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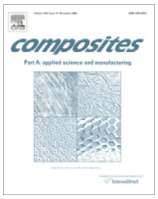

Investigation of process-induced strains development by fibre Bragg grating sensors in resin transfer moulded composites ☆

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ABSTRACT

A comprehensive understanding of the development of residual strains in composite processing is essential to manufacture high quality composite parts. In this paper, the use of fibre Bragg grating (FBG) optical sensors was investigated to measure in situ the build-up of the process-induced strains in composite panels manufactured by resin transfer moulding. The FBG sensors, embedded in the composite laminate, successfully measured the evolution of the composite in-plane strains due to the temperature history. The sensors also captured a strain discontinuity during the cool-down related to the debonding of the composite from the mould. Finite element models were then proposed to simulate the strain development measured by the FBG sensors. Three different contact interactions between the tool and the laminate were investigated: no bonding, perfect bonding and frictional contact. The model using the frictional contact interaction described well the evolution of the measured strains.

1. Introduction

The development of residual strains and stresses are one of the major issues while manufacturing composite structures as they can lead to strength reduction, cracks and delamination, and dimensional variability such as spring-in, warpage or thickness variation. Over the last decade, several researchers investigated experimentally and numerically the factors leading to the development of residual stress and their effects on dimensional stability [1–12]. The dominant factors are thermal strain, volumetric chemical shrinkage and tool–part interaction. In order to measure experimentally the strain development throughout the cure cycle in a composite laminate, strain gages are generally used [10,13]. However, embedding strain gages into the composite laminate can be difficult and they are therefore usually mounted on the tool surface. Alternatively, fibre optic sensors appear to be an interesting method to measure the development of the residual strains in situ during composite manufacturing [12,14–21]. Their advantage over strain gages is that they can be easily integrated into the composite at the preforming stage of the manufacturing. Small and non intrusive, they also have a minimal impact on the mechanical properties of the composite. They are also applied to monitor the cure and control the manufacturing process [17,18,22] as well as to measure the material transitions (gel point, glass transition) [16]. Different types of fibre optic sensors are used, such as fibre Bragg grating (FBG) sensors [12,15,16,20,21], extrinsic Fabry–Perot interferometric (EFPI) sensors [14,17,19,22] or FBG/EFPI hybrid sensors [18]. Fibre optic sensors have been successfully used in hot press and autoclave processing for cure and strain monitoring [12,14,17,18,20,22], however few studies demonstrated their potential in liquid moulding process [23].

In this study, FBG sensors were used to measure the development of internal strain in a composite laminate manufactured by Resin Transfer Moulding (RTM), as the cure progresses. The effect of the cure cycle on the internal strains was investigated. The measured strains were then compared to finite element analyses modelling the RTM process. The effect of the tool–part interaction was examined using different boundary conditions at the composite/mould interface and correlated to experimental observations.

2. Fibre Bragg grating sensor principle

A fibre Bragg grating sensor is an optical fibre with a periodic modification of the core refractive index along a small segment of the fibre. A phase mask technique is commonly used to imprint the periodic pattern to the optical fibre. This technique uses the optical fibre photosensitivity property: by exposing an optical fibre under ultraviolet light, the refractive index of its core can be modified permanently. Then, when a broad-band source of light

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is connected to the optical fibre containing the FBG sensor, a narrow-band of the light is reflected back around the Bragg wavelength λ_B, given by [24]:

$$\lambda_B = 2n\Lambda_B \tag{1}$$

where n is the effective refractive index of the core and Λ_B is the grating period.

Any change in the optical fibre properties which varies the grating period or the refractive index, such as strain or temperature variations, will then modify the Bragg wavelength. The Bragg wavelength shift $\Delta\lambda_B$ can be related to the applied strain ε_{app}, and temperature T as follows:

$$\frac{\Delta\lambda_B}{\lambda_{B0}} = \{1 + p_e\}\Delta\varepsilon_{app} + \{\alpha_f + \xi\}\Delta T = K_\varepsilon\Delta\varepsilon_{app} + K_T\Delta T \tag{2}$$

where K_ε and K_T are the strain and temperature sensitivities of the optical sensor, p_e is the strain-optic coefficient, α_f is the fibre's coefficient of thermal expansion (CTE) and ξ is the fibre thermo-optic coefficient.

When the FBG optic sensor is embedded in a host structure made of a different material, such as a composite laminate, the thermal strain of the host structure can influence the response of the FBG sensor, assuming a perfectly bonded interface between the two. In a first approximation, Eq. (2) can be then modified as follows [12]:

$$\frac{\Delta\lambda_B}{\lambda_{B0}} = K_s[\Delta\varepsilon_{app} + \Delta\varepsilon_{th}] + \xi\Delta T = K_\varepsilon\Delta\varepsilon_{tot} + \xi\Delta T \tag{3}$$

where $\Delta\varepsilon_{tot}$ is the total strain transferred to the optical fibre, including the effect of the applied strain and the thermal strain. Assuming that the CTE of the optical fibre is small compare to the CTE of the host material, $\Delta\varepsilon_{th}$ can be expressed in the following manner:

$$\Delta\varepsilon_{th} = \alpha_H\Delta T \tag{4}$$

where α_H is the coefficient of thermal expansion of the host material.

