COMPARING FLOW-FRONT PROPAGATION SENSED BY FBGS WITH PAM-RTM SIMULATION

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ABSTRACT: This study is part of a larger project, in which the potential of fibre Bragg grating sensors for monitoring liquid composite moulding processes is deeper investigated. In an earlier study, experimental data was obtained for preform compaction and flow-front propagation [1]. By then, the question arose whether Bragg response could be related to process parameters such as pressure. In that sense, a study was started that had the main objective to relate the Bragg response to simulation results from PAM-RTM. As an intermediate step, the Bragg responses were compared to the local change in preform thickness measured by a three-dimensional contactless and full-field measuring technique. Process points such as resin arrival, increase in pressure, and inlet closing were identified. Establishing a relation was however difficult. For the simulations, it turned out that, although several models were developed describing material characteristics, a 'dry-wet compressibility model' was certainly needed to address the lubrication effect causing compaction of the preform just after resin arrival. This part was therefore left for future work.

KEYWORDS: flow sensing, fibre Bragg grating, PAM-RTM, vacuum infusion, 3D camera system

INTRODUCTION

To gain a better understanding of the sensing capabilities of fibre Bragg grating (FBG) sensors, a step-by-step approach has been adopted to investigate the influence of each stage in the liquid composite moulding process. In Ref. 1 the influence of preform compaction and flow-front propagation on the Bragg response were already discussed. In both types of experiments a vacuum infusion set-up was used. Preform compaction was achieved by applying vacuum at different levels, whereas flow-front propagation of a resin system was imitated by a test fluid, an aqueous glycerine solution. Both steps were clearly distinguishable in the Bragg response. Although preform compaction seemed to have a rather randomness behaviour, a trend was clearly observed in the flow-front propagation experiments.

In this study, a closer look is taken on the response of FBGs to flow-front propagation. It was the intention to compare experimental results, obtained from embedded FBG sensors in vacuum infused thin glass fibre reinforced (GFR) laminates, to the output of a commercial-on-the-shelf simulation tool called PAM-RTM 2008 [2]. To support the correlation, a three-dimensional contactless and full-field measuring technique, called LIMESS Vic3D, Limess Messtechnik & Software GmbH (ref. 3), supplied information about the instantaneous thickness of the infused preform.

THEORETICAL BACKGROUND

Due to the presence of a fluid and thus a fluid pressure, the compaction pressure in a saturated preform changes locally. At the inlet the fluid pressure is at ambient conditions, whereas the fluid pressure equals the applied vacuum at the flow-front. As soon as the flow-front passes the total pressure at a local point changes according to the simplified rule: compaction pressure = atmospheric pressure – inside pressure [4]. While the flow-front propagates, the local compaction pressure changes constantly because of the increasing fluid pressure. This affects automatically the thickness of the preform (i.e., the preform expands/contracts).

Fibre optics with FBG sensors, which are illuminated by a broadband spectrum light, reflect a narrow-band optical signal. The reflected peak wavelength, λ_B, is a function of the effective refractive index and the grating period. Strain and thermal effects that modify these geometric and physical properties are monitored by the shift in peak wavelength. Using strain and thermal sensitivities, S_ε and S_T, the Bragg response can be represented by the following expression:

$$\frac{\partial \lambda_B}{\lambda_B} = S_\varepsilon \Delta\varepsilon + S_T \Delta T \tag{1}$$

where ε and T are strain and temperature, respectively. Deformation of the preform due to flow-front propagation may thus be monitored with FBG sensors.

EXPERIMENTAL WORK AND SIMULATION

Materials and embedded sensors

In this investigation, a bicomponent thermosetting resin system (EP04908 supplied by Hexion™ Specialty Chemicals, Germany) and an 8-harness satin weave E-glass fabric (Hexforce® G-300-7581-Z6040 supplied by Hexcel, France) were selected. Low processing temperatures and extended pot life at room temperature were the main characteristics of this resin system. After mixing properly, the epoxy-amine resin system was degassed for at least 30 minutes prior to infusion. The fabric was fine woven and had a dry fabric weight of 303 g/m^2. In each experiment eight plies with dimensions of 300 mm x 200 mm were carefully and symmetrically stacked (i.e., $(0/90)_{4s}$) resulting in a thickness of ~2 mm. The fibre optics, which were embedded between the fourth and fifth ply (i.e., on the neutral line of the laminate), had two 4 mm uniform FBG sensors and were delivered by FOS&S, Belgium. The Bragg wavelengths were in the range of 1540 nm to 1550 nm. Each fibre optic was protected by an Ormocer® coating that resulted in an outer diameter of 195 μm. Each FBG sensor was accompanied by a K-type thermocouple for recording temperature locally.

