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Evaluation of bending strain measurements in a composite sailboat bowsprit with embedded fibre Bragg gratings

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A B S T R A C T

Acrylate-coated Fibre Bragg Gratings (FBGs) were embedded in a sailing boat bowsprit tubular section manufactured using the vacuum bagging process in autoclave with the aim of measuring strains under realistic loading conditions. In order to establish an effective procedure for sensor integration, flat tensile specimens with embedded sensors were firstly produced under different processing conditions, using advanced composite material employed in the marine industry. Information obtained in this way was used to manufacture a sailboat bowsprit with an array of gratings embedded between the last inner plies. In order to assess the sensitivity and accuracy of the embedded sensors, the bowsprit was subjected to bending tests and the results were compared to analytical values and to data obtained from electrical strain gages. Results are very encouraging but reveal that great attention must be paid both to the integration process and to the *in situ* calibration of the embedded sensors.

1. Introduction

Composite materials, especially CFRP laminates, are currently widely used for the construction of light, durable and strong structures in many fields of application. Due however to the complexity of modelling and therefore predicting their mechanical behaviour, they call for efficient and reliable monitoring systems in order to improve structural design, maintenance and therefore performance and safety issues [1,2].

In recent years, optical fibre sensors have shown great potential for the in-service monitoring of different mechanical parameters, by virtue for example of their light weight, durability and insensitivity to electromagnetic interference. Furthermore, they are suitable for integration into fibrous composite materials especially due to their small dimensions.

As far as the detection of surface or internal strains in composites are concerned, Fibre Bragg Gratings (FBGs) are the most used optical fibre sensors, but their performance can actually be affected by the embedding process and the presence of the surrounding material. Therefore it has to be accurately evaluated. Indeed, when integrating fibre Bragg grating sensors into a fibre-based composite, the manufacturing process actually introduces a number of issues due to the mechanical and thermal stresses which may damage the sensors or alter their performances [3,4]. For example, optical losses due to the locally concentrated and distributed stresses along the embedded fibres [5] may decrease the signal-to-noise ratio to values that may be critical when long measurement distances are involved, such as in the case of large structures. Also, residual stresses may generate birefringence effect and peak splitting in the Bragg spectrum of the embedded sensors [4]. Furthermore, strain gradients can occur in the structure and

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therefore along the grating length, affecting the frequency width and the determination of the wavelength shift. This is the case, for example, of structures subjected to bending load [6].

This paper intends to investigate these critical issues through the manufacturing of composite tensile specimens with embedded FBG and of a typical nautical structure, i.e. a bowsprit with an embedded FBG array, subjected to bending load. In particular, results from previous investigation [7] on the manufacturing process through the vacuum bagging technique in autoclave to produce tensile specimens made of advanced composite material and with embedded FBG sensors are presented, expanded and discussed with respect to the optical losses introduced for example by microbending [8] and the possible existence of residual transverse stress causing deformation of the Bragg spectra [3,9]. Unlikely what was usually done, i.e. to employ an Optical Spectrum Analyser (OSA) (see [8] for example), optical losses were evaluated using both the OTDR (Optical Time Domain Reflectometry) and the OLCR (Optical Low Coherence Reflectometry) techniques which are powerful methods to determine the spatial distribution of both the losses and the return losses with high resolution. Furthermore, investigation on the specimens during both tensile and three-point bending tests was carried out to evaluate the strain transfer after embedding, which can actually be critical [3,6].

Results from tensile specimens, especially for what concerns the manufacturing process parameters, are then exploited to produce a bowsprit with embedded arrays of FBGs. The OTDR technique is used again to evaluate optical losses and possible spectra deformation. Bending tests are finally performed in order to assess the strain transfer by using both analytical and experimental reference data from electrical strain gages and therefore the correct the value of the calibration factor needed to perform correct measurements with embedded FBGs in bending load condition.

The work was carried out in close collaboration with Riba Composites, an Italian well-established company manufacturing advanced composite structures for the marine, automotive and aerospace industry applications and Sestosensor srl, an Italian SME with relevant expertise in optical fibre sensors development for the civil sector, with the aim of verifying the effectiveness of using optical fibres for reliable strain monitoring of composite structures produced in the industrial environment.

2. Materials and methods

2.1. Tensile specimens

In order to study the effect of the industrial production process and parameters on the embedding of fibre Bragg gratings, firstly tensile specimens were produced and tested (see Fig. 1). Different CFRP laminates were manufactured in autoclave by means of the vacuum bag technique at two different temperatures (90 °C and 120 °C) and at a pressure of 3 bar. Before curing, the specimens were instrumented with fibre Bragg gratings with two different coatings (acrylate and polyimide), placed on the specimen surface or embedded. Traditional electrical strain gages were surface-mounted on the specimens and used as a reference for comparison. More details on the specimens manufacturing are reported in [7].

Acrylate-coated sensors failed at 120 °C, while polyimide-coated gratings were able to withstand the highest temperature. Moreover, special technological solutions were needed in order to protect the fibre ingress–egress points in the material, also bearing in mind that the fibre may break outside the laminate as well, at the interface between the special Sterling sleeve or the PTFE foil used to protect the fibre and the fibre itself. After manufacturing, the Bragg spectra of the gratings where checked for possible distortion using an optical spectrum analyser and the optical losses inside the fibres and the sensors were measured with high spatial and spectral resolution by the Optical Low-Coherence Reflectometry (OLCR) technique. Finally, the specimens were subjected both to tensile and three-point bending tests.

2.2. Bowsprit

Following the manufacturing and testing of the small specimens, information obtained on the embedding process and sensor performance was used to produce a composite bowsprit, i.e. the pole extending forward from the boat's prow, usually providing support for the jib or the gennaker. The composite material used for the manufacturing of the bowsprit in autoclave was a GG630T-DT120-37 pre-preg of 600 g/mm^2 density and the fabric type a Toray T700 type with 2 × 2 twill weave. The bowsprit had a 100 mm × 80mm rectangular hollow cross-section of 4.6 mm width and was 2 m long.

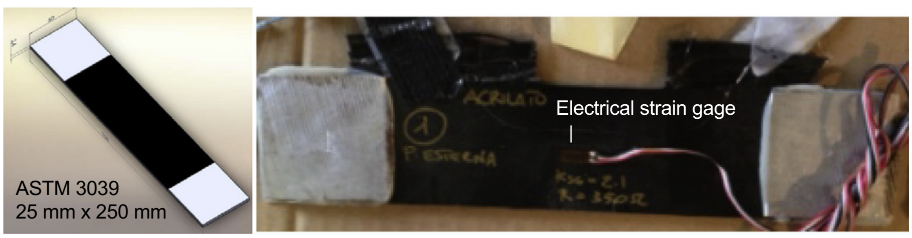

Fig. 1. Example of composite tensile specimen manufactured according to the ASTM 3039 standard, with embedded fibre Bragg grating and surface-mounted electrical strain gage.