The FBG sensors used in this study were provided by Technica SA. Their initial wavelength was 1562 ± 0.5 nm with a bandwidth less than 0.3 nm. The FBG strain sensitivity K_ε, the temperature sensitivity K_T and the thermo-optic coefficient ξ were calibrated experimentally [25], and their values were found to be $K_\varepsilon = 7.7 \times 10^{-7}\ \mu\varepsilon^{-1}$, $K_T = 6.92 \times 10^{-6}\ {}^\circ\mathrm{C}^{-1}$ and $\xi = 6.1 \times 10^{-6}\ {}^\circ\mathrm{C}^{-1}$. Once the fibre optic sensor is embedded into the laminate, its strain and temperature sensitivities can be modified due to the influence of the host's transverse strain and the host's thermal expansion. From [26], it was demonstrated that no coupling or a negligible coupling occurred between the host strain and the fibre transverse strain when the fibre coating modulus was inferior to 1 GPa and the host thickness and the embedment length were large. In the RTM experiment carried out, the laminate had large dimensions and the non-coated FBG sensor was assumed to be surrounded by a thin layer of resin. From a previous study on the epoxy resin characterization [27], it was observed that the resin modulus remained below 1 GPa during most of the entire cure and reached a maximum of 3.2 GPa at the end of the process. The relative error between the strain sensitivity with and without strain coupling was then determined to be inferior to 5% at the end of the cool down. Thus, in this study, the strain sensitivity was assumed to remain constant after the embedment of the fibre optic sensor. In order to avoid the dependence of the temperature sensitivity from the host thermal expansion, the fibre thermo-optic coefficient was used in Eq. (3).

3. RTM procedure

Radial injections were carried out at constant pressure in a rectangular steel mould to manufacture carbon/epoxy laminates with a 50% fibre volume fraction and the following dimensions: 34.5 cm × 24.5 cm × 0.2 cm. Six heating cartridges on each side of the mould (top and bottom) were used to apply the desired cure cycle. The mould surfaces were treated with release agent (Frekote 770-NC) and flexible silicone joints were used to seal the mould. Five plies of 5-harness satin G30-500 6k carbon fabric [28,29] were stacked with the following layup [(0/90)(90/0)(0/90)(0/90)(90/0)]. The preform was debulked 30 min under vacuum to remove the eventual entrapped air. Once the preform was placed into the mould, the mould was closed and the system was preheated at 180 °C prior to the resin injection. The CYCOM 890RTM one-part epoxy resin [30] was preheated at 80 °C in the injector to reach its optimal viscosity and injected in the mould with an injection pressure of 0.35 MPa.

Two different cure cycles were applied:

- *Cure cycle 1*: 2 h isotherm at 180 °C followed by a cool down by natural convection (CYCOM 890RTM epoxy typical cure cycle).
- *Cure cycle 2*: two holds cure cycle, 2 h at 170 °C followed by 30 min at 190 °C and then cooled down by natural convection.

Two plates were manufactured for each cycle.

For each laminate, three FBG sensors were positioned as shown in Fig. 1, through the thickness of the laminate, at the bottom surface, middle and top surface. Small incisions were performed on the flexible silicone joints in order to allow the optic fibres to exit the mould while keeping the mould sealed. The variation of the FBG wavelength λ_B during the entire cure was monitored by an optical sensing interrogator sm125–500, from Micron Optics, with a quasi un-polarized light source. The use of quasi un-polarized light source permits to strongly reduce the measurement error due to strain-induced birefringence [12]. Previous studies reported a decrease in the fibre optic wavelength followed by a stabilisation while ramping up the temperature [31]. Hence, in order to assure the thermal stability of the Bragg wavelength with temperature during the RTM experiment, a preconditioning or thermal annealing of the sensors was first performed. It consists of heating the FBG sensor in an oven at an elevated temperature to accelerate the wavelength decay phenomenon and reach the stabilized Bragg wavelength. As the curing temperature of the composite part was 180 °C, the FBG sensors were preconditioned 24 h at 200 °C in an oven before use. The initial optical fibre wavelength, λ_{B0}, was then recorded prior to embedding the sensor in the laminate. A type K thermocouple was also placed in the mould cavity to monitor the temperature of the composite part inside the mould. The thermocouple was guided outside the mould through the silicone joints.

After cure, the laminates were placed in an oven and subjected to a set of 15 min isotherms at 35 °C, 50 °C, and 70 °C with 1 °C/min temperature ramp in between. Using the FBG sensor already embedded in the laminate, the strain variation was measured during these particular conditions in order to determine the coefficient of thermal expansion of the cured laminate.

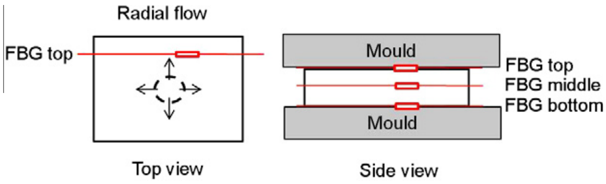

Fig. 1. FBG sensors position in the laminate.