Experimental set-up and procedure

In Fig. 1 the experimental set-up is shown together with the LIMESS Vic3D camera system (including the lamps). Not shown in this figure, but definitely important, are: (1) the resin pot, (2) the resin trap and vacuum pump, (3) the FBG interrogator (FOS&S, Belgium), (4) DAQ unit for the thermocouples (Keithley, USA), and (5) two standard

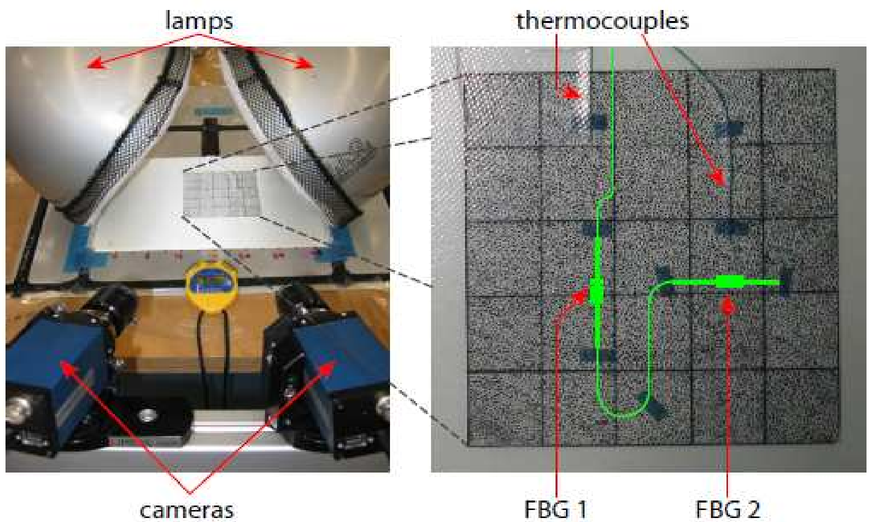

Figure 1. LHS: Experimental set-up, RHS: grid with stochastic pattern and position of sensors (path of fibre optic is highlighted in green) (right-hand side)

desktop PCs with installed software packages. On the top-side of the vacuum bag a grid (100 mm x 100 mm) was introduced that had a stochastic pattern. After performing calibrations, the LIMESS Vic3D camera system captured two images every 10 seconds. Using the software, a 3D representation of this grid was created that allowed for measuring relative changes in preform thickness.

The line infusion (from right to left in Fig. 1) was performed at an absolute pressure level of 50 mbar (step 1). When fully impregnated and flushed for a while, the pressure was raised to 500 mbar (step 2). Secondary flushing took about 1-2 hrs before the inlet was clamped (step 3). The measurement continued for a while after this. Resin curing and its effect on preform thickness and Bragg response were not monitored.

Simulation

PAM-RTM 2008, a software package developed by the ESI Group, was used for simulating the resin flow. For the vacuum infusion process, the VARI module was selected because of the interaction between compaction pressure and fluid pressure that caused the preform thickness to change. For this purpose, experimental data was already gathered on permeability, compressibility and natural thickness of dry fabric, and resin's viscosity. The preform was represented by a flat surface (300 mm x 200 mm) with two groups of nodes representing the inlet and vent. The ambient pressure was set to 1012 mbar and the resistance of the inlet tube was neglected.

RESULTS AND DISCUSSION

A series of experiments have been performed, in which FBGs were placed parallel and/or perpendicular to the flow-front. The following discussion highlights the results for the experiment shown in Fig. 1 (FBG 1 and FBG 2 were placed perpendicular and parallel, respectively). In Fig. 2 the flow-front and change in thickness ($w = \Delta H = H - H_0$) are shown as a function of time. For the latter, the average was taken for three points (marked with 'o' in surface plot), which were close to the FBGs (marked with 'X').

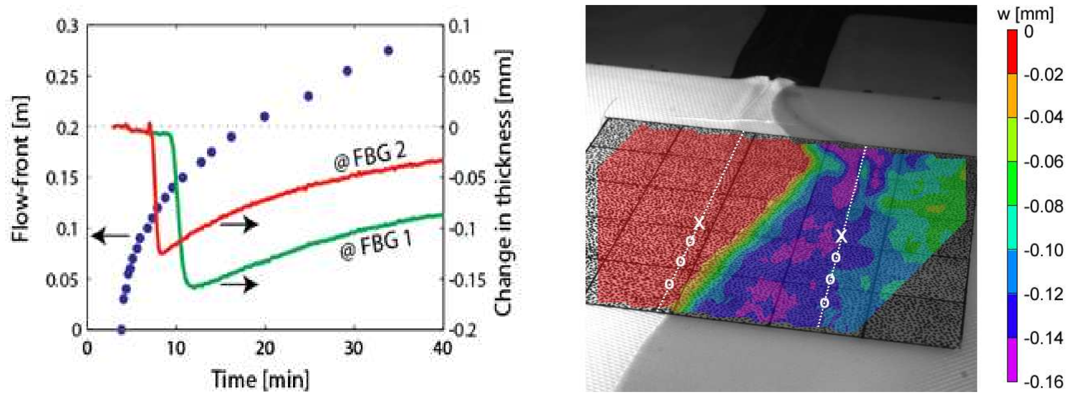

Figure 2. LHS: average position of flow-front and change in thickness close to FBGs, RHS: surface plot of change in thickness at t = 9.33 min

The preform was impregnated in 38 minutes, but another 47 minutes were needed to fill the vent tube before increasing the pressure to 500 mbar, which resulted therefore in a gross time of 85 minutes for step 1. Upon resin arrival, the preform showed a steep decrease in thickness before it was followed by expansion due to the loss of compaction pressure (Fig. 2). The decrease was caused by the lubrication effect [4] and was significantly (e.g., @ FBG 1 about 0.15mm for an initial preform thickness of ~2 mm).

