dimensions (up). Strain profile along the axial direction for different applied loads (down). The FBGs positions are also depicted.

2.3 Chamfered plate

Two sections with different width are joined through a triangular chamfer. The chamfer helps the stress redistribution between sections allowing a greater difference between the strain sensitivity of each section. As happens in the triangular design, there is a maximum allowable gradient to take advantage of the width reduction. A simulated chamfered plate of 150 mm length with a width decrease from 30 mm to 10 mm is depicted in Fig. 3.

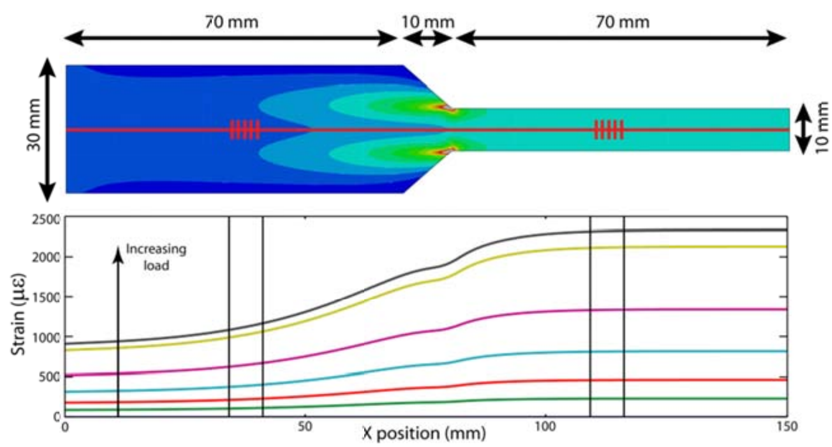

Figure 3.Strain distribution over the plate surface and plate dimensions (up). Strain profile along the axial direction for different applied loads (down). The FBGs position is also depicted.

This design keeps the properties of the triangular plate from the manufacturing point of view: the fiber alignment is not a critical issue but the lay-up process can be more complex. Different strain sensitivity is obtained due to the different width sections created by this design. The difference is improved by the inclusion of the chamfer that helps the stress redistribution from the narrower to the wider section. As the two sections have constant widths, the deformation applied to the FBGs is flatter than in the triangular design, improving the sensor's dynamic range.

3. STRAIN ANALYSIS

The strain profiles are used to calculate the simulation of the spectral response of two uniform FBGs embedded in the middle of the CFRP plates. The spectral response of each FBG is calculated using the T-Matrix method implemented over the Matlab platform. All of the simulated FBGs have a total length of L=7 mm and their deformation profiles are applied with a spatial resolution of ΔL=0.15 mm. The achieved peak drifts for each plate are showed in Fig. 4.

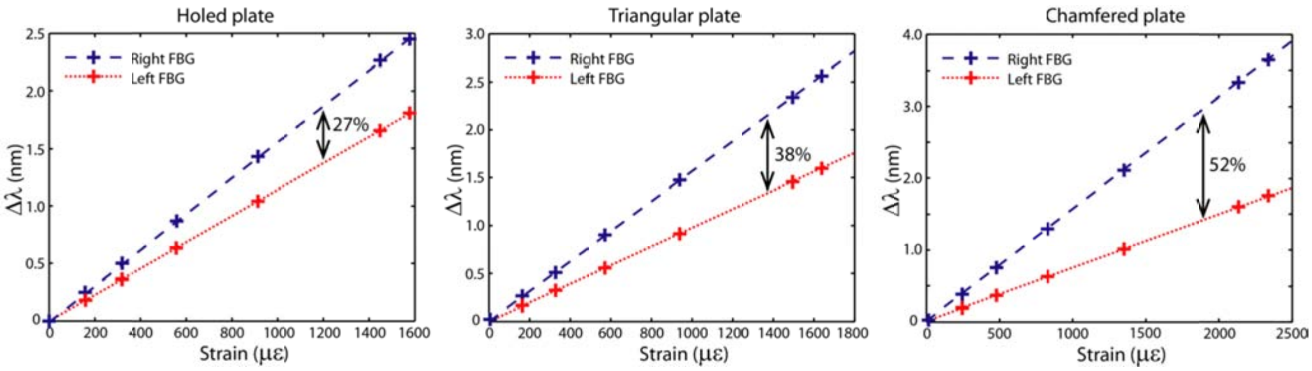

Figure 4. Simulated wavelength drift of the FBG pairs of each design: holed (left), triangular (center) and chamfered (right).

In order to obtain accurate measurements of the strain-temperature discrimination, the difference of the sensitivities between the strain parameter in the same composite plate should be as high as possible [9]. The difference between the strain slopes of each FBG pair is showed over the peaks drift in Fig. 4 being the lowest in the holed plate (~27%) followed by the triangular design (~38%) and achieving the highest for the chamfered design (~52%). These three values are good enough for the discrimination [9]. For the temperature measurements, similar responses for all FBGs are expected with sensitivities ~12 pm/ºC [10].

4. CONCLUSIONS

In this work, several designs have been simulated both mechanically and optically trying to obtain CFRP plates capable of measuring simultaneously strain and temperature when instrumented with FBGs. Three different geometries, based on constant thickness carbon laminates, have been optimized to exhibit two different strain sensitivities in the areas where the FBGs are located. The results show very different strain sensitivities (above 50% of difference) using relatively simple designs, being suitable to solve the strain-temperature discrimination problem. Several plates have been manufactured following this guideline and the experimental results will be detailed in the conference.

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