The Bragg responses ($\Delta\lambda_B/\lambda_B$) are shown in Fig. 3. For the initial part, in which the resin arrived and the thickness of the preform decreased rapidly due to the lubrication effect, the FBG responded steeply but randomly. Based also on other experiments, the conclusion was drawn that this behaviour could not be related to the orientation of the FBG sensor. However, it may still be used as an indicator of flow-front arrival. Also the moments of increase in pressure and inlet closing, at 85 and 184 minutes respectively, were traced back in the Bragg response. For FBG 2 a trend was observed for steps 2 and 3: a decrease in preform thickness led to an increase in Bragg response. When correlating (not shown here), an almost linear behaviour was obtained, which indicated that the response was dictated by the deformation of the preform. This was also observed in other experiments, but for some Bragg responses this observation did not always hold (see for instance the Bragg response of FBG 1).

Since lubrication caused significant preform compaction just after the flow-front had passed and the FBGs responded sharply to this, it was important to perform simulations using a 'dry-wet compressibility model', which addressed this lubrication effect [4]. Unfortunately, this type of model was not yet implemented in this version of

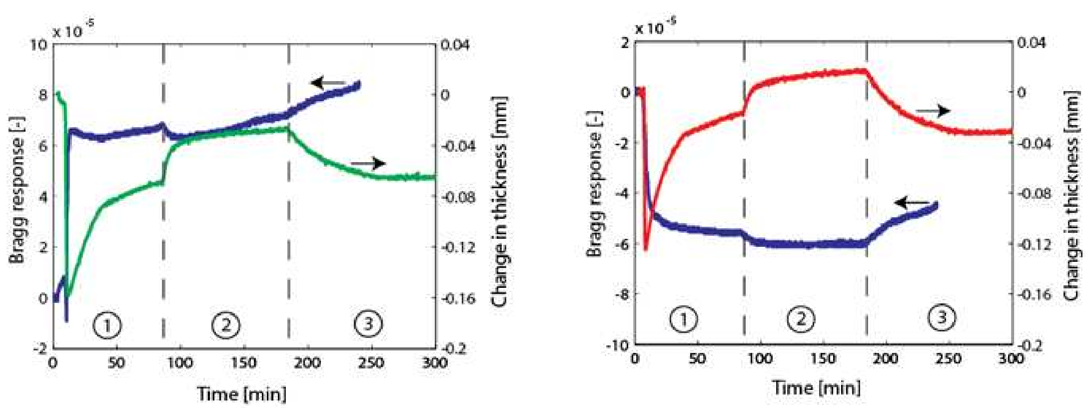

Figure 3. Bragg responses and changes in thickness for FBG 1 (LHS) and FBG 2 (RHS)

PAM-RTM. Furthermore, the simulation automatically stopped when all elements were filled. This means that subsequent increasing of pressure to 500 mbar and inlet closing, for which changes in preform thickness occurred, could not be incorporated. These shortcomings forced the correlation of the Bragg response to simulated pressure to be part of future work.

CONCLUSION AND FUTURE WORK

Based on the preliminary results in this study the following is concluded:

- The VARI-module of PAM-RTM 2008 is not capable of simulating the complete infusion stage. Pressure changes and inlet closing after fully impregnation had to be excluded despite the fact that significant changes were observed in preform thickness and Bragg response.
- Initial wetting out of dry fabric resulted in a measurable compaction of the preform before it started to expand due to a decrease in compaction pressure. This phenomenon, linked to lubrication [4], cannot yet be simulated by the VARI-module of PAM-RTM 2008.
- FBGs responded unpredictably when flow-front passed. Main source: the relative movement of the fabric surrounding the fibre optic, which causes straining, depends on initial compaction conditions.
- Interesting points such as resin arrival, changing of pressure, and closing inlet can be traced back in the Bragg response. Qualitative information is limited.

Since it is an ongoing project, the following points may be addressed in the future:

- With the LIMESS Vic3D camera system an improved set of experimental data may be obtained, which may be used as a starting point for modification of the VARI-module such that changes in thickness of the preform are more accurately predicted.
- It will be interesting whether the LIMESS Vic3D camera system is also capable of monitoring the curing stage (i.e., measure the change in thickness due to resin shrinkage